Characterizing Contaminated Sites in the San Francisco Bay Region and Their Exposure to Future Sea-Level Rise and Groundwater Flooding

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Executive Summary

Climate change-induced sea level rise is expected to push shallow, unconfined groundwater upwards in coastal areas. A preliminary study assessed the potential impacts of rising groundwater on contaminated sites around San Francisco Bay and found that more than 1,500 active contaminated sites are potentially exposed to inundation from below with a 1-meter sea level rise. Contaminants such as volatile organic compounds (VOCs), including benzene and tetrachloroethene (also known as perchloroethylene or PCE), can be mobilized and enter sand or gravel trenches and sewer pipes. If this occurs, liquid components can travel up to 685m downhill from the point of entry and 228m uphill, entering sewer laterals and infiltrating the indoor air of buildings. This form of indoor air pollution poses an imminent risk to public health and is not well understood or anticipated by most researchers, public policy leaders, and the public. Although metals are also of concern and can adversely affect Bay ecosystems and the health of individuals who consume fish or shellfish, metal contamination has been more extensively studied and is not currently associated with similarly unexpected or acute exposure pathways.

In this study, we focused on understanding and predicting the widespread potential for VOCs to spread from contaminated sites via utility trenches and sewer lines as sea level and groundwater rise. By prioritizing this contaminant, we seek to avoid new potential human exposures and new health risks before they occur. We developed a method to characterize the risk at contaminated sites where rising groundwater could mobilize volatile organic compounds (VOCs). Although not all important information about these types of sites is easily accessible, the method we developed uses key sources to characterize and categorize these sites for prioritization by public agencies or other shoreline stewards.

We worked closely with State-level staff at the California Department of Toxic Substances Control (DTSC) and the California State Water Resources Control Board (Water Board) to understand the feasibility of our method. Through that collaboration, we learned that the site managers at DTSC and the Water Board have more detailed information about each site that are not publicly accessible in a systematic way. Internal reporting systems would need to change to make those data available for a statewide prioritization of contaminated sites in relation to sea level rise. Our goal was to develop a method to support current state, regional, and city efforts to prioritize contaminated sites for further study and remediation to prevent new public health risks based on publicly available data. We conclude that sharing our methods with public agencies and the general public will advance this process. However, access to detailed site information will be needed as a second step to confirm the results of our sites' characterization.

Our method is designed to serve as a preliminary screening tool for the prioritization of contaminated sites exposed to rising and increasingly saline groundwater. We developed a list of 21 pilot sites for the study (Table 2.1 and Map 2.1) by selecting sites from Greenaction's "Ticking Time Bomb" report, which identifies contaminated sites containing VOCs that communities are concerned about in the San Francisco Bay Area. We used the best available science on future sea-level rise and groundwater projections to select sites that are within projected surface and below-surface inundation zones. We gathered site-specific information from databases such as GeoTracker, Envirostor, Baykeeper Shoreview, and the Environmental Protection Agency Facility Registry Service (in addition to other data sources) to better understand the risk of inundation, contaminant concentrations, site characteristics that influence contaminant mobility, social/demographic data that reflect the existing environmental health burdens on specific neighborhoods, and potential exposure pathways. We worked closely with our partners at Greenaction for Health and Environmental Justice to strengthen our approach through their feedback and by reporting to the SF Bay Shoreline Contamination Cleanup Coalition to seek additional input.

Because our method is flexible and disaggregated, users may wish to prioritize different aspects of our site characterization approach. We constructed a four-digit code that uses indexed scores from 1-9 to

represent ranges in criteria such as social vulnerability, contaminant toxicity, contaminant mobilization potential, and the potential for new exposure pathways (i.e., ways in which a person may come into contact with a contaminant, such as when a volatile chemical enters indoor air). The resulting four-digit code allows thresholds to be set at different levels of each index score that would indicate a high, medium, and low priority for further investigation and potential clean-up. For example, an index score of 7 in contaminant concentration could be used to represent a threshold in measured VOC concentration that merits concern. If the threshold is set higher or lower in each index score, or if certain index scores are weighted more heavily than others, a different number of sites would be prioritized. We concluded that this ability to screen different scores will be important in public policy discussions since site clean-up is a resource-limited process.

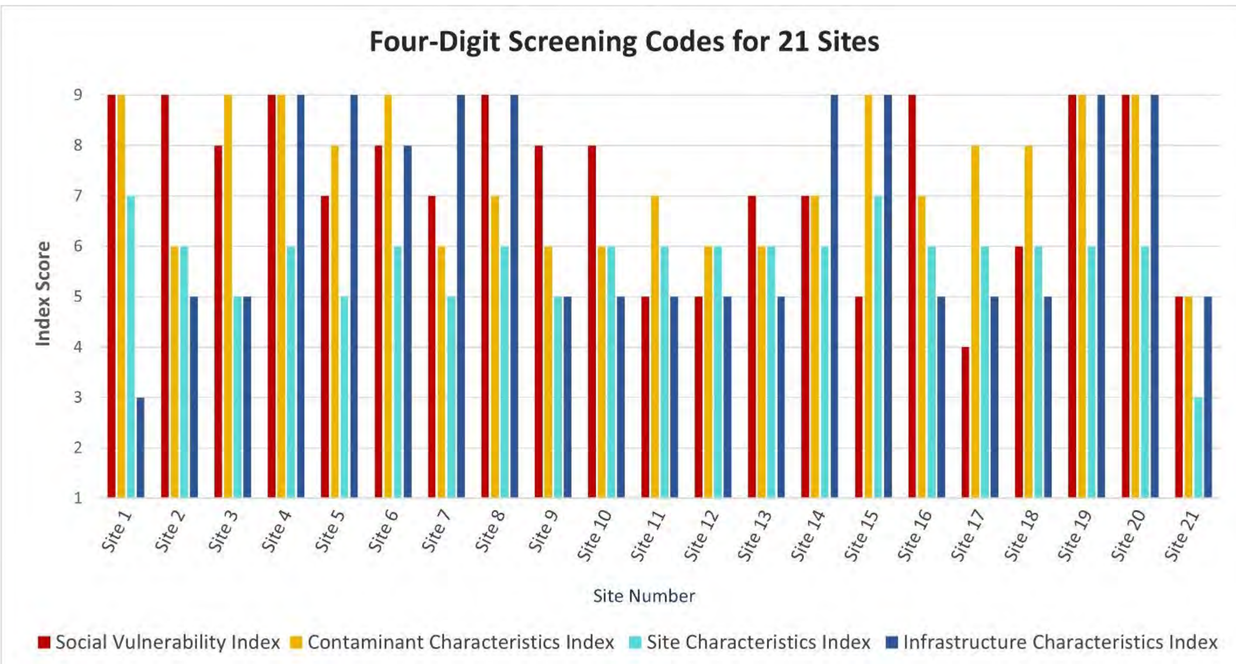
Each digit represents one of the following categories for screening: social vulnerability of the community around the contaminated site, contaminant characteristics such as concentration and persistence, site characteristics that influence contaminant mobility, and infrastructure connectivity that creates the potential for exposure to contaminants inside buildings. We tested this index on 21 pilot sites and found that it worked well to distinguish sites, although the availability of information varies across complex former military or industrial sites that have large numbers of wells and widely-distributed contamination versus simpler sites with only one parcel and a limited history of contamination events. Reviewing these aspects of the contaminated sites led us to identify the Zeneca Ag Products site, the former JH Baxter Facility, and the six former military sites as high-priority for further investigation, and potentially, accelerated clean-up, depending on the results of additional studies.

From an advocacy perspective, all the sites investigated in this study contained contaminants of concern and are of interest for further investigation and potentially accelerated clean-up, since they were included in the Greenaction environmental justice report we used to select study sites. Ultimately, site prioritization will depend on contaminants' ability to travel outside the parcel of origin and create exposure pathways for humans and ecosystems.

We include recommendations for simplifying or supplementing the data needs we found difficult to meet consistently. For example, building use data and the year in which a building was built are not always available in parcel data, but may be available in County tax assessment data or in private real estate value databases (Zillow, Redfin, etc.). We also recommend new data collection, such as creating a registry of pumps and pumping rates, and collecting contaminant data in sewer pipes and utility trenches near contaminated sites. Finally, we recommend that this screening method be used by city, regional, and state agencies as well as advocacy groups to characterize the urgency of additional investigations at contaminated sites. Hundreds of those sites may require additional remediation actions as the rate of sea level and groundwater rise accelerates over the next decade and beyond. Using this screening method will allow for much greater transparency than current databases alone are able to provide. This transparency will support value-driven conversations about how and whether to prioritize specific sites within the framework of transparent data that is organized using explicit threshold criteria and indices.

Most importantly, although we developed this screening method with a focus on VOCs, due to their imminent public health risks and potential to create unexpected exposure pathways, we designed it to be adaptable to other forms of contamination. Contaminants such as metals, radioisotopes, and other pollutants of increasing concern can be evaluated through our four index categories, but the indices would need to be modified to reflect the contaminant’s respective movement in the environment using the framework that structures our site characteristics and infrastructure indices. New scientific findings on contaminants and projected inundation patterns based on changes in rainfall intensity, as well as sea level, can be incorporated into the screening process. This can be done by setting thresholds in these new variables and including them in how the four indices used in our code are constructed and applied. Similarly, changes in proposed housing areas can be assessed using our infrastructure index, and changes in census areas' demographics can be assessed using our social vulnerability index. We see this screening method as a process that can expand and be applied repeatedly, either on a regular basis or as new scientific projections are released, and as new planning proposals are being reviewed in draft form. In conclusion, we see clear advantages to implementing this screening method as a shared framework for data collection, analysis, and categorization that can increase alignment among advocacy organizations, local governments, and state agencies that manage contaminated sites.

We used our method to produce a site score for each of the four screening indices (shown in the bar chart below). Together, these scores form a four-digit code that can be used for site screening and prioritization (shown in the table below). The codes vary across the 21 study sites and aid in site characterization.



Site Number and Site Name	Four-Digit Code	Site Number and Site Name	Four-Digit Code
Site 1: Mare Island Naval Shipyard	**9973**	Site 12: Ashland Chemical Co., Newark	**5665**
Site 2: Reaction Products	**9665**	Site 13: Safety-Kleen of California Inc.	**7665**
Site 3: Richmond (Point Molate) Naval Supply Center (NSC)	**8955**	Site 14: Sunnyvale NIROP	**7769**
Site 4: Zeneca Richmond AG Products	**9969**	Site 15: Moffett Federal Airfield	**5979**
Site 5: Berkeley Industrial Complex	**7859**	Site 16: Romic Environmental Technologies Co.	**9765**
Site 6: Alameda NAS (Naval Air Station)	**8968**	Site 17: G-C Lubricants Co.	**4865**
Site 7: Former J.H. Baxter Facility, Alameda	**7659**	Site 18: VWR Facility	**6865**
Site 8: Associated Aerospace Activities, Inc.	**9769**	Site 19: Hunters Point Naval Shipyard	**9969**
Site 9: Electro-Forming Co., Hayward	**8655**	Site 20: Naval Station Treasure Island	**9969**
Site 10: Fujicolor Processing	**8665**	Site 21: San Quentin State Prison	**5535**
Site 11: FMC Corporation - Newark	**5765**		

Definitions of Frequently Used Terms and Acronyms

Sea Level Rise
A phenomenon associated with climate change, defined as an increase in sea level height at global (absolute) and local (relative) scales. Sea level rise results from changes in ocean volume due to increases in ocean water mass (e.g., melting of glaciers and ice sheets), changes in ocean water density (e.g., thermal expansion under warmer conditions), alterations in the shape of ocean basins, as well as from local land subsidence or uplift.

Groundwater Rise
A subsurface phenomenon influenced by sea level rise, tidal fluctuations, precipitation patterns, and human activities (e.g., pumping) that increases groundwater levels.

Shallow Groundwater
Groundwater that fills pore spaces in near-surface soils and is not confined by an overlying impermeable layer. This water may be fresh, originating from precipitation or leaking water supply infrastructure, or saline, resulting from saltwater intrusion.

Volatile organic compounds (VOCs)
A group of chemicals that easily change from a liquid state to a gas at mild temperatures. Chlorinated VOCs are a subgroup that can be more toxic and persist longer in the environment than fuel-spill-related VOCs, such as benzene.

Exposure (contaminant)
Coming into contact with an external contaminant via inhalation, ingestion, or touch.

Vulnerability
It is defined differently depending on context. In public health, *vulnerability* is the likelihood of being susceptible to mental or physical harm associated with exposure.

Contamination
The presence of hazardous substances at levels that exceed background levels or pose a significant hazard to human health or environmental health.

Contaminated Sites
Parcels classified by federal or state agencies to contain hazardous substances in need of, undergoing, or with completed remediation.

Hazard
A process, condition, or event with the potential to cause harm, damage, or injury to people, property, or the environment.

Characterization
Assessing and recording the unique characteristics of each site studied in this report.

Criteria
The set of factors or screening conditions, expressed through one or more threshold values applied to key variables that are significant for defining, describing, classifying, and prioritizing site conditions for analysis and comparison within the scope of this study. For example, a groundwater depth of 8 feet or less may be used as a criterion that defines “shallow groundwater.”

Categorization
The process of classifying or grouping study sites into defined categories based on shared characteristics or attributes.

Screening
Determining the set of sites that require urgent attention in relation to sea level rise impacts. Not all of these screened sites will require additional investigation, but that determination can only be confirmed with additional data from previous detailed investigations.

Prioritization
Ranking groups of sites to identify those with the most concerning characteristics that may require the most urgent additional investigation.

Index
In this study, an *index* refers to a set of criteria developed to categorize the selected variables.

Index Score
In this study, the index score (1–9) was derived from characteristics used to define criteria for the four indices.

Four-Digit Code
A series of digits comprised of the four index scores in the following order: social vulnerability index score, contaminant characteristics index score, site characteristics index score, and infrastructure characteristics index score. The Four-Digit Code is intended to provide a multi-characteristic overview of a site's potential level of concern with regard to public and environmental health.

Acronyms:

SVI: Social Vulnerability Index
CCI: Contaminant Characteristics Index
SCI: Site Characteristics Index
ICI: Infrastructure Characteristics Index

VOCs: Volatile Organic Compounds

DTSC: California Department of Toxic Substances Control
SWRCB: California State Water Resources Control Board (CA Water Board)

1. Introduction

Low-lying coastal regions, such as the San Francisco Bay Area, are already experiencing multiple consequences of sea-level rise (SLR), including chronic inundation, more frequent and severe coastal flooding, saltwater intrusion into freshwater aquifers, and rising groundwater levels, and their associated impacts (Befus et al., 2020; Habel et al., 2020; Intergovernmental Panel on Climate Change (IPCC), 2019). The focus area of this study is sea-level rise-induced subsurface groundwater inundation and its potential to mobilize contaminants with implications for public health. It emphasizes screening and characterizing contaminated sites in coastal areas where elevated groundwater levels may increase the risk of exposure to hazardous substances, including volatile organic compounds (VOCs).

1.1. Global and Regional Sea-Level Rise

Global Mean Sea Level (GMSL [1]) is rising, and the rate of rise is accelerating (IPCC, 2021). Global tide gauge records show that GMSL increased at an average rate of about 1.4 mm/yr between 1901 and 1990 (Oppenheimer et al., 2019). From 1993 to October 2025, satellite altimeter observations indicate that the global mean sea level has risen by approximately 10.3 cm (Figure 1.1a), at an average rate of 3.3 mm/yr, with evidence of ongoing acceleration (Guérou et al., 2023; Nerem et al., 2018). Recent NASA analyses (Hamlington et al., 2024) revealed that the rate of sea-level rise, which was about 2.1 mm per year in 1993, has doubled to 4.5 mm per year by 2024, and if this trajectory continues, global sea levels are projected to rise by more than 16.9 cm (6.6 in.) over the next three decades (Figure 1.1b).

Like shorelines worldwide, California is also experiencing long-term sea-level rise. The National Oceanic and Atmospheric Administration (NOAA) maintains 12 tide gauges along the outer California coast that record sea level relative to the land. These records, spanning from 46 to 127 years, document relative sea-level rise rates ranging from –0.77 mm/yr (–3 in. per 100 years) at Crescent City to +5.04 mm/yr (+19.8 in. per 100 years) at North Spit, Eureka. Excluding these two northernmost tide gauges, which are situated in a different tectonic regime where subduction is affecting the coastline, the sea level rise values for the remaining ten gauges range from 0.98 to 2.22 mm/yr. (3.8 to 8.8 in./100 yrs.), and average 1.57 mm/yr. or 6.2 in./100 yrs. Sea levels in California are projected to continue to rise ~24 cm (0.8 ft) by 2050 and ~94 cm (3.1 ft) by 2100 in the intermediate scenario (Table 1.1) (California Ocean Protection Council (OPC) & California Ocean Science Trust (OST), 2024).

1.2. Sea-Level Rise-Induced Groundwater Rise

Rising groundwater levels are among the less visible yet significant consequences of sea-level rise in low-lying coastal regions. Early literature on climate change-induced sea-level rise, including the Intergovernmental Panel on Climate Change (IPCC) assessment reports (Intergovernmental Panel on Climate Change (IPCC), 2007, 2014), as well as many of the sea level rise impacts studies over the last decades, have primarily emphasized surface inundation, flooding, and saltwater intrusion as the dominant threats to coastal systems under future SLR scenarios. However, in recent years, as scientific understanding advanced, empirical evidence accumulated, and coastal communities began to experience subsurface flooding and infrastructure impacts, sea-level rise-driven groundwater rise emerged as a recognized hazard and was featured in more literature and news (e.g., Werner and Simmons, 2009; Bjerklie et al., 2012; Rotzoll & Fletcher, 2013; Masterson et al., 2014; Plane et al., 2019; Habel et al., 2020; Befus et al., 2020; Bosserelle et al., 2022; Hill et al, 2023).

[1] Global mean sea-level (GMSL) rise refers to the increase in ocean volume resulting from two primary processes: thermal expansion of seawater as it warms, and the addition of mass from melting land ice and net terrestrial water storage losses. The dominant cause of the rise in GMSL since 1970 is anthropogenic forcing (Oppenheimer et al., 2019).

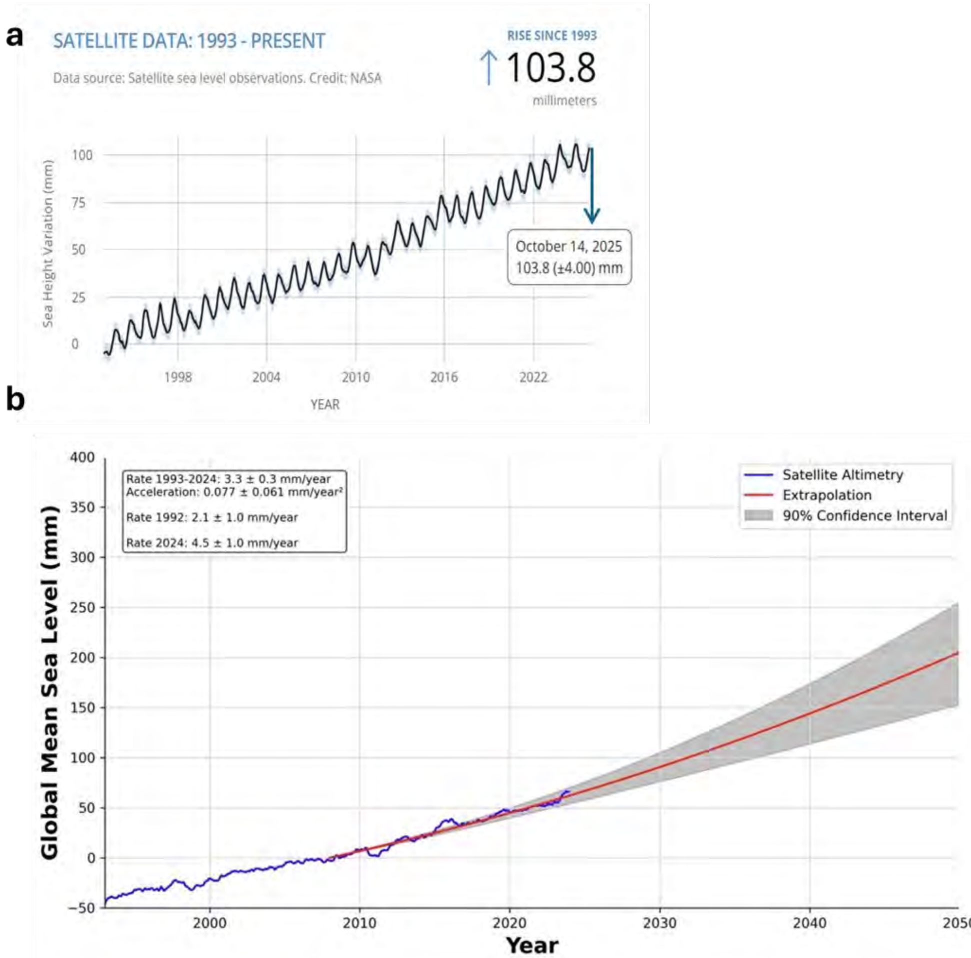


Figure 1.1 (a) Sea level observations by satellite altimeters since 1993 (from https://sealevel.nasa.gov/understanding-sea-level/key-indicators/global-mean-sea-level/) (b) Global sea levels are projected to rise by more than 16.9 cm over the next three decades (from Hamlington et al., 2024).

Table 1.1 Statewide averages for five California sea level scenarios (OPC and OST, 2024).

YEAR	LOW		INT-LOW		INTERMEDIATE		INT-HIGH		HIGH	
	ft	m	ft	m	ft	m	ft	m	ft	m
2020	0.2	0.06	0.2	0.06	0.2	0.06	0.2	0.06	0.3	0.09
2030	0.3	0.09	0.4	0.12	0.4	0.12	0.4	0.12	0.4	0.12
2040	0.4	0.12	0.5	0.15	0.6	0.18	0.7	0.21	0.8	0.24
2050	0.5	0.15	0.6	0.18	0.8	0.24	1.0	0.30	1.2	0.36
2060	0.6	0.18	0.8	0.24	1.1	0.34	1.5	0.46	2.0	0.61
2070	0.7	0.21	1.0	0.30	1.4	0.43	2.2	0.67	3.0	0.91
2080	0.8	0.24	1.2	0.37	1.8	0.55	3.0	0.91	4.1	1.25
2090	0.9	0.27	1.4	0.43	2.4	0.73	3.9	1.19	5.4	1.65
2100	1.0	0.30	1.6	0.49	3.0	0.94	4.9	1.49	6.6	2.01
2110	1.1	0.34	1.8	0.55	3.8	1.16	5.7	1.74	8.0	2.44
2120	1.1	0.34	2.0	0.61	4.5	1.37	6.4	1.95	9.1	2.77
2130	1.2	0.37	2.2	0.67	5.0	1.52	7.1	2.16	10.0	3.05
2140	1.3	0.40	2.4	0.73	5.6	1.71	7.7	2.35	11.0	3.35
2150	1.3	0.40	2.6	0.79	6.1	1.86	8.3	2.53	11.9	3.63

A recent study of the potential for sea-level rise-induced groundwater rise in California (Befus et al., 2020) predicted that with a 1 m rise in sea level, a larger land area could be impacted by rising groundwater than by tidal inundation. The study also noted that low-lying coastal communities surrounding San Francisco Bay face significant risks from rising groundwater.

The hydraulic connection between the ocean and a coastal aquifer governs the mechanism of driving groundwater rise in coastal regions (Werner & Simmons, 2009). As sea levels rise, groundwater elevation (also referred to as groundwater head) is predicted to increase in some watersheds, while in others, groundwater head is constrained by pumping or topography (Befus et al., 2020; Habel et al., 2024). In coastal areas where groundwater head is limited by topography or pumping, the saltwater boundary is expected to move inland (Werner and Simmons, 2009). In coastal areas with permeable sediments and low topographic slopes, this upward pressure can propagate several miles inland, even if the groundwater surface is above sea level (Bjerklie et al., 2012; Masterson et al., 2014). Two primary flooding processes result from this groundwater response: subsurface groundwater inundation (Figure 1.2) and groundwater emergence (Figure 1.3 and Figure 1.4). Subsurface inundation occurs when rising groundwater saturates soils and infiltrates buried infrastructure, such as building foundations, utility corridors, and sewer systems, without producing visible surface flooding. In contrast, groundwater emergence occurs when the water table intersects or rises above the ground surface, resulting in seepage, ponding, or surface flooding (Rotzoll & Fletcher, 2013). Groundwater emergence occurs under geologic conditions similar to those at shallow, contaminated coastal sites, where artificial fill overlying low-permeability wetland and alluvial deposits facilitates groundwater rise during atmospheric rivers, the highest astronomical tides, and rising sea levels. Figure 1.4 shows emerging groundwater at Manzanita and Tamalpais Valley in southern Marin County, California, which occurs under geologic conditions similar to those at shallow contaminated coastal sites.

The potential impacts of groundwater rise and emergence are extensive. Persistent high-water tables and salinization of groundwater can corrode underground infrastructure, weaken building foundations, and compromise soil stability. Additionally, elevated groundwater can mobilize legacy contaminants from industrial or landfill sites, increasing risks to water quality and public health (Befus et al., 2020; Hill et al., 2023). These combined effects reduce the drainage capacity of coastal areas and heighten the overall flood hazard, compounding the impacts of sea-level rise on natural ecosystems and urban communities in low-lying coastal areas.

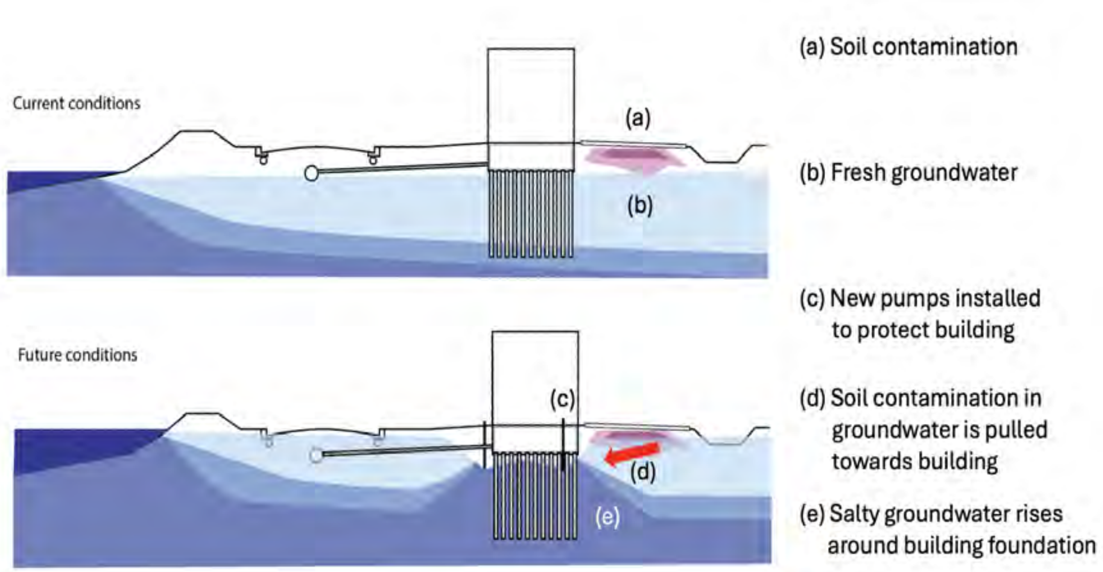


Figure 1.2 A schematic illustration of groundwater rise and subsurface inundation due to sea-level rise, interacting with soil constituents, soil chemistry, urban infrastructure, and pumping. Current conditions are shown in the upper diagram and future conditions in the lower diagram. Dark blue represents ocean water; medium blue represents saline groundwater with a diffusion zone; light blue represents fresh groundwater; and pink represents contaminated soil. Under future conditions, building foundations are exposed to corrosive saline groundwater, particularly when pumping causes up-coning of the saltwater interface (red arrow). 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. Stream water levels will increase as groundwater discharge increases (Adopted from Hill et al., 2023).

Figure 1.3 Veterans Court in the City of Alameda during King Tides. Groundwater intrusion into the sewer system provides a pathway for inland flooding when Bay tides are high. A high groundwater table and emergent groundwater flooding have caused pavement failures (May et al., 2023). (Photo credit: Kristina Hill)

Figure 1.4 (a) Emerging groundwater at Tamalpais Valley, built on artificial fill over wetland deposits; electrical conductivity indicated freshwater conditions following multiple atmospheric rivers, contrasting with brackish conditions recorded on 23 December 2022 during the highest astronomical (king) tides. (Photo credit: O. and J. Jacobs).
(b) Emerging groundwater at Manzanita, built on ~3 m of artificial fill over former wetland deposits; although only meters from a tidal inlet, electrical conductivity indicated freshwater conditions several days after atmospheric river storms (Photo credit: O. and J. Jacobs, Taken 4 April 2024).

1.3. Groundwater Rise and Contaminant Mobilization

Rising groundwater can affect the mobility of contaminants left behind in soil from former industrial, military, and commercial land uses. Metals, VOCs, and radioisotopes can be mobilized and transported laterally even if the contaminated soils have intact caps on the surface (Sultana et al., 2024). VOCs and some radioisotopes can de-gas into pipes and utility trenches, creating the potential for these chemicals to enter the indoor air of buildings (Beckley & McHugh, 2020). Recent research shows that salinity can specifically increase the mobility of metals and radioisotopes (Miranda et al., 2021). Unlike metals, VOCs can travel upgradient when released in gas form through sewer lines and generate surprising patterns of exposure (Beckley & McHugh, 2020). Beckley and McHugh (2020) found that VOCs can travel as far as 685 m (2,250 feet) from a point of origin within a sewer pipe in the down-gradient direction, and 228 m (750 feet) in the upgradient direction. The average city block is approximately 200 m in length, indicating that VOCs can travel several blocks beyond the point of origin. While the gradient of the groundwater surface may be reduced by rising sea levels, adaptation efforts typically include pumping, which can alter gradients, flow directions, and the depth of the saltwater boundary (Werner & Simmons, 2009). The combined influence of sea-level rise, saltwater intrusion, pumping, coastal flooding, heavy precipitation, and groundwater rise is likely to alter, and potentially increase, the dispersal of harmful chemicals from contaminated soils along coastal rivers and urban areas (Richardson et al., 2024). Contaminated sites currently managed by public agencies must be reviewed and prioritized to determine the likelihood of exposure and vulnerability to these new dynamics, and the extent to which they represent future public health risks.

1.4. Public Health Implications (Specifically CVOC, Benzene)

Research focused on the intersections between human health, pollution, and climate change is an emerging public health topic. An abundance of scientific evidence indicates that sudden climate events such as heat waves, flooding, hurricanes, and droughts often result in acute health impacts. The nexus between climate disasters, such as sea-level or groundwater rise, and chronic health implications is less well studied. Sea-level rise, high astronomical tides, and heavy rains such as atmospheric river events can inundate buried contaminants at waste sites along California's coast. The influence of groundwater rise on public health is an under-researched and exceptionally relevant topic in coastal urban environments that continue to expand in population. Nearly three-quarters of the 39 million people who reside in California live in coastal counties. While the exposure pathways for metals are likely to remain centered on consuming fish and shellfish, changes in the elevation of the groundwater table can result in unexpected new exposures to VOCs for people living near former industrial, military, or commercial sites. If VOCs enter sanitary sewer lines or even just utility trenches, exposure pathways can form through faulty plumbing seals and foundation cracks that are especially common in older buildings, including schools and multi-family residential buildings.

Volatile organic compounds are a broad class of chemicals that include known carcinogens and endocrine-disrupting compounds, such as tetrachloroethylene, benzene, and carbon tetrachloride. Contaminated sites, such as those investigated in this report, can drift through the air, water, and soil, spreading beyond the site itself. As chemicals spread, they enter areas with unsuspecting people, leading to an increased risk of adverse health outcomes for those exposed to harmful toxicants (Brender et al., 2011; Fazzo et al., 2017). Empirical studies have shown that the presence and spread of these chemicals at contaminated sites can lead to adverse health outcomes such as endocrine disruption, cancer, and asthma (Wu et al., 2023).

If left unremediated and subject to surface or groundwater flooding, contaminated sites can negatively affect the health of people and other organisms in surrounding areas, extending up to 2.9 km from the site of origin (Mascarenhas et al., 2021). People who live in proximity to contaminated sites are more likely to experience adverse health outcomes, such as cancer or asthma, than those who live a greater distance from these sites. Unremediated sites further perpetuate the harms inflicted on nearby communities that are more likely to be socially and economically disadvantaged (Mohai & Saha, 2007). Poor communities of color are more likely to reside near contaminated sites, known as fenceline communities, than wealthier people, including wealthy people of color, highlighting a distinct and intersectional social difference in exposure to harmful chemicals (Bullard, 1990; Downey & Hawkins, 2008; Mohai et al., 2009). Therefore, research on potential exposure to harmful chemicals near contaminated sites is both an environmental justice issue and a broader public health concern

1.5. The Focus Area of This Research

According to Befus et al. (2020), the San Francisco Bay is at high risk of sea-level rise-driven groundwater rise and its associated impacts, including contaminant mobilization and exposure. A preliminary study identified over 1,400 active contaminated sites in the region at risk of subsurface flooding under 1 meter of sea-level rise (Hill et al., 2023), which could potentially mobilize contaminants buried in the soil. Legacy soil contamination in the San Francisco Bay Area is largely associated with former military bases, shipyards, lumber treatment facilities, industrial chemical plants, and smaller-scale operations such as dry-cleaning establishments and fueling stations. This study focused on sites contaminated with VOCs, such as benzene and tetrachloroethene, which pose significant risks to public health and the environment. Rising groundwater can mobilize these contaminants, leading to subsurface inundation and potential spread through soil, utility trenches, and sewer systems, while VOCs may also pose vapor intrusion hazards to overlying buildings, creating additional exposure pathways.

To support management and the prioritization of these legacy sites, we applied a screening framework based on four indices: Social Vulnerability Index (SVI), Contaminant Characteristics Index (CCI), Site Characteristic Index (SCI), and Infrastructure Characteristic Index (ICI), each comprising multiple sub-criteria. This multi-criteria approach enables systematic assessment of site vulnerability, contaminant mobilization pathways, and the relative urgency of intervention, facilitating informed decision-making for allocating resources to risk reduction and preventing future human exposure to VOCs.

2. Study Area and Research Method

The San Francisco Bay Area is a large, complex metropolitan region with a major influence on the California and the global economy. It has a population of 7.7 million people (SF Bay Area Vital Signs, 2025 estimate) and includes nine counties and 101 incorporated cities and towns. The Bay is a depression (basin) formed by the movement of tectonic plates between major fault lines (San Andreas and Hayward), which was subsequently flooded by the rising sea levels.

Much of the historic Bay shoreline is characterized by alluvial fans and paleochannels, as well as broad, gently sloped mudflats exposed at low tide and bordered by tidal wetlands and salt marshes. Large portions of the current urban shoreline consist of artificial urban land created by filling marshes and mudflats with sediment from upland areas, building rubble, or other municipal waste. This low-lying ground typically has a very shallow unconfined groundwater condition and is particularly vulnerable to liquefaction during earthquakes and to the impacts of sea-level rise. The region has a history as a major resource port for trans-Pacific trade and served as an industrial hub for smelters, lumber mills, flour mills, slaughterhouses, canneries, shipbuilding, and explosive and chemical production. During World War II, the San Francisco Bay Area served as the primary naval hub for the Pacific, with dozens of large and small military installations and private shipyards dedicated to rapid production. Sites with soil contamination include former military bases, shipyards, lumber treatment mills, and industrial chemical factories, as well as small dry cleaners and fueling stations.

Hill et al. (2023) provided statistical evidence that sites with contamination remaining in the soil are more likely to be in areas with socially vulnerable populations, many of which are also located in low-lying areas that are subject to surface flooding and high groundwater conditions. According to the California YIMBY website [2], housing stock in the Bay Area is also significantly older than the US national average, particularly in the Central Bay Area. Frequent seismic activity creates stressors for both pipe networks and building foundations in the SF Bay Area, leaving them increasingly vulnerable to groundwater infiltration.

The State of California maintains two separate databases of contaminated sites: Envirostor, which contains information in PDF format about sites managed by the California Department of Toxic Substance Control (DTSC), and GeoTracker, which contains readily downloadable spreadsheet data on chemicals and concentrations for all wells sampled at sites managed by the California State Water Resources Control Board (Water Board). Hill et al. (2023) reviewed all sites managed by these agencies in the region and concluded that 1,482 sites are located over shallow groundwater that is predicted to rise by at least 0.1 m with 1 m of sea-level rise. Unlike the sites managed by the Water Board, DTSC database records do not summarize the complete list of contaminants; instead, they rely on the hundreds of PDF files organized by site managers.

2.1. Study Site Selection

Many communities in the region are concerned about differential exposure to contaminants ranging from airport and seaport air pollution to industrial and groundwater contamination. People exposed to a higher number of cumulative contaminants face compounded health risks. Greenaction has used health data to advocate for communities in this region that bear the health burdens of environmental injustice, and developed a report titled *Ticking Time Bomb: Climate Change, Sea Level and Groundwater Rise, Shoreline Contamination, and Environmental Justice in the San Francisco Bay Area* that identified 55 sites of interest to communities impacted by environmental injustice (Greenaction for Health and Environmental Justice, 2023). This report was completed shortly before we began our research collaboration and became the point of departure for our joint efforts to develop screening methods that could be used to prioritize more detailed investigations of the risks posed by rising groundwater as sea level rises and rainfall becomes more intense.

Our team was aware from the outset that the exposure pathways generated by VOCs are more likely to result in unexpected impacts on public health than the exposure pathways for metals and non-volatile organic pollutants that could also be mobilized at contaminated sites. This is primarily because VOCs can travel upgradient in pipes and utility trenches, entering indoor air. Metals and non-volatile organic chemicals travel downgradient in groundwater, and while pumping may alter the directions of flow, these contaminants are unlikely to enter indoor air. We selected the 21 sites from the Greenaction report that contained VOCs to develop a screening method that addresses what we understand to be an imminent public health concern. We numbered 21 study sites clockwise around the Bay Area (Table 2.1). The method we developed can be applied to other contaminants as well by developing criteria appropriate to the relative toxicity, mobility, and fate of metals and other non-volatile chemicals. Figure 2.1 shows the location of the 21 sites we selected to develop our screening method.

[2] California YIMBY, A 501(c)4 Non-Profit Organization.
https://cayimby.org/maps/median-age-of-housing-in-california/

Table 2.1 List of 21 contaminated sites selected to develop the screening method in this study.

Site Number	Site Number in Greenaction Report	Site Name	Oversight Agency	Site Status	County	City
Site 1	25	Mare Island Naval Shipyard	DTSC, CA Water Board Region 2	Active	Solano	Vallejo
Site 2	35	Reaction Products	DTSC	Active	Contra Costa	Richmond
Site 3	33	Richmond (Point Molate) Naval Supply Center (NSC)	CA Water Board Region 2	Active	Contra Costa	Richmond
Site 4	49	Zeneca Richmond AG Products	DTSC	Active	Contra Costa	Richmond
Site 5	5	Berkeley Industrial Complex	CA Water Board Region 2	Active	Alameda	Berkeley
Site 6	1	Alameda NAS (Naval Air Station)	DTSC, CA Water Board Region 2, US EPA*	Active	Alameda	Alameda
Site 7	15	Former J.H. Baxter Facility Alameda	DTSC	Active	Alameda	Alameda
Site 8	4	Associated Aerospace Activities, Inc.	CA Water Board Region 2	Active	Alameda	San Leandro
Site 9	11	Electro-Forming Co., Hayward	DTSC	Active	Alameda	Hayward
Site 10	18	Fujicolor Processing	DTSC	Active	Alameda	Hayward
Site 11	13	FMC Corporation - Newark	CA Water Board Region 2	Active	Alameda	Newark
Site 12	3	Ashland Chemical Co., Newark	CA Water Board Region 2	Active	Alameda	Newark
Site 13	37	Safety-Kleen of California Inc.	DTSC	Active	Alameda	Newark
Site 14	43	Sunnyvale NIROP	CA Water Board Region 2	Active	Santa Clara	Sunnyvale
Site 15	27	Moffett Federal Airfield	CA Water Board Region 2	Active	Santa Clara	Mountain View
Site 16	36	Romic Environmental Technologies Corp	US EPA	Active	San Mateo	East Palo Alto
Site 17	19	G-C Lubricants Co.	DTSC	Active	San Mateo	San Carlos
Site 18	46	VWR Facility	CA Water Board Region 2	Active	San Mateo	Brisbane
Site 19	23	Hunters Point Naval Shipyard	US EPA, DTSC, CA Water Board Region 2	Active	San Francisco	San Francisco
Site 20	29	Naval Station Treasure Island	CA Water Board Region 2, DTSC	Active	San Francisco	San Francisco
Site 21	38	San Quentin State Prison	CA Water Board Region 2	Active	Marin	San Quentin

US EPA: United States Environmental Protection Agency
DTSC: California Department of Toxic Substances Control
SWRCB: California State Water Resources Control Board (CA Water Board)

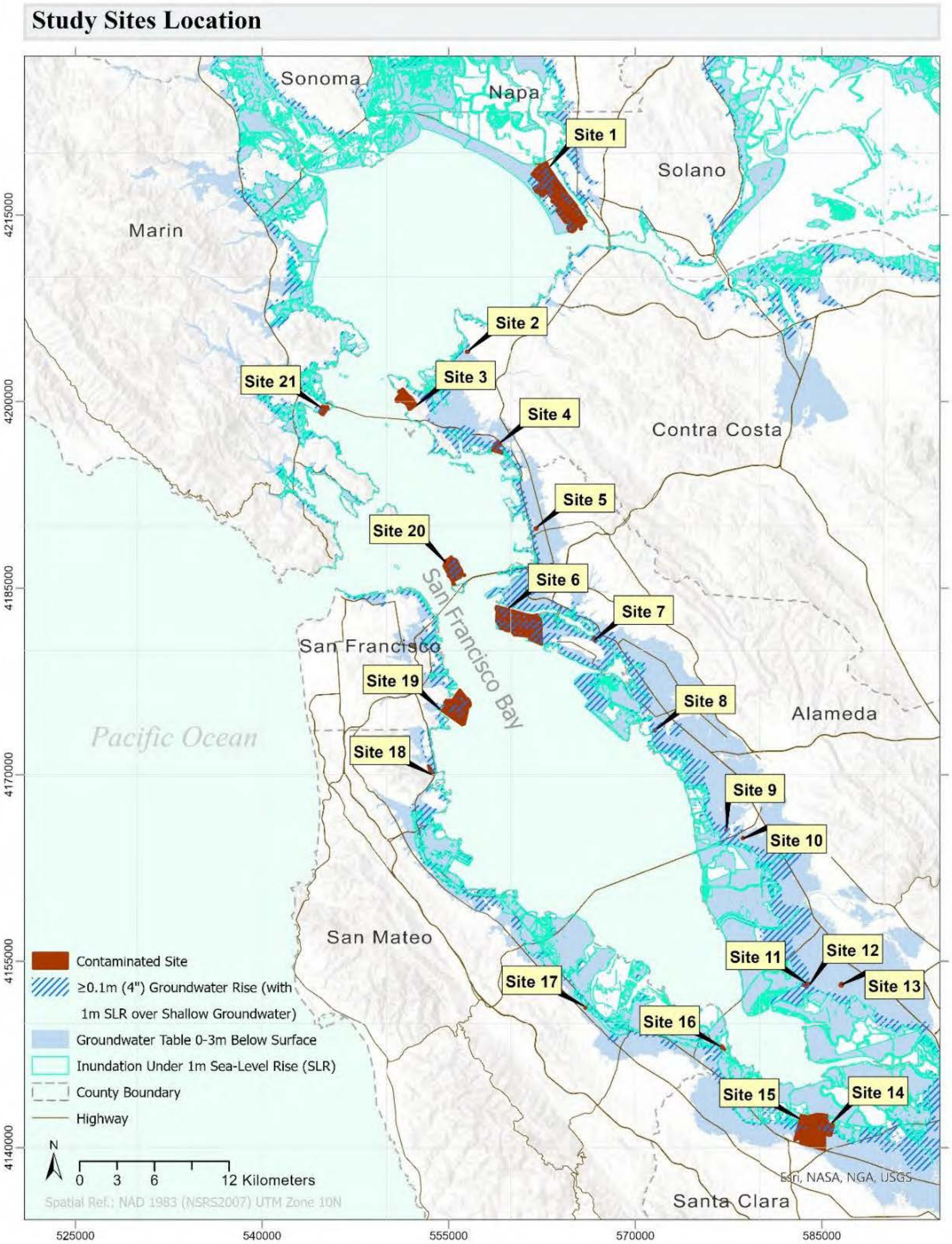


Figure 2.1 Spatial distribution of the study sites and their location relative to the projected groundwater rise zone, SLR surface inundation zone, and shallow groundwater (0-3m below surface) in San Francisco Bay. Layer sources: The groundwater table, the surface inundation layer with 1 meter SLR, and the groundwater rise layers used in this map are from the Hill et al. (2023) datasets, based on data from Befus et al. (2020).

2.2. Regional Data and Projections for Sea Level and Groundwater Rise

Our study uses the work of Befus et al. (2020) to predict where inundation and groundwater rise are likely to occur due to sea-level changes. The relative sea-level trend in San Francisco, as measured by the NOAA Golden Gate Tide Gauge, has been rising at an average rate of 1.98 mm/yr, based on monthly mean sea level data from 1897 to 2024. This rate corresponds to an approximate rise of 20 cm (8 in.) over the past century. Observations of annual mean relative sea level since 1960, combined with regional projections, indicate that sea level in the San Francisco Bay is expected to continue rising through 2100, posing increasing risks to coastal communities, infrastructure, and low-lying areas (Figure 2.2).

Befus et al. relied on tide gauges and well data from the San Francisco Bay for their regional projections. We did not quantify or include any projected changes in precipitation or any new pumping activities for this study.

a

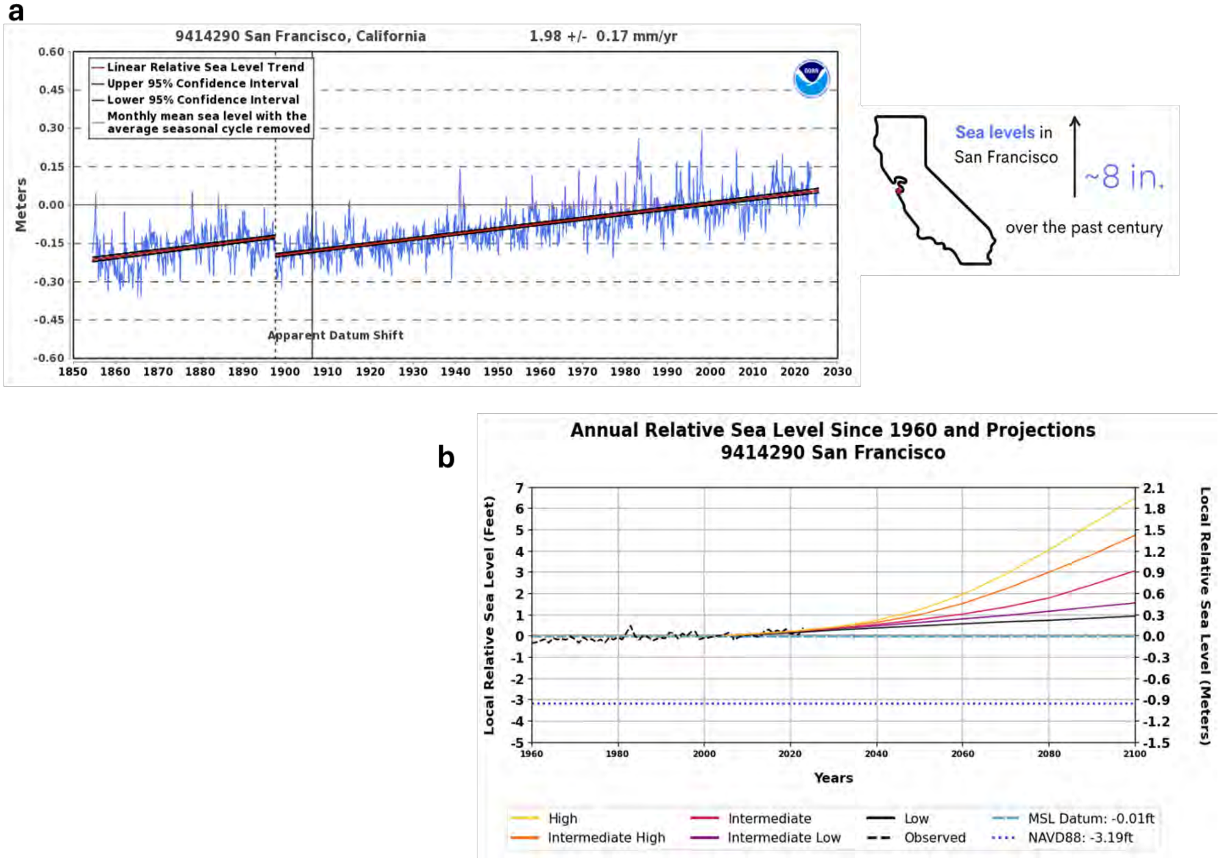


Figure 2.2 (a) The relative sea-level trend in San Francisco, as observed by the NOAA tide gauge at the Golden Gate. It is 1.98 millimeters/year, based on monthly mean sea level data from 1897 to 2024, equivalent to about 20 cm (~8 in.) over 100 years. (b) Annual mean relative sea level since 1960 and regional sea-level rise projection by 2100 (https://tidesandcurrents.noaa.gov/).

2.3. Research Process

The research team included faculty, researchers, doctoral students from the University of California, Santa Cruz (UCSC) and the University of California, Berkeley (UCB), as well as staff from Greenaction. We adopted a collaborative approach, meeting weekly to refine project aims and methods, and organized biweekly exchanges with our public agency partners (CA DTSC and CA SWRCB) during the period when we were developing our methods. We reported developments in our approach and our preliminary results quarterly to the San Francisco Bay Shoreline Contamination Cleanup Coalition (Shoreline Coalition), an environmental justice advocacy organization made up of representatives from several communities in the San Francisco Bay Area, where contaminated soils are a serious concern. The Shoreline Coalition is supported by Greenaction staff. Figure 2.3 illustrates the collaboration framework used in this study.

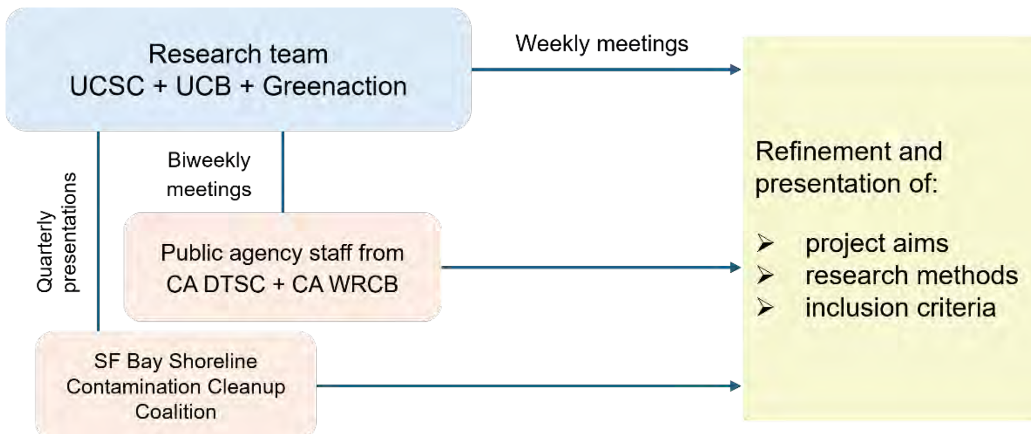


Figure 2.3 This chart shows the research process framework linking the research team with community and agency partners through regular meetings and feedback loops.

We developed a process for characterizing contaminated sites that evaluates their potential for elevated chemical exposure risks that could seriously impact public health as groundwater rises. Our method emphasizes potential exposures that could affect children, since the developmental phases of growing bodies make them particularly sensitive to toxins. The approach we developed considers the concentrations and toxicity of contaminants, the likelihood of migration of the contaminants based on groundwater depth and soil characteristics, the potential for contaminants to enter sewer pipes and utility trenches connected to buildings, as well as the ages and uses of the buildings, and the social vulnerability of the community living in proximity to the site. All of these variables can be significant for screening purposes when identifying greater potential for human exposure and vulnerability to VOCs.

Since these characteristics are measured or estimated on various numerical scales, our study used an index-based approach to standardize the numerical values we used to represent different levels of risk at the contaminated sites. We defined risk as a combination of contaminant behavior and toxicity, exposure potential determined by site and infrastructure characteristics, and social vulnerability. Each of these four categories includes multiple specific criteria, which are aggregated into a four-digit code in the final screening assessment, with each digit representing an index value from 1 to 9.

Indices have been used to quantify environmental variables in habitat and housing suitability studies, and in assessments of capability and hazard. They are useful because they allow measurements or estimates on different scales to be standardized to a common scale. An index converts measured or estimated values to a scale that may be ordinal, interval, or ratio. Each type of scale contains mathematical limitations for how it can be manipulated (Hopkins, 1976). Regardless of the numerical scale used for the original characteristics and criteria for significant thresholds, index values can be used to represent a range from low to high. The purpose is to be able to consider multiple characteristics while standardizing differences across the units of the original assessed variables. For example, the Federal Highway Administration uses an index to characterize bridges in the United States to screen them for risk of failure. This index ranks each individual variable on a 0-9 scale and then uses the minimum value of these 0-9 indices to rate the bridge.

Since the purpose of our four-digit code is to identify sites that urgently need investigation, we treat unknown characteristics such as concentration or building use as very important. The index score for an unknown characteristic receives the maximum value of 9 in our coding. A site represented by the code 9999 would represent high levels in all four characteristics (social vulnerability, contaminant characteristics, site characteristics, and adjacent infrastructure characteristics) but might also indicate that one or more of the important characteristics is unknown.

This four-digit index code is useful for screening sites because sites can be categorized once they are assigned a code. Sites with an index score of 8 or 9 in toxicity and concentration might all be grouped together, for example. The four-digit code should not be read literally as a numerical value, however, since the index scores are relative and don't represent any specific numerical scale. The four-digit code simplifies the representation of four complex categories of hazard, exposure, and vulnerability, rather than a numerical count. Its purpose is to allow policymakers and the public to set priorities for further site investigations and clean-up.

For example, if the index score shows a high number for social vulnerability, it could justify placing a more urgent priority on a site with a medium index score for contaminant concentration and toxicity (contaminant characteristics). If site characteristics represented in the third digit represent low potential mobility for a toxicant, then the site should be ranked among lower priority sites even if the concentration of that chemical is high and the community is socially vulnerable. In that case, the degree of hazard may be low because the chemical is unlikely to move off-site. We expect that advocacy groups and state agency managers may categorize sites differently using our index codes. Our purpose is to make the risk-related differences among the hundreds of contaminated sites explicit, creating a common language that allows users to unpack the index scores and debate the appropriate prioritization of hundreds of sites in an efficient way, so that time will not be lost through misunderstandings about the characteristics of the sites. Further investigations are urgently needed in some cases, since high groundwater and pumping may already have altered the direction and rate of movement of some contaminants.

2.4. Screening Method for Site Characterization

Our approach to screening sites and buildings that may pose a significant public health risk employs a two-step process. The first step excludes sites that are unlikely to represent new or emerging sources of risk using a series of binary ("yes/no") screening questions. The second step establishes thresholds for key variables that characterize site-specific sources of risk. These thresholds are used to construct four screening indices, Social Vulnerability Index (SVI), Contaminant Characteristics Index (CCI), Site Characteristic Index (SCI), and Infrastructure Characteristic Index (ICI), each represented by an explicit table of scores (Tables 3.1.8, 3.2.4, 3.3.8, and 3.4.3 for SVI, CCI, SCI, and ICI, respectively. After scoring each index, the resulting numerical values are combined to generate a four-digit screening code for each site.

Step 1:

The following conditions must be met before a site can be categorized as a potential public health threat in relation to rising sea level / rising groundwater:

a. Is the contaminated site located over rising groundwater or within the surface inundation zone in a scenario with 1m of sea-level rise, and is the groundwater beneath the site within 3m of the land surface (these are the same criteria that were used in Hill et al, 2023) (Y/N)?

b. Are target contaminant/s (VOCs in this study) present (Y/N)?

c. Are sewer lines present within the flowline polygon that are connected to buildings that are in use or anticipated in a planned development, and are those pipes or utility trenches located within 100m of the parcel inside the flowline polygon (Y/N)?

d. Are permeable or conductive subsurface conditions present, or are urban fill materials present that often have very mixed levels of hydraulic conductivity (Y/N)?

Step 2:

Once the initial step is complete, the remaining sites are assessed using a second pass through the method. In this step, a crosswalk table is constructed that represents an entire category of characteristics, such as contaminant toxicity and concentration. Thresholds in the range of values present in the underlying variables are used to assign values from 1 to 9 to an index. The four index scores form the final four-digit code that can be used to make an initial assessment of the relative risk represented at each site. The goal here is to allow judgments within the site characterization process to be made explicit, to support clear dialogue between science-based public agencies, site owners, and advocacy groups.

Based on the literature, we determined that the following four categories of characteristics are most likely to influence the risk of new public health impacts: social vulnerability, contaminant characteristics, site characteristics, and infrastructure characteristics. Each category comprises multiple variables (criteria) derived from a range of data sources and combined into an index to produce a single numerical score (1–9) for each of the four categories at each site. Together, these scores of four indices form a four-digit code that can be used for site screening and prioritization. For example, the four-digit screening code for a site might be “2758,” which means that a site has low social vulnerability, high risk from contaminant characteristics, medium risk from site characteristics, and a theoretically high potential to enter the indoor air of schools or residential buildings via utility pipes or trenches. The code highlights sites with a high score in one or more of the digits.

Figure 2.4 presents the conceptual framework used to develop the screening tool. The framework illustrates how four indices, the social vulnerability index, the site characteristics index, the contaminant characteristics index, and the infrastructure characteristics index, interact to influence the mobilization of volatile organic compounds (VOCs), the migration of contaminants through subsurface and utility pathways, and the resulting risk of indoor air pollution under rising groundwater and sea-level conditions. This conceptual model provides the foundation for integrating diverse data sources into a consistent, screening-level approach for prioritizing contaminated sites.

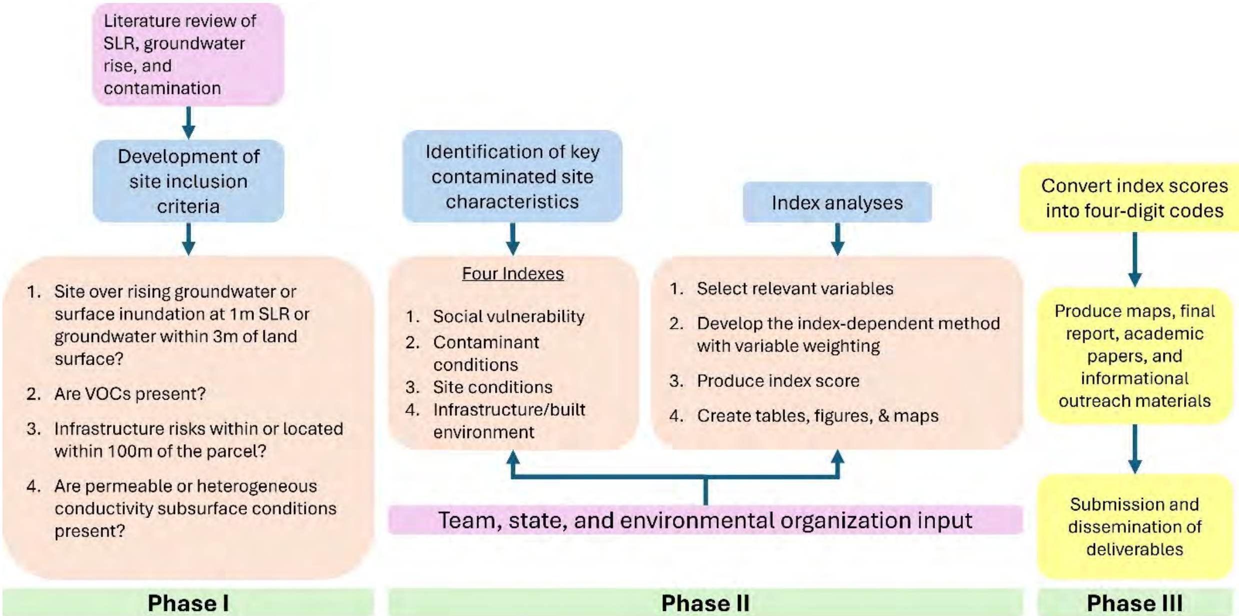


Figure 2.4 Conceptual framework of screening tool development.

In the following section, we describe the underlying variables and thresholds used to construct each index, calculate and assign index scores to generate the final four-digit screening code for each study site, along with the literature supporting those thresholds.

3. Contaminated Sites Characterization Screening Tool

To support the management and prioritization of these legacy sites, we developed and employed a screening framework comprising four indices: Social Vulnerability Index (SVI), Contaminant Characteristics Index (CCI), Site Characteristic Index (SCI), and Infrastructure Characteristic Index (ICI), each consisting of multiple sub-criteria. This multi-criteria framework is as follows:

3.1. Social Vulnerability Index

Flood risk is not determined by natural hazards alone but emerges from their interaction with human vulnerability, shaped by social, economic, political, and environmental conditions that significantly influence how hazards impact people (Cushing et al., 2023; Wisner, 2003). In addition to studying physical hazards, it is also crucial to examine social conditions and potential vulnerability. Social vulnerability can be defined as the characteristics of a community that affect its capacity to anticipate, confront, and recover from the effects of a disaster (Wisner et al., 2004) or the susceptibility of people to damage and harm (Morss et al., 2011). Poverty, community demographics, the distribution of resources such as information or recovery supplies, infrastructure quality, and decisions related to the allocation of funds and aid all influence the severity of flood risk (Wisner, 2003). Additionally, communities that are ill-equipped to manage hazards are more likely to reside in hazard-prone locations, live in substandard housing, have fewer resources, and lack access to preparedness education (Parry et al., 2019).

Flood preparedness and recovery efforts often overlook social vulnerability by implicitly assuming that hazards affect all populations similarly. In reality, flooding can intensify existing vulnerabilities, particularly in communities shaped by historical policies and discriminatory settlement patterns, such as redlining and the disproportionate siting of low-income housing in high-risk areas (Blaikie, 1994). Factors shown to affect social vulnerability include, but are not limited to, socioeconomic status, household composition, health status, and vehicle access (Cushing et al., 2023). These factors often result in greater difficulties during hazard mitigation and evacuation and contribute to more health and safety risks (Dunning & Durdan, 2011). Evidence indicates that children, the elderly, and disabled people are more vulnerable at all stages of a hazard event (Morrow, 1999). Socially vulnerable groups are more likely to experience higher rates of fatality and property destruction and are less likely to fully recover from natural hazards compared to groups that are less socially vulnerable (Morrow, 1999).

The increased frequency of future flooding will lead to the release of toxic substances from hazardous sites, disproportionately affecting socially vulnerable communities that already face high cumulative pollution burdens. Living near contaminated sites exposes communities to various health risks, including exposure to toxic chemicals, polluted air, and contaminated water. These environmental hazards can lead to a range of health problems (Cushing et al., 2023). Incorporating social vulnerability analysis into our index will improve understanding of relative site risk and inform site prioritization.

3.1.1. Method and Materials

Social vulnerability indexes can inform policy decisions and the allocation of scarce resources to communities disproportionately burdened by the impacts of natural hazards. They can identify communities that may need help preparing for hazards or recovering from flooding. Additionally, they can relieve marginalized communities of the burden of determining and proving vulnerability themselves. Indexes typically use census data along with other data sources, such as air quality data and health records, to produce an overall social vulnerability ranking. Quantifying social vulnerability is challenging and subjective. Each social vulnerability index (SVI) or screening tool we studied includes different data sources, variables, spatial scales, and overall methodology. Because social factors are complex and interdependent, each tool quantifies social vulnerability in a unique way.

We analyzed a wide range of national, state, and regional indices and, through discussions with our community and agency partners, selected three relevant and insightful indices for inclusion in our study. We chose to use existing databases and social vulnerability mapping tools that have undergone numerous iterations by experts, are widely used by state agencies and community groups, and provide critical data on vulnerability factors that influence people's susceptibility to damage or harm from contaminant exposure. Each tool has its own strengths, such as transparency, data accessibility, and user-friendliness, and weaknesses such as data gaps, blind spots, and biases.

We used multiple social vulnerability indices for the analysis to capture different dimensions of quantifying vulnerability, as each tool uses different indicators, weighting schemes, and assumptions. The spectrum of vulnerability indicators across tools ranges from income and education to pollution exposure and healthcare access. The spatial resolution, census block versus census tract, of a tool has a significant impact on the vulnerability score of a site (Maantay, 2002). Using smaller geographic units can capture pockets of vulnerability that would be averaged at larger scales, but larger geographic units can include the area surrounding contaminated sites that might be affected if contaminants are mobilized. Any single tool may be sensitive to modeling changes and overlook important communities, so using multiple tools enables us to mitigate bias from single model assumptions (Huynh et al., 2024). We chose to take the highest score produced among the tools for each site rather than combine scores to produce a mean score in order to use the most conservative approach and ensure vulnerable sites received recognition in our analysis.

Criterion #1: CalEnviroScreen 4.0

CalEnviroScreen (CES) helps identify California communities most affected by multiple sources of pollution, where residents are often particularly vulnerable to the associated health effects.

CalEnviroScreen 4.0 (CES 4.0), released in 2021, is a statewide environmental-justice screening tool maintained by the California Office of Environmental Health Hazard Assessment within the California Environmental Protection Agency. It maps and scores cumulative environmental burdens and population vulnerabilities for every census tract in the state to help identify communities disproportionately affected by pollution.

CES measures 21 indicators, 13 Pollution Burden indicators related to exposure and environmental effects, and 8 Population Characteristics indicators related to sensitive populations and socioeconomic factors (Table 3.1.1). Each indicator is converted to a percentile score by census tract, and indicator percentiles are averaged into four components: Exposures, Environmental Effects, Sensitive Populations, and Socioeconomic Factors. The score (Table 3.1.2) can be used to compare tracts relative to one another statewide, but it is not a direct health-risk calculator.

Pollution Burden = average (Exposures, 0.5 × Environmental Effects)

Population Characteristics = average (Sensitive Populations, Socioeconomic Factors)

Overall CES score = Pollution Burden × Population Characteristics

CalEPA uses CES results to designate “Disadvantaged Communities” for California climate investments as well as to carry out AB 1550, “Greenhouse gases: investment plan for disadvantaged communities”. CES provides an interactive results map, indicator maps, and a data dashboard that filters by district and any combination of indicators. Users can also download shapefiles, a geodatabase, and an Excel data dictionary. We found CES to be the tool that most consistently assigned test sites the highest vulnerability scores compared to other SVI tools. The lower spatial resolution actually resulted in the inclusion of adjacent neighborhoods that might be affected by migrating contamination.

Criterion #2: BCDC Community Vulnerability Index

The San Francisco Bay Conservation & Development Commission (BCDC), through its Adapting to Rising Tides program, built a dataset to identify SF Bay Area neighborhoods that may be more vulnerable to current and future flooding from sea-level rise and storms and subsequent contaminant exposures. The index supports shoreline adaptation planning and the implementation of BCDC’s Environmental Justice & Social Equity Bay Plan policies and helps community members understand their potential vulnerability.

The BCDC Community Vulnerability Index (CVI) is a regional tool tailored for the San Francisco Bay Area at finer spatial resolution. The nine-county Bay Area is analyzed at the census block-group level. The latest CVI update (2023) includes data from CalEnviroScreen 4.0, along with a variety of vulnerability indicators. The index comprises social vulnerability indicators, contamination vulnerability indicators, exposure indicators, and complementary screening layers (Table 3.1.3). The CVI flags block groups when specific socioeconomic characteristics are higher compared to the Bay Area. To reflect pollution-related stressors that can worsen with flooding, the CVI uses the Environmental Effects portion of CalEnviroScreen 4.0.

Table 3.1.1 CalEnviroscreen 4.0 tool attributes

Tool/Method:	CalEnviroScreen 4.0
Website:	[CalEnviroScreen 4.0 | OEHHA]
Variables:	**Pollution Burden:** Exposure indicators (8): Ozone, PM2.5, Children's lead risk from older housing, Diesel particulate matter, Drinking water contaminants, Pesticide use, Toxic releases from facilities, Traffic impacts. Environmental effects (5): Cleanup sites, Groundwater threats, Hazardous waste generators & facilities, Impaired water bodies, Solid waste sites & facilities
	Population Characteristics: Sensitive populations (3): Asthma, Cardiovascular disease, Low-birth-weight infants. Socioeconomic factors (5): Educational attainment, Housing burden (low-income households paying >50% of income on housing), Linguistic isolation, Poverty, Unemployment.
Spatial Resolution:	Census tract
Classification system	Percentile relative to the state.
Scoring methods	The overall CalEnviroScreen score is relative to the state and calculated by multiplying the Pollution Burden and Population Characteristics scores.
Data Source(s):	California Air Resources Board (CARB) ambient monitoring network, CARB ambient monitors plus satellite observations, TrafficMetrix roadway volumes and updated roadway network, U.S. EPA Toxics Release Inventory (TRI) processed with EPA's Risk-Screening Environmental Indicators (RSEI) model, California Dept. of Pesticide Regulation (DPR) Pesticide Use Reporting (PUR), State Water Resources Control Board (SWRCB) compliance monitoring & violations; water-system service boundaries from Tracking California's Water Boundary Tool; GAMA ambient groundwater program for areas outside systems, Digital Map Products SmartParcels (year built); HUD CHAS (low-income households with children), DTSC EnviroStor + U.S. EPA Superfund NPL boundary updates, SWRCB GeoTracker cleanup sites; CIWQS dairies & feedlots, DTSC hazardous waste tracking (generators 2018–2020; facilities to June 2021); CARB list of chrome platers, SWRCB 2018 Integrated Report, CalRecycle (active/closed/illegal sites, waste tires, violations); DTSC scrap metal recyclers; anaerobic digestion facilities, Tracking California modeling of ED visits; underlying counts from OSHPD, California Dept. of Public Health (CDPH) vital statistics, U.S. Census Bureau American Community Survey (ACS) 5-year estimates (Housing-burdened low-income & component of lead-risk indicators)

Table 3.1.2 CalEnviroScreen 4.0 scores for 21 test sites

Site Number	Site Name	Pollution Burden Percentile	Population Characteristics Percentile	Overall Percentile
1	Mare Island Naval Shipyard	83	79	**86**
2	Reaction Products	75	83	**85**
3	Richmond (Point Molate) Naval Supply Center (NSC)	92	42	**71**
4	Zeneca Richmond AG Products	75	68	**75**
5	Berkeley Industrial Complex	91	42	**66**
6	Alameda NAS (Naval Air Station)	78	69	**77**
7	Former J.H. Baxter Facility Alameda	67	58	**66**
8	Associated Aerospace Activities, Inc.	92	71	**87**
9	Electro-Forming Co., Hayward	80	61	**74**
10	Fujicolor Processing	80	61	**74**
11	FMC Corporation - Newark	32	56	**48**
12	Ashland Chemical Co., Newark	32	56	**48**
13	Safety-Kleen of California Inc.	65	57	**65**
14	Sunnyvale NIROP	82	50	**67**
15	Moffett Federal Airfield	66	29	**42**
16	Romic Environmental Technologies Corp	73	49	**63**
17	G-C Lubricants Co.	76	14	**31**
18	VWR Facility	85	34	**55**
19	Hunters Point Naval Shipyard	69	84	**83**
20	Naval Station Treasure Island	89	78	**89**
21	San Quentin State Prison	70	5	**15**

BCDC estimates the number of housing units exposed at each modeled water level by joining the Metropolitan Transportation Commission's (MTC) 2010 residential parcel dataset with the 2017 ART Bay Area sea-level-rise and shoreline analysis, plus FEMA 100- and 500-year flood zones and San Francisco 100-year precipitation layers. A notable conservative rule is applied: if any part of a parcel is inundated, all units in that parcel are counted as impacted. Finally, to help users compare approaches, the dataset includes fields for CalEnviroScreen 4.0 total score, MTC's Communities of Concern, and UC Berkeley displacement/gentrification typologies.

To score sites, the CVI counts the number of indicators that exceed the 70th and 90th percentile thresholds to determine the site's vulnerability category: Highest, High, Moderate, or Low vulnerability (Table 3.1.4). The CVI is ultimately intended to aid adaptation planning & public outreach.

Table 3.1.3 BCDC CVI tool attributes

Tool/Method:	BCDC Community Vulnerability Index
Website:	Community Vulnerability (BCDC 2020) | California State Geoportal
Variables:	**Social Vulnerability Indicators:** renters, children under 5, very low income, non-U.S. citizens, households without a vehicle, households with a person with a disability, single-parent families, people of color, seniors 65+ living alone, limited English-speaking households, adults without a high school diploma, and severely housing cost-burdened households
	Contamination Vulnerability Indicators: Environmental Effects portion of CalEnviroScreen 4.0 (hazardous cleanup activities, groundwater threats, hazardous waste facilities, impaired water bodies, solid waste sites/facilities)
	Residential Exposure to Sea Level Rise: ART Bay Area sea-level-rise and shoreline analysis, FEMA 100- and 500-year flood zones, San Francisco 100-year precipitation
	Complementary Community Vulnerability Screening Tools: CalEnviroScreen 4.0 total score, MTC's Communities of Concern, UC Berkeley displacement/gentrification typologies
Spatial Resolution:	Census block group (larger than Census block, smaller than Census tract)
Classification system	Highest, High, Moderate, Low, and Not calculated relative to the nine-county Bay Area
Scoring methods	Indicators in each category are weighted equally. Highest social vulnerability: 8 or more social vulnerability indicators with rates in the 70th percentile, and/or six or more social vulnerability indicators with rates in the 90th percentile. High social vulnerability: doesn't meet "highest" category, but has 6-7 indicators in the 70th percentile, and/or 4-5 indicators in the 90th percentile. Moderate social vulnerability: 4-5 indicators in the 70th percentile, and/or 3 indicators in the 90th percentile
Data Source(s):	American Community Survey 2020 data, CalEPA Office of Environmental Health Hazard Assessment (OEHHA) for use in CalEnviroScreen 3.0, joining Metropolitan Transportation Commission 2010 residential parcel data with 2017 ART Bay Area Sea Level Rise and Shoreline Analysis data, FEMA 100 and 500 year flood zone data, and San Francisco 100-year precipitation data, CalEnviroScreen 4.0 total score, Metropolitan Transportation Commission Community of Concern designation, UC Berkeley Displacement and Gentrification Typologies

Table 3.1.4 BCDC CVI scores for 21 test sites

Site Number	Site Name	Social Vulnerability Category
1	Mare Island Naval Shipyard	Low
2	Reaction Products	High
3	Richmond (Point Molate) Naval Supply Center (NSC)	Low
4	Zeneca Richmond AG Products	Highest
5	Berkeley Industrial Complex	Moderate
6	Alameda NAS (Naval Air Station)	High
7	Former J.H. Baxter Facility Alameda	High
8	Associated Aerospace Activities, Inc.	Highest
9	Electro-Forming Co., Hayward	Low
10	Fujicolor Processing	Low
11	FMC Corporation - Newark	Low
12	Ashland Chemical Co., Newark	Low
13	Safety-Kleen of California Inc.	Low
14	Sunnyvale NIROP	Low
15	Moffett Federal Airfield	Moderate
16	Romic Environmental Technologies Corp	Highest
17	G-C Lubricants Co.	Low
18	VWR Facility	Low
19	Hunters Point Naval Shipyard	Moderate
20	Naval Station Treasure Island	High
21	San Quentin State Prison	Moderate

Criterion #3: Healthy Places Index

The Healthy Places Index (HPI), created by the Public Health Alliance of Southern California, is a statewide tool used to shape public health policy in California. The tool, intended to highlight potential public health risk, produces a census-tract composite score of social and place-based conditions that empirically affect life expectancy.

HPI 3.0 organizes 23 risk indicators into eight policy domains: economic indicators, education indicators, social indicators, transportation indicators, healthcare access, neighborhood conditions, housing indicators, and clean environment indicators (Table 3.1.5). Each indicator is Z-scored, indicator Z-scores are averaged to form 8 domain scores, domain weights are estimated via weighted quantile sums regression to maximize association with tract-level life expectancy at birth, and the overall HPI score is computed (the weighted sum of domain scores). The domain weights are economic 35%, education 18%, transportation 13%, social 13%, housing 5.3%, healthcare access 5.3%, clean environment 5.2%, and neighborhood 5.2%. Both the domains and their weights were chosen to reflect widely accepted social determinants of health and to produce an index empirically tied to life expectancy at birth. HPI weights domains using an empirical model that estimates the extent to which each domain predicts life expectancy at birth across tracts. Finally, tracts are ranked and shown as percentiles (Quartile 1 = least healthy conditions, Quartile 4 = most healthy). HPI is positively framed, so higher indicator/domain/HPI values mean healthier community conditions relative to other places in the state (Table 3.1.6).

HPI is an open-data-access policy-oriented platform. It offers an interactive map that shows HPI percentiles and all indicators. Users can request the HPI data file (overall score, domains, indicators) for their own analysis. Additionally, HPI provides policy action guides. Agencies and local partners use HPI to prioritize investments, target outreach, and align policies with policy guides linked to each indicator. We noted that HPI centers on social determinants that drive health and longevity. For example, environmental exposures are a small share of the score (≈5%). By contrast, other SVI tools such as CalEnviroScreen, center pollution burden or population vulnerability more broadly.

Table 3.1.5 HPI tool attributes

Tool/Method:	**Healthy Places Index**
Website:	Healthy Places Index
Variables:	**Economic Indicators:** Percent above 200% FPL, employment (25–64), per-capita income
	Education Indicators: bachelor's degree or higher, high-school enrollment (15–17), pre-school enrollment (age 3–4)
	Social Indicators: Voter turnout (2020), 2020 census response rate
	Transportation Indicators: automobile access, active commuting (walk/bike/transit to work)
	Healthcare Access: insured adults (18–64)
	Neighborhood conditions: park access, tree canopy, retail density
	Housing Indicators: homeownership, housing habitability (complete kitchen & plumbing), severe housing cost burden (low-income renters), severe housing cost burden (low-income owners), uncrowded housing
	Clean Environment Indicators: ozone, PM2.5, diesel PM, drinking-water contaminants (from CalEnviroScreen 4.0
Spatial Resolution:	Census tract
Classification system	Tracts are shown as percentiles relative to the state; Quartile 1 = least healthy conditions, Quartile 4 = most healthy conditions.
Scoring methods	Each indicator is Z-scored, Indicator Z-scores are averaged to form 8 domain scores, Domain weights are estimated via weighted quantile sums regression to maximize association with tract-level life expectancy at birth, Compute the overall HPI score (the weighted sum of domain scores).
Data Source(s):	U.S. Census Bureau, ACS 2015–2019 5-year, UC Berkeley Statewide Database Voter participation (2020 General Election), U.S. Census Bureau 2020 Decennial Census, HUD CHAS 2013–2017, CDPH Office of Health Equity (HCI), Access to Parks indicator, National Land Cover Database, U.S. EPA Smart Location Database v3.0, CalEnviroScreen 4.0

Table 3.1.6 HPI scores for 21 test sites

Site Number	Site Name	Social Vulnerability Percentile
1	Mare Island Naval Shipyard	Data missing
2	Reaction Products	39
3	Richmond (Point Molate) Naval Supply Center (NSC)	8
4	Zeneca Richmond AG Products	92
5	Berkeley Industrial Complex	71
6	Alameda NAS (Naval Air Station)	73
7	Former J.H. Baxter Facility Alameda	48
8	Associated Aerospace Activities, Inc.	67
9	Electro-Forming Co., Hayward	67
10	Fujicolor Processing	80
11	FMC Corporation - Newark	73
12	Ashland Chemical Co., Newark	96
13	Safety-Kleen of California Inc.	Data missing
14	Sunnyvale NIROP	44
15	Moffett Federal Airfield	39
16	Romic Environmental Technologies Corp	85
17	G-C Lubricants Co.	Data missing
18	VWR Facility	51
19	Hunters Point Naval Shipyard	54
20	Naval Station Treasure Island	91
21	San Quentin State Prison	84

3.1.2. Social Vulnerability Index Calculation

After criteria selection and data gathering, we evaluated the 21 sites to assign each a social vulnerability score. Because the SVI tools employ different ranking methods, we developed a scoring protocol to convert rankings from the indices to a 1-9 score (Table 3.1.7), and we used the highest of the three criteria scores for each site. Two of the indices produced percentile rankings, while one produced categorical rankings. For the categorical rankings, we assigned numerical values for each quartile.

Table 3.1.7 Social vulnerability rank conversion to 1-9 score.

Rank	1-9 score
81-100	9
71-80	8
61-70	7
51-60	6
41-50	5
31-40	4
21-30	3
11-20	2
1-10	1

Rank	1-9 score
Highest	9
High	7
Moderate	5
Low	3

3.1.3. Social Vulnerability Index Results

The SVI calculation results and the assigned final digit for each of the 21 sites are presented in Figure 3.1.1 and Table 3.1.8. The spatial distribution of study sites and their Social Vulnerability Index (SVI) scores is shown in Figure 3.1.2. The social vulnerability final score will be included in each site's four-digit screening code to provide a rapid, high-level assessment of potential site risk. Ultimately, through our social vulnerability score, we seek to highlight vulnerable communities that may be exposed to hazardous contaminants and reduce allocative harm. The screening tool can aid just decision-making in contexts such as disaster response and public health remediation.

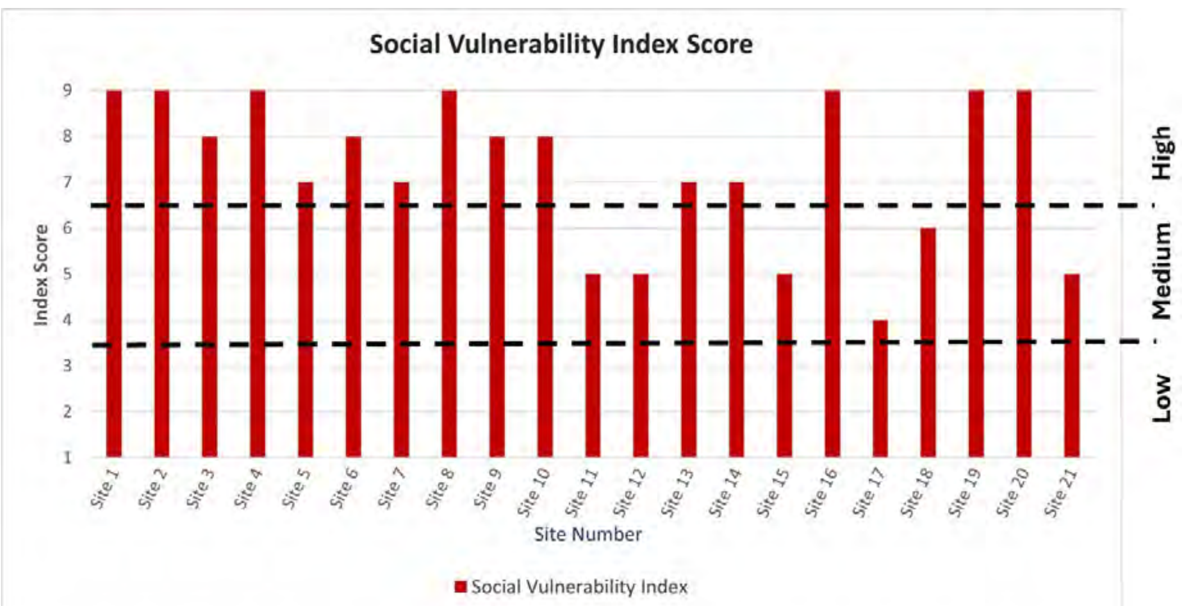


Figure 3.1.1 Social vulnerability Index score for each site. Scores 1-3 indicate low vulnerability, 4-6 indicate medium vulnerability, and 7-9 indicate high vulnerability.

Table 3.1.8 Social vulnerability study site results.

Site Number	Site Names	CalEnviroScreen 4.0 Score	BCDC Community Vulnerability Index Score	Healthy Places Index Score	Final Score
Site 1	Mare Island Naval Shipyard	9	3	6	**9**
Site 2	Reaction Products	9	7	5	**9**
Site 3	Richmond (Point Molate) Naval Supply Center (NSC)	8	3	1	**8**
Site 4	Zeneca Richmond AG Products	8	9	2	**9**
Site 5	Berkeley Industrial Complex	7	5	1	**7**
Site 6	Alameda NAS (Naval Air Station)	8	7	5	**8**
Site 7	Former J.H. Baxter Facility Alameda	7	7	2	**7**
Site 8	Associated Aerospace Activities, Inc.	9	9	4	**9**
Site 9	Electro-Forming Co. - Hayward	8	3	2	**8**
Site 10	Fujicolor Processing	8	3	2	**8**
Site 11	FMC Corporation - Newark	5	3	3	**5**
Site 12	Ashland Chemical Co., Newark	5	3	3	**5**
Site 13	Safety-Kleen of California Inc.	7	3	1	**7**
Site 14	Sunnyvale NIROP	7	3	4	**7**
Site 15	Moffett Federal Airfield	5	5	n/a	**5**
Site 16	Romic Environmental Technologies Corp	7	9	6	**9**
Site 17	G-C Lubricants Co.	4	3	1	**4**
Site 18	VWR Facility	6	3	1	**6**
Site 19	Hunters Point Naval Shipyard	9	5	n/a	**9**
Site 20	Naval Station Treasure Island	9	7	9	**9**
Site 21	San Quentin State Prison	2	5	n/a	**5**

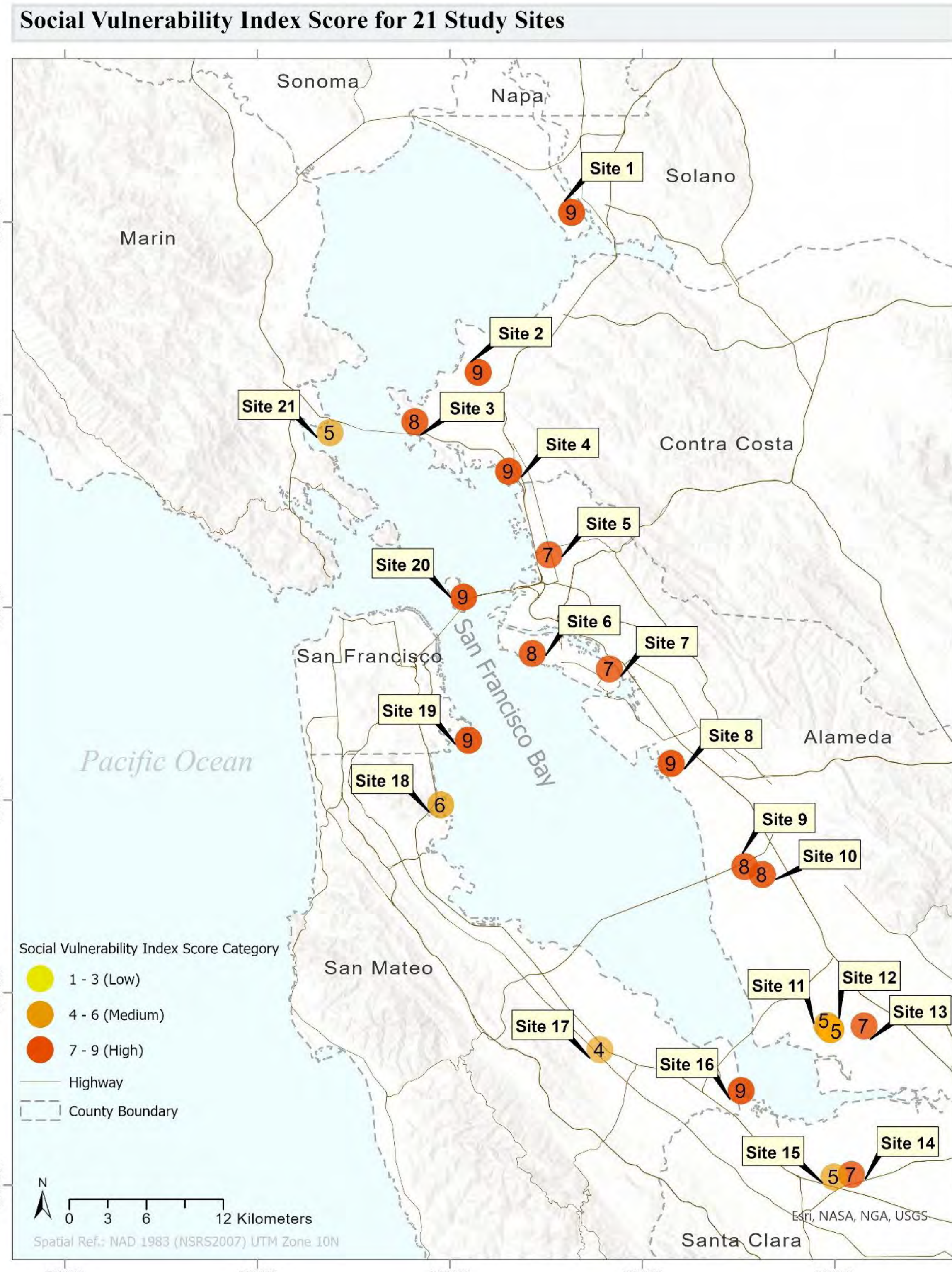


Figure 3.1.2 Spatial distribution of study sites and their Social Vulnerability Index (SVI) scores. Scores 1-3 indicate low vulnerability, 4-6 indicate medium vulnerability, and 7-9 indicate high vulnerability.

3.1.4. Social Vulnerability Index Limitations and Uncertainties

The databases used for the SVI present significant limitations that should be considered for their ethical use. CES is a screening tool that provides relative rankings; it is not a site-specific health risk assessment and not a substitute for a CEQA cumulative-impact analysis. Agencies may need additional tools or datasets depending on the decision context. Some indicators have missing values or rely on models/interpolation (such as ambient groundwater, where monitoring is sparse). Results are at the census-tract scale, which can be used for planning, but may not be precise enough for parcel-level decision-making. The CVI is a regional screening tool, so the site category is not a parcel-level risk assessment or regulatory determination. BCDC recommends caution when considering potential margins of error. For example, the residential exposure method counts all units on a parcel as impacted once flooding is present, which can overcount on large parcels. Because HPI is an area-level screening and planning tool, it does not describe individual people and requires further analysis to determine site-specific conditions. Three of our test sites are missing HPI scores because not all census tracts are included due to eligibility criteria, such as having too few residents or too many group quarters. For example, 7,790 of 8,057 California tracts were eligible in HPI 3.0, so 268 tracts were excluded (136 for low population, 68 for group quarters, 63 for both).

The databases and SVI tools we used are specific to the state of California or the San Francisco Bay Area, so although this social vulnerability ranking method could be replicated elsewhere, each region would need to use tools with data from its respective region.

3.2. Contaminant Characteristics Index

The Contaminant Characteristics Index (CCI) was developed to systematically evaluate the properties of site contaminants that govern their potential to migrate through subsurface environments and pose risks to human and ecological receptors. The index integrates four criteria: contaminant profile, number of contaminant classes, highest current contaminant concentration, and contaminant persistence into a weighted scoring system. Following the DRASTIC framework (Aller et al., 1987), each parameter was assigned a weight proportional to its influence on contaminant transport or exposure potential, ensuring that the overall CCI reflects the relative importance of each factor.

The DRASTIC framework was selected for this study based on its simplicity, transparency, and global recognition as a standardized groundwater assessment framework. Its integration with Geographic Information System (GIS) further enhances its utility for spatial planning and environmental screening (Barbulescu, 2020; Fannakh & Farsang, 2022, Patel et al., 2022). The model has been successfully applied across a range of environmental contexts (Bera et al., 2021; Kirlas et al., 2023; Maqsoom et al., 2021; Shirazi et al., 2012; Wang et al., 2012). In the San Francisco Bay Area, DRASTIC has been used to assess groundwater vulnerability to various contaminants. Pierno (1999) evaluated pesticide and nitrate risks in South Bay aquifers. Mohr (2007) assessed chlorinated solvent contamination, particularly PCE and TCE, linked to historical dry-cleaning sites. Todd and Kennedy-Jenks (2010) expanded on these studies by using a modified DRASTIC model integrated with GIS to evaluate threats from PCE, TCE, and nitrate contamination, informing long-term water resource protection. Jurek (2014) applied a similar method in southern Alameda County to examine PCE risks in the Niles Cone Groundwater Basin. Collectively, these efforts confirm the utility of DRASTIC as a regional screening tool for groundwater vulnerability in both agricultural and industrial contexts.

While the DRASTIC framework provides a foundational method for assessing intrinsic groundwater vulnerability, it requires adaptation to reflect the dynamic conditions introduced by sea level rise, flooding, and extreme weather. The standard model assumes static hydrologic conditions, vertical contaminant migration from the surface, and homogeneous subsurface materials (Aller et al., 1987). These assumptions limit the model’s ability to characterize coastal systems where contamination may originate from buried sources, become mobilized by lateral groundwater shifts, or be influenced by saltwater intrusion and tidal fluctuations (Jiao & Post, 2019). In response to these limitations, this study develops an enhanced DRASTIC-based screening method that can serve as a reliable tool for prioritizing high-risk sites vulnerable to SLR for future investigation and mitigation.

Many VOCs are characterized by their high water solubility and mobility, making them a dominant class of groundwater contaminants at both former and active industrial facilities in the study area. For this study, seven VOCs were considered as possible proxy compounds to represent target contaminant concentrations. This group includes chlorinated solvents such as carbon tetrachloride (CT), tetrachloroethylene (PCE), dichloroethane (DCA), dichloroethene (DCE), trichloroethylene (TCE), and 1,1,1-trichloroethane (1,1,1-TCA). The selection of these chemical proxies was guided by prior research identifying the most widely used and released VOCs over recent decades. Unlike non-chlorinated VOCs such as benzene, toluene, ethylbenzene, and xylenes (BTEX), which tend to degrade under aerobic conditions, chlorinated solvents like PCE, TCE, DCE, DCA, and 1,1,1-TCA are persistent in groundwater due to their low biodegradability, high density, and resistance to rapid natural attenuation. PCE and TCE in particular can remain in subsurface environments for decades and have been detected at moderate concentrations in approximately 5% of primary aquifer systems in the San Francisco Bay Area (Mathany et al., 2009; Parsons et al., 2013). Given their prevalence across the studies, PCE and TCE were selected as contaminant proxies for potential mobilization within shallow, unconfined groundwater.

3.2.1. Method and Materials

For each contaminated site, available records, monitoring data, and regulatory files were reviewed to extract contaminant-specific information. This included chemical properties (solubility, partitioning coefficients, degradation half-lives), regulatory sampling results, and site investigation reports. Each parameter was scored on a categorical rating scale, multiplied by its weighting factor, and summed to provide the site-specific CCI. Weighting factors were determined based on the degree to which each parameter directly or indirectly influences contaminant mobility or exposure risk, with rating values ranging from 1 (very low impact) to 5 (critical impact). The CCI is calculated using the following equation:

$$\mathbf{CCI = (CP \times 5) + (NCC \times 4) + (HCCC \times 5) + (PC \times 5)}$$

Where CCI is the Contaminant Characteristics Index, CP = contaminant profile, NCC = number of contaminant classes, HCCC = highest current contaminant concentration, and PC = persistence of the contaminant. The numbers after the parameters are the weighting factors, in this case, either 4 (amplifying influence) or 5 (direct influence).

Criterion #1: Contaminant Profile (CP)

This parameter represents the intrinsic solubility and mobility of the most soluble contaminants present at a site. Chemicals with high aqueous solubility and low sorption potential score highest, reflecting their enhanced capacity for transport in groundwater systems. Based on project design, the study focused on sites containing trichloroethylene (TCE) or tetrachloroethylene (PCE).

Criterion #2: Number of Contaminant Classes (NCC)

This factor accounts for the diversity of contaminant types (e.g., chlorinated solvents, petroleum hydrocarbons, metals). Sites with multiple contaminant classes receive higher scores because the presence of diverse chemical groups complicates remediation, increases potential chemical reactions, increases co-occurrence risks, and broadens exposure pathways.

Criterion #3: Highest Current Contaminant Concentration (HCCC)

This criterion uses the maximum recent contaminant concentration detected at a site to represent the current potential risk. Higher concentrations are more likely to exceed regulatory thresholds, stabilize contaminant plumes, and persist in groundwater, and therefore receive higher scores. The highest values correspond to free product (defined as 1% concentration for PCE, TCE, or benzene), with scores decreasing in successive orders of magnitude below this benchmark.

Criterion #4: Persistence of Contaminant (PC)

Persistence captures the chemical and biological stability of contaminants under typical subsurface conditions. Compounds resistant to natural attenuation (e.g., chlorinated solvents, PCBs, PFAS) are given higher scores, while those subject to rapid degradation receive lower values.

Contaminant Characteristics Index Data Sources

The data used for CCI were from the California State Water Resources Control Board (SWRCB) Geotracker website (https://geotracker.waterboards.ca.gov/). Site data associated with oversight by the Department of Toxic Substances Control (DTSC) can be found on the EnviroStor website (https://www.envirostor.dtsc.ca.gov/public/).

Fate, transport, and persistence studies by the U.S. Environmental Protection Agency (U.S. EPA) provide information (https://comptox.epa.gov/dashboard/), and chemical characteristics are included in the manufacturer's Chemical Safety Data Sheets (SDS) and information from the Hazard Communication Standard (HCS) (29 CFR 1910.1200(g)), revised in 2012. This document requires that the chemical manufacturer, distributor, or importer provide Safety Data Sheets (SDSs) (formerly MSDSs or Material Safety Data Sheets) for each hazardous chemical to downstream users to communicate information on these hazards [3]. Toxicity, mobility, solubility, and persistence information are included in the SDS and U.S. EPA documents and databases.

3.2.2. Contaminant Characteristics Index Calculation

This structured approach enables the Contaminant Characteristics Index (CCI) to serve as a transparent, reproducible metric for prioritizing site vulnerability based on the nature of contaminants present. By integrating chemical properties, the number of contaminant classes, current maximum concentration levels, and chemical persistence into a single weighted framework, the CCI provides a consistent and objective method for identifying sites most susceptible to contaminant mobilization under sea-level rise and groundwater emergence scenarios. The summary of parameter ratings and weighting factors is presented in Table 3.2.1, and the conversion of the weighted index values to a 1-9 score is presented in Table 3.2.2.

Military bases and industrial sites were indexed and scored as part of the CCI evaluation. The resulting index values (Tables 3.2.3 and 3.2.4) identify the sites exhibiting the highest contaminant characteristic vulnerability. Military installations were classified as complex sites and assigned the highest ratings and weighting factors due to the diversity and persistence of contaminants typically associated with defense-related activities.

[3] https://www.osha.gov/sites/default/files/publications/OSHA3514.pdf

Table 3.2.1 Contaminant Characteristics Index rating and weighting factors.

Contaminant Profile (Solubility and Mobility); Weighting = 5		Contaminant Classes: (VOCs-PFOS, Hydrocarbons, Pesticides, Metals, PAHs); Weighting = 4		Contaminant Concentration: Primary contaminants (proxy for all contaminants), free product (dense non-aqueous phase liquid; DNAPL) with reductions in magnitude. Example of 1% of solubility for TCE and PCE and benzene in parts per million (ppm); Weighting = 5		Persistence of Contaminant (PC) in the Environment; Weighting = 5	
Solubility and Mobility	**Rating**	**Number of Classes**	**Rating**	**HCCC**	**Rating**	**PC**	**Rating**
Chlorinated Solvents (e.g., Tetrachloroethylene, Trichloroethylene): fluorinated organic compounds, radioactive wastes	10	5	10	TCE: 11 mg/L (DNAPL); PCE: 1.5 mg/L (DNAPL); benzene: 17.8 mg/L (LNAPL)	10	Very High Persistence; Per- and Polyfluoroalkyl Substances (PFAS, PFOS)	10
Gasoline and Petroleum Hydrocarbons-	8	4	8	TCE: 1.1 mg/L; PCE: 0.15 mg/L; benzene: 1.78 mg/L	8	High Persistence; PCBs, Chlorinated VOCs (TCE, PCE)	8
Pesticides (e.g., Atrazine, Glyphosate)	6	3	6	TCE: 0.11 mg/L; PCE: 0.015 mg/L; benzene: 0.178 mg/L	6	Moderately High Persistence; SVOCs	6
Toxic Metals (e.g., Lead, Mercury, Arsenic)	4	2	4	TCE: 0.011 mg/L; PCE: 0.0015 mg/L; benzene: 0.0178 mg/L	4	Moderate Persistence; Hydrocarbons, BTEX Compounds	4
Polycyclic Aromatic Hydrocarbons (PAHs)	2	1	2	TCE: 0.0011 mg/L; PCE: 0.00015 mg/L; benzene: 0.00178 mg/L	2	Moderately Low Persistence	3
Polychlorinated biphenyls (PCBs)	1	1	1	TCE: <0.0011 mg/L; PCE: <0.00015 mg/L; benzene: <0.00178 mg/L	1	Low Persistence; Non-Chlorinated VOCs	1

Table 3.2.2 Conversion of the Contaminant Characteristics Index criteria weighted rates to a 1–9 score.

The range of weighted rates	Final Score
174 - 190	9
157 - 173	8
140 - 156	7
123 - 139	6
106 - 122	5
89 - 105	4
72 - 88	3
55 - 71	2
19 - 54	1

3.2.3. Contaminant Characteristics Index Results

The results of the weighted rate calculation, the conversion to a 1 to 9 score, and the assignment of the final index score for each of the 21 sites are presented in Table 3.2.3, Table 3.2.3, and Figure 3.2.1. The contaminant characteristics index score for each site is combined with the scores derived from indexing the other three indexes (SVI, SCI, and ICI) to generate a final four-digit code representing the site's potential priority for management and mitigation measures.

Table 3.2.3 Contaminant Characteristics Index criteria rating, weighting, and Scoring.

Site Number	Site Name	CP r	CP w	CP rw	NCC r	NCC w	NCC rw	HCCC r	HCCC w	HCCC rw	PC r	PC w	PC rw	Total CCI Score
1	Mare Island Naval Shipyard	10	5	50	10	4	40	10	5	50	10	5	50	190
2	Reaction Products	10	5	50	4	4	16	6	5	30	8	5	40	136
3	Richmond (Point Molate) Naval Supply Center (NSC)	10	5	50	10	4	40	10	5	50	10	5	50	190
4	Zeneca Richmond AG Products	10	5	50	10	4	40	10	5	50	8	5	40	180
5	Berkeley Industrial Complex	10	5	50	8	4	32	8	5	40	8	5	40	162
6	Alameda NAS [Naval Air Station]	10	5	50	10	4	40	10	5	50	10	5	50	190
7	Former J.H. Baxter Facility Alameda	8	5	40	8	4	32	8	5	40	4	5	20	132
8	Associated Aerospace Activities, Inc.	10	5	50	8	4	32	6	5	30	8	5	40	152
9	Electro-Forming Co., Hayward	10	5	50	4	4	16	6	5	30	8	5	40	136
10	Fujicolor Processing	10	5	50	4	4	16	6	5	30	8	5	40	136
11	FMC Corporation - Newark	10	5	50	6	4	24	8	5	40	8	5	40	154
12	Ashland Chemical C., Newark	10	5	50	4	4	16	6	5	30	8	5	40	136
13	Safety-Kleen of California Inc.	10	5	50	8	4	32	2	5	10	8	5	40	132
14	Sunnyvale NIROP	10	5	50	4	4	16	10	5	50	8	5	40	156
15	Moffett Federal Airfield	10	5	50	10	4	40	10	5	50	10	5	50	190
16	Romic Environmental Technologies Corp	10	5	50	10	4	40	4	5	20	8	5	40	150
17	G-C Lubricants Co.	10	5	50	8	4	32	8	5	40	8	5	40	162
18	VWR Facility	10	5	50	6	4	24	10	5	50	8	5	40	164
19	Hunters Point Naval Shipyard	10	5	50	10	4	40	10	5	50	10	5	50	190
20	Naval Station Treasure Island	10	5	50	10	4	40	10	5	50	10	5	50	190
21	San Quentin State Prison	10	5	50	4	4	16	2	5	10	8	5	40	116

Key:
Contaminant Profile (CP)
Number of Contaminant Classes (NCC)
Highest Current Contaminant Concentration (HCCC)
Persistence of Contaminant (PC)
r = rating, w = weighting, rw = rated and weighted

Table 3.2.4 Contaminant Characteristics Index and final score (1–9)

Site Number	Site Names	Contaminant Profile Score	Number of Contaminant Classes Score	Highest Current Contaminant Concentration Score	Persistence of Contaminant Score	Final Score
Site 1	Mare Island Naval Shipyard	50	40	40	50	**9***
Site 2	Reaction Products	50	16	30	40	**6**
Site 3	Richmond (Point Molate) Naval Supply Center (NSC)	50	40	40	50	**9***
Site 4	Zeneca Richmond AG Products	50	40	50	40	**9**
Site 5	Berkeley Industrial Complex	50	32	40	40	**8**
Site 6	Alameda NAS (Naval Air Station)	50	40	40	50	**9***
Site 7	Former J.H. Baxter Facility Alameda	40	32	40	20	**6**
Site 8	Associated Aerospace Activities, Inc.	50	32	30	40	**7**
Site 9	Electro-Forming Co. - Hayward	50	16	30	40	**6**
Site 10	Fujicolor Processing	50	16	30	40	**6**
Site 11	FMC Corporation - Newark	50	24	40	40	**7**
Site 12	Ashland Chemical Co., Newark	50	16	30	40	**6**
Site 13	Safety-Kleen of California Inc.	50	32	10	40	**6**
Site 14	Sunnyvale NIROP	50	16	50	40	**7**
Site 15	Moffett Federal Airfield	50	40	40	50	**9***
Site 16	Romic Environmental Technologies Corp	50	40	20	40	**7**
Site 17	G-C Lubricants Co.	50	32	40	40	**8**
Site 18	VWR Facility	50	24	50	40	**8**
Site 19	Hunters Point Naval Shipyard	50	40	40	50	**9***
Site 20	Naval Station Treasure Island	50	40	40	50	**9***
Site 21	San Quentin State Prison	50	16	10	40	**5**

* Military installations (Sites # 1, 3, 6, 15, 19, and 20) were assigned a Contaminant Characteristics Index (CCI) score of 9 (on a 1–9 scale) because they commonly contain multiple potential source areas and contaminant classes within the same property. These sites are often operationally complex, may include historical activities with incomplete records, and may have overlapping releases from different eras and land uses, making the nature and extent of contamination difficult to define without a targeted and more detailed evaluation of the regulatory records.

Accordingly, a score of 9 is used to flag a site where additional subsurface characterization is likely required (e.g., focused records review, expanded sampling, and refined conceptual site modeling) before contaminant conditions can be confidently identified for the vulnerability assessment and possible funding for additional site mitigation efforts.

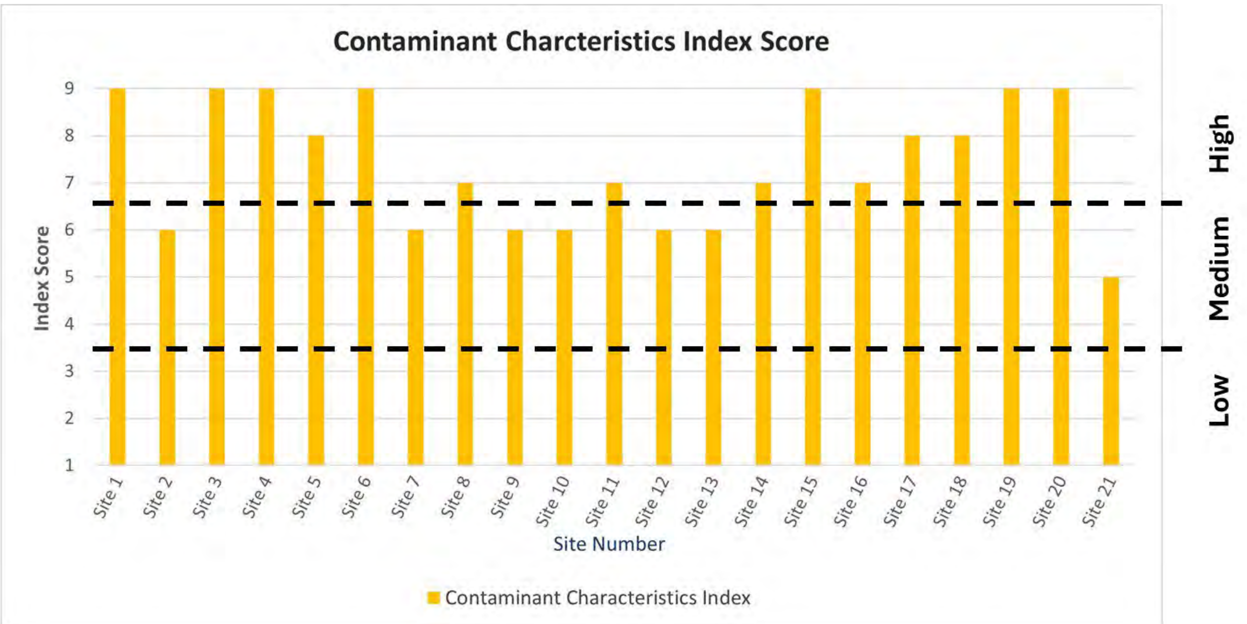


Figure 3.2.1 Contaminant characteristics Index score for each site. Scores 1-3 indicate low vulnerability, 4-6 indicate medium vulnerability, and 7-9 indicate high vulnerability.

3.2.4. Contaminant Characteristics Index Limitations and Uncertainties

The CCI is subject to several limitations and uncertainties inherent in the available datasets and chemical information sources. While the SWRCB Geotracker and DTSC EnviroStor databases provide extensive site-specific records, they may contain incomplete or outdated information regarding contaminant concentrations, plume extent, or cleanup status. The U.S. EPA CompTox and Safety Data Sheet (SDS) databases offer standardized chemical properties such as solubility, mobility, persistence, and toxicity, but these values often reflect laboratory conditions rather than complex field environments. Chemical behavior can vary significantly with soil type, redox conditions, and mixed-contaminant interactions that are not fully captured in regulatory datasets. Additionally, differences in reporting conventions and temporal gaps among databases introduce uncertainty when integrating multiple data sources. As a result, the CCI should be interpreted as a comparative, screening-level indicator of contaminant mobility and persistence rather than an absolute measure of environmental risk. Publicly available site data may be incomplete, inconsistent, or outdated, limiting the reliability of the contaminant characteristics index. To support automated, large-scale indexing, these public datasets would need to systematically report the key contaminant parameters used or derived in this study so that large-scale indexing can be applied rapidly, cost-effectively, and consistently across sites.

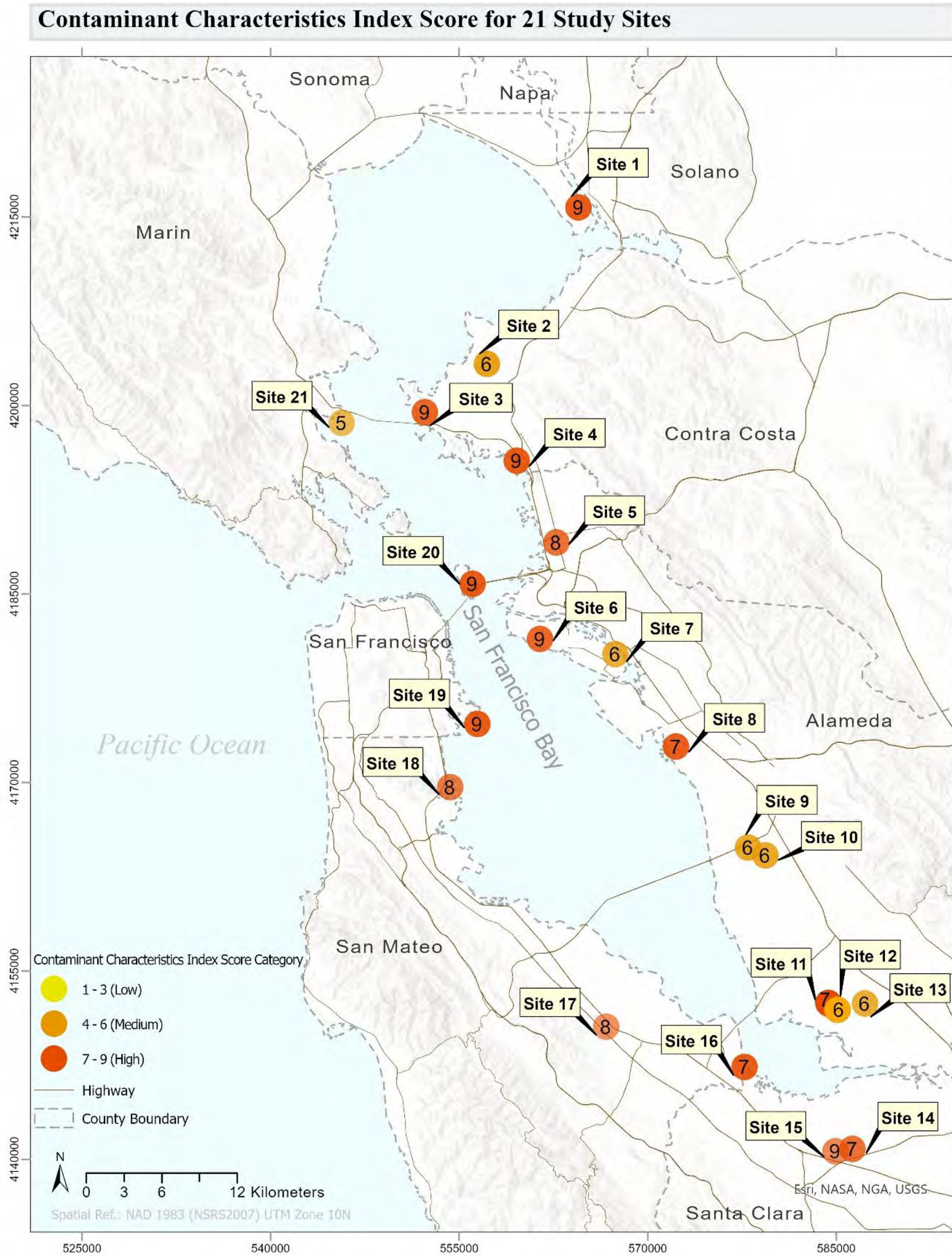


Figure 3.2.2 Spatial distribution of study sites and their Contaminant Characteristics Index (CCI) scores. Scores 1-3 indicate low vulnerability, 4-6 indicate medium vulnerability, and 7-9 indicate high vulnerability.

3.3 Site Characteristics Index

The mobilization of contaminants in sediments due to rising groundwater is influenced by several factors, particularly the site's characteristics. In this study, depth to groundwater, soil permeability, and surface permeability were selected as site characteristics criteria and evaluated along with three other site-specific factors: social vulnerability, contaminant characteristics, and infrastructure condition, in order to identify and index sites for future management prioritization. The following section outlines the method and results of indexing 21 contaminated pilot sites using the selected site characteristics criteria.

3.3.1. Method and Materials

The site characteristic index (SCI) began with selecting criteria informed by a review of literature on groundwater rise effects on contaminant mobilization and exposure, vapor intrusion mechanisms, and discussions within the research team and state agency experts. Most criteria were adopted from the DRASTIC groundwater vulnerability assessment model (Aller et al., 1987), a widely recognized and extensively tested framework for evaluating groundwater susceptibility to contaminants worldwide (Khosravi et al., 2021; Shirazi et al., 2012; Wang et al., 2012), including the United States (Jurek, 2014; Mohr, 2007; Pierno, 1999; Todd Engineers & Kennedy/Jenks Consultants, Inc., 2010), in both its original and modified forms. The DRASTIC model is discussed in detail in Section 3 (Contaminant Characteristics).

Given the core goal of this study - to provide a simplified, rapid, and replicable method for indexing contaminated sites for management prioritization, we selected criteria for which relevant data, particularly spatial datasets, are publicly available or can be accessed quickly for vulnerability assessment. After selecting the criteria, the associated spatial data and relevant reports were gathered from available sources, then prepared and organized into defined categories with specified ranges for each criterion. The criteria were then rated, weighted, and scored, producing a final digit for each of the 21 sites that indicates their status with respect to contaminant mobilization risk from groundwater rise and their priority for management. The selected site characteristics criteria, the rationale for their inclusion, and the indexing method are described below.

Criterion #1: Depth to Groundwater (DTGW)

Sea-level rise-driven groundwater rise can bring the saturated zone into contact with contaminated soil, facilitating the mobilization of contaminants (VOCs in this study) along groundwater flow paths and promoting vapor migration (Barnard et al., 2025; Befus et al., 2020; Hill et al., 2023; May et al., 2023). The proximity of the water table to contaminants buried in the soil, which is common in industrial, commercial, and military zones, increases the likelihood of groundwater rise impact, making depth to groundwater a key factor in contaminant mobilization and exposure (Aller et al., 1987; Crimmins & others, 2023; Eberts et al., 2013; Kauffman & Chapelle, 2010; Paul et al., 2022; Woodard & Curran & Todd Groundwater, 2018). Volatile organic compounds transported by impacted groundwater can migrate far from their source, extending vapor intrusion risk through multiple pathways (Zogorski et al., 2006) (Figure 3.3.1). Hence, depth to groundwater (DTGW) was selected as one of the influential criteria in indexing the vulnerability and exposure of contaminated sites, with categories, ratings, and weightings adapted from Aller et al. (1987) (Table 3.3.1). The groundwater map of the study area and category classification are shown in Figure 3.3.2.

(a) (b)

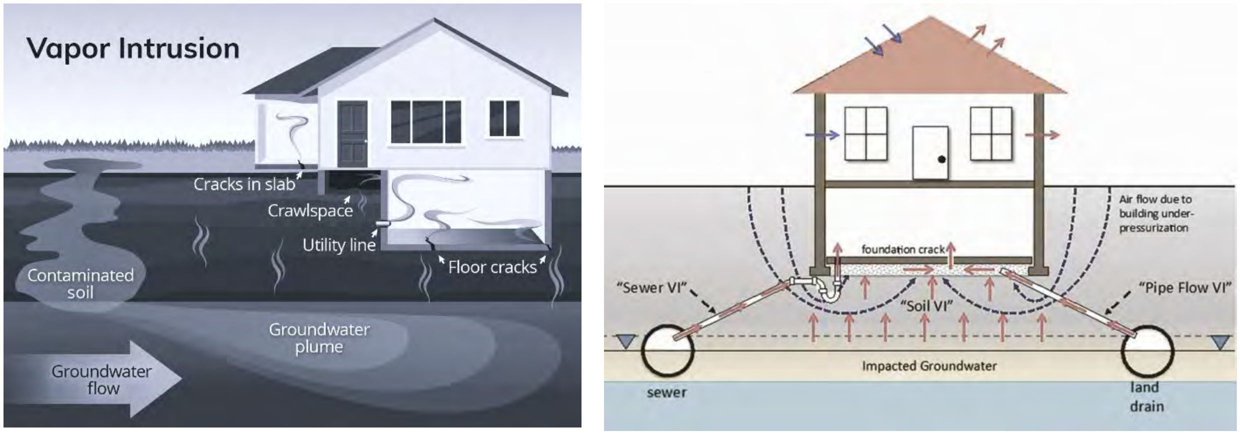


Figure 3.3.1 Figures (a) and (b) illustrate the undersurface vapor intrusion (VI) mechanism- the depth to groundwater, soil permeability, and surface permeability are among the factors that influence subsurface contamination mobilization and vapor intrusion.
Figure source: (a) https://ecology.wa.gov/spills-cleanup/contamination-cleanup/cleanup-sites/uw-tacoma/vapor-intrusion - (b) Guo et al. 2015.

Table 3.3.1 Depth to groundwater categories, rates, and weight.

Depth to Groundwater (within contaminated site parcel)

Category		Rate (1-9) *	Criteria Weight
1	0-1 m	9	
2	1-2 m	8	
3	2-3 m	7	5
4	3-10 m	3	
5	>10 m	1	

* Rating method: If two or more categories occur within the study site boundary (parcel), the site will receive the higher rate.
- Higher rate indicates greater potential for contaminant mobilization.
- The source of the groundwater depth data: Hill et al., 2023, after Befus et al., 2020.

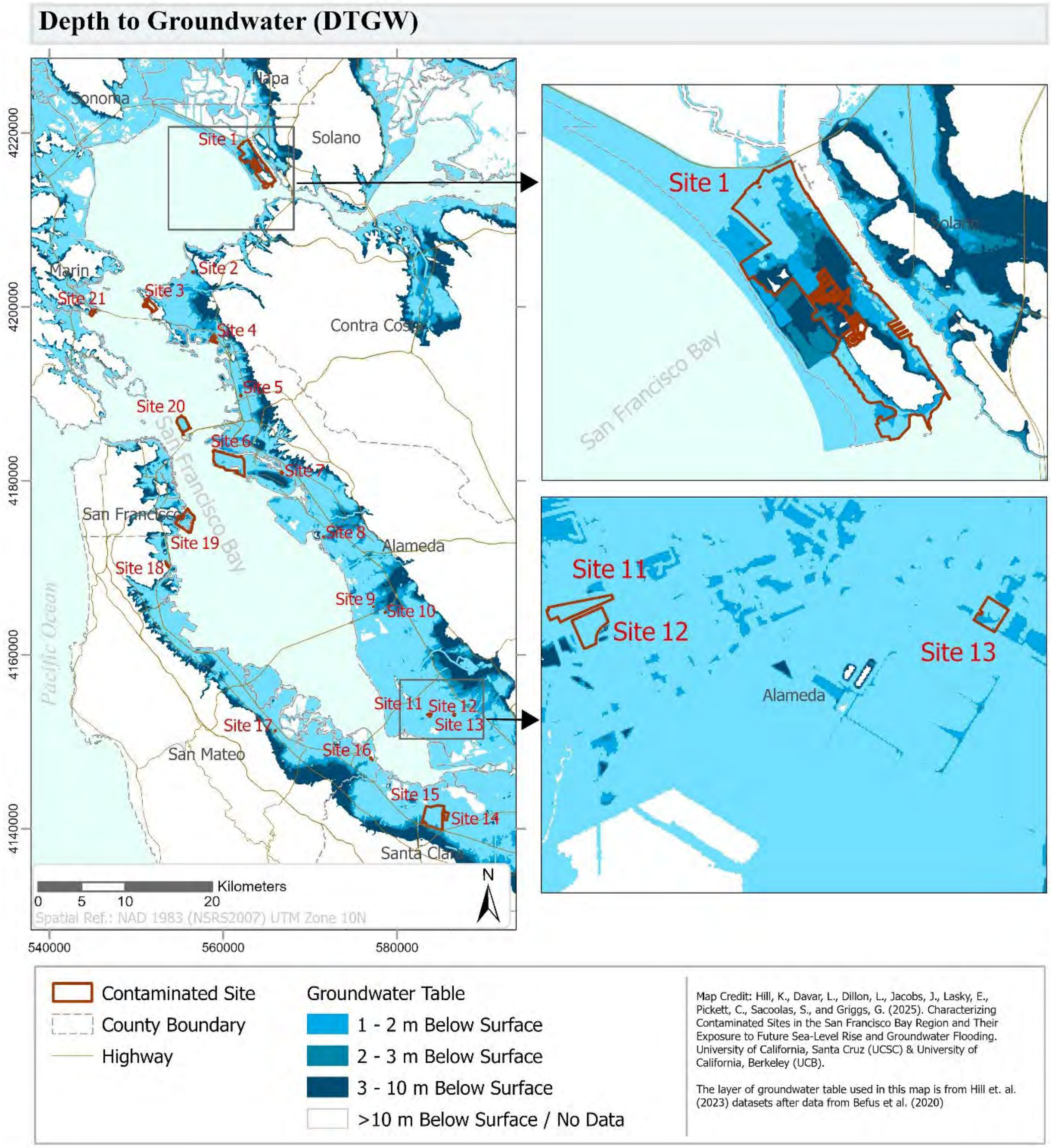


Figure 3.3.2 Map of depth to groundwater in the study area.

Criterion #2: Soil Permeability (SP)

Volatile organic compounds are among the most frequently detected pollutants in soil at abandoned landfills, dumps, and numerous industrial, commercial, and military sites across the United States (Zogorski et al., 2006). When groundwater rises and comes into contact with VOC-contaminated soil, it can mobilize contaminants along groundwater flow paths and release vapors into the soil or other preferential pathways. Three primary vapor intrusion pathways, illustrated in Figure 3.3.3, that can transport vapor into buildings include:

A. Conventional VI pathways – VOCs in soil or groundwater turn into gases, which diffuse upward, accumulate under building foundations, and enter through cracks or openings.
B. Preferential VI pathways – Gases travel through man-made subsurface conduits (e.g., sewer lines, drains, utility ducts) that provide easy access into buildings.
C. Direct infiltration – When buildings sit on contaminated land or on land with fluctuating water tables, VOCs can saturate the foundation and walls, allowing chemicals to enter directly.

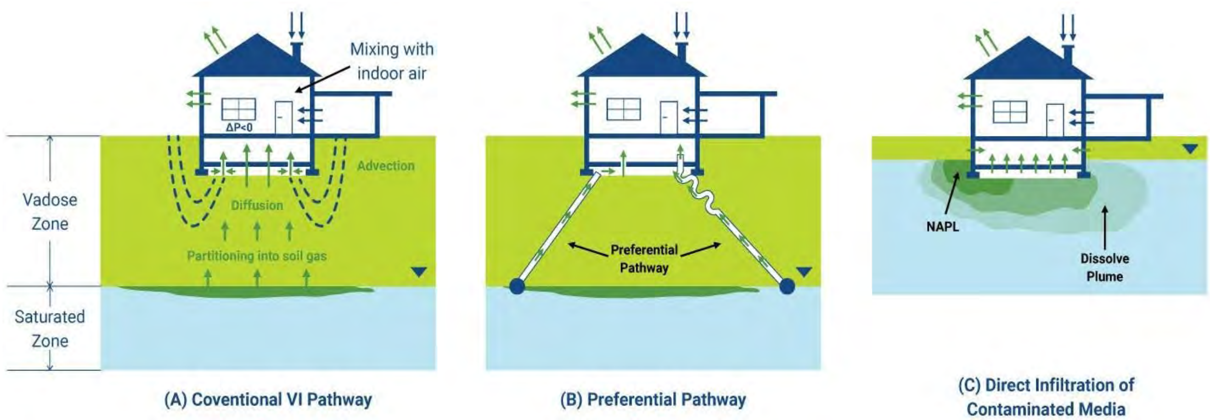


Figure 3.3.3 Three different subsurface Vapor Intrusion (VI) pathways (adopted from Torrent Laboratory Inc. (https://torrentlab.com/heres-how-vapor-intrusion-can-impact-you/)

Considering the groundwater rise-derived contaminant mobilization mechanism and vapor intrusion pathways, soil condition is a critical physical factor influencing contaminant exposure (Environmental Quality Management, Inc., 2004; Guo et al., 2015; Hugh et al., 2017; Ma et al., 2020; Miller et al., 2020; Sultana et al., 2024). Accordingly, soil permeability, corresponding to the Soil Media (S) parameter in the DRASTIC model, was selected as the second criterion for indexing site characteristics. This parameter reflects the ease with which water and contaminants percolate through the soil profile, and vapors migrate toward the ground surface through pore spaces. The soil permeability categories, modified from Aller et al. (1987), are presented in Table 3.3.2. DRASTIC vulnerability ratings show how aquifer vulnerability changes with soil properties. Coarse materials have higher vulnerability scores, allowing contaminants to migrate more easily in the subsurface than fine-grained soils. The data used to assess soil permeability include soil spatial layers (Figures 3.3.4) from the United States Department of Agriculture (USDA) (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture (USDA), 2025) and soil properties from the UC Davis Resource Lab (Walkinshaw et al., 2023). Additionally, soil boring data, available on the websites of the State Water Resources Control Board (SWRCB) [4] and the Department of

[4] https://geotracker.waterboards.ca.gov/

Toxic Substances Control (DTSC)[5], were reviewed by the research team through a technical judgment process to assess the consistency of soil data across sources.

Table 3.3.2 Soil Permeability (SP) categories, rates, and weight.

Soil Permeability (within site boundary)			
	Category	Rate (1-9)*	Criteria Weight
1	Sand or gravel/well-drained (very high)	9	
2	Sand/loam/moderately to well drained (high)	7	
3	Fine silty clay loam/poorly drained (moderate)	5	3
4	Fine silty clay/made land/urban land/artificial fill/poorly drained (low)	3	
5	Impermeable surfacing or confining layer (very low)	1	

* Rating method:
a. If a single category covers more than 70 percent of the area/site parcel, then assign its associated rate.
b. If two or more categories occur within the site boundary, then the site will receive the higher rate.
Note: Due to the complexity of the soil data and the study area, technical judgment played an essential role in assigning the appropriate rate to each study site.
- Higher rate indicates greater potential for contaminant mobilization.
- Soil Data Source: https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

[5] https://www.envirostor.dtsc.ca.gov/public

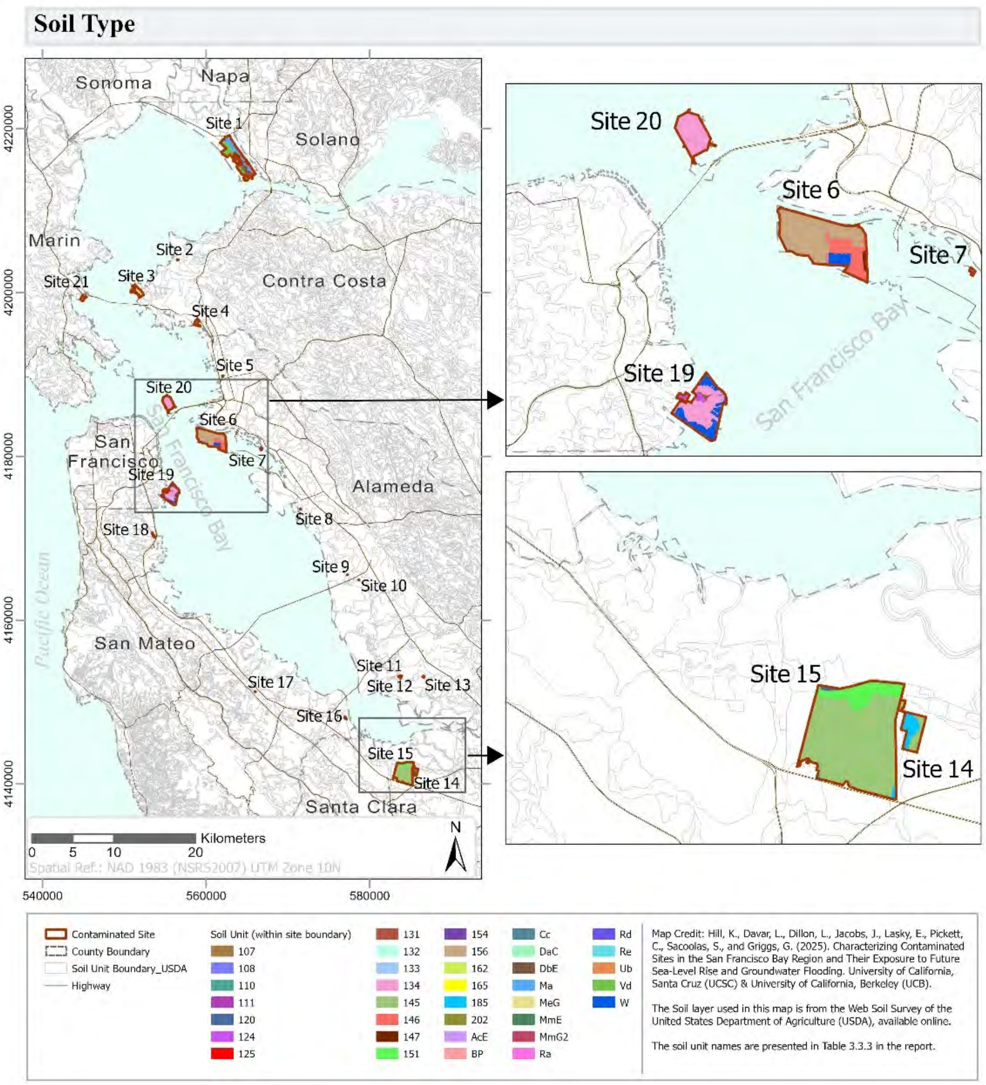


Figure 3.3.4 Map of soil type, used in soil permeability analysis and rating (see Table 3.3.2). The soil Unit names are presented in Table 3.3.3.

Table 3.3.3 The soil unit names and drainage classes.

Map Unit Symbol	Map Unit Name + Drainage class	Map Unit Symbol	Map Unit Name + Drainage class	Map Unit Symbol	Map Unit Name + Drainage class
107	Clear Lake clay - Poorly drained	146	Urban land	DaC	Diablo-Ayar clays - Well drained
108	Botella-Urban land complex - Well drained	147	Urban land-Baywood complex - Somewhat poorly drained	DbE	Dibble-Los Osos loams - Well drained
110	Candlestick-Kron-Buriburi complex - Well drained	151	Embarcadero silty clay loam - Very poorly drained	Ma	Made land - Well drained
111	Danville silty clay loam - Well drained	154	Willows clay - Poorly drained	MeG	Millsholm loam, moist - Well drained
120	Aquic Xerorthents, bay mud subtratum - Poorly drained	156	Xeropsamments, fill	MmE	Millsholm loam - Well drained
124	Orthents, cut and fill-Urban land complex - Well drained	162	Saurin-Bonnydoon complex - Well drained	MmG2	Millsholm loam - Well drained
125	Marvin silt loam - Somewhat poorly drained	165	Saurin-Urban land-Bonnydoon complex - Well drained	Ra	Novato silty clay- Very poorly drained
131	Urban land	185	Urban Land - Bayshore complex - Poorly drained	Rd	Reyes silty clay loam - Poorly drained
132	Urban land-Orthents, cut and fill complex - Well drained	202	Urban land-Xerorthents complex	Re	Reyes silty clay - Poorly drained
133	Pescadero clay - Poorly drained	AcE	Altamont clay - Well drained	Ub	Urban land
134	Urban land-Orthents, reclaimed complex - Well drained	BP	Borrow pit	Vd	Valdez silty clay loam - Poorly drained
145	Urbanland-Hangerone complex - Poorly drained	Cc	Clear Lake clay - Poorly drained	W	Water

Criterion #3: Impervious Surface/Surficial Material Permeability (SMP)

Surface infiltration is a key pathway for mobilizing soil contaminants. Water infiltrating permeable land surfaces percolates through the unsaturated zone, often called the vadose zone, until it reaches the saturated zone at the top of the groundwater table (Queensland Government, 2017). VOCs may move through the unsaturated zone via recharge, soil vapor, or as a non-aqueous-phase liquid (NAPL). Rapid infiltration, which reduces residence time in the unsaturated zone, can increase VOC flux to the groundwater. In coastal areas prone to groundwater rise, water from precipitation, irrigation, or flooding can transport contaminants toward shallow water tables, where a thin vadose zone accelerates migration and elevates contamination risk (Appelo & Postma, 2004; Fetter, 2018).

Hence, surface permeability, which influences the rate and extent of contaminant transport, was selected as the third criterion for indexing site characteristics. Unlike the standard DRASTIC model, Surface Material Permeability (SMP) is not explicitly included. This study used data from the USGS, which employs remote sensing to assess impervious surfaces. Surface permeability is influenced by soil type, land cover, and surface conditions: sandy or gravelly soils allow rapid infiltration, whereas clay or compacted soils restrict it, increasing surface runoff and flood risk. Impervious surfaces further limit infiltration, while vegetation enhances it by preventing compaction. Engineered fills, when compacted to 95%, substantially reduce permeability. Categories, rating ranges, and weighting for surface permeability are summarized in Table 3.3.4, with Figure 3.3.5 illustrating the impervious (surface permeability) map of the study area.

Table 3.3.4 Impervious Surface (Surface Material Permeability)

Impervious Surface/ Surface Material Permeability (within site boundary)			
	Category	Rate (1-9)*	Criteria Weight
1	0 – 20 % Impervious Surface	9	
2	20 - 40 % Impervious Surface	7	
3	40 – 60 % percent Impervious Surface	5	2
4	60 – 80 % Impervious Surface	3	
5	80 – 100 % Impervious Surface	1	

*** Rating method:**
a. If a single category covers more than 80 percent of the area/site parcel, then assign its associated rate.
b. If categories 1 and 2 collectively cover more than 60 percent of the area/site parcel, then assign rate 7.
c. If categories 2 and 3 collectively cover more than 60 percent of the area/site parcel, then assign rate 5.
d. If categories 3 and 4 or 4 and 5 collectively cover more than 60 percent of the area/site parcel, then assign rate 3.
c. When more than two categories occur within a site parcel and have comparable coverage areas, assign the rate corresponding to the two categories with the higher rates, in accordance with the rating method.
- A higher rate indicates greater potential for contaminant mobilization.
- Data source: USGS, Annual National Land Cover Database (NLCD) Collection 1 Impervious Descriptor.

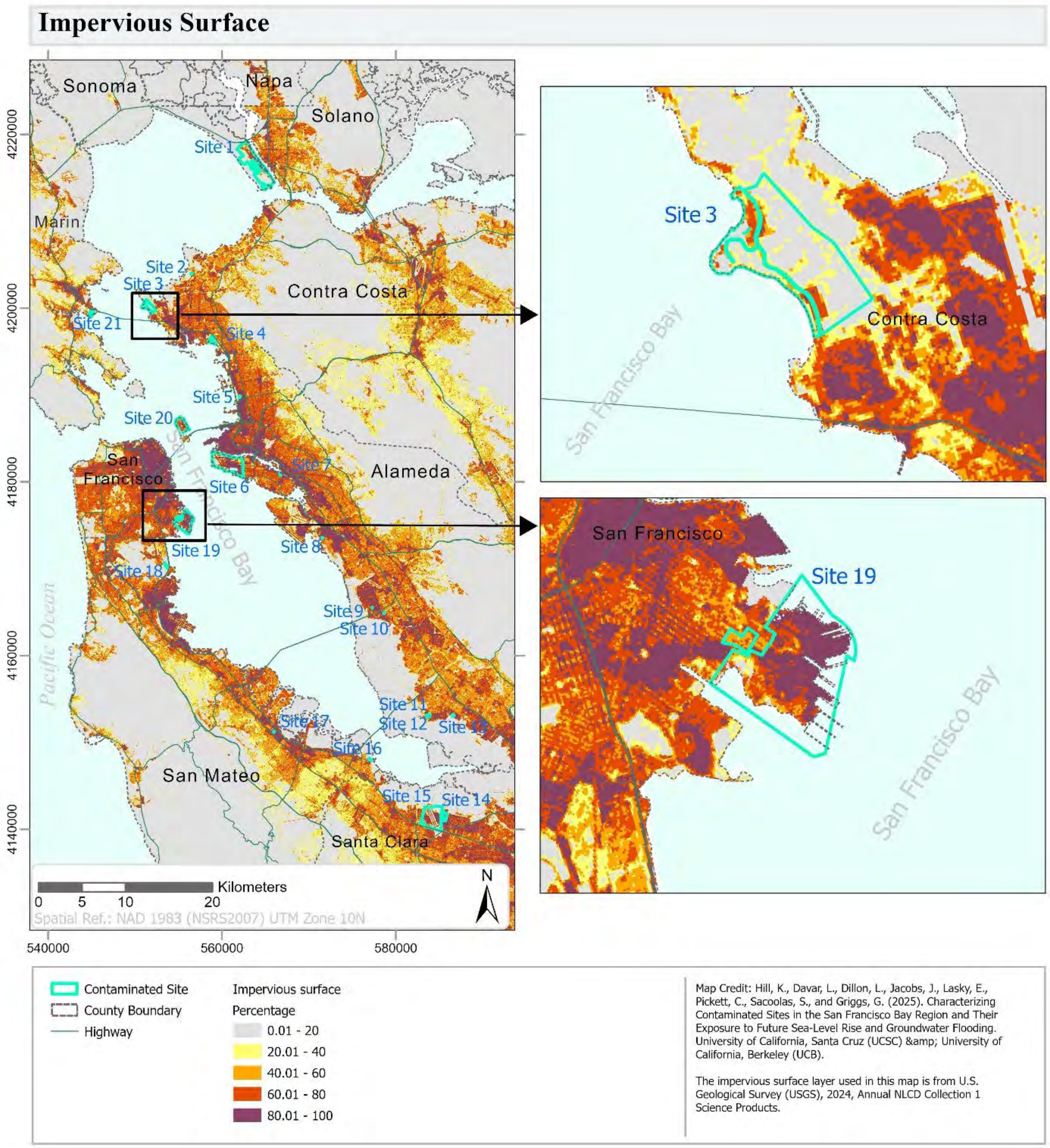


Figure 3.3.5 The map of impervious surfaces (surface permeability).

Site Characteristics Index Data Sources

For the selected criteria, we used publicly available data, which are cited in Table 3.3.5.

Table 3.3.5 Site characteristics criteria data sources.

Data Type (Criteria)	Data Source	Title	Link
Groundwater depth	Befus et al., 2020	Rising Coastal Groundwater as a Result of Sea-Level Rise Will Influence Contaminated Coastal Sites and Underground Infrastructure	https://www.sciencebase.gov/catalog/item/5bda14abe4b0b3fc5cec39b0
Rising groundwater and current groundwater depth	Hill et al., 2023	Rising Coastal Groundwater as a Result of Sea-Level Rise Will Influence Contaminated Coastal Sites and Underground Infrastructure	https://datadryad.org/stash/dataset/doi:10.6078/D15X4N
Soil permeability	United States Department of Agriculture (USDA).	Web Soil Survey	https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx
	UC Davis - California Soil Resource Lab	Soil Properties	https://casoilresource.lawr.ucdavis.edu/soil-properties/
Impervious surface data	U.S. Geological Survey (USGS)	Annual National Land Cover Database (NLCD) Collection 1 Impervious Descriptor	https://www.sciencebase.gov/catalog/item/664e0db2d34e702fe874457d

3.3.2. Site Characteristics Index Calculation

After criteria selection, data gathering, preparation, and categorization, 21 sites were evaluated, assigning ratings and weightings to three key parameters: depth to groundwater (maximum rating of 9, weighting of 5), surface permeability (maximum rating of 9, weighting of 2), and soil permeability (maximum rating of 9, weighting of 3). The specific ratings and weightings assigned to each of the 21 sites are detailed in Tables 3.3.1, 3.3.2, and 3.3.4. The weightings (5, 3, and 2) reflect the relative significance of each factor in influencing contaminants mobilization and groundwater vulnerability. Further details on parameter weighting are provided in Table 3.3.6.

Then the SCI was calculated by integrating these three criteria using a weighted formula (Equation) as follows:

Equation A: $$SCI = (DTGW \times 5) + (SP \times 3) + (SMP \times 2)$$

Where:
SCI = Site Characteristics Index
DTGW = Depth to Groundwater
SP = Soil Permeability
SMP = Surface Material Permeability

For the final single-digit score for each site, the scores resulting from the SCI calculation (Equation A) were categorized and converted to a single digit (Table 3.3.7).

Table 3.3.6. Site characteristics criteria selection, and their weightings justifications.

Criteria	Index	Influence	Influence Type	Weight	Justification
Depth to Groundwater	Site Characteristics Index (from DRASTIC)	High Influence	Direct Influence	5	A shallow depth increases vulnerability as contaminants have a shorter pathway to groundwater and significantly increases the risk of contaminant migration.
Soil Permeability	Site Characteristics Index (from DRASTIC)	Medium Influence	Dependent Influence	3	Affects contaminant transport, which varies with material properties like sand or clay.
Surface Material Permeability	Site Characteristics Index (From Literature and DRASTIC concept)	Lower Influence	Amplifying Influence	2	Impervious surfaces concentrate runoff while permeable surfaces increase contaminant infiltration and amplify risk.

Table 3.3.7. Site characteristics, criteria score range, and conversion to the final score

Score range (rate*weight)		Final Score
Low	High	
89	100	9
78	88	8
67	77	7
56	66	6
45	55	5
34	44	4
23	33	3
12	22	2
1	11	1

3.3.3. Site Characteristics Index Results

The results of applying these criteria to calculate the Site Characteristics Index (SCI) score and the assigned final score for each of the 21 sites are presented in Table 3.3.8, Figure 3.3.6, and Figure 3.3.7. The site characteristics score for each site will be combined with the scores derived from indexing the other three characteristics (social, contaminant, and infrastructure) to generate a final four-digit screening code that represents the site's potential priority for management and mitigation measures.

Table 3.3.8 Site characteristics criteria rating, weight, score, and final score.

Site Number	Site Names	Depth to Groundwater Rating	W	Soil Permeability Rating	W	Surface Permeability Rating	W	TOTAL (RxW)	Final Score*
Site 1	Mare Island Naval Shipyard	9	5	3	3	7	2	68	**7**
Site 2	Reaction Products	9	5	3	3	5	2	64	**6**
Site 3	Richmond (Point Molate) Naval Supply Center (NSC)	3	5	7	3	7	2	50	**5**
Site 4	Zeneca Richmond AG Products	9	5	3	3	3	2	60	**6**
Site 5	Berkeley Industrial Complex	8	5	3	3	1	2	51	**5**
Site 6	Alameda NAS (Naval Air Station)	9	5	3	3	3	2	60	**6**
Site 7	Former J.H. Baxter Facility Alameda	8	5	3	3	1	2	51	**5**
Site 8	Associated Aerospace Activities, Inc.	8	5	5	3	1	2	57	**6**
Site 9	Electro-Forming Co., Hayward	8	5	3	3	1	2	51	**5**
Site 10	Fujicolor Processing	9	5	3	3	1	2	56	**6**
Site 11	FMC Corporation - Newark	9	5	5	3	3	2	66	**6**
Site 12	Ashland Chemical Co., Newark	9	5	5	3	3	2	66	**6**
Site 13	Safety-Kleen of California Inc.	9	5	3	3	3	2	60	**6**
Site 14	Sunnyvale NIROP	9	5	3	3	1	2	56	**6**
Site 15	Moffett Federal Airfield	9	5	3	3	7	2	68	**7**
Site 16	Romic Environmental Technologies Corp	9	5	5	3	1	2	62	**6**
Site 17	G-C Lubricants Co.	9	5	3	3	1	2	56	**6**
Site 18	VWR Facility	9	5	3	3	3	2	60	**6**
Site 19	Hunters Point Naval Shipyard	9	5	3	3	3	2	60	**6**
Site 20	Naval Station Treasure Island	9	5	3	3	3	2	60	**6**
Site 21	San Quentin State Prison	3	5	3	3	3	2	30	**3**

* A higher score indicates a greater vulnerability of the site to contaminant mobility driven by groundwater rise.

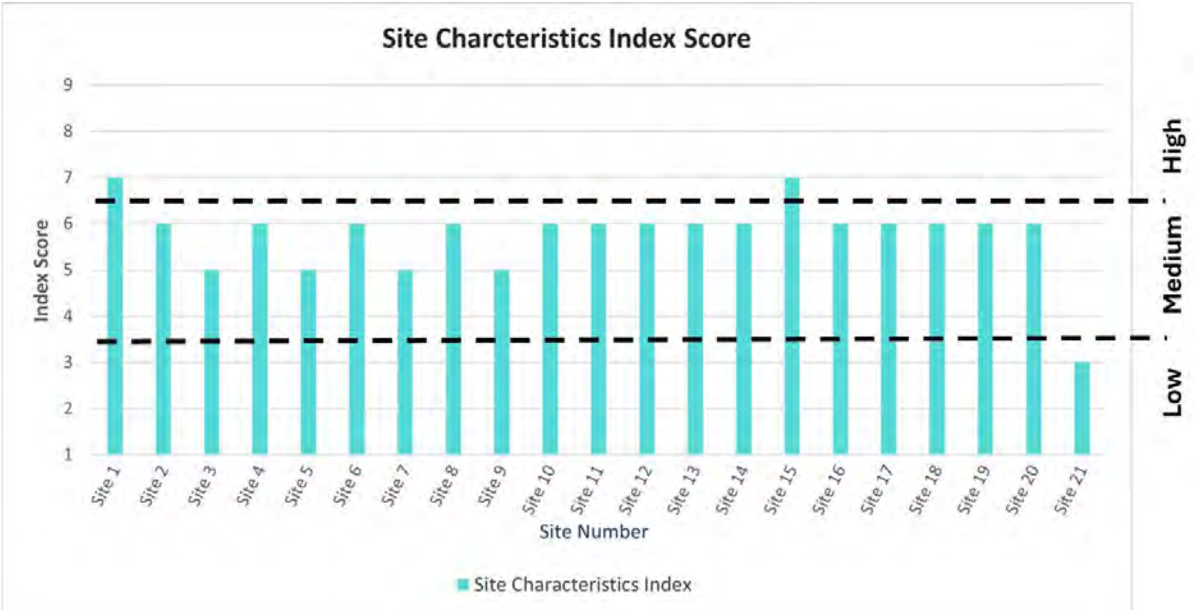


Figure 3.3.6 Site characteristics Index score for each site. Scores 1-3 indicate low vulnerability, 4-6 indicate medium vulnerability, and 7-9 indicate high vulnerability.

3.3.4. Site Characteristics Index Limitations and Uncertainties

The resolution and complexity of the available soil maps posed a key limitation in this analysis. The coarse spatial resolution, along with the need to prepare and refine the soil layers attribute tables according to the indexing categories, ranges, and soil types defined for site characterization, required expert-driven interpretation. This process introduces subjectivity and limits the replicability of the method through automation. In several cases, multiple soil units were present within a single site boundary, adding further uncertainty in selecting representative characteristics. These challenges are particularly pronounced in the San Francisco Bay region, where extensive areas are built on artificial fill with highly variable composition and uncertain subsurface properties. To enable the developed site-characteristics indexing framework to be applied to a larger number of sites, these inherent limitations must be addressed through additional efforts to refine spatial resolution and improve soil unit classification, allowing for more precise and consistent characterization of soil permeability.

In addition, the site characteristics analysis primarily relies on spatial data; therefore, the absence of a spatial layer defining precise site locations and boundaries constrains site characterization, spatial analysis, and the efficient automation of screening tools needed to prioritize large numbers of contaminated sites for further investigation and management.

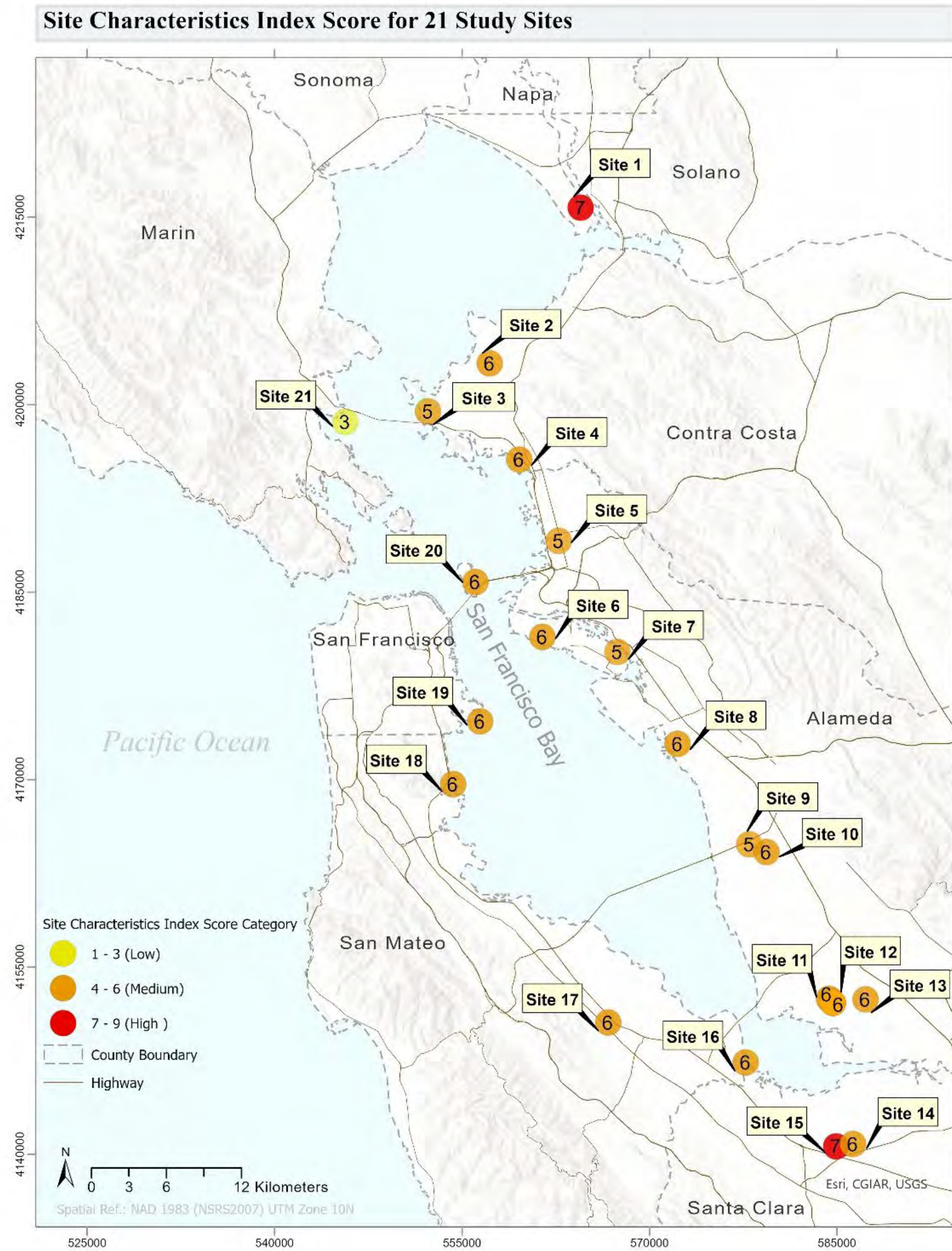


Figure 3.3.7 Spatial distribution of study sites and Site Characteristics Index (SCI) score for each site. Scores 1-3 indicate low vulnerability, 4-6 indicate medium vulnerability, and 7-9 indicate high vulnerability.

3.4. Infrastructure Characteristics Index

Modeling the spatial zone in which groundwater contaminants could flow from contaminated sites into the surrounding area (the flowzone) provides insights into the potential trajectory of contamination. In this section, flowzone models were developed and overlaid with sewer system proxies and building footprints to identify and characterize building use types that are potentially exposed to harmful contaminants. Buildings of particular interest were those with land use designations associated with susceptible populations, such as residences, schools, and eldercare centers. The resulting infrastructure characteristics index (ICI) score reflects building age and building use type, both of which may influence the risk of vapor intrusion and associated health effects.

3.4.1. Methods and Materials

The selected infrastructure characteristics criteria, the rationale for their inclusion, and the indexing method are described below.

Criterion #1: Contaminant Flowzone

To model the hydrogeologic fate of dissolved VOCs in groundwater that originates within contaminated parcel boundaries, we used MODPATH 7 (Pollock, 2016). The particle tracking was based on high-resolution (10 m x 10 m) one-layer, steady-state groundwater flow models conducted previously to quantify unconfined groundwater responses to sea-level rise under a 1m SLR scenario (Befus et al., 2020) (Figure 3.4.1). These models used a homogeneous, isotropic hydraulic conductivity of 1 m/day and a constant head for San Francisco Bay, set to the mean higher high water (MHHW) tidal datum that was raised to simulate SLR. No groundwater pumping or other remediation activities (e.g., enhanced drainage or impermeable barriers) were included in these models.

For particle tracking, each site parcel identified within the San Francisco Bay Area was seeded with one particle per model grid cell, entering the flow model via recharge at the top of the model. The San Francisco Bay Region's groundwater basins are composed of aquifer materials ranging from unconsolidated fill to fractured metamorphic rock complexes and surficial geologic features (e.g., paleochannels, alluvial fans) that influence the movement of groundwater flow (Elder, 2013). Therefore, all particles were allowed to flow until either a strong sink or a discharge location caused particles to leave the model, and the San Francisco Bay was set as a secondary stop condition for particles. MODPATH 7 calculates sub-grid-scale particle trajectories, such that each trajectory can include multiple vertices within a single groundwater cell (Pollock, 2016).

Criterion #2: Sewer Connectivity Model for Potentially Exposed Buildings

We developed a spatial model to identify potential infiltration locations and transport of VOCs through sewer systems into buildings, using particle tracking paths for the 21 sites. Based on the pathline perimeter, we generated a spatial footprint of a potential plume at each contaminated site, assuming contaminant concentrations and site conditions allowed. We defined this as the potential VOC flowzone. Since spatial data for sewer lines is not publicly available or collated for multiple jurisdictions across the San Francisco Bay Area, we used roads as proxies for sewer lines (OpenStreetMap contributors, 2025), with the exclusion of "road" types such as stairs, pedestrian walkways, interstate highways and highway ramps that were unlikely to have sewer lines beneath them (Figure 3.4.1).

Beckley and McHugh (2020) used tracers to estimate the distance contaminants may travel through sewer systems based on sewer elevation gradients, providing a maximum uphill distance of 228.6 meters (750 feet) and a downhill distance of 685.8 meters (2250 feet) to represent the farthest distance that VOCs might travel through a sewer line. To establish the likely slope direction of a sewer line, our automated method samples land surface elevations at 76.2-meter (250 feet) intervals, starting from 0 and extending up to 685.8 meters from an intersection of the flowline footprint features with streets (Figure 3.4.1). Elevation data was obtained from the USGS 10-meter resolution DEM topographic layer (USGS, 2017). If the difference in the extracted elevations at 0m and 228.6m was negative, indicating a downhill slope, our model extended the potential VOC travel distance by 685.8m along the street network. If the difference in the extracted elevations at 0m and 228.6m was positive, indicating an uphill slope, the model limited the potential VOC travel distance to 228.6m along the street.

Two special conditions received unique treatments. Of the nine counties in the San Francisco Bay Area, San Francisco County is unique in having a combined sanitary sewer and stormwater system. This system contains maintenance hole covers with grate openings that allow gases to escape from the underground pipes. To represent this difference, we modified the model for San Francisco County to restrict VOC movement to within the block of origin. Our assumption was that pipes would convey VOCs only as far as the nearest road intersection from the modeled flowzone. The second exception was made where converging flowline footprints were produced at sites 11 and 12 (FMC Corporation and Ashland Chemical), and at sites 14 and 15 (Sunnyvale NIROP and Moffett Federal Airfield). To recognize the likely convergence of VOC migration pathways, sites 11 and 12 were grouped and treated as a single site, as were sites 14 and 15. These grouped sites are referenced in this analysis as sites 11 and 14, respectively (Figure 3.4.2).

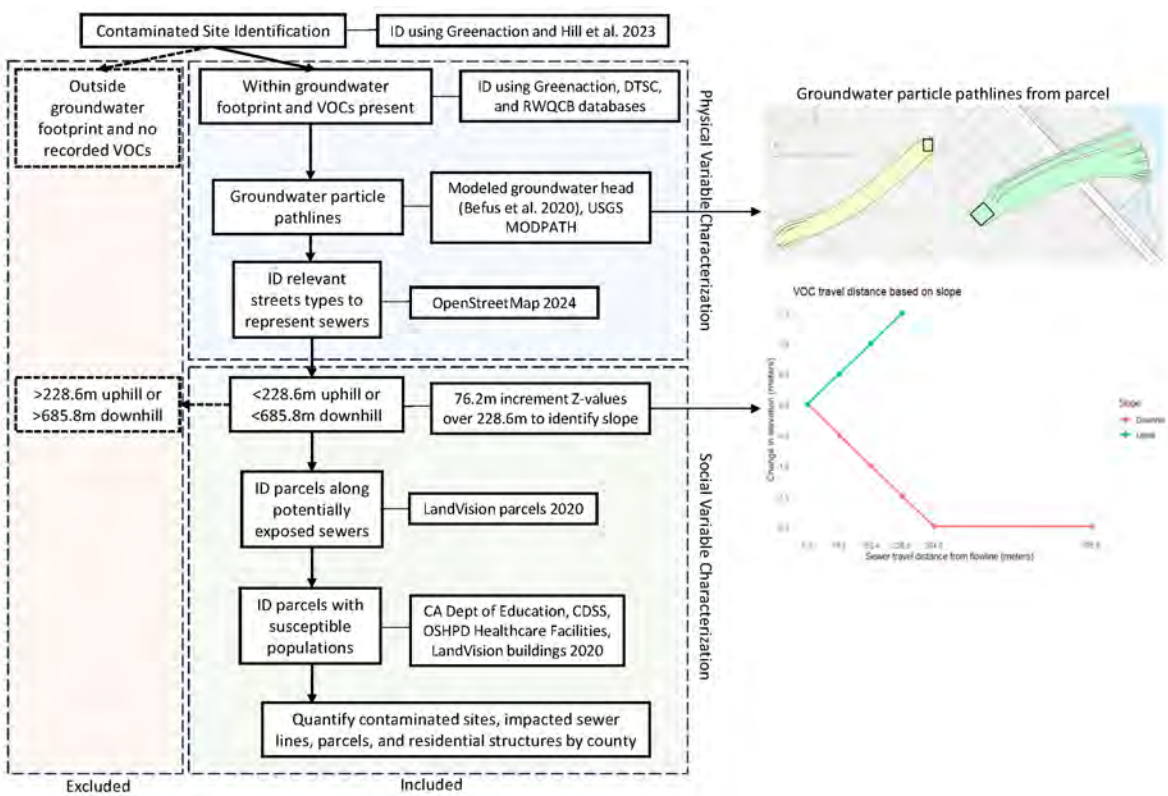


Figure 3.4.1 Flow chart of the different phases of modeling and data sources completed and used in this study.

To identify buildings that could be impacted by vapor intrusion from VOCs in sanitary sewer pipes or trenches, we used parcel data to map buildings in proximity to sewer lines. Sewer laterals typically extend across private parcels to connect buildings to main sewer lines. We created a 30m buffer around main sewer lines to account for the typical distance between main sewer lines and the building footprints used in this study (Figure 3.4.3).

Criterion #3: Identifying and Characterizing Vulnerable Buildings

We identified the structures located within the flow zones from the main sewer lines. Parcel data from Landvision was used to classify buildings' uses (LightBox, 2019). The total number of potentially impacted buildings was determined for each of the 17 individual and four combined sites. Our building use categories highlight residential buildings, schools, and daycares because they may house populations particularly vulnerable to the health effects of VOC inhalation (Kuang et al., 2021; Madaniyazi et al., 2022) (Figure 3.4.3).

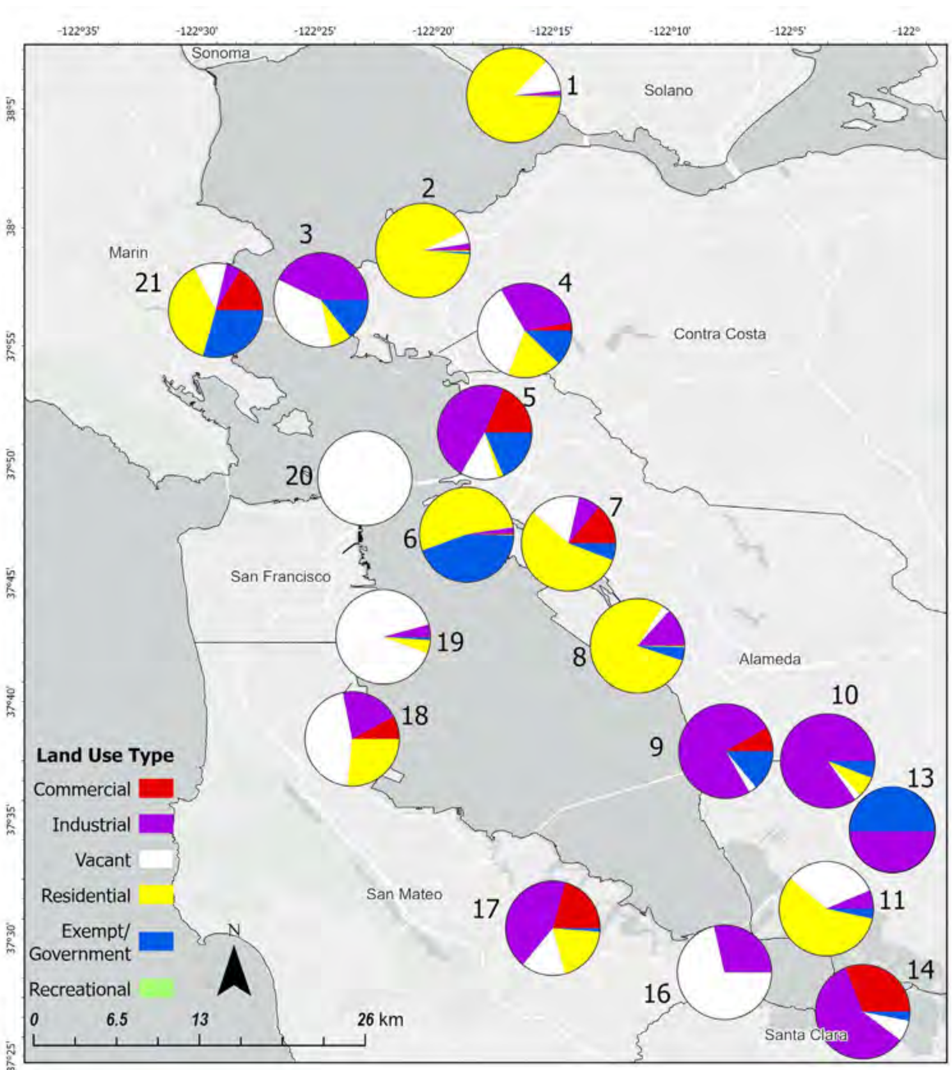


Figure 3.4.2 Pie charts show the proportion of each land use category within each property point that may be exposed to new vapor intrusion risks in the vicinity of each contaminated site based on the ICI model.

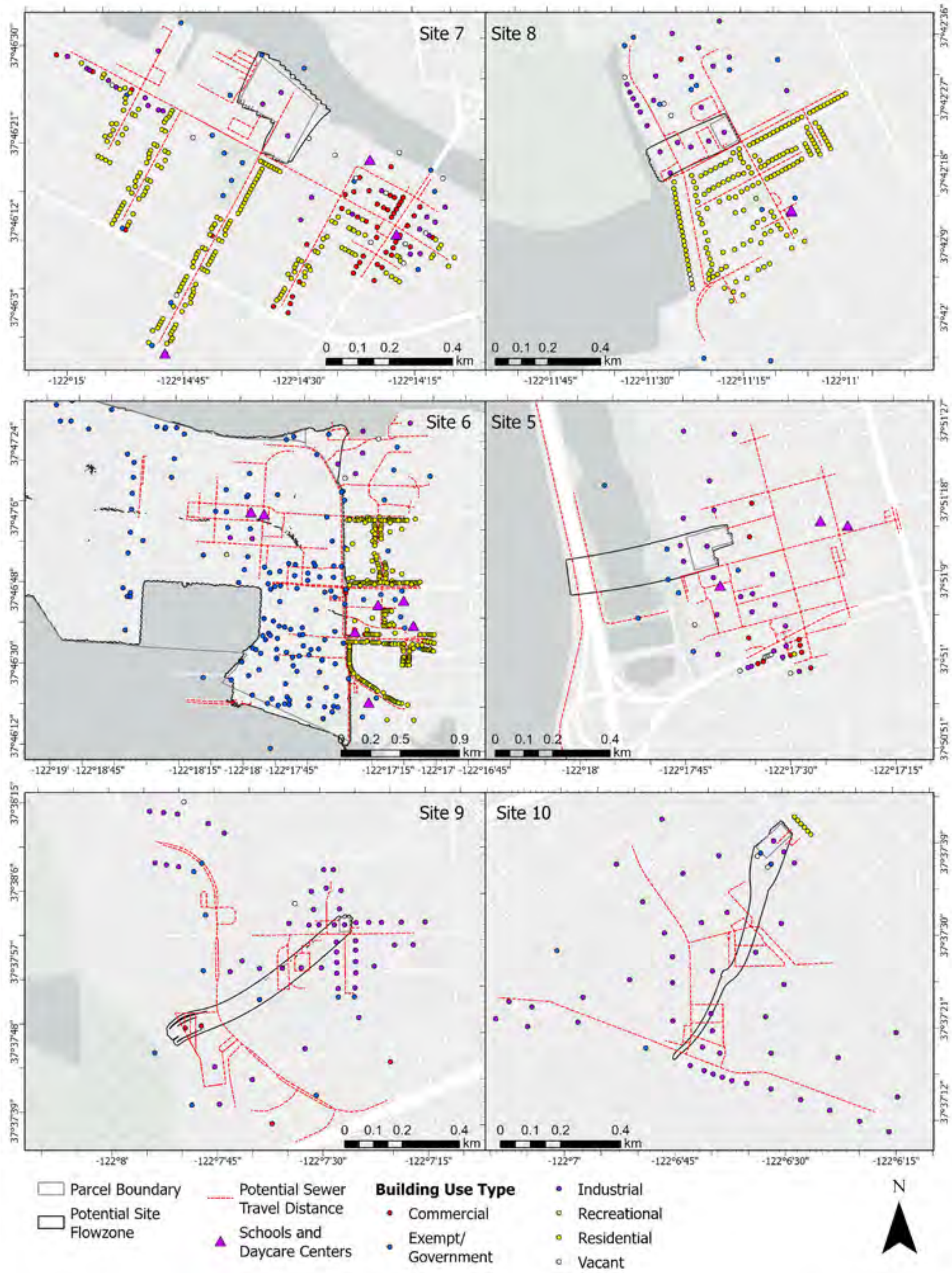


Figure 3.4.3 Example maps illustrating sewer lines that could potentially be exposed to VOC infiltration, as well as the locations of impacted schools, daycares, or multifamily residential parcels that are likely to be attached to those sewer lines.

Infrastructure Characteristics Index Data Sources

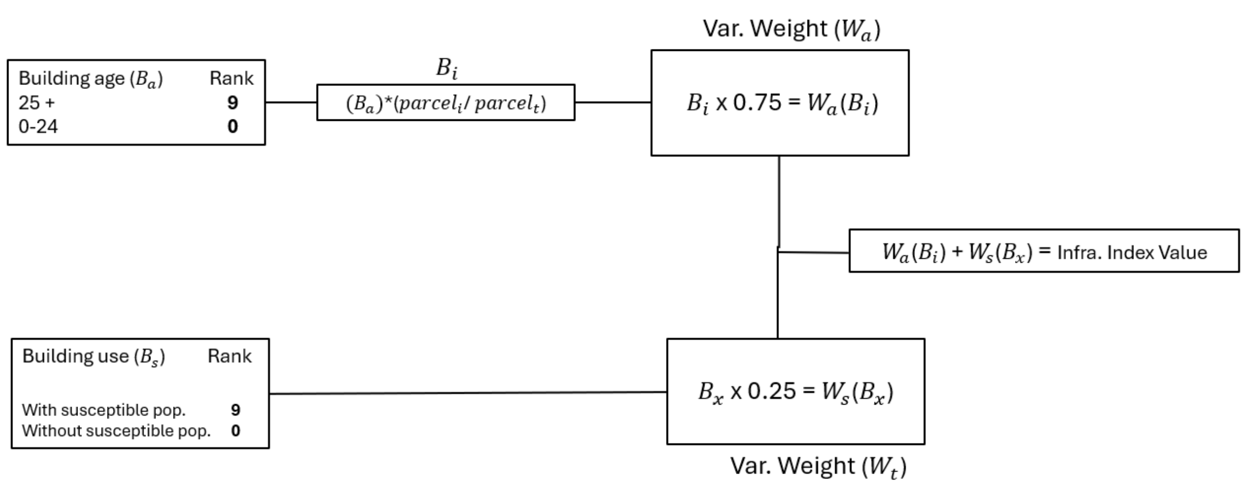
For the selected criteria analysis, the data sources are presented in Table 3.4.1.

Table 3.4.1 Infrastructure Characteristics Index Data Sources.

Data Type (Criteria)	Data Source	Title	Link
Groundwater head model	Befus et al., 2020	Projected groundwater head for coastal California using present-day and future sea-level rise scenarios	https://www.sciencebase.gov/catalog/item/5bda14abe4b0b3fc5cec39b0
Rising groundwater and current groundwater depth	Hill et al., 2023	Rising Coastal Groundwater as a Result of Sea-Level Rise Will Influence Contaminated Coastal Sites and Underground Infrastructure	https://datadryad.org/stash/dataset/doi:10.6078/D15X4N
Roads (sewer proxy)	OpenStreetMap	OpenStreetMap	https://download.geofabrik.de/north-america/us/california.html
CSCD School Footprints	CSCD Website	California School Campus Database	https://www.californiaschoolcampusdatabase.org/#download
CDSS	CDSS	California Department of Social Services	https://www.ccld.dss.ca.gov/carefacilitysearch/?rewrite=downloaddata
Regulatory boundaries	CA 30X30	30X30 California	californianature.ca.gov/datasets/0038e5d00e7a4048b51dba6ee140ef76
Property Points	LandVision	California Property Points 2020	Private Dataset

3.4.2. Infrastructure Characteristics Index Calculation

The method for calculating the Infrastructure Index score is presented in Figure 3.4.4.



$parcel_i$ = count of over 25 years old parcels at site

$parcel_t$ = total number of parcels in study

Figure 3.4.4 The Infrastructure Index is calculated using building use and building age.

The Infrastructure Index relies on building age to infer the likelihood of foundation cracks and faulty plumbing seals or improperly capped pipes. Building age is heavily weighted in the Index calculation, since it is associated with the primary mechanisms of VOC penetration into indoor air. The threshold value of 25 years has been chosen because manufacturers note that plumbing seals at the base of toilets can be expected to last between 15 and 30 years (Figure 3.4.4). Next, the Index relies on building use to infer the presence of an especially susceptible population inside the buildings. Schools, daycare facilities, prisons, and residential buildings were all considered likely to contain people who are more susceptible to health impacts from VOCs due to age or cumulative exposure to other contaminants. This characteristic is weighted lower than building age because people of all ages and cumulative pollution exposure levels can be expected to be somewhat susceptible to long-term exposure to VOCs.

3.4.3 Infrastructure Characteristics Index Results

We found more than 254.4 km (158 miles) of sewer lines that could be exposed to VOCs if those contaminants are mobilized along groundwater flowlines at the 21 studied sites. The buildings connected to those sewer lines included 22 school or daycare uses and more than 1,200 residential structures, representing 54% of all structures connected to exposed sewer pipes. Residential structures are currently located along potentially exposed sewer lines at 15 of the 21 sites, and school or daycare facilities are present along sewer lines at 7 of the 21 sites. We identified the oldest, newest, and average ages for buildings associated with all 21 contaminated sites (Table 3.4.2). Table 3.4.3 presents the final crosswalk table for these criteria and the weights that were used to generate a final index score for the infrastructure context of the 21 sites. Figure 3.4.5 shows the infrastructure characteristics index (ICI) score across 21 sites, and Figure 3.4.6 presents the spatial distribution of the ICI score.

While it is unlikely that VOCs will be mobilized by rising groundwater at all 21 sites where VOCs currently exist, the potential for groundwater transport, pipe infiltration, and entry into indoor air does exist at each site. Further investigation of dynamic groundwater-mediated transport at each of these sites could determine whether VOCs are already being mobilized by high astronomical tides or by elevated water tables after heavy or repeated precipitation events. Long-term monitoring of groundwater levels and VOCs on timescales relevant to these groundwater dynamics could further our understanding of these potential mobilization mechanisms.

Currently, there is no standard policy guiding consideration of sea-level rise or rising groundwater in vulnerability assessments presently conducted by the Water Board. In contrast, the DTSC now requires an assessment of the risks associated with sea level rise in their characterization of contaminated sites using a Sea Level Rise Vulnerability Analysis (SLRVA) (DTSC, 2024). Both the DTSC and Water Board typically limit required investigations of groundwater and contaminants to areas within the legal parcel of origin, which, as we have shown, could underestimate the spatial extent of the impacts if VOCs enter sewer pipes and trenches.

Our initial expectation was that the exposed parcels would be located primarily in commercial and industrial districts where the majority of the VOC sites were, and that few to no schools and residences would be located in these areas. However, our results show that dozens of schools and more than a thousand residential structures exist in proximity to sites contaminated with VOCs in the San Francisco Bay Area. Moreover, 11 of our 21 VOC study sites are located within Priority Development Areas designated in Plan Bay Area 2050 (MTC-ABAG 2021) as part of a regional effort to develop more housing (Madrigal, 2025). Since some of these Priority Development Areas encourage new housing in areas where groundwater is shallow and projected to rise with sea level, we speculate that additional groundwater pumping is likely to be implemented as an adaptation method and could alter the flow directions and salinity of groundwater and accelerate the dispersal of contaminants (Bosserelle & Hughes, 2024). Without monitoring contaminant flows in sewers and trenches near property lines (i.e., an underground application of “fenceline monitoring”), regulatory agencies may have only a limited understanding of the full extent of public health risks associated with sea-level and groundwater rise at and around sites that are planned for future housing.

Table 3.4.2 The minimum, mean, and maximum year in which buildings that could potentially be exposed to VOCs from sewer lines and trenches were initially constructed (“year built”) at each of the 21 sites. The percentage of buildings for which no “year built” date is available is shown in the table under the column labeled “No Data (%)”.

	Site #	Mean Year Built	Min, Max Year Built	No Data (%)
Aerospace Activities, Inc.	8	1953	1900, 2008	20.9
Alameda Naval Air Station	6	1960	1889, 2009	53.9
Joint Ashland Chemical & FMC Corporations	11	2009	1968, 2017	43.1
Berkeley Industrial Complex	5	1956	1989, 2016	59.3
Electro-Forming Co.	9	1979	1958, 1998	43.1
Former J.H. Baxter Facility Alameda	7	1919	1880, 2017	83.1
Fujicolor Processing	10	1982	1957, 2016	22.7
Safety-Kleen of California Inc.	13	1984	1976, 1989	76.9
Point Molate/Richmond NSC	3	nd	nd	100
Reaction Products	2	1951	1947, 2009	6.6
Zeneca Richmond AG Products	4	1972	1938, 2005	49.1
San Quentin State Prison	21	1962	1878, 2007	
Hunters Point Naval Shipyard	19	1965	1920, 2003	56.5
Naval Station Treasure Island	20	nd	nd	100
G-C Lubricants Co.	17	1963	1945, 2007	56.7
Romic Environmental Technologies Corp.	16	nd	nd	100
VWR Facility	18	1970	1936, 2015	79.1
Joint Moffett Federal Airfield & Sunnyvale NIROP	14	1988	1971, 2009	79.1
Mare Island Naval Shipyard	1	2001	1900, 2010	27.3

Note: “nd” indicates the year built was not provided. For sites with partial data on year built, “nd” values were removed from the analysis for that site. The percentage of “nd” observations for each site is listed under “No Data (%)”

Table 3.4.3 Infrastructure criteria with site names, building characteristics, raw score, intermediate score, and final index score. The intermediate score reflects the building characteristic score with its respective weight, following the method shown in Figure 3.4.4. (Suscep. Pop. Bldgs. refers to buildings that may contain susceptible populations. Age refers to the age of the building in 2025.)

Site Number	Site Names	Building Characteristics	Raw Score	Intermediate Score	Final Score
Site 1	Mare Island Naval Shipyard	Age	20	5.16	**3**
		Suscep. Pop. Bldgs.	0	0	
Site 2	Reaction Products	Age	20-25	8.93	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 3	Richmond (Point Molate) Naval Supply Center (NSC)	Age	30+	9	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 4	Zeneca Richmond AG Products	Age	20-30	8.7	**9**
		Suscep. Pop. Bldgs.	23	9	
Site 5	Berkeley Industrial Complex	Age	20-30	8.78	**9**
		Suscep. Pop. Bldgs.	5	9	
Site 6	Alameda NAS (Naval Air Station)	Age	25-30	7.93	**8**
		Suscep. Pop. Bldgs.	280	9	
Site 7	Former J.H. Baxter Facility Alameda	Age	25-30	8.89	**9**
		Suscep. Pop. Bldgs.	201	9	
Site 8	Associated Aerospace Activities, Inc.	Age	25-30	8.82	**9**
		Suscep. Pop. Bldgs.	175	9	
Site 9	Electro-Forming Co. - Hayward	Age	25-30	8.96	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 10	Fujicolor Processing	Age	25-30	8.03	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 11	FMC Corporation - Newark	Age	25-30	7.79	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 12	Ashland Chemical Co., Newark	Age	25-30	7.79	
		Suscep. Pop. Bldgs.	0	0	
Site 13	Safety-Kleen of California Inc.	Age	30+	9	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 14	Sunnyvale NIROP	Age	25-30	8.87	**9**
		Suscep. Pop. Bldgs.	0	0	
Site 15	Moffett Federal Airfield	Age	25-30	8.87	
		Suscep. Pop. Bldgs.	2	9	
Site 16	Romic Environmental Technologies Corp	Age	30+	9	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 17	G-C Lubricants Co.	Age	25-30	8.81	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 18	VWR Facility	Age	25-30	8.79	**5**
		Suscep. Pop. Bldgs.	0	0	
Site 19	Hunters Point Naval Shipyard	Age	25-30	887	**9**
		Suscep. Pop. Bldgs.	19	9	
Site 20	Naval Station Treasure Island	Age	30+	9	**9**
		Suscep. Pop. Bldgs.	4	9	
Site 21	San Quentin State Prison	Age	25-30	8.82	**5**
		Suscep. Pop. Bldgs.	0	0	

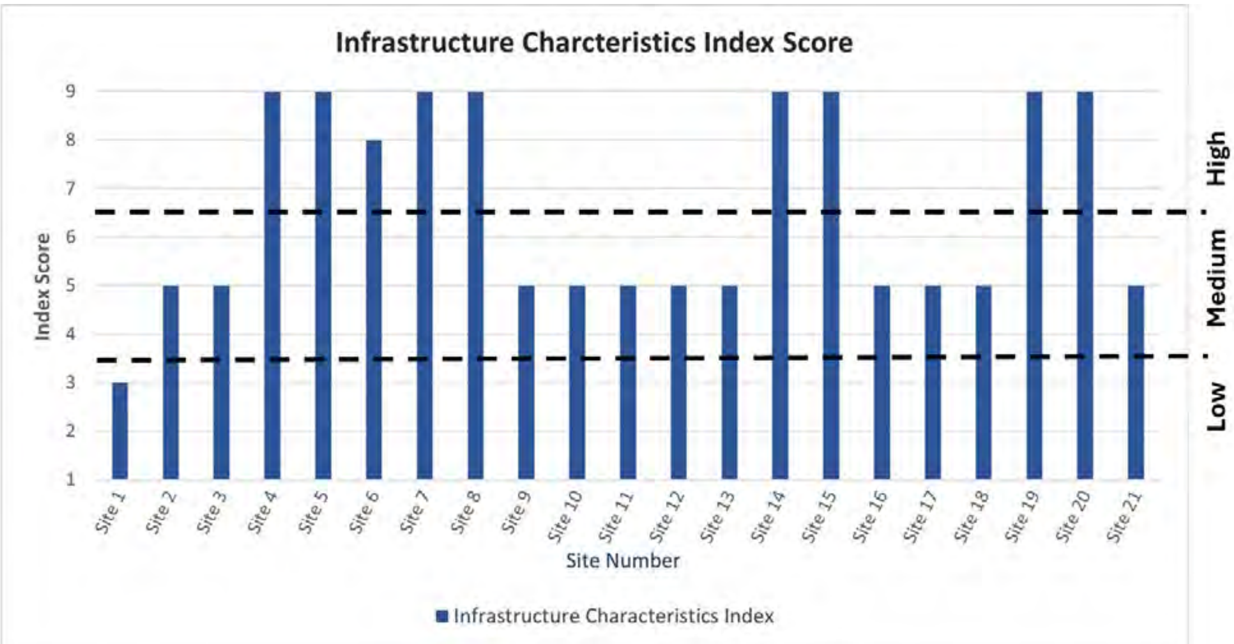


Figure 3.4.5 Infrastructure characteristics score for each site. Scores 1-3 indicate low vulnerability, 4-6 indicate medium vulnerability, and 7-9 indicate high vulnerability.

3.4.4 Infrastructure Characteristics Index Limitations and Uncertainties

There are several ways in which our method could overestimate risks of exposure. In some cases, contaminant concentrations may be low, or the surrounding soil medium may have low hydraulic conductivity, be highly compacted, or contain a high percentage of clay. These conditions reduce the movement of VOCs, whether in vapor or liquid form, into sewer pipes (Ma et al., 2020). That is the rationale for separating this digit in our screening method from the contaminant and site characteristic digits, so that the likelihood of mobilization and transport can be assessed independently from the infrastructure context. The method developed in this study could also misassign spatial risks. For example, a paleochannel or utility trench may exist that does not follow our approximation that utility trenches and sewers are located under roads. In that case, different or fewer buildings could face exposure risks than those identified in our analysis. Additionally, our method for assessing the slope of pipes and trenches aggregates uphill and downhill slopes across the potential flow distance, rather than assessing these slope directions block by block. This aggregate slope calculation could miss changes in slope caused by pumping or by unexpected routing at intersections.

Finally, groundwater pumping effects that can alter the flow of contaminants were not mapped or estimated in other ways in the groundwater modeling used to generate the depth to water and particle flow paths that were used to build the flow zones in this study and identify potential points of intersection with pipes and trenches under streets. Pumping already occurs in low-lying urbanized areas of the region, managed by public agencies as well as countless private landowners, with no required registration of groundwater pumps and volumes that impact shallow, unconfined coastal groundwater. The impacts of existing pumps on salinization and flow direction are largely unknown, and the number of sites that employ pumping is likely to increase dramatically as flooding becomes more frequent.

Ultimately, accurate predictions of exposure require dynamic hydrological modeling that includes all pumping activities; site-scale field studies that include soil and contaminant sampling; and measurements of VOC concentrations in sewer gas during high tides and post-precipitation events, both near contamination source and in distal locations (Barnard et al., 2019). Furthermore, predictions of local groundwater rise should be studied at the watershed scale with attention to local geologic heterogeneity and interactions with underground infrastructure, rather than at the relatively low resolution of the regional modeling used here (Befus et al., 2020).

One of our primary predictive variables for the penetration of indoor air by VOCs was building age. Even with the availability of a higher-resolution land use dataset for our team, building age was often not listed in parcel data. This made it difficult to predict whether plumbing systems may not follow current building codes or have been renovated in ways that left some pipes dangerously uncapped, or whether it is likely to have old, cracked seals at toilets. We also used building age to estimate the likelihood of cracks in foundations. For example, Table 3.4.2 shows that over 50% of the buildings have “no data” for the year they were built. To account for this lack of data and to take a conservative approach, we scored buildings with “no data” for year built as 9. As a result, sites may be scored higher than they would if data were available. Sites that score exceptionally high and have large proportions of “no data” regarding the year buildings were constructed should be investigated more closely using updated local data. Future uses of this screening tool could identify and scrape new sources of data on building age, such as real estate data sites (Zillow, Redfin, etc.). It is also possible that sources we did not explore might have more data on building age, such as data available through county property tax assessment records.

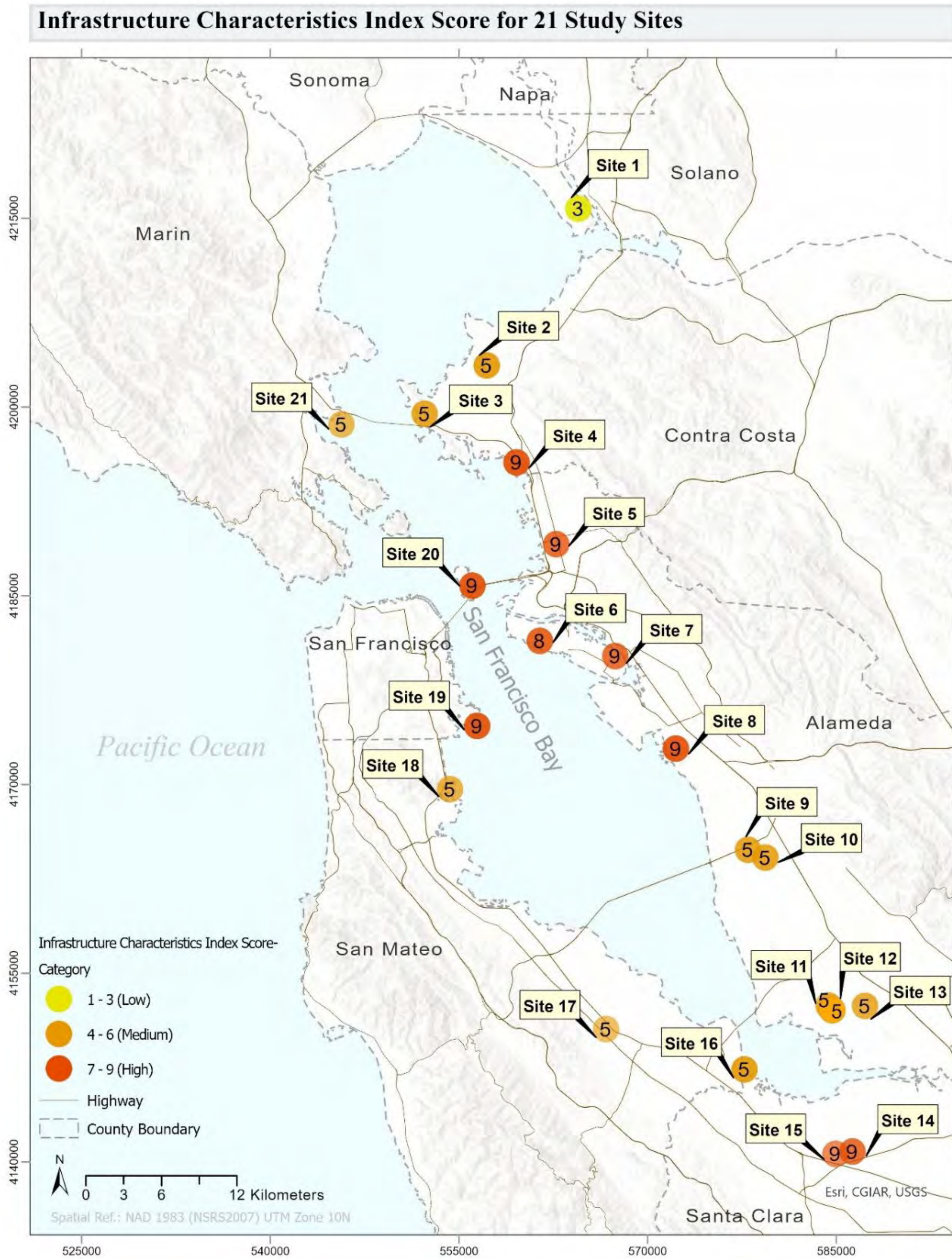


Figure 3.4.6 Spatial distribution of study sites and Infrastructure Characteristics Index (ICI) score for each site. Scores 1-3 indicate low vulnerability, 4-6 indicate medium vulnerability, and 7-9 indicate high vulnerability.

4. Results of the Screening Method Across All Four Indices

The previous sections describe the components of the screening method we have developed. This method allows users to assess the potential for new public health risks in neighborhoods around contaminated sites where VOCs are present. It is explicit at every stage and prioritizes sites where there are uncertainties driven by a lack of relevant data. The method uses VOCs as a "pilot contaminant" because of their ability to migrate uphill into indoor air, posing an imminent and potentially unexpected public health risk. This method can be used as a template for representing potential risks from metals and persistent organic pollutants that migrate only downgradient in groundwater and/or in pipes and trenches. The method can be adapted to other contaminants by altering the criteria used for toxicity, mobility, and exposure pathways in digits 2, 3, and 4.

In this section, we discuss the results for VOCs only as a demonstration of the interpretations that can be made of the four-digit code we built, presented in Table 4.1 and Figures 4.1 and 4.2, using our four index scores that address social vulnerability as well as contaminant, site, and infrastructure characteristics. By focusing on a coastal subset of industrial sites with similar coastal settings, social vulnerability, and solvent-type contaminants (e.g., TCE and PCE), this study reduces the variability inherent in the full statewide database of all environments and contaminant types, allowing clearer interpretation of index performance and vulnerability rankings. If all California contaminated sites were included, the much wider range of settings, social vulnerabilities, site conditions, contaminant classes, and data quality would introduce greater variability in the digital scores.

4.1. Interpretation of the Coding Results

Each of the 21 sites we included in this study has been assigned a four-digit code (Table 4.1) that represents the potential for new public health risks driven by VOC exposure as sea level and groundwater rise. When significant uncertainties arise from a lack of data in one of the individual index values, the index is assigned a value of 9 and marked with an asterisk in the table. For example, our review found that some contaminant data were missing for Mare Island Naval Shipyard (Site #1). For that reason, its four-digit code, 9973, includes a 9 in the second digit to represent uncertainty about contaminant concentrations. The first digit contains a 9 because of high social vulnerability in the census area that includes this site. The third digit contains a 7 because the site characteristics represent a high risk of mobility for the contaminants, and the fourth digit is a 3, indicating that the infrastructure context either does not include sewer pipes or utility trenches, and/or that there are no buildings currently connected to those utilities, and/or that the buildings do not contain susceptible populations, and/or the buildings were built very recently. Our method allows the Mare Island Naval Shipyard (Site 1) to be categorized as unlikely to pose an imminent danger to public health from VOCs, even though contaminants are present and could migrate through the soil as sea level and groundwater rise.

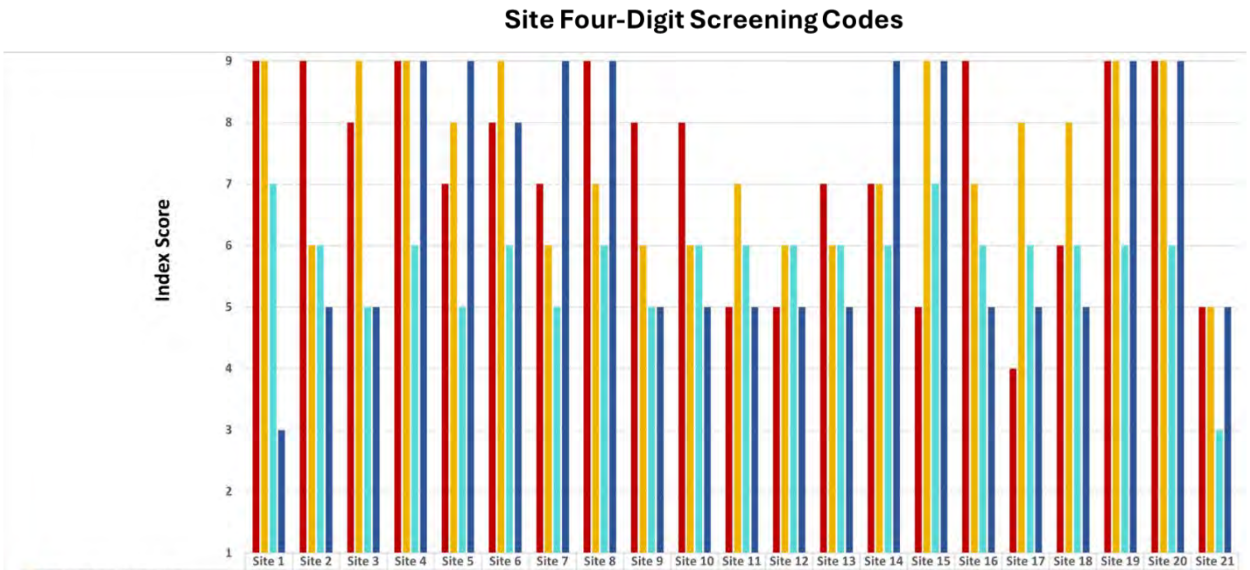
It should be noted that the site's final score would increase to a high number if new residential, daycare, or school buildings are proposed within 686 meters of the contaminant flowzone, reflecting the greater risk that VOCs from sewers or utility trenches could enter indoor air where people, especially children, spend significant time. We are aware that there are proposals for new development on Mare Island and would recommend that these should be delayed until the site is cleaned up or the risk of migration of contaminants is reduced in some other way.

Table 4.1. Final Four-Digit Screening Code assigned to each study site.

Site Number	Site Name	Social Vulnerability Score	Contaminant Characteristics Score	Site Characteristics Score	Infrastructure Characteristics Score	Four-Digit Code [1]
1	Mare Island Naval Shipyard	9	9*	7	3	**9973**
2	Reaction Products	9	6	6	5	**9665**
3	Richmond (Point Molate) Naval Supply Center (NSC)	8	9*	5	5	**8955**
4	Zeneca Richmond AG Products	9	9	6	9	**9969**
5	Berkeley Industrial Complex	7	8	5	9	**7859**
6	Alameda NAS (Naval Air Station)	8	9*	6	8	**8968**
7	Former J.H. Baxter Facility Alameda	7	6	5	9	**7659**
8	Associated Aerospace Activities, Inc.	9	7	6	9	**9769**
9	Electro-Forming Co. - Hayward	8	6	5	5	**8655**
10	Fujicolor Processing	8	6	6	5	**8665**
11	FMC Corporation - Newark	5	7	6	5	**5765**
12	Ashland Chemical Co. Newark	5	6	6	5	**5665**
13	Safety-Kleen of California Inc.	7	6	6	5	**7665**
14	Sunnyvale NIROP	7	7	6	9	**7769**
15	Moffett Federal Airfield	5	9*	7	9	**5979**
16	Romic Environmental Technologies Co.	9	7	6	5	**9765**
17	G-C Lubricants Co.	4	8	6	5	**4865**
18	VWR Facility	6	8	6	5	**6865**
19	Hunters Point Naval Shipyard	9	9*	6	9	**9969**
20	Naval Station Treasure Island	9	9*	6	9	**9969**
21	San Quentin State Prison	5	5	3	5	**5535**

* Index values marked with an asterisk reflect significant uncertainty and were assigned a score of 9 due to insufficient data.

[1] The four digits are derived from four index scores arranged in a fixed order. The first digit represents the Social Vulnerability Index score, the second represents the Contaminant Characteristics Index score, the third represents the Site Characteristics Index score, and the fourth digit represents the Infrastructure Characteristics Index score. Together, these indices provide a screening tool to prioritize sites for more detailed investigation.



	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11	Site 12	Site 13	Site 14	Site 15	Site 16	Site 17	Site 18	Site 19	Site 20	Site 21
Social Vulnerability Index	9	9	8	9	7	8	7	9	8	8	5	5	7	7	5	9	4	6	9	9	5
Contaminant Characteristics Index	9	6	9	9	8	9	6	7	6	6	7	6	6	7	9	7	8	8	9	9	5
Site Characteristics Index	7	6	5	6	5	6	5	6	5	6	6	6	6	6	7	6	6	6	6	6	3
Infrastructure Characteristics Index	3	5	5	9	9	8	9	9	5	5	5	5	5	9	9	5	5	5	9	9	5

Figure 4.1 Four index scores and four-digit code for each of the contaminated sites.

The Reaction Products site (Site 2) also has very high social vulnerability in its census area, and the contaminant characteristics reflect a moderate-high level (7) of potential to create new public health risks as groundwater rises. The site characteristics index (6) and infrastructure index (5) show a moderate level of potential to generate new public health risks. Our method allows users to categorize this site as having a moderate potential for new public health risks. The site characteristics index is unlikely to change, but similar to the Mare Island site, the infrastructure index would increase if new development is proposed within 686 meters of the potential flowzone for contaminants.

The highest score in our final set is 9969, shown in Table 4.1 and Figure 4.1. This score has been assigned to Zeneca Ag Products (Site 4), Hunters Point Naval Shipyard (Site 19), and Naval Station Treasure Island (Site 20). Data on contaminant concentrations are available for the Zeneca site, and therefore this score reflects very high potential for new public health risks from VOCs as sea level and groundwater rise. The two military sites at Hunters Point and Treasure Island have this very high score because there are uncertainties about contaminant characteristics (marked with an asterisk in the column for that index) that should be resolved in the short term in order to prevent potential public health risks.

While the first digit of our four-digit code, social vulnerability, reflects the sensitivity of a census area to additional health burdens given existing conditions, it is essential to note that schools and residential buildings in any census area contain susceptible populations. Protecting the most vulnerable populations requires attention to both digit 1 (social vulnerability index) and digit 4 (infrastructure index), in relation to digit 2 (contaminant characteristics). If there is a medium to high potential (index values of 4–9) for a contaminant to migrate into sewer pipes or utility trenches, and schools and/or homes are connected to those utilities (index values of 4–9), the site should be categorized as a high priority for additional near-term investigation. According to this logic, all of the sites we used for this pilot project would be ranked as having a high priority for additional investigation.

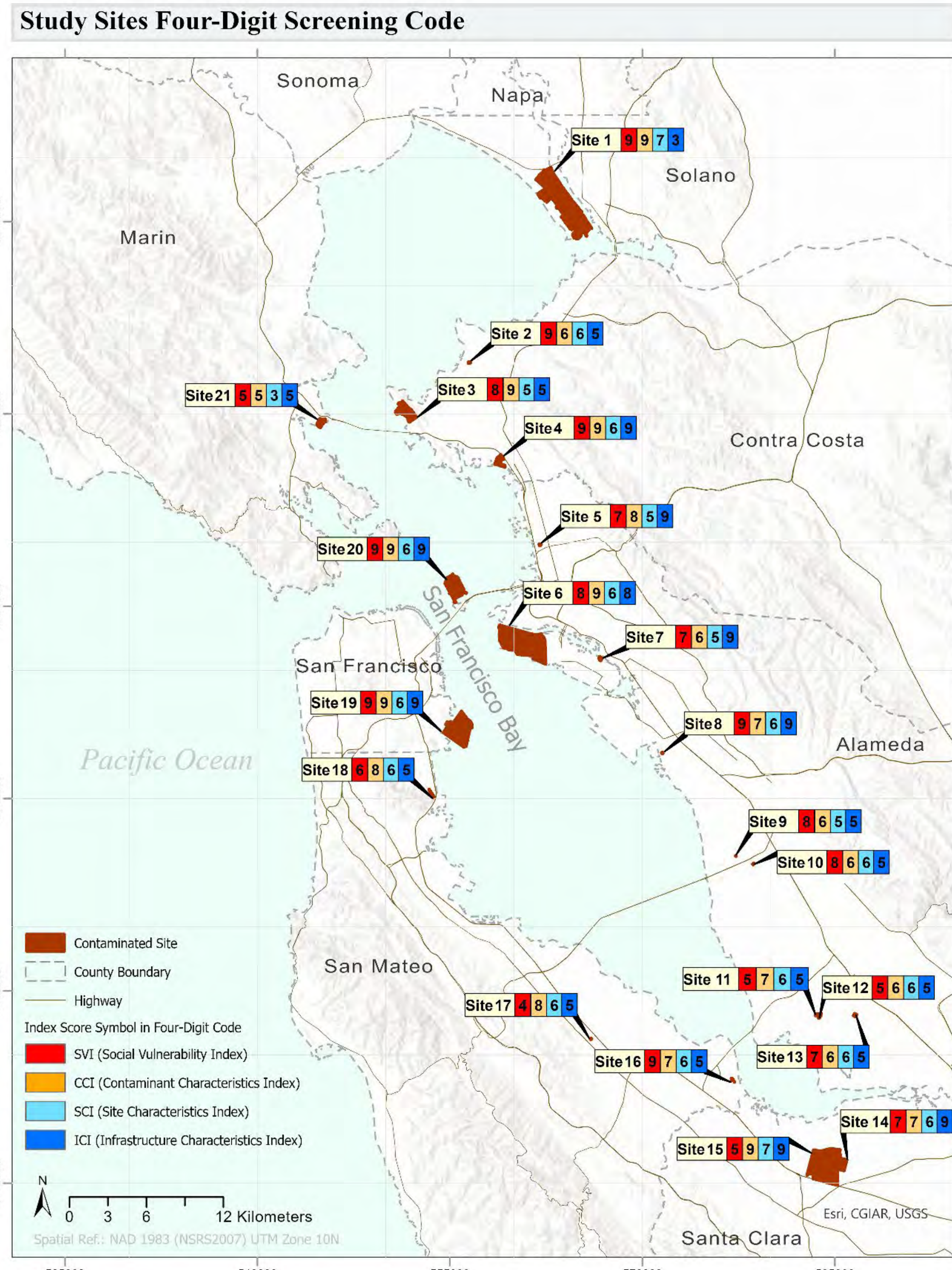


Figure 4.2 Spatial distribution of study sites and their associated four-digit screening code. A four-digit code was constructed by combining the final index scores for the four indices: the social vulnerability index, the contaminant characteristics index, the site characteristics index, and the infrastructure characteristic index.

The sites considered for this pilot study are of immediate concern to surrounding communities due to the toxicity of present contaminants, and nearly all could be impacted by rising groundwater or surface inundation. Therefore, it is not surprising that they would all be ranked by our screening method as a high priority for additional investigation. In contrast, a statewide or regional assessment of all sites that could be impacted by inundation or rising groundwater under sea level rise may identify sites where contaminant concentrations are very low and unlikely to be mobilized, and there are no homes or schools connected to sanitary sewer utilities. These sites would be assigned a relatively low priority for additional investigation and clean-up.

The screening method we developed also allows for new research or clarifications by site managers to remove sites from the high priority category for potential public health risks within an active and informed dialogue with community advocacy groups. We see this as an advantage because previously, there was no consistent basis for dialogue at contaminated sites in California about imminent public health risks in relation to sea level rise, groundwater rise, and increased rainfall intensity. Community groups have expressed concern that the goals for investigation and remediation have been constantly shifting, and that timelines for cleanup activities are too slow to prepare for new environmental conditions. Our intention was to address those concerns by creating a consistent set of methods for characterizing sites that could be used by both DTSC and the Water Board and would support the categorization and prioritization of sites within the context of limited resources at these public agencies.

Next, the method should be tested in similar landscapes in Southern California, where VOCs are present at contaminated sites, and groundwater is expected to rise to determine how well this approach to categorization and prioritization would work statewide.

4.2. Potential Uses of the Screening Method

As we noted above, the screening method developed here could be adapted to consider metals and other contaminants that do not have a vapor component, but could migrate at faster rates to creeks, marshes, and nearshore environments in the Bay as sea level and groundwater rise and as groundwater becomes more saline. This would require modification of our second digit in the code (contaminant characteristics) to reflect the increased salinity that is likely to occur in shallow groundwater, particularly if the site is in an area where groundwater elevation is limited by either topography or pumping. In those areas, the saltwater wedge is predicted to move inland more rapidly as sea level rises. This second index will also need to be modified to reflect increased mobility of some metals in a more saline groundwater environment. In addition, the last digit of our code (infrastructure characteristics) should be simplified to consider only downhill directions for movement in pipes, groundwater, or sediments, which are infiltrated by metals and other contaminants that do not have a vapor component. This application will help identify contaminated sites that pose the greatest potential risk to ecosystem health in creeks and nearshore environments, and to the health of people who eat fish or shellfish that are caught locally, or who come in contact with sediment in creeks, marshes, and the nearshore aquatic environment.

Ultimately, the health of human beings is dependent on the health of animals and plants in the environments that surround us. Our screening method recognizes this and can be expanded to include contaminants that are found to have serious impacts on aquatic ecosystems, such as tire particles, PFAS chemicals, and nutrients such as phosphorus and nitrogen. However, our initial focus was on contaminants containing VOCs at known contaminated sites, due to their high volatility and the limited recognition of the associated risks from sea-level rise–induced groundwater rise by both regulators and the public.

5. Discussion and Conclusions

The method developed in this study is dependent on the availability of recent data at each contaminated site. Accurate, recent data are essential for all parties involved in determining the future of these sites, including site managers, site owners, the governments of California regions, counties, cities or towns, and community organizations. Ideally, these data would be available consistently for each contaminated site and be available using a map-based data viewer that is legible to a broad public audience, as well as spreadsheets that allow analysis by people with special skills.

Transparency is one important key to the successful negotiation of the future of these sites. It creates the potential to avoid having to rely on lawsuits and the courts to determine the outcomes of disputed development or conservation proposals. Transparency also supports critical public education about the changes that are coming with rising sea levels and the potential for more intense rain events. An informed public will include informed insurance and investment companies that support new development in coastal areas. Design changes that allow new housing to be sufficiently built in these vulnerable locations may be necessary, and sharing knowledge widely about the impacts of rising water will help developers move from conventional designs to adaptive designs. Policies may also shift to consider the protection of aquatic environments in the context of higher groundwater, contaminant mobilization, and future urban development.

5.1. Lack of Consistent Access to Site-Scale Contaminant Data

All six of the complex former military sites reviewed in our study had critical information gaps that created uncertainty about the categorization and prioritization of those sites. Similarly, because of limited information on the population living and working within San Quentin State Prison, the site had a relatively moderate four-digit final score, which is unrepresentative of the true social vulnerability and public health risks associated with contamination at the site. In addition, many DTSC sites that are suspected of having VOCs are not fully transparent about the presence and concentrations of VOCs and other contaminants, because the names and concentrations of contaminants are contained in PDF documents that cannot be searched easily within the databases that DTSC currently provides (Envirostor). The PDF documents must be downloaded individually and then searched, but even once they are downloaded, the formats of these documents vary significantly, so that automatic PDF scraping tools are difficult to design using today's software tools. In the current database situation, site managers would need to be queried directly to identify all contaminants present and their most recently measured concentrations.

5.2. Data Availability for Future Wet Soil Conditions

Most contaminant data are obtained from groundwater samples collected from wells. These data reflect the presence of contaminants in groundwater, indicating that the contaminated soils are already inundated. The question for those contaminants is whether the rate and direction of mobility could be affected by rising seas and groundwater, or by adaptive pumping, rather than whether they are mobile at all. If they have been identified in groundwater samples, they are potentially mobile.

The presence and concentration of contaminants in dry soil are not checked as frequently as groundwater concentrations at contaminated sites. Soil grab samples may have been collected during initial site investigations decades ago and not repeated because the soil is presumed to have remained dry. New soil samples are needed to identify any changes in the concentrations of contaminants in soil over time, and to help prepare for those soils to become inundated by either surface water or groundwater.

5.3. Data Availability for Pumping and Infiltration of Groundwater

Pumping shallow groundwater alters flow directions and rates within the zone influenced by the pump. For small household sump pumps, this zone of influence is likely minimal. However, for large pumps, such as those used in buildings with underground levels, deep construction sites, highways, or subway systems, sanitary sewer systems, and municipal stormwater networks, data on capacity and frequency of operation are needed to model the likelihood and timing of inundation under changing climate conditions. A newly installed pump may unexpectedly draw contaminated groundwater toward sewer pipes or trenches. Additionally, pumps can induce a rise in the saline boundary in groundwater, a phenomenon known as “upconing,” which can mobilize metals more readily and allow larger quantities to migrate into nearshore aquatic environments.

Similarly, data are often collected periodically on rates of groundwater infiltration into sanitary sewer pipes. Once groundwater enters pipes, it flows more freely and faster, discharging into creeks, marshes, or bays rather than remaining in the soil. Modeling of future groundwater levels will require information about the location of infiltration and the volumes/rates of infiltration into pipes. Without these data, public agencies' ability to estimate future public health risks from contaminated sites is limited. A pipe repair or replacement project could allow groundwater to rise locally and mobilize contaminants quickly and unexpectedly in an area where homes and schools are connected to those pipes.

5.4. Scale Limitations for Applying the Screening Method

We developed our contaminated site screening method in ways to facilitate statewide application. The availability of data for contaminated sites should be consistent at a statewide scale with the problems and opportunities we found in the San Francisco Bay Area. It is currently easier to work with sites managed by the Water Board, since contaminant data for wells are listed in publicly downloadable spreadsheets that are relatively easy to analyze. DTSC sites have not required private contractors to submit data in spreadsheets; instead, they have used PDFs in various formats. Wells at DTSC-managed sites are also typically located by street address, which does not reflect the spatial distribution of the contaminants and the exact location of the site, making it very difficult for public agencies or third parties, such as advocacy or science organizations, to create maps and spatial visualizations of the contaminants.

Similarly, our method of using roads as proxies for pipes and utility trenches is also available at the state scale, although it contains errors where pipe connections extend under highways and create conduits to additional neighborhoods, or where pipes are missing in areas served by septic systems instead of sewers. Sewer spatial data is generally unavailable to the public; therefore, regional, statewide, or national sewer agency organizations could be engaged to share specific sewer network data with a state agency responsible for mapping potential contaminant flows. State and other public agencies should have greater access to this critical data on underground network patterns that influence the movement of contaminants in groundwater and the depth or flow directions in the water table.

The land use data we employed came from a proprietary database that a UC Berkeley researcher was able to access. These data were important for determining whether a building has residential use when the zoning category might not explicitly indicate that use (for example, if the zoning category is “mixed use”). Similarly, many parcels did not have data on building age. New sources of building age data will be needed for greater accuracy in this initial screening process. At the statewide, regional, and local scales, it may be possible to obtain building age and residential use data more reliably from real estate data sites or from county property tax assessment databases. State agencies should be able to access the property tax databases more easily than we could for statewide application of the screening method.

6. Recommendations

We recommend the following future actions to more effectively screen for relative site vulnerability and to address potential public health concerns.

6.1. Recommendations for Environmental Justice Partner Organizations

Advocacy organizations concerned about public health and the health of coastal ecosystems can use the score tables we provide, such as Table 4.1 for VOCs, as the basis for asking for policy changes at the scale of a single site, a shoreline reach, a watershed, or an entire jurisdiction.

The most likely use would be to advocate for a faster clean-up schedule at sites that represent moderate to high potential for generating new public health risks. As groundwater and surface inundation hazards increase in frequency or affect a larger area, it is essential that agencies responsible for determining the need for investigations and clean-up by site owners consider the changing hydrological environment as a contributor to risk. For example, any site over shallow and rising groundwater that has a moderate to high contaminant characteristics index value should be considered a candidate for prioritized remediation. Site and infrastructure characteristics can be uncertain, so the best use of the precautionary principle would be to assume that if a contaminant is present at reasonably high concentrations, it is possible that it could be mobilized. f there is evidence of site and infrastructure characteristics that would suggest a greater likelihood of mobilization and penetration of indoor air at schools and residences, that supports the urgency of investigations that would either rule out the presence of those conditions or support earlier clean-up options.

By advocating for investigations at sites with moderate to high scores for contaminant characteristics, advocacy organizations can create a meaningful dialogue with state and regional agencies that manage those sites. Site and infrastructure characteristics in our four-digit code can be investigated with additional field samples or ongoing monitoring, leading to informed decisions on whether cleanup is urgent at those sites. The social vulnerability of communities in the surrounding census area should be considered an additional reason to accelerate the cleanup. Beginning the advocacy process by considering contaminant characteristics can help avoid spending advocacy efforts on sites unlikely to pose new public health hazards related to sea-level rise, groundwater, or flooding from heavier rainfall.

VOCs were the focus of this project because they could already be entering the indoor air of homes and schools, particularly during the wet season when groundwater levels reach their annual maximums. Current monitoring requirements do not specify that contaminants must be sampled at these times of maximum inundation, when winter rains and high tides can combine to mobilize contaminants in soil. The primary concern for advocates of human health should be the imminent impact of VOCs entering indoor air from sewer or utility trenches.

As groundwater rises and becomes saltier due to saltwater intrusion, metals may be readily mobilized and transported downgradient. Water and contaminants can travel much more quickly when they enter pipes, utility trenches, and geologic features such as old riverbeds, where gravel deposits can increase flow rates. Fish, shellfish, algae blooms, and birds are impacted by metals and other contaminants (tire particles, PFAS or POP chemicals, and nutrients such as nitrogen and phosphorus). Human health is also affected if people eat fish or shellfish or come into contact with algal toxins. Hence, contaminated sites with metals, PFOS and PFAS chemicals, POPs, radioisotopes, and nutrients need to be assessed to protect the health of the nearshore marine and freshwater environments with which children, fishers, and other people interact.

Sea level rise will also lead to increased wave erosion of existing shores at landfills and in areas of mixed urban fill, which can include municipal garbage and toxins, as well as soil. Advocacy organizations can argue for new erosion protection and monitoring, as well as covering or removing garbage and toxins in erosion-prone shore zones.

6.2. Recommendations for Community Members

- Resources are needed for testing for vapor intrusion in sewer lines and utility trenches, both adjacent to contaminated sites and across a broader spatial area to identify unexpected VOCs. Contaminate site owners should pay for this testing if it is required by State agency site managers.
- Pumping registries - private and public pumping needs to be tracked in order to identify vulnerable sewer lines and buildings
- Plumbing inspections - Wax or plastic plumbing seals need replacement every 15-20 years, p-traps must be kept wet in showers and sinks, and old pipes must be properly capped.
- Foundation inspections - cracks must be sealed if VOC plumes pass under buildings.
- Elevator shaft VOC testing - utility trenches in streets and VOC plumes that extend under buildings can allow high concentrations of VOCs to occur in elevator shafts, and move upwards to higher floors.
- How to keep self safe - advocate for registries of pumping activities, “fenceline” testing of sewer pipes and utility trenches adjacent to contaminated sites, and city-wide testing of sewer pipes. Monitors and sampling devices can also be purchased for homes and schools, but all of these have accuracy problems at low concentrations. The burden of monitoring near their sites should be borne by the site owner to the greatest extent possible, not by residents or school departments.
- Case studies to show what is or is not working: Provide examples of how communities have dealt with VOCs testing and vapor intrusion.
- PACT East Palo Alto example - an alliance of local and regional organizations led by Nuestra Casa and SPUR plans to test for VOCs in sewers in East Palo Alto near the Romic site, where VOCs are known to be present. Their advocacy has led the city manager to agree to testing more widely in the sanitary sewers in that city.
- The City of Richmond is including contamination concerns in its new SLR adaptation plan, which every coastal community will have to develop to follow State law (SB 272). This process will include an inventory of contaminated sites and an assessment of the number of schools and residences within the maximum distance VOCs can travel from those sites. The City will be able to advocate for accelerated clean-up at sites where homes and schools could be impacted by migrating VOCs.
- Hunter’s point EPA conversation re slurry walls - the existing remediation structure does not provide complete isolation of contaminants from rising groundwater in one key parcel at Hunters’ Point Naval Shipyard, because it is a hanging slurry wall, not deep enough to be connected to bay mud. This was not communicated to the former EPA Region 9 Superfund Director by EPA staff. Similar misunderstandings of site conditions may be occurring elsewhere at complex, highly contaminated sites.

6.3. Recommendations for State Agencies

- Site managers in DTSC and Water Board districts are the most logical audience for this screening method. They could apply it to their sites in anticipation of community and science advocacy organizations applying the same method. State and regional agencies should invite local governments and advocacy groups to join them in the process of applying this screening tool. This joint dialogue would significantly increase transparency and could lead to both better policies for conservation and development and avoid unnecessary lawsuits.

- For example, DTSC staff could apply this screening approach at the state level and request participation of local site managers to create a publicly-accessible database of answers to the questions asked about each site in the two phases of our screening approach.
- The Water Board staff could recommend consideration and adoption of this screening method at the District level, where site managers are concerned about how to reasonably review sites for future risks without becoming vulnerable to lawsuits from site owners. Applying a consistent approach would avoid any appearance of favoring or disfavoring property owners in an arbitrary manner. It would also provide a framework for assessing the ways that landfill operators and managers are addressing sea level and groundwater rise in their 5-year plans. Including proposals for adaptation at landfills is already required by the San Francisco Regional Water Quality Control Board (SF RWQCB), but we are not aware of a framework that would allow the SF RWQCB to evaluate the adequacy of those proposals. Our screening method could be valuable as a model for evaluation.
- The Water Board staff could recommend consideration and adoption of this screening method at the District level, where site managers are concerned about how to reasonably review sites for future risks without becoming vulnerable to lawsuits from site owners. Applying a consistent approach would avoid any appearance of favoring or disfavoring property owners in an arbitrary manner. It would also provide a framework for assessing the ways that landfill operators and managers are addressing sea level and groundwater rise in their 5-year plans. Including proposals for adaptation at landfills is already required by the SF RWQCB, but we are not aware of a framework that would allow the SF RWQCB to evaluate the adequacy of those proposals. Our screening method could be valuable as a model for evaluation.
- Regional planning agencies such as the Association of Bay Area Governments (ABAG) within the Metropolitan Transportation Commission (MTC) could also review Planned Development Areas (PDAs) in their draft Plan Bay Area 2050+ using an application of this screening method. Planned Development Areas and new housing quotas are essential as a response to California's housing crisis. However, promoting new development in areas where contaminants have not yet been removed or neutralized puts people and ecosystems at risk as the climate changes.

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Appendix I

Shareable Fact Sheets

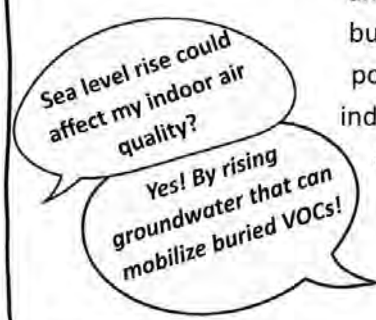
Indoor Air Pollution Risk

VOC Contamination and Groundwater Rise in the Bay Area

Rising groundwater, caused by sea level rise, could mobilize Volatile Organic Compounds (VOCs) buried underground and push the VOCs through sewer lines and under buildings where it can travel into indoor air through pipes, *like the ones in your kitchen or bathroom!* This is especially dangerous when there is already existing air pollution in your community, from sources like trucks, heavy industry, or contamination.

WHAT'S THE RISK?

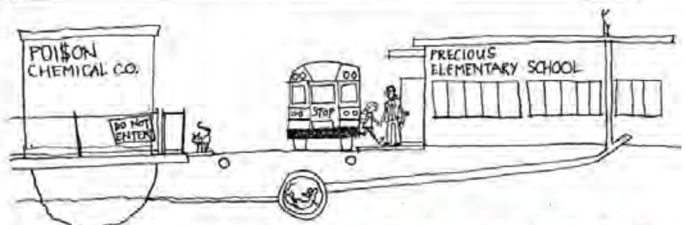
Groundwater rise will impact hundreds to thousands of sites along the San Francisco Bay shoreline that are contaminated with VOCs. These **volatile** contaminants can travel *up* through underground infrastructure and enter buildings, polluting indoor air quality



Deeper Dive Into Definitions

Volatile Organic Compounds (VOCs): include a variety of chemicals that can have short- and long-term adverse health effects. **Volatile** means that they evaporate easily and can be released into the air as gases, making the contamination airborne.

Sea Level Rise: Climate change causes higher temperatures that melt ice caps and expand water molecules, both increasing the amount and size of water molecules, which will impact our Bay Area and coastal communities



Based on the report "*Characterizing Contaminated Sites in the San Francisco Bay Region and Their Exposure to Future Sea-Level Rise and Groundwater Flooding (2025)*. *Contact skylar@greenaction.org with questions.*

GREENACTION for Health & Environmental Justice

DID YOU KNOW THAT RISING SEA LEVELS & GROUNDWATER CAN THREATEN INDOOR AIR QUALITY?

Rising groundwater, caused by sea level rise, could mobilize Volatile Organic Compounds (VOCs) buried underground and push the VOCs through sewer lines and under buildings where it can travel into indoor air through pipes, like the ones in your kitchen or bathroom. This is especially dangerous when there is already existing air pollution in your community, from sources like diesel trucks or heavy industry.

Sea Level Rise & Groundwater Rise, Caused by Climate Change

Buried or Untreated Contamination Moves and Spreads, Increasing Exposure Pathways

Airborne Pollutants Can Enter Cracked or Damaged Underground Infrastructure and Can Travel Up Into Buildings, Impacting the Indoor Air Quality

KEY DEFINITIONS:

Volatile Organic Compounds (VOCs): include a variety of chemicals, some having short- and long-term adverse health effects. **Volatile** means that they evaporate easily and can be released into the air as gases, making the contamination airborne.

Sea Level Rise: Climate change causes higher temperatures and is driven by human activity, especially fossil fuels (oil and gas). Climate change makes sea levels rise because warmer temperatures melt the ice caps, adding water to the ocean.

UNDERSTANDING THE RISK

Groundwater rise will impact hundreds to thousands of sites along the San Francisco Bay shoreline that are contaminated with VOCs. These volatile contaminants can travel up through underground infrastructure and enter buildings, polluting indoor air quality

Based on the report "*Characterizing Contaminated Sites in the San Francisco Bay Region and Their Exposure to Future Sea-Level Rise and Groundwater Flooding (2025).* *Contact skylar@greenaction.org with questions.*

GREENACTION for Health & Environmental Justice

Project Brief

Understanding the Report

Characterizing Contaminated Sites in the San Francisco Bay Region and Their Exposure to Future Sea-Level Rise and Groundwater Flooding

Flooding from sea-level and groundwater rise will mobilize hazardous contaminants buried along the shoreline and increase the potential pathways for public exposure. In this study, we focused on understanding and predicting the widespread potential for volatile organic compounds (VOCs, which can exist as both liquids and gases) to spread from contaminated sites and come into contact with people. We developed a method to serve as a preliminary screening tool for prioritizing contaminated sites exposed to rising and increasingly saline groundwater. To assess the priority of each site, we generated a four-digit code that uses indexed values from 1-9 to represent ranges in social vulnerability, contaminant characteristics, site characteristics, and infrastructure characteristics.

Site 1: Mare Island Naval Shipyard
Site 2: Reaction Products
Site 3: Richmond (Point Molate) Naval Supply Center (NSC)
Site 4: Zeneca Richmond AG Products
Site 5: Berkeley Industrial Complex
Site 6: Alameda NAS [Naval Air Station]
Site 7: Former J.H. Baxter Facility, Alameda
Site 8: Associated Aerospace Activities, Inc.
Site 9: Electro-Forming Co., Hayward
Site 10: Fujicolor Processing
Site 11: FMC Corporation - Newark
Site 12: Ashland Chemical Co., Newark
Site 13: Safety-Kleen of California Inc.
Site 14: Sunnyvale NIROP
Site 15: Moffett Federal Airfield
Site 16: Romic Environmental Technologies
Site 17: G-C Lubricants Co.
Site 18: VWR Facility
Site 19: Hunters Point Naval Shipyard
Site 20: Naval Station Treasure Island
Site 21: San Quentin State Prison

Site Four-Digit Code

FIRST DIGIT **Social Vulnerability**	Criterion #1: CalEnviroScreen 4.0 Criterion #2: BCDC Community Vulnerability Index Criterion #3: Healthy Places Index
SECOND DIGIT **Contaminant Characteristics**	Criterion #1: Contaminant Profile Criterion #2: Number of Contaminant Classes Criterion #3: Highest Current Contaminant Concentration Criterion #4: Persistence of Contaminant
THIRD DIGIT **Site Physical Characteristics**	Criterion #1: Depth to Groundwater Criterion #2: Soil Permeability Criterion #3: Impervious Surface/Surficial Material Permeability
FOURTH DIGIT **Infrastructure Characteristics**	Criterion #1: Contaminant Flowzone Criterion #2: Sewer Connectivity Model for Potentially Exposed Buildings Criterion #3: Identifying and Characterizing Vulnerable Buildings

We identified four categories of characteristics most likely to influence the risk of new public health impacts from VOCs. Each category contains multiple criteria that are analyzed across a range of data sources and then converted into an index to produce a single numerical score (1-9). The four scores can be used as a four-digit code to characterize each site.

VOCs present imminent human health threats such as damage to the central nervous system, respiratory system, internal organs, and increased cancer risk. The contaminants can come into contact with people in unexpected ways via underground pipes and foundation cracks, and they can enter buildings such as homes and schools undetected. Our contaminated site screening method can be adapted and replicated in areas where VOCs are present, especially in previously contaminated areas proposed for development. This method, a shared framework based on public data and transparent analysis, can increase alignment among agencies that manage contaminated sites, local governments, and community health advocates.

Research Process & Findings

Example of a 4-digit Code

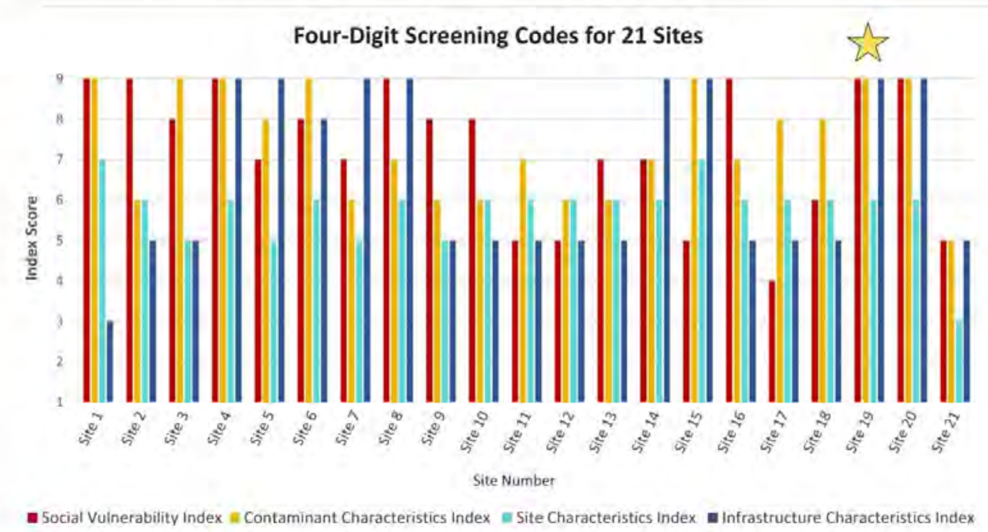
Site 19 (Hunters Point Naval Shipyard):

9 9 6 9 ☆

This is an example of a site with high scores. The code shows which characteristics make the site most vulnerable. In this case, social vulnerability, contaminant characteristics, and infrastructure characteristics all scored 9s, indicating this site as a high-priority for further investigation.

We included 21 sites of community concern that met our site inclusion criteria in our study. We used each of the four indexing methods (defined in detail in our report) to produce four scores for each study site. The resulting four-digit site code represents the potential for new public health risks driven by VOC exposure as sea level and groundwater rise. Our results show moderate to high scores, validating community concerns.

The screening method we developed supports new research, encourages clarifications by site managers and owners to address future public health risks, and promotes active and informed dialogue with community advocacy groups. The method addresses the cumulative impact of legacy contaminated sites by framing social vulnerability as a core issue that should drive the prioritization of sites for additional investigation. Our site scoring method allows users to assess the potential for new public health risks in neighborhoods around VOC-contaminated sites and flags sites where there are uncertainties driven by a lack of relevant data. Our method can be adapted and scaled up to the state level or applied in other regions of the US and the world.



The report was prepared by researchers at the University of California, Santa Cruz (UCSC), the University of California, Berkeley (UCB), and Greenaction for Health and Environmental Justice with funding from the California Ocean Protection Council (OPC).

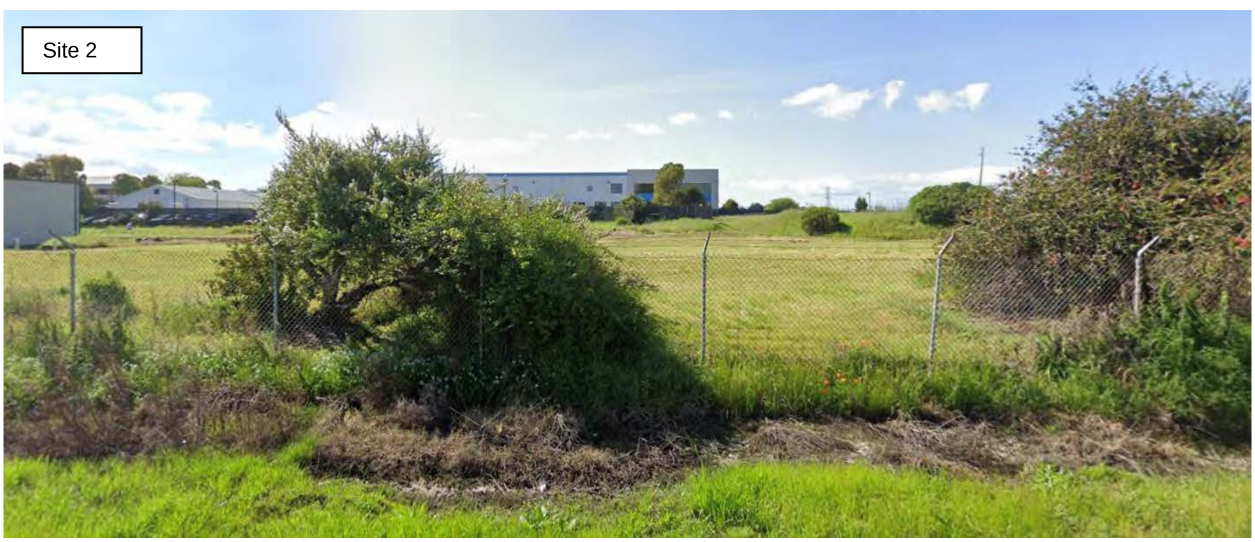
Appendix II

Images of 21 Contaminated Study Sites

Site # 1: Mare Island Naval Shipyard

From: Visit Vallejo. "Mare Island History." Accessed October 26, 2025. https://www.visitvallejo.com/about-vallejo/mare-island-history.

Site # 2: Reaction Products



Google Map Street View

Site # 3: Richmond (Point Molate) Naval Supply Center (NSC)

https://www.pointrichmond.com/wp-content/uploads/2020/05/PtMolateAerialDG.jpg

Site # 4: Zeneca Richmond AG Products

https://ww2.kqed.org/app/uploads/sites/35/2022/12/RS55424_024_KQED_EduardoMartinezRichmond_04072022-qut-1020x680.jpg

Site # 5: Berkeley Industrial Complex

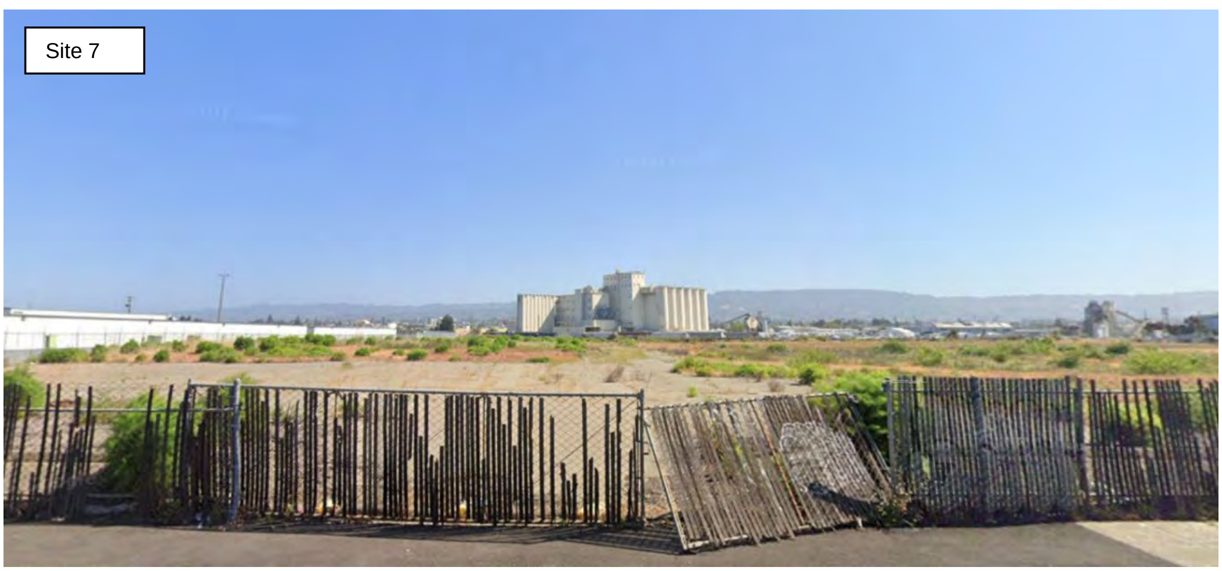
Google Map Street View

Site # 6: Alameda NAS (Naval Air Station)

https://www.saildrone.com/news/saildrone-hq-nas-alameda-history

https://www.saildrone.com/news/saildrone-hq-nas-alameda-history

Site # 7: Former J.H. Baxter Facility, Alameda

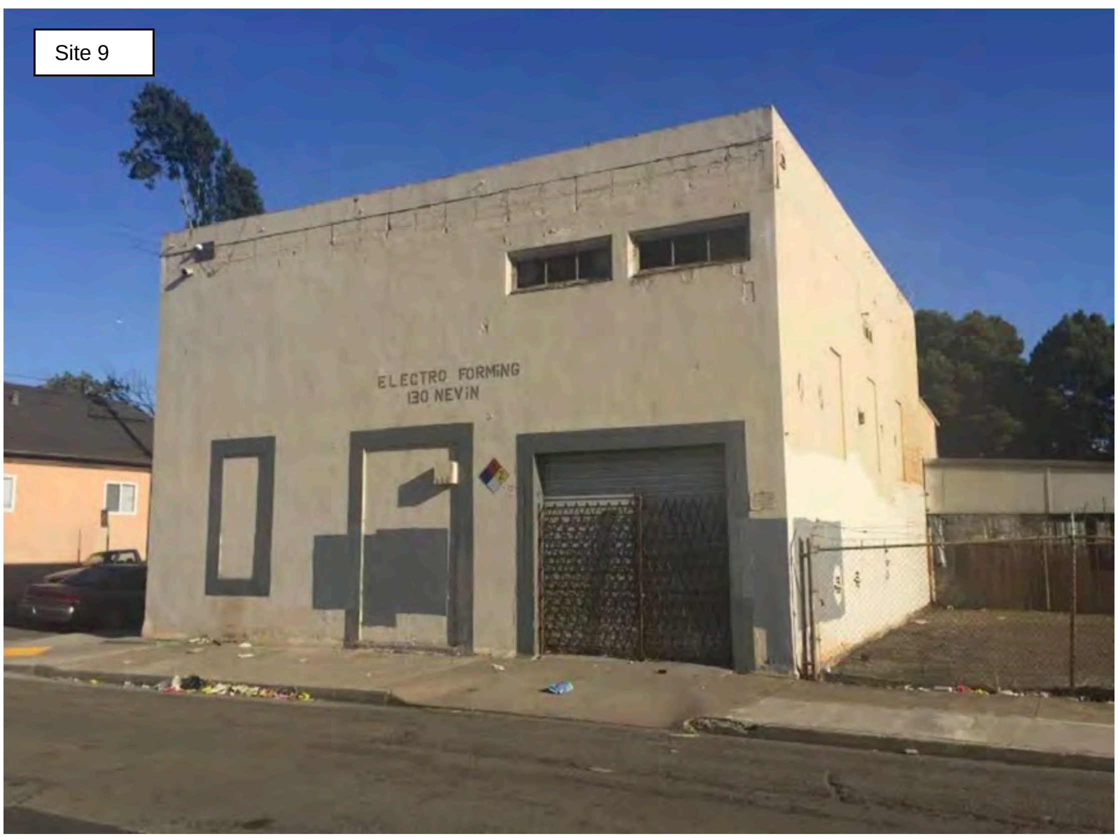


Google Map Street View

Site # 8: Associated Aerospace Activities, Inc.

Google Map Street View

Site # 9: Electro-Forming Co. – Hayward

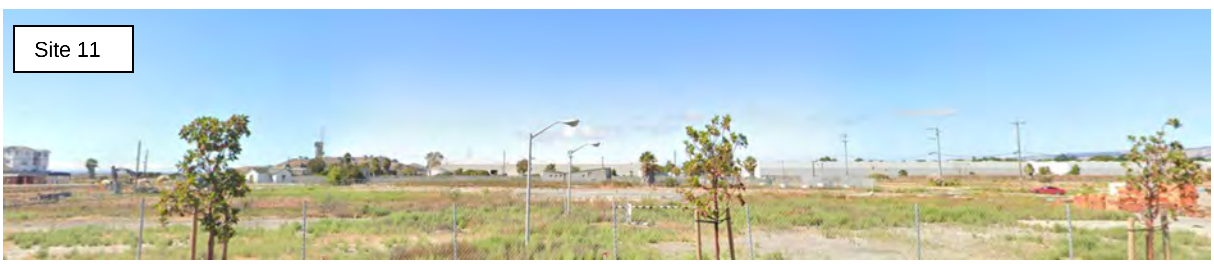


https://www.mercurynews.com/wp-content/uploads/2017/07/electro-plating4.jpg?w=857

Site # 10: Fujicolor Processing

Google Map Street View

Site # 11: FMC Corporation – Newark



Google Map Street View

Site # 12: Ashland Chemical Co., Newark

Google Map Street View

Site # 13: Safety-Kleen of California Inc.

Google Map Street View

Site # 14: Sunnyvale NIROP

https://cnrsw.cnic.navy.mil/Portals/84/CNRSW/Documents/Environmental_Support/NIROP%20Sunnyvale%20CCDEA_v2.pdf?ver=Z8uiVhpZ6gf_zkcVXUzg5Q%3D%3D

Site # 15: Moffett Federal Airfield

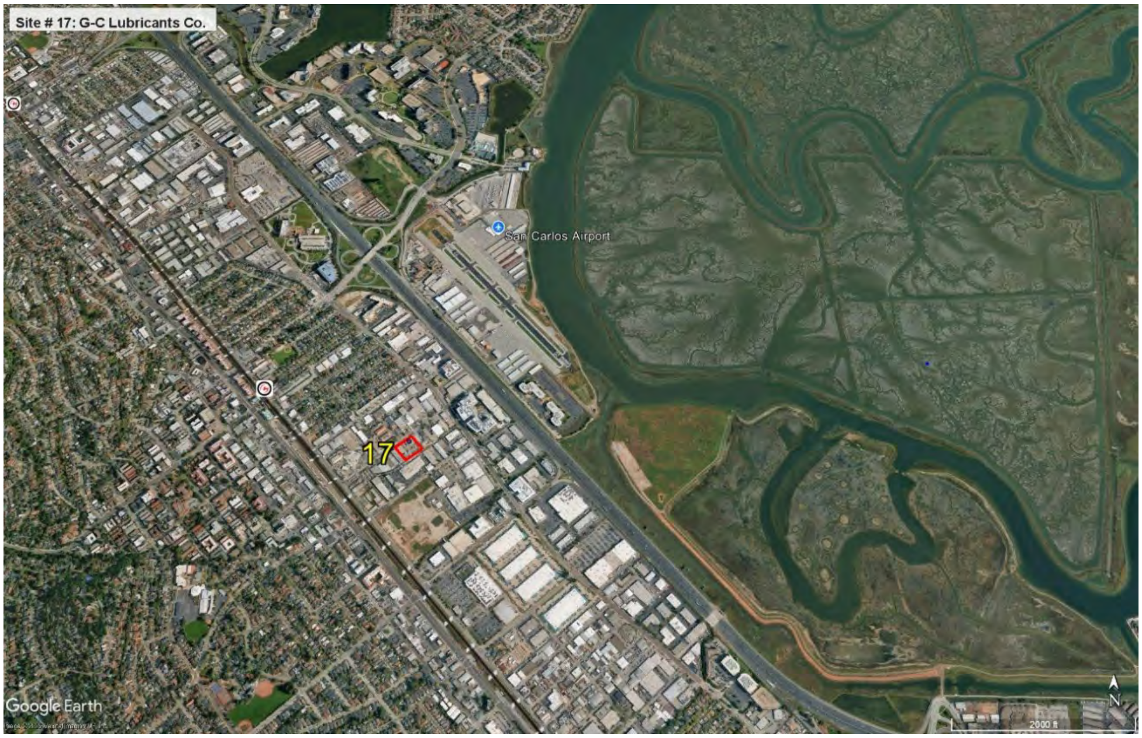
https://historicproperties.arc.nasa.gov/h3historysite/wp-content/uploads/1-1.jpg

https://sfyimby.com/wp-content/uploads/2022/05/Hangar-One-at-Moffett-Federal-Airfield-circa-1940-image-from-NASA.jpg

Site # 16: Romic Environmental Technologies Corp

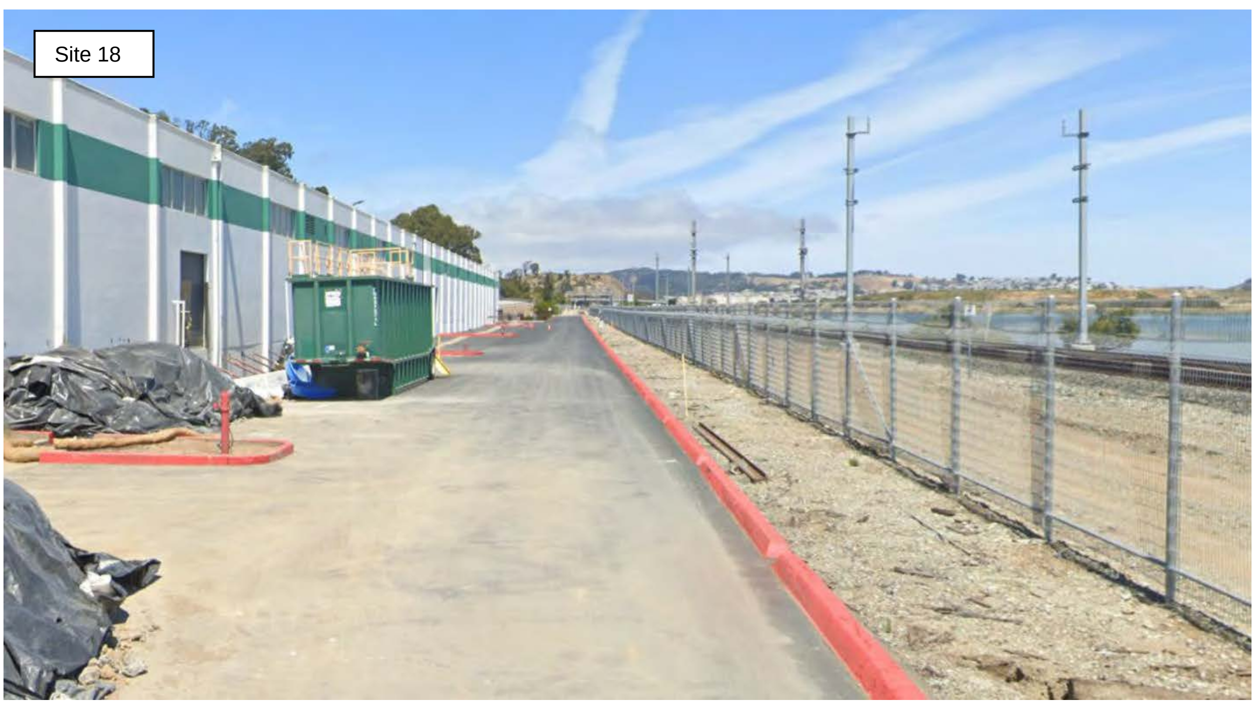
https://www.epa.gov/sites/default/files/styles/medium/public/2017-09/romic-east-palo-alto-2008.jpg?itok=How63atY

Site # 17: G-C Lubricants Co.



Google Map Street View

Site # 18: VWR Facility



Google Map Street View

Site # 19: Hunters Point Naval Shipyard

https://specials-images.forbesimg.com/imageserve/6533fb142d3c367840527687/three-aircraft-carriers-getting-maintained-at-Hunters-Point/960x0.jpg?fit=scale

https://clui-files.s3.us-east-2.amazonaws.com/s3fs-public/styles/presentation_large/public/ludb/ca/4917/07_hunters_point2.jpg?itok=v9FlVgOj

Site # 20: Naval Station Treasure Island

https://upload.wikimedia.org/wikipedia/commons/thumb/7/77/Aerial_view_of_Treasure_Island%2C_San_Francisco%2C_California_%28USA%29%2C_on_30_March_1944_%2880-G-227011%29.jpg/1124px-Aerial_view_of_Treasure_Island%2C_San_Francisco%2C_California_%28USA%29%2C_on_30_March_1944_%2880-G-227011%29.jpg?20201208201609

https://patelder.weebly.com/uploads/1/0/3/6/10362012/published/treasure-island.jpg?1568926371

Site # 21: San Quentin State Prison

https://cdn.britannica.com/70/196070-050-2BD5DB32/view-San-Quentin-State-Prison-California-Francisco.jpg

Appendix III

How to Categorize the Four-Digit Screening Codes for Prioritization

Our method allows users to develop their own approach to categorizing the four-digit code used to characterize each site. The index code is more like a fingerprint than a ranking, and a final step is required to determine which combinations of index codes (i.e., the site scores) should be placed into each of three final categories (“High, Moderate, and Low Concern”). These final categories can be used to prioritize contaminated sites for further investigation and perhaps even for accelerated cleanup relative to the trend of rising tides and rising groundwater.

The final categorization process to create sets of “high,” “moderate”, and “low” priority sites describes each of the four index score numbers that characterize a site as high (> 6.5), moderate (<=6.5 and >3.5), or low (<=3.5). For example, the Hunters Point Naval Shipyard has a four-digit index of 9969, which means that social vulnerability is high (>6.5), the contaminant characteristics score is high (>6.5), the site characteristics score is moderate (<=6.5 and >3.5), and the infrastructure characteristics score is high (>6.5). Using that logic, the Hunters Point Naval Shipyard site can be described using the ranking “high, moderate, and low” for each index score.

Next, a decision flowchart converts these category rankings into three levels of concern into which sites can be placed (“High, Moderate, and Least Concern”) (Figure AIII.1). Once the sites are placed in one of these categories, the documented conditions at sites with a “High Concern” designation should immediately be studied to confirm or refute the initial characterization of the social vulnerability of the surrounding residents, or the contaminant characterization, or the site characteristics, or the infrastructure characteristics. Once the sites are categorized, a rationale should be provided to the public for each site in the High Concern category that states either (a) why the site should not be prioritized to prevent new public health risks as tides and groundwater rise, or (b) when and how it will be prioritized to prevent new public health risks with rising seas. The same can be done for sites in the Moderate Concern category, once this first set of High Concern reviews is complete.

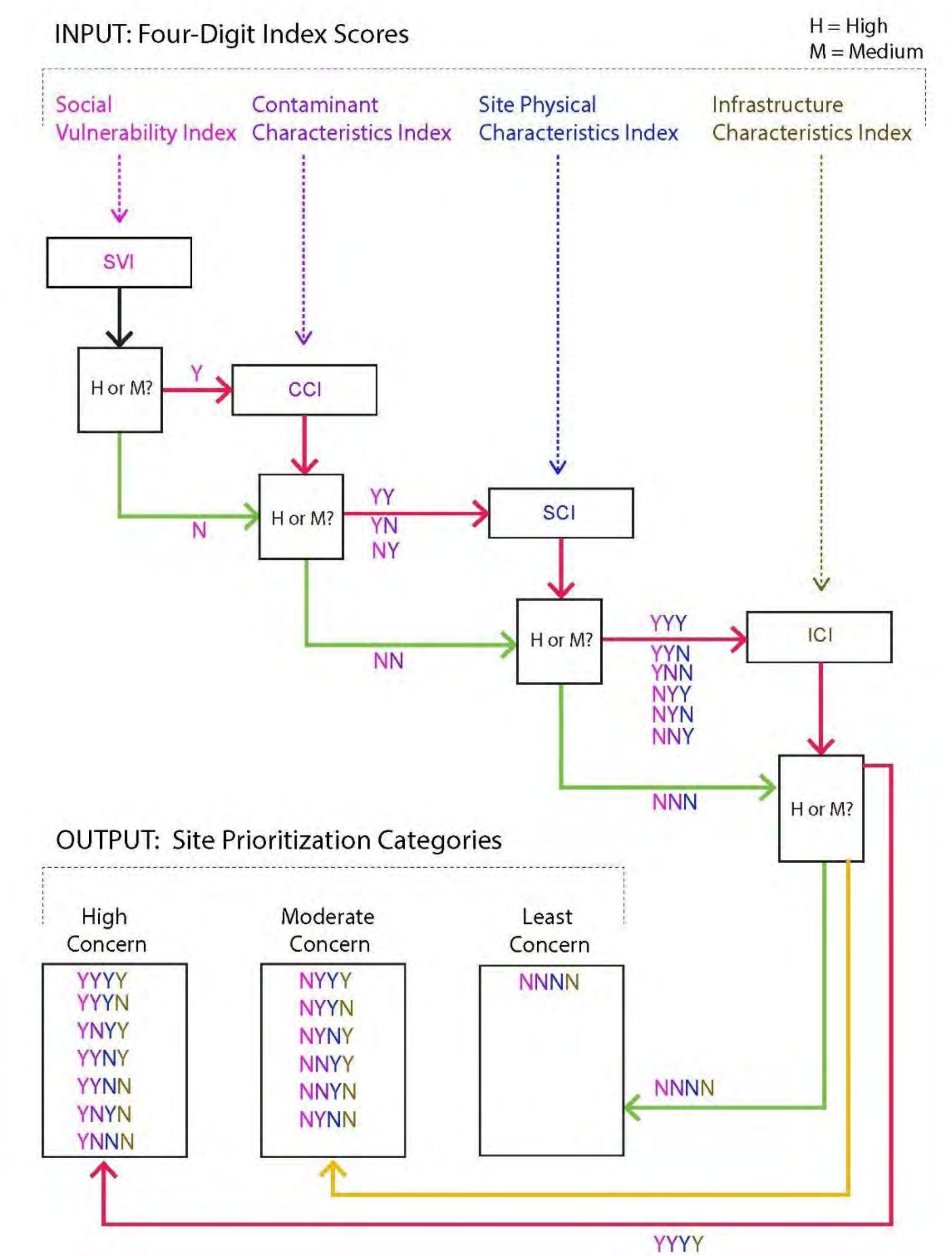
We recommend that social vulnerability be used as the primary criterion for inclusion in the High Concern category of sites. Previous research (Hill et al., 2023) showed that contaminated sites in areas of higher social vulnerability were statistically less likely to be administratively closed, which indicates a satisfactory level of safety for the health of people and the nearshore aquatic environment. By prioritizing sites with high or moderate social vulnerability, we hope to produce a stronger focus on these neighborhoods where multiple environmental pollution stressors typically co-exist and often create a higher health burden for residents than is typical in California.

As the index codes are evaluated, prioritizing social vulnerability would mean placing all the sites that are high or moderate in their social vulnerability index score into the High Concern category for site investigation/review and remediation actions. Since high-profile California cases exist of instances when site owners falsified or withheld important information about contaminants from the public, rebuilding trust will require scrupulous attention to contaminant characteristics, even if the initial index scores for a site indicate that contaminant characteristics are “low” in terms of potential for mobility and the toxicity of specific chemicals, further investigation might identify problems using newer methods. Trust requires careful explanations of why particular contaminants are present but do not pose an appreciable risk with rising waters.

Similarly, if the present-day infrastructure characteristic index score appears to be low, users would also need to consider whether permits for housing development have been granted within several blocks of the site. Housing uses are just one example of a use that may be incompatible with remediation and/or site investigation activities. Location within designated Priority Development Areas (PDAs) or Priority Conservation Areas (PCAs) set by the regional Council of Governments in a metropolitan area should also raise a flag about the site, even if the Infrastructure Characteristic is currently low, and cause such a site to be considered of High Concern regarding rising seas and groundwater. Future housing and the utility trenches or pipes that would serve those units should be considered in an actual site investigation or review to evaluate the level of exposure to a potential plume from the contaminated site.

Finally, if the social vulnerability of a census area around a contaminated site is low but the contaminant characteristics index is high or moderate, and the infrastructure characteristics index is high or moderate, we would argue that the site should be placed in the Moderate Concern category for further investigation. This would mean it is not among the first sites to be investigated, but that it would be in the second tier. There may well be vulnerable children and pregnant people in that area who deserve careful evaluation of any new risks posed by the contaminated sites in proximity, but that neighborhood is less likely to expose residents to other forms of health burdens as well, so it would not rise to the same level of importance as census areas with high or moderate social vulnerability. Pockets of high social vulnerability can be obscured within census tracts, however, so a careful check of social vulnerability information with higher spatial resolution would be ideal in these future site reviews.

Figure AIII.1 A recommended decision flowchart for converting index scores into categories for prioritization of sites.



This decision-making flowchart begins with the four-digit code as input and produces three categories of sites that reflect exposure to rising groundwater or tidal inundation, priorities for review, and potentially accelerated remediation. If the value of an index score is "High" or "Medium," that produces a "Y" (Yes) output. If it is "Low," that produces a "N" (No) output. The unique sequences of Y's and N's are categorized into the final three sets of contaminated sites - those that are of High Concern, Moderate Concern, and Least Concern. Social Vulnerability is prioritized as a way of re-establishing trust with communities that bear high environmental pollution burdens.