Impacts of Predicted Sea-Level Rise and Coastal Inundation on Power Infrastructure in the San Francisco Bay Area

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ABSTRACT

As climate change progresses, the San Francisco Bay Area, a key economic and technological hub, faces increasing risks from sea-level rise (SLR) and coastal inundation. Although no immediate risks are identified associated with the power infrastructure in the Bay Area, future projections of SLR and related extreme events could increase the vulnerability of key power infrastructures such as transmission lines, electric substations, and power plants. Using a Geographic Information System (GIS), the study mapped and analyzed the vulnerability of the power infrastructure to various projected SLR scenarios (2 ft, 4 ft, and 6ft). It employed the most updated inundation maps from the National Oceanic and Atmospheric Administration to simulate moderate to extreme SLR scenarios, providing a comprehensive assessment of risk across the Bay Area. The analysis identified significant portions of the Bay Area's power infrastructure at increased risk of flooding, including approximately 19% more inundation areas, up to 12% of power plants, 10% of electric substations, and 3-5% of transmission lines. This could lead to operational disruptions, elevated maintenance costs, and a higher need for emergency restoration services. The study highlighted the critical need for integrating climate change projections into current and future infrastructure planning to minimize risks and prepare for inevitable environmental changes. It offered actionable insights for policymakers, urban planners, and utility providers, aiming to fortify the region's infrastructure against the encroaching tides and ensure sustainable operation and service continuity.

KEYWORDS

Climate change, infrastructure planning, inundation models, geographic information systems, climate adaptation

INTRODUCTION

Under the impacts of climate change, rising sea-levels and related weather events are posing increasing challenges to coastal regions worldwide (Williams 2013; Cazenave and Cozannet 2014; Ohenhen et al. 2024). By 2100, the average sea-level along the California coast may rise between 1.0 and 1.4 meters (3.3 and 4.6 feet), coupled with an increased rate of extreme high sea level events (Cayan et al., 2008; Cayan et al. 2009). The increasing trends of mean sea levels, mean high water, and extreme surge events at high tide pose a growing risk to coastal energy infrastructure, including power plants, transmission lines, as well as gas storage, and pipeline systems (Flick et al. 2003). It was found that a 100-year flood event could inundate as many as 25 power plants, a large number of electricity substations, and at least one natural gas storage facility located along California's coast in a 1.4 m (4.6 ft) sea level rise scenario (Sathaye et al. 2012).To understand how sea level rise (SLR) will affect these facilities in the future and prevent potential damage to them, it is necessary to assess their current characteristics against projected SLR scenarios for future adaptation strategies.

In the San Francisco Bay Area, the largest estuary along the Pacific Coast of North America with an economy of almost 300 billion and over 7 million inhabitants, a large and complex power infrastructure system is maintained to support the functionality of the area (Biging et al. 2012). As a critical part of urban functionality, power infrastructure includes the state's natural gas-fired power generation facilities, electric transmission and distribution system, and oil and natural gas pipelines (Sathaye et al. 2012). In the Bay Area, the resilience of the region's power infrastructure is put to the test by the increasing occurrence of climate-related incidents, such as the notable flooding of substations due to storm surges and the erosion of foundational supports for transmission lines from rising waters. Examples like the inundation risks to the Embarcadero during high tide events (Melillo et al. 2014) and the power outages during the severe storms of recent years underscored the pressing need for fortified energy systems. For the future development of urban power infrastructure, it is important to incorporate the impacts of climate change into the local planning, design, and maintenance of the power infrastructure.

This study adopted a similar approach from Dismukes and Narra 2018 where they examined the impacts of sea level rise on the energy infrastructure along the Gulf Coast, United

States. The approach involved detailed mapping of existing power infrastructure locations against the most-updated projected inundation maps that account for various sea-level rise scenarios (NOAA, 2021). This method not only highlighted the areas of immediate concern but also helped in understanding the long-term implications of climate change on the stability and functionality of the power systems (Dismukes and Narra 2018).

The purpose of this study was to evaluate the extent of the impact of the sea level rise on power infrastructure in the San Francisco Bay Area. First, I identified the distributions of major power infrastructure in the Bay Area. Second, I examined the future SLR scenarios to analyze the potential impacts of SLR on power infrastructure in the area. And lastly, I examined adaptation methods, and the limitations to these methods and opportunities for future research.

SLR projections and scenarios

According to the 2022 Sea Level Rise Technical Reports by the National Oceanic and Atmospheric Administration (NOAA), a significant acceleration in sea level rise is anticipated along the U.S. coastline over the next three decades (2020-2050). Projections indicate an increase of 10 to 12 inches (0.25 to 0.30 meters), which is roughly equivalent to the total rise observed during the entire previous century (1920-2020). This accelerated rise is attributed to a combination of thermal expansion of seawater as the ocean warms and increased melting of glaciers and ice sheets.

In the San Francisco Bay Area, the situation is particularly critical due to its unique geographical and infrastructural characteristics. The Bay experiences semidiurnal tides, which include two high and two low tides each day, with king tides—exceptionally high tides that occur several times annually, mainly between December and February (Mukhopadhyay et al. 2023). These king tides are now significantly intensified by the ongoing sea level rise, leading to recurring flooding in low-lying coastal areas. Notably, regions such as the San Francisco Embarcadero and Mill Valley have experienced increased annual flooding events.

Historically, much of the San Francisco Bay shoreline was composed of wetlands and open bays. Over time, extensive development has occurred through the placement of fill in these areas, rendering them particularly vulnerable to flooding and subsidence-induced sea level rise impacts. The Bay's diverse shoreline features, including tidal marshes, mudflats, levees, and engineered structures, serve as primary defenses against coastal hazards, safeguarding critical inland areas. However, these natural and artificial defenses are under increasing stress from the compounded effects of higher sea levels.

Inundation maps are used to effectively illustrate the impacts of sea level rise (SLR) and showcase specific SLR scenarios or extreme tide levels. For SF Bay, instead of selecting single SLR scenarios, a range of scenarios is represented in 10 sets of inundation maps for each county, covering SLR from 12 to 108 inches and extreme tides from annual to centennial events. This approach, based on a detailed water level analysis, aims to represent both permanent and temporary flooding conditions anticipated before 2100. For instance, in Marin County, a map might depict both a scenario with 36 inches of SLR and one with 24 inches of SLR plus a one-year extreme tide. The mapped scenarios aim to align with current National Research Council SLR projections and consider a spectrum of storm surge events, making them adaptable to evolving SLR science. The scenarios are consistent across counties but vary in specific SLR and storm surge combinations due to differing water levels throughout the Bay.

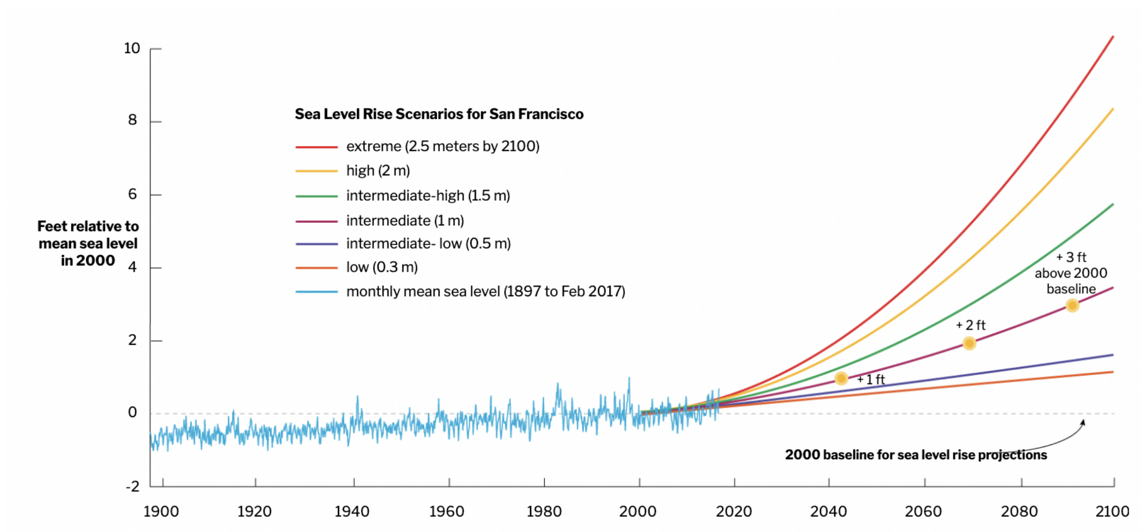


Figure 1. Sea level rise projections for San Francisco for several global scenarios (NOAA, 2017)

Overview of power infrastructure in the Bay Area

The San Francisco Bay Area plays a pivotal role in supporting Northern California's power infrastructure, which includes an extensive network of transmission lines, power plants, and substations. This region notably meets about one-third of Northern California's peak energy demand through a diverse mix of resources. Significant sources include electricity imported via major transmission pathways like Path 66, which not only connects the area to other parts of California but also to the broader western United States grid. Additionally, renewable energy sources such as Sierra-region hydropower and geothermal plants in Northern California contribute to the energy mix, complemented by the phased-out coastal nuclear power (CEC, 2021).

Despite a strong focus on renewables, natural gas facilities continue to play a crucial role, particularly in meeting base-load demands and providing energy during peak usage. Many of these plants are strategically positioned throughout the Bay Area (Sathaye et al. 2012). The region's power system is interconnected through a robust network of substations and transmission lines that manage the distribution of electricity from power plants to consumers. These facilities convert high-voltage electricity transmitted over long distances into lower voltages suitable for domestic and commercial use. As the Bay Area continues to grow and evolve, ongoing efforts to modernize the grid and enhance its resilience are critical in addressing the challenges posed by aging infrastructure, increasing loads, and climate change impacts.

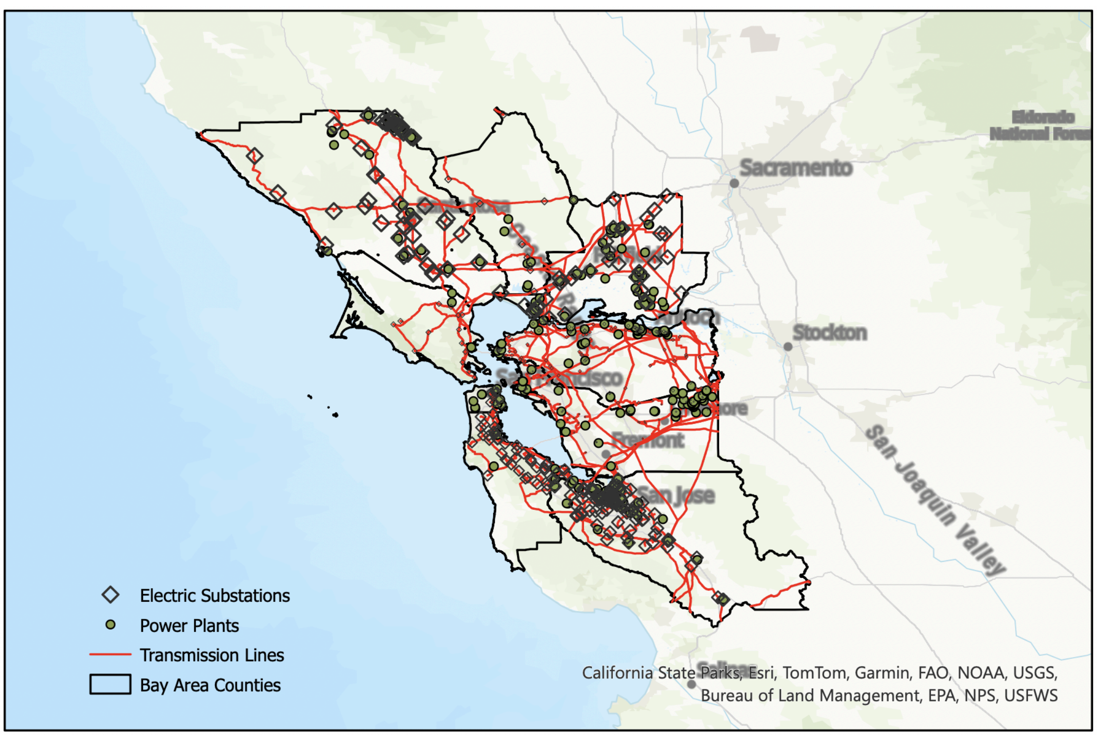


Figure 2. Electric substations, power plants, and transmission lines in the SF Bay Area (Liu, 2024)

METHODS

Study site

The San Francisco Bay Area, encompassing nine counties and housing around 7 million people, is the fifth most populated urbanized area in the United States. Its rich economic, cultural, and ecological landscape is supported by an extensive energy infrastructure system. The primary provider of energy within the San Francisco Bay Area is the Pacific Gas and Power Company (PG&E). The composition of the energy supply includes 20% from natural gas, 18% from large-scale hydropower facilities, 27% sourced from nuclear energy, and a significant 33% derived from various renewable energy sources. Additionally, 2% of the electricity is procured from external regions. Notably, the utility company does not utilize coal-fired power plants, thus maintaining a zero percentage in its energy mix (Weijie et al. 2019).

Historically, the shoreline's low-lying areas have been subject to coastal flooding, notably during king tides and El Niño high tides. With sea-level rise projections, such events are anticipated to become more frequent, prolonged, and intense, posing risks to the functionality of the energy infrastructure in the Bay Area. For instance, previous research found that among 25 power plants that are at risk of a 100-year flood with a 1.4 m sea level rise, 13 of them are in the San Francisco Bay Area (Sathaye et al., 2012). Ongoing efforts by various entities aim to develop tools for assessing vulnerabilities to inundation by SLR, highlighting the need for comprehensive and consistent shoreline mapping to inform future planning and resilience strategies.

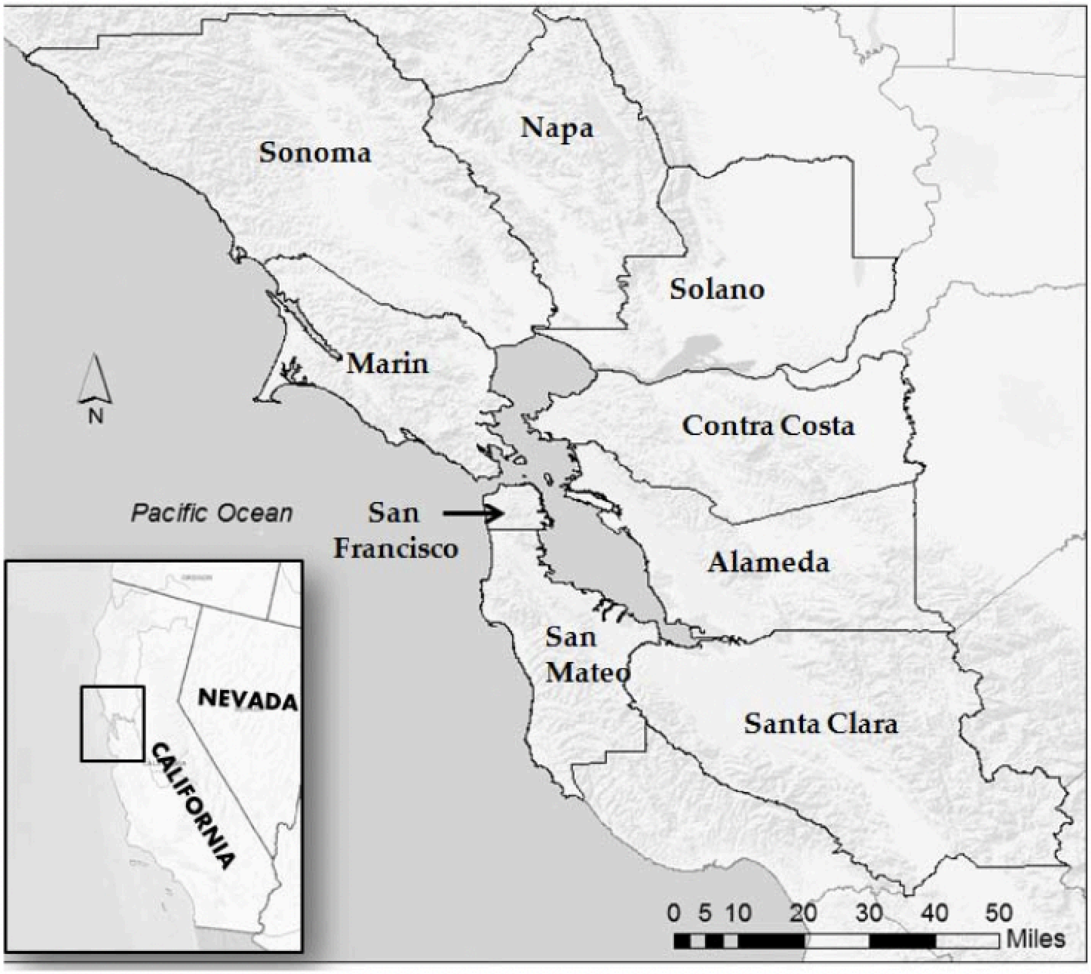


Figure 3. Nine Counties in the SF Bay Area (Ekstrom and Moser 2012)

Inundation model

The inundation model was adapted from the NOAA Office for Coastal Management's most updated sea level rise inundation mapping, which aimed to use the best publicly available elevation data to map predicted sea level rise, building on the baseline of mean higher high water (MHHW) and adjusting for local and regional tidal variations (Detailed Method for Mapping Sea Level Rise Inundation, 2017). This model was distinguished from other national sea level rise mapping efforts by its adherence to rigorous criteria designed for consistent national-scale mapping. The modeling approaches evaluated hydrological connectivity to identify potential flooding zones while also preserving and separately displaying hydrologically unconnected areas larger than one acre. Unlike simplistic "bathtub" models, this approach accounted for local tidal variability and hydro-connectivity, providing a more nuanced view of the impact of sea level rise. Additionally, the tool incorporated updated sea level rise scenarios from the 2022 Technical Report, offering a direct comparison of local impacts under various future scenarios.

To evaluate the potential impacts of predicted sea level rise (SLR) on key energy infrastructure, I charted the current inventory along the Bay Area using a Geographic Information System (ArcGIS 10.5). This mapping incorporated three conceivable SLR scenarios—0.61 meters (2 feet), 1.22 meters (4 feet), and 1.83 meters (6 feet)—to ascertain the potential effects on coastal energy facilities.

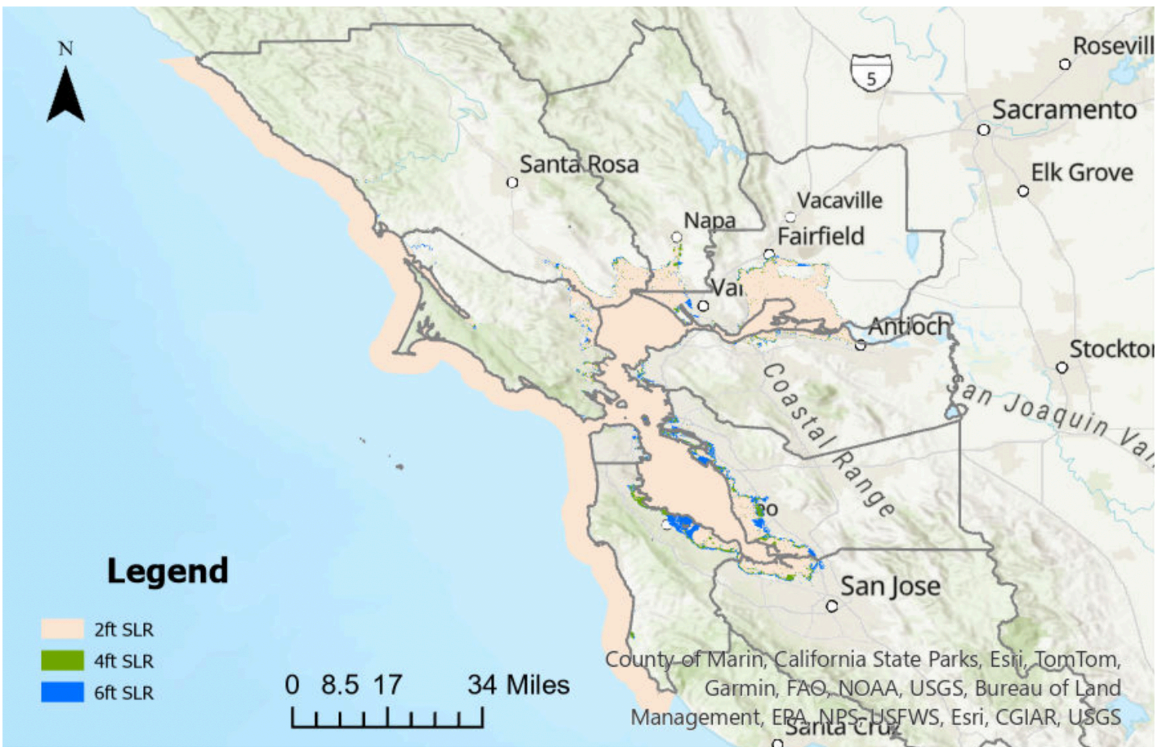


Figure 4. Three SLR Scenarios (2ft, 4ft, 6ft) used in inundation analysis (Liu, 2024)

Geospatial data

Data on the extent of inundation for various sea level rise (SLR) scenarios were collected from the Digital Coast website by the Office for Coastal Management for the nine counties in the SF Bay Area. These datasets were provided in ESRI geodatabase format, including both vector shapefiles and raster datasets, with resolutions ranging between 3 meters and 10 meters. The data depicted the projected footprint and relative depth of future SLR inundation, from the current mean higher high water level up to a six-foot increase in sea level. An example of the projected inundation extent under three SLR scenarios for the SF Bay Area is presented in Figure 4.

Predicting future inundation involved uncertainties due to factors such as wetland restoration, changes in barrier islands, local elevation shifts, and subsidence. As a result, the depicted inundation areas in the SLR datasets may lack precision. Therefore, it's crucial to consider not only the inundation extent but also the confidence levels associated with these datasets across different SLR scenarios. Confidence maps, which accounted for errors in elevation and tidal adjustments, were also obtained to gauge the reliability of these inundation predictions. When identifying infrastructure at potential risk, areas where confidence was high were differentiated from those where uncertainty prevailed.

Energy infrastructure assessment

The critical energy sub sectors selected are power plants, transmission lines, and electric substations as mentioned earlier. These types of infrastructure were chosen in the SF Bay Area due to their significant presence and critical role in the energy supply chain, along with the region's dependence on these energy sources. Historically, such facilities have been the most vulnerable to damage during severe weather events and hurricanes in the area (Knowles 2010).

The model framework as shown in figure 5 was adapted from Dismukes and Narra 2018 which conducted a similar research on the Gulf Coast of the United States. The potential structural risk to energy facilities due to inundation was explored with a focus on the transmission and power generation capacities that could be affected by disturbances to energy systems. Detailed geospatial and facility-specific data were sourced from the California Energy Commission (CEC). The mapping database for transmission lines, substations, and power plants was initiated in 1990 by the GIS staff at the CEC. This project was completed in October 2010. Subsequently, the GIS Unit took charge of leading the development of the enterprise GIS system on CEC's critical infrastructure database, beginning in November 2014 and implemented in May 2016. These infrastructure types were mapped against future sea level rise (SLR) scenarios of 0.61 meters (2 feet), 1.22 meters (4 feet), and 1.83 meters (6 feet) to identify facilities within inundation zones, including transmission lines, electric substations, and power plants.

For structures not immediately within inundation zones, proximity analysis was conducted to assess the risk of impact from SLR, along with associated flooding and storm surges due to receding shorelines. The proximity of these structures to future shorelines serves as an indicator for assessing storm surge and flood risks. Facilities located within 1 km, 2 km, and 5 km of inundation zones were specifically noted. The National Oceanic and Atmospheric Administration highlights the particular vulnerability of some Bay Area regions to storm surges, attributed to a flat continental shelf and extensive low-lying inland areas. Given the complex interplay between storm surges, flooding, and local geophysical features, no uniform set of variables is suitable for all scenarios concerning these at-risk facilities (NOAA, 2017).

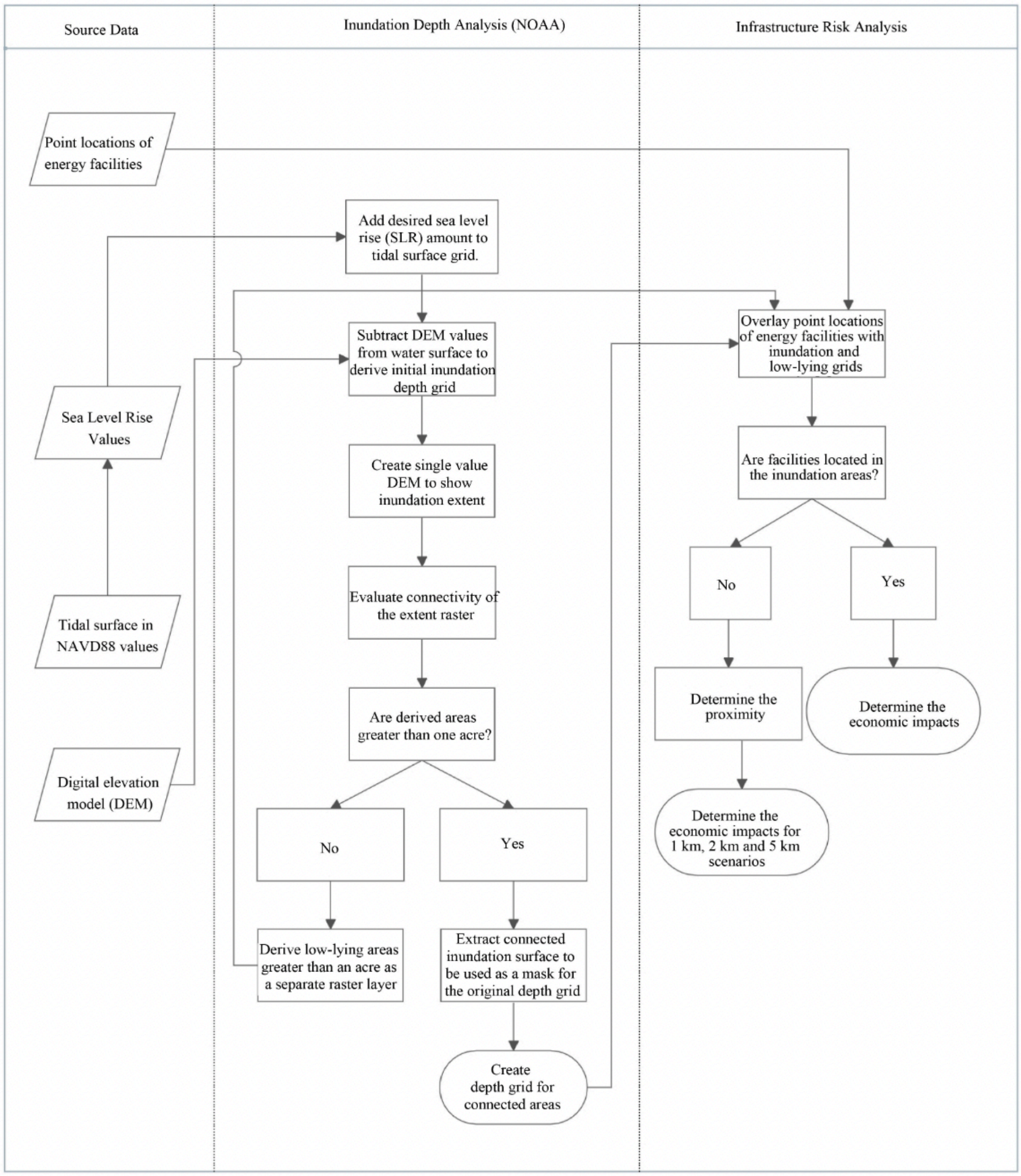


Figure 5. Model framework used to determine inundation extent for different SLR scenarios. The SLR depth grids for different scenarios are obtained from NOAA (Dismukes and Narra 2018)

RESULTS

SLR scenarios and Inundation extent

The analysis revealed that under a scenario of 0.61 meters (2 feet) of sea-level rise (SLR), an additional 3511.2 square kilometers of the Bay Area could be flooded, marking a 19% increase in land susceptible to coastal flooding compared to a scenario without SLR. With a 1.22 meters (4 feet) rise, the at-risk area expanded by another 99 square kilometers, and a 1.83 meters (6 feet) rise could add 237 square kilometers to the flood zone. Figure 6 displays a representative example of how far flooding might extend in the Bay Area under various sea level rise (SLR) scenarios, in relation to the location of energy facilities. It highlights regions where inundation is highly probable, as opposed to areas where flooding likelihood is uncertain, pinpointing which facilities are at risk.

Potential impacts on power plants

Using spatial analysis, it was found that up to 12% of the power plants in the area could be impacted by SLR. In the scenarios of a 2-foot SLR, it is projected that 5 power plants, with a combined capacity of 46.5 megawatt (MW), would be affected. A more significant rise of 4 feet doubles the stakes, with 12 power plants likely to experience impacts, tallying a substantial 700.54 MW of capacity at risk. With a 6-foot sea level increase, the analysis indicates that 27 power plants could be within the affected zone, which collectively contribute a considerable capacity of 3248.02 MW.

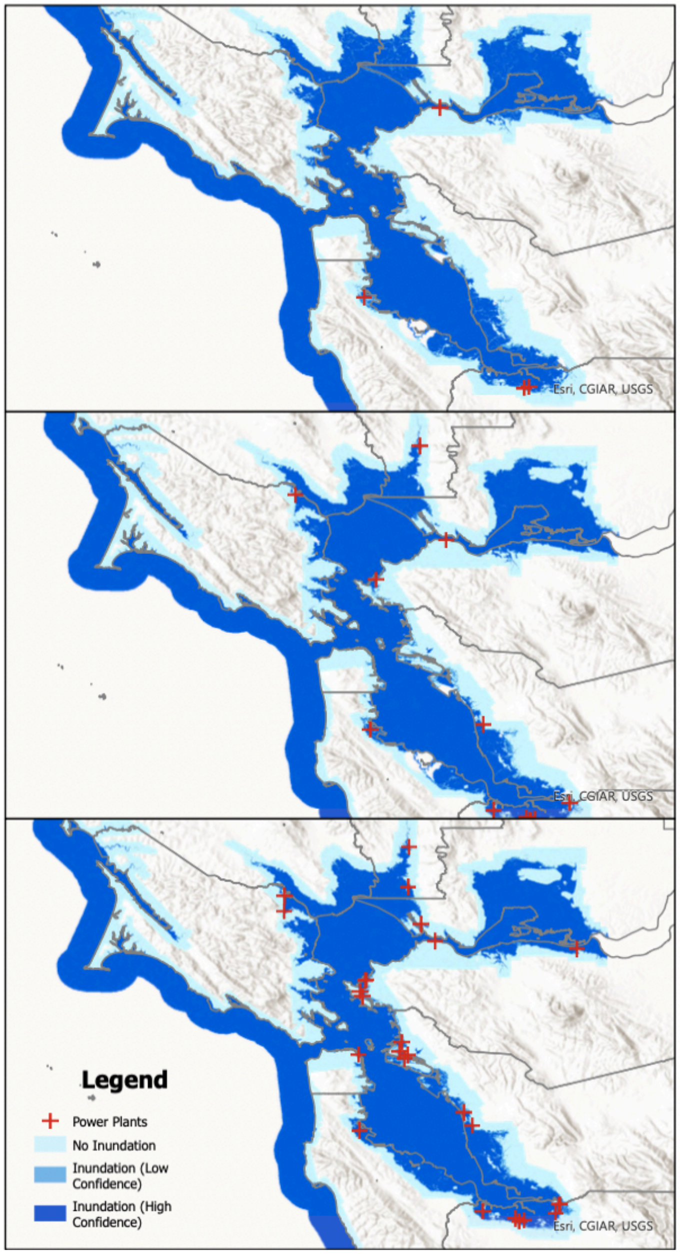
Potential impacts on transmission lines

The integrity of transmission lines is essential for the maintenance of electrical distribution systems. The study has found that approximately 3% - 5% of the transmission lines could be impacted by the SLR scenarios. Compared to power plants which are more densely distributed along the coast, less transmission lines are under impacts due to its even distribution in the inland areas. In the 2-feet SLR scenario, approximately 257.096 miles of transmission lines are projected to be impacted. At the 4-feet scenarios, the affected transmission lines would extend to about 317.141 miles. The most severe scenario, a 6-foot rise in sea levels, could impact as much as 393.048 miles of transmission lines. The potential impacts could directly correlate to the proportion of the network that may face operational shutdowns, affecting the distribution of power and potentially causing widespread disruptions in service.

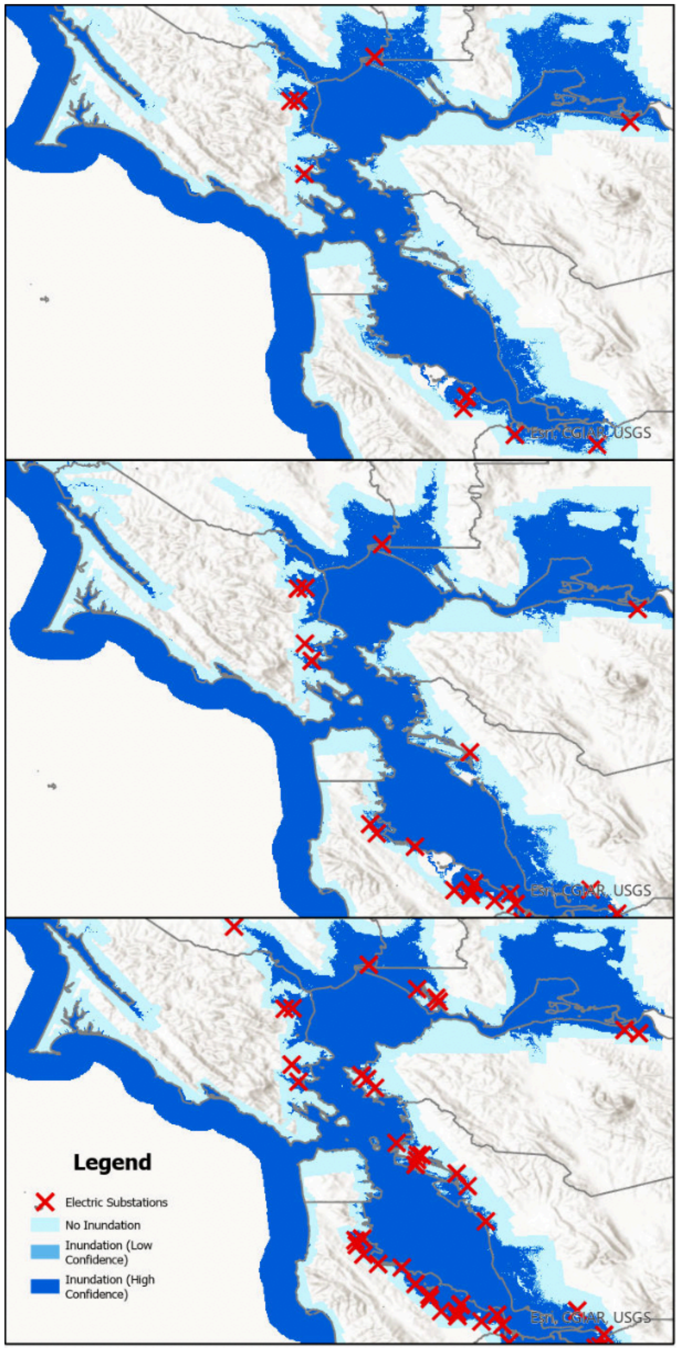
Potential impacts on substations

With a 2-foot increase in sea level, I identified 10 substations that could potentially be affected. This number more than doubles to 24 substations when the sea-level rise is projected at 4 feet. In the most extreme scenario of a 6-foot rise, up to 47 substations face the risk of being impacted. These findings highlight a significant challenge for maintaining continuous electricity supply and necessitate preemptive action to safeguard these critical infrastructure assets against the adverse effects of rising sea levels.

(a)


Esri, CGIAR, USGS
Esri, CGIAR, USGS
Legend
Power Plants
No Inundation
Inundation (Low Confidence)
Inundation (High Confidence)
Esri, CGIAR, USGS

(b)


Esri, CGIAR, USGS
Esri, CGIAR, USGS
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Electric Substations
No Inundation
Inundation (Low Confidence)
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Esri, CGIAR, USGS

(c)

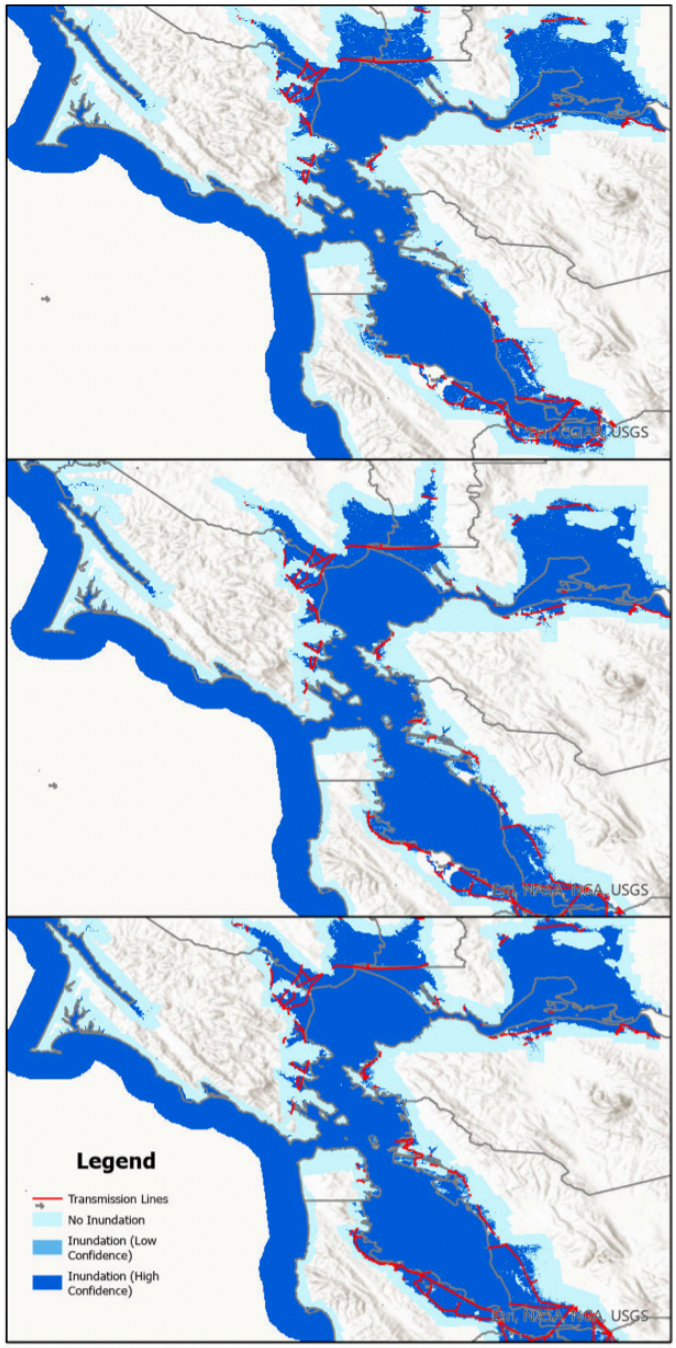

Figure 6. Inundation extent and confidence levels at 0.61 m (2 ft), 1.22 m (4 ft) and 1.83 m (6 ft) SLR scenarios (top to bottom) with infrastructure facilities overlaid: (a) Power plants; (b) Electric Substations; (c)Transmission Lines.

DISCUSSION

Future adaptations and resilience

This study has highlighted significant vulnerabilities in the San Francisco Bay Area's power infrastructure due to projected sea-level rise and coastal inundations. The most critical risks identified include the inundation of low-lying substations, the erosion of foundational supports for transmission lines, and the susceptibility of coastal power plants to flooding. These vulnerabilities pose a serious potential threat to the reliability and operational stability of the region's power supply, especially during extreme weather events.

Critical to effectively counter the impacts of sea-level rise is a three-tiered strategy that includes updated regulatory frameworks, investment in adaptive technologies, and robust public-private collaborations. Recent research has indicated that regulatory adjustments are necessary so as to have a stronger legal and structural basis, with all adaptation efforts remaining in line with current needs and future projections (Najafi et al. 2021). They stressed that advanced infrastructure investments, such as seaports, flood-resistant materials, and predictive flooding analytics, need to be made, but at the same time, there could also be public-private partnerships injecting innovative defenses against the rising sea level (Najafi et al. 2021; NOAA 2022). This may increase the chances of achieving public support for the initiatives by progressively increasing the ability to meet the local needs and preferences of the local population.

In addition to policy and community-focused strategies, specific attention should be paid to the direct challenges posed to infrastructure by changes in environmental conditions. The design and upgrade of urban systems must account for increased wave action, precipitation variability, and the heightened intensity and frequency of storms due to climate change (Griggs 2021). Changes in groundwater levels, particularly in coastal regions, necessitate innovative engineering solutions to prevent structural damage from subsidence and saltwater intrusion (Schweikert et al. 2019). Addressing these challenges requires a comprehensive understanding of both the current landscape and projected changes, ensuring that both new developments and retrofitted structures are capable of withstanding future climatic conditions.

Limitations

This study did not provide a comprehensive risk assessment of all energy infrastructures in the SF Bay Area but offer a preliminary estimation of critical facilities that would face growing risks due to sea level rise (SLR) and secondary extreme weather events. Key factors not considered include the likelihood of local hurricane strikes at specific locations, the depth of inundation, and the extent of damage that would occur to each facility exposed to flooding or storm-related wind damage (Knowles 2010). This analysis also does not take into account potential mitigation strategies against SLR, such as the construction of physical barriers like storm levees, berms, or the elevation of key infrastructure components or equipment.

Moreover, the actual risk from SLR may vary significantly among the facilities identified as at risk, and this study did not account for the potential reduction in risk due to the relocation of facilities over the coming decades, which falls within the timeframe of the SLR projection scenarios. Although the likelihood of relocating some of these large facilities is relatively low, it remains a factor. Another critical issue that exacerbates the risk of storm surges and SLR is land subsidence, which, according to some estimates, is occurring at rates faster than previously observed in the SF Bay Area (Shirzaei and Bürgmann 2018). The projected inundation levels from future SLR scenarios assume that current geomorphological settings will persist. As understanding and predictions of these natural processes improve, better estimates of SLR can be expected, leading to more refined risk assessments in the future.

Conclusions

This research evaluates the increasing risk of sea level rise (SLR) on crucial energy infrastructure situated along the San Francisco Bay Area. Historical data from tide gauge stations over decades indicate that coastal regions near the SF Bay Area may experience a notably higher rate of SLR compared to other locations along the coastline. This region also hosts a large network of energy facilities, not just in the SF Bay Area but across the entire U.S. This study identifies certain types of critical energy infrastructure as being particularly susceptible to a range of SLR scenarios, including power plants, electric substations, and transmission lines. Due to their relatively close proximity to the coast, these plants are potentially at greater risk compared to other infrastructural facilities, which are typically located slightly more inland. A significantly higher number of facilities are located within 1000 meters of the predicted future inundation zones under various SLR scenarios, highlighting their vulnerability to storm surges and their inland effects.

This research emphasizes that if SLR is not addressed, it will likely disrupt critical energy infrastructure and the connected energy systems, with national and global consequences. The future use of expert system-based, integrated climate change impact assessment models is essential to better understand the interplay between industry and environmental variables and the resulting policy implications. Proactive adaptation practices and enhanced awareness that identify potential hazards and prepare for future SLR need to be more broadly implemented in at-risk areas. Existing energy infrastructure facilities should consider conducting periodic risk assessments and developing protective strategies to adapt to changing environmental conditions to preserve the economic value of their initial investments.

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APPENDIX A: Types of power plants

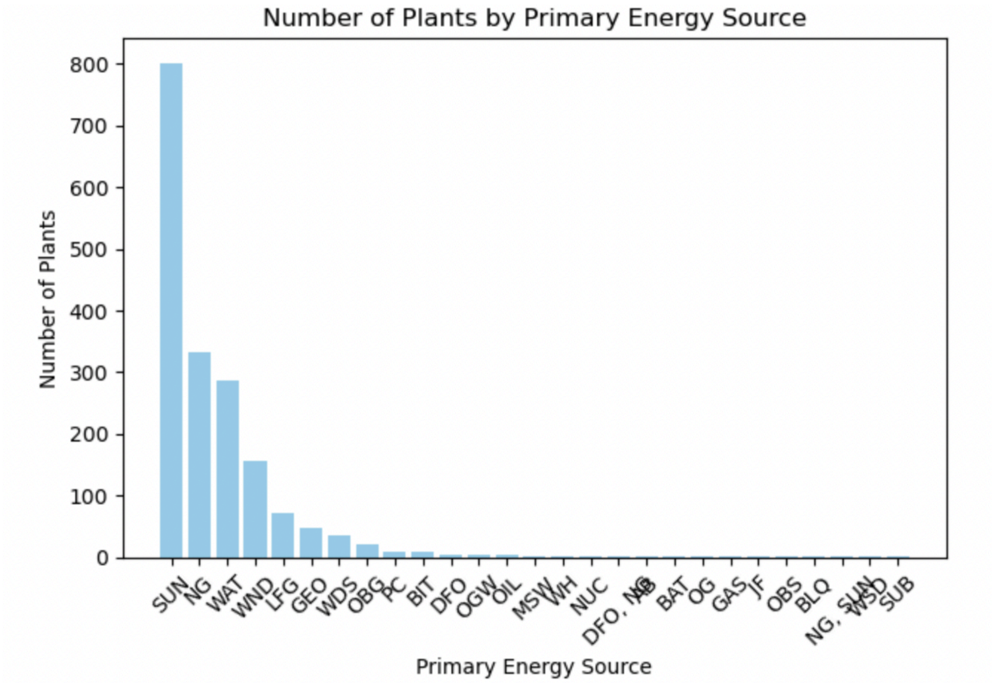

Figure A1. Types of power plants distributed in the SF Bay Area

APPENDIX B: Visualizations of impacts on power plants, electric substations, and transmission lines

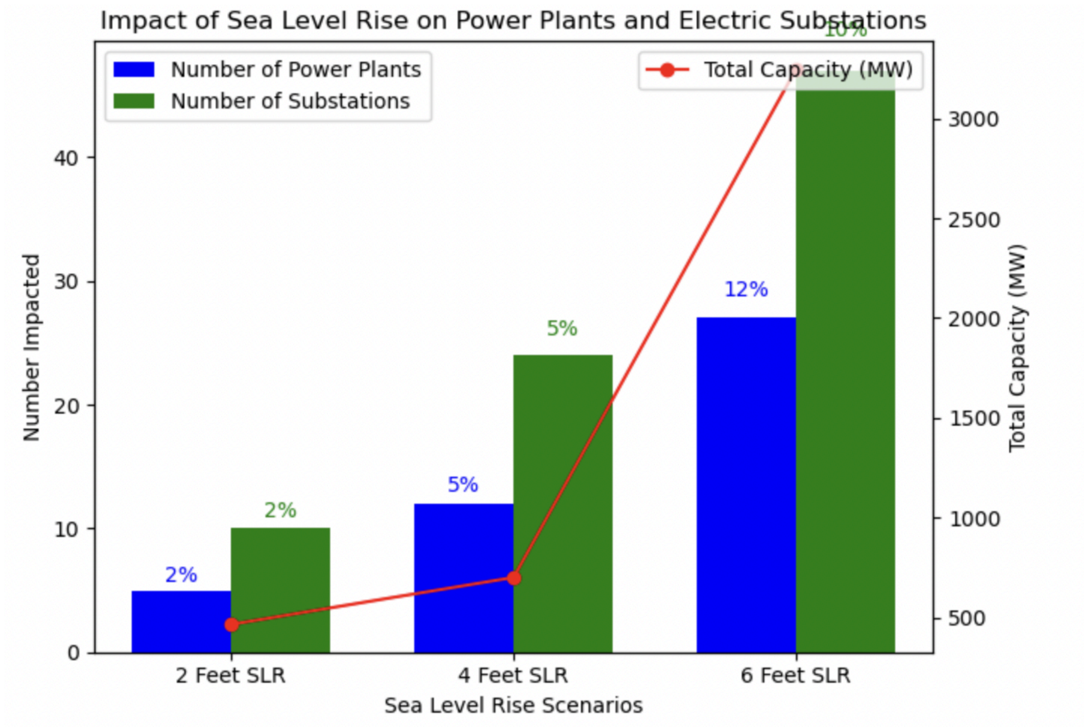

Figure B1. Impacts of SLR on power plants and electric substations

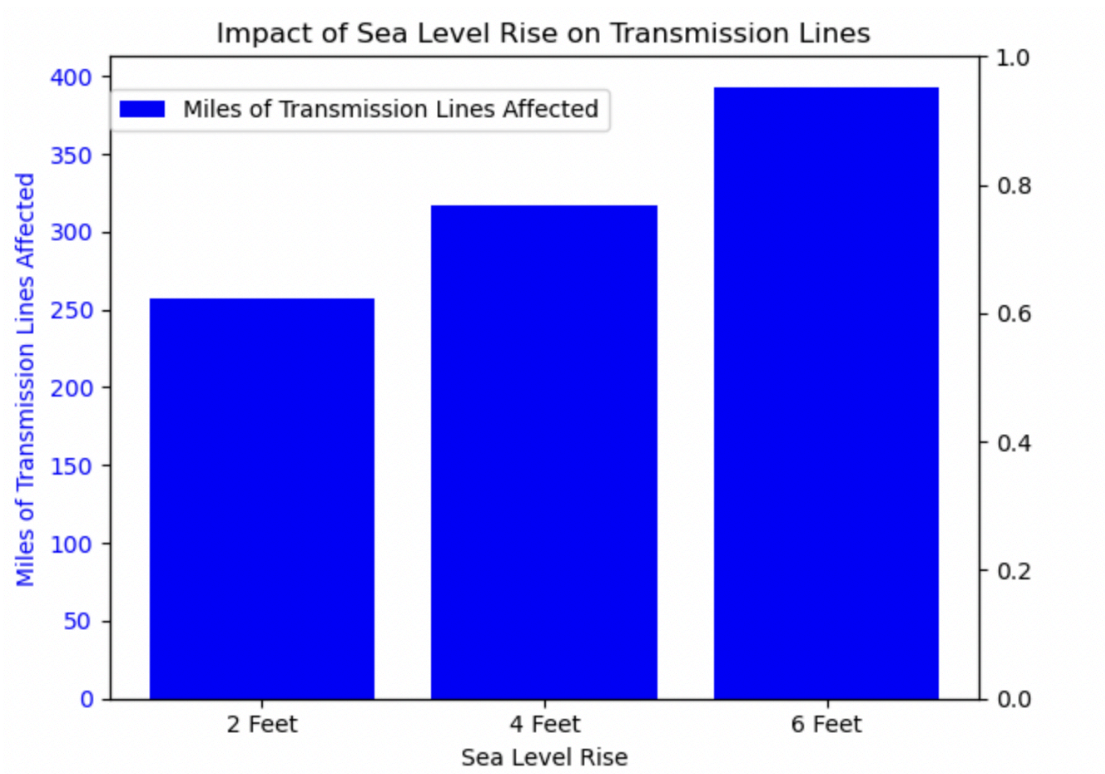

Figure B1. Impacts of SLR on transmission lines