2021

The Shoreline Vulnerability Index for the San Francisco Bay

METHODOLOGY REPORT

Story Map Link:

https://bcdc.maps.arcgis.com/apps/Cascade/index.html?appid=a90eb7b4eb7249809505e8d940bb2419

Web Application Link:

https://bcdc.maps.arcgis.com/apps/webappviewer/index.html?id=b05c634171d14d46aebc011aebe97697

GitHub Link:

GitHub - BCDC-GIS/shoreline-vulnerability-index: San Francisco Bay Conservation & Development Commission (BCDC): Shoreline Vulnerability Index

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GLOSSARY

Adapted from SFEI San Francisco Bay Shore Inventory Mapping for Sea Level Rise Planning

Berm: Features with a "levee" shape (having two side slopes) were classified as 'Berms' by default. The term 'Berm' for this report refers to a raised feature that was created without specific engineering for flood risk management. Examples of this include berms around the salt ponds in the South Bay, or duck clubs in Suisun Bay managed for wildlife habitat. Refer to "Engineered Levee" description for information about features reclassified which were specifically designed as flood protection.

Engineered Levee: Shoreline segments are designated as 'Engineered' if a feature 1) was assigned as 'accredited' or 'once accredited' in FEMA's 2014 Mid-term Levee Inventory or 2) a city, county, or agency representative confirmed that the levee had been engineered specifically for flood protection. Generally, these features have the classic levee shape with two side slopes, but in some cases engineered levees only have one slope.

Primary shoreline protection: The first shoreline that has a significant break in elevation. Beach and/or wetland "Frontage" is not classified as the primary shoreline protection, even though they may be first to interface with the Bay's waters. In some locations, such as in Mill Valley Bayfront Park, the SFEI dataset did not designate a primary shoreline protection. Therefore, in the Shoreline Vulnerability Index, some geographical portions around the bay are not mapped. (Also see Secondary shoreline protection)

Fortified: If features are artificially hardened, indicated by the presence of concrete, riprap (large boulders), or buttressing, then the 'Fortified' category was assigned a value of 'Yes'. The best available aerial and satellite imagery (e.g., Bing Maps Aerial Imagery) was used to assign this field. The 'Fortified' field was assigned to all ten shoreline classifications. Hardening could have been completed in an ad hoc manner or specifically designed to address wave erosion.

Frontage: The presence of beaches and/or wetlands which interface with the Bay before the primary shoreline protection. The dataset classified the frontage in four ways: Beach, Wetland, Beach/Wetland and No Frontage. The extent of the frontage (e.g. the length of a beach) was not taken into consideration.

MHHW: The Bay experiences two high tides and two lows tides every day. The height of the highest daily tides, averaged over time, is called "Mean Higher High Water" or "MHHW

Natural Shoreline: The edge of natural land (e.g., cliffs, bluffs) were mapped as natural shoreline at the first major slope break along the Bay shoreline (natural shoreline was not mapped inland of the Bay shoreline). Beach and/or wetland frontage was classified separately and not as "Natural Shoreline."

Overtopping: "Shoreline overtopping" occurs when water pours over shorelines, overtopping spots that were previously preventing inland areas from flooding.

Riprap: human-placed rock or other material used to protect shoreline structures against scour and water, wave, or ice erosion.

Shoreline Protection Structure: Man-made features that protect an area of fill and are located in areas of heavy development along the Bay shoreline. For example, much of the San Francisco shoreline and Alameda Island is classified as shoreline protection structure. Many of these locations are hardened to reduce wave erosion; the 'Fortified' field within the dataset identifies these areas specifically.

Secondary shoreline protection: The presence of additional shoreline protection landward of the primary shoreline protection. This Index focuses on assessing the primary shoreline protection. However, there are many areas in the Bay that have additional shoreline behind this first break in elevation, for example a road that had additional marsh behind it. (Also see Primary shoreline protection)

Shoreline Type: The Bay has a variety of Shoreline Types such as beaches, wetlands, roads, railroads, levees, and berms). Each of these Shoreline Types are vulnerable to storm surge, erosion and sea level rise in a different way. The Bay's shoreline has structures engineered expressly for flood risk management (such as accredited levees) and features that affect flooding at the shore but are not designed or maintained for this purpose (such as berms, road embankments, railroads and marshes).

Shoreline Vulnerability Characteristic: There are 6 characteristics that make up the Shoreline Vulnerability Index: 1) Shoreline Type, 2) Adaptability, 3) Fortification, 4) Frontage & Secondary Protection, 5) Shoreline Elevation and 6) Wave Energy. These are further described in Section 2.

Vulnerability Characteristic: (see Shoreline Vulnerability Characteristic)

Acronyms and Abbreviations

ART: BCDC's Adapting to Rising Tides Program

BCDC: San Francisco Bay Conservation and Development Commission

Ft: feet

Index: Shoreline Vulnerability Index

MHHW: Mean Higher High Water (see Glossary for definition)

SLR: Sea level rise

SFEI: San Francisco Estuary Institute

SVI: Shoreline Vulnerability Index

SECTION 1: BACKGROUND AND METHODS

The Bay shoreline has a variety of shorelines, from the highly urbanized and engineered shoreline of San Francisco to the natural marshes of Suisun Marsh. Different shorelines vary in levels of vulnerability due to erosion from waves and flooding from storm surge or sea level rise.

WHAT IS THE SHORELINE VULNERABILITY INDEX?

This San Francisco Bay Shoreline Vulnerability Index (Index) is **a measure of shoreline vulnerability to erosion and/or overtopping** due to extreme tides, waves, storm surges, and sea level rise. The Index gives a comprehensive look at how different sections of the Bay respond to storm surge, erosion from waves, and sea level rise. It ranks each shoreline segment's vulnerability to impacts such as erosion and overtopping relative to other types of shoreline by by scoring characteristics that affect shoreline vulnerability. The Shoreline Vulnerability Index (SVI) uses the following 6 characteristics to determine shoreline vulnerability for the primary shoreline protection (see Glossary), which is the first elevated shoreline from the Bay. These characteristics are weighted in their importance towards shoreline vulnerability to flooding.

Figure 1 - Shorelines, such as this beach, are susceptible to erosion from wind and waves. (Source: .Martin. on flickr.com, Creative Commons license https://creativecommons.org/licenses/by-nd/2.0/legalcode)

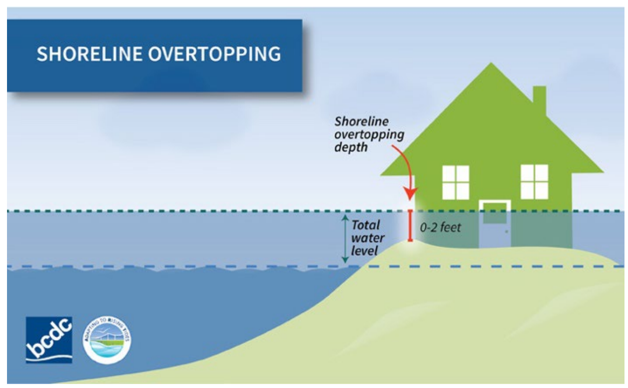


Figure 2 - Shoreline overtopping is when water exceeds the elevation of the shoreline, allowing water to flow inland.

Table 1 - Shoreline Vulnerability Characteristics Used to Determine the Shoreline Vulnerability

Shoreline Vulnerability Characteristics
1. Vulnerability of shoreline type to flooding and sea level rise
2. Adaptability to sea level rise by shoreline type
3. Presence of fortification
4. Presence of frontage and/or secondary shoreline protection
5. Elevation
6. Wave energy

WHY IS UNDERSTANDING SHORELINE VULNERABILITY IMPORTANT?

The Bay Area's seven million residents rely on the Bay's various shoreline protections to prevent flooding from storms and sea level rise. As sea levels rise and storm energy increases, the effectiveness of these shoreline protections becomes even more critical to protecting homes, infrastructure, facilities, and more. By understanding where the shoreline is vulnerable, we can better plan for the future of sea level rise.

HOW CAN THE SHORELINE VULNERABILITY INDEX BE USED?

Ranking relative shoreline vulnerability can assist the Adapting to Rising Tides (ART) program within the San Francisco Bay Conservation and Development Commission (BCDC), as well as other planners or city managers around the Bay, in identifying areas most at risk of flooding in the near-term from existing hazards of shoreline erosion or overtopping. While the existing Bay Shoreline Flood Explorer already identifies areas of overtopping, the Index provides more detailed information that can help prioritize highest vulnerability shoreline segments based on the vulnerability characteristics.

This information, in conjunction with other data such as consequence data, can inform priorities about where adaptation solutions should be developed and funded first. For example, high vulnerability shoreline segments as identified by the Index that are adjacent to communities with high socioeconomic vulnerability or highway segments that serve a large regional population may be identified as high priority areas for adaptation. The ART Program developed consequence indicators in the ART Bay Area report (March, 2020) for transportation, jobs, housing, natural areas, and socially vulnerable communities that measure the potential impacts of flooding on each of these sectors. This data can be found in the Bay Shoreline Flood Explorer and BCDC's Community Vulnerability Mapping Tool.

Background and Initial Research

Building Off of SFEI's Bay Shore Inventory

This project builds upon the Bay Shore Inventory created by the San Francisco Estuary Institute (SFEI), which inventoried 100 foot segments of elevated Bay shore features for all nine Bay Area counties. These elevated Bay shore features were mapped and classified as: **levees, berms, embankments, transportation structures, wetlands, natural shoreline, channel openings,** and **water control structures.**

Mapped shoreline features in the Bay Shore Inventory dataset were assigned an elevation (with a vertical accuracy of <5cm reported in 100 ft segments), FEMA accreditation status, fortification (e.g., riprap, buttressing), frontage (e.g., whether a feature was fronted by a wetland or beach), ownership, and entity responsible for maintenance. Water control structures, ownership, and maintenance attributes were captured where data was available (not complete for entire dataset). The dataset was extensively reviewed and corrected by city, county, and natural resource agency staff in each county around the Bay.

Initial analysis by SFEI showed over 150 unique combinations of shoreline types and attributes. However, the Bay Shore Inventory does not show the qualitative information about shoreline vulnerability that is necessary for flood risk assessment, which is why BCDC built the Shoreline Vulnerability Index using SFEI's Bay Shore Inventory.

Existing Research and Research Gaps On Shoreline Vulnerability

This project addresses gaps in shoreline vulnerability research for the Bay. Most research on shoreline vulnerability focuses on the open coast[3,7–16], which is not directly applicable to the San Francisco Bay. There is also little scientific literature that assesses the vulnerabilities of artificial fill shorelines, which comprises about 85% of the Bay shoreline [1–3]. After consulting literature on shoreline vulnlerability and finding it lacking, it became clear that local knowledge and expertise based in on-the-ground project experience ranging from habitat restoration to levee engineering is the best source for understanding the unique challenges specific to the San Francisco Bay shoreline.

Methodology

Constructing A Shoreline Vulnerability Index

Many approaches to creating vulnerability indices were researched[11,30–32] with most approaches combining the characteristics of the physical environment (wave energy, erosion rates, SLR and storm modeling) with the known response of the shoreline (erosion rates, sediment accretion, etc.). The Index utilized here combines known methodology with characteristics specific to the needs of the Bay Area.

Data Collection

Characteristics 1 to 4 were gathered by administering a survey to expert practitioners in the field and then mathematically analyzing their responses[17,18]. Diverse expert opinion ranged from engineers, planners, county managers, and restoration scientists to transportation analysts but was limited to participants who were experts in engineering, planning and restoration that had considerable experience with the shoreline and could parse out **how the six different criteria changed the shoreline vulnerability.**

Two separate surveys were administered:

1. The first survey was used to determine the baseline vulnerability of that particular Shoreline Type, adaptability to SLR, and the role that frontage and a 2nd line of defense plays in the functioning of that Shoreline Type.
2. The second survey we conducted asked questions about the impacts of fortification (either engineered/maintained, ad-hoc, or no fortification) on shoreline function and vulnerability. It also asked for response about each component included in the index's relative importance against the other components.

For more information on the survey methodology, see the Appendix.

Shoreline Characteristic Weights

The 6 characteristics described previously do not all contribute equally to shoreline vulnerability and therefore are weighted differently. While there are many methods to determine weights[14, 33,34,35] using GIS analysis, gathering expert opinion through surveys seemed the most logical and consistent with the aim of the project.

To calculate the shoreline vulnerability score, each characteristic is assigned two weights: one for the characteristic's contribution to shoreline vulnerability and a second for the characteristic's relative importance when compared to the other characteristic.

The total score was then calculated with:

$W1V1 + \dots + W6V6$

Where:

V = the contribution of each individual characteristic to shoreline vulnerability

W = the weight of the characteristic relative to the other characteristics

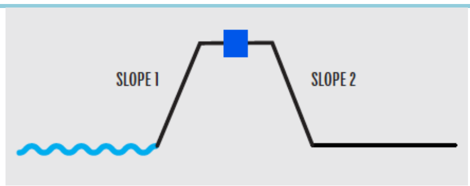
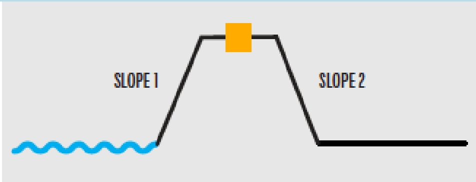
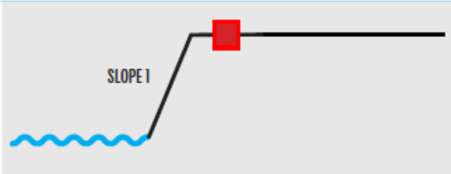
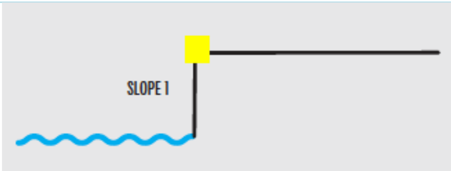
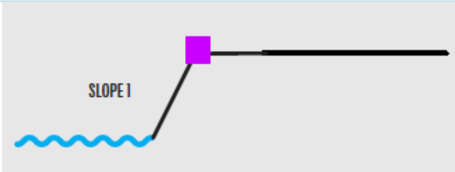
SECTION 2: VULNERABILITY CHRACTERISTICS OF THE INDEX

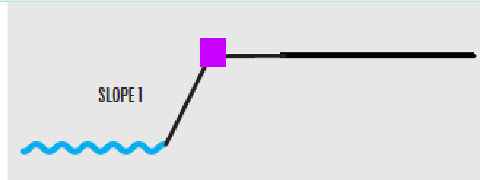
This section provides an overview of each characteristic and how the shoreline vulnerability score of each shoreline type for each characteristic was developed. By looking at how each Shoreline Type performed for each the six Vulnerability Characteristics, an averaged score was created that led to a final ranking of shoreline vulnerability by Shoreline Type.

VULNERABILITY CHARACTERISTIC #1: VULNERABILITY OF SHORELINE TYPE TO FLOODING AND SEA LEVEL RISE

Shoreline types in the Index, based on the Bay Shore Inventory, include levees, berms roads and railroads (see Table 2 below and the Glossary). Some shoreline types are engineered expressly for flood risk management, such as accredited levees, while other types unintentionally fortify the shoreline against flooding but are not designed or maintained for this purpose, such as berms, road embankments, and railroads. These features are at risk of failure during major flooding. There are also many stretches of shoreline that are not engineered or fortified but still offer some degree of flood protection, such as beaches or other natural shorelines like marshes. However these features can be eroded by repeated exposure to waves, reducing their natural flood protection abilities.

Table 2 - Shoreline Types Used in the Shoreline Vulnerability Index

Shoreline Type	Description	Picture
Engineered levee	Features were designated as 'Engineered' if a feature 1) was assigned as 'accredited' or 'once accredited' by FEMA or 2) a city, county, or agency representative confirmed that the levee had been engineered for flood protection. Generally these features have two slopes, a classic levee shape, but in some cases engineered levees only had one slope.	
Berm	Features with a "levee" shape (two slopes) were classified as 'Berms' by default. The term 'Berm' for this dataset refers to a raised feature that was created without specific engineering for flood risk management.	
Shoreline protection structure	Shoreline protection structures were classified as features which only have one sloped side, often protecting an area of fill and located in areas of heavy development along the Bay shoreline. Many of these locations are fortified or hardened to reduce wave erosion.	
Natural Shoreline	The edge of predominantly natural land (e.g., cliffs, bluffs) were mapped as natural shoreline at the first major slope break along the Bay shoreline.	
Major road	Only roads that were elevated from the surrounding landscape were mapped, irregardless if they had 1 or 2 slopes.	

Railroad	All railroads were mapped regardless if they had 1 or 2 slopes.	

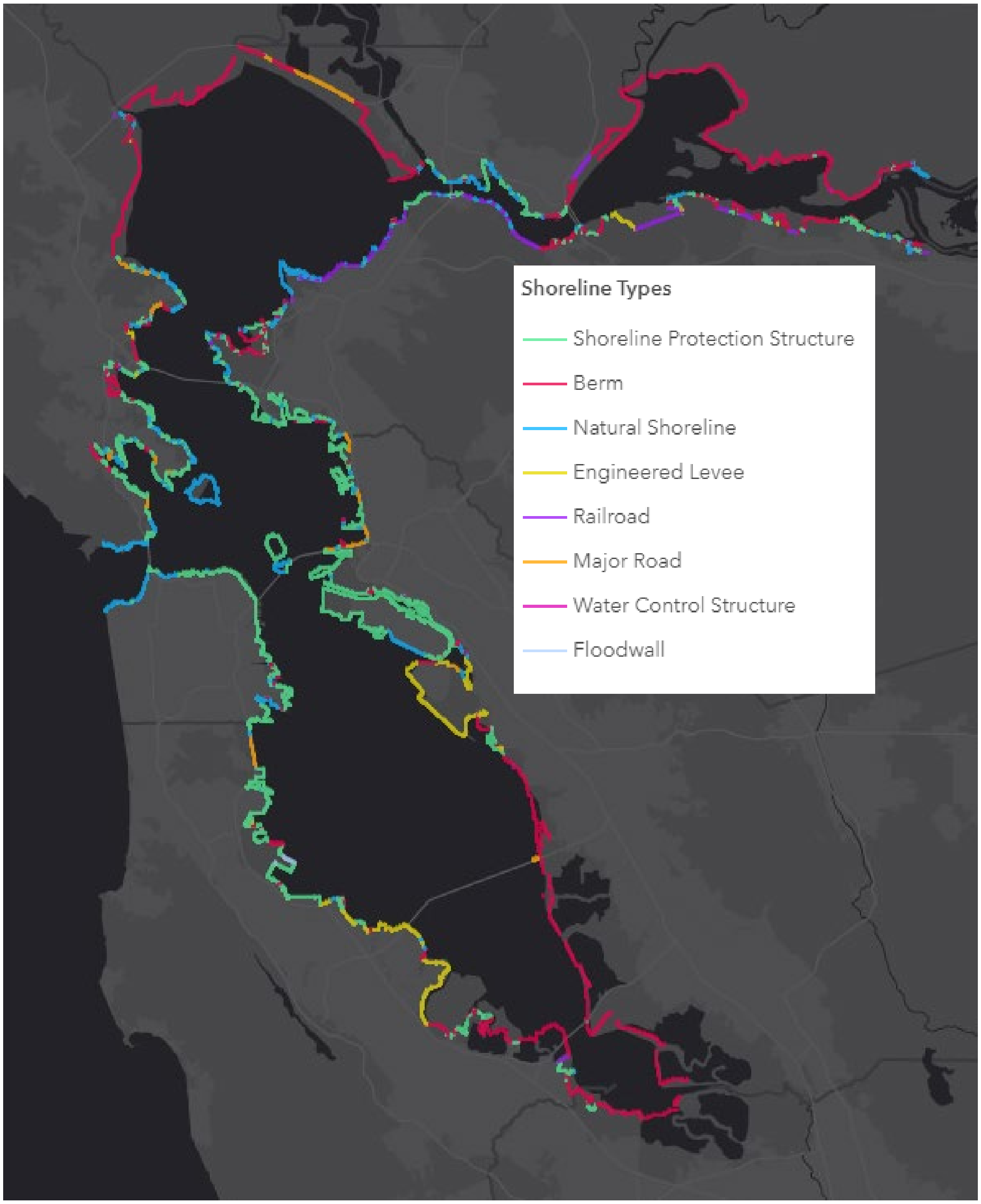


Figure 4 - Shoreline Types of the Bay: engineered levee, shoreline protection structure, natural shoreline, major road, railroad, or berm.

To establish a baseline vulnerability of the six Shoreline Types, the survey asked respondents compared Shoreline Types against each other to determine a relative "score" from the magnitude of difference.

Discussion of Survey Responses:

Survey respondents identified berms as the shoreline type most vulnerable to flooding, erosion, and sea level rise when compared to the other shoreline types. Railroads were identified as the second most vulnerable. Both of these shoreline types often act as ad-hoc flood protection, yet were not designed nor built to withstand significant flooding, meaning they are susceptible to failure under extreme flood events.

The resulting rank 1-6 (with 1 being the highest vulnerability and 6 being the lowest vulnerability) of shoreline types is below. The ranks come from the applied score based on shoreline type and attribute, discussed above.

Vulnerability Characteristic #1 Score: Shoreline Type

Shoreline Type	Vulnerability Rank	Applied Score
Berm	1 (highest vulnerability)	32
Railroad	2	21.8
Major Road	3	19.7
Natural Shoreline	4	11.5
Shoreline Protection Structure	5	9.2
Engineered Levee	6 (least vulnerability)	5.8

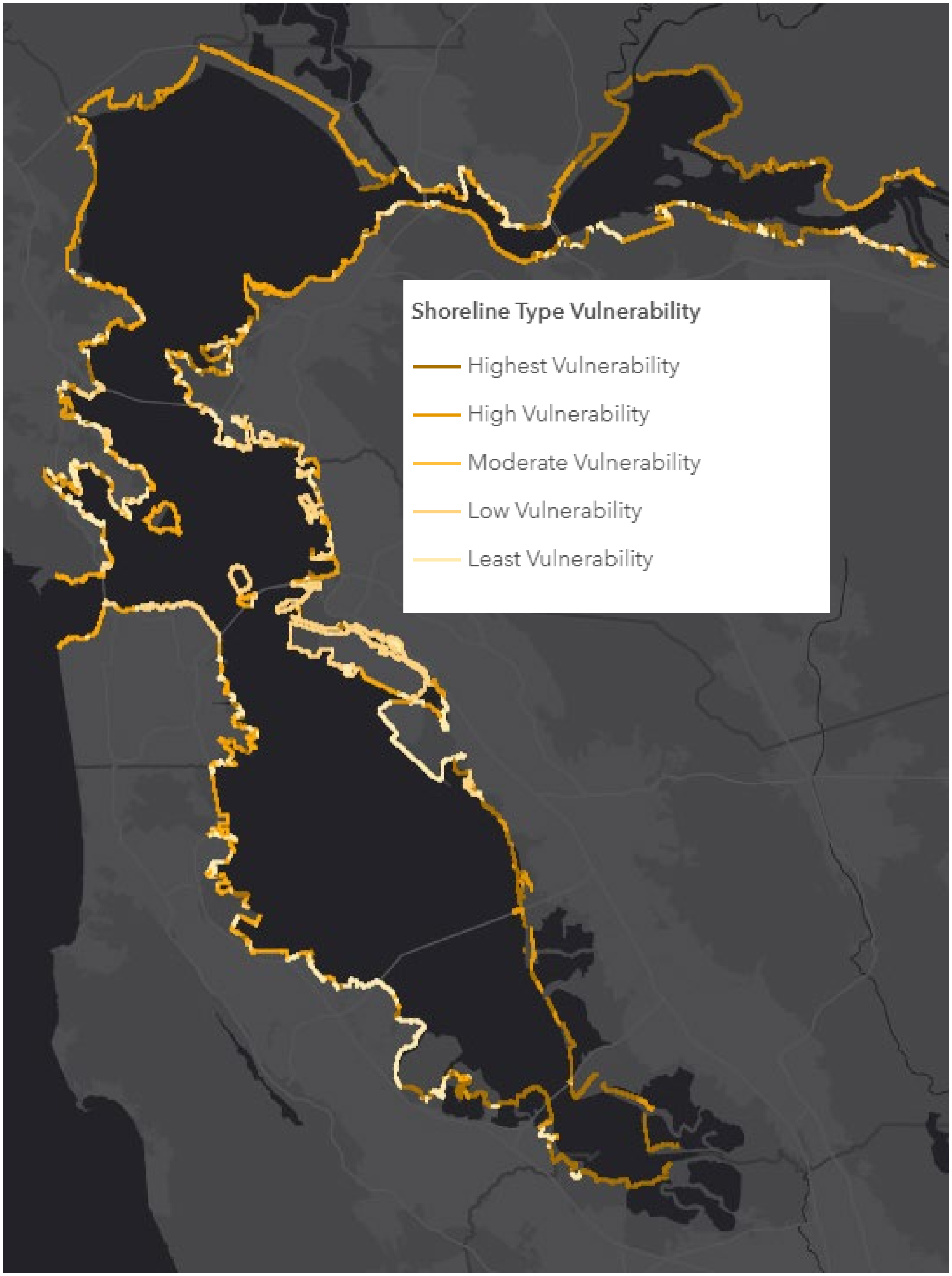


Figure 5 - Relative vulnerability of shoreline segements based on their Shoreline Type.

VULNERABILITY CHARACTERISTIC #2: ADAPTABILITY TO SEA LEVEL RISE BY SHORELINE TYPE

This shoreline characteristic scores the adaptability of each shoreline type to sea level rise. Survey participants considered varying aspects of adaptability, such as physical constraints (i.e. the feasibility to engineer and build additional elevation or protection in that location or the ability of the shoreline type to relocate) and institutional constraints (i.e. difficulties with altering railroad infrastructure, including cost and privatized ownership and management). Similar to Vulnerability Characteristic 1, scores were gathered through survey responses.

Discussion of Survey Responses:

Railroads and roads have the highest vulnerability when it comes to adaptability, meaning they have the lowest adaptive capacity. These shoreline types are very difficult to relocate because they require large amounts of land in already urbanized areas. They are also both relied upon by daily users for commuting and moving goods, so repair or replacement of the infrastructure would require a shutdown of service that would have major ripple effects throughout the economy.

Natural shorelines were identified as the most adaptable to sea level rise (ie, least vulnerability when it comes to adaptability). However, it is important to note that while “natural shorelines” in the survey was explained to pertain to only cliffs and bluffs, the general understanding of a natural shoreline is analogous to wetlands and/or beaches to many people. We suspect the survey participants understood that this shoreline type has natural processes that allow it to adapt to rising water levels (such as natural migration of wetland areas through the build up of sediment). The geology of cliffs and bluffs are not “adaptable” in the way that other types of natural areas are. While cliffs and bluffs have the ability to change over time, these changes may result in the reduction of flood protection. For example, cliffs and bluffs are susceptible to large erosive events with increased wave energy, as the steeper the slope, the larger the wave energy, meaning wave energy at cliffs and bluffs may actually increase at rates faster than sea level rise itself.

Shoreline Vulnerability Characteristic #2 Score: Adaptability of Shoreline Type		
Shoreline Type	**Vulnerability Rank**	**Applied Score**
Railroad	6 (highest vulnerability)	32.2
Major Road	5	20
Shoreline Protection Structure	4	17.6
Berm	3	16.5
Engineered Levee	2	7.5
Natural Shoreline	1 (least vulnerability)	6.2

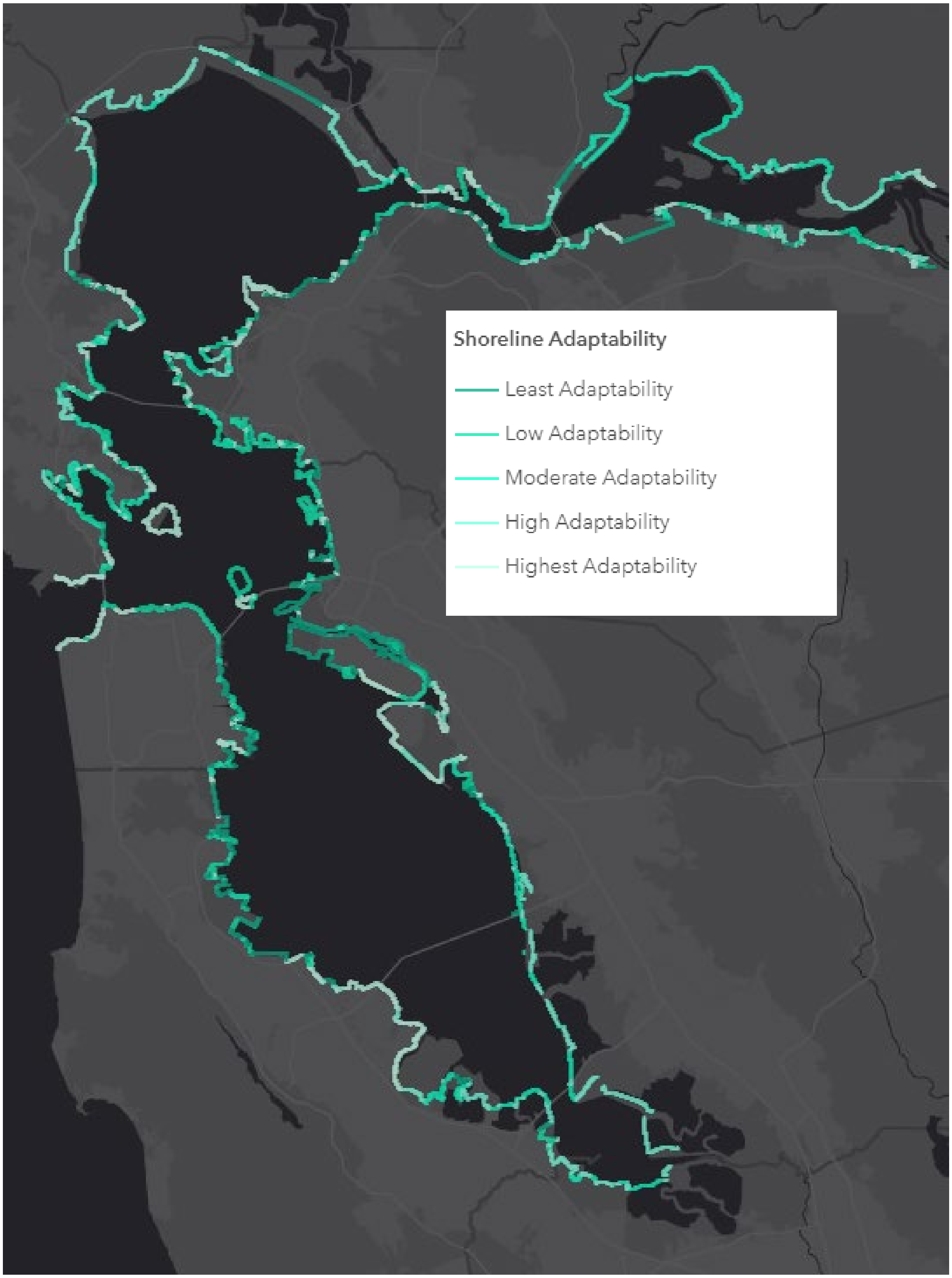


Figure 6 - Relative adaptability to sea level rise by Shoreline Type

VULNERABILITY CHARACTERISTIC #3: PRESENCE OF FORTIFICATION

About half of the Bay shoreline's primary shoreline protection is classified as having fortification. If features are artificially hardened, indicated by the presence of concrete, riprap (large boulders), or buttressing, then the 'fortified' category was assigned a value of 'yes'. The best available aerial and satellite imagery (e.g., Bing Maps Aerial Imagery) was used to assign this field. However, much of the fortification of the Bay was placed in an ad-hoc, or non-engineered way.

Figure 7 - An example of 'fortification' at Point Isabel, Contra Costa County (photo by Shira Bezalel, 2015).

For this characteristic, the survey asked about the relative impact on shoreline protection for 1) engineered/maintained fortification, 2) fortification (not confirmed as engineered/maintained and identified only by aerial imagery), and 3) no fortification. This question was asked for each individual shoreline type and provides an assessment of how fortifying the different shoreline types affects its vulnerability to flooding and erosion.

Discussion of Survey Responses:

Survey respondents overwhelmingly agreed that fortification does improve shoreline protection, but that engineered or maintained fortification was best. However, this vulnerability characteristic generated the largest amount of concern and debate among the shoreline community, and there were differing perspectives on how fortification affected a shoreline's protection from flooding and erosion. While having properly engineered fortification can reduce the shoreline's vulnerability to flooding and erosion, there are also changing attitudes and debate in the scientific community about whether hardened shorelines reduce or contribute to vulnerability[16,20,21].

In addition, much of the shoreline fortification in the Bay Area is ad-hoc, of unknown structural integrity, or susceptible to erosion or failure, and therefore may not contribute greatly to shoreline protection. At this time, there is very little data available to classify shoreline protection as Engineered/Maintained. Investigating this topic highlighted informational gaps about the placement of much of the fortification around the Bay, its maintenance history, and the unique history of the Bay shoreline. For example, ballast stones along Chrissy Field in San Francisco were placed as early as the 1800's by ships offloading prior to picking up goods at the Port. These haphazardly placed stones still serve as shoreline protection. There are no records of the placing of these stones or the maintenance of this shoreline.

A process to incorporate more site-specific information about the quality of shoreline fortification would greatly improve this Index, and is included in future next steps. This, and further conversation about the efficacy of fortification in shoreline protection, is discussed in further detail in the Appendix.

Shoreline Vulnerability Characteristic #3 Score: Fortification			
Shoreline Type	**Applied Score (high score = high vulnerability)**		
	Maintained/Engineered Fortification	Fortification (not confirmed Maintatined/ Engineered	No Fortification
Railroad	11.3	23.7	65.0
Major Road	9.1	21.8	69.1
Shoreline Protection Structure	8.9	22.6	68.4
Berm	7.9	24.6	67.5
Engineered Levee	11.5	24.6	63.9
Natural Shoreline	12.4	28.2	59.5

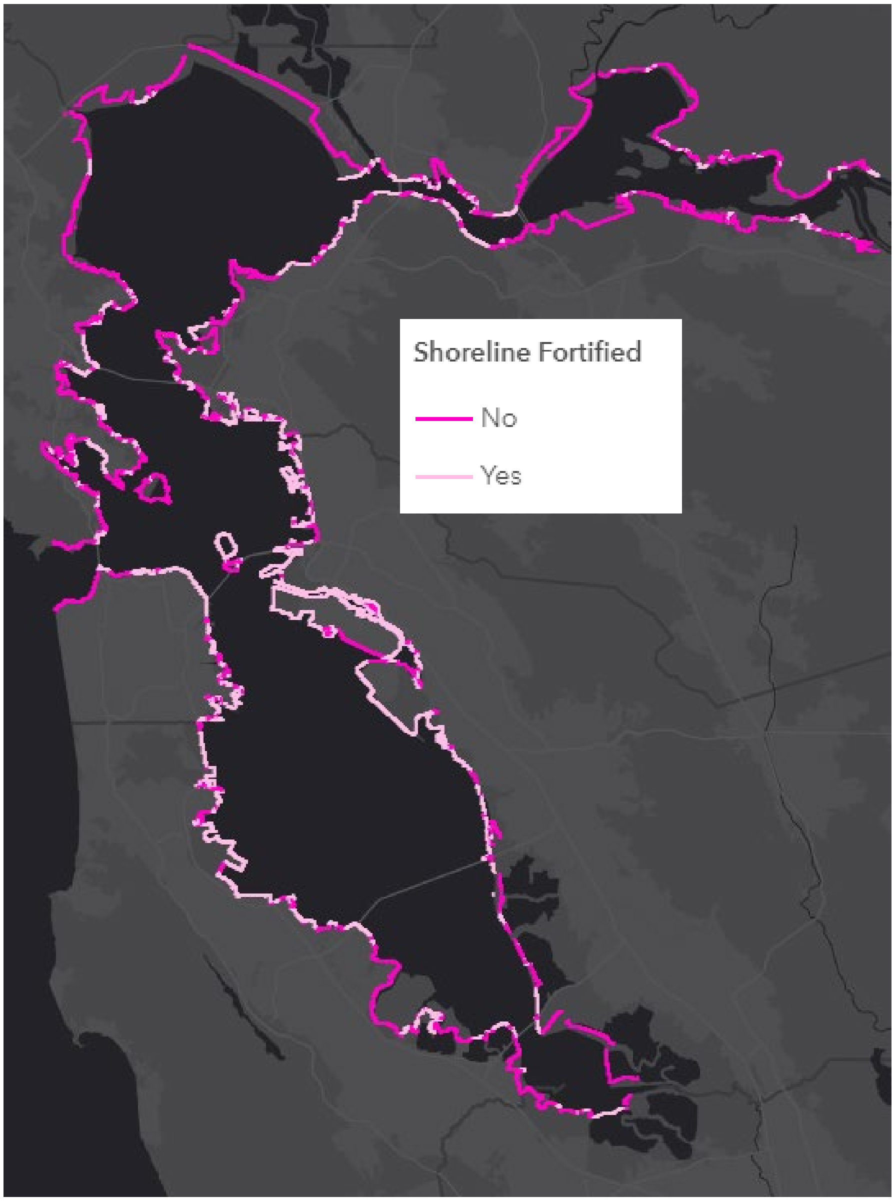


Figure 8 - Presence of fortification along the Bay's shoreline.

VULNERABILITY CHARACTERISTIC #4: PRESENCE OF FRONTAGE AND/OR SECONDARY SHORELINE PROTECTION

This shoreline vulnerability characteristic evaluates how additional lines of defense to the primary shoreline protection impacts the shoreline vulnerability to flooding and erosion. Two components are included in this characteristic:

1. **Frontage**, which is defined as the presence of beaches and/or wetlands which interface with the Bay before the primary shoreline protection. SFEI's Bay Shore Inventory dataset classified the frontage in four ways: **Beach, Wetland, Both Beach & Wetland,** and **No Frontage**. The extent of the frontage (e.g. the depth of a beach) was not taken into consideration.
2. **Secondary shoreline protection**, which is defined as the presence of additional shoreline protection landward of the Bay. There are many areas in the Bay that have additional shoreline behind this first break in elevation; for example, a road that has additional marsh behind it.

In many areas in the Bay, non-engineered berms separate managed marshes and ponds from the Bay and can also provide a low level of flood protection. However, berms are classified as primary defense and not as frontage in the Index. Marshes often serve as buffers which help reduce incoming wave heights, protecting shoreline structures from wind, waves, and tidal energy. Fully tidal marshes are either exposed to the open Bay or are protected from wave and tidal energy by offshore mudflats.

Secondary shoreline protection is defined as contributing to the overall flood protection of the primary shoreline protection for the assets behind the primary shoreline. The analogy we used when introducing this concept to survey participants was a house with a gate and fence to the front yard (frontage), the front door to the house (primary shoreline protection), and then an additional door inside to the apartment (secondary shoreline protection). However, if assets exists between the primary shoreline protection and secondary shoreline (including parking lots and industrial lands), that shoreline would *not* be counted as having secondary shoreline protection because those assets are not protected by the secondary shoreline protection.

Secondary shoreline protection was assigned as an attribute based solely on the presence of additional bayshore that was classified by SFEI as "flood infrastructure, not primary shoreline protection." This designation was assigned manually through visual inspection of aerial imagery. Road development does count as secondary shoreline protection. It may be providing flood protection elsewhere.

Figure 9 - Highway 580 and the Bay Trail fronted by wetlands in Albany (Source: photo by Carylyn Doehring, SFEI).

Figure 10 - Berm fronted by wetlands at Don Edwards National Wildlife Refuge (Source: photo by Shira Bezalel, SFEI).

Figure 11 - Beach frontage at Keller Beach. (Source: Photos by Shira Bezalel, SFEI, January 2015.)

Discussion of survey responses:

Survey participants ranked the importance of frontage and secondary shoreline protection by the primary shoreline type. Results indicated little variance by shoreline type. In future work, measuring the spatial extent of frontage could improve understanding of wave attenuation potential, and other characteristics of shoreline protection.

"Beyond the scientific literature, headline stories on the benefits marine habitats such as marshes, wetlands, coral and oyster reefs, mangroves, and dunes provide to people and property in the face of major storms and tsunamis are increasingly prevalent in mainstream media. Missing from these public narratives is the important detail that spatial context greatly affects the potential value of ecosystem services as a solution to consider (Plummer 2009). The next generation of ecosystem service science - demonstrating feasibility, but also nuances in the conditions for success of these approaches (Guerry et al. 2015) - has now leaped ahead of the public discourse. This disconnection between the state of the science and practice has left a gap in guidance for implementing habitat-based solutions for coastal protection (Moser, Williams, and Boesch 2012);" [22–25] Efficacy of frontage is counted in the wave portion, as opposed to only all frontage being categorized as presence or absence as an attribute in the dataset. ART Corte Madera Baylands[26] looks at characteristics of wetlands that give them capacity to attenuate waves: http://www.adaptingtorisingtides.org/project/corte-madera-baylands-conceptual-sea-level-rise-adaptation-strategy/

Shoreline Vulnerability Characteristic #4 Score: Frontage and Secondary shoreline protection		
Shoreline Type	**Applied Score (high score = high vulnerability)**	
	Secondary Shoreline Protection	NO Secondary Shoreline Protection

Shoreline Vulnerability Index for San Francisco Bay

	Frontage							
	Beach	Wetland	Beach & Wetland	None	Beach	Wetland	Beach & Wetland	None
Berm	3.9	3.45	2.325	11.25	11.325	8.7	5.325	28.725
Engineered Levee	3.825	3	2.325	10.875	11.1	8.85	5.775	29.25
Natural Shoreline	3.375	2.7	2.1	9.825	11.925	8.7	6	30.375
Shoreline Protection	3.375	3.15	2.175	8.925	12.075	9.6	6.375	29.1
Major Road	3.75	3	2.4	9.75	11.85	8.85	6.225	29.175
Railroad	3.675	3.075	2.325	9.3	12.6	9.15	6.3	28.575

Figure 12 - Presence of Frontage and/or Secondary shoreline protection

VULNERABILITY CHARACTERISTIC #5: SHORELINE ELEVATION

The elevation of a Primary Shoreline Protection is directly related to an area's risk of overtopping and flooding. The higher the elevation of the shoreline structure, the less vulnerable it is to flooding. To understand where overtopping of the shoreline may occur under a variety of sea level rise scenarios, the heights of shoreline segments above high tide were broken down into six categories based on various elevations to rank their vulnerability to flooding. The high tide we used is the mean higher high water (MHHW) mark, which is the mean of the highest high tides. There are two high tides in the Bay per day, and typically one is higher than the other.

Data

San Francisco Bay Mean Higher High Water (MHHW) Surface Raster (Feet-NAVD88) was calculated using water levels extracted from SF Bay MIKE21 model developed by DHI for FEMA's San Francisco Bay Area Coastal Study (DHI 2013), calculated over National Tidal Datum Epoch (1983 through 2001) and prepared by AECOM for BCDC in 2017. Mapped features were also attributed with elevation (vertical accuracy of <5cm reported 100 feet (ft) ft segments from LiDAR derived digital elevation models (DEMs).[6] The MHHW elevation was averaged for each 100 ft segment. After some analysis we decided this segmentation was acceptable but it is worth noting that the elevation is not at the finest level possible from the 1 or 2m LIDAR sources nor are the breaks representative of stretches of contiguous Shoreline Types.

Discussion of Survey Responses:

This ranking is not a comprehensive risk estimate. One problem that we identified was that much of the fill shoreline is susceptible to subsidence and compaction, which was observed by comparing the surveyed elevation of levees with their elevation when it was built.

Shoreline Vulnerability Characteristic #5: Shoreline Elevation		
Category	**Vulnerability Rank**	**Applied Score**
Over 78" above MHHW	1 (least vulnerability)	4
54"-78" above MHHW	2	9
36"-54" above MHHW	3	14
24"-36" above MHHW	4	19
12"-24" above MHHW	5	24
Up to 12" above MHHW	6 (highest vulnerability)	29

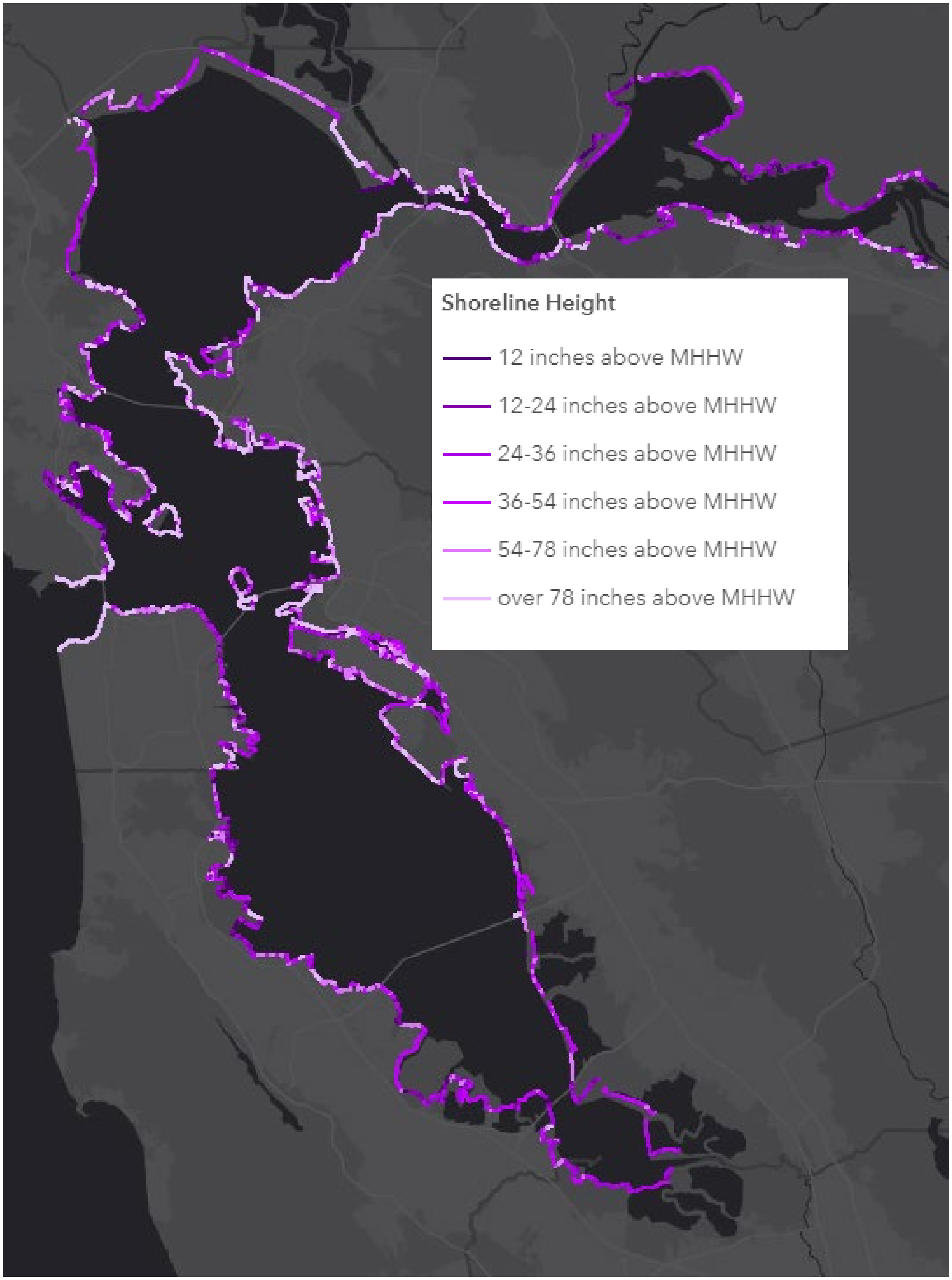


Figure 13 - Elevation of 100-foot shoreline segments

VULNERABILITY CHARACTERISTIC #6: WAVE ENERGY

Wave activity on the shoreline can weaken structures or erode natural areas, decreasing the effectiveness of the shoreline protection. Adaptation would therefore need to include maintaining and strengthening existing structures as well as realigning and redesigning areas of the Bay shore to lower the rate of shoreline erosion. There may also be opportunities for incorporating natural and nature-based features in future flood risk management.[6]

Data

The FEMA San Francisco Bay Area Coastal Study was the first detailed coastal hazard assessment of San Francisco Bay that analyzed wave dynamics along the complex Bay shoreline. The study used a hindcast model over a 54-year period (1956-2009) of Bay water levels and waves to calculate water elevations that statistically constitute the 1% annual chance stillwater elevations (in the absence of near-shore waves) and the 1% annual total water elevations (with wave hazards and wave runup at the shoreline). While the 1% wave hazards represent an extreme event, coastal erosion is generally driven by extreme events and not average wave conditions. Coastal flood protection and adaptation strategies should be resilient to extreme conditions, particularly given that the extremity of future storms is volatile and likely to increase with climate change. The FEMA study provided water level and wave information at over 900 points around the Bay, and wave runup was analyzed directly at the shoreline. The calculation of wave runup takes into consideration the wind direction, wave climate, shoreline slope, shoreline and nearshore bathymetry, and the shoreline roughness. The division into 100 foot segmentation was for planning purposes; it is an acceptable unit of shoreline to study because observations along the shore do not indicate great changes from one 100 foot segment to the next.

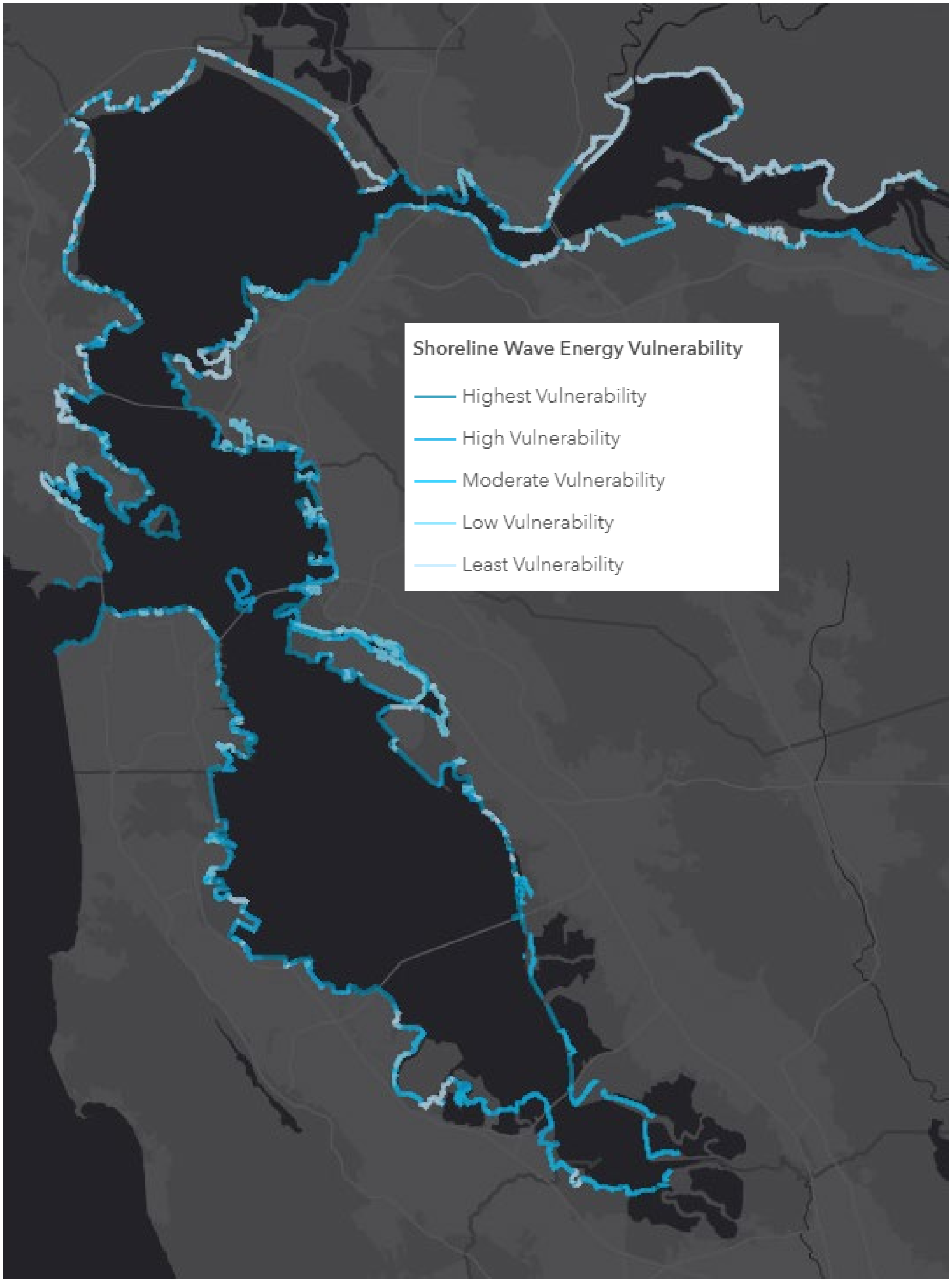


Figure 14 – Vulerability based on relative FEMA Wave Energy.

Characteristic 6: Wave energy		
Category	**Vulnerability Rank**	**Applied Score**
AE, BFE 9, 10 “No wave hazard” – includes zone A”	1 (least vulnerability)	4
AE, BFE 11, 12 “Wave hazard less than 1.5 feet”	2	9
VE, BFE 10, 11, 12 “Wave hazard around 3 feet”	3	14
FEMA VE, BFE 13, 14 “Wave hazard around 4 feet”	4	19
FEMA VE, BFE 15, 16 “Wave hazard around 5 feet”	5	24
FEMA VE, BFE 17+ “Wave hazard 6 feet and greater”	6 (highest vulnerability)	29

SECTION 3: COMPARING SHORELINE VULNERABILITY CHARACTERISTICS

WEIGHTING THE SIX SHORELINE VULNERABILITY CHARACTERISTICS

The next aspect of creating the Shoreline Vulnerability Index is to evaluate how to weigh the different Shoreline Vulnerability Characteristic for each shoreline type so that one final shoreline vulnerability rank can be assigned for each of the Shoreline Types. A survey was conducted solely to determine the weights of the Shoreline Vulnerability Characteristics. Survey participants were limited to experts in engineering, planning and restoration who had considerable experience with the shoreline and could differentiate how the Shoreline Vulnerability Characteristics affects the Shoreline Vulnerability.

Results of the survey and the final weights used for the Vulnerability Characteristics can be found in Table 3 below.

Table 3 - Shoreline Vulnerability Characteristic Weights

	Shoreline Vulnerability Characteristic Weights					
	Berm	Engin-eered Levee	Natural Shoreline (cliffs, bluffs)	Shoreline Protection Structure	Transportation - Road	Transportation - Railroad
Shoreline Type	11.4	7.3	10.4	6.8	6.2	6.0
Adaptability	8.2	12.8	8.4	12.6	6.3	6.2
Fortification	6.2	8.1	6.0	10.0	8.3	10.3
Frontage/Secondary Shoreline	4.3	5.3	4.4	5.5	5.9	6.0
Elevation	20.1	33.5	20.7	32.3	36.0	27.8
Wave Energy	49.8	33.0	50.1	32.8	37.3	43.7

Discussion of Results

For determining shoreline vulnerability, the results of the survey overwhelmingly determined that **wave energy** was the most significant Shoreline Vulnerability Characteristic (almost 50% of the overall weight), followed by **elevation**. Wave energy is important to consider for the strength of a shoreline because it can lead to erosion or overtopping. Erosion can quickly degrade a shoreline, which could lead to reduced effectiveness in protecting the shoreline. Elevation is important because it determines at what height water will overtop the shoreline. Having a shoreline with a low height would create a very vulnerable shoreline as the shoreline could be overtopped more easily.

TOTAL SHORELINE VULNERABILITY SCORE

Calculating the Shoreline Vulnerability Score

The final SVI score was calculated by adding up each of the 6 characteristics multiplied by their individual weights from the 1st survey and further multiplying each Characteristic by the relative weights for each shoreline type from the 2nd survey, which is described above. Any shoreline segments that were missing one or more characteristics received "NA" in their SVI Score and Descriptive Rank.

Mapping the Shoreline Vulnerability Score

By creating maps that display the Shoreline Vulnerability Score, it is easier to understand where in the Bay the vulnerable stretches of shoreline are located. This information can lead to regional planning efforts to prioritize investment in highly vulnerable areas of the shoreline.

To map the final Shoreline Vulnerability for the Bay, the Shoreline Vulnerability Score was broken into 5 relative categories (highest, high, moderate, low, and least vulnerable), which was determined to be the best way to see the range and complexity of vulnerability along the shore. This categorization was achieved through distributing the SVI scores into 5 quantiles.

Discussion of Results

When looking at maps displaying the Shoreline Vulnerability Score, the main question is where are the vulnerable stretches of shoreline? The answer, much like the construction of our shoreline is an assortment of results.

There were five regional conclusions from mapping the Shoreline Vulnerability Scores of the Bay:

- **There is high variability along the shoreline, with high and low vulnerability scores near each other**, which reflects the haphazard fill of the Bay's shoreline.

- **Some of the most densely populated areas— San Francisco—have the highest shoreline vulnerability.** These areas have little to no frontage of wetlands or beaches, a low-lying shoreline, and high wave energy. This is based solely off of the "highest vulnerability" shoreline score.
- If instead of focusing only on the "most vulnerable" shoreline segments and instead widen the scope to include the "moderately vulnerable" to "most vulnerable," **much of San Francisco, San Mateo and Marin are very vulnerable**. This reflects the impacts of wave energy, lack of frontage, and the ad-hoc fortification nature of shoreline at these locations. These findings are also reflected in the individual counties assessments of their shoreline, for example the County of Marin (who participated in the survey) has areas that are prone to flooding now and suffered damage in storm events this past year.
- **Areas that have stretches of shoreline vulnerability have the characteristics of being low-lying, high wave energy areas facing south**, which is the predominant wind direction.
- However, much of Alameda and parts of Oakland have low lying and high wave energy, yet end up being less vulnerable to flooding and erosion. This is because **the engineered and fortified aspects of the shoreline reduces the shoreline vulnerability in these regions, even though they are low-lying and high wave energy**.

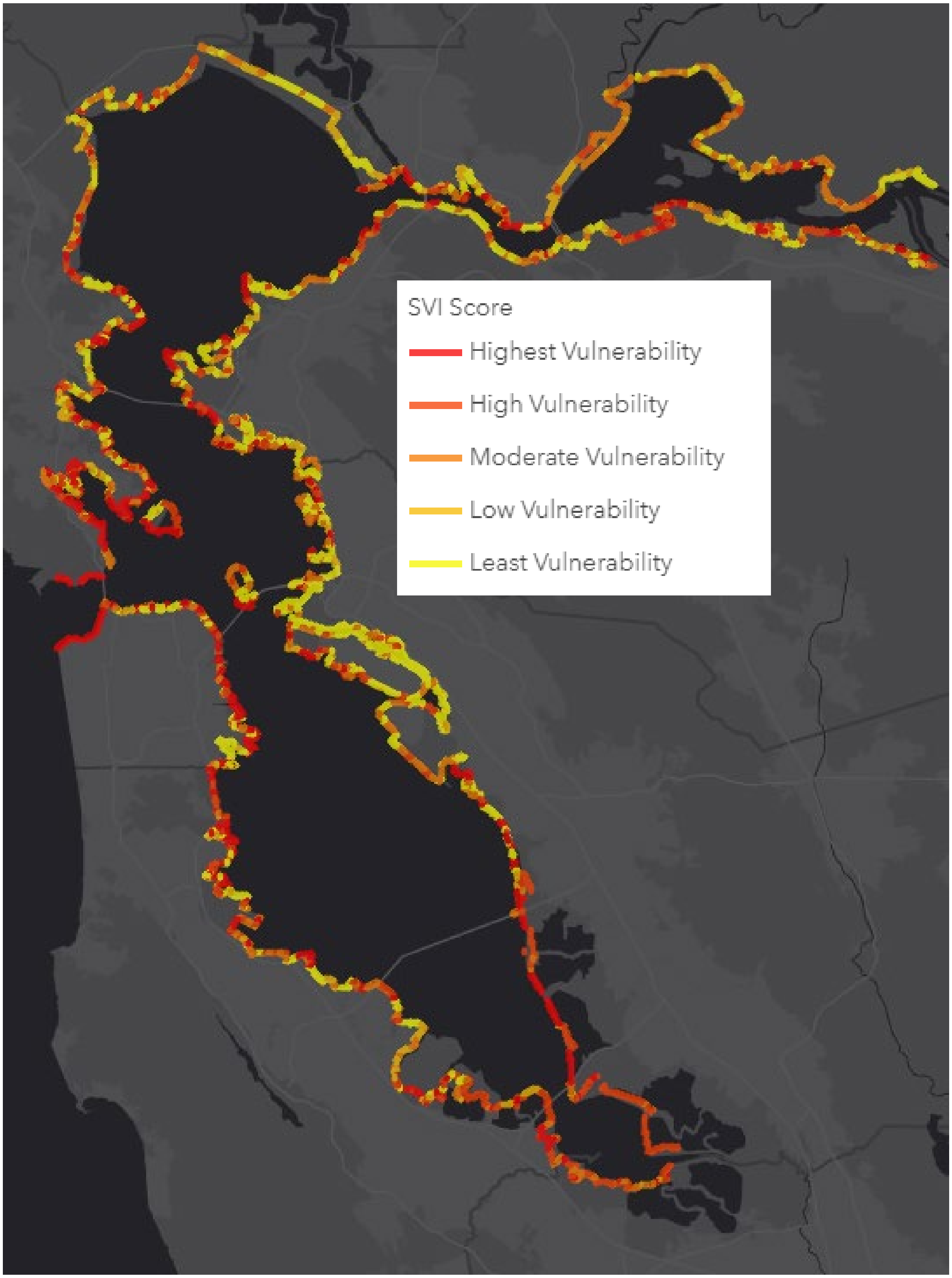


Figure 155 – Total relative score of the Shoreline Vulnerability Index in the Bay Area for each 100-ft segment of shoreline.

SECTION 4: LIMITATIONS & NEXT STEPS

There were several aspects of the Index that had data gaps and limitations. The segments were broken into 100ft segments and the elevation was calculated for the mean of each segment. After some analysis we decided this segmentation was acceptable, but it is worth noting that the elevation is not at the finest level possible from the 1 or 2m LIDAR sources nor are the breaks representative of stretches of contiguous Shoreline Types. There was also very limited information regionwide regarding the quality of fortification (see section 5) so the ability to adding Engineered or Maintained fortification was limited. More refinement and data would improve our understanding considerably. For example, when we interviewed Caltrans we identified a data gap in the shore side maintenance records of major roads. More data on the location of engineered fortification is needed.

In future work, measuring the spatial extent of frontage could improve understanding of wave attenuation potential, and other characteristics of shoreline protection.

There are some limitations to seeing the results on a regional scale with shoreline data that is separated into 100 ft segments. While this is an accurate reflection of the nature of the construction of the Bay shoreline, if we visualized the data with larger stretches of shoreline (for example, dividing up the shoreline segments by Shoreline Type rather than by a distance of 100 ft) it would be easier to see larger scale results.

Transportation Structures:

Transportation structures were mapped on the edge (or centerline of narrower structures) of a railroad track or a major road. All railroads and a subset of major roads were classified as transportation structures regardless of the feature shape (e.g., one vs. two slopes). Smaller roads (e.g., private property access roads) were not attributed within the dataset, which was determined by referencing aerial imagery and existing GIS road layers. Only roads that were elevated from the surrounding landscape were mapped. Thus, the dataset does not constitute a comprehensive layer of all roads within the mapped extent. If a road was part of an engineered levee, then the feature was mapped as an engineered levee.

More refined expert opinion as knowledge grows: This process was the first time that BCDC tried to aggregate shoreline understanding on a regional scale and to encompass a wide variety of perspectives. As the Shoreline Types and vulnerabilities becomes better known revisiting this process would help improve the understanding of the local expertise.

FUTURE CHARACTERISTICS TO INCLUDE

Characteristics not included in index that would be useful in the future:

1. **Seismic activity:** liquefaction and ground shaking. To complete this analysis a mapping of the impacts of predicted earthquake ground shaking and liquefaction

susceptibility would need to be incorporated. These characteristics could greatly impact the effectiveness of shoreline protection structures such as levees or roadways, as, for example, liquefaction could cause failure or slumping of a levee or road leading to failure and overtopping.

2. **Subsidence:** This is a two-pronged addition. First look at the subsidence of the land behind the shoreline (are there more "bowls" developing?) for example in Solano or the South Bay due to groundwater depletion. The second is to analyze the subsidence that has already happened (for example the difference in as built elevations of engineered levee's and their current elevation) and the rate at which fill land (such as much that is classified as shoreline protection structure) is compacting and subsiding to account for not decreased elevation with SLR and provide more accurate assessments of areas of low elevation.
3. **Negligence characteristic i.e. deferred maintenance:** The data gap of maintenance of shoreline fortification was substantial including from individual counties and by transportation sectors. To improve this some site level assessment and some more detailed analysis with individual counties would greatly improve our understanding of the quality of fortification and reduce the false sense of protection much of the "yes" category of fortification provides. The problem with not knowing the maintenance can be seen for example in Alameda in Robert Crown Memorial Beach where much riprap has been pulled into the water away from the shoreline.
4. **Elevation of shore behind primary shoreline:** Is the first line sitting on a bowl or a hill? If it erodes or is breached will water fill a portion (a bowl) behind it or will the shoreline behind provide protection due to higher elevation? An analysis of the additional shoreline would help clarify how much shoreline relies on the first line not being overtopped.
5. **Extent of frontage wetlands and other frontage:** One significant finding is that frontage alone does not provide much mitigation of shoreline vulnerability. It is only when the shoreline frontage is significant enough to mitigate wave energy that it will reduce shoreline vulnerability. Therefore, measuring the extent, determine the extent that mitigates wave and then delineating the shoreline that has this frontage from the other that only has frontage would better direct future efforts of either restoration or protection projects.
6. **Assigning characteristics about elevation and wave activity to the segments that would make for a continuous shoreline:** i.e. flood wall, areas where no "primary shoreline protection" is present; including these in overall dataset in some way
7. **Scouring of breached areas:** Scouring is the erosion of material caused by swiftly flowing water, and can compromise the structural integrity of shoreline structures. Breaches in berms or levees can lead to a large flow of water through the tiny breached area, leading to significant scouring. Alameda County Flood Control District has been collecting data on how quickly breached areas have been scouring in Alameda and other counties, this could be userful data to integrate.

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Appendix

SFEI's Bay Shore Inventory Methods

Elevated Bay shore features in SFEI's Bay Shore Inventory were mapped and classified as engineered levees, berms, embankments, transportation structures, wetlands, natural shoreline, channel openings, or water control structures. Mapped features were also attributed with elevation (vertical accuracy of <5cm reported in 30 meter (100 ft) segments from LiDAR derived digital elevation models (DEMs), FEMA accreditation status, fortification (e.g., riprap, buttressing), frontage (e.g., whether a feature was fronted by a wetland or beach), ownership, and entity responsible for maintenance. Water control structures, ownership, and maintenance attributes were captured where data was available (not complete for entire dataset). The dataset was extensively reviewed and corrected by city, county, and natural resource agency staff in each county around the Bay. This report provides further description of the Bay shore inventory and methods used for developing the dataset. The result is a publicly accessible GIS spatial database (www.sfei.org/projects/SFBayShoreInventory).

Mapping of Bay shore features was accomplished by digitizing the highest ridge or edge of the highest surface that was visible in the LiDAR derived DEM datasets. This was completed for the first raised feature along the Bay shoreline and a sub-set of raised features within the landscape and along waterways inland to Mean Higher High Water (MHHW) plus three meters (10ft) in elevation.

SFEI has a full report, "San Francisco Bay Shore Inventory: Mapping for Sea Level Rise Planning,"outlining the methods and datasets behind the Bay Shore Inventory. Please see this document for further details.

Survey Methods

To establish a baseline vulnerability of the 6 Shoreline Types, we created a survey using the AHP process, where respondents compare Shoreline Types against each other to generate a numerical "score" of magnitude of difference. Beach and/or wetland frontage was not included in this comparison, as this project built off the shoreline segments which represented a significant break in elevation and were classified as the primary shoreline protection.

Analytical Hierarchy Process (AHP) Background

The Analytical Hierarchy Process (AHP) was created by Thomas Saaty in the late 1970's as a method to breakdown multicriteria decision making. It is particularly useful in processes that synthesize opinions and judgements.

> "We must answer such questions as the following: Which consequences weigh more heavily than others? Which aims are more important than others? What is likely to take place? What should we plan for and how do we bring it about? These and other questions demand a multicriteria logic. It has been demonstrated over and over by practitioners who use the theory discussed in this paper that multicriteria logic gives different and often better answers to these questions than ordinary logic and does it efficiently. To make a decision one needs various kinds of knowledge, information, and technical data.
>
> (1) Structure a problem with a model that shows the problem's key elements and their relationships.
>
> (2) Elicit judgments that reflect knowledge, feelings, or emotions.
>
> (3) Represent those judgments with meaningful numbers.
>
> (4) Use these numbers to calculate the priorities of the elements of the hierarchy.
>
> (5) Synthesize these results to determine an overall outcome.
>
> (6) Analyze sensitivity to changes in judgment
>
> AHP is about breaking a problem down and then aggregating the solutions of all the subproblems into a conclusion. It facilitates decision making by organizing perceptions, feelings, judgments, and memories into a framework that exhibits the forces that influence a decision."[17,18]

This process allowed us to cast a wide net of professional expertise and judgement to determine shoreline vulnerability. The survey participants had a variety of backgrounds and expertise in working with the varying Shoreline Types around within San Francisco Bay. By capturing this collective knowledge, can begin to establish consensus in understanding and best practices. This expert opinion would warrant refinement as both local knowledge and subject-matter knowledge grows and changes over time. The survey itself used pairwise comparison where respondents ranked one criteria against another. Copies of the surveys Appendix C.

Dr. Klaus Goepel[19] of Buisness Performance Management Singapore institution provides a spreadsheet as a resource for recording AHP survey response. We input survey responses to the provided excel spreadsheet, which also calculated the consistency of individual survey responses. Best practices in AHP methodology with 6 criteria or greater are to achieve a consistency ratio of around 10-15%. The surveys included surpassed this standard and ranged from 1.1%-6.73%, demonstrating a high degree of consistency in individual's responses. Additionally, survey participants could self-categorize their knowledge and experience in the field as novice, proficient, or expert. From this categorization we weighed each survey by experience (highest weight: expert, middle weight: proficient, lowest weight: novice). In testing our survey results we compared novice only to expert only results and found the novice participants had a higher rate of inconsistency, which seemed intuitive.

Limitations of AHP

One limitation of using this spreadsheet is that it only allowed for 20 inputs. We excluded 5 surveys based on respondents' self-identified level of expertise, years of experience, and the inconsistency of their responses (greater than 15%). We feel comfortable excluding these surveys based on best practices mentioned in section above.

The AHP spreadsheet tool generated weights based on survey response, which add up to 100 in each category. Different topics in the index contained different numbers of categories, which results in inconsistent weighting by topic area. For example, the topic of fortification will receive higher weights overall (and skew as more important), because it only has three categories, whereas the frontage and secondary shoreline protection topic will skew as less important because it has 8 categories. This difference in number of categories was unintentional, and due to inexperience with survey design.

Survey Participants

Two separate surveys were administered:

3. The first survey was used to determine the baseline vulnerability of that particular Shoreline Type, adaptability to SLR, and the role that frontage and a 2nd line of defense plays in the functioning of that Shoreline Type. This survey is appropriate for a wide range of participants that understand these unique Shoreline Types in the context of restoration projects, permits, planning, conservation work, engineering site level assessments, climate change adaptation planning, and more. Respondents included the planning and permitting departments at San Francisco Bay Conservation and Development Commission, staff at the CA Coastal Conservancy, GIS and planning departments in the Counties of Marin and San Mateo, the staff at San Francisco Estuary Institute, sediment engineers at Greater Farallones National Marine Sanctuary, engineers at ESA, the coastal engineers at AECOM, and climate change program managers at the City of San Francisco.

4. The second survey we conducted asked questions about the impacts of fortification (either engineered/maintained, ad-hoc, or no fortification) on shoreline function and vulnerability. It also asked for response about each component included in the index's relative importance against the other components. The second survey we conducted was limited to those that had extensive experience in planning and vulnerability assessment or in coastal engineering. For these components of the index, it was determined that expert knowledge was necessary. See survey input results in Appendix B.