U.S. Virgin Islands Coastal Vulnerability Index

February 2023

Table of Contents

Abstract
This report presents a first assessment of coastal vulnerability in the U.S. Virgin Islands, following and adapting the method developed by the USGS in the late 1990s. It presents a detailed inventory of coastal geomorphic types and coastal infrastructure, estimates of the flooding risk due to sea-level rise and storm surge, and of the wave climate around the islands. The report also presents estimates of rates of accretion and erosion for select beaches. The final estimate of coastal vulnerability shows that St. Croix is the most vulnerable of all islands because of the preponderance of long stretches of sandy beaches and higher wave climate. We also find that on all islands, and on St. Thomas and St. John specifically, economically important beaches, some of them near hotels, are highly vulnerable. Finally, we find that many beaches and wetlands are moderately to highly vulnerable to coastal hazards, especially to sea-level rise and storm surge. Based on these findings, we provide a series of recommendations to better understand these vulnerabilities and develop adaptation and mitigation activities to protect beaches, coastal ecosystems and assets. The results presented herein are based on a slight modification of the approach originally developed by the USGS because 1) the scale of the analysis is much smaller than the coasts of the U.S., and thus some processes cannot be approximated the same way, and 2) there is now an improved understanding of the impacts of some coastal hazards that make the approximations used by the USGS method inadequate. Specifically, we added coastal armoring in the geomorphology description, we ignored mean tide range, we replaced relative sea level change by sea-level inundation distance, we replaced coastal slope by storm surge inundation distance, and we replaced mean wave height with mean wave power.

Suggested citation: Guannel, G., Beck, N., Dwyer, J., Buchanan, J., Bove, G., Hamlin, T., 2022: U.S. Virgin Island Coastal Vulnerability Index. Caribbean Green Technology Center Technical Report, prepared for the U.S. Virgin Islands Department of Planning and Natural Resources. University of the Virgin Islands, St. Thomas, U.S. Virgin Islands.

This report was supported by a grant from the USVI Department of Planning and Natural Resources and the U.S. National Oceanic and Atmospheric Administration (grant NA18NOS4190154)

1 Introduction and Motivation

The U.S. Virgin Islands (USVI) is exposed to a host of coastal hazards, from storm surges, waves and swells, to sea-level rise. At the same time, the USVI is lacking critical information about its coastal environment. As a result, it is unclear how vulnerable or resilient the USVI coasts can be from the impacts of these hazards.

We present in this document the results of the computation of a Coastal Vulnerability Index (CVI) for the USVI, following the method developed by the USGS[1]. The CVI is computed by ranking and combining the values of six physical indicators along equidistant segments (500 ft) of shorelines. The indicators are 1) coastal geomorphology, 2) coastal slope, 3) relative sea-level change, 4) shoreline change, 5) mean tidal range, and 6) mean wave height. Ranks vary from very low exposure (rank=1) to very high exposure (rank=5), and ranks are determined based on the range of observed values of these indicators in the area under consideration.

This effort used a lot of existing data, but it also required the creation of new data: inventory of coastal environment types, inventory of coastal infrastructure and man-made structures, shoreline change rates for the USVI, and compilation of a nearshore wave climate database. Results of this effort will help the Virgin Islands Department of Planning and Natural Resources, as well as various decision makers and stakeholders, with long-term coastal zone management efforts and the protection of coastal assets.

2 Methods

The coastal vulnerability index represents an estimate of the vulnerability of a coastal area based on the relative characteristics of 6 variables that represent the exposure of a coastal area to coastal hazards and its ability to resist the impacts of that hazard. The variables are:

- Geomorphology
- Mean Tide Range
- Relative Sea-Level Change
- Coastal Slope
- Shoreline Erosion/Accretion
- Mean Wave Height

We discuss in this section the methods used to quantify these variables, and how values will be allocated to shoreline segments.

2.1 Geomorphology

The geomorphology variable expresses the relative erodibility of different landform types. Coastal landforms erode at different time and forcing scales: sandy beaches regularly erode under the action of moderate to high waves; bluffs erode over a longer period, especially under the action of more powerful waves; rocky shorelines are harder to erode than other landforms.

The USGS geomorphic classes were developed to compute the CVI for large areas that span thousands of miles, and they omit man-made structures. However, given the relatively small size of the USVI, we also incorporated man-made structures in the ranking. As a result, we classify geomorphology into the 5 following categories[1]:

- Rank 1: Rocky, Cliffed Coasts; Fiords; Fiards; Bulkhead or Seawalls[*]; Sheet Pile Walls

[*] Here, the words bulkhead and seawalls are used interchangeably. Although the USVI code does not mention seawalls but bulkhead, many coastal structures are in effect seawalls, especially in the most energetic sites

- Rank 2: Medium Cliffs; Indented Coasts; Riprap Revetment in Good Condition[†]
- Rank 3: Low Cliffs; Alluvial Plans; Riprap Revetment in Bad Condition[‡]; Miscellaneous Revetment (e.g., broken concrete, rock and concrete, etc.).
- Rank 4: Cobble Beaches, Estuary, Lagoons
- Rank 5: Barrier Beaches; Sandy Beaches; Salt Marsh; Mud Flats; Mangroves; Coral Reefs

We created a geomorphology layer for the USVI using the initial classification made by NOAA Environmental Sensitivity Index[2]. We modified the classification based on a visual assessment of the shoreline classes using high resolution (3 m) ortho-photos captured by the USVI Office of the Lieutenant Governor in 2020. We also identified and classified all coastal structures and other forms of coastal armoring. Finally, to better understand the motivations behind coastal hardening and the construction of infrastructure, we looked at the zoning of the land where the construction took place, as well as the ownership type of the land. We obtained this information from the USVI Cadastral Office, which is part of the Lieutenant Governor Office. We simplified the ownership type into 6 categories: USVI Government (USVI Government and its agencies, WAPA and UVI), VIPA (USVI Port Authority), Federal, Corporation (LLC, LLP, Inc., Ass.), Person (an individual or group of individuals), and Trust.

2.2 Mean Tide Range

The tide range variable is a proxy for a particular region to be at risk of tidal flooding, or "sunny day flooding"[3]. Regions with higher tide range are more at risk than regions with lower tide range.

We obtained mean tide range data for the USVI from NOAA tide gauge records[4].

2.3 Relative Sea Level Change

Sea level rise at a particular location is the sum freshwater influx added from the melting of glaciers, the expansion of a warming ocean, the relative land motion at that location, the variability in ocean circulation, and changes in the volume of water retained on land. Regions with positive sea-level change values (e.g., most of the contiguous United States but not some parts of Alaska), experience varied levels of inundation based on the relative severity of sea-level rise and coastal elevation.

We obtained the rate of sea level rise experienced in the USVI from NOAA Sea-Level Trends calculations[5] available for St. Thomas and St. Croix. We also obtained sea level rise flooding estimates from NOAA Sea-Level Rise Viewer databases[6] to quantify how sea-level rise will impact different parts of the islands.

2.4 Coastal Slope

The coastal slope variable qualifies the risk of inundation as well as the potential speed of coastal retreat: low-sloping coastal regions should flood and/or retreat faster than steeper regions[1]. The USGS computes coastal slope by taking the average slope of a coastal location from approximately 50 km (31 miles) landward to the submerged continental shelf.

The USGS coastal slope approach cannot be exactly replicated for the USVI because the islands are too small; they are less than 30 mile long or wide. Furthermore, although the continental shelf is 30 miles away from St. Thomas and St. John on their north side, it is around 6 miles on their south side, and for St. Croix is less than 2 miles: the shelf around the islands is narrow, sometimes narrower than the islands. Finally, regardless of the slope averaging distance limitations, it is unclear whether this variable

---

[†] Riprap Revetment in Good Condition is a revetment without large gaps where rocks used to be and few rocks have been moved offshore or nearshore

[‡] Riprap Revetment in Bad Condition is a revetment that lost many rocks, with gaps in coverage, and with many rocks moved offshore or nearshore.

truly represents flooding and coastal recession vulnerability, especially given the abundance of storm surge and sea-level rise inundation estimate databases.

To assess the ability of the coastal slope variable to qualify coastal inundation risk, we used the 30 m resolution seamless topographic and bathymetric dataset generated by Moore and Arcas[7]. We also quantified coastal inundation risk by estimating the landward extent of inundation using outputs from the model SLOSH developed by the National Hurricane Center and Central Pacific Hurricane Center[8,9]. This approach is, arguably, a better representation of the risk of inundation as it represents the *actual* risk of inundation due to storms of a coastal region, as opposed to the potential estimate provided by a slope computation approach.

2.5 Mean Waves Height

The CVI as developed by the USGS uses offshore average wave height as a proxy for offshore wave energy, and thus for coastal erosion potential[1]. This variable was chosen because wave energy is a function of the square of wave height[10]. However, the erosion potential of waves is also a function of the velocity at which this energy travels, which is a function of the wave period. In other words, it is a function of wave power[10]. Here, we replace the wave height variable with offshore wave power variable.

We compute the average wave power offshore of the islands using CARICOOS[11] modeling results from 2013 to 2020. This dataset provides offshore wave information for most of the coastal areas, except for estuaries which are sheltered from ocean waves. To identify sheltered regions, we used the InVEST Coastal Vulnerability model[12], where they are identified as regions where the majority of fetch distances are lower than a few miles. In those regions, we assume that waves are mostly locally generated by winds, and thus wave power is lowest compared to regions exposed to the open ocean.

2.6 Shoreline Erosion/Accretion

Shorelines, especially long stretches of sandy beaches, accrete and erode seasonally. They can also erode or accrete over longer time periods (years)[10]. The impact of waves and sea level rise on shorelines and coastal assets in regions that are experiencing a net loss of shoreline will be more pronounced than regions that are experiencing a net gain of shoreline. Thus, regions experiencing a net loss of sand are more vulnerable than those experiencing a net gain of sand.

There are no current datasets of historical shoreline change for the USVI. (Results from a global dataset of shoreline change[13] show inconsistent and counter-intuitive results for the USVI, and thus were discarded.) Therefore, we computed the rate of shoreline erosion and accretion for the USVI using the USGS model DSAS (Digital Shoreline Analysis System) version 5.1[14,15]. This model compares shoreline positions at a particular location throughout decades to estimate the overall rate of shoreline erosion or accretion.

Although the USVI is relatively small, its shoreline is characterized by having a high number of pocket beaches. This reality makes it difficult to comprehensively compute shoreline change in a timely manner. Consequently, we limited our shoreline change analysis to a limited amount of beaches.

We collected historical ortho images of coastal USVI from two major sources: ortho photos from the USGS and satellite imagery from Google Earth Pro. Cloud free imagery data from which shorelines could be clearly identified and digitized were available as ortho-photos for 1954, 1974, 1989, 1990 and 1995. The same overall quality satellite imagery was available, in general, from Google Earth Pro from 2002-2021. We geo-rectified each image to ensure that all recognizable features were located at the same overall position. This proved particularly difficult for the 1954 imagery dataset which has few features that are can be used to cross reference between historical and modern imagery.

The calculations of positional change calculated in DSAS are only as reliable as the underlying data used in the model. Therefore, positional uncertainty of the shorelines needs to be accounted for when creating and compiling shoreline positions[16–19]. Ideally, positional uncertainty caused by both natural (e.g., wind, waves and tides) and introduced (e.g., alignment of images from different times, analyst error when digitizing) should be accounted for in the analyses[20].

We accounted for image alignment uncertainty by estimating the shift in position of key features for each image included in the model. To estimate this shift, we used the following method. First, we tried, when possible, to choose images from similar seasons through the different years to account for potential seasonal changes. Next, we added control points to the images using recognizable features in the image (ex. buildings, docks) and geo-rectified the images accordingly based on a base image to maximize alignment. Image alignment tended to be poorest for the oldest images (2002-2004), therefore the most recent image in the series was chosen as the base image from which all others will be rectified. To quantify uncertainty, we measured changes in position for a few key features in each image from their position in the most recent image. The uncertainty value for that image, or stretch of beach, was summarized as the average of the positional shifts.

Finally, we identified the shoreline position on each image. The DSAS software uses these positions to determine regions of the beach that experience erosion or accretion, and to estimate the overall net loss or gain of sand on the beach of interest. Shoreline position was taken as the interface between water and beach, or the most visible wet/dry line. This approach neglects any change in shoreline position caused by tidal fluctuations. However, given the relative low tidal range, we assume that this error is probably relatively low.

2.7 Coastal Vulnerability Index

To allocate a CVI value to different portions of the shoreline, we segmented the coastlines of the USVI into discrete points regularly spaced 500 ft apart, and assigned a score from 1 (Low Vulnerability) to 5 (Very High Vulnerability) to each of them for each of the variable. We built the shoreline points by identifying the zero contour line from the 2018 Digital Elevation Model (DEM)[21].

The geomorphic characteristics are ranked according to the USGS methodology[1]. We ranked sea level rise and storm surge (coastal slope) based on a quartile approach, where values less than the 20th percentile (e.g., flatter regions) are ranked as a 5, whereas values higher than the 80th percentile (e.g., steeper regions) are ranked as a 1. We took a similar approach for wave power, where regions with average wave power values below the 20th percentile are ranked as a 1 (low vulnerability), whereas those with wave power values above the 80th percentile are ranked as a 5 (high vulnerability); sheltered regions were assigned a rank of 1. We will ignore mean tide range because this value does not change significantly around the three islands. We did not include shoreline change because of the limited dataset; however we present values for the beaches for which we computed this quantity.

We compute the final vulnerability rank by computing the geometric mean of all indices calculated: $CVI = \sqrt[4]{V_1 * V_2 * V_3 * V_4}$, where V_i represents the rank of the geomorphology, sea level rise, storm surge (coastal slope) and wave power variables.

3 Results

3.1 Geomorphology

As discussed in Section 2.1, we identified geomorphic features using high resolution ortho-photos of the USVI. Figure 1 shows the distribution of shoreline types and geomorphology ranks around the islands, and Figure 2 shows examples of shoreline types. Note that – as shown in Imange 16 with the presence of a seawall on the left hand side and a riprap revetment on the left hand side – we did not take into consideration the presence of structures in the backshore. However, these structures will likely prevent beaches or vegetation from migrating landward as sea level rises.

We find that most of the shoreline of the USVI is rocky or made of consolidated material, from high cliffs to wave cut platforms. The second most common shoreline type is sandy beaches, followed by mangroves and coastal vegetation, armoring and gravel beaches (Figure 3). However, the relative distribution of shoreline types varies between islands. For example, while St. Croix has 38% of its coastline classified as rocky; St. Thomas and St. John have more than half of their coastline classified as such (61% and 57%, respectively). On the other hand, St. Croix has 30% of its shoreline made of sand, while St. Thomas and St. John sandy beaches are present on 10% and 13% of their coast, respectively. Also, while St. John only has 2% of its coastline armored, St. Thomas and St. Croix have armoring on more than 10% of their coastline (12% and 13%, respectively). It is noteworthy that the total length of beaches and the total length armoring on St. Thomas are nearly the same. Even St. Croix has “only” three times as much beaches as armoring, from a cumulative length point of view. In other words, St. Thomas coastal environment is quite developed. St. Croix coast is also developed, but has more natural coastlines. St. John is the least developed of the islands. The three islands have unique geomorphologies, and thus unique responses to hazards.

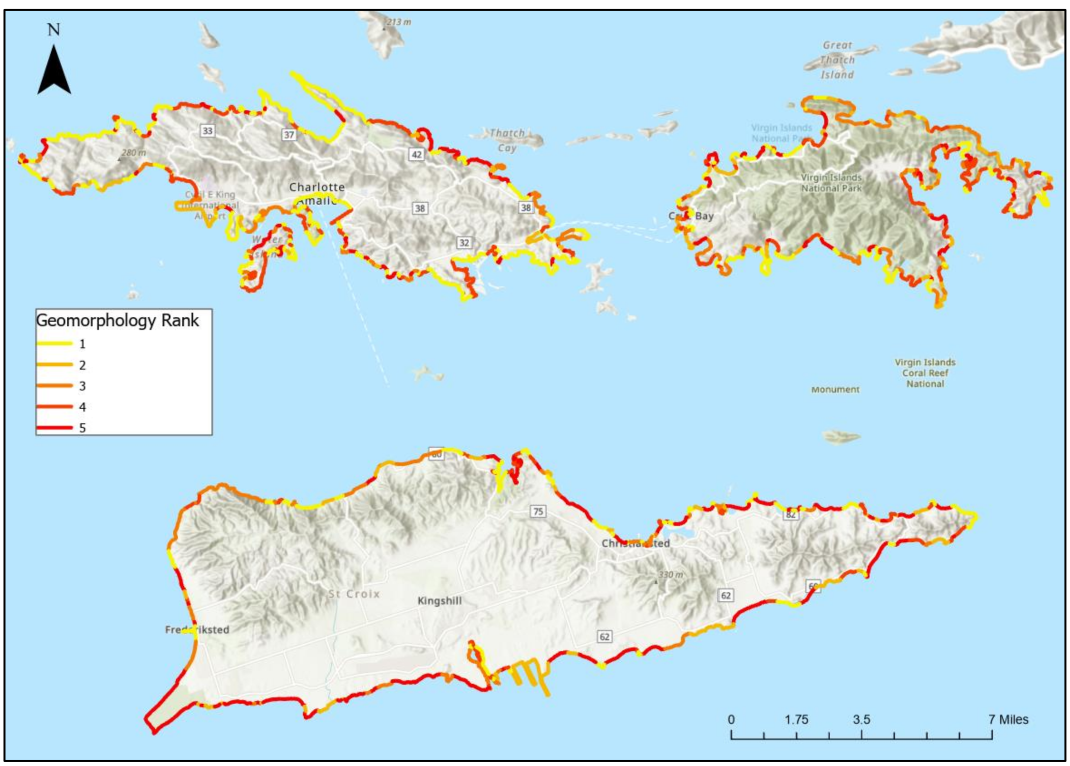


Figure 1: Shoreline type distribution in the USVI.

Figure 2: Aerial imagery of different shoreline types. Shot 1: High rocky cliff (rank 1); shot 2: medium erodible cliff (rank 2); shots 3 to 6: Low erodible cliff (rank 3); shot 7 and 8: gravel beach (rank 4); shot 9 and 10: riprap revetment (rank 3 or 4); shot 11:bulkhead or seawall (rank 1); shot 12: pier and boat ramp (rank 1); shot 13: jetty built with riprap (rank 2 to 3); shots 14 and 15: groin built with riprap (rank 2 to 3); shots 16 and 17: sandy beach (rank 5); shot 18: vegetated shoreline (rank 5).

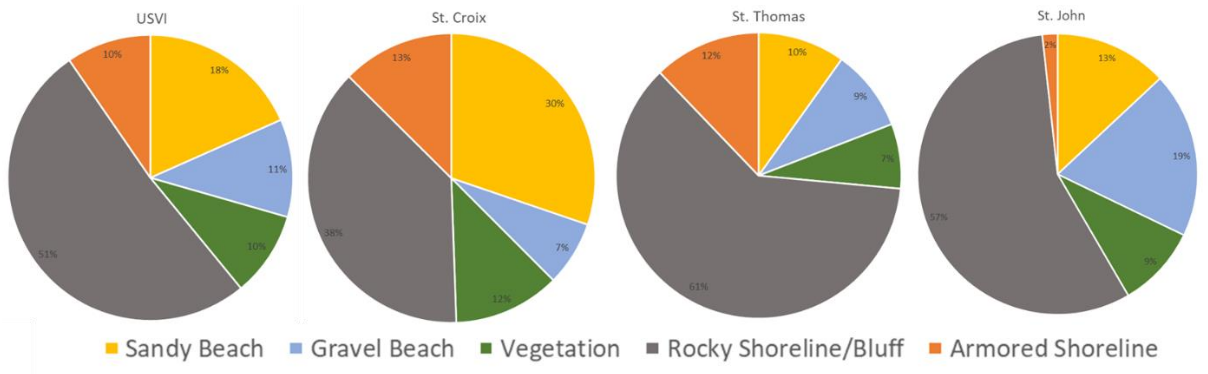


Figure 3: Shoreline type distribution in the USVI

Looking at the distribution of beaches, one of the main cultural and economic assets of the coastal areas of the VI, we find that St. Croix has approximately 110 beaches and exhibits the widest range of sandy beach lengths (Figure 4). Many beaches are tens of feet long, a handful of beaches are half a mile to a mile long (e.g., Pelican Cove), and one beach is two miles long (Sandy Point). St. Thomas has approximately 61 beaches. They also exhibit a range of length, but they are in general smaller than on St. Croix, with the longest beaches (e.g., Magen's Bay; Lindquist) slightly more than half a mile. Lastly, St. John has approximately 49 beaches, which are in general longer than on St. Thomas but smaller than on St. Croix, with the longest beaches (e.g., Cinnamon Bay, Maho Bay) around half a mile.

In general, St Croix has many long stretches of beaches, with some small, isolated pocket beaches. St. Thomas on the other hand has many small pocket beaches with a few long beaches. St. John has a mixture of both, but does not have beaches as long as St. Croix'. These differences can also be found in the number of bays that each isle has: St. Croix has 53 bays, whereas St. Thomas has 83 and St. John 70.

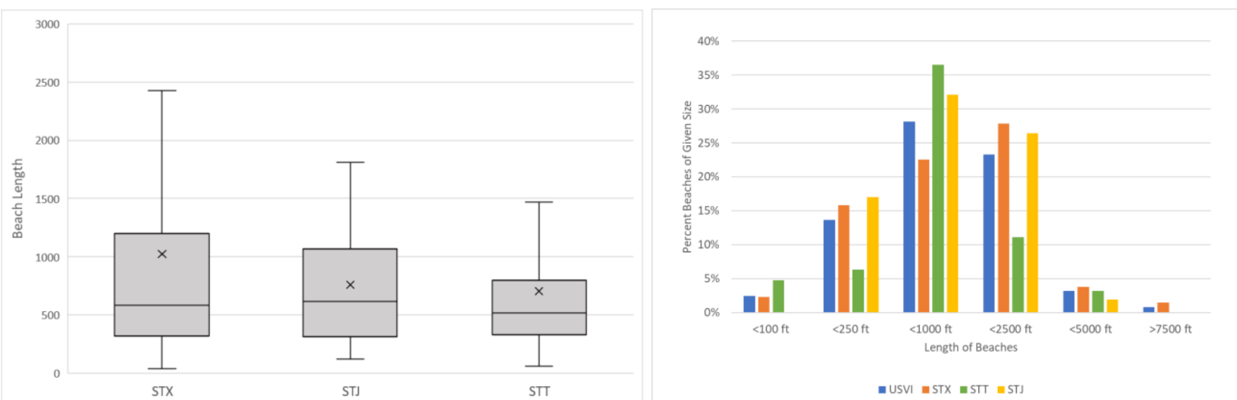


Figure 4: Distribution of sandy beach length in the USVI.

As mentioned earlier, a fair amount of St. Thomas and St. Croix is hardened, or has large coastal infrastructure. This is somewhat in line with what has been observed in the US[22]. Most of the coastal structures, measured by cumulative length, are seawalls or bulkheads (Figure 5), and they mostly consist of docks for port operations or to protect urban centers and critical infrastructure (e.g., Water and Power Authority (WAPA) facilities).

The second most common type of infrastructure, by length, are jetties. Although there are a few jetties on St. Thomas, very long jetties are built on St. Croix to facilitate operations at Limetree Terminals. The third most abundant type of structure are riprap revetments. They are used to protect a lot of transportation infrastructure and port infrastructure. Lastly, there are a few groins, especially on the south shore of St. Croix. However, they do not seem to perform as originally intended as the shoreline is showing signs of extreme erosion. In addition, some of these groins seem to have stopped the movement of sand westward, and they are probably exacerbating long-term erosion downdrift.

Overall, few coastal structures are near buildings and private residences. This may be because of the imposition of setback distances for coastal buildings. However, we find that many coastal structures are built in the backshore, near buildings or residences. So, although coastlines are not armored in this case, it is likely that, as sea level rises, these structures in the backshore might become coastal armoring[23].

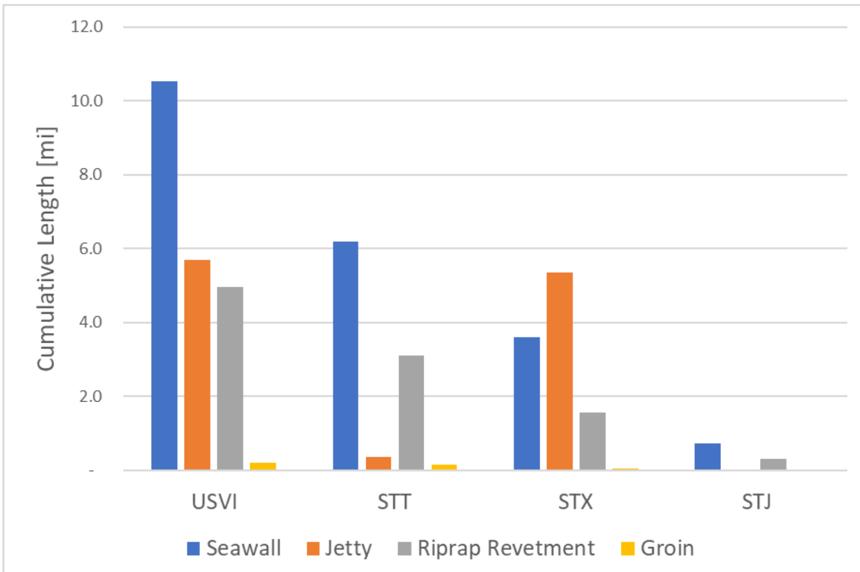


Figure 5: Distribution of large coastal infrastructure around the USVI

Even though there is a relatively small amount of the coastline that is hardened for protection against erosion or inundation, most of the coastal infrastructure seems to have been built to facilitate transportation (Figure 6). Most of the seawalls mentioned above were built to protect roads, and most of the jetties were built to facilitate commercial marine transportation. In addition, there are a fair number of piers (outside of marinas), used by small boats and other large vessels. St. Thomas has the largest number of piers, followed by St. Croix and St. John, to a smaller extent. Next are docks, with or without a pier, where once again St. Thomas surpasses the other two islands. Surprisingly, St. Thomas and St. Croix have the same amount of boat ramps, while St. John only has a few. The next two categories are groins and jetties, which are located mostly on St. Croix, as discussed above. In addition to these structures, the USVI has a total of 13 marinas: 9 on St. Thomas, and 4 on St. Croix. Most of these marinas are located near mangroves, seawalls, and beaches.

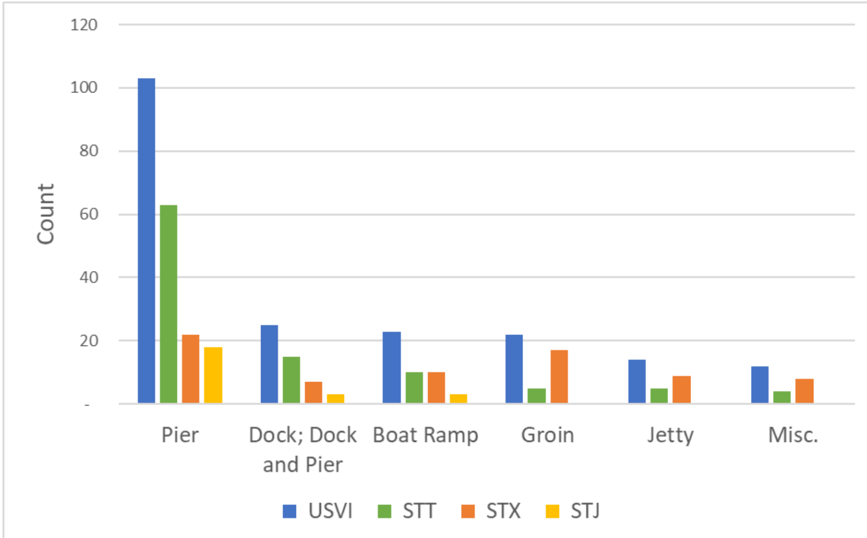


Figure 6: Distribution of navigation coastal structures in the USVI.

To further understand the motivations for coastal hardening, we looked at the zoning of the land protected, as well as the ownership type of the land. We find that most properties protected by armoring are zoned as Public, then Residential, Waterfront[§], Industry, and Business (Figure 7). St. Thomas has by far the highest number of individual structures, for all categories. The longest structures are found to protect land classified as Industry, but this is due to the length of the port assets managed by Limetree on St. Croix. Limetree aside, the distributions of length and count are similar. Port Authority and other public agencies own most of the structures, then residential structures.

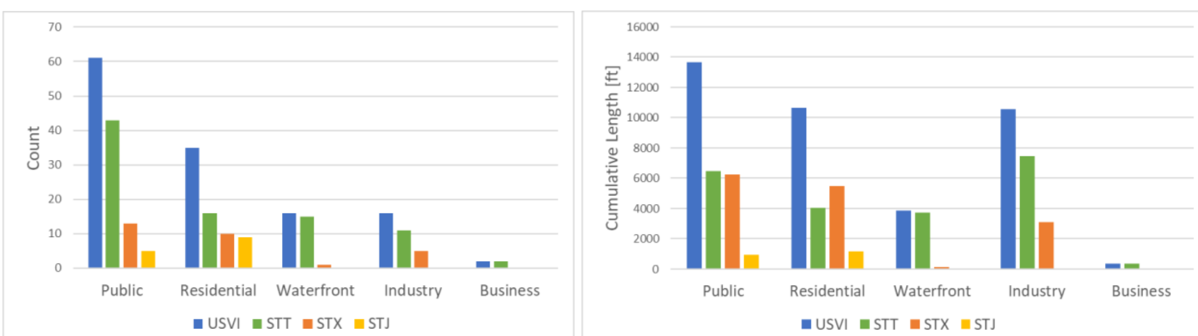


Figure 7 : Amount and length of coastal armoring along different land zone type

Further, to better understand the types of residential structures protected by armoring, we looked at the ownership type of the land protected by structures (Figure 8). We find that corporations (LLC, LLP, Inc., Corp., etc.) own most of the structures, with Limetree owning the longest amount by length. Corporations also own most of the structures in front of land classified as residential, and these residential structures are condos, hotels, etc. The second highest owner of land protected by structures is the VI Government. Private citizens and trust also own some of the protected land, where structures tend to protect houses or small buildings.

[§] Waterfront zoning refers to areas where special considerations need to be made for public access, aesthetics, etc.

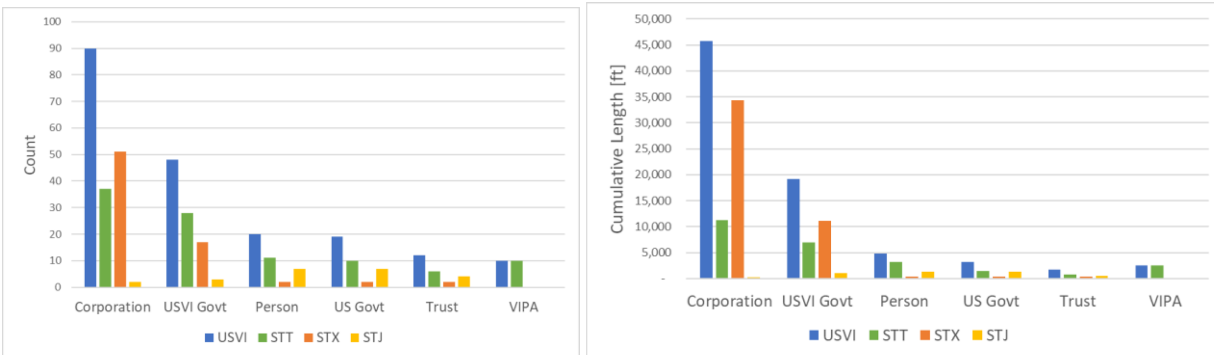


Figure 8: Amount and length of coastal armoring by different types of owners

This analysis of land zoning and ownership type shows that a lot of the land protected by hard, major infrastructure like seawalls and riprap revetments are used primarily for industrial and commercial purposes, or protection of public property (e.g., waterfronts). Protection of private residences is less common.

We also looked at the types of buildings that are with 20, 50 and 100 ft from the shoreline to understand what is being protected. We find that valuable government buildings are located near the coast, although many of them are on low to medium cliffs. In addition, although some private residences are in front of beaches, most assets are at least 50 ft from the shoreline, and few are fronted by sandy beaches. Commercial buildings tend to have their coastal waterfront armored, which is in line with findings above, and limit risk. Finally, we find that hotels are by far the most expensive coastal assets, especially since so many valuable properties are in front of beaches, which will erode and/or flood due to sea-level rise and storms. Since hotels are so vital for the USVI economy, further investigation and dialogue with property owners about their risk might be warranted.

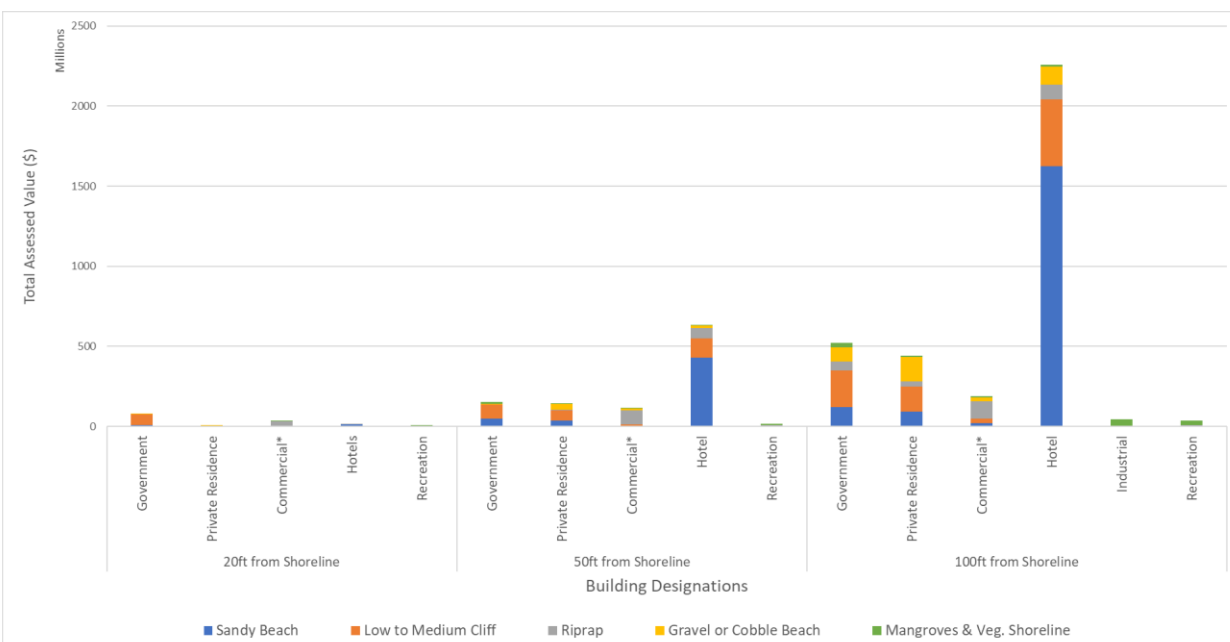


Figure 9: Total assessed value of buildings in the USVI by shoreline type and distance from shoreline

Lastly, similar to buildings, we looked at the types of coastal infrastructure protecting roads (Figure 10). We find that most roads that are at least 100 ft from the shoreline are protected by cliffs. However, many roads 100 ft from the shoreline are also protected by beaches and mangroves. Seawalls and other harder shoreline types come after, with the exception of cobble or gravel beaches. Looking at roads that are 50 or 20 ft from the shoreline, sandy beaches and mangroves are also very common, although many are protected again by rocky shorelines or structures. Fortunately, very few roads are built within 20 ft from the shore. Nevertheless, even if some of those are access roads to beaches and mangroves, the fact that the majority of roads, whether 100, 50, or 20 ft from the shoreline, are protected by erodible features is worrisome. The roads themselves are in danger of experiencing erosion of their foundation or experiencing flooding due to sea-level rise or storms. Conversely, beaches and mangroves might experience limits in their ability to migrate inland over time. Some of these issues will be revisited in Sections 3.3 and 3.4.

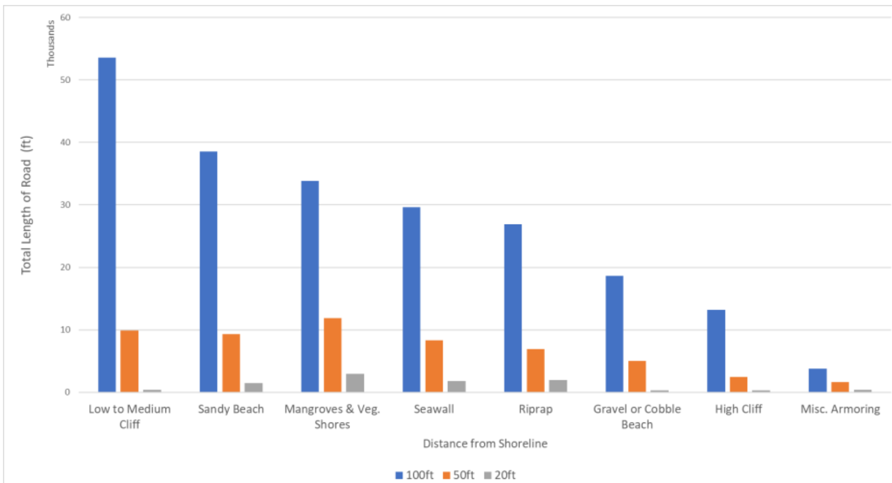


Figure 10: Shoreline type fronting roads

3.2 Mean Tide Range

The tidal range in the USVI is fairly small. On St. Thomas, in Charlotte Amalie, the mean tidal range (difference between Mean High and Mean Low Water) is 0.82 feet, and the great diurnal range (difference between Mean Higher High and Mean Lower Low Water) is 1.09 feet. On St. Croix, in Christiansted, the tide range is smaller, with a mean tidal range of 0.69 feet, and great diurnal range of 0.74 feet. Near Limetree, the mean range is similar, but the great diurnal range is 0.71 feet. These differences are probably linked to larger oceanic processes around the islands.

The tide range is small enough for the USVI to be classified as a microtidal environment, which means that most beach processes are mostly dictated by wave processes. For the CVI, we ignore mean tidal range as it has similar value for all islands.

3.3 Relative Sea Level Change

Sea level in the USVI has increased by 9.6 cm (3.8 in) on St. Thomas since 1975, and 11.6 cm (4.6 in) on St. Croix since 1977[5]. This translates to an average rate of 2.63 mm/yr (0.1 in/yr) on St. Croix, and 2.1 mm/yr (0.08 in/yr) on St. Thomas. Other estimates from satellite imagery and gauges estimate that sea level has risen by 8 cm (3.1 in) between 2000 and 2020[24], which represents a rate of 4 mm/yr (0.15 in/yr), which is in line with, but slightly above, observed global sea level rise values of 3.6 mm (0.14 in/yr) between 2006 and 2015[25]. This rate is also faster than the NOAA estimate above, which was computed over a longer time scale. This difference in rate is likely a sign that sea-level rise is accelerating.

Projections to 2050 indicate that sea level is likely to continue to rise by similar values in the USVI (Figure 11). Sea level is projected to rise by 0.22 m in 2050, or 0.72 ft, above 2020 levels. This assumes a SSP1 2.6 scenario, or a projected increase in temperature of 1.8°C by 2100[26]. The Intermediate scenario in Sweet et al.[24] predicts 0.19 m (0.62 ft) by 2050 from 2020, and the Intermediate High predicts 0.26 m (0.85 ft) by 2050 from 2020. Regardless of the projection tool and method, it is predicted that local sea levels are going to rise by 0.7-0.9 ft by 2050 from 2020 levels.

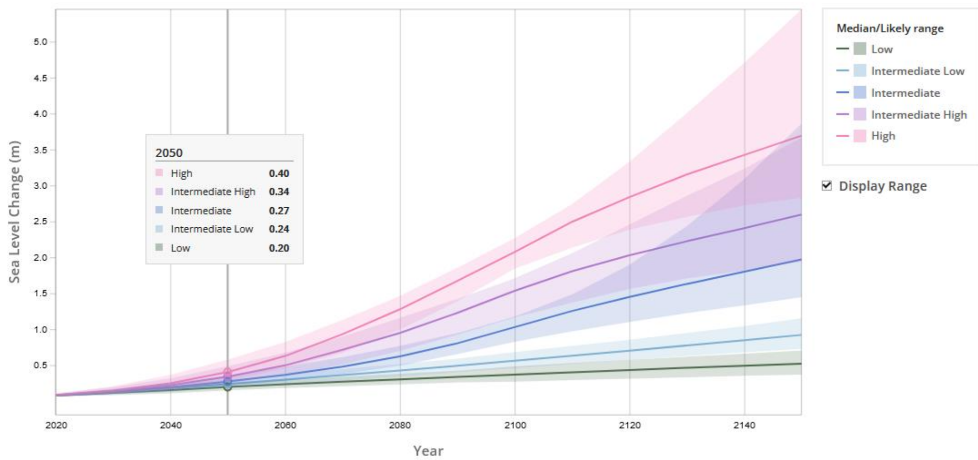


Figure 11: Projections of sea-level rise values on St. Croix. Screenshot from NASA online tool[26]

Because of the very small difference in sea level rise between the islands, for the CVI, a unique value of 3 could be assigned to all regions, or sea-level rise could be ignored all together as a variable. However, this approach would underestimate the tidal flooding risk in some areas. In Figure 12 we show the tidal flooding extent expected for a 1 ft increase in sea level. We find that although all coastal regions will experience flooding, the inundation extent is relatively limited with most regions experiencing less than 30-40 ft of inundation inland. Tidal inundation represents a risk for most beaches and mangroves, which have flatter slopes and will experience permanent change, but not for most assets, as discussed in the previous section. However, a few regions will experience greater flooding and loss of habitats.

As illustrated in Figure 13, we find that the most vulnerable areas to sea level rise inundation are Mangrove Lagoon and Smith Bay on St. Thomas, which are home to extensive wetlands. On St. John, Coral Bay and most of the northern coast of the island are also vulnerable to tidal flooding. This is due to the fact that many of the longest beaches of St. John are on the northern coast. On St. Croix, the central southern coast, home to mangroves and beaches, and Salt River Bay, a wetland, are most at risk. In other words, aside from the loss of footprint for many beaches and coastal areas, the most extreme impacts of sea level rise will be felt by mangroves and some beaches. Given the fact that roads and other infrastructure are built landward of these important habitats, it is likely that the territory will experience an irreversible loss of wetlands and of beaches, to a lesser extent. It is also likely that impacts from coastal hazards on the infrastructure buffered by these habitats will be more pronounced.

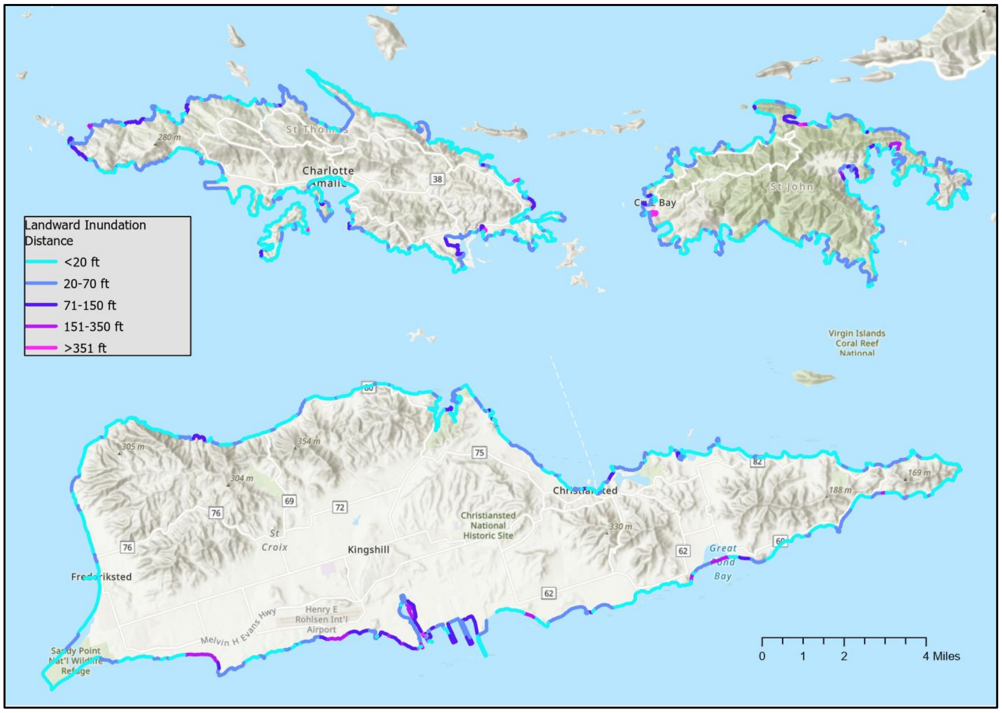


Figure 12: Landward inundation distances expected by tidal flooding assuming a 1 ft sea-level increase

Figure 13: Regions experiencing tidal flooding 100 ft from the shoreline assuming a 1 ft sea-level increase.

This analysis shows that although sea-level rise will be experienced at similar rates in the Virgin Islands, the impacts of sea-level rise will not be felt similarly everywhere. To capture the different impacts of sea level rise around the islands, we rank tidal inundation distance using a quantile approach where regions less inundated will receive a lower rank, and regions that are more inundated will receive a higher rank. Sea-level rise ranking is shown in Figure 14.

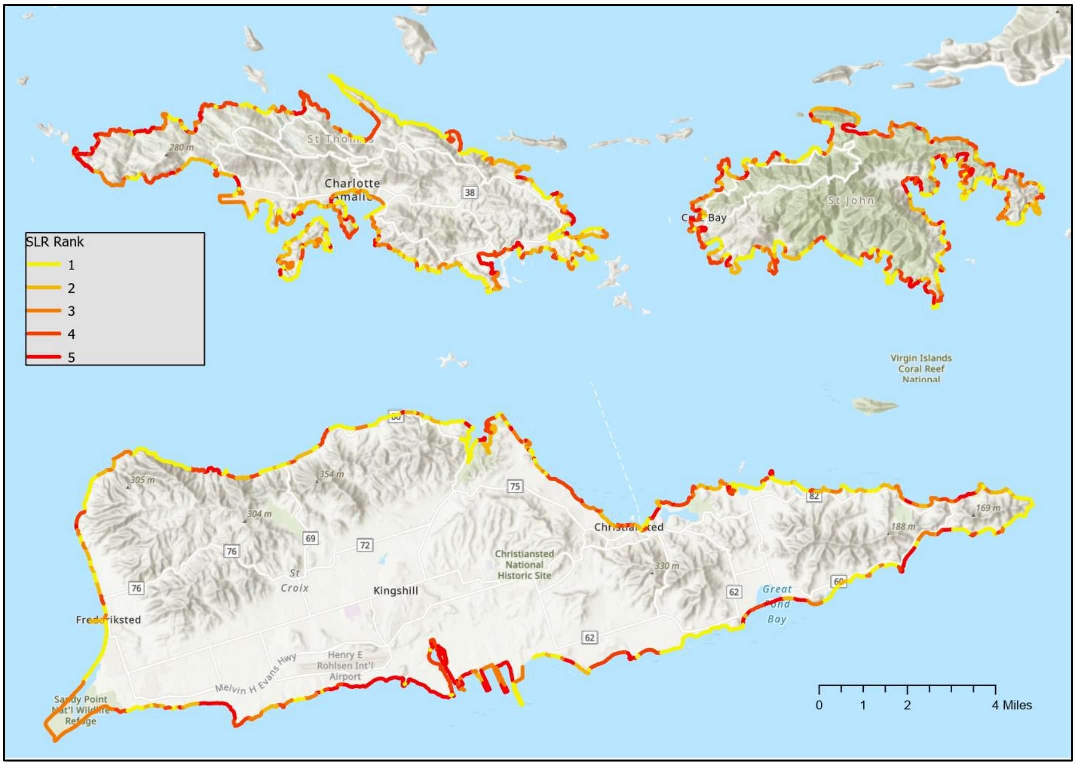


Figure 14: Sea-level rise ranking

3.4 Coastal Slope

As discussed in Section 2.4, the Coastal Slope variable is used to estimate the risk of inundation as well as the potential speed of coastal retreat[1]. Inundation here can be caused by two processes. Sea-level rise and storm surge. And as discussed, this assessment is made difficult in the USVI because of the small size of the islands, and the small continental shelf, especially around St. Croix.

Figure 15 shows the coastal slope around the islands, using an averaging distance of 1 km. We obtained similar results using a radius of 2 km and 500 m. These results could indicate that the southern and northeast coast of St. Thomas could be more at risk of inundation than the rest of the island. On St. John, the southern and west coast could be more at risk. And on St. Croix, the north central, northeast, southern and western coasts could be more at risk due to flatter slopes allowing for larger wave runup.

However, these results do not compare well against sea-level rise modeling results (Figure 12) as there are limited regions that will experience large tidal inundation by 2050. More importantly, these results do not compare well against storm surge modeling results published by NOAA[8] (Figure 16). The reason for this discrepancy is that storm surge inundation is not a static process where a simple bathtub approach provides an answer for which region is more at risk than another. Storm surge buildup is a complex function of storm direction and characteristics, as well as nearshore and shoreline bathymetry. In other words, it is a highly nonlinear process, which a simple coastal slope approximation does not capture.

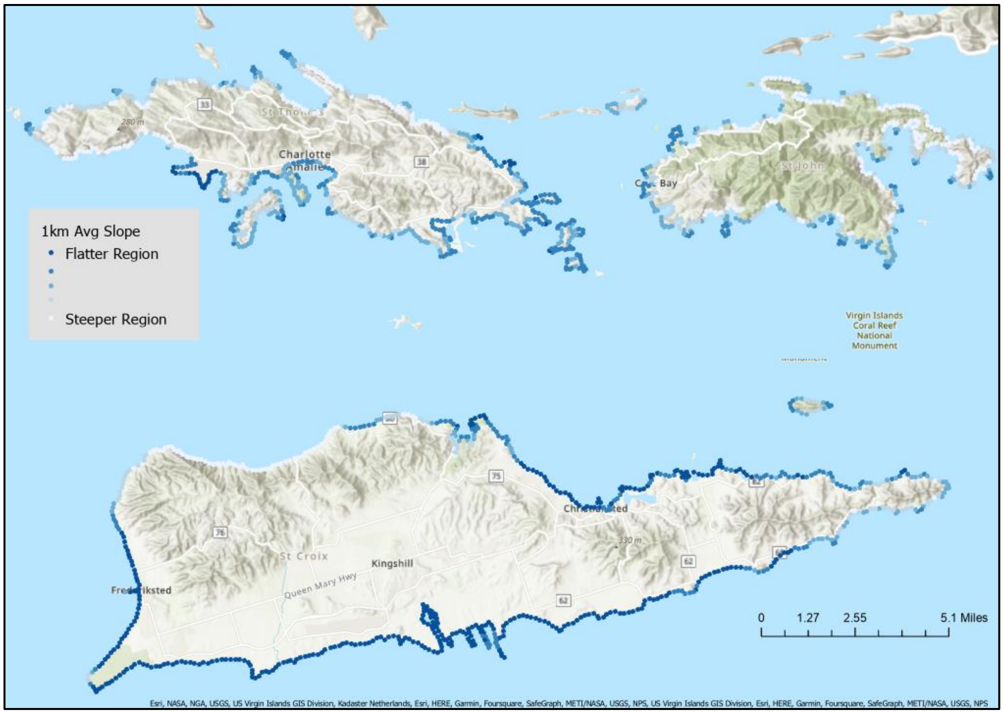


Figure 15: Distribution of coastal slopes (quartile approach) around the USVI.

Figure 16 shows storm surge inundation distance from the coast estimated by the NOAA model SLOSH[8,9]. The results indicate that surge inundation risk is highest on the southern coast of St. Thomas, in Magen's Bay, and other smaller regions. On St. John, inundation risk is highest around Coral Bay and the southeast coast, the north central coast, and other smaller regions. On St. Croix, inundation risk is highest along the southern coast and Salt River Bay. These results are in line with some of the regions that are also more at risk of tidal inundation.

These results show that inundation risk, whether computed from sea-level rise projections or storm surge, is different from the estimate provided by coastal slope. This is likely due to the small footprint of the islands as well as a narrower shelf. As a result, we will not use the coastal slope result in our analysis. Instead, we will replace it by the coastal inundation risk as computed from SLOSH model results (Figure 17).

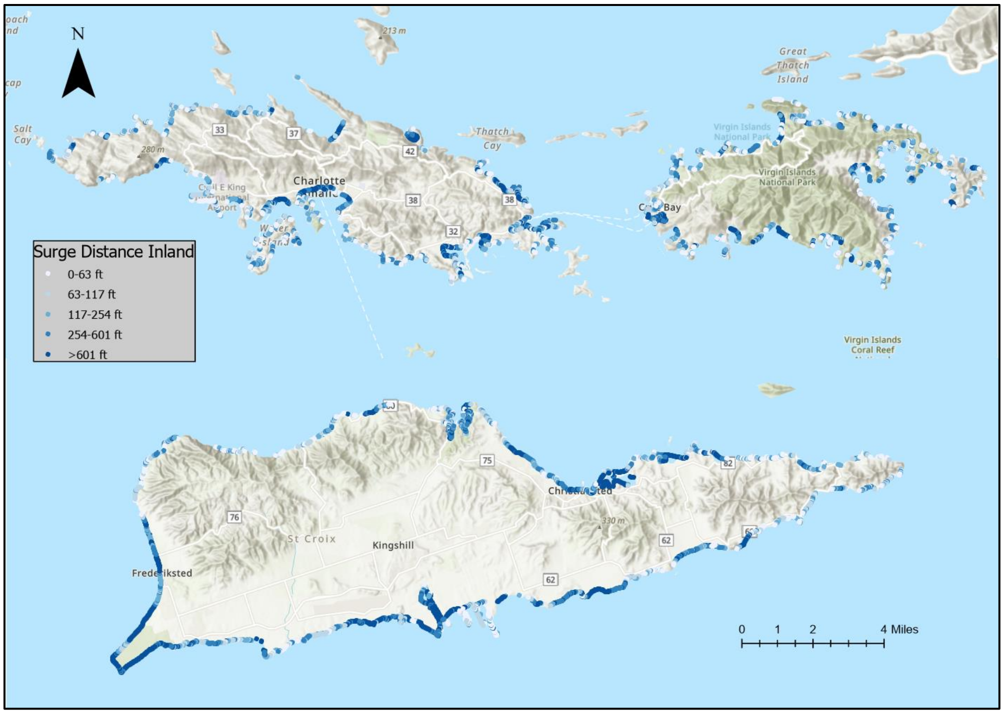


Figure 16: Storm surge inundation distance from the coast as computed by the SLOSH model[9]

We note that the coastal slope variable as designed by the USGS was supposed to capture inundation risk from, presumably, sea-level rise and storms. Here we changed both sea-level rise and coastal slope variable with estimates of tidal and storm surge inundation. Although this approach gives more weight to flooding, we believe that this approach is reasonable as the intent of the CVI is to quantify coastal vulnerability to coastal hazards, and inundation is probably the most damaging hazard.

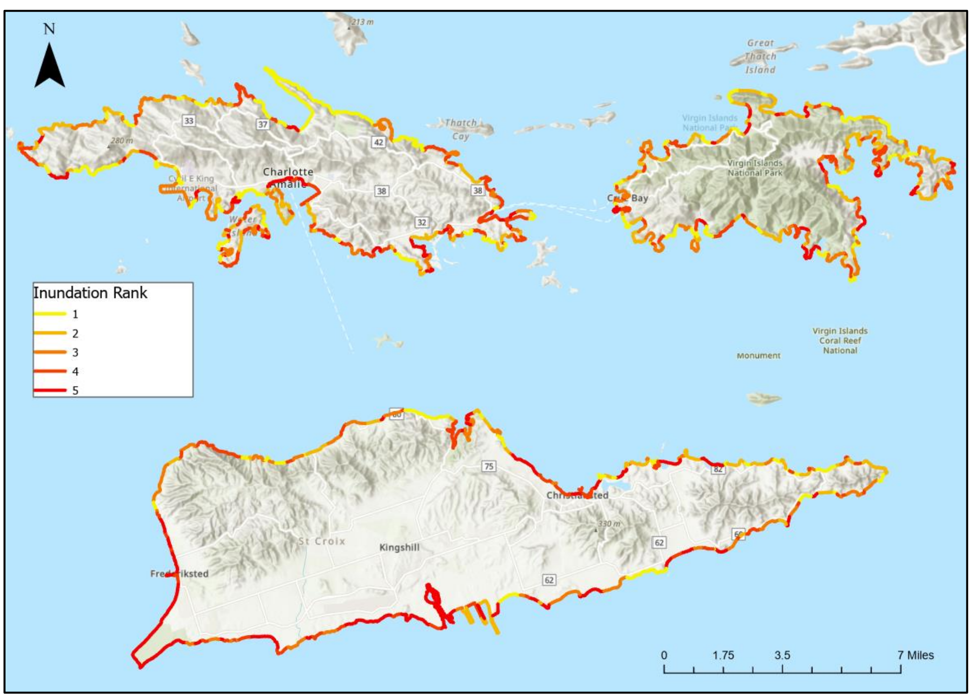


Figure 17: Final coastal inundation/coastal slope rank.

3.5 Mean Wave Power

Aside from flooding due to sea-level rise and storm surge, waves can erode coastlines and increase flooding depth and impact. We find that St. John is mostly sheltered by the British Virgin Islands (BVI), and thus experiences the milder wave climate of all the islands (Figure 18; Figure 19). However, the south of the island can be impacted by higher waves moving from the southeast, even though they seem to dissipate as they move closer to shore. St. John is also exposed to higher waves from the Eastern Atlantic that impact the northwest side of the island during the months of September through March (herein referred as winter months). Milder waves impact these beaches the rest of the year from April through August (herein referred as summer months).

St. Thomas also benefits from the protection of BVI, as well as from the protection of St. John. As a result, most of the southern and northeast coasts of St. Thomas experience a mild wave climate, with waves moving westerly throughout the year. The northwest coast, on the other hand, experiences the highest wave climate, a combination of easterly waves propagating from the Eastern Atlantic Ocean that are not impacted by the presence of the BVI, and westerly swells propagating from the Northern Atlantic Ocean.

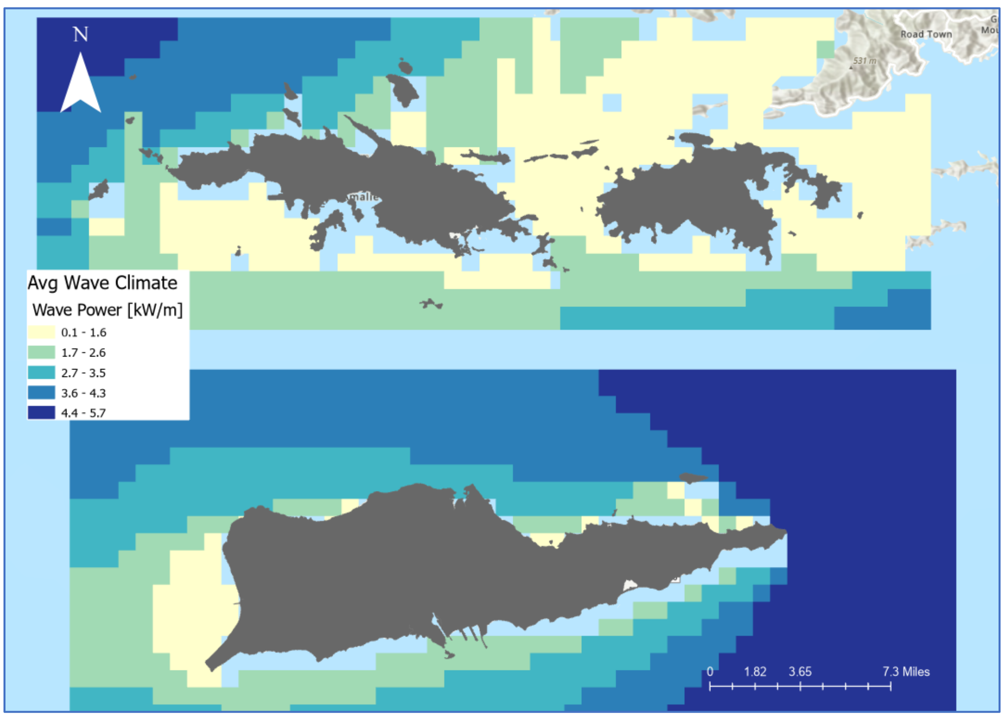


Figure 18: Wave power climate around the USVI

St. Croix is the most exposed of the U.S. Virgin Islands. It experiences the full force of waves from the Eastern Atlantic Ocean; few waves propagate from the northern Atlantic. As a result, waves are the most powerful on the eastern coast of the island, weakening somewhat as they travel westward. Only the western coast is sheltered, as westerly waves must wrap around the island, and thus lose some of their energy. The southern and northern coasts experience similar wave exposure. However, the large reef offshore of the southern coast moderates some of the impacts of the waves. The reef north of Christiansted also provide some protection to the city and neighboring regions. Figure 19 summarizes the wave climate around the islands, where we not only show the average wave power relative strength and direction. We also show the average power of the top 10% most powerful waves to give a sense of where the potentially most erosive and destructive wave come from, and their relative distribution around the islands. Figure 20 shows the wave power ranking for the islands, created using the average wave height distribution.

Figure 19: Wave Climate of the USVI

Implications of these results are that most beaches on St. John are not likely to experience significant cycles of erosion, except beaches on the northwest of the island. This is compounded from the fact that these beaches are also vulnerable to sea-level rise, as shown in the previous section. St. John beaches probably experience some level of erosion from September to March, and recover from April through August. Longshore currents generated by these waves probably move westerly, but the most powerful waves probably move the sediment east.

On St. Thomas, the few beaches on the northwest side of the island also probably experience cycles of erosion and accretion throughout the year. The other beaches, especially south facing beaches, are likely to be more stable, or at least experience less severe cycles of erosion and accretion. On St. Croix, coastlines are more energetic, and beaches are probably experiencing varied levels of erosion, followed by accretion, except for beaches on the western side of the island that are probably more protected against erosion. The difference in wave regime between the south and west coast of the island probably led to the creation of Sandy Point, where sand movement slows as waves wrap around the island. The general easternly direction of the waves indicates that longshore currents probably move sand from east to west on both the north and south side, except when northernly large swells move sand in the other direction on the north side. On the western side, sand is probably moving north to south, but longshore currents are likely to be milder. A more detailed analysis of the wave climate for each of the island is presented in Appendix B.

Figure 20: Wave power ranking for the USVI.

3.6 Shoreline Erosion/Accretion

3.6.1 Large Scale Changes

We compared historical shoreline positions of the USVI throughout the years to estimate, overall, how much the coastal environment has changed. This qualitative assessment provides some insight into the major shifts and potential drivers of coastal change.

On St. Thomas, we find that most of the coastal change has been driven by the construction of the airport, roads, and port facilities. Most of the development also occurred on the south side of the island, probably because of its milder wave climate and proximity to Charlotte Amalie. The Cyril E. King airport runway extension occurred in the late 1970s, early 1980s (Figure 21). Brewers Bay seemed to have at that time a sandy beach on its northern side, and a wetland on southern side. The wetland seems to have been damaged by the extension of the runway. However, the new runway seems to now act as a major breakwater for waves, and moderates the wave climate in Brewers Bay as they mostly move from the southeast to the northwest. As a result, sand moved from the west side of the beach to the east.

Figure 21: St. Thomas airport and Brewers Bay in 1954 (top left), 1970 (top right), 1980 (bottom left), and 2020 (bottom right).

On the other side of the runway, it appears that the land was also filled and leveled to expand the terminal and other facilities (Figure 22). The whole airport and surrounding land has been armored to protect the newly placed fill.

Figure 22: St. Thomas airport, south side of the runway in 1954 (top left), 1980s (top right), 1990s (bottom left), and 2020 (bottom right).

The road to the airport along Lindbergh Bay was built shortly after the expansion of the runway, and new infrastructure and buildings were built at the same time (Figure 23). The construction of the road was followed by the armoring of the beach area sometime in that period.

Figure 23: Lindberg Bay and the construction of the road infrastructure for the airport in 1954 (top left), 1980 (top right), 1990 (bottom left), and 2010 (bottom right).

Krum Bay, where WAPA facilities are located, was filled and armored to accommodate the construction of the power plant in the 1970s (Figure 24). Further construction and armoring of the shoreline continued into the 2010s.

Figure 24: Krum Bay and WAPA power plant construction in (from left to right): 1954, 1970, 1990, and 2010

In Crown Bay and Little Krum Bay, the Port was expanded sometime in the 1960s, on top of what appears to be a vegetated shoreline (Figure 25). Significant filling activities occurred in the 1980s to build the marina and other port facilities, including a cruise ship terminal. The terminal was further expanded on fill in the 1990s, and construction was finalized in the late 1990s/early 2000s.

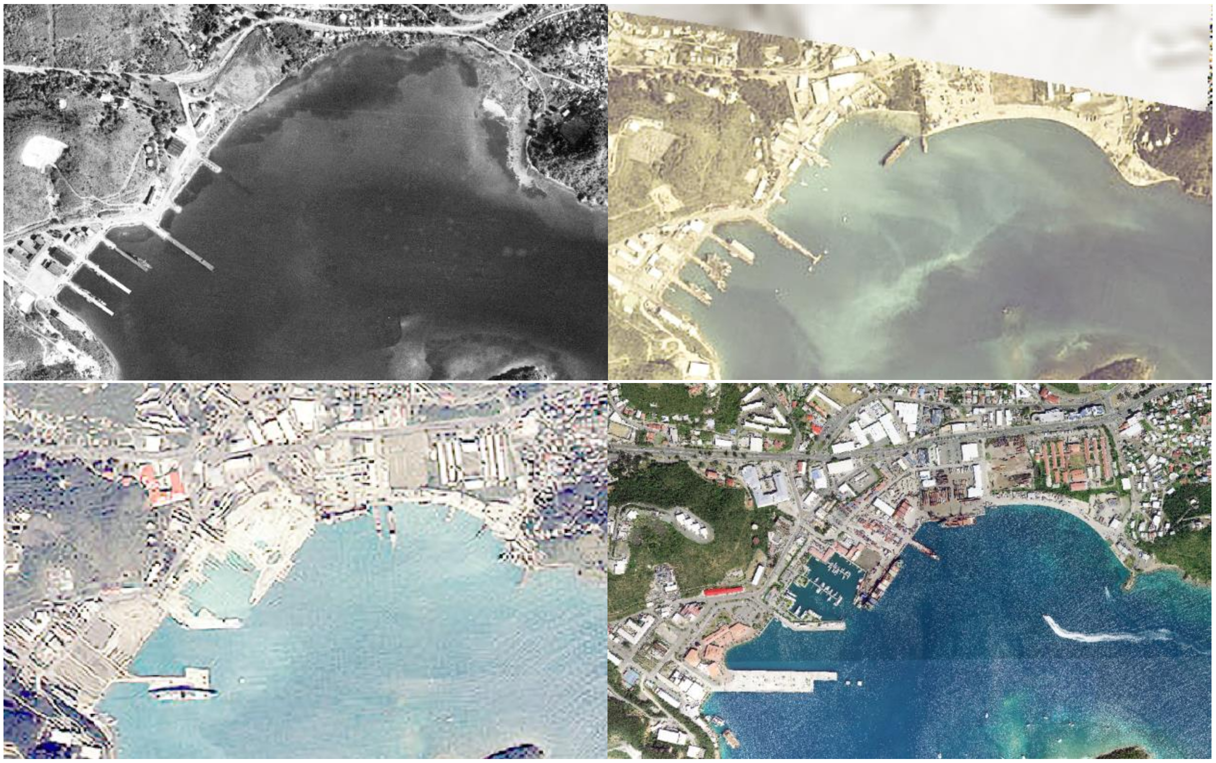


Figure 25: Expansion of the port infrastructure in St. Thomas from 1954 (top left), 1970 (top right), 1980 (bottom left), to 2020 (bottom right).

Veteran's Drive, which runs along the waterfront, was built on fill and has remained untouched, for the most part, prior to the road extension that was finalized in 2019/2020 (Figure 26).

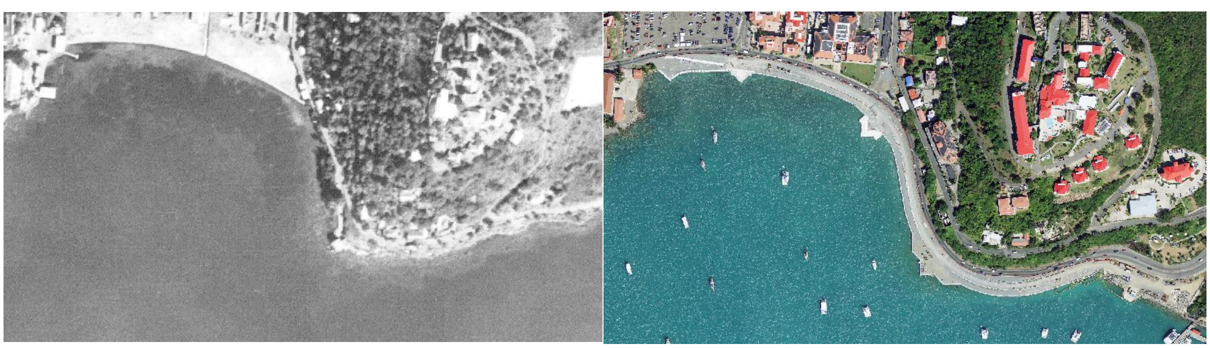


Figure 26: Veteran's Drive in 1954 and 2020

Another major shoreline change on St. Thomas is the construction of Yacht Haven Grande (Figure 27). In the 1950s it was a beach with some moorings, a small dock, and a larger dock to the west. In the 1970s, this area had a small marina. In the 1980s, the coastline was filled to build what is now a larger marina. In the 1990s, the cruise ship dock was extended.

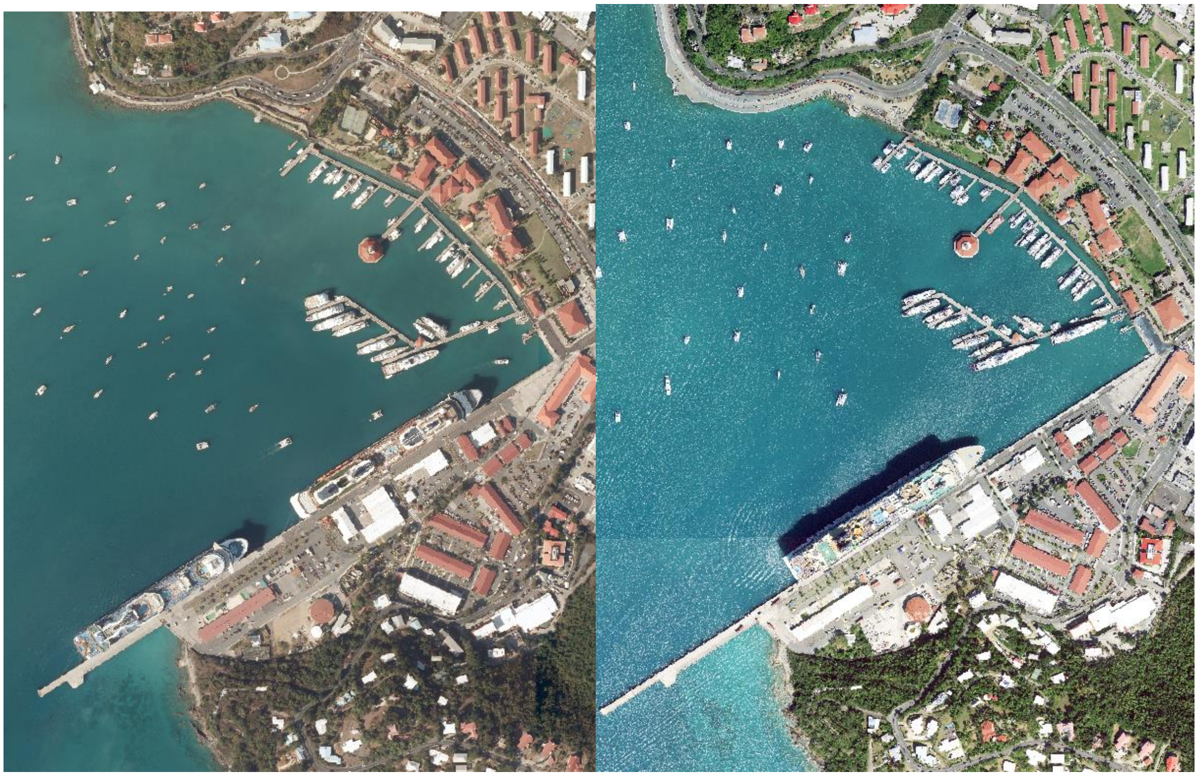


Figure 27: Long Bay Yacht Heaven Grande in 1954 (top left), 1970s (top right), 1980s (center left), 1990s (center right), 2010s (bottom left) and 2020 (bottom right).

The landfill and the racetrack were also built sometime in the 1960s, altering the wetlands in the process (Figure 28). The construction of the landfill significantly cut into the wetlands as well. The marina in the lagoon eastward was built in the 1980s, further encroaching on the mangroves through time (Figure 29).

Figure 28: Mangrove Lagoon in 1954 (top left), 1970s (top right), 1980s (bottom left), and 2020 (bottom right).

Figure 29: Mangrove Lagoon in 1954 (top left), 1990s (top right), 2010s (bottom left), and 2020 (bottom right).

The Red Hook region also saw some significant changes due to the construction of the port facilities, in the 60s and 70s, the expansion of the port area to the east with the construction of a dock in the 1980s, and the accompanying filling of part of the bay (Figure 30). In the late 2000s, early 2010s, a car ferry dock was also built on a wetland and/or beach.

Figure 30: Red Hook in 1954 (top left), 1970s (top right), 1990s (bottom left), and 2010s (bottom right).

One exception to the filling of land was the construction of the Sapphire Beach marina, which led to the opening of a lagoon to the sea in the 1960s (Figure 31).

Figure 31: Construction of Sapphire Beach marina from (left to right) 1954, 1980, and 2000

On St. John, changes are mostly limited to two major projects to improve maritime connections between the islands. The first major shoreline modification occurred in the 60s with the expansion of the Cruz Bay lagoon to accommodate more vessel traffic (Figure 32). The area continued to expand with the construction the National Park Service facilities in the 70s and 80s, and other infrastructure thereafter.

Figure 32: Crux Bay in 1954 (top left), 1980s (top right), 2000s (bottom left), and 2020s (bottom right).

Also, in the early 2000's the Car Ferry Dock was built where a sand barrier between the sea and Large Pond was opened (Figure 33). The pond was partially filled, dredged, and opened to the sea.

Figure 33: Large Pond in (from left to right) 1970s (top left), 2004, and 2020

On St. Croix, the largest change to the coastal environment was the construction of the Hovensa refinery, now known as Limetree (Figure 34). The site has seen a wide range of development over the years to better accommodate the higher volume and size of ships coming in, and gasoline being shipped out. By 1977, an additional pier was already in existence at the site to house more ships and by 1992, another was added on the edge of what was once most likely a mangrove. The site continued to be expanded until the late 2000s

Figure 34: Hovensa and Limetree Refinery construction in 1954 (top left), 1970 (top right), 1990 (bottom left), and 2020 (bottom right).

Like what was observed near the St. Thomas airport, the construction of the port infrastructure has changed the nearby coastal area. Over the years, east of the facility (Canegarden Bay), the shoreline smoothed out (Figure 35). This is probably caused by a change in coastal currents. West of the facility (Negro Bay, Manning Bay and west), the shoreline also changed (Figure 36). Mangroves in front the racetrack receded, but sediment also piled up slightly westward and a spit formed eastward. It is unclear if these changes are a result of sediment transport modifications caused by the presence of the facility, the filling of the bay using dredged material, or both. Further west, the shoreline also shows signs of erosion, but again the role of the refinery is not clear, as waves in the area also probably play a role, especially since the reef has degraded and thus plays a reduced protection role (Figure 37).

Figure 35: Canegarden Bay in 1954 and 2020.

Figure 36: Negro and Manning Bay in 1954 (top left), 1970 (top right), 1980 (center left), 1990 (center right), 2010 (bottom left), and 2020 (bottom right).

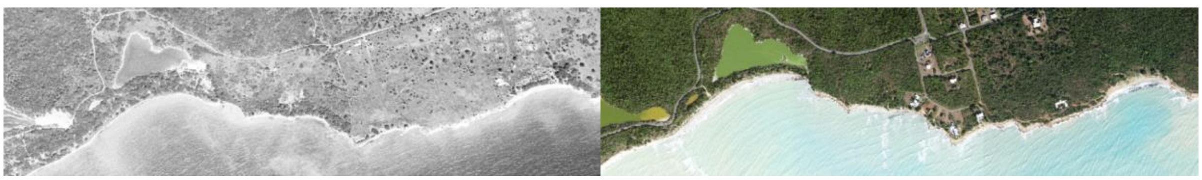


Figure 37: Shoreline near Sandy Point in 1954 and 2020.

On the north side of the island, the Salt River system changed shape through time, but it seems that this change was caused by mangrove growth and recession (Figure 38). The construction of hard infrastructure did not seem to impact the bay.

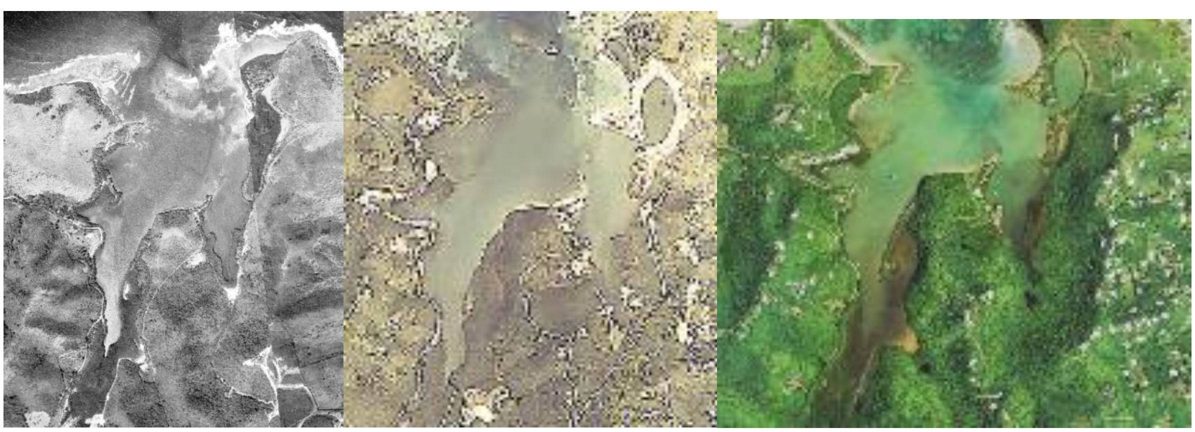


Figure 38: Salt River in 1954 (left), 1980s (center) and 2020 (right).

North of the island, the land near Christiansted was filled sometimes in the 1960s or 70s, and port facilities were built up (Figure 39). East the harbor, the port of St. Croix was built and Altona beach was filled on the lagoon side. The beach has been slowly eroding since (Figure 40).

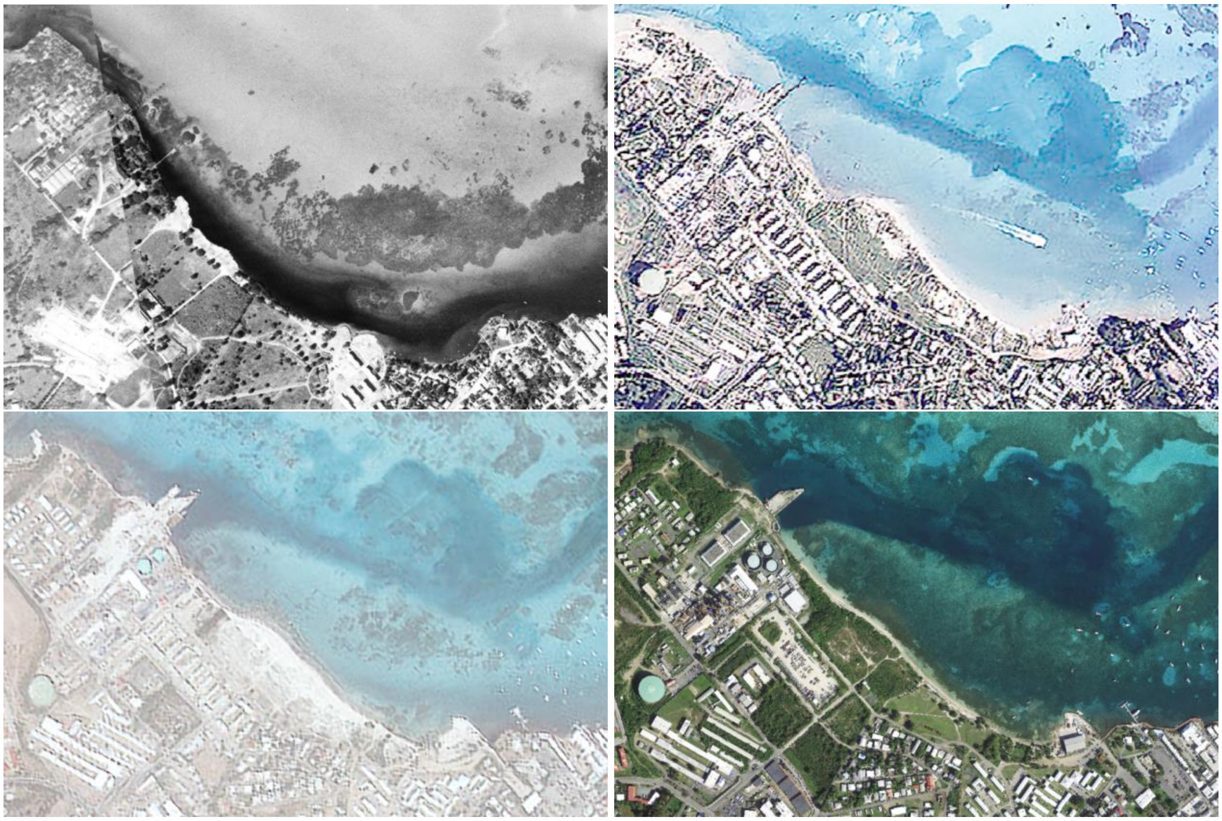


Figure 39: West side of Christiansted Harbor in 1954 (top left), 1970 (top right), 1980 (bottom left), and 2020 (bottom right).

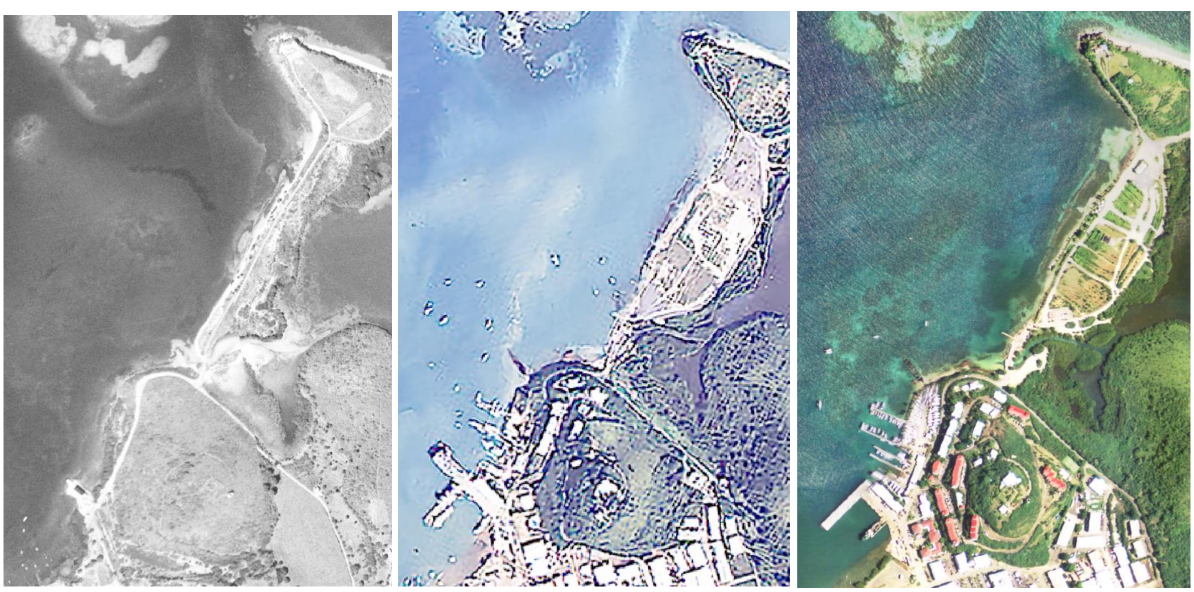


Figure 40: Port of St. Croix and Altona Lagoon in 1954 (left), 1980s (center) and 2020 (right).

3.6.2 Small Scale Change

In addition to these large scale changes, there are many small scale changes caused by structures. On St. Thomas, the construction of the riprap revetment along the airport road altered the cross-shore transport of sand to the point where sand eroded from the shoreline after the 2017 hurricanes has not come back (Figure 41).

Figure 41: Lindbergh Bay and riprap revetment protecting the road in early 2017, pre-hurricanes, and in 2020.

On Protestant Cay, a groin is altering longshore transport and help keep some of the sand from moving southward. It is unclear why this groin was created however, as its impacts seem to be limited in space (Figure 42). Further east, Green Cay Marina was built by opening a portion of a lagoon to the sea and closing a portion of it (Figure 43). The marina expanded and led to the construction of new hard infrastructure where natural systems used to be. To help maintain navigation depths, a jetty was also built, which altered the longshore sediment transport in that location. Areas west of the jetty seemed to have lost some sediment, which has been accumulating next to the jetty. Areas east of the jetty did not seem to have changed much, which indicates that most of the sediment transported longshore was probably accumulating in the lagoon.

Figure 42: Groin in Protestant Cay

Figure 43: Green Cay marina in 1970s (top left), 1970s (top right), 1990s (bottom left) and 2020 (bottom right).

On the south side of the island, in Grapetree Bay, the construction of groins in front of the Grapetree Bay Hotel and Villas seems to have altered the longshore transport of sediment. Sediment has accumulated east of the first groin (Figure 44), but the beach has eroded further west, especially in regions far from the first groin. In Figure 45, we can observe a drastic reduction of shoreline width, which caused the groins to be fully submerged. Hurricane Maria further accelerated the erosion of the coastline in that region (Figure 45).

Figure 44: Groins built in front of the Grapetree Bay Hotel and Villas do not seem to stop the (probably cross-shore) movement of sand and coastal erosion (1990 picture on the left, and 2020 on the right).

Figure 45: Groins west of the Grapetree Bay Hotel and Villas did not prevent erosion at this location (2010 on the left, 2020 on the right).

3.6.3 Shoreline Change Estimates

Outputs of the shoreline change analysis indicate that most of the beaches of the USVI are eroding at a relatively modest rate of roughly around than 0.5 m/yr (Figure 46, Table 1). On St. John, most beaches are erosive, despite its mild wave climate. Similarly, St. Thomas beaches are eroding at various rates.

St. Croix beaches also exhibit a definite eroding trend. The erosion of the beaches on the southwest shore is probably related to the construction of the refinery, which altered waves, currents, and ultimately sediment transport, as suggested by the analysis in Section 3.6.1. The beaches on the west coast of the island appears to be stable, but since the uncertainty is relatively high, more data is required to better ascertain the trend.

The nearly constant loss of sand on the various beaches of St. Croix, and the USVI in general, can have many causes. As mentioned above, shoreline construction and modification can play a role. Degradation of offshore reefs and ensuing increase in wave climate can also play a role. But the steady increase in sea-level rise cannot be neglected in the loss of shoreline footprint.

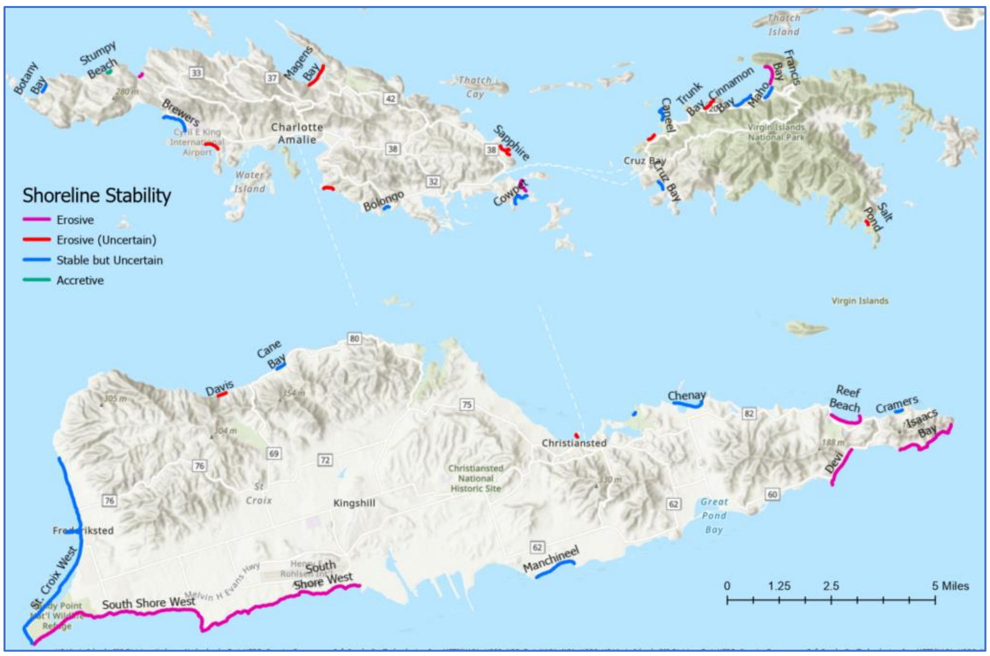


Figure 46: Estimates of stability of select beaches

Table 1: Average rates of erosion/accretion for select beaches

Island	Beach	Avg. Erosion	Error
St John	Cinnamon Bay	-0.21	N/A
St John	Maho Bay	-0.05	N/A
St John	Francis Bay	-0.35	0.19
St John	Salt Pond	-0.25	0.00
St Thomas	Ritz Club	-0.27	0.17
St Thomas	Ritz Carlton	-0.38	0.19
St Thomas	Cowpet Bay	-0.23	0.10
St Thomas	Bolongo Bay	-0.37	0.20
St Thomas	Morningstar Beach	-0.70	N/A

Island	Beach	Avg. Erosion	Error
Little Isle STX	Protestant Cay	-0.40	N/A
St Croix	South Shore West	-0.32	0.15
St Croix	Davis	-0.88	N/A
St Croix	St. Croix West	-0.14	0.23
St Croix	Manchineel	0.14	0.00
St Croix	Divi	-0.41	0.06
St Croix	Isaacs Bay	-0.48	0.08
St Croix	Cramer’s Park	-0.50	N/A
St Croix	Reef Beach	-0.39	0.09

St Thomas	Lindbergh	-0.80	N/A
St Thomas	Brewers	-0.57	0.10
St Thomas	Botany Bay	-0.22	0.09
St Thomas	Santa Maria	-1.20	0.16
St Thomas	Stumpy Beach	0.16	0.32
St Thomas	Sapphire	-0.07	N/A
St Thomas	Magen's Bay	-0.15	N/A
St Croix	Cane Bay	-0.02	0.10
St Croix	Chenay Bay	-0.22	0.16
St Croix	Mermaid	-0.09	0.43
St John	Cruz Bay	-0.20	N/A
St John	Honeymon Beach	-0.40	N/A
St John	Caneel Beach	-0.10	N/A
St John	Trunk Bay	-0.14	N/A

3.7 Coastal Vulnerability

To allocate a CVI value to different portions of the shoreline, we segmented the coastlines of the USVI into discrete points regularly spaced 500 ft apart and assigned a score from 1 (Low Vulnerability) to 5 (High Vulnerability) to each of them for each of the variable, as described in the sections above. We built the shoreline points by identifying the zero foot contour line from the 2018 DEM[21].

Results are presented in Figure 47. We find that the northern and southern shores of St. Croix are the most vulnerable in the territory. Although the region surrounding Christiansted is heavily armored, and somewhat protected by a reef, it is still susceptible to tidal and storm surge flooding. East of Christiansted, many beaches are vulnerable to coastal hazards, as well as most of the beaches on the north and south side of the island. Limetree, which is heavily armored, is less vulnerable. However, the region downstream of Limetree, especially near the racetrack, is quite vulnerable. Powerful waves, sea-level rise and the abundance of beaches and erodible bluffs, and storm surge to a lesser extent, are the key drivers of the vulnerability of St. Croix.

Figure 47: Coastal Vulnerability Indices for various portions of the USVI

St. Thomas and St. John are, overall, less vulnerable than St. Croix. But they do have highly vulnerable regions. On St. Thomas, the north shore of the island (around Hull Bay), Magen's Bay, the Red Hook region, Smith Bay, and Mangrove Lagoon to a lesser extent, are the most vulnerable regions. These results can be explained by the fact that the north shore of the island is exposed to the highest waves and has many beaches. Other regions that have low wave exposure, such as Mangrove Lagoon, are also vulnerable because of the high risk of inundation from sea-level rise and storm surge.

On St. John, the north shore of the island, home to its most prized beaches, are also the most vulnerable to coastal hazards. Coral Bay is also vulnerable, because of the tidal and storm surge inundation risks. The region south of Cruz Bay has also some vulnerable spots, which is important given the high population density and large number of hotel assets there. The reasons for this finding are similar to St. Thomas's: large waves and high inundation risk drive the vulnerability of many regions with sandy beaches.

4 Summary

This report presents estimates of the relative vulnerability of different coastal regions throughout the USVI. In the process, we developed unique databases of the characteristics of coastal environments such as the characterization of shoreline types, inventory of coastal infrastructure, estimates of coastal wave climate, and estimates of sea-level rise and storm surge inundation extent.

The island of St. Croix is more vulnerable to coastal hazards than St. Thomas or St. John. The island has the highest number of beaches and the most extreme wave climate on all coasts except its western coast. This island is experiencing relatively high levels of coastal erosion, as highlighted by some of the results we obtained on select beaches.

Although St. Thomas and St. John are overall less vulnerable, they also have very vulnerable regions, which also have an important cultural and economic role, such as Magen's Bay, the northern beaches of St. John, and Great Cruz Bay, where the Westin hotel is located. In addition, even though they do not register as the most vulnerable because of the mild wave climate, wetland regions in Mangrove Lagoon and Smith Bay on St. Thomas, Coral Bay and other regions on St. John are also quite vulnerable to the impacts of coastal hazards, especially flooding from storms and sea-level rise. And in most cases, these wetlands are blocked from migrating landward by infrastructure, which will reduce their overall footprint.

In addition, we find that the USVI Government is one of the main drivers of coastal development, mostly to improve transportation and trade sectors. However, even though few private residences have built coastal protection structures (e.g., bulkhead, groins), many are relatively close to the shoreline[**], and/or have hardened the backshore environment. This might create some issues in the future as sea level rise and storms intensify coastal erosion and landward extent of flooding. In addition, as mentioned above, we also find that critical habitats such as mangroves or beaches are under the threat of development impact. These habitats, which provide essential ecosystem services, are expected to migrate landward as sea level continues to rise, but are likely to be squeezed by roads and other infrastructure. As a result, roads and infrastructure systems might be more impacted by coastal hazards as sea level rises and they lose the protection buffer provided by these habitats.

In conclusion, the coastal systems of the USVI were shaped and transformed to meet the economic and cultural needs of the society. The coastal systems of the USVI are also dynamic and shaped by climatic

[**] The USVI Code allows a setback distance of 50 ft from mean high tide or vegetation line or rock

and environmental forces. Coastal erosion and inundation, supercharged by climate change and past coastal development, are reshaping a lot of those systems, potentially threatening infrastructure, ecological and economic systems in the long run. Future studies should focus on understanding how wetlands and beaches ecosystems will adapt to sea-level rise and other coastal hazards, how critically important economic coastal tourist destinations (e.g., beaches, hotels, etc.) are impacted by coastal hazards, and what types of adaptation strategies can allow for these systems to perform their function.

5 References

1. Hammar-Klose, E. S. & Thieler, E. R. Coastal vulnerability to sea-level rise: a preliminary database for the U.S. Atlantic, Pacific, and Gulf of Mexico coasts. Data Series https://pubs.er.usgs.gov/publication/ds68 (2001) doi:10.3133/ds68.
2. National Oceanic and Atmospheric Administration (NOAA). Environmental Sensitivity Index (ESI) Maps and Data. https://response.restoration.noaa.gov/resources/environmental-sensitivity-index-esi-maps (2000).
3. National Oceanic and Atmospheric Administration (NOAA). What is high tide flooding? https://oceanservice.noaa.gov/facts/high-tide-flooding.html.
4. National Oceanic and Atmospheric Administration (NOAA). NOAA Tides and Currents. https://tidesandcurrents.noaa.gov/ (2022).
5. National Oceanic and Atmospheric Administration (NOAA). Sea Level Trends - NOAA Tides & Currents. https://tidesandcurrents.noaa.gov/sltrends/ (2022).
6. National Oceanic and Atmospheric Administration (NOAA). Sea Level Rise Viewer. https://coast.noaa.gov/slr/#/layer/slr (2022).
7. Moore, C. & Arcas, D. Modeling tsunami inundation for hazard assessment of the U.S. Virgin Islands. (2018).
8. National Hurricane Center and Central Pacific Hurricane Center. Sea, Lake, and Overland Surges from Hurricanes (SLOSH). https://www.nhc.noaa.gov/surge/slosh.php (2022).
9. Zachry, B. C., Booth, W. J., Rhome, J. R. & Sharon, T. M. A National View of Storm Surge Risk and Inundation. Weather Clim. Soc. **7**, 109–117 (2015).
10. Dean, R. G. & Dalrymple, R. A. Coastal Processes with Engineering Applications. (Cambridge University Press, 2001). doi:10.1017/CBO9780511754500.
11. Canals Silander, M. F. & García Moreno, C. G. On the spatial distribution of the wave energy resource in Puerto Rico and the United States Virgin Islands. Renew. Energy **136**, 442–451 (2019).
12. Arkema, K. K. et al. Coastal habitats shield people and property from sea-level rise and storms. Nat. Clim. Change **3**, 913–918 (2013).
13. Luijendijk, A. et al. The State of the World’s Beaches. Sci. Rep. **8**, 6641 (2018).
14. Himmelstoss, E. A., Henderson, R. E., Kratzmann, M. G. & Farris, A. S. Digital Shoreline Analysis System (DSAS) version 5.1 user guide. Open-File Report https://pubs.er.usgs.gov/publication/ofr20211091 (2021) doi:10.3133/ofr20211091.
15. U.S. Geological Survey (USGS). Digital Shoreline Analysis System (DSAS). https://www.usgs.gov/centers/whcmsc/science/digital-shoreline-analysis-system-dsas (2022).
16. Anders, F. J. & Byrnes, M. Accuracy of shoreline change rates as determined from maps and aerial photographs. Shore Beach **59**, 17–26 (1991).
17. Crowell, M., Leatherman, S. P. & Buckley, M. K. Historical Shoreline Change: Error Analysis and Mapping Accuracy. J. Coast. Res. **7**, 839–852 (1991).
18. Thieler, E. R. & Danforth, W. W. Historical shoreline mapping (II): Application of the Digital Shoreline Mapping and Analysis Systems (DSMS/DSAS) to shoreline change mapping in Puerto Rico. J. Coast. Res. **10**, 600–620 (1994).
19. Moore, L. J. Shoreline Mapping Techniques. J. Coast. Res. **16**, 111–124 (2000).

20. Ruggerio, P. et al. National assessment of shoreline change: historical shoreline change along the Pacific Northwest coast. Open-File Report https://pubs.er.usgs.gov/publication/ofr20121007 (2013) doi:10.3133/ofr20121007.
21. Office for Coastal Management (OCM). NOAA Office for Coastal Management Coastal Inundation Digital Elevation Model: USVI from 2010-06-15 to 2010-08-15. NOAA National Centers for Environmental Information https://www.fisheries.noaa.gov/inport/item/65812 (2022).
22. Gittman, R. K. et al. Engineering away our natural defenses: an analysis of shoreline hardening in the US. Front. Ecol. Environ. **13**, 301–307 (2015).
23. Tavares, K.-D., Fletcher, C. H. & Anderson, T. R. Risk of shoreline hardening and associated beach loss peaks before mid-century: Oʻahu, Hawaiʻi. Sci. Rep. **10**, 13633 (2020).
24. Sweet, W. et al. Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html (2022).
25. Lindsey, R. Climate Change: Global Sea Level. NOAA Climate.gov http://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level (2022).
26. NASA Sea Level Change. IPCC AR6 Sea Level Projection Tool. NASA Sea Level Change Portal https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=1393 (2022).

Appendix A: Coastal Geomorphic and Structural Features

Table B-1: Description of the geomorphic and structural coastal features and their rank

Rank	Geomorphology	Type
1	Armored Shoreline	Armored Shoreline
		Boat Ramp
		Concrete Dock
		Groin
		Groin or Seawall
		Groin Riprap
		Pier Dock
		Seawall
	High, Hard Cliff	Rocky Shoreline
	Seawall	BVI Ferry dock
		Cruise ship pier
		Diageo Dock
		Dock
		Ferry Dock
		Fort Christian
		Industrial Dock
		Industrial Seawall
		Jetty Seawall
		Limetree Dock
		Limetree pier
		Mangrove Sheet pile Wall
		Marina Seawall
		Pier
		Pier for STJ Boat Ambulance
		Port and Marina Dock
		Public Dock
		Riprap Protecting Seawall
		Seaplane dock
		Seawall
		Seawall protecting property
		St. John Ferry Dock
		St. Thomas Waterfront
		STJ passenger ferry
		STX Boardwalk Seawall
		UVI Dock
		WAPA Seawall
2	Armored Shoreline	Boat Ramp
		Concrete Boat Ramp

	Medium Erodible Cliff	Rocky Shoreline
	Riprap	Airport Riprap
		Ferry Dock
		Jetty and Pier Riprap
		Jetty Riprap
		Riprap
		WAPA Riprap
3	Low Erodible Cliff, Wave Platform	Rocky Shoreline
	Riprap	Groin Riprap
		Jetty Loose Riprap
		Jetty Riprap
		Loose riprap
		Loose Riprap
		Riprap
4	Gravel or Cobble Beach	Gravel Beach
	Mangroves	Mangroves
	Riprap	Jetty Riprap
	Vegetated Shoreline	Vegetated Shoreline
5	Mangroves	Mangroves
	Sandy Beach	Sandy Beach

Appendix B: Analysis of Wave Climate Around the USVI

St. John

Analysis of the wave distribution around St. John provides more insight into its wave climate. Figure B1 shows values of wave power, wave height and direction for select location around the island (points in Red on the map, where the number next to the points are also shown in the legend of the plots).

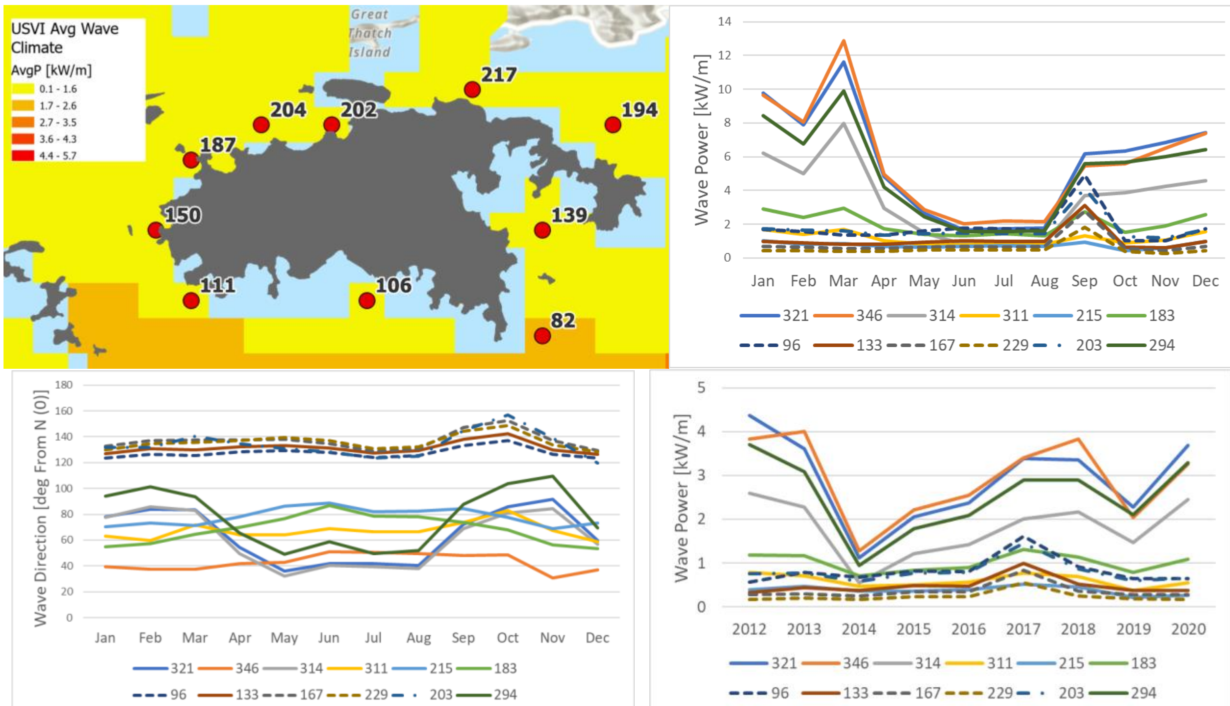


Figure B1: Wave climate around St. John and monthly averaged time series of wave power (upper right) and wave direction (lower left), and yearly averaged time series of wave power (lower right).

As discussed above, the eastern coast of St. John is sheltered by the BVI, which moderates waves coming from the east (points 194 and 217, Figure B1). The southeast coast of St. John experiences a more intense climate (Point 82), where waves come predominantly from the southeast. However, as they propagate closer to the island and water depth decreases, wave power decreases to levels like what is observed on the northern east coast (points 111, 106 and 139 have similar values as points 194, 217).

Waves on the northwest coast (points 150, 187, 204), although mild on average, exhibit a seasonal pattern. They are as powerful as waves offshore of the southern coast (point 82) during the months of September through March (Winter), and milder from April through August (Summer). Looking at the wave rose for Point 204, we find that during the winter, waves are predominantly coming from the North, and the most powerful waves come from the northwest. They are probably generated by storms in the north Atlantic propagating south. During the summer, waves on the northwest are nearly 10 times weaker, and they predominantly come from the northeast (Figure B2). The exception is Maho Bay (point 202), which does not exhibit a strong seasonality and experiences a mild wave climate. This is probably due to the presence of the headland and general orientation of the bay.

We observe a peak of wave power at all locations in September. This is due to the passage of hurricanes Irma and Maria in 2017 that generated extremely powerful waves; the relative short duration of the time series prevents the influence of this anomaly to be moderated.

Analysis of the wave power values from year to year shows that, as expected, 2017 was the most active year. On the north-west coast (points 150, 187, 204), the year 2014 was a calm one, and subsequent years seeing higher levels of energy. The northeast coast, protected by the British Virgin Islands (points 217 and 194) and Maho Bay (point 202) are well protected as they experience the same climate year to year.

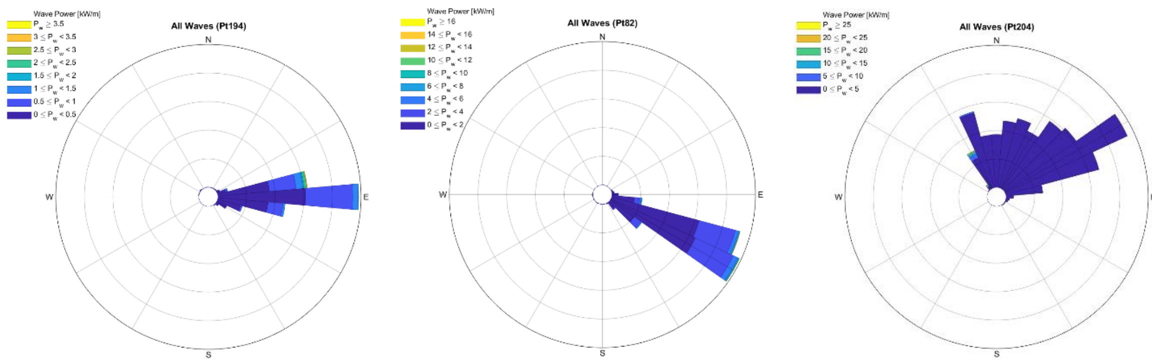


Figure B2: Wave rose for discrete points around St. John: Northeast (Pt. 194), Southeast (Pt. 82), and Northeast (Pt. 204).

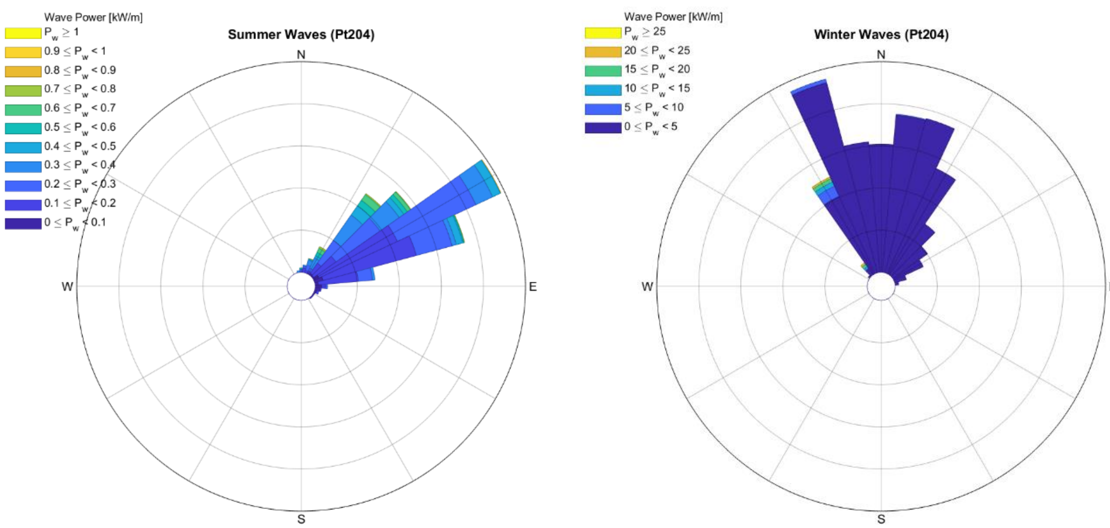


Figure B3: Summer and winter wave climate northeast of St. John.

Implications of this climate are that most beaches on St. John are not likely to experience significant cycles of erosion, except beaches on the northwest of the island. These beaches probably experience some level of erosion from September to March with longshore currents probably moving from west to east. They probably recover from April through August, with currents probably moving from east to west.

St. Thomas

The wave climate around St. Thomas is also heavily influenced by the presence of the BVI, St. John, and the North Atlantic (Figure B4). The southern coast of St. Thomas and northeast coast experience relative mild wave climate (the September peak is an expression of the 2017 hurricanes; Figure B4). Waves affecting these portions (points 215, 183, 96, 133, 167, 229 and 203) of the island come from predominantly and almost consistently from the eastern region (northeast for the northeast coast and southeast for the south coast), and exhibit little to no seasonality. The northwest coast, on the other hand, experiences the impact of powerful waves during the winter, and milder waves in the summer. However, this seasonality in power is not accompanied with a seasonality in direction, with most waves in the summer and winter coming from the northeast direction. Nevertheless, looking at the distribution of the highest waves, the most powerful waves tend to come from the north-northwest (Figure).

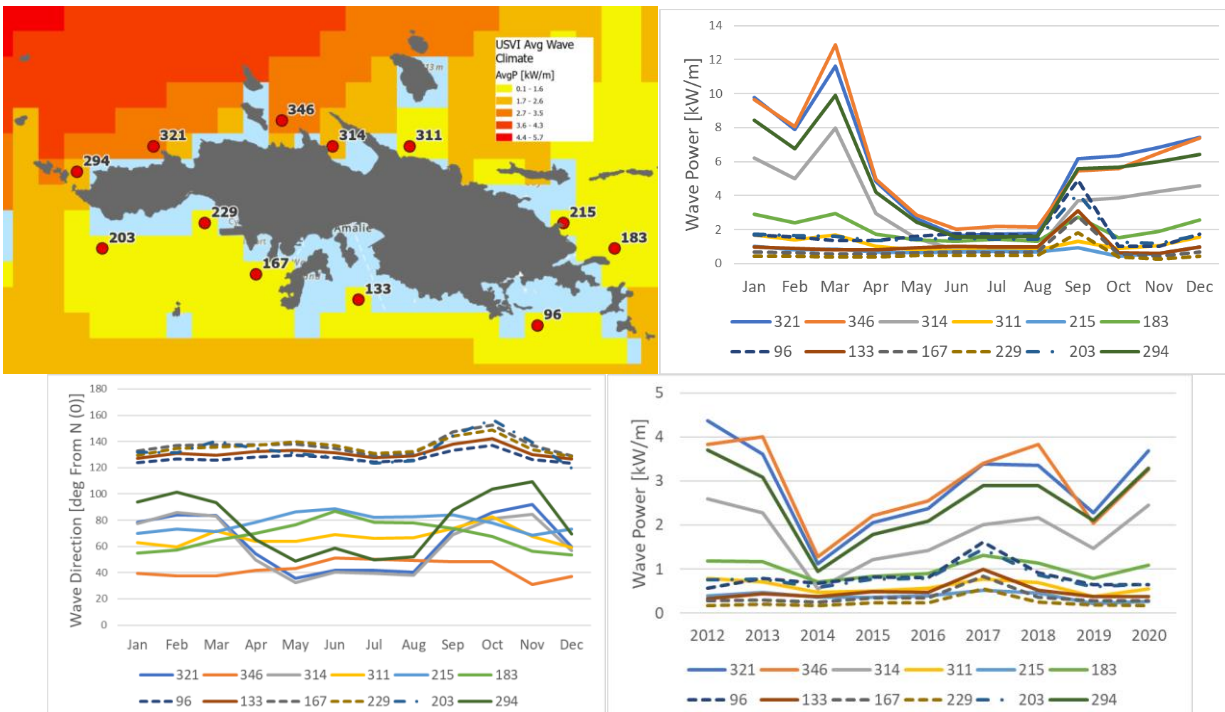


Figure B4: Wave climate around St. Thomas and monthly averaged time series of wave power (upper right) and wave direction (lower left), and yearly averaged time series of wave power (lower right).

Finally, looking at the wave statistics from year to year, like St. John, the year 2014 was an anomaly for this region, and wave power has been increasing since. The rest of the island has experienced consistent wave climate in the past 10 years (Figure B4).

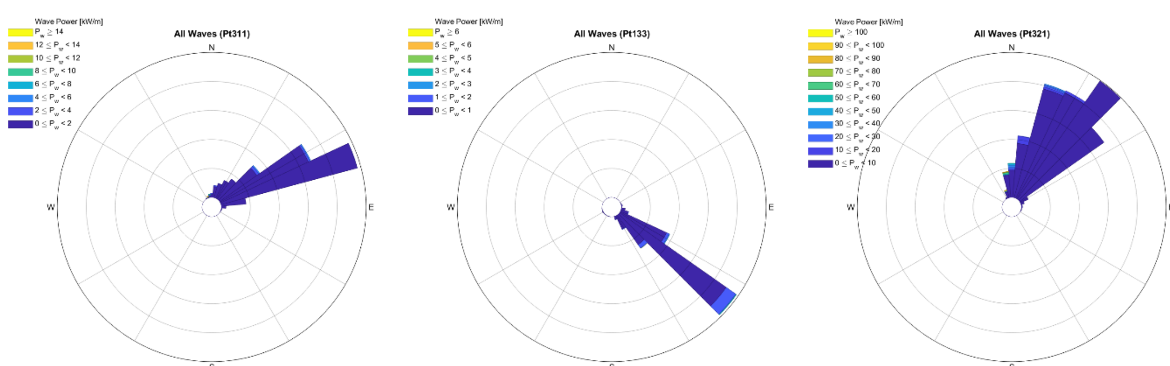


Figure B5: Wave rose for discrete points around St. Thomas: Northeast (Pt. 311), Southeast (Pt. 133), and Northeast (Pt. 321).

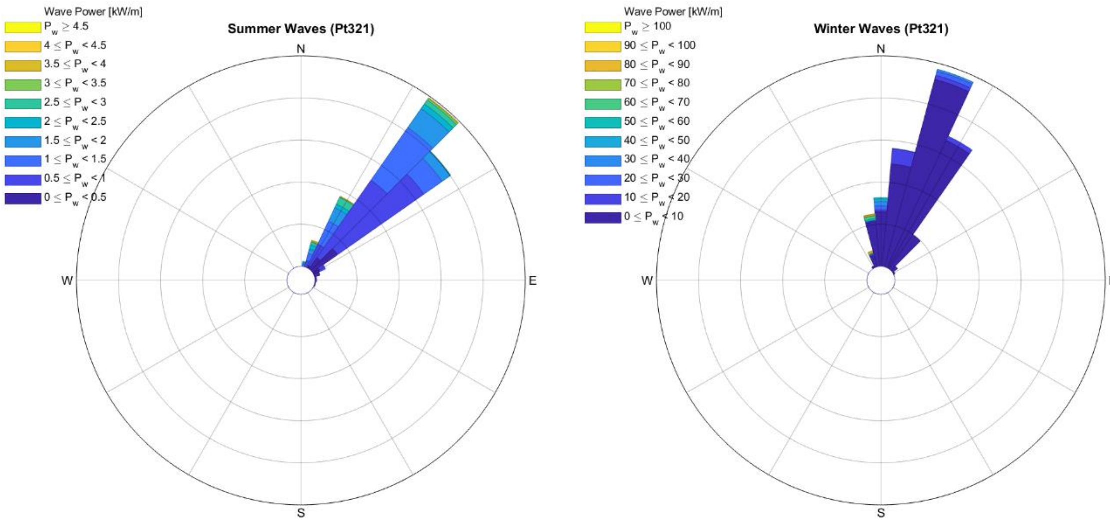
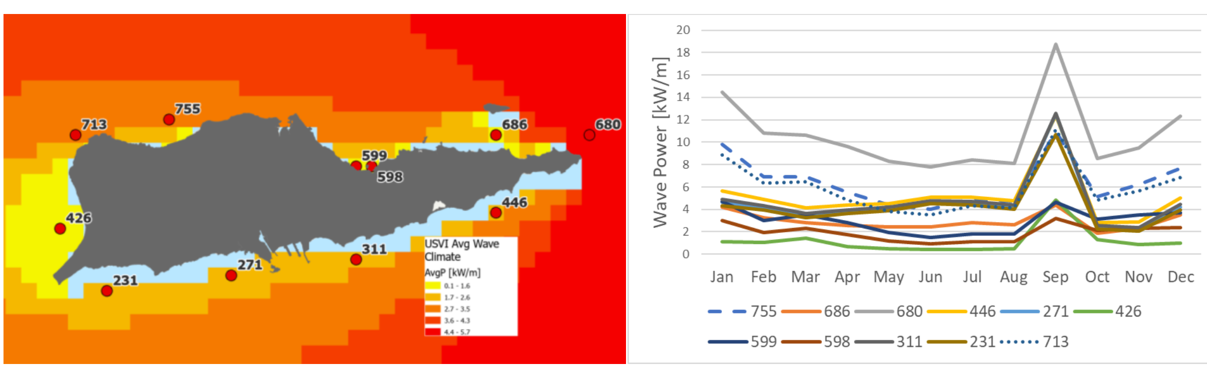


Figure B6: Summer and winter wave climate northeast of St. Thomas

Implications of this climate are that the few beaches on the northwest side of St. Thomas probably experience cycles of erosion and accretion throughout the year. The other beaches, especially south facing beaches, are likely to be more stable, or at least experience less severe cycles of erosion and accretion.

St. Croix

The wave climate around St. Croix is different from the other two islands. Waves are most energetic on the eastern side of the island (point 680, Figure B7), but they are also energetic on the northern coast and southern coasts. Only the western side of the island point (426) and the region protected by the reef offshore of Christiansted (points 598 and 599) have milder climates.



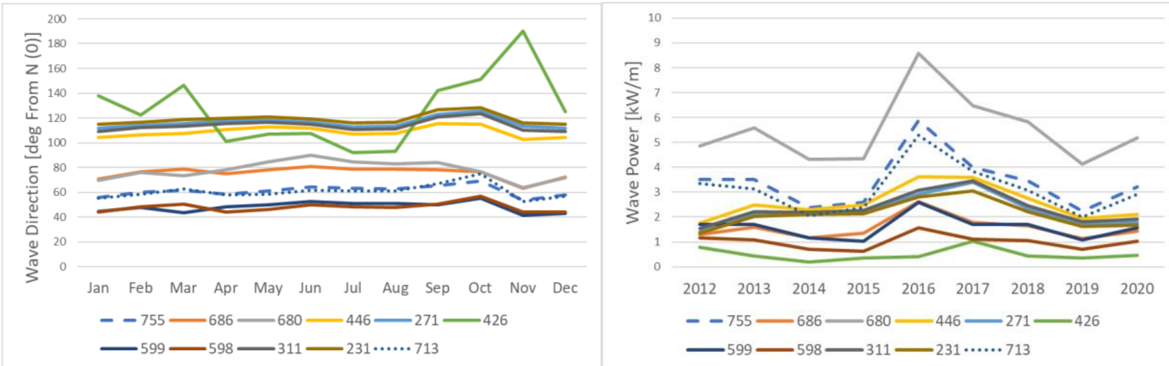


Figure B7: Wave climate around St. Croix and monthly averaged time series of wave power (upper right) and wave direction (lower left), and yearly averaged time series of wave power (lower right).

With the exception of waves on the west coast, the most intense climate occurs in the winter, with September and December/January being the most active months. Despite the seasonality in power, there is little to no directional seasonality. Waves come predominantly from the east, with some northerly directions for waves on the north coast, and southerly direction for waves on the south coast.

On the west coast, waves come from all directions. There is also, surprisingly, some seasonality in their direction. Summer waves have a south easterly direction. The more energetic winter waves come from the northeast, with the most powerful waves coming from the northwest. Powerful northwestern waves hit the north coast as well, but they merge with waves coming from the east often. Year to year, the wave climate has changed slightly, with 2016 being, surprisingly, the most intense year.

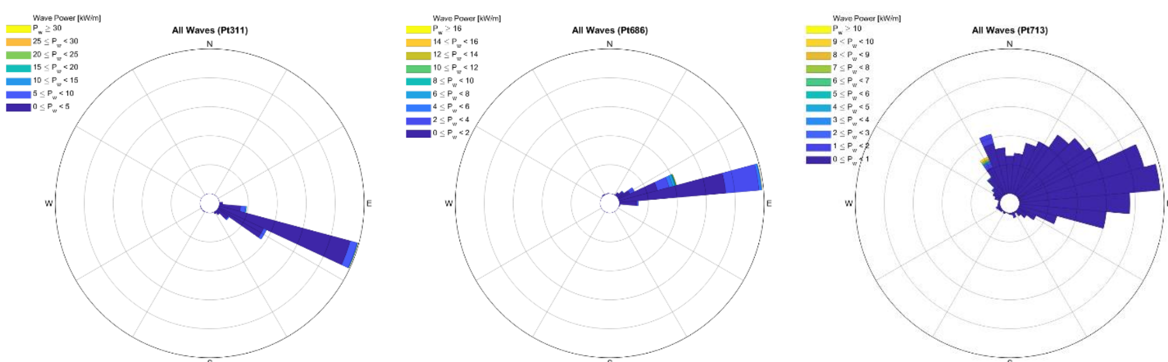


Figure B8: Wave rose for discrete points around St. Croix: Northeast (Pt. 311), Southeast (Pt. 686), and Northeast (Pt. 713)

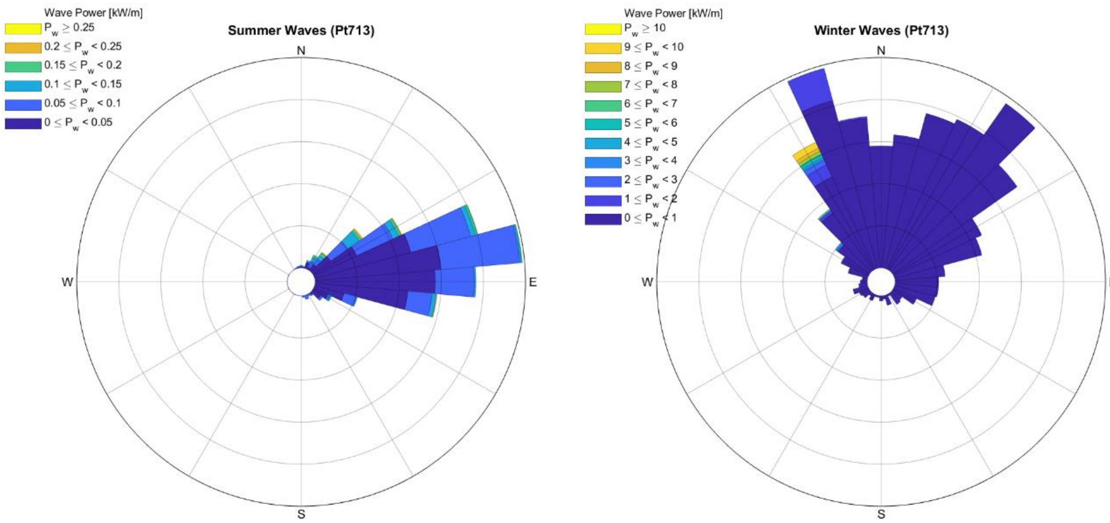


Figure B9: Summer and winter wave climate northeast of St. Croix

Implications of this climate is that most waves on St. Croix are likely to be energetic, and beaches will experience varied levels of erosion, followed by accretion, presumably. Beaches on the western side of the island are probably more protected against erosion. The easternly direction of the waves indicates that longshore currents probably move sand from east to west on both the north and south side, except when northernly large swells move sand in the other direction on the north side. West, sand is probably moving north to side, but longshore currents are likely to be mild.