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**Assessing the Sea-Level Rise Vulnerability in Coastal Communities: A Case Study in the
Tampa Bay Region, US**

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Acknowledgement

This research is supported by the University of Florida Graduate Student Fellowship.

Abstract

Sea-level rise (SLR) has drawn unprecedented attention from coastal communities around the world. In fact, many are already being affected and, in response, SLR vulnerability assessments have increasingly emerged in the US as the local communities' first attempt on the adaptation planning agenda. However, to date, little is known about these early planning endeavors in terms of how vulnerability is conceptualized and operationalized. By reviewing the current local SLR vulnerability assessments in the US, we find that most are only focusing on their biophysical exposure to SLR overlooking other important vulnerability factors including sensitivity and adaptive capacity. The limited number of SLR scenarios and the lack of consideration for extreme events are also considered as the major deficiencies. To fill these gaps, we propose a conceptual vulnerability assessment framework to operationalize the full concept of vulnerability and test it through a case study in the Tampa Bay region, Florida. By comparing the vulnerability results of the common practice with our proposed framework, we find large variances in the resulting findings stressing the importance of selecting the proper assessment approach. This paper finally concludes with planning implications and future research directions. Coastal planner and managers wanting to improve their understanding of the communities' vulnerability to SLR will benefit from this study.

Introduction

The coastline is on the frontier of natural and anthropogenic stressors (Fischer 2018). Coastal regions are especially sensitive because they are highly populated and densely developed (Hinkel et al. 2014; Neumann et al. 2015). Therefore, the impacts of natural hazards are usually the costliest in these regions (Kron 2013). Climate change and particularly sea-level rise (SLR) further increase their risk and vulnerability to the hazardous consequences (Moftakhari et al. 2017; NOAA 2016). Potential SLR impacts generally include recurrent tidal flooding and inundation, coastal erosion, saltwater intrusion and coastal ecosystem changes (Cazenave and Cozannet 2014; Nicholls and Cazenave 2010). Urban planners and coastal managers in these regions are thus facing escalating challenges to ensure the sustainability and resilience of their communities (Hurlimann et al. 2014; Jabareen 2013). In response, adaptation has been advocated as the primary strategy to cope with the rising sea (IPCC 2014; Nicholls and Cazenave 2010). Although adaptations are usually highly costly, they are sound investments over the long term (Hinkel et al. 2014; Reguero et al. 2018). Nevertheless, proactive adaptation requires forward thinking and early investments in an issue that is less urgent as compared to other competing planning agendas. Consequently, the progress of translating adaptations into actions is commonly found to be delayed (Berrang-Ford et al. 2011; Bierbaum et al. 2013; Measham et al. 2011). Despite the lack of action, many US communities have started to invest in adaptation planning for climate change (Fu et al. 2017; Woodruff and Stults 2016) and such planning endeavors in the coastal regions often focus exclusively on the impacts of SLR owing to their concerns about the increasing risk to inundation, coastal erosion and storm surge (Stults and Woodruff 2017; Sweet and Park 2014).

The SLR vulnerability assessments have proliferated as the starting act for adaptation planning by coastal communities in the US. As a concept, vulnerability is highly contextual and fuzzy due to its various applications by multiple disciplines, and so is its assessments (Füssel 2007a). In the climate-change domain, vulnerability is generally defined as a function of the system's exposure, sensitivity and adaptive capacity to external stressors such as SLR (Adger 2006; IPCC 2014; Smit and Wandel 2006). How vulnerability is conceptualized has great potential in affecting how vulnerability assessments will be undertaken. Although much

1 research has tried to operationalize this contested concept at different spatial scales (Tonmoy
2 and El-Zein 2018; Weis et al. 2016), to date, we have little empirical knowledge of how
3 vulnerability has been considered and measured by the coastal communities in practice as
4 well as how the outcomes of these vulnerability studies are and will be used by decision-
5 makers to inform adaptation planning.

6 In addition, the lack of certainties in the SLR projections is also a principal barrier
7 facing coastal communities wanting to invest in adaptations (Hallegatte 2009; Stults and
8 Larsen 2018). The proliferation of SLR projections and their uncertainties are likely to confuse
9 coastal planners and policymakers. Also, the global, regional and local SLR projections vary
10 significantly from each other adding additional layers of complexity (Nicholls et al. 2008;
11 Stammer et al. 2013). Because the SLR scenarios can directly affect the vulnerability
12 assessments and their resulting findings, selecting the proper scenarios is critically important
13 yet highly challenging. It has now become a common practice to choose one or several integer
14 SLR scenarios for vulnerability assessments (e.g., Heberger et al. 2011 and Cooper et al. 2013),
15 while it ignores the fact that SLR is a continuous and non-linear process (Zhang 2011; Fu and
16 Song. 2017). Additionally, mean higher high water (MHHW) levels have also been commonly
17 used as the tidal event for SLR studies (Sweet and Park 2014). However, because what have
18 caused the most significant impacts and triggered adaptation actions are usually extreme
19 events (e.g. Hurricane Sandy in New York, Rosenzweig and Solecki 2014), the sufficiency of
20 employing the MHHW alone while failing to account for the less frequent extreme events for
21 SLR vulnerability assessments is debatable.

22 In summary, the vulnerability findings are highly sensitive to the selection of SLR
23 scenarios, conceptualization of vulnerability and assessment methods. To date, little is known
24 about the existing vulnerability assessments calling for research to identify needs for
25 challenges and opportunities for improvements. To address this gap, this paper addresses the
26 following specific questions: (1) How has the vulnerability to SLR induced coastal flooding
27 been assessed by coastal communities in the US? (2) How should vulnerability to SLR induced
28 coastal flooding be locally conceptualized and assessed? (3) To what extent will different
29 assessment approaches affect the resulting findings?

Background

To answer these questions, this paper first collected the local SLR vulnerability assessments in the US and investigated how they assessed their vulnerability. This background study helped identify the gaps in the existing assessments studies. The sample was primarily collected by searching online using keywords (i.e. search for “jurisdiction name” + “sea level rise vulnerability assessment” in Google). The Georgetown Climate Center (<http://www.georgetownclimate.org/>) and the Climate Central (<http://sealevel.climatecentral.org/>) were also later used to complement the initial sample collection. Given that the focus of this research at the local levels, only the assessments from the local communities including counties, cities, and towns were collected. In total, 51 local SLR vulnerability assessments in the US were sampled (see Appendix A for the full sample list). Most of the studies (40 out of 51, 80%) are stand-alone SLR vulnerability assessments and the rest are climate-change adaptation plans with integrated assessments for SLR. These sampled documents were analyzed in two steps. First, we investigated how they chose SLR scenarios. Specifically, we examined whether they adopted local SLR projections, considered uncertainties by including a series of plausible scenarios, and included extreme events in their assessments. Second, we studied how the vulnerability was locally conceptualized and assessed. To this end, we investigated how the vulnerability was defined in these local assessments and what methods they employed to assess their vulnerability.

According to the analysis, most of the coastal communities (73%) adopted local SLR scenarios. They were primarily from two sources: (1) US Army Corps of Engineers Sea Level Change Calculator (USACE 2013) and (2) National Research Council’s report on SLR along the coasts of California, Oregon, and Washington (NRC 2012). There was still over a quarter of the sample (27%) that employed global or regional SLR projections (e.g. IPCC 2013; Parris et al. 2012). Two-thirds of the communities (65%) considered extreme events such as the 100-year return flooding and storm surge events when assessing their vulnerability to future SLR. Although many (65%) considered multiple scenarios, none of them analyzed these scenarios from the standpoint of probabilities. Given the large uncertainties, a probability distribution of the possible SLR projections could offer local communities the flexibility to assess and

1 manage their vulnerability at a tangible risk level (Buchanan et al. 2016). In addition, existing
2 assessments usually selected several fixed scenarios that failed to consider the nonlinearity of
3 SLR and its impacts. By analyzing the gradual, non-linear impacts of future SLR, coastal
4 communities could advance their local knowledge of future potential thresholds (Zhang 2011).
5 Such thresholds could also serve as the critical tipping-points that helps identify adaptation
6 timeframes and guide policy making (Kwadijk et al. 2010; Sweet and Park 2014).

7 Although vulnerability in the climate-change domain is commonly defined as a
8 function of a system's exposure, sensitivity and adaptive capacity (Adger 2006; Füssel and
9 Klein 2006; Ofori et al. 2017), only 15 assessments (29%) adopted this definition. Therefore, it
10 was not surprising to find that almost all the assessments only analyzed their biophysical
11 exposure to SLR while only 17 (33%) and 15 (29%) considered their sensitivity and adaptive
12 capacity respectively. Failing to consider all the important vulnerability factors would lead to
13 biased results and findings that affect the rigor and quality of the assessments. When
14 assessing the local sensitivity and adaptive capacity to SLR, the adopted approach varied
15 significantly, and the assessment results were mostly qualitative. It can be explained, in part,
16 by the lack of resources and expertise to conduct quantitative studies at this nascent stage of
17 adaptation planning (Hayes et al. 2018). For the SLR impact analytical methods, the 'bathtub'
18 model was the most commonly adopted approach (84%) to analyze the potential flooding
19 areas. It should also be noted that five California communities employed a more sophisticated
20 method developed by the US Geological Survey (USGS), the Coastal Storm Modeling System
21 for Southern California (CoSMoS 3.0), to simulate the potential coastal flooding that accounts
22 for the integrated impacts of SLR, storms, and coastal evolution. This exemplifies the
23 importance for local communities to work collaboratively with other agencies to expand their
24 capacities for adaptation planning.

25 **Methodology**

26 To address the gaps found in the existing practice, this paper proposed a conceptual
27 vulnerability assessment framework and conducted a case study area in Florida. In the end,
28 we compared the resulting vulnerability finding to test its sensitivity to the different
29 assessment approaches.

1 Case Study Area

2 The Tampa Bay (i.e. Tampa-St Petersburg Metropolitan Area, Figure 1) in Florida was
3 chosen as the case area for numerous reasons. In general, Florida coastlines are highly
4 vulnerable to SLR due to its long shorelines, low plain elevation, and highly concentrated
5 population and development on its coastline (Hauer et al. 2016). This is especially true for the
6 Tampa Bay region. The City of Tampa is considered one of the top ten cities with the highest
7 asset value exposed to coastal flooding (Nicholls et al. 2008). The region is also the second
8 largest metropolitan area in Florida, accommodating a total population of 2.9 million
9 (according to the US Census in 2014). Lastly, the tidal station (St Petersburg, Tampa Bay FL
10 8726520) has a continuous record of over 50 years' hourly water levels which satisfy the data
11 needs to model local tidal events (Tebaldi et al. 2012).

12 FIGURE 1 ABOUT HERE

13 Developing a Vulnerability Assessment Conceptual Framework

14 The main goal of this paper was to develop a vulnerability assessment framework that
15 can be transferable and easily applied by coastal communities. Specifically, a wide range of
16 localized SLR scenarios was developed by coupling local projections and extreme events into
17 a probability matrix (see Appendix B). To account for the non-linearity impacts of SLR, all the
18 local SLR scenarios were modeled and analyzed. Because vulnerability can be analyzed at
19 different scales serving varying purposes, it is preferred to undertake analysis at a finer spatial
20 scale for local studies when data is available. Hence, this paper focused on the parcel-level
21 properties data, the finest spatial data available usually used by the local planning and tax
22 appraisal departments for land-use, zoning and tax purposes, to assess the communities'
23 physical exposure and sensitivity to SLR. However, socioeconomic data was not readily
24 available at the parcel level and we thus used census tracts as the spatial scale to assess local
25 adaptive capacity. Please refer to Figure 2 for an example illustration of the spatial relationship
26 between the census-tract and parcel-level data. To generate an integrated index that
27 considered the full conceptualization of vulnerability, the parcel-level exposure and sensitivity
28 results were later aggregated to the census tracts by summing the results from parcel-level
29 analysis within each census tract to enable combining them with the results from the adaptive

1 capacity analysis. Lastly, we compared how different assessment approaches would generate
2 the vulnerability findings. The overarching framework is illustrated in Figure 3. The following
3 elaborates our proposed framework in terms of how local scenarios was generated and how
4 local vulnerability to SLR was operationalized.

5 FIGURE 2 ABOUT HERE

6 FIGURE 3 ABOUT HERE

7 Local SLR Scenarios

8 The SLR scenarios in this study consist of two parts. They are (1) the stationary local
9 SLR projections (i.e. sea-level baseline) and (2) the tidal variations including the extreme
10 events. To situate our SLR scenarios in a risk-management approach, we coupled the localized
11 SLR scenarios developed by Kopp et al. (2014) with the extreme value analysis (EVA) calibrated
12 by using the data from the local tide gauge. They both can provide localized probability
13 distribution functions (PDFs) that enable coastal communities to derive the local SLR scenarios
14 considering SLR and extreme events simultaneously.

15 The local SLR PDFs under different major future representative concentration
16 pathways (RCPs) were considered in building the SLR scenario matrix but only the RCP 8.5 was
17 later used for the vulnerability assessments. In practice, the choice of SLR scenarios should
18 depend on numerous factors such as the time scale of analysis, the system of concern and its
19 risk tolerance. The reasons for choosing RCP 8.5 for this research were twofold. First, since we
20 were not targeting a specific system for analysis, we chose the RCP 8.5 primarily for
21 presentation as it was generally considered to be the baseline scenario (i.e. “business as usual”
22 model) used for policy analysis (Riahi et al. 2011). Second, the risk matrix for the RCP 8.5 in
23 this study covered a full range of potential SLR projections containing the other RCP matrices.
24 As this study analyzed all the possible SLR scenarios to account for its nonlinear impacts,
25 selecting the RCP 8.5, therefore, provided an exhaustive analysis.

26 FIGURE 4 ABOUT HERE

27 Besides the SLR projections, local astronomical tides are constantly changing. Existing
28 assessments usually assume a stationary mean sea level (e.g. MHHW) which is biasedly low
29 (Buchanan et al. 2016). Since the disastrous impacts are usually occurring during extreme

1 events, considering the low-probability yet potential extreme events are becoming
 2 increasingly necessary. Thus, we employed the EVA approach in Buchanan et al. (2016) to
 3 assess local flood return levels by analyzing 52 years of hourly water level data (from January
 4 01, 1965 to March 31, 2017) from the local tide gauge (St. Petersburg/Tampa Bay Station).
 5 Prior to the EVA analysis, the hourly tide-level data was de-cluttered by at least one day apart
 6 to avoid overestimation from double-counting the extreme events. In addition, SLR was also
 7 linearly detrended so that it could capture the distribution of exceedances influenced by
 8 decadal sea-level variability, day-to-day weather conditions, seasonal cycles, and other
 9 extreme events like storm surges (Figure 4). The historic extreme water value distribution was
 10 finally estimated by using the generalized Pareto distribution (GPD) and peak-over-threshold
 11 (POT) approach:

$$P(z - \mu > y | z > \mu) = \begin{cases} \left(1 + \frac{\xi y}{\sigma}\right)^{-\frac{1}{\xi}} & \text{for } \xi \neq 0 \\ \exp\left(-\frac{y}{\sigma}\right) & \text{for } \xi = 0 \end{cases} \quad (1)$$

12 Where z is the expected tidal level and μ is the tidal-level threshold above which
 13 exceedances are estimated. ξ and σ are respectively the shape and scale parameters. The
 14 threshold for estimating the GPD is set to the 99th percentile of the daily maximum water
 15 levels because it has been tested to give reasonable results according to Tebaldi et al. (2012).
 16 By assuming the probability of $z > \mu$ is Poisson-distributed with mean ε , the expected
 17 number of annual exceedances of tidal level z is:

$$N(z) = \begin{cases} \varepsilon \left(1 + \frac{\xi(z - \mu)}{\sigma}\right)^{-\frac{1}{\xi}} & \text{for } \xi \neq 0 \\ \varepsilon \exp\left(-\frac{y}{\sigma}\right) & \text{for } \xi = 0 \end{cases} \quad (2)$$

19 We assumed the extreme tidal events ($z > \mu$) a Poisson distribution because they
 20 were commonly considered as the discrete probability events occurring within a fixed
 21 temporal interval. After we estimated the PDFs of the extreme water levels, we derived the
 22 flood depth for any extreme events given their probability of occurrences. By combining the
 23 computed water height with the local SLR projections, the local SLR risk matrices were finally
 24 generated (Appendix B).

1 Assessing Exposure and Sensitivity

2 Exposure and sensitivity usually go hand in hand to determine the actual physical
3 impacts (Smit and Wandel 2006). Nevertheless, many current vulnerability assessments failed
4 to consider to what extent their system(s) of concerns would be affected by the hazardous
5 conditions, usually referred to as the sensitivity (Turner et al. 2003). In this paper, local
6 exposure to SLR is defined as the potential of local properties to be flooded by future SLR,
7 while the sensitivity is defined to be the extent of potential losses to the properties due to
8 SLR-induced flooding. To this end, both exposure and sensitivity represent the local physical
9 vulnerability to SLR and they are quantified by potential monetary losses. In a nutshell, the
10 exposure analysis computed the total monetary losses of all the exposed properties, whereas
11 the sensitivity analysis accounted for the sensitivity of different types of properties and the
12 respective flooding depth under various SLR scenarios to calculate the “real” potential losses.

13 For the exposure analysis, there are several SLR models and they all have strengths
14 and weaknesses satisfying distinct management objectives (Mcleod et al. 2010). This paper
15 chose the ‘bathtub’ model because it was widely adopted and recognized by the coastal
16 communities as well as key governmental agencies (e.g. NOAA) to simulate the impacts of SLR.
17 In addition, the simplicity of the ‘bathtub’ model and the availability of high-quality digital
18 elevation model (DEM) both eased the modeling endeavors to analyze multiple SLR scenarios.
19 The 5-m DEM of the study area was retrieved from NOAA (Sea Level Rise Viewer:
20 <https://coast.noaa.gov/slr/>). The local SLR scenarios calculated in the previous section were
21 later used to produce the SLR exposure maps. Local parcel data in 2016 with property assessed
22 valuation information was collected from the Hillsborough and Pinellas County GIS data
23 services for monetary reference. To account for the non-linear impacts of SLR, 41 SLR
24 inundation maps were generated based on the SLR risk matrix of RCP 8.5 ranging from 0.9 to
25 4.9 m by 0.1 increments (see Appendix B). These exposure maps were then overlaid with the
26 local parcel data to identify properties that would be potentially flooded under the respective
27 SLR scenarios. Specifically, the properties with their geometric centroid points inside the SLR
28 exposure areas were assumed inundated.

1 To determine the sensitivity of the structures to potential hazards, information such
2 as the building materials and floor elevation are critically important yet not readily available.
3 Thus, the depth-damage function (DDF) developed by USACE was employed to calculate the
4 potential flooding damages due to future SLR (Scawthorn et al. 2006a, b; USACE 2006). The
5 DDF offers damage estimation curves for various types of buildings based on previous
6 empirical flooding studies. The DDFs for various building types enabled the calculations of the
7 potential damages for each parcel by incorporating the assessed property value, the
8 respective building types (i.e. based on the use of parcel), and the flooding depth from the
9 SLR 'bathtub' models.

10 Assessing Adaptive Capacity

11 Unlike the exposure and sensitivity analysis, the adaptive capacity analysis is focusing
12 on the socioeconomic perspective of the vulnerability. How to measure adaptive capacity
13 remains heatedly debated because the term is as fuzzy as vulnerability and is also closely
14 related to a diverse community of concepts such as adaptability, robustness, coping capacity,
15 flexibility, and resilience (Engle 2011; Füssel and Klein 2006; Smit and Wandel 2006; Tompkins
16 and Adger 2004). This paper adopted the widely accepted definition of adaptive capacity as
17 'the ability of systems to adjust to potential damages' (IPCC 2014). To measure it, we
18 employed the concept of social vulnerability index (i.e. SoVI) developed by Cutter and
19 colleagues (2003) as a proxy. There are several reasons for using this proxy. First, the SoVI was
20 initially developed in the hazard mitigation domain to describe a group of the population
21 lacking coping capacity and, thus, considered to be, namely, socially vulnerable (Cutter et al.
22 2003). This concept measuring the existing inability to cope with the hazards can also be
23 translated into the long-term lack of adaptive capacity because the population or
24 communities that are presently unable to cope with the natural hazards are considered to be
25 lacking the capability to adapt in the future without external interference (e.g. governmental
26 assistance). In addition, many of the socioeconomic variables in compositing the SoVI such as
27 income, race, and gender are also considered to be key predictors of adaptive capacity (Smit
28 and Wandel 2006). This paper directly used the SoVI data retrieved from the SoVI module in

1 the NOAA Sea Level Rise Viewer and please refer to Cutter and Emrich (2017) for the
2 methodology and limitations of computing the SoVI.

3 Comparing Vulnerability Findings

4 In general, the vulnerability findings are probably the most important information in
5 these assessments. Hence, how different SLR scenarios and conceptual approaches affect
6 their findings is of great concern to decision-makers. To answer this, we compared the findings
7 from different assessment approaches over a wide range of SLR scenarios in the case study
8 area. Specifically, we first compared the exposure-only (EO) approach with the coupled
9 exposure-and-sensitivity (ES) approach in terms of to what extent the EO affected the
10 vulnerability findings as compared to the ES. When comparing the vulnerability findings, we
11 used the ranking fitness as the primary indicator because to identify the most vulnerable area
12 is usually one of the essential information local communities employ to inform adaptation
13 decisions. As an indicator, the ranking fitness is to compare the ranking lists from the two
14 assessment approaches (i.e. EO and ES) to calculate the percentage of convergence between
15 the two rankings. Thus, a higher rate of the ranking fitness indicates the vulnerability results
16 between the two approaches are similar and vice versa.

17 We then compared the proposed approach (i.e. assessing the full conceptualization
18 of vulnerability by considering exposure, sensitivity, and adaptive capacity, ESA thereafter)
19 with the two other approaches (i.e. EO and ES). To compute the vulnerability index for the
20 ESA, we needed to integrate the indexes of adaptive capacity, exposure, and sensitivity. One
21 could simply calculate the sum of these indexes, but such a method might result in losing
22 important information from each of the indexes. Additionally, because of their different
23 mathematical scales, simply adding them together would make interpretation even more
24 challenging. Thus, we employed the method of standard deviation from mean to categorize
25 these different indexes into the same categorical scales. The final vulnerability ranking was
26 computed by cross-ranking the physical impact index (i.e. exposure and sensitivity) and social
27 vulnerability (i.e. adaptive capacity) based on 9 categories: low, medium, and high for both
28 physical and social vulnerability (Figure 7). It should also be noted that we assigned equal
29 weights to the physical impact index and social adaptive capacity so that HM (i.e. high physical

1 impact and medium social vulnerability) and MH (i.e. medium physical Impact and high social
2 vulnerability) categories were considered equally important for comparison. As a result, the
3 ranking list of top 15, for example, might have list elements more than 15.

4 Research Limitations

5 This research has several limitations that should be noted before interpreting the
6 results and findings. First, it only considered the coastal flooding impact due to SLR, while
7 other impacts of SLR such as coastal erosion, saltwater intrusion, and ecosystem change were
8 not studied. Since SLR could cause various adverse consequences, ideally, a sound
9 vulnerability assessment should examine all the potential impacts. However, at this early
10 stage, coastal communities are generally incapable of conducting such a holistic assessment
11 due to technical and financial constraints (Hayes et al. 2018; Measham et al. 2011). Similarly,
12 assessing the local vulnerability to numerous SLR impacts requires expertise and efforts that
13 go beyond what a single paper can achieve. Thus, like most local vulnerability assessments
14 and scholarly research on this topic, this paper was also primarily focusing on the impact of
15 coastal flooding due to SLR.

16 Additionally, this research combined SLR scenarios linearly with the tidal heights for
17 the vulnerability assessments. Sea levels will not rise linearly and with SLR local tidal trends
18 may also change its distribution. Although we have limited knowledge on how the distribution
19 of local tidal levels will react to SLR, with advancing knowledge regarding this issue in the
20 future it should be considered. In addition, it simply focused on the flood height due to SLR
21 while other important hydraulic factors (e.g. coastal erosion) were not considered.

22 Finally, the 'bathtub' model used in this study added additional layers of modeling
23 uncertainties and errors (Mcleod et al. 2010; Poulter and Halpin 2008). Also, this research
24 used proxies to estimate the sensitivity and adaptive capacity for the full vulnerability
25 assessment, while they could not fully truly reflect the local sensitivity and adaptive capacity.
26 Thus, the results should be interpreted carefully by understanding what these proxies entail
27 and what their limitations are. All the assessments in this study were present what-if analyses
28 considering future potential SLR scenarios. Future changes in urbanization and socioeconomic

1 status were not considered though they would dynamically affect the communities'
2 vulnerability to SLR (Fawcett et al. 2017).

3 **Result and Finding**

4 Figure 5 illustrates the potential flooding areas due to the combined impacts of future
5 SLR (99% confidence) and various flooding events in 2030, 2050 and 2100. Figure 6 illustrates
6 the potential economic losses from SLR inundation aggregated from the parcel-level analysis
7 to the census tracts under all the scenarios for Hillsborough and Pinellas County. Due to a
8 large number of census tracts in each county, it should be noted that the x-axis does not
9 display an exhaustive list of all the census tracts. Owing to the heterogeneous topography and
10 spatially uneven development, potential economic losses are not homogenously distributed
11 in the various tract areas in either of the counties.

12 FIGURE 5 ABOUT HERE

13 FIGURE 6 ABOUT HERE

14 By comparing the findings from between the EO and ES analysis, Figure 7 shows the
15 extent of the overestimation for both counties. The absolute potential losses reach their
16 maximum under the 3.9-m SLR scenario (Figure 7.a). Compared to the ES, the EO analysis
17 overestimates the monetary losses by up to 15.3 and 33.0 billion dollars for Hillsborough and
18 Pinellas County respectively. On average, the EO approach overstates the losses by 9.3 billion
19 dollars for Hillsborough County and 23.3 for Pinellas County. Also, the simplistic EO approach
20 averagely overestimates the potential economic losses by 4 times (up to 6.1 times at 1.6-m
21 SLR) and 5 times (up to 7.3 times at 1.7-m SLR) for the Hillsborough and Pinellas County
22 respectively (Figure 7.b).

23 FIGURE 7 ABOUT HERE

24 Besides overestimating the potential losses, the largest concern of the simplistic EO
25 approach is whether it affects the identification of the most vulnerable areas. Thus, we ranked
26 the potential losses for all the census tracts of each county and then compared them under
27 each SLR scenario. Specifically, we compared the rank fitness for the lists of the top 3, 5, 10,
28 15 and 20 for both counties. On average, the ranking fitness is 85% for Hillsborough County
29 and 79% for Pinellas County (Table 1). The mismatches also vary over the chosen rank number

1 and the SLR scenarios. In other words, depending on how coastal communities choose to rank
2 their vulnerable areas, the resulting findings from the two approaches will differ at least
3 moderately as tested in this study.

4 TABLE 1 ABOUT HERE

5 Lastly, we compared our proposed ESA approach to the two other approaches. For
6 presentation purposes, we only chose three representative SLR scenarios to illustrate the
7 variances in resulting findings. They were the scenarios of the 99-percent confidence SLR and
8 100-year flooding return event in 2030, 2050 and 2100 (Figure 8). As Table 2 demonstrates,
9 the ranking fitness between the ESA approach and two other approaches is considerably low.
10 On average, the convergence between the ESA and EO approach is 23% and 10% for
11 Hillsborough and Pinellas county respectively in 2030. Despite the small variations among the
12 different SLR scenarios, it generally implies that the commonly adopted EO approach will
13 generate considerable varying vulnerability findings as compared to the preferable ESA
14 approach that considers the full conceptualization of vulnerability.

15 FIGURE 8 ABOUT HERE

16 TABLE 2 ABOUT HERE

17 **Discussion and Conclusion**

18 The proliferation of vulnerability assessments reflects the coastal communities'
19 growing concerns about SLR in the US. It also indicates a significant step forward in the
20 practice of local adaptation planning, but these "early birds" only represent a limited number
21 of the entire coastal communities in the US that are and will be potentially vulnerable to SLR.
22 Meanwhile, it also raises questions about the quality and rigor of these recently emerged
23 assessments. Two common shortcomings have been identified from our preliminary analysis
24 of the 51 sampled local SLR vulnerability assessments. One is related to the selection of SLR
25 scenarios and the other is on how the local communities conceptualize and operationalize
26 vulnerability. It is thus evident that there are still critical gaps in conducting vulnerability
27 assessments at the community level. In addition, these are the central elements of
28 vulnerability assessments that can significantly alter the resulting findings concerning local
29 decision-makers. In fact, by comparing the empirical method (i.e. focusing on biophysical

1 exposure only) commonly adopted by the coastal communities with our proposed conceptual
2 framework based on the climate-change vulnerability theories through a case study, we find
3 that the resulting vulnerability findings greatly vary. To generalize what our findings mean,
4 the following summarizes several key implications as well as future research pathways.

5 First, selecting the proper SLR scenarios remains a great challenge to local
6 communities and many existing studies are not keeping pace with the state-of-art approaches.
7 Although many are recognizing the importance of coupling localized SLR scenarios and
8 extreme events, the extent of scenarios considered is still limited. The prevalent practice of
9 assuming the fixed increases of SLR over extreme events is inadequate because sea level is
10 continuously and gradually rising at an uncertain rate. Considering only one or a few potential
11 SLR scenarios overlooks the wide range of plausible SLR projections. In addition, existing
12 practice is generally not compatible with the preferred risk-management approach as the
13 fixed SLR scenarios along with the extreme events are usually static and cannot offer
14 flexibilities in selecting the risk tolerance at the user's preference (Buchanan et al. 2016). This
15 can be explained, in part, by that the emerging methods might not be available at the time of
16 their publication because of the rapid developments of this field and the study panel might
17 also lack the expertise or knowledge to employ these newly developed methods. To address
18 the gaps, this paper coupled a wide range of local SLR scenarios and extreme events using EVA
19 aiming to provide coastal communities with a transferable method to derive an exhaustive list
20 of potential SLR scenarios. However, our approach still has numerous limitations as previously
21 discussed and can be significantly improved by addressing the limitations. Nevertheless, with
22 science being advanced and new methods being developed, future research should not only
23 focus on developing better methods or approaches to derive more rigorous scenarios but also
24 evaluate whether coastal communities are adopting the best methods and sciences, and, if
25 not, why.

26 Second, vulnerability remains a fuzzy concept in practice. It appears that vulnerability,
27 in operation, usually loses its contextual meaning and, in most cases, it simply means the
28 communities' biophysical exposure to SLR. Although some assessments have explicitly
29 conceptualized vulnerability as a product of local exposure, sensitivity, and adaptive capacity,

1 they generally fail to analyze it in the way they define vulnerability. Thus, it is imperative to
2 provide a consistent and precise definition and usage for the term in both academia and
3 practice. Otherwise, the concept becomes, according to Füssel (2007b), “useless for the
4 careful description”, which will undermine risk communications and knowledge sharing
5 among scholarly and policy communities.

6 Third, the existing community-level vulnerability assessments are still in the early
7 stage of transitioning from the impact assessment considering only the biophysical impacts
8 into the first-generation assessment accounting for the socioeconomic dimensions of
9 vulnerability (see Füssel and Klein 2006 for the evolutions of vulnerability assessment).
10 McDowell and colleagues (2016) identify the same pattern in the scholarly communities
11 concerning the usability of these studies in adaptation decision-making. Future research and
12 practice should move towards the second-generation assessment analyzing the outcome
13 vulnerability after considering feasible adaptations and eventually the policy-driven
14 assessment focusing on identifying the “best” adaptation to inform decision-making. This
15 research only represents an initial step on the long journey of building resilient and
16 sustainable communities in the face of climate change.

17 Fourth, even when we have a consistent definition of vulnerability, to assess all its
18 elements remain a highly challenging task. One of the reasons is the lack of applicable
19 methods (McDowell et al. 2016), which motivates this research, and others include the lack of
20 availability of high-quality data, local expertise, and financial capacity. Our proposed method
21 offers a transferable and simplified solution, but readers should pay careful attention to
22 interpret the vulnerability findings in our case study, and, indeed, any other vulnerability
23 indicators that aim to describe the complex issues like SLR in a simple qualitative term or
24 quantitative parameter. The reason is the paradoxical dilemma of using indicators to describe
25 the complex issues due to the preferences of decision-makers for simplified results and
26 findings, while their complexities are usually non-reducible (Hinkel 2011). The research
27 direction of developing simple vulnerability indicators is essential as early-stage efforts to
28 invoke public and political awareness. Moving forward, the development of rigorous
29 vulnerability assessments is urgently needed that coastal communities can rely on to inform

1 adaptation decisions. We hope this research can be the stepping stone for more future
2 research to improve such endeavors and, hopefully, to trigger adaptations.

3 Finally, as the elements of vulnerability correspond to different aspects of the
4 concerned vulnerable systems, when coastal planners and policymakers are relying on the
5 vulnerability assessments to inform their decision making they should fully understand and
6 carefully apply the appropriate information. Specifically, the exposure and sensitivity findings
7 describe a system's physical vulnerability to SLR and they should be used to decide if a seawall,
8 for example, should be built to reduce the exposure or the properties near the coast should
9 be elevated to reduce their sensitivity. However, as the adaptive capacity describes the social
10 perspective of the system, its information alone cannot be used to inform the physical
11 adaptation decisions. It should be used, for example, to identify the most vulnerable
12 population and to support decisions such as prioritizing the allocations of resources to the
13 disadvantaged groups. These concepts and the methods to operationalize them are becoming
14 the focal point of research and are constantly evolving along with our growing knowledge
15 from both theory and practice. However, from our analysis, it is evident that public
16 participation in the vulnerability assessment is almost non-existent. The methods provided by
17 the scholarly communities are mostly theoretical and conceptual so that future research and
18 practice should seek for public input to empirically test and verify the vulnerability findings as
19 well as to provide insights for methodological shortcomings and pathways for improvements.

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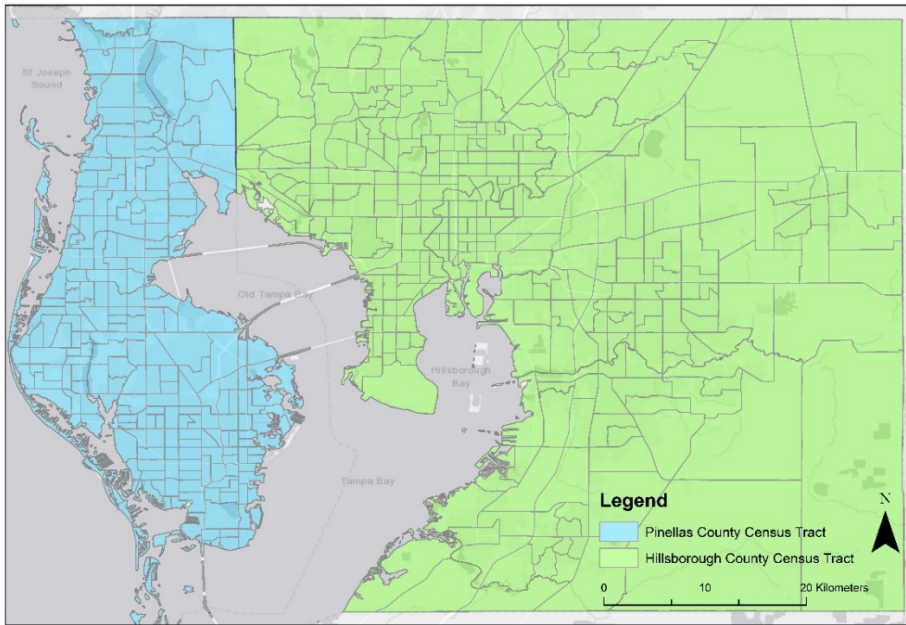


Figure 1 Study Area: Pinellas (Blue) and Hillsborough County (Green)



Figure 2 Census Tract and Parcel Data

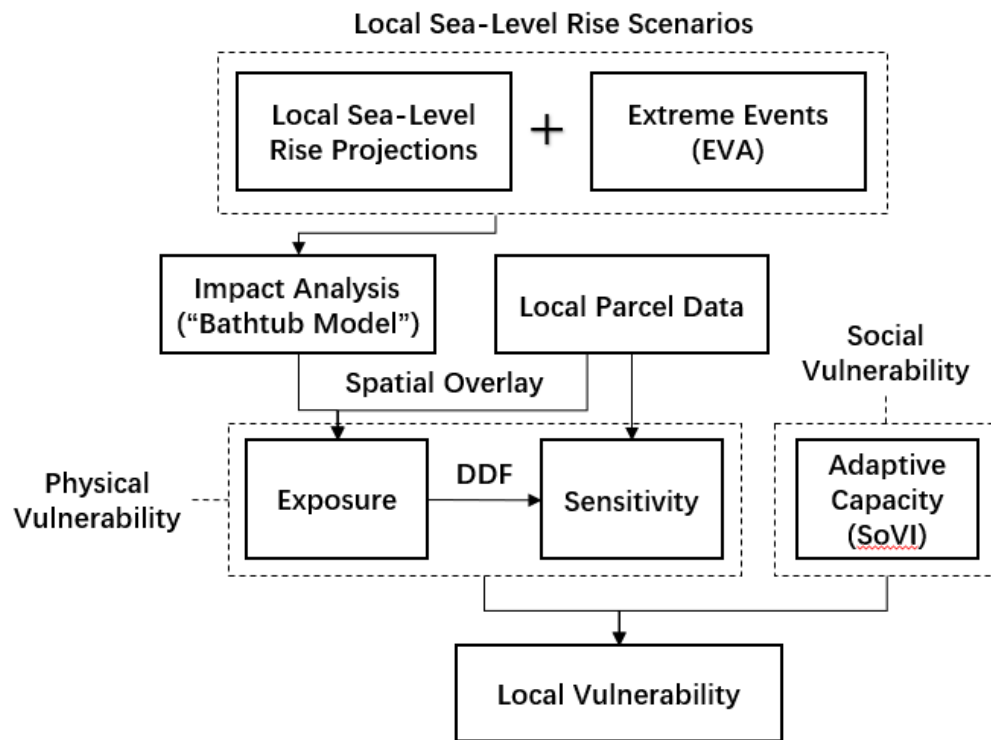


Figure 3 Research Framework (EVA denotes Extreme Value Analysis; DDF denotes Depth-Damage Function; SoVI denotes Social Vulnerability Index)

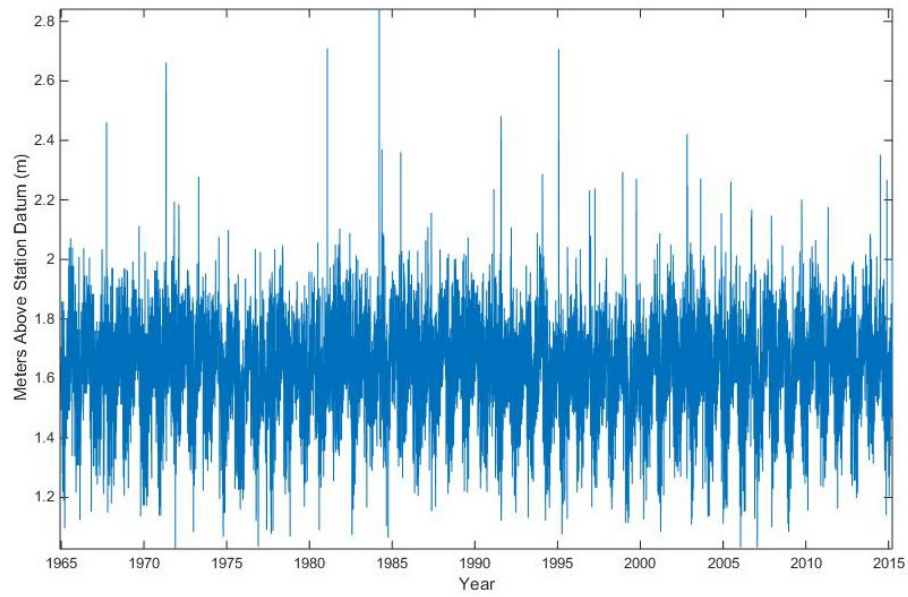


Figure 4 Decluttered and Linearly Detrended Hourly Water Level Data from 1965 to 2017 in Respect to Present Station Datum Epoch 1983-2001

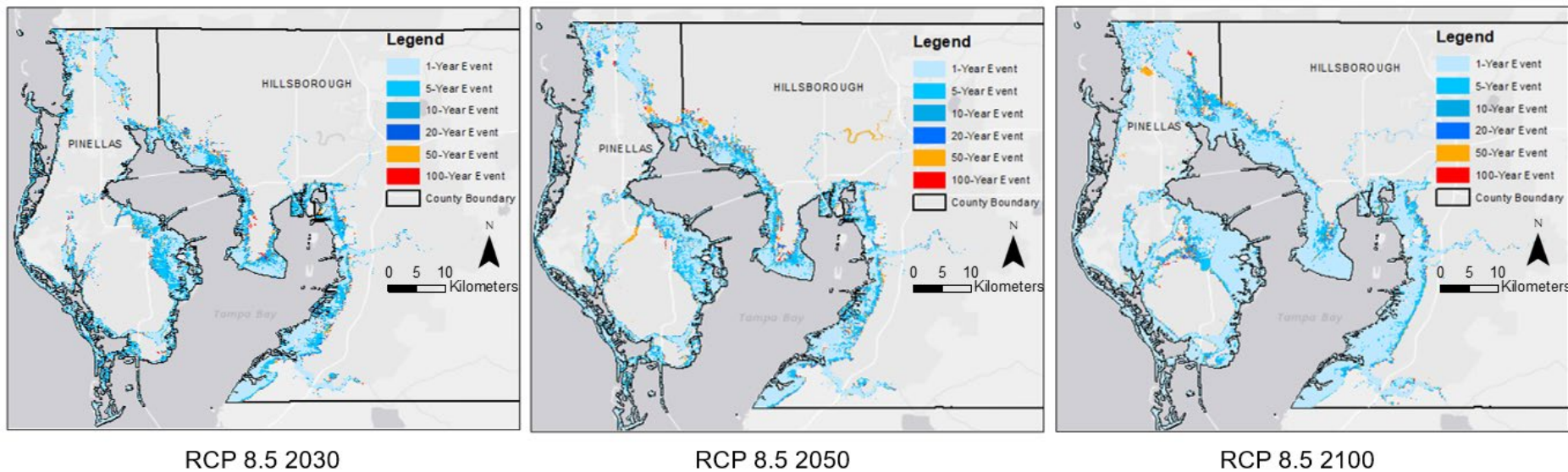
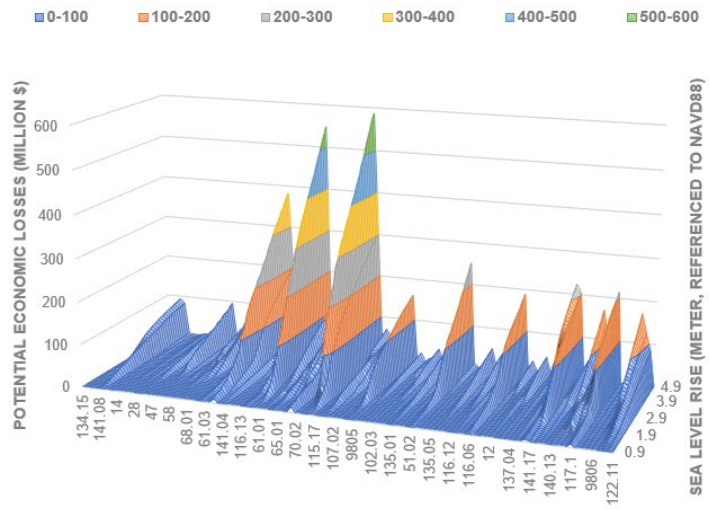
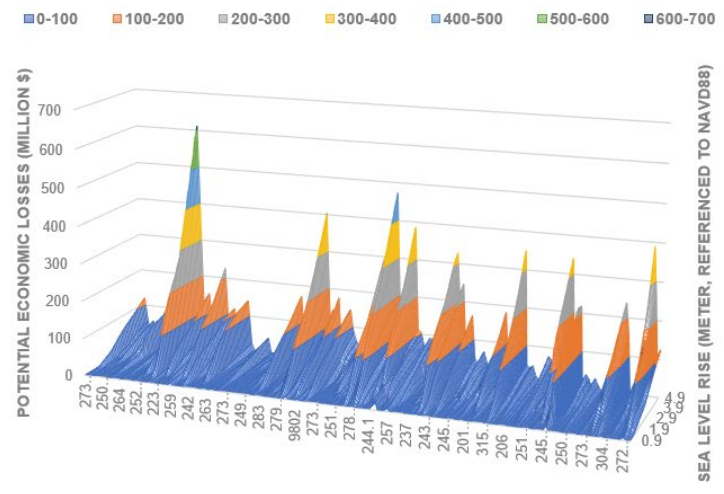


Figure 5 RCP 8.5 Local Sea-Level Rise Scenario at Tampa Bay Area with 99 Percent Confidence

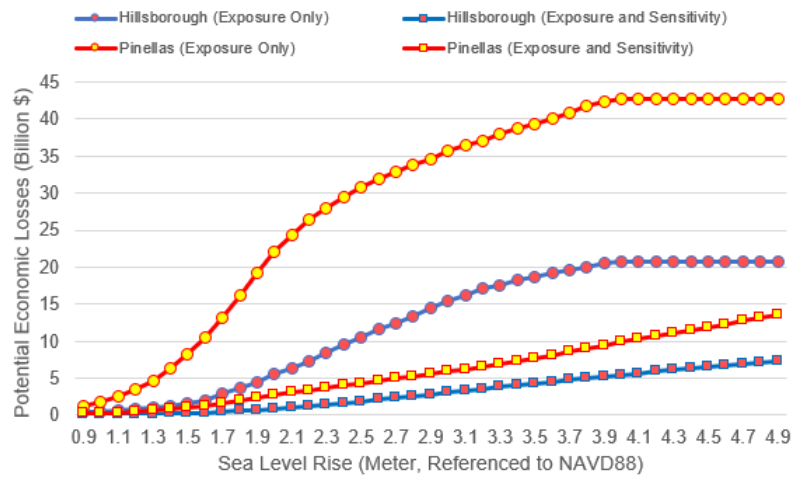


(a)

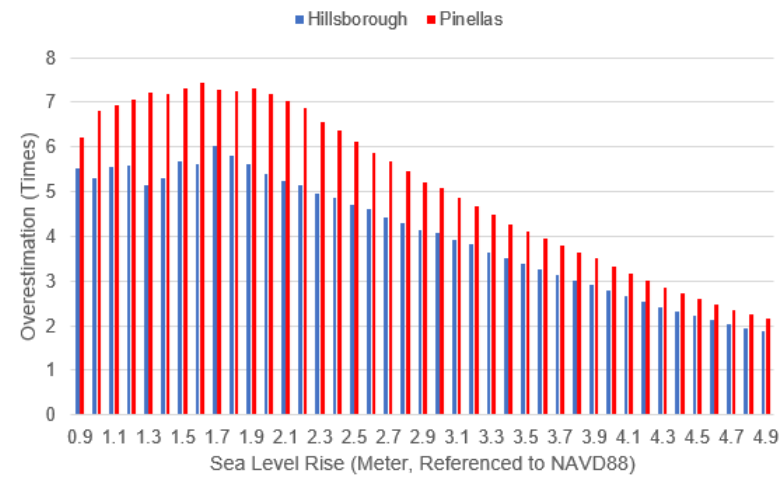


(b)

Figure 6 Potential Economic Losses Aggregated to US Census Tracts in the County of Hillsborough (a) and Pinellas (b) under Different SLR Scenarios



(a)



(b)

Figure 7 Comparisons between the Exposure-Only (EO) and the Coupling Exposure-and-Sensitivity Analysis (ES) for the Hillsborough County and Pinellas County under Different SLR scenarios: (a) the Absolute Estimated Economic Losses; (b) How Many Times the EO approach Overestimates as Compared to the ES approach (NAVD88 denotes The North American Vertical Datum of 1988)

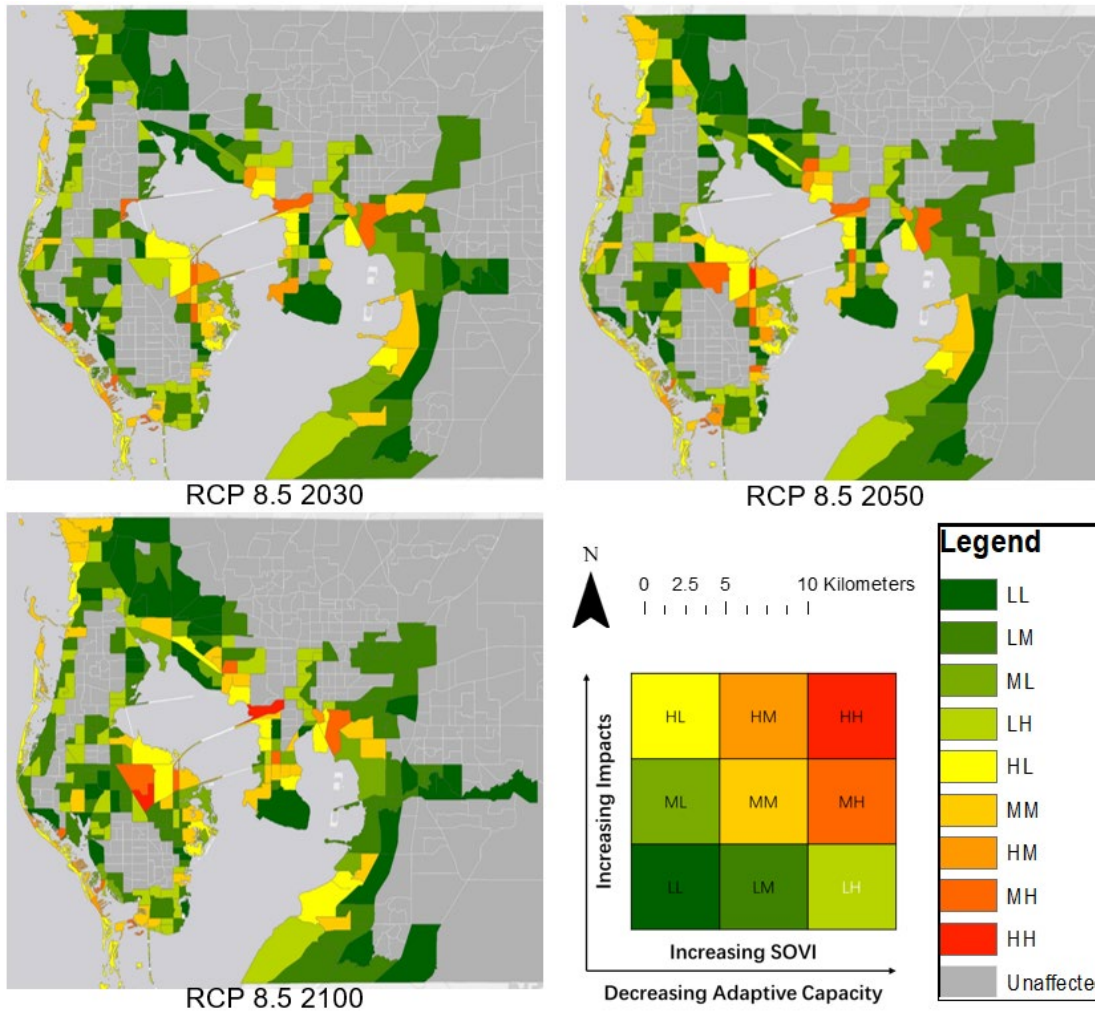


Figure 8 Vulnerability Index for the Tampa Bay Region (L, M and H Denote Low, Medium and High Respectively)

Table 1 Average Ranking Fitness for Comparing the Exposure-Only (EO) and Coupling Exposure-and-Sensitivity (ES) Approaches

County Name	Top 3	Top 5	Top 10	Top 15	Top 20	Average
Hillsborough County	92%	81%	75%	83%	92%	85%
Pinellas County	63%	73%	82%	87%	88%	79%

Table 2 Ranking Fitness for Comparing the Exposure-Only (EO), Coupling Exposure-and-Sensitivity (ES), and Comprehensive Approaches (i.e. Exposure + Sensitivity + Adaptive Capacity, ESA)

County Name	Comparison	Top 3			Top 5			Top 10			Top 15			Average		
		2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100
Hillsborough	EO and ESA	0%	0%	0%	0%	20%	0%	30%	30%	20%	60%	60%	27%	23%	28%	12%
	CES and ESA	0%	0%	0%	0%	0%	0%	30%	30%	0%	60%	67%	27%	23%	24%	7%
Pinellas	EO and ESA	0%	0%	0%	0%	0%	0%	20%	20%	20%	20%	20%	20%	10%	10%	10%
	CES and ESA	0%	0%	0%	0%	0%	0%	20%	10%	10%	27%	27%	20%	12%	9%	8%