IMPACT OF SEA LEVEL RISE ON AGING POPULATION'S ACCESSIBILITY TO ESSENTIAL SERVICES IN HONOLULU, HAWAI'I

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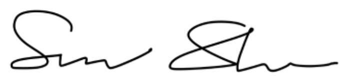
I certify that I have read this thesis and that, in my opinion, it is satisfactory in scope and quality as a thesis for the degree of Bachelor of Science in Global Environmental Science.

THESIS ADVISOR



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For everyone who supports me on my journey. For communities in Honolulu, Hawai‘i.

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ABSTRACT

Demographic studies have shown two trends: (1) elderly population is growing as a consequence of longer life expectancy; (2) population in low elevation coastal zones will significantly increase. One of the potential risks of living in low elevation coastal zones is the projected sea level rise. As sea level rises, more and more frequent flooding can cause disruptions and damage to the roadways in coastal areas. Seniors could be especially vulnerable to such disruptions given their need for emergency services, which could also increase because of the adverse impacts climate change has on health. This study aims to investigate the impacts of sea-level rise on the aging population's accessibility to essential services and its implication for long term adaptation planning using Honolulu, Hawai'i as a case study. Using Cohort Change Ratio (CCR), the study projects the elderly population in each Traffic Analysis Zones (TAZs) in future decades. Road segments and essential facilities (grocery stores, police stations, fire stations, and hospitals and clinics) at risk under different sea-level rise scenarios (1.1 feet, 2.0 feet, and 3.2 feet) are identified. Network connectivity from each TAZs to nearest essential services are analyzed. The results show that while the physical impacts on infrastructures are mild, some vulnerable communities' access to essential services will be greatly affected even under 1.1 feet sea-level rise scenarios. Especially some areas with a high projected density of the elderly population will be cut off to essential services due to transportation bottlenecks. For the rest of the population, sea level rise could significantly reduce the number of people with timely access to essential services. The results not only urge transportation network planners to take actions to make sure transportation connectivity to vulnerable elder population at-risk are protected, but also suggest that over the long-term land use planning would be one of a key factors to adapt to climate change. These findings have broad implications for other coastal locations with similar development and growth patterns, and the methodology used could be easily adapted to be used in a variety of other metropolitan areas across the country to conduct similar vulnerability analyses to aid in adaptation planning in practice. Also, audience will learn the emergent needs of sea level rise adaptation planning.

Key words: Elderly population; Accessibility; Coastal road infrastructure; Sea level rise adaptation

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1 INTRODUCTION

Thanks to the increase of level of life expectancy and decreasing fertility rate, the age structure of the global population is undergoing an unprecedented change. The senior population is growing due to longer life expectancy (United Nations, 2020). It is reported that the global urban population has exceeded half of the world population, and it is predicted that it will reach 60% of the world population by 2030 (WHO, 2014). At the same time, the population in the low elevation coastal zones is expected to increase significantly (Neumann, 2015). As an isolated archipelago with a pleasant climate year around, Hawai‘i has a faster aging rate than the rest of the United States (Age-friendly Honolulu, 2020). Age-Friendly Honolulu, a report issued by the City and County of Honolulu, had addressed that by 2040, 27% of the population in Hawai‘i's largest city Honolulu will be aged 65 or older. In the meantime, Hawai‘i residents have the longest healthy life expectancy in the United States. On October 11th, 2018, Honolulu mayor Caldwell signed Bill 54, marking a commitment of the City and County of Honolulu to be an age-friendly city (Caldwell, 2018). Age-friendly Honolulu shares visions of all people with access to safe and affordable transportation, which not only make elders able to access community support and health service but also reduce the stress of the family members of elders (Age-friendly Honolulu, 2020).

Climate change research has a long history of trying to understand climate system dynamics and modeling in the 20th century (IPCC, 2014). However, community-based adaptation to climate change impact was not introduced until the mid-1990s (Ayers and Dodman, 2010; IPCC, 2014). As one of the consequences of climate change, sea level is rising by a rate of 3.3 mm per year on average (Cazenave and Llovel, 2010). Ongoing global warming will accelerate the speed of sea level rise (Nerem et al, 2018). Sea level rise adaptation empowers coastal communities to reduce the potential negative impact of sea level rise (Tol et al, 2008). In particular, transportation infrastructure is exceedingly vulnerable with even a minimal increase of sea level rise (Oawald and Treat, 2013). Studies have examined the vulnerability of transportation networks under sea level rise (Lu and Peng, 2011; Sun et al, 2020; Bloetscher et al, 2012). However, there is a lack of research exploring the impacts of vulnerable transportation networks on the aging population under sea level rise scenarios.

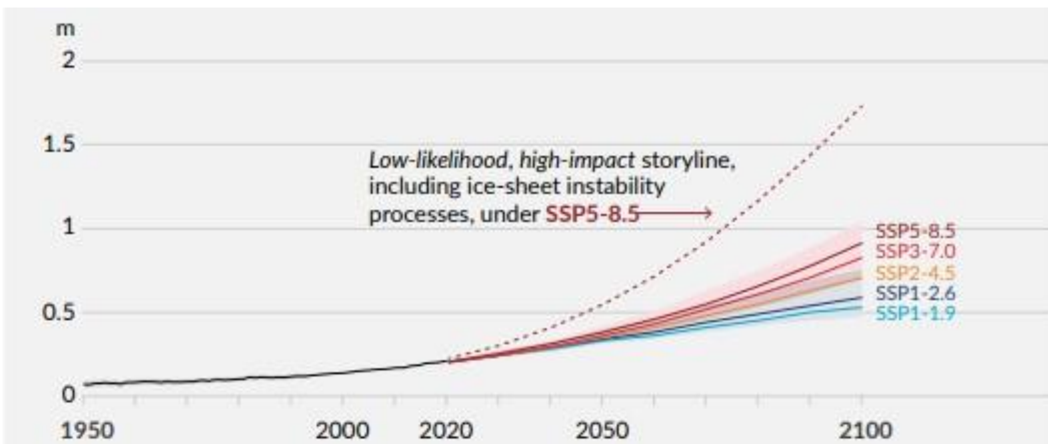


Figure 1. Global mean sea level in the past and as projected for the 21st century (IPCC, 2021)

Figure 1 shows the global mean sea level changes in meters in the past (1950-2020) and projected from 2021-2100 , relative to 1900. The projection sea level rise are based on five illustrative scenarios, SSP 1-1.9, SSP 1-2.6, SSP 2-4.5, SSP 3-7.0, SSP 5-8.5 (IPCC, 2021).

The purpose of this study is to evaluate the impact of sea level rise on the accessibility of the aging population to essential services and facilities (i.e. grocery stores, hospitals and clinics, fire stations, and police stations) in Honolulu, Hawai‘i to support long term adaptation decision making.

2 LITERATURE REVIEW

The majority of climate change research has focused on global or national levels (Sheppard, 2011). It is clear that global climate change will ultimately affect local people and communities (Lujala et al., 2014). Every region is expected to experience an increase in the probability of compound hazards exaggerated by climate change, such as heatwaves, flooding, and droughts (IPCC, 2021). The increased natural hazards are related to social and economic characteristics, and the elderly are at high risk when facing the increased hazards (Wang and Yarnal, 2012; Morrow, 1999; Zimmerman et al, 2007; King, 2000). Specifically, seniors may lack the physical and economic resources necessary for effective response to natural hazards (Morrow, 1999). To minimize harm and economic loss, planning efforts to mitigate the future impacts of climate change on elderly population in urban development must be enhanced (King, 2000).

2.1 Vulnerability of Aging Population to Flooding and Climate Change

Seniors are often considered "vulnerable populations" (Aday, 1994; Tompson and Spacapan, 1991; Shi et al, 2021). The term "vulnerability" is frequently referred to in the risk, hazards, and disaster literature, and it is becoming more important in the studies of climate change adaptations (Cutter, 1996). Vulnerability can be described as the degree of loss (UNDRO, 1980) or the potential for loss (Mitchell, 1989). Although all age groups can be considered as vulnerable to some extent, elders are at higher risk of being exposed to certain challenges with greater probability of pre-existing medical conditions and limitation in mobility (Grundy, 2016). The vulnerability of elderly is reflected in multiple ways. For example, as seniors usually have slow reaction times and many medical issues, many elders must give up their driving licenses in the late 70s and early 80s (Rosenbloom, 1993; Roberston and Vanlaar, 2008; Liu and Engels, 2012). Elders can be identified as being “social exclusion” as they have difficulties traveling outside their homes to access services and facilities (Liu and Engels, 2012). The travel difficulties can be intensified as the seniors live in very low density places or vulnerable low lying areas. However, the travel demand can grow as they need to go to doctors more frequently (Rosenbloom, 1993; Liu and Engels 2012). Poor public transportation systems magnify the disadvantage for non-driving seniors (Liu and Engels, 2012). Climate change-driven hazards such as intensed coastal flooding have led to route closures, detours, and the immobility of roads, which increase the disruptions of the transportation system (Shen and Kim, 2020; Erikson et al, 2018; Kirshen et al, 2007). In addition, many researchers have predicted an increasing elderly population in coastal areas (Neumann et al, 2015; Qiang, 2019; Wang and Yarnal, 2012), which would make the elderly more vulnerable to the more frequent coastal hazards.

2.2 Accessibility to Essential Services

In urban transportation planning, accessibility is a critical element that affects travel demand and transportation network efficiency (Liu and Zhu, 2004). The accessibility-based analysis was first introduced in the 1930s to describe people’s demand to reach their destinations (Merlin et al., 2018). Researchers have developed dozens of approaches to measure accessibility (Siddiq and Taylor, 2021). Accessiblity can be simply defined as “the ease of reaching destinations” (Alsnih and Hensher, 2003). Many accessibility metrics have been developed for urban research and planning practices (Siddiq and Taylor, 2021). In recent years, given the attention to equity and vulnerable populations, there are studies of accessibility to essential services with a strong focus on vulnerable populations such as the elderly (Mayaud et al. 2018; Somenahalli and Shipton, 2013; Cheng et al., 2020). Johnson et al. (2018) shows accessibility, especially in rural coastal communities, can be impacted significantly by climate change due to limited road networks, longer travel times, and a more isolated and aging population. Population growth has varying implications for future accessibility demand in different areas of the city. For example, in Surry, Canada, more than half of seniors will not be able to access a hospital in 30 minutes (Mayaud, 2019). Somenahalli and Shipton (2013) found the distribution of people aged 75 years old and over is related to socio-economic, migration, or housing-related statistics, and there are usually more elderly in areas with easy access to essential services. Some accessibility analyses (e.g., Balomenos et al. 2019; Shen and Kim, 2020) have analyzed spatially how coastal hazards impact accessibility on vulnerable populations. Balomenos et al. (2019) developed a framework to survey how hurricanes caused transportation networks disruptions by classifying inundation conditions and structural failures to quantify accessibility after a hurricane and calculating the minimum travel cost (distance or time) from a demand location to the closest supply facility. Shen and Kim (2020) identify roadway segments under flooding risk and ranked traffic analysis zones (TAZs) regarding accessibility changes to measure transportation opportunities with and without tidal inundation. However, there is no study analyzing how the sea-level rise and projected coastal hazards impact senior population in the future.

2.3 Transportation Vulnerability and Adaptation

Transportation infrastructures and roadways, in particular, could be at flood risk caused by a variety of events, such as storms or hurricanes (Jacob, 2015; Lämmel et al., 2010), high tides (Shen and Kim, 2020), tsunamis (Williams et al., 2020), and sea level rise (Lu and Peng, 2011; Sun et al., 2020; Bloetscher et al., 2012). Compared to other factors, sea level rise inundations are permanent. Sea level rise will increase water table levels and damage roadway beds, and inundate coastal roads (Bloetscher et al., 2012). Transportation infrastructure inundation not only costs a lot of money to repair but also causes a severe impact on transportation services due to network effects (Hodges, 2011; Oawald and Treat, 2013; Gorman, 2005; Chen et al., 2015). Considering the vulnerability of the transportation network, Chen et al. (2012) assessed sea level rise will cause Saint Petersburg, Florida a 12.41% reduction of accessibility in 2035. However, adaptation strategies can notably change the performance of transportation systems (Sun et al., 2020). Adaptation strategies should involve all parts of society, and address issues of inequality and environmental justice (Hodges, 2011). As a vulnerable group, the need of the elderly population is extremely important in the adaptation considerations.

The goal of this study is to apply the existing approach of accessibility to evaluate the impacts of different sea level rise scenarios on the island of Oahu, with an emphasis on the aging population. As accessibility can be interrupted by flooding and can be varied because of the change of travelers' needs (Shen and Kim, 2020), the road disruptions caused by different sea level rise scenarios will be investigated based on a projected distribution of the aging population.

3 METHOD

To achieve the study objective, the following data and methods are applied. First, population and age information are collected at the TAZ level. Sea level rise, road network, and essential facilities (grocery stores, hospitals and clinics, fire stations, and police stations) data were obtained (Table 1). Then, the cohort change ratio method (equation 1 and equation 2) was applied to project the future elderly population in each traffic analysis zone for the projected year 2050. Four origin-destination network analysis (current, 1.1 feet sea level rise, 2.0 feet sea level rise, and 3.2 feet sea level rise) were conducted under different sea level rise scenarios in ArcGIS Pro. To calculate the accessibility from each TAZ to essential facilities, normalized Hansen index of accessibility is applied (equation 3), followed by spatial pattern analysis of elderly population density and accessibility reduction.

3.1 Data Resources

Center for Training Transportation Professionals (CTTP) designed a special tabulation TAZ level census data for transportation analysis, which was developed based on the 2012-2016 American Community Survey (ACS). Sea level rise exposure scenarios model was accessed through Pacific Islands Ocean Observing System (PacIOOS). The model was based on the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Street network was extracted from the Hawai‘i State Office of Planning, and hospitals and clinics, fire stations, and police stations were obtained from Honolulu Open Geospatial Data.

Table 1: Data Resource

Data	Resource	Publisher	URL
CTPP data product based on 2012 – 2016 5-year American Community Survey (ACS) Data	CTPP based on 2012 – 2016 ACS	American Association of State Highway and Transportation Officials	https://ctpp.transportation.org/2012-2016-5-year-ctpp/
Street networks	Hawai‘i Statewide GIS Program	Hawai‘i State Office of Planning, 2019	https://geoportal.Hawai‘i.gov/datasets/cchnl::street-names/explore?location=21.350410%2C-157.750153%2C13.76
SLR exposure	State of Hawai‘i Sea Level Rise Viewer | PacIOOS	Tetra Tech, Inc. and University of Hawai‘i Coastal Geology Group. 2017	https://www.pacioos.Hawai‘i.edu/shoreline/slr-Hawai‘i/
Grocery Stores	Google map search	Google	https://www.google.com/maps
Hospitals and Clinics	Honolulu Open Geospatial Data	City & County of Honolulu, 2016	https://honolulu-cchnl.opendata.arcgis.com/datasets/hospitals-and-clinics/explore?location=21.474611%2C-157.942850%2C10.97

Table 1: (Continued) Data Resources

Fire Stations	Honolulu Open Geospatial Data	City & County of Honolulu, 2016	https://honolulu-cchnl.opendata.arcgis.com/datasets/fire-stations/explore?location=21.473561%2C-157.944200%2C10.97
Police Stations	Honolulu Open Geospatial Data	City & County of Honolulu, 2016	https://honolulu-cchnl.opendata.arcgis.com/datasets/police-stations-1/explore?location=22.036233%2C-158.333716%2C8.25

3.2 Cohort Change Ratio

To analyze the accessibility of the elderly population, we first project the elderly population (i.e., 65+) in each TAZ for the year of 2026, 2036, 2046, and 2056 respectively. The data for population projection is 2012-2016 Census Transportation Planning Program (CTPP) based on 2012 – 2016 5-year American Community Survey (ACS) data. The CCR of each TAZ is estimated by equation (1)

Equation 1

$$nCCR_X = \frac{(nP_{x,t,i})}{(nP_{x-t,t-k,i})}$$

Where $nP_{x,t,i}$ is the population aged x to x+n at time t for area i, which is typically the most recent census, $nP_{x-t,t-k,i}$ is the population aged x-k to x-k+n at a preceding point in time (t-k) for area i, which is typically the 2nd most recent census. k is the number of years between the most recent census at time t and the one preceding it at time t-k. The aging population (i.e. 65 years and old) in 2026, 2036, 2046, and 2056 were projected by equation (2)

Equation 2

$$nP_{x+t,t+k,i} = (nCCR_{x,i}) * (nP_{x,t,i})$$

Where $nP_{x+k,t+k,i}$ is the projected population aged x+k to x+k+n at time (t+k) for area i, $nCCR_{x,i}$ is the cohort change ratio as described earlier, and $nP_{x,t,i}$ is the population aged x to x+n at the most recent census (t) for area i.

One of the limitations of CCR is if a TAZ was newly developed and had a large number of populations moved in between two census records, CCR will return an unreasonable number. For example, TAZ 565, which is located in Ewa Beach, Oahu, has a census data of 25 in the 2006-2010 estimation, but the population has grown to 1,810 in the 2012-2016 estimation. According to the United States Census Bureau, the population growth of Ewa Beach from 2010 to 2020 is 9.8%. Therefore, we estimated these two TAZs (TAZ 565 and TAZ 566) by multiplying the 10-year growth instead of using CCR.

3.3 OD Network Analysis

Origin-Destination network analysis was then conducted in ArcGIS Pro. Transportation networks datasets is a particular vector data type contain edges, junctions, and nodes, those datasets are used to model travelling behaviors (Silalahi, 2020). OD matrix is a traditional approach which has been widely used for find solution from a plausible solution space that matches demand estimating flow with a definite constraint for traffic planning, management and control (Silalahi, 2020; Cik and Fellendorf, 2019; Osorio, 2019). The centroid points of each TAZ were assumed to be the origin point and destination point. The OD Cost Matrix calculated the shortest travel distances between two TAZs under no sea level rise, 1.1 feet sea level rise, 2.0 feet sea level rise, and 3.2 feet sea level rise scenarios.

3.4 Accessibility Measurement

Hansen integral accessibility index (Hansen, 1959) is one of the most popular accessibility indices (Shen and Kim, 2020). The index measures the accessibility of zone i, A_i as:

Equation 3

$$A_i = \frac{\sum B_j f(c_{ij})}{\sum_j B_j}$$

Where B_j is the opportunity in zone j, referring to grocery stores, hospitals and clinics, fire stations, and police stations. $f(c_{ij}) = d_{ij}^{-\alpha}$, which stands for the friction factor between two TAZs' centers, is represented by the inverse of shortest travel distance from the center of TAZ i to another center of TAZ j. The shortest travel distances between two TAZ were calculated in the OD Cost Matrix. The letter α is a constant that represents the degree of needs to different essential services. Baht et al (2002) gave the α value of emergency-related trips is 2.0347, and 2.5000 for grocery shopping. $\sum_j B_j$represents the total number of essential facilities on the island of Oahu.

4 RESULTS

4.1 The Roads and Essential Services Affected by Sea Level Rise

Among four types of essential services, grocery stores have the greatest number of inundations (Table 2; Figure 2). None of the hospital and clinics will be impacted by even 3.2 feet sea level rise, while one fire station and one police station may be inundated by 2.0 feet sea level rise (Table 2; Figure 3; Figure 4)). Most inundated grocery stores are located in urban Honolulu (Figure 2), while the north shore and west Oahu all have facilities at risk with 3.2 feet sea level rise. For roadways, 3.2 feet sea level rise will inundate triple the length of roads at risk compared to 2.0 feet sea level rise, up to a total length of 4.3% roads over the island.

Table 2: The inundation of facilities and roads

Sea Level Rise	Hospit al & Clinics	Groceries	Fire Station	Police Stations	Road Inundated Length (Miles)	Road Length Percent	Road Percentage
1.1 feet	0	1	0	0	13.37	0.0000928%	1.4%
2.0 feet	0	2	1	1	24.84	0.000172%	2%
3.2 feet	0	12	2	1	69.31	0.000481%	4.3%

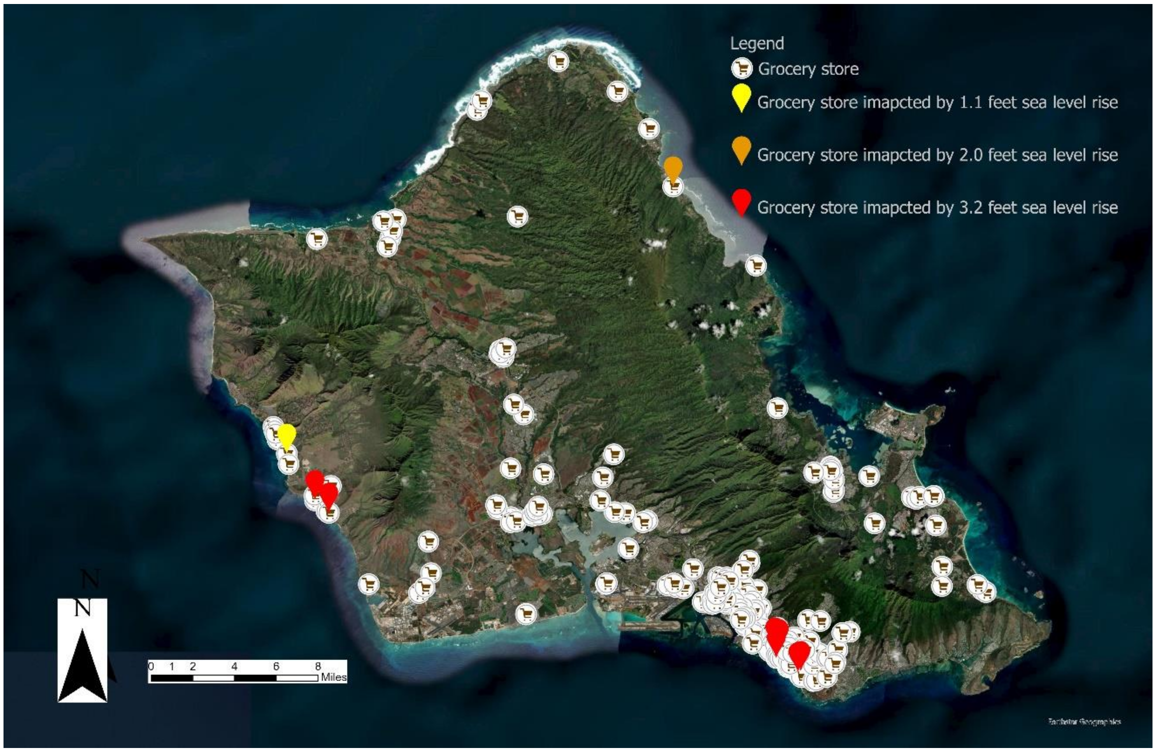


Figure 2. Impacted grocery stores by different sea level rise scenarios

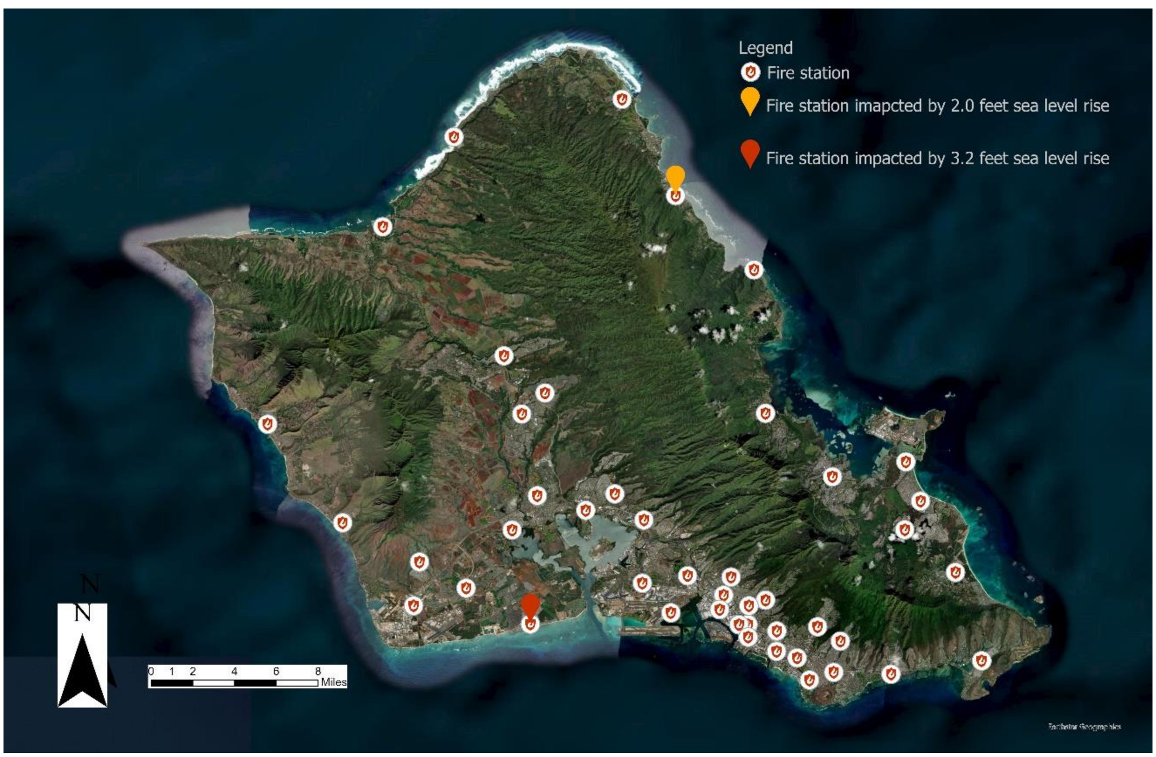


Figure 3. Impacted fire stations by different sea level rise scenarios

Figure 4. Impacted police stations by different sea level rise scenarios

4.2 The Change of Accessibility

Due to coastal road inundation, accessibility of each TAZ to essential services will reduce significantly. 1.1 feet sea level rise and 2.0 feet sea level rise will result in a significant reduction in hospital/clinic accessibility, while 3.2 feet sea level rise will result in a significant reduction in police station accessibility. Access to the police station has a large standard deviation, which suggests that accessibility to the police station varies significantly between TAZs. Table 3 shows the mean, mean reduction, median, standard deviation, and maximum of accessibility to essential services of each TAZ.

It must be highlighted that even a 1.1-foot sea level rise will cut certain coastal roads off and render some coastal TAZs, especially TAZs in the North Shore, inaccessible to essential services.

Table 3: Summary of accessibility statistics in different sea level rise scenarios

Scenario	Type	Mean	Mean reduction	Median	Standard deviation	Maximum
Current	Grocery	0.412	/	0.019	1.544	34.358
	Hospital/clinic	0.111	/	0.039	0.200	2.501
	Fire station	0.093	/	0.031	0.186	1.772
	Police station	3.283	/	0.434	6.136	67.822
1.1 feet sea level rise	Grocery	0.357	13.5%	0.022	1.047	15.485
	Hospital/clinic	0.087	21.6%	0.033	0.141	1.636
	Fire station	0.092	1.0%	0.023	0.184	1.772
	Police Station	2.957	9.9%	0.479	5.604	48.602
2.0 feet sea level rise	Grocery	0.354	14.2%	0.021	1.046	15.485
	Hospital/clinic	0.087	21.9%	0.032	0.141	1.636
	Fire station	0.092	1.4%	0.022	0.184	1.772
	Police station	2.928	10.8%	0.465	5.589	48.579

Table 4: (continued) Summary of accessibility statistics in different sea level rise scenarios

3.2 feet sea level rise	Grocery	0.298	27.7%	0.014	0.984	15.446
	Hospital/clinic	0.090	15.0%	0.012	0.234	3.085
	Fire station	0.080	14.3%	0.015	0.180	1.918
	Police station	2.359	28.1%	0.319	5.082	47.707

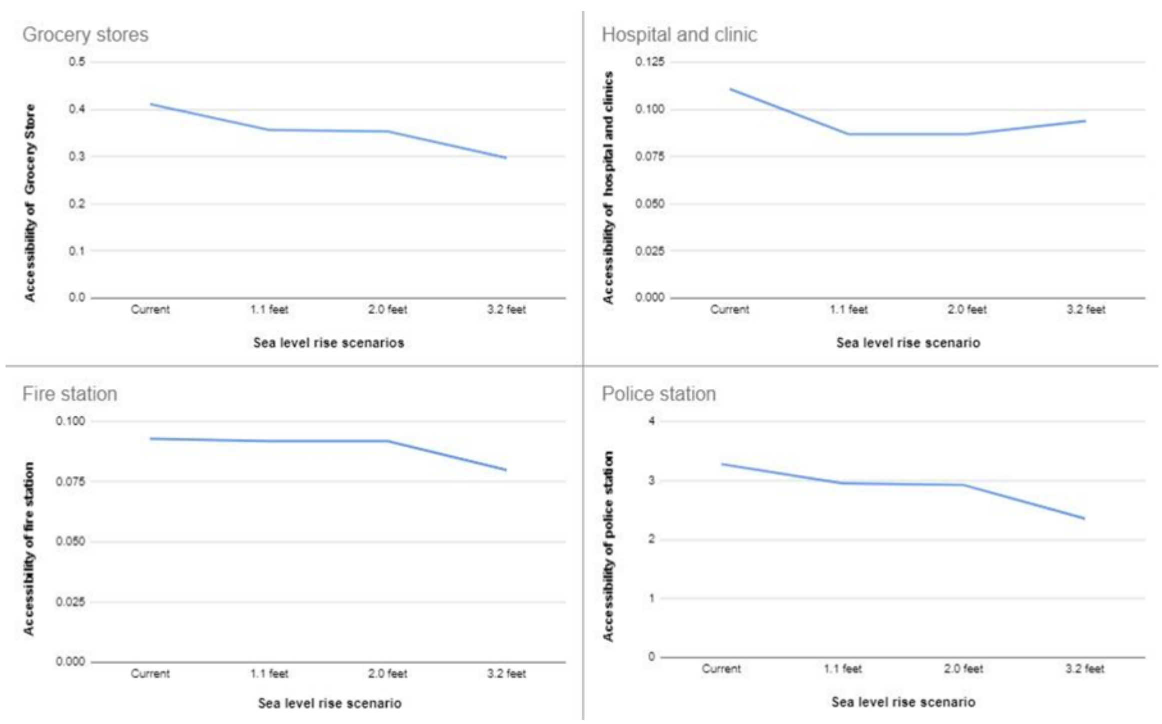
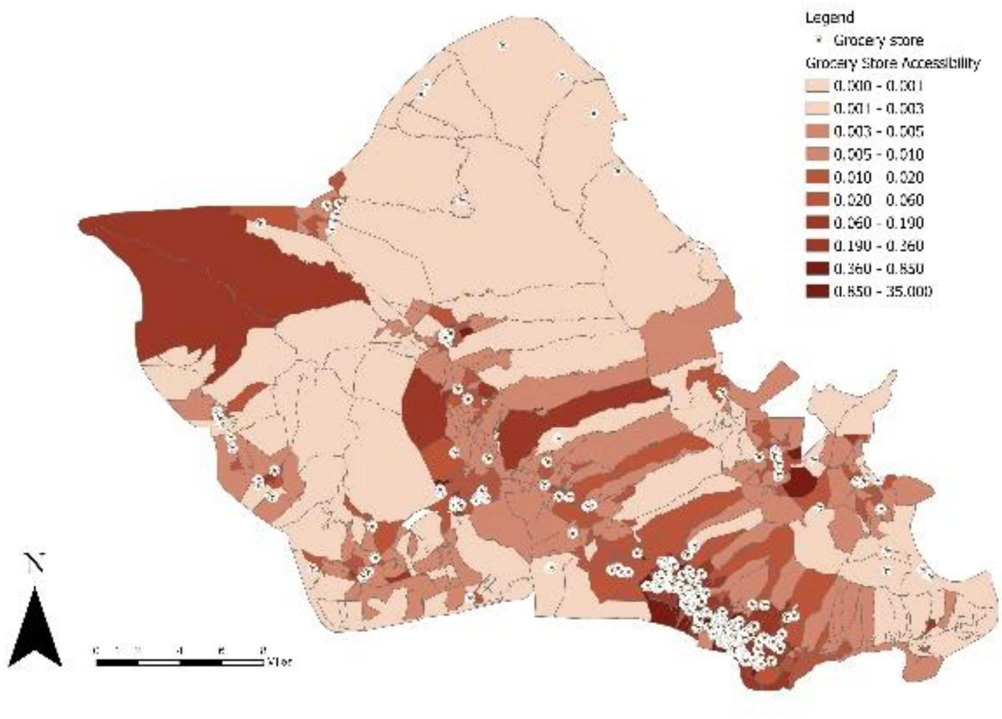


Figure 5. The reduction percentage of mean TAZs' accessibility to essential services in different sea level rise scenarios

The mean accessibility to essential services in each TAZ decreases as sea level increases (figure 5). Under 3.2 feet sea level rise, there are 3.4% mean grocery store accessibility reduction, 18.91% mean hospital and clinic accessibility reduction, 13.98% mean fire station accessibility reduction, and 28.14% mean police station accessibility reduction. Compared to the 1.1 feet and 2.0 feet sea level rise, 3.2 feet sea level rise will cause significant accessibility reduction. It is worth noting under the 3.2 ft SLR scenario that serval TAZs distance to the nearest service center has slightly decreased compared to the 2.0ft scenario. We repeated the analysis multiple times and checked for possible errors, but it shows the same results. This is a phenomenon that we cannot explain and worth future exploration.



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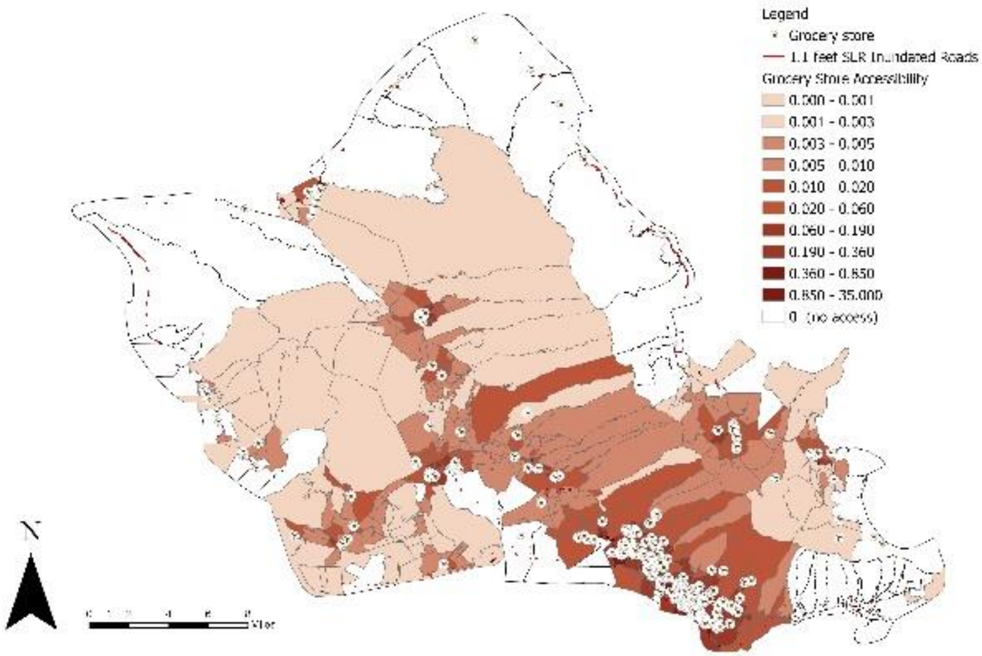

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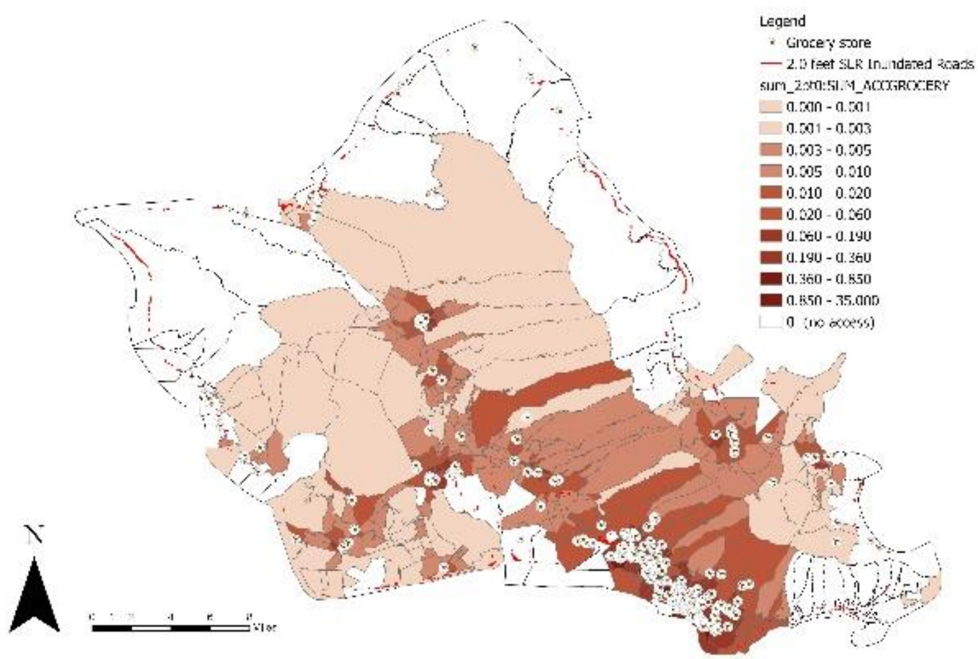

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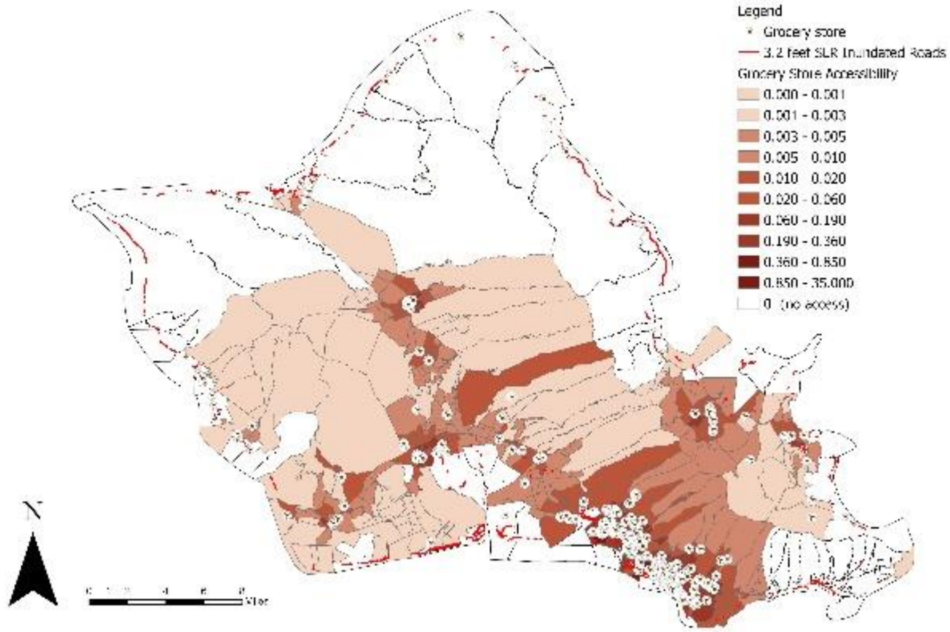
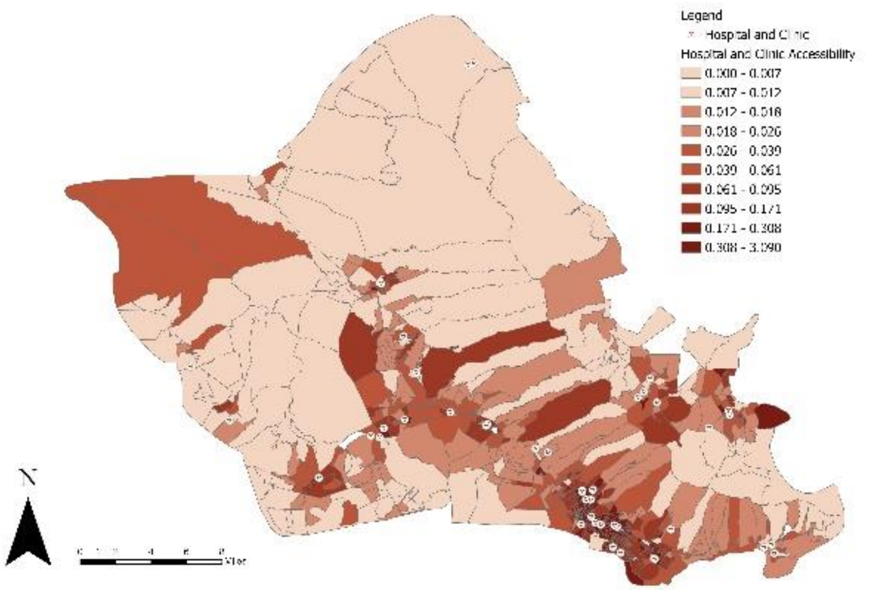


3.2 feet

Figure 6. Changes of accessibility to grocery stores of each TAZ



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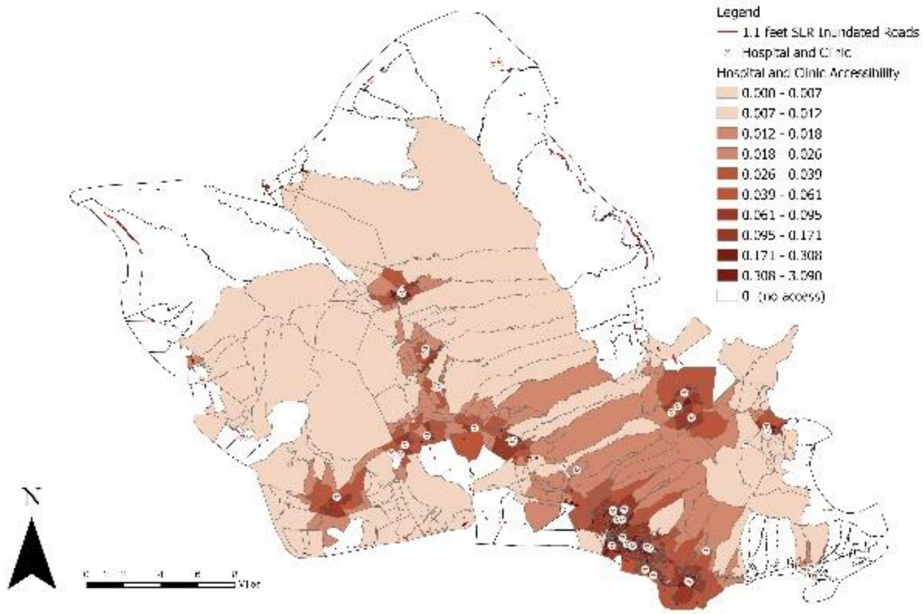

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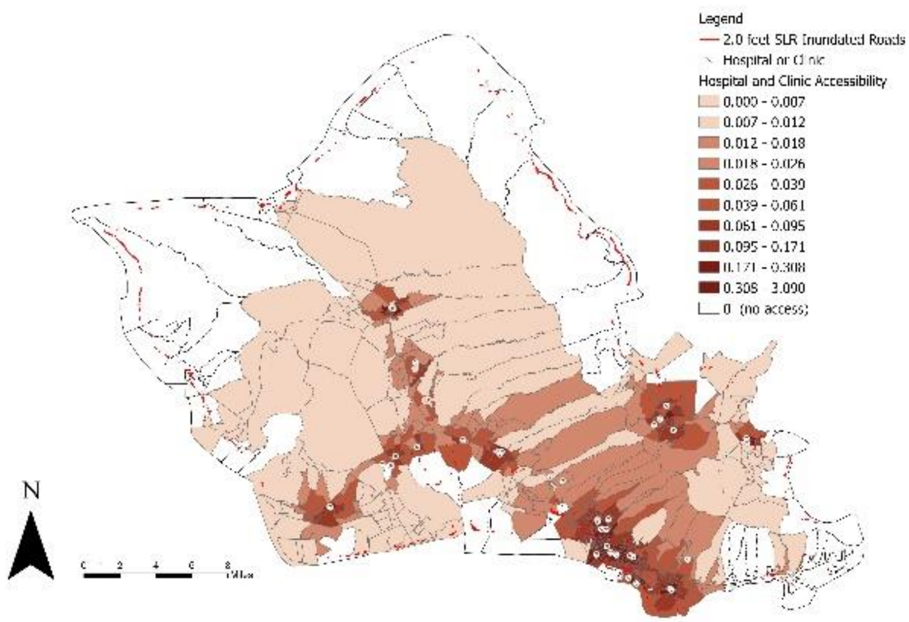

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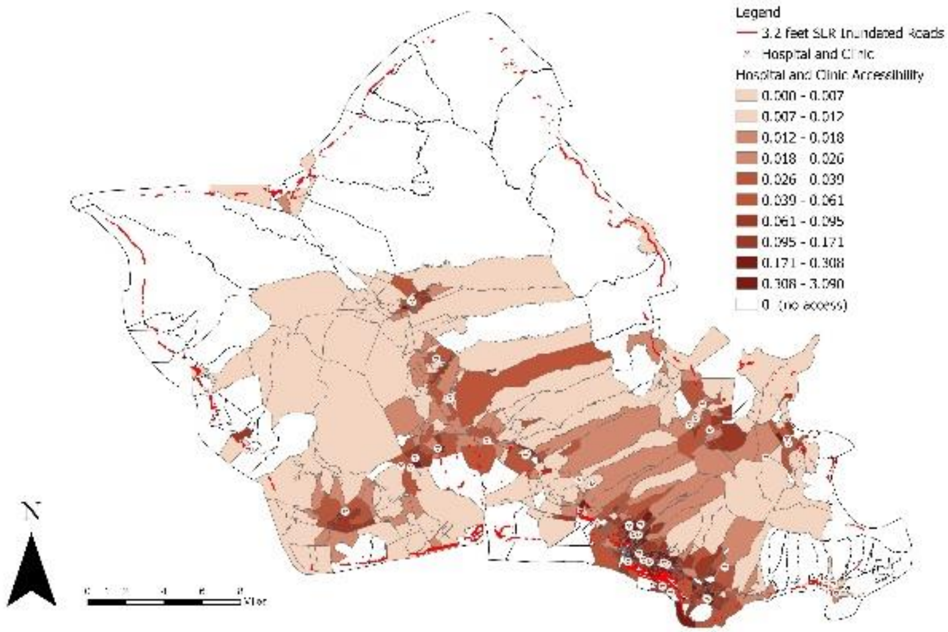
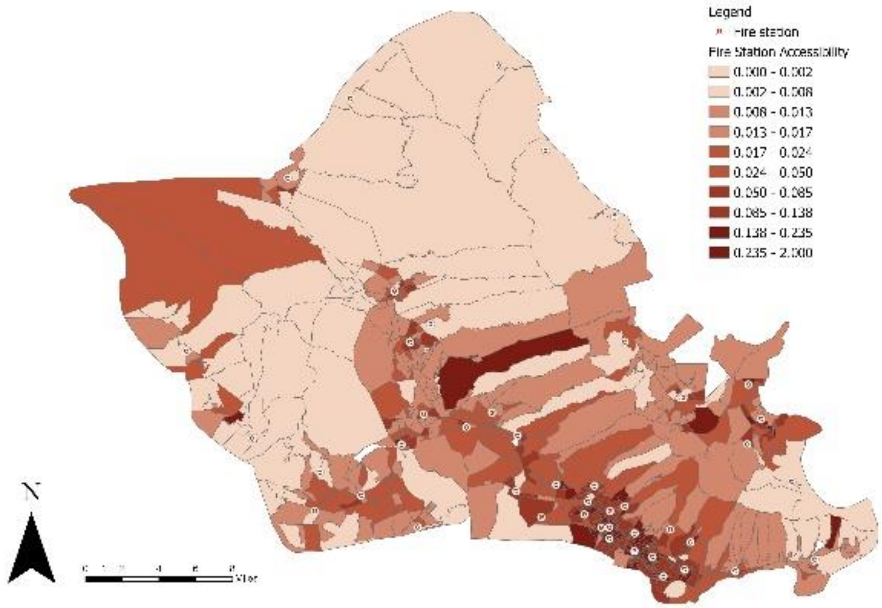


3.2 feet

Figure 7. Changes of accessibility to hospital/clinic of each TAZ



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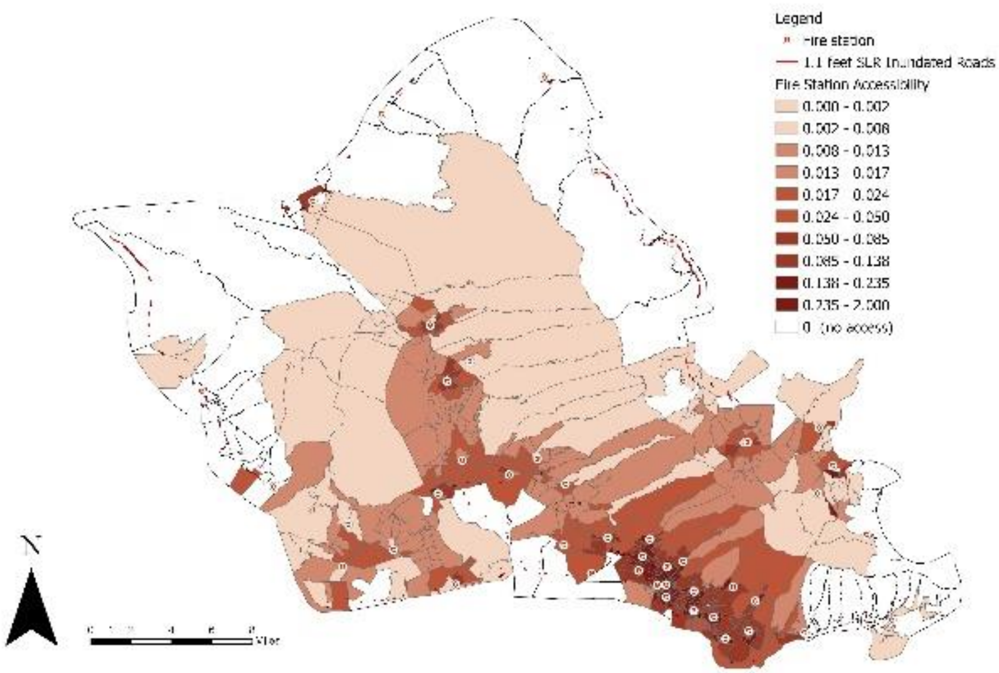

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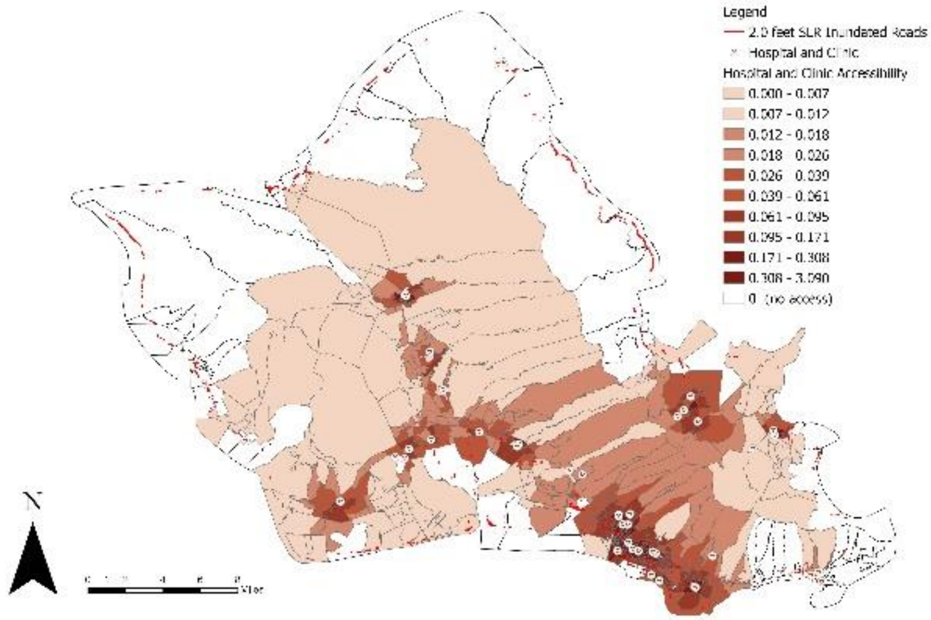

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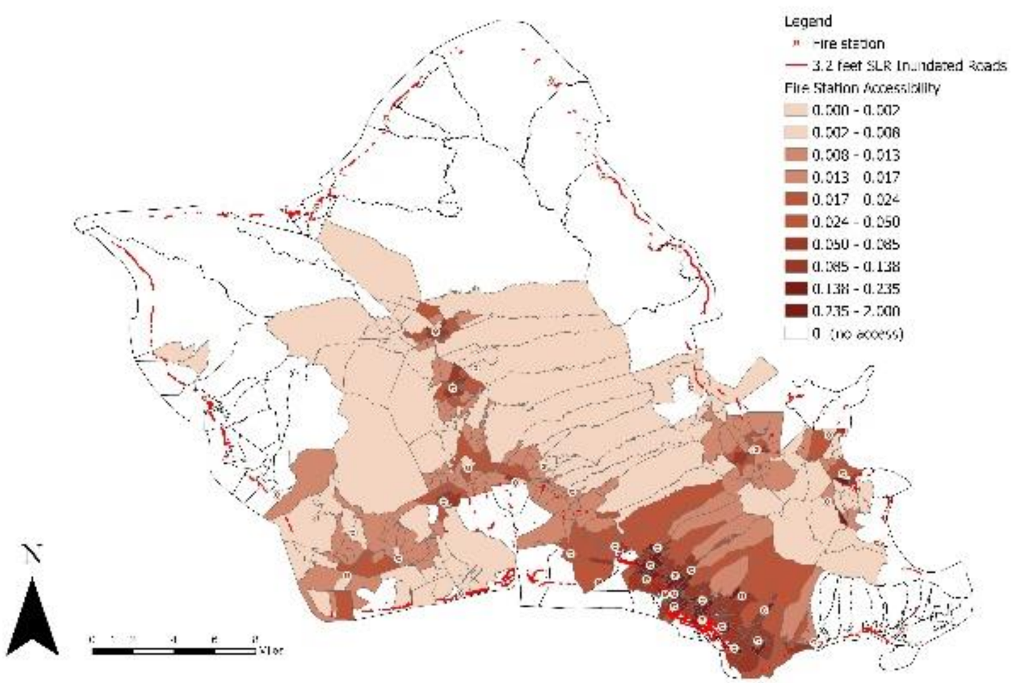
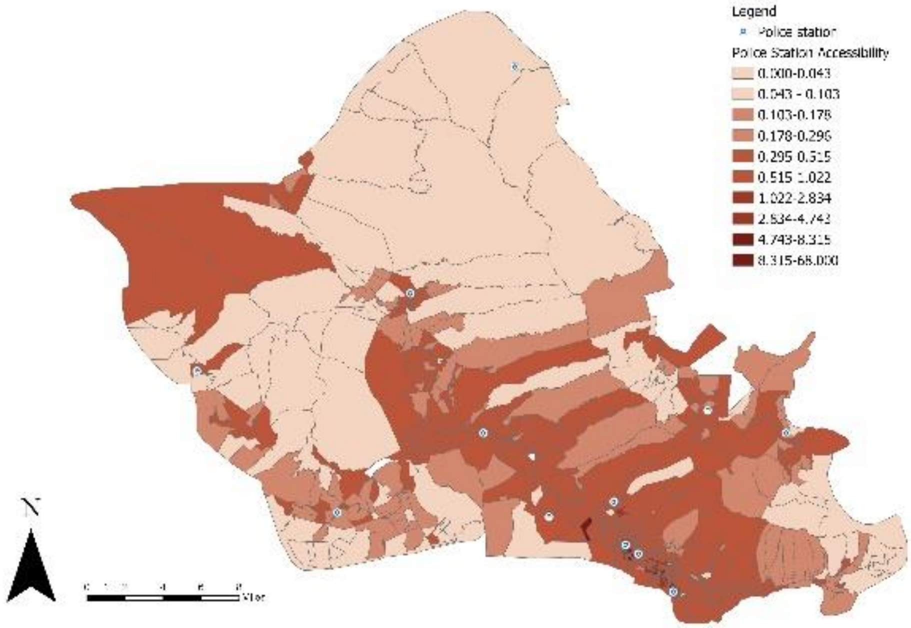
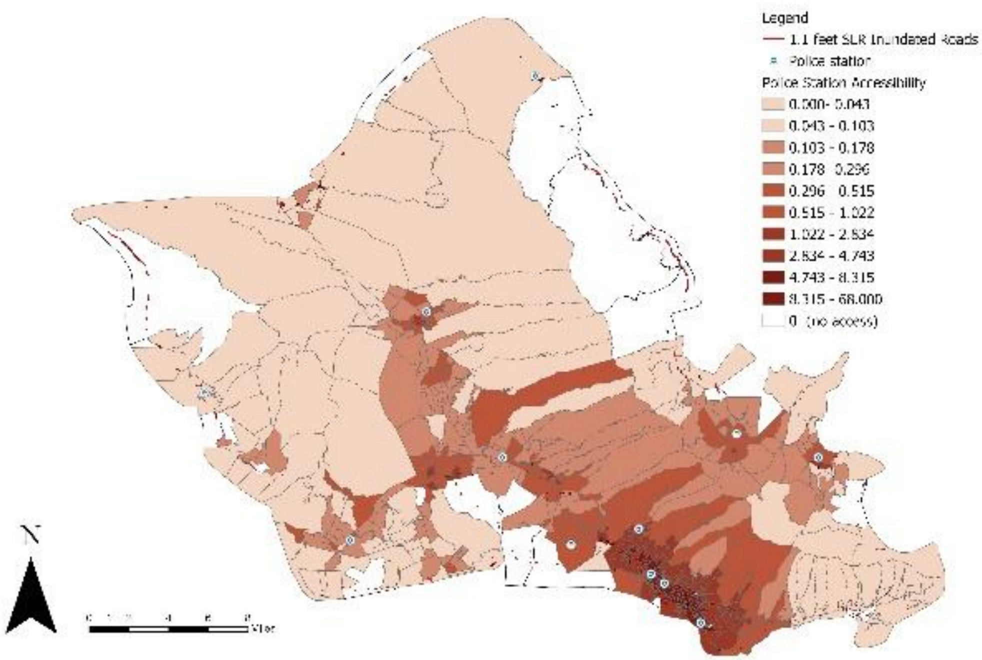


3.2 feet

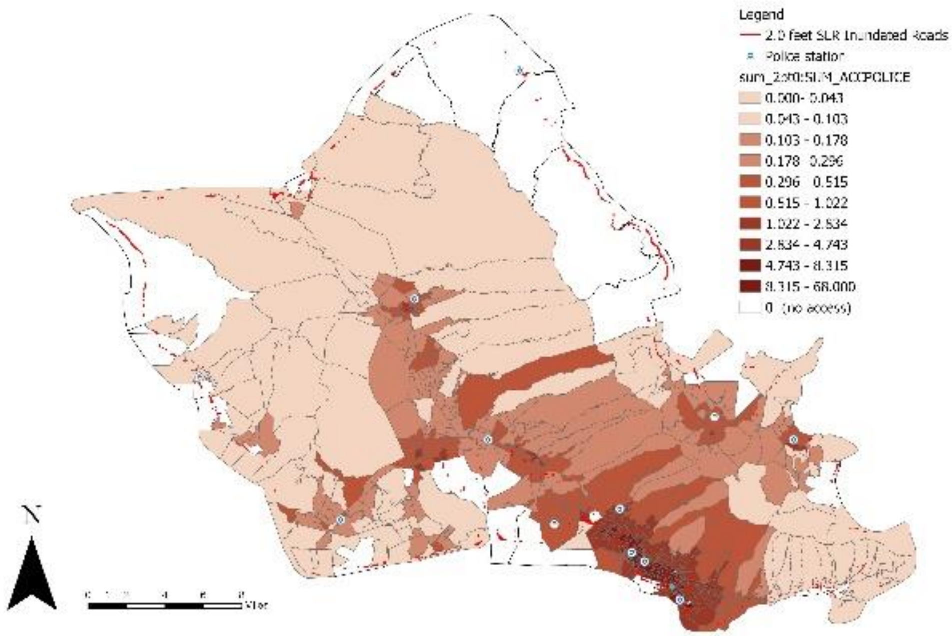
Figure 8. Changes of accessibility to fire station of each TAZ



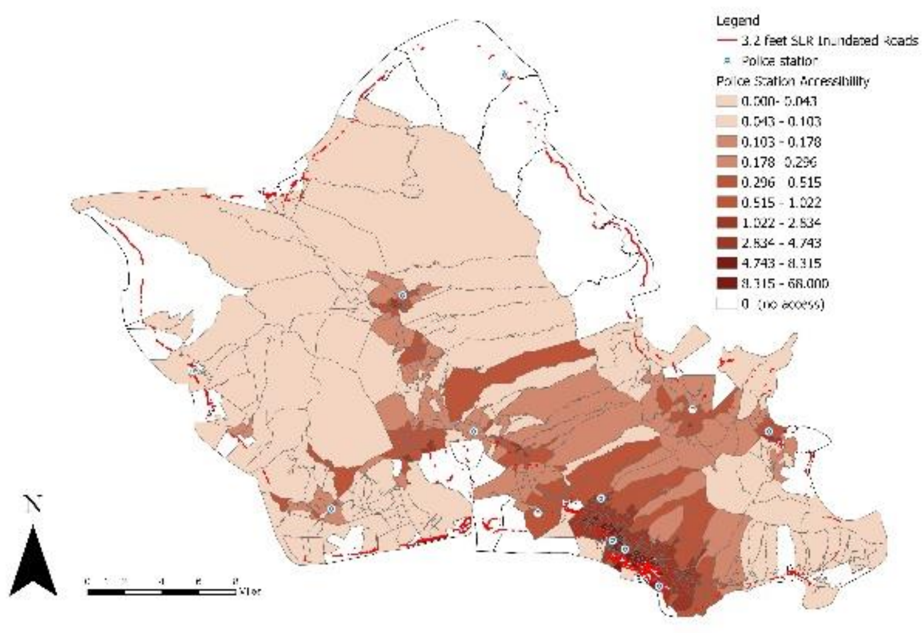
Current



1.1 feet



2.0 feet



3.2 feet

Figure 9. Changes of accessibility to police station of each TAZ

4.3 Accessibility Reduction of TAZs with Cluster of Elderly Population

According to the prediction by IPCC (2007), average sea level rise will be 1.1 feet in the middle of 21st century worldwide. Using CCR, the population in each TAZ has been predicted. Bivariate maps (Figure 10 - Figure 13) show the density of projected 65 years and older population (65+ population) in the mid-21st century for the year of 2056 and each TAZs' accessibility reduction to essential services under the projected 1.1 feet sea level rise scenario. TAZs with more population 65+ and high accessibility reduction are identified as the most vulnerable zones.

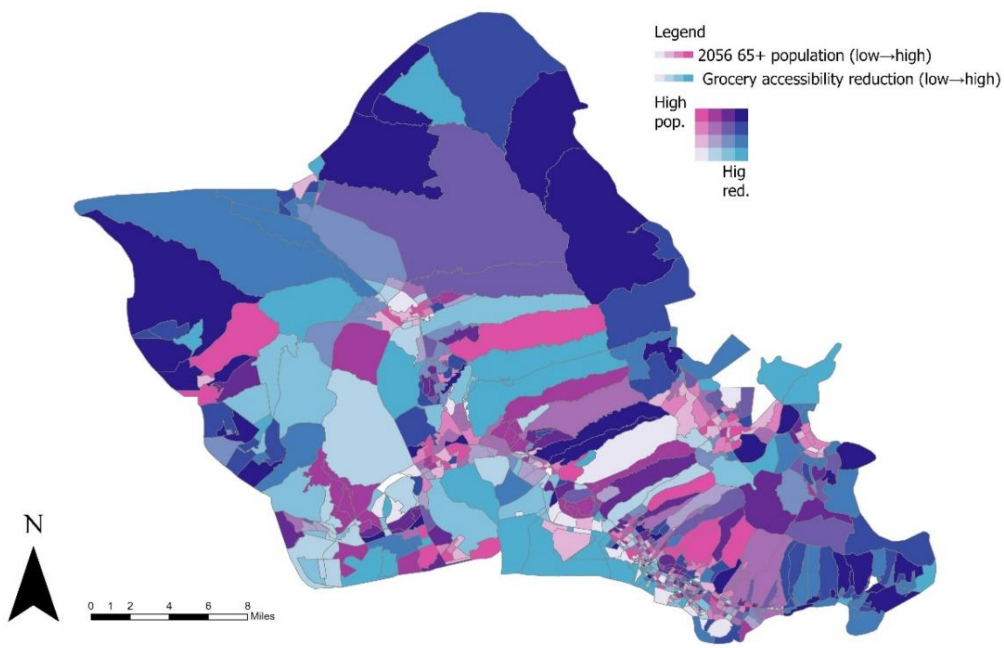


Figure 10. Bivariate map of 65+ population and grocery accessibility reduction in mid-21st century

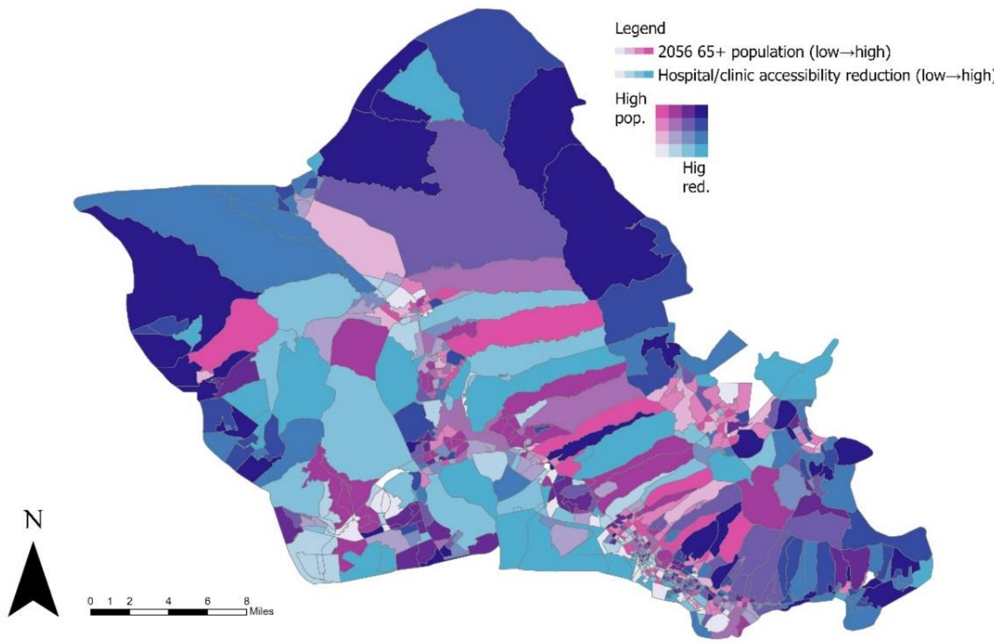


Figure 11: Bivariate map of 65+ population and hospital/clinic accessibility reduction in mid-21st century

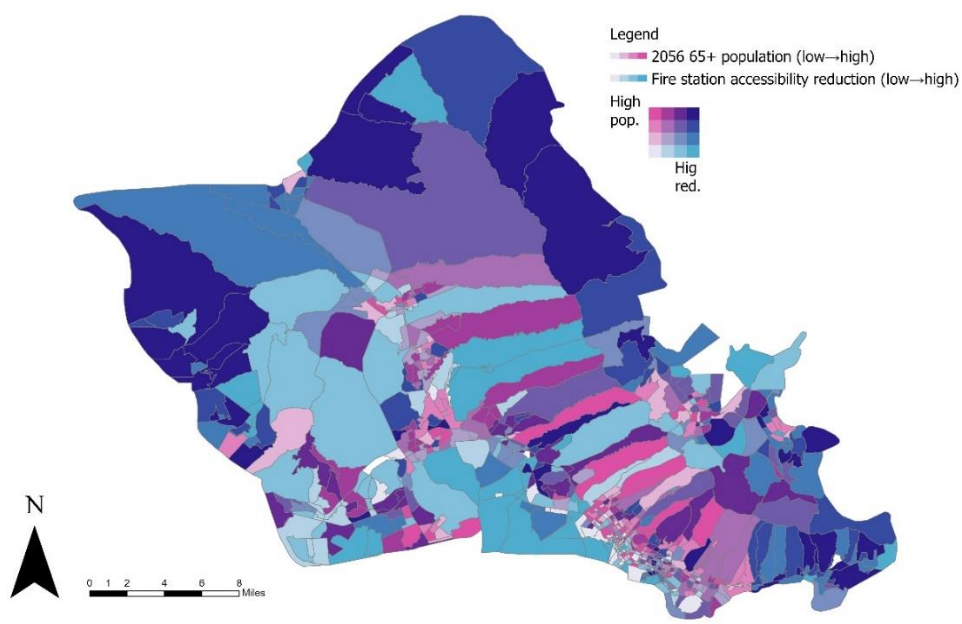


Figure 12. Bivariate map of 65+ population and fire station accessibility reduction in mid-21st century

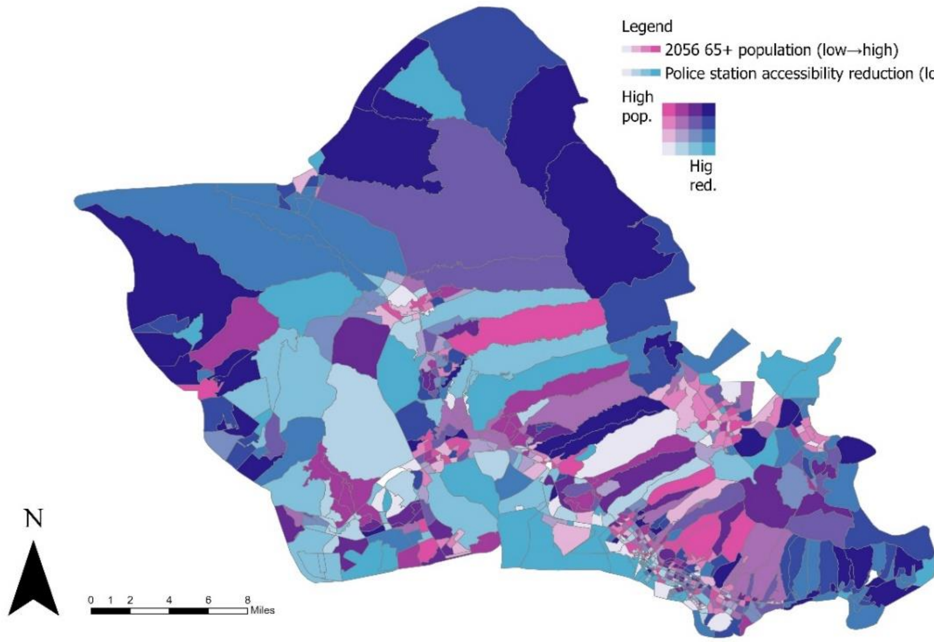


Figure 13. Bivariate map of 65+ population and police station accessibility reduction in mid-21st century

5 DISCUSSION

The result shows with the aging trend and transportation vulnerability, senior's accessibility to essential services will be significantly affected in the coming decades due to sea level rise. Honolulu urgently needs to apply strategies to adapt to the impact of sea level rise. If the current development and population growth trend continues, many coastal TAZs, especially the ones with clusters of new or planned development at the moment, will have a high 65+ population concentration in the mid-21st century, which will also have a huge accessibility reduction due to sea level rise. Some TAZs will lose accessibility due to sea level rise if the coastal roads remain *status quo*. IPCC (2007) also predicted the sea level will rise to 3.2 feet by the end of 21st century. It will cause even more significant damage to the coastal roads. Since all those scenarios are ascertain in decades, there are at least three basic strategies to mitigate the impact of road network cut: 1) rebuild coastal roads and lift roadbeds; 2) relocate residents; 3) relocate essential services. How to plan these adaptation strategies require careful and holistic planning across different sectors, with consideration of the tradeoffs between various objectives and goals as well as tradeoffs between present day needs verse future risk.

The opportunity-based accessibility applied in the study provides a good comparison of different types of accessibility under several sea level rises scenarios. The output of accessibility visualizes the change of accessibility in all TAZs. While many researchers agree that most accessibility measurements and tools are not enough to represent a fully developed picture of accessibility (Siddiq and Taylor, 2021), they also admit that a complicated accessibility measurement is hard to explain to government officials and the public. The opportunity-based accessibility model presented in bivariate maps in this study can provide a technically sound, multi-facet, yet easy-to-understand communication tool to identify where the most vulnerable areas are.

5.1 Elderly Population Patterns in the Mid-21st Century

According to the elderly population projection, elderly population will grow significantly in coastal areas in Honolulu in the mid-21st century. The elderly population high density areas are not only in the urban Honolulu but distributing all around the island (Figure 14). A TAZ with high density of older population is vulnerable to sea level rise and has high a need of all kinds of services. However, high elderly density TAZs outside urban are lack of essential services, and the inundation of certain essential services will make the situation worse.

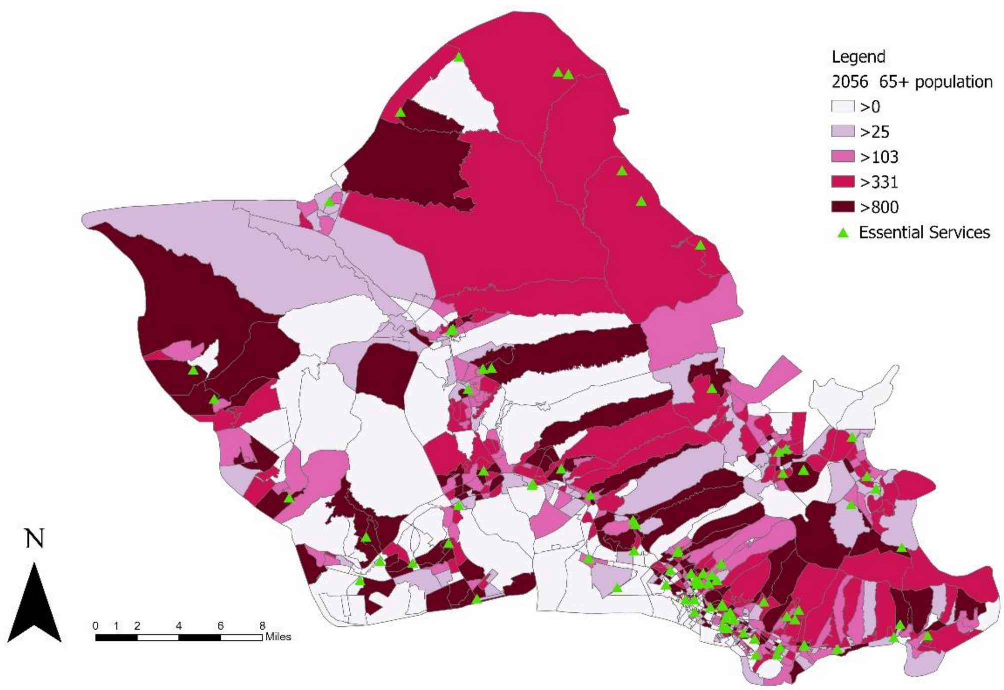


Figure 14. Projected 2056 65+ population in each TAZ

5.2 The Preferred Living Areas of Elders and Challenges of Relocation

When considering relocation as an adaptation strategy, there are two characteristics of elderly living preferences that should be noted: 1) elders prefer to live in the community they have the feeling of belonging (Wiles et al, 2012); 2) elders would rather live by oceans (Wang and Yarnal, 2012). Usually, older people desire opportunities to participate and attach to the community. Urban planners should consider mitigating the “mismatch” of the community design and needs of older people (Iecovich, 2014). People usually have a strong emotional bond with people and places they live (Hummon, 1992). Moreover, the low lying coastal areas in Hawaiʻi is quite appealing due to its charming climate and beauty. If affordable, many older seniors are willing to live in a house by beaches and enjoy the views. Those highlight the potential challenges of relocation. Castle (2001) reviews some successful relocation and finds three key elements: 1) an interdisciplinary team; 2) an appropriate assessment tool; 3) the environment of the receiving facility. In the case study, since the 1.1 feet sea level rise may not happen until mid-21st century, government should plan to relocate people currently in their 30s or 40s living in the risk zone to safe zones or at least plan future development in safer zones, so that by the mid-century, those cohorts of people who turns to their 60s or 70s, will have the strong community attachment in the safe zones, where they can have also maintain good accessibilities to essential services. Future research could be devoted to creating a relocation model that synthesizes projected population changes, accessibility reduction, and willingness to relocate to plan relocation holistically.

The relocation of essential services is another option. Essential services that will be impacted by sea level rise should consider relocating when there are opportunity windows. However, essential services should be relocated concurrently with resident relocation. That also provides opportunities to improve the spatial disparity in the existing accessibility to essential services, such as police stations. Planning for multimodal mobility hubs, mutual aid emergency programs, cross-jurisdiction collaboration are other options that should be enhanced with the projected risk (Shen, Feng, and Peng, 2016).

5.3 Limitation of the Research

The CCR population projection as a simplified projection model does not consider some demographic change elements, such as international immigrants, interstate immigration, and future land use changes. If data is available, future analysis should enhance the population projection with these considerations. This study does not project the entire population and calculate the ratio of elderly population. Calculating the ratio of elderly population in a TAZ helps planners evaluate the need of elders care. To improve the accuracy for facility vulnerability assessment, future study also should acquire more accurate geodata produced by latest technologies such as LiDAR and drone technologies to estimate flooding depths (Shen and Kim, 2020), especially the flood maps and elevation data acquired in this study may not capture the elevated interchange roads or bridges. While some corrections include eliminating flooding on elevated freeways have conducted on ArcGIS Pro manually to the best of the researchers' knowledge in this study, it may not capture all of those errors. With road surface elevation data obtained in future, a more accurate impact assessment can be performed. Another constraint is the population data with age distribution is provided at the TAZ level. However, some TAZs are large, and assuming the origin and destination points are the centroids of TAZs are not accurate. For example, some centroid locations of large TAZs don't have residents. Future studies could combine the density of housing parcels to generate the disaggregated distribution of population in large TAZs to improve the network analysis. The opportunity-based accessibility also only considers the trip between-TAZs. If more essential services can be captured within a TAZ, the accessibility of the TAZ would be greatly increased. However, the equations of accessibility used in this study are not considering travel within a TAZ. Future work could explore adaptation strategies to improve the intra-zonal trip generations. Finally, the future work can take traffic congestion into consideration and develop different accessibility scenarios with peak hour adjustment (Lei et al, 2012).

6 CONCLUSION

This study illustrates that the sea level rise will reduce accessibility to essential services in Honolulu, Hawaiʻi, and it will particularly impact elders' access to essential services. As the sea level rising, some essential services will be impacted by seawater and the damage to the coastal road and entire road network is increasing. Among the four types of essential services, access to hospitals and clinics in Honolulu will have less impact of sea level rise, while grocery stores, fire stations, and police stations are all vulnerable to the sea level rise.

This study highlights that some coastal TAZs will no longer have the accessibility to essential services by the mid-21st century. For communities at risk of being cut off, measures of lifting coastal roads or relocation should be considered in the short term. With the projected sea level rise and population growth in coastal zones, most coastal areas will face inaccessibility, relocation is strongly recommended for those at-risk areas. As many populated coastal areas, some essential services will be impacted by sea water in urban Honolulu, but the accessibility of most TAZs in urban Honolulu will not decrease as sharp as rural areas due to the high density of essential services. Considering the age-friendly Honolulu, there is still a lot of efforts to do to ensure better accessibility to the essential services for senior residents. Besides physical adaptation measures to infrastructures, integrated transportation and land use adaptation planning, the establishment of mutual aid programs, improvement in cross-sector collaboration, and enhancement of neighborhood multimodal mobility hubs are options that worth to be examined in future studies.

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