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Assessing the Vulnerability of Coastal Wastewater Infrastructure to Climate Change

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PACIFIC ISLANDS CLIMATE ADAPTATION SCIENCE CENTER

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Table of Contents

List of Figures

List of Tables

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Executive Summary

This study assessed the vulnerability of coastal wastewater infrastructure to climate change risks. Projected impacts to both central sewer systems and on-site disposal systems from several climate change and coastal hazard scenarios were evaluated using a vulnerability framework. Climate and coastal hazard scenarios included: future sea-level rise (SLR), category 4 hurricane and a tsunami. The island of Oʻahu, Hawaiʻi was selected as the study area for this project to develop a methodology, planning tools and assess potential impacts that could be applied to other islands. The specific objectives of this project were to:

- Estimate wastewater asset exposure to sea-level rise and other coastal hazards;
- Estimate sensitivities of wastewater assets to exposures;
- Map system-wide exposure and sensitivity of wastewater infrastructures to sea-level rise and other coastal hazards on Oʻahu;
- Develop planning tools to project potential impacts of wastewater exposures and sensitivities to climate risks;
- Identify opportunities and challenges for adaptation.

Study Area

Oʻahu is located near the middle of the Pacific Ocean, part of the chain of Hawaiian Islands that was formed with the Pacific Tectonic Plate passing over the mid-ocean hotspot. Oʻahu is the third largest Hawaiian island with 180 km of coastline and the state's vast majority of residents and tourists. With over 900,000 permanent residents, it hosts, on average, over 4.5 million tourists every year (Hawaiʻi Tourism Authority, 2015). Residential development, commercial and centers of tourism dominate the shoreline, along with supporting infrastructure. The vast majority of the resident population and tourists are concentrated in Honolulu in the southern portion of the island, much of which is connected to a centralized sewer system. Several small urban and newer suburban centers extend southwest into the Ewa Plains, along the eastern coastline of Kailua and Kaneohe, and into the center of the island. These areas contain a mixture of parcels that are either connected to a sewer or use an on-site disposal system to process their waste. The northern portion of the coastline contains a number of small rural towns most of which is dominated by on-site wastewater disposal systems.

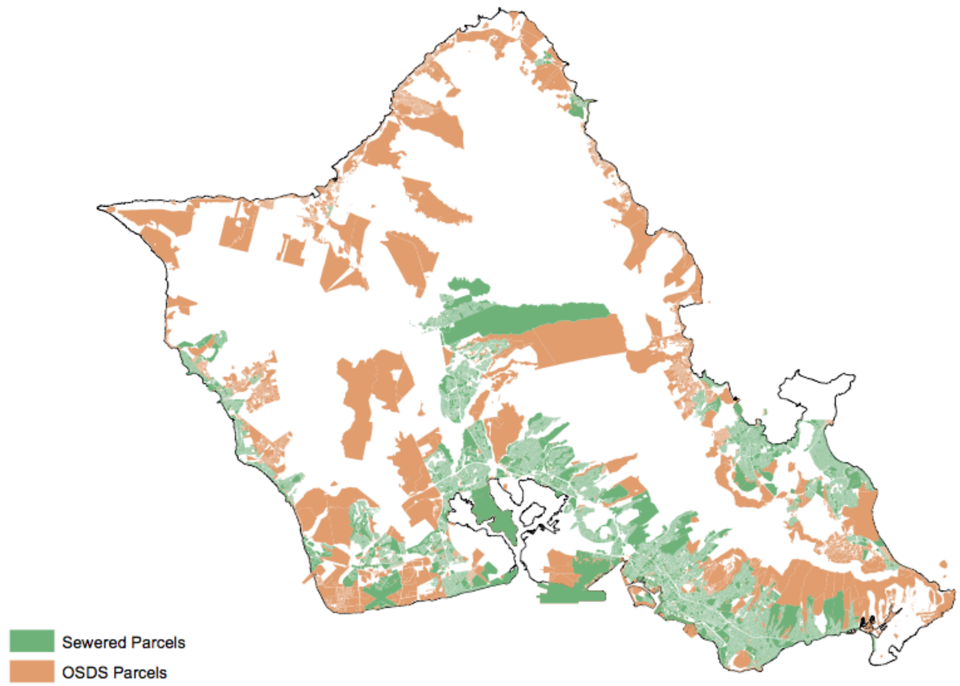

Figure ES-1: Map of centralized and decentralized wastewater infrastructure on O'ahu showing parcels that are sewered and unsewered with on-site disposal systems (OSDS)

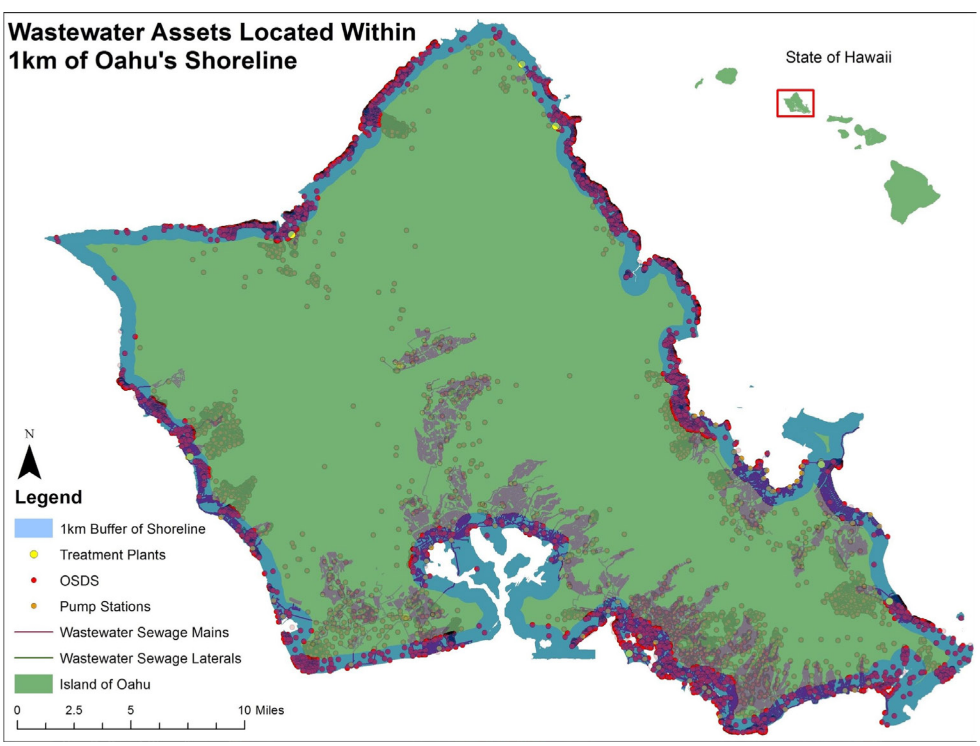

Figure ES-2: Map of all wastewater assets within 1km of coastline

Vulnerability Assessment

We adopted a vulnerability framework from the IPCC. Our approach involved:

- Mapping and estimating wastewater exposure by overlaying GIS data of climate scenarios and wastewater assets;
- Modeling and quantifying sensitivities of wastewater assets to sea-level rise;
- Integrating wastewater exposure data with sensitivities to develop a wastewater vulnerability index;
- Engaging key stakeholders throughout the research process.

Climate scenarios included in this project:

Table ES-1: Climate and coastal hazards scenarios

Climate scenario	Description
SLR-XA 1.1 feet	Three chronic flooding hazards modeled with 1.1 feet SLR: passive "bathtub" flooding, annual high wave flooding, and coastal erosion.
SLR-XA 3.2 feet	Three chronic flooding hazards modeled with 1.1 feet SLR: passive "bathtub" flooding, annual high wave flooding, and coastal erosion.
SLR 6.0 feet	Passive "bathtub" flooding modeled with 6 feet SLR by NOAA.
Hurricane Cat. 4	Category 4 hurricane storm surge of south shore Honolulu, modeled by UH- SOEST.
Tsunami	Tsunami inundation model using FEMA tsunami zones.

Wastewater assets we evaluated included sewer mains, laterals, pump stations, manholes, treatment plants, and on-site disposal systems.

Table ES-2. Wastewater asset categories

Wastewater Asset	Data Source
Sewer Main	Honolulu Land Information System (HoLIS)
Sewer Lateral	Honolulu Land Information System (HoLIS)
Manholes	Honolulu Land Information System (HoLIS)
Pump Stations	Honolulu Land Information System (HoLIS)
Wastewater Treatment Plants	Honolulu Land Information System (HoLIS)
On-site Disposal Systems	Hawaiʻi Statewide GIS Program

Wastewater Asset Exposure to Climate Hazards

Wastewater asset exposures were estimated using five climate hazards scenario layers.

Table ES-3. Wastewater asset exposures

Wastewater Asset	**Total Units on Oʻahu**	*1.1 ft. SLR-XA*	*3.2 ft. SLR-XA*	*6 ft. SLR (Bathtub)*	*Category 4 Hurricane*	*Tsunami Inundation*
Sewer Mains	1,601 miles (mi.)	50 mi.	112 mi.	192 mi.	138 mi.	190 mi.
Sewer Laterals	1,189 miles (mi.)	3 mi.	27 mi.	83 mi.	54 mi.	98 mi.
Manholes	49,514 manholes	130 manholes	1,128 manholes	3,845 manholes	3,101 manholes	3,804 manholes
Pump Stations	92 stations	1 station	5 stations	33 stations	14 stations	27 stations
WW Treatment Plants	9 plants	0 plants	0 plants	1 plant	1 plant	2 plants
On-site Disposal Systems	13,684 systems	475 systems	1,322 systems	1,105 systems	441 systems	4,592 systems

Wastewater Vulnerability Index

We developed a vulnerability index incorporating information about the sensitivity of each asset to a particular hazard exposure. To calculate the index, we use the formula:

$$V_i = \Sigma\ (w_k\ x_k)$$

Where V_i is the vulnerability for a specific type of climate exposure (*i*) and x_k is potential rating for each indicator (*k*). w_k is the weight of the indicator (*k*).

Results from the vulnerability index suggest:

- Sewer mains and OSDS assets are the most vulnerable across all of Oʻahu.
- The length of sewer mains and number of OSDS that are considered very vulnerable increases with the severity of the hazard.
- In the near term, over 10 miles of sewer mains are potentially exposed to 1.1 feet of SLR in the downtown Honolulu, Waikiki, Ewa Beach of Pearl Harbor, and Kaneohe areas and are highly vulnerable to SLR impacts.
- Also in the near term, approximately 475 OSDS will be vulnerable to 1.1 feet of SLR. Over 95% of these systems are highly vulnerable, most of them located in Hawaiʻi Kai, Kaneohe Bay, as well as clusters of older systems in Kalihi Kai industrial area and Waikiki.
- Waikiki and Mapunapuna contain vulnerable OSDS near vulnerable sewers.
- Very few (< 1%) of manholes appear vulnerable to SLR in the near-term. However, the number at risk increases nearly 10-fold under a 3.2 ft. SLR scenario and again more than triples under the three severe scenarios: 6 ft. SLR, category 4 hurricane and Tsunami.
- Similarly, only one pump station, the Enchanted Lake Wastewater Pump Station, is at risk under the 1.1 ft. of SLR scenario. However, the number of vulnerable pump stations increase exponentially with future SLR.
- The nine City & County of Honolulu operated wastewater treatment plants on Oʻahu remain safe from flooding in the near- and mid-term SLR scenarios. However, in the long-term scenario of 6 feet of SLR the Kahuku plant on the North Shore is flooded.
- In the event of a tsunami, the Kahuku and Waiʻanae plants are vulnerable to flooding.
- The Sand Island WWTP is vulnerable to potential flooding in the event of a category 4 hurricane storm surge.

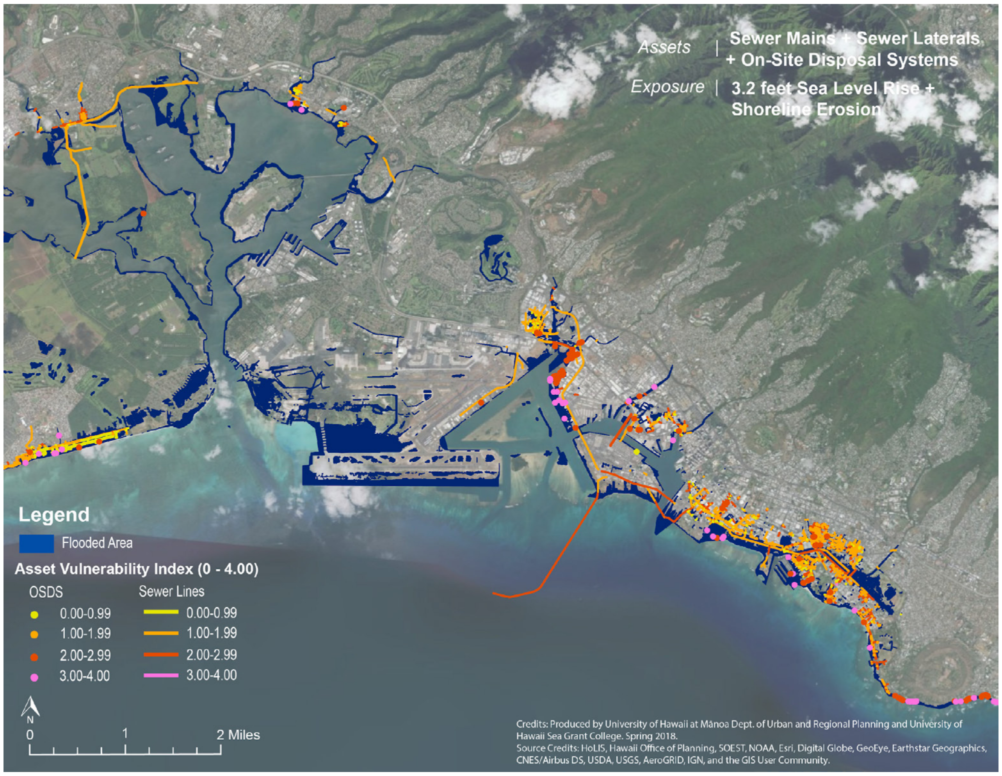

Figure ES-3: Map of vulnerable sewer mains and laterals and OSDS in Urban Honolulu with 3.2 ft. SLR

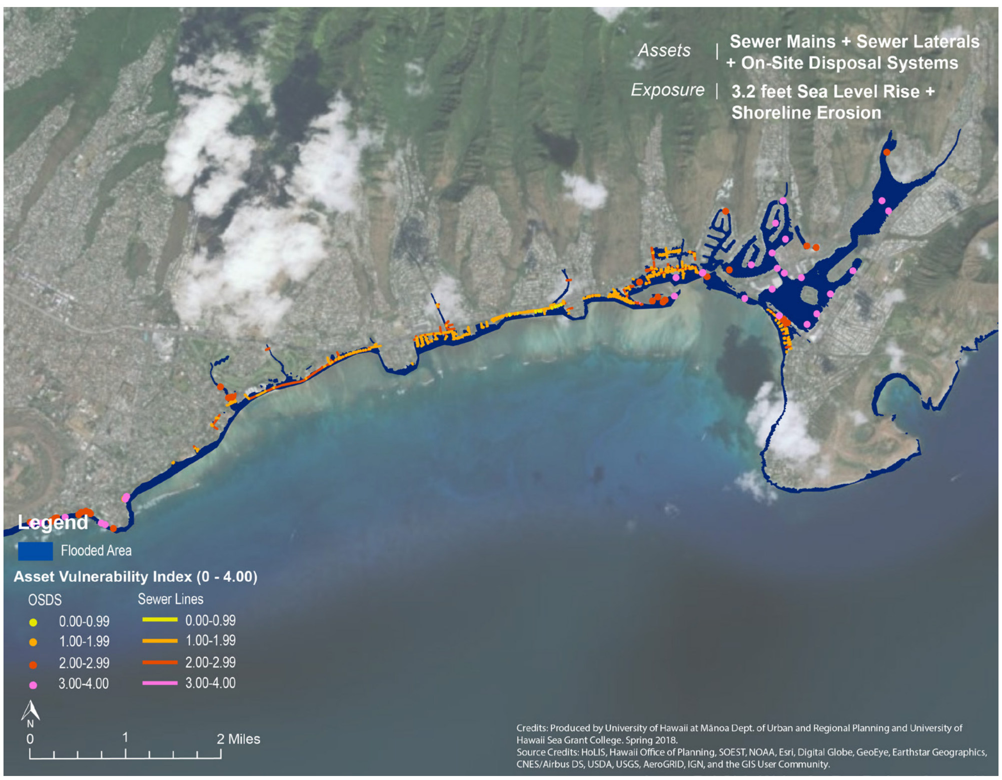

Figure ES-4: Map of vulnerable sewer mains, laterals and OSDS in East Honolulu with 3.2 ft. SLR

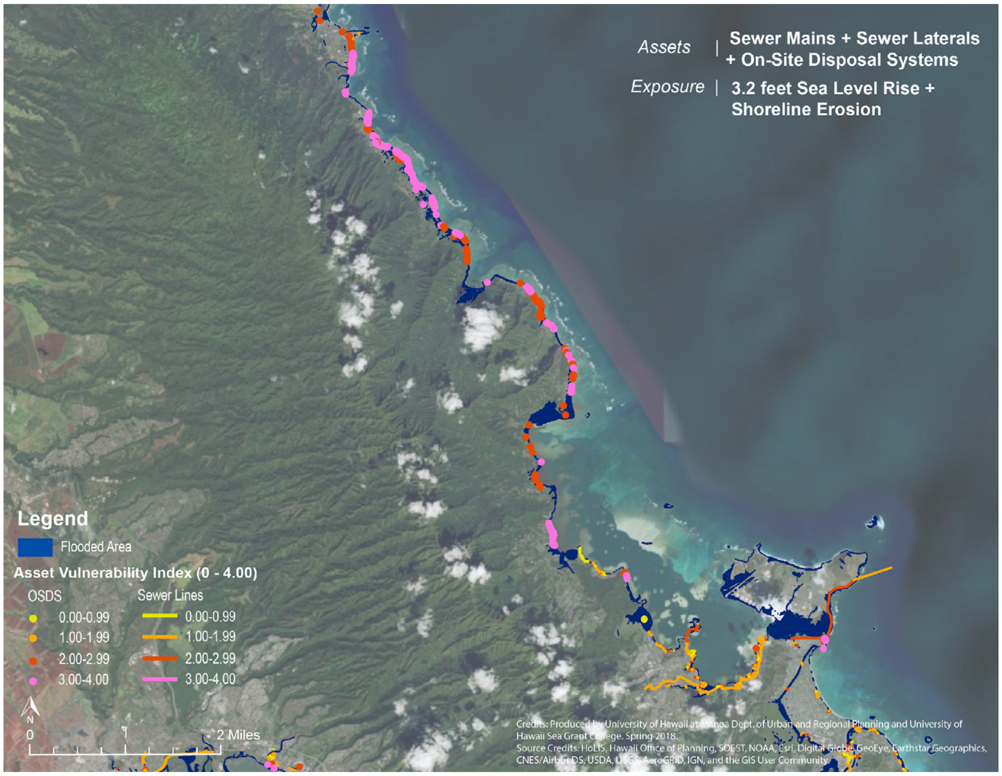

Figure ES-5:Map of vulnerable sewer mains and laterals and OSDS in Windward O'ahu with 3.2 ft. SLR

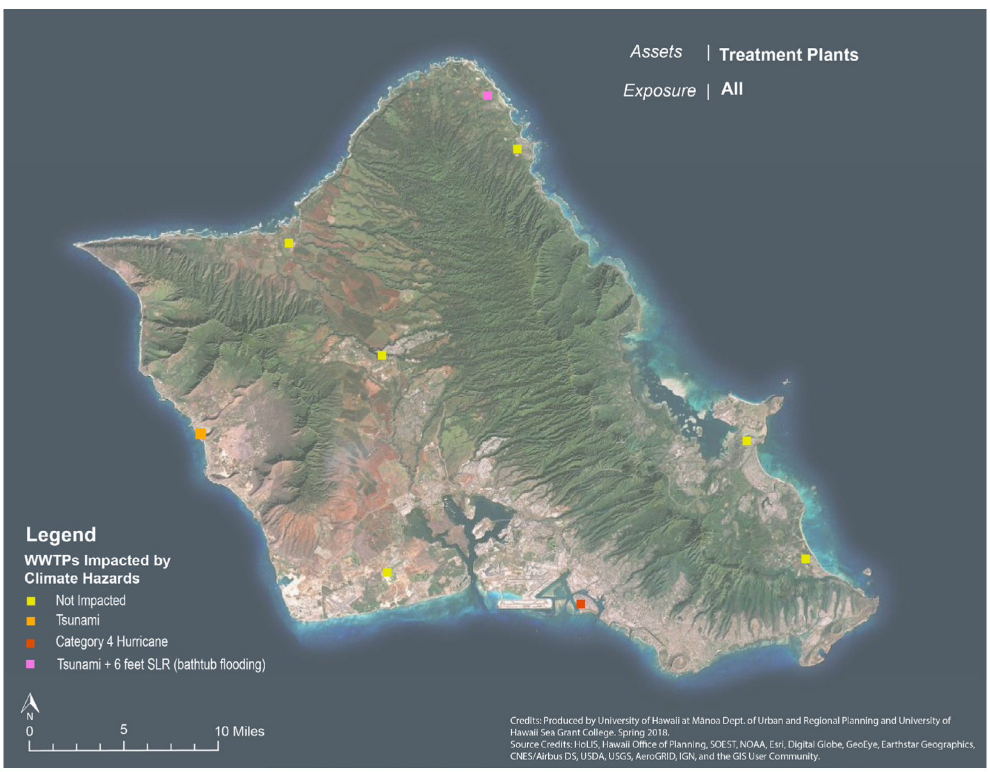

Figure.ES-6:Wastewater treatment plants vulnerable to climate and coastal hazards

Groundwater Infiltration of Coastal Sewer Pipes

Sensitivity Analysis of infiltration hydraulics

Two case studies were used to estimate how sensitive a sewer collection system is from future groundwater (GW) infiltration and the potential increase in sewer flows to the treatment plant. As the GW level (GWL) increases, the higher GW head above the pipes will lead to greater groundwater infiltration (GWI) into pipes through leaks and cracks. SLR will increase GWI entering the sanitary sewer system and will bring the total volume of sanitary sewer flow closer to the threshold that could trigger a sewer overflow. The two case studies we used were: downtown Honolulu collection system and an island coastal city (specific location is undisclosed at request of data owner). Together they present a practical method to add the computation of GWI to sewer system models in coastal collection systems that will be affected by SLR. This planning tool helps with projecting higher GWI flows and with prioritizing portions of the sanitary sewer system for adaptation.

We used GIS sewer main pipe data and a 2-dimensional solution for GWI into a sewer pipe, based on Darcy's law of flow through porous media and orifice flow into a pipe (Guo et. al, 2013).

- ***Results from downtown Honolulu:*** a relatively small percentage of the pipes in downtown Honolulu are currently affected by GWII (about 1.4% (1,705 ft.) of the total length) and as SLR increases, the amount of pipes affected initially increases slowly, such that only 2,400 ft. are affected when SLR reaches 1 ft. and 4,500 ft. are affected at 3 ft. of SLR. This might occur by 2050 in Honolulu and it should be entirely feasible to rehabilitate less than one mile of sewer pipes before then. However, after that the increases become larger and the penalty for waiting to start rehabilitation or not doing it at all becomes problematic/severe.
- ***Results from the tropical coastal city:*** After a SLR of 1.0 and 2.5 meters, the GWI increases to 0.11 MGD and 0.21 MGD, respectively. Averaging the percent changes over the dry weather flow days, these equate to 211 percent (%) and 500% flow increases, respectively. These are clearly very large increases that should be considered in planning exercises, especially, the 1.0 meter case (3.2 ft.), which could occur between 2060 and 2100.
- Projections from this tool can be used in combination with other tools, such as mapping, to visualize sections of the sanitary sewer system that will be more prone to sea level rise impacts and to prioritize areas in the sanitary sewer system that needs rehabilitation and adaptation to future sea level rise.

On-site Disposal Systems and Policy Gaps in Wastewater Management

The state has made important strides to improve decentralized wastewater management by requiring cesspool conversions in priority areas by 2050 to either another on-site technology or sewer hook-up. On Oʻahu, a large number of OSDS are located close to the shoreline, which, with the advent of sea level rise compounds the need to replace these systems due to the impacts of future erosion, flooding and groundwater levels rising. While more advanced OSDS technologies offer a potential solution to cesspools, best practices for OSDS wastewater management is critical to ensure future systems function in the long run and watersheds retain the capacity to sufficiently process effluents and nutrients.

We performed a policy gap analysis to help identify program gaps in Hawaiʻi's wastewater management programs. Results suggest that future OSDS may also fail due to insufficiencies in programs, activities and regulations in key management areas:

- ***Need to integrate land use planning with decentralized (OSDS) wastewater planning***: DOH rules set site criteria (e.g. soils, set back distances) but there is no mechanism for considering the cumulative impact of increasing numbers or density of OSDS. County land use zoning does not address OSDS directly. ***Recommendation: Counties develop wastewater management plans (similar to existing Water Use and Development Plans that set performance goals and aim to integrate land use).***
- ***Establish performance based management goals*** for individual on-site treatment systems based on landscape, soils, proximity to sensitive ecosystems, future environmental conditions.
- ***Create and maintain an inventory of all OSDS*** to help plan, manage, monitor and report on systems, and to share data across agencies.
- ***Need policy and/or systematic education & outreach to ensure homeowners maintain OSDS systems.*** *At minimum, use construction permits and public outreach. More advanced programs include preventative Maintenance Ordinance, counties inspect existing systems by requiring time of transfer inspection or require mandatory inspections using renewable permits.*

Opportunities and Challenges for Adaptation

Challenges:

- Very high concentration of vulnerable OSDS north of Kaneohe Bay right along the coast where there is no sewer service. If these systems convert to either another on-site technology or sewer system, will need to make future technology is resilient to future SLR conditions.
- Policy gaps in decentralized wastewater management require policies and actions at county level, state levels as well as coordination across county-state agencies.

Opportunities:

- A large number of OSDS are within areas with sewer service availability. But the City & County need to consider how vulnerable these same sewers are to future SLR.
- Priority areas for sewer rehabilitation should consider groundwater infiltration (GWI) from future SLR. Impacts appear minor in the near-term (with 1 ft. of SLR) however GWI impacts to sewer flows could increase dramatically by mid to late century. A planning model that takes into account existing pipe defects and the length of pipe submerged can help prioritize areas for adaptation.
- In the near-term, pump stations and treatment plants are safe from SLR induced flooding or erosion, but similarly, we can expect by mid- to late century, some of these assets will become vulnerable. In the near-term, resizing or increasing redundancy of systems within the plant may be possible. However, in the long-term, the City and County will need to assess cost and feasibility of either hardening or relocating some of these facilities.

Definitions & Acronyms

Definitions

The terms that are defined below come from the City and County of Honolulu Wastewater System Design Standards (2017):

"Infiltration" means water other than sanitary wastewater that enters a sewer system from the ground through defective pipes, pipe joints, connections or manholes. Infiltration does not include inflow.

"Inflow" means water other than sanitary wastewater that enters a sewer system from sources such as roof leaders, cellar/foundation drains, yard drains, area drains, drains from springs and swampy areas, manhole covers, cross connections between storm sewers and sanitary sewers and catch basins. Inflow does not include infiltration.

Sewer System – the system of piping, pumping station, force main, and treatment plant with appurtenances for collecting, conveying and treating sewage from source to discharge. Used interchangeably with *collection system*.

Wastewater – means the spent water of a community, which may include a combination of the liquid and water-carried wastes from residence, commercial building, industrial plants, and institutions, together with any groundwater, surface water, and storm water that may be present. Used interchangeably with *sewage*.

Wastewater Asset – a comprehensive term, which includes facilities for collecting, transporting, pumping, treating and disposal of wastewater.

Wastewater System – the category of all wastewater and wastewater sludge conveyance, treatment, use, and disposal systems, including all wastewater collection systems (sewers, pump stations and force mains), treatment works, wastewater sludge facilities and recycled water systems.

The definitions below come from the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (2014):

Climate Change – A change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties that persist for an extended period, typically decades or longer.

Climate Variability – The variations in the mean state and other statistics (e.g., standard deviations, the occurrence of extremes) of the climate on all spatial and temporal scales beyond that of individual weather events. Examples of climate variability include inter-annual El Niño and La Niña events that occur every two to seven years and influence weather patterns over vast regions of the globe.

Exposure – The presence (location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage.

Vulnerability – The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Sensitivity – The nature and degree to which a system is exposed to significant climatic variations. Sensitivity and exposure lead to impacts as consequences of climate change on natural and human systems.

Adaptive Capacity – the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Acronyms

ART	The Adapting to Rising Tides Project
ATU	Aerobic Treatment Unit
CO2	Carbon Dioxide
CZMP	State of Hawai‘i Coastal Zone Management Program
EPA	US Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
GW	Groundwater
GWI	Groundwater Infiltration
GWL	Groundwater Level
Hawai‘i OP	Hawai‘i State Office of Planning
HoLIS	Honolulu Land Information System
IPCC	International Panel on Climate Change
MGD	Million Gallons per Day
MSL	Mean Sea Level Rise
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
OSDS	On-site Disposal System
RDII	Rainfall Derived Inflow and Infiltration
SLR	Sea Level Rise
SLR-XA	Sea Level Rise Exposure Area
SSO	Sanitary Sewer Overflow
WWTP	Wastewater Treatment Plant

I. Introduction

Clean water is vital for stable economic growth as well as human and environmental health. Water, wastewater services, and other critical infrastructure enables communities to prosper while protecting sensitive habitats and species. Our increasing understanding of climate change suggests that our infrastructure is vulnerable to disruptions and failures. The Hawai‘i Sea Level Rise Vulnerability and Adaptation Report (2017) found infrastructure in Hawai'i's coastal areas to be especially vulnerable to sea level rise impacts, such as chronic flooding and erosion. Disruptions and failures of wastewater services resulting from these impacts can lead to major societal costs and have adverse impacts on coastal and aquatic ecosystems, as well as public health.

Wastewater Treatment Infrastructure On O‘ahu

The goal of wastewater treatment is to reduce or remove organic matter, solids, nutrients, disease-causing organisms and other pollutants from the wastewater prior to it being discharged into the environment. On O‘ahu, there are different forms of wastewater pollution control, namely publically owned wastewater treatment systems and privately owned systems. Publically owned and managed wastewater collection systems, also known as sanitary sewers, are designed to only carry wastewater, while a separate drainage system collects storm water run-off (Department of Environmental Services, 2018).

Wastewater treatment and collection systems collect, convey, treat, and discharge wastewater through an interconnected network of underground pipes, structures and facilities (San Francisco Conservation and Development Commission, 2012). These pipes, structures and facilities, which are called wastewater assets, function together to provide critical services to the communities they serve. These structures and facilities can be categorized into three groups: wastewater collection assets, wastewater treatment assets, and wastewater discharge assets. Below we summarize publically owned wastewater assets.

Wastewater Collection Assets

Wastewater collection assets transport wastewater from its source to treatment and discharge facilities. These assets include sewers, manholes, and pump stations. Sewers are pipes that convey and carry wastewater and are the most prevalent wastewater collection asset. On O‘ahu, the City and County of Honolulu operates and maintains public sewer pipes, which convey wastewater with the assistance of gravity along a downward-sloping pipe gradient (Owens, 2010). Sewer laterals connect individual properties to the main collection system, and sewer mains transport wastewater into a larger sewer, a pump station or directly to a treatment facility (Department of Environmental Services, 2018).

Manholes are simple openings in a sewer built for the purpose of convenient access to maintain or repair a sewer line.

Pump stations are important components of conventional gravity wastewater collection systems. Pump stations lift wastewater at points throughout the transport system. In pump stations, also called "lift stations," force mains use pressure to transport wastewater from lower to high elevation to a point where wastewater flows by gravity towards treatment and discharge assets.

Oʻahu generates approximately 117 million gallons of wastewater per day (Department of Environmental Services, 2018). The wastewater originates from a myriad of domestic and industrial sources from homes and workplaces connected to the sewer system, travels through a network of 2,100 miles of pipes, assisted by gravity and 92 pump stations, and eventually reaches one of the nine treatment plants on the island (Department of Environmental Services, 2018).

Wastewater Treatment Assets

Wastewater treatment plants (WWTPs) are assets that treat wastewater by separating solids, removing dissolved organic material, and killing harmful micro-organisms before being discharged into receiving waters (Owens, 2010). Wastewater treatment is categorized into four levels:

- Primary treatment – removes solids by filtration, sedimentation, and chemical coagulation;
- Secondary treatment – removes most of the organic matter in the wastewater using biological processes to breakdown of solid particles;
- Tertiary – removes additional organic matter, nitrogen, phosphorus, or toxics resulting in 95 percent of suspended matter removed; and
- No discharge – includes facilities that reuse wastewater, discharge to an underground aquifer, or disperse of wastewater via methods such as irrigation or evaporation (State of Hawaiʻi Department of Health – Clean Water Branch, 2018; Department of Environmental Services, 2017)

On Oʻahu, the City and County of Honolulu operates nine publically owned WWTPs with varying levels of treatment (Table 2-1). These plants treat the wastewater before discharging it back into the environment through various means.

Wastewater Discharge Assets

After treatment, the treated water is released into the environment. Most of Oʻahu's treated wastewater is released into the ocean or underground. Wastewater discharged into the ocean use deep ocean outfalls, which discharge more than one mile offshore. Wastewater can also be discharged underground into injection wells, which place fluid underground into isolated wells so that injected fluids do not migrate or pollute underground sources of drinking water (State of Hawai‘i DOH – Clean Water Branch, 2018).

Table 1-1: Public wastewater treatment assets on O‘ahu

WWTP	Service Area	Average Daily Treatment Capacity	Level of Treatment	Discharge
Honouliuli WWTP	Halawa, Foster Village, Aiea, Waimalu, Pearl City, Pacific Palisades, Waipio, Waikele, Waipahu, Ewa Beach, Barbers Point, Kapolei, Ko Olina, Makakilo, Kunia, and Mililani	27.71 million gallons per day (mgd)	Advanced Primary & Secondary	Deep ocean outfall – 1.6 miles offshore
Kahuku WWTP	Kahuku	180,000 gallons per day (gd)	Secondary	Injection wells – 100 foot depth
Kailua Regional WWTP	Ahuimanu, Kaneohe, Kailua, Aikahi Park, Maunawili, Kailua Heights, Enchanted Lake, and Lanikai	14.17 mgd	Secondary	Deep ocean outfall – 5,083 feet offshore
Laie WRF	Laie	480,000 gd	Secondary	Secondary party for reclamation
Paalaa Kai WWTP	Paalaa Kai (between Haleiwa and Waialua)	110,000 gd	Secondary	Injection wells
Sand Island WWTP	Kuliouou, Kahala, Kaimuki, Waikiki, Manoa, Makiki, downtown Honolulu, Kalihi, and Salt Lake	68.58 mgd	Advanced Primary	Deep ocean outfall – 2.3 miles offshore
Wahiawa WWTP	Wahiawa Town, Whitmore Village, and a U.S. Military Facility (NCTAMS EASTPAC)	1.48 mgd	Tertiary	Wahiawa Reservoir freshwater outfall
Waianae WWTP	Nanakuli, Lualualei, Maili, Waianae, and Makaha	3.69 mgd	Advanced Primary & Secondary	Deep ocean outfall – 1.2 miles offshore
Waimanalo WWTP	Makapuu Point to Bellows AFB (not all of the area is sewered)	540,000 gd	Secondary	Injection wells – 200 foot depth

Private Wastewater Assets

Not all wastewater collection systems on Oʻahu are publically owned and managed by the City & County of Honolulu. The largest private system is located in east Honolulu and is owned and operated by the American Water Works Company (Whittier and El-Kadi, 2014). Major military bases also operate their own treatment systems including Schofield Barracks, Marine Corps Base Kaneohe and Pearl Harbor. The Navy Wastewater Treatment Plant located on Joint Base Pearl Harbor-Hickam in the Ewa district of Oʻahu treats approximately 5.5 million gallons of both domestic and industrial wastewater per day (NAVFAC, 2013).

The domestic wastewater of nearly one quarter of all households in Hawaiʻi is treated on site with an individual on-site wastewater treatment systems, also called an on-site disposal system (OSDS) (Whittier and El-Kadi 2014). Decentralized OSDS are used worldwide as a means to treat domestic wastewater from individual households or small groups of buildings on-site. Common individual systems include septic systems with absorption beds, cesspools, aerobic treatment units (ATUs) and composting toilets. In Hawaiʻi, over 80 percent of the estimated 110,000 on-site systems are cesspools. Cesspools are simple, infiltration structures that provide only collection and retention of solid materials with immediate release of liquid waste into the subsurface soils (Whittier and El-Kadi 2009). On Oahu there are an estimated 14,606 number of OSDS (Whittier and El-Kadi, 2014).

On Oʻahu, the majority of the population is concentrated along the southern coastal plain from the east end of the island to the Ewa Plain on the southwestern side of Pearl Harbor. There are also smaller residential urban areas such as Mililani, Waiʻanae, Kaneohe, and Kailua. These more densely populated areas are served by central wastewater collection systems. Less populated rural areas on the North Shore and along the Windward coast utilize on-site wastewater disposal systems.

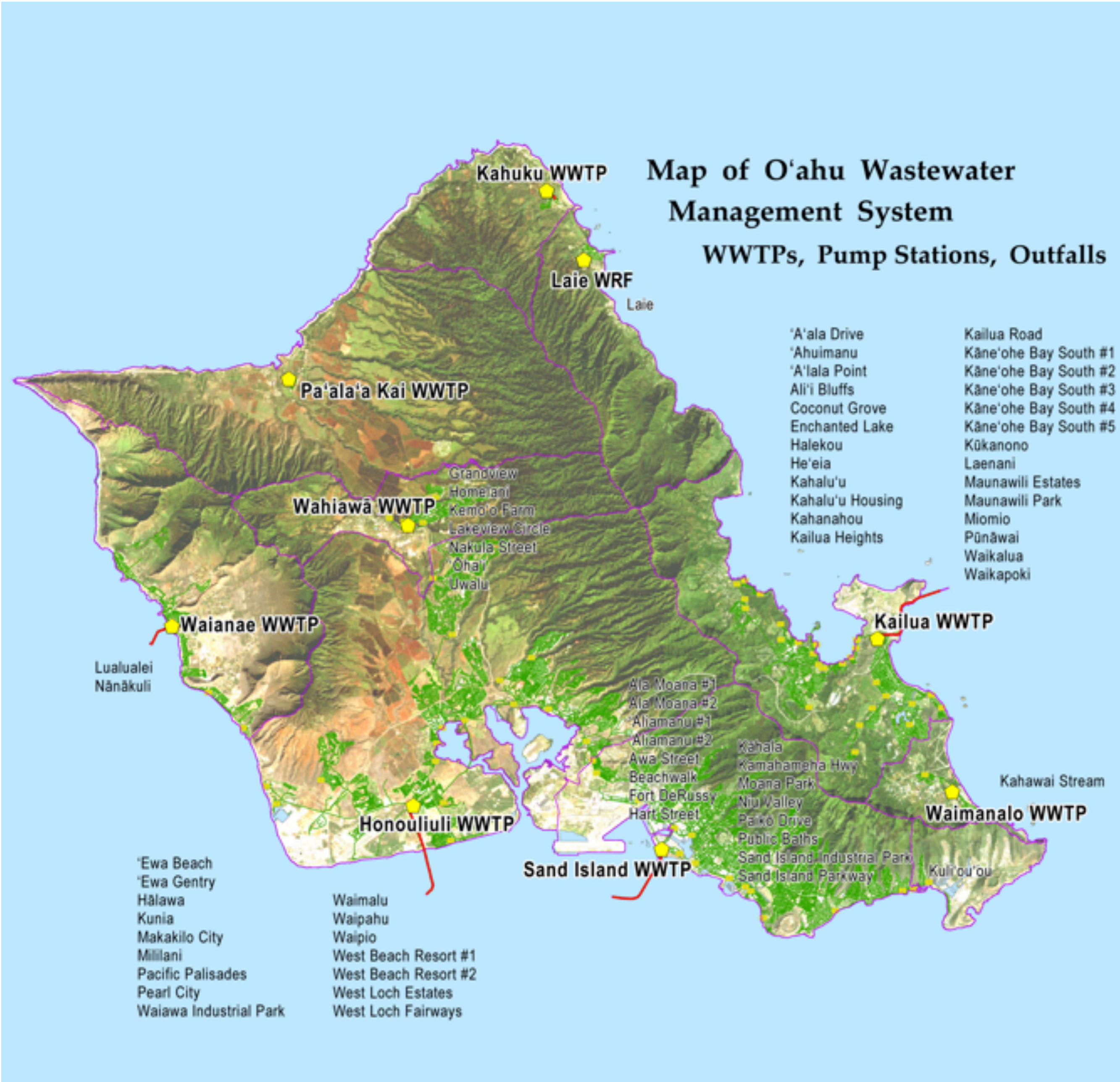

Figure 1-1: Map of Oʻahu Wastewater Management System (City and County of Honolulu Department of Environmental Services)

Vulnerability of Wastewater Infrastructure to Climate Change

Climate change is projected to increase coastal flooding due to rising sea levels, coastal erosion, and stronger and more frequent coastal storms (Marra et al., 2017). Climate variations caused by climate change are also expected to alter precipitation patterns with longer periods of drought and more intense and extreme rainfall patterns. In Hawaii, projections indicate that the windward slopes will see enhanced trade wind showers but an overall drier wet season (Marra et al., 2017).

The changes in precipitation patterns and sea level rise raise concerns for wastewater and drainage systems on Oʻahu (Hawaiʻi Climate Change Mitigation and Adaptation Commission, 2017). Existing wastewater infrastructure are vulnerable when exposed to saltwater intrusion, groundwater inundation, increased heavy rainfall, or any combination of the three. The projected increases in coastal flooding events could overwhelm portions of existing systems, particularly those with insufficient design and/or capacity to withstand the impacts.

In coastal areas, wastewater assets close to the shoreline may also be impacted due to receding shorelines and wave run up. Exposure of assets to climate variation and related hazards results in greater vulnerability of system as a whole. Events such as prolonged flooding and saltwater inundation can disrupt wastewater conveyance, treatment, and discharge processes if components such as pumps, motor controls, and other electrical systems cease to operate when they get wet (San Francisco Conservation and Development Commission, 2012). Saltwater inflow into a system could also lead to early corrosion of equipment and pipes (Azevedo de Almeida and Mostafavi, 2016). Furthermore, erosion adds pressure on buried pipes and can also impact the topographical gradient driving gravity flow systems, thus causing backups or overflow during flooding events (Azevedo de Almeida and Mostafavi, 2016).

When wastewater infrastructure fails, the consequences are felt in the public realm. When sewage systems are overwhelmed, there is an increased risk of overflow or spillage known as sanitary sewer overflows (SSOs). SSOs are permit violations that result in fines, cause property damage and threaten public and environmental health. Raw sewage may out of manholes onto public streets, into streams or into coastal waters before it can reach treatment facilities. Other consequences include back-ups of toilets and structural damage of septic tanks and mixing of sewage with floodwaters that could result in direct human contact.

Long-term chronic flooding from impacts such as sea level rise or short-term flooding from extreme weather events may cause sewage to contaminate streams and coastal waters. Understanding which infrastructure is most vulnerable in order to develop and implement appropriate adaptation strategies can, however, substantially reduce disruptive risks. Thus, the goals of this research was to: 1) Estimate wastewater asset exposure to sea-level rise and other coastal hazards; 2) Estimate sensitivities of wastewater assets to exposures; 3) Map system-wide exposure and sensitivity of wastewater infrastructures to sea-level rise and other coastal hazards on Oʻahu; 4) Develop planning tools to project potential impacts of wastewater exposures and sensitivities to climate risks; and 5) Identify opportunities and challenges for adaptation.

II. Conceptual Framework

For this study, we adopt the Intergovernmental Panel on Climate Change (IPCC) definition of vulnerability, which defines vulnerability as the propensity or predisposition to be adversely affected by climate variations. Vulnerability encompasses a variety of concepts including the magnitude or rate of climate variations or hazards to which a system is exposed, the sensitivity or susceptibility to harm of a system, and the capacity of a system to cope and adapt to climate variations or hazards (IPCC 2014). As such, vulnerability to climate change is a function of the potential climate change exposures, the sensitivity to climate change exposures, and the adaptive capacity of the system.

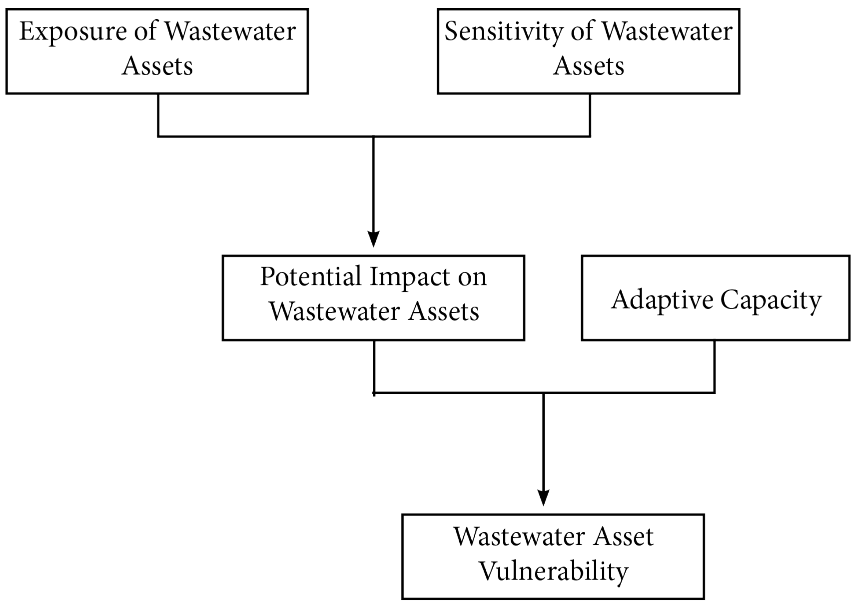

Figure 2-1: Conceptual framework used to assess the vulnerability of wastewater infrastructure to climate change (adapted from IPCC WG2, AR4, 2007)

Wastewater Assets

A wastewater asset is a public or private infrastructure that is part of system or network, such as a sewer collection system (Ugarelli et al., 2007). We consider several different kinds of wastewater assets that are potentially exposed to climate change: sewer mains and laterals, manholes, pumping stations, and wastewater treatment plants. We also include individually owned and operated on-site disposal systems, which are not connected to a central sewer collection system.

Sea Level Rise and Coastal Hazards

The conceptual framework above (2-1) adapts the IPCC framework for assessing vulnerability to focus on factors that affect the vulnerability of wastewater assets to SLR and other coastal hazards tied to climate change. These scenarios include:

1. 1.1 feet of sea level rise
2. 3.2 feet of sea level rise
3. 6 feet of sea level rise
4. Category 4 hurricane storm surge
5. Tsunami inundation

According to the IPCC and the National Oceanic and Atmospheric Administration (NOAA), sea levels are projected to continue rising into the future. Though scientific projections have estimated temporal frames, for each of the sea level rise scenarios above, the rate of increase is uncertain. The scenarios we use in our framework should be viewed as dynamic and are an approximation of changes that will likely happen over an extended period of time.

Additional factors affecting the vulnerability of wastewater assets will be compounded or induced by increasing sea levels. SLR is expected to induce more frequent flooding from wave run-up or seasonal high tides and intensify shoreline erosion (Marra, et al., 2017). Additionally, SLR will also affect freshwater resources and cause inland flooding in low-lying areas due to elevated groundwater levels and saltwater intrusion.

We chose to look at category 4 hurricane storm surge and tsunami inundation scenarios, which are based on current conditions and model the impacts of each climate hazard with the current context. These dynamic hazards are different from long-term hazards like SLR because they cause sudden and severe effects in a short period of time

Exposure

Our conceptual framework takes into account the exposure of wastewater assets to each of the scenarios above along with the sensitivity of different assets to understand the potential impacts of SLR on the wastewater system.

Exposure refers to the presence of specific assets and services in places and settings that are adversely affected by SLR or other coastal hazards tied to climate change. The exposure units within our conceptual framework are wastewater assets that are subjected to any of the SLR and coastal hazards outlined above.

Sensitivity

Sensitivity is the "nature and degree to which a system is exposed to significant climatic variations" (IPCC, 2014). This denotes the response relationship between a system's exposure to changes to the climate and the resulting impacts. Thus, within our conceptual framework, sensitivity is the degree to which a wastewater asset would be physically or functionally impaired if exposed to SLR or other coastal hazards tied to climate change (San Francisco Conservation and Development Commission, 2012).

Adaptive Capacity

Lastly, adaptive capacity is defined as "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (IPCC, 2014). When implemented successfully, actions that increase a system or asset's adaptive capacity may lessen or eliminate impacts by reducing its exposure or sensitivity to changes to the climate or hazards (Fussell & Klein, 2006).

Together, these factors influence how we conceptualize wastewater asset vulnerability to climate change.

Our Approach

Building from our conceptual framework, this project takes a stakeholder-driven approach, engaging key stakeholders throughout the research process. Our approach encompasses three phases:

Phase I – identify key knowledge gaps in understanding wastewater infrastructure to sea level rise.

Phase II - Assess facility-level and individual on-site system vulnerability of critical assets (e.g. pumps, pipes, on-site disposal systems); and determine importance of each asset by identifying the sensitivity of assets to various sea level rise stressors.

Phase III – Estimate a system-wide vulnerability of wastewater treatment using specific case study areas; project potential impacts with future sea level rise scenarios; and assess adaptive capacities of system.

Stakeholder Engagement

Key to this project is engaging vital stakeholders in the research process and outcomes with three goals in mind: 1) raise awareness of the need for climate ready utilities and infrastructures; 2) integrate climate change into long-term land use and wastewater infrastructure planning and investment decisions; 3) identify climate adaptation options, including planning, operational and capital/infrastructure strategies.

Stakeholder engagement took place with individuals who were specifically identified for their expertise and professional experience in wastewater or a related field. This engagement took place between Fall 2016 and Fall 2017 and included workshops and individual focal interviews with utility engineers, civil servants, and other key stakeholders.

Workshop 1 – June 21, 2016 at Frank F. Fasi Municipal Building

This initial meeting with city managers and state department representatives was organized to present an overview of the project, discuss the project utility and seek feedback. Those in attendance offered input on wastewater asset identification, indicators of vulnerability, sources of data, and geographical areas of interest.

Stakeholder Interviews – Fall 2016 through Fall 2017, various locations

Stakeholder interviews were conducted with individuals representing agencies in the City and County of Honolulu, the State of Hawaiʻi and Federal Government. The stakeholders were asked a series of questions that fell under seven focused themes:

1. *General background* – broadly identifying top issues for Honolulu in next 5-10 years.
2. *Asset inventory and "criticality"* – Identifying critical systems and how those systems may be impacted by climate change over the next few decades.
3. *Exposure questions* – classifying the different environmental conditions that make wastewater systems more vulnerable and the specific watershed areas most at risk.
4. *Sensitivity questions* – identifying certain conditions or characteristics about wastewater systems that make them more vulnerable to climate hazards.
5. *Adaptive capacity* – identifying current actions underway and articulating ideal improvements to make wastewater systems less vulnerable to climate change risks
6. *Consequences of failure* – understanding the consequential impacts of system failure and measures and indicators used to track functionality.
7. *Data & decision making* – identifying wants and needs in terms of data and information regarding climate change.

Workshop 2 – June 20, 2018 at Honolulu Hale and June 27, 2018 at Hawaiʻi State Department of Health

The two culminating meetings re-convened city managers and state department representatives to present the research and preliminary findings of this project. Those in attendance asked questions and offered input on the information presented. The meeting also provided space for representatives of various agencies to discuss key issues and possible opportunities related to climate change and wastewater infrastructure

Report Overview

This report presents the results of our team's research. The remaining sections of this report are intended to provide background information regarding future climate change scenarios, report on exposures of wastewater assets to climate hazards, and present two planning tools to help assess the vulnerability of wastewater assets to sea level rise. Section III identifies wastewater assets that are exposed to sea level rise, hurricane storm surge, and tsunami inundation. Section IV presents a constructed vulnerability index to map hotspots of vulnerable assets. Section V reports on a modeling tool for assessing the sensitivity of sewer pipes to SLR induced groundwater inundation and applies it to two coastal sewer systems. Section VI focuses on OSDS and the policy and regulatory ecosystems affecting OSDS vulnerability. Building from the conceptual framework, Section VII summarizes lessons and strategies for adaptation. Lastly, Section VIII re-visits the vulnerability index to take a look at areas on Oʻahu that exhibit vulnerable wastewater assets – central sewer, OSDS, or both – and discusses factors affecting decision making, the limitations of our study, and future research opportunities.

III. Wastewater Asset Exposure

Sea Level Rise

In 2015, the International Panel on Climate Change (IPCC) released its fifth assessment report, synthesizing the most relevant climate science. The report leaves little doubt about the current state of climate change, noting that each of the last three decades has been successively warmer (IPCC, 2014). As the most isolated concentrated population on earth, Hawai'i faces unique challenges in that the archipelago, while not a large contributor to climate change, will likely bear the brunt of the burden along with other Pacific Island nations.

The Mauna Loa Observatory on the island of Hawai'i has been tracking carbon dioxide (CO2) emissions for over half a century. The data collected has shown an unprecedented increase in CO2 concentration, measuring a 20% percent increase since 1958 and a 40% increase since the industrial revolution. Ice core data taken from glaciers in Antarctica show just how unprecedented these levels are – the CO2 levels that are being measured today are the highest in 800,000 years.

Climate change is more than just changes to the average conditions, it also means more extreme weather and climate variability. Studies have also shown that as the world gets warmer, we are seeing more powerful El Niños, with record setting rainfall and record setting heat, which affects the variability of tropical cyclones around the world (Chand et al., 2016). The global average temperature has increased 1 degree Celsius since 1880 and most of that change has occurred since 1940. These impacts seem to be even more prevalent now as we have seen sixteen of the hottest years on record in the last seventeen years and just this last year, July 2017 tied the hottest month in history. With these observed changes, the IPCC finds that it is "extremely likely" that more than half of the observed increase in global temperatures from 1951 to 2010 was caused by human-related greenhouse gas emissions (IPCC, 2014).

Sea levels are rising at increasing rates due to the warming of the atmosphere and the melting of glaciers and ice sheets. Sea level rise is contributed to by two main process – thermal expansion and ice mass melt (Church et al., 2013). Thermal expansion occurs when water at a higher temperature or under greater pressure (i.e., at greater depth) expands more for a given heat input, so the global average expansion is affected by the distribution of heat within the ocean (IPCC, 2007). The long-term process that created glaciers and ice near the north and south poles are rapidly deteriorating. The GRACE Observatory in Greenland has recorded an average of 200 billion tons of ice loss each year since 2002. Similar ice melt has been measured in the South Pole as well where Antarctica is losing about 125 billion tons per year. In these locations the equilibrium line along the slope continues to move higher in elevation as net loss increases.

Sea Level Rise Projections

As the sea level rises, the high water line will migrate landward in proportion to the slope of the coastal area, leaving low-lying areas and wetlands more susceptible to changes in sea level (Zhang et al. 2004). In Hawai‘i, these changes will likely result in increase severity and extent of beach erosion, wave flooding and over wash from annual high waves, increased groundwater flooding from water table rising, drainage failure, and more severe tsunami and hurricane inundation. In response to these projections, the Hawai‘i Climate Change Mitigation and Adaptation Committee published the Hawai‘i Sea Level Rise Vulnerability and Adaptation Report in 2017). The report uses the best available science from sources such as the IPCC, NOAA and the National Aeronautics and Space Administration (NASA) and provides the first state-wide assessment of Hawai‘i's vulnerability to sea level rise and recommendations to reduce exposure and sensitivity to sea level rise.

The Hawai‘i Sea Level Rise Vulnerability and Adaptation Report (2017) uses the IPCC's 2014 sea level rise projections. The IPCC (2014) provides projects for four scenarios based on how much greenhouse gases are emitted (Figure 3-1). The Hawai‘i SLR Report uses the upper boundary of IPCC global mean sea level rise (SLR) scenario, their "business as usual" scenario, where greenhouse gas emissions continue at the current rate or increase. This scenario predicts global sea level rise up to 0.5 feet in 2030, 1.1 feet in 2050, and 3.2 feet in 2100 (Hawai‘i Climate Change Mitigation and Adaptation Commission, 2017).

The upper boundary of this IPCC scenario (RCP8.5) was used in modeling coastal hazards with sea level rise in the Hawai‘i SLR Report. This upper boundary of the business-as-usual scenario of 3.2 feet is the likely scenario because ice sheets and glaciers are melting at rates greater than accounted for in the IPCC report (NASA, 2015 via Hawai‘i Climate Change Mitigation and Adaptation Commission, 2017)

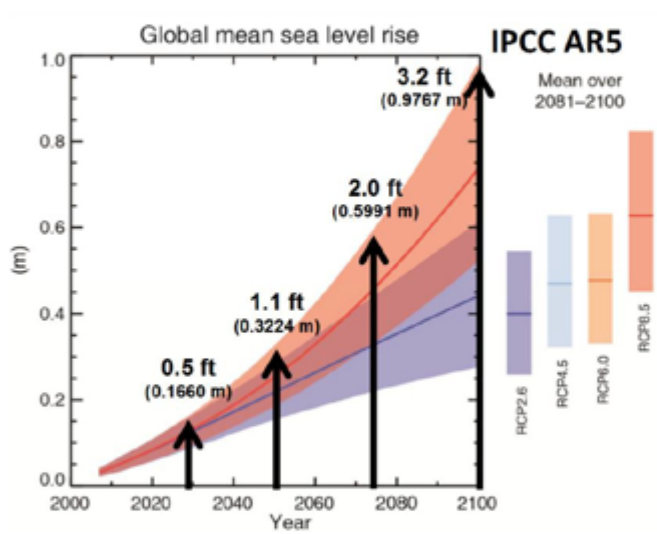

Figure 3-1: IPCC's projected rate of global mean SLR under different GHG scenarios (IPCC, 2014)

In a recent technical report prepared by The Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force in the United States, projections suggest that 3.2 feet of SLR could occur as early 2060 (Sweet et al., 2017). These new projections show far higher Global Mean SLR in the high and extreme emissions scenarios, showing the potential for more than 6 ft. of SLR by the end of this century (Table 3-1).

Table 3-1: Global mean sea level rise scenario heights (Sweet et al. 2017)

Global Mean SLR Scenario (feet)	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Low	0.10	0.20	0.30	0.43	0.52	0.62	0.72	0.82	0.92	0.98
Intermediate-Low	0.13	0.26	0.43	0.59	0.79	0.95	1.15	1.31	1.48	1.64
Intermediate	0.13	0.33	0.52	0.82	1.12	1.48	1.87	2.33	2.79	3.28
Intermediate-High	0.16	0.33	0.62	0.98	1.44	1.97	2.59	3.28	3.94	4.92
High	0.16	0.36	0.69	1.18	1.77	2.53	3.28	4.27	5.58	6.56
Extreme	0.13	0.36	0.79	1.35	2.07	2.95	3.94	5.25	6.56	8.20

Because questions still remain around the exact timing of SLR, the Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report recommends planning for 3.2 ft. of SLR now while remaining ready to adjust as new projections emerge from the scientific community (Hawaiʻi Climate Change Mitigation and Adaptation Commission, 2017). Thus, for the purpose of this research, we chose to analyze vulnerability based on the best available projections for near-term (1.1 ft.), mid-term, mid-century (3.2 ft.), and long-term, end of century (6 ft.) SLR.

Summary of Wastewater Asset Exposure

Modeling used the best available public data to determine potential future exposure of wastewater assets to different climate change hazards associated with sea level rise. Six types of wastewater assets were modeled: (1) sewer mains, (2) sewer laterals, (3) manholes, (4) pumping stations, (5) wastewater treatment plants, and (6) on-site disposal systems.

Table 3-2: Oʻahu Wastewater Asset Data Sources

Wastewater Asset	Data Source
Sewer Main	Honolulu Land Information System (HoLIS)
Sewer Lateral	Honolulu Land Information System (HoLIS)
Manholes	Honolulu Land Information System (HoLIS)
Pumping Stations	Honolulu Land Information System (HoLIS)
Wastewater Treatment Plants	Honolulu Land Information System (HoLIS)
On-site Disposal Systems	Hawaii Statewide GIS Program

Each of these asset groups were analyzed using five climate change hazard scenarios: (1) 1.1 feet sea level rise exposure area, (2) 3.2 feet sea level rise exposure area, (3) 6 feet of sea level rise, (4) storm surge based on a category 4 hurricane, and (5) tsunami from the FEMA tsunami zones. The three SLR scenarios are based on scientific models, which estimate future, chronic flooding scenarios. The tsunami and category 4 hurricane inundation models are based on existing conditions and are examples of extreme weather events.

The sea level rise exposure area (SLR-XA) is the model used in the Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report. The SLR-XA model combines three chronic flooding hazards: passive "bathtub" flooding, annual high wave flooding, and coastal erosion. The SLR-XA was available for the short-term (1.1 ft.) and mid-term (3.2 ft.) SLR scenarios. The additional long-term scenario for 6 feet of SLR only takes into account passive "bathtub" flooding and comes from NOAA.

The tsunami data comes from the FEMA tsunami evacuation zones, which encompasses the inland areas where the tsunami is expected to go beyond just the immediate shoreline plus an additional buffer area for safe evacuation. The category 4 hurricane data set was created by the University of Hawaiʻi School of Ocean and Earth Science and Technology and is available through the Pacific Islands Oceans Observing System (PaciOOS). The model shows the impact of a category 4 hurricane–modeled after Hurricane Iniki which made landfall on Kauaʻi in 1992–entering Pearl Harbor on the south shore of Oʻahu. The exposure and vulnerability information presented in this report are based on the one specific scenario of a storm surge entering Pearl Harbor, however, more recently University of Hawaiʻi SOEST published updated models for category 4 hurricanes making landfall for all shorelines on Oʻahu. This newer data can be accessed and downloaded from the PacIOOS website.

Table 3-3: Climate Change Hazard Data Sources

Climate Change Hazard	Description	Data Source
SLR-XA 1.1 Feet of SLR	Three chronic flooding hazards modeled with 1.1 feet SLR: passive "bathtub" flooding, annual high wave flooding, and coastal erosion.	Hawai'i Sea Level Rise Vulnerability and Adaptation Report & PacIOOS
SLR-XA 3.2 Feet of SLR	Three chronic flooding hazards modeled with 1.1 feet SLR: passive "bathtub" flooding, annual high wave flooding, and coastal erosion.	Hawai'i Sea Level Rise Vulnerability and Adaptation Report & PacIOOS
Bathtub flooding 6 Feet of SLR	Passive "bathtub" flooding modeled with 6 feet SLR	National Oceanic and Atmospheric Administration (NOAA)
Category 4 Storm Surge	Category 4 hurricane storm surge entering Pearl Harbor	Dr. Ning Li, University of Hawai'i School of Ocean and Earth Science and Technology (UH-SOEST)
Tsunami Zones	Tsunami inundation model using FEMA tsunami evacuation zones	Hawaii Statewide GIS Program

GIS analysis modeling each of the five climate change hazard scenarios produced data estimating the total number of wastewater assets affected on O'ahu for each scenario (Table 3-4).

The results show that the exposure of each wastewater asset group increases with the severity of each climate change hazard. While the affected number of assets is relatively minimal in the near-term (1.1 ft.) SLR scenario, in the long-term, the amount of assets potentially affected increases exponentially. The results show a substantial increase from the near- and mid-term SLR-XA scenarios to the end of century 6 foot SLR scenario. The total length of sewer mains potentially affected more than doubles from a 1.1 feet SLR scenario to 3.2 feet and nearly doubles again with bathtub flooding caused by 6 feet of SLR. Pumping stations appear most vulnerable to a 6 foot SLR scenario, with 33 of the 92 total pumping stations potentially exposed to chronic flooding by the end of the century.

A tsunami results in the second largest number of assets exposed and is the only scenario where two wastewater treatment plants could flood.

The category 4 hurricane data used only models impacts to the south shore of O'ahu surrounding Pearl Harbor. Because of the limited scope of this model, the more extreme exposure is limited to the areas included in the model.

Table 3-4: O'ahu Wastewater Assets Exposed to Climate Change Hazards

Wastewater Asset	**Total Units on O'ahu**	*1.1 ft. SLR-XA*	*3.2 ft. SLR-XA*	*6 ft. SLR (Bathtub)*	*Category 4 Hurricane*	*Tsunami Inundation*
Sewer Mains	1,601 miles (mi.)	41 mi.	98 mi.	192 mi.	138 mi.	190 mi.
Sewer Laterals	1,189 miles (mi.)	3 mi.	27 mi.	83 mi.	54 mi.	98 mi.
Manholes	49,514 manholes	130 manholes	1,128 manholes	3,845 manholes	3,101 manholes	3,804 manholes
Pump Stations	92 stations	1 station	5 stations	33 stations	14 stations	27 stations
WW Treatment Plants	9 plants	0 plants	0 plants	1 plant	1 plant	2 plants
On-site Disposal Systems	13,684 systems	475 systems	1,322 systems	1,105 systems	441 systems	4,592 systems

The maps below show the exposure of each wastewater asset type by climate change scenario. The white points or lines are assets that are not exposed and the violet points and lines are the assets that are exposed.

1.1 Feet SLR Chronic Flooding

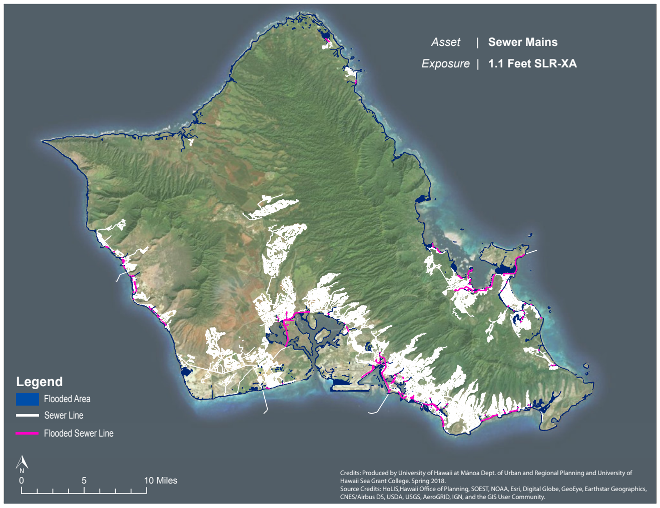

Figure 3-2: Sewer Mains with 1.1 feet SLR-XA

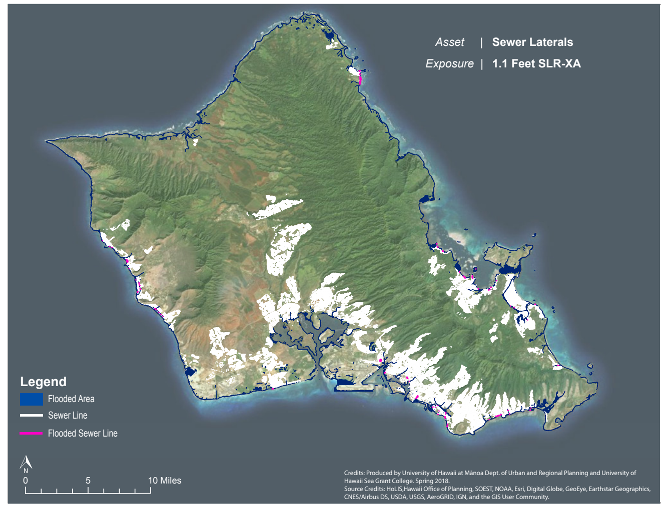

Figure 3-3: Sewer Laterals with 1.1 feet SLR-XA

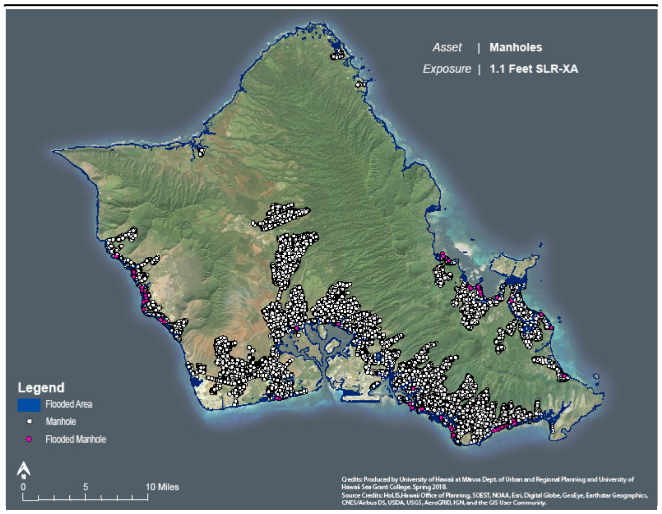

Figure 3-4: Manholes with 1.1 feet SLR-XA

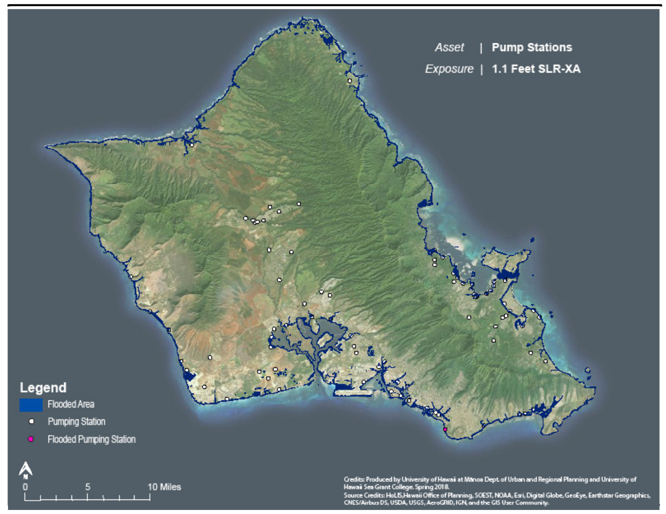

Figure 3-5: Pump Stations with 1.1 feet SLR-XA

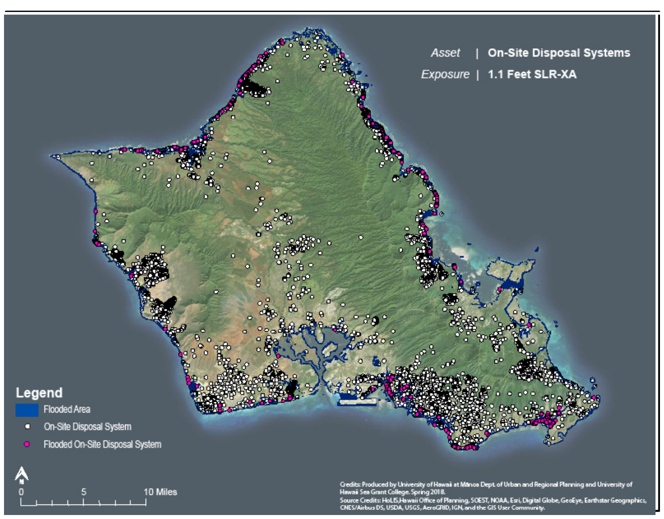

Figure 3-6 OSDS with 1.1 feet SLR-XA

3.2 Feet SLR Chronic Flooding

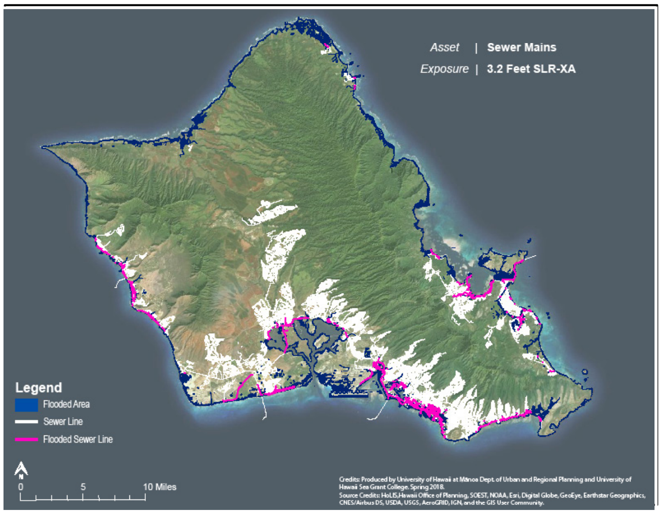

Figure 3-7: Sewer Mains with 3.2 feet SLR-XA

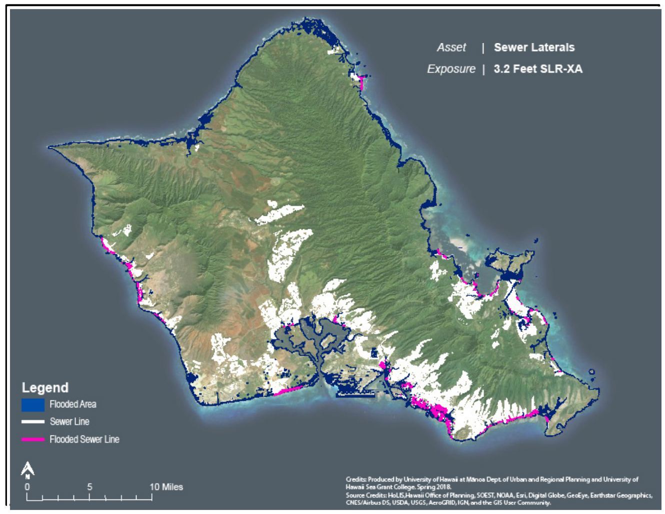

Figure 3-8: Sewer Laterals with 3.2 feet SLR-XA

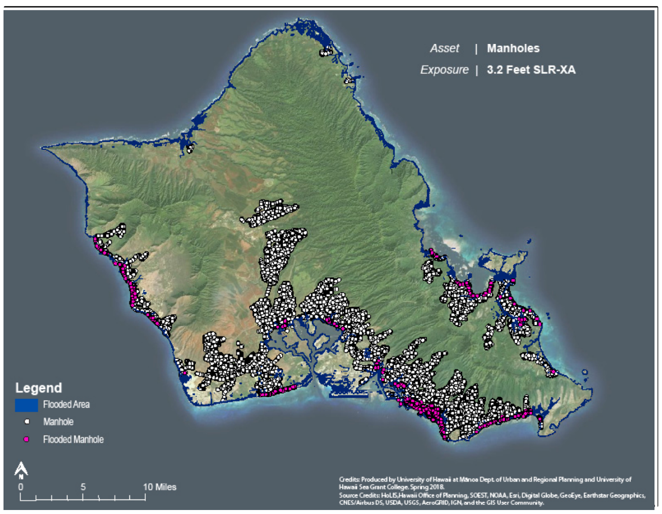

Figure 3-9: Manholes with 3.2 feet SLR-XA

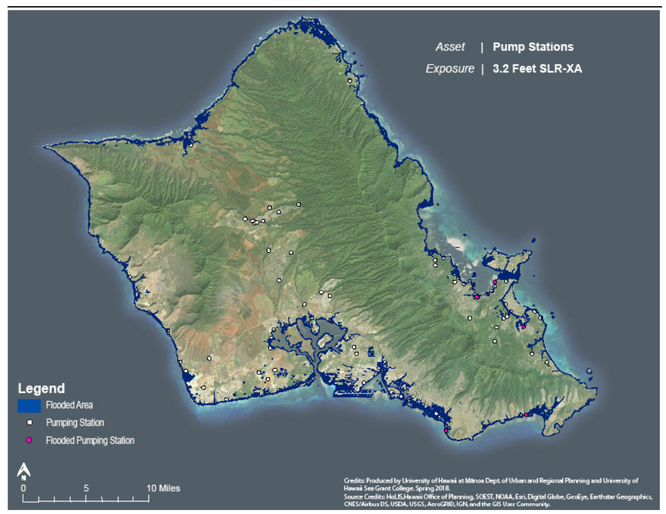

Figure 3-10: Pump Stations with 3.2 feet SLR-XA

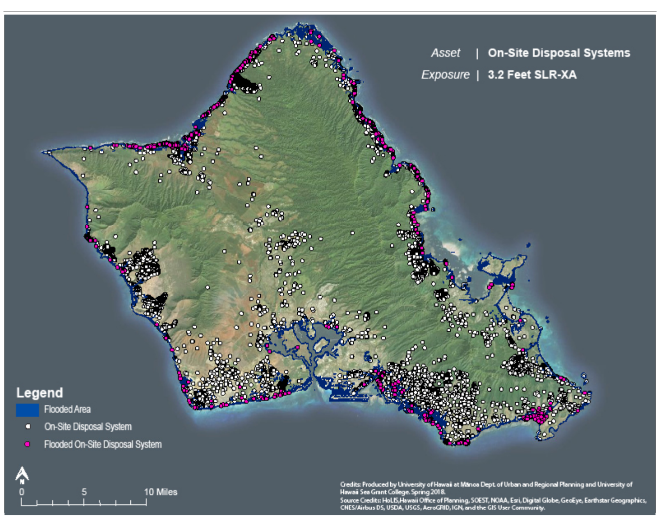

Figure 3-11: OSDS with 3.2 feet SLR-XA

6 Feet Sea Level Rise (Bathtub flooding)

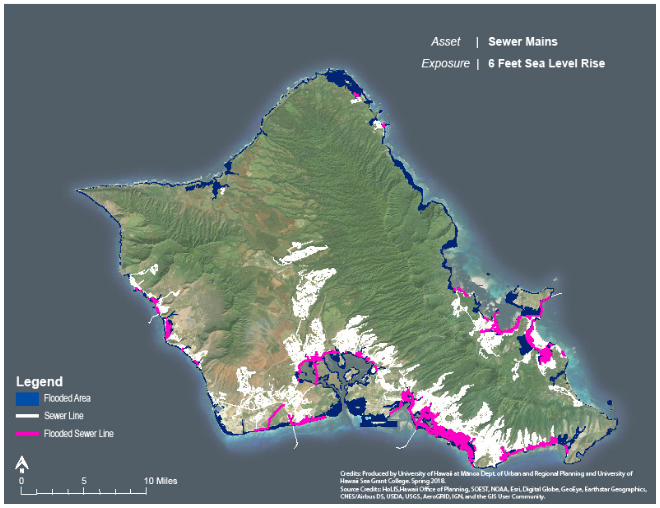

Figure 3-12: Sewer Mains with 6 feet SLR

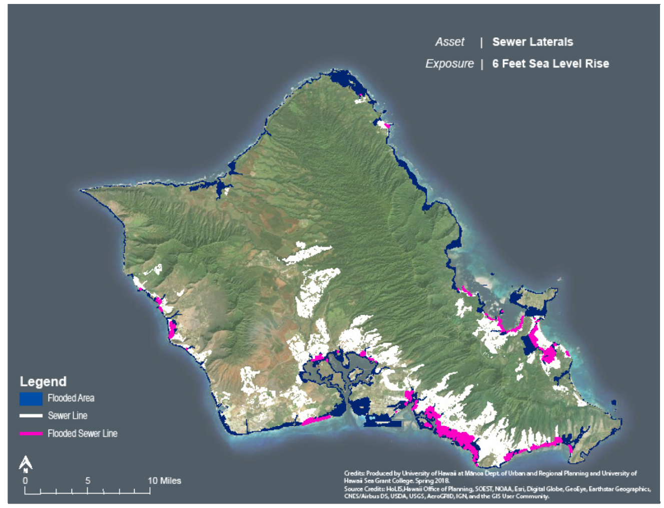

Figure 3-13: Sewer Laterals with 6 feet SLR

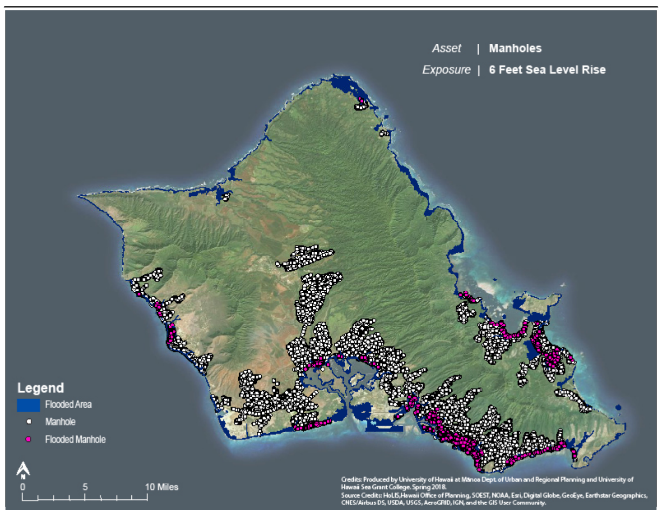

Figure 3-14: Manholes with 6 feet SLR

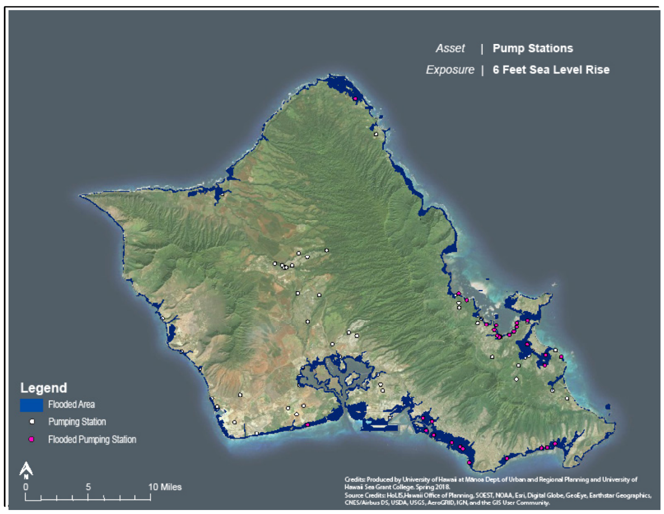

Figure 3-15: Pump Stations with 6 feet SLR

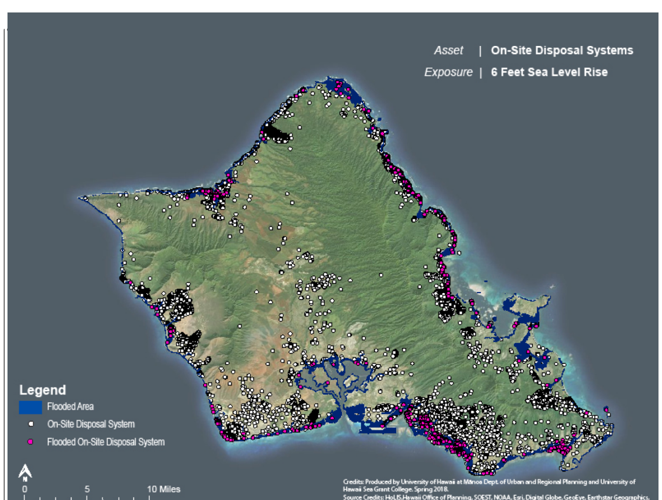

Figure 3-16: OSDS with 6 feet SLR

Tsunami

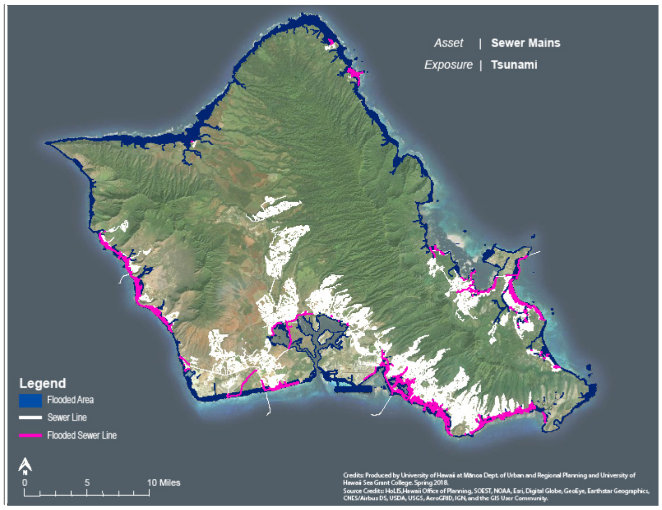

Figure 3-17: Sewer Mains with Tsunami Inundation

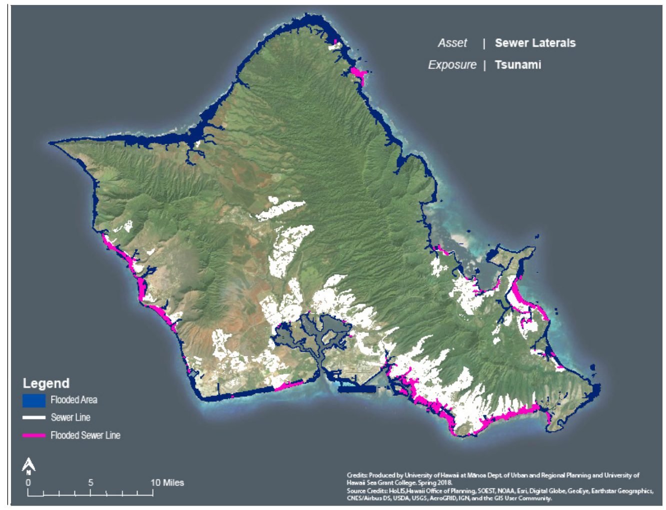

Figure 3-18: Sewer Laterals with Tsunami Inundation

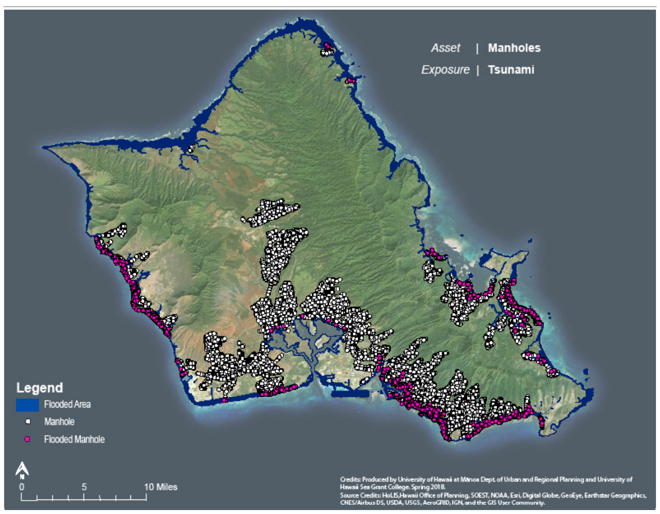

Figure 3-19: Manholes with Tsunami Inundation

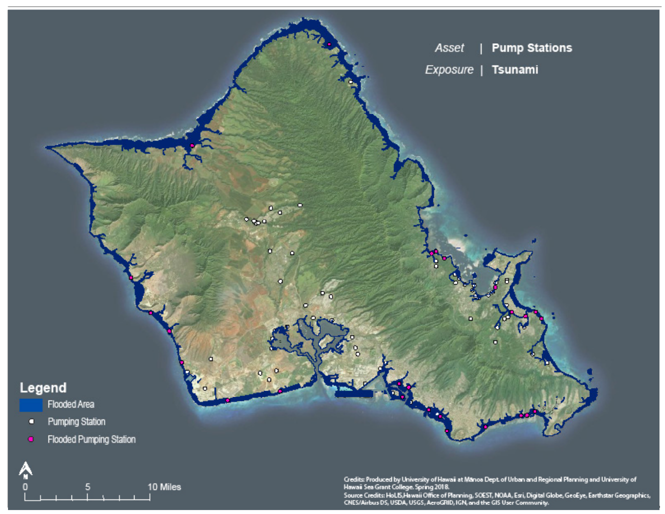

Figure 3-20: Pump Stations with Tsunami Inundation

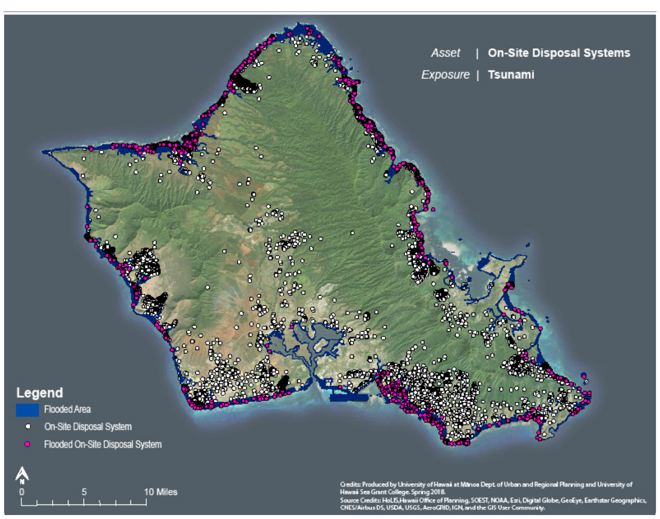

Figure 3-21: OSDS with Tsunami Inundation

Hurricane (Category 4)

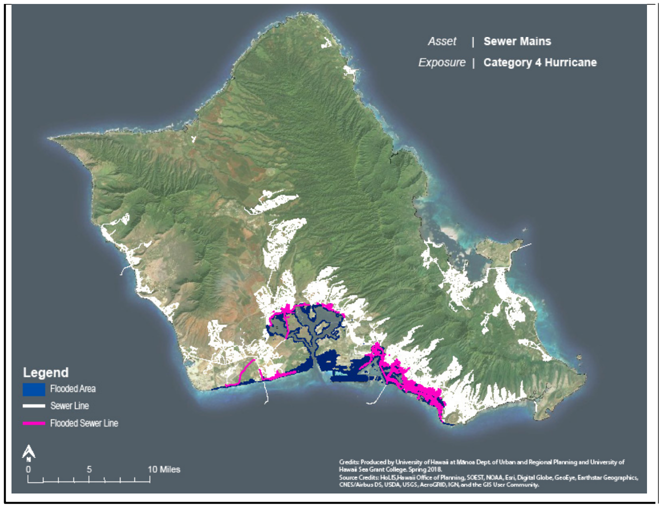

Figure 3-22: Sewer Mains with Category 4 Hurricane Storm Surge

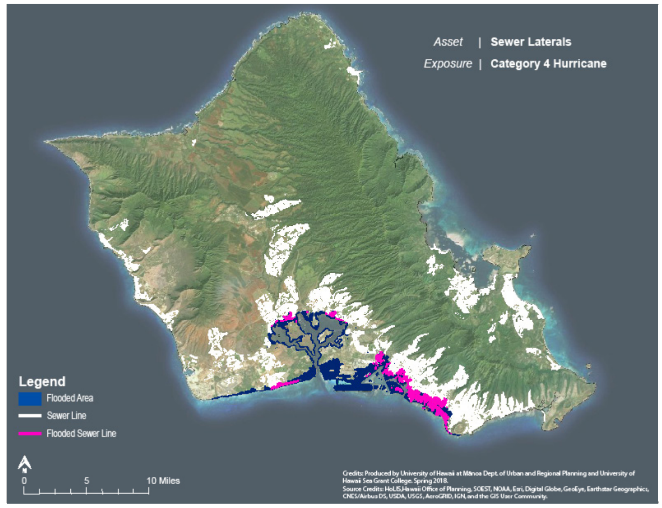

Figure 3-23: Sewer Laterals with Category 4 Hurricane Storm Surge

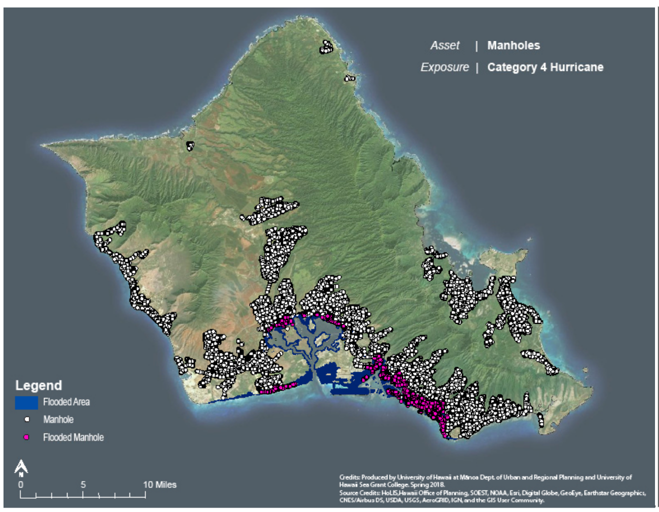

Figure 3-24: Manholes with Category 4 Hurricane Storm Surge

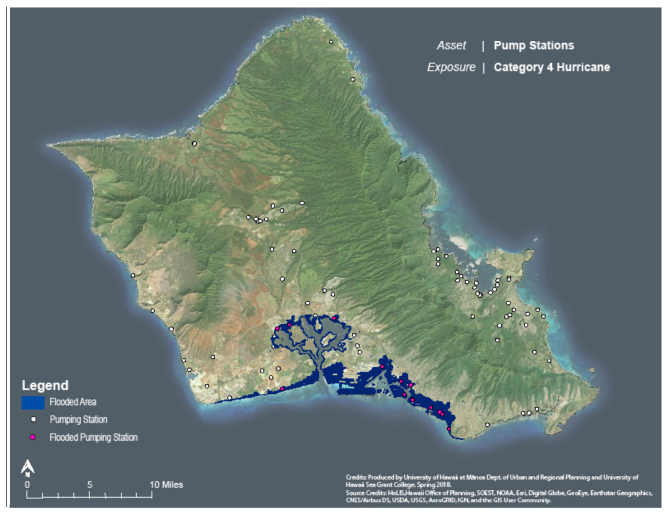

Figure 3-25: Pump Stations with Category 4 Hurricane Storm Surge

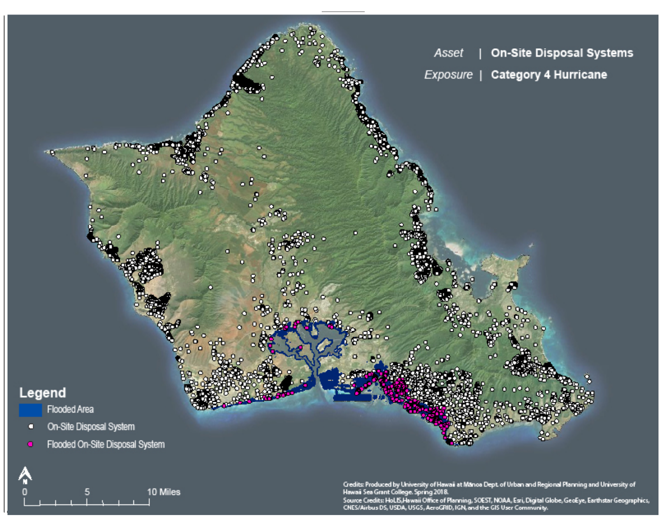

Figure 3-26: OSDS with Category 4 Hurricane Storm Surge

IV. Vulnerability Index

Vulnerability assessments help assess the risk of potential damage related to specific disasters (FEMA, 2015). A vulnerability index incorporates multiple quantitative indicators of vulnerability, which are normalized and put into a formula to deliver a single numerical result. Results generated by the index allow asset managers, engineers, planners, and decisions makers to perform rapid assessments of the relative vulnerability of assets to different climate change exposures. The use of vulnerability indices is becoming more common in disaster management and urban planning because it offers a useful tool for identifying and monitoring vulnerability over time, for developing a better understanding of the processes underlying vulnerability, for developing and prioritizing strategies, and for determining the effectiveness of strategies (Rygel, O'Sullivan, and Yarnal, 2005). Vulnerability indices can look at one specific type of vulnerability, such as physical or structural vulnerability, or incorporate other aspects of vulnerability, such as economic or social factors (Balica, Wright, & van der Meulen, 2012). A vulnerability index allows the consideration of all relevant factors, giving us a more holistic picture of features that are vulnerable to different exposures (Kumar et al., 2010).

Previous work has focused on developing area-based vulnerability indices using social, economic, and physical factors. The majority of indices developed to assess physical infrastructure have been done at a national or regional scale and are aimed at understanding the economic implications. Myung et al. (2009) analyzed the exposure of physical infrastructure to climate change and assessed its vulnerability using a survey of professionals. Brooks et al. (2005) identified key indicators of vulnerability and the capacity of countries to adapt to climate change based on mortality rates from climate-related disasters and emergency events. The Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report (2017) focuses on estimating the potential economic loss caused by climate exposure. Kim et al. (2017) takes a more specific focus creating a vulnerability index based on three performance indicators in order to evaluate the vulnerability of advanced wastewater treatment processes to climate change and to identify adaptive strategies.

Building on the information garnered from the stakeholder interviews, existing literature and public data sets, we created an index to assess the vulnerability of facility-level assets using a set of available quantifiable indicators.

Methodology

We assessed the vulnerability of facility-level assets and individual on-site disposal systems using a mixed methodology drawing from previous studies and data from stakeholder interviews to identify the climate change hazards of greatest concern and existing sensitivities of critical assets. Assets were assessed based on the sensitivity indicators identified under the five climate change hazard scenarios.

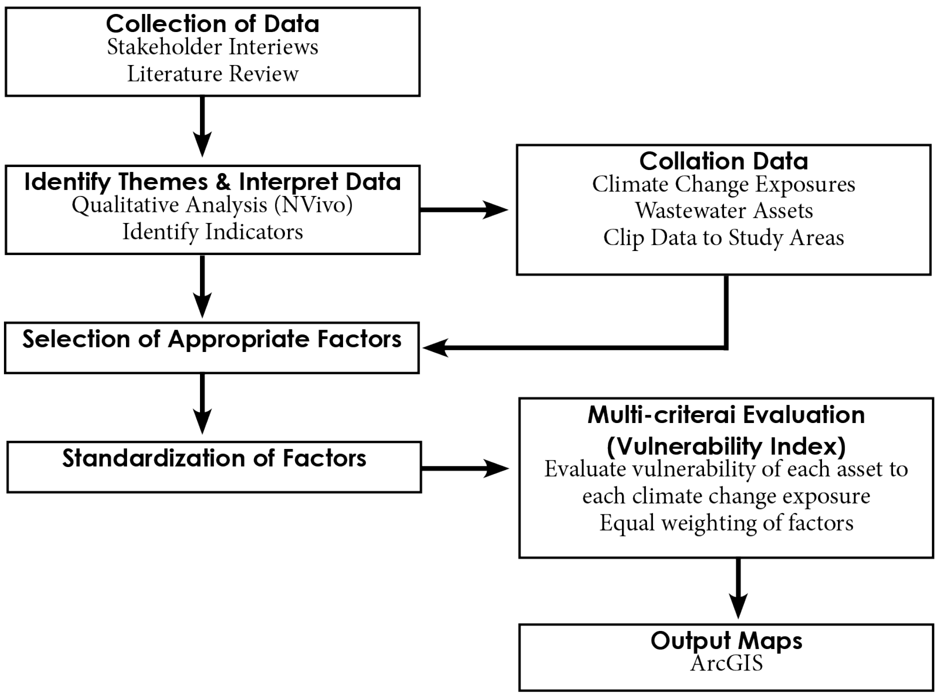

Figure 4-1: Vulnerability index methodology

Collection of Data

Stakeholder interviews took place with individuals who were specifically identified for their expertise and professional experience in wastewater or a related field. The interview transcripts were upload onto the qualitative data analysis software, NVivo and coded to identify the prevalent themes for each of the following seven focus areas:

1. General Background
2. Asset inventory
3. **Exposure**
4. **Sensitivities**
5. Adaptive Capacity
6. Consequences of Failure
7. Data & Decision Making

For the vulnerability index, answers related to climate change exposure and sensitivities were the main focus.

Following the stakeholder interviews, literature was reviewed to confirm and build on the input gathered from stakeholders. The following climate change exposures and wastewater system sensitivities were identified as important for assessing system-wide vulnerability:

Climate Exposures

1. Sea level rise
2. Extreme weather events – localized flooding
3. Saltwater inflow and infiltration
4. Groundwater inflow and infiltration
5. Shoreline Erosion

System Sensitivities

1. Aging systems
2. Drainage capacity – especially in extreme weather events
3. Pipe corrosion and breakdown
4. Structural integrity of systems when exposed to waves or tides
5. Proximity to coastline
6. Depth to groundwater and soil drainage

Collation of Data

A Geographical Information System (GIS) based approach was developed to quantify the physical vulnerability of wastewater assets based on the sensitivities identified for specific exposures. The selected sensitivity indicators were limited to the available data pertaining to each of the wastewater assets being assessed. The data was obtained from public databases including the National Oceanic and Atmospheric Administration (NOAA), the Pacific Islands Oceans Observing System (PaciOOS), the Hawaiʻi State Office of Planning, and the Honolulu Land Information System (HoLIS).

Data was also obtained for each of the five climate change scenarios. After calculating the number of wastewater units impacted in each scenario, the index was constructed using selected sensitivity indicators (see Table 4-1).

Calculating the Vulnerability Index

Table 4-1: Selection of Indicators

Sensitivity Indicators	Wastewater Assets					
	Sewer Mains	*Sewer Laterals*	*Manholes*	*Pump Stations*	*WW Treatment Plant*	*On-site Disposal Systems*
Age	●	●	●	●	●	
Maintenance History	●	●				
Pipe Material	●	●				
Pipe Diameter	●	●				
Elevation	●	●	●	●	●	
Proximity to Coastline	●	●	●	●	●	●
Proximity to Flood Zone	●	●	●	●	●	●
Soil Drainage	●	●				●
Depth to Water						●
Depth to Rock						●
Proximity to Drinking Water						●
Proximity to Stream						●
OSDS Density						●

A vulnerability index takes multiple quantitative indicators, which are normalized and calculated using the following equation to deliver a single numerical result. For this study, the indicators were normalized and given a ranking from 0-4, 0 being least vulnerable and 4 being most vulnerable (see 4-2). For the purposes of this study, all indicator variables were evenly weighted. For each asset (e.g., sewer pipe, pump station, etc.) the indicators are combined by applying a weight of 1 to each, followed by a summation of the results to yield a vulnerability index (Eastman et al. 1995).

$$V_i = \Sigma \left(w_k \, x_k\right)$$

Where V_i is the vulnerability of the selected asset to a specific type of climate exposure (*i*) and x_k is potential rating for each indicator (*k*). w_k is the weight of the indicator (*k*), which for this stage of the study is 1 across all indicators.

Table 4-2: Vulnerability Index Scoring

Vulnerability	**Vulnerability Index Ranking Range**
Low Vulnerability	0.00-0.99
Medium Vulnerability	1.00-1.99
High Vulnerability	2.00-2.99
Very High Vulnerability	3.00-4.00

Table 4-3: Indicator Ranking

Sensitivity Indicators	*Wastewater Asset*	*Potential Ranking*					*Reference*
		4	*3*	*2*	*1*	*0*	
Age	Sewer Mains (SM)	≤1939	1940-1959	1960-1979	1980-1999	≥2000	
	Sewer Laterals (SL)	≤1939	1940-1959	1960-1979	1980-1999	≥2000	
	Manholes (MH)	≤1939	1940-1959	1960-1979	1980-1999	≥2000	
	Pump Station (PS)	≤1939	1940-1959	1960-1979	1980-1999	≥2000	
	Wastewater Treatment Plant (WWTP)	≤1939	1940-1959	1960-1979	1980-1999	≥2000	
Maintenance History	SM	No Maintenance record		Maintenance record			
	SL	No Maintenance record		Maintenance record			
Pipe Material	SM	Terracotta Clay		Asbestos Concrete		All Other	EPA – "Wastewater Technology Fact Sheet"

Sensitivity Indicators	*Wastewater Asset*	*Potential Ranking*					*Reference*
		4	*3*	*2*	*1*	*0*	
	SL	Terracotta Clay		Asbestos Concrete		All Other	sites/epagov/www.epa.gov/OWM/mtb/pipe_construction.pdf
Pipe Diameter	SM	≤8 inches		9-41 inches		≥42 inches	10 State Standards - "Recommended Standards for WW Facilities "
	SL	≤3 inches				>3 inches	
Elevation	SM	<0 ft.		0-3.2 ft.		>3.2 ft.	
	SL	<0 ft.		0-3.2 ft.		>3.2 ft.	
	MH	<0 ft.		0-3.2 ft.		>3.2 ft.	
	PS	<0 ft.		0-3.2 ft.		>3.2 ft.	
	WWTP	<0 ft.		0-3.2 ft.		>3.2 ft.	
Proximity to Coastline	SM	<40 ft.				≥40ft.	ROH Ch. 21, Art. 4 – Setback

Sensitivity Indicators	*Wastewater Asset*	*Potential Ranking*					*Reference*
		4	*3*	*2*	*1*	*0*	
	SL	<40 ft.				≥40ft.	
	MH	<40 ft.				≥40ft.	
	PS	<40 ft.				≥40ft.	
	WWTP	<40 ft.				≥40ft.	
	OSDS	<200 ft.				≥200 ft.	
Proximity to Flood Zone	SM	V/VE		A		All Other	FEMA
	SL	V/VE		A		All Other	
	MH	V/VE		A		All Other	
	PS	V/VE		A		All Other	
	WWTP	V/VE		A		All Other	

Sensitivity Indicators	*Wastewater Asset*	*Potential Ranking*					*Reference*
		4	*3*	*2*	*1*	*0*	
	OSDS	V/VE		A		All Other	
Soil Drainage	SM	Fast		Mod		Slow	NRCS Soil Survey
	SL	Fast		Mod		Slow	
	OSDS			See Appendix I for full Risk Scoring (Hawaii DOH 2009)			
Depth to Water	OSDS			See Appendix I for full Risk Scoring (Hawaii DOH 2009)			
Depth to Rock	OSDS			See Appendix I for full Risk Scoring (Hawaii DOH 2009)			
Proximity to Drinking Water	OSDS			See Appendix I for full Risk Scoring (Hawaii DOH 2009)			
Proximity to Stream	OSDS			See Appendix I for full Risk Scoring (Hawaii DOH 2009)			
OSDS Density	OSDS			See Appendix I for full Risk Scoring (Hawaii DOH 2009)			

Findings

The tables below summarize the vulnerability rankings of wastewater assets in each of the climate hazard scenario for O‘ahu.

Table 4-4: Vulnerability Index results 1.1 feet SLR-XA

Wastewater Asset	**Total Units Impacted**	*Low Vulnerability (0.00-0.99)*	*Medium Vulnerability (1.00-1.99)*	*High Vulnerability (2.00-2.99)*	*Very High Vulnerability (3.00-4.00)*
Sewer Mains	218,174 ft.	--	161,052 ft.	56,890 ft.	231 ft.
Sewer Laterals	15,590 ft.	1,575 ft.	13,205 ft.	810 ft.	--
Manholes	130 manholes	11 manholes	98 manholes	21 manholes	--
Pump Stations	1 station	--	1 station	--	--
WW Treatment Plants	0 plants	--	--	--	--
On-site Disposal Systems (OSDS)	475 systems	1 system	4 systems	188 systems	281 systems

Table 4-5: Vulnerability Index results 3.2 feet SLR-XA

Wastewater Asset	**Total Units Impacted**	*Low Vulnerability (0.00-0.99)*	*Medium Vulnerability (1.00-1.99)*	*High Vulnerability (2.00-2.99)*	*Very High Vulnerability (3.00-4.00)*
Sewer Mains	520,247 ft.	2,695 ft.	309,249 ft.	207,108 ft.	1,195 ft.
Sewer Laterals	140,549 ft.	39,729 ft.	99,293 ft.	1,527 ft.	--
Manholes	1,128 manholes	152 manholes	933 manholes	43 manholes	--
Pump Stations	5 stations	2 stations	3 stations	--	--
WW Treatment Plants	0 plants	--	--	--	--
OSDS	1,322 systems	1 system	4 systems	188 systems	281 systems

Table 4-6: Vulnerability Index results 6 feet SLR (bathtub flooding)

Wastewater Asset	**Total Units Impacted**	*Low Vulnerability (0.00-0.99)*	*Medium Vulnerability (1.00-1.99)*	*High Vulnerability (2.00-2.99)*	*Very High Vulnerability (3.00-4.00)*
Sewer Mains	1,014,635 ft.	15,648 ft.	666,393 ft.	336,197 ft.	212 ft.
Sewer Laterals	440,750 ft.	152,188 ft.	272,849 ft.	15,614 ft.	98 ft.
Manholes	3,845 manholes	1,625 manholes	2,198 manholes	22 manholes	--
Pump Stations	33 stations	18 stations	14 stations	1 station	--
WW Treatment Plants	1 plant	--	1 plant	--	--
OSDS	1,105 systems	4 systems	27 systems	713 systems	361 systems

Table 4-7: Vulnerability Index results Tsunami Inundation

Wastewater Asset	**Total Units Impacted**	*Low Vulnerability (0.00-0.99)*	*Medium Vulnerability (1.00-1.99)*	*High Vulnerability (2.00-2.99)*	*Very High Vulnerability (3.00-4.00)*
Sewer Mains	1,003,939 ft.	29,324 ft.	741,978 ft.	232,194 ft.	443 ft.
Sewer Laterals	517,147 ft.	243,573 ft.	263,751 ft.	9,724 ft.	98 ft.
Manholes	3,804 manholes	2,073 manholes	1,711 manholes	20 manholes	--
Pump Stations	33 stations	18 stations	14 stations	1 station	--
WW Treatment Plants	2 plants	--	--	--	--
On-site Disposal Systems	4,592 systems	15 system	289 systems	3,225 systems	1,063 systems

Table 4-8: Vulnerability Index results Category 4 Hurricane Storm Surge (Pearl Harbor)

Wastewater Asset	**Total Units Impacted**	*Low Vulnerability (0.00-0.99)*	*Medium Vulnerability (1.00-1.99)*	*High Vulnerability (2.00-2.99)*	*Very High Vulnerability (3.00-4.00)*
Sewer Mains	727,837 ft.	9,268 ft.	486,308 ft.	231,817 ft.	433 ft.
Sewer Laterals	286,097 ft.	92,454 ft.	180,536 ft.	13,009 ft.	98 ft.
Manholes	3,101 manholes	1,340 manholes	1,751 manholes	10 manholes	--
Pump Stations	14 stations	6 stations	8 stations	--	--
WW Treatment Plants	1 plant	--	--	--	--
On-site Disposal Systems	441 systems	12 system	34 systems	348 systems	47 systems

Mapping Wastewater Asset Vulnerability

Results from the vulnerability index are presented in the following maps (Figures 4-2 through 4-26). These maps illustrate the extent of combined exposure and sensitivity to the exposure for each asset grouped by climate change hazard scenario. The colors on the maps are derived from the vulnerability index, which, based on the indicators in Table 4-3, ranks vulnerability on a scale of 0-4, 0 being least vulnerable and 4 being most vulnerable. As such, assets on the maps displayed as yellow and orange are exposed assets, but are less vulnerable, while assets displayed as red and magenta are more exposed and are more vulnerable.

The case study maps below show "hotspots" of vulnerability for specific climate change hazards. According to our vulnerability index, sewer mains and OSDS assets rank the most vulnerable across the entire island. In addition, the total count of these highly vulnerable assets increases as the projected exposure area expands with increasing SLR or the increasing severity of the climate hazard. For sewer mains, we find key hotspots in urban Honolulu, specifically concentrated in the area between downtown and Diamond Head. We also find hot spots of wastewater assets with rankings of vulnerability in the mid- to high-range surrounding Kaneohe Bay and along the Leeward Coast. As found in urban Honolulu, total counts of these highly vulnerable assets increase with projected SLR.

For OSDS, hotspots of highly vulnerable OSDS in the 3.00-4.00 range are located in the Hawaiʻi Kai area, along the Windward Coast and across the North Shore. The Hawaiʻi Kai area is most immediately affected. We find over 250 OSDS ranked as highly vulnerable (index between 3.00-4.00) that are potentially exposed with just 1.1 feet of SLR. 3.2 feet of SLR exposes a far greater number of vulnerable OSDS; many of the most vulnerable OSDS are located along the Windward Coast and North Shore. Although the urban Honolulu area has sewer service, we find evidence of an important hotspot of highly vulnerable OSDS concentrated between Kalihi and the Diamond Head, including downtown and Waikiki.

Table 4-9: Vulnerability Index Rankings

Vulnerability	Vulnerability Index Ranking Range	Color on Map
Low Vulnerability	0.00-0.99	Yellow
Medium Vulnerability	1.00-1.99	Orange
High Vulnerability	2.00-2.99	Red
Very High Vulnerability	3.00-4.00	Magenta

1.1 Feet Sea Level Rise & Coastal Erosion (SLR-XA)

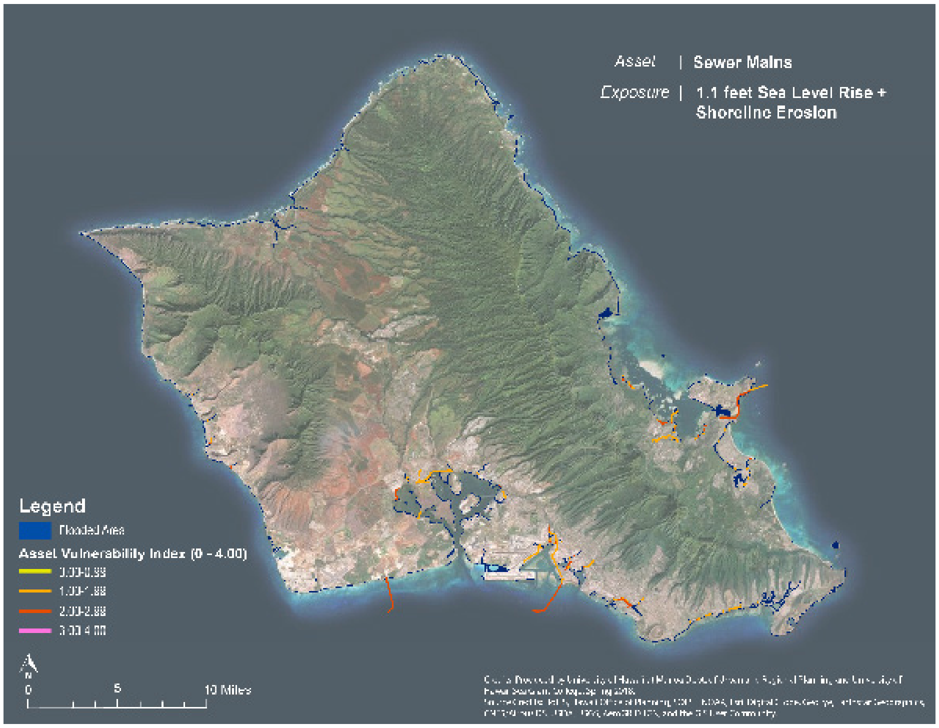

Figure 4-2: Sewer Mains with 1.1 feet SLR (SLR-XA)

Sewer Mains with 1.1 Feet of Sea Level Rise
Approximately 40 miles of sewer main pipes are flooded with 1.1 feet of SLR. While none of the exposed mains rank in the most vulnerable range, approximately 10 miles of sewer mains ranking rank highly vulnerable (2.00-2.99) with hotspots in downtown Honolulu, Waikiki, Ewa Beach, and Kaneohe. Just 231 feet of sewer mains rank in the very high vulnerability range (3.00-4.00).

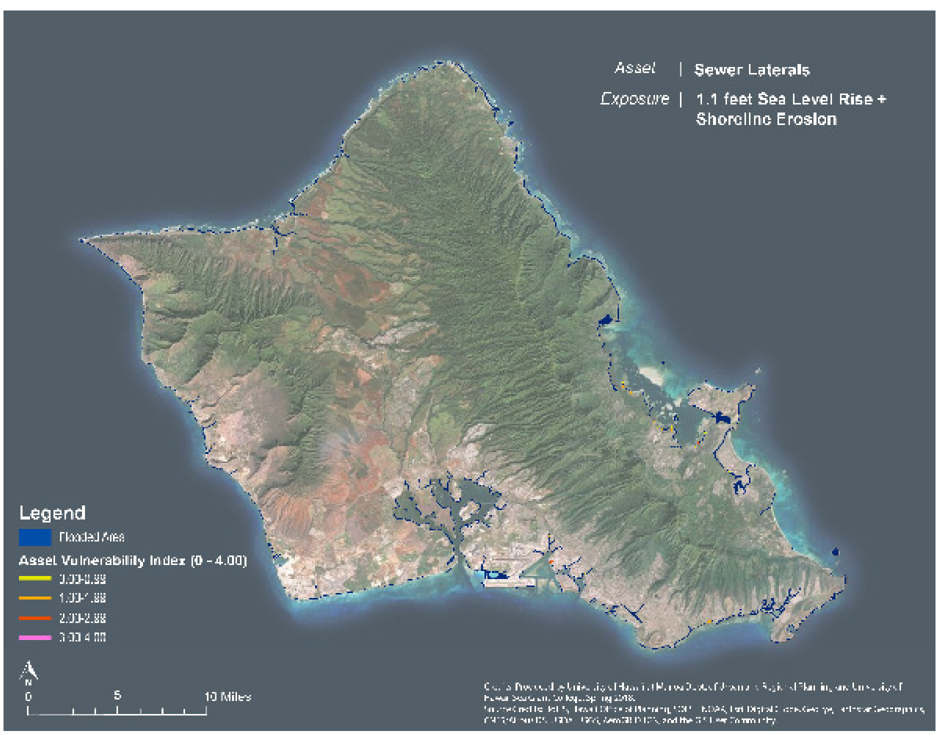

Figure 4-3: Sewer Laterals with 1.1 feet SLR (SLR-XA)

Sewer Laterals with 1.1 Feet of Sea Level Rise
Approximately 3 miles of sewer laterals are exposed to 1.1 feet of SLR. Clusters of hotspots appear around Kaneohe Bay, Aina Haina and Kalihi Kai. Just 810 feet of sewer laterals rank as highly vulnerable (2.00-2.99).

Manholes with 1.1 Feet of Sea Level Rise

130 manholes are flooded with 1.1 feet of SLR. There are 21 highly vulnerable manholes as well as clusters of vulnerable (1.00-1.99) manholes surrounding Kaneohe Bay. Another cluster appears along the south shore in the Wailupe area.

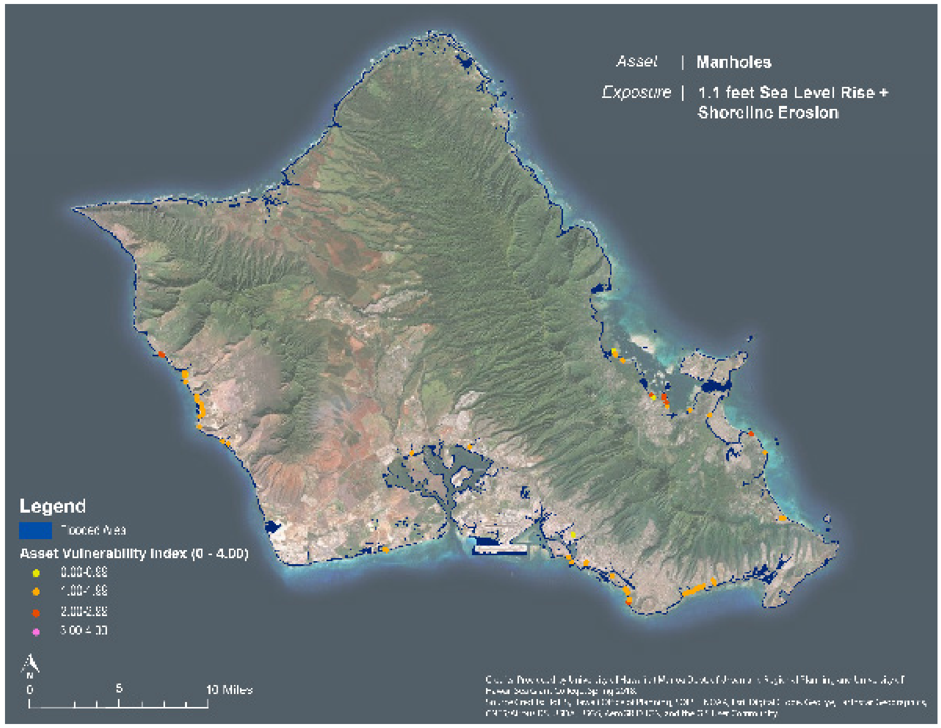

Figure 4-4: Manholes with 1.1 feet SLR-XA

Pump Stations with 1.1 Feet of SLR

Pump stations are not greatly impacted by 1.1 feet of SLR. In this scenario only one pump station, the Enchanted Lake Wastewater Pump Station, is at risk ranks as medium vulnerability (1.00-1.99). The Enchanted Lake Pump Station is within the Kailua Regional WWTP service area.

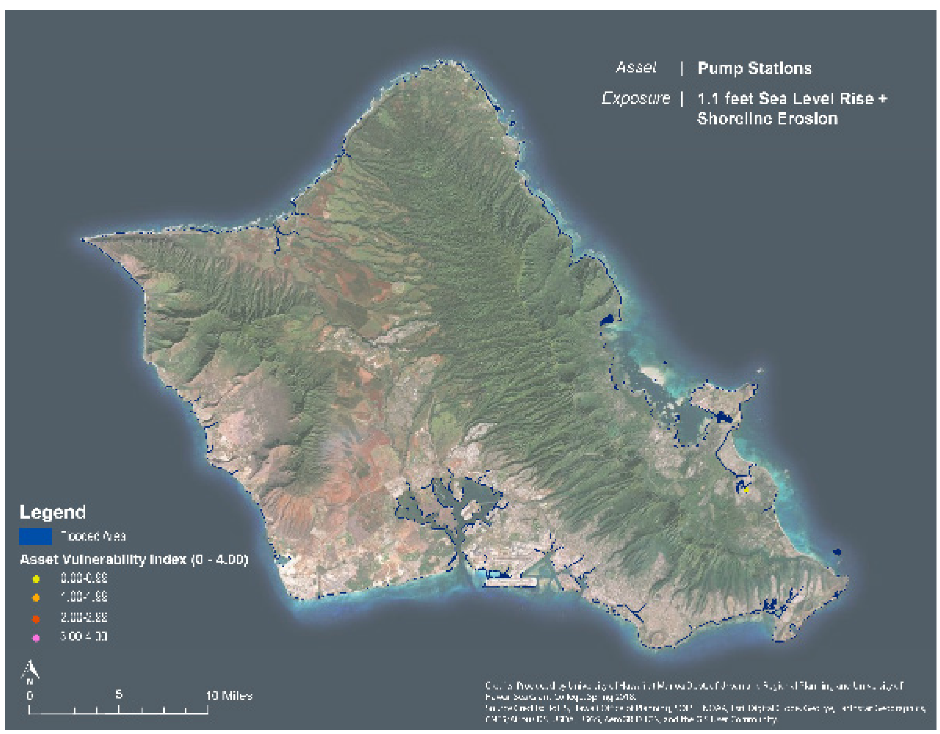

Figure 4-5: Pump Stations with 1.1 feet SLR (SLR-XA)

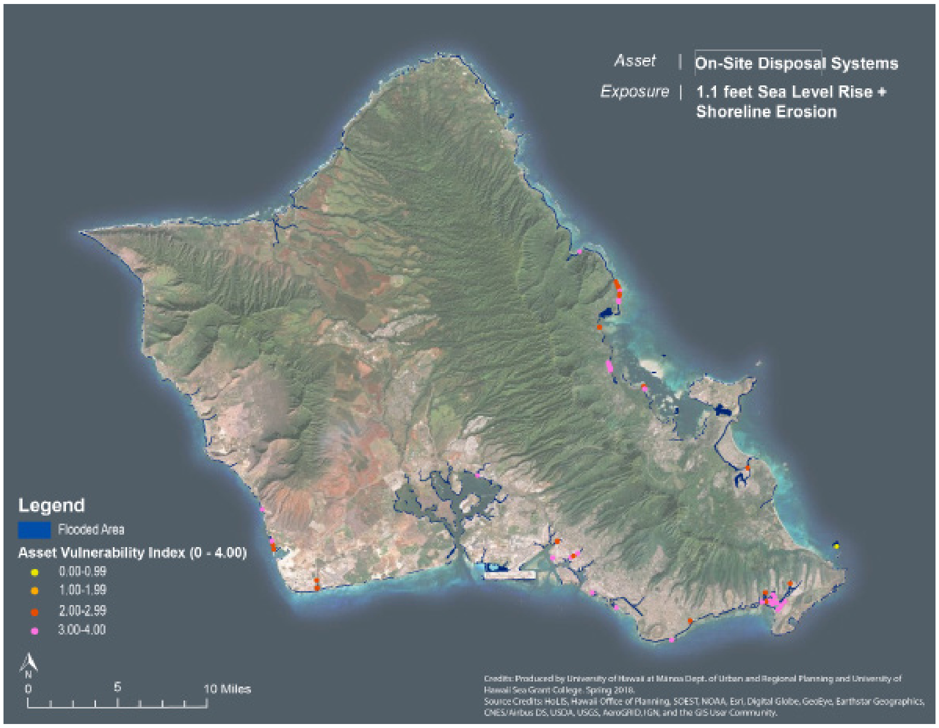

Figure 4-6: OSDS with 1.1 feet SLR (SLR-XA)

OSDS with 1.1 Feet of Sea Level Rise

475 OSDS are affected by 1.1 feet of SLR. The largest clusters of highly vulnerable systems are located in Hawai'i Kai and Kaneohe Bay. Smaller clusters of vulnerable OSDS are also present in urban Honolulu and Waikiki.

3.2 Feet Sea Level Rise & Costal Erosion (SLR-XA)

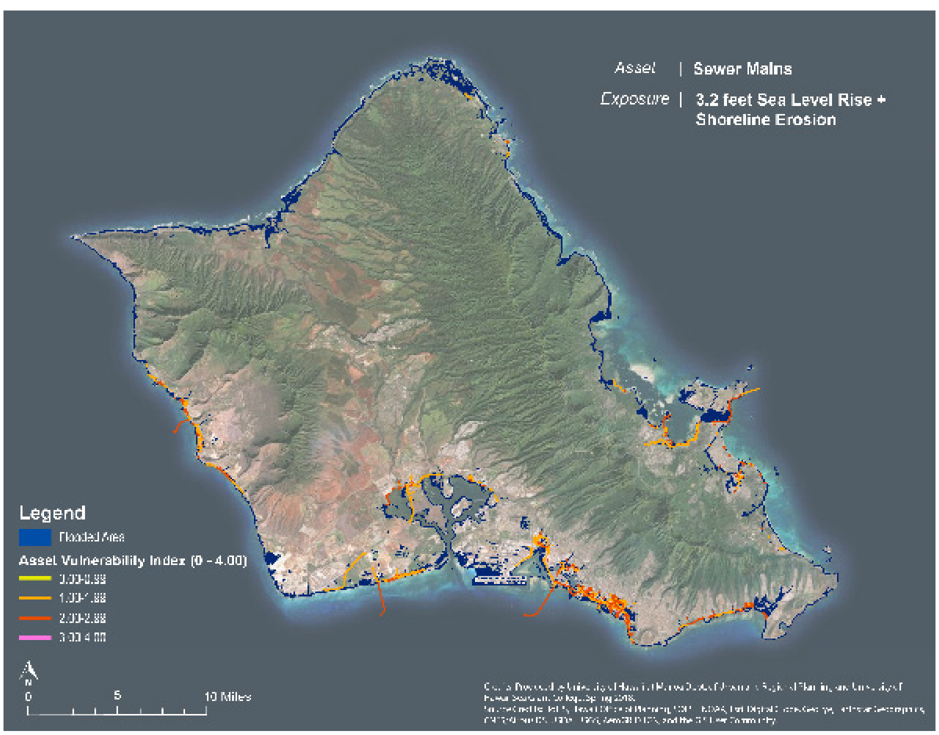

Figure 4-7: Sewer Mains with 3.2 feet SLR (SLR-XA)

Sewer Mains with 3.2 Feet of Sea Level Rise

Approximately 110 miles of sewer main pipes are exposed. 39 miles rank as highly vulnerable. Just under 0.25 miles rank in the very high vulnerability range (3.00-4.00). The most vulnerable pipes are located in Urban Honolulu and East Honolulu with other hotspots in Pearl Harbor, the Wai'anae Coast, and Ewa.

Sewer Laterals with 3.2 Feet of Sea Level Rise

Approximately 27 miles of sewer lateral pipes are exposed. Small hotspots with a few highly vulnerable laterals (2.00-2.99) are visible in East Honolulu and Waikiki. We also see more exposure of les vulnerable laterals on the Wai'anae Coast and in Ewa Beach.

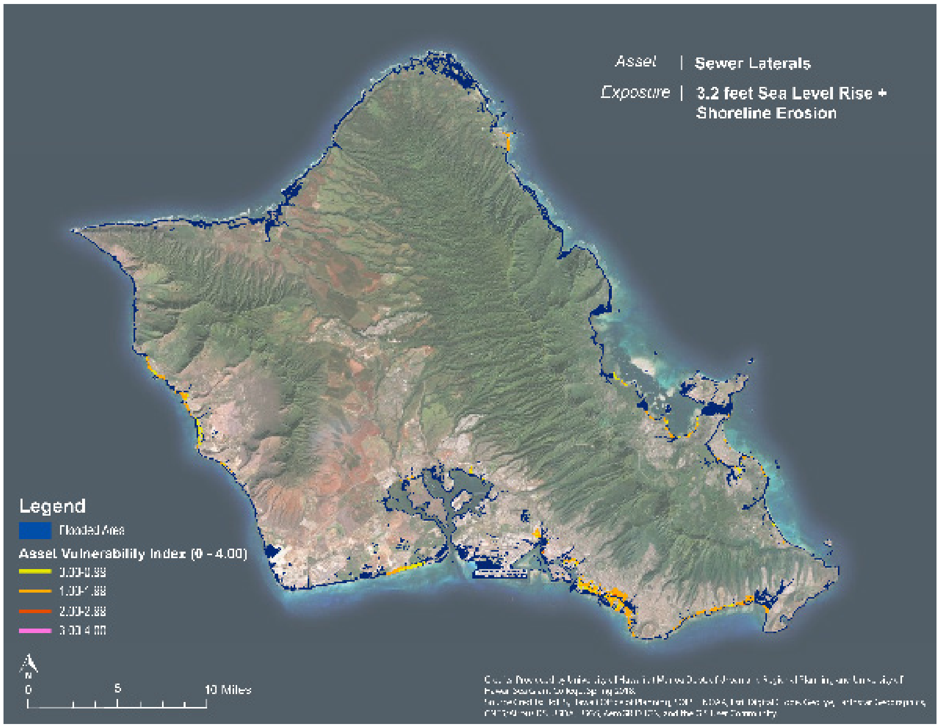

Figure 4-8: Sewer Laterals with 3.2 feet SLR (SLR-XA)

Manholes with 3.2 Feet of Sea Level Rise

A total of 1,128 manholes are flooded. 43 manholes rank as highly vulnerable (2.00-2.99), most of which are located near Kaneohe Bay and in East Honolulu. Other highly vulnerable manholes are located in Waikiki, Kailua, Waipahu, and Makaha

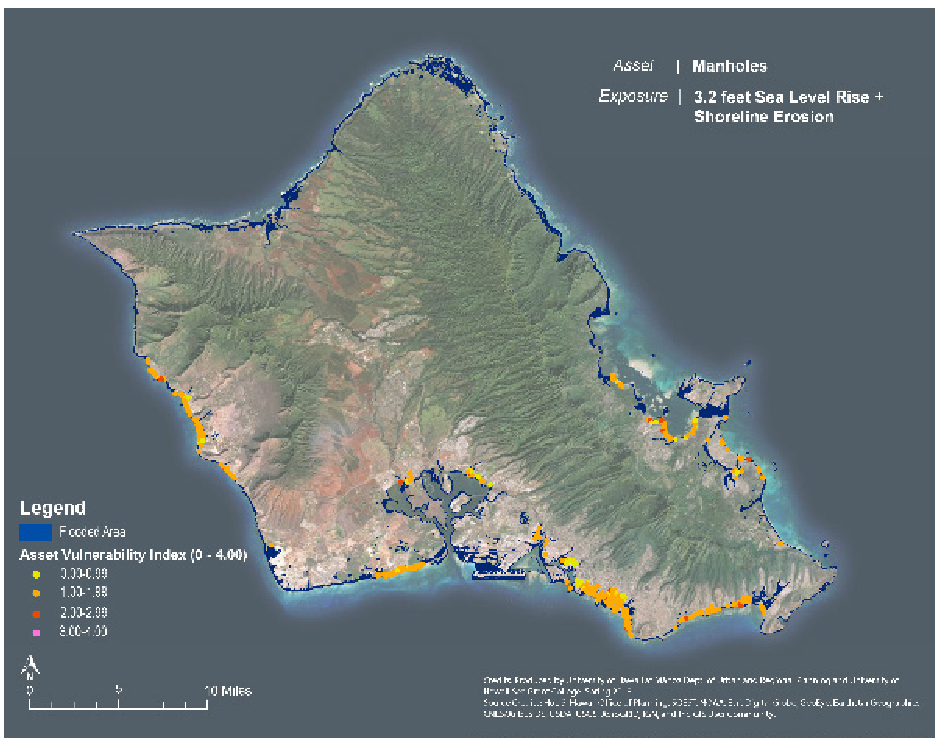

Figure 4-9: Manholes with 3.2 feet SLR (SLR-XA)

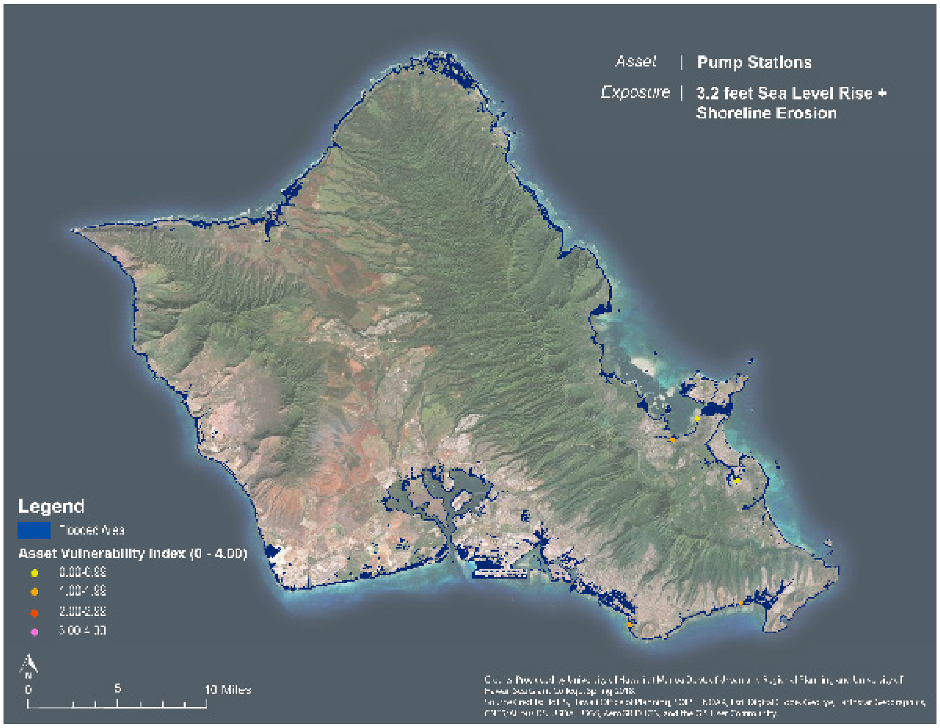

Figure 4-10: Pump Stations with 3.2 feet SLR (SLR-XA)

Pump Stations with 3.2 Feet of Sea Level Rise

Five pumping stations are exposed with 3.2 feet of SLR. Two of the exposed pumping stations help convey wastewater to the Sand Island WWTP and three are with the Kailua Regional WWTP area. None of the exposed pumping stations rank as high or very highly vulnerable.

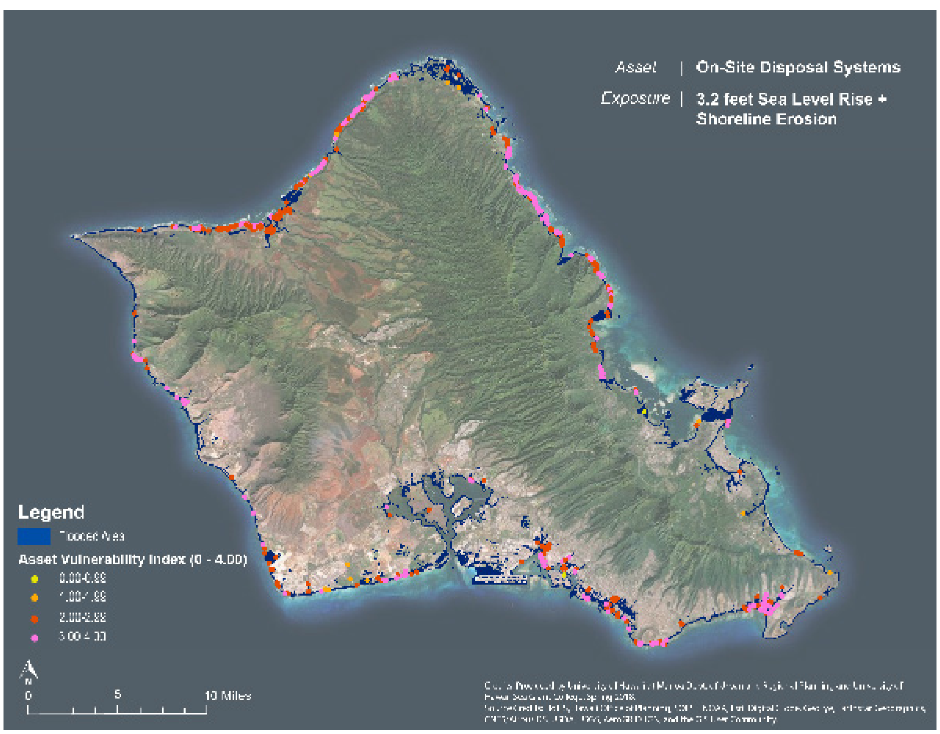

Figure 4-11: OSDS with 3.2 feet SLR (SLR-XA)

OSDS with 3.2 Feet of Sea Level Rise

1,322 OSDS systems are exposed with 3.2 feet of SLR. The majority of systems ranking in very high vulnerability (3.00-4.00) are located in the North Shore and along the Windward coast, north of Kaneohe Bay. Other hot spots of concentrated highly vulnerable OSDS include Hawai‘i Kai and Kalihi.

6 Feet Sea Level Rise (Bathtub flooding)

Sewer Mains with 6 Feet of Sea Level Rise

With 6 feet of SLR the total miles increases to approximately 192 miles of sewer mains are exposed. Roughly 64 miles rank as highly vulnerable (2.00-2.99), which are mostly located in the downtown Honolulu and Waikiki areas. Of the exposed sewer mains, just one 212 foot main located McCully ranks as very highly vulnerable (3.00-4.00).

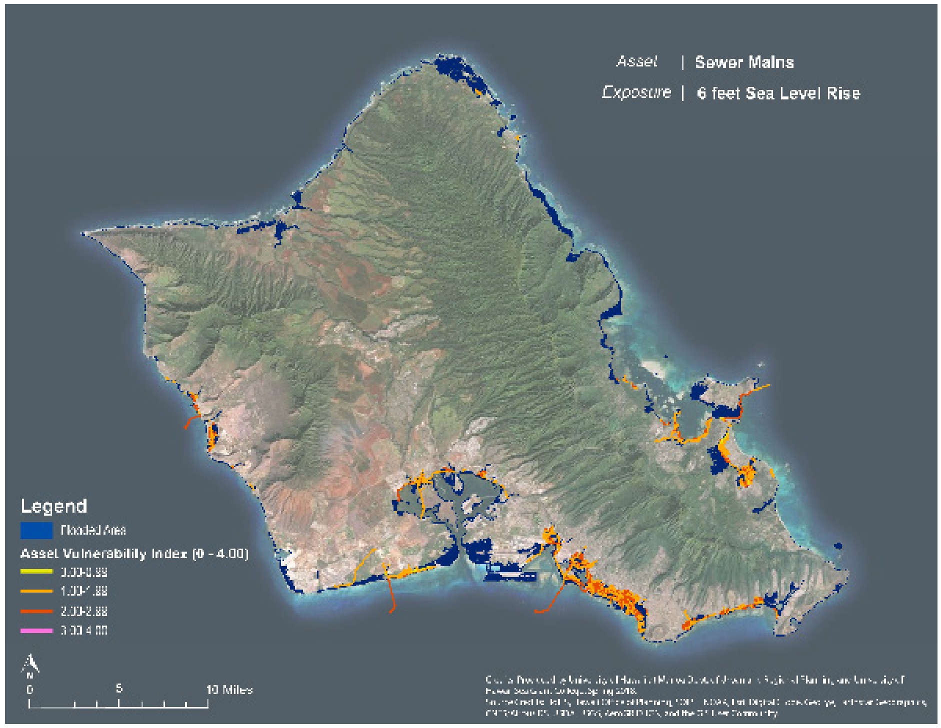

Figure 4-12: Sewer Mains with 6 feet SLR (bathtub flooding)

Sewer Laterals with 6 Feet of Sea Level Rise

With bathtub flooding caused by 6 feet of SLR, approximately 83 miles of sewer laterals are exposed. Approximately 6 total miles of sewer laterals rank as highly vulnerable (2.00-2.99) with hotspots in downtown Honolulu, Waikiki, and Kaneohe. Smaller clusters of highly vulnerable laterals are also located in Wai‘anae and East Honolulu.

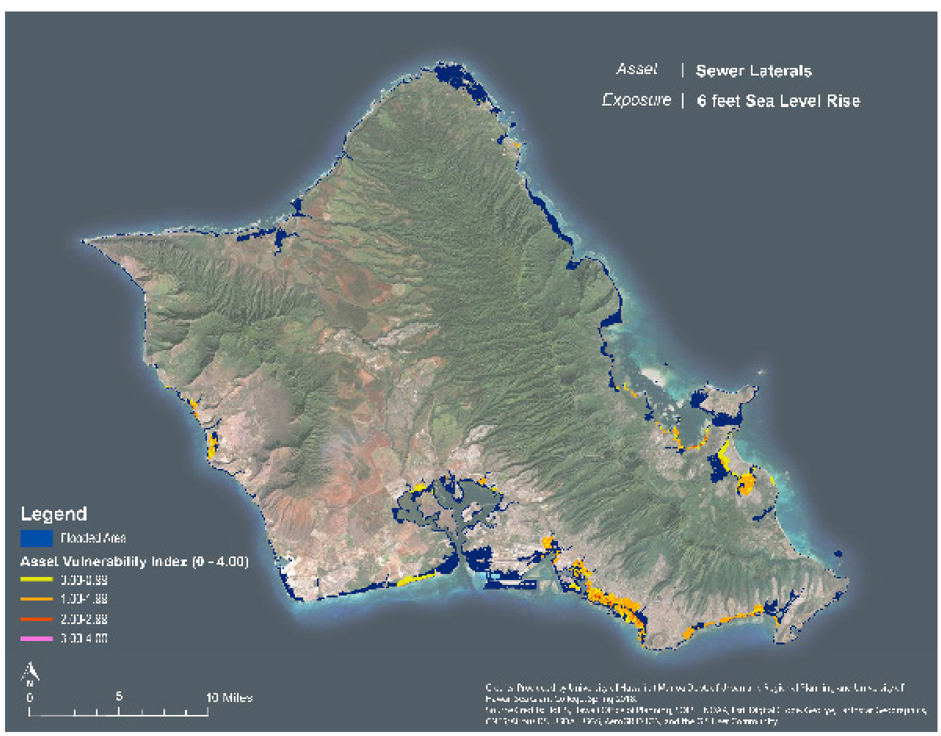

Figure 4-13: Sewer Laterals with 6 feet SLR (bathtub flooding)

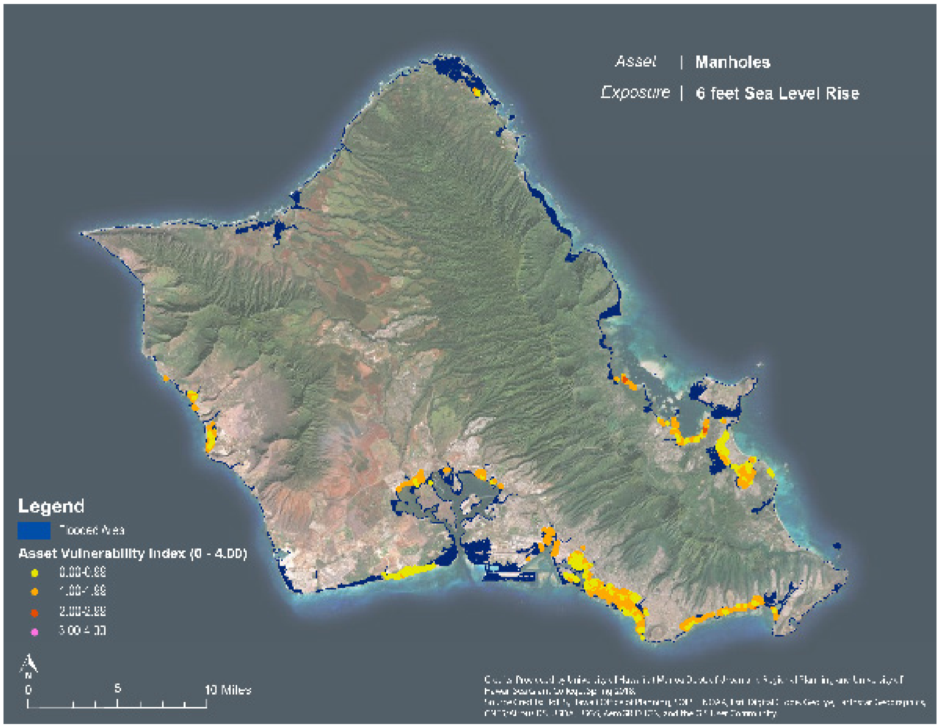

Figure 4-14: Manholes with 6 feet SLR (bathtub flooding)

Manholes with 6 Feet of Sea Level Rise

3,845 manholes are exposed to bathtub flooding caused by 6 feet of SLR. 22 manholes rank as highly vulnerable (2.00-2.99) in this scenario and 2,198 rank in the 1.00-1.99 range. Again the most vulnerable manholes are located near Kaneohe Bay with other hotspots in downtown Honolulu and East Honolulu.

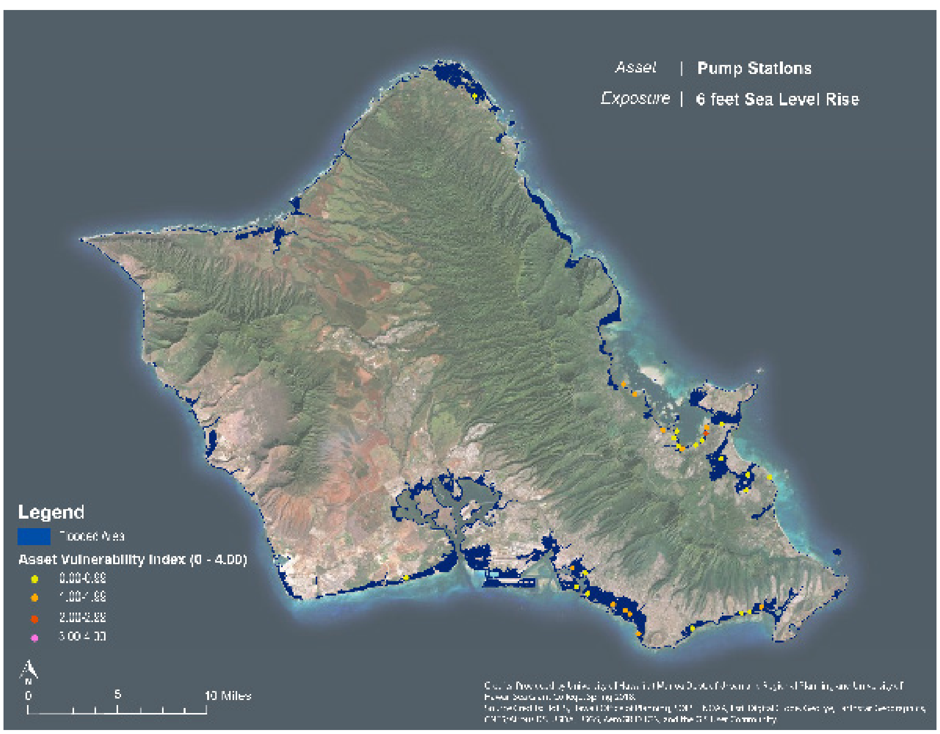

Figure 4-15: Pump Stations with 6 feet SLR (bathtub flooding)

Pump Stations with 6 Feet of Sea Level Rise

33 of O‘ahu’s 92 pumping stations are impacted with 6 feet of SLR. The majority of these pumps surround Kaneohe Bay and rank in the low (0-0.99) to mid (1.00-1.99) vulnerability range. The other pumping stations exposed in downtown Honolulu and East Honolulu also rank low to medium vulnerability.

OSDS with 6 Feet of Sea Level Rise

1,105 OSDS are exposed. Because the 6 feet of SLR scenario only accounts for bathtub flooding, the total number of OSDS affected is less than the 3.2 feet SLR-XA model.. Here the largest hotspots of highly vulnerable OSDS are located in Hawai'i Kai and along the Windward coast north of Kaneohe Bay where we find clusters of very highly vulnerable OSDS (3.00-4.00). Urban Honolulu has the highest density of affected OSDS, mostly in the 2.00-2.99 range on vulnerability index.. On the North Shore, the largest cluster is located along the shoreline between Hale'iwa and Waialua with the majority of vulnerability rankings between 2.00 and 2.99. Smaller clusters of highly vulnerable (2.00-2.99) OSDS exist in Ewa Beach, Kalaeloa, and Wai'anae.

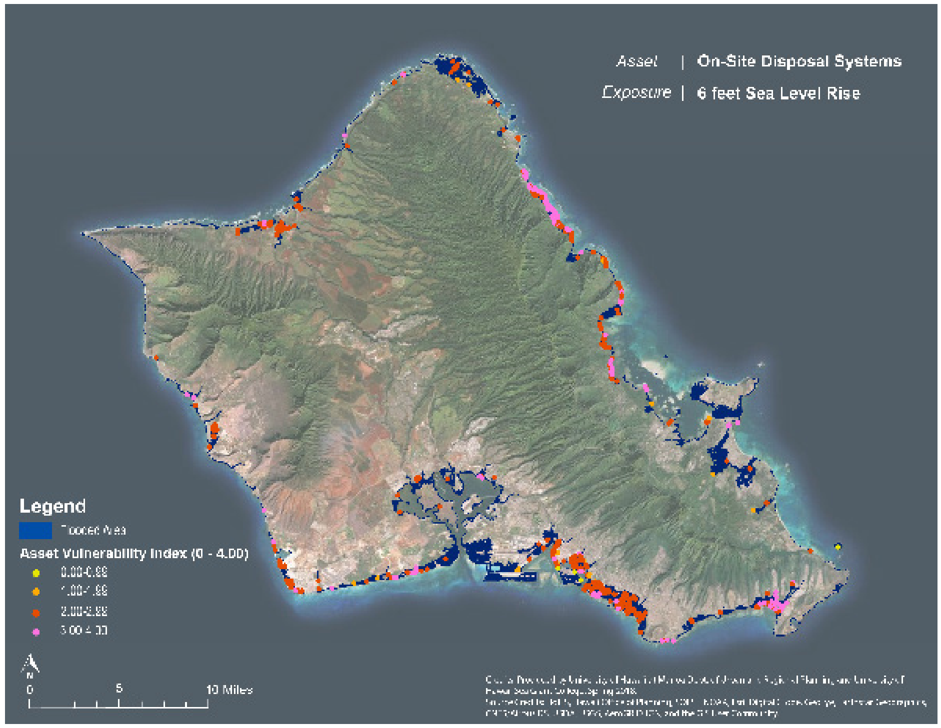

Figure 4-16: OSDS with 6 feet SLR (bathtub flooding)

Tsunami

The tsunami modeling used does not account for changes in sea level or shorelines due to coastal erosion. It models tsunami inundation based on present conditions and projections. A tsunami has the potential to impact the entire island. In terms of numbers, the total impact on assets is closest to our long-term scenario of 6 feet of sea level rise. However, because the projected tsunami impact is more evenly distributed across the island, all wastewater assets near coastlines are exposed. The vulnerability index highlights hotspots of vulnerability for the sewer system along the south shore and west side of the island. The area around Kaneohe Bay and Kailua area also vulnerable with low- to mid-range vulnerability rankings sewer mains, laterals, and manholes. For OSDS, huge swathes of vulnerable systems emerge on the north shore, along the windward side, and in urban Honolulu. Other areas with slightly smaller clusters of vulnerable OSDS are also impacted in Ewa Beach and along the west side. The maps below show the project impact on sewer mains, sewer laterals, manholes, and pumping stations.

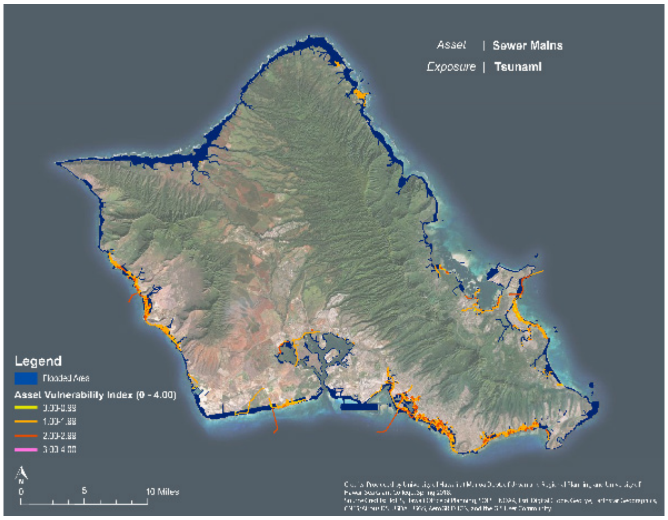

Figure 4-17: Sewer Mains with Tsunami Inundation

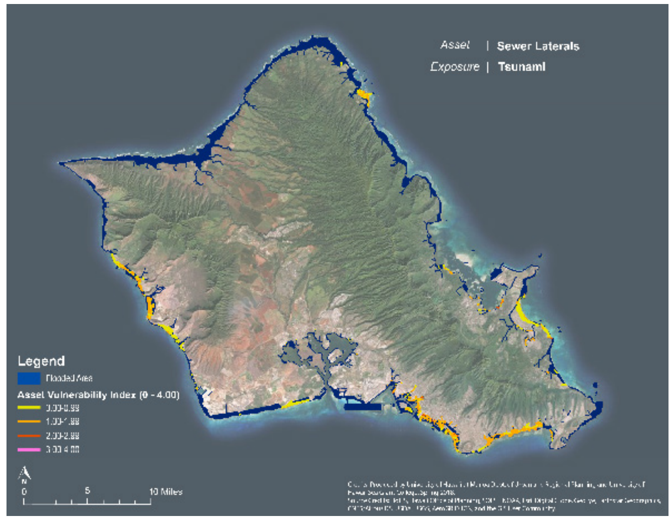

Figure 4-18: Sewer Laterals with Tsunami Inundation

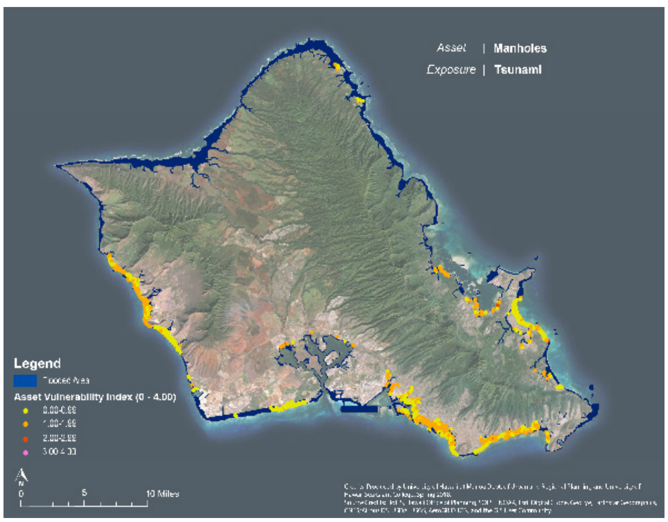

Figure 4-19: Manholes with Tsunami Inundation

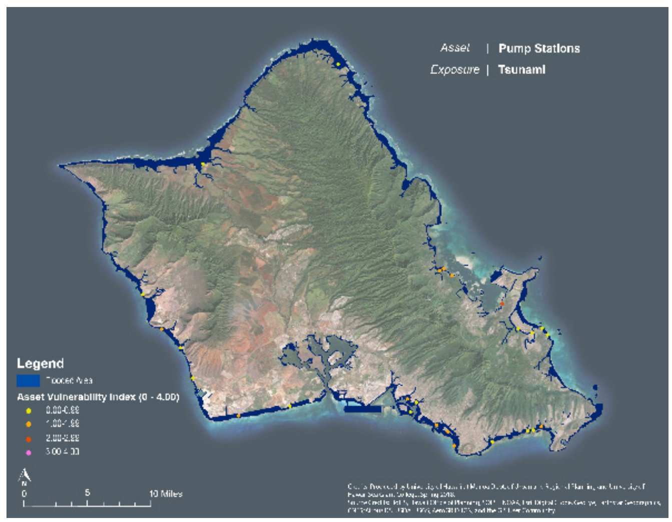

Figure 4-20: Pump Stations with Tsunami Inundation

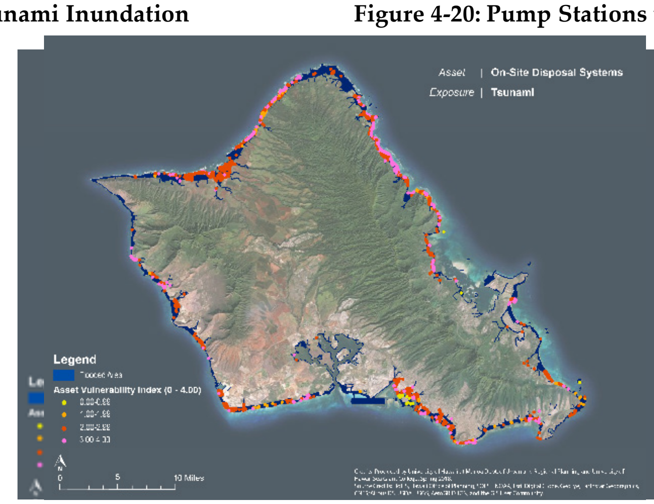

Figure 4-21: OSDS with Tsunami Inundation

Hurricane (Category 4)

The Category 4 hurricane data models a storm surge inundation area along the south shore of O‘ahu (PaciOOS, 2016). The model does not account for any changes in sea level or shorelines coastal erosion, but models hurricane storm surge for present conditions based on Hurricane Iniki. Though only a portion of the island is impacted, the south shore is where the majority of the population and wastewater infrastructure is located. The maps below show the projected impact on sewer mains, sewer laterals, manholes, and pumping stations. Applying the vulnerability index, the urban Honolulu area stretching from Kalihi to Diamond Head is highly vulnerable. The sewer mains in particular show high vulnerability rankings in the range of 2.00-2.99 with laterals and manholes also scoring mostly in the mid-range (1.00-1.99).

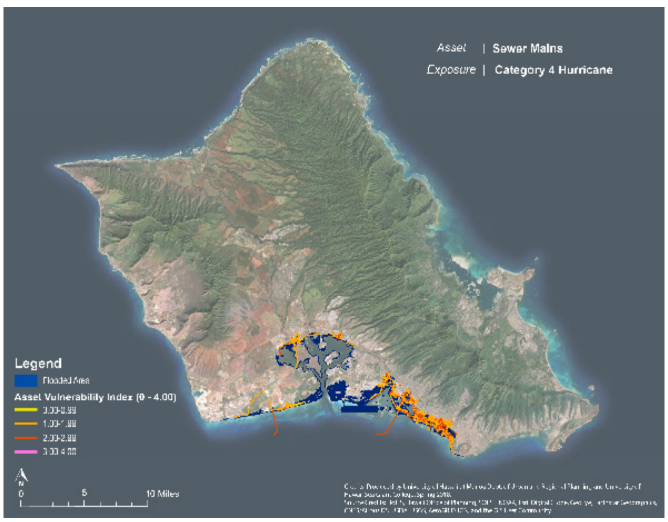

Figure 4-22: Sewer Mains with Category 4 Hurricane Storm Surge

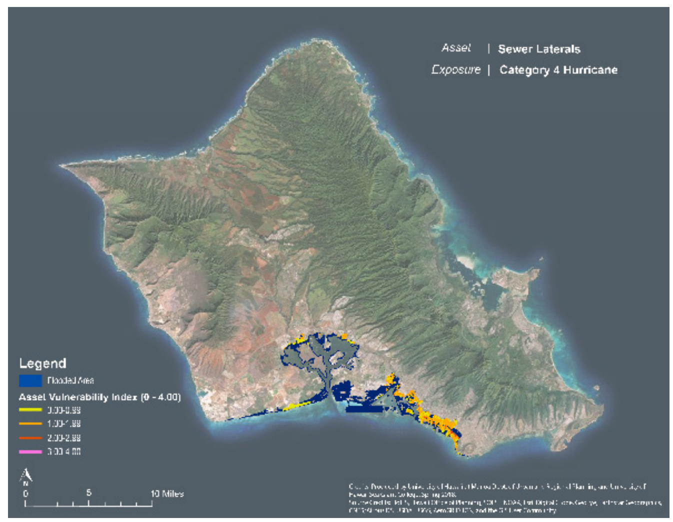

Figure 4-23: Sewer Laterals with Category 4 Hurricane Storm Surge

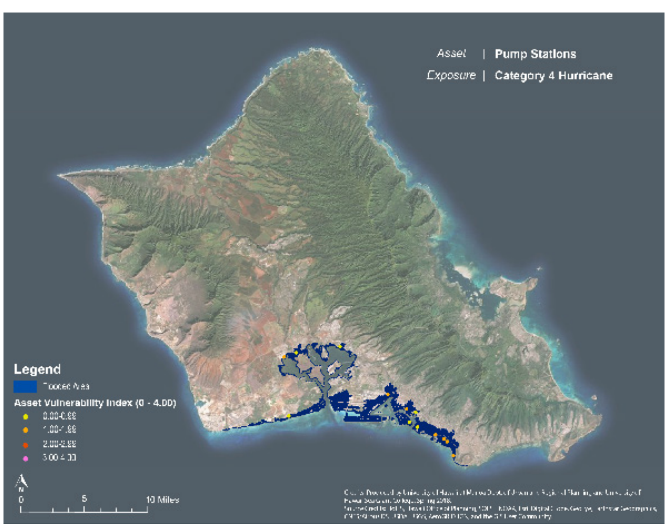

Figure 4-24: Pump Stations with Category 4 Hurricane Storm Surge

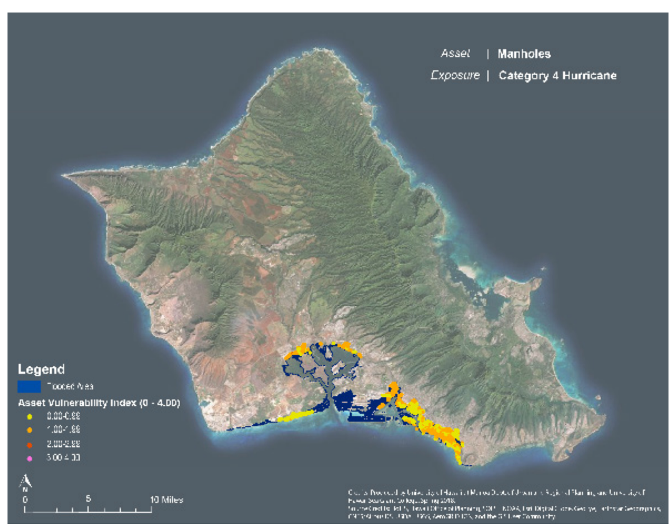

Figure 4-25: Manholes with Category 4 Hurricane Storm Surge

All Hazards – Wastewater Treatment Plants

The nine wastewater treatment plants on Oʻahu remain safe from flooding in the near- and mid-term SLR scenarios. However, in the long-term scenario with 6 feet of SLR the Kahuku WWTP on the north shore is vulnerable to flooding. Because this plant uses injection wells, prolonged flooding may impact the well, mixing wastewater with flood water. The results from the tsunami inundation model show the Kahuku and Waianae WWTP are also potentially vulnerable to a tsunami. The Sand Island plant is vulnerable to flooding from a category 4 hurricane storm surge. Any kind of prolonged flooding event would require a significant amount of time and resources to repair, which raises concerns as there are no back-up treatment options in any of the service areas. The impacted treatment plants are shown in a combined map, Figure 4-26 below.

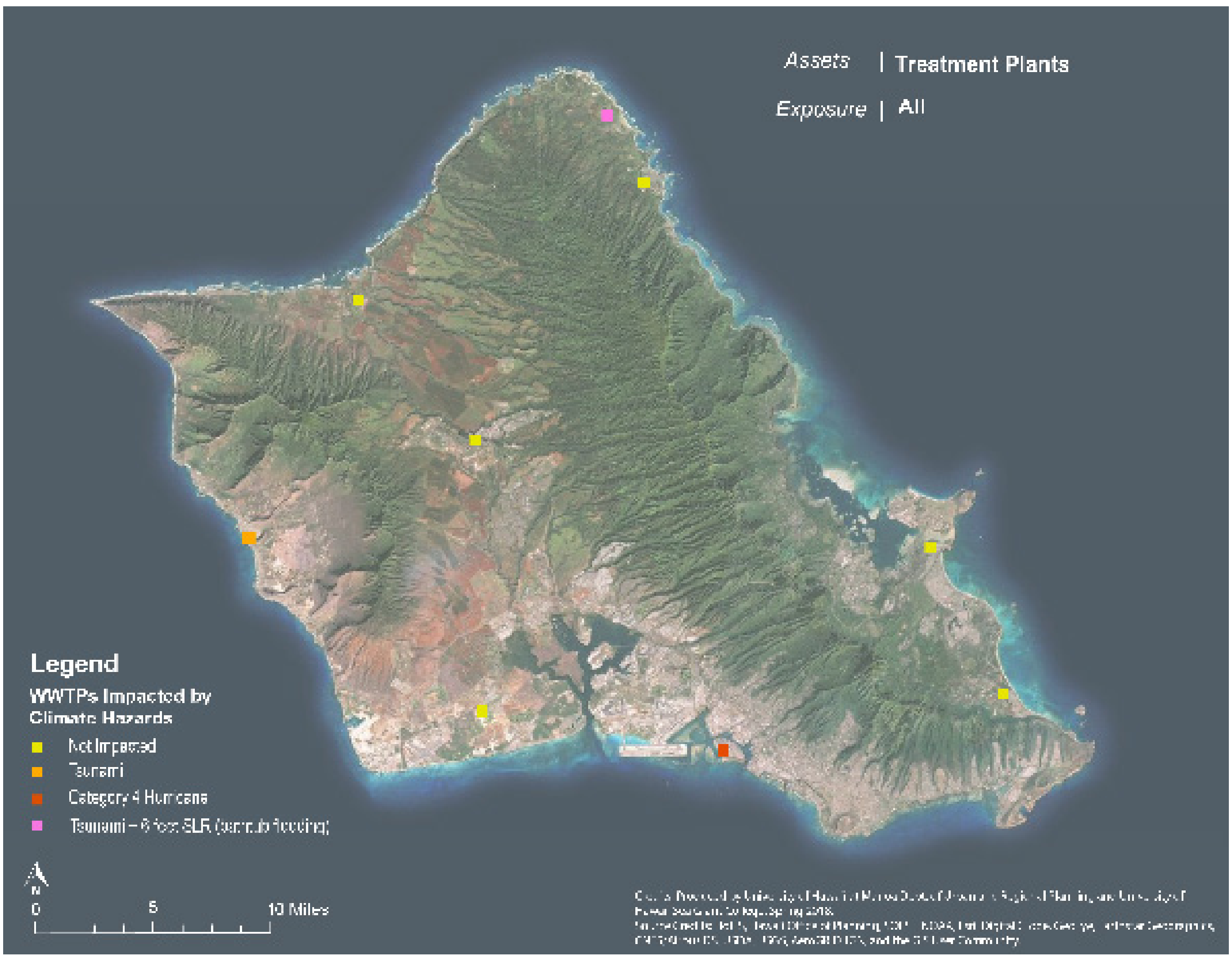

Figure 4-26: Wastewater Treatment Plants Impacted by Climate Change Hazards

The vulnerability index is an example of a tool that can be used to understand the larger patterns of climate change impacts and coastal hazards. The tool uses available data to identify areas or hotspots of higher vulnerability, which can aide with prioritization and decision making for adaptation. More in-depth vulnerability indices may prioritize certain indicators and apply a weighting system to build a more comprehensive scoring system.

The following section takes a narrower view to provide a practical method for applying impacts from groundwater inundation caused by SLR to sewer models. The method is applied to case studies of two vulnerable areas: Downtown Honolulu and another island coastal city.

V. Groundwater Infiltration of Coastal Sewer Pipes

Sensitivity Analysis of Infiltration Hydraulics

Presently, some sewer pipes on O'ahu are located below the water table and in the future additional pipes will become inundated. As the GW level (GWL) increases, the higher GW head above the pipes will lead to greater groundwater infiltration (GWI) into pipes through leaks and cracks. Collection system computer models used by engineers and planners consider sewage flow inputs based on land use (unit flows based on type), rainfall derived inflow and infiltration (RDII) based on infiltration models calibrated by flow monitoring of design storms, and groundwater infiltration (GWI). The GWI is affected by soil-moisture, GWLs, and sewer system depths relative to GWL (WERF 1999). With measured flow data, GWI can be considered in multiple ways. GWI can be calculated by subtracting baseflow from total flow during dry weather days (USEPA, 2013). Another method is to consider the average low nighttime flows per day; these nighttime flows are typically 12 AM to 4 AM and exclude known industrial or commercial flows (USEPA, 2013). GWI can also be considered as the product of population and a calibrated GWI unit rate. A commonly utilized dry weather infiltration rate is 5 to 15 gallons per capita per day. Commercial collection systems computer models are generally not capable of calculating GWI directly based upon system conditions such as pipe size, soil type, groundwater head, and other features.

This section presents a practical method to add the computation of GWI to sewer system models in coastal collection systems that will be affected by SLR (or anywhere the GWL will/could increase). Such model predictions can facilitate planning for collection system rehabilitation/replacement in advance of increases in GWI in order to limit or prevent possible SSO violations. These increases could be added to future flow predictions and therefore allow for more realistic collection system design and capacity analysis for coastal sewer systems like Hawai'i. The method was used to conduct a case study for downtown Honolulu, without the use of sanitary sewer flow monitoring data. A second case study was performed using sewer flow and rainfall monitoring data for another island coastal city.

Development of Calibration Method

The method utilizes the approximate 2-dimensional solution for GWI into a sewer pipe, based on Darcy's law of flow through porous media and orifice flow into a pipe (Guo et. al, 2013):

$$Q=2\pi K(h-P_i)\ln^{-1}(4\pi\beta(hr-\sin\alpha))$$

where:

K = hydraulic conductivity [m/s]

h = groundwater head above pipe centerline [m]

P_i = internal pressure head above defect [m]

β = defect size (angle) [radian]

r = pipe radius [m]

α = defect location [radian]

This model assumes a homogeneous, isotropic aquifer and horizontal groundwater table. Additionally, the defect size must be fairly small, since the washing of soil particles into the sewer pipe is not captured in this model. Both local and global sensitivity analyses (SA) of this equation were performed using the techniques in Bilal (2014). A local sensitivity analysis involves calculating the effects of varying one parameter at a time while holding all other parameters constant. Global SA techniques vary all parameters simultaneously and look at effects on output. The output for the global SA are shown in Figures 5-1 and 5-2 The most important input parameters were determined to be the hydraulic conductivity (K), and the head (h).

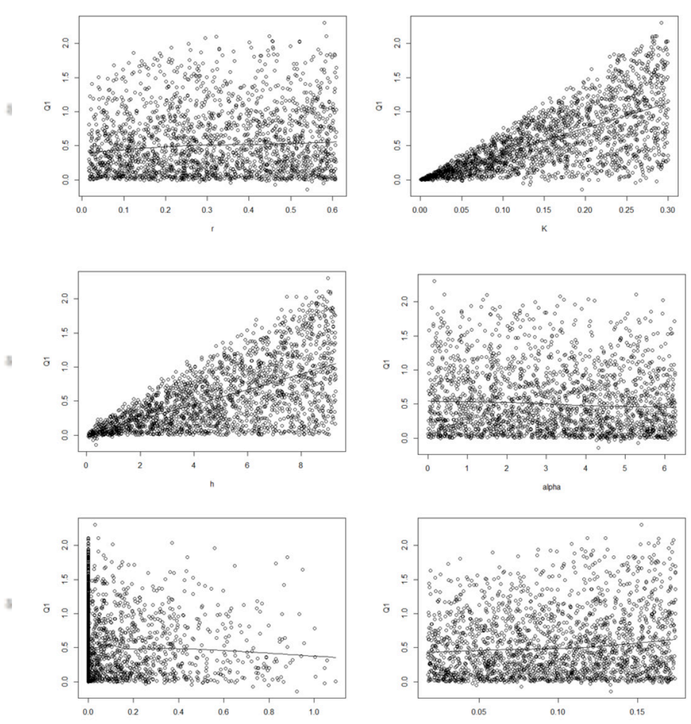

Figure 5-1: Groundwater infiltration scatter plots for a random sample (n=2,000).
GWI units are m3/day/m; pressure head(P), radius (r), groundwater head (h) units are m; defect location (α) and size (β) units are radians; hydraulic conductivity (K) units are m/s.

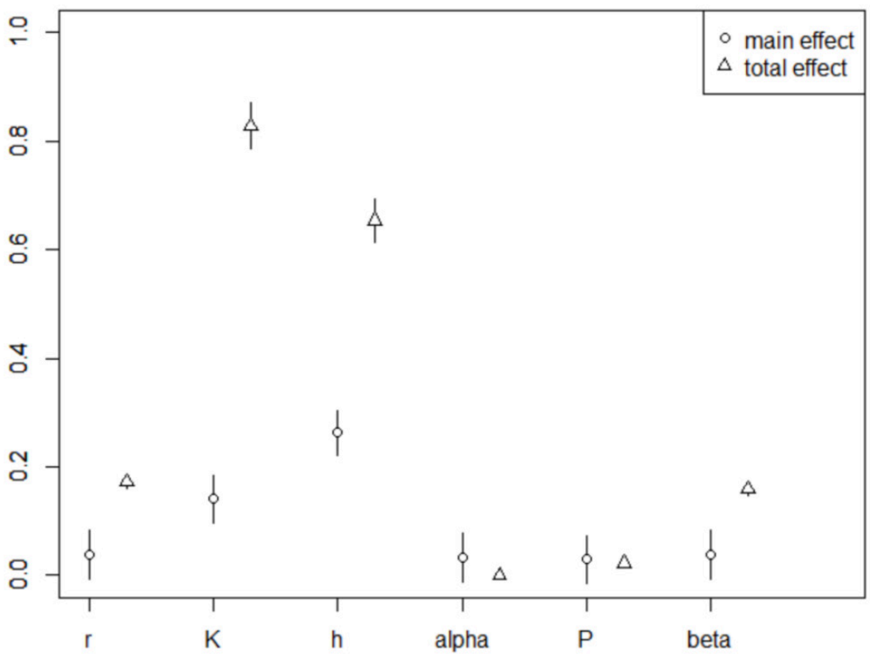

Figure 5-2: Main and total Sobol-Martinez sensitivity indices for the GWI model.

Application of Sea Level Rise Impacts Following Model Calibration

The latest prediction by the National Oceanic and Atmospheric Administration (NOAA) is a 2.5 meter rise (8.2 feet) in global mean sea level by 2100 in the extreme scenario (NOAA 2017). SLR will increase GWI entering the sanitary sewer system and bring the total volume of sanitary sewer flow closer to the SSO threshold such that less RDII will be needed to trigger an SSO. Therefore, it is important to prepare for the increase in GWI. A planning tool, as described in this section, will help with projecting the higher GWI flows and with prioritizing portions of the sanitary sewer system for adaptation.

Case Studies

Online GIS data for downtown Honolulu (see Figure 5-3) was used for the first case study. A second case study for another study area in an island coastal city (specific location is undisclosed at request of data owner) capitalizes on a complete sewer model, flow monitoring at 10 locations, rainfall data, groundwater monitoring data, and detailed soil maps.

Figure 5-3: Downtown Honolulu Collection System Used for Case Study #1

Case Study 1: Downtown Honolulu

For the downtown Honolulu case study, the sewer main pipe inventory data (diameter, length, invert elevations) were extracted from available online GIS data. Pipe diameters and lengths are shown in Table 5-1 (total pipe length is 174,166 ft. [33 miles]). The assumed value of K (average value for whole area) is 99 ft./day (0.00035 m/s) based on Finstick (1996). For this study, actual groundwater elevations were not available and thus the GWL was assumed to be the same as mean sea level (MSL) even though the GWL is known to progressively increase above MSL as one moves inland from the shoreline (thus flows calculated here are likely underestimated) (Habel et al., 2017). The head (h) for each pipe was considered a variable calculated by comparing invert elevations and MSL (current value and future values with SLR). Figure 5-5 shows the lengths of pipe affected by each increment of SLR. For this study, the internal pressure (P_i) was assumed to be zero, which means that the defect (crack) is located above the water level inside the pipe. The value of α was assumed as $\pi/2$, which means that the defect is located at the crown and leads to the highest rates of infiltration. The value of β (defect [crack] size) and percentage of pipes affected with defects were considered variables. Nine combinations (cases) were considered as shown in Figure 5-4 (pipe condition severity matrix). The relationship between values of β and crack size are shown in Table 5-2 for an 8-inch pipe.

Table 5-1: Pipe Lengths for Downtown Honolulu Case Study

Diameter (in)	Laterals (ft)	Mains (ft)
4	188	0
6	54613	5345
8	1214	56050
10	239	6051
12	70	5936
14	0	680
15	0	1685
16	0	111
18	0	2486
21	0	487
24	0	2013
28	0	1665
30	0	5205
32	0	1768
34	0	858
36	0	8057
42	0	574
48	0	3165
54	0	1317
60	0	8888
66	0	1534
78	0	3968
TOTAL	56324	117842

Table 5-2: Values of β and related crack size for 8-inch pipe

β		Crack size for 8-in pipe	
radians	degrees	inch	mm
π/90	2	0.153	4
π/30	6	0.460	12
π/18	10	0.766	19

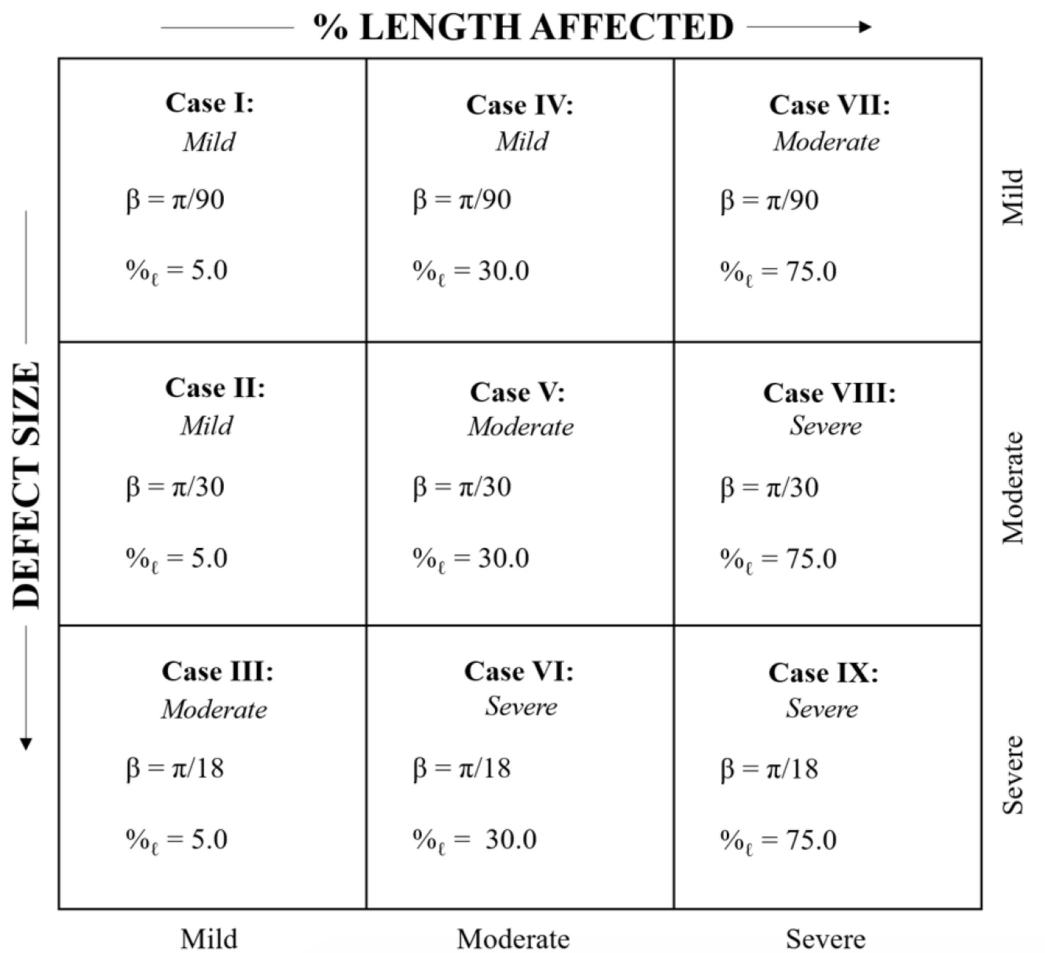

Figure 5-4: Pipe Condition Severity Matrix

The modeled values of GWI as a function of SLR for Case Study #1 are shown in Figure 5-6. There are nine curves; one for each severity case. Cases 1-2-3, 4-5-6, and 7-8-9 group together based upon the percentage of pipes affected; 5, 30, and 75%, respectively. Within each grouping, the effect of defect size is indicated (blue line is π/90, orange line is π/30, and green line is π/18). It can be seen that increasing the defect size (β) has a less dramatic effect than increasing the percentage of pipes affected (see the large trend lines with labels). At the left. edge of Figure 5-5, "SLR=0 ft." represents the current (existing) condition. At SLR=0 ft. for cases 1-2-3 where only 5% of the pipes are affected (essentially all new pipes or perhaps recently rehabilitated pipes), the amount of GWI varies from 0.71 to 0.83 to 0.90 MGD as β is increased. If 30% of the pipes have cracks, then the corresponding GWI flows are 4.3, 5.0, and 5.4 MGD. Similarly for 75% defective pipes, the corresponding GWI flows are 10.7, 12.4, and 13.5 MGD for current conditions prior to SLR. An estimate of the actual current GWI for downtown Honolulu is about 3 to 4 MGD, and this sewershed drains to a pump station with a capacity of approximately 100 MGD. If flow monitoring and CCTV data were available, then the model could be calibrated (estimate the percent affected based on collected data and correct the assumed value of β to match measured flows by sewershed). With a calibrated model, the curve of expected increases in GWI for given SLR could be plotted for different scenarios, such as no-further-action (no change in β or % affected), and also for various scenarios of sewer rehabilitation which would be very helpful for future project and adaptation planning.

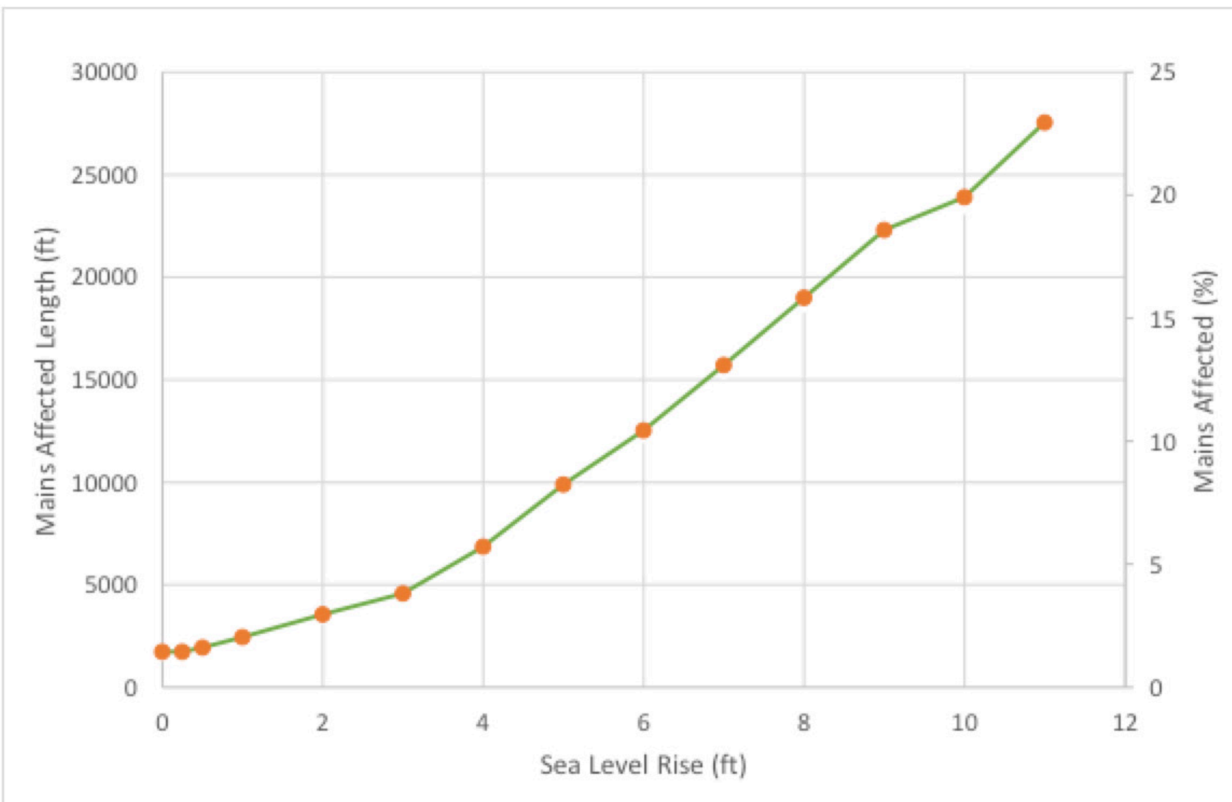

Figure 5-5: Length of sewer mains affected by SLR in feet and as percentage of total for Case Study #1: Downtown Honolulu

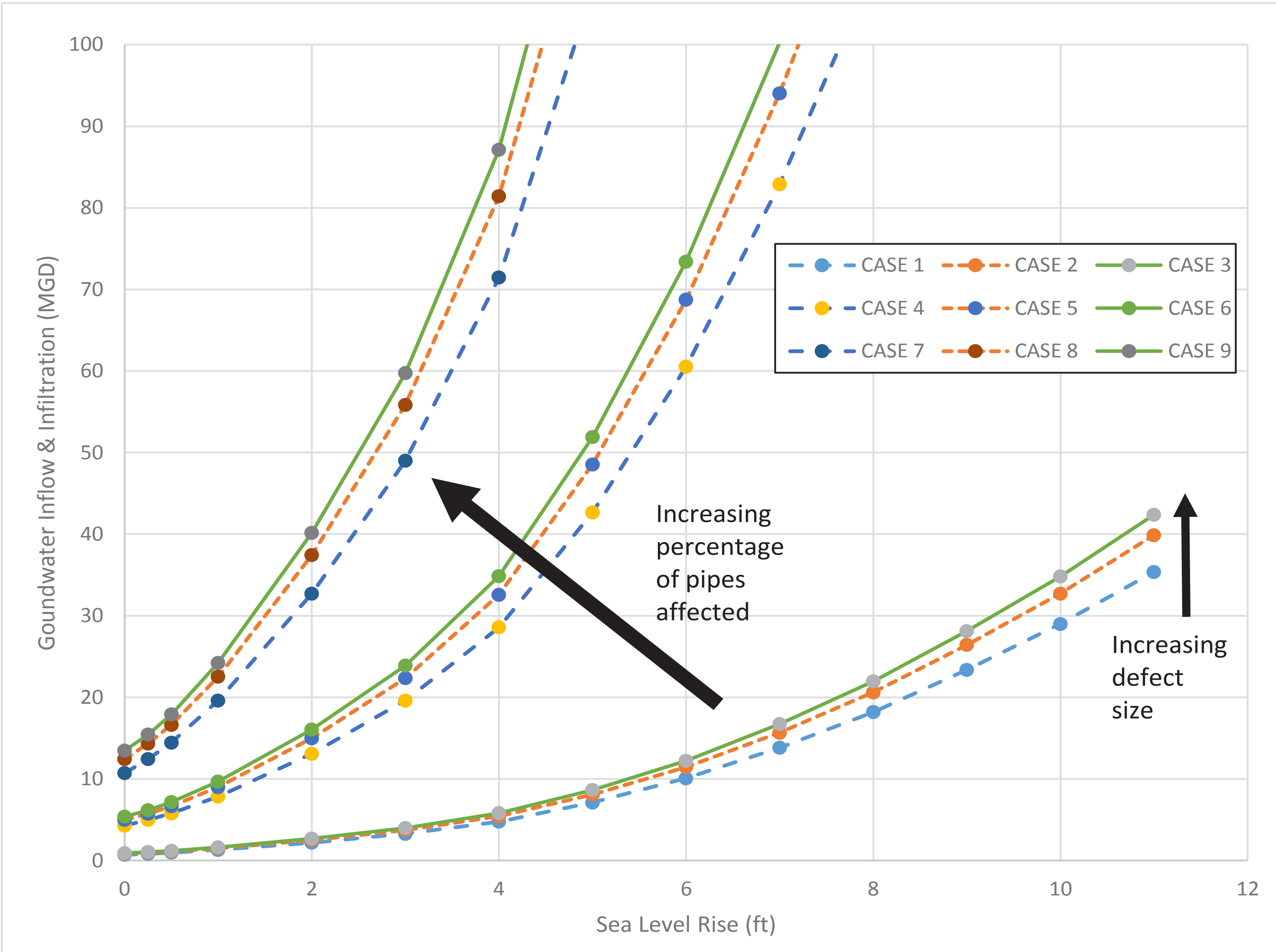

Figure 5-6: Severity Case Studies for SLR Impact on GWI into Sanitary Sewer System in Case Study #1: Downtown Honolulu

It is noteworthy that a relatively small percentage of the pipes in downtown Honolulu are currently affected by GWII (about 1.4% (1,705 ft.) of the total length) and as SLR increases, the amount of pipes affected initially increases slowly, such that only 2,400 ft. are affected when SLR reaches 1 ft. and 4,500 ft. are affected at 3 ft. of SLR. This might occur by 2050 in Honolulu and it should be entirely feasible to rehabilitate less than one mile of sewer pipes before then. However, after that the increases become larger and the penalty for waiting to start rehabilitation or not doing it at all becomes problematic/severe. The affected pipe lengths are 6,732 ft., 12,300 ft. and 22,000 ft. at SLR of 4, 6, and 9 ft., respectively. It would be prudent to have a rehabilitation plan in place to deal with these eventualities. The consequences of inaction would be that the GWII would occupy existing system capacity that is designed to handle RWII as well as normal sewage flows (either with or without new connections), thus potentially leading to sanitary sewer overflow violations which are already a problem.

Case Study 2: Study Area of Tropical Island Coastal City

The model was also used by our team to evaluate SLR impacts in a study area within a tropical island coastal city (specific location is undisclosed at request of data owner). The following summarizes the procedure for model calibration using collected data, followed by applying SLR effects to observe the outcomes.

It was first necessary to compile an inventory of data from flow and rainfall monitoring, as well as a database of the area's sanitary sewer pipes. A flow and rainfall monitoring program was implemented by the wastewater agency for about 10 weeks from November 2014 to January 2015. Ten flow meters and two rain gauges were strategically installed throughout the sanitary sewer lines. The flow meters were programmed to collect level and velocity readings every five minutes, and the rain gauges were set to record rainfall data every five minutes. Weekly operation and maintenance and data downloads were performed.

After the monitoring program, the U.S. EPA software SSO Analysis and Planning Toolbox was utilized to calculate flow (based on level and velocity readings) and assess the data for quality and usability. For example, data from a meter installed in a manhole subject to frequent surcharging could not be used for the model. Under circumstances of typical gravity flow behavior, there should be a general increasing trend between flow and level, as flow volume increases with level. When surcharging occurs, the accuracy of flow measurements is impacted because flow within the pipe may shift from gravity flow to pressure flow, flow volume may have spilled out and left the system, or backups are causing a low velocity to be measured.

Data describing "typical" or expected sanitary sewer system performance, as discussed below, was needed to estimate GWI. Ultimately, data from a flow meter was selected for use in the model. This meter was installed downstream of approximately 4,700 feet (ft.) of sewer line length. A geographic information system (GIS)-based asset management system database was obtained from the wastewater agency and included information such as pipe material, length, radius, installation date, slope, and invert elevations. These data were used later to attain model input variables.

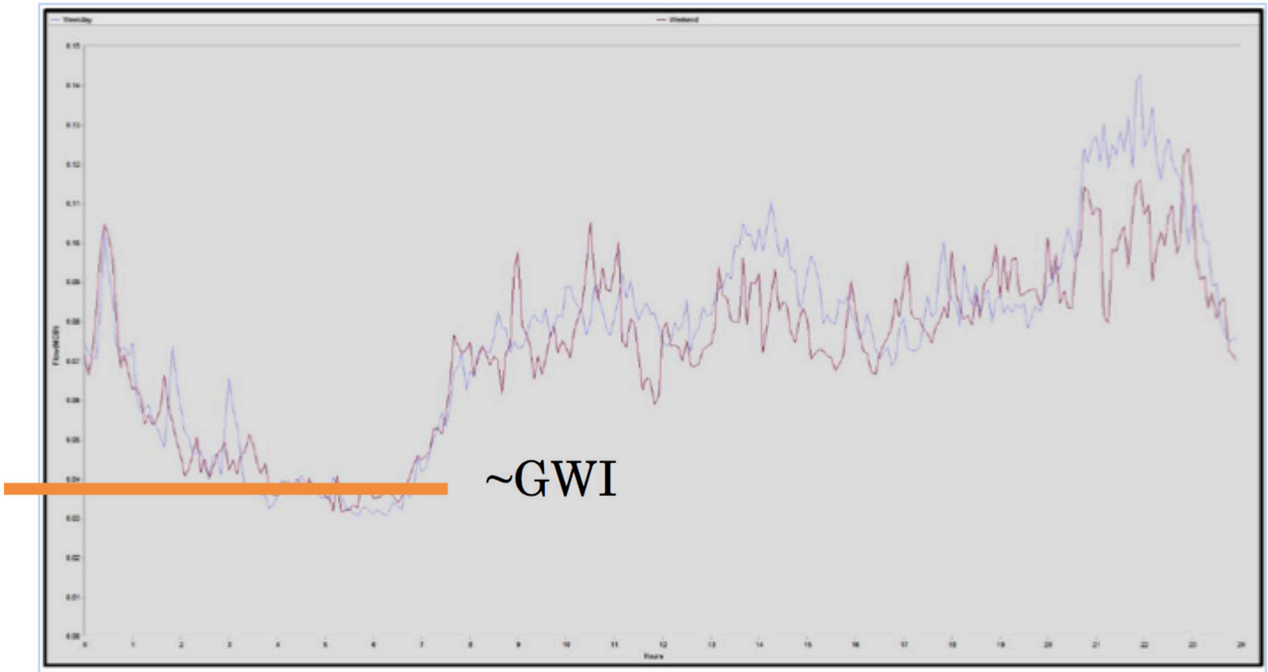

Figure 5-7: Example Hydrograph and Estimate of GWI

The SSO Analysis and Planning Toolbox software was then used to analyze the flow and rainfall data and estimate a Q_{actual} to represent GWI in the pipe. This value is based on the nighttime minimum dry weather flow (DWF). As mentioned earlier, data exhibiting "typical" sanitary sewer performance is needed in order to use diurnal flows, which rise during the day and fall during the night. BWF and RDII flows are negligible at night and during dry weather, allowing the assumption that the measured flow at that time is primarily GWI. Figure 5-8 is an average DWF hydrograph for weekday and weekend flow, with the orange bar approximating the amount of GWI. As observed in the figure, flow starts increasing when water users are getting ready for the day. The water usage fluctuates around an average value throughout the day, increasing slightly again when water users return home and prepare dinner or get ready for bed. The flow decreases after water users head to bed. DWF days were selected based on measured rainfall that did not exceed a maximum amount of rainfall over a given number of preceding days. For this study area, eight DWF days met the criteria, and a Q_{actual} was determined for each day.

It is important to note that Q_{actual} is measured by the flow meter downstream of the study area sewer lines. Therefore, this value is the sum of GWI in *all* upstream pipes. Therefore, another step was taken to calculate flow in *each* pipe segment. The pipes were divided into 10-ft. segments, and a potential GWI was determined for each section. Potential GWI is a representation of the GWI that could occur. As depicted in Figure 5-9, this is based on multiplying the pipe length, which is 10 ft. in the case of our 10-ft. segments, diameter, and **h**. A potential GWI is calculated for each pipe section, and these are summed up to obtain a total potential GWI.

A proportion equation can then be set up as the following:

$$\frac{Potential\ GWI\ for\ one\ pipe\ segment}{Total\ potential\ GWI\ for\ all\ pipes} = \frac{Q_{Pipe\ Segment}}{Q_{Actual}\ measured\ at\ the\ flow\ meter}$$

This will allow for the GWI of an individual pipe segment ($Q_{Pipe\ Segment}$) to be calculated.

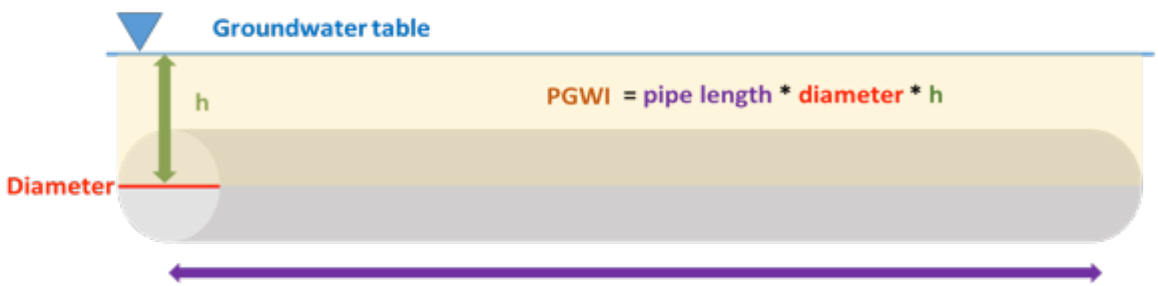

Figure 5-8: Diagram of Potential GWI Calculation

The remaining parameters of the model were obtained: hydraulic conductivity **K**, hydraulic head **h**, and radius **r**. The GIS database contains a layer map with the pipe locations. This was coupled with another layer map of soils in the study area. After determining the soil type that was surrounding the 10-ft. pipe segment, a U.S. Department of Agriculture (USDA) and Natural Resources Conservation Service (NRCS) Custom Soil Resource Report was generated for the location. The report gave a range of hydraulic conductivities for each soil type (U.S. Department of Agriculture and Natural Resources Conservation Service, 2017). For a conservative approach, the lower limit was used.

Afterwards, **h** was calculated for each pipe segment. The pipe invert and groundwater elevations were used to calculate this value. Pipe invert elevations were provided in the GIS database. Groundwater elevations were interpolated based on daily historical groundwater elevation measurements from a nearby U.S. Geological Survey monitoring well. Finally, **r** was gathered from the GIS inventory.

Remaining parameters were α and P_i. The value of α was assumed to be $\pi/2$, which is equivalent to a defect at the crown of the pipe. According to Guo et al.'s parametric study, a defect located at the top causes the largest infiltration rate, while a defect at the bottom causes the smallest infiltration rate. To avoid underestimating the results, an α of $\pi/2$ was used. For P_i, since the defect is located at the crown, it is above the pipe content level; therefore, P_i is equal to the atmospheric pressure and can be taken as zero.

With all model input parameters determined, model calibration was performed. The Microsoft® Excel Solver program was used to calculate a defect size β and calculate a Q_{Model}, with the criteria of minimizing the difference between Q_{Model} and $Q_{Pipe\ Segment}$.

Once calibration was completed, the groundwater elevation was increased by the projected amount of sea level rise. This calculated a new **h**, which in turn calculated a new Q_{Model} for GWI, based on the increase in sea level.

Calibration Results

The initial β calibration resulted in unrealistic β values that were too large. For example, a one-ft. radius pipe would need a β of nearly 7 radians to calculate a Q_{Model} matching the associated $Q_{Pipe\ Segment}$. This does not make physical sense, as a β of 7 radians is a 7-ft.-long arc, which exceeds the pipe circumference. Additionally, the model is recommended for small defect sizes, such as a β of $\pi/18$.

Based on assessing the other model input variables, another parameter that could be further investigated was the hydraulic conductivity **K**. Since the lower value of the USDA and NRCS Custom Soil Resource Report was used in the initial calibration, we used the higher value in another round of calibration. With these higher **K** values, the β values were within a reasonable range. Using these calibrated β values, we proceeded with applying sea level rise effects in various scenarios, as described in the following.

Effect of SLR on Only Pipes Currently Affected by GWI

GWI primarily affects pipes that have defects below the groundwater table. If the defect is above the groundwater table, then it is high enough to prevent groundwater from infiltrating into the pipe. During the monitoring period in the study area, not all pipes were submerged under the groundwater table. Of the approximate 4,700 ft. of sewer line, roughly 6% were affected by GWI. Table 5-4 summarizes the effects of sea level rise on just these pipes alone.

Based on current monitoring data, about 0.035 million gallons per day (MGD) of GWI occur, which is averaged as 0.00012 MGD per ft. of sewer line. After a SLR of 1.0 and 2.5 meters, the GWI increases to 0.11 MGD and 0.21 MGD, respectively. Averaging the percent changes over the DWF days, these equate to 211 percent (%) and 500% flow increases, respectively. These are clearly very large increases that should be considered in planning exercises, especially, the 1.0 meter case (3.2 ft.) which could occur between 2060 and 2100.

Additional Effect of SLR on Newly Submerged Pipes

In addition to impacts of SLR on pipes already affected by GWI during the monitoring period, another scenario was created to observe SLR impacts on pipes currently above the groundwater table. With increased groundwater elevations, these pipes may end up being below the groundwater and subject to GWI. Twelve case studies were developed for varying degrees of defect size and percent of affected sewer line length, as conveyed in Table 5-5. Each case study was applied to the pipes that were not affected by GWI during the monitoring period. The amount of GWI in these pipes was added to the GWI in pipes already affected by GWI during the monitoring period . As demonstrated in Figure 5-10, there is a larger effect of the percentage of pipes affected, compared to the defect size. Furthermore, Cases 1, 2, and 3 set a lower limit on the amount of GWI, whereas Cases 10, 11, and 12 set an upper limit. Using the sea level rise predictions from NOAA or other sources, this figure can be used to project increases in GWI. Table 5-4 is a tabular version of Figure 5-10 for estimating the SLR that can be expected in future years.

Table 5-3: NOAA Predictions for Global Mean Sea Level Rise Scenarios Relative to Year 2000 (NOAA, 2017)

Global Mean SLR Scenario (feet)	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Low	0.10	0.20	0.30	0.43	0.52	0.62	0.72	0.82	0.92	0.98
Intermediate-Low	0.13	0.26	0.43	0.59	0.79	0.95	1.15	1.31	1.48	1.64
Intermediate	0.13	0.33	0.52	0.82	1.12	1.48	1.87	2.33	2.79	3.28
Intermediate-High	0.16	0.33	0.62	0.98	1.44	1.97	2.59	3.28	3.94	4.92
High	0.16	0.36	0.69	1.18	1.77	2.53	3.28	4.27	5.58	6.56
Extreme	0.13	0.36	0.79	1.35	2.07	2.95	3.94	5.25	6.56	8.20

Table 5-4: Increase in GWI in Pipe Currently Affected by GWI in Case Study #2: Tropical Island Coastal City

	Pre-SLR (measured by USGS and flow meter)			SLR of 1.0 meter			SLR of 2.5 meters			Percent Change of GWI	
DWF Day	Sewer Line Length affected by GWI (ft)	GWI (MGD)	Average GWI / Foot of Sewer Line (MGD/ft)	Sewer Line Length affected by GWI (ft)	GWI (MGD)	Average GWI / Foot of Sewer Line (MGD/ft)	Sewer Line Length affected by GWI (ft)	GWI (MGD)	Average GWI / Foot of Sewer Line (MGD/ft)	Pre-SLR vs. 1.0 m SLR	Pre-SLR vs. 2.5 m SLR
11/27/2014	332.4	0.041	0.00012	332.4	0.12	0.00037	332.4	0.24	0.00071	200%	471%
12/1/2014	322.4	0.041	0.00013	322.4	0.12	0.00038	322.4	0.23	0.00072	199%	469%
11/30/2014	332.4	0.021	0.00006	332.4	0.076	0.00023	332.4	0.15	0.00046	255%	611%
12/2/2014	312.4	0.037	0.00012	312.4	0.11	0.00036	312.4	0.22	0.00069	208%	491%
12/6/2014	282.4	0.038	0.00014	282.4	0.11	0.00040	282.4	0.22	0.00077	196%	464%
12/7/2014	282.4	0.038	0.00013	282.4	0.11	0.00040	282.4	0.21	0.00076	198%	468%
12/8/2014	282.4	0.026	0.00009	282.4	0.088	0.00031	282.4	0.17	0.00061	236%	560%
12/9/2014	272.4	0.037	0.00014	272.4	0.11	0.00040	272.4	0.21	0.00077	197%	465%
AVERAGE	**302.4**	**0.035**	**0.00012**	**302.4**	**0.11**	**0.00036**	**302.4**	**0.21**	**0.00069**	**211%**	**500%**

Table 5-5: Case Studies for Pipes Newly Submerged due to SLR

	Increasing % of Sewer Line Length Affected →			
↓ Increasing Defect Size	**Case 1** $\beta = \pi/90$ % affected = 5%	**Case 4** $\beta = \pi/90$ % affected = 30%	**Case 7** $\beta = \pi/90$ % affected = 75%	**Case 10** $\beta = \pi/90$ % affected = 100%
	Case 2 $\beta = \pi/30$ % affected = 5%	**Case 5** $\beta = \pi/30$ % affected = 30%	**Case 8** $\beta = \pi/30$ % affected = 75%	**Case 11** $\beta = \pi/30$ % affected = 100%
	Case 3 $\beta = \pi/18$ % affected = 5%	**Case 6** $\beta = \pi/18$ % affected = 30%	**Case 9** $\beta = \pi/18$ % affected = 75%	**Case 12** $\beta = \pi/18$ % affected = 100%

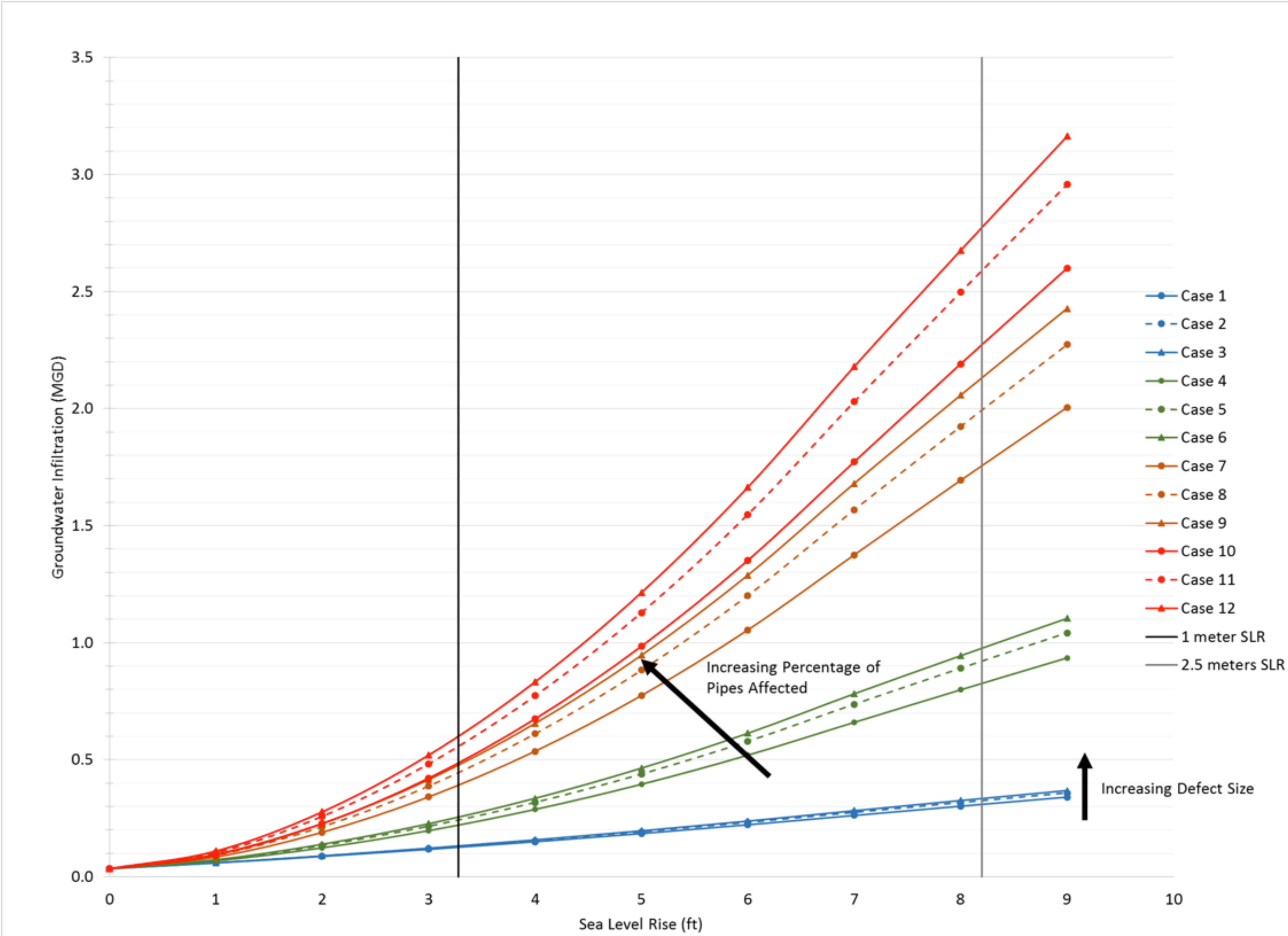

Figure 5-9: Severity Case Studies for SLR Impact on GWI into Sanitary Sewer System in Case Study #2: Area of Tropical Island Coastal City

Conclusions and Next Steps: Model Use for our Study Area and Other Sanitary Sewer Systems

Due to sea level rise, GWI into the sanitary sewer system is projected to increase over the years. Therefore, it is important to develop a planning tool to help prioritize areas of the sanitary sewer system for rehabilitation or improvements. Data was obtained from a wastewater agency's sanitary sewer flow and rainfall monitoring program within a study area of a tropical island coastal city. Our team used the measurements and the agency's sanitary sewer system GIS database to determine input parameters to calibrate a model for estimating GWI through a pipe line defect. In our initial β calibration, it was observed that the hydraulic conductivities potentially underestimated the true values. Following this, we used the higher limit of the hydraulic conductivities from the USDA and NRCS Custom Soil Resource Report, and the resulting βs were then within a reasonable range. To implement the model, the groundwater elevations were increased according to NOAA's SLR predictions, and Figure 5-10 was generated to demonstrate the GWI increases in the wastewater agency's sanitary sewer system within that study area.

Furthermore, the model can be re-calibrated with sanitary sewer flow and rainfall monitoring data within other locations, and then applied to observe the level of GWI increases in those places. The projections can be used in combination with other tools, such as mapping, to visualize sections of the sanitary sewer system that will be more prone to sea level rise impacts. This will provide cities, municipalities, and other stakeholders with an additional method for planning sanitary sewer system rehabilitation and adapting to future sea level rise.

VI. On-site Disposal Systems

On-site sewage disposal systems are both an efficient and economical means of disposing wastewater in rural or less densely populated communities (USEPA, 2007). However, these systems can cause water contamination when they fail due to improper installation, poor maintenance, or when they are sited in areas with unsuitable soil or hydrological conditions (Siegrist et al, 2000). In turn, poor water quality due to failing systems threatens the long-term health and vitality of communities and coastal ecosystems (Marsh, 2010). This section reports on a policy gap analysis of wastewater management policies and programs responsible for the proper permitting, construction and maintenance of on-site disposal systems on O'ahu.

On-site disposal systems are a decentralized form of wastewater treatment technology that are located on individual homeowner or business property. Different systems vary in the quality of wastewater treatment, as well as by their cost to install and maintain. Systems can provide a relatively small amount of treatment, such as septic tanks, or just dispose of wastewater, such as cesspools. Typically the more advanced the system, the higher the cost to install and maintain, however the installation costs can also depend on soil and topographic features.

Septic systems receive wastewater from the household or community center and solids are settled out in the septic tank. Liquids are discharged to an absorption field where it then filters through the ground. These systems rely on naturally occurring chemical and biological process such as dilution, chemical decomposition and biological consumption of the components of wastewater in order to effectively treat and dispose of the effluent (On-site Wastewater Treatment Survey & Assessment, 2008). Cesspools, however, provide no treatment to the effluent before it is discharged into the ground. Cesspools are containers with permeable sides that discharge raw sewage directly into the soil and must be installed in soil characteristics to retain the wastewater long enough to prevent water contamination (Marsh, 2010). Table 6-1 summarizes all of the different on-site sewage disposal types present in Hawai'i.

Table 6-1: On-site disposal types (Adapated from State of Hawai'i, DOH)

OSDS Type	Disposal Description
Septic with soil treatment	Includes bed, trench, and infiltration chambers which receive treatment from the soil – nutrient and bacteria removal through soil filtration and sorption
Aerobic treatment unit	Inject oxygen to support bacterial breakdown of wastewater inside unit. Effluent receives primary and secondary treatment and degrades organic matter prior to dispersion
Septic tank	A wastewater storage unit that allows for both settling and skimming. Effluent receives primary treatment – settling of solids in septic tank prior to dispersion
Cesspool	A large, cylindrical excavation used to receive untreated wastewater. Effluent receives no treatment

Identifying Vulnerable Areas

Most on-site disposal systems are a combination of treatment and disposal methods. Cesspools, however, are the exception and are considered substandard systems because they allow for raw sewage to be directly discharged into the ground without treatment (Water Resource Research Center & Engineering Solutions, Inc., 2008). There are an estimated 14,606 OSDS on Oahu, some found in very high densities (Figure 6-1) (Whittier and El-Kadi 2014). Several coastal communities contain densities that exceed 150 on-site systems per square mile. The highest densities are found in the coastal communities of Waialua, Ewa Beach, Waikane, Kahalu'u, Hau'ula and Punalu'u. Most of these areas have been identified by the state as priority areas in need of upgrade from cesspools to either some other on-site technology or connection to a sewer (State of Hawaii Department of Health 2017).

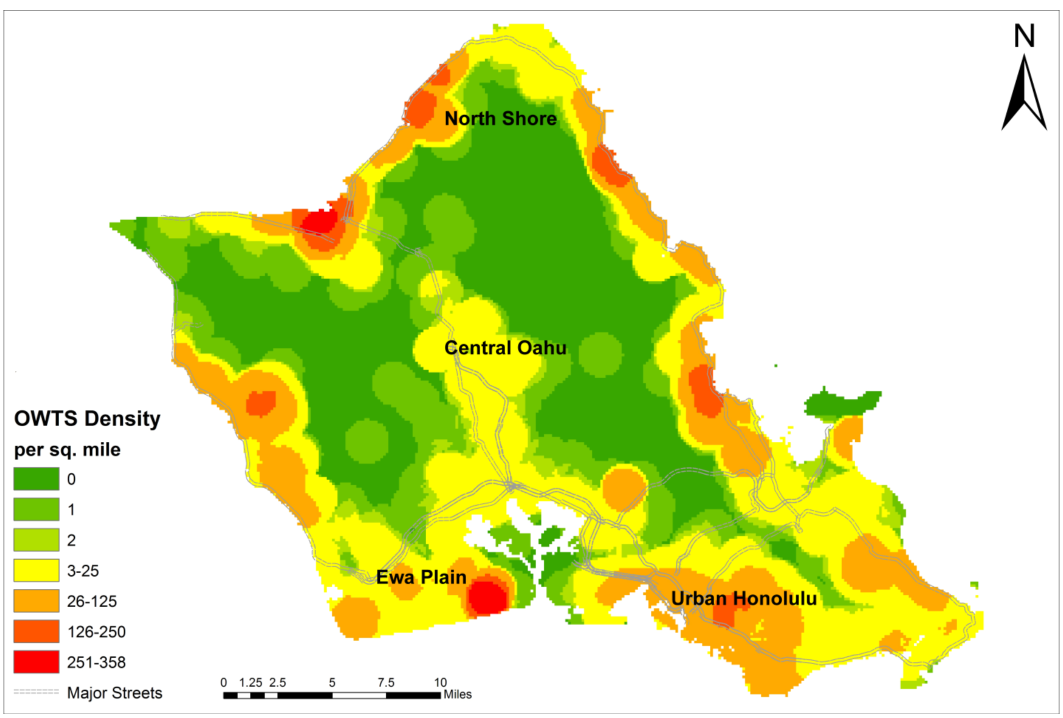

Figure 6-1: Density of on-site wastewater disposal systems on O'ahu

Using the wastewater vulnerability index, we assessed the vulnerability of areas with high densities of OSDS to SLR and coastal hazards scenarios. Table 6-2 shows the OSDS impacted by: 1.1 feet of SLR, 3.2 feet of SLR, 6 feet of SLR, a category 4 hurricane, and tsunami inundation. Section IV includes maps of OSDS with vulnerability rankings based on the vulnerability index. The vulnerability rankings are adapted from the Hawai'i Department of Health Human and Environmental Risk Ranking of On-site Sewage Disposal Systems (2009). The points on the map show OSDS that are exposed in the given scenario with colors designating the level of vulnerability. Higher vulnerability rankings mean that the OSDS is more vulnerable and higher risk to fail due to one of these factors or a combination of factors that make them more sensitive: their proximity to the coastline, proximity to flood zones, soil drainage, depth to groundwater, depth to rock, proximity to drinking water, proximity to streams, and OSDS density.

Table 6-2: OSDS Exposure of OSDS to SLR and coastal hazards scenarios

Wastewater Assets	**Total Units on O'ahu**	*1.1 ft. SLR-XA*	*3.2 ft. SLR-XA*	*6 ft. SLR (Bathtub)*	*Category 4 Hurricane*	*Tsunami Inundation*
All Types of OSDS	13,684 systems	475 systems	1,322 systems	1,105 systems	441 systems	4,592 systems
Aerobic	199	9 systems	20 systems	9 systems	1 system	66 systems
Cesspool	11,253	371 systems	1,008 systems	874 systems	439 systems	3,378 systems
Septic	534	11 systems	20 systems	5 systems	NONE	103 systems
Systems Receiving Soil Treatment	2,620	74 systems	252 systems	205 systems	1 system	947 systems
Other		10 systems	23 systems	12 systems	NONE	98 systems

Wastewater Management Regulations, Standards, and Guidelines

Wastewater management for OSDS is primarily the responsibilities of government entities but also involves individual land- and homeowners.

Federal wastewater policies fall within the National Pollutant Discharge Elimination System (NPDES), established by the 1972 Water and Pollution Control, better known as the Clean Water Act. The program, administered by the U.S. Environmental Protection Agency (EPA), focuses on "end of pipe" discharge from industrial and wastewater outlets as well as "nonpoint" source pollution resulting from land use changes and activities that transform the natural landscape, and includes disease causing bacteria and nutrients from failing OSDS (Cosens and Stow 2014). As such, federal policies that address wastewater pollution direct U.S. States to implement regulatory programs .

In Hawaiʻi, the State Department of Health (DOH) maintains authority to regulate, oversee, and enforce all activities pertinent to OSDS across the state. The DOH administers the Non-Point Source Pollution Management Program to address water quality degradation under the Clean Water Act. Within the DOH the Wastewater Branch is responsible for formulating and enforcing wastewater rules, regulating and enforcing existing wastewater systems, and reviewing and approving new systems. The Clean Water Branch is responsible for water quality monitoring, permitting and enforcement of NPDES permits, and managing the polluted runoff control program.

Recently, two laws were passed to address cesspools. Act 120, passed in 2016, prohibits any new housing construction with cesspools. In 2017, state legislators passed Act 125, which requires the replacement of all cesspools by 2050. In response, the DOH identified fourteen areas in the state to focus actions for conversions.

Hawaii's land use law established a statewide land use management system and grants Hawaii's four counties the power to zone through a comprehensive general plan (Haw. Rev. Stat. § 46-4). County land use policies and plans, known as General Plans are required to (among other priorities) "contain objectives to be achieved and policies to be pursued with respect to […] water and sewage system locations" (Haw. Rev. Stat. § 226-58). As such, the City and County of Honolulu builds and maintains the sanitary sewer system on Oʻahu.

Policy Gaps in Hawaʻi

Regulatory agencies at different levels are responsible for permitting on-site systems, establishing watershed scale land use plans, and monitoring and mitigating non-point source pollution. And while these agencies address on-site systems in both direct and indirect ways, there is currently no coordinated approach to ensure these systems are planned, sited, inspected and managed effectively. Sea level rise promises to exacerbate current weaknesses in the on-site wastewater management structure as more systems partially or fully fail and agencies are unable to respond efficiently and appropriately.

EPA Framework

The U.S. E.P.A recognizes OSDS as viable and economical if properly installed, managed, and maintained (US EPA 1997). Best practices are articulated via guidance and EPA policy documents. EPA's *Voluntary National Guidelines for Managing On-site and Clustered (Decentralized) Wastewater Treatment Systems* (US EPA 2003) outlines a programmatic framework for a comprehensive program and provides guidance for evaluating gaps in state run programs (US EPA, 2003). According to the recommendations, a comprehensive program involves three components: Administration, Installation, and Operation and Compliance. Policies and activities that fall within these three areas cross management sectors, responsible agencies and various levels of government.

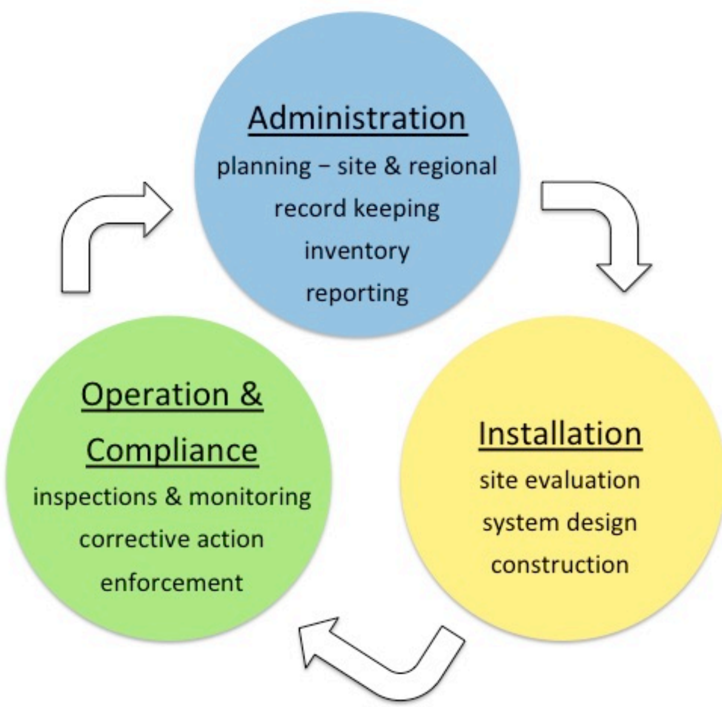

Figure 6-2: EPA Framework for Decentralized Wastewater Management

This framework was applied to assess the policies, rules, and programmatic activities that regulate and manage OSDS on O'ahu. All policies and related program activities that manage OSDS are summarized in Table 6-3. The Table is organized by the three program components (Administration, Installation, and Operation/ Compliance). The first column identifies the program element followed by columns that specify basic activities and advanced activities that encompass that component of the management program. The fourth column identifies the institutional level that implements the activities. The final column summarizes current rules, and OSDS program activities currently taking place in Hawaii, and identifies gaps in the current management regime.

Table 6-3: Summary of program activities and policy gaps

Program Element Administration	**Basic Activities**	**Advanced Activities**	**Institution**	**Program activities and policy gaps**
Performance requirements	Prescribe acceptable site characteristic; stipulate types allowed	Stipulate system performance standards	State of Hawaii Department of Health	Siting standards include minimum distance to adjacent property and setbacks (HAR 11-62). Cesspools outlawed for future development (HAR 11-62; Eff 3/21/16). System performance standards not stipulated or required
Planning	Identify minimum lot sizes; surface, groundwater separation distances; critical areas requiring protection	Monitor & model pollutant loads Development patterns tailored to environmental & physical limitations of systems; Land use plans and zoning take into account OWTS;	State of Hawaii Department of Health Coastal Zone Management Program County	Siting standards include minimum depth to water table, minimum lot size (HAR 11-62; Eff 12/10/88; Amended 3/21/16) Critical Wastewater Disposal Areas are identified for all Hawai'i islands, which allow for stricter rules (HAR 11-62) Coastal Non-Point Pollution Control Program outlines management measures for on-site systems to guide watershed planning. State water quality standards based on CWA, DOH monitors waters and identifies impaired water bodies.

Program Element Administration	Basic Activities	Advanced Activities	Institution	Program activities and policy gaps
		Require clustering for large developments.		County land use plans and zoning do not consider environmental & physical limitations of all OWTS. No current requirement for clustering large developments
Record Keeping, Inventory, Reporting	Provide inventory information on all systems, maintenance, upgrades, record performance	Provide GIS-based comprehensive inventories, including web-based monitoring	State of Hawaii Department of Health	By law, no required recordkeeping or monitoring of management and maintenance programs for OWTS, except for more advanced treatment units (University of Hawai'i-Mānoa Water Resources Research Center 2008) Basic inventory estimated based on engineer site inspection and system plan submitted to the Department of Health. Inventory not maintained. Geospatial layers created based on basic inventory & risk assessments conducted (Whittier, R. B. and El-Kadi, A. 2009).

Program Element Administration	Basic Activities	Advanced Activities	Institution	Program activities and policy gaps
Funding	Establish basic legal authority to implement revenue-generation fees. Full financial & legal support for program	Initiate monthly or quarterly service fees; Repair/ replacement programs.	State of Hawaii Department of Health Clean Water Branch	Legal authority from CWA (33 U.S.C. §1251 et seq. (1972)) & HAR 11-62 ([Eff 12/10/88; Amended 3/21/16) Act 120 (enacted 6/12/15) provides an income tax credit for qualifying cesspools to be upgraded or converted. No state or county ordinance or law stipulating the legal authority to generate revenue-generation fees No service fees collected No mandatory repair or replace program
Public Education & Participation	Sponsor public meetings, forums, updates and education programs	Public advisory groups, review groups, & other involvement opportunities	State of Hawaii Department of Health	General information on cesspools, Act 120 tax credit, watershed funding opportunities, water quality plans and HRS 11-62 and contact information provided on Department of Health website. No educational programs, public meetings and other public outreach methods.

Policy Gaps and Recommendations

The analysis highlights several important policy gaps within Hawaii and Honolulu's regulatory system. These gaps are summarized below along with recommendations to address shortcomings and examples from practice.

Need to integrate land use planning with decentralized (OSDS) wastewater planning

DOH rules set site criteria (e.g. soils, set back distances) but there is currently no mechanism for considering the cumulative impacts of increasing numbers or density of OSDS. County land use zoning does not address OSDS directly. Thus, there is a need to adopt land use-wastewater plans and zoning that take into account the environmental and physical limitations of all OSDS with local development plans that tailor development patterns accordingly. One way of doing this is by developing wastewater management plans at the County level. This could be a mandated part of the Hawaii Water Plan. These plans could be developed at the watershed level (similar to the County Water Use Plans).

Examples from practice:

In California, the State Water Resources Control Board, which regulates on-site wastewater treatment systems, created regional water quality control boards to develop "basin plans." Each regional basin plan identifies water quality objectives, policies, and programs within their respective jurisdiction, and includes general guidelines for siting, design, and construction of new OSDS. California, like Hawai'i has extreme ranges of geological and climatic conditions and this approach provides a multi-tiered strategy with the intent of efficiently utilizing and improving upon existing local programs through coordination between the State and local agencies (County of Marin Environmental Health Services 2016).

Massachusetts has been a national leader in promoting wastewater management. Comprehensive wastewater plans at the local jurisdictional level are subject to the state environmental policy regulations which require an assessment and public comments on the direct and indirect impacts of wastewater alternatives, requiring the planning effort be consistent with local and regional plans.

Rhode Island passed legislation in 1987 enabling municipalities to establish OSDS management districts. Since then, local governments across the state have adopted ordinances in response to their local community's concerns. As a result, programs have been adopted on the local level out of concern for issues such as water quality, overdevelopment, and to protect aquifers and public drinking water (Macrellis and Douglas, 2009).

Establish performance based management goals

OSDS are designed and installed to meet prescriptive codes where certain types can be installed at certain sites. However, not all suitable sites are the most appropriate to develop due to other conditions that affect the system's performance. Establishing performance-based codes for OSDS assists regulators, decision-makers and planners to implement total maximum daily load (TMDL) best management practices, including the best selection of OSDS technologies for given locations. Establishment of such an assessment for individual on-site treatment would broaden the assessment to include vital factors that influence performance of systems such as: landscape, soils, proximity to sensitive ecosystems, and future environmental conditions.

Examples from practice:

Florida has implemented management programs throughout the state in connection to performance-based standards. The state certifies maintenance providers to service aerobic systems following annual DOH inspections. These certified contractors helped one county with maintenance and monitoring in conjunction with a program of targeted sewer extensions and on-site system replacements with advanced treatment.

A recent study for the Chesapeake Bay Program Office reviewed the scientific literature and engaged experts to determine the performance of OSDS treatment technologies based on their potential removal efficiencies of nitrogen (e.g. percent nitrogen reduction) (Adler et al. 2014). The purpose was to develop total nitrogen (TN) reduction credits that can be assigned to individual OSDS technologies. One of the recommendations from the study was to broaden the assessment from individual technologies to take into account the role of the landscape, soils and proper operations and management.

Create and maintain an inventory of all OSDS

Creating an inventory of OSDS helps with planning, managing, monitoring, and reporting on systems to oversight agencies. Further, a well maintained inventory helps to facilitate the sharing and exchange of data between agencies, which will only gain importance as decisions around prioritizing and conversion of systems from OSDS to sewer increase with sea level rise and climatic hazards. Currently, Hawai‘i has little or no record keeping.

Examples from practice:

In Wisconsin, 2008 state code revisions mandated counties to create an inventory of all on-site systems within their jurisdiction within three years, and implementation of maintenance reporting programs at the county level within five years (Macrellis and Douglas, 2009). In Wood County (WI), which experienced a viral outbreak due to illegal wastewater disposal in the 1990's, the implementation of a web-based data management and reporting system has resulted in proper maintenance of 84% of all holding tanks and greater than 94% of all septic systems (Kaminski, 2009 via Macrellis and Douglas, 2009).

In Washington, the state legislature required local county health departments in a 12-county area surrounding the Puget Sound to identify and inventory all systems (Macrellis and Douglas, 2009). In other states such as Vermont and Louisiana, local jurisdictions used Section 319 funding and EPA's National Community Wastewater Demonstration project to inventory all systems.

Need for a policy and/or systematic education & outreach to ensure homeowners maintain OSDS
The US EPA's recommended management model relies primarily on construction permits and periodic contact with homeowners to remind them of their system's basic maintenance needs. Under this model, an agency has the capacity to maintain "a record of the location of all systems and periodically provides the Owner/User with notices regarding operation and preventive maintenance recommendations" (US EPA 2003, p. 33). Hawai'i does not meet the program requirements for communication with homeowners. We recommend, at minimum, the use of construction permits and public outreach to educate and ensure homeowners maintain OSDS. More advanced programs include preventative maintenance ordinances where counties inspect existing systems by requiring time of transfer inspection (with purchase of new home) or require mandatory inspections using renewable permits.

Examples from practice:
Some State Universities facilitate outreach and public education. Virginia Tech has published a series of public educational materials. The University of Minnesota Extension operates a network, which includes a library of publications and resources as well as regional on-site wastewater extension specialists and educators (Macrellis and Douglas, 2009).

In Marin County, California, the Local Area Management Plan (LAMP) includes information intended for public education and outreach. The LAMP includes information to inform OSDS owners about: standard and alternative systems, the permitting process, special provisions for flood plain areas, and more (County of Marin Environmental Health Services, 2016). In addition, the LAMP includes materials on how to locate, operate, and maintain an OSDS, system performance evaluation guidelines and maintenance, and information on the operating permitting program.

Challenges and Opportunities for Adaptation

The state has made strides to improve decentralized wastewater management by requiring cesspool conversions by 2050 and establishing the cesspool conversion working group through 2018 legislation. However, the program gaps identified in this section suggests that future OSDS may also fail due to insufficiencies in programs, activities and regulations in key management areas. While more advanced OSDS technologies offer a potential solution to cesspools, best practices for operation, maintenance, data management, monitoring and land use planning remain critical to ensure systems function in the long run and watersheds retain the capacity to sufficiently process effluents and nutrients.

Given the exposure, risk ranking, and policy gaps that were identified, a few key challenges and opportunities emerged.

Challenges

Future conversion must take a broader view of performance standards, environmental conditions, and alternative technologies based on the location and potential climate change related hazards. For instance, there is a very high concentration of vulnerable OSDS along the coastline north of Kaneohe Bay. If these systems convert to either another on-site technology or sewer system, decision makers will need to ensure that the selected technology is resilient to future SLR conditions.

Currently, the state DOH writes, administers and enforces OSDS codes and administers all permits. Counties have no role in rule-making, enforcing state codes or managing systems, but are responsible for managing and operating sewers and treatment plants. With the projected impacts to both on-site and central wastewater treatment systems caused by climate change and SLR, the need for a comprehensive wastewater management program in Hawaiʻi will only increase.

Opportunities

A large number of OSDS are within areas with sewer service availability. Central sewers can be built or maintained to function while underwater, however when connecting OSDS parcels to the sewer system, the City & County need to consider how vulnerable the sewers are to future SLR.

Recent legislation, which establishes a working group and provides funding for future studies on upgrading, converting or connecting cesspools offers an excellent jumping off point for enhanced interagency coordination. Having coordination between agencies at different levels of government will greatly benefit future decision making processes and provide an opportunity for state and county actors to develop joint priorities and management plans.

VII. Implications for Adaptation

Literature Review

In general, the goal of climate change adaptation is to avoid, withstand, or take advantage of current and projected climate change impacts by decreasing vulnerabilities and increasing resilience. As such, the IPCC Response Strategies Working Group identifies three different approaches to SLR adaptation:

- *Accommodation* – adjustment of an existing system to changing natural conditions (e.g., expanding hazard zones or strengthening regulations)
- *Protections* – hardening of a system in its existing location to withstand impacts from changing conditions (e.g., seawalls or revetments)
- *Retreat* – relocating existing structures to avoid impacts (Dronkers et al., 1990)

Another term, adaptive capacity, is defined as "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (IPCC, 2014). Adaptation refers to actions taken while adaptive capacity refers to the inherent ability of a system to adapt to climate change impacts. For wastewater, adaptive capacity refers to the ability of an asset or the collection of assets to accommodate or adjust to a climate impact and maintain or quickly resume function (San Francisco Bay Conservation and Development Commission, 2012). Thus, the ability of an asset to withstand and adapt to changing conditions is crucial to ensuring long-term sustainability of the asset and the wastewater system as a whole (Spiller, 2017).

Adaptation, or the adjustment of natural and human systems in response to climate change (Fussel & Klein, 2006), can be planned for and adopted by public and private institutions in an anticipatory or reactive way (Fussel & Klein, 2006). Anticipatory adaptation measures are planned actions that are put in place to reduce the sensitivity and exposure of climate related hazards (Fussel & Klein, 2006). Anticipatory adaptation measures can help prepare communities for expected changes while also necessitating the need to address current limitations and gaps in human systems (Fussel & Klein, 2006). Addressing problems now in order to prepare for anticipated future problems can help build community resilience which is the ability of a system to respond to sudden climate related shocks (sudden and often catastrophic events) and stressors (gradual changes that weaken impacted people or systems) while maintaining its basic form, function and structure (Eraydin, 2012; Fussel & Klein, 2006).

While the importance of adaptive capacity in the wastewater system is supported and agreed upon in the literature, methods for evaluating adaptive capacity are not well defined (Daigger 2009; Spiller 2017). Typically, approaches are based on expert judgment. For example, Kalber et al. (2012) used expert opinion to ranking the adaptability of various kinds of wastewater infrastructure and technology on a scale of 0 to 100, 100 being most flexible. Milman and Short (2008) used a questionnaire in three different cities to identify indicators of adaptive capacity. The Adapting to Rising Tides project in California also administered a questionnaire to a working group and topical experts to solicit input on vulnerability and risk, of wastewater infrastructure to sea level rise and climate variability, coming up with the following metrics to guide analysis of adaptive capacity:

1. Potential for partially compromised asset to maintain key functions and continue to provide necessary community services
2. Asset redundancy, e.g., alternative comparable asset available
3. Capacity of the system to function without an asset or if an asset is compromised
4. Ability to restore asset function quickly, easily, or in a low-cost manner if compromised
5. Disaster or emergency response resources, e.g., on-site staff, backup power, equipment for cleanup, temporary flood protection, pumps, "friends of" organizations or volunteers
6. Operation and maintenance costs
7. Capital improvement costs
8. Potential for reengineering or redesign
9. Status of existing plans, e.g., emergency or disaster response plan, master plans, etc.
10. Complexity of regulations governing operations, maintenance or capital improvements
11. Complexity of decision-making regarding operations, maintenance or capital improvement planning and implementation (Adapting to Rising Tides Program, 2012)

Stakeholder Interviews

In our study, stakeholder interviews provided expert judgments related to adaptive capacity and consequences of wastewater system failure. The indicators that were identified for each asset are summarized below, however, due to the scope of this project, weighting tied to adaptive capacity was not applied to the vulnerability index:

Table 7-1: Summary from Stakeholder Interviews - Factors for Adaptive Capacity

Impact on the Asset	**Wastewater Assets Affected**			
	Central Sewers	*WW Treatment Plants*	*Pump Stations*	*On-site Disposal Systems*
Inflow & Infiltration	• Ability to adapt to increases in flow/ liquefaction • Pipe material/ability to withstand being submerged, saltwater, corrosion • Cost of upgrades	• Ability to treat higher salinity		
Elevated Groundwater	• Pipe material/ability to withstand being submerged, saltwater, corrosion			• Volume of old systems impacted
Storm Flooding	• Ability to maintain function if compromised • Cost of redesign/ relocation • Duration and frequency of flooding	• Reliance on electricity • Redundancy • Feasibility and cost of hardening or relocation		
Wave inundation	• Cost of redesign/relocation • Size of system and service population	• Feasibility of retreat	• Cascading effects • Size of pump station • Redundancy	
Coastal Erosion	• Cost of redesign/ relocation	• Available land that meets criteria • Feasibility and cost of hardening or re-location	• Location • Feasibility and cost of relocation	• Cost of centralized collection system

The responses captured in stakeholder interviews tie back to the three approaches to SLR adaptation: accommodation, protection, and retreat. The responses seem to align well with the literature and help to highlight factors affecting the ability of different types of wastewater assets in Hawaiʻi to adapt to sea level rise and climate variability. For instance, when discussing the adaptive capacity of central sewer systems, responses mainly centered on the ability to accommodate changing conditions (e.g., cost of system redesign). Responses concerning the adaptive capacity of pump stations and treatment plants also focused on the feasibility of relocation (e.g., available land that meets criteria), while bringing greater attention to possible protection measures (e.g., redundancy or hardening). Lastly, the adaptive capacity of OSDS brings to light concerns about areas with higher concentrations of systems affected and costs of transitioning to centralized collection systems.

VIII. Vulnerability and Decision Making

The vulnerability of different wastewater assets varies by location. On O‘ahu, the majority of the population is concentrated along the south shore. This settlement pattern is mirrored by the centralized sewer system, which is also heavily concentrated within the southern portion of the island. Conversely, many of the rural areas of the island are not serviced by the existing sewer system and use on-site systems. As climate change impacts worsen, agencies and decision makers will have to determine how and when to implement adaptation measures. The opening sections of this report provide context with regard to the existing wastewater infrastructure on O‘ahu, the best available climate science, and the potential impacts of climate change on coastal wastewater infrastructure. The report also provides several planning tools. One tool is a vulnerability index that incorporates the sensitivity of assets to climate hazard exposures and aids in identifying hotspots of vulnerability across the wastewater network and system. A second planning tool integrates SLR induced groundwater inundation into the sewer flow monitoring system to prioritize sections of sewer pipes that will require adaptation as sea levels rise. Lastly, this report recommended critical wastewater management policies and actions that address shortcomings in the current management regime, and support adaptation to sea level rise and climate change.

The study areas below were selected to highlight the impact of sea level changes on both centralized and on-site sewage systems as well as illustrate relationships between the two. The maps show the assets impacted in 1.1 feet SLR-XA and 3.2 feet SLR-XA models, which were developed and used in the 2017 Hawai‘i Sea Level Rise Vulnerability and Adaptation Report.

Urban Honolulu SLR-XA

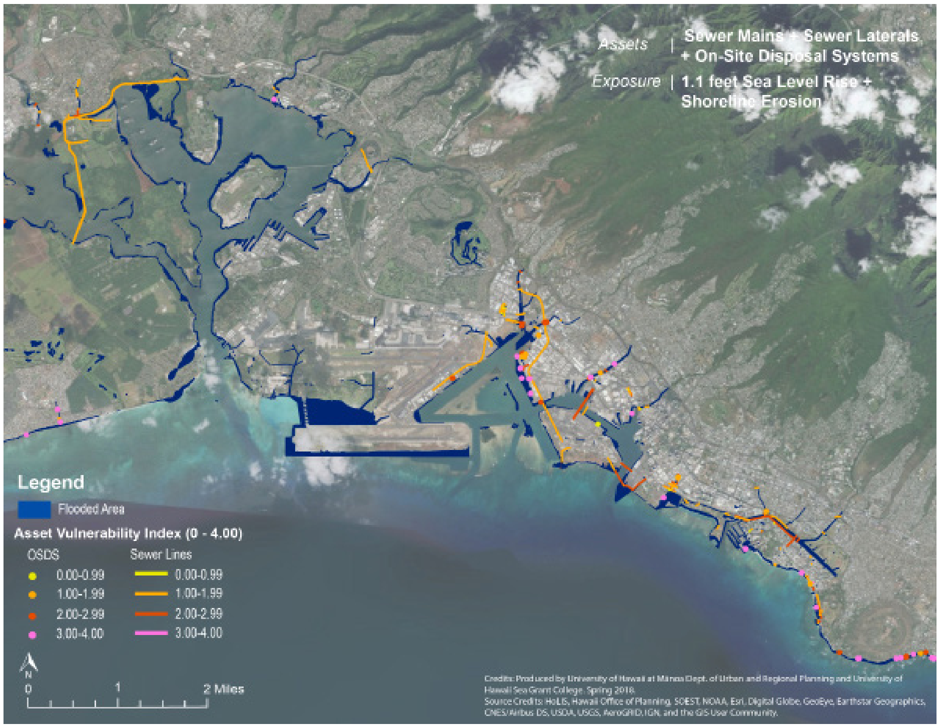

Figure 8-1: Urban Honolulu with 1.1 feet SLR (SLR-XA)

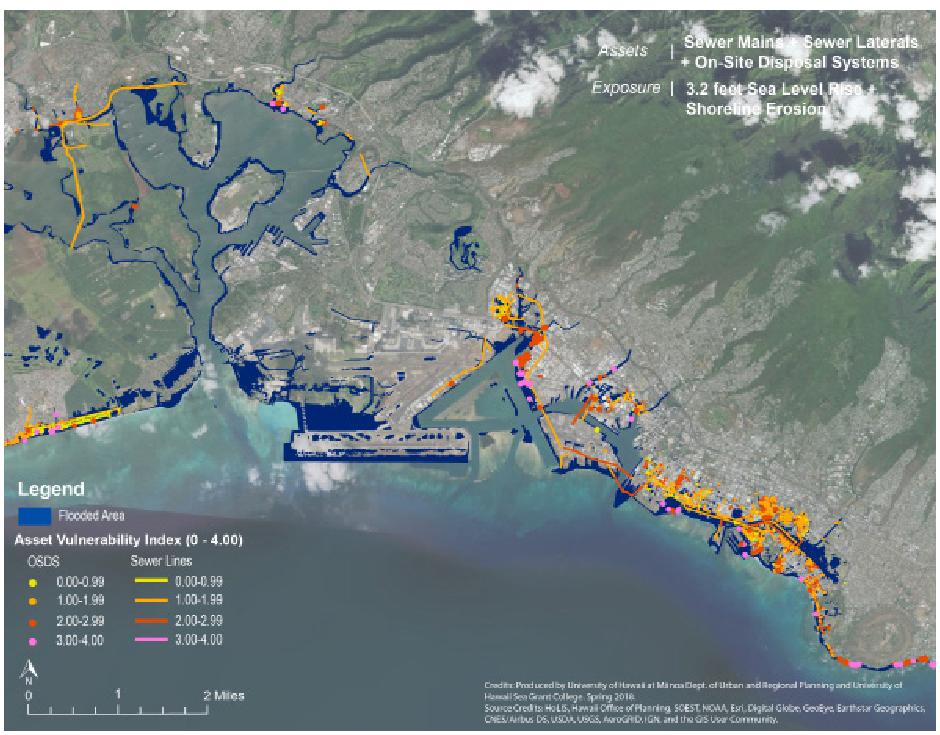

Figure 8-2: Urban Honolulu with 3.2 feet SLR (SLR-XA)

Summary of Vulnerability

The primary urban center of Honolulu stretches westward from Diamond Head to Pearl City. This region contains the vast majority of central sewer infrastructure as well as a relatively high concentration of older OSDS. The largest cluster of vulnerable OSDS within this region is located in the Kalihi Kai industrial area along the shore of Ke‘ehi Lagoon. This cluster is impacted with 1.1 feet of SLR and grows slightly with 3.2 feet of SLR. The sewer mains and laterals in Kaka‘ako and Waikiki are most heavily impacted by the increase from 1.1 feet to 3.2 feet of SLR with assets near the Ala Wai and in low lying areas of Kaka‘ako and Downtown flooding.

Key Takeaways

- Large numbers of OSDS are within areas with sewer service available
- Areas near Waikiki and Mapunapuna have vulnerable OSDS near vulnerable sewers
- Approximately 20 miles of sewer mains and laterals will be impacted with 1.1 feet of SLR, increasing to 62 miles with 3.2 feet of SLR
- In Urban Honolulu, approximately 22 miles of sewer mains ranked in the high or very high vulnerability range with 3.2 feet of SLR
- 31 OSDS will be impacted within Urban Honolulu with 1.1 feet of SLR, increasing to 94 with 3.2 feet of SLR
- In Urban Honolulu, 24 OSDS systems ranked in the very high vulnerability range with 3.2 feet of SLR

Kaneohe Bay & Windward O‘ahu SLR-XA

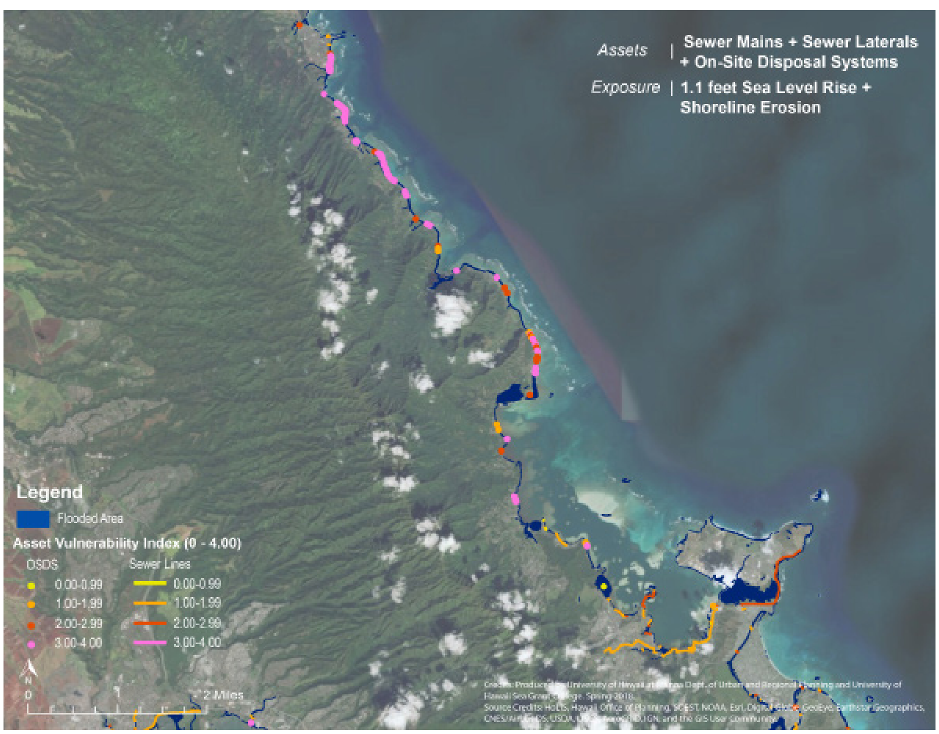

Figure 8-3: Kaneohe Bay with 1.1 feet SLR (SLR-XA)

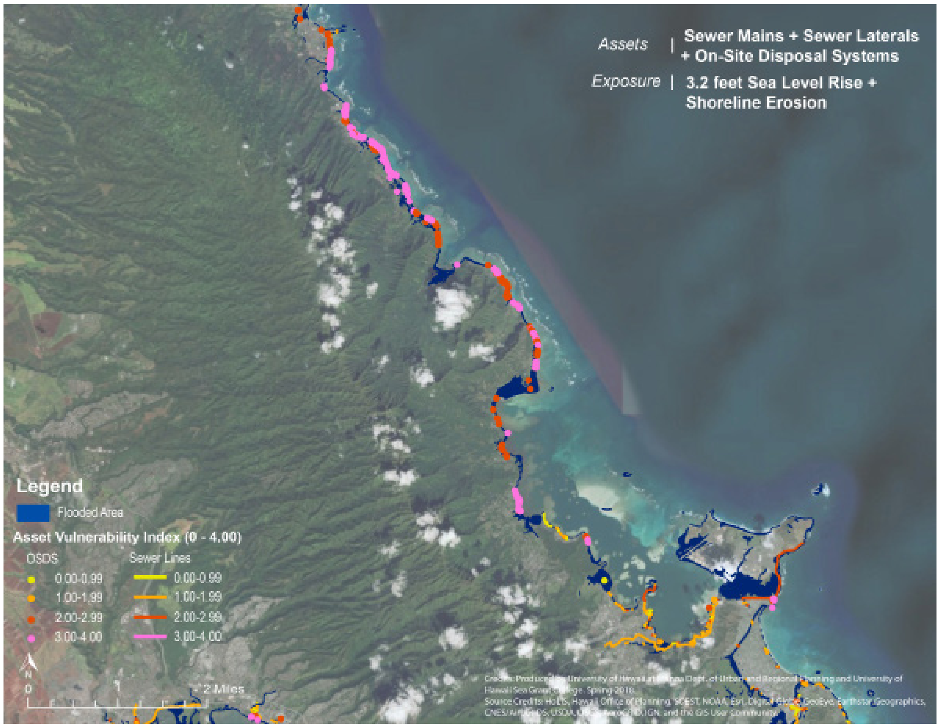

Figure 8-4: Kaneohe Bay with 3.2 feet SLR (SLR-XA)

Summary of Vulnerability

Though the area surrounding Kaneohe Bay is connected to sanitary sewer service, communities north of Kaneohe Bay along O'ahu's Windward coast have very high concentrations of OSDS. Roughly the same amount of sewer mains and laterals are affected with 3.2 feet of SLR as with 1.1 feet, however we see a much greater increase in the number of OSDS units flooded with 3.2 feet of SLR. While the City and County of Honolulu have an on-going project to better convey wastewater from Kaneohe to the Kailua WWTP and protect the Bay from sewage spills, if left. unaddressed, the high concentration of OSDS in flooded areas has the potential to release wastewater into near-shore waters and contaminate coastal habitats.

Key Takeaways

- Very high concentration of vulnerable OSDS north of Kaneohe Bay
- Vulnerable sewer assets are mostly sewer mains
- Approximately 6 miles of sewer mains and laterals will be impacted with 1.1 feet of SLR, increasing to 10 miles with 3.2 feet of SLR
- In Windward O'ahu, x feet of sewer mains ranked in the high or very high vulnerability range with 3.2 feet of SLR
- 160 OSDS will be impacted in Windward O'ahu with 1.1 feet of SLR, increasing to 380 with 3.2 feet of SLR
- Of the 380 OSDS exposed with 3.2 feet of SLR in Windward O'ahu, 228 OSDS systems ranked in the very high vulnerability range – 60%

East Honolulu SLR-XA

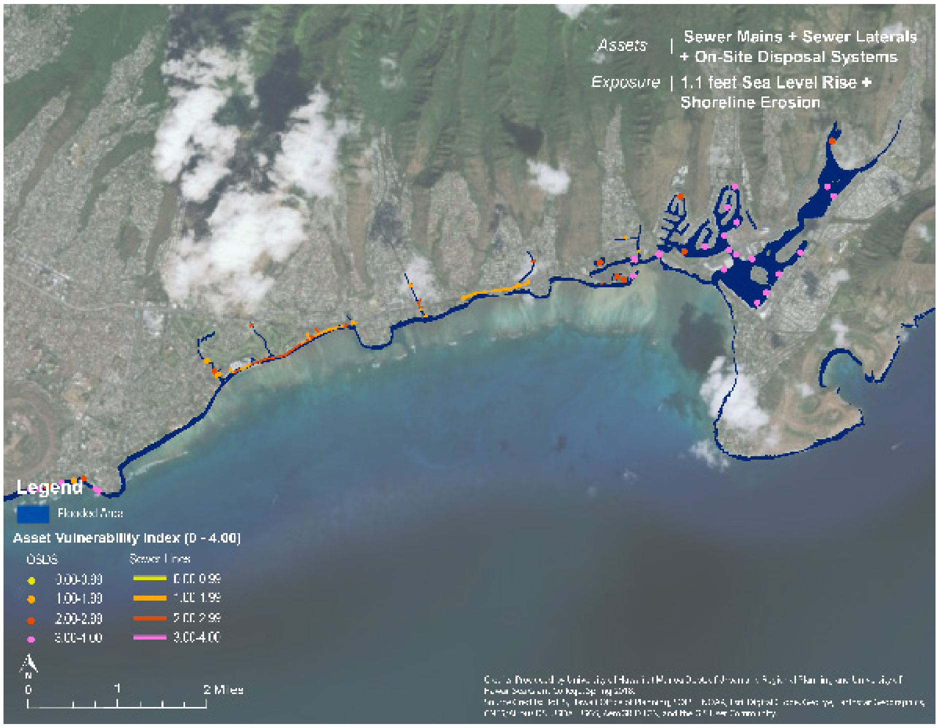

Figure 8-5: East Honolulu with 1.1 feet SLR (SLR-XA)

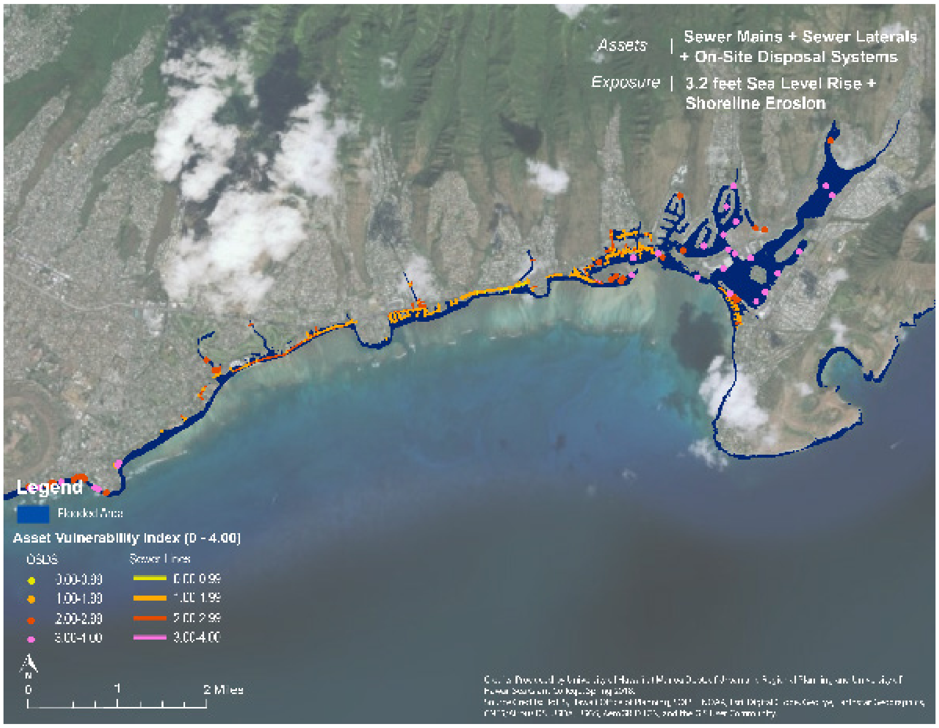

Figure 8-6: East Honolulu with 3.2 feet SLR (SLR-XA)

Summary of Vulnerability

East Honolulu is a region with a high concentration of housing located near the shoreline. As such, both OSDS and sewer mains and laterals face flooding impacts from SLR. The majority of the impacted OSDS are located in the Hawaiʻi Kai community of Portlock. These OSDS are impacted with 1.1 feet of SLR, but the number of OSDS increases only slightly with 3.2 feet of SLR. However, with 3.2 feet of SLR more sewer laterals and mains are flooded, especially in the Wailupe Penisula and along the coast of the Aina Haina and Niu Valley communities.

Key Takeaways

- OSDS near Port Lock are vulnerable in the near-term while sewer assets are more vulnerable in the long-term
- Sewer laterals along shoreline residential communities are most vulnerable to SLR in this study area
- Approximately 3 miles of sewer mains and laterals will be impacted with 1.1 feet of SLR, increasing to 9 miles with 3.2 feet of SLR
- Of the 9 miles of sewer pipes impacted by 3.2 feet SLR in East Honolulu, approximately 4.75 miles ranked in the high or very high vulnerability range with 3.2 feet of SLR
- The number of lateral pipes exposed in this study area increases from 26 with 1.1 feet of SLR to a total of 349 different pipes with 3.2 feet of SLR
- 37 OSDS will be impacted within Urban Honolulu with 1.1 feet of SLR, increasing to 57 with 3.2 feet of SLR
- Of the 37 OSDS impacted by 1.1 feet SLR in East Honolulu, 24 systems ranked in the very high vulnerability range – 65%
- Of the 57 OSDS exposed with 3.2 feet SLR in East Honolulu, 28 systems ranked in the very high vulnerability range

Implications for Adaptation

Adaptation measures should take into consideration how proximity and siting conditions contribute to the exposure of systems to sea level rise. The exposure assessment illustrates the extent to which wastewater infrastructure is exposed to sea level rise impacts and coastal hazards. These findings highlight the need for anticipatory adaptation concerning wastewater treatment for both on-site and central sewer systems.

Priority areas for sewer rehabilitation should consider groundwater infiltration (GWI) from future SLR. Impacts appear minor in the near-term (with 1 ft. of SLR) however GWI impacts to sewer flows could increase dramatically by mid to late century. A planning model that takes into account existing pipe defects and the length of pipe submerged can help prioritize areas for adaptation.

In the near-term, pump stations and treatment plants are safe from SLR induced flooding or erosion, but similarly, we can expect by mid- to late century, some of these assets will become vulnerable. In the near-term, resizing or increasing redundancy of systems within the plant may be possible. However, in the long-term, the City and County will need to assess cost and feasibility of either hardening or relocating some of these facilities.

The Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report suggests that State and County agencies consider potential long-term cost savings from implementing SLR adaption measures as early as possible, such as relocating infrastructure away from areas projected to experience chronic flooding over the next 30 to 70 years (Hawaiʻi Climate Change Mitigation and Adaptation Commission, 2017). When prioritizing adaptation projects, coordination will be especially important for areas with high concentration of both OSDS, which is regulated by the State, and central sewer system assets, which are managed by the City and County.

Study Limitations

This project relied on publically available data and the best available science and models during the two-year span of our research and analysis. Climate change and the related science are dynamic and growing fields. As such, some of the available information and data was incomplete while other information or data, which may have benefited our study was unavailable, including riverine flooding models and hurricane storm surge models for all regions of Oʻahu.

During our meetings with stakeholders, we learned that the available data for OSDS across the State is not up-to-date and likely contains some inaccuracies. To alleviate this uncertainty would require fieldwork to ground-truth the GIS data.

Additionally, the data we used to estimate exposure of wastewater assets is quite conservative. Again the data available to us limited the scope and ability to estimate the full extent of chronic impacts such as flooding cause by ground water inundation (GWI) and extreme weather scenarios such as hurricanes.

We did not include data for GWI with the SLR data, however, a recent paper published by Habel et al. (2017) estimates that 23% of Waikiki would be flooded with 3.2 feet of SLR and 86% of the cesspools in the area are likely to be inundated. The impacts in this small study area suggest that including GWI data will more than likely result in a higher percentage of wastewater assets exposed.

Lastly, the hurricane model provides the projected storm surge caused by a category 4 hurricane entering Pearl Harbor on the south shore of Oʻahu. Since our study was conducted, new models for hurricane storm surge impacts have become available for all areas of the island.

Future Research Opportunities

This project was intended to raise awareness of the need for climate ready utilities and infrastructures, support the integration of climate change into long-term land use and wastewater infrastructure planning and investment decisions, and identify possible adaptation options. As such, we have identified future opportunities to build on the research.

Expand Sensitivity Analysis of Sewer Pipes

The groundwater infiltration model in Section V is an example of a tool that can help with the identification of vulnerable sections of pipes to groundwater infiltration . Future opportunities for research include obtaining flow-monitoring data from the city and county of Honolulu of the sewer system to calibrate the model, and to facilitate a more comprehensive and complete inventory of vulnerable sewers, and to assist with identifying and prioritizing upgrades of sewer pipes. From there, the study area can be expanded first to all of Honolulu County followed by the whole state. A parallel effort would be to create a computer code module that implements our calibration method and model that could be used internally to support the commercial sewer hydraulics models (none of which are currently able to deal with SLR).

Integrate Adaptive Capacity into Vulnerability Index

As our conceptual model illustrates, fully quantifying vulnerability requires the integration of factors tied to adaptive capacity. This could include cost estimates of different adaptation options as a proxy for adaptive capacity. Additional stakeholder and expert input with regard to the adaptive capacity of specific assets, materials, and locations will build a more complete picture of vulnerable wastewater infrastructure.

Furthermore, additional stakeholder and expert input is needed to identify appropriate weights to sensitivity indicators in the vulnerability index.

Build Awareness and Public Will Around OSDS Conversion

Future climate change scenarios highlight the need for long-term planning for OSDS, particularly in rural areas where it is the primary mode of wastewater treatment. To support long-term planning efforts, more research is needed to better understand community knowledge and attitudes related to OSDS, as well as reactions to potential policies or management options that could be taken by the state or county. This research could focus on how certain communities will respond to policy changes or new management requirements and potentially include pilot projects to test and evaluate how recommendations identified in this report might be implemented in different priority areas.

Additionally, cross-coordination between agencies and jurisdictions to identify and understand the vulnerability of both OSDS and centralized sewer systems to climate change is crucial for long-term planning and the conversion of communities from OSDS to a centralized sewer system. Future research and pilot programs can support and facilitate the interfacing of these stakeholder agencies.

Understand Economic Impacts and Opportunities

Throughout the project it became evident that more detailed research on the economic impact of climate change on wastewater infrastructure is necessary. This includes estimating the cost and value of damage to existing infrastructure as well as putting a price tag on different adaptation options for wastewater infrastructure projected to be impacted by climate change. Research should build on the exposure data from this project to estimate the costs for elevating, converting, rehabilitation, and potential re-location of different types of wastewater assets (e.g., treatment plants, pumping stations, and sewer pipes).

Economic research should also explore and present information on how revenue can be generated to support necessary projects and programs. This may include researching standards and best practices that have been implemented elsewhere to support new programs and the added cost of hiring new staff or expanding duties of existing agencies and staff.

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Appendix I

OSDS Risk Factors

Risk Factor	Weighting Percent	Score
Drinking Water Zone B	14	0, 100
Stream Buffer	11	0, 100
Flood Risk Zones	11	0, 40, 100
Shoreline 200 ft setback	9	0, 100
Depth to Water	8	0, 100
Insufficient Filtration	8	0, 100
OSDS Density	8	1, 10, 60, 100
Groundwater Impact	8	0, 25, 50, 75, 100
Depth to Rock	5	0, 25, 50, 75, 100
Drinking Water Zone C	8	0, 100
Soil Septic Unsuitability	5	0, 25, 50, 75, 100
Shoreline 2 year Setback	5	0, 100

(Whittier and El-Kadi, 2014)

Appendix II

Stakeholder Interview Material & Findings

August, 2017

Interviewees were asked a series of questions that fell under seven focused themes:

1. General background – broadly identifying top issues for Honolulu in next 5-10 years.
2. Asset inventory and "criticality" – Identifying critical systems and how those systems may be impacted by climate change over the next few decades.
3. **Exposure questions – classifying the different environmental conditions that make wastewater systems more vulnerable and the specific watershed areas most at risk.**
4. **Sensitivity questions – identifying certain conditions or characteristics about wastewater systems that make them more vulnerable to climate hazards.**
5. Adaptive capacity – identifying current actions underway and articulating ideal improvements to make wastewater systems less vulnerable to climate change risks
6. Consequences of failure – understanding the consequential impacts of system failure and measures and indicators used to track functionality.
7. Data & decision making – identifying wants and needs in terms of data and information regarding climate change.

Stakeholders consulted thus far were from the following organizations or agencies:

- C&C of Honolulu Department of Environmental Services (DES)
- C&C of Honolulu Department of Facility Maintenance (DFM)
- C&C of Honolulu Department of Planning and Permitting (DPP)
- Hawaii Community Development Authority (HCDA)
- Hawaii Department of Health, Environmental Management Division (DOH)
- Marine Corps Base Hawaii (MCBH)
- US Environmental Protection Agency (EPA)

PRIORITY WATERSHEDS IDENTIFIED

Setting	*Areas*
Urban	Honolulu Urban Core (Downtown–Makiki) Kalihi/Sand Island Waikiki/Ala Wai
New Development/Suburban	Kahala
Rural	North Shore – Waialua Windward – Kahaluʻu, Kaneohe Bay

EXPOSURES & SENSITIVITIES

Setting	*Exposures*	*Sensitivities*
Urban	1. *Sea level rise* 2. *Extreme weather events – localized flooding* 3. *Saltwater inflow and infiltration*	1. *Aging systems* 2. *Location – ability access in extreme weather/flooding* 3. *Impervious surfaces – drainage capacity (esp. in extreme weather events)*
New Development/ Suburban	1. *Higher temperatures for large regional systems (e.g., Honouliuli)* 2. *Sea level rise* 3. *Shoreline erosion*	1. *Structural integrity of sewer systems and manholes when exposed to waves or tides* 2. *Pipes are susceptible to corrosion due to sulfates and gases from sewage*
Rural	1. *Sea-level rise* 2. *Low-lying areas – groundwater charge levels* 3. *Shoreline erosion*	1. *OSDS along streams or near shore waters are susceptible to flood in heavy rains* 2. *OSDS – depth to groundwater and soil quality could lead to more contamination* 3. *Sewer lines/manholes near shoreline are susceptible to high tides* 4. *Age for both OSDS and Sewer lines*

STAKEHOLDER QUOTES

EXPOSURE

"I can say that because of recent storm events where we had such a high amount of rainfall in such a short amount of time, the storm drain system and other systems that we have to carry away stormwater were really stressed past capacity and we had a lot of overflowing infrastructure because of the intensity of some storm events…Those things are a clear indication that what we used before or previously as a design standard, may not be applicable as we move forward in to periods of greater climate change."
~ Stakeholder, DFM

"I think that with rising sea levels and the close proximity to the sewer lines to the shorelines, I could probably see higher influence of I&I –infiltration inflow– meaning more saltwater is going to enter into the system and get discharged into the

treatment plant, which actually disturbs/affects the treatment because of high chlorides, high TDS. Just to be pumping water that shouldn't even be in the system."
~Stakeholder, DOH

"Of course nature likes to reclaim what was originally there, it doesn't want the manmade fill so the erosion happens. So we actually have some places where now the manholes are in water."
~Stakeholder, DPP

"Some of these housing areas are also at risk from beach erosion, so as long as our houses are there the sewers are fine, they can service. But as soon as that house gets undermined, washing out then, we would also be in trouble."
~Stakeholder, DPP

SENSITIVITIES

"But the fact is that the pipes are always susceptible to the infiltration because they are below the groundwater table and the amount of pressure that is on them is an ongoing problem so we line pipes and we do other things to reduce the potential for that infiltration which is helpful from both protecting the public health and making sure that the materials, that the wastewater gets to where it is suppose to go."
~Stakeholder, DES

"[M]ost of the OSDS are located near the coast. Sea level rises then the coastal risk from OSDS also increases because you decrease distance to the coast and you also decrease distance to groundwater, which is a major method of conveyance of contamination from the OSDS to the coast."
~Stakeholder, DOH

CONSEQUENCES OF FAILURE

"[I]f it's a catastrophic failure of a plant and there is not place for 80-90 million gallons per day of wastewater to go, that becomes a human health problem in a hurry."
~Stakeholder, EPA

"Well if there were a failure of the wastewater system it would impact the public within the service area that we have a failure in. So if the Sand Island wastewater treatment plant were to be impacted then it may mean that all of metropolitan Honolulu will not be able to flush."
~ Stakeholder, DFM

IRB Human Subjects Release

University of Hawai‘i

Consent to Participate in Research Project:
Assessing the Vulnerability of Coastal Wastewater Infrastructure to Climate Change

Researchers from the University of Hawai'i- Mānoa Sea Grant are conducting research on wastewater infrastructure vulnerabilities to climate change. You have been selected to participate in informal interviews and/or workshops because of you are 18 years of age or older and are an expert in your field.

Activities and Time Commitment: If you decided to participate, the head researcher will meet with you for an informal interview at a location and time convenient for you. The interview will consist of open ended questions. It will take one (1) to two (2) hours. The interview questions will pertain to your specific area of expertise surrounding wastewater infrastructure. Discussions may also involve assessing how certain climatic variability may impact your role. Interviews may be conducted either on a one-on-one basis or in a group setting. An audio-recording of the interview will be taken so that your responses can later be transcribed and analyzed. You have the right to decline being audio-recorded, if you so choose, and can indicate your preference at the bottom of this page. You may still participate in the study if you do not wish to be audio-recorded.

Benefits and Risks: There will be no direct benefit to you for participating in this interview. The results of this project may help improve the wastewater infrastructure planning and preparedness: for climate change adaptation. There is little risk to you in participating in this research project. You may become stressed or uncomfortable answering any of the interview questions or discussing topics during the interview. If you do become stressed or uncomfortable, you can skip the question or take a break. You can also stop the interview or you can withdraw from the project altogether.

Privacy and Confidentiality: All information will be kept in a safe place. Only researchers involved in the project will have access to the information. Other agencies that have legal permission have the right to review research records. The University of Hawaii Human Studies Program has the right to review research records for this study. After the audio-recorded interviews have been transcribed, the audio-recordings will be erased or destroyed. When the research findings are presented and published, your name will not be used. I will not use any other personal identifying information that can identify you.

Voluntary Participation: Your participation in this project is completely voluntary. You may stop participating at any time. If you stop participating in the study, there will be no penalty or loss to you. Your choice to participate or not participate will not affect your rights to services at the UH Sea Grant College Program.

Questions: If you have any questions about this study or any questions about your rights as a research participant please call or email UH Human Studies Program at 808.956.5007 or uhirb@hawaii.edu.

If you agree to participate in this project, please sign and date this signature page and return it to the person obtaining consent.

Please keep the section above for your records.
If you consent to be in this project, please sign the signature section below and return it.

Tear or cut here

Signature(s) for Consent:

Please indicate your consent to participate in the research project entitled, *"Assessing the Vulnerability of Coastal Wastewater Infrastructure to Climate Change"*

Please initial next to either "Yes" or "No" to the following:

____ Yes ____ No I give permission to be a participant for the interview portion of this research.

____ Yes ____ No I consent to be audio-recorded

Name of Participant (Print):
____

Participant's Signature: ____

Signature of the Person Obtaining Consent: ____________________________________

Date: _____________________