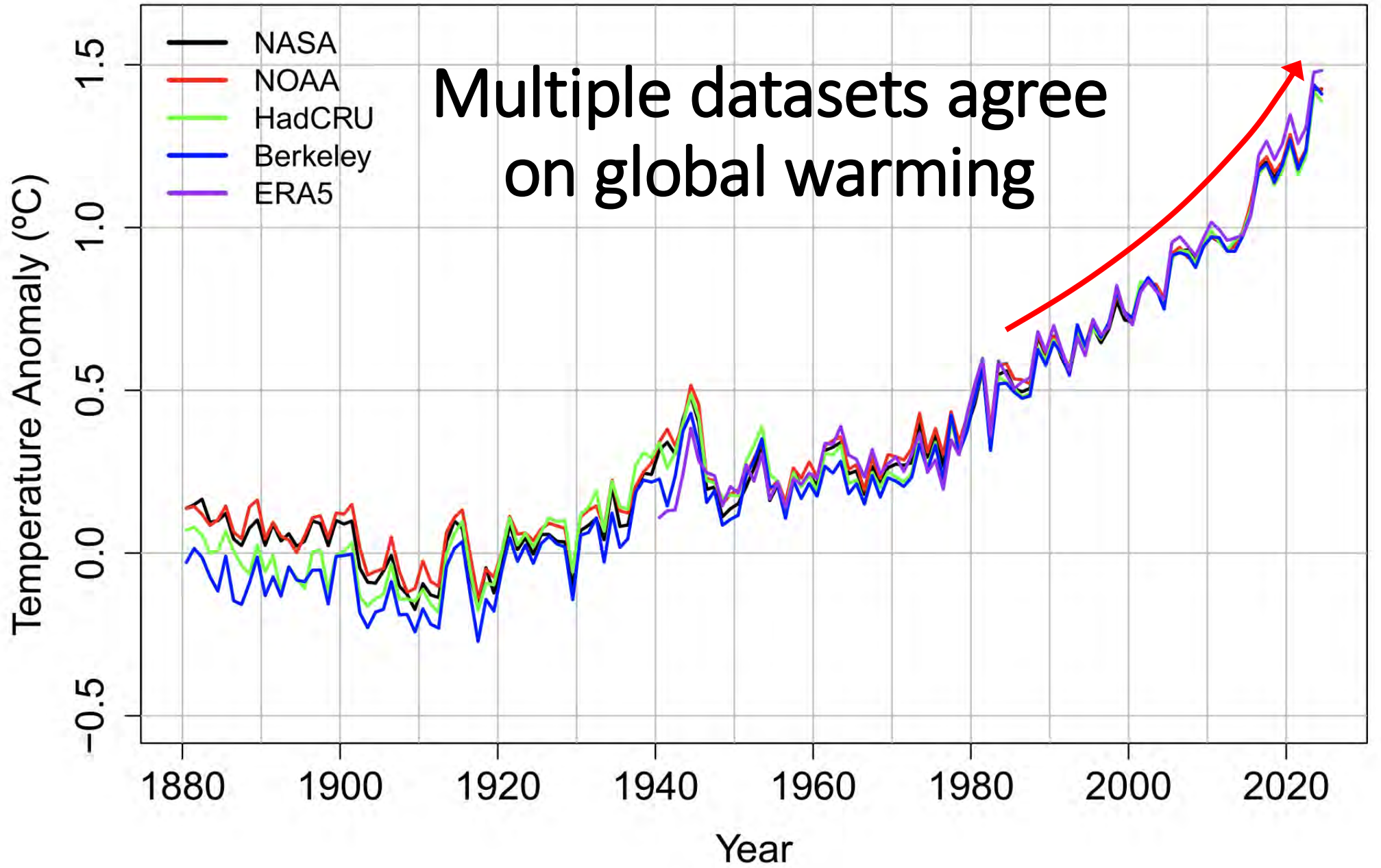


# Risk Assessment of Sea Level Rise



C. Fletcher  
University of Hawai'i



# Global Warming Has Accelerated Significantly

## Geophysical Research Letters

### RESEARCH LETTER

10.1029/2025GL118804

#### Key Points:

- During the last decade, the rate at which Earth warmed increased substantially
- After removing the influence of known natural variability factors, the increase of the warming rate is statistically significant
- At the present rate, we will exceed the 1.5°C limit of the Paris Climate Accord by 2030

#### Correspondence to:

S. Rahmstorf,  
rahmstorf@pik

Foster, G., & Rahmstorf, S. (2026). Global warming has accelerated significantly. *Geophysical Research Letters*, 53, e2025GL118804. <https://doi.org/10.1029/2025GL118804>

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#### Author Contributions:

**Conceptualization:** G. Foster, S. Rahmstorf

**Data curation:** G. Foster

**Formal analysis:** G. Foster

**Methodology:** G. Foster

**Software:** G. Foster


**Validation:** S. Rahmstorf

**Visualization:** G. Foster

**Writing – original draft:** S. Rahmstorf

**Writing – review & editing:** G. Foster, S. Rahmstorf

## Global Warming Has Accelerated Significantly

G. Foster<sup>2</sup> and S. Rahmstorf<sup>1</sup> 

<sup>1</sup>Potsdam Institute for Climate Impact Research, University of Potsdam, Potsdam, Germany, <sup>2</sup>Retired, Orono, ME, USA

**Abstract** Recent record-hot years have caused discussion over whether global warming has accelerated. Previous analysis found acceleration (i.e., increase in warming rate) has not yet reached a 95% confidence level, given natural temperature variability. We remove the estimated influence of three main natural variability factors: El Niño, volcanism, and solar variation. The resulting adjusted and thus less “noisy” data show that there has been acceleration with over 98% confidence, with faster warming over the last 10+ years than during any previous decade.

**Plain Language Summary** The rise in global temperature has been widely considered to be quite steady for several decades since the 1970s. Recently, however, scientists have started to debate whether global warming has accelerated since then. It is difficult to be sure of that because of natural fluctuations in the warming rate, and so far no statistical significance (meaning 95% certainty) of an acceleration (increase in warming rate) has been demonstrated. In this study we subtract the estimated influence of El Niño events, volcanic eruptions and solar variations from the data, which makes the global temperature curve less variable, and it then shows a statistically significant acceleration of global warming since about the year 2015. Warming proceeding faster is not unexpected by climate models, but it is a cause of concern and shows how insufficient the efforts to slow and eventually stop global warming under the Paris Climate Accord have so far been.

### 1. Introduction

The years 2023 and 2024 have been Earth's hottest on record, and in 2024 global temperature exceeded 1.5°C above pre-industrial temperatures, although to breach the 1.5°C limit of the Paris Climate Accord this level would need to be exceeded not for a single year but for an average over 20 years (Bevacqua et al., 2025).

Since the 1970s, global mean surface temperature (GMST) has followed a rather steady upward trend, rising at an average rate of about 0.2°C/decade, together with ubiquitous fluctuations about that trend. Random variations can be very suggestive of a change in the trend, which caused speculation in the early 2000s that global warming had slowed or even stopped (the infamous “pause”), but detailed analysis found that this slowing was at no point statistically significant (Risbey et al., 2018).

More recently, discussion has focused on whether global warming has accelerated. Past change point analysis showed a clear acceleration around 1970 (Cahill et al., 2015; Minière et al., 2023), at the end of a plateau phase starting ~1940 usually attributed to a masking of the effects of increasing greenhouse gases by cooling aerosols in the atmosphere. This plateau is also the key reason robust acceleration is diagnosed for the period 1960–2020

“...there has been acceleration with over 98% confidence, with faster warming over the last 10+ years than during any previous decade.”



**Jason 3**  
2016

**OSTM/Jason 2**  
2008

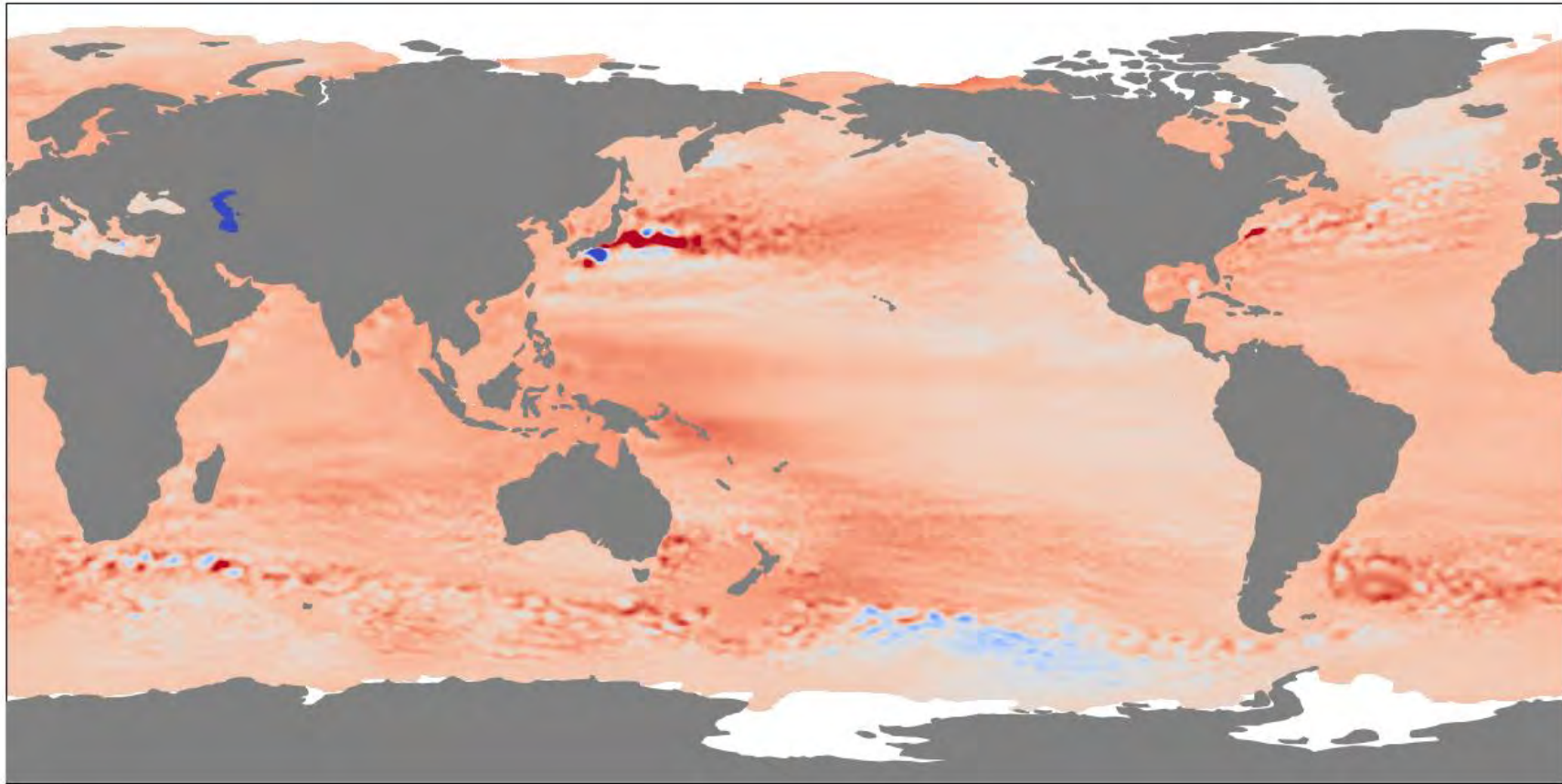
**Jason 1**  
2001

**TOPEX/Poseidon**  
1992-2006

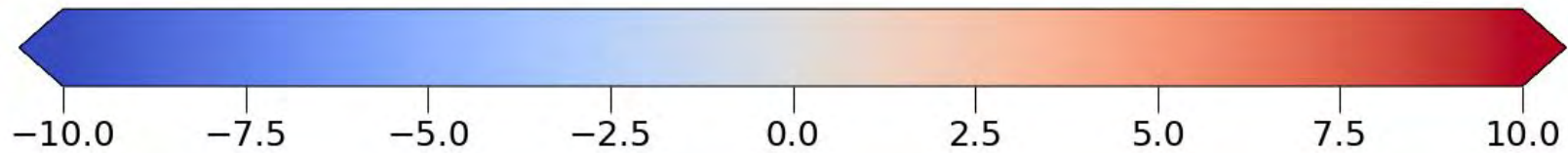
# Gridded Regional Sea Level Trends

Period: 1993-01-01 - 2023-06-07

© CNES/LEGOS/CLS, 2024



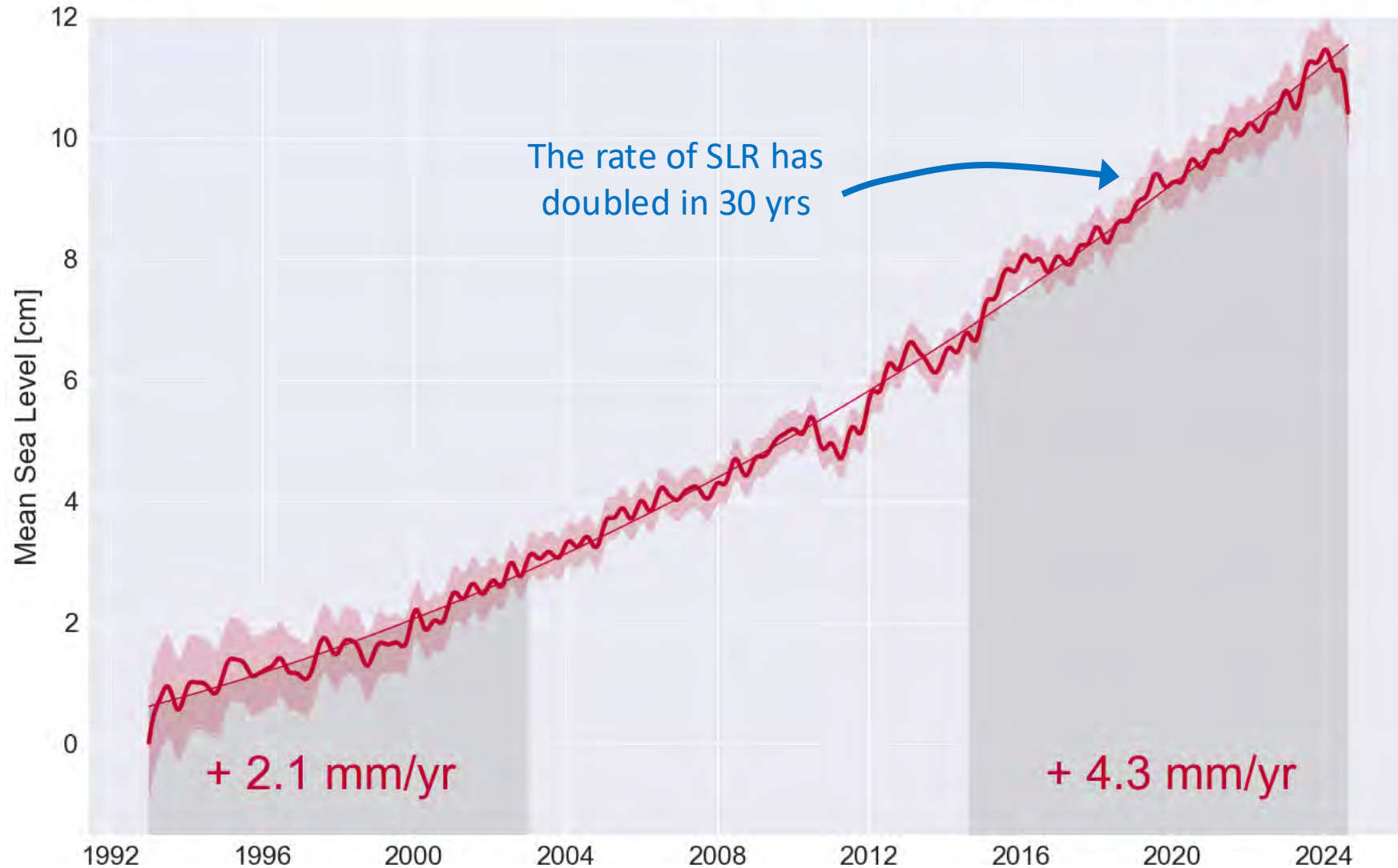
Regional Sea Level Trend: mm/yr



# Global Mean Sea Level Rise

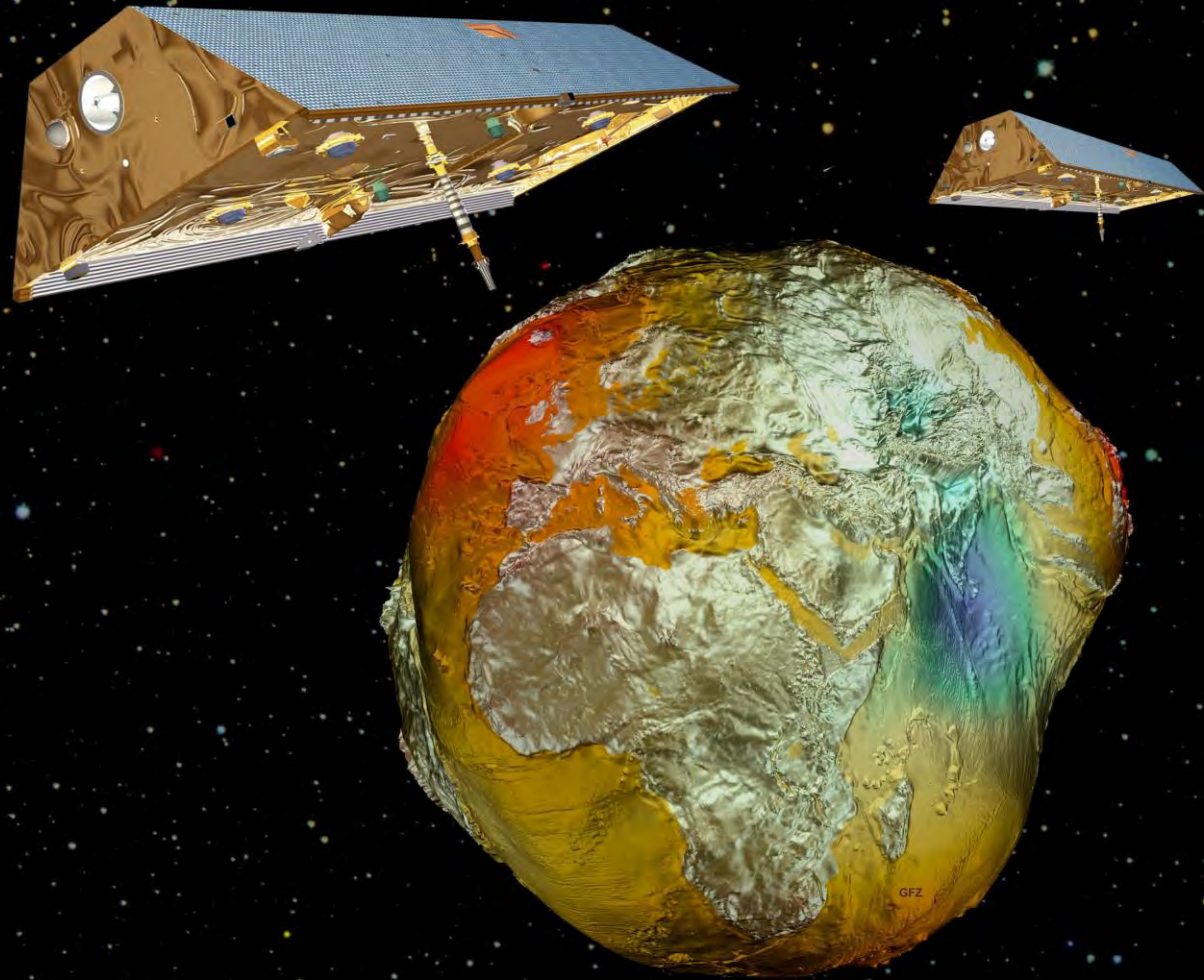
Latest MSL Measurement  
2024-08-21

**Acceleration:  $0.11 \pm 0.05 \text{ mm/yr}^2$**



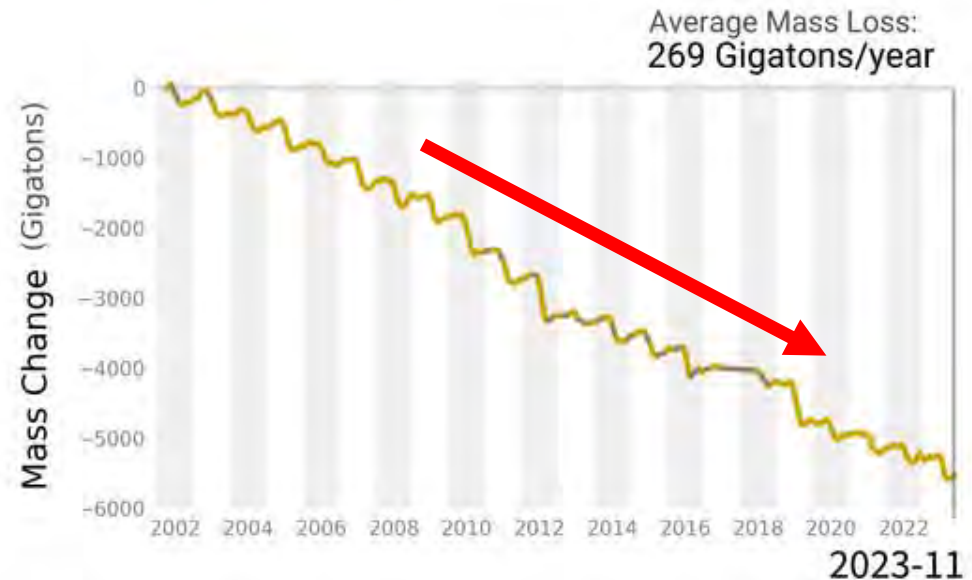
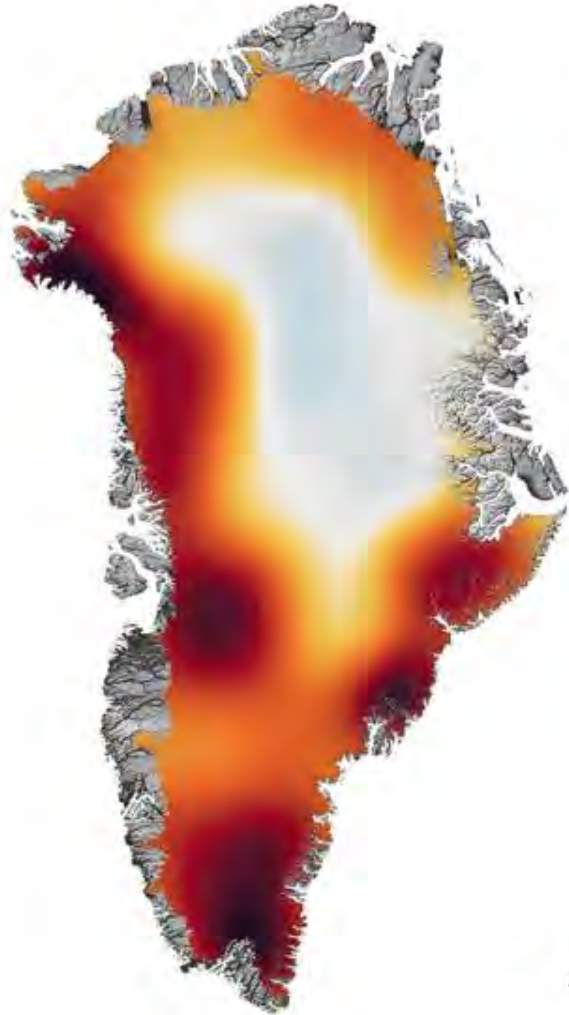
<https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html>

Hamlington, B.D., *et al.* The rate of global sea level rise doubled during the past three decades. *Commun Earth Environ* 5, 601 (2024). <https://doi.org/10.1038/s43247-024-01761-5>



# Greenland melting has quadrupled since 2010

~20% of global sea level rise

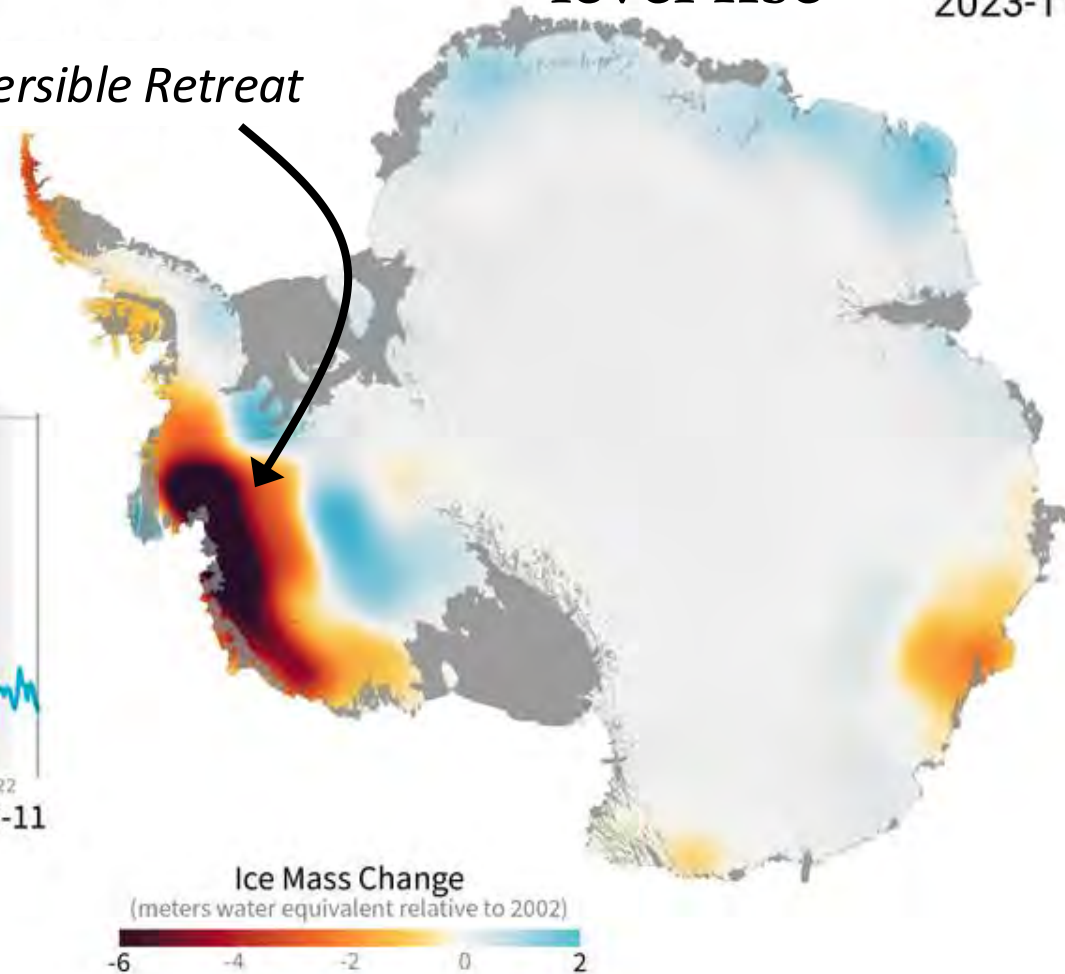
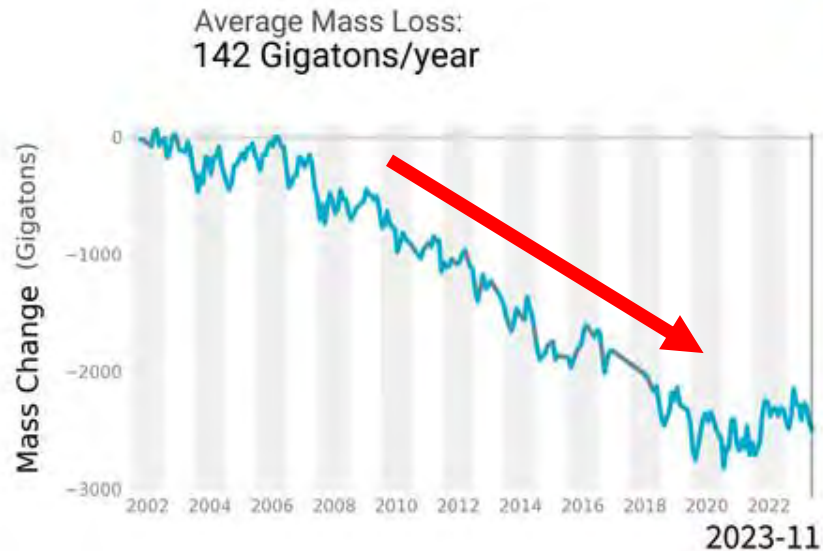


# Antarctic ice melt has tripled since 2010 ~9% of global sea level rise

GRACE AND GRACE-FO

*West Antarctic Glaciers are in Irreversible Retreat*

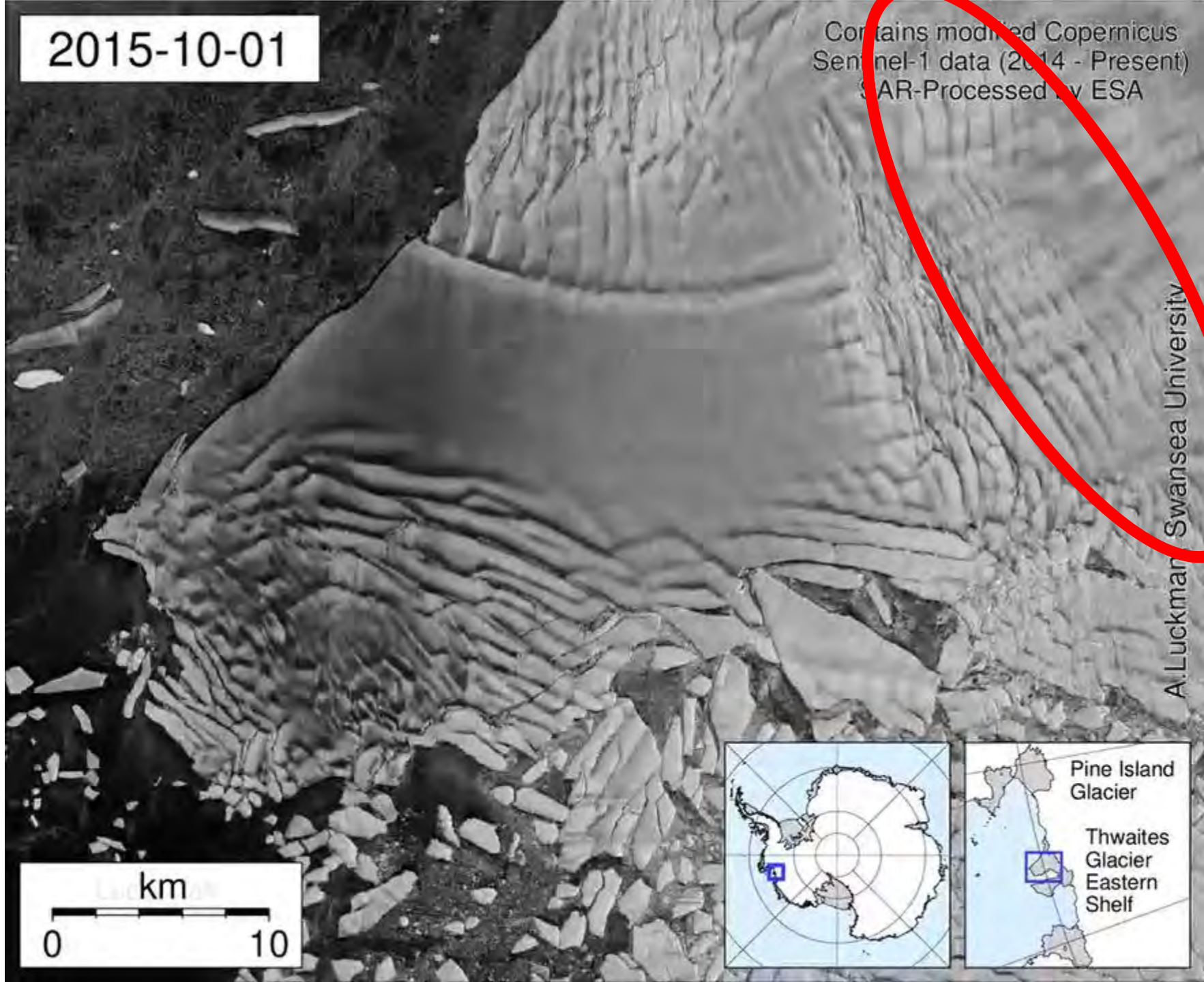
## Ice loss, Gigatons

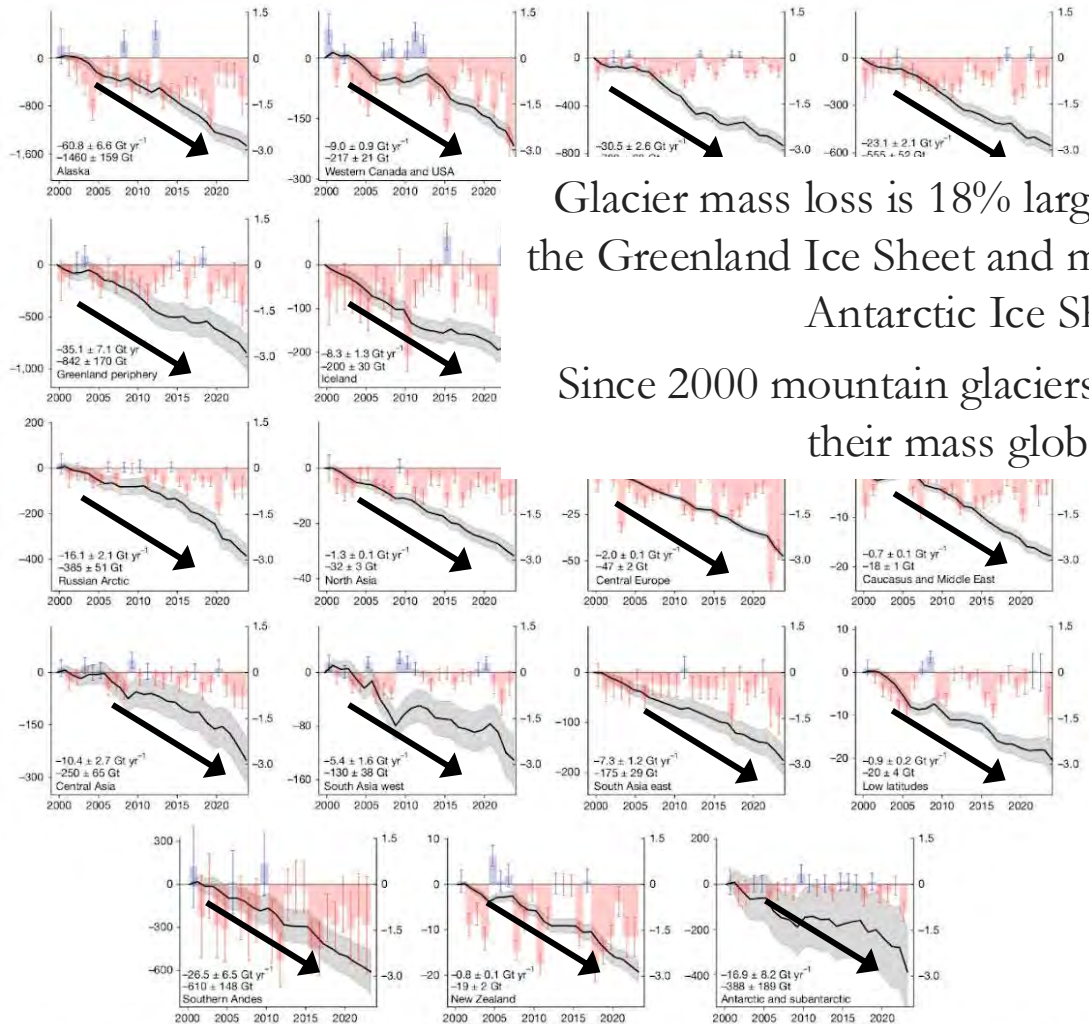


2015-10-01

Contains modified Copernicus  
Sentinel-1 data (2014 - Present)  
SAR-Processed by ESA

Thwaites  
Glacier –  
fractures  
migrating  
upstream, rate  
of ice loss has  
tripled since  
1990's

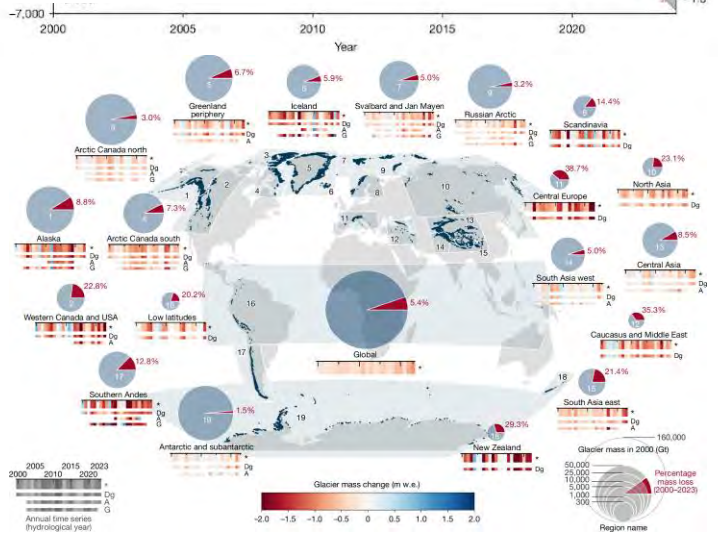
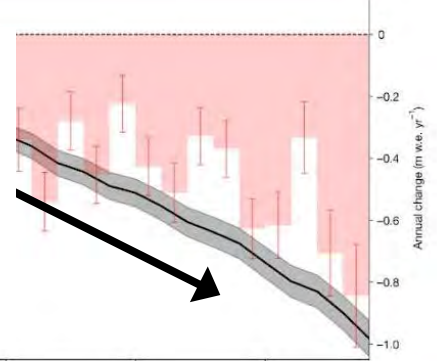




Cumulative and annual glacier mass changes since 2000 for the 19 glacier regions (hydrological years) and aggregated to global sums (calendar years).

## Glacier Mass Change 2000-2023

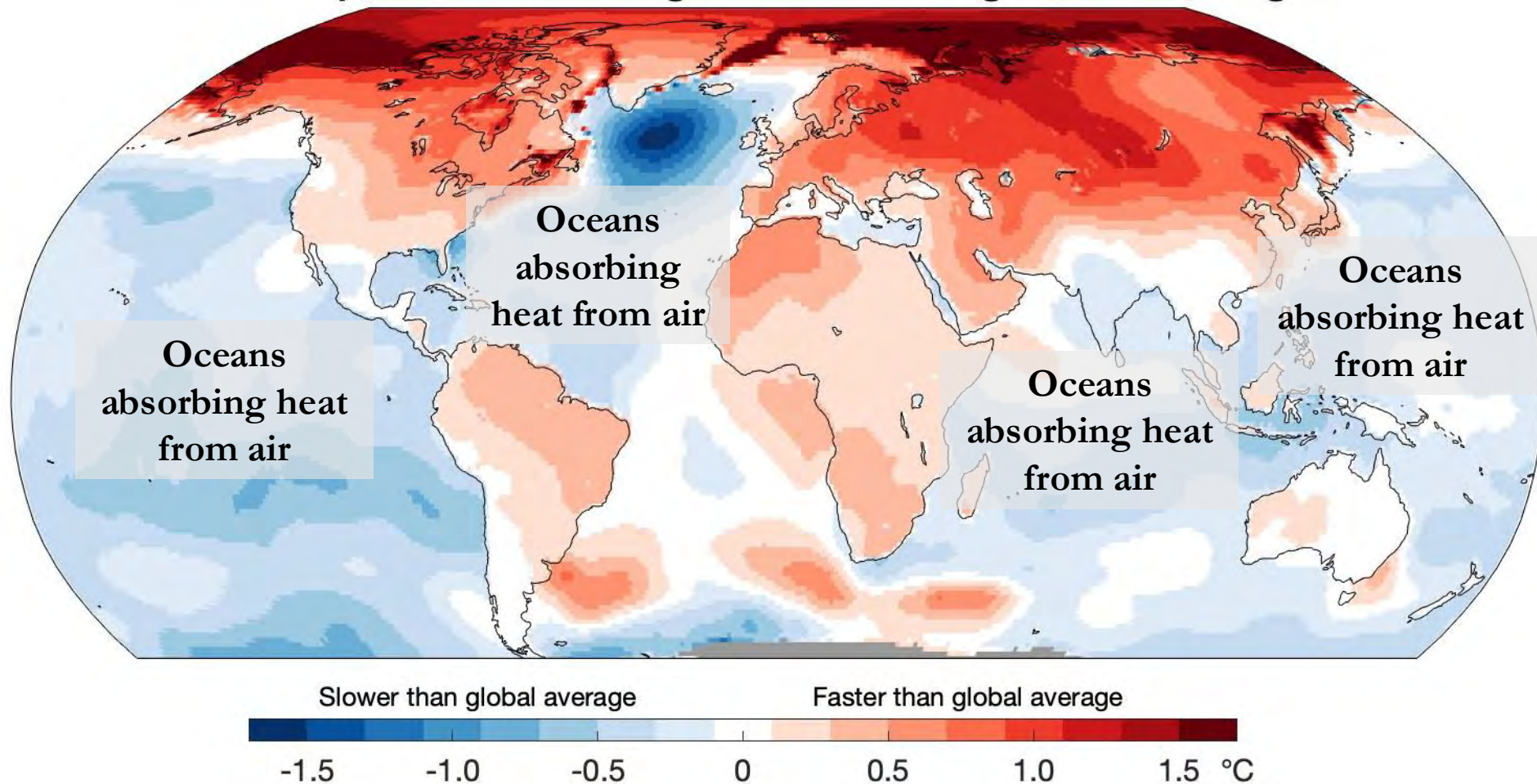
Glacier mass loss is 18% larger than loss from the Greenland Ice Sheet and more than twice the Antarctic Ice Sheet  
 Since 2000 mountain glaciers have lost 5% of their mass globally.



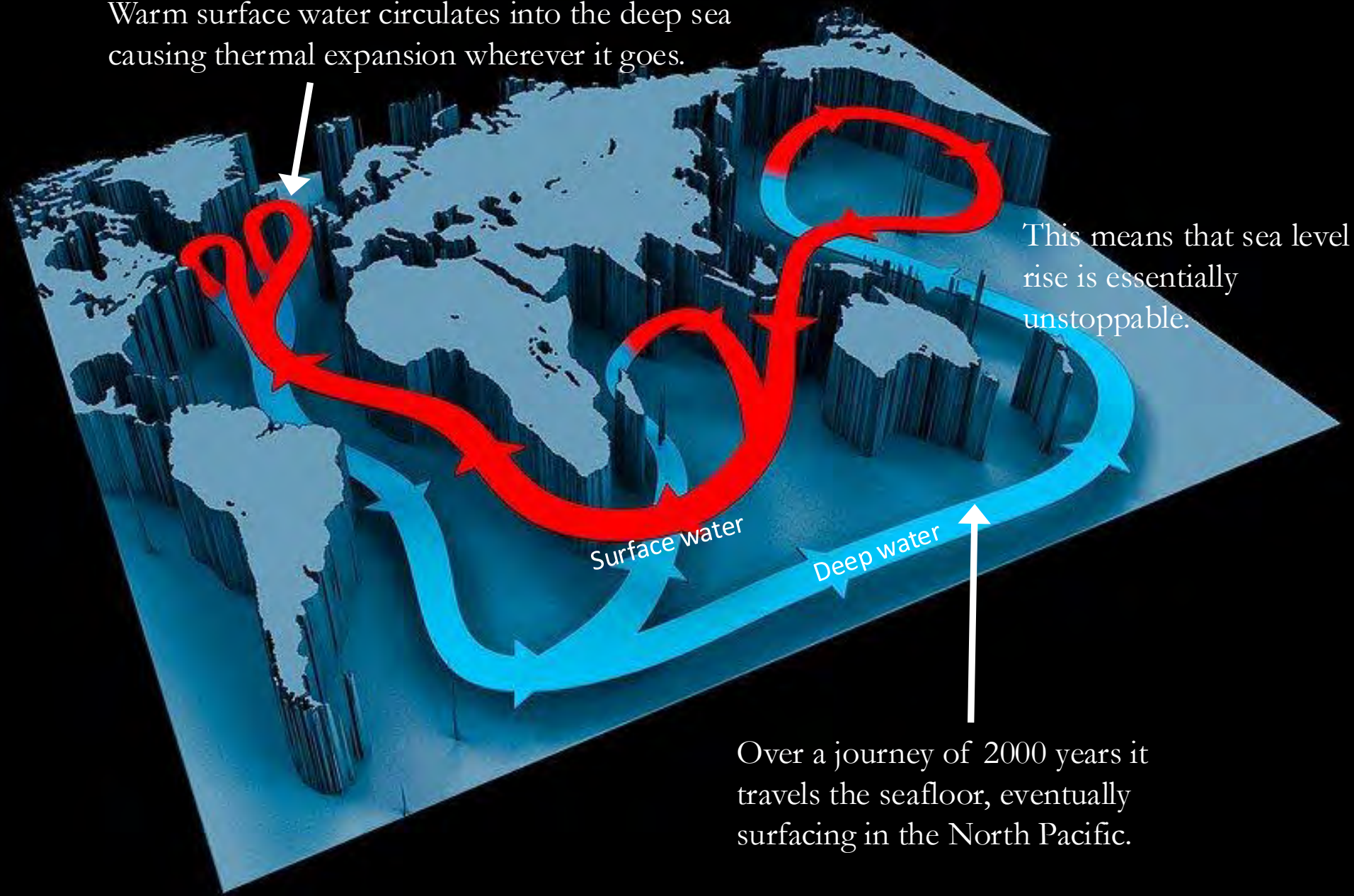
The GLMBIE Team. Community estimate of global glacier mass changes from 2000 to 2023. *Nature* (2025). <https://doi.org/10.1038/s41586-024-08545-z>

# Temperature change relative to global average

*Thermal expansion ~38% of SLR*



Warm surface water circulates into the deep sea causing thermal expansion wherever it goes.



# IPCC, 2021 Assessment Report 6

Sea level is committed to rise for centuries to millennia due to continuing deep-ocean warming and ice-sheet melt and will remain elevated for thousands of years (high confidence). *[AR6 WGI SPM p.21 B.5.4]*



**Sea level rise, an unstoppable reality**

*Photo, S. Habel*

# National Task Force – SLR Scenarios



# HONOLULU

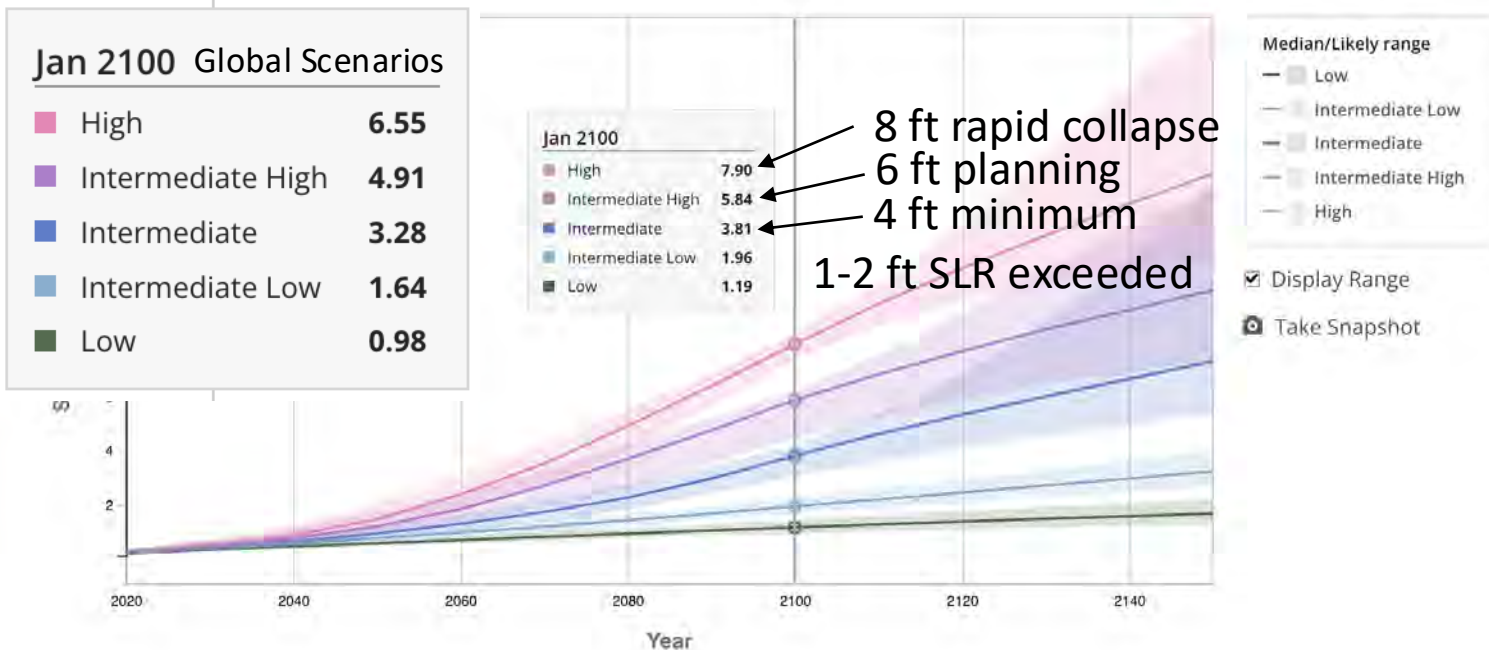
## National Task Force – SLR Scenarios

← RETURN TO MAP

UNITS English

### Sea Level Rise for Different Sea Level Scenarios

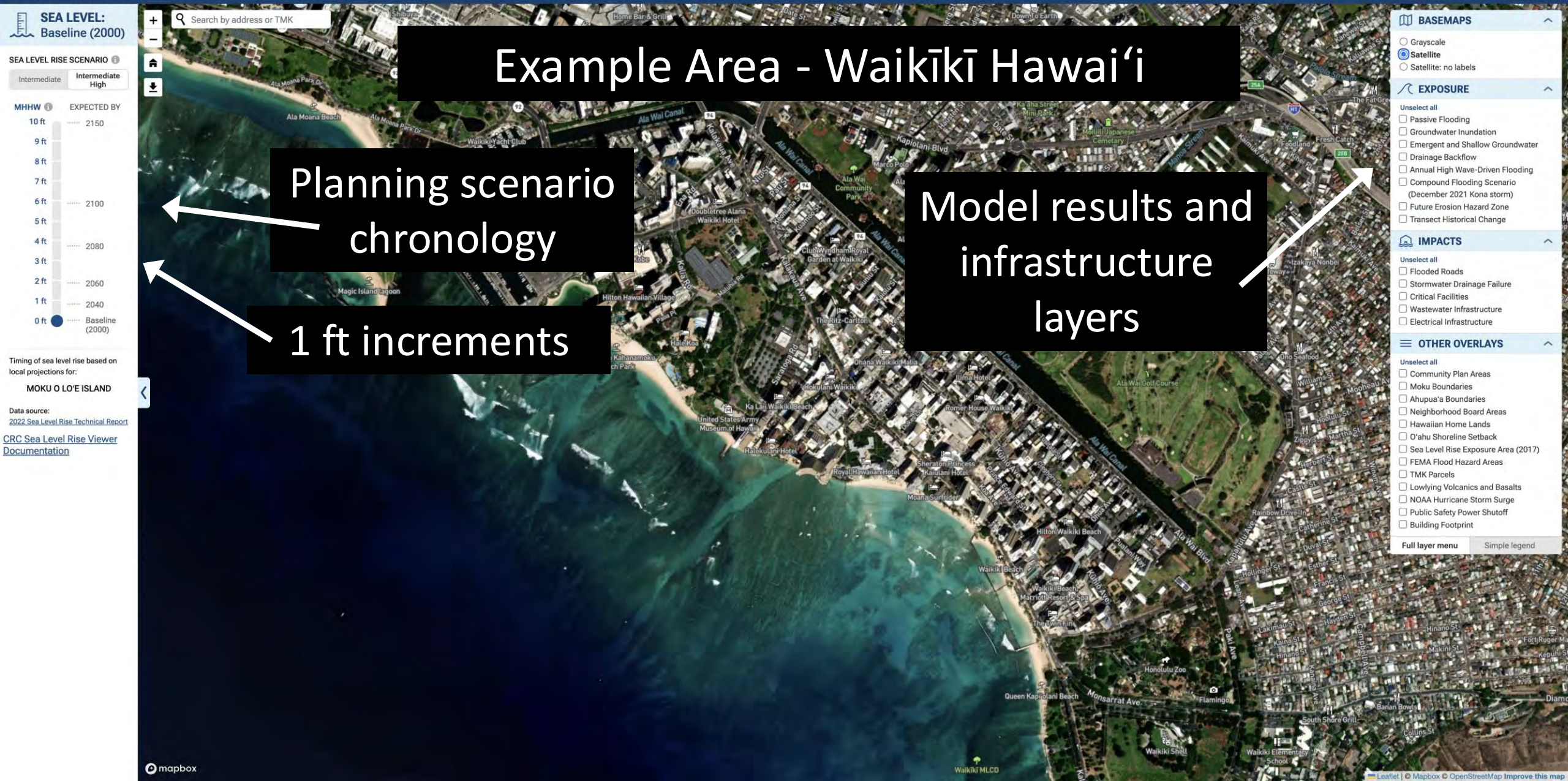
Depicted here are sea level change time series for the 5 sea level scenarios: low, intermediate-low, intermediate, intermediate-high and high. These scenarios are defined by a target global mean sea level (GMSL) values in 2100. Median values are provided for each scenario, along with likely ranges represented by shaded regions showing the 17<sup>th</sup>-83<sup>rd</sup> percentile ranges. For comparison to the model-based scenarios and as an additional line of evidence, extrapolations of available tide gauge observations are also provided. Rates and accelerations are estimated from tide gauge observations from 1970 to 2020 and then extrapolated to 2050 (see [here for more info](#)). For individual tide gauges, unresolved local variations or gaps in the tide gauge sampling may cause substantial departure from the modeled-scenarios in some locations. For tide gauges with record lengths shorter than 30 years, observation extrapolations are not shown. All values are relative to a baseline year of 2000. Data for the individual contributions can be downloaded under 'Get Data'.



**Hawai'i will see 15-20% more SLR than the  
global mean**



# SOEST Coastal Viewer



Example Area - Waikīkī Hawai'i

Planning scenario chronology

1 ft increments

Model results and infrastructure layers

**BASEMAPS**

- Grayscale
- Satellite
- Satellite: no labels

**EXPOSURE**

Unselect all

- Passive Flooding
- Groundwater Inundation
- Emergent and Shallow Groundwater
- Drainage Backflow
- Annual High Wave-Driven Flooding
- Compound Flooding Scenario (December 2021 Kona storm)
- Future Erosion Hazard Zone
- Transect Historical Change

**IMPACTS**

Unselect all

- Flooded Roads
- Stormwater Drainage Failure
- Critical Facilities
- Wastewater Infrastructure
- Electrical Infrastructure

**OTHER OVERLAYS**

Unselect all

- Community Plan Areas
- Moku Boundaries
- Ahupua'a Boundaries
- Neighborhood Board Areas
- Hawaiian Home Lands
- O'ahu Shoreline Setback
- Sea Level Rise Exposure Area (2017)
- FEMA Flood Hazard Areas
- TMK Parcels
- Lowlying Volcanics and Basalts
- NOAA Hurricane Storm Surge
- Public Safety Power Shutoff
- Building Footprint

Full layer menu Simple legend

**SEA LEVEL: Baseline (2000)**

SEA LEVEL RISE SCENARIO

Intermediate Intermediate High

MHHW EXPECTED BY

10 ft	2150
9 ft	
8 ft	
7 ft	2100
6 ft	
5 ft	
4 ft	2080
3 ft	
2 ft	2060
1 ft	2040
0 ft	Baseline (2000)

Timing of sea level rise based on local projections for:

MOKU O LO'E ISLAND

Data source: 2022 Sea Level Rise Technical Report

[CRC Sea Level Rise Viewer Documentation](#)

**SEA LEVEL: Baseline (2000)**

SEA LEVEL RISE SCENARIO

Intermediate Intermediate High

MHHW EXPECTED BY

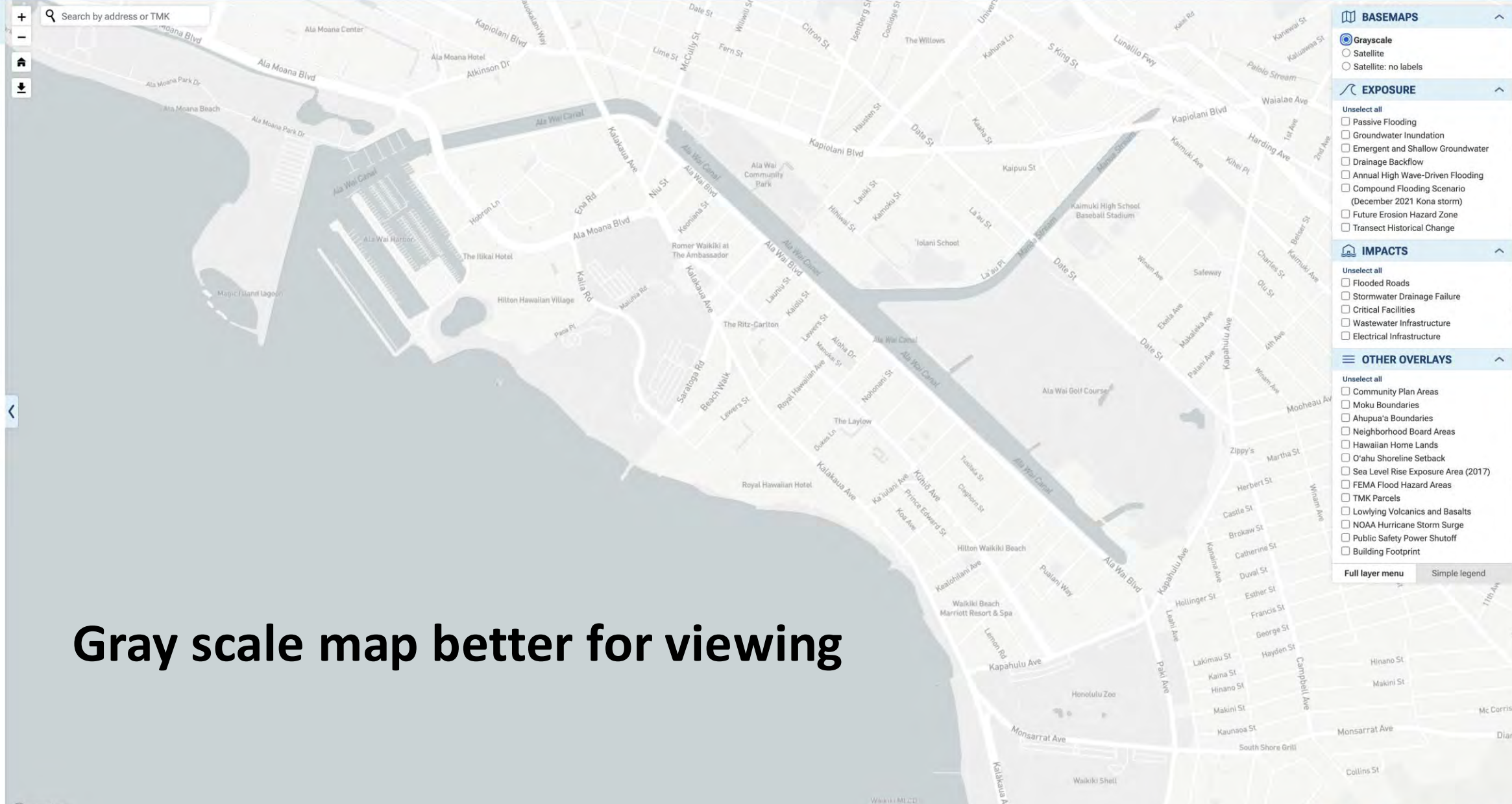
10 ft	2150
9 ft	
8 ft	
7 ft	
6 ft	2100
5 ft	
4 ft	2080
3 ft	
2 ft	2060
1 ft	2040
0 ft	Baseline (2000)

Timing of sea level rise based on local projections for:

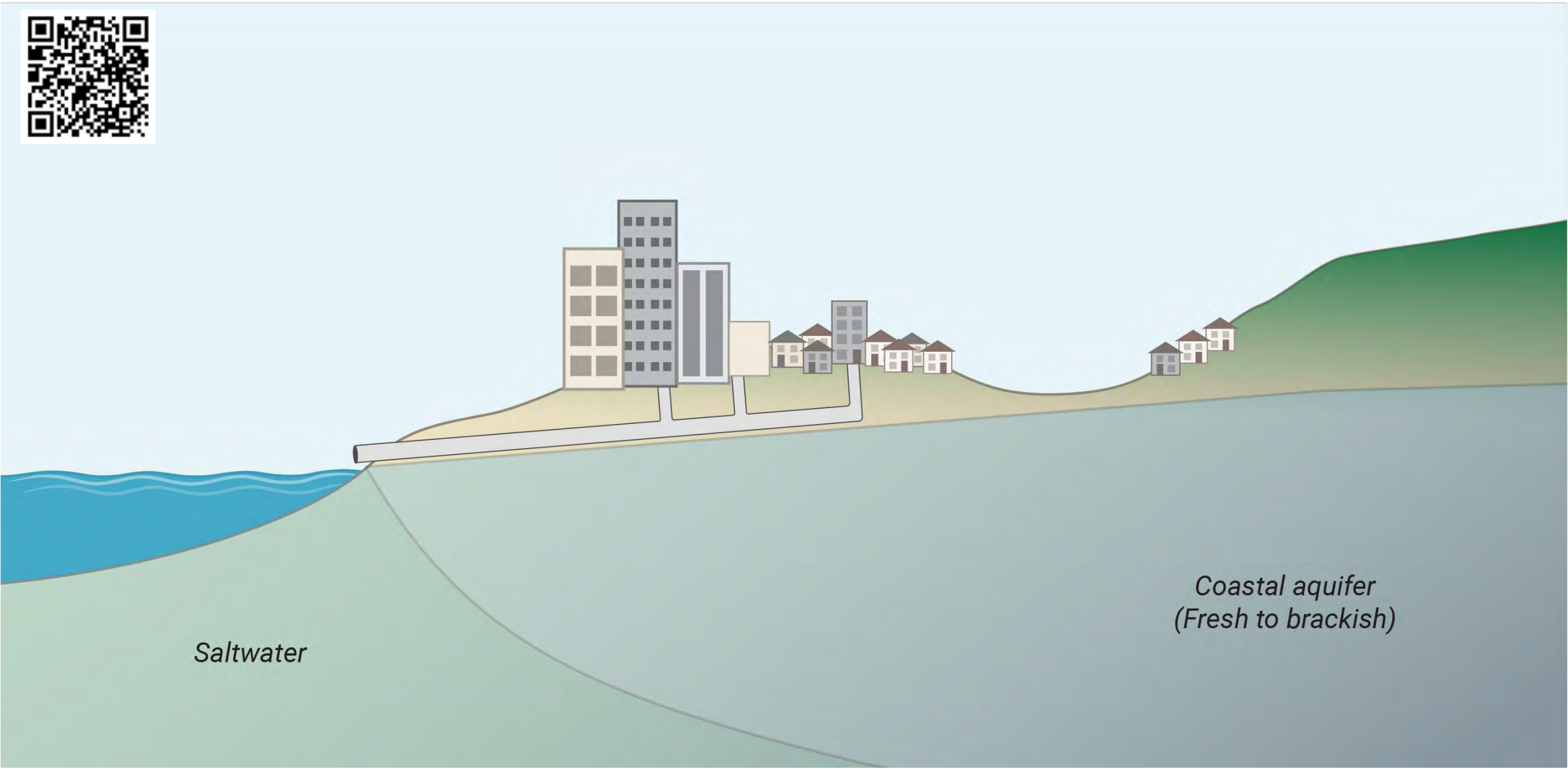
**MOKU O LO'E ISLAND**

Data source:  
[2022 Sea Level Rise Technical Report](#)

[CRC Sea Level Rise Viewer Documentation](#)



Gray scale map better for viewing



*Saltwater*

*Coastal aquifer  
(Fresh to brackish)*



**Marine  
flooding**

**HIGHER SEA LEVEL**

*Saltwater*

*Coastal aquifer  
(Fresh to brackish)*

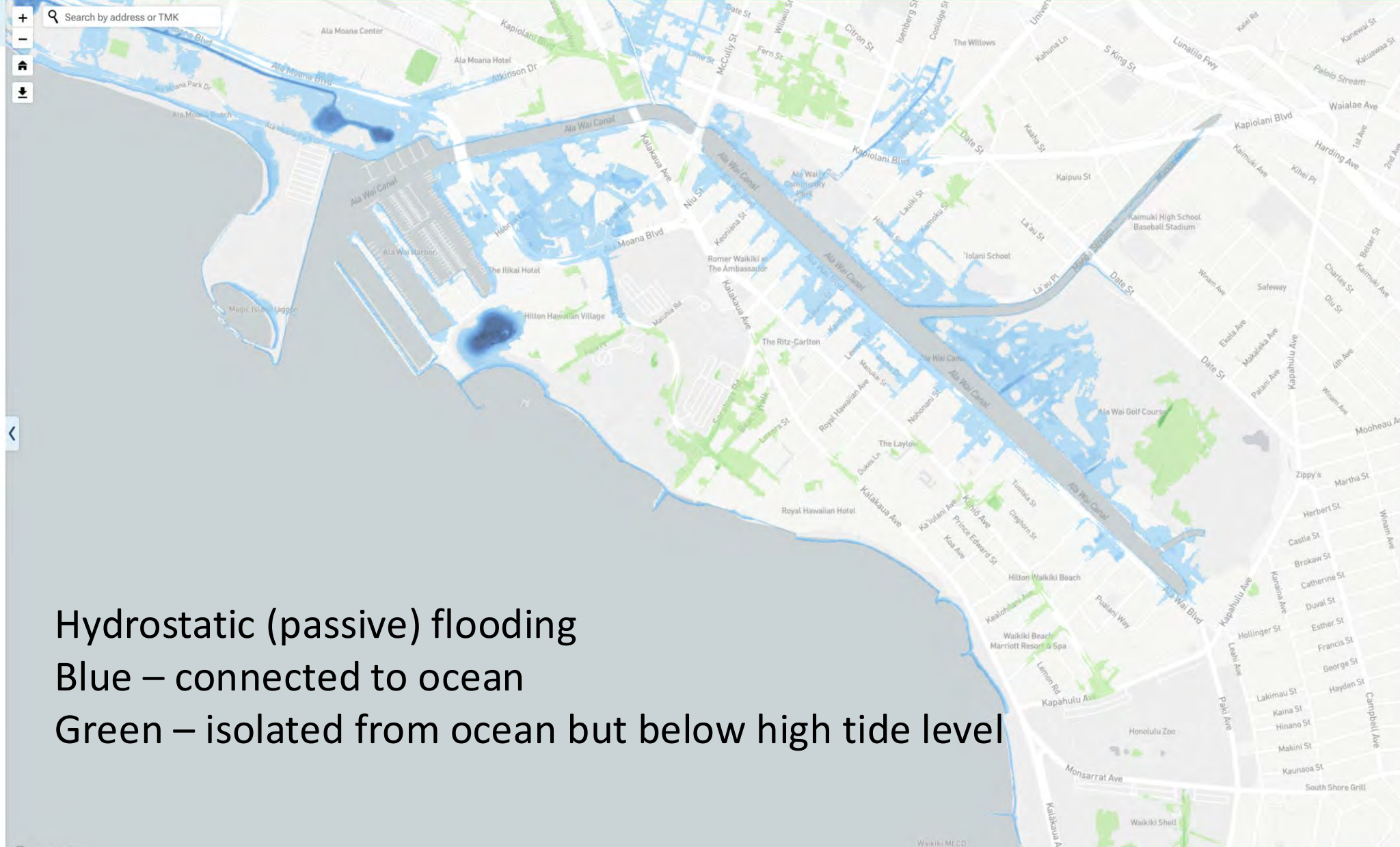
**SEA LEVEL:**  
+ 4 ft

**SEA LEVEL RISE SCENARIO**

Intermediate High

**MHHW** EXPECTED BY

10 ft	2150
9 ft	
8 ft	
7 ft	
6 ft	2100
5 ft	
4 ft	2080
3 ft	2060
2 ft	2040
1 ft	
0 ft	Baseline (2000)



**BASEMAPS**

- Grayscale
- Satellite
- Satellite: no labels

**EXPOSURE**

Unselect all

- Passive Flooding**
- Marine Connected Flooding**

**Marine flooding: water depth**

0 ft 10+ ft

- Lowlying Area**

**Lowlying: depth below sea level**

0 ft 10+ ft

- Groundwater Inundation
- Emergent and Shallow Groundwater
- Drainage Backflow
- Annual High Wave-Driven Flooding
- Compound Flooding Scenario (December 2021 Kona storm)
- Future Erosion Hazard Zone
- Transect Historical Change

**IMPACTS**

Unselect all

- Flooded Roads
- Stormwater Drainage Failure
- Critical Facilities
- Wastewater Infrastructure
- Electrical Infrastructure

**OTHER OVERLAYS**

Unselect all

- Community Plan Areas
- Moku Boundaries
- Ahupua'a Boundaries
- Neighborhood Board Areas
- Hawaiian Home Lands
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- Sea Level Rise Exposure Area (2017)
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- NOAA Hurricane Storm Surge
- Public Safety Power Shutoff
- Building Footprint

Full layer menu Simple legend

Hydrostatic (passive) flooding  
Blue – connected to ocean  
Green – isolated from ocean but below high tide level



Wave  
run-up



HIGHER SEA LEVEL

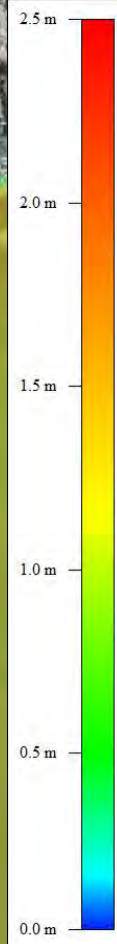


Saltwater

Coastal aquifer  
(Fresh to brackish)

# Ewa Beach – Wave Flooding, 1ft

2050



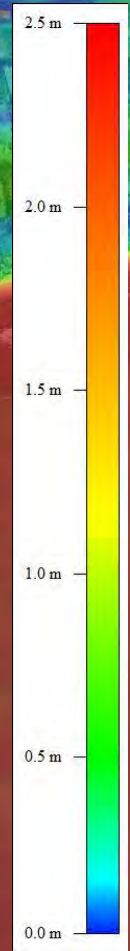
# Ewa Beach – Wave Flooding, 2-3ft

2060-2070

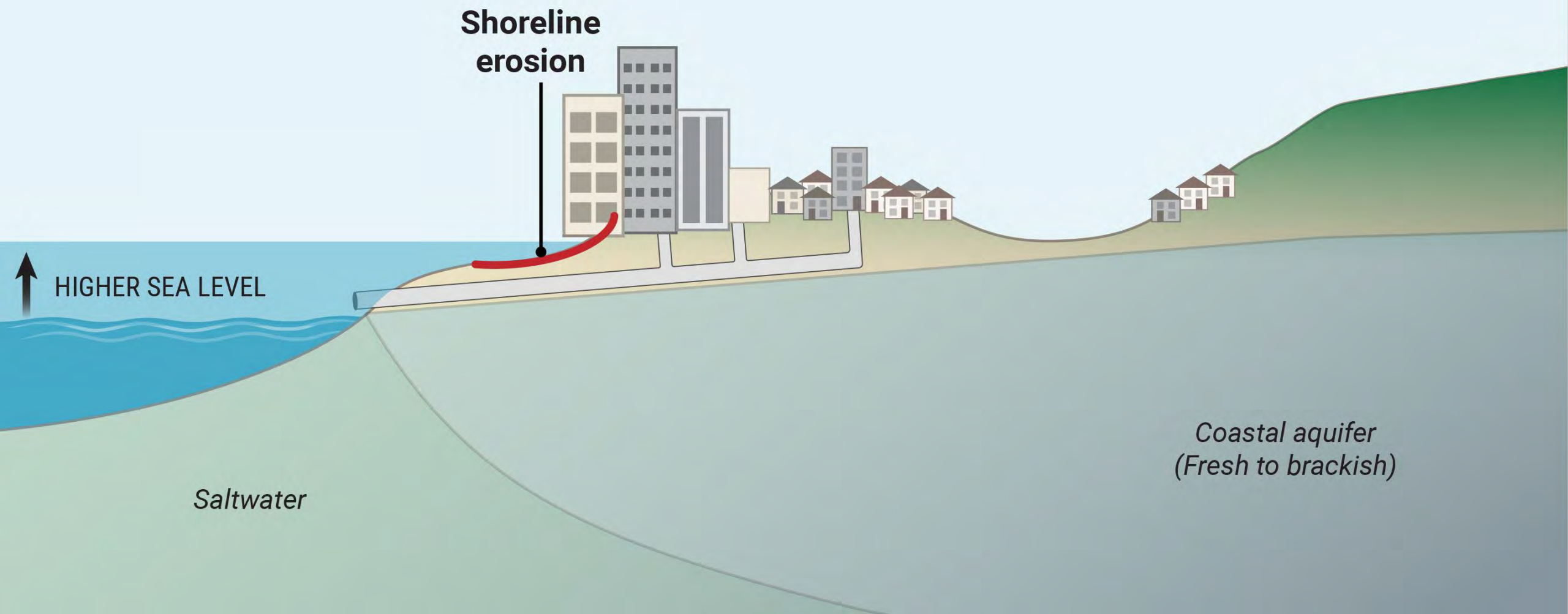


# Ewa Beach – Wave Flooding, 4ft

2080-2100



Annual wave driven flooding  
*Seasonal high waves, not storm surge*



**Shoreline  
erosion**

HIGHER SEA LEVEL

Saltwater

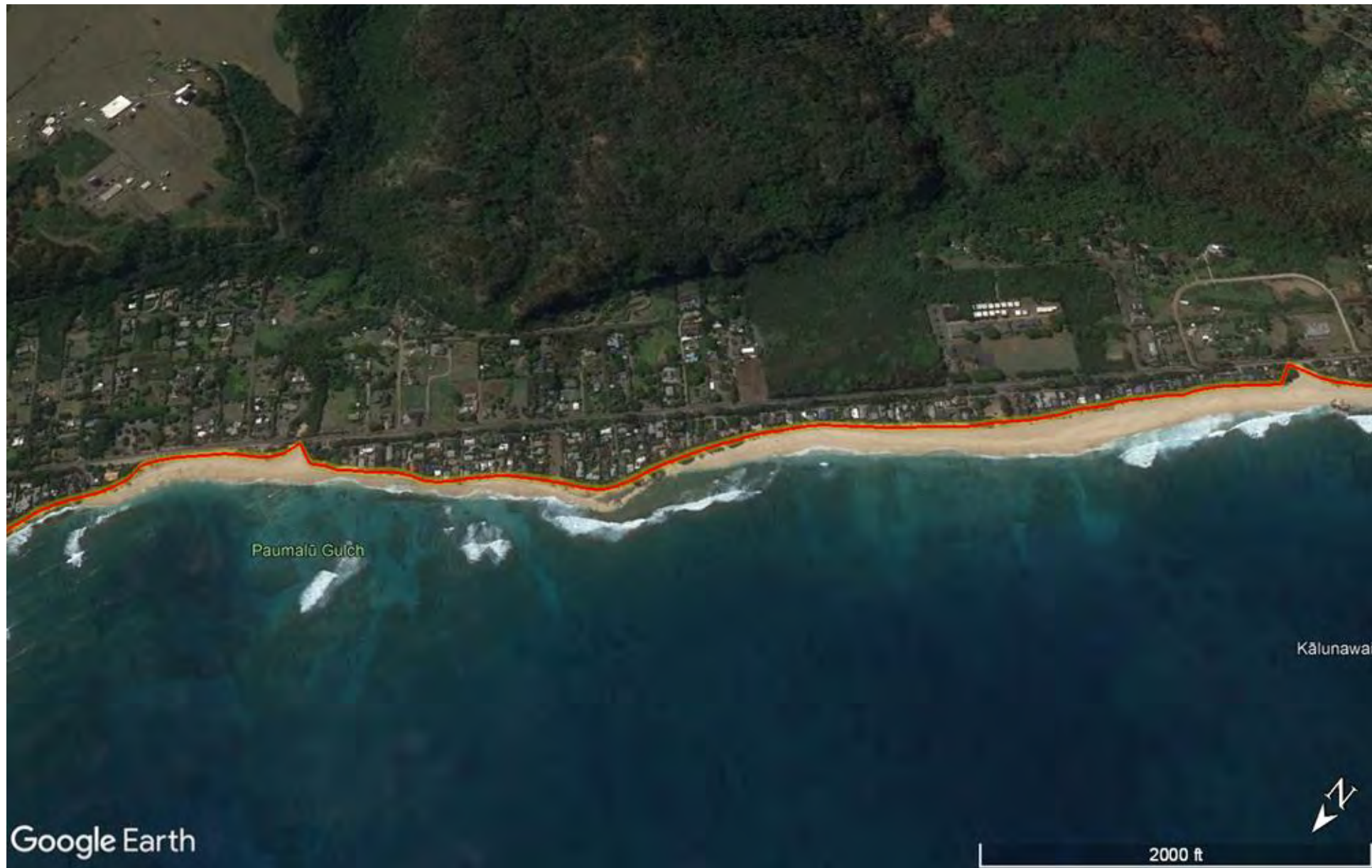
Coastal aquifer  
(Fresh to brackish)



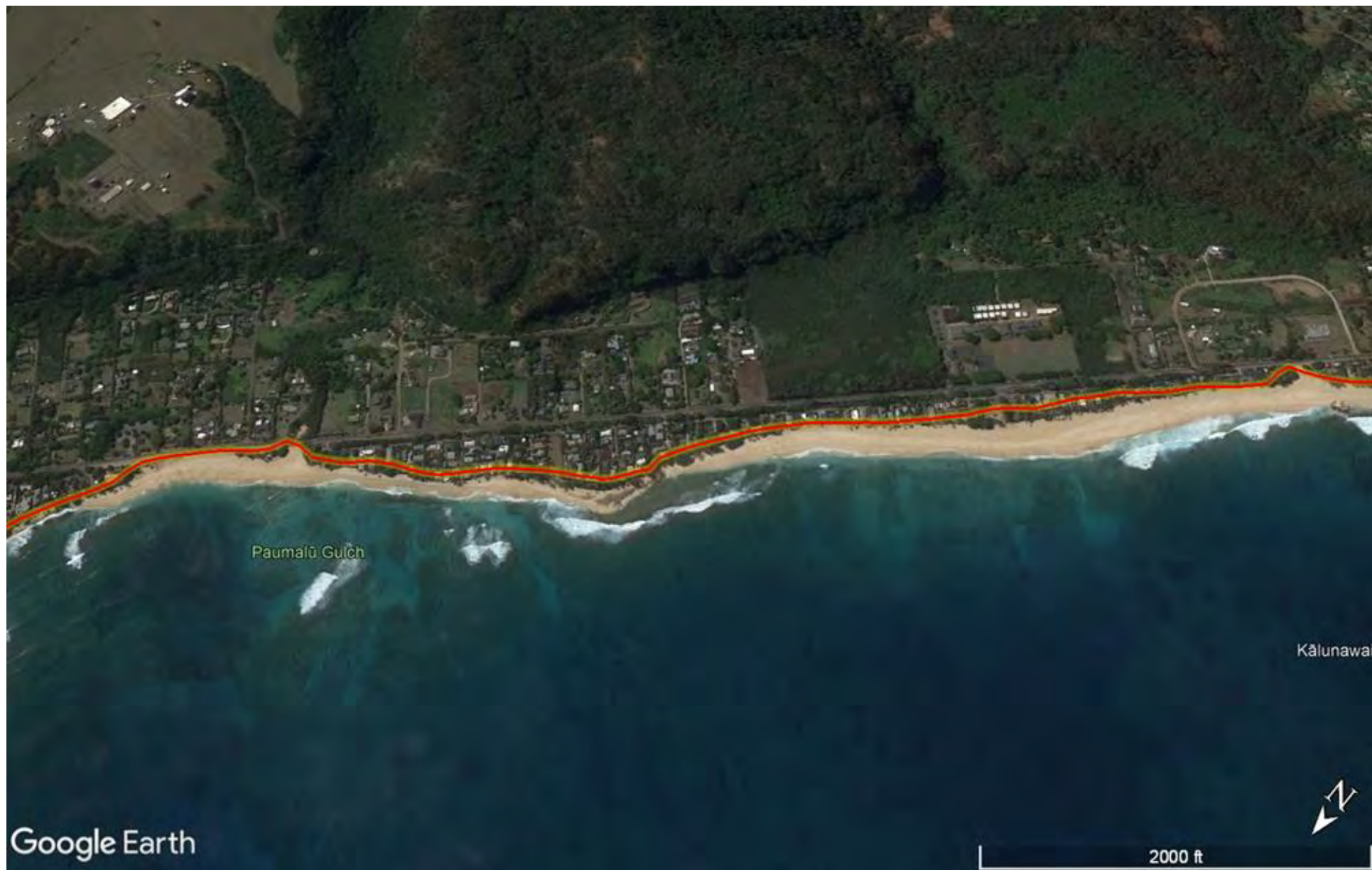
52 million  
gallons of  
wastewater  
per day



# Sunset Beach – Coastal Erosion, 0 ft



# Sunset Beach – Coastal Erosion, 1 ft



# Sunset Beach – Coastal Erosion, 2 ft

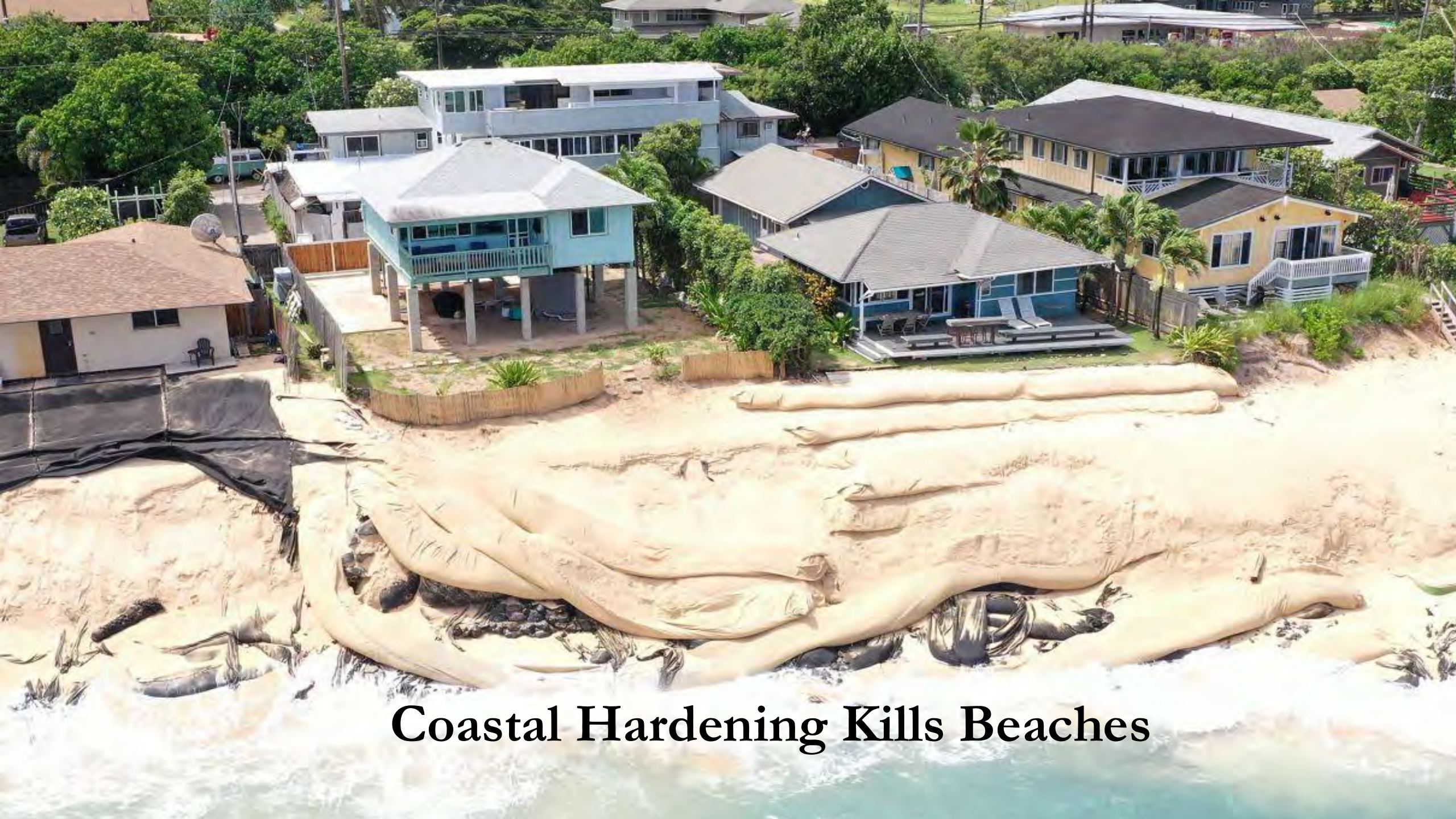


# Sunset Beach – Coastal Erosion, 3 ft



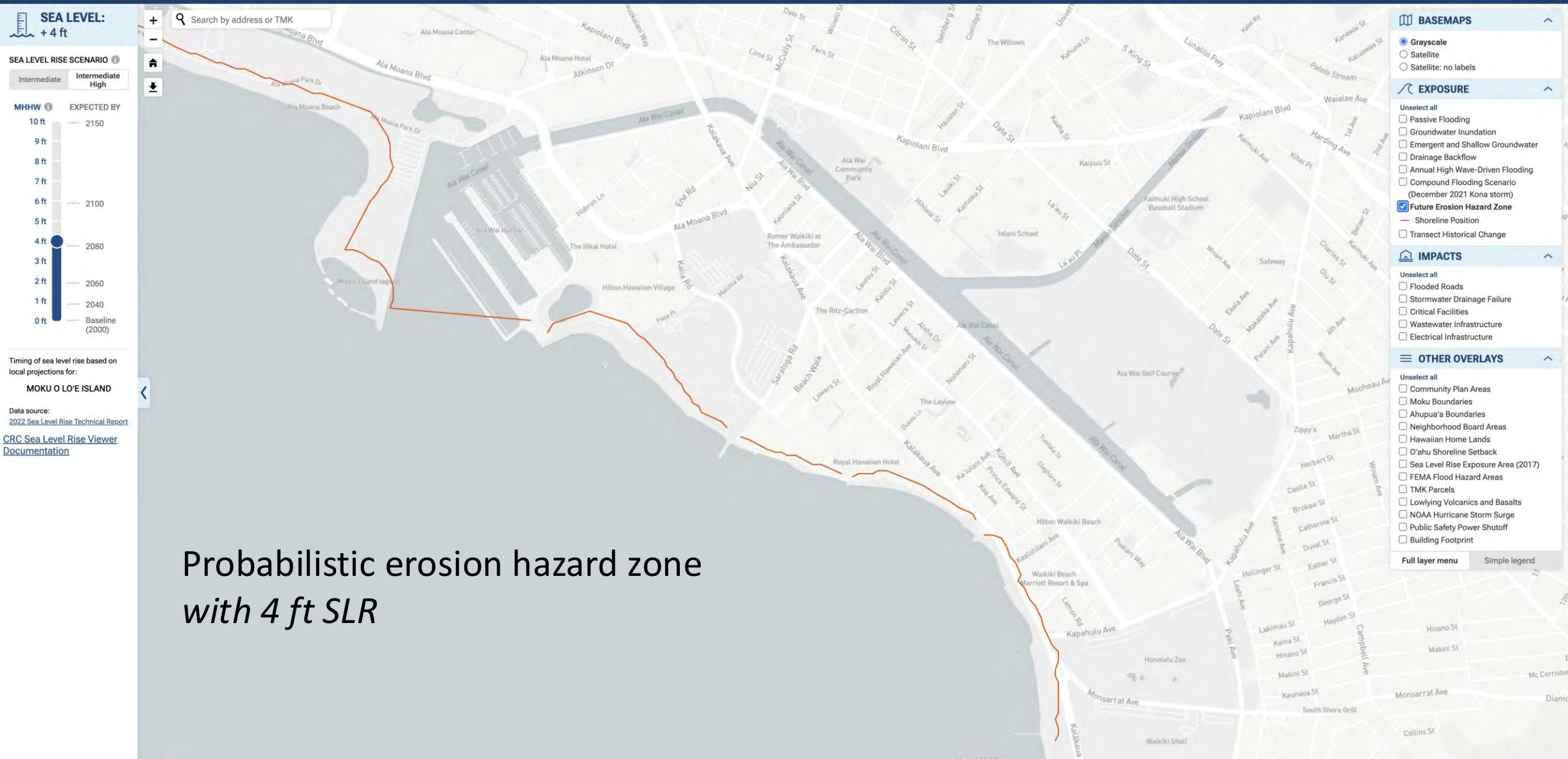
# Sunset Beach – Coastal Erosion, 4 ft



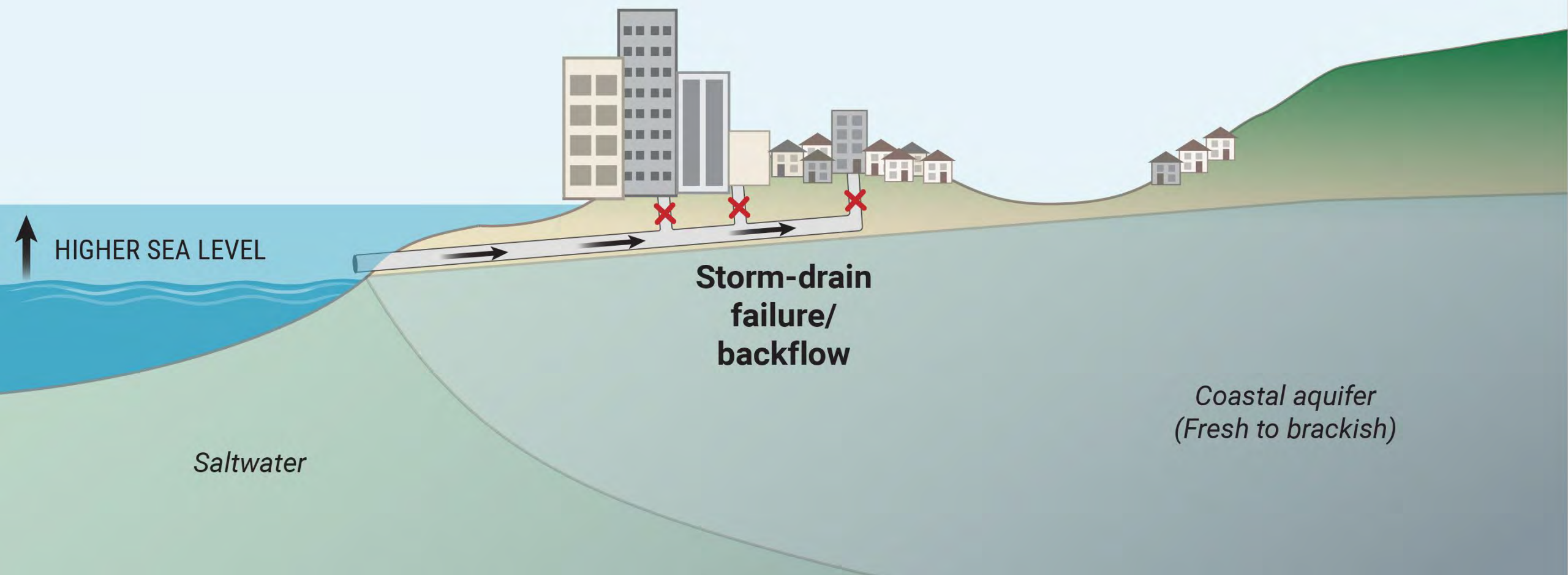


**Coastal Hardening Kills Beaches**

# SOEST Coastal Viewer



Probabilistic erosion hazard zone  
with 4 ft SLR



HIGHER SEA LEVEL

Storm-drain  
failure/  
backflow

Saltwater

Coastal aquifer  
(Fresh to brackish)

Storm  
drain  
backflow



# SOEST Coastal Viewer

**SEA LEVEL:**  
+ 4 ft

**SEA LEVEL RISE SCENARIO**  
Intermediate High

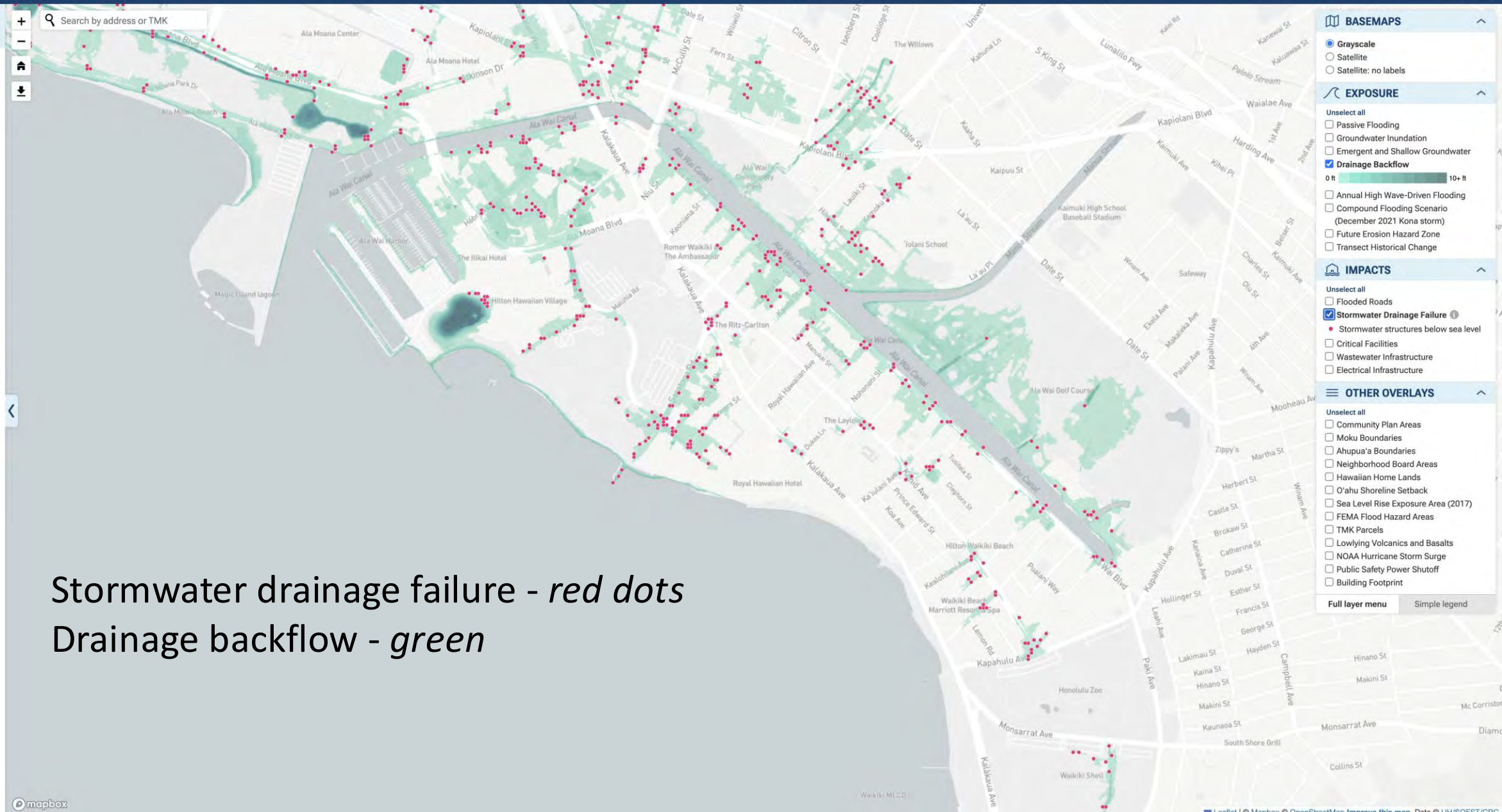
**MHHW** EXPECTED BY

10 ft	2150
9 ft	
8 ft	
7 ft	
6 ft	2100
5 ft	
4 ft	2080
3 ft	
2 ft	2060
1 ft	2040
0 ft	Baseline (2000)

Timing of sea level rise based on local projections for:  
**MOKU O LO'E ISLAND**

Data source:  
2022 Sea Level Rise Technical Report

[CRC Sea Level Rise Viewer Documentation](#)



**BASEMAPS**

- Grayscale
- Satellite
- Satellite: no labels

**EXPOSURE**

Unselect all

- Passive Flooding
- Groundwater Inundation
- Emergent and Shallow Groundwater
- Drainage Backflow**

0 ft 10+ ft

- Annual High Wave-Driven Flooding
- Compound Flooding Scenario (December 2021 Kona storm)
- Future Erosion Hazard Zone
- Transect Historical Change

**IMPACTS**

Unselect all

- Flooded Roads
- Stormwater Drainage Failure**
- Critical Facilities
- Wastewater Infrastructure
- Electrical Infrastructure

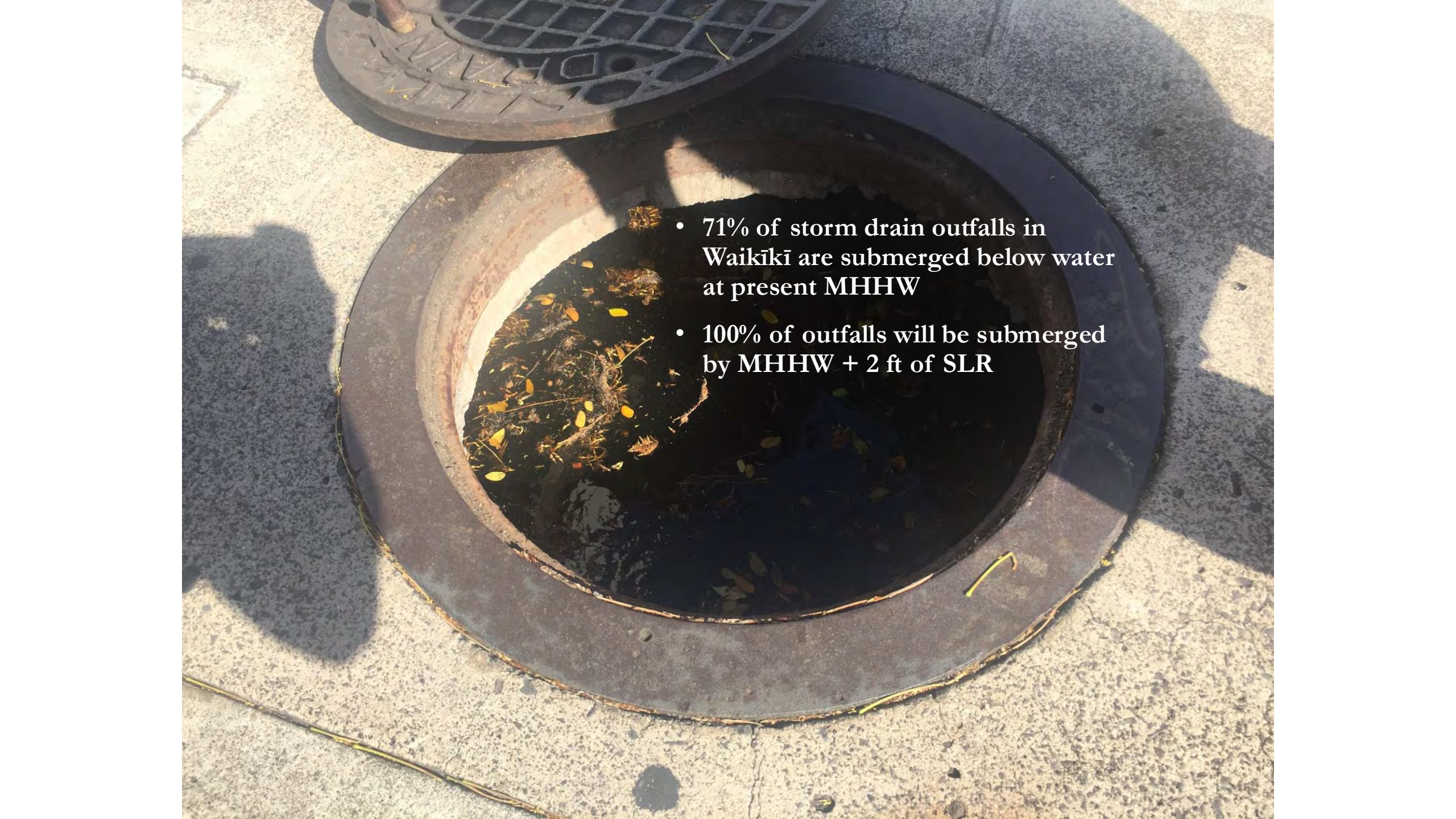
**OTHER OVERLAYS**

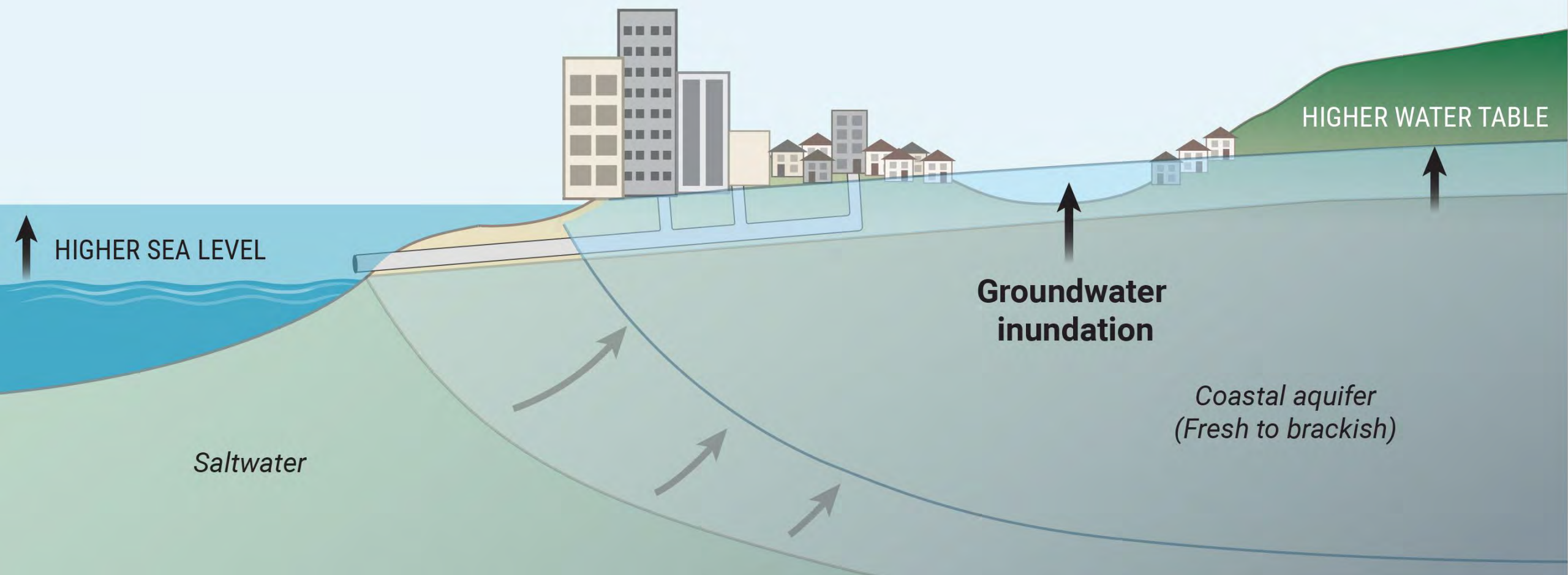
Unselect all

- Community Plan Areas
- Moku Boundaries
- Ahupua'a Boundaries
- Neighborhood Board Areas
- Hawaiian Home Lands
- O'ahu Shoreline Setback
- Sea Level Rise Exposure Area (2017)
- FEMA Flood Hazard Areas
- TMK Parcels
- Lowlying Volcanics and Basalts
- NOAA Hurricane Storm Surge
- Public Safety Power Shutoff
- Building Footprint

Full layer menu | Simple legend

Stormwater drainage failure - *red dots*  
Drainage backflow - *green*

- 
- 71% of storm drain outfalls in Waikīkī are submerged below water at present MHHW
  - 100% of outfalls will be submerged by MHHW + 2 ft of SLR



HIGHER SEA LEVEL

Saltwater

Groundwater  
inundation

Coastal aquifer  
(Fresh to brackish)

HIGHER WATER TABLE

As sea level rises, so does  
the water table



# SOEST Coastal Viewer

**SEA LEVEL:**  
+ 4 ft

**SEA LEVEL RISE SCENARIO**

Intermediate High

**MHW EXPECTED BY**

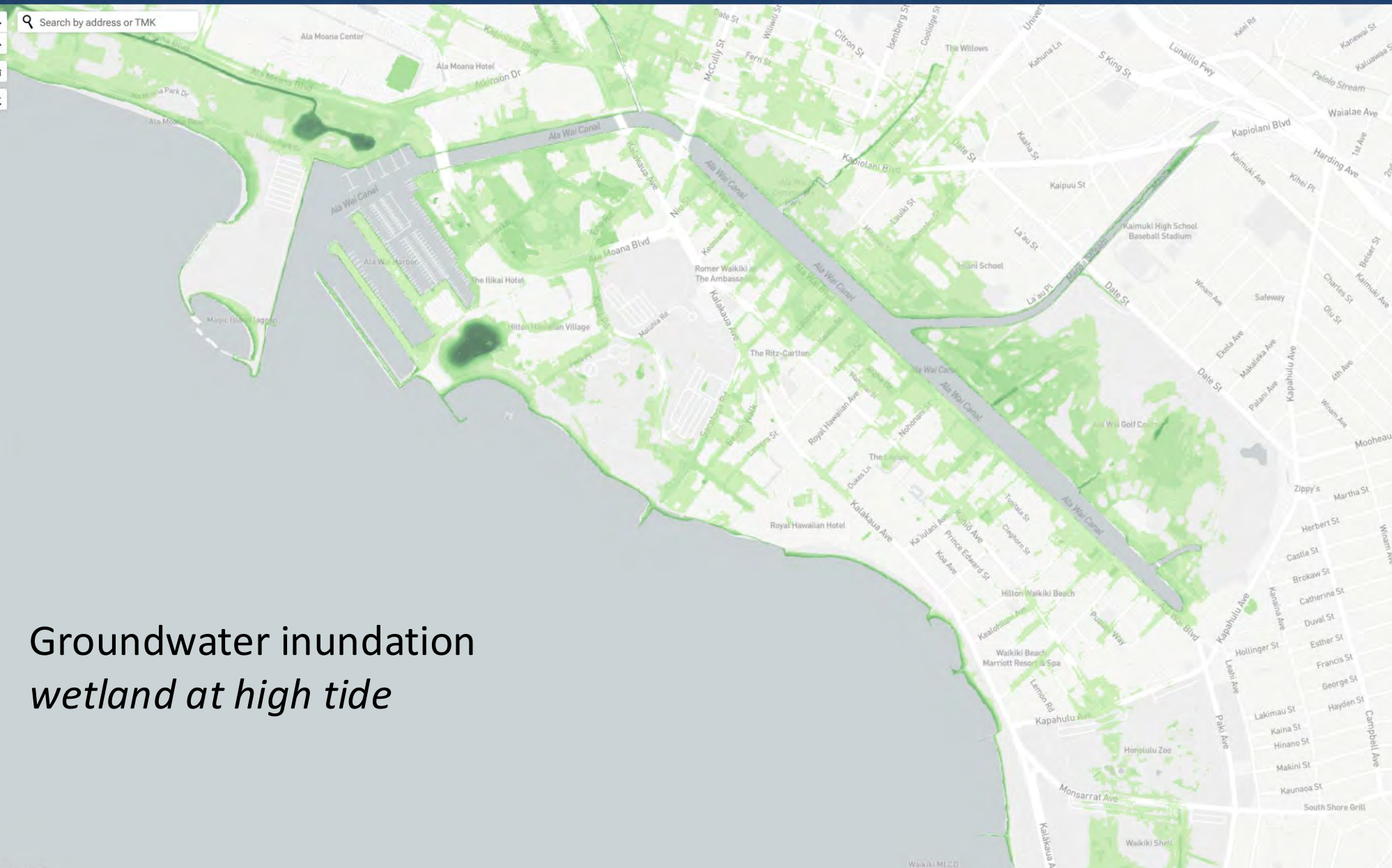
10 ft	2150
9 ft	
8 ft	
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2 ft	2060
1 ft	2040
0 ft	Baseline (2000)

Timing of sea level rise based on local projections for:

**MOKU O LO'E ISLAND**

Data source:  
2022 Sea Level Rise Technical Report

[CRC Sea Level Rise Viewer Documentation](#)



**BASEMAPS**

- Grayscale
- Satellite
- Satellite: no labels

**EXPOSURE**

Unselect all

- Groundwater Inundation
- Emergent and Shallow Groundwater
- Drainage Backflow
- Annual High Wave-Driven Flooding
- Compound Flooding Scenario (December 2021 Kona storm)
- Future Erosion Hazard Zone
- Transect Historical Change

**IMPACTS**

Unselect all

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- Stormwater Drainage Failure
- Critical Facilities
- Wastewater Infrastructure
- Electrical Infrastructure

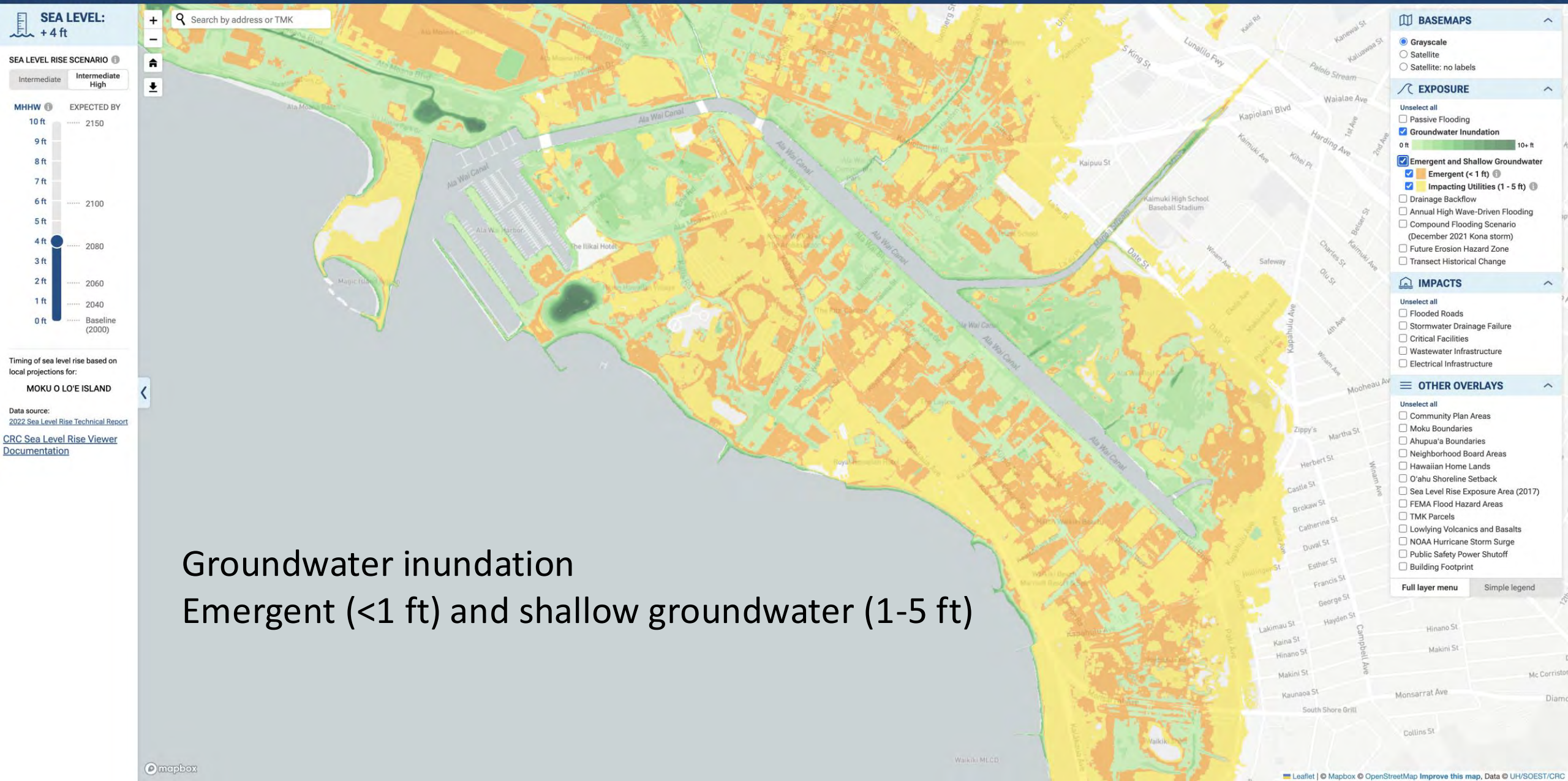
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- Moku Boundaries
- Ahupua'a Boundaries
- Neighborhood Board Areas
- Hawaiian Home Lands
- O'ahu Shoreline Setback
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- FEMA Flood Hazard Areas
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- Lowlying Volcanics and Basalts
- NOAA Hurricane Storm Surge
- Public Safety Power Shutoff
- Building Footprint

Full layer menu | Simple legend

Groundwater inundation  
*wetland at high tide*



**SEA LEVEL:**  
+ 4 ft

**SEA LEVEL RISE SCENARIO**

Intermediate High

**MHW** EXPECTED BY

10 ft	2150
9 ft	
8 ft	
7 ft	
6 ft	2100
5 ft	
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3 ft	
2 ft	2060
1 ft	2040
0 ft	Baseline (2000)

Timing of sea level rise based on local projections for:

**MOKU O LO'E ISLAND**

Data source:  
[2022 Sea Level Rise Technical Report](#)

[CRC Sea Level Rise Viewer Documentation](#)

**BASEMAPS**

- Grayscale
- Satellite
- Satellite: no labels

**EXPOSURE**

Unselect all

- Passive Flooding
- Groundwater Inundation
- Emergent and Shallow Groundwater
- Emergent (< 1 ft)
- Impacting Utilities (1 - 5 ft)
- Drainage Backflow
- Annual High Wave-Driven Flooding
- Compound Flooding Scenario (December 2021 Kona storm)
- Future Erosion Hazard Zone
- Transect Historical Change

**IMPACTS**

Unselect all

- Flooded Roads
- Stormwater Drainage Failure
- Critical Facilities
- Wastewater Infrastructure
- Electrical Infrastructure

**OTHER OVERLAYS**

Unselect all

- Community Plan Areas
- Moku Boundaries
- Ahupua'a Boundaries
- Neighborhood Board Areas
- Hawaiian Home Lands
- O'ahu Shoreline Setback
- Sea Level Rise Exposure Area (2017)
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- TMK Parcels
- Lowlying Volcanics and Basalts
- NOAA Hurricane Storm Surge
- Public Safety Power Shutoff
- Building Footprint

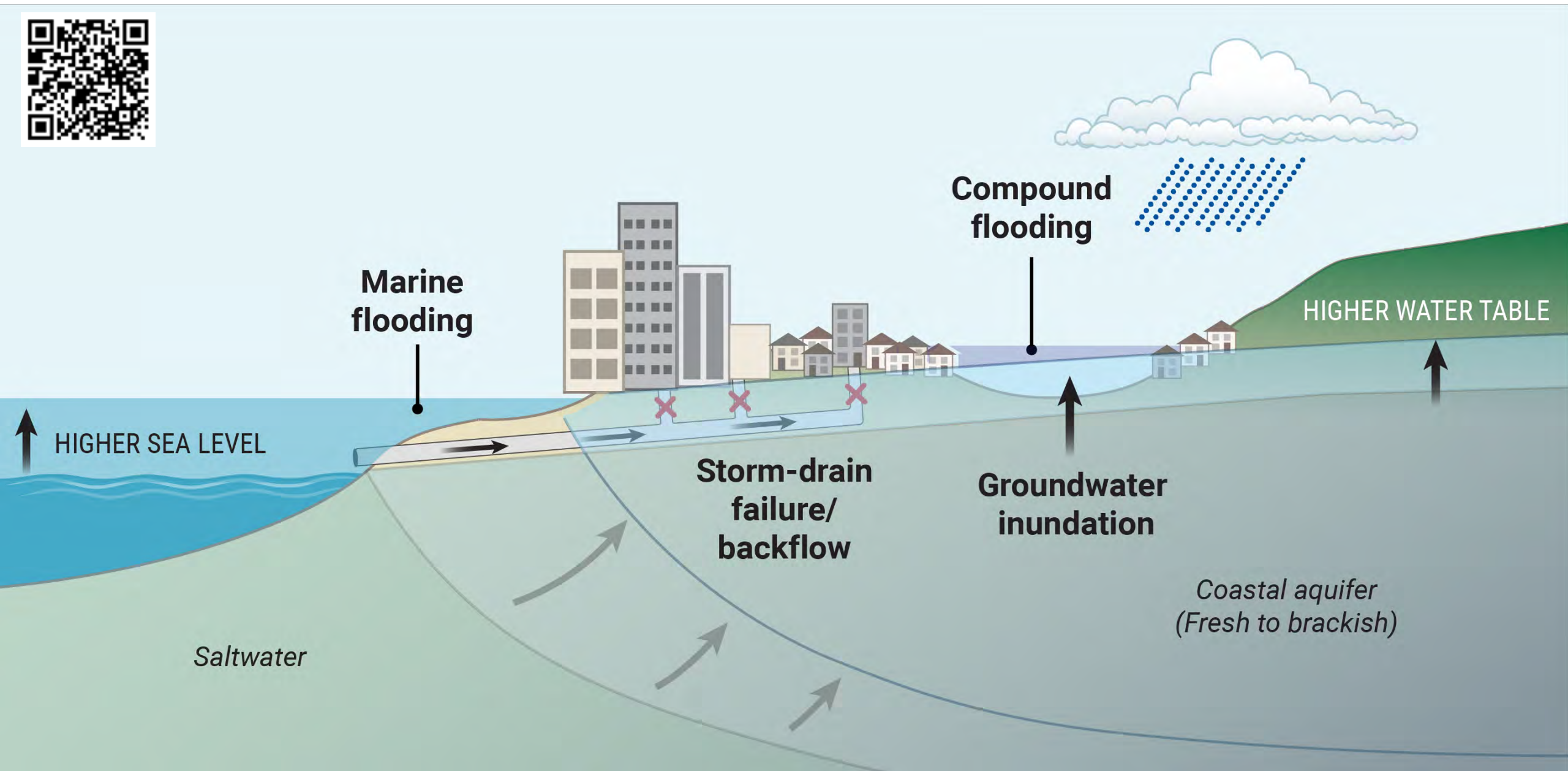
Full layer menu Simple legend

Groundwater inundation  
Emergent (<1 ft) and shallow groundwater (1-5 ft)

SLR will bring  
polluted  
groundwater to  
the surface

*Groundwater  
Pollution*





**Marine flooding**

HIGHER SEA LEVEL

**Storm-drain failure/backflow**

**Compound flooding**

**Groundwater inundation**

HIGHER WATER TABLE

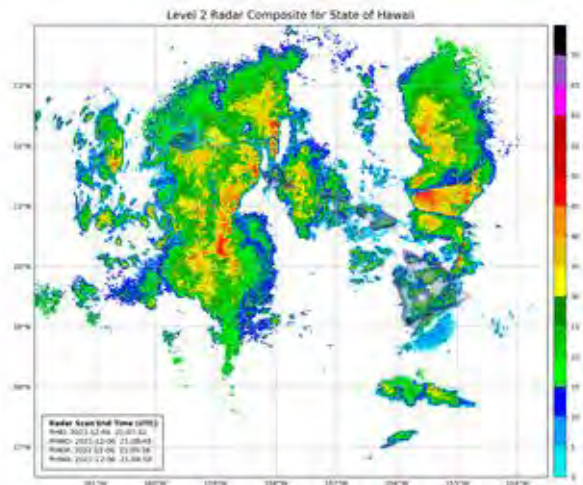
Saltwater

*Coastal aquifer  
(Fresh to brackish)*

# Waikiki

## Dec. 5, 2021

- Sea level rise flooding today involves
  - Rain
  - Extreme tides
  - Onshore winds
  - Large waves



# SOEST Coastal Viewer

**SEA LEVEL:** +4 ft

**SEA LEVEL RISE SCENARIO**

Intermediate | Intermediate High



Timing of sea level rise based on local projections for:

**MOKU O LO'E ISLAND**

Data source: 2022 Sea Level Rise Technical Report

[CRC Sea Level Rise Viewer Documentation](#)

**BASEMAPS**

- Grayscale
- Satellite
- Satellite: no labels

**EXPOSURE**

Unselect all

- Passive Flooding
- Groundwater Inundation
- Emergent and Shallow Groundwater
- Drainage Backflow
- Annual High Wave-Driven Flooding
- Compound Flooding Scenario (December 2021 Kona storm)

Floodwater Depth

0 ft 10+ ft

- Future Erosion Hazard Zone
- Transect Historical Change

**IMPACTS**

Unselect all

- Flooded Roads
- Stormwater Drainage Failure
- Critical Facilities
- Wastewater Infrastructure
- Electrical Infrastructure

**OTHER OVERLAYS**

Unselect all

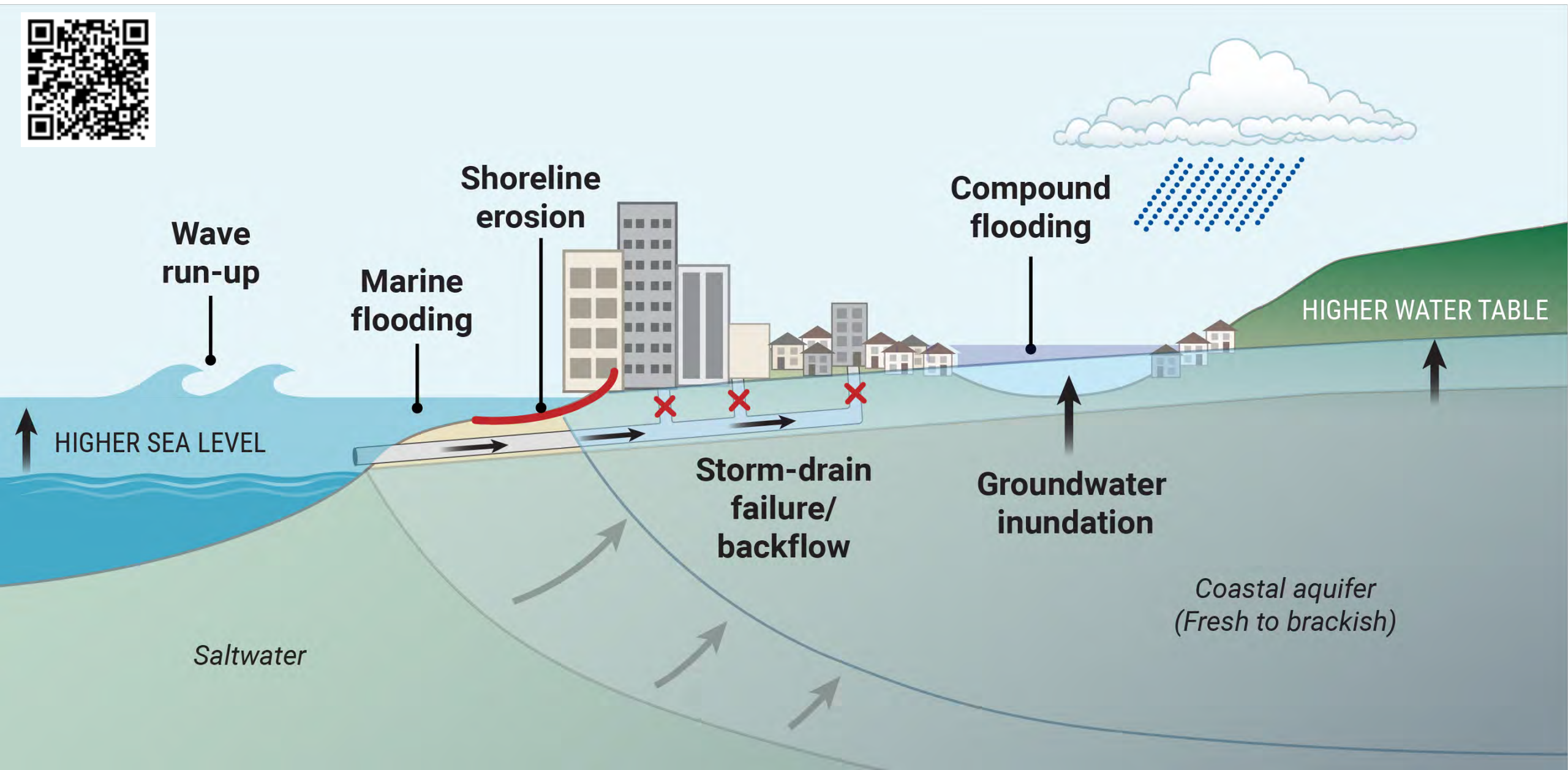
- Community Plan Areas
- Moku Boundaries
- Ahupua'a Boundaries
- Neighborhood Board Areas
- Hawaiian Home Lands
- O'ahu Shoreline Setback
- Sea Level Rise Exposure Area (2017)
- FEMA Flood Hazard Areas
- TMK Parcels
- Lowlying Volcanics and Basalts
- NOAA Hurricane Storm Surge
- Public Safety Power Shutoff
- Building Footprint

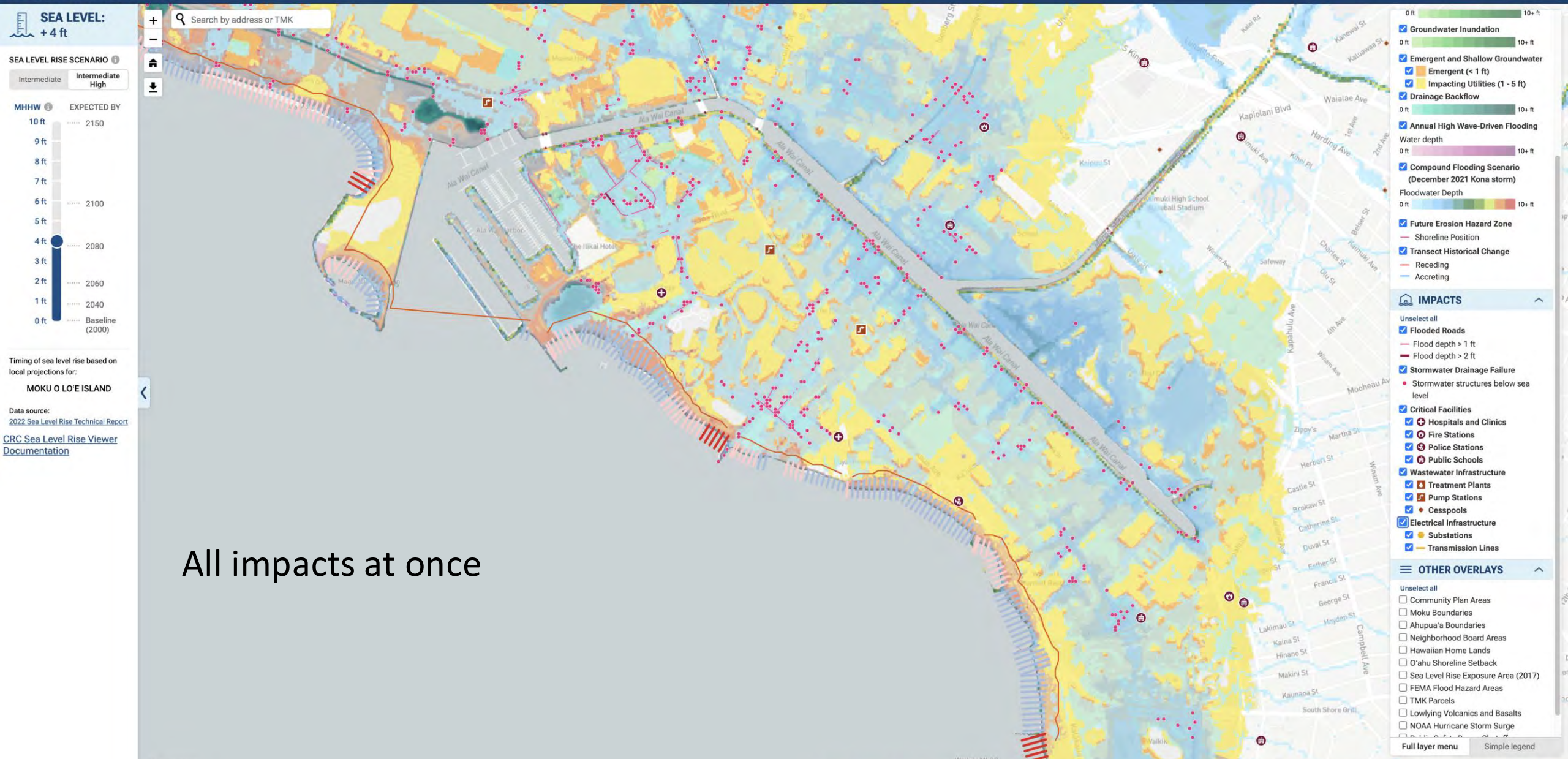
Full layer menu | Simple legend

Compound flooding (rain at high tide)  
*December 2021 Kona storm*

# Rain + High Tide = Compound Flooding







All impacts at once

# Climate Research Collaborative Data in Hawai'i Law

## Statewide:

- **Mandatory disclosure of sea level rise in real estate transactions**
  - Hawai'i Revised Statutes § 508D-15(5)
- **Required analysis of sea level rise in the Hawai'i Environmental Policy Act**
  - Hawai'i Revised Statutes Chapter 343
  - Hawai'i Administrative Rules §§ 11-200.1-13, -18, -21, -24

## County Ordinances:

- **Shoreline Setback Ordinances in Kaua'i County, Maui County, and the City & County of Honolulu**
  - Hawai'i Revised Statutes § 205A-45
  - Maui County Administrative Rules, Title 12 Chapter 203
  - Revised Ordinances of Honolulu, Chapter 26
  - Kaua'i County Code, Title IV, Chapter 8, Article 27
- **Special Management Area in Maui County and the City & County of Honolulu**
  - Hawai'i Revised Statutes §§ 205A-21 et seq.
  - Maui County Administrative Rules, Title 12 Chapter 202
  - Revised Ordinances of Honolulu, Chapter 25
- **Kaua'i County Sea Level Rise Constraint District**
  - Kaua'i County Code, Title IV, Chapter 8, Article 12.5

## DRIP Committee

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**From:** Fletcher, Charles <fletcher@soest.hawaii.edu>  
**Sent:** Thursday, May 28, 2026 1:39 PM  
**To:** DRIP Committee; Jarret P. Pascual  
**Subject:** presentation for published agenda  
**Attachments:** Sea Level Rise Intro FLETCHER.pdf

You don't often get email from fletcher@soest.hawaii.edu. [Learn why this is important](#)

Please find attached a PDF of my presentation scheduled for the June 3 meeting of the DRIP committee.

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**Chip Fletcher** ([bio](#))

*Dean*

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