A scenario-based approach to assessing changes in coastal flood magnitude and frequency under a changing climate, with an exemplar application to ecosystem vulnerability assessment on the Island of Hawai`i.

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The Problem

High Tide flooding in Hilo, HI

High Tide flooding in Miami, FL

Built and Natural Infrastructure at Risk due to increasing potential for Coastal Flooding with a Changing Climate

Coastal flooding and erosion attributable to sea level extremes is due to a variety of processes. As a result, estimates of future coastal flood potential must account for patterns of sea level variability and storminess as well as global and regional sea level rise.

A scenario-dependent framework that accounts for the full range of factors affecting sea level extremes is used to formulate estimates of future coastal flood potential.

How high, how often, for how long, when?

Source organichawaii.org

The Problem

Source Flickr.com

‘Ōpae‘ula, *Halocaridina rubra*

Source TNC

Anchialine pools are land-locked bodies of water of varying salinity, adjacent to the ocean with indirect, underground connections to the sea, and that show tidal fluctuations in water level.

More than half of the world’s known anchialine pools are found in the Hawaiian Islands with the vast majority on the island of Hawai`i – 600+.

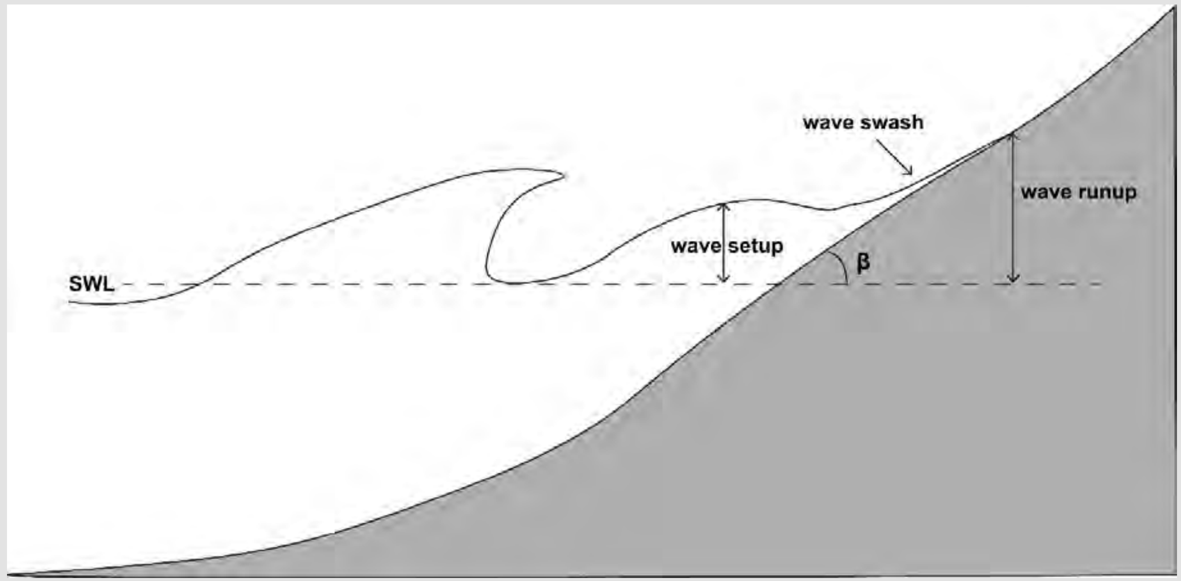
Anchialine pools have their own unique ecosystems populated by rare species including Hawaii’s legendary **red shrimp**.

Threats include contamination of water sources and introduction of alien species, especially alien fish. **Opportunities** exist to create new habitat.

Source NOAA and TNC

Total Water Level

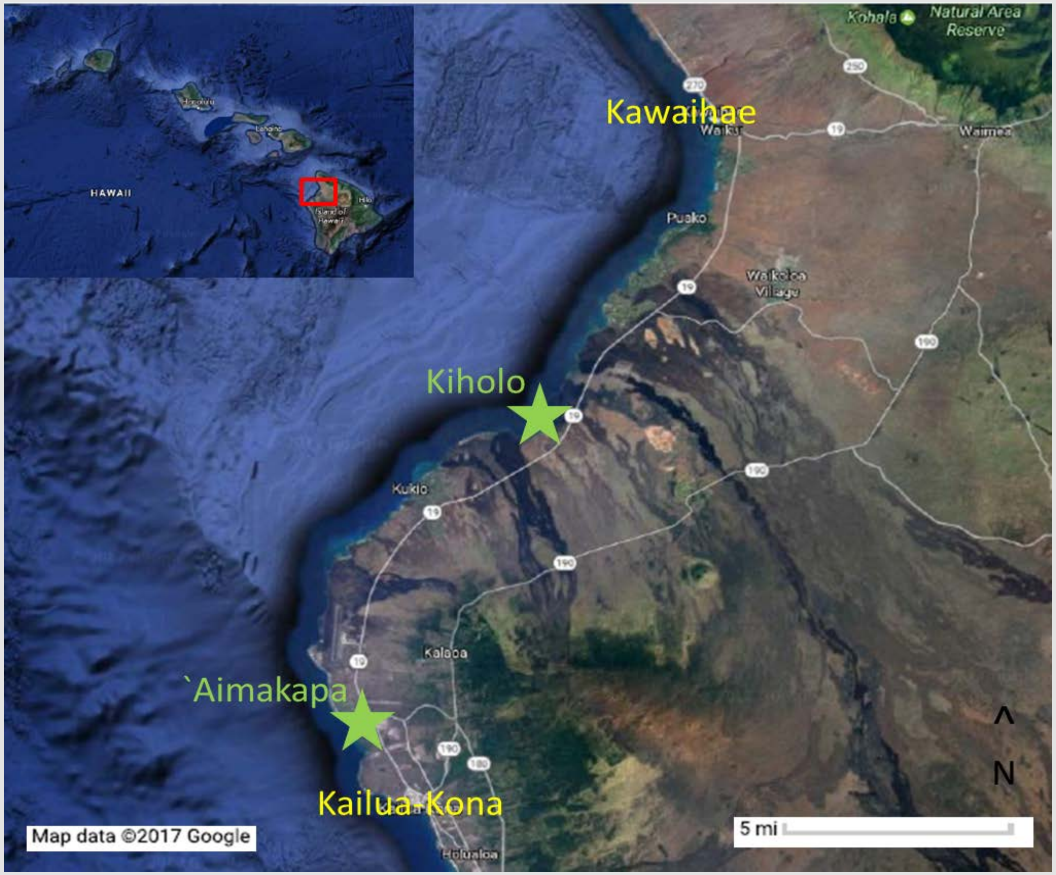
Phenomena
Tropical and Extra-tropical Storms
Wave Runup
Storm Surge
Tidal Fluctuations
Annual to Mult-Decadal Variability
Seasonal Fluctuations
Inter-Annual Fluctuations
Inter-Decadal Fluctuations
Ocean Circulation
Eddies
Gyres
Sea Level Rise
Mass Transfer
Thermal Expansion
Vertical Land Motion
Aseismic Subsidence
Glacial Isostatic Adjustment
Seismic uplift and Coseismic subsidence



The Total Water Level (TWL) **is the Still Water Level** (SWL) **plus wave runup.** Wave runup is the sum of wave setup plus swash; β is the slope of the beach and it, along with beach composition, has as an important influence on the inland extent of flooding. Adapted from Komar et al (1999).

After Marra et al (2012).

Study Area

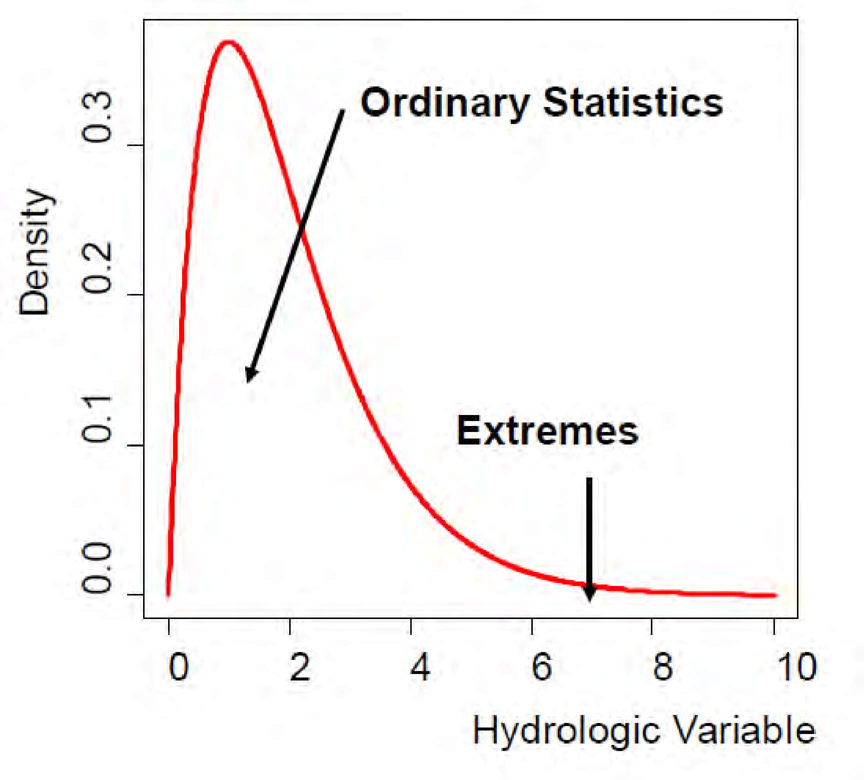


The Kohala-Kona coast of the Island of Hawai`i, from Kawaihae on the north to Kailua-Kona on the south.

Methods and Results

Overall, **the approach taken here can be described as "scenario-based"** - different sources of data are used and different types of analyses are conducted so as to generate a range of results at different time periods that are within scientifically plausible bounds.

Two basic types of analysis were conducted as part of this study:
1) **Analyses of flood extremes** derived from a GEV distribution; and
2) **Analyses of flood frequencies** derived from a normal distribution. The results were used to establish changes in the SWL, the DWL, the TWL, and Extent of Shoreline Retreat at different time periods.



Analysis of Flooding Extremes - SWL

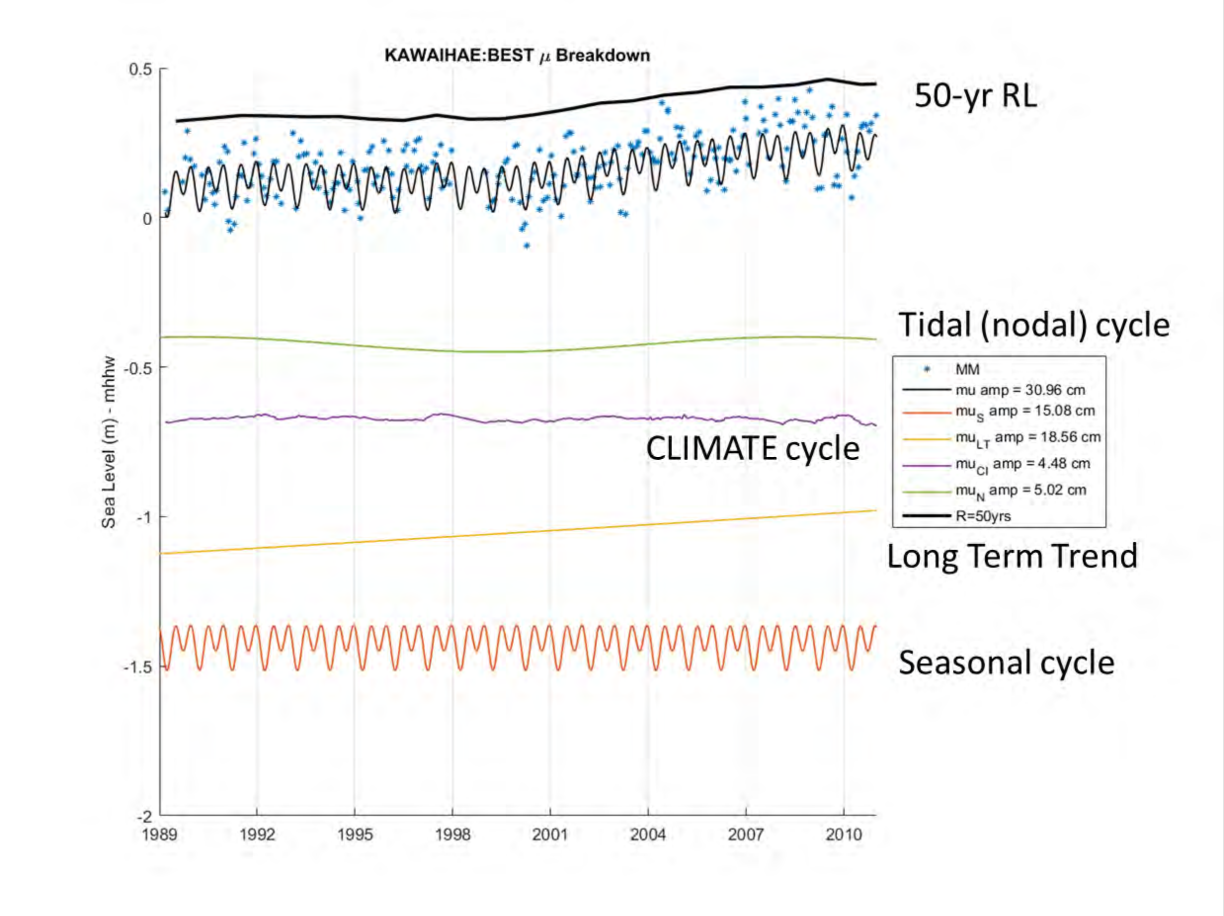
- **Stationary EVA** - Annual Maxima Method (AMM), where the GEV distribution is fitted to the sea-level annual maxima in the Kawaihae tide gauge record.

- **Regional Frequency Analysis** (RFA) - A heterogeneity "H" score determines the homogeneity of different stations data. Once the stations are selected, a local scaling factor ("index event') is used to pool the data from different stations and the results are analyzed using EVA.

SWL ANALYSIS			
		Original	Updated
Timeframes		Present (2005)	Present (2010)
Station-based	RI	MHHW (m)	
Stationary EVA	1yr	--	0.28
	2yr	0.26	0.31
	10yr	0.32	0.36
	25yr	0.34	0.39
trend removed	50yr	0.36	0.41
observed	100yr	0.37	0.42
	RI	MHHW (m)	MHHW (m)
RFA-based	1yr	--	0.25
stationary EVA	2yr	0.26	0.3
	10yr	0.34	0.39
	25yr	0.38	0.43
trend removed	50yr	0.41	0.47
observed	100yr	0.44	0.5

Analysis of Flooding Extremes - SWL

- **Non-Stationary EVA** - time varying approaches employed by Mendez et al. 2007, Menéndez et al. 2009, and Menéndez and Woodworth 2010 among others, that fit a GEV model to monthly tide station maxima so as to decipher long-term tidal cycles, intra-annual seasonal cycles and covariability with climate patterns as well as trends.



Decomposition of the extreme SWL at the Kawaihae tide station.

Analysis of Flooding Extremes - SWL

The **three different analyses** described above generated a range of results that were used **to establish a set of "current" values for SWL elevations** at different return intervals.

Probabilistic projections of **future regional sea level trends** under different greenhouse gas emission scenarios **developed by Kopp et al. (2014) were added to these values** to move them up in height and in time in response to global mean sea level rise.

Scenarios		Extreme Value Return Level (m)	SLC trend (Kopp et al 2014) (m)	Climate Variability (m)	Projected SWL Value (m) MHHW
2025	LOW	0.26	0.15	0	0.4
	HIGH	0.44	0.15	0.02	0.6
2035	LOW	0.26	0.25	0	0.5
	MEDIUM	0.38	0.25	0.02	0.7
	HIGH	0.44	0.35	0.02	0.8
2050	LOW	0.26	0.35	0	0.6
	MEDIUM	0.38	0.35	0.02	0.8
	HIGH	0.44	0.48	0.02	0.9
2080	LOW	0.26	0.57	0	0.8
	MEDIUM	0.38	0.57	0.02	1.0
	HIGH	0.44	1.03	0.02	1.5

Table 2. SWL Scenarios.

LOW, MEDIUM, and HIGH scenarios correspond to roughly once every 1-2 years, once every 25-50 years, and once every 100plus years respectively

Analysis of Flooding Extremes - DWL

Using **the standard deviation of the measurements with the 6 minute segments (i.e., sigma) of tide gauge measurements** Sweet et al. (2015) found a correlation to significant wave height measured in wave buoys. **Adding the sigma to SWL produces a dynamical water level (DWL) that contains a wave component.**

We found the DWL observed in the tide gauge to show reasonable agreement with wave setup calculated by Vitousek et al., 2010 using the dynamical Simulating Waves Nearshore (SWAN) model.

Scenarios		Projected SWL Value (m)	Projected "setup" (m)	Climate Variability (m)	Projected DWL Value (m) MHHW
2025	LOW	0.41	0.4	0	0.8
	HIGH	0.61	0.8	0.18	1.6
2035	LOW	0.51	0.4	0	0.9
	MEDIUM	0.65	0.6	0.18	1.4
	HIGH	0.81	0.8	0.18	1.8
2050	LOW	0.61	0.4	0	1.0
	MEDIUM	0.75	0.6	0.18	1.5
	HIGH	0.94	0.8	0.18	1.9
2080	LOW	0.81	0.4	0	1.2
	MEDIUM	0.97	0.6	0.18	1.8
	HIGH	1.51	0.8	0.18	2.5

Table 3. DWL Scenarios.

Analysis of Flooding Extremes - TWL

Wave generation, transformation, and runup.

Low End - EVA of "Top 3" Deep-water significant wave heights (H_0) per year, within a narrow swell window modeled in SWAN (Vitousek et al., 2010)

High End – EVA of Annual non-directional Deep-water significant wave heights (H_0)

Applied to Stockdon's et al. (2006) "R_2" runup equation for a range of beach slopes and then added to the SWL estimates to generate a TWL

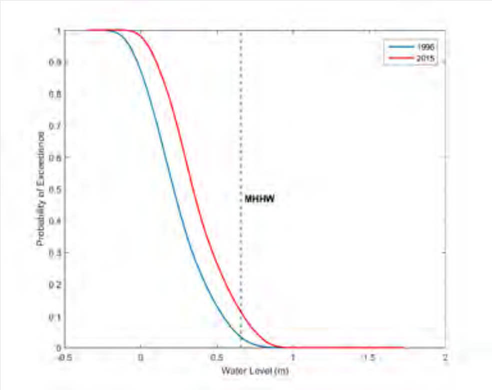
Scenarios		Projected SWL Value (m) MHHW	Projected Runup Value (m)	Projected TWL Value (m) MHHW
2025	LOW	0.41	2.30	2.7
	HIGH	0.61	3.06	3.7
2035	LOW	0.51	2.30	2.8
	MEDIUM	0.65	2.59	3.2
	HIGH	0.81	3.06	3.9
2050	LOW	0.61	2.30	2.9
	MEDIUM	0.75	2.59	3.3
	HIGH	0.94	3.06	4.0
2080	LOW	0.81	2.30	3.1
	MEDIUM	0.97	2.59	3.6
	HIGH	1.51	3.06	4.6

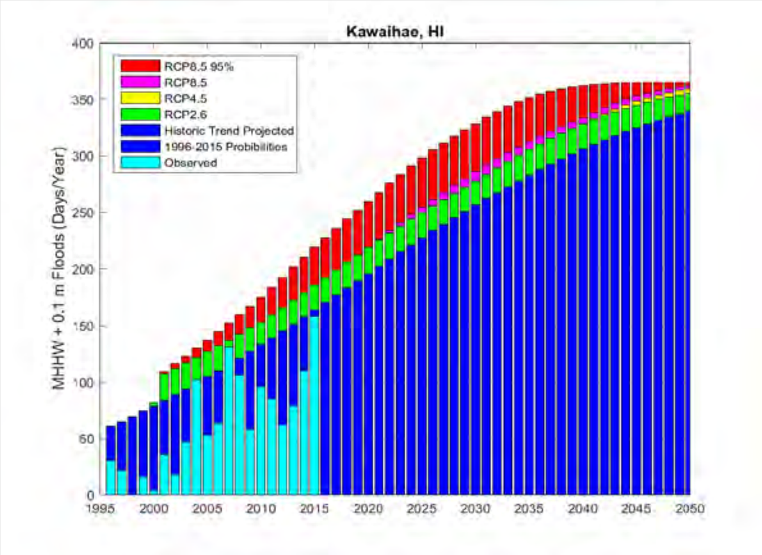
Table 4b. TWL Scenarios at 'Aimakapā.

Analysis of Flood Frequency

One particularly important consequence from rising sea levels is the increased frequency of coastal flooding due to storms, tides, and other climatic forcings.

Similar to Sweet et al. (2014) and Sweet and Park (2014), based on an analyses of flood frequencies derived from a normal distribution we calculated the number of days in a year the daily maximum SWL exceeded a nuisance threshold for a range of regionally adjusted sea level rise projections from Kopp et al. (2014)





Analysis of Flood Frequency

Scenarios		Floods (Days/Year) Threshold = MHHW + 0m	0.1m	0.2m	0.3m	0.4m	0.5m	0.6m	0.7m	0.8m	0.9m	1m
2025	LOW	331	255	148	57	11	1	0	0	0	0	0
	HIGH	351	298	202	98	28	3	0	0	0	0	0
2035	LOW	354	306	214	107	33	4	0	0	0	0	0
	MEDIUM	357	313	224	117	38	6	0	0	0	0	0
	HIGH	364	351	298	202	98	28	3	0	0	0	0
2050	LOW	365	359	322	240	132	47	8	0	0	0	0
	MEDIUM	365	362	333	259	153	61	12	1	0	0	0
	HIGH	365	365	364	347	286	186	85	22	2	0	0
2080	LOW	365	365	365	363	343	277	175	76	18	2	0
	MEDIUM	365	365	365	365	364	350	294	197	93	26	3
	HIGH	365	365	365	365	365	365	365	365	359	322	240

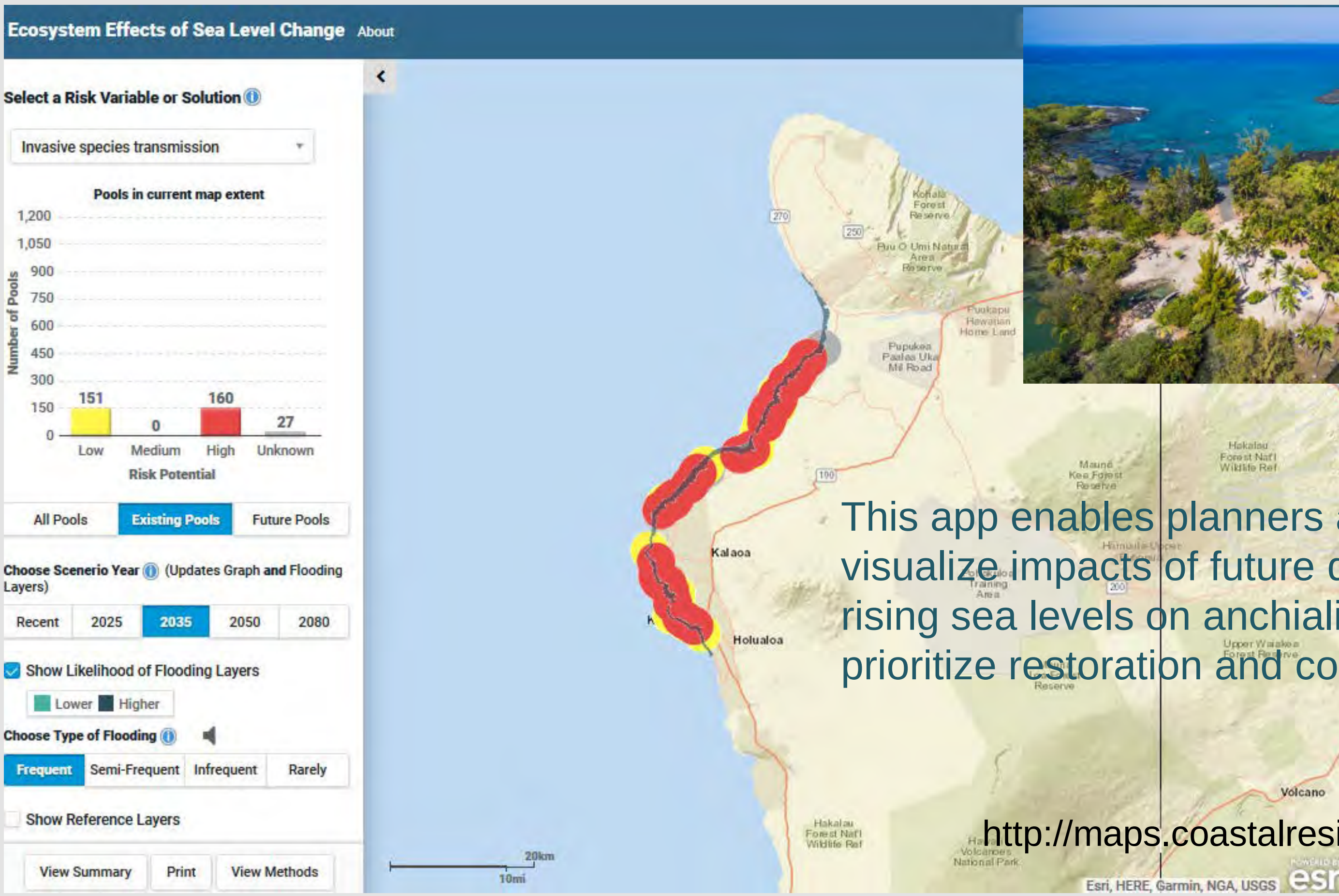
Table 6. Flood Frequency. *Note that MHHW occurs ~180 days a year, or every other day. Also flood elevations are SWL values, so they do not include wave runup. As a result, actual observed flood elevations are expected to be significantly higher.*

The low, medium, and high scenarios correspond to RCP 4.5 Mean, RCP 8.5 Mean, and RCP 8.5 @95% SLR scenarios respectively.

Management Applications

TNC Tool: Ecosystem Effects of Sea Level Change

Kiholo Fishpond.
Source Chad Wiggins, TNC.



This app enables planners and managers to visualize impacts of future development and rising sea levels on anchialine pools to help prioritize restoration and conservation over time.

http://maps.coastalresilience.org/hawaii/#

Summary of Flood Frequency for Application

Ht above MSL (m)		0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	Extremes (m)
2025	LOW	331	255	148	57	11	1	0	0	0	0	0	0.8
	HIGH	351	298	202	98	28	3	0	0	0	0	0	1
2035	LOW	354	306	214	107	33	4	0	0	0	0	0	0.9
	MEDIUM	357	313	224	117	38	6	0	0	0	0	0	1
	HIGH	364	351	298	202	98	28	3	0	0	0	0	1.2
2050	LOW	365	359	322	240	132	47	8	0	0	0	0	1
	MEDIUM	365	362	333	259	153	61	12	1	0	0	0	1.2
	HIGH	365	365	364	347	286	186	85	22	2	0	0	1.4
2080	LOW	365	365	365	363	343	277	175	76	18	2	0	1.2
	MEDIUM	365	365	365	365	364	350	294	197	93	26	3	1.4
	HIGH	365	365	365	365	365	365	365	365	359	322	240	1.9

Elevations that experience flooding daily to every other day. (purple)

Elevations that experience flooding once a week to once a month. (blue)

Elevations that experience flooding once to several times a year. (yellow)

Elevations that flood in extreme SWL events (Once per decade). (red)

Flood frequency used in the TNC EESLR Web Tool. The tool represents a blending of the two analyses.Purple, blue, and yellow colors represent the range of days of flood frequency per year. Extremes are highlighted in red.

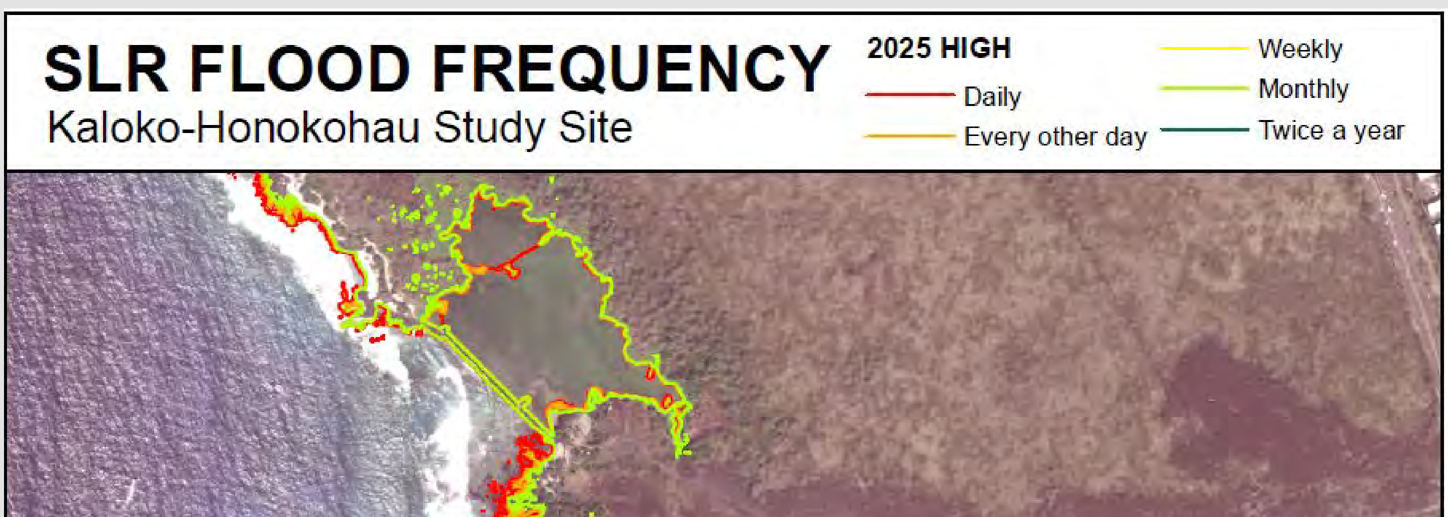
Management Applications

NPS `Aimakapa Fishpond.

Source NPS

Extremes analysis suggests the seawall is overtopped at present under the LOW scenario, and much of the land area southeast flooded by 2025-2035..

Flood frequency analysis suggests the seawall is overtopped monthly by 2025-2035; weekly by 2050?, and at least every other day by 2080



Conclusions

A series of analyses were conducted to evaluate how coastal flood magnitude and frequency might change along a section of shoreline on the Island of Hawai‘i **in response to a changing climate** using a scenario-based approach.

Consistent with results reported elsewhere, changes in flood magnitude track mean sea level trends - high tides and storms will ride the rising seas.

Owing to the nature of the factors affecting coastal flooding along this segment of shoreline, ‘major’ floods are unlikely to change significantly in terms of frequency and magnitude. However, t**he frequency of ‘minor’ floods** (~0.3m or 1 foot above MHHW) **is expected to increase dramatically** under all GMSL scenarios. **What were relatively rare events will quickly become relatively common.**

This suggestion has important implications to resource managers locally, and decision-makers more broadly.

NCEI

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