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Sea level rise risk interactions with coastal property values: a case study of Oʻahu, Hawaiʻi

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Abstract

Climate change-induced sea level rise (SLR) will affect a range of coastal assets and prompt difficult decisions about coastal land use across the world. Several recent studies find that current and projected SLR is associated with relatively lower property values. We contribute to this growing body of research with a case study of Oʻahu, Hawaiʻi, which is famed for its beaches as well as valuable coastal real estate. We leverage a dataset that unpacks multiple types of SLR exposure and coastal parcel attributes. We apply property transaction data for the island of Oʻahu through 2019 to investigate the effect of current and expected SLR exposure on residential property prices. We find that exposed properties have already experienced declines in transaction prices, at 9 to 14%, attributed to expectations of exposure to chronic inundation (as opposed to seasonal flooding). The price declines are mainly for multi-dwelling homes as opposed to single family homes. The market response of residential properties to SLR has important implications for coastal management strategies, in particular the viability and timing of programs for retreat.

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1 Introduction

Climate change-induced sea level rise (SLR) will dramatically affect coastal communities and ecosystems across the world (IPCC 2021). The IPCC (2021) predicts a range of expected mean SLR by 2100 under a set of shared socio-economic pathways, ranging from 0.28 to 0.55 m under very low emissions scenarios to 0.63–1.01 m under business-as-usual emissions, with even higher values possible due to uncertainties in ice-sheet dynamics. An early and growing body of literature has explored how real estate markets are responding to climate change in the US context (Bakkensen and Barrage 2017; Bunten and Kahn 2014; Gibson and Mullins 2020; Hino and Burke 2021; Keenan et al. 2018; Walsh et al. 2019). Several studies investigate whether and the extent to which coastal properties are losing value as a result of current and expected SLR (Bernstein et al. 2019; Baldauf et al. 2020; Murfin and Spiegel 2020; Tyndall 2021). Bernstein et al. (2019) is the most spatially comprehensive US study to date. It uses residential real estate transactions data between 2007 and 2019 and found an average 7% decline in coastal properties that will be exposed to 6 ft. of SLR (as defined by NOAA, Marcy et al. 2011). Several US regional case studies illustrate variation in local market response (Catma 2021; McAlpine and Porter 2018; Tyndall 2021; Walsh et al. 2019) and therefore the importance of understanding place-based housing market dynamics for the purposes of informing local climate adaptation policy.

Our hedonic study — comparing properties of the same type and attributes in the same neighborhood with similar distance from the coastline and elevation — contributes to this growing body of literature by adding a case study of O'ahu, Hawai'i. We use available housing transaction data going back to 1994, and find that SLR impacts are becoming increasingly salient within O'ahu's housing market. Using a near-term time period, from 2014 to 2019, when SLR impacts would be more widely understood, we find that residential properties identified within a 1-m SLR exposure risk area were associated with a 9 to 14% transaction price discount. We find that the measured SLR discount is driven by impacts to multi-dwelling residences.

2 Prior work on SLR, flooding, and real estate values

Bernstein et al. (2019) national study found that the 7% decline in average home values exposed to SLR was driven almost entirely by non-owner occupied homes. Murfin and Spiegel (2020), in a study of single-family homes and duplexes, on the other hand, found no effect on housing price from SLR exposure. Tyndall (2021) found a relative year-to-year property price decline of 1.4% using real estate transactions from 2000 to 2017 for Long Island. Early studies suggest that there is likely to be considerable regional variation in how SLR affects real estate markets across the USA.

Numerous empirical analyses focus on Florida because of its particular vulnerability to SLR (Keenan et al. 2018; McAlpine and Porter 2018; Conyers et al. 2019; Keys and Mulder 2020). Keys and Mulder (2020) found that housing in SLR-exposed communities across the state experienced a 5% discount between 2018 and 2020, with no price effect in the 5 years previous, even as sales volume declined 16–20% from 2013 to 2018. Conyers et al. (2019), using a SLR vulnerability measure based on levels of exposure and readiness, found SLR was not priced into the local Miami-Dade County housing market, arguing that real estate professionals failed to disclose the predicted effects

of SLR. A survey of realtors in the city found a majority of buyers did not ask about climate change when purchasing property (Bendixen and Amandi International 2017). Keenan et al. (2018) found that higher elevation properties within flood prone areas experienced higher rates of appreciation, indicating Miami has also been experiencing "climate gentrification." Between 2005 and 2016, the Miami-Dade real estate market was estimated to have lost $465 million from SLR-affected inundation risk (McAlpine and Porter 2018). Expanding their hedonic work to other locations in a First Street Foundation (2019) report, McAlpine and Porter found a $15.9 billion loss in SLR-exposed home values across the 18 coastal states along the East Coast and Gulf Coast, with Florida and New Jersey having the greatest loss at $5.4 B and $4.5 B, respectively. Their methodology was used in the creation of the First Street Foundation Flood Model underlying Flood Factor (First Street Foundation 2019), a communicator of proper flood risk for homeowners in the continental USA.

Information and individual beliefs surrounding flood and SLR exposure play a role in determining whether inundation risk is properly incorporated into housing prices (Bakkensen and Barrage 2017; Baldauf et al. 2020; Gibson and Mullins 2020; Hino and Burke 2021). Hino and Burke (2021) examined the national market of flood zone housing and found a $43.8 billion overvaluation based on publicly available flood hazard maps. Even if flood risk information is available, beliefs about climate change may preclude some homeowners from internalizing risk (Bakkensen and Barrage 2017). A survey by Palm and Bolsen (2020) found that while South Florida residents in flood-prone areas did, in general, believe that climate change is occurring and anthropogenic, they did not believe their homes were at risk or that their property values were vulnerable to SLR. Furthermore, the study found that individual's exposure within flood maps may reduce belief in climate change and belief that SLR threatens their property's value. Owner-occupied properties have been found to be discounted in line with local concerns about SLR, while sophisticated investors tend to account for SLR risk regardless of beliefs (Bernstein et al. 2019; Giglio et al. 2021). Heterogeneity in climate change and SLR risk beliefs has been found to correlate with believers often selling to non-believers (Bunten and Kahn 2014; Bakkensen and Barrage 2017).

Along with typical explanatory variables for housing prices, like property size and the number of bedrooms that are contained in all hedonic models, additional variables are important to capturing characteristics of coastal properties in particular. Waterfront properties, and those with proximity to the beach or the coastline, have been found to command a premium (Bin et al. 2008, 2011; Krause 2014; Jin et al. 2015; Dumm et al. 2016; Walsh et al. 2019). Jin et al. (2015) compiled 17 studies in this area, with all but one finding a significant negative relationship between home price and increasing distance from the water or beach. Dumm et al. (2016) found waterfront properties had a 7% premium in Tampa Bay, Florida, during the 2000 to 2012 time period. On the other hand, houses in recently flooded areas are found to experience a discount, even if short-lived (Bin and Landry 2012; Atreya et al. 2013). In addition, coastal homes experiencing flooding may resort to armoring with seawalls or other structures, which have been found to have mixed effects on waterfront property values. Walsh et al. (2019) found a positive interaction for 0–2 ft SLR zone properties with bulkheads in Chesapeake Bay, while Brucal and Lynham (2020) found no strong evidence that seawalls were positively related to protected home values in a study of Santa Cruz and San Diego counties. Lastly, SLR can interact with other types of coastal risks to exacerbate hazards, including the presence of on-site disposal systems (OSDS, i.e., cesspools and septics) (Habel et al. 2017; Mezzacapo et al. 2020).

3 Brief context of shoreline considerations for Oʻahu, Hawaiʻi

The Hawaiian Islands naturally erode into the Pacific Ocean, but the phenomenon is accelerated by SLR and shoreline infrastructure. Over 29% of Oʻahu's sandy shoreline is already hardened, with 61% eroding as of 2020 (Tavares et al. 2020). The proportion of eroding beaches is projected to increase to 80% and 89% with 0.25 m and 0.74 m of SLR, respectively (Tavares et al. 2020).

The shoreline in Hawaiʻi, legally classified as a public trust resource in the State constitution, is marked by the high wash of seasonal waves. This definition came about through a series of Hawaiʻi Supreme Court decisions, which cited Native Hawaiian tradition and customs (Sproat 2009; Vance and Wallsgrove 2006). Beaches in Hawaiʻi hold a wide range of uses and values including, for example, nearshore and onshore recreation, subsistence, tourism, cultural and historical significance, and ecological functions (Bremer et al. 2022). Although the public in Hawaiʻi enjoys strong beach access rights (Vance and Wallsgrove 2006), the disappearing shoreline along many sections of sandy coastline can make traversal difficult and often impossible. As beaches erode, waves wash increasingly inland, sometimes extending State jurisdiction landward to the point where private land becomes public. This leads many homeowners to attempt to protect their private property, often illegally, by using land protection measures such as moving sand or building seawalls (Cocke 2014, 2020a, b, 2021).

A compounding public health impact of SLR is the inundation of OSDS (Whittier and El-Kadi 2014; Habel et al. 2017). A large amount of waste disposal on Oʻahu occurs on-site and nearly 1500 OSDS are located within 200 ft of the shoreline; over 75% of total OSDS were cesspools as of 2014 (Whittier and El-Kadi 2014). State tax credits of up to $10,000 for homeowner cesspool upgrades were passed in 2015 (Act 120, 2015) and expanded in 2017 (Act 125, 2017). Upgrading every cesspool in the state, a legal requirement by 2050, is estimated to cost $2B at an average of $23,000 each (Act 125, 2017; State of Hawaiʻi Department of Health, 2021).

4 Data and methods

This study's methods build upon the body of literature evaluating the impacts of SLR exposure on residential property values. A contribution of our study is that we employ more comprehensive measures of SLR impacts than what are typically applied in the literature. In addition to the impacts of expected passive flooding on current property values that have been used in other studies (Bernstein et al. 2019; Murfin and Spiegel 2020; Tyndall 2021), we use projections of expected annual high wave run-up and exacerbated coastal erosion. The hedonic model also controls for other important aspects of coastal property values on Oʻahu: OSDS, seawalls (both on the property and adjacent properties), sandy beachfronts (in comparison to rocky coastline), and waterways that are also impacted by SLR-induced flooding (like canals).

4.1 Data

4.1.1 Sea level rise data

We employ two different datasets for SLR. The first was developed by the Hawaiʻi Climate Change Mitigation and Adaptation Commission (2021) and represents 3.2 ft of SLR in a
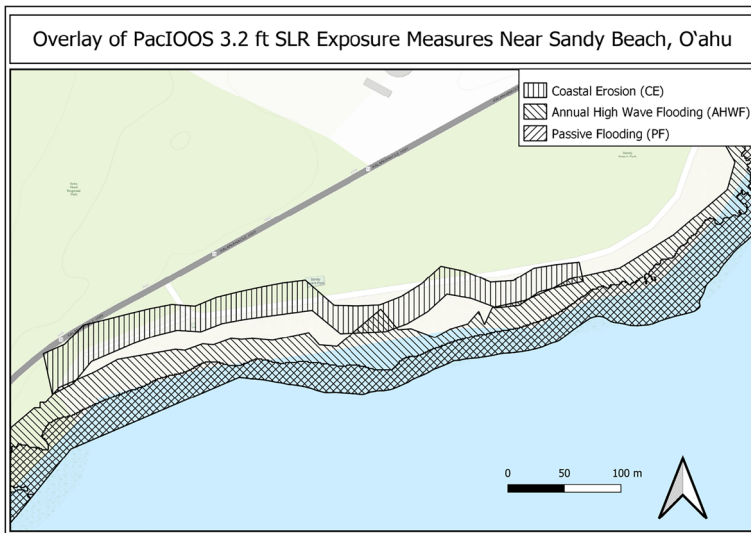
Fig. 1 Visualization of PacIOOS SLR attributes

passive flooding ("bathtub") model (called SLR-PF) along with separable projections for expected coastal erosion and high wave run-up. Annual high wave flooding (called SLR-AHWF) estimates average annual exposure to wave activity and its inland migration with SLR (Anderson et al. 2018). Coastal erosion (called SLR-CE) measures the exacerbated erosion of sandy beaches based on historical beach erosion patterns and projected inland migration under SLR.[1] A comprehensive measure (called SLR-XA) is the greatest boundary of all three (Anderson et al. 2018). We identify a parcel to be affected by SLR if more than 30% of its area is projected to be inundated.[2] Figure 1 shows each attribute's projections under 3.2 ft of SLR and Fig. 2 visualizes the percentage of exposed coastal properties.

Figure 1 illustrates how the three main PacIOOS SLR definitions interact and in some cases overlap using Sandy Beach on Oʻahu as a representative stretch of coastline.

Figure 2 displays the percentage of TMK parcels within .25 miles of the coastline (coastal only sample) which are exposed to the PacIOOS 3.2 ft SLR-XA measure for each census tract on Oʻahu. These percentages are calculated based on exposed parcels rather than properties, so multi-family dwellings and apartment buildings are counted as single parcels in this illustration.

The second SLR dataset we use is from NOAA, which measures passive flooding up to 6 ft (Marcy et al. 2011). We use this to compare our analysis to prior work as well as higher projections of SLR.

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[1] This modeling is done only for sandy beachfront areas and ignores the existence of seawalls (University of Hawaiʻi Coastal Geology Group and Tetra Tech Inc., 2017).

[2] In sensitivity analysis, we look at a range of cutoffs for identifying parcels as "inundated by SLR," from 10 to 50%. As expected, a lower cut-off narrows the sample size substantially while a higher cut-off puts too many parcels that are substantially impacted by SLR into the control group. As a second robustness check, we also looked at other definitions of inundation, such as the inundation of the centerpoint of the parcel. Results are qualitatively similar.
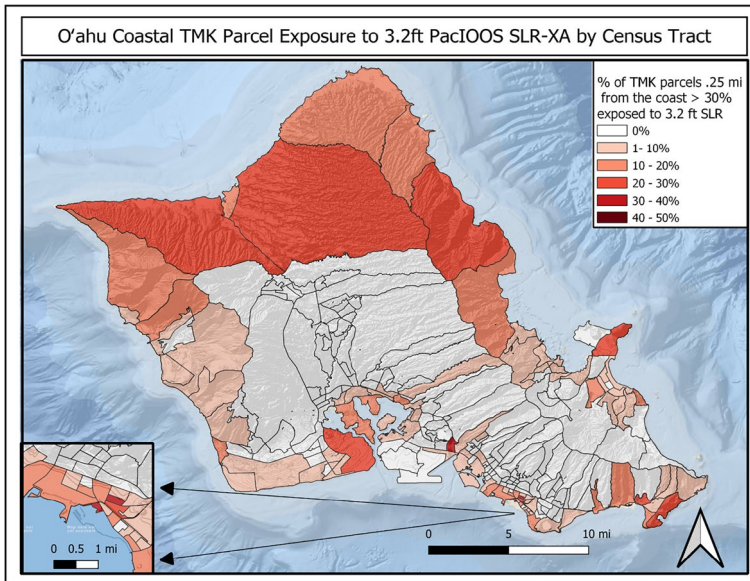
Fig. 2 Share of the parcels within .25 miles from the coastline that are exposed to 3.2 ft SLR-XA

4.1.2 Housing characteristics data

Our housing transaction price data comes from Zillow (ZTRAX), provided from 1994 to 2019, and is illustrated in Fig. 3. The ZTRAX dataset contains basic property and building attributes including square footage, building age, number of bedrooms, transaction date, and sale price for each transacted property.

imilar to prior studies like Keys and Mulder (2020), we separate our analysis into several time periods. Though we have data going back to 1994, we use a main specification from 2014 to 2019 (and do sensitivity analysis around this cutoff). We decided on the time period from 2014 for two reasons. The first is that IPCC AR5 was published in 2014, drawing increased attention to SLR. The second, perhaps a reflection of the first, is that there was an increased magnitude of Google searches for "sea level rise" starting in 2014, both nationwide and in Hawai'i (Google Trends (n.d)).

We add data relating to the presence of seawalls, FEMA flood zones, OSDS, proximity to the coast, and whether the coast has a sandy beach. Data on OSDS were collected from this Statewide GIS Program and included locations of OSDS across O'ahu as of 2010. The FEMA flood zone data, last updated for 2021, was similarly sourced from the Hawai'i Statewide GIS Program. We employ a shapefile of shoreline armoring across O'ahu compiled through satellite photography analysis (Romine 2013; Romine and Fletcher 2012; Romine and Fletcher 2013) and updated by site visits as part of unpublished research by Amaya et al. (2021).[3]

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[3] Amaya, A., Brucal, A., and Lynham, J. (2021) Beggar-thy-neighbor's beach: The social cost of adaptation to sea-level rise. Unpublished manuscript. Properties neighboring seawall installations (though not protected themselves) were identified by applying 20 m buffers to the seawall geometries and selecting properties which are within these buffer zones yet not protected by seawalls themselves.
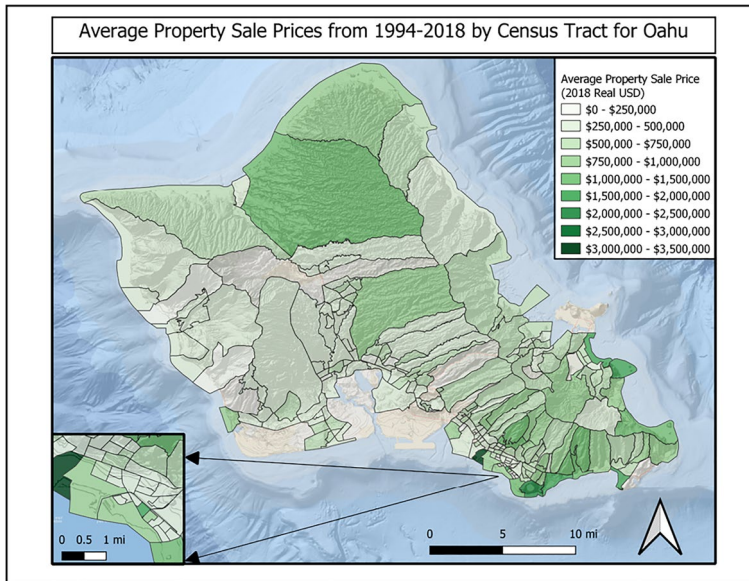
Fig. 3 Average property transaction prices in 1994–2018 (inflation-adjusted) by census tract on Oʻahu

4.1.3 Data compilation and descriptive statistics

To better control for the premium placed on Oʻahu properties near sandy beachfront areas, we create two samples as well as several additional variables. Our two samples are *coastal* and *coastal + waterway*. In our *coastal* sample, we include all properties within 0.25 miles of the physical coastline of Oʻahu. In our *coastal + waterway* sample, we include the *coastal* sample as well as parcels that are within 0.25 miles of SLR impacted waterways, such as canals and ocean-connected marsh areas. Figure 4 illustrates an example of an urban waterway in the area around Waikīkī, Oʻahu, with 1 m of SLR flooding. The "study area boundary" represents the quarter mile buffer area.

The additional variables created to help control for the price premiums placed on beach and waterfront adjacent housing include indicators for *waterfront*, *beachfront*, and *non-coastal* properties. *Waterfront* properties are identified as any parcels that lie within a 50-m buffer zone surrounding Oʻahu's physical coastline. *Beachfront* properties are similarly identified as parcels that lie within 50- and 100-m buffer zones drawn around sandy beaches. *Non-coastal* properties are identified in the *coastal + waterway* sample as those which are at least 85 m closer to the nearest waterway than to the nearest stretch of coastline.[4] Lastly, we also use an *ocean view* variable (provided by Zillow's ZTRAX dataset) that describes whether each property has a clear view of the ocean.

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[4] We chose 85 m as the identification threshold for *Non-coastal* properties by testing thresholds between 20 and 105 m at 5-m intervals for model performance and identification strength. From this testing, we found that 85 m performed best as a *Non-coastal* identification threshold in terms of model R^2 values, though the magnitude and statistical significance of our primary results were confirmed to be highly robust to the use of different identification thresholds for *Non-coastal* properties.
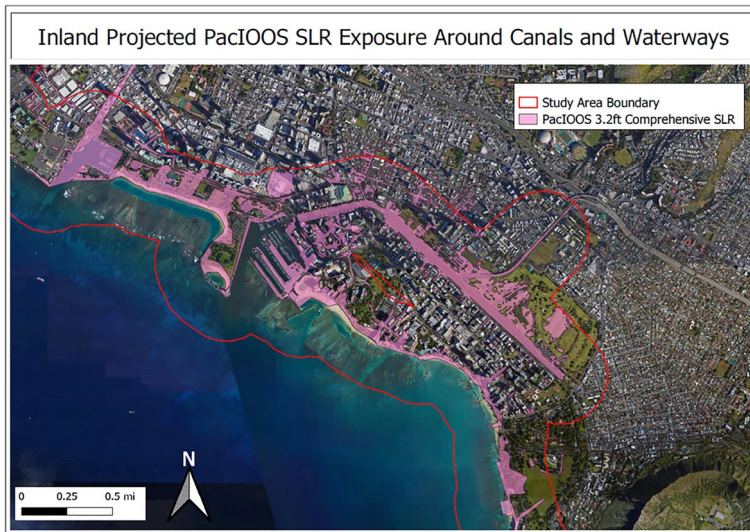
Fig. 4 3.2 feet SLR exposure along the coastline and the canal around Waikīkī, Oʻahu

Table 1 provides the descriptive statistics by SLR exposure as measured by SLR-XA. for all variables used within the main hedonic analysis (sample 2014–2019), and Table 2 breaks the same data apart by SLR exposure (as measured by SLR-XA).

The average sale price of a single-family property on Oʻahu from 2014 to 2019 was $1.28 million (*coastal + waterway* sample), and multi-family dwelling units had a lower average sale price, at $650,000 (see Supplementary Information). Our sample transactions are 37% for single family homes, the remainder for multi-family. The transaction prices within the smaller *coastal* sample are quite similar in their range. In addition, about a fifth of properties in our sample have an ocean view. Within the *coastal* sample, 16% of properties are adjacent to a sandy beach (beach front). About 5% of properties in the *coastal* sample have a seawall, and 6% of properties that lack a seawall have at least one neighbor with one. Lastly, 6% of properties in the *coastal* and 4% in the *coastal + waterway* samples have OSDS. As Table 1 indicates, the *coastal + waterway* sample includes transactions of houses that are more than 1.8 miles (2.9km) away from the coast but are within 0.25 miles from the nearest waterway. This sample captures many SLR-exposed transactions that the conventional coastal sample does not contain.

Table 2 further illustrates the distinctions between our *coastal* and *coastal + waterway* samples. The mean and standard deviation values for each variable differ in both samples between properties which are exposed to PacIOOS 3.2ft comprehensive SLR (SLR-XA) and those which are not exposed. Additional *t*-tests have been conducted to determine whether the differences between the exposed and non-exposed means can be considered statistically significant.

The mean sales price for SLR-exposed properties is higher in both of our samples, in comparison to unexposed properties, with the difference being statistically significant at the 5% level for the *coastal + waterway* sample. The transaction price of single-family homes tends to be higher for those exposed to SLR than those unexposed. The opposite holds for multi-family (apartment) units: those exposed to SLR are priced lower on average than those unexposed (see Supplementary Information). Aside from climate change-related risks, homes closer to

Table 1 Descriptive statistics (2014–2019)

	Coastal				Coastal + Waterway			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Sales Price (USD)	897,616	1,298,059	50,000	25,527,300	771,233	1,042,409	50,000	25,527,300
Sales Price (2018USD)	935,453	1,345,242	50,000	27,458,680	805,572	1,082,323	50,000	27,458,680
Sq. footage	1,383	1,020	360	17,408	1,182	845	315	17,408
Single-Family	0.37		0	1	0.25		0	1
#bedrooms	2.52	1.35	1	13	2.21	1.22	1	14
Age (years)	40.6	18.5	1	102	38.3	18.1	1	108
Dist. from coast (m)	192.5	113.9	0.016	402.1	452.8	399.3	0.016	2901.5
Elevation (m)	5.42	7.75	-0.01	101.3	4.62	7.23	-0.01	109.7
Ocean view	0.12		0	1	0.13		0	1
Cesspool	0.05		0	1	0.035		0	1
Flood zone	0.27		0	1	0.4		0	1
Water front	0.19		0	1	0.11		0	1
Beach front (50m)	0.11		0	1	0.06		0	1
Beach front (100m)	0.16		0	1	0.084		0	1
Seawall	0.049		0	1	0.026		0	1
Neighbor with seawalls	0.056		0	1	0.03		0	1
Observations	7,679				14,539			

Table 1 illustrates the differences in property attributes between transacted properties within 0.25 miles of the coast (coastal only) and transacted properties within 0.25 miles of either the coast or the nearest SLR-exposed waterway (coastal + waterway). Single-family (=1 for single-family units; =0 for multi-family or apartment units), ocean view, cesspool (presence of onsite cesspool), flood zone (whether the parcel belongs to the 1-percent-annual-chance flood event as classified by FEMA), waterfront, beach front (proximity to a sandy beach within 50m or 100m), seawall, and neighbor seawalls (the parcel does not face seawalls but its neighbor within 20m does) are indicator variables. These samples consist of property transactions priced between $50,000 and $50,000,000

the beach tend to be more valuable (Atreya and Czajkowski 2019; Conroy and Milosch 2011; Tyndall 2021). Other housing attributes (building square footage and the number of bedrooms) as well as coastal risk factors demonstrate statistically significant differences between exposed and non-exposed properties within our two samples. Notably, a higher proportion of the properties exposed to 3.2 ft SLR are in the flood zone, in the waterfront, and have seawalls. They also tend to have a smaller square footage and fewer bedrooms. There are multiple potential explanations for this, including simply a response to higher prices. These basic statistical observations of our datasets indicate the need to control for observable differences when estimating the price differences between SLR-exposed and non-exposed properties.

Lastly, Fig. 5 shows the proportion of transacted properties in our main study period (2014–2019) that are exposed to SLR as estimated by the NOAA data. In both *coastal* only and *coastal + waterway* samples, approximately 10% of transacted properties are exposed with 3 ft of SLR, jumping to 36% and 51%, for the *coastal* and *coastal + waterway* samples, respectively, when SLR reaches 6 ft.

4.2 Identification strategy

Our basic hedonic model controls for housing value characteristics to isolate the measure of exposure to SLR:

$$\ln P_{it} = \beta SLRE_i + X_{it}\gamma_x + \mu_b + \varepsilon_{it} \tag{1}$$

The variable P_{it} represents the price of property i in transaction year t; *SLRE* is a time invariant binary indicator that represents expected exposure to SLR (1 if parcel i is exposed; 0 otherwise). The vector X_{it} represents the property characteristics (property

**Table 2** SLR exposure descriptive statistics (2014–2019)

	Coastal			Coastal + Waterway		
	Not exposed	Exposed	Difference	Not exposed	Exposed	Difference
Sales Price (USD)	893,920	907,971	-14,052	760,155	826,794	-66,639**
	(1,277,880)	(1,353,261)	(-0.41)	(994,557)	(1,253,946)	(-2.46)
Sales Price (2018USD)	932,097	944,852	-12,755	794,643	860,382	-65,738**
	(1,325,022)	(1,400,626)	(-0.36)	(1,033,665)	(1,298,017)	(-2.35)
Sq. footage	1472.95	1131.78	341.2***	1199.81	1093.45	106.4***
	(1,007.50)	(1,013.30)	(13.01)	(824.30)	(938.32)	(5.19)
Single-Family	0.42	0.24	0.18***	0.25	0.21	0.045***
	(0.49)	(0.43)	(15.19)	(0.44)	(0.41)	(4.90)
#bedrooms	2.7	2.01	0.69***	2.27	1.94	0.33***
	(1.33)	(1.26)	(20.89)	(1.22)	(1.20)	(12.16)
Age (years)	38.81	45.71	-6.90***	36.83	45.61	-8.78***
	(19.05)	(15.62)	(-16.06)	(18.33)	(14.86)	(-25.44)
Dist. from coast (m)	208.6	147.44	61.2***	499.85	217.08	282.8***
	(106.80)	(120.82)	(20.12)	(411.94)	(203.23)	(50.72)
Elevation (m)	6.46	2.5	3.96***	5.09	2.26	2.83***
	(8.76)	(1.44)	(32.82)	(7.81)	(1.43)	(36.95)
Ocean view	0.11	0.15	-0.044***	0.13	0.16	-0.029***
	(0.31)	(0.36)	(-4.97)	(0.33)	(0.36)	(-3.70)
Cesspool	0.05	0.04	0.013**	0.04	0.03	0.0024
	(0.23)	(0.20)	(2.54)	(0.19)	(0.18)	(0.59)
Flood zone	0.18	0.51	-0.33***	0.37	0.56	-0.19***
	(0.38)	(0.50)	(-26.97)	(0.48)	(0.50)	(-17.02)
Water front	0.15	0.3	-0.14***	0.08	0.25	-0.17***
	(0.36)	(0.46)	(-12.84)	(0.27)	(0.43)	(-18.70)
Beach front (50m)	0.07	0.24	-0.18***	0.03	0.2	-0.17***
	(0.25)	(0.43)	(-17.46)	(0.17)	(0.40)	(-20.64)
Beach front (100m)	0.12	0.28	-0.16***	0.05	0.23	-0.18***
	(0.32)	(0.45)	(-15.06)	(0.23)	(0.42)	(-20.27)
Seawall	0.01	0.16	-0.16***	0	0.14	-0.13***
	(0.09)	(0.37)	(-18.83)	(0.06)	(0.34)	(-19.07)
Neighbor with seawalls	0.05	0.08	-0.036***	0.02	0.07	-0.047***
	(0.21)	(0.28)	(-5.32)	(0.15)	(0.25)	(-8.87)
Observations	5,659	2,020	7,679	12,122	2,417	14,539

"Exposed" ("Not Exposed") represents the transactions of properties that are exposed (not exposed) to 3.2ft SLR-XA. Standard deviations in parentheses for "Not Exposed" and "Exposed"; t statistic in parentheses for "Difference." The property prices are not adjusted for inflation. *$p<0.1$, **$p<0.05$, ***$p<0.01$. Single-family (=1 for single-family units; =0 for multi-family or apartment units), ocean view, cesspool (presence of onsite cesspool), flood zone (whether the parcel belongs to the 1-percent-annual-chance flood event as classified by FEMA), waterfront, beach front (proximity to a sandy beach within 50m or 100m), seawall, and neighbor seawalls (the parcel does not face seawalls but its neighbor within 20m does) are indicator variables. These samples consist of property transactions priced between $50,000 and $50,000,000

size, the age of the house, the number of bedrooms), and ε_{it} the error term. As in Bernstein et al. (2019),[5] we introduce the variables μ_b to classify each transaction into a

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[5] Unlike Bernstein et al. (2019), we are unable to account for either climate change beliefs or investor/owner-occupied homes. Because we are using data within only one county, and we do not have survey data mirroring home transactions, the role of beliefs is unfortunately outside the abilities of our analysis. For investor/owner-occupied homes, our limitation is related to the ZTRAX database for Hawai'i. This field has numerous incomplete data entries and dropping these observations would give us an untenably small sample size. Other regional studies, such as Tyndall (2021), are also unable to incorporate beliefs and do not separate investor-owned properties from owner-occupied ones. Table A2 in our Supplementary Information summarizes the estimation result when the sample is limited to those zip code areas without recent disaster events.

Fig. 5 NOAA SLR exposure statistics for transacted properties (2014–2019)
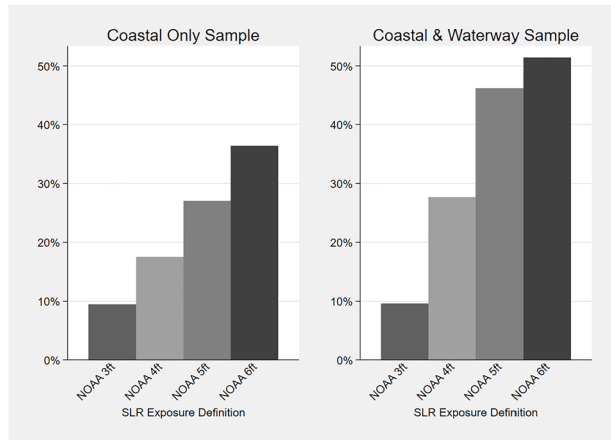
bin defined by the interaction of dummy variables that help us identify the effects of SLR exposure on the transaction price. They consist of the interactions of property type (single vs. multi-family), the year in which transaction took place, location (zip code), elevation (0m, 2m, 4m, 6m, 8m, and above), and the distance from the coastline (0m, 16m, 32m, 64m, 128m, 256m).[6]

A potential threat to our identification method is that *SLRE* may capture coastal attributes of the properties that are distinct from the SLR risks. For example, properties subject to SLR may be waterfront or close to sandy beaches, which would likely raise the property value. In addition, the presence of shoreline hardening may also affect the property value. Thus our next two models address additional coastal amenities and risk factors to improve identification by more fully accounting for factors that affect coastal real estate values in Hawai'i:

$$\ln P_{it} = \beta SLRE_i + R_{1i}\gamma_r + X_{it}\gamma_x + \mu_b + \varepsilon_{it}, \tag{2}$$

$$\ln P_{it} = \beta SLRE_i + R_{1i}\gamma_r + R_{2i}\beta_2 + X_{it}\gamma_x + \mu_b + \varepsilon_{it}, \tag{3}$$

where R_{1i} represents the presence of *ocean view*, the presence of a *cesspool*, whether the parcel is located in a FEMA *flood zone*, whether the property is *water front*, and whether the property is *beach front* (i.e., whether the property is located within 50m or 100m of a sandy beach). Vector R_{2i} indicates whether the property has a *seawall* and whether a property without a seawall has a *neighbor with seawalls*.

$$\ln P_{it} = \beta SLRE_i + R_{1i}\gamma_r + R_{2i}\beta_2 + \left(SLRE_i * R_{2i}\right)\beta_3 + \beta_4 * \left(SLRE_i * SF_{it}\right)X_{it}\gamma_x + \mu_b + \varepsilon_{it}, \tag{4}$$

In our last specification, we add an interaction term between SLR exposure and the sea wall indicator, as well as the property type (single family housing) indicator *SF*. For all specifications, we cluster the standard errors at the zip code level.

With these four model specifications, we use several different assumptions about SLR exposure. In the first, we measure SLR exposure by the SLR-XA, meaning the union of

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[6] The indicator for investor-owned versus primary residence is not used because it has many missing observations in the ZTRAX data.

passive flooding, wave run-up, and coastal erosion. Next we unpack these different types of SLR risks and hazards (into SLR-PF, SLR-AHWF, and SLR-CE). We also make runs only with NOAA's passive flooding measure of SLR, and increase in one foot increments from 3 to 6 ft. Lastly, we estimate model (3) for different time periods going back to 1994.

5 Results

5.1 Results with and without coastal risk factors

Table 3 lists the main regression results of models (1), (2), and (3) by using SLR-XA 3.2ft as the measurement of SLR exposure.

The result of model (1), which follows the identification strategy by Bernstein et al. (2019) and includes distance, elevation, neighborhood, and transaction-year bins, fails to find a statistical relationship between our measure of SLR exposure and transaction prices (in either the *coastal* or *coastal + waterway* samples).

Models (2) and (3) demonstrate that, once we incorporate other coastal risk factors, there is a statistically measurable relationship between SLR and transaction price, for both the *coastal* and *coastal + waterway* samples. Whereas there is a negative 10–12% estimate in the *coastal* sample, it is larger, negative 13–15%, in the *coastal + waterway* sample. The magnitude of the effects of SLR exposure on the property price is comparable to the estimates by Bernstein et al. (2019) (i.e., about −0.14 for 2–3ft SLR and about −0.075 for 4–5ft SLR).

We find that coastal attributes such as being water- and/or beachfront, as well as having an ocean view, are positive and statistically significant. We find some evidence of a relationship between the parcel having a seawall, and it is positive with a large magnitude (45%), though only significant at the 10% level in model (2), *coastal + waterway* sample. This finding, though not consistent through model specifications, suggests that the private economic incentive to harden the shoreline in the face of SLR could be substantially large. However, we do not detect negative spillover effects of neighbors' seawalls on the property prices.

We find across both samples of models (2) and (3) that the presence of OSDS has a statistically significant negative relationship to transaction price. The magnitude is negative 16% in the *coastal* sample and negative 10% in the *coastal + waterway* sample. We find no evidence that houses in our sample located in the FEMA flood zone are priced lower than comparable houses outside of the flood zone. This result is consistent with the finding of Hino and Burke (2021) that the property owners do not seem to fully incorporate the discount associated with flood zone designation in the housing prices across the USA. Lastly, we find in model (4) that our results for the effects of SLR exposure on transaction prices are largely explained by multi-family units.[7]

Table 4 reports the regression results with SLR-XA decomposed to different types of exposures (passive flooding, annual high wave flooding, and coastal erosion).

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[7] Both AIC and BSC indicate that model (4) is the most preferred followed by (3) and then (2) for both the coastal and coastal + waterway samples.

Table 3 Main regression results with SLR-XA 3.2ft.

	Coastal				Coastal+Waterway			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
SLXA32	-0.080	-0.099**	-0.119***	-0.226***	-0.055	-0.133***	-0.156***	-0.220***
	(0.065)	(0.039)	(0.038)	(0.051)	(0.042)	(0.032)	(0.033)	(0.036)
Ocean view		0.296***	0.295***	0.296***		0.352***	0.349***	0.352***
		(0.080)	(0.080)	(0.076)		(0.057)	(0.055)	(0.053)
Cesspool		-0.161***	-0.165***	-0.163***		-0.100*	-0.108*	-0.108
		(0.052)	(0.055)	(0.057)		(0.058)	(0.060)	(0.063)
Flood zone		0.111	0.084	0.131		0.025	0.007	0.025
		(0.098)	(0.109)	(0.106)		(0.114)	(0.120)	(0.112)
Water front		0.343***	0.273***	0.267***		0.260***	0.207***	0.198***
		(0.105)	(0.088)	(0.083)		(0.069)	(0.050)	(0.046)
Beach (50)		0.012	-0.084	-0.068		0.029	-0.104	-0.092
		(0.146)	(0.175)	(0.163)		(0.144)	(0.178)	(0.153)
Beach (100)		0.249**	0.249**	0.253**		0.198*	0.200*	0.205*
		(0.094)	(0.089)	(0.102)		(0.101)	(0.099)	(0.102)
Seawall			0.370	-0.121			0.488	-0.069
			(0.269)	(0.620)			(0.286)	(0.565)
Neighbor with seawalls			0.105	0.118			0.186	0.193
			(0.107)	(0.096)			(0.167)	(0.161)
SLRXA32 X Seawall				0.531				0.596
				(0.591)				(0.578)
SLRXA32 x Single-family				0.265**				0.255***
				(0.095)				(0.084)
Noncoastal						-0.162***	-0.171***	-0.197***
						(0.057)	(0.057)	(0.049)
R2	0.75	0.77	0.77	0.77	0.66	0.68	0.68	0.68
AIC	8,590	8,021	7,978	7,916	18,988	18,142	18,070	18,003
BIC	8,679	8,166	8,123	8,061	19,086	18,316	18,243	18,177
N	7,242	7,242	7,242	7,242	14,084	14,084	14,084	14,084

The table represents the regression results of models (1)–(4) with SLR-XA 3.2 ft as the indicator of SLR risk exposure. Beach (50) and Beach (100) are dummy variables that are equal to 1 for the transaction of properties that are located within 50m or 100m of a sandy beach. The standard errors are clustered by zip code. *$p<0.10$, **$p<0.05$, ***$p<0.01$. All specifications (1)–(4) include the zip code X transaction year X distance-to-coast bin X elevation bin X property type (single family vs. condominium) fixed effects as well as categorical variables for the property age, the number of bedrooms, and property square footage. Akaike information criterion (AIC) and Bayesian/Schwarz information criterion (BIC) are listed at the bottom

The results indicate that the effect of SLR on transaction prices are related to passive flooding rather than the measures of high wave run-up or coastal erosion. One explanation is that passive flooding of this magnitude represents a more chronic event, whereas both high wave run-up and coastal erosion can be more seasonal in nature. The positive coefficient estimates for both high wave run-up and coastal erosion are potentially puzzling (statistically significant in multiple specifications), but we explain this finding as a reflection of being close to high surf and sandy beaches for which O'ahu is world renowned. Though

Table 4 Regression results with SLR exposure by type at 3.2 ft

	Coastal			Coastal+Waterway		
	(1)	(2)	(3)	(1)	(2)	(3)
SLR PF	-0.172	-0.226***	-0.213***	-0.268***	-0.363***	-0.355***
	(0.113)	(0.069)	(0.062)	(0.095)	(0.075)	(0.066)
SLR AH	0.018	0.108	0.102	0.165	0.221*	0.213*
	(0.147)	(0.110)	(0.097)	(0.164)	(0.121)	(0.108)
SLR CE	0.460***	0.283*	0.265**	0.448***	0.240	0.222
	(0.116)	(0.164)	(0.126)	(0.112)	(0.210)	(0.139)
Ocean view		0.294***	0.294***		0.359***	0.356***
		(0.076)	(0.076)		(0.055)	(0.053)
Cesspool		-0.168***	-0.172***		-0.106	-0.113*
		(0.057)	(0.059)		(0.063)	(0.064)
Flood zone		0.125	0.097		0.001	-0.015
		(0.095)	(0.104)		(0.094)	(0.096)
Water front		0.275***	0.215***		0.199***	0.152***
		(0.080)	(0.075)		(0.040)	(0.044)
Beach (50)		-0.026	-0.101		-0.026	-0.128
		(0.104)	(0.130)		(0.085)	(0.106)
Beach (100)		0.226***	0.229***		0.163***	0.168***
		(0.070)	(0.067)		(0.055)	(0.056)
Seawall			0.294			0.378*
			(0.206)			(0.213)
Neighbor with seawalls			0.051			0.086
			(0.094)			(0.120)
R2	0.73	0.77	0.77	0.64	0.68	0.68
AIC	9,689	7,972	7,946	20,429	17,955	17,915
BIC	9,793	8,117	8,090	20,542	18,129	18,089
N	7,537	7,242	7,242	14,389	14,084	14084

The table represents the regression results of models (1)–(4) with SLR-PF, AHWF, CE 3.2 ft as the indicators of SLR risk exposure. The standard errors are clustered by zip code. *$p<0.10$, **$p<0.05$, ***$p<0.01$. Beach (50) and Beach (100) are dummy variables that are equal to 1 for the transaction of properties that are located within 50m or 100m of a sandy beach. All specifications (1)–(4) include the zip code X transaction year X distance-to-coast bin X elevation bin X property type (single family vs. condominium) fixed effects as well as categorical variables for the property age, the number of bedrooms, and property square footage. Akaike information criterion (AIC) and Bayesian/Schwarz information criterion (BIC) are listed at the bottom

Fig. 6 The SLR (bathtub) impacts on property prices by the extent of exposure (based on Table 4 specification (2)). Note: The figure demonstrates the relationship between the % change in house price of exposed properties (relative to unexposed properties) based on exposure to different levels of NOAA passing flooding SLR exposure. The coefficient estimates and the associated 95% confidence intervals are based on model (2)
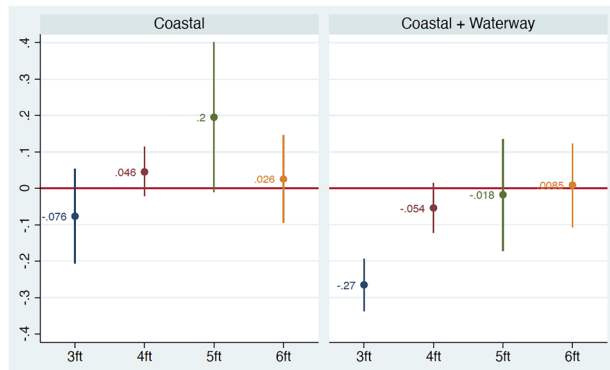
we attempted to control for this attribute via our two *beach front* indicators, we conclude that these variables imperfectly capture the premium associated with proximity to sandy beaches.[8] Specifically, our beach front indicator does not capture whether a parcel is across the street from a sandy beach or on the same side as the beach, which would have a potentially large impact in terms of parcel protection from SLR-induced hazards. In addition, our measure of coastal erosion, based on a modeling assessment, is also an imperfect measure of erosion because it does not take into account the presence of seawalls. As noted earlier, the measure of SLR-induced coastal erosion is subject to a larger degree of uncertainty than passive flooding and annual high wave flooding indicators (Anderson et al. 2018, and personal communication with SLR modelers).

5.2 Property price effects by the extent of exposure

Figure 6 represents the coefficient estimate of exposure to passing flooding based on NOAA SLR measures with 95% confidence intervals.

In contrast to the finding by Bernstein et al. (2019) for the US national sample, we find that the negative and significant relationship between SLR and transaction price dissipates after the 3 ft scenario.[9] While our restricted sample size is clearly an issue in comparison to a US-wide analysis, the localized result indicates that home buyers did not discount housing values for SLR risks that are not expected, on average, to be realized by 2100.[10]

5.3 Market saliency

In this section, we look at alternative sample periods, going back to 1994 as this is what is available to us from ZTRAX. For simplicity, we break our sample into four time periods:

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[8] To address this challenge, we ran multiple sensitivity tests for the measure "beach front," with alternative definitions ranging from 50- to 150-m buffer zones. Our results remained similar to what is presented in Tables 6 and 7.

[9] We find that SLR does not statistically significantly impact transaction prices when measured at 2 feet; however, this is likely an issue of quite small sample size. The magnitude of the coefficients remain similar.

[10] We note that the point estimates for 3ft SLR according to NOAA's passive flooding measures are different from what Table 4 indicates given the SLR-XA indicator for 3.2ft exposure because the two measures identify overlapping but different sets of parcels as exposed to SLR.

Fig. 7 The SLR impacts on property prices by sample period. Note: The figure demonstrates the % change in house price of the properties exposed to SLR-XA 3.2ft (relative to unexposed properties) based on different sample periods for the coastal + waterway sample. The coefficient estimates and the associated 95% confidence intervals are based on model (2)
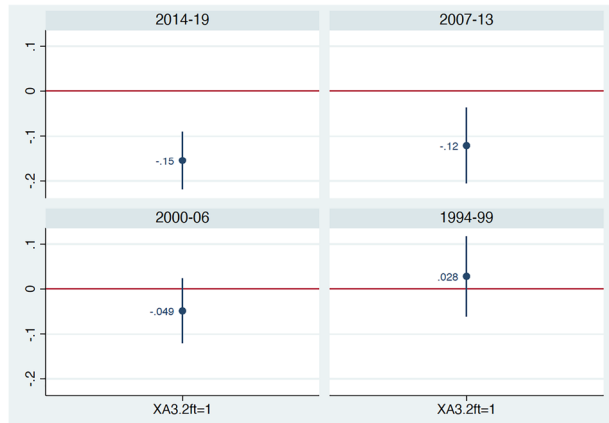
2014–2019 (main model), 2007–2013, 2000–2006, and 1994–2000. Supplementary Information contains additional sensitivity analyses regarding the sample period specification. Our core findings that more recent transactions reflect negative market impacts as a result of SLR considerations and that transactions prior to the year 2000 do not remain. Figure 7 shows our findings in regard to the SLR coefficient (model (2) with *coastal + waterway* sample).

We find that SLR is negatively associated with housing transaction prices back to the year 2000, and from 1994 to 1999, it is positive. The magnitude of the estimated coefficients are increasingly negative in each more recent block of time, showing the increasing salience of SLR and associated risks in Oʻahu's housing market.

5.4 Behavioral implications

Following Bernstein et al. (2019) and similarly leveraging Giglio et al. (2015a, b), we estimate the average Oʻahu home buyer's risk perception as it relates to housing prices and SLR. We consider that a house provides net benefits to the homeowner each year (B), with a positive annual discount rate ($r>0$). The net present value of the house (V_u), if it is not exposed to SLR and provides the net benefit indefinitely, is given by:

$$V_u = \sum_{t=0}^{\infty} \frac{B}{(1+r)^t} = B/r.$$

However, suppose a house with the same annual net benefits is subject to SLR and is expected to be flooded in T years, whereby the annual net benefit drops to zero after year T. The net present value of the house facing SLR (V_e) is then given by:

$$V_e = \sum_{t=0}^{T} \frac{B}{(1+r)^t} = \frac{B}{r} - \frac{B}{r(1+r)^T}.$$

Our estimate of $\hat{\beta}$ in models (1)-(3) informs the relationship between V_u and V_e:

$$\ln\left(V_e/V_u\right) = \ln\left(1 - \frac{1}{(1+r)^T}\right) = \hat{\beta}.$$

Table 5 Market-expected timing of SLR risk

Discount rate		Coastal			Coastal + Waterway		
		T*	[95% Conf. Interval]		T*	[95% Conf. Interval]	
1%	Model (2)	237.4	181.1	406.1	209.1	171.1	277.1
	Model (3)	220.3	173.5	323.2	195.5	163.7	246.2
2.6%	Model (2)	92.0	70.2	157.4	81.1	66.3	107.4
	Model (3)	85.4	67.3	125.3	75.8	63.4	95.5
5%	Model (2)	48.4	36.9	82.8	42.6	34.9	56.5
	Model (3)	44.9	35.4	65.9	39.9	33.4	50.2

With $r = 0.026$ (Giglio et al. 2015a), our estimates indicate that the expected inundation time for 3.2ft SLR ranges between 75.8 years (with 95% confidence interval [63.4, 95.5]) and 92 years ([70.2, 157.4]). We can interpret these figures as the "market-expected timing of SLR risk," which appear to be in line with the IPCC's central projections of 3.2 ft SLR by the end of this century. Table 5 summarizes the expected inundation time T for 3.2 ft SLR under alternative discount rates of 1% and 5%. This exercise indicates that the estimated SLR discount on housing value for O'ahu is, on average, in line with the scientific risks of SLR.

5.5 Aggregate effects

According to the Hawai'i Climate Change Mitigation and Adaptation Commission (2017), the value of projected flooded land and dwellings exposed to 3.2 ft SLR amounts to over $19 billion across the State of Hawai'i. Our study indicates that the current housing market has already incorporated a part of the losses ($222 to $542 million 2020 US dollars based on our range of model point estimates). This equates to $16.1–39.3 million of lost property sales tax revenue within SLR exposure areas for the City and County of Honolulu, based on applying effective property sales tax rates for residential parcels.

6 Conclusion

Our hedonic study for O'ahu finds a 9–14% price discount for housing property transactions expected to be impacted by 3.2 ft of passive flooding SLR between 2014 and 2019. Property transactions do not seem to incorporate seasonal SLR risk exposure (annual high wave run-up or future coastal erosion factors). This may be because exposure to seasonal flooding or coastal erosion is not as salient as chronic SLR, and is viewed as a more dynamic process in comparison to general inundation.

Our analysis has several implications to inform coastal management strategies in the face of SLR. Our results robustly show that residential properties on O'ahu, particularly multi-family dwelling units, have already experienced sizable relative discounts in their sales price due to current and expected SLR. As such, single family homes are yet to have measurable negative transaction price impacts from current and expected SLR. We hypothesize that first measurable impacts appear in multi-family dwelling residences due to the complexity of coordinating building-scale SLR response within condominium and/or apartment regimes, for example, in gaining agreement amongst unit owners on SLR response actions within homeowners associations. Moreover, buyers are increasingly accounting for SLR within transaction prices—and this trend is likely to

continue with increasing SLR and public information about the localized impacts of climate change. This finding therefore helps to inform the timing and form of potential government programs aimed at coastal realignment—i.e., that would attempt to proactively retreat from Oʻahu's coastline to preserve its sandy beaches. Many government buyout programs, particularly for those exposed to natural disasters, use pre-disaster, fair market values—as under FEMA (Greer and Brokopp Binder 2017). More aggressive condemnation approaches would similarly require just compensation of homeowners (Craig, 2019). However, this kind of large-scale buyout scheme is often thought to be infeasible given the magnitude of the challenge posed by accelerated SLR (Griggs and Reguero 2021). Understanding the pricing trends of homes within the SLR-XA, especially for those closest to the ocean, can therefore productively guide decision-makers to better understand average homeowner risk tolerance, expectations around collective action problems prompted by multi-dwelling units, and guide the development of retreat programs in comparison to, and the context of, market forces.

Our research also points to the importance of incorporating a comprehensive model of housing and coastal attributes within local SLR research, as we find the impact of related factors such as the presence of an ocean view, OSDS, and proximity to the ocean or beach. A particularly robust finding within the specifications of our model is that the presence of an OSDS, including cesspools, lower property transaction prices. The State's ACT 125 (2017) requires the replacement of all cesspools (more than 4700 in the area, 550 in SLR-XA) by 2050, and this has been primarily approached with government financing of cesspool upgrades (to septics) without consideration of SLR exposure (Spirandelli et al., 2019). Our finding that the value of OSDS is statistically significant and negatively capitalized into home transaction prices suggests that OSDS could potentially be converted effectively and efficiently upon sale. SLR-enhanced coastal erosion and groundwater inundation of these systems pose substantial public health and ecological threats. Conversion of such systems should be duly managed within the coastal zone. Such coastal management issues are an area for future inquiry. Lastly, in 2021, the State of Hawaiʻi passed Act 179 that mandates properties in the SLR-XA to disclose this risk to potential real estate buyers. The law went into effect in May 2022 and thus provides for an excellent future study of market adjustment to increasing information about homebuyer risk within Hawaiʻi's coastal zone.

Declarations

Ethics approval and consent to participate This article does not contain any studies with human or animal participants performed by any of the authors.

Consent for publication All authors agreed with the content and all gave explicit consent to submit the manuscript.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

Disclaimer The results and opinions are those of the authors and do not reflect the position of Zillow Group.

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