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Evaluating erosion management strategies in Waikiki, Hawaii

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A B S T R A C T

Waikiki is an internationally recognized tourist destination and a major source of economic activity in Hawaii. Erosion is a constant threat to Waikiki's beaches and coastal properties. This applied study presents an assessment and comparison of three erosion management approaches – beach nourishment, armoring and managed retreat – in the context of Waikiki. A geographic information system (GIS) is used to project erosion rates to 2050 and 2100, while approximating effects of sea level rise (SLR). The spatial extent of erosion and costs of each management approach are estimated. Suitability of each approach is evaluated based on management impacts to economy, environment, recreation, storm protection, and resources. This framework provides a comparative analysis that can be replicated in similar settings. The findings indicate that nourishment may be a beneficial and economical approach to manage erosion in this densely developed, economically significant beach setting. Nourishment costs are on the same order of magnitude as armoring, while retreat costs are an order of magnitude higher. The larger indirect impacts and economic losses associated with armoring (beach loss) and retreat (property loss) make nourishment the least impactful option for addressing erosion in Waikiki. As the projections and understanding of climate change impacts improve, solutions may evolve. Nourishment may provide a no-regrets, suitable approach for managing erosion in Waikiki until other solutions emerge. This paper presents opportunities and implications of nourishment for planning and future research in Waikiki.

1. Introduction

Waikiki is a world renowned tourist destination on the south shore of Oahu in the Hawaiian Islands. Since the construction of the first hotels in the late 19th century (Wiegel, 2008), Waikiki has become the focal point of the tourism industry and a significant contributor to the economy in Hawaii. In 2015, Waikiki generated 41% of the state's visitor industry activity, and contributed 7% to the state's Gross State Product (State of Hawaii, 2015a). The economic importance of Waikiki is closely linked to its beaches. Beaches in general have been found to support the tourism industry (Klein et al., 2004; Houston, 2013). In Waikiki, the total loss of the beach due to erosion could result in economic losses of $2.2 billion per year according to a survey of visitor activity (Tarui et al., 2018). Preserving the beach at Waikiki has become a priority for the State of Hawaii and the City and County of Honolulu (CCH). A Special Improvement District was established by city ordinance in 2015 with the purpose of managing the beach in Waikiki (City and County of Honolulu, 2014). The Waikiki Beach Special Improvement District Association (WBSIDA) is authorized to collect and utilize district tax assessments for shoreline improvement and protection projects, and is tasked with developing a comprehensive beach management plan. Recent state legislation provides funding for beach restoration, recognizing the importance of beaches to tourism-dependent areas, such as Waikiki (State of Hawaii, 2015b).

Waikiki is a largely engineered coastline, consisting of a man-made beach fronting dense waterfront development (Miller and Fletcher, 2003), as seen in Fig. 1. Constructed in a piecemeal fashion with little consideration for down-drift effects, the beaches in Waikiki have long been threatened by erosion. A survey of stakeholders found that erosion is recognized above other threats to Waikiki such as hurricane, tsunami, and terrorism (Francis et al., 2019). Because of continued development along the coast, there have been many attempts to mitigate erosion in Waikiki. Beginning with seawalls to protect coastal property, efforts shifted towards maintaining the beach as an important asset (Miller and Fletcher, 2003; Wiegel, 2008). As early as 1928, groins and beach nourishment were proposed as methods of restoring the beaches lost to

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erosion (Miller and Fletcher, 2003). The first nourishment effort was conducted in 1939, when 7 000 yd^3 (5352 m^3) of sand was placed at Kuhio Beach (Wiegel, 2008). Beach nourishment has become the predominant method in maintaining beaches in Waikiki, with approximately 252 300 m^3 placed with numerous nourishment projects at various locations along the coast (DLNR, 2013).

A comprehensive beach management plan requires evaluation of erosion management options. The objective of this paper is to evaluate the suitability of three prevalent erosion management alternatives – beach nourishment, armoring, and managed retreat - in Waikiki. Many studies have evaluated these strategies focusing on economic costs (Daniel, 2001; Landry et al., 2003; Landry, 2011; Parsons and Powell, 2001; Pompe, 1999). We build on these and other studies to assess and compare both the economic and non-economic impacts of these three strategies, and identify the planning implications for Waikiki. The contribution of this paper is twofold. First, this analysis contributes to a growing inventory of erosion and economic data that can be used to inform policy making and plan development in Waikiki. Second, a flexible method and framework for evaluating impacts of erosion management alternatives is presented. Applying this method to Waikiki can be used to inform stakeholders and decision makers in Waikiki and elsewhere.

The paper begins with a review of the known uses, advantages, and disadvantages of beach nourishment, armoring and managed retreat. This review informs the methods and framework used for the assessment. We develop a classification scheme for the (dis)advantages of each strategy – defined as 'management impacts' (both positive and negative) – to facilitate and support comparative analysis. Placing the management impacts in context of future erosion, historical erosion rates along the Waikiki coastline are projected through the years 2050 and 2100 using a modified Bruun Rule approach and data available at the time of the analysis (2015). Given management and erosion impacts, the suitability of each strategy is considered within the context of Waikiki.

2. Background – erosion management alternatives

Erosion management is necessitated by the dependency of coastal economic functions on the social and environmental benefits the beach provides (Bernd-Cohen and Gordon, 1999; Daniel, 2001). These functions are threatened by erosion and beach loss. In developed areas where the shoreline moves landward over time (either due to natural processes or human impacts on those processes), the beach narrows and coastal properties are at risk. Erosion management alternatives have been classified in different ways. Williams (2018) distinguish management options as *defense* (hard or soft engineering), *accommodation* (flooding mitigation), *managed retreat*, and *sacrificial* areas (no-intervention). Similarly, Rangel-Buitrago et al. (2018) identify five approaches: *protection* (hard or soft engineering), *accommodation*, *planned retreat*, *ecosystem-based* approaches, and *sacrifice*. Others characterize management options into three specific strategies of *beach nourishment* (soft engineering), shoreline *armoring* (hard engineering), and managed *retreat* (Daniel, 2001; Landry et al., 2003; Landry, 2011; Parsons and Powell, 2001). This analysis focuses on comparison of these three strategies for the Waikiki coastline. Beach nourishment and armoring are considered varying forms of defense or protection (Rangel-Buitrago et al., 2018; Williams, 2018). In this sense, this analysis is a comparison of two defense strategies (hard and soft) and managed retreat. Although other strategies exist, such as breakwaters, artificial reefs, groins, and other structures, they are typically site-scale solutions and are difficult to assess as a broad-based approach. In this section we summarize the uses, advantages, and disadvantages of beach nourishment, armoring and managed retreat as identified in the literature. This synthesis informs the framework for comparison detailed in the methods section.

2.1. Beach nourishment

Since its rise as a mainstream coastal solution in the 1950s, beach nourishment has become a common method to combat erosion in the United States (Trembanis et al., 1999) and internationally (Alexandrakis et al., 2015; Pranzini, 2018; Williams, 2018). Nourishment is considered a soft engineering protection method (Williams et al., 2018) and involves the placement of offsite sand, from either offshore or inland sources, to create an artificial beach or widen an eroding beach for storm protection or recreation (NOAA, 2000). The arguments for nourishment are typically focused on the economic benefits of beaches. Economic activity, often driven by tourism-related expenditures, significantly increases in areas with nourished beaches (Klein, 2010; Houston, 2013). Economic activity generated by a wider beach has been found to outweigh the costs of nourishment projects (Feagin et al., 2014; Houston, 2013). Beach width is positively associated with coastal property values (Gopalakrishnan et al., 2011; Landry, 2011; Pompe, 1999) contributing to local tax revenues. In addition to economic benefits, other advantages of nourishment include the recreational value, storm protection, and wildlife habitat provided by beaches (Hoagland et al., 2012; Jones and Mangun, 2001).

There are also disadvantages associated with beach nourishment. Nourishment maintains beach widths, but is a short-term solution which requires recurring maintenance and funding (Morgan and Hamilton, 2010; Pompe, 1999; Trembanis et al., 1999). One concern is financing, as well as who pays and who benefits from beach improvements. Financing can come from federal subsidies, state and local general tax revenue, or a special tax, such as visitor taxes (Parsons and Noailly, 2004). Studies have examined payment schemes with varying conclusions (Black et al., 1990; Kreisel et al., 2004; Landry et al., 2003; Landry,

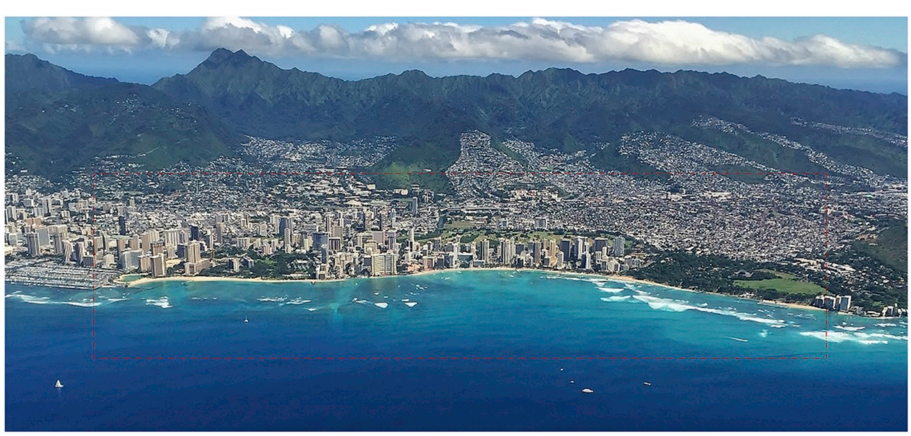

Fig. 1. The Waikiki coastline. The Waikiki coastline extends from Ala Wai Boat Harbor to the West (left) and Kapiolani Park in the East (right), as outlined in red. [Image: R. Porro]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2011; Morgan and Hamilton, 2010; Pompe, 1999). An argument against beach nourishment is that it may promote additional growth and development, creating a false sense of security from coastal hazards (Bagstad et al., 2007; Burby et al., 1999). Although nourishment may provide habitat space, it may bury or displace the fauna within the tidal zone or at the borrow site (Peterson and Bishop, 2005), and sedimentation can harm coral (Jordan et al., 2010) and seagrasses (Aragones et al., 2015)). Suitable beach sand, moreover, is a finite resource. As nourishment efforts continue and sediment sources become more limited, the cost of nourishment may increase (Daniel, 2001).

2.2. Managed retreat

Managed retreat – preventing or relocating development away from the coastline – has been gaining attention as an adaptation and erosion management strategy in Hawaii (Office of Planning, 2019) and elsewhere (Hino et al., 2017). A managed retreat policy can reduce erosion risk by placing structures away from the shoreline (Landry et al., 2003). This can be done through land use measures such as increasing shoreline setbacks, implementing rolling easements, phasing out development, and relocating structures (Klein et al., 2001). In addition to reducing erosion damage and risk to coastal properties, a managed retreat policy allows coastlines to migrate landward while maintaining beach width, allowing for the continued recreational value, habitat and storm protection the beach provides (Landry et al., 2003; Nordstrom and Jackson, 2013). Natural sediment can be released from coastal dunes or bluffs as the coastline migrates landward unimpeded by structures (Fletcher et al., 1997; O'Connell, 2010).

Although managed retreat has advantages, there may be resistance to this strategy. Landowners are often reluctant to relinquish their property, there are challenges with displacing residents, and politicians hesitate to give up land that contributes to tax revenue and economic activity (Landry, 2011; Hino et al., 2017). These disadvantages of a managed retreat policy make it politically challenging to implement (Gibbs, 2016), and it could result in the loss of land that has economic importance (Daniel, 2001). A third disadvantage of retreat is that it could potentially be more costly than a hold-the-line strategy such as beach nourishment (Parsons and Powell, 2001), although costs are dependent on the density of development, the housing market, and costs of nourishment (Kriesel et al., 2004; Landry et al., 2003; Parsons and Powell, 2001). Retreat involves the relocation of structures and possible compensation for property losses, making this strategy financially unfeasible in highly developed areas (Kriesel et al., 2004). Although initial costs may be high, once in place, a retreat strategy requires no recurring maintenance costs (Hino et al., 2017). Lastly, managed retreat is limited by the availability of land for relocation; therefore, the approach may not be viable in some locations (Mcglashan, 2003). This is a particular challenge in island settings, such as Hawaii (Office of Planning, 2019).

2.3. Armoring

Shoreline armoring is a strategy that has been most used in the past. Armoring can include either shoreline hardening measures (e.g. seawalls), or shoreline stabilizing measures that alter coastal processes (e.g. breakwaters and groins) (Ndour, 2018). For this analysis, we focus on shoreline hardening, or shoreline-parallel hard structures that halt the landward migration of the shore and includes bulkheads, seawalls, and revetments (Daniel, 2001; Landry et al., 2003; O'Connell, 2010). The advantage of this strategy is the protection of coastal lands from erosion, allowing for future development or the protection of existing coastal property. Armoring also provides protection against storm events, however only the level of protection to which they are designed (Daniel, 2001). While a seawall may protect against landward migration, it typically will not protect against extreme storm events, if not designed for it. The storm protection provided by armoring is dependent on design factors, such as design wave conditions, desired maintenance requirements, and available budget (USACE, 2008). In terms of comparison with other erosion management strategies, armoring may be more or less expensive, depending on these factors.

Shoreline armoring has disadvantages. Armoring on an eroding beach can result in steepening, narrowing, and loss of the beach fronting the structure as well as accelerated erosion of adjacent beaches (Fletcher et al., 1997; Pilkey and Wright III, 1988). There may be loss of recreational opportunities and beach access and a reduction in marine habitat (Landry et al., 2003). For these reasons, some states in the United States have banned the use of hard structures to protect against erosion (Kittinger and Ayers, 2010; O'Connell, 2010). Yet, armoring is often used to protect critical infrastructure (O'Connell, 2010), such as roads, utilities and facilities along the coastline. The loss of beach due to armoring may be outweighed by the societal benefits of infrastructure. The use of armoring may depend on whether the objective is to maintain the beach or protect property.

3. Methods

3.1. Framework for comparison

The advantages and disadvantages of each erosion management approach discussed above are characterized as management impacts (positive or negative) and summarized in Table 1. The impacts are grouped according to following categories: *economy*, *environment*, *recreation*, *storm protection*, and *resource* (non-monetary). Organizing the impacts in this manner provides the framework for comparative analysis in Waikiki (Fig. 2). Strategies are assessed by considering erosion projections and economic costs of each strategy, along with qualitative assessment of the impacts in each category.

3.2. Two-pronged analysis

The analysis employs a two-pronged approach. First, future erosion impacts using geographic information system (GIS) software are quantified and mapped to identify at-risk areas along the Waikiki coastline. This analysis considers the effects of sea level rise (SLR) on projected erosion rates. The years 2050 and 2100 are used, as they are common benchmarks in the climate change literature (IPCC, 2013) and sea level rise studies in Hawaii (Anderson et al., 2018; Habel et al., 2016). Second, the suitability of each erosion management approach is evaluated in the context of Waikiki for each category of impact. To assess the economic impacts of each approach, an estimate of costs for each alternative is provided. This analysis provides initial estimates and does not constitute a complete cost-benefit analysis. Over time, as more data on environmental change and policy impacts become available, the estimates can be updated.

3.3. Projecting erosion and SLR

Waikiki has been altered and divided into seven littoral cells – coastal systems in which sediment sources and processes are restricted to manmade (e.g. groins) or natural (e.g. headlands) boundaries (Inman, 2005). These littoral cells include Kaimana, Queens, Kapiolani, Kuhio, Royal Hawaiian, Halekulani, and Fort Derussy (Miller and Fletcher, 2003; Eversole et al., 2018). These divisions are important when analyzing erosion impacts, as each cell has distinct erosion and accretion trends.

Coastal erosion in Hawaii has been well researched (Anderson et al., 2015; Fletcher et al., 1997, 2012; Romine and Fletcher, 2012; Romine et al., 2013), with specific attention to Waikiki (Miller and Fletcher, 2003; Sea Engineering, 2010; Conger and Eversole, 2011; Habel et al., 2016). Shoreline change has been analyzed using historical aerial imagery to determine the movement of shoreline positions over time (Miller and Fletcher, 2003; Fletcher et al., 2012). Mean rates of shoreline change vary among studies depending on the period of time from which the aerial imagery is analyzed. For example, Fletcher et al. (2012)

Table 1
Management impacts of erosion management alternatives.

Management Alternative	Impact Category	Advantages	Disadvantages
BEACH NOURISHMENT	**Economic**	• Supports tourism industry • Increases coastal property values • Maintains land for development and economic activity • Cost is typically less than induced economic activity	• Requires recurring maintenance – perpetual funding requirement. • Equity challenges in funding
	Environmental	• Creates habitat for wildlife	• May impact fauna at fill location or borrow site. • May impact coral and seagrasses
	Recreational	• Maintains recreational value and use of beach	
	Storm Protection	• Provides buffer between development and ocean hazards.	• May increase density of development, increasing vulnerability to large disasters.
	Resource		• Limited by beach quality sand source. Declining resource may increase costs in future.
MANAGED RETREAT	**Economic**	• No recurring maintenance costs	• Relinquishes land for development and tax revenue • Costs can be significant in densely developed areas • May encounter strong opposition
	Environmental	• No negative environmental impacts • Maintains wildlife habitat	
	Recreational	• Maintains recreational value and use of beach	
	Storm Protection	• Moves development away from hazards • Maintains beach width – buffer	
	Resource		• Limited by availability of land for relocation or alternative development sites.
ARMORING	**Economic**	• Protects coastal properties. • Maintains upland for future development. • Cost dependent on design factors (can be low).	• Recurring maintenance required. • Cost dependent on design factors (can be high).
	Environmental		• Results in loss of beach and marine habitat.
	Recreational		• Results in loss of recreational value and use of beach.
	Storm Protection	• Protects against chronic erosion. • Storm protection dependent on design of structure.	• Storm may exceed structure design capacity.
	Resource	• Limited only by construction materials.	

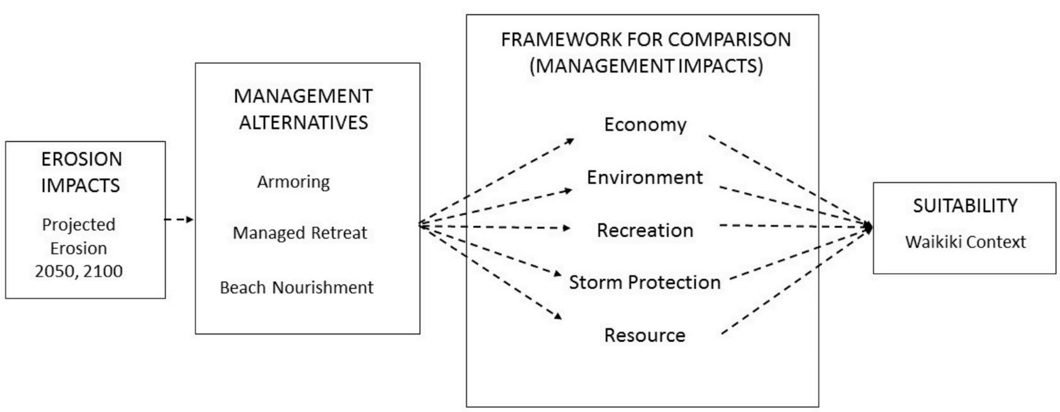

Fig. 2. Framework for Comparative Analysis. Figure shows framework used to evaluate impacts of erosion management alternatives. It includes the impacts (management & erosion) that are considered in the evaluation of the suitability of erosion management alternatives for Waikiki.

determined the historical shoreline change rates for the islands of Maui, Kauai, and Oahu using aerial imagery from 1927 to 2005. These change rates, however, differ slightly from Miller and Fletcher (2003) which analyzed shoreline positions in Waikiki between 1951 and 2001. Also, an environmental impact assessment conducted for the 2012 nourishment at Royal Hawaiian Beach analyzed the shorelines from 1982 to 2005 (Sea Engineering, 2010). It is important to note that the fluctuation of erosion rates may be influenced by changing coastal dynamics, the construction of coastal structures, and nourishment. For this study, the most extreme erosion rate for each littoral cell among available studies was used, as shown in Table 2. Utilizing the worst-case rate from available studies is an attempt to minimize the influence of past nourishments, but provides a conservative approach. This rate was projected to 2050 and 2100 to estimate future erosion for each cell.[1]

The historic rates take into account historic SLR trends in Hawaii (Romine et al., 2013), but not the effects of accelerated future SLR that will have a positive influence on erosion (IPCC, 2013; UH Sea Grant, 2014). The latest Intergovernmental Panel on Climate Change (IPCC)

[1] Shoreline change varies along a littoral cell (Fletcher et al., 2012); however, average rates across the entire length of each cell were used due to data availability and simplification of calculation.

Table 2
Shoreline change rates as reported in Waikiki studies.

Littoral Cell	Shoreline Change Rate (meters/year) *Years of shoreline study*		
	Miller & Fletcher, (2003) *1951–2001*	Fletcher et al., (2012) *1927–2005*	Sea Engineering, (2010) *1982–2005*
Kaimana	0.7	**0.36***	
Queen's	−0.6	**−0.9***	
Kapiolani	**−0.1***	0.21	
Kuhio	**−0.2***	−0.11	
Royal Hawaiian	−0.2	0.19	**−0.7***
Halekulani	0.2	**0.03***	
Fort Derussy	0	**−0.19***	

*Highlighted rates indicate the values used for this analysis (+) value = accretion, (−) value = erosion.

projections of SLR range from 0.25m–0.98m by 2100 for various emissions scenarios (IPCC, 2013). In order to estimate the influence of accelerated SLR on erosion in Waikiki, a modified Bruun Rule approach was used following Yates et al. (2011) and Doody et al. (2004) (Equation (1)). This approach combined historical erosion trends with the Bruun Rule, a geometric model that estimates landward migration of a shoreline relative to a specified rise in sea level by assuming a constant equilibrium beach profile (Schwartz, 1967). We expand on the limitations of this approach in the discussion. For this analysis, the highest SLR projections for the worst-case climate scenario, Representative Concentration Pathway (RCP) 8.5, are used – approximately 0.33m rise by 2050, and 0.98m rise by 2100 (IPCC, 2013). Using the upper limit of the IPCC projections is conservative, but appropriate for an erosion analysis in Waikiki considering that recent studies find that sea levels may rise even higher, and more so in the Pacific region (Habel et al., 2016).

Equation (1) represents the shoreline change from both historic erosion trends and the Bruun Rule, represented by the far right term. Beach slopes for each littoral cell were obtained from Miller and Fletcher (2003). Historic SLR in Hawaii is roughly 1.5 mm/yr (Romine et al., 2013).

$$\textit{Total Shoreline Change} = \textit{Historic Change Rate} * \Delta \textit{time} + \underbrace{\frac{(\textit{Projected SLR} - \textit{Historic SLR})}{\textit{Beach Slope}}}_{\textit{Bruun Rule}} \quad (1)$$

Shoreline changes for 2050 and 2100 were estimated and mapped using ArcGIS, 10.2.2. Erosion zones were constructed by placing and connecting points along shore-perpendicular transects (from Fletcher et al., 2012) the projected landward distance from the current mean higher high water line. The analysis facilitates the examination of the spatial extent of erosion and estimation of mitigation costs along the coastline. The projected erosion zones represent the landward shoreline migration in the absence of structures and mitigation efforts. Although parts of Waikiki are lined with seawalls or structures, the approach allows for the identification of areas where structural repair or beach loss may be a concern and the comparison of costs to mitigate erosion risk. For armoring and nourishment, this means maintaining current shoreline position. For retreat, mitigation removes assets within the erosion zone. For simplification, we compare these strategies as if implemented exclusively across Waikiki. More sophisticated methods for estimating SLR-induced erosion in Hawaii have been developed (Anderson et al., 2015). The focus of this paper is on the comparison of strategies and planning and management considerations.

4. Results

4.1. Erosion impacts

The resulting shoreline changes including sea level rise are shown in Table 3. Positive values indicate a cell experiencing accretion, while negative values represent shoreline erosion.

The 2050 and 2100 erosion zones for the Waikiki coastline are shown in Fig. 3. Six of the seven littoral cells were characterized by an erosion trend in the presence of SLR. The lone cell characterized by accretion through to 2100 is Kaimana Beach, therefore no erosion zone is shown. This is because the SLR-induced shoreline retreat is not significant enough to counter the extrapolated historical accretion in the cell in that time. All other cells experience erosion through 2100. Based on the projected erosion rates and SLR, the total area eroded is approximately 36 600 m^2 by 2050 and roughly 93 300 m^2 by 2100. The greatest erosion over these time periods is experienced in the Royal Hawaiian and Queens cells.

4.2. Management impacts

4.2.1. Economy

To assess economic impacts, the costs of each management approach are evaluated. Utilizing ArcGIS geoprocessing tools, the costs for each erosion management strategy (armoring, retreat, and nourishment) were estimated based on the projected erosion zones and available structure and property data. For the purposes of comparison, the direct and indirect costs are presented separately. Direct costs are the estimated construction costs to implement a strategy, either as public or private expenditures. Indirect costs are those economic impacts resulting from each strategy – land or property losses, economic activity. To simplify comparison, all costs are estimated in 2015 dollars, and it is assumed that each strategy is implemented exclusively for each scenario.

4.2.1.1. Direct costs

4.2.1.1.1. Direct costs of armoring. Much of the Waikiki coastline is lined with either seawalls protecting beachfront properties or low concrete walls along pedestrian pathways. A GIS layer showing the location of these walls (Romine and Fletcher, 2012) was overlain with the projected erosion zones to identify impacted walls. Many existing walls are not currently subject to wave forces and not designed as erosion barriers. To simplify estimation of armoring costs, it is assumed areas impacted by future erosion would require the demolition of current walls and construction of new armoring. Costs are calculated for the length of wall impacted in each erosion zone (2050 and 2100). Unit costs of ~ \$1640/meter of wall for demolition and ~\$9840/meter for new seawall construction were used.[2] Table 4 summarizes the costs associated with armoring for 2050 and 2100. Total costs through 2100 include costs to

[2] Unit costs for typical seawall demolition/construction obtained from Hawai'i-based coastal engineering firm. Costs are for budgetary purposes. Actual costs are project and site specific.

Table 3
Projected Waikiki shoreline change through 2050 and 2100.

Littoral Cell	Historic Erosion Rate (m/yr)	Erosion Rate Source	2050 Projected Shoreline Change (m)	2100 Projected Shoreline Change (m)	2050 Eroded Area (m^2)	2100 Eroded Area (m^2)
Kaimana	0.36	Fletcher et al., (2012)	10.4	23.8	n/a	n/a
Queen's	−0.9	Fletcher et al., (2012)	−33.7	−83.3	12 100	30 000
Kapiolani	−0.1	Miller & Fletcher, (2003)	−5.4	−14.5	1 600	4 300
Kuhio	−0.2	Miller & Fletcher, (2003)	−10.1	−26.4	4 000	10 500
Royal Hawaiian	−0.7	Sea Engineering, (2010)	−26.6	−65.9	13 600	34 500
Halekulani	0.03	Fletcher et al., (2012)	−1.2	−4.3	600	1 900
Fort Derussy	−0.19	Fletcher et al., (2012)	−9.4	−24.7	4 700	12 100

Note: (+) value = accretion, (−) value = erosion; Eroded area rounded to nearest hundred square meters.

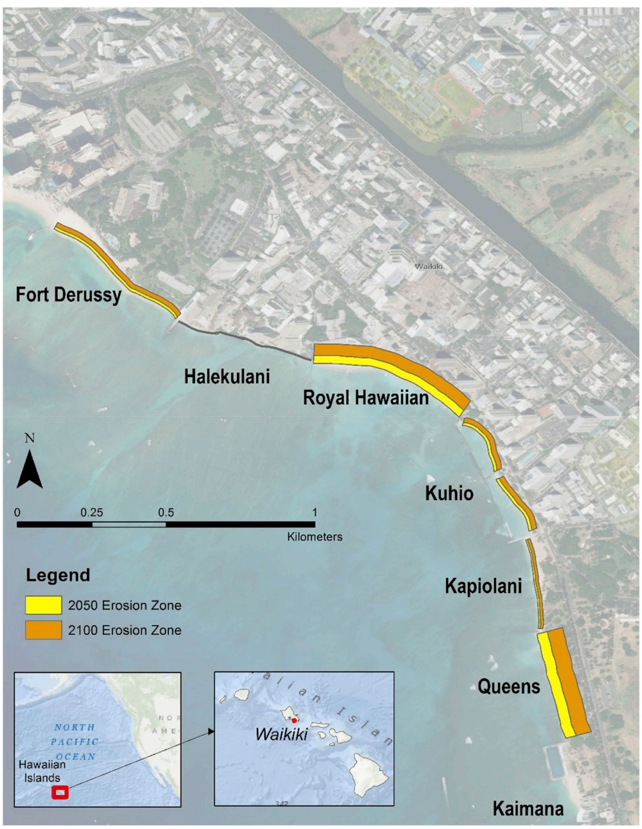

Fig. 3. Projected Erosion along Waikiki. Map of projected erosion zones along Waikiki coastline through 2050 (yellow) and 2100 (orange), created using worst-case erosion rates for each littoral cell among Waikiki studies: Miller and Fletcher (2003), Sea Engineering (2010), and Fletcher et al. (2012). (Basemap imagery from ArcGIS database). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reconstruct walls impacted by 2050, since coastal structures have a typical design-life of 50 years.

4.2.1.1.2. Direct costs of retreat. The costs of a retreat strategy were estimated using established methods and grouped under four categories: *land loss*, *capital loss*, *transition loss*, and *proximity loss* (Kriesel et al., 2004; Kriesel et al., 2005; Parsons and Powell, 2001). Land loss and capital losses are the values of land and structures lost to erosion. Transition loss is the cost of demolishing and/or relocating structures within the erosion zone, while proximity loss is the welfare loss of steering development away from the shoreline (Parsons and Powell, 2001). Transition loss is treated as the only direct cost. Land and capital losses are categorized as indirect costs, since compensation isn't always required to implement a retreat strategy; however, the demolition of

Table 4
Estimated armoring costs through 2050 and 2100.

Littoral Cell	2050 Length of Impacted Armoring (m)	2050 Total Armoring Cost ($000)	2100 Length of Impacted Armoring (m)	2100 Total Armoring Cost ($000)
Queens	380	4 322	380	8 643
Kapiolani	n/a	n/a	100	1 198
Kuhio	60	733	360	4 853
Royal Hawaiian	430	4 912	560	11 360
Halekulani	230	2 672	250	5 525
Fort Derussy	80	867	240	3 595
Total	**1180**	**13 506**	**1890**	**35 174**

Notes: Length of armoring rounded to nearest 10 m; Total cost through 2100 includes reconstruction costs of walls impacted by 2050.

those structures is necessary to allow for shoreline migration and maintaining beach width. Abandonment of the structures is not considered, as the abandoned structures would act as barriers for shoreline migration (i.e., seawalls) and would result in beach loss. Proximity loss can also be considered an indirect cost, but is not considered here since this loss is not applicable to fully developed areas such as Waikiki (Kriesel et al., 2005).

To estimate the direct costs, or transition loss, the structures within the erosion zones were identified by overlaying the building footprints from municipal GIS records. In similar studies, lost structures were identified as those that would become unusable if within the erosion zone (Landry et al., 2003). For this analysis, all buildings within the erosion zone are considered unusable and would be demolished. This includes many of the waterfront hotels in Waikiki. Approximate demolition costs were estimated using a unit demolition cost per area (~ $160/m^2), with the area of demolished buildings estimated from the footprint and number of stories in each building.[3] The total costs of building demolition for the 2050 and 2100 zones are presented in Table 5. To allow for shoreline migration, it is further assumed that all armoring structures along the coast would also have to be demolished in addition to the shorefront buildings. Combining the building demolition costs with the demolition costs for armoring results in a total direct cost of approximately $47 million by 2050 and $129 million by 2100.

4.2.1.1.3. Direct costs of nourishment. The projected erosion zones indicate the area that would erode without mitigation efforts. This also represents the width of beach that would need to be constructed over time to maintain the current shoreline through 2050 and 2100. Nourishment costs are included in cells lined with seawalls, since the

[3] Unit cost obtained from Hawai'i -based cost estimating firm (J. Uno & Associates). This is a rough unit cost for preliminary budgeting purposes. Actual demolition cost would be building and project specific.

Table 5
Estimated building demolition costs by 2050 and 2100.

Littoral Cell	2050 # of Buildings	2050 Demolition Cost ($000)	2100 # of Buildings	2100 Demolition Cost ($000)
Queens	3	292	8	450
Kuhio	n/a	n/a	4	88
Royal Hawaiian	7	44 925	10	62 450
Halekulani	n/a	n/a	1	62 753
Fort Derussy	n/a	n/a	2	13
Total	**10**	**45 217**	**25**	**125 754**

objective is to compare costs of each strategy to mitigate erosion risk, absent other methods. Absent nourishment, these walls would require replacement or maintenance to keep current shoreline position.

Beach nourishment is typically estimated based on cost per unit volume. To estimate these costs the change in beach width was correlated to the change in volume. Miller and Fletcher (2003) approximated this relationship in Waikiki through consecutive beach profiles and aerial imagery and defined this relationship by G_p, where

$$Gp = \frac{volume\ change\ per\ unit\ shorelength}{change\ in\ beach\ width}. \quad (2)$$

The G_p term can be used to estimate the volume of sand lost across a littoral cell, given the projected shoreline recession (Miller and Fletcher, 2003). We use this relationship to approximate the volume of sand required (for nourishment) to increase beach width by the distance receded. To approximate G_p for a nourishment project in Waikiki, we use the parameters from the 2012 Waikiki restoration project, which added a total of 18 350 m^3 on approximately 518 m of shoreline to increase beach width by 11.3 m (DLNR, 2013). Thus, this nourishment added approximately 3.16 cubic meters per meter of shoreline per meter of beach width increased (3.16 m^3/m/m). This value of G_p was applied to all littoral cells to calculate volume needed for nourishment, assuming similar methods and designs for future nourishments in Waikiki. The resulting volume of sand needed through 2050 and 2100 would be approximately 115 800 m^3 and 293 500 m^3, respectively. The unit cost for nourishment in Hawaii is approximately \$130/m^3.[4] This is higher than reported costs in other states where greater economies of scale are possible due to longer stretches of coastline and lower labor and material costs than in Hawaii. For example, an average nourishment project on the Atlantic coast involves the placement of 282 000 m^3 of sand along 3.5 km of beach, resulting in average unit costs of approximately \$10.5/m^3 (Hoagland et al., 2012). At a unit cost of ~\$130/m^3, the cost for nourishment in Waikiki would be roughly \$15.1 million through 2050 and \$38.2 million through 2100, as shown in Table 6[5]

Table 6
Estimated nourishment costs by 2050 and 2100.

Littoral Cell	2050 Volume Change (m^3)	2050 Nourishment Cost ($000)	2100 Volume Change (m^3)	2100 Nourishment Cost ($000)
Kaimana	4 260	n/a-	9 770	n/a-
Queens	(38 520)	5 008	(95 180)	12 373
Kapiolani	(5 170)	672	(13 750)	1 787
Kuhio	(12 900)	1 677	(33 860)	4 402
Royal Hawaiian	(42 860)	5 571	(106 240)	13 811
Halekulani	(1 640)	214	(6 000)	780
Fort Derussy	(14 730)	1 915	(38 570)	5 015
Total		**15 057**		**38 168**

Notes: Volume change rounded to nearest 10m^3.

Table 7
Estimated direct costs of erosion management alternatives through 2050 and 2100.

Strategy	2050 ($000)	2100 ($000)
Armoring	13 506	35 174
Retreat	47 152	128 849
Nourishment	15 057	38 168

The total direct costs of each erosion management strategy are shown in Table 7. Based on these cost estimates, nourishment and armoring costs would be on the same order of magnitude, while a retreat strategy would be the most expensive by an order of magnitude. While there is uncertainty in these estimates and there are project specific factors that would affect costs, the values provide relative order of magnitude estimates for comparative purposes.

4.2.1.2. Indirect costs. In Waikiki, a major driver of investment and decision-making is economic activity which generates jobs, livelihoods and tax revenues. Waikiki generates almost half of the tourism revenue in Hawaii. Each approach must be weighed against the impacts on the visitor industry and other indirect costs.

We equate the indirect costs of **armoring** to the impacts associated with the loss of beach fronting the armored coastline. Tarui et al. (2018) found that the economic impacts associated with the total erosion of Waikiki Beach would equate to annual losses of \$2.2 billion due to reduced visitor activity. Taking the length of armoring impacted by erosion as a proxy for length of beach lost, this strategy would result in roughly 31% of beach loss by 2050 and 65% by 2100 when compared to

Table 8
Land and building value in erosion zone (indirect costs of retreat) by 2050 and 2100.

Littoral Cell	2050 Building Value ($000)	2050 Land Value ($000)	2100 Building Value ($000)	2100 Land Value ($000)
Queens	1 436	37 532	1 714	95 070
Kapiolani	n/a	261	n/a	2 779
Kuhio	n/a	3 787	2	12 106
Royal Hawaiian	150 503	42 497	150 503	102 069
Halekulani	n/a	837	288 320	3 162
Fort Derussy	n/a	n/a	3 859	5 894
Total	**151 939**	**84 914**	**444 398**	**221 080**

[4] Unit costs obtained from Hawai'i-based coastal engineering firm (Sea Engineering, Inc). Costs are for budgetary purposes. Actual cost is project and site specific.

[5] These volume approximations are based only on horizontal beach width changes and assume constant beach slope and crest heights.

Table 9
Estimated economic costs of each erosion management strategy through 2100.

Strategy	Direct Cost ($000)	Indirect Cost
Armoring	35 174	Partial loss of $2B annual input from beach
Retreat	128 849	~$665M in land and bldg. losses
Nourishment	38 168	No economic impacts*

Note: *In terms of effects on current economic activity. Impacts during nourishment efforts considered minimal.

the current length of beach in Waikiki.[6] These losses would reduce the attractiveness of Waikiki resulting in at least a partial loss of the $2.2 billion estimate.

With regard to the economic impacts of **retreat**, the losses discussed in section 4.2.1.1 must be considered. The land and capital losses are not accounted for in direct cost estimates. These losses would equal the total land and building (capital) value within the projected erosion zones (Kriesel et al., 2005). These values were obtained from municipal parcel data and overlain with the 2050 and 2100 erosion zones. The land and building losses for 2050 and 2100 are summarized in Table 8.

The value of lost land is calculated based on the eroded area and a unit cost per area. This unit cost is the unit value of land further inland. This is because the amenity value of oceanfront land transfers to the land which would become oceanfront after erosion occurs (Kriesel et al., 2005; Parsons and Powell, 2001). Following Kriesel et al. (2005), the unit cost was calculated based on values of parcels away from the beach, in this case along Kuhio Avenue. The cost for parcels along Kuhio Avenue is approximately $13.0 million per acre (~$3212/m^2). Applying this unit cost to the eroded land results in a loss of approximately $85 million by 2050 and $221 million by 2100. The capital losses are equivalent to the total value of the demolished buildings. Adding the capital losses, land losses, and the transition losses, the economic cost of a retreat policy would sum to approximately $284 million by 2050 and $794 million by 2100. This does not include lost government tax revenue from lost properties or reconstruction costs elsewhere.

Nourishment would prevent the financial losses associated with the loss of beach, buildings and land. Moreover, there would be no indirect costs in terms of impacts to current economic activity. There may be some losses due to reduced use of the beach during nourishment, but we consider this negligible. During the 2012 Waikiki nourishment project, construction hours and methods were adjusted to minimize disruption to beach use (DLNR, 2013). If nourishment is employed in areas that currently contain no beach, it is possible that the appeal of Waikiki and economic activity may increase; however, this requires further investigation.

A summary of the economic impacts of each strategy through 2100 is presented in Table 9. Based on these estimates, nourishment is the most economically viable choice of the three approaches. This follows other findings that nourishment is economically preferable in densely developed areas (Daniel, 2001; Kriesel et al., 2004; Parsons and Powell, 2001).

4.2.2. *Impacts to environment, recreation, storm protection, and resources*

Most of this and other analyses comparing erosion management alternatives focus on economic costs and impacts. These impacts are not the only consideration. Consideration of the impacts to the environment, recreation, storm protection, and resources needed for implementation provides a more comprehensive comparison among strategies.

As to **environmental impacts**, a managed retreat policy seems most beneficial, as armoring often results in the loss of the beach and there are negative impacts associated with nourishment. While some have asserted that nourishment does not result in negative environmental impacts, Peterson and Bishop (2005) report that many of these studies are not thorough enough and do not reflect the true environmental impacts of nourishment. As acknowledged in the final report for the 2012 nourishment in Waikiki (DLNR, 2013), further research is needed to understand the full environmental impacts.

With **recreational** impacts, nourishment is preferred. Retreat and nourishment have similar benefits since beach width is maintained. However, nourishment provides immediate width while retreat requires coastal processes over time for the beach to develop. Armoring results in the loss of recreational value of the beach as it disappears.

As to **storm protection**, risk is best minimized by diverting development away from the hazard zone (retreat). Because nourishment and armoring may encourage further coastal development, managed retreat might be the better option as it further reduces vulnerability to disasters (Burby et al., 1999). Waikiki is susceptible to many coastal hazards including hurricanes and tsunamis as well as erosion (Wiegel, 2008). A coastal disaster could have significant impacts due to the exposure and high population densities in Waikiki. Managed retreat may be more suitable from a long-term resilience perspective as Burby et al. (1999) suggest.

With regard to the **resources** needed for each approach, Waikiki has limited resources for both retreat and nourishment. Land for retreat is scarce in Waikiki. Identification of new lands for relocation may also be challenging in Hawaii (Office of Planning, 2019). Sand for nourishment is also a limited resource. With diminishing sources of suitable sand, nourishment can become more costly and challenging (Gopalakrishnan et al., 2011). This is a concern for Hawaii, where the availability of suitable sand and the impacts associated with acquiring sand need further investigation (DLNR, 1999; Romine et al., 2015). Without an adequate supply of suitable sediment and equipment, erosion management may trend towards armoring solutions, as in Italy (Pranzini, 2018) and Argentina (Isla, 2018).

5. Discussion

5.1. *Nourishment as a viable strategy*

Nourishment is a viable erosion management approach in Waikiki in comparison to armoring and retreat, considering current erosion projections and associated management impacts of alternatives. This finding is based on the economic impacts associated with the strategies and the advantages of nourishment over other approaches in this tourist destination. This finding is supported by other studies that correlate beach nourishment and beach width with tourism-driven revenue (Alexandrikas et al., 2015; Houston, 2013). In examining the impacts of erosion in the coastal tourism city of Rethymnon in Crete, Alexandrakis et al. (2015) combine erosion projections and economic data to estimate erosion risk, and also find that interventions such as nourishment are viable. While the costs of armoring and nourishment are on the same order of magnitude in Waikiki, the indirect costs associated with beach loss and reduced economic activity make nourishment a more optimal choice. The costs of retreat are an order of magnitude higher than other strategies due to the density of development in Waikiki. In spite of positive environmental impacts and reduction of storm risk, economic impacts of a retreat strategy may make it impractical to implement in Waikiki, and dense urban areas in general (Williams, 2018). A managed retreat strategy may be more appropriate in areas of lower density and value, as was found in a study of nourishment feasibility in coastal Portugal (Stronkhorst, 2018). Other than being less dependent on limited resources, armoring is less optimal across all other categories. This analysis does not assign a weight to each category. Future work might involve determining priorities and preferences of stakeholders.

5.1.1. *Beneficiaries of erosion management*

The analysis focuses on the impacts each strategy would have on the economy, environment, recreation, storm protection and resources.

[6] The Waikiki shoreline is approximately 2650 m in length. Approximately 500 m of shoreline currently contains no beach fronting an existing seawall.

Another factor to consider in evaluating strategies is the beneficiaries of each strategy. Beneficiaries of erosion management strategies in Waikiki include beach users, hotels, businesses, government (state and local), and residents. In the case of armoring, protection would be provided to waterfront properties – mainly hotels and government owned parks. The impacts of armoring are likely to harm hotels and government, as well as businesses, due to lost economic activity resulting from beach loss. The loss of the beach due to armoring also impacts beach users, as this public resource would no longer exist. In the case of retreat, beneficiaries include only beach users and residents who gain proximity to the coast, as the lost land and capital is likely to hurt all other stakeholders due to lost revenue and property loss. A nourishment policy benefits the most stakeholders in Waikiki, as economic activity and use of the beach would be maintained. While more in-depth stakeholder analysis on erosion is needed, Francis et al. (2019) found that beach nourishment and green approaches are strongly supported and there are opportunities to build coalitions across business, community and environmental stakeholder groups.

5.1.2. A No-regrets approach

Beach nourishment may offer a more flexible, no-regrets solution to erosion. A no-regrets solution provides benefits which exceed costs, regardless of the effects of climate change or SLR (De Bruin et al., 2009; Fussel, 2007; Heltberg et al., 2009; Spalding et al., 2014). If SLR-induced erosion is less than projected, nourishment still offers the benefits of sustaining visitor activity and maintaining recreational and cultural use of Waikiki beaches. Armoring, if implemented exclusively, would not guarantee these same benefits and retreat would require significant irreversible investment. With the uncertainty of SLR projections, nourishment offers an adaptive approach that can be implemented and adjusted incrementally if needed (Stronkhorst, 2018). In an analysis of past beach nourishment in Florida, Houston (2019) reports that nourishment may result in wider beaches in the future even under all current IPCC scenarios. Stronkhorst et al. (2018) also find that nourishment is a viable adaptation strategy in the Netherlands into the future. No-regret solutions are recommended for coastal areas and ecosystem-based adaptation (Spalding et al., 2014; Tang, 2013). A no-regrets attribute has been used in evaluating adaptation options (De Bruin et al., 2009), and can be added as a criteria to this framework depending on the priorities of the community.

5.2. Implications for beach management planning and policy

5.2.1. Location and timing of erosion risk and intervention

The analysis compares the viability of armoring, nourishment, and retreat as a broad-brushed approach across Waikiki. This is useful in gauging order of magnitude costs and impacts of each strategy. In practice, erosion management interventions will likely be site-specific and may include a combination of these and other strategies. Based on projected erosion in each littoral cell, the analysis identifies the location and timing of erosion impacts and management interventions at the cell-level. Armoring and retreat estimates provide an indication of existing seawalls, land and buildings at risk and the general timing of that risk (2015–2050, 2050–2100) in each cell, while nourishment values inform the timing and scale of replenishment for each of the cells.

Erosion risk is a combination of projected erosion and the assets within the affected area. The Royal Hawaiian and Queens cells are the most erosive, and the most at risk over both time periods. This is due to their high historic erosion rates and the land and structures that fall within the erosion zones. The Halekulani cell has the lowest erosion rate, however is the most at risk in the 2050–2100 time period, due to the thirty-story hotel within the 2100 erosion zone. The Halekulani and Queens cells are both characterized by narrow beaches backed by seawalls which are at risk and will need repairs in the short and long-term in the absence of nourishment.

The uses within the cells may also factor into risk and interventions. The beaches within the Royal Hawaiian and Kuhio cells are the most popular among beach users and visitors. Erosion may pose a high risk even in the absence of property in the erosion zone, such as in Kuhio. Intervention efforts may be prioritized in these cells to maintain activity and focus on beach restoration. Considering its current use and assets, the Royal Hawaiian cell is the most at risk. This cell has been the focus of the most recent nourishment effort and repair projects (Eversole et al., 2018).

Beach preservation is a priority action in the City and County of Honolulu's resilience strategy (City and County of Honolulu, 2019). Nourishment will be a key tool among other strategies to manage the beach, maintain the appeal and increase the resilience of Waikiki. Existing groins and structures form the boundaries of littoral cells and influence sediment dynamics in Waikiki. These structures will need repairs or upgrades to maintain or improve sediment processes and ensure nourishment efforts are successful over time. New designs and innovations to coastal structures in Waikiki may improve existing erosion rates and reduce projected nourishment costs. With climate change and increased risk of storms, minimizing new development will help reduce risk from extreme events. Over time, strategies such as land acquisition, elevation or relocation may be appropriate to reduce the occurrence of repetitive damage.

5.2.2. Waikiki beach management financing

A long-term nourishment policy requires commitment to a recurring maintenance program, adequate sand supply and significant investments (Stronkhorst, 2018). Identifying sediment sources and financing are long-term goals of the Waikiki Beach Management Plan developed by the WBSIDA (Eversole et al., 2018). This analysis provides order of magnitude estimates of nourishment costs through 2050 and 2100. The WBSIDA provides a financing mechanism for beach restoration. The WBSIDA collects special assessments from commercial properties in the district at a rate of seven cents per thousand dollars of property value (WBSIDA, 2019), generating roughly $550k annually in assets for beach management (Miyaki, 2018). It should be noted that the order of magnitude costs for nourishment may underestimate actual costs due to erosion and SLR uncertainties and inflation of construction costs. WBSIDA revenues, therefore, may not be sufficient to fund future nourishment efforts and other improvements in Waikiki. Other dedicated sources will be needed to fund beach management efforts in the future. These could include the State Beach Restoration Fund, for which recent legislation dedicates revenue from the Transient Accommodation Tax (TAT) (State of Hawaii, 2015a). This fund is dedicated to beach restoration statewide and not solely for Waikiki. Public/private partnerships such as those used for the 2012 nourishment project may also supplement these state and local sources (Eversole et al., 2018). There will need to be collective actions and building of coalitions across stakeholders in order to plan, finance, and implement mitigation and adaptation strategies to address erosion into the future (Francis et al., 2019).

Since future and recurring nourishment efforts will be location-based, the cost-sharing schemes can be tailored to the location of each project. A possible approach could employ a similar to the most recent nourishment in 2012, which cost $2.4 million. Approximately 20% of the costs were funded by the abutting property owner, 20% by the Hawaii Tourism Authority (HTA), and 60% by the State Beach Restoration Fund - for a total allocation of 80% state government funds and 20% private funds (DLNR, 2013). Future nourishment projects could utilize a similar 80/20 share between public and private sources. HTA's cost share can be accounted for in the State fund. The new public funding source through the WBSIDA could contribute to the 80% government share. It is expected that private contributions will be needed in the future. The 20% private share could be funded by abutting property owners (as in the 2012 project), but prorated by the amounts contributed via the WBSIDA special tax. This sample allocation structure would be project and location dependent, as in some cases the abutting property owner may be government. Cost-sharing arrangements would require state/county agreements for the public share of nourishment costs, as well as the coordination of public-private partnerships, for which the WBSIDA is well situated and authorized to do. This analysis and framework can support identifying stakeholders, tradeoffs and appropriate cost-share arrangements by littoral cell.

5.2.3. Federal disaster assistance

Planning efforts should identify federal funding sources to supplement state and local financing. Coastal disasters often involve severe beach erosion. It is important for Waikiki Beach to be restored as quickly as possible to ensure economic recovery. Disasters offer unique federal funding opportunities tied to recovery and mitigation. Nourishment and other beach restoration efforts may be eligible for funding under several U.S. Federal Emergency Management Agency (FEMA) grant programs: Pre-Disaster Mitigation Program (PDM), Hazard Mitigation Grant Program (HMGP), and Public Assistance Program (PA). The PDM program is an annual competitive grant meant for planning or projects to reduce risk to future hazards. The HGMP provides mitigation planning or project implementation grants for affected states and communities after a federal disaster declaration (FEMA, 2015). Beach nourishment and other major coastal protection measures have been deemed eligible for PDM and HMGP funding as of 2014 (FEMA, 2014). PA grants are given to state and local governments for *emergency* (protective) and *permanent* (public facilities repair) work related to disaster response and recovery after a disaster declaration (FEMA, 2018). Eligible *emergency* beach restoration efforts include construction of protective sand berms to restore protection against a 5-year flood, while eligible *permanent* work includes restoration of beaches meeting certain criteria (to be considered a public facility): 1) the beach is not an Army Corps of Engineers-constructed beach, 2) the beach was engineered and constructed via nourishment, and 3) the beach is periodically nourished under a recurring maintenance program (FEMA, 2018).

Other potential federal funding sources include the Department of Housing and Urban Development (HUD) Community Development Block Grant-Disaster Recovery (CDBG-DR) program. CDBG-DR funds are appropriated after a federal disaster declaration for projects related to community and economic recovery (HUD, 2018). Funds are appropriated to the affected state government, which is required to work with local governments and communities to develop a CDBG-DR Action Plan describing the unmet needs and use of funds (HUD, 2018). CDBG-DR projects have included beach restoration and coastal protection elements in the past. The Rebuild by Design competition, funded by CDBG-DR after Hurricane Sandy, awarded funding for a *Living Breakwaters* project, which included submerged breakwaters and beach restoration in Staten Island, New York (GOSR, 2018). The North Carolina CDBG-DR Action Plan also included beach restoration as possible solutions after Hurricane Matthew (State of NC, 2016).

5.2.4. Waikiki beach management planning

The Waikiki Beach Management Plan is to "serve as an overarching framework for the development, evaluation and implementation of technical beach management alternatives for Waikiki" (Eversole et al., 2018, p.25). This analysis can help inform the *Needs Assessment*, *Alternatives Analysis* and *Economic Value Analysis* phases in the plan, as well as the implementation objectives to "identify and evaluate potential management and engineering strategies" and "assess advantages and disadvantages of potential…strategies" (Eversole et al., 2018, p.27). The erosion projections and valuation of assets can inform priorities within each cell, while the comparative framework can be useful for the evaluation of other strategies and stakeholder priorities.

The criteria for federal disaster funding have several implications for Waikiki beach management planning. PDM project grants, HMGP grants, and PA require an approved state hazard mitigation plan (FEMA, 2019). Applications for these programs must also be submitted by the state government. It is important for Waikiki planners to work closely with city and state hazard mitigation planners to ensure beach restoration efforts are integrated into mitigation planning and grant application processes. Also, it is imperative that a recurring maintenance program is established for Waikiki Beach. This includes a detailed plan with identified funding sources and details on nourishment schedule (FEMA, 2018). The Waikiki Beach Management Plan is a first step in this process, but more planning and research is needed to formalize a maintenance plan to meet FEMA criteria. For the use of CDBG-DR funds, a project must include community and economic revitalization elements. A well planned CDBG-DR project for Waikiki can include beach management elements in conjunction with broader goals of the Waikiki community visioning process outlined in the Waikiki Beach Management Plan.

5.3. An adaptable foundation for targeted inquiry

This analysis represents a first pass at estimating erosion management costs and impacts in Waikiki. The strength of the analysis lies in the identification of management considerations, its adaptability and its findings in this local context. Management considerations specific to densely developed tourist beaches in island settings are identified. These include the economic considerations related to the visitor economy, the inventory of risk and challenges in waterfront resort areas, the stakeholder impacts of erosion management strategies, and the importance of flexibility in management. The comparative framework identifies six criteria for evaluating management strategies, but offers opportunities for modification and more comprehensive comparison as needed. Two additional criteria include stakeholder impacts and flexibility (no-regrets). The findings provide insight for Waikiki planning and identify opportunities for future study.

5.3.1. Limitations and assumptions

This simple method allows for easy adaptation for other settings and strategies. Other methods may better absorb sensitivities in erosion and cost projections. This analysis is sensitive to historical erosion rates, SLR projections, and unit costs for nourishment, construction, and demolition. Several assumptions were made due to data availability and simplification. For erosion projections, this included using average historic erosion rates across the entire littoral cell and utilizing a modified Bruun Rule approach for SLR influences. Variation within each cell was not available for all studies reviewed (Miller and Fletcher, 2003; Sea Engineering, 2010). Including the in-cell variation of historical erosion trends would better identify erosion hotspots within the cells, but significant changes in order of magnitude costs would not be expected, nor would this affect the qualitative assessment of management impacts. The Bruun Rule provides a simple method with few parameters for approximating SLR effects on shoreline retreat, but ignores sediment sources and the presence of fringing reefs, such as in Hawaii (Anderson et al., 2015). Anderson et al. (2015) develop a model to estimate SLR-induced erosion in Hawaii to include historic trends and known sediment sources and sinks. This and other studies used in this analysis, do not account for the effects of past nourishments on erosion rates in Waikiki (with the exception of Sea Engineering, 2010). Applying Anderson et al. (2015) while removing the effect of previous nourishments may yield more accurate erosion volume and cost projections in this analysis.

Topics not addressed in this analysis include risks from other hazards (e.g. flooding, waves, storm surge), uncertainty, and the influence of coastal structures. Habel et al. (2016) model groundwater inundation due to SLR and tidal flooding in Waikiki. Under the same SLR scenario used in this analysis (0.98m), over 40% of Waikiki will be inundated during high tides and heavy rainfall (Habel et al., 2016). Anderson et al., (2018) assess multiple SLR-influenced hazards in Honolulu (passive flooding, annual wave inundation, and chronic erosion), showing dramatic increases in exposure to combined hazards. An evaluation of strategies in this multi-hazard context may find other mitigation strategies, or a combination of strategies, may be more appropriate.

Uncertainty exists in the available coastal data and projections, including historical erosion rates, sea level rise, and beach slope (Anderson et al., 2015), as well as the influence of storms (Revell, 2011), when projecting to 2100. For erosion, uncertainty increases the further out in time it is projected, especially when extrapolated based on historical imagery (Leatherman et al., 1997; Smith and Zarillo, 1990). For simplification, uncertainty is not included here and current worst-case scenarios are used, however these scenarios can change. Including uncertainty would result in a range of cost estimates for each strategy and capture possible fluctuations in future observations. Addressing uncertainty by revealing the probabilities of erosion impacts can assist in adaptation decision-making (Spirandelli et al., 2016).

5.3.2. Opportunities for future research in Waikiki

The findings of this analysis provide a foundation and highlight opportunities for further study in Waikiki. Future research can integrate stakeholder input to validate and weigh criteria to inform future planning efforts. This can involve more detailed multi-decision criteria analysis techniques, which have been used to inform adaptation planning in tourist areas in Greece (Michailidou et al., 2016). The economic analysis can be augmented with quantification of benefits and the value of ecosystem services, important information for beach planning in Waikiki (Tarui et al., 2018). Future research is needed to estimate how partial beach loss would affect tourism activity in Waikiki, as well as the timing of nourishment activities. Landry and Hindsley (2011) explore the effect of beach width on coastal property values in Georgia, while Alexandrakis et al. (2015) examine the correlation between gradual beach narrowing and potential tourism revenue losses in Crete using tourism-related economic data and a hedonic pricing approach. Stronkhorst et al. (2018) compare two nourishment approaches – 1) estimating volume to maintain current shorelines (similar to this study) and 2) a sediment balance approach which nourishes high value areas based on expected sediment sources and sinks. In doing so, Stronkhorst et al. (2018) estimate the volume, frequency, and costs of nourishment in Portugal and the Netherlands through 2100. These studies along with Tarui et al.'s (2018) study serve as foundations for future research on the effects of partial beach loss on visitor activity in Waikiki, as well as the design of optimal nourishment schemes. This information and the incorporation of erosion probabilities (Spirandelli et al., 2016), can also inform the timing of management interventions. This analysis focuses on nourishment, armoring, and retreat. Future planning would benefit from comparing other management strategies as identified by others (Rangel-Buitrago et al., 2018; Williams, 2018), especially in the context of multiple hazards and climate change. Examining the links between erosion and other hazards, as well as the co-benefits of strategies, can also help adaptation decision-making in Waikiki.

6. Conclusion

Beach nourishment has been the predominant method to mitigate erosion in Waikiki in the past, and is likely to be an integral part of beach management into the future. The evaluation and comparison of the management impacts of nourishment, armoring, and retreat reveals that this approach is warranted in Waikiki under current scenarios. Although the approximate costs of nourishment are on the same order of magnitude as armoring, the indirect impacts associated with property and beach loss, as well as impacts to stakeholders, justify using beach nourishment over armoring and retreat to mitigate erosion in Waikiki. Through an analysis of future erosion and an adaptable comparative framework to assess management impacts, the study concludes that nourishment provides an appropriate, flexible, no-regrets approach to beach management in this setting. While it treats Waikiki as a whole, the evaluation could also be applied at the littoral cell scale and in other coastal settings. Further work at the cell level could better inform the evaluation of cell-specific solutions for the Waikiki Beach Management Plan.

Several implications for planning in Waikiki emerge from this analysis. Beach management must be integrated with hazard mitigation planning at the state and city level to take advantage of federal funding opportunities. This also requires establishment of a formal recurring beach maintenance program to meet federal funding requirements. The findings and framework present opportunities for stakeholder participation and engagement in future planning and deliberation of alternative approaches to financing beach improvements. Future planning would also benefit from incorporation of uncertainties of SLR effects and contingencies based on the timing of interventions in Waikiki. Evaluating strategies in a multi-hazard context may reveal other approaches and facilitate adaptation decision-making.

Managing beach erosion is important to communities which rely on coastal resources for livelihoods, recreation, and other human activities. Strategies to mitigate erosion must balance beach preservation, the public's access to coastal resources, and the economic activity the beach supports. The analysis demonstrates that nourishment as an erosion management strategy better balances these factors in Waikiki compared to managed retreat or armoring. Climate change poses significant threats to Waikiki in terms of increased erosion and storm events. As the understanding of these threats improves, solutions may evolve beyond nourishment. Informed planning and evaluation of strategies can ensure solutions align with community goals and address risks into the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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