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A Science and Community-Driven Approach to Illustrating Urban Adaptation to Coastal Flooding to Inform Management Plans

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Abstract: Academic research plays a pivotal role in illustrating and testing potential future adaptation strategies to sea level rise in low-lying coastal communities and enhances local municipalities' adaptation plans. In Waikīkī, Hawaiʻi, the built environment is increasingly impacted by flooding from multiple drivers: sea level rise-induced direct marine inundation, storm-drain backflow, and groundwater inundation (GWI), compounded by high-wave runup, extreme tides, heavy rainfall, and a shallow groundwater table. Given Waikīkī's economic and cultural importance, in-place accommodation of flooding is desired, yet implementation plans have not been developed. By combining current scientific research, urban design visualizations, and community feedback, the interdisciplinary research team advanced intentional communication between the many parties seeking increased flood resilience through the end of the 21st century. Site-specific architectural renderings were a key tool to prompt structured community input on the coordination, prioritization, policy, and feasibility of adaptation measures for buildings, utilities, transportation, and open space. Public outreach reports document that the majority of participants thought all adaptation strategies presented were applicable, especially relocating critical equipment in buildings and streets. Proposed methods to develop sea level rise-adjusted minimum building elevation requirements may inform local municipalities' future codes to minimize coastal property damage. The multi-year iterative process fostered growing participation in hosted and invited events, further improving the publicly distributed research products.

Keywords: sea level rise adaptation; climate change; resilient design; architecture research

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1. Introduction

Waikīkī is a 3.89 km^2 (1.5 mi^2) intensely developed commercial, residential, resort beachfront urban area in Honolulu, HI [1]. This economic hub is a popular recreational and cultural destination for tourists and locals and contributes to approximately 42% of the state's visitor industry revenue and $5 billion of the Gross State Product [2]. Waikīkī is located in a low-lying area, and challenges of flooding include sea level rise-induced direct marine inundation, storm-drain backflow, and groundwater inundation (GWI) [3,4], compounded by high-wave runup, extreme tides, heavy rainfall, and a shallow groundwater table [4,5]. Figure 1a–c shows high wave run-up and a king tide washing over the beach and impacting existing structures. Consistent investment in the beachfront includes beach nourishment [6], groin repair/replacement to address present-day erosion [2], and future flooding from sea level rise.

Figure 1. Images in summer 2022 during a king tide event at high tide showing (**a**) high wave run-up and loss of vegetation, (**b**) inundation of the beach and building edge, and (**c**) exposed infrastructure. Credit: Eric Teeples, Melanie Lander, and Wendy Meguro.

Currently, there is no comprehensive guidance on sea level rise adaptation in Waikīkī. Honolulu's first draft climate adaptation strategy, Climate Ready O'ahu [7], identifies the desire to retrofit city facilities at risk from storms and flooding; however, the implementation timeline, funding, and strategies are not yet defined in local area plans. Guidance is needed for all existing and new buildings and infrastructure to accommodate episodic flooding through 2050. With permanent inundation likely around 2100, accommodation and retreat will need to be approached through planning, policy, regulatory, and financing tools [8]. Although retreat is outside of the scope of this research, retreat should only be considered with community agreement and within the context of other adaptive approaches, along with a careful cost–benefit analysis [8].

The team sought to answer the following questions: (1) Can coordinated discussion of conceptual architectural renderings increase people's knowledge of sea level rise impacts and adaptation strategies? (2) How may renderings of future flooding and potential site-specific sea level rise adaptation strategies support a systematic investigation of public sentiment and result in new knowledge of people's opinions on the strategy's applicability? [9] (3) How may applied academic research inform local area plans, infrastructure design criteria, and building codes?

This paper illustrates a replicable process in which academia plays a vital role in addressing public problems [8] by providing new visualizations to the community and government, utilizing and recording input from participating community members, and creating reports to inform future guides and policy. This research builds upon successful examples of collaboration between governments and existing citizen groups, including Lynnhaven River Now, a non-profit organization in Virginia, which "acts as a bridge between the city government and citizens, collaborating between the two, to address the effects of sea level rise" [10]. Local governments in Washington found early outreach with the public on sea level rise planning helped build consensus around the need to take action and understand the concerns of private landowners [11], and, similarly, this research utilized public workshops to increase understanding of sea level rise and capture valuable feedback in an online report (Stakeholder Report, 2023) [12]. This research builds upon applied research at the Louisiana State University [13] seeking to increase a community's adaptive capacity, the ability to prepare for environmental stressors in advance to make it more resilient to disturbances (e.g., sea level rise) [14] This research facilitates and documents deliberation amongst diverse stakeholders during public presentations, which is one of the key elements needed to build adaptive capacity [14].

Academic design research involving input from the government and the community may influence future laws and regulations [11], such as the Waikiki Special District Guidelines [15] or the forthcoming Adapt Waikiki 2050 project [16]. Similar to research in Paris, France, this research utilizes a replicable process for climate-resilient urban design that integrates analysis of climate impacts with concerns of local communities and applies it to a specific location to suggest possible adaptation measures [17]. This research informs and precedes future assessment of feasibility and cost of implementation.

2. Materials and Methods

This academic design research utilizes scientific knowledge, precedent studies, and community participation to generate new illustrations of potential modifications to the built environment that accommodate future flooding. The team's public presentations, followed by voluntary surveys and discussions are rigorously documented to provide information to guide sea level rise adaptation policy and design. Two modes of scholarly production are utilized: (1) design practice in which systematic investigation results in new knowledge, replicable processes, and adaptable information through deliverables (drawings) that provide a solution to a problem to organize actions to achieve it [9]; and (2) community engagement through collaboration between institutions of higher education and their larger communities for the mutually beneficial exchange of knowledge in a context of reciprocity [9].

The American Institute of Architects Resilient Project Process Guide [18] outlines actions for climate adaptation projects in the visioning, pre-design, design, construction, and post-occupancy phases. This research partially addresses the visioning phase by identifying and collaborating with stakeholders, identifying flood hazards, risks, vulnerabilities, and opportunities, and establishing performance goals for the continuous operation of Waikiki recreation, businesses, and residences by analyzing flood adaptation standards and guides. This research primarily addresses pre-design issues by visualizing flood hazards on at-risk sites, illustrating potential new performance guidance and strategies for adapting buildings, open space, transportation, and utilities, and querying diverse stakeholders on the strategies' relevance and soliciting discussion.

The research presented in this paper was conducted in 2022–2023 and is part of an ongoing research effort initiated in 2020 by an interdisciplinary team at the University of Hawai'i (UH) School of Architecture (SOA)'s Environmental Research and Design Laboratory (ERDL); the School of Ocean and Earth Science and Technology (SOEST)'s Climate Resilient Collaborative (CRC); and Sea Grant College Program's Center for Smart Building and Community Design (CSBCD). The team, composed of students and faculty from architecture, landscape architecture, environmental design, climate science, geology, and Sea Grant, allowed for enhanced research outcomes by utilizing individual expertise to share knowledge, networks, and validate the research. Two-dimensional maps of modeled future flooding and the 3D LiDAR topography were provided by the SOEST CRC, and the adaptation research, renderings, and outreach organization were created by the SOA ERDL and SG CSBCD. There are parallels between this research and other university-led community-applied research, such as Cal Poly Humboldt's SLR community partnership, which recognizes that the preeminent higher education institution in the region can lead climate resilience education and research by incubating new solutions and combining different ways of knowing in geographic areas affected soonest [19].

Through coursework and research, the team iteratively utilized the following process three times.

1. Survey and summarize existing standards, guides, and precedent projects with flood adaptation strategies that may be viable in Waikīkī.
2. Identify episodic and chronic flood hazards in 2050 and 2100.
3. Identify study sites that are flooded soonest [20]; represent a variety of building typologies [21]; include older, at-grade, or below-grade spaces vulnerable to flooding that may be redeveloped sooner [22,23].
4. Visit sites and analyze site-specific potential sea level rise adaptation strategies for buildings, open space, transportation, and utilities.
5. Produce conceptual 3D architectural renderings incorporating flood adaptation strategies utilizing newly proposed sea level rise-adjusted design flood elevations.
6. Present and discuss potential adaptation strategies in a public webinar between academia, community, and government.
7. Summarize and share public feedback.

This paper presents three replicable products: (1) a method to establish sea level rise-adjusted design flood elevations (DFEs) for assets that will exist in 2050 and 2100; (2) a process to conceive of and produce architectural renderings of site-specific flood adaptation strategies; (3) a framework for public outreach, survey, and reporting.

2.1. Development of SLR-DFE

To establish performance standards in line with climate projections over a building's service life [18] and considering sea level rise scenarios, king tide, freeboard, and a 1% annual chance flood event, this research offers a method to determine the appropriate elevation of a building's occupied floors to increase its resilience and minimize coastal property damage. The following terms are used to discuss the height of future elevated buildings:

Base Flood Elevation (BFE) is the elevation of surface water resulting from a flood, including riverine and coastal flooding due to tropical storms, heavy rainfall, and—in some areas—tsunami or levee failure [24], that has a 1% chance of equaling or exceeding that level in any given year [25];

Design Flood Elevation (DFE) is typically the BFE plus any freeboard adopted by the community. Some communities adopt flood maps with elevations that exceed the BFEs and become their adopted DFEs [26];

Freeboard is the additional amount of height above the BFE used as a factor of safety (e.g., 0.61 m (2′) above the Base Flood) in determining the level at which a structure's lowest floor must be elevated or floodproofed to be in accordance with state or community floodplain management regulations. Freeboard is not required by the National Flood

Insurance Program (NFIP) [27] standards but results in significantly lower flood insurance rates due to lower flood risk [28].

Current FEMA FIRMs [29] do not account for sea level rise, leaving local municipalities to provide adaptation guidance for the built environment, including infrastructure, that will be more vulnerable to flooding as water levels increase. When this research started in 2020, the City and County of Honolulu (CCH) used the 2012 International Building Code (IBC), which "requires new construction to be designed with one foot freeboard* above current Base Flood Elevation (BFE) in hazardous flood zones," but, does not offer methods for design teams to implement DFEs with the BFE, SLR, king tides, and freeboard [30,31]. First, the team identified the present-day BFE at a study site utilizing the FEMA FIRMs. Second, the team estimated future sea level rise in 2050 and 2100 using the National Oceanic and Atmospheric Administration (NOAA) at the Honolulu tide gauge [32]. Per guidance from the Honolulu Climate Change Commission, the Intermediate-High sea level rise scenario was used due to the low tolerance for flood risk for long-term infrastructure and high-risk assets [33], such as buildings in Waikīkī. For projects that do not tolerate high levels of coastal flood risk, it is prudent to plan for a high-impact outcome in which there is a 50% chance of exceeding the Intermediate scenario, given the growing instability of the Greenland and Antarctic ice sheets [33]. The king tide was estimated in conversation with scientists at the University of Hawaiʻi. Based on design guidelines from various cities such as Boston and New York, the team selected a freeboard of 0.30 m (1′) because of the study building's use of the ground floor as non-residential [34]. This methodology has since been adopted into Boston's Zoning Code in October 2021, Article 25A [35]. Combined, the present-day BFE, SLR, king tide, and freeboard comprise the sea level rise-adjusted design flood elevation (SLR-DFE). The application of this method can be applied to a site and is discussed further in Section 3.

During the course of this research, however, the revised "Sea Level Rise II—Guidance Document," the CCH Climate Change Commission recommends using at a minimum "[t]he Intermediate or higher level sea level rise scenario as a benchmark, adding 0.30 m (1′) of freeboard to accommodate a King Tide, and adding an additional 0.30 m (1′) of freeboard to accommodate heavy rainfall at high tide when there is no drainage capacity in the coastal zone, would provide an even greater buffer against flood damage" [33]. This recommendation improves flood prevention and acknowledges the reality of multi-mechanism flooding.

2.2. Rendering Site-Specific Adaptation Strategies

To develop site-specific architectural renderings of flood adaptation strategies, the team identified and addressed the flood hazards and vulnerabilities and created design responses while pursuing design excellence and beautiful, functional projects [18]. The design phase gives form to the performance goals and supports the discoveries made during pre-design [18]. Other researchers find that "visualization aspects that are important for spurring reflection on adaptive action are specifying various climate parameters, relating climate impacts to established practices for managing weather risks, and emphasizing diverse concrete short- and long-term measures." [36]. This research addresses all three aspects by visualizing flood hazards three-dimensionally, modifying established building and street design practices, and illustrating adaptations in two timeframes.

During 2020–2022, earlier members of the research team identified the current flood hazards, exposure, and future projections in Waikīkī in order to identify study sites (Figure 2a,b) [21,37]. In 2050, passive flooding (dark blue) will impact a few areas, annual high waves inundate limited shoreline areas, and many areas have an elevated groundwater table leading to a narrow unsaturated space (defined here as having a vertical thickness of less than 0.33 m (1′ 1″), (yellow) (Figure 2a) [3,38]. The narrowing and loss of the vertical unsaturated subsurface space has implications for the dense network of below-grade and low-lying infrastructure, including utilities and roads that exist throughout the Waikīkī District [3]. By 2100, passive flooding will occur in nearly the entire district (Figure 2b) [38,39].

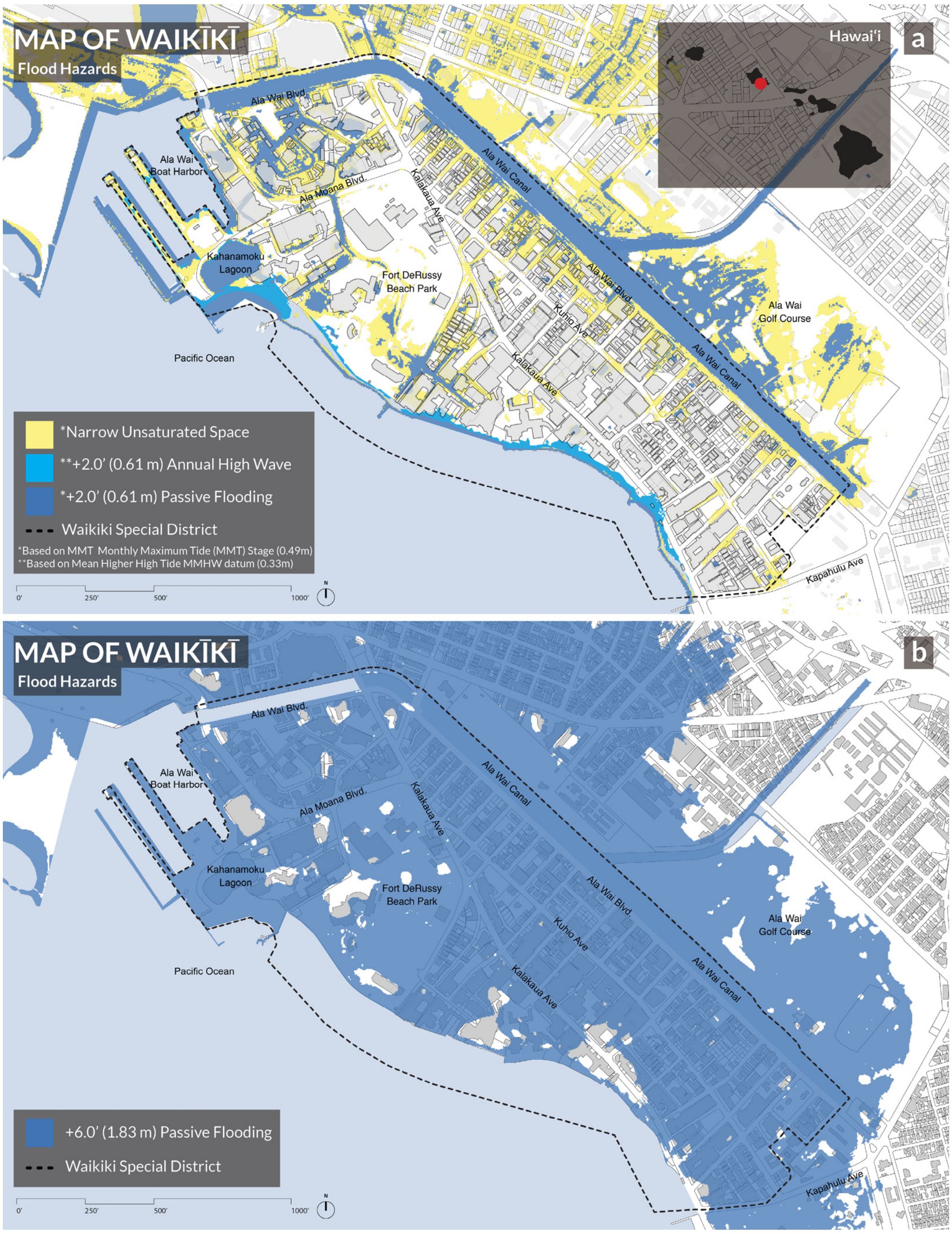

Figure 2. Flood hazards in Waikīkī District at (**a**) 0.61 m (2.0′) and (**b**) 1.83 m (6.0′) of SLR [3,38,39]. Image credit: Josephine Briones.

The 2022–2023 team studied a beachfront site near Kalia Road and Saratoga Road with a high-rise mixed-use residential and commercial building with below-grade parking, adjacent open space, and street. The team observed severe beach erosion and recession along the coastal edge, signs of inundation within below-grade and at-grade building spaces, and walkway and building material degradation due to high wave runup and high tide/king tide.

Based on earlier research on guides and standards, knowledge of flood hazards, public feedback from the two earlier public presentations, and site visits, the team developed architectural renderings of site-specific flood adaptation measures, including on-site stormwater retention calculations, and presented and discussed them in a public webinar hosted in June 2023. Precedent studies informed the rendered designs, such as TK Studio's Forest Pavilion in Thailand's elevated walkways over flood-prone areas [40]; Turenscape's Qinhuangdao Beach multi-purpose levee to detain water and preserve open spaces and circulation [41]; SCAPE Studio's, "Living Breakwaters" in Staten Island, New York to reduce erosion and dissipate high wave energy [42].

The 3D digital model included a 3D mesh of Waikīkī's existing topography from LiDAR data in a clipped digital elevation model (DEM) of Waikīkī from NOAA [43], in cooperation with the research group, the CRC in UH SOEST. This is the same model used to produce the Hawai'i Sea Level Rise Viewer [20] and was utilized with the intention of depicting future flooding consistent with other UH products. Using the 3D digital modeling tool Rhinoceros (Rhino) 3D [44] with Rhino Terrain™ [45] and Geographic Information System (GIS) data from local county [21] and state agencies [37], a scale model of the site was created and used to produce 3D renderings with software, Lumion 12.5 [46].

On-Site Stormwater Retention

Due to the limits of infiltration from a high groundwater table and limited drainage due to storm drain backflow, the team calculated the study site's rainfall volume and visualized on-site storage for a 95th percentile rain event. The study site areas for the building, street, and open space were multiplied by the rainfall depth to estimate the volume.

Based on a 28-year historical record for Waikīkī from 1992 to 2020 (due to data availability), a 95th percentile rain event would be 0.04 m (1.8″) over a 24-h period (station number GHCND: USC00519397) [47]. The calculation method is from the EPA Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects [48]. Note that although the EPA guidance calls for a 30-year data set, only a 28-year data set was available through February 2020. The site-specific diagrams depicting on-site stormwater filtration and storage in bioretention areas and cisterns give form to the performance goal and address the pre-design discovery of [18] the rising groundwater table.

2.3. Public Outreach and Survey

This research's public outreach seeks to improve community resilience [18] by soliciting and recording community input on flood hazards, potential adaptations, and preferences to inform future State, City, or area cost–benefit analyses or plans. Consistent community engagement through presentation, discussion, and survey on potential flood adaptation strategies at different study sites in 2021 and 2022 provided feedback from nearly 200 participants. The outcome of discussion themes, endorsements, and critiques informed the conceptual design renderings of a beachfront site in 2023. For instance, past renderings showed adaptations for low-rise and high-rise residential buildings along a primary road adjacent to the Ala Wai Canal, where many flood adaptations were focused on preserving the building and vehicular access for residents in the future and did not include extensive open space. Participant feedback suggested incorporating greater expertise in landscape architecture and integrating more research on adaptations for building systems, waste/sewer/stormwater, alternative transportation, and pedestrian access. With these additions and more, the 2023 online public webinar included architectural renderings of potential site-specific flood adaptation strategies for the beach and recreational open spaces and addressed community feedback regarding the phasing of different areas and more large-scale cooperation between public and private owners. From 2020 onward, the team intentionally sought participants with diverse relationships to Waikiki by first defining categories of desired participants and populating them with individuals identified through web searches, personal contacts, recommendations, and previous participation. The invitation encouraged those to share the event with colleagues.

Zoom [49] was used to host the webinar, and polls were conducted anonymously using the integrated app Mentimeter 3.0.0 [50]. The team polled the participants on the applicability of each potential flood adaptation strategy for Waikīkī, facilitated a panel discussion with guest experts, and hosted comments, questions, and answers with participants via the Zoom chat. The team also asked all participants if the public presentation and discussion increased their knowledge of sea level rise impacts and adaptation strategies. Through this recursive process, the team was able to cultivate relationships with key community members and improve design adaptations based on feedback. The project website includes slides, recordings, and stakeholder feedback reports as a public resource.

3. Results

Section 3 includes a method to develop an SLR-adjusted DFE, which facilitates conversations about future building design guides or codes. The rendering results demonstrate how visualizations of future flooding and potential adaptation strategies may support a systematic investigation of public sentiment. The results survey section produces new knowledge of people's opinions on each strategy's applicability. Survey results also show that coordinated discussion of conceptual architectural renderings increased knowledge of sea level rise impacts and adaptation strategies for about 75% of the respondents in 2023.

3.1. Development of SLR-DFE

The following renderings represent a Waikīkī site located at 2161 Kālia Rd, Honolulu, HI 96815. The current site includes a high-rise mixed-use residential and commercial building with below-grade parking, an adjacent open space known as Fort Derussy Beach Park, and a streetscape along Kālia Road. The site lies within the high-risk FEMA AE flood zone with the BFE at 2.44 m (8′) above local mean sea level (LMSL). The SLR-adjusted base flood elevation (SLR-BFE) is calculated by adding the present-day BFE, future SLR, and king tide. Using the NOAA intermediate-high scenario based on the Honolulu tide station, an increase of 0.37 m (1′ 2′′) SLR and a 0.20 m (8′′) KT, rounded to a total of 0.56 m (1′ 10′′) was used for the 2050 design adaptations. For 2100, an increase of 1.78 m (5′ 10′′) SLR and 0.26 m (10′′) KT rounded to 2.03 m (6′ 8′′) was used. For the SLR-adjusted DFE (SLR-DFE), a freeboard of 0.30 m (1′) is added to the SLR-BFE for each scenario. The proposed SLR-DFE is at 3.30 m (10′ 10′′) in 2050 and 4.78 m (15′ 8′′) in 2100, above the 2021 local mean sea level (LMSL) (Figure 3).

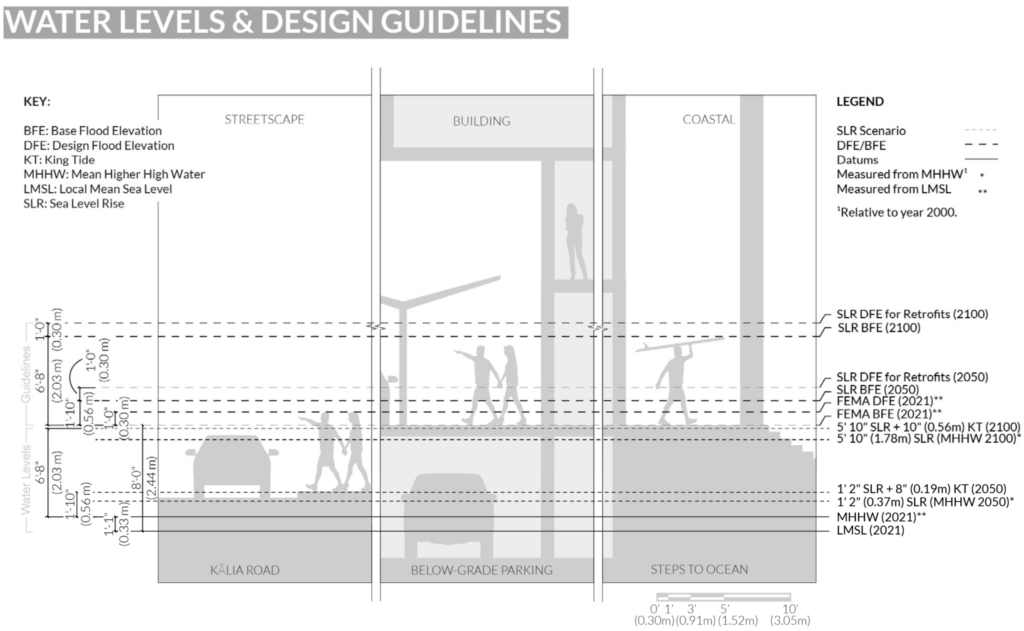

Figure 3. Water levels and design guidelines [32,51,52]. Image credit: Eric Teeples and Josephine Briones.

3.2. Rendering Site-Specific Adaptation Strategies

The site-specific proposed flood adaptation strategies include retrofitting the existing building and street infrastructure, reforming the open space, storing stormwater, and proposing green, nature-based, and hard infrastructure on the beachfront. Referencing the City and County of Honolulu Complete Streets Design Manual [53] and the Waikīkī Special District Design Guidelines [15], proposed adaptations align with similar goals to preserve the resort character of Waikīkī, prioritize multi-modal access, and offer recreational opportunities. Other supporting strategies that are not directly related to coastal flood risk [34] but aim to address climate change impacts, such as rising temperature, loss of habitat and native ecosystem, and food security, were incorporated to promote future sustainability. Examples include using shade trees, native and salt-tolerant plant species, recycled materials, and green and grey infrastructure throughout the entire site. A summary booklet compiles the research for each adaptation strategy available as an online resource (see the Data Availability Statement below).

3.2.1. Building and Street

Built-in 1959 [22], the 15-story, high-rise mixed-use building on site is primarily residential, with commercial space on the first floor and below-grade parking. The building's main entrance and first floor are at an elevated parking deck, and a vehicular ramp leads from the street down to the below-grade parking entrance. The height of LMSL and MHHW suggests the vulnerability of the building's below-grade space to unintentional groundwater seepage through cracks or joints (Figure 4a). Currently, the elevation of the FEMA BFE and DFE exceeds the below-grade parking and roughly meets the elevation of the building's first floor (Figure 4a). Parallel to the shoreline, Kālia Road, is the main access for the beachfront site, where people gather at numerous nearby resorts, restaurants, shops, and recreational areas. The streetscape includes two to three lanes of vehicular traffic with turning lanes and pedestrian islands at the intersection and roughly 1.22 m (4′) sidewalks on either side of the street. During high tide, storm drain backflow deposits salt water and sand onto the street [6].

In 2050, without adaptation, a combined 0.56 m (1′ 10″) SLR and king tide would inundate most of the below-grade parking and parts of the streetscape, limiting their use. In 2100, without adaptation, a combined 2.03 m (6′ 8″) SLR and king tide would cause major flooding to the entire streetscape and surrounding areas of the site, reaching the building's first floor. Raising the streetscape 0.58 m (1′ 11″) above the existing street in 2050 will protect the road base and bed while providing vehicular access to buildings. Proposed walkways elevated 4.88 m (16′) above the proposed streetscape in 2050 accommodate pedestrians and cyclists and remain functional during a 1% annual chance storm when the at-grade sidewalk cannot (Figure 4b). These integrated covered rest areas are made with photovoltaic panels. The former below-grade parking space is filled to the nearest adjacent grade to allow water to drain out of the structure slowly by gravity [34]. The former parking area volume above the nearest adjacent grade contains new rainwater cisterns to store runoff for filtration and use in the irrigation of the open space. Relocating critical systems for the building protects important utilities and infrastructure from rising sea levels and groundwater tables. Dry floodproofing minimizes the impacts on businesses, residents, and interior functions of the building during flood or annual high wave events by preventing the entry of floodwaters into interior spaces. Utilities, such as sewer, electrical, and water systems, are vaulted and elevated to protect them from inundation. To prioritize social space, the former parking deck that meets the elevation of the 2050 DFE would be limited to vehicle pick-up and drop-off only. Wet floodproofing and a trench drainage system to collect and redirect flood water at the building's first-level outdoor spaces and any space below the DFE reduces damage to the building components.

Figure 4. Building and street: (**a**) present conditions, (**b**) 2050 Adaptations, (**c**) 2100 Adaptations. Letters and numbers on the renderings correspond to the icons of adaptation strategies. Image credit: Eric Teeples.

Major changes from the 2050 to the 2100 adaptations include conversion of the streetscape to a canal for multi-modal transportation, reconstruction of the first floor at the elevation of 2100 DFE and making the space pedestrian dominant, planters for farming and water reuse opportunity in residential units, and increasing the cistern holding capacity (Figure 4c). Both scenarios allow for continued use of the building during a 1% annual chance storm with future sea level rise and create opportunities for integration of greywater and stormwater collection and retention that can be used for irrigation or slowly discharged to sewer after a flood event.

3.2.2. Open Space

Adjacent to the building is the largest open space in Waikīkī, Fort DeRussy Beach Park. Currently, the area is frequently used as recreational space and public access to the beach (Figure 5a). If no adaptations are made, in 2050, some of the parks will have a shallow groundwater table, and there are limited areas near Kalia Road experiencing groundwater inundation and limited annual high-wave flooding (Figure 2). According to the DEM, the majority of the open space ranges from 0.30–0.91 m (1–3′) above mean sea level. Aside from a man-made hill where the Hawai'i Army Museum sits, reaching an elevation of 4.88 m (16′) above MSL, the area would suffer major flooding in 2100 with roughly 2.13 m (7′) of SLR and king tide, and the social and recreation amenities would be lost.

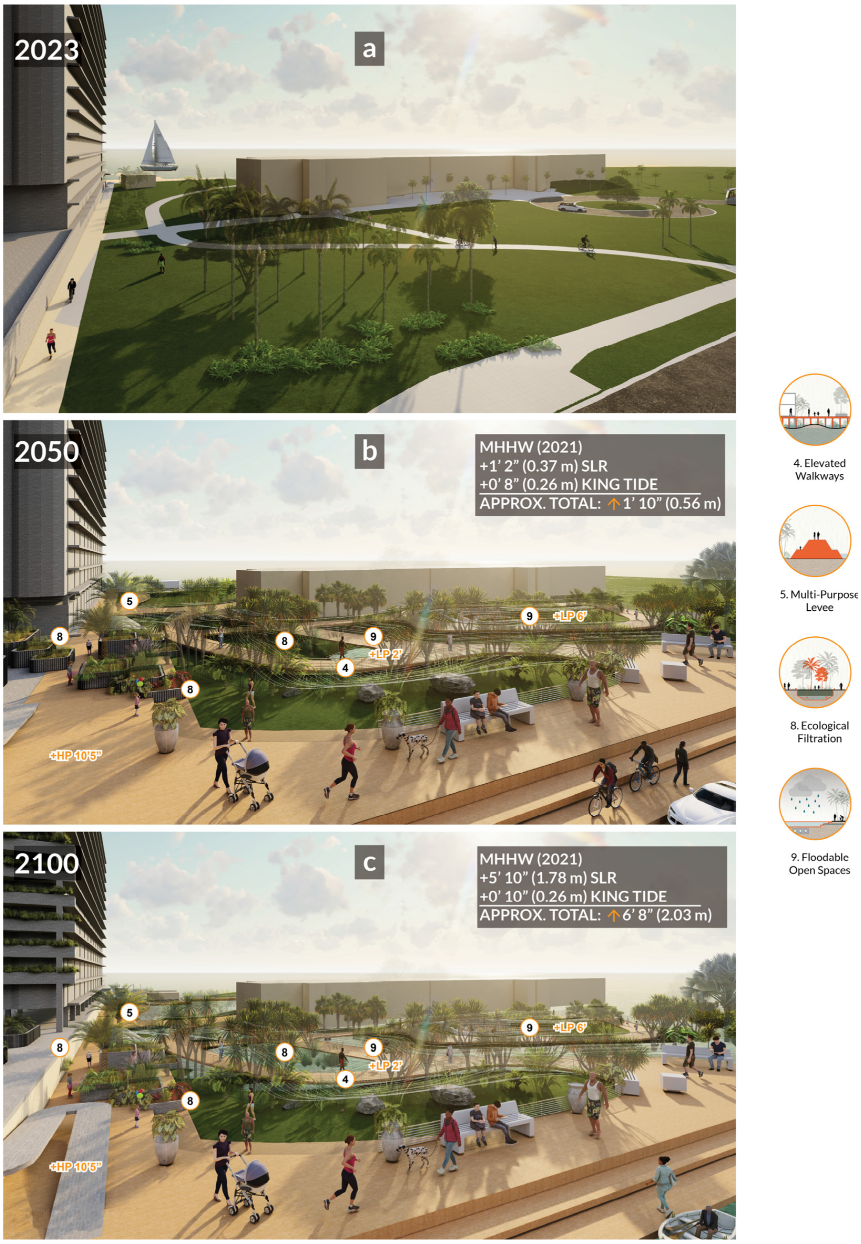

Figure 5. Open space: (**a**) present conditions, (**b**) 2050 Adaptations, (**c**) 2100 Adaptations. Letters and numbers on the renderings correspond to the icons of adaptation strategies. Image credit: Gerry Failano.

With the lack of available fill material, a cut-and-fill method would be used to reshape the topography. In 2050, a multi-purpose levee will create a barrier to block annual high wave run-up from the ocean and separate the stormwater bioretention areas (Figure 5b). Elevated walkways made from recycled materials 2.44 m (8′) above the current topography connect the open space to the building's first floor at the SLR-DFE, preserving human circulation throughout the area even during a 1% annual chance flood. New floodable open spaces direct stormwater runoff in swales toward bioretention basins for filtration and storage, protecting the surrounding built environment from flooding. Ecological filtration utilizes salt-tolerant and native vegetation for phytoremediation of the existing contaminated fill used to reshape the topography.

By 2100, the area's previous adaptations remain functional, even with some chronic flooding from direct marine inundation. The bioretention basins permanently accommodate saltwater (Figure 5c). The multi-purpose levee and elevated walkways connect pedestrians to the building and open space as water flows beneath. During a 1% annual chance flood in 2100, the walkways will be temporarily unusable.

The addition of team members from marine science, climate resilience, and landscape architecture disciplines to the original architecture, climate science, geology, and Sea Grant team generated more expertise on new strategies such as multi-purpose levee, wave energy dissipation, and greywater developed specifically for the beachfront site. Using a holistic approach to create resilience for the whole site, the open space and building adaptation strategies aim to perform cohesively.

On-site stormwater retention is calculated using a 95th percentile rain event for Waikīkī, collected on the surfaces of the open space, roads, sidewalks, and building roofs (Table 1, Figure 6a). The runoff is directed via piped gravity drainage, street flow, and a stormwater pump to the bioretention basins in the open space above future groundwater inundation and cisterns located above the nearest adjacent grade in the former parking garage (Table 1, Figure 6b). Combined, the total volume of runoff stored on-site in the 2050 scenario exceeds the volume of rainfall for a 95th percentile rain event (Table 1, Figure 6b).

Table 1. Calculations of stormwater management on the study site.

Stormwater Management Calculations (2050)			
Total Surface Area (Open Space, Roads, and Sidewalks (Highlighted in Yellow in Figure 6) + Building Surfaces (Highlighted in Green in Figure 6))	Rainfall Depth (95th Percentile Rain Event)	Volume of Rainfall on Highlighted Areas (Total Surface Areas × Rainfall Depth)	Total Volume Stored on-Site (Cisterns + Bioretention Basin)
20,261 m^2 (225,120 ft^2)	0.05 m (0.15 ft)	1013 m^3 (33,770 ft^3)	1053 m^3 (35,100 ft^3)

Water may be filtered and utilized for non-potable uses such as irrigation or toilet flushing. Additional water may be captured by adding cisterns in the available below-grade space, which could be used to store greywater from the building. Managing the on-site stormwater helps mitigate flooding in the area; however, it is acknowledged that there are limitations to below-grade water storage once the area becomes permanently inundated by sea level rise, especially in the 2100 scenario. Visualizing the water storage required to hold the volume of stormwater that falls on the site sparks discussion on replicability and feasibility of a similar approach throughout Waikīkī.

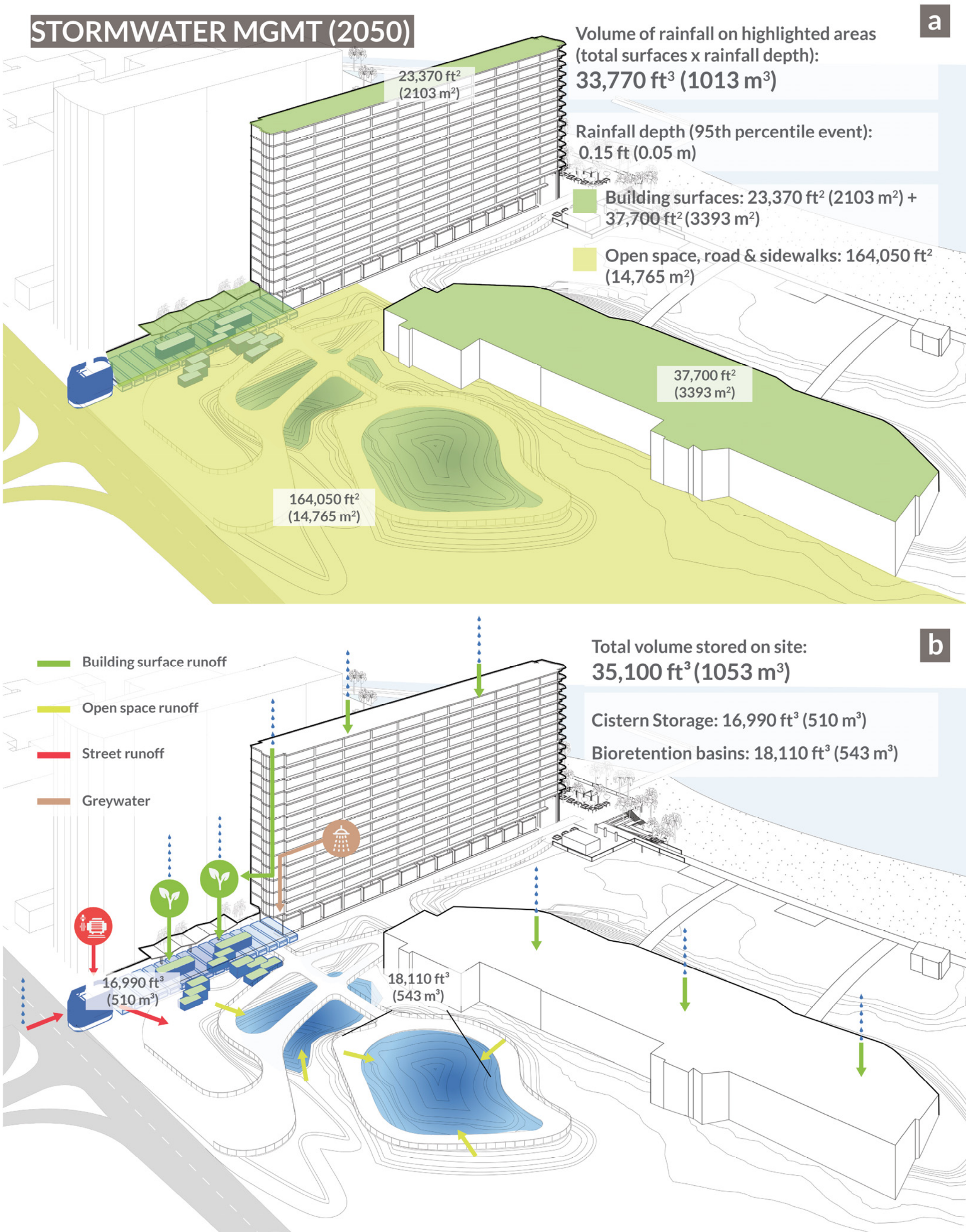

Figure 6. (**a**) Diagram of surfaces included in hydrology calculation and (**b**) diagram of water storage capacity on-site, including potential building greywater reuse. Image credit: Georgina Casey and Josephine Briones.

3.2.3. Coastal

The present conditions at the coastal area include a small stretch of beach, a man-made groin perpendicular to the shoreline, and access to the building's first floor, where a lanai (or veranda) of retail, food, and recreational, commercial spaces connect to the sand via stairs and ramps (Figure 7a). The area experiences limited beach access due to erosion, requiring beach nourishment to maintain access [6]. At-grade walkways along the beach are flooded by seawater at high tide and king tide events, preventing beach access and posing hazards to the public. Existing buildings and infrastructure show signs of corrosion from saltwater exposure from high wave run-up. In 2050, without adaptation, a combined 0.56 m (1′ 10″) SLR and king tide would increase the severity of coastal erosion and limit public access to the shoreline. In 2100, without adaptation, a combined 2.03 m (6′ 8″)

SLR and king tide would inundate the entire beach, and the commercial spaces would flood. To address SLR impacts for this area, adaptation strategies are proposed to preserve public accessibility to the beachfront and improve the building's resilience to flooding for continued operation.

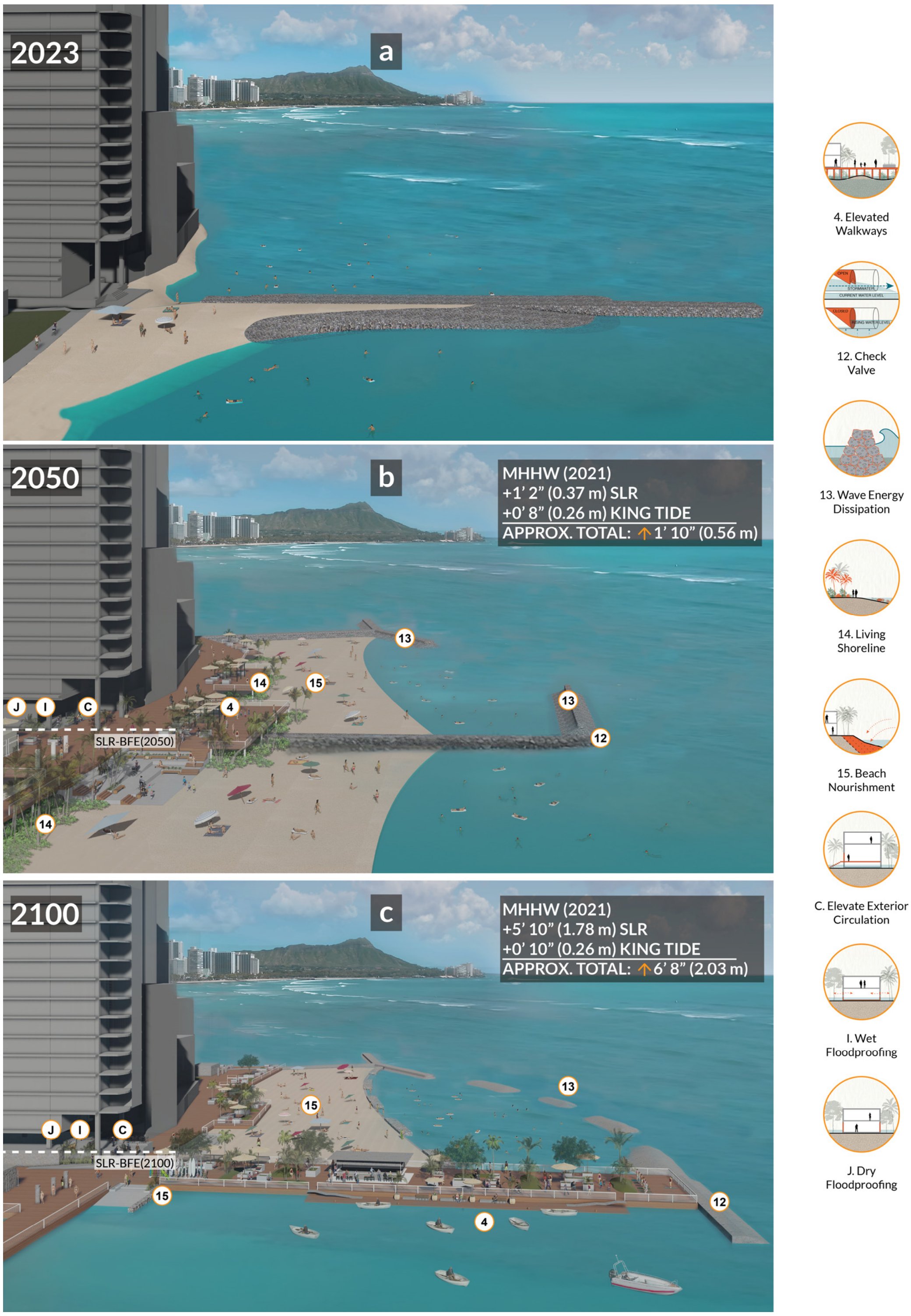

Figure 7. Coastal: (**a**) present conditions, (**b**) 2050 Adaptations, (**c**) 2100 Adaptations. Letters and numbers on the renderings correspond to the icons of adaptation strategies. Image credit: Desiree Malabed and Georgina Casey.

Adaptations in 2050 align with the current plans for Waikīkī, including beach nourishment and man-made groins (Figure 7b) [2]. Beach nourishment increases the width and height of the beach and slows the rate of erosion [6]. Engineered T-head groins dissipate wave energy and slow erosion. A one-way check valve installed on stormwater conduit outlets prevents the backward flow of marine and stormwater. Living shorelines include vegetation to stabilize sand closer to the building, and coral restoration in the sheltered area landward of the T-head groins helps dissipate wave energy, create habitat, and support recreation. Elevated walkways preserve beach access and provide space for recreation and gathering. During a 1% annual chance flood in 2050, it is assumed the area would have fewer visitors, allowing the beach and surrounding open space to flood; however, the elevated walkways would remain accessible. Other supporting strategies discussed in the building and street adaptations include elevated exterior circulation and wet/dry floodproofing that would minimize impacts to the building at the shoreline to support operation soon after a flood event. In 2100, to continue functioning as a place of recreation and public access, beach nourishment would cease, and a perched beach with an engineered retaining wall and additional sand would be constructed (Figure 7c). In addition, engineered breakwaters parallel to the shoreline would dissipate wave energy and protect swimmers, marine habitats, perched beaches, and building facades from high wave runup. A new recreational dock for various commercial and public activities provides an opportunity for water-based alternative transportation via water taxi.

Collectively, the study site renderings of the flood adaptation strategies are a key visual tool for curating and planning outreach events to facilitate discussion with the community.

3.3. Public Outreach and Survey

The 2023 public presentation of adaptation strategies gathered 220 diverse participants, nearly double the number of participants in the project’s 2022 public presentation. Anonymous feedback was collected from more than half the number of participants on a total of 39 polls using the integrated online survey tool Mentimeter [50]. The first poll asked: How do you identify yourself in relation to Waikīkī? Participants’ interests and backgrounds ranged from landowners, government employees, hotel owners, urban planners, architects, residents, and design professionals, see Figure 8. A significant number of individuals’ backgrounds and interests were in government and urban planning.

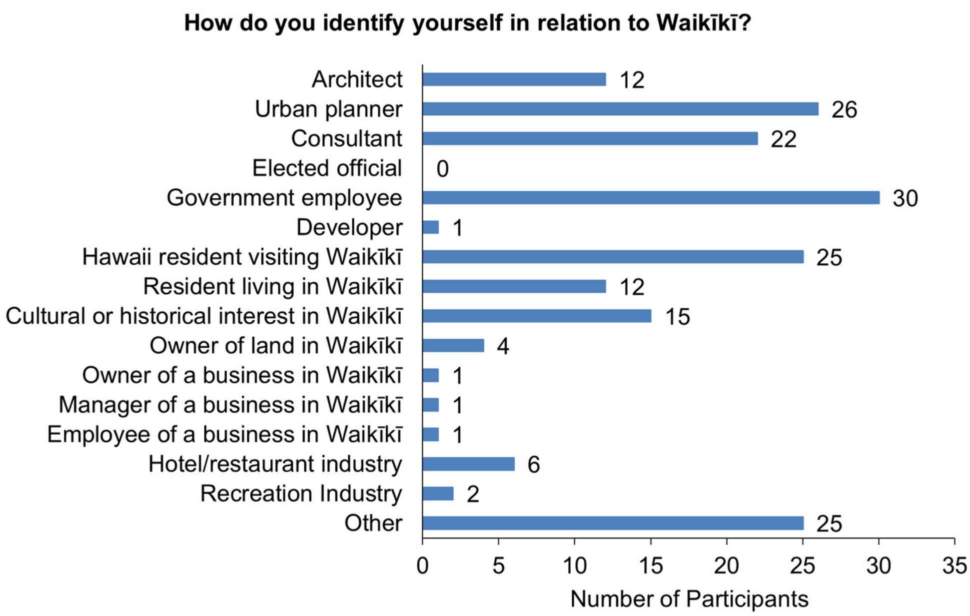

Figure 8. Chart of participant’s relations to Waikīkī.

For each adaptation strategy presented (a total of 37), participants were asked, on a scale of 1 (strongly agree) to 5 (strongly disagree), do you think this strategy is applicable to Waikīkī? The adaptation strategies were polled following their presentation at each focus area for the building and street, open space, and coastal areas for the 2050 and 2100 scenarios. In total, the survey received 3428 votes; 79% (2693) of votes indicated participants strongly agreed or agreed that the adaptation strategies presented were relevant to Waikīkī. In contrast, only 10% (348) of votes indicated strongly disagree or disagree. The remaining votes were neutral (11% or 387).

The strategies that participants rated most relevant to Waikīkī were to relocate critical [building] systems (average score: 1.2) in the 2050 building and street scenario, elevate critical equipment (average score: 1.4), and relocate ground floor use (average score: 1.4) in the 2100 building and street scenario. Although most participants strongly agreed or agreed that the strategies presented had relevance to Waikīkī, the strategies that participants thought had less relevance were wave energy dissipation in the 2050 coastal adaptation scenario (average score: 2.3) and the perched beach in the 2100 coastal adaptation scenario (average score: 2.4).

The visualizations of adaptation strategies integrated at a specific site enhanced participants' questions and comments since they could use them as references when posing their thoughts. Discussion held within the Zoom [49] chat function and panel Section 4 of the presentation covered themes on policy, planning, financial, sequencing, water level datums (BFE/DFE), infrastructure (coastal infrastructure), structural, tourism, public transportation, cultural, and stormwater management. Participants recognized the complexity of implementation when dealing with multiple landowners with varying levels of responsibility, liability, and financial incentive. One challenge of polling on adaptation strategies was retaining engagement throughout the presentation, peaking at 119 respondents early in the presentation and slowly decreasing to 85 as it went on. Based on the exit poll, overall, 75% of participants strongly agreed or agreed that the discussion increased their knowledge of sea level rise impacts and adaptation strategies (Figure 9).

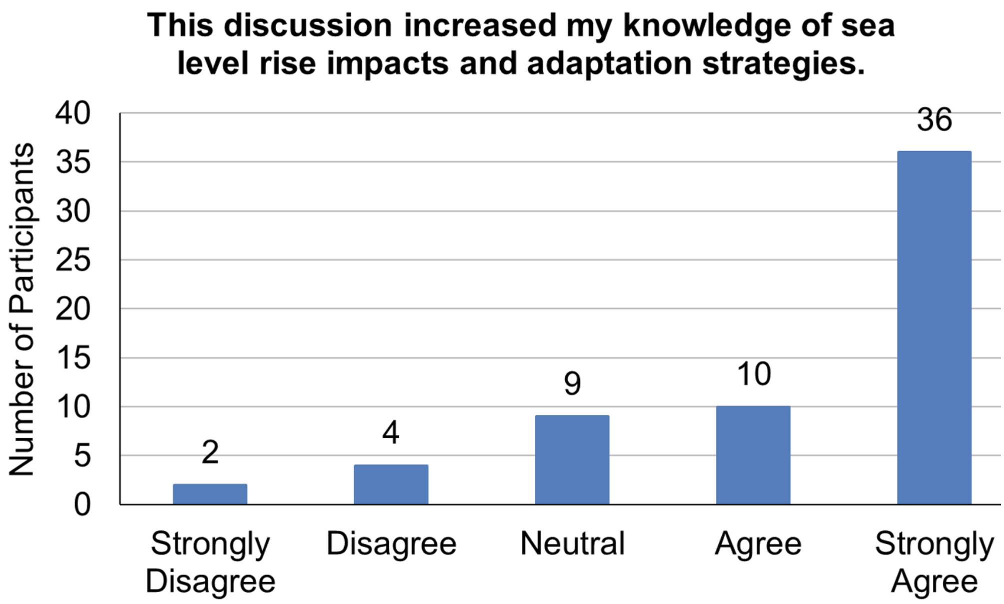

Figure 9. The graph above shows 46 of 61 (or 75%) participants agreed or strongly agreed the discussion increased their knowledge of sea level rise impacts and adaptation strategies.

Additionally, invitations to present the project to various focus groups, including Waikīkī's business communities, have led to targeted discussions from different perspectives about the required coordination, prioritization, and feasibility of implementing adaptation strategies. The response from these outreach events continues to inform the future proposed adaptation strategies, guide the next steps of the project, and serve as public information for community planning and policy. In contexts where government agencies may lack resources to conduct community outreach, planning, and envisioning, academic researchers play an important role in generating information and gathering community input for use in the development of future local area sea level rise adaptation plans. The Florida Department of Economic Opportunity document "Integrating Sea Level Rise Adaptation in Local Mitigation Strategies" suggests municipalities establish adaptation goals that consider common themes from outreach with a wide range of stakeholders [54], and this research provides that in written reports. It suggests the creation of a planning team that includes experts in sea level rise, academia/research, environmental/community organizations, and elected officials to help integrate these strategies [54], indicating that academia may also serve during plan development.

4. Discussion

State and County planning and policies for flood adaptation strategies are required to meet the challenges posed by SLR [55]. Facilitated discussion between academia, government, and community benefits the implementation process by addressing the priorities of multiple perspectives and building key partnerships. Identifying buildings and infrastructure vulnerable to flooding, researching and proposing site-specific adaptation strategies for SLR, and obtaining community input highlights a recursive process that can lead to the identification of relevant opportunities for planning across agencies and cost–benefit analysis.

This research demonstrates a replicable method for applied academic research informing local area plans, infrastructure improvements, and building codes through the generation of new design criteria, envisioning possible futures, and surveying public sentiment. Researching and visualizing site-specific theoretical designs to establish future DFEs and adaptation strategies for buildings, open spaces, transportation, and infrastructure is an effective method that can be tested and revised based on feedback from the community. The survey results from public outreach on the applicability of adaptation strategies for Waikīkī consistently showed overall support for adapting for future SLR. As a result, these resources can be valuable to the design community when proposing adaptations, government agencies for shaping guidelines and creating policies, and the private sector for prioritizing adaptations.

With the diverse backgrounds of the team, ranging from public relations, environmental design, architecture, climate science, geology, and political science, a strong collaborative effort reinforced the research and design component. The challenge with cross-disciplinary research is knowledge translation, in particular, when modeling data are shared between disciplines, but it showcases the opportunity to enhance accuracy and understanding when successfully integrated. This, in turn, provided the well-rounded research of flood adaptation strategies.

To implement flood adaptation strategies, phased guidelines, regulations, and incentives are needed and several challenges are recognized. To determine if/how buildings can be retrofitted to withstand indefinite inundation, saltwater exposure, and hydrostatic pressures, structural building evaluations are necessary and will need to be addressed on a case-by-case basis. Large-scale analysis of the Waikīkī district on the effectiveness and feasibility of stormwater management is required. In Portland, Oregon, the Bureau of Environmental Services analyzed the value of stormwater management systems for homeowners, businesses, and developers and concluded that they had long-term benefits of heat mitigation, habitat creation, and carbon sequestration [56]. Similarly, local governments may conduct cost–benefit analysis studies to determine the effectiveness of stormwater management strategies in the Waikīkī district. Guidelines on sequencing large-scale infrastructure changes in cooperation across private and public sectors will be necessary to limit the amount of disruption to the area.

The proposed adaptation strategies achieve sustainability goals by promoting building retrofitting (instead of demolition), water management, conservation and reuse, native ecosystems, and shoreline maintenance. Local implementation is required to understand the long-term impact of these adaptations, and it will remain necessary to address the challenges of rising sea levels.

Although the managed retreat was not within the project's scope, it is possible that discussions on the community's willingness to invest in flood adaptations will inform new zoning policies or area plans for retreat. Continued, structured community input is needed on trigger points for an evaluation of the cost of continued infrastructure investment versus the benefits and alternatives such as managed retreat. To garner community willingness and support, public feedback and involvement would help to address alternatives to managed retreat. The Palm Beach County Local Mitigation Strategy emphasizes the importance of the opportunity for the public to comment on a plan during the drafting stage prior to approval [54]. This hands-on community approach would provide the necessary feedback on the development of mitigation activities and perhaps further alternatives to managed retreat. Given the challenges many government planning agencies have dedicating staff time or funding to SLR community outreach, planning, and envisioning [11], this applied research demonstrates the valuable role of academia in accomplishing a replicable process to visualize and synchronize understanding toward adapting coastal communities for SLR and flooding.

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Institutional Review Board Statement: On 15 January 2021, the University of Hawaii (UH) Human Studies Program approved this study as exempt from federal regulations pertaining to the protection of human research participants per the Code of Federal Regulations at 45 CFR 46.104(d) 2. Exempt studies are subject to the ethical principles articulated in The Belmont Report.

Informed Consent Statement: Not applicable.

Data Availability Statement: The project website includes a summary booklet, slides, recordings, and stakeholder feedback reports: https://seagrant.soest.hawaii.edu/meguro-adapting-waikiki/, accessed on 1 September 2023.

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