Highlighting the Use of UAV to Increase the Resilience of Native Hawaiian Coastal Cultural Heritage

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1. Introduction

Globally, the long-term preservation of coastal cultural heritage sites is becoming increasingly vulnerable to sea level rise (SLR). This is especially true in equatorial regions like Hawai‘i, which will experience rates of SLR 16% to 20% higher than the global average [1]. The state of Hawai‘i has been proactive in planning for SLR impacts and mitigation and has released two SLR vulnerability and adaptation reports, as mandated by the Hawai‘i
Remote Sens. 2024, 16, 2239

Legislature [2,3]. The preservation of coastal cultural heritage, specifically Native Hawaiian Culture and Communities with SLR, has been identified as a priority by the State of Hawai’i Department of Land and Natural Resources [3]. While significant progress has been made to integrate SLR adaptation plans and policies into private and public entities [4], a substantial inequity exists for many coastal locations as little to no information is available which is specifically related to the types and severity of impacts upon coastal cultural heritage across Hawai’i. Here, we seek to fill this gap by using UAVs (uncrewed aerial vehicles) to assess the effects of elevated water levels upon loko i’a, a sophisticated form of traditional coastal aquaculture developed by Native Hawaiians.

Throughout this paper, we equate the definition of cultural heritage to the Hawaiian term of Wahi Kūpuna (ancestral places), which is thoroughly defined in the Kali’uokapa‘akai Collective Report (2021) to, “broadly encompass ancestral landscapes where kūpuna (ancestors) repeatedly and purposefully interacted (i.e., lived, worked, played, sustained life from), but also places of purposeful non-use (wao akua or mountain summit realms). Often, these places provide evidence of kūpuna interactions via physical manipulation of the space, such as burials, heiau (places for observation and ceremony), lo‘i kalo (taro patches), loko i’a (fishponds), ala loi (trails), kuahiwi (agricultural field systems), and ahu (shrines)” [5]. This definition of Wahi Kūpuna reinforces our connection as Kanaka ‘Oiwi (Indigenous to Hawai’i) in cultural heritage sites such as loko i’a and how they continue to feed us mentally, physically, and spiritually from the past to our present and into the future.

Loko i’a once was, and continues to be, widely regarded as one of the world’s most advanced and sustainable Indigenous aquaculture systems [6]. Commonly compared to a community refrigerator, loko i’a are predicted to originate as early as the 14th century AD and may have been constructed even earlier [7]. This understanding is based on legendary sources where loko i’a are documented in the literature ascribed to the 14th through to the 19th century [7]. Prior to Western contact, estimates have shown that over 400 loko i’a across Hawai’i provided nearly two million pounds of i’a (any marine animal, most commonly fish) per year [7,8]. Historical shifts away from traditional Hawaiian economic and political systems resulted in complete transformations of Hawai’i’s environmental landscape, including the capacity to provide sustainable seafood via loko i’a. Such actions diverted and polluted freshwater resources, leading to overdevelopment and the filling-in of many loko i’a, which ultimately made these areas less productive and capable of providing sustainable food resources [9]. Despite these challenges, knowledge of the practice of loko i’a persists and has been passed down through generations. Presently, there are approximately at least 40 loko i’a in some form of restoration and producing varying quantities of seafood while supporting the ecological health of these places [10–13].

Traditionally there were six general types of loko i’a found across the Hawai’i archipelago: loko kuapā, loko pu‘uone, loko wai, loko i’a kalo, loko ‘ume‘iki, and kāheka or hāpunapuna [6,14]. However, this project focuses on three loko i’a types: loko kuapā, loko wai, and kāheka (Figure 1). These loko i’a and their distinguishing features are described here.

Loko kuapā (rockwall fishponds) are located in shallow areas along the coastline and contain a man-made wall constructed of nearby lava rocks or coral rubble. Kuapā structures were built to be permeable for water mixing and protect loko i’a from wave energy and impact. In addition, loko kuapā consist of one or multiple mākahā (sluice gates) to allow for the exchange of seawater and freshwater during low and high tides. Mākahā were also essential for stocking and harvesting fish. Loko kuapā are one of the most common fishponds known throughout Hawai’i. Loko wai (freshwater-dominant fishponds) are located inland on rocky coastlines in low-lying depressions. While not directly connected to the ocean, they are dominated by freshwater inputs fed by groundwater springs or diverted streams. Loko wai are still influenced by tidal regimes as the freshwater lens fluctuates. These types of loko are compared to anchialine pond environments with similar hydrologic functions. Kāheka (natural pools) are not considered a main type of loko i’a [15]; however, they do serve as essential resources for fishing communities. Kāheka are natural pools or
ponds located along rocky coastlines with direct exposure to the ocean and are heavily flooded by tidal waves. Traditionally, these ponds usually served as temporary holding places for fish.

**Figure 1.** Examples of different types of loko i’a included in this study that are labeled with significant natural, cultural, and modern features. Loko kuapā (A) have rock wall enclosures, Loko wai (B) are freshwater-dominated ponds, and Kāheka (C) are natural pools with more direct wave exposure.

Currently, most planning agencies in Hawai’i and across the U.S. rely upon publicly available SLR flood maps (e.g., NOAA sea level rise viewer) derived by ‘flooding’ Light Detection and Ranging (LiDAR)-derived digital elevation models (DEM). Commonly known as the bathtub method, this approach identifies those cells in a DEM at or below a specified elevation or sea level scenario [16–20]. While this approach has been identified as a useful first step [21], several limitations exist for assessing potential impacts on coastal cultural heritage. For example, along the Eastern Hilo coastline on Hawai’i island, LiDAR DEMs available in SLR flood maps are almost 20 years old and have lower vertical and horizontal resolutions than UAV-derived products. As restoration efforts expand among these coastal cultural heritage sites, these older DEMs may not accurately reflect the current landscape due to topographical changes (e.g., removal of tall invasive vegetation or the reconstruction of culturally significant fishpond features). Furthermore, we recognize that bathtub modeling does not effectively factor any local hydrodynamics and assumes that all sites less than or equal to a specific sea level will become flooded [22]. In reality, the hydrological flow through the porous basalt substrate can directly influence flooding associated with tidal fluctuations and SLR along nearshore coastal habitats.

To address the shortfalls of the currently available data, this study describes the use of UAVs as an alternative tool to assess the impacts of elevated sea water levels. Here, we map flooding during the 2023 summer King Tides as a proxy for the projected 2060–2080 mid-to-end of the century’s global mean sea level under the high scenario (0.67–1.28 m) [1]. The overarching goal is to assess the ability of UAV and LiDAR-derived DEMs to model observed flooding to inform the growth of traditional loko i’a practices and coastal cultural heritage sites. The specific goals of this study are to (1) provide kia’i loko i’a or fishpond stewards with updated DEMs of their loko i’a for use in future scenario modeling, (2) identify from drone imagery the areas flooded during the King Tide, and (3) compare observed flooded areas to bathtub flood models created by UAV-SfM (Structure-from-Motion) DEMs and LiDAR-derived DEMs.

2. Study Area

The Keaukaha coastline is located along the eastern side of Hawai’i island. As the youngest island within the Hawaiian archipelago, Hawai’i is subsiding due to vertical land motion [23]. SLR recorded by the local NOAA tide gauge at Kuhio Bay, Hilo, HI (19°43.8N, 155°3.6W), is currently 3.11 ± 0.28 mm/yr, which is greater than anywhere else in Hawai’i [24]. Our study focuses on five loko i’a along two perpendicular shore
transects: Transect 1 (Honohononui) and Transect 2 (Hui Ho’oleimaluō) (Figure 2). The markers located within each transect represent the location of the in situ water sensors at each loko i’a. Each transect allowed us to assess how proximity and exposure to ocean swells influences local salinity and water levels. Inland, the loko i’a are mainly fed by subterranean groundwater springs originating from high-elevation sources on Mauna Kea and Mauna Loa, the two highest peaks on Hawai’i island [25].

Figure 2. Location of where the study sites are located within the Hawai’i archipelago (A). The loko i’a are situated along the Eastern Keaukaha Coastline on Hawai’i island (B). Each marker in both Transects represents the location of an in situ water sensor. The loko i’a within Honohononui (Transect 1) are Laehala (orange), Hale o Lono (green), and Waiāhole (green). Within Hui Ho’oleimaluō (Transect 2), the loko i’a are Honokea (green) and Kaumaui (purple). The location of the barometer (white) is also indicated.

Transect 1 has three loko i’a: Laehala, Hale o Lono, and Waiāhole. Laehala, although not an active fishpond, is a semi-exposed tidal pool or kāheka that is naturally sheltered from ocean swells, with coral species, juvenile fish, urchins, and intertidal habitat populations throughout. Hale o Lono is a loko kuapā with multiple mākahā to allow water circulation in the pond and is moderately impacted by high tides and high surf. Waiāhole is heavily dominated by freshwater, but traditionally was identified as a loko kuapā. It is inland from the shoreline and connected to the ocean through a 1.2 m culvert pipe underneath the main coastal roads. An in situ water sensor was submerged at each loko i’a to understand the gradient of the water level change from direct exposure to the coastline moving toward inland areas. Collectively, these sites are managed by the Kamehameha Schools and stewarded by the community-based organizations of the Edith Kanaka’ole Foundation and the Kumuola Marine Science Education Center, who engage local students and community members in research and restoration efforts.

Transect 2 consists of the Honokea and Kaumaui loko i’a. Honokea is a loko kuapā with a semi-cemented wall and a single mākahā that allows for water exchange with the ocean at the surface. Kaumaui contains six loko wai, inland ponds fed by groundwater springs, and although not directly connected to the ocean’s surface, it is connected underground and fluctuates with the tides. Kaumaui makai (oceanside) and Kaumaui mauka (inland) are labeled as such to represent the two ponds where in situ water sensors were submerged.
Honokea and Kaumaui loko i’a are managed by Hui Ho’oleimalu¯o. This community-led non-profit organization has been actively restoring these sites, reforming the landscape since 2011 through vegetation removal and the cultural restoration work of the ponds.

3. Materials and Methods

3.1. UAV Surveys

UAV Aerial imagery was collected using a DJI Phantom 4 Pro V.2.0 quadrotor to document flooding of cultural heritage sites during King Tide events (extreme high and low tide events). The DJI Phantom 4 Pro V.2.0 weight is about 1.3 kg and is classified as a micro drone (0.2–2 kg) [26]. Automated flights were generated using the flight planning software app DroneDeploy, Version 5.31.0 which collected images along a specified transect with 75% front and 75% side overlap for 30–40 min at each site. The UAV height was flown at 60 m above ground level, with the 20-megapixel red–green–blue (RGB) camera in a nadir position and optimized image resolution while adhering to Federal Aviation Administration (FAA) airspace regulations. Aerial imagery data collection took place on two days to allow for the projected lowest and highest tides to be captured during that month, one day for each site. Flight operations were executed on dates identified as King Tide events here in Hawai‘i during the summer of 2023. Documenting these King Tide events will assist local coastal communities, especially those working in and around cultural heritage sites like loko i’a, to enhance their comprehension and readiness for predicted SLR and flooding events.

Each UAV survey was ground-truthed with high-resolution GPS data. An Emlid Reach RS2+ real-time kinematic (RTK) positioning receiver collected centimeter-precise ground control points (GCP) at each study site. The base occupied a permanent benchmark point and a total of 10 GCPs were surveyed within each transect and referenced to the horizontal North American Datum 1983 (NAD83) and the North American Vertical Datum 1988 (NAVD88) with a local GEOID12B model applied. These GCP reference points were then used to align images properly during the UAV-SfM process. During the imagery collection of the high tide at Transect 1, six GCPs were moved, and position was recorded due to the risk of losing the targets due to elevated water levels.

3.2. Digital Elevation Models

3.2.1. UAV-SfM-Derived DEM

The UAV imagery and RTK-GPS data were used to create high-resolution, 3 cm DEMs and orthomosaic products of each loko i’a using Agisoft Metashape Software Version 1.8.4 [27,28]. This process involved creating a dense point cloud product that was exported into a free, open-source 3D point cloud and mesh processing software called CloudCompare Version 2.12.4 [29]. A Cloth Simulation Filter (CSF) plugin [30] used within CloudCompare was applied and optimized for each site to eliminate dense vegetation, buildings, and other outstanding infrastructure. Loko i’a walls and other significant cultural heritage features, such as umu (traditional fish houses), were not removed from the imagery. The newly generated dense point cloud was then imported into Agisoft and used to create the final bare-earth DEM. The final UAV DEMs had a 3 cm vertical and 1 cm horizontal accuracy.

3.2.2. NOAA-LiDAR-Derived DEM

This study compares flooding observed using a UAV to modeled flooding using UAV- and LiDAR-derived DEMs. A 3 m publicly available LiDAR DEM was obtained from the NOAA SLR viewer Version 3.0.0 developed by the Office for Coastal Management, USA [31]. The LiDAR dataset was collected in 2007 by the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) for the U.S. Army Corps of Engineers (USACE). USACE reports an average point spacing of 1 m, a horizontal positional accuracy better than ±0.75 m (1σ), and a vertical positional accuracy better than ±0.20 m (1σ). Data were collected in geographic coordinates and ellipsoid heights referenced to the NAD83 HARN. Ellipsoid elevations were transformed to orthometric elevations using the Geoid03 model.
These elevations were adjusted to the Local Tidal Datum of local mean sea level (LMSL). The final LiDAR DEM was hydro-flattened, ensuring water elevations were at or below −0.5 m.

3.3. Accuracy Assessment

The vertical accuracy of UAV- and LiDAR-derived DEMs was assessed by comparing DEM elevation to a total of 20 GCPs obtained using the RTK-GPS. Measured vertical accuracy of each DEM is reported as the root mean square error in Table 1. The measured vertical accuracy was determined by subtracting the GCP elevation from the DEM elevation at the same location. The mean error was calculated to provide a general elevation bias within a DEM. A significant positive mean error would indicate that the elevation of the DEM on average is too high, and a significantly negative mean error would indicate that the elevation of the DEM on average is too low [32]. The DEM and the reference point datasets were both referenced to LMSL using the NOAA Hilo tide gauge as a benchmark to avoid any artificial biases in the vertical uncertainty assessment.

<table>
<thead>
<tr>
<th>DEM</th>
<th>Cell Size (m)</th>
<th>Measured Vertical Accuracy (RMSE in m)</th>
<th>Mean Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAV (Transect 1)</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>LiDAR (Transect 1)</td>
<td>3.00</td>
<td>0.94</td>
<td>−0.47</td>
</tr>
<tr>
<td>UAV (Transect 2)</td>
<td>0.03</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>LiDAR (Transect 2)</td>
<td>3.00</td>
<td>0.57</td>
<td>−0.13</td>
</tr>
</tbody>
</table>

3.4. Local In Situ Water Sensors

Water level, conductivity, and water temperature within each loko i’a were recorded using Solinst Levelogger 5 LTC Water Level and Conductivity Loggers M10, which can be submerged up to 10 m. Data were collected at six-minute intervals to match the frequency of data collected at the NOAA Hilo Tide Gauge #1617760 [24]. Local water sensors were attached to a cement block and placed in adequate water depths to ensure the water sensors did not move and remained submerged during the entire tidal cycle. In situ water sensors were submerged for 72–106 days from June to September 2023 to capture summer King Tide events. The water level accuracy of these sensors is ±0.005 m with a resolution of 0.0006% [33]. In addition, the temperature sensor accuracy is ±0.05 °C with a resolution of 0.003 °C.

The conductivity sensor in the loggers was calibrated before deployment. A two-point calibration was carried out using Solinst Levelogger software Version 4.6.3 and two conductivity solutions, 1413 and 5000 µS/cm. The conductivity sensor had an accuracy of ±15 µS/cm at a resolution of ±0.1 µS/cm. Post-survey, each water level sensor was corrected for atmospheric pressure using Solinst Barologger 5 Barometric Pressure Logger data. Additionally, the location of each water sensor was referenced to Zone 5N and LMSL. An orthometric adjustment (+0.529 m) was applied to the elevation of each water sensor after comparing the calculated orthometric height (2.889 m) at the closest tidal benchmark [34] to the LMSL orthometric value (2.360 m) based on the leveling network. Water levels were evaluated based on the day the drone survey occurred since these were noted on King Tide days. The minimum, maximum, and median water level value and tidal range at each water sensor was compared to the NOAA Hilo tide gauge to improve understanding of how water levels vary along the coast and across the coastal plain.

3.5. Inundation Mapping

For this study, we compare observed King Tide flooding mapped in UAV imagery to flooding modeled by the UAV and LiDAR DEMS.
3.5.1. Observed Flooding of King Tides Using a UAV Orthomosaic

The King Tides of 3 July 2023 (Transect 2) and 2 August 2023 (Transect 1) were captured in real time by collecting aerial imagery at the extreme low and high tides. The survey dates were decided based on the highest tidal recording each month on the Tide Predictions from the NOAA Hilo Tidal Gauge [24]. All inundated areas were manually digitized from the UAV orthomosaics using ArcGIS Pro Version 3.2.2 [35]. Inundated areas were ground-truthed using additional images collected in the field (Figure 3). The maximum high water levels of each loko i’a were collected from the in situ water sensors. Additionally, the imagery primarily collected during high tide allowed for consideration of coastal hydrodynamic processes to which bathtub inundation modeling may be limited.

Figure 3. Observed UAV King Tide flooding (0.64 m) documented on 3 July 2023 at Honokea loko i’a with ground-truthed photos in the field. Observations include inundation at the main freshwater spring (A), high water levels intruding on Native bird habitat (B), and flooding causing debris to spread (C).

3.5.2. UAV and LiDAR DEM Modeled Flooding

To determine how well the UAV and LiDAR DEMs model the observed King Tide flooding, we modeled observed water levels at the 80% confidence interval based on the given vertical accuracy of the DEM [36]. The linear error at an 80% confidence interval (LE80) represents how probable the extent of the area will be flooded at the modeled water level. To determine the value of King Tide flooding during high tide, maximum water levels recorded by the local in situ water sensors were averaged across the loko i’a so that a single high tide value was obtained for Transect 1 and Transect 2. (Table 2). The LE80 value was added to the average water level at each site, which is the increment used for flooding the UAV and LiDAR DEMs. A mean water level of 0.88 ± 0.10 m is recorded at Transect 1 and 0.64 ± 0.14 m for Transect 2. All modeled flooding was executed in ArcGIS Pro Version 3.2.2 using the bathtub model method [22,37] and represents areas that are predicted to flood at 80% confidence at the specified water level (e.g., 0.88 m for Transect 1).
Table 2. Summary statistics on water levels at cultural heritage sites at each Transect.

<table>
<thead>
<tr>
<th>Site</th>
<th>Min (m)</th>
<th>Max (m)</th>
<th>Median (m)</th>
<th>Tidal Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transect 1—2 August 2023</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laehala</td>
<td>−0.21</td>
<td>0.87</td>
<td>0.28</td>
<td>1.08</td>
</tr>
<tr>
<td>Hale o Lono</td>
<td>−0.07</td>
<td>0.99</td>
<td>0.36</td>
<td>1.06</td>
</tr>
<tr>
<td>Waiahole</td>
<td>−0.09</td>
<td>0.81</td>
<td>0.33</td>
<td>0.90</td>
</tr>
<tr>
<td>* NOAA Predicted (Hilo, HI)</td>
<td>−0.49</td>
<td>0.63</td>
<td>0.02</td>
<td>1.12</td>
</tr>
<tr>
<td>** NOAA Verified (Hilo, HI)</td>
<td>−0.34</td>
<td>0.75</td>
<td>0.13</td>
<td>1.09</td>
</tr>
<tr>
<td>Transect 2—3 July 2023</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Honokea</td>
<td>−0.40</td>
<td>0.46</td>
<td>−0.06</td>
<td>0.86</td>
</tr>
<tr>
<td>Kaumaui Makai</td>
<td>−0.53</td>
<td>0.69</td>
<td>−0.06</td>
<td>1.22</td>
</tr>
<tr>
<td>Kaumaui Mauka</td>
<td>−0.45</td>
<td>0.75</td>
<td>0.07</td>
<td>1.20</td>
</tr>
<tr>
<td>* NOAA Predicted (Hilo, HI)</td>
<td>−0.53</td>
<td>0.64</td>
<td>−0.04</td>
<td>1.17</td>
</tr>
<tr>
<td>** NOAA Verified (Hilo, HI)</td>
<td>−0.39</td>
<td>0.70</td>
<td>0.07</td>
<td>1.09</td>
</tr>
</tbody>
</table>

* NOAA-predicted values represent forecasted estimates of tidal levels based on mathematical models. ** NOAA-verified values represent observed tidal data collected and confirmed through monitoring stations with a ±0.02 m error.

UAV-observed and -modeled and LiDAR-modeled flooding were compared to identify areas where the DEMs overestimated or underestimated flooding across each loko i’a. The percentage change in the flooded areas was calculated by dividing the overestimated or underestimated areas by the total area of the observed UAV flooding (Equation (1)). Additionally, a percentage of the area of agreement was calculated where both bathtub models agreed that they would be inundated.

\[
\% \text{ Change in Flooded Area} = \frac{\text{Over/Under estimated Area}}{\text{Observed UAV Area}} \times 100 \quad (1)
\]

4. Results

4.1. Variations in Local Water Levels across Coastal Cultural Heritage Sites

The NOAA Hilo tide gauge was compared to six in situ water sensors to determine how the water level varies across coastal cultural heritage sites (Figure 2). First, it is necessary to note that when the forecasted and verified values for the Hilo tide gauge are compared, the forecasted values overestimated the magnitude of the low tide by 0.14–0.15 m and underestimated the magnitude of the high tide by 0.06–0.12 m at both transects. The maximum water levels were subtracted from the minimum values to calculate the Tidal Range column (Table 2).

On August 2nd, during the high-tide event in Transect 1 (Figure 2), all water sensors recorded lower tidal ranges than the predicted (1.12 m) and verified water level (1.09 m) at the Hilo tidal station. However, each in situ sensor recorded the highest water level. For instance, at Hale o Lono, a loko kuapā along the shoreline recorded the highest water level at 0.99 m, approximately 0.36 m higher than the Hilo tide gauge prediction. Conversely, during the lowest tide that day, the tidal station predicted and verified lower water levels by 0.13–0.28 ± 0.02 m compared to the Laehala sensor, which recorded the lowest in situ water level below LMSL (0.21 m) in Transect 1 (Table 2).

At Transect 2 (Figure 2), Honokea loko i’a experienced a notably smaller tidal range (0.86 m) between high and low tides compared to Kaumaui Makai (1.22 m), Kaumaui Mauka (1.20 m), and the NOAA-predicted (1.17 m) and -verified (1.09 m) levels, despite Honokea’s close exposure to the ocean in this Transect. On the contrary, Kaumaui Makai exhibited the greatest water level variation, with its maximum water level at 0.69 m and the lowest reading at 0.53 m below LMSL. Moreover, Kaumaui Makai’s measurements closely resembled the minimum, maximum, and median values predicted by the NOAA tidal gauge (Table 2).
4.2. Observed Flooding

Here, we compare the area (m²) of loko i’a observed inundated during low and high tide. At Transect 1, the most seaward site, Laehala, increased by 187% (Supplementary Figure S2) between low and high tide. The rocky shoreline that protects the kāheka from waves was submerged entirely at high tide. At Hale o Lono, areas inundated increased by 61.0% (Supplementary Figure S3), and the kuapā was compromised by the wave action until it was unsafe to walk across. Waiāhole, the most inland fishpond, is connected to the ocean by a culvert underneath the road, and at high tide, increased in area by 16.2%, causing two ponds that were initially separated by a grassy patch to coalesce into a single pond (Supplementary Figure S4).

At Transect 2, Honokea, the coastal loko kuapā, experienced a 47.7% increase in area from low to high tide. Significant areas such as the main freshwater spring (Figure 3A), Native bird habitat (Figure 3B), and trees at the perimeter of the loko i’a (Figure 3C) were observed to be inundated (Figure 3). Kaumaui, the inland loko wai, saw a 28.0% increase in area between low and high tide. Impacts included the coalescing of individual ponds (e.g., five ponds reduced to four) and the flooding of the coastal road at the site’s main entrance (Supplementary Figure S1).

4.3. Modeled Inundation Using UAV and LiDAR DEMs

UAV and LiDAR DEMs were used to model and map the area inundated by the maximum King Tide water level at all five loko i’a (Tables 3 and 4, Supplementary Figures S1–S4). Modeled inundation maps were compared to the high tide orthomosaics to assess how well the UAV and LiDAR DEMs replicate observed flooding. To quantify the robustness of our models, we compare the location of flooding, the total area flooded, and the percentage area that overestimated, underestimated, or agreed with the observed flooding. This comparison amongst modeled datasets is important because it helps loko i’a practitioners to understand the limitations and benefits of each DEM-derived flood model as they plan for current and future impacts from SLR.

Table 3. Comparing UAV-modeled flooding to observed flooding.

<table>
<thead>
<tr>
<th>Site</th>
<th>Area (m²) UAV Observed Flooded</th>
<th>Area (m²) Flooded in UAV Model</th>
<th>% Area Underestimated by UAV Model</th>
<th>% Area Overestimated by UAV Model</th>
<th>% Area of Agreement between UAV Observed and UAV Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laehala</td>
<td>7969</td>
<td>7729</td>
<td>10.85%</td>
<td>7.84%</td>
<td>89.15%</td>
</tr>
<tr>
<td>Hale o Lono</td>
<td>7536</td>
<td>7541</td>
<td>6.09%</td>
<td>6.16%</td>
<td>93.91%</td>
</tr>
<tr>
<td>Waiāhole</td>
<td>12,628</td>
<td>12,420</td>
<td>1.65%</td>
<td>0.00%</td>
<td>98.35%</td>
</tr>
<tr>
<td>Honokea</td>
<td>2103</td>
<td>2377</td>
<td>3.71%</td>
<td>12.93%</td>
<td>100%</td>
</tr>
<tr>
<td>Kaumaui</td>
<td>3414</td>
<td>3486</td>
<td>9.29%</td>
<td>11.75%</td>
<td>90.25%</td>
</tr>
</tbody>
</table>

Table 4. Comparing LiDAR-modeled flooding to observed flooding.

<table>
<thead>
<tr>
<th>Site</th>
<th>Area (m²) UAV Observed Flooded</th>
<th>Area (m²) Flooded in LiDAR Model</th>
<th>% Area Underestimated by LiDAR Model</th>
<th>% Area Overestimated by LiDAR Model</th>
<th>% Area of Agreement between the UAV Observed and LiDAR Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laehala</td>
<td>7969</td>
<td>17,984</td>
<td>0.00%</td>
<td>125.67%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Hale o Lono</td>
<td>7536</td>
<td>39,093</td>
<td>0.00%</td>
<td>158.64%</td>
<td>99.95%</td>
</tr>
<tr>
<td>Waiāhole</td>
<td>12,628</td>
<td>36,493</td>
<td>0.30%</td>
<td>188.98%</td>
<td>99.70%</td>
</tr>
<tr>
<td>Honokea</td>
<td>2103</td>
<td>4358</td>
<td>0.00%</td>
<td>101.81%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Kaumaui</td>
<td>3414</td>
<td>5461</td>
<td>19.80%</td>
<td>81.90%</td>
<td>78.09%</td>
</tr>
</tbody>
</table>
4.3.1. Comparing UAV-Modeled Flooding to Observed Flooding

There is an 89% or higher agreement between the modeled UAV flooding and observed flooding at all loko i’a (Table 3). For Transect 1, the UAV models slightly underestimated flooding at all loko i’a sites: 10.85% at Laehala (Supplementary Figure S2), 6.09% at Hale o Lono (Supplementary Figure S3), and 1.65% at Waiāhole (Supplementary Figure S4). The UAV models also overestimated flooding at two loko i’a at Transect 1: 7.84% at Laehala and 6.16% at Hale o Lono. At Transect 2, the UAV models both over and underestimated flooding. At Honokea, the UAV model overestimated flooding by 12.93% and underestimated flooding by 3.71% (Figure 4). At Kaumaui, the UAV model overestimated flooding by 11.75% and underestimated flooding by 9.29% (Supplementary Figure S1).

Figure 4. Modeled Inundation Area of Honokea loko i’a with the UAV observed at low tide (dotted line) and at high tide (purple), with UAV-modeled (light blue) and LiDAR-modeled (yellow) flooding overlaid. Areas of agreement between observed and modeled flooding are overlapping (light purple). The in situ water sensor is located near the rock wall (blue dot).

4.3.2. Comparing LiDAR-Modeled Flooding to Observed Flooding

The LiDAR-derived models largely overestimated flooding across all loko i’a (Table 4). Nearly all loko i’a were modeled to increase in area two-to-three times what was observed during the King Tide, and at Hale o Lono, it was modeled to increase in area up to five times more than what was observed. At Transect 1, the dominant trend was that the LiDAR model largely overestimated flooding at each site: 125% for Laehala (Supplementary Figure S2), 158% for Hale o Lono (Supplementary Figure S3), and 189% for Waiāhole (Supplementary Figure S4). Less than 1% of the observed flooded areas were not captured by the LiDAR DEMS: Laehala and Hale o Lono (0.00% area underestimated by LiDAR model) and Waiāhole (0.30%). Similar results were noted at Transect 2, where
the LiDAR model overestimated flooding by 101.8% at Honokea (Figure 4) and 81.90% at Kaumaui (Supplementary Figure S1). Kaumaui was the only site where the LiDAR model significantly underestimated flooding (19.80%). There is a high percentage of areas of agreement across both Transect 1 and 2 because the UAV observed area falls within the large LiDAR-modeled area.

5. Discussion
5.1. Providing Fishpond Stewards with Updated Digital Elevation Models

This project shows that UAVs are an effective tool that can be used to quickly develop high-resolution DEMs of cultural heritage sites such as loko i’a. Accurate, high-resolution DEMs are especially important for loko i’a as these sites are actively being restored and revitalized across Hawai‘i as a resurgence of this traditional practice occurs. Kia‘i loko i’a (fishpond stewards) are particularly interested in adaptive approaches that proactively address how SLR impacts the magnitude, location, and timing of flooding, changes in water quality (e.g., salinity), and the viability of raising Native fish species [38,39]. High-resolution UAV DEMs and imagery allow greater detail and understanding of where exactly low-elevation areas within individual loko i’a are most prone to current and future flooding.

UAV-derived DEMs accurately model (89% or more agreement) observed flooding. LiDAR-derived flood models vastly overestimate (as much as two-to-five times) observed flooding and provide a more conservative and cautious approach for planning future SLR impacts upon these cultural heritage sites. Currently, there is a pressing need for high-accuracy DEMs and imagery in many rural coastal and island communities that are becoming increasingly vulnerable to coastal flooding. In many island nations, high-resolution datasets such as LiDAR are either non-existent or outdated and do not actively reflect the coastal topography [40]. Here, we show an example in Hawai‘i where the active restoration and future planning of coastal cultural heritage sites could be better guided through the availability of UAV-derived data to improve the resolution of publicly available models that are nearly 20 years old.

To better understand how UAV datasets can be used to improve the resilience of coastal cultural heritage sites we compare the cost, spatial resolution, accuracy, and time associated with acquiring LiDAR- and UAV-derived datasets (Table 5). LiDAR datasets and collections are costly and, as a result, LiDAR data in Hawai‘i and many remote islands experience infrequent updates based on multiple factors (e.g., quality and extent of new elevation data) that can take half a decade or longer. For example, in our study area, the most recent LiDAR DEM used in the NOAA SLR Viewer was created by data collected in 2007. This DEM does not reflect the current coastline as it has been altered at loko i’a by community restoration efforts such as the removal of invasive plant species, the opening of new ponds, the introduction of Native herbivorous fish, and the re-building of integral fishpond structures such as the kuapā (rockwall) or umu (traditional fish houses). A benefit of LiDAR datasets is that they can be used to map relatively large areas (entire islands) fairly quickly (within months). However, the processing time to make LiDAR data is intensive and typically DEMs are not released for several years depending on the entities in charge of processing the data (e.g., NOAA Office for Coastal Management). On the other hand, UAV imagery can be collected within less than an hour and a DEM and orthomosaic of a single cultural heritage site can be created within a few hours or less. Furthermore, UAV-derived DEMs and imagery have an order of magnitude higher resolution and accuracy than LiDAR datasets. Centimeter accuracy and resolution UAV-derived datasets allow for loko i’a features such as kuapā or mākahā to be identified. We recognize that operating a UAV has limitations, such as needing a Federal Aviation Administration (FAA) 107 licensed pilot and special clearance to fly in restricted zones (e.g., near airports). In addition, depending on the sensor of the UAV, it may not be able to penetrate highly dense areas to capture ground elevation as accurately as LiDAR datasets [41]. Even with these potential limitations, this project supports previous studies that have shown that UAVs provide
value in the form of updated DEMs that are useful for environmental, conservation, and cultural heritage management [42].

Table 5. Comparison of LiDAR- and UAV-derived DEMs used in this study.

<table>
<thead>
<tr>
<th>Operational Costs</th>
<th>JALBTCX-LiDAR Collection and Products</th>
<th>UAV + RTK-GPS Collection and Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>~USD 20,000 *</td>
<td>January–February, 2007</td>
<td>3 July and 2 August 2023</td>
</tr>
<tr>
<td>Collection period</td>
<td>80–90 min</td>
<td>30–40 min</td>
</tr>
<tr>
<td>Flight time (mins)</td>
<td>3.00 m</td>
<td>0.03 m</td>
</tr>
<tr>
<td>Spatial resolution (m)</td>
<td>0.75 m</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Horizontal Accuracy (m)</td>
<td>0.20 m</td>
<td>0.03 m</td>
</tr>
<tr>
<td>Vertical Accuracy (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial coverage</td>
<td>Northern coast of Hawai‘i Island</td>
<td>Two shoreline transects along the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Keaukaha, Hilo coastline</td>
</tr>
</tbody>
</table>

* This dataset is part of a larger project that collected LiDAR for the Northern coasts of Hawai‘i, Kauai, Maui, Molokai and Oahu. This estimated value only considers flight and processing costs for the Northern coast of Hawai‘i Island and does not account for extra costs such as mobilization, calibration, contingency, etc. and in reality may be a lot higher.

5.2. UAVs Can Be Used to Rapidly Assess Real-Time Coastal Flooding at Cultural Heritage Sites

Globally, the use of UAVs is growing as a preferred method to support integrated coastal zone management encompassing cultural heritage sites [43,44]. Previous studies have used UAVs to document and preserve historical sites [45], conduct geometric surveys in inaccessible coastal environments [46], monitor Indigenous heritage sites in the face of climate change [47], and conduct geoarchaeological surveys [48]. UAVs have also been used to capture and monitor real-time changes caused by environmental and anthropogenic factors [49,50], document changes to the nearshore marine environments [51–55], and characterize flooding caused by natural disasters [56,57]. Our study contributes to this growing body of research in remote sensing [58] by showing that UAVs can identify and quantify real-time flooding at loko i’a. Furthermore, building upon bathtub flood modeling that only considers elevation, flooding captured by our UAV-derived orthomosaic improves the understanding of how other environmental variables, such as the groundwater, wave action, geology, and infrastructure, may influence local water levels. Other environmental variables, such as precipitation, air temperature, and swell strength, have been studied to increase groundwater flooding impacts on West Hawai‘i [59], which is currently observed to impact the loko i’a on the east side. Additionally, high-surf advisories issued for the Hilo district during extreme tides have been reported to break makahā, collapse kuapā, and restrict road access due to extremely rough and high water action along the coasts.

5.3. Implications of the Use of UAV-SfM Techniques to Map Shallow Water Environments

Cultural heritage sites such as loko i’a were intentionally located at the intersection of marine and terrestrial environments, creating a nutrient-rich nursery for native herbivorous fish and brackish water species. Fishpond-types such as a loko kuapā are commonly located in shallow shoal areas [7] and the enclosing rock wall is typically built as tall as the highest possible tide, with an additional foot [6]. The strategic placement of these loko i’a in shallow water environments highlights the intimate environmental knowledge that original caretakers needed and the adaptiveness of this practice to adjust to changes in the water level. However, with exacerbated climate change, the location of loko i’a near shallow waters makes them exceedingly prone to SLR which may cause loko i’a to become completely submerged in the future. Presently, the most common methods to monitor the shallow water depth include Single- and Multibeam Echo Sounders [60] or acquiring airborne LiDAR data [61]. Despite their global application, these methods are often expensive, suited for covering large spatial areas, and, in the case of LiDAR-derived bathymetry, fail to accurately measure the water depth [62]. UAV-SfM techniques have been proven successful for mapping shallow water environments [63–65] as an alternative method to acquire shallow bathymetry and coastal topography. In this study, we underline
the value of using UAV to map coastal cultural heritage sites located within shallow-water environments at a community level. For example, the measured vertical accuracies and mean errors observed from the UAV-SfM-derived DEMs (Table 1) demonstrate their capability to capture shallow nearshore environments at a high spatial resolution based on UAV imagery coupled with RTK-GPS data. This allows for significant cultural features of a loko i’a such as the kuapā, umu, and mākāhā to be captured and measured in high detail. Furthermore, UAVs can be mounted with compact LiDAR sensors which have been proven effective at mapping shallow-water environments with high resolution and accuracy [66]. This study contributes to the growing use of UAV-SfM techniques applied to shallow-water environments, which support the restoration and preservation efforts of coastal cultural heritage sites in the face of climate change.

5.4. Implications for Sea Level Rise Vulnerability Assessments and the Use of Publicly Available Datasets

King Tides are the highest predicted tides of the year and can be used as a metric to understand future sea levels [67]. Furthermore, understanding the tidal range of the loko i’a also allows insight into how each site experiences these King Tide events (Table 2). The 2023 observed local King Tides (0.64–0.88 m) are projected to represent the mean sea level expected as early as 2060 when compared to the Intermediate High (0.63 m) and High (0.80 m) scenarios for Hilo, Hawai’i. After analyzing both the UAV and LiDAR models in relation to the observed flooding, we found that the UAV-modeled flooding captured 89% or more of the observed flooded areas (Table 3). The LiDAR models overestimated the flooding (as much as two-to-five times) across all loko i’a. UAVs provide a more accurate representation of observed flooding by considering real-time environmental factors such as wave overwash and groundwater inundation. UAVs are also optimal for monitoring restoration efforts that could potentially expand or reduce areas prone to flooding. These restoration efforts can happen over short periods, enabling UAVs to capture the most recent changes in the landscape. Modeled flooding using UAV DEMs provides a more detailed understanding of which specific areas will flood at a given water level. Information derived from UAV-modeled flooding benefits loko i’a stewards to plan for future SLR scenarios accurately and frequently monitor their sites as changes occur. For example, the height of the kuapā could be adjusted accordingly to help mitigate high water levels, or inland areas of future inundation could be identified as the next generation of loko i’a.

Although LiDAR models overestimated flooding, they allow for more conservative future planning. Kia’i loko i’a also confirmed that some areas that are flooded during high wave events were captured in the LiDAR-modeled flooding. For example, at Kaumaui loko i’a, the LiDAR model estimated parts of the main road to flood, which has been observed to be accurate during huge winter swells in combination with high tide events. Certain areas predicted in the LiDAR model have also been observed to have flooded previously, according to other sites such as at Waiahole. These overestimated areas determined by LiDAR models may also incorporate future estimations of pond expansion. This may include more areas for loko i’a stewards to manage and restore, which may require more capacity and financial support to effectively manage the space. The greater intrusion of SLR may also introduce and spread invasive species, both marine and terrestrial [16,68,69], and displace native plant communities [70]. When assessing the mean error of the LiDAR DEM (Table 1), the negative mean values indicate that this dataset is underestimating the topography of these sites. This could be an additional reason why the LiDAR DEMs are overestimating flooding. Our findings support the use of publicly available datasets as a beneficial tool. However, we suggest they should be supplemented with UAV technology and local in situ water sensors, especially at a community level to provide more actionable data.

5.5. Limitations and Ways to Improve the Use of UAVs to Monitor Cultural Heritage Sites

This study showed that UAVs are an effective tool for monitoring and planning for future impacts of SLR on coastal cultural heritage sites; however, there is still room for
improvement. Previous studies have found that DEM-derived modeling can assist in the preliminary research of areas impacted by high water flooding [17,18,20,21]. UAV-SfM modeling methods can provide high-resolution DEMs, yet they are limited in capturing accurate ground elevation, particularly around densely vegetated areas and shorelines with high wave action [71]. LiDAR, on the other hand, may be better at penetrating these noisy areas [72]. Regardless, neither UAV- nor LiDAR-modeled flooding alone has the capability to capture the local hydrology movement, such as groundwater-inundated areas. Since coastal environments are dynamic, there is a need to better understand what environmental factors significantly influence local water levels and the subsequent vulnerability of coastal cultural heritage to SLR. Future studies should consider analyzing the impact of additional environmental variables like the wave run-up [73] and rocky coastal habitat [74] that may drive water levels higher than expected. Furthermore, our study mitigates this oversight by submerging in situ water sensors that obtain the real-time water level at each loko i’a. However, other factors like swell and rainfall have been documented to increase coastal flooding, but are not considered in this study [59].

6. Conclusions

Using UAV technology to monitor coastal cultural heritage sites such as loko i’a has proven to be beneficial in the face of increasing sea levels. Publicly available resources such as the NOAA SLR Viewer and the NASA SLR Interagency tool are effective sources for coastal preparedness planning and risk management activities. They provide cautious estimates of future SLR impacts based on credible data which are useful for long-term planning. These resources are also designed to be user friendly and provide data specific to local regions. However, in combination with local in situ water sensors, UAV-derived products offer a much more rapid and robust assessment at a community level. The LiDAR dataset used in this study and applied in the NOAA SLR Viewer for this region is nearly 20 years old, which may not reflect changes in the landscape from loko i’a restoration or modern development. Publicly available SLR data can be enhanced when supplemented with UAV-SfM methods to monitor coastal cultural heritage sites in detail. DEMs developed from UAV-SfM techniques are proven to have high horizontal and vertical resolutions and centimeter accuracy with minimal errors when conducted alongside high-grade GPS surveys. Although the LiDAR dataset is outdated and has a lower resolution, it still can provide loko i’a managers with a more conservative estimate of flooding at each site. This can also be beneficial when considering ponds that may expand in surface area or experience flooding during significant swell advisories. On the other hand, UAVs are valuable tools for coastal cultural heritage sites to identify elevation and flooding at a high resolution unlike LiDAR datasets. Moreover, we highlight the advantages of using inexpensive UAVs for natural hazards such as coastal flooding. DEMs derived from UAV can also inform loko i’a practitioners by offering detailed insights into significant features such as the kuapā or ‘auwai (channel) which are integral to the functioning of these aquaculture systems. This high level of detail can aid management decisions to adjust these features accordingly (e.g., construct the kuapā higher or in a different direction).

King Tide events are practical for assessing extreme flooding locally and can be used as a proxy to understand the timing and magnitude of future SLR. For example, 2023 observed that King Tide water levels are expected to be the average sea level experienced at these loko i’a between 2060 and 2080, and likely sooner. The ability to monitor the water level at each site using local in situ water sensors also gives loko i’a managers more insight into tidal influences and their relation to the different loko i’a types based on their varying exposures to the ocean. Bathtub flood modeling offers a considerable first step in mapping flooding based on topography alone. However, we determined that the methods in this study are limited to environmental factors such as wave run-up or coastal habitat complexity. Additionally, bathtub flood modeling does not consider the effects of groundwater inundation, which is known to be abundant along the Hilo coastline through freshwater springs and discharge.
Our kupūna (ancestors) have historically adapted to changes in the climate, which is evident in the cultural practices embedded at loko iʻa. Activities such as building up kuapā according to the moon phases and tides or allowing them to fall at the mercy of swells during certain seasons represent forms of adaptation. These practices have evolved through keen observation and intimate relations with the environment over generations. Loko iʻa are not just coastal cultural heritage sites, but are manifestations of Indigenous technologies that continue to thrive and feed our communities mentally, physically, and spiritually. This study moves beyond using UAVs as a modern tool to assess flooding and future SLR impacts alone. Overall, we see the value of UAVs as integral to enhancing coastal community adaptation. By integrating technology with ancestral wisdom at the foundation, UAVs may further support Indigenous practices to adapt, persist, and thrive in a changing climate. Here, we stress the relevance of these technologies to increase the resilience of Native Hawaiian coastal cultural heritage sites and the perpetuation of loko iʻa within our communities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs16122239/s1, Figure S1: Modeled Inundation Area of Kaumau loko iʻa with the UAV observed at low tide (dotted line) and at high tide (purple), with UAV-modeled (light blue), and LiDAR modeled (yellow) flooding overlaid. Areas of agreement between observed and modeled flooding are overlapping (light purple). There are two in-situ water sensors located at the makai (seaward) and mauka (inland) ponds (blue dot). Figure S2: Modeled Inundation Area of Laehala with the UAV observed at low tide (dotted line) and at high tide (purple), with UAV-modeled (light blue), and LiDAR modeled (yellow) flooding overlaid. Areas of agreement between observed and modeled flooding are overlapping (light purple). The in-situ water sensor is located within the large natural pool (blue dot). Figure S3: Modeled Inundation Area of Hale o Lono loko iʻa with the UAV observed at low tide (dotted line) and at high tide (purple), with UAV-modeled (light blue), and LiDAR modeled (yellow) flooding overlaid. Areas of agreement between observed and modeled flooding are overlapping (light purple). The in-situ water sensor is located within the main loko iʻa (blue dot). Figure S4: Modeled Inundation Area of Waihōle loko iʻa with the UAV observed at low tide (dotted line) and at high tide (purple), with UAV-modeled (light blue), and LiDAR modeled (yellow) flooding overlaid. Areas of agreement between observed and modeled flooding are overlapping (light purple). The in-situ water sensor is located near the 1.2m culvert pipe that connects flow to the ocean (blue dot).


Funding: This research was funded by the National Aeronautics and Space Administration Award No. 80NSSC21K1656: Quantifying vulnerability to sea level rise across multiple coastal typologies.

Data Availability Statement: Data can be made available upon request. The data will not be publicly available until the funding awards are completed and data are archived in public repositories.

Acknowledgments: This work was funded in part by the National Aeronautics and Space Administration (NASA) agency through the Minority University Research and Education Project (MUREP). Just like the collective restoration of a loko iʻa, this project took many hands and minds that have contributed to its success, from the fieldwork to the insightful conversations and everything in between. This work has been accomplished because of the support and valuable feedback from the kiaʻi loko iʻa (fishpond stewards), who are on-the-ground dedicated to the perpetuation of traditional Hawaiian aquaculture practices. We would like to extend our deepest mahalo to those kiaʻi loko iʻa serving the Keaukaha community, including the Kumuola Marine Science Education Center—Kamehameha Schools Hawaiʻi (Luke Mead, Maikalani Glendon-Baclig, and Trisha Olayon); Hui Hoʻoleimaluʻu (Kamala Anthony, Nāhōkū Kahana, Manoa Johansen, Joseph Henderson, and
Cerie Kauahi); and the Edith Kanaka‘ole Foundation (Luka Mossman). We would also like to thank the number of undergraduate and high-school students who have played a vital role in the collection and processing of data through the following internship programs: the Pacific Internship Program for Exploring Science (PIPES) (Kim Yumul, Dylan Kelling, Kieran Mitchell, and Raz Wachtel); and five local high-school students that participated in the 2023 Project Hokūlani STEM internship program. Additionally, we would like to give thanks to folks from our team at the Multiscale Environmental Graphical Analysis (MEGA) lab based in Hilo (Makoa Pascoe, Kailey Pascoe, Manuela Cortes, Chloe Molou, Jacob Wessling, Alexander Spengler, Crispin Nakoa, Cliff Kapono, John Burns, and Haunani Kane) for their support in various aspects of the project including fieldwork, media support, and providing meaningful feedback. This work was carried out with our future generations in mind, while highlighting our ancestors’ knowledge relevant to today. We remain dedicated to supporting coastal community resilience to sustain thriving loko i’a across Hawai‘i.

Conflicts of Interest: The authors declare no conflicts of interest.

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