Stakeholder Driven Sensor Deployments to Characterize Chronic Coastal Flooding in Key West Florida

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Key Points:

- The accelerometers were easy to deploy by researchers and stakeholders and accurately captured flooding in locations of interest.
- Inundation was variable across the island of Key West and was not successfully predicted by the NOAA water level alone.
- Patterns to inundation events were not found, water level and timing of inundation varied between and within sites.

Abstract

A changing climate and growing coastal populations exacerbate the outcomes of environmental hazards. Large-scale flooding and acute disasters have been extensively studied through historic and current data. Chronic coastal flooding is less well understood and poses a substantial threat to future coastal populations. This paper presents a novel technique to record chronic coastal flooding using inexpensive accelerometers. This technique was tested in Key West, FL, USA using storm drains to deploy HOBO pendant G data loggers. The accuracy and feasibility of the method was tested through four deployments performed by a team of local stakeholders and researchers between July 2019 - November 2021 resulting in 22 sensors successfully recording data, with 15 of these sensors recording flooding. Sensors captured an average of 13.58 inundation events, an average of 12.07% of the deployment time. Measured flooding events coincided with local National Oceanic and Atmospheric Administration (NOAA) water level measurements of high tides. Multiple efforts to predict coastal flooding were compared. Sensors recorded flooding even when NOAA water levels did not exceed the elevation or flooding thresholds set by the National Weather Service (NWS), indicating that NOAA water levels alone were not sufficient in predicting flooding. Access to an effective and inexpensive sensor, such as the one tested here, for measuring flood events can increase opportunities to measure chronic flood hazards and assess local vulnerabilities with stakeholder participation. The ease of use and successful recording of loggers can give communities an increased capacity to make data-informed decisions surrounding sea level rise adaptation.

Plain Language Summary

Floods occurring outside of storm events are increasing in number due to low-lying coastal communities' exposure to rising sea levels. The extent and impacts of localized and recurrent flooding events are under-studied compared to extreme storm events. Damaging floods can occur during a high tide or a rain event, and with these chronic floods increasing in frequency, the cumulative impacts caused by sequential events need to be better understood. Therefore, this paper presents a deployment method and results of low-cost sensors that can capture flood occurrences and durations in targeted areas using storm drains as a deployment location. A team of researchers and local government employees deployed these sensors between July 2019 - November 2021 with success. Flooding was recorded on 15 of the 22 deployed sensors recording an average of 13.58 inundation events causing the storm drains to be inundated on average 12.07% of the deployment time.

1 Introduction

The threat of sea-level rise (SLR) and global climate change is well-studied and expected to worsen under current global trends (Pielke et al., 2008; Neumann et al., 2015; Campbell et al., 2021). Severe flooding or storm surge events can cause significant property and infrastructure damage, mental stress, and economic loss (Adger et al., 2016; Maldonado et al., 2016; O'Donnell et al., 2022). Additionally, flooding and disaster impact research shows how environmental hazards and social vulnerability often overlap, which exacerbates these impacts (Emrich and Cutter, 2011; Wing et al., 2022). Climate models continue to predict that SLR will increase given the current emissions scenario (Pachauri and Meyer, 2015). SLR not only causes higher inundation during extreme events (e.g., hurricanes), but it also increases the frequency, magnitude, and duration of chronic coastal flooding (Marsooli et al. 2019; Li et al. 2021; Gold et al. 2023). Chronic coastal flooding, also called "sunny day flooding" or "high-tide flooding," refers to inundation events that occur outside of acute storm events (Moftakhari et al., 2018; Campbell et al., 2021; Gold et al. 2023). Chronic coastal flooding often causes disruption to routine activities and infrastructure systems, and it may lead to rapid degradation of existing infrastructure (Campbell et al., 2021; Gold et al. 2022; Moftakhari et al., 2017). Many low-lying coastal cities experience multiple days of flooding, and reoccurring inundation can add more strain to coastal systems (Gold et al. 2022). The cumulative impacts of inundation events have the potential to exceed the economic destruction seen in large-scale events (Adger et al., 2016; Hino et al., 2019; Moftakhari et al., 2017). However, the extent and impacts of localized and recurrent flooding events are under-studied compared to acute storm events (Moftakhari et al., 2018). To understand the impacts caused by these floods, a better understanding of how often chronic coastal flood events occur, their relationship to current water level records, and what locations are most vulnerable to chronic coastal flooding is needed, particularly as these events are projected to increase under future SLR scenarios.

There are varying levels of flooding events that affect coastal and inland populations in the United States. Many of these events are captured by water level sensors maintained by organizations such as the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS). Water level gauges operated by government organizations have been used previously to measure flood events, king tides, and water levels during extreme events such as hurricanes or Nor'easters (Li et al. 2021). However, chronic coastal flooding events are harder to monitor and record since these events are typically low levels of inundation and can occur where water level stations are not located (i.e., inland streets or residential canals). Recent work creating low-cost monitoring networks that capture chronic coastal flooding have used ultrasonic flood sensors (<$200 per unit) and pressure sensors paired with game cameras ($650 per unit) (Gold et al. 2023; Silverman et al. 2022). While communities can deploy and maintain local sensor networks with pressure loggers or ultrasonic sensors to record local water levels, project budgets may only allow placement of a few around the community. Therefore, chronic flooding events may be missed by sparsely located sensors due to local variations in SLR, topography, and geological features. Additionally, widely separated gauges and sensors that only measure coastal water levels may not account for land-based sources of coastal flooding (e.g., rainfall, runoff, groundwater).

Risk and impact assessments typically start with understanding the hazard (Wing et al., 2022). This study focuses on improving the understanding of chronic coastal flooding through a case study in Key West, Florida where we test a novel technique to record and monitor inundation events. Throughout the project researchers and city leadership tested the feasibility, accuracy, and functionality of these sensors, as well as ease of deployment for potential as tools for community science and education. The research team aims to measure the occurrence and duration of inundation events along local roadways and compare inundation events to current local water level recordings. HOBO pendant G data loggers are inexpensive sensors that could allow for greater than six times the spatial resolution of pressure loggers for measuring the occurrence of chronic coastal flooding. Flood events recorded through the pendant G data loggers are tested for accuracy by comparing the recorded inundation events to potential inundation events predicted using the closest NOAA tide gauge data. The timing of inundation and the NOAA water levels at the start and end of inundation were further compared to find patterns of inundation for the future prediction of chronic coastal flooding around Key West. A secondary aim was to assess the feasibility of citizen scientists to deploy and maintain the sensors. Through testing the accuracy of the accelerometers, the NOAA tide gauge, the timing of inundation events, and the feasibility to deploy the sensors we have set up HOBO pendant G data loggers to successfully be used as sensors to monitor inundation.

2 Materials and Methods

2.1 Study Site

This research was conducted in the City of Key West, located in Monroe County, Florida, USA. Key West is along the southernmost part of the US Route 1, the only road connecting this island to the mainland of Florida. It is a densely populated area with 1,846 people per km^2 (4,782 people per sq. mi.) (U.S. Census Bureau 2021). It is a popular tourist destination, and the economy relies heavily on tourism revenue (Mozumder et al., 2011). In 2018, Monroe County tourism generated about \$492 million USD in tax receipts and supported about 26,500 jobs for residents (44% of all Monroe County jobs) (Rockport Analytics 2019). This economic hub and highly populated location face coastal flood risk from global climate change, such as increased sea levels and major storms (Li et al., 2021; O'Donnell et al., 2022). Average ground elevations around the Lower Florida Keys were about 0.87 m (2.85 ft) above mean high water (MHW), and the area is prone to hurricanes (Mozumder et al., 2011). The National Hurricane Center (NHC) has recorded 48 tropical storms and 12 major hurricanes (category 3 or higher) since 1852 within an 80 km (50 mile) radius of the Lower Florida Keys (NOAA Office for Coastal Management, 2022).

As Key West's population is exposed to future climate hazards, the impacts of coastal floods may increase. The local NOAA Tides and Currents Station (# 8724580), located at the western end of Key West, has measured an increase in sea level of 0.23 m (0.75 ft) from 1913 to 2021 (NOAA CO-OPS, 2022). The combination of a large population, high exposure, and increased hazards within Key West creates an area with high risk and emphasizes the need to understand future coastal flood hazards that may affect this area (Pachauri & Meyer, 2015).

2.2 Sensors and Deployment

The research team - which included a Key West municipal employee, researchers from Northeastern University, and researchers from the United States Naval Academy - used HOBO pendant G data loggers to collect flooding data in Key West. The instrumentation used are inexpensive (<\$100 USD) small loggers weighing about 18 g (0.6 oz) with dimensions of 58 x 33 x 23 mm (2.3 x 1.3 x 0.9 in.) (ONSET, 2013). The loggers record acceleration and angular displacement (tilt) in three dimensions, allowing for characterization of three-dimensional motion. Previous work used these accelerometers to record the movement of animals such as lobsters and dairy cows (Jury et al., 2018; Rayas-Amor et al., 2017). For chronic coastal flooding, the acceleration and tilt were used to record flood events since rising water changes the orientation of the buoyant sensors, causing angular displacement and a change in the axis experiencing gravitational acceleration. A schematic of the loggers and their deployment are displayed in Figure 1. Data was logged by the sensors continuously at specified sampling rates until the data was offloaded to the logger software HOBOware v3.7.21 (ONSET, 2013). Tilt data was used in the post processing as described in section 2.3 Data Analysis and Processing.

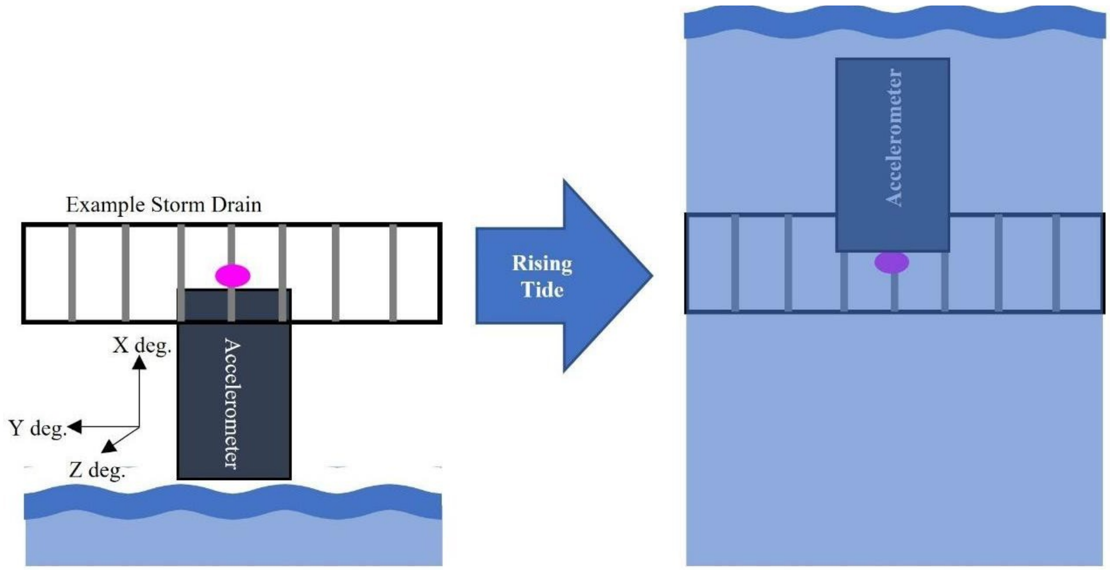

Figure 1. Deployment displaying a storm drain with a HOBO logger attached via the pink circle (string). As the tide rises and the location floods, the sensor floats, altering the orientation of the sensor and indicating a flooding event.

Storm drains are often the first areas to be inundated during flooding events and are sometimes the source of inundation (Hino et al., 2019). They are often designed to be the lowest area along a road to facilitate drainage. In coastal areas such as Key West, these low elevations are more prone to flooding and can be the first to flood. Additionally, failing infrastructure or a buildup of debris could cause increased flooding at a storm drain (Gold et al. 2022). Therefore, storm drains were selected for deployments, providing publicly accessible areas that were both prone to frequent inundation and a fixed locations for sensor deployment. Noting that the loggers are positively buoyant, the research team hypothesized that tying the logger to a fixed axis, such as a storm drain, would allow 360° movement during flooding events while keeping the logger at the deployment location. As illustrated in Figure 2, the logger hangs vertically and points downward along the x-axis when the logger is hanging (Figure 2a), and the logger rotates such that it points upward along the x-axis when the logger is submerged (Figure 2b). In the field deployments, loggers were tied to storm drains, further secured with tape, and left to hang freely underneath the grates of the storm drains (Figure 2c). An example deployment is displayed in Figure 2c and Figure 2d.

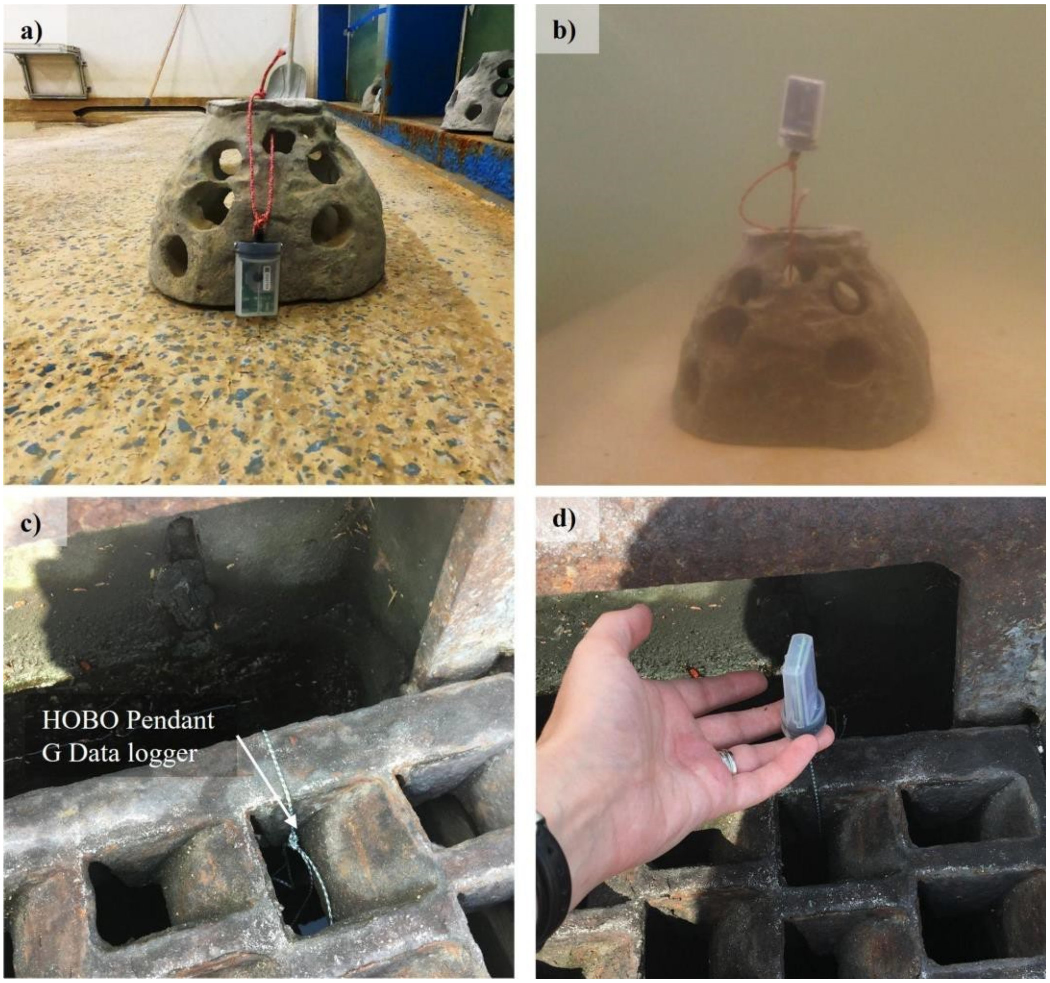

Figure 2 Photographs showing concept for accelerometer deployments. Photograph a) shows the accelerometer hanging by the string; photograph b) shows the buoyant accelerometer under submerged conditions; photograph c) shows the accelerometer hanging by a string beneath the storm drain at deployment location 12) Jose Marti; and photograph d) shows the accelerometer held above the storm drain displaying its orientation during an inundation event. Future deployments added tape to the string to further secure the sensors.

Using knowledge of previous flooding events and local expertise, 14 total deployment locations were selected (Figure 3). Each location had a publicly accessible storm drain to attach the loggers. The research team deployed loggers four different times over the period from July 2019 to November 2021 (Table 1). Loggers were programmed to record continuously after a user-specified launch time and recorded a data point consisting of acceleration and angular displacement (tilt) in three dimensions at a specified frequency. Sampling rates were specified such that loggers recorded measurements every one minute for the first two deployments and every five minutes for the third and fourth deployments. Loggers were memory-limited; that is, the logger's battery capacity was greater than that of its memory. Thus, logging acceleration and tilt in all three dimensions at a sampling rate of one minute provided 15.1 days of recordings, and logging acceleration and tilt for all three dimensions at a sampling rate of five minutes provided 75.3 days of recordings. For each deployment, researchers manually recorded the time and date loggers were deployed (i.e., secured to storm drains or locations of interest) and retrieved. During the initial deployments, researchers recorded latitude and longitude at each deployment site for subsequent geospatial analyses. Loggers were left to record for durations ranging from one week to three months depending on the set recording time and research team availability (Table 1). Deployment 3 was the longest deployment, lasting almost 6 months due to research team availability during the COVID-19 pandemic.

Table 1 Deployment details of accelerometers in Key West, FL during this study. Columns indicate deployment number, total number of sensors that were deployed, total number of sensors retrieved with data available to download, and the span of dates over which sensors were left deployed.

	Sensors/ Locations	Number Retrieved	Dates Deployed
Deployment 1	5	5	7/6/19 - 7/16/19
Deployment 2	14	11	7/30/20 - 8/14/20
Deployment 3	14	5	11/06/20 - 04/01/21
Deployment 4	5	5	8/17/21 - 11/20/21

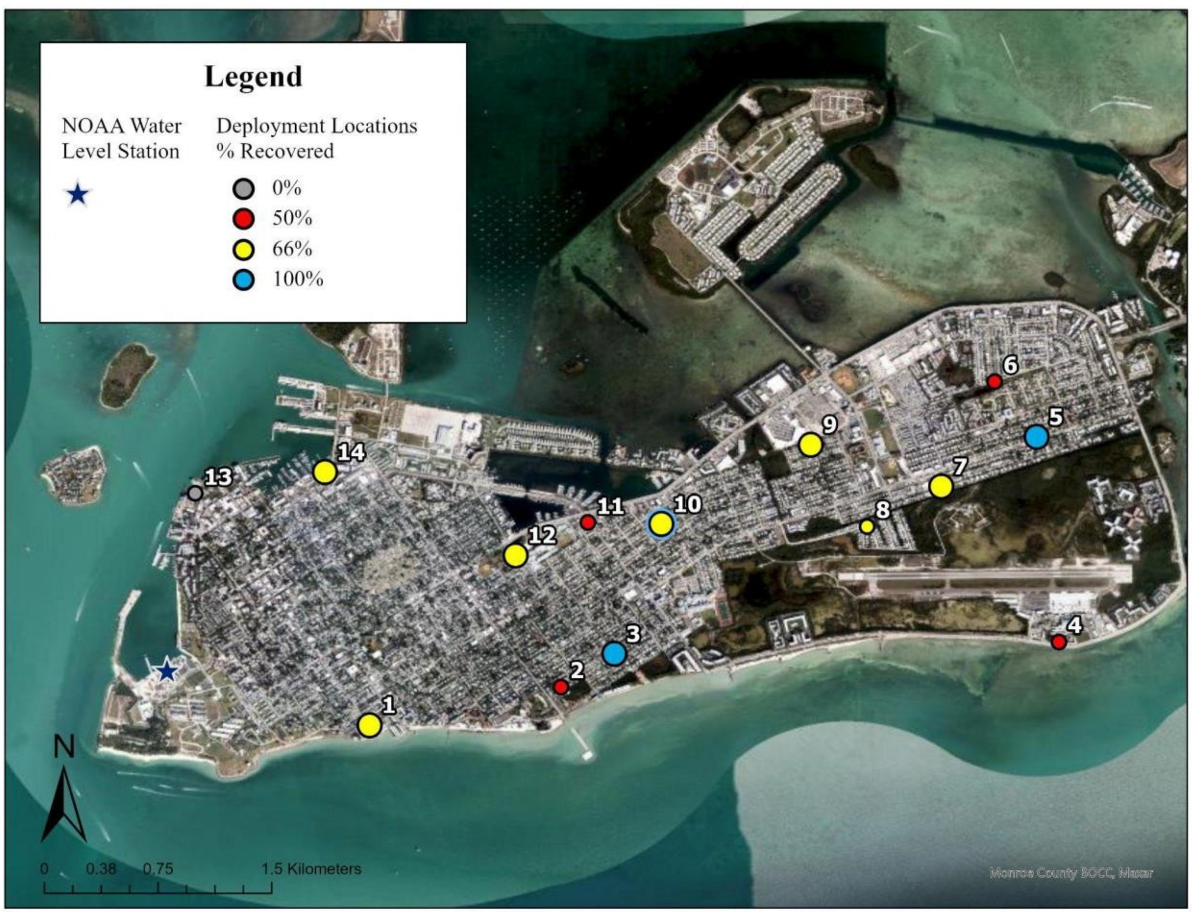

Figure 3 Aerial image of Key West, FL displaying the deployment locations of accelerometers. Smaller circles represent a location with two deployments and larger circles represent a location

with three deployments. The colors of dots represent the proportion of sensors successfully retrieved at each location for all deployments. Locations are labeled by ID number corresponding to the station locations in Table 2. The highlighted blue location (ID 10) is used in Figure 4 as an example of data processing.

2.3 Data Analysis and Processing

Data from retrieved loggers was downloaded into software (HOBOware v3.7.21) and exported for future analysis in RStudio v1.4.1717. Any data points outside the deployment window (Table 1) were removed from the data to eliminate tilt and acceleration collected during logger set up or retrieval. The time at which a sensor recorded a flooding event was identified using tilt in the x-direction and z-direction. Theoretically, tilt in the x-direction (x-degree) reads exactly 180° when the logger is hanging below the storm drain, 90° when the logger is lying flat, and 0° when the logger is floating above the drain during an inundation event (Figure 1) (ONSET, 2013). Additionally, tilt in the z-direction (z-degree) reads 90° when the logger is hanging below the storm drain, 0° or 180° when the logger is lying flat (depending on which side of the logger faced up), and 90° when the logger is fully floating above the drain (ONSET, 2013). To account for the potential spin of the logger during flooding events (i.e. z-degree equals 0° or 180° depending on which side of the logger faced up), an adjusted z-degree was calculated by taking the absolute value of the recorded z-degree minus 90°. Therefore, the adjusted z-degree reads 0° when the logger is hanging below the storm drain, 90° when the logger is lying flat, and 0° when the logger is fully floating above the drain. However, the x- and z-degree scenarios described above are ideal conditions where the logger was fully submerged or fully hanging below the storm drain. Since chronic coastal flooding can occur at depths as shallow as 3 cm (Moftakhari et al. 2018), and the storm drains did not always allow for ideal conditions (i.e., clogs, maintenance, debris etc.), the post processing method used allowed for semi-submerged accelerometers to indicate flooding. Locations were marked as flooded if the logger's recorded x-degree was less than or equal to 92° and the absolute value of the recorded z-degree-adjusted was greater than or equal to 45°. Both criteria needed to be met before flooding was marked. Flooding/non-flooding times series for each logger were compared to water levels recorded by the NOAA Key West station #8724580 by time (EDT/EST), and flooding events were matched to their concurrent high tide events.

Deployment locations were mapped in ArcGIS Pro 2.4.0 using the latitude and longitude collected. The distance to the closest NOAA tidal station, the distance to the closest coastline or canal, and the elevation were determined for each deployment location. The elevation of each deployment location was collected from a digital elevation model from NOAA's National Geophysical Data Center, which provided elevation with a resolution of one-third arc-second (10 m) with reference to the vertical tidal datum of Mean High Water (MHW) and horizontal datum of World Geodetic Systems 1984 (National Geophysical Data Center, 2019). The 10 meter resolution provides general elevation for the locations used and a more exact elevation should be collected during deployments for more complex analysis into the drivers of coastal inundation. The general elevation is then used to predict the frequency of inundation near the deployment locations by calculating the number of times NOAA water level exceeded the location elevation. Water level data from NOAA station #8724580 was downloaded using the MHW vertical tidal datum through NOAA Tides and Currents. Inundation thresholds for a minor (0.362 m or 1.188 ft. MHW), moderate (0.515 m or 1.688 ft. MHW), or major (0.667 m or 2.188 ft. MHW) flood event at the NOAA Station #8724580 was given by the NOAA National Weather Service (NWS)

(NOAA CO-OP, 2022). Data from the accelerometers was compared to predicted flood events using both NOAA water level exceeding the NWS inundation thresholds and deployment elevations. Time locations were inundated was normalized by the total duration for which sensors were deployed and recording for comparisons across the four deployments. Elevations were compared to average NOAA water levels during the recorded inundation periods, and flood occurrences were compared to occurrences when the NOAA water level station exceeded elevations. The time difference between inundation onset and inundation end recorded by the accelerometers and the closest NOAA reported high tide was calculated for each recorded flood event. The water level at the start of inundation and the end of inundation was also collected for comparison across elevation. Once post processing was complete, all data was mapped, and Global Morin's I was calculated for both the normalized inundation time and the difference between the onset of inundation and NOAA high tides to look at the spatial correlation. Moran's I statistics for both normalized inundation time and difference in inundation onset were calculated using an inverse distance relationship.

3 Results

Sensor deployments and retrieval were completed by the research team. The number of deployed and retrieved sensors for each deployment are shown in Table 1. In total, 38 sensors were deployed between July 2019 and November 2021. 5 sensors had measurement errors and were not processed, 11 were lost, and 22 provided flood estimates for future analysis. Deployment locations and the percent recovered at each location are displayed in Figure 3 with the station ID number assigned to each location. Deployments were possible during travel restrictions associated with the COVID-19 pandemic owing to the small, shippable size of the sensors and the research team's partnership with community stakeholders. When comparing the flooding events captured by the loggers against water levels recorded by the NOAA water level station #8724580, flood events generally corresponded with NOAA high tides. Figure 4 shows an example of the logger sum acceleration (a), x-tilt (b), and adjusted z-tilt (c) time series with the corresponding NOAA water levels (d) (referenced with respect to MHW). This figure displays the variables used for identifying flood events and shows how the sum acceleration, x-degree, and adjusted z-degree changed when the location was flooded. This pattern was similar at the other stations, and floods were readily identified with the data collected.

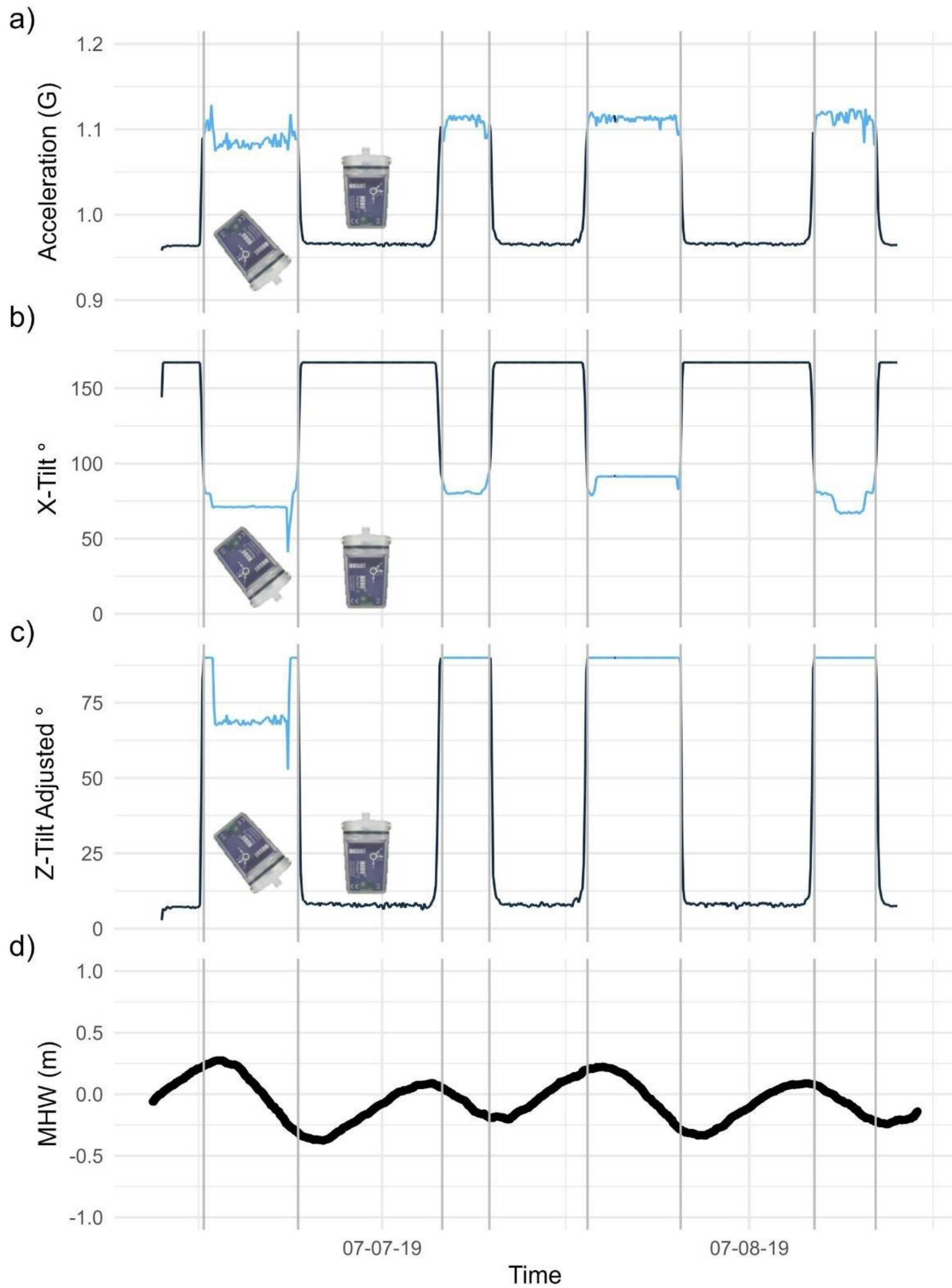

Figure 4. Example time series from accelerometer with flooding data from 7/6/19 09:00 – 7/8/19 11:00. The multiple panels show a) sum acceleration, b) x-tilt, c) adjusted z-tilt, and d) water levels recorded by NOAA station #8724580 referenced to MHW during the same time period. The data used to specify flooding occurrences are shown with plots a, b, and c. Light blue lines indicate when the accelerometer was determined to be in a flooded condition given the defined specifications. The grey vertical lines indicate the start and end time of flood events. An image of the HOBO logger's approximate orientation during the deployment for the first flood event is displayed for plots a, b, and c. The location is 4th & Fogarty (ID 10), which is highlighted blue in Figure 3.

The number of inundation events and the total time that each location was inundated were variable throughout the study area. Table 2 shows the number of floods and total time inundated for each deployment location during each deployment. ID numbers at each sensor location correspond to those indicated in Figure 3. The number of times and the amount of minutes NOAA water level exceeded NWS inundation thresholds are shown for each deployment period at the top of Table 2. The three locations inundated most often throughout the deployments were 7) Riviera Kayak Launch (elevation of 0.281 m or 0.923 ft., referenced to MHW), 3) Rose & Thompson (elevation of 0.422 m or 1.386 ft., MHW) and 5) Flagler & 18th (elevation of 0.554 m or 1.818 ft., MHW). The locations 7) Riviera Kayak Launch and 3) Rose & Thompson had an elevation above the NOAA NWS minor inundation threshold. Flagler & 18th (5) had an elevation above the minor and moderate inundation NOAA NWS thresholds. However, these locations recorded more inundation events than the NOAA water level exceeded NWS flooding thresholds. From July 30th to August 14th, 2020 (second deployment), Riviera Kayak Launch (7) was inundated 23 times for a total of 8,495 minutes, resulting in this location being flooded 44.2% of the deployment time. During the third deployment, Rose & Thompson (3) was inundated 49 times for a total of 12,250 minutes over the period November 6th, 2020, to January 8th, 2021, 12.4% of the deployment time, while Flagler & 18th (5) was inundated 29 times for a total of 7,340 minutes between November 6th to December 4th, 2020, 15.3% of the deployment time. The HOBO accelerometers recorded many more inundation events than the NOAA water level. According to the minor, moderate, and major flood levels from the NWS, Key West experienced 0 major floods, 1 moderate flood, and 24 minor floods across all four deployments.

Table 2. Number of flood events and total minutes of inundation for each deployment and each location. Number and total minutes of NOAA NWS minor, moderate, and major flood events are displayed for each deployment. Dates are displayed under deployment number for when sensors are recording data. Cells with a '-' indicate no sensor was deployed at the corresponding location for that deployment. Cells with an 'NR' indicate the sensors that were deployed but not recovered for that deployment. And cells with an 'ERROR' indicate sensors that were deployed and recovered but there was an error in collecting the data and it was unable to be processed.

		Deployment 1		**Deployment 2**		**Deployment 3**		**Deployment 4**	
		7/6/19 - 7/8/19 7/12/19 - 7/16/19		7/31/20 - 8/14/20		11/06/20 - 01/08/21		8/17/21 - 10/31/21	
NOAA water level	Elevation (m)	Number of Flood events	Minutes Inundated	Number of Flood events	Minutes Inundated	Number of Flood events	Minutes Inundated	Number of Flood events	Minutes Inundated
NWS Minor Flood (0.362 m)		0	0	3	168	10	1860	11	1128
NWS Moderate Flood (0.515 m)		0	0	0	0	1	102	0	0
NWS Major Flood (0.667 m)		0	0	0	0	0	0	0	0
Sensor Locations									
1. Duval & South St	0.576	-	-	4	1005	*NR*	*NR*	0	0
2. Atlantic Dr & Sirugo	0.234	-	-	5	985	*NR*	*NR*	-	-
3. Rose & Thompson	0.422	-	-	2	245	49	12250	2	110
4. East Martello/ Airport	0.694	-	-	0	0	*NR*	*NR*	-	-

5. Flagler & 18th	0.554	-	-	4	965	29*	7340*	0	0
6. Donald & 17th	0.448	-	-	0	0	*NR*	*NR*	-	-
7. Riviera Kayak Launch	0.281	*ERROR*	*ERROR*	23	8495	*NR*	*NR*	-	-
8. Venetian Dr.	0.593	-	-	0	0	4	440	-	-
9. 11th & Patterson	0.391	-	-	7	1030	*NR*	*NR*	19	3325
10. 4th & Fogarty	0.487	6	1650	2	245	*NR*	*NR*	-	-
11. Vivian & 1st	0.187	-	-	*NR*	*NR*	*NR*	*NR*	-	-
12. Jose Marti	0.268	4	1165	*NR*	*NR*	*ERROR*	*ERROR*	-	-
13. Zero Duval	0.484	-	-	*NR*	*NR*	*NR*	*NR*	-	-
14. Ferry Terminal	0.906	-	-	0	0	3*	205*	0	0

*Sensor was retrieved at 12/04/20

Comparing water levels to land elevation along the coast is one method for capturing flooding events. Therefore, the average NOAA water level during the inundation periods was calculated for each sensor that documented a flood event during the deployments. Figure 5 compares the NOAA recorded water levels during sensor recorded inundation periods to the elevations of sensor deployment locations. Points above the 1:1 line indicate sensor locations that were flooded when the NOAA average water level was below the elevation of the deployments. All sensors that recorded flooding were above this 1:1 line, showing that comparing NOAA water levels to land elevation is not sufficient to predict flooding in Key West. The sensor located at the highest elevation (number 14 – Ferry Terminal) recorded 3 floods during the second deployment. During these floods, the NOAA water level averaged 0.250 m, well below the sensor elevation of 0.906 m, and exceeded the sensor elevation 0 times. The sensor located at the lowest elevation (number 2 – Atlantic Dr & Sirugo) recorded 5 floods during the first deployment. During these floods, the NOAA water level averaged 0.170 m and exceeded the sensor elevation of 0.234 m 5 times. Points below the 1:1 line would indicate water levels above deployment elevations. Since there were no locations found below this line floods recorded by the accelerometers were not solely due to NOAA water levels. Comparing tidal water levels to nearby land elevations does not account for other drivers of flooding, such as rainfall, as well as the performance (or failure) of the network of man-made canals and stormwater infrastructure that can allow the landward movement of water further inland.

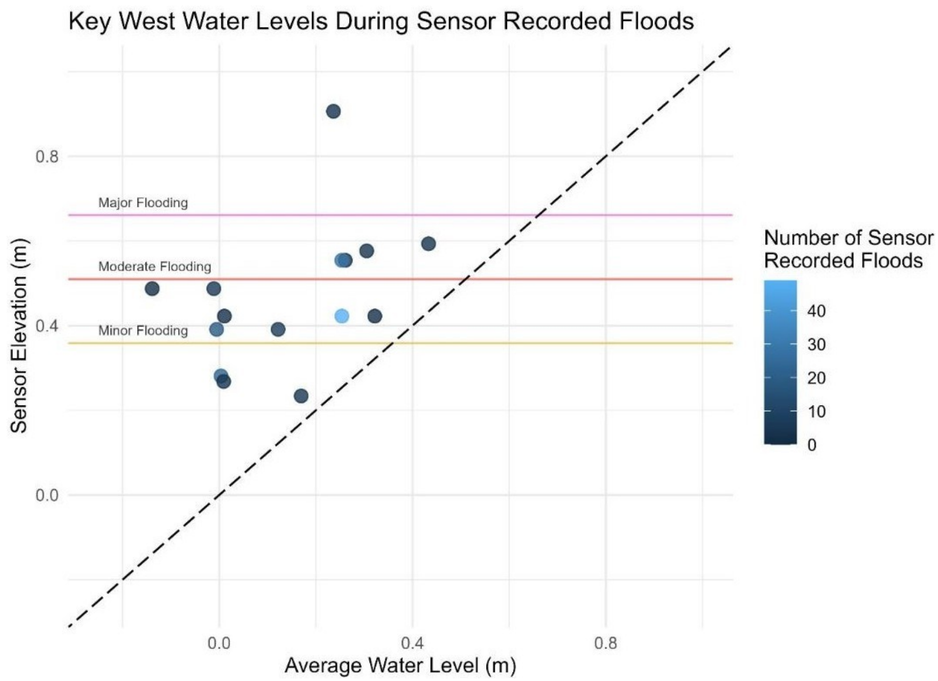

Figure 5 Elevation of sensor deployments vs. average NOAA water levels during the inundation periods recorded by accelerometers. NOAA NWS minor, moderate, and major flooding elevations for Key West are plotted as horizontal yellow, orange, and pink lines, respectively. The dashed 1:1 line indicates when the NOAA water levels would also predict flooding given deployment elevations. All elevations and water levels are referenced to MHW. The color of the points shows the number of floods the accelerometers recorded. There are 7 sensors that did not record flooding and therefore are not included in the figure. Their elevations ranged from 0.448 m – 0.906 m.

For direct comparison between accelerometers and the NOAA water levels in documenting flood occurrences, a NOAA flood was marked for every time the NOAA water level exceeded a sensor location's elevation during the deployment periods. Figure 6 displays a comparison between the number of accelerometer-recorded floods at the deployment locations and the number of times that NOAA water levels exceeded the sensor elevations at the deployment locations. The 1:1 line is displayed as the dashed line and values above this line suggest areas that the accelerometers record flooding more frequently than the NOAA station records water levels above the sensor's elevation. Values below this line suggest areas that the NOAA station predicts flooding to occur more often than the accelerometers recorded floods. Values plotted on the line mean that the NOAA water level and the accelerometers recorded similar flooding occurrences for that sensor location. As indicated in Figure 6, the accelerometers recorded significantly more flood occurrences than suggested by NOAA water levels and deployment elevations. Similar to Figure 5, Figure 6 indicates the possibility of storm drain (and roadway) flooding caused by drivers beyond high tides, potentially including flooding due to precipitation and water infrastructure connectivity and performance.

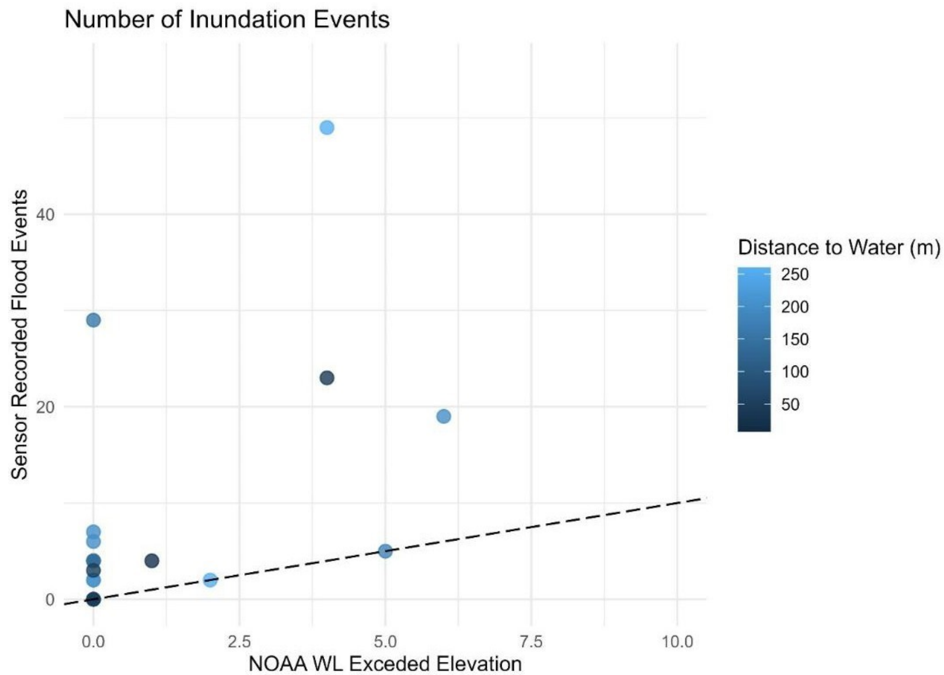

Figure 6. Number of instances the accelerometers recorded flooding vs. number of instances when the NOAA water level exceeded sensor deployment elevations. Points are colored based on the distance the location is to a water source (ocean, man-made canal, or man-made pond). The dashed 1:1 line indicate when NOAA predicted inundation match with sensor recorded inundation events. Values below this line suggest the location floods more often than suggested by NOAA values and values above this line suggest the location floods less than suggested by the NOAA gauge.

Figure 7 displays the spatial distribution of the average fraction of time inundated for each deployment location. No significant spatial patterns were found throughout the stations in Key West (i.e., sensors closer to the shoreline or on one side of the island were not more vulnerable to flooding). The duration of inundation resulted in a slightly dispersed spatial correlation (I = -0.453, *z-score* = -1.885, p = 0.059). Stakeholders at the City of Key West requested a better understanding of the flood onset at vulnerable roadways around the island in relation to the NOAA station, and whether NOAA water level measurements could consistently be used for future planning of roadway closures and cleanups associated with extreme high tides. Table 3 shows the average time in hours before or after a NOAA high tide that flooding started and ended at each sensor location. The onset of flooding at the deployment locations ranged from almost one hour preceding to two hours after the nearest high tide recorded at the NOAA station. The end of inundation events ranged between 1.5 hours to five hours after NOAA high tide. There was no spatial pattern to the timing of the inundation events around the island and was randomly spatially correlated (I = -0.004, *z-score* = 0.499, p = 0.618). Therefore, the time difference between the onset and end of sensor flooding and high tide at the NOAA station showed significant variability. The variability of flooding was further analyzed by finding the NOAA water level at the start and end of inundation. Figure 8 compares the water levels at the start (a) and end (b) of each inundation event for the 10 sensors that recorded flooding. The NOAA water levels at the start and end of sensor inundation periods were highly variable across elevations (Figure 8). Due in part to the variability in the timing of flooding and the variability in water levels at the start and end of flooding identifying chronic coastal flooding around Key West requires local monitoring and reporting, as floods may occur outside of the NOAA high tide.

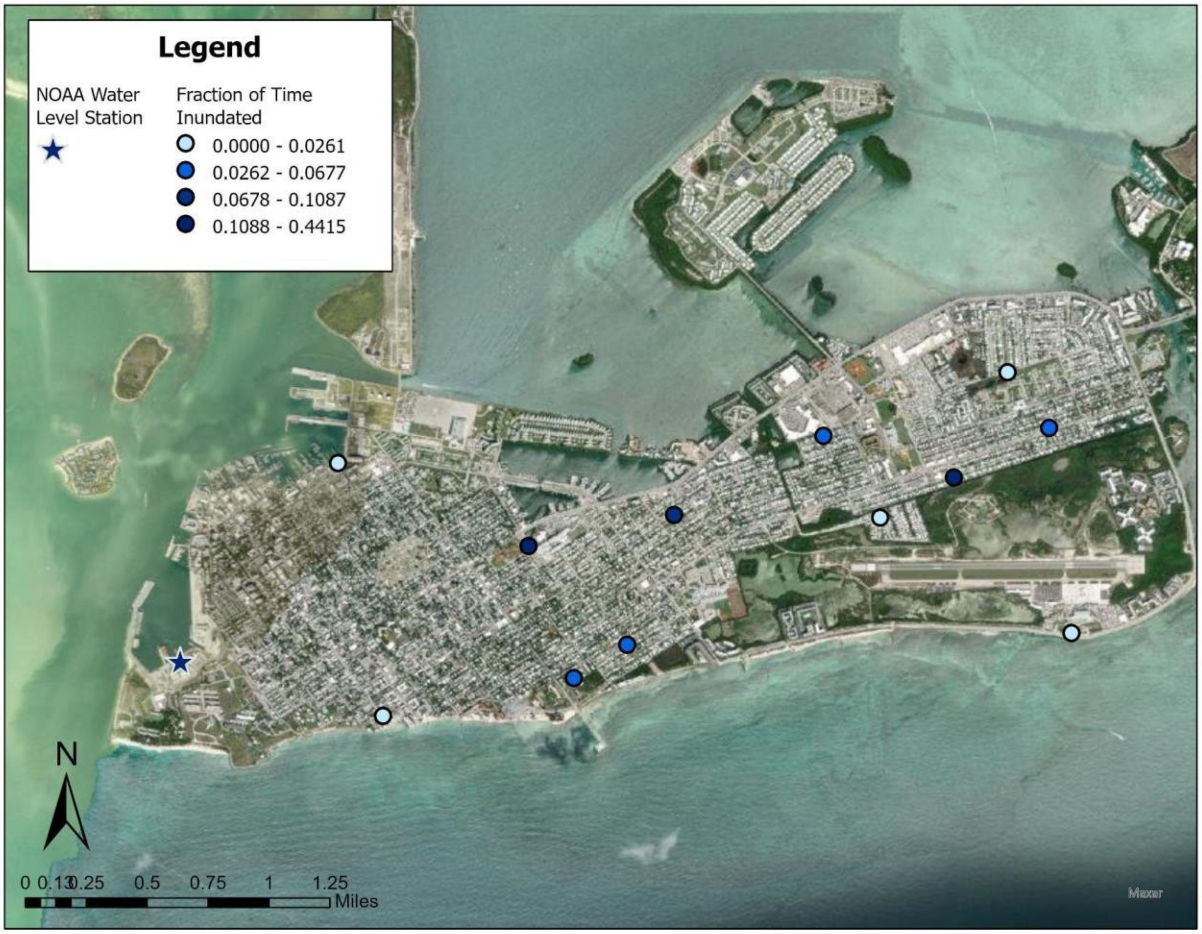

Figure 7. Map of the fraction of time each location was inundated and the NOAA station (star).

Table 3. Average time (in hours) from the closest NOAA measured high tide for both the start and the end of the inundation event. Negative values are hours before the NOAA high tide, and positive values are hours after the NOAA high tide.

	Inundation Start from closest High Tide (hrs.)	Range	Inundation End from closest High Tide (hrs.)	Range
Ferry Terminal	-0.84	-2.15 - 1.08	-1.98	-3.07 - -1.08
Rose & Thompson	-0.58	-6.15 - 4.60	-3.06	-6.82 - -1.02
11th & Patterson	-0.53	-5.58 - 6.32	-1.58	-7.4 - 6.07
Venetian Dr.	-0.34	-1.03 - 0.97	-2.17	-3.20 - -1.40
NOAA Sensor	0.00		0.00	
Duval & South St	0.00	1.22 - 2.97	-4.83	-1.53 - -0.03
Jose Marti	0.00	-1.13 - 1.05	-4.83	-5.12 - -4.22
Atlantic Dr & Sirugo	0.17	-1.83 - 2.72	-2.56	-5.08 - -1.28
4th & Fogarty	0.88	-2.27 - 5.43	-1.51	-5.67 - 4.77

Flagler & 18th	1.25	-5.37 - 5.20	-2.69	-5.87 - 4.8
Riviera Kayak Launch	2.53	-4.92 - 5.33	-3.03	-5.45 - 4

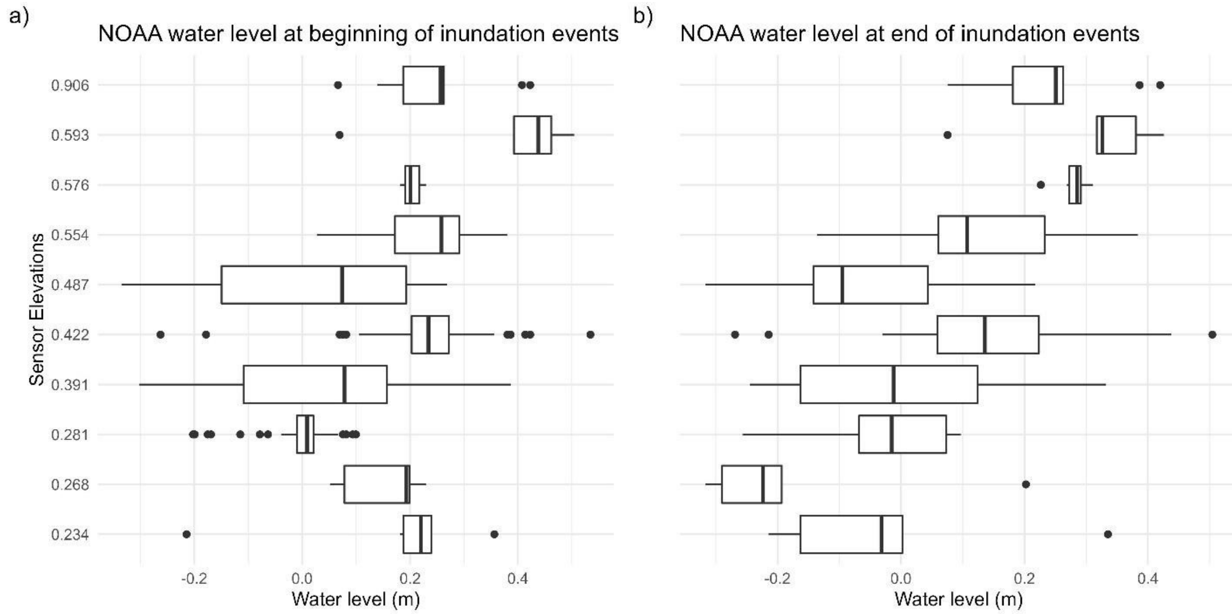

Figure 8. The water level at the beginning of inundation (a) and the water level at the end of inundation (b) plotted by sensor location elevations.

4 Discussion

The aims of this study were to assess HOBO pendant G data loggers on their ability to measure inundation and the feasibility of deployments for future citizen science applications. The low-cost sensors tested in this study were able to record the occurrence and duration of inundation events at locations of interest in Key West. Across all four deployments, data was successfully recorded by 22 sensors, 15 of which recorded flooding events. Sensors were readily deployed by both local stakeholders and the research team, with deployments taking several hours to one day, depending on the number of loggers installed. The ease of the deployment method provides individuals with the ability to easily measure flooding occurrences and durations at various roadways, allowing for further investigation into the effects of chronic floods. The recorded flooding events generally overlapped with high tides recorded at the NOAA Key West water level station, although the onset of flooding and the duration of flooding in an area was variable throughout the study. Generally, accelerometers recorded more inundation events than predicted by NOAA water levels. However, there was no clear trend of time before/after a NOAA high tide or height of water level to predict when a location would record flooding. Future work is needed to better understand the factors causing the inundation to occur and the depth of inundation events.

Based on the four deployments described here, we are confident in the ability of these sensors to record flooding events, giving communities the ability to learn more about chronic coastal flooding trends in Key West. The accelerometers were able to capture the variability found in the timing and the number of flooding events around Key West. However, further work is needed to explore the uncertainty in the height of the inundation events. Chronic coastal flooding in Key West is due in part to tidal levels and frequency, however it does not explain all the inundation events found during the deployments. Only three sensors were found on the 1:1 line in figure 6, suggesting that using the location elevation to predict flooding mostly underestimates the amount of potential flooding occurring. We hypothesize that other factors at play are rainfall and storm events or infrastructure age and maintenance (e.g., debris or another clog). Future work is needed to assess the causes of inundation throughout Key West. Even with these limitations, this study highlights areas that appear to be vulnerable to inundation (regardless of the driver). Further, access to an inexpensive sensor for measuring floods provides additional opportunities to monitor future flooding extents and durations at these vulnerable locations, with community members empowered to collect their own flooding data. Future deployments may allow for further research into chronic coastal flooding causes and impacts at specific locations and provides opportunities for outreach and community engaged science.

To test the ability of the NOAA tidal gauge for future inundation predictions, the accelerometer recorded inundations were compared to NOAA water levels and high tide timing. The onset of flooding at the deployment locations was highly variable, ranging from almost one hour before to two hours after the high tides recorded by the NOAA station (Table 3). These results, along with the variability in number of floods throughout Key West, again indicate that flooding at a specific location may be influenced by factors in addition to tidal anomalies. Previous studies on chronic coastal flooding show evidence that inundation events may be caused by changes in the magnitude of the tide, local landscape characteristics, and local SLR (Li et al., 2021). Key West is an island composed of naturally porous lime rock, and human modifications made around the island could alter and change the natural flow of water throughout the island. In agreement with previous studies, the three sensors with the highest proportion of inundation are all located inland and near human modification (Gold et al., 2022; Li et al., 2021). Riviera Kayak Launch (7) is along a canal system, 4th & Fogarty (10) is a residential stormwater drain, and Jose Marti (12) is located near a manmade pond. The variation in the water level and timing of the onset and end of inundation is also large within one location (Table 3, Figure 8A), showing that subsequent tides may inundate Key West differently and may depend on antecedent conditions at local sites such as storm drain and roadway maintenance and previous flooding events. The difference in inundation onset at one location may also point to the importance of local or meteorological factors such as rain events or local topography. This study does not attempt to separate flooding due to rainfall, high wind events, or magnitude of the NOAA high tide, which could account for the earlier onset of inundation or the later end of inundation. More work is needed at local scales to find hot spots of inundation risk, particularly associated with future climate hazards including increased precipitation and local SLR.

The methodology presented here successfully recorded inundation present along storm drains, allowing for identification of a potential chronic coastal flooding event. However, while information on the occurrence and duration of flooding events is readily available, the sensors did not record water levels, which may be an important and required measurement for some communities. Future work may consider incorporating water level loggers and other sensors with accelerometers to better understand both the extents and magnitude of local floods. Modifications to the deployment method (e.g., positioning the sensors on stakes at pre-specified elevations of interest, or changing the length of the string used such that the sensors record when water levels reach a specific depth) may allow for threshold flooding levels to be recorded in order to better understand when a flood becomes high enough to make roads impassable or when home damage may start to occur. The current inundation events recorded in this study are any force on the accelerometers that push them up above the storm drain. Modifications to the deployment method or co-locating a pressure logger with the accelerometers is the next step in testing the deployment technique.

Thirteen sensors in total were lost over the four deployments. Sensors were most likely lost due to the duration of deployment or the amount of vehicular and foot traffic in the area. The lowest sensor retrieval rates were in areas of high foot- and car-traffic, suggesting that lost sensors were likely destroyed or removed by passing cars or pedestrians. Duval Street is a hotspot of tourism in Key West, and two of the deployments were located on this street. Specifically, the deployment location Zero Duval (13) is located between two 4-star hotels, and the location Duval & South St (1) is located near a public park. At Zero Duval, deployed accelerometers were not recovered for the two attempted deployments, and at Duval & South, deployed accelerometers were recovered for two of the three attempted deployments. Although locations with high pedestrian or vehicular traffic posed a risk of nonrecovery, the ease of access to all locations also provided easier set-up for the research team to deploy sensors. Time was also a potential factor in successful recovery. Although the loggers were able to record for longer periods of time based on the logging interval, the researchers suggest only leaving the sensors out for 1-3 months given the current deployment method. The first and second deployment were a week and a month respectively, during both times less than 20% of the sensors were lost. The most sensors were lost during the 3rd deployment, when sensors were left out for longer than 3 months, about 65% loss. The fourth deployment was about 3 months, and the research team was able to retrieve all the sensors. Future work using this deployment method must find a balance between access, deployment duration, and sensor security to ensure that loggers can be retrieved for subsequent analyses.

The size of the loggers and the ease of setup proposed here are critical for managers and collaborators to record daily events occurring locally and to allow avenues for future research. These sensors and the deployment method allow for data collection at many points of interest throughout a region. Their ability to measure flooding at locations of interest when NOAA tidal stations do not indicate water levels above NWS minor flood thresholds is shown in Table 2. Minor, moderate, and major floods are the NWS flood levels and some studies use the minor flood levels as thresholds to mark instances of low level flood events (Hino et al., 2019; Li et al., 2021). However, the number of potential floods recorded outside of minor and moderate thresholds show that street level monitoring may also be needed to fully assess the impact of chronic coastal flooding. Because we did not record the height of inundation in this method, it is unclear which inundation events make it past the height of the storm drains. Future deployments may account for elevation of flood through string length or game cameras similar to the set up used in Gold et al. (2023), or through co-location with pressure sensors used to measure water levels. Such co-location can also be used to validate the sensor-recorded flood durations to identify uncertainty in recorded flood durations owing to sensors getting stuck in debris or on the storm grate. Even without elevation data, the type of monitoring used here may be used to identify "near misses," or water elevations that could be an issue under future projections of sea level rise (Kriebel et al. 2015).

Low flood levels can make areas impassable, creating added stress and potentially dangerous conditions for residents who use the impacted roads to commute to work or are traveling for recreation. Vehicles may lose control or stall in water levels of 15.2 cm and can float in water levels as low as 30.5 cm (FEMA 2023). Minor levels of flooding have been shown to negatively impact the amount of recreation activity and visits to flooded locations in Annapolis, MD (Hino et al., 2019). Due to these potential impacts of chronic coastal flooding on safety and tourism, additional studies are needed in popular tourist areas such as Key West to better prepare for and respond to increasing inundation events. Low levels of flooding, when occurring often, can cause cumulative impacts, creating more destruction and erosion to roadways than a single storm (Campbell et al., 2021; Gold et al., 2022). Identifying which roadways flood most often in a municipality provides planners with information on what areas need protection and may allow for anticipation and proactive mitigation of future issues. Large-scale studies use NOAA sensors to map potential flooding events using factors such as high tide flooding estimates, or a station's mean higher high water level highlighting cities or towns vulnerable to coastal inundation (Gold et al. 2022; Li et al. 2021; Moftakhari et al. 2017). Such characterization may be particularly important in coming decades, as recent models have indicated that early stages of sea level rise will cause the greatest increase in coastal areas exposed to inundation (Vernimmen & Hooijer 2023). The ability to measure flood events on smaller spatial and temporal scales allows for characterizing chronic coastal flooding extents and changes over time in a specific community. For example, local decision-makers could use these sensors and set-ups to determine where local flooding is occurring most often and how long inundation typically lasts to inform and prioritize future mitigation efforts. With the deployments presented here, Riviera Kayak Launch, Rose & Thompson and Flagler & 18th locations were inundated most often. Therefore, these three locations are areas of elevated risk and may benefit from near-term flood mitigation efforts.

An inexpensive flooding sensor provides interested parties with the ability to measure local chronic coastal flooding (e.g., interested homeowners, schools, outreach programs). Since this method can be deployed on any storm drain or similar ground anchor, the sensors can be used to record chronic coastal flooding occurring on other city roadways or locations of interest. Other major cities at risk of increasing flood events also see inundation occurring at or around storm drains, providing support for the proposed deployment (Gold et al., 2022; Hino et al., 2019). Programs that use these or similar sensors can improve awareness of chronic coastal flooding issues by providing data at high-resolution spatial scales and involving local communities in the collection of the data. The method proposed here provides an avenue for residents to take ownership of their local flooding information. Being able to collect flooding information at these highly resolved spatial scales can inform residents of their landscape and the changing climate, providing them with more knowledge about their surrounding environment.

5 Conclusion

This study has shown that HOBO pendant G Accelerometers are a tool that can be used to successfully measure the occurrence and duration of flooding events. Given the changing climate and the uncertainties surrounding chronic coastal flooding, providing an easy tool to collect informative data is imperative. Providing data on the frequency and duration of coastal flood hazard events can lead to additional studies on the differences between large-scale and small-scale sensors, the impacts of chronic coastal flooding on the built environment and social systems, and perceptions surrounding flooding events. As sea level rise accelerates and storm conditions are affected by the changing climate, both chronic coastal flooding and acute flooding events will increase in frequency. For communities to be better prepared to combat these coastal flood hazards, the processes and trends associated with inundation events specific to these communities must be better understood. Due to the low-cost nature, commercial availability, and the ease of set-up of these sensors, this method provides many avenues for collaboration with local communities for greater understanding and effective communication of coastal flood hazards.

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Open Research

The data collected using the HOBO Pendent G data loggers, the code (RStudio v1.4.1717) used to process the data and plot the figures, and supplemental figures are available in O'Donnell (2024).

[Dataset]. The elevation data can be freely obtained from https://www.usgs.gov/the-national-map-data-delivery/gis-data-download.

[Dataset]. Both the NOAA water level data and the NOAA high tide data can be freely obtained from https://tidesandcurrents.noaa.gov/stationhome.html?id=8724580.

References

Adger, W. N., Quinn, T., Lorenzoni, I., & Murphy, C. (2016). Sharing the Pain: Perceptions of Fairness Affect Private and Public Response to Hazards. *Annals of the Association of American Geographers.* https://doi.org/10.1080/24694452.2016.1182005

Campbell, L., Cheng, H., Svendsen, E., Kochnower, D., & Bunting-Howarth, K. (2021). Living with Water: Documenting Lived Experience and Social Emotional Impacts of Chronic Flooding for Local Adaptation Planning. *Cities and the Environment*.

Emrich, C. T., & Cutter, S. L. (2011). Social Vulnerability to Climate-Sensitive Hazards in the Southern United States. *Weather, Climate, and Society*. https://doi.org/10.1175/2011WCAS1092.1

Federal Emergency Managements Agency. (2023). Be Prepared for a Flood. Retrieved October 2023, from https://community.fema.gov/ProtectiveActions/s/article/Flood

Gold, A., Anarde, K., Grimley, L., Neve, R., Srebnik, E. R., Thelen, T., et al. (2023). Data from the drain: A sensor framework that captures multiple drivers of chronic coastal floods.

Water Resources Research, *59*(4). https://doi.org/10.1029/2022wr032392

Gold, A. C., Brown, C. M., Thompson, S. P., & Piehler, M. F. (2022). Inundation of stormwater infrastructure is common and increases risk of flooding in coastal urban areas along the US Atlantic coast. *Earth's Future*, *10*(3). https://doi.org/10.1029/2021ef002139

Hino, M., Belanger, S. T., Field, C. B., Davies, A. R., & Mach, K. J. (2019). High-tide flooding disrupts local economic activity. *Science Advances*, *5*(2), eaau2736. https://doi.org/10.1126/sciadv.aau2736

Jury, S. H., Langley, T., Gutzler, B. C., Goldstein, J. S., & Watson, W. H. (2018). Monitoring the behavior of freely moving lobsters with accelerometers. *Bulletin of Marine Science*, *94*(3), 533–553. https://doi.org/10.5343/bms.2017.1117

Kriebel, D. L., Geiman, J. D., & Henderson, G. R. (2015). Future Flood Frequency under Sea-Level Rise Scenarios. *Journal of Coastal Research*, *31*(5), 1078–1083. https://doi.org/10.2112/JCOASTRES-D-13-00190.1

Li, S., Wahl, T., Talke, S. A., Jay, D. A., Orton, P. M., Liang, X., et al. (2021). Evolving tides aggravate nuisance flooding along the U.S. coastline. *Science Advances*, *7*(10). https://doi.org/10.1126/sciadv.abe2412

Maldonado, A., Collins, T. W., Grineski, S. E., & Chakraborty, J. (2016). Exposure to flood hazards in Miami and Houston: Are hispanic immigrants at greater risk than other social groups? *International Journal of Environmental Research and Public Health*. https://doi.org/10.3390/ijerph13080775

Marsooli, R., Lin, N., Emanuel, K., & Feng, K. (2019). Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. *Nature Communications*, *10*(1), 3785. https://doi.org/10.1038/s41467-019-11755-z

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., & Matthew, R. A. (2017). Cumulative hazard: The case of nuisance flooding. *Earth's Future*, *5*(2), 214–223. https://doi.org/10.1002/2016EF000494

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M., & Matthew, R. A. (2018). What Is Nuisance Flooding? Defining and Monitoring an Emerging Challenge. *Water Resources Research*, *54*(7), 4218–4227. https://doi.org/10.1029/2018WR022828

Mozumder, P., Flugman, E., & Randhir, T. (2011). Adaptation behavior in the face of global climate change: Survey responses from experts and decision makers serving the Florida Keys. *Ocean & Coastal Management*, *54*(1), 37–44. https://doi.org/10.1016/J.OCECOAMAN.2010.10.008

National Geophysical Data Center. (2019). Key West, Florida 1/3 arc-second NAVD 88 Coastal Digital Elevation Model [Data set]. Retrieved from https://data.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/3121.xml&view=getDataView&header=none#

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding—a global assessment. *PloS One, 10(3),* e0118571.

NOAA Center for Operational Oceanographic Products and Services. (2022). Inundation

Dashboard/ 8724580 Key West, FL. Retrieved January 2023, from https://tidesandcurrents.noaa.gov/inundationdb/inundation.html?id=8724580

NOAA Office for Coastal Management. (2022). Historical Hurricane Tracks. Retrieved March 23, 2022, from https://coast.noaa.gov/hurricanes/#map=4/32/-80

O'Donnell, Kiera (2024). Capturing local nuisance flooding events with HOBO pendant G data loggers in Key West, Florida US [Dataset]. Dryad. https://doi.org/10.5061/dryad.d7wm37q5d.

O'Donnell, K. L., Tomiczek, T., & Scyphers, S. B. (2022). Resident Perceptions and Parcel-Level Performance Outcomes of Mangroves, Beaches, and Hardened Shorelines After Hurricane Irma in the Lower Florida Keys. *Frontiers of Environmental Science & Engineering*, *10*. https://doi.org/10.3389/fenvs.2022.734993

ONSET. (2013). *HOBO Pendant G Data Logger (UA-004-64) White Paper* (Version 16920-A). ONSET HOBO Data Loggers.

Pachauri, R. K., & Meyer, L. (2015). *Climate Change 2014: Synthesis Report*. Intergovernmental Panel on Climate Change. Retrieved from https://play.google.com/store/books/details?id=SAfZsgEACAAJ

Pielke, R. a., Jr., Gratz, J., Landsea, C. W., Collins, D., Saunders, M. A., & Musulin, R. (2008). Normalized Hurricane Damage in the United States: 1900–2005. *Natural Hazards Review*, *9*(February), 29–42. https://doi.org/10.1061/(ASCE)1527-6988(2008)9:1(29)

Rayas-Amor, A. A., Morales-Almaráz, E., Licona-Velázquez, G., Vieyra-Alberto, R., García-Martínez, A., Martínez-García, C. G., et al. (2017). Triaxial accelerometers for recording grazing and ruminating time in dairy cows: An alternative to visual observations. *Journal of Veterinary Behavior: Clinical Applications and Research*, *20*, 102–108. https://doi.org/10.1016/j.jveb.2017.04.003

Rockport Analytics. (2019). *2018 Tourism in the Florida Keys & Key West: Stable Growth Despite Challenging Times*. Rockport Analytics. Retrieved from https://www.monroecounty-fl.gov/DocumentCenter/View/21667/Economic-Impact-of-Tourism-in-The-Florida-Keys-?bidId=

Silverman, A. I., Brain, T., Branco, B., Challagonda, P. S. V., Choi, P., Fischman, R., et al. (2022). Making waves: Uses of real-time, hyperlocal flood sensor data for emergency management, resiliency planning, and flood impact mitigation. *Water Research*, *220*, 118648. https://doi.org/10.1016/j.watres.2022.118648

U.S. Census Bureau. (2021). American Community Survey 5-year estimates. Retrieved January 2023, from https://censusreporter.org/profiles/16000US1236550-key-west-fl/

Vernimmen, R., & Hooijer, A. (2023). New LiDAR-based elevation model shows greatest increase in global coastal exposure to flooding to be caused by early-stage sea-level rise. *Earth's Future*, *11*(1). https://doi.org/10.1029/2022ef002880

Wing, O. E. J., Lehman, W., Bates, P. D., Sampson, C. C., Quinn, N., Smith, A. M., et al. (2022). Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*. Retrieved from https://www.nature.com/articles/s41558-021-01265-6