Prepared in cooperation with the Hawai‘i Emergency Management Agency

Community Exposure to Tsunami Hazards in Hawai‘i

Scientific Investigations Report 2016–5053

U.S. Department of the Interior
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COVER
Photograph of Hanauma Bay in the Hawaiʻi Kai neighborhood of East Honolulu on the southeast coast of the Island of Oʻahu, Hawaiʻi (photograph by DJ Shane courtesy of Freeimages.com).

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By Jamie L. Jones, Matthew R. Jamieson, and Nathan J. Wood

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Abstract

Hawai‘i has experienced numerous destructive tsunamis and the potential for future inundation has been described over the years using various historical events and scenarios. To support tsunami preparedness and risk-reduction planning in Hawai‘i, this study documents the variations among 91 coastal communities and 4 counties in the amounts, types, and percentages of developed land, residents, employees, community-support businesses, dependent-care facilities, public venues, and critical facilities in a composite extreme tsunami-inundation zone associated with two great Aleutian moment magnitude (M_w) 9.3 and 9.6 earthquake scenarios. These earthquake scenarios are considered to provide the maximum tsunami scenario for the Hawaiian Islands. According to 2010 U.S. Census Bureau data, the Hawai‘i extreme tsunami-inundation zone contains approximately 248,749 residents and 91,528 households (18 and 20 percent, respectively, of State totals). The residential population in tsunami-prone areas is racially diverse, with most residents identifying themselves as White (47 percent of the total exposed population), Asian (48 percent), or Native Hawaiian and Other Pacific Islander (29 percent), either alone or in combination with one or more other races (note that race categories do not sum to 100 percent because individuals were able to report multiple races in the 2010 U.S. Census). A total of 50,016 households are renter-occupied, making up 55 percent of total households in the extreme inundation zone. The extreme tsunami-inundation zone contains 18,693 businesses (37 percent of State totals) and 245,827 employees (42 percent of the State labor force). The employee population in the extreme tsunami-inundation zone is largely in the accommodation and food services and retail-trade sectors. Although occupancy values are not known for each facility, the extreme tsunami-inundation zone also contains numerous community-support businesses (for example, religious organizations and markets), dependent-care facilities (for example, child-day-care facilities and schools), public venues (for example, colleges and entertainment venues), and critical facilities (for example, fire stations and electric companies).

Community exposure to tsunamis in Hawai‘i varies considerably—some communities may experience great losses that reflect only a small part of their community and others may experience relatively small losses that devastate them. Among the 91 communities and 4 counties, Urban Honolulu has the highest number of people and businesses in the extreme tsunami-inundation zone, and Hanalei has the highest percentages of its people and businesses in this zone. Urban Honolulu has the highest combination of the number and percentage of people, businesses, and facilities in the hazard zone. This report will further the dialogue on societal risk to tsunami hazards in Hawai‘i and help identify future preparedness, mitigation, response, and recovery planning needs within coastal communities and economic sectors of the State of Hawaii.

Introduction

Recent disasters, such as the 2004 Indian Ocean, 2007 Solomon Islands, 2009 Samoa, 2010 Chile, 2011 Tohoku, and 2013 Solomon Islands events, demonstrated to the world how tsunamis are significant threats to the safety, security, economic well-being, and natural resources of many coastal communities. The State of Hawaii has not been immune to tsunami-related destruction and has experienced extensive damage from several catastrophic tsunamis in the past century, including the 1946 Aleutian, 1952 Kamchatka, 1957 Aleutian, 1960 Chile, and 1964 Aleutian events (Lander and Lockridge, 1989; Dudley, 1999; Butler and others, 2014). Surrounded by tsunami-generating tectonic plate boundaries around the Pacific Ocean basin, the State of Hawaii is likely to experience more tsunamis in the future, generated either by near-field sources in the Hawaiian Islands or by far-field sources from around the basin.

Near-field tsunamis that affect Hawai‘i are generated when local earthquakes, submarine slides, or landslides cause a vertical displacement of the overlying or adjacent water column (Walker, 1999; Walker and Cessaro, 2002). Although locally devastating to nearby shorelines and striking within minutes of the initial ground disturbance, near-field events in Hawai‘i typically lack the energy to travel long horizontal distances (Lockridge, 1998). Tsunami-related geologic deposits found at more than 300 meters (m) above sea level on the Island of Lāna‘i are believed to be the result of a nearby submarine slide that occurred more than 100,000 years ago (Moore and Moore, 1984). A recent near-field event was the 1975 tsunami, generated by a moment magnitude (M_w) 7.5 earthquake on the Island of Hawai‘i, that killed two people and caused $1 million in property damage (Lander and Lockridge, 1989; Goff and others, 2006; National Geophysical Data Center/World Data Service, 2015). A review of locally generated tsunamis indicates average recurrence intervals of approximately 20 years for destructive tsunamis (Walker, 1999).

Far-field tsunamis, also referred to as teletsunamis, are created by earthquakes generated on the seismically active Pacific Ocean margin and strike Hawaiian coastlines several hours after such earthquakes (Walker, 2005a; Walker, 2005b; Tang and others, 2006). Primary sources for previous far-field tsunamis that have struck Hawai‘i include the Kuriles-Kamchatka-Aleutian region to the north and northwest and South America to the southeast (Cox and Mink, 1963). A far-field tsunami in 1960, generated by a M_w 9.5 Chilean earthquake, had a maximum run-up height of 35 feet in Hilo, killed 61 people and caused $20 million (1960 dollars) in property damage in Hawai‘i (Eaton and others, 1961; Lachman and others, 1961; Cox and Mink, 1963; Mader and Curtis, 1991; Johnston, 2003; Atwater and others, 2005; National Geophysical Data Center/World Data Service, 2015). Another significant far-field event was the 1946 tsunami, generated by a magnitude (M_w) 8.6 earthquake in the Aleutian Islands, which killed 167 people and caused $26 million (1946 dollars) in property damage (Lander and Lockridge, 1989; Dudley and Stone, 2000; National Geophysical Data Center/World Data Service, 2015). Tsunami deposits discovered in the Māhā‘ulepū Sinkhole on Kaua‘i suggest that a very large earthquake originating off the Aleutian Islands in Alaska between 350 and 600 years ago generated a tsunami large enough to overtop the south wall of the sinkhole and deposit nearly 1 m of debris (Burney and others, 2001; Butler, 2014). Recent work on far-field tsunami potential suggests that wave run-up is fairly focused and, given a detailed tsunami warning, limited evacuations of specific areas may be more appropriate than statewide evacuations (Walker, 2004). The most recent tsunami-related damage in Hawai‘i was the more than $30 million (2011 U.S. dollars) in damages resulting from the tsunami generated by the 2011 Tohoku earthquake in Japan (Trusdell and others, 2012).

Tsunamis, both near-field and far-field events, are constant threats to coastal communities, and the potential for inundation is significant for low-lying areas along the Hawaiian coast. Occupation and use of tsunami-prone land, however, varies considerably in Hawai‘i, from small villages (fig. 1*A*) to dense residential communities (fig. 1*B*) to large cities with significant industrial and commercial sectors (fig. 1*C*, *D*). These variations in the geographic distribution of human settlement influence how communities are vulnerable to tsunamis. A tsunami may cause damage to individual assets and communities, but the cumulative choices a society makes with regards to land use prior to an event can influence the potential for these losses (Mileti, 1999; Wisner and others, 2004).

In 2006, the Civil Defense Division (HSCD) of the State of Hawaii Department of Defense contacted the U.S. Geological Survey (USGS) seeking technical assistance in assessing community vulnerability to tsunami hazards in Hawai‘i. Tsunami-evacuation zones had been developed in 1991 for the State (Curtis, 1991; Hawai‘i Office of Planning, 2015) that were based on one-dimensional modeling that reconstructed inundation zones of five destructive tsunamis in Hawai‘i (1946 Aleutian, 1952 Kamchatka, 1957 Aleutian, 1960 Chile, and 1964 Aleutian). The HSCD (now referred to as Hawai‘i

Figure 1. Oblique photographs of communities in the tsunami inundation zone in the State of Hawaii—(*A*) the community of Punalu‘u on the Island of Hawai‘i and (*B*) the community of Ewa Beach, (*C*) the Ala Wai Boat Harbor near Waikīkī Beach, Honolulu, and (*D*) Honolulu Harbor, all on the Island of O‘ahu. (Photographs by Andrew Short, School of Geosciences at the University of Sydney, Australia, used with permission.)

Emergency Management Agency, HI-EMA) was interested in knowing what community assets were in these areas and how community vulnerability to tsunamis varies across the State. This collaboration yielded an analysis of community exposure to tsunami hazards (Wood and others, 2007) that was based on the Curtis (1991) hazard zones. In the late 2000s, tsunami inundation maps were updated across the State still based on the historic events but using two-dimensional modeling and high-resolution light detection and ranging (lidar) data (Cheung, 2015).

In the aftermath of the 2011 Tohoku earthquake and tsunami, researchers and emergency managers reexamined their mapping assumptions for future tsunamis in Hawaiʻi, which led them to develop an extreme inundation scenario beyond what can be inferred from historical data. The two new primary sources for devastating tsunamis in Hawaiʻi were great Aleutian earthquake scenarios of M_w 9.3 and 9.6 (Butler, 2014). The proposed scenarios are consistent with the preferred maximum magnitude of 9.42 for this area, which was recommended by researchers convened by Global Earthquake Model (GEM) to develop a consistent characterization of the world's subduction zones (Berryman and others, 2013). The University of Hawaiʻi at Mānoa has recently completed new extreme tsunami-inundation maps based on the M_w 9.3 and 9.6 great Aleutian earthquake scenarios (Cheung, 2015), which are now being used to develop new extreme tsunami-evacuation maps in various counties (for example, City and County of Honolulu, 2015). The new extreme tsunami-inundation zones and continued interest in potential community vulnerability to tsunamis in Hawaiʻi prompted USGS to update the original 2007 analysis using new hazard, demographic, land-cover, and business data.

Purpose and Scope

This report documents geographic variations in community exposure to extreme tsunami hazards in Hawai'i. Community exposure is described by the amount and relative percentage of various populations and population-related indicators in tsunami-prone areas as defined by a composite extreme tsunami-inundation zone associated with M_w 9.3 and 9.6 great Aleutian earthquake scenarios. To describe tsunami-prone landscapes and community exposure to tsunamis on the Hawaiian coast, we used geographic-information-system (GIS) tools and geospatial data to identify the presence of populations and businesses in tsunami-prone areas. Data presented in this report include descriptions of land cover, residents, employees, community-support businesses, dependent-care facilities, public venues, and critical facilities (emergency services and infrastructure) relative to the extreme tsunami-inundation zone. These inventories cannot be considered estimates of potential losses because this study does not address the short-term adaptive capacity and long-term resilience of households or communities relative to tsunami threats. Potential losses would only match reported inventories if all residents, employees, and visitors in tsunami-prone areas were unaware of tsunami risks, were unaware of what to do if warned of an imminent threat (either by natural cues or official announcements), and failed to take protective measures to evacuate. This assumption is unrealistic, given the current level of tsunami-awareness efforts in Hawaiʻi (Hawaiʻi State Civil Defense and Pacific Disaster Center, [n.d.]; National Weather Service, 2015).

Understanding how communities vary in their exposure to tsunamis helps emergency managers, land-use planners, public-works managers, and the maritime community understand potential tsunami impacts and to determine where to complement regional risk-reduction strategies with site-specific efforts that are tailored to local conditions and needs (for example, targeted education programs and evacuation procedures for specific schools or assisted-living facilities). This report provides an initial estimate of community exposure to tsunamis in Hawaiʻi, and results of this community-level analysis are intended to serve as a foundation for additional risk-related studies and outreach efforts. Knowledge of regional exposure issues generated by this project will help identify and tailor future preparedness, mitigation, response, and recovery planning efforts within specific communities and economic sectors in the State of Hawaii.

Study Area

This study focuses on all land within the State of Hawaii, including the counties of Hawaiʻi, Honolulu, Kauaʻi, and Maui. Aside from the consolidated city-county of Honolulu, the State of Hawaii does not have incorporated cities; therefore, census-designated place (CDP) boundaries from the U.S. Census Bureau were used to delineate communities (Hawaiʻi Office of Planning, 2015; U.S. Census Bureau, 2015). A census-designated place is a delineation used by the U.S. Census Bureau to identify areas of settled concentrations of populations that are identifiable by name and are often defined in cooperation with local or tribal officials but are not legally incorporated and lack separate municipal governments (U.S. Census Bureau, 2015).

Tsunami-prone land was spatially delineated by a composite extreme inundation zone created by the University of Hawaiʻi at Mānoa to characterize inundation associated with M_w 9.3 and 9.6 great Aleutian earthquake scenarios. This composite inundation zone provides the probable maximum tsunami scenario (Cheung, 2015) and is considered now to be the basis for describing the tsunami threat in Hawaiʻi (Kevin Richards, HI-EMA, oral commun., April 30, 2015). The two events have an estimated recurrence interval of 1,000 years for an earthquake with 35 m of average slip, based on current understanding of the convergence rate (7 centimeters/year, cm/yr) and preferred coupling coefficient (0.5) of the Aleutian subduction zone (Berryman and others, 2013). Full discussion of the seismic parameters for each earthquake scenario can be found in Cheung (2015). In brief, the M_w 9.3 earthquake scenario has a uniform fault width of 100 kilometers (km) along its 700-km length with concentrated slip distribution that mimics the 2011 Tohoku earthquake. The M_w 9.6 scenario has uniform slip of 35 m but variable widths of 50, 100, and 150 km along its 1,400-km rupture length, which more resembles the seismic characteristics of the 2004 Indian Ocean earthquake. Modeling resolutions for the inundation zones were 9 m for inhabited areas with high-resolution elevation data and 90 m elsewhere (Cheung, 2015). Maximum inundation from both tsunami scenarios at the two resolutions were merged into a single inundation zone by researchers at the University of Hawai‘i at Mānoa (Cheung, 2015) and subsequently used in our exposure analysis.

Based on a spatial overlay of CDP and extreme tsunami-inundation-zone data, there are 91 CDPs (hereafter called communities) in the State of Hawaii that contain tsunami-prone land (fig. 2). Note that figure 2 does not show all community boundaries in the State of Hawaii, only those that overlap with the extreme tsunami-inundation zone. The Island of Ni‘ihau is not shown in the Kaua‘i County part of the map because it contains no community boundaries; any assets on this island are reflected in Kaua‘i County totals. Community assets in the area formerly known as Kalawao County, now considered a Maui County judicial district, are reported in the unincorporated land (occupied areas which are not within the census-designated boundaries of a community) of Maui County. Further spatial analysis to characterize land in the extreme tsunami-inundation zone and to assess socioeconomic variations focuses on 95 geographic units, which includes the 91 communities and the unincorporated land of the four counties. Official names and spellings of geographic features and communities throughout the report follow recommendations of the Hawai‘i Board on Geographic Names (2015).

Because the extreme tsunami-inundation zone identifies the maximum areas of inundation from two earthquake scenarios, it is not meant to imply that all delineated areas would be inundated by a single future tsunami, especially if generated by a source other than the Aleutian subduction zone. Also, the areas in the identified extreme tsunami-inundation zone are not equally at risk from inundation; areas closer to the shoreline are more likely to be affected than areas on the landward edge of the zone because of a presumed greater flooding depth and stronger currents. Finally, the extreme tsunami-inundation zone does not provide any indicator of the probability of the tsunami or of damages from the tsunami. The extreme tsunami-inundation zone used in this study is a guide for emergency planning and is not a prediction for a future event, because the actual inundation extent, depth, speed, and impact forces of a future tsunami will be determined by specific aspects of the source (for example, the location, depth, and magnitude of an earthquake), the ocean conditions through which the tsunami travels, and the topography over which it moves (for example, the influence of vegetation and human structures on changing flow dynamics).

Variations in Community Exposure

Results of the GIS-based analysis are summarized by community. Because of the vast amounts of data used in this analysis, this report focuses on overviews of the geospatial data, regional trends, and graphics. The report is organized around seven community characteristics—(1) land cover, (2) residents, (3) employees, (4) community-support businesses, (5) dependent-care facilities, (6) public venues, and (7) critical facilities (specifically, emergency services and infrastructure). In each section, third-quartile values are noted on bar graphs so that readers can quickly identify those communities that are above the 75th percentile in a given category.

Community-exposure calculations and comparisons are limited to the number and percentage of the above socioeconomic characteristics (developed land, residents, employees, community-support businesses, dependent-care facilities, public venues, and critical facilities) found in extreme tsunami-inundation zones. The selected socioeconomic assets were chosen because U.S. jurisdictions are encouraged to collect similar data when they inventory community assets in the development of State and local mitigation plans (Federal Emergency Management Agency, 2001). We calculate the number and percentage of various socioeconomic characteristics and report the results for each community. Finally, certain values are normalized and combined to create overall indices of the amount and percentage of community exposure to extreme tsunami hazards in Hawai‘i.

Before calculating the amount and percentage of exposed community assets, all geospatial data were processed using GIS software to share the same datum (North American Datum of 1983) and projection (Universal Transverse Mercator coordinate system zone 4N). This particular datum and coordinate system were chosen to conform to existing GIS data from the State of Hawaii's GIS database. Spatial analysis of vector data (for example, business points and census block polygons) focused on determining if points or polygons were inside the extreme tsunami-inundation-zone polygons. Slivers of polygons that overlap administrative boundaries and tsunami zones are taken into account during analysis, and final values were adjusted proportionately. Spatial analysis of raster-grid data (for example, land-cover data) was conducted in a raster environment to maintain data quality.

Because of the short project timeline established by project partners, no new datasets were generated and no fieldwork was conducted to verify the accuracy of any geospatial data discussed in this report. Therefore, we cannot guarantee initial data accuracy; results should be considered first approximations and developed solely for the purposes of generating discussions for additional, more-detailed studies.

Land Cover

A first step in understanding the potential impacts from tsunamis is to determine what kind of land use and land cover

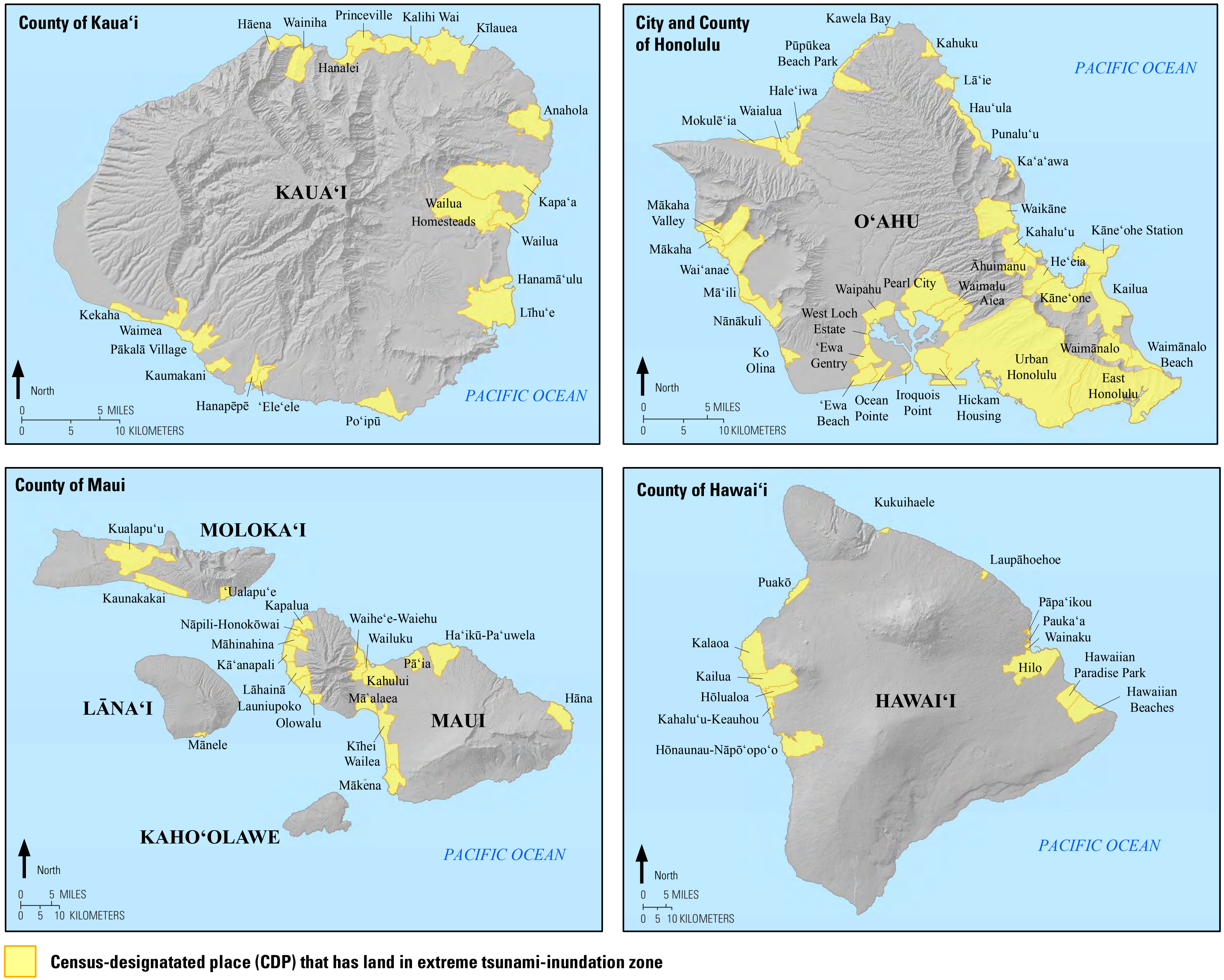

Figure 2. Maps of counties in the State of Hawaii showing census-designated places that intersect the extreme tsunami-inundation zone.

(LULC) are in predicted hazard zones, with specific attention given to patterns of human development. To characterize land cover in tsunami-prone areas, we use 2010-2011 land-cover data prepared by the National Oceanic and Atmospheric Administration’s (NOAA) Coastal Change Analysis Program (C-CAP), a nationally standardized land-cover database for the coastal regions of the United States (National Oceanic and Atmospheric Administration, Office for Coastal Management, 2015; Dobson and others, 1995) and part of the National Land Cover Database (NLCD) effort through the interagency Multi-Resolution Land Characteristics (MRLC) Consortium (Homer and others, 2004; Loveland and Shaw, 1996). NLCD products, including LULC, percent impervious cover, and percent canopy cover, are automatically derived from Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM) digital satellite imagery, which is produced for the majority of the United States at a 30-m spatial resolution. C-CAP data have a reported accuracy standard of 85 percent (Dobson and others, 1995). In Hawai‘i, current land-cover data are available with a pixel resolution of either 2.4 or 30 m. For this analysis, we use the higher-resolution 2.4-m C-CAP data.

NOAA C-CAP 30-m resolution data have 25 land-cover classes, with human development primarily represented by three developed classes—low-intensity developed, medium-intensity developed, and high-intensity developed classes. To classify a 30-m cell as low-, medium-, or high-intensity developed, high-resolution spatial data are classified as either impervious or not impervious. The resulting classification is summarized to 30-m resolution to calculate percent imperviousness for each cell. Low-intensity developed cells contain 25 to 50 percent of impervious surfaces, are a mix of constructed and vegetated surfaces, and typically represent small buildings, streets, and cemeteries. Medium-intensity developed cells contain 50 to 75 percent of impervious surfaces, have a relatively balanced amount of vegetation and constructed surfaces, and typically represent small buildings like single-family housing and large sheds. High-intensity developed cells contain more than 75 percent impervious surfaces, have little or no vegetation, and typically represent heavily built-up urban centers, large buildings, and large paved surfaces, such as runways and interstate highways (Dobson and others, 1995). For the finer resolution 2.4-m C-CAP data, high-, medium-, and low-intensity developed classes are represented by a single impervious surface class (hereafter referred to as developed land) because too little land-cover variation could be seen within the smaller 2.4-m cells to identify development percentages (NOAA OCM, 2015). Figure 3 shows 2010 land-cover data for the Island of O‘ahu, in which the high concentration of developed land-cover cells in the southeastern corner denote the highly developed areas of Urban Honolulu and East Honolulu.

As one indicator of community exposure to tsunami hazards, we calculate the amount and percentage of developed land, defined here as land-cover cells classified as impervious surface, in relation to the extreme tsunami-inundation zone and to community boundaries. This information does not

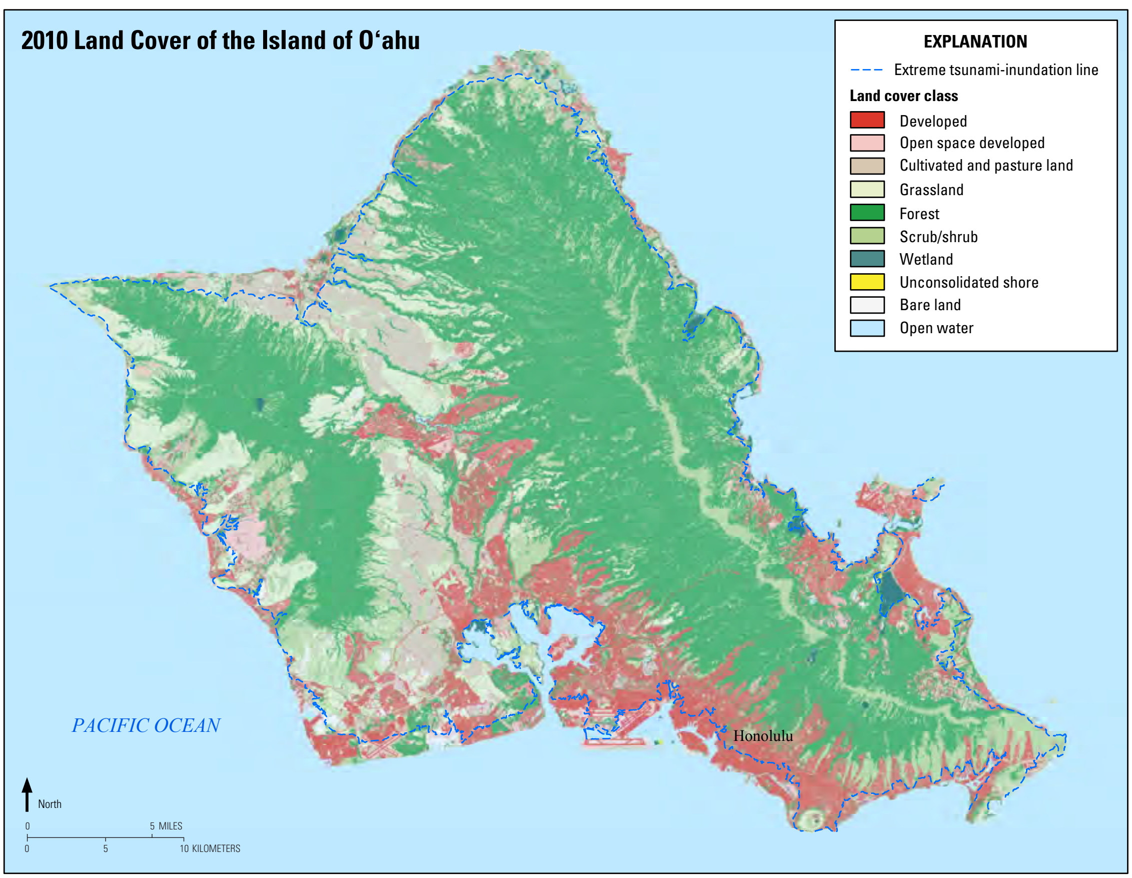

Figure 3. Map of National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP) 2010 land-cover types for the Island of O‘ahu, Hawai‘i.

translate to loss potential of any specific asset within a cell, as land classified as impervious surface could be, for example, interstate highways, parks, residential homes, or commercial parks. However, comparing landscape compositions at the regional scale does provide some insight into the relation between developed areas and predicted hazards within communities (Wood, 2009), and we assume that community exposure to tsunamis increases with greater amounts and percentages of cells classified as developed in tsunami-prone areas.

Based on the spatial overlay of 2010-2011 C-CAP data with community boundaries and the extreme tsunami-inundation zone, the distribution of land-cover types (by area) in tsunami-prone land was determined for the entire Hawaiian coast (fig. 4). Percentages represent the amount of land area classified as a specific land-cover class (for example, grassland) relative to the total hazard-prone area. For the purposes of this report, all wetland-related C-CAP categories are aggregated into one class. Results indicate that the dominant land-cover classes in the extreme tsunami-inundation zone are forest (21 percent), developed land (21 percent), developed open space (11 percent), scrub/shrub land (9 percent), and bare land (8 percent). A value of 21 percent for developed land may seem low but is fairly high, considering that the percentage of developed land in the northern Piedmont ecoregion (which includes the western parts of New York City, Philadelphia, Baltimore, and the District of Columbia and is considered one of the most developed areas in the Nation) was only 27 percent in 2000 (Auch, 2006).

Although most tsunami-prone land is not classified as developed land, these areas may attract recreationists and other transient populations, such as tourists, who can dominate the daily population of many coastal communities (Wood and others, 2002; Wood and Good, 2004). In addition, these undeveloped areas may represent significant natural resources or ecosystem services (for example, water-quality improvement), and their damage or loss due to a tsunami could negatively impact nearby communities or the region.

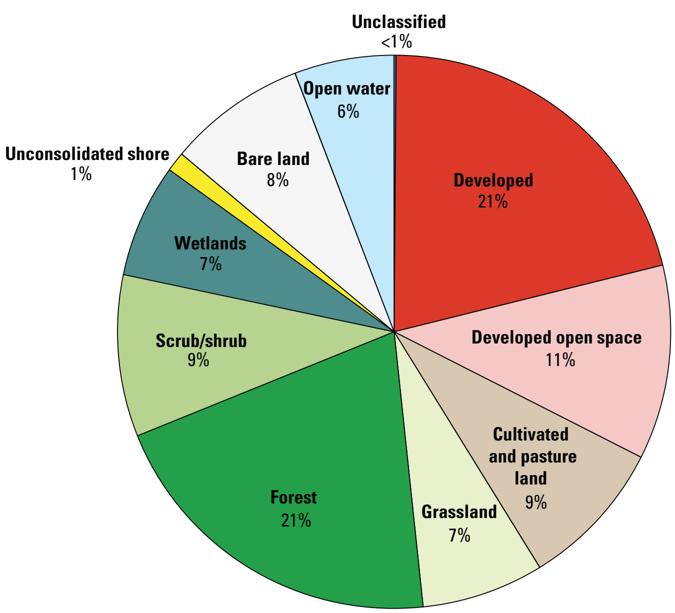

Figure 4. Pie diagram showing distribution of National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP) land-cover classes (by area) in the extreme tsunami-inundation zone for the State of Hawaii. %, percent; <, less than.

Results indicate that the amount (fig. 5*A*) and percentage (fig. 5*B)* of developed land in the extreme tsunami-inundation zone (cells classified as impervious surface) varies significantly across the State of Hawaii. The median and third quartile (75th percentile) for the amount of developed land in community and unincorporated land is 0.20 and 0.72 square kilometers (km^2), respectively, suggesting most communities have small amounts of developed land in the extreme tsunami-inundation zone. However, certain communities, such as the Urban Honolulu, Hilo, and Kailua CDPs in Honolulu County (fig. 5*A*), are well above the third quartile. The greatest amounts of developed land in the extreme tsunami-inundation zone overall are in Hilo and the City and County of Honolulu.

Although only a few communities have high amounts of developed land in the extreme tsunami-inundation zone, many have a large percentage of their urban footprint in those zones (fig. 5*B*). For example, communities like Hanalei and Kawela Bay have low amounts of developed land in the extreme tsunami-inundation zone (0.28 and 0.30 km^2, respectively), but these lands represent close to 100 percent of their communities. Conversely, some communities have relatively high amounts of developed land (such as the City and County of Honolulu) in the extreme tsunami-inundation zone, but this developed land represents a relatively small percentage of total land in these communities. Thus, in regards to development patterns, results indicate that certain communities have high numbers of assets exposed to tsunami hazards, but other communities have high percentages of their assets exposed to the same threats.

Residents

All individuals in tsunami-prone areas have the potential to be injured or killed, but demographic factors like age, race, gender, and socioeconomic status can amplify the potential for losses and create varying recovery times (Morrow, 1999; Cutter and others, 2003; Laska and Morrow, 2007). In addition, risk-reduction, response, and recovery strategies will differ for each community depending on their relative number of residents, employees, dependents, and tourists that may be at risk from tsunamis.

To determine the number and type of residents in the extreme tsunami-inundation zone, we use block-level population counts and demographic data from the 2010 U.S. Census (U.S. Census Bureau, 2010). Additional demographic attributes are available for larger census areas (for example, block groups and census tracts); however, we believe it is inappropriate to use data at these scales because of the significant size differences between inundation polygons and larger census

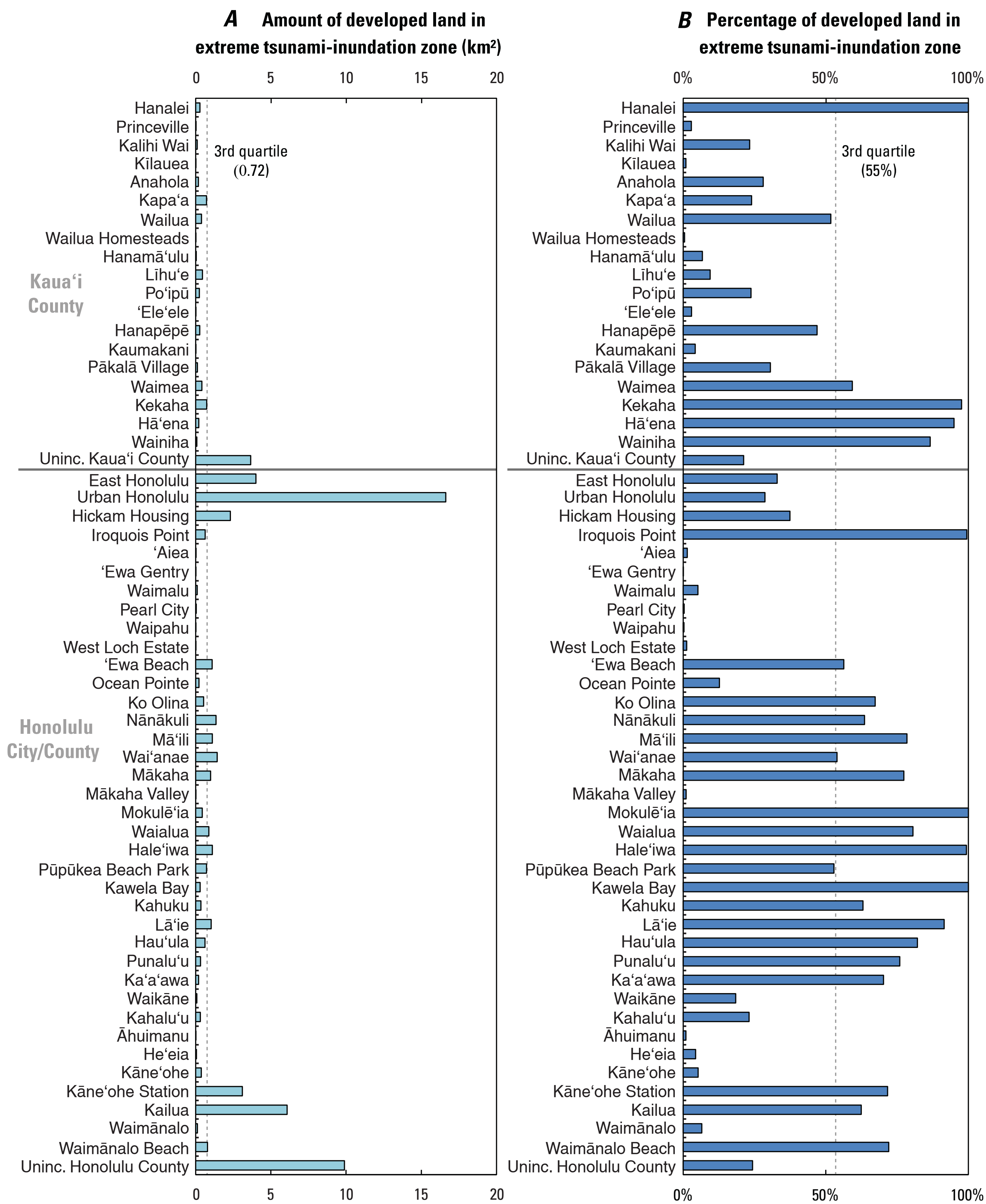

Figure 5. Bar graphs showing (*A*) amount and (*B*) percentage of National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP) land-cover area (in square kilometers, km²) classified as developed in the extreme tsunami-inundation zone, organized by census-designated place for the State of Hawaii. Dashed lines indicate 3rd quartile. Uninc., unincorporated; km², square kilometer; %, percent.

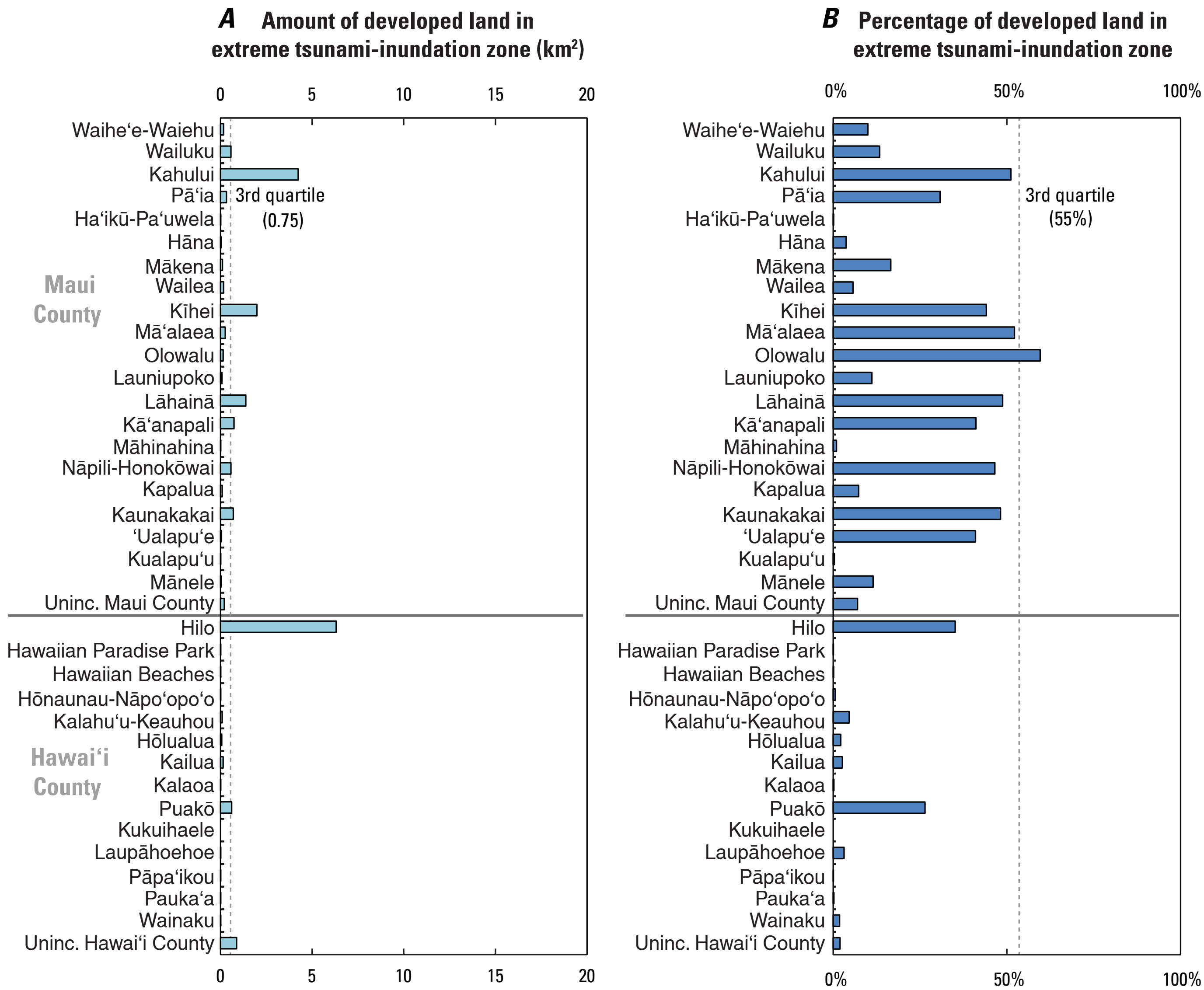

Figure 5.—Continued

units. Results presented later in the report portray the sum of population or demographic values and not the total number of blocks for the following residential-population characteristics of Census block-level data:

- Total population;
- Hispanic or Latino population;
- White alone or in combination with one or more other races;
- Black or African American alone or in combination with one or more other races;
- American Indian and Alaska Native alone or in combination with one or more other races;
- Asian alone or in combination with one or more other races;
- Native Hawaiian and other Pacific Islander alone or in combination with one or more other races;
- Population less than 5 years in age;
- Population more than 65 years in age;
- Female population;
- Institutionalized group quarters population;
- Noninstitutionalized group quarters population;
- Households;
- Renter-occupied households; and
- Female-headed households, with children.

Results indicate that the extreme tsunami-inundation zone contains approximately 248,749 residents and 91,528

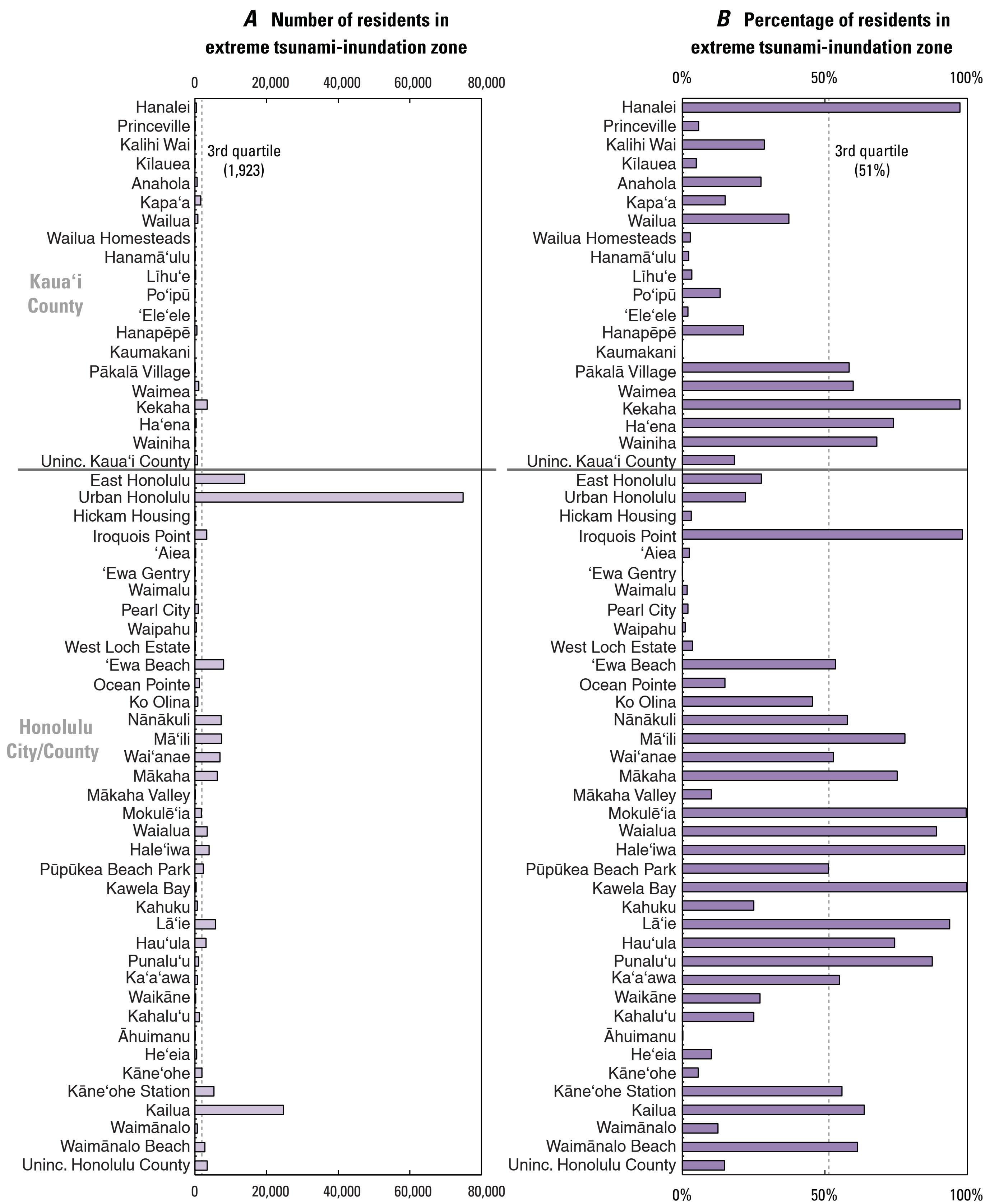

Figure 6. Bar graphs showing (*A*) number and (*B*) percentage of residents in the extreme tsunami-inundation zone in the State of Hawaii, organized by census-designated place. Dashed lines indicate 3rd quartile. Uninc., unincorporated; %, percent.

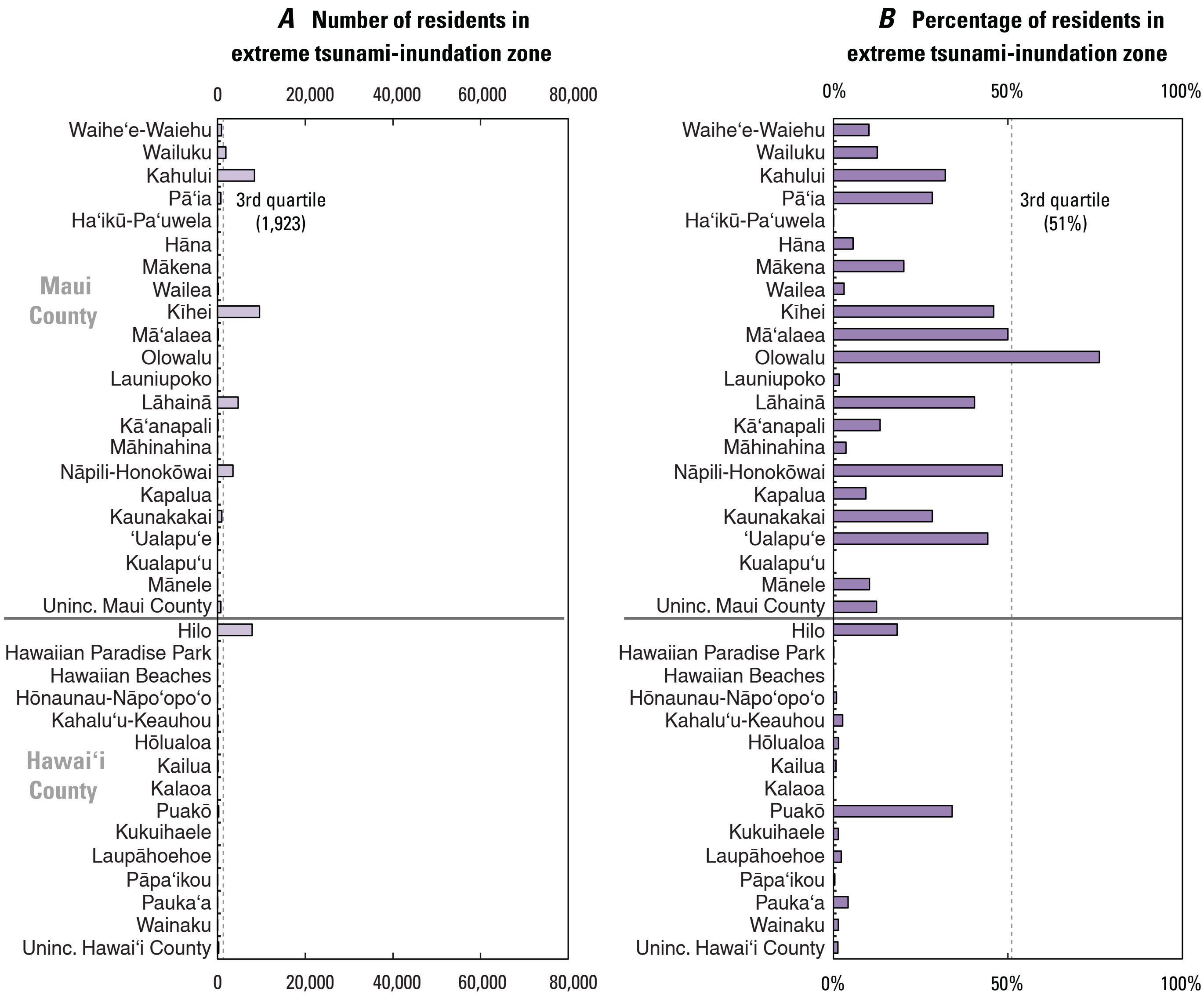

Figure 6.—Continued

households (table 1), representing 18 percent and 20 percent of State-level totals, respectively. The total number (fig. 6*A*) and community percentage (fig. 6*B*) of residents in the tsunami-inundation zone varies significantly across the State of Hawaii. The median and third quartile (75th percentile) in community and unincorporated land is 319 and 1,923 residents, respectively. Similar to land-cover results, certain communities have high numbers of residents in the extreme tsunami-inundation zone (for example, Urban Honolulu and Kailua in Honolulu County), whereas others have high percentages of their residents living in the extreme tsunami-inundation zone (for example, Kawela Bay and Mokulē‘ia). Results indicate that Urban Honolulu has the highest number of residents (74,855) in the extreme tsunami-inundation zone, whereas Kawela Bay has the highest percentage (100 percent) of residents in the extreme tsunami-inundation zone.

Studies have shown that certain demographic groups can have unique needs during an evacuation and in post-disaster recovery (Morrow, 1999; Ngo, 2001; Laska and Morrow, 2007). Comments on demographic sensitivity of residents are based on trends observed by social scientists in past disasters throughout the world and are not meant to imply that all individuals of a certain demographic category will exhibit identical behavior in the event of a specific tsunami. In addition, variations in local cultures and individual or community resilience, aspects not covered in this report, will influence the extent of these unique needs.

One demographic characteristic that influences an individual's sensitivity is age (Morrow, 1999; Ngo, 2001; Balaban, 2006; Laska and Morrow, 2007; McGuire and others, 2007). For example, a survey of Indonesian households impacted by the 2004 Indian Ocean tsunami demonstrated that mortality was highest for the youngest and oldest age groups (Rofi and others, 2006). Younger populations, defined here as less than 5 years in age, often require direction and assistance to evacuate due to their immaturity and size. They are also prone

Table 1. Demographic characteristics for residential populations in relation to the extreme tsunami-inundation zone in the State of Hawaii.

[n/a, not applicable; %, percent]

Population	In extreme tsunami-inundation zone	State total (2010)	Tsunami inundation-zone percentage[1]	State percentage[1]	Maximum community percentage
Total population	248,749	1,360,301	n/a	n/a	100%
Hispanic or Latino population	22,525	120,842	9%	9%	23%
Race—White alone or in combination with one or more other races	116,434	564,323	47%[2]	41%[2]	100%
Race—Black or African American alone or in combination with one or more other races	7,063	38,820	3%[2]	3%[2]	16%
Race—American Indian and Alaska Native alone or in combination with one or more other races	6,222	33,470	3%[2]	2%[2]	6%
Race—Asian alone or in combination with one or more other races	120,507	780,968	48%[2]	57%[2]	75%
Race—Native Hawaiian and Other Pacific Islander alone or in combination with one or more other races	72,394	355,816	29%[2]	26%[2]	79%
Race—Other Races alone or in combination with one or more other races	6,498	34,199	3%[2]	6%[2]	9%
Population less than 5 years old	15,030	87,407	6%	6%	13%
Population more than 65 years	34,706	195,138	14%	14%	39%
Female population	122,889	679,058	49%	50%	58%
Institutionalized group quarters population	2,068	11,306	1%	1%	38%
Noninstitutionalized group quarters population	9,974	31,574	4%	2%	44%
Number of households	91,528	455,338	n/a	n/a	99%
Renter-occupied households	50,016	192,656	55%	42%	100%
Single-mother households	6,148	32,983	7%	7%	23%

[1]In-hazard percentages refer to the percentage of individuals (or households for the last two rows) in the extreme tsunami-inundation zone of a specific demographic category. State percentages refer to the percentage of individuals (or households for the last two rows) in the State of a specific demographic category.

[2]The sum of percentages by race will not sum to 100 percent, as individuals are able to report multiple race categories in U.S. Census Bureau reports.

to developing post-traumatic stress disorders, depressions, anxieties, and behavioral disorders as a result of their inability to comprehend and process effects of a disaster (Balaban, 2006). Our results indicate that 6 percent of individuals in the extreme tsunami-inundation zone are less than the age of 5 years, equal to the State percentage (table 1). For the 91 communities, the percentage of individuals in the extreme tsunami-inundation zone that are less than the age of 5 years ranges from 0 to 13 percent, with the maximum value found in Waipahu in Honolulu County.

Older populations, defined here as more than 65 years in age, are also disproportionately more vulnerable than other age groups. Research suggests the individuals aged 65 years or older may require assistance in evacuation due to potential mobility and health issues, are often reluctant to evacuate, may require special medical equipment at shelters (McGuire and others, 2007), and are more apt to lack social and economic resources to recover (Morrow, 1999; Ngo, 2001). Results indicate that 14 percent of individuals in the extreme tsunami-inundation zone are more than 65 years old, equal to the percentage for the entire State. For the 91 communities, the percentage of individuals in the extreme tsunami-inundation zone that are more than the age of 65 ranges from 0 to 39 percent, with the maximum value found in Pauka‘a in Hawai‘i County.

Gender differences have also been found to influence an individual’s sensitivity to a stressor (Enarson and Morrow, 1998; Bateman and Edwards, 2002). Preliminary work by Oxfam (2005) in the wake of the 2004 Indian Ocean tsunami suggests that women had a disproportionately higher mortality rate. In general, research suggests that although women tend to be more risk-averse and more likely to respond to warnings than men, there are more documented reports after disasters of women with posttraumatic stress (Ollenberger and Tobin, 1998) and a higher incidence of abuse against women (Enarson, 1999). Women tend to have a higher risk perception and demonstrate higher preparedness planning but also are more likely to be single parents or primary caregivers and have lower incomes, special medical needs, and less autonomy. These aspects of heightened vulnerability for women to extreme natural events are believed to be reflections of broader cultural, political, and economic inequalities within a society (Morrow, 1999; Bateman and Edwards, 2002). Results indicate that 49 percent of individuals in the extreme tsunami-inundation zone are women, slightly lower than 50 percent for the entire State. For the 91 communities, the percentage of residents in the extreme tsunami-inundation zone that are female ranges from 0 to 58 percent, which is found in Hōnaunau-Nāpoʻopoʻo in Hawaiʻi County. Single-mother households may have unique evacuation and recovery issues, as they are more likely to have limited mobility during an evacuation from a sudden-onset hazard and fewer financial resources to draw on to prepare for natural hazards and to recover from a disaster (Laska and Morrow, 2007). Results indicate that 7 percent of households in the extreme tsunami-inundation zone are single-mother households, equal to the percentage for the State. For the 91 communities, the percentage of households in the extreme tsunami-inundation zone that are single-mother households ranges from 0 to 23 percent, with the maximum value found in Waimānalo in Honolulu County (38 out of 163 households exposed).

Tenancy is another factor that influences individual sensitivity to stressors, as studies have shown that renters are less likely to prepare for catastrophic events than homeowners (Morrow, 1999; Burby and others, 2003). Theories on why this is the case include that (1) higher turnover rates for renters may limit their exposure to hazard-related outreach efforts, (2) renters typically have lower incomes and fewer resources to recover, (3) renters may lack the motivation to invest in mitigation measures for property they do not own (owners may also lack this motivation because costs may be hard to recover), and (4) many preparedness campaigns pay less attention to renters (Burby and others, 2003). After a disaster, renters also have little control over the speed with which rental housing is repaired or replaced (Laska and Morrow, 2007). Results indicate that 55 percent of households in the extreme tsunami-inundation zone are renter-occupied, higher than the 42 percent State average (U.S. Census Bureau, 2010). For the 91 communities, the percentage of households in the extreme tsunami-inundation zone that are renter-occupied ranges from 0 to 100 percent, with maximum values found in Pākalā Village in Kauaʻi County and Hickam Housing on Joint Base Pearl Harbor-Hickam in Honolulu County.

Another group of residents who will require special attention during and before a tsunami are those in group quarters, either institutionalized (for example, adult correctional, juvenile, and nursing facilities) and noninstitutionalized (for example, college/university student housing and military quarters). Individuals in noninstitutionalized group quarters may not have the same level of access to preparedness and risk-reduction information if local outreach is focused on homeowners. Kāneʻohe Station has a relatively high percentage of residents in the tsunami-inundation zone that are in noninstitutionalized group quarters (44 percent of the community's total exposure) because of the large military population in its jurisdiction. Unincorporated Kauaʻi County also has a relatively high percentage of institutionalized residents in group quarters (38 percent of the total exposed population) located in the tsunami-prone area as a result of the presence of a correctional facility in the area. This population is a concern during a tsunami because they will require a structured evacuation and continued supervision to ensure the safety of both the institutionalized populace and the neighboring communities.

In addition to certain age, gender, and tenancy characteristics, households of racial and ethnic minorities also tend to be more vulnerable to extreme events and have higher mortality rates (Morrow, 1999). This does not reflect characteristics of the individual but rather historic patterns of racial and ethnic inequalities within a society that result in minority communities more likely to have inferior public services, infrastructure, and building stock (Laska and Morrow, 2007) and to be excluded from disaster planning efforts (Morrow, 1999). Minorities that speak a language other than the primary language of an area can also have higher vulnerability, as language barriers could hinder the effectiveness of awareness campaigns, evacuation procedures, and post-disaster recovery opportunities. Racial diversity is high for residents in the extreme tsunami-inundation zone and the dominant races are Asian (48 percent), White (47 percent), and Native Hawaiian and other Pacific Islander (29 percent). Percentages in table 1 in the race categories do not sum to 100 percent because individuals were able to report multiple races in the 2010 Census.

Self-reported racial and ethnic characterizations for individuals in the extreme tsunami-inundation zone largely mimic State-level characteristics (table 1). For example, 3 percent of the residents in the extreme tsunami-inundation zone and 3 percent of residents in the State report themselves as Black or African American alone or in some combination with one or more other races. The only large differences between in-tsunami-zone percentages and State percentages were observed for individuals who reported their races as White or Asian. For those individuals that report their race as White alone or in combination with one or more other races, the in-tsunami-zone percentage (47 percent) is higher than the State average (41 percent), suggesting that this demographic group is more likely to be living in low-lying areas along the coast. The opposite is true for individuals that report their race as Asian alone or in some combination with one or more races. For this demographic group, the in-tsunami-zone percentage (48 percent) is lower than the State average (57 percent), suggesting that this group is more likely to live inland.

Employees

For coastal States like Hawaiʻi, most businesses are near the shore; therefore, many individuals go into tsunami-prone areas for their jobs every day, representing a significant evacuation issue for emergency managers. Comments on regional and local labor-market conditions, such as the dominance of

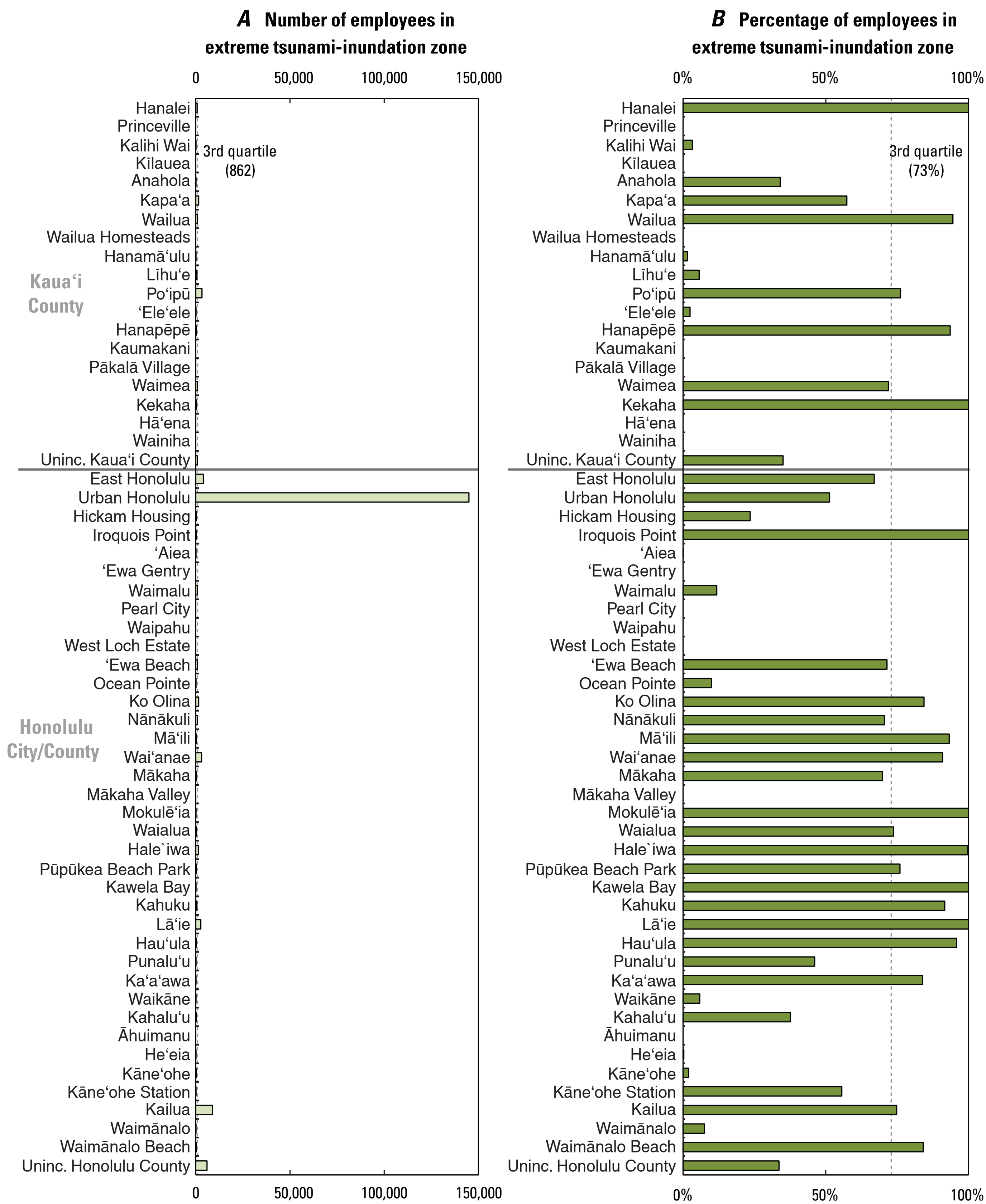

Figure 7. Bar graphs showing (*A*) number and (*B*) percentage of employees in the extreme tsunami-inundation zone in the State of Hawaii, organized by census-designated place. Dashed lines indicate 3rd quartile. Uninc., unincorporated; %, percent.

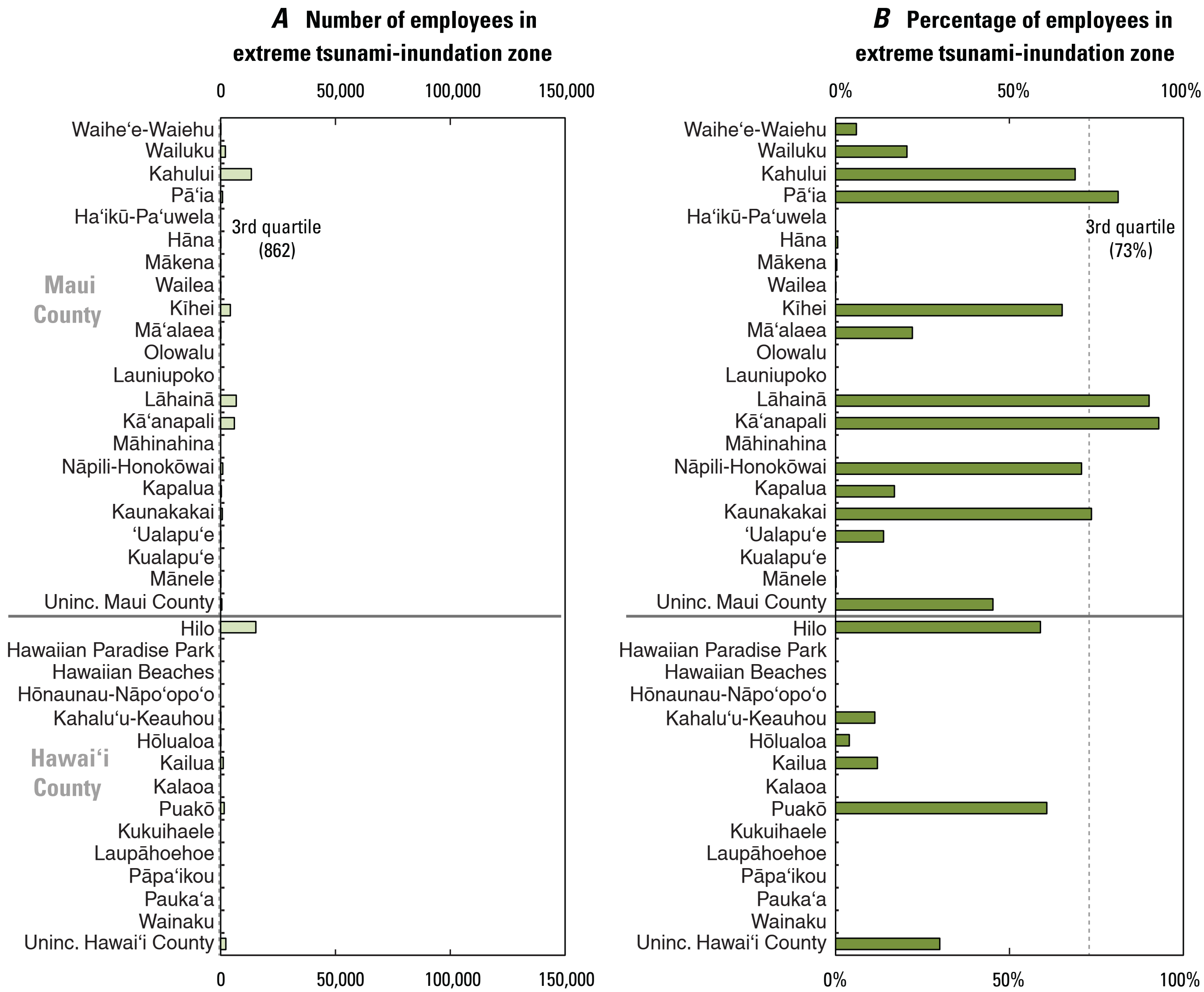

Figure 7.—Continued

specific sectors in the extreme tsunami-inundation zone and for the entire State, are based on the number and distribution of employees, an indicator routinely used by the private and public sector to evaluate economic health and market trends (Marshall, 1989; Bureau of Labor Statistics, 2007). Employee analysis is based on the 2012 Infogroup Employer Database, a proprietary database comprised of georeferenced point files representing businesses, each with attributes of employee size, sales volume, and North American Industry Classification System (NAICS) codes (Infogroup, 2012). Analysis is based on a point's location within the extreme tsunami-inundation zone.

Results indicate that 245,827 people are employed at 18,693 businesses located in the Hawaiian extreme tsunami-inundation zone, representing 42 percent of the employees in the State of Hawaii. The median value for the community percentage of employees working in the extreme tsunami-inundation zones is 14 percent for the region, and the third quartile (75th percentile) is 72 percent. Similar to residential populations, the amount (fig. 7*A*) and percentage (fig. 7*B*) of employee populations in the extreme tsunami-inundation zone vary considerably in the State of Hawaii. Again, certain communities such as Urban Honolulu and Hilo in Hawai‘i County have high numbers of employees in the extreme tsunami-inundation zone (144,935 and 15,351, respectively) that represent relatively lower percentages of total employees (51 percent and 59 percent, respectively). Other communities have much lower numbers of employees in the extreme tsunami-inundation zone, including Mokulē‘ia (34 employees) and Kawela Bay (133 employees) in Honolulu County; however, in both of these cases, these employees represent 100 percent of the community's workforce.

High percentages of employees in the extreme tsunami-inundation zone may represent economic fragility for a community, as unemployment could increase dramatically overnight if a tsunami injures or kills employees or if it damages or destroys businesses. Even if a business escapes damage or physical disruption from an extreme event, it may still experience significant customer and revenue loss if the neighborhood and other businesses around it are damaged, leading customers to shop elsewhere. Neighborhood effects have been found to be especially important for retailers that rely on foot traffic (Chang and Falit-Baiamonte, 2002), a potentially significant issue for tourist-related retail along the Hawaiian coast. Therefore, knowing where there are high amounts and percentages of employees helps identify potential economic recovery issues.

The distribution of employees by business type (fig. 8) indicates that the highest numbers of employees in the State of Hawaii are in accommodation and food services (17 percent), health care and social assistance (14 percent), and retail trade (12 percent). The percentage of employees in the accommodation and food-services sector is more than double the national average of 7.1 percent (2014 value) for the same industry sector (Bureau of Labor Statistics, 2015), reflecting the dominance of the tourism sector in the State of Hawaii economy. The employee distribution for businesses in the extreme tsunami-inundation zone largely mimics the distribution for businesses in the entire State. The only deviations from the State-level distribution to the inundation-zone businesses are the increase in the accommodation and food-services businesses (from 17 percent up to 25 percent) and the decrease in health care and social assistance businesses (from 14 percent down to 6 percent). Again, the results reaffirm that tourism-related businesses dominate tsunami-prone areas (25 percent of employees compared to a national average of 7.1 percent) and that many accommodation and food services businesses in the State occupy low-lying areas near the coastline.

Community-Support Businesses

To provide further insight on population dynamics in the various coastal communities, we used the 8-digit NAICS code attached to each business in the 2012 Infogroup Employer Database to identify certain types of businesses that may attract additional people to tsunami-prone areas, including community-support businesses, dependent-care facilities, and public venues. The high number of businesses and the dynamic nature of populations at these locations preclude our ability to determine exact visitor counts at each business; therefore, discussions of these locations are limited to the number of venues and facilities. The first category—community support—includes businesses that attract significant populations throughout a workday because they provide basic necessities primarily to residents (although visitors may use them also). These community-support businesses include:

- *Banks and credit unions*;
- *Civil and social organizations*;
- *Department stores*;
- *Government offices*, such as courts and international affairs offices;
- *Libraries*;
- *Markets*;
- *Religious organizations*;
- *Retail*, such as clothing stores and car dealers;
- *General services*, such as auto repair shops and beauty salons;
- *Shipping*, such as freight trucking and freight-transportation arrangement; and
- *Shopping centers and malls*.

Many businesses that primarily provide community support are in the extreme tsunami-inundation zone (table 2). These facilities include retail (4,274), general services (2,171), religious organizations (279), shipping facilities (120), banks and credit unions (156), government offices (473), and markets (156). Urban Honolulu has the highest number of community-support facilities in the extreme tsunami-inundation zone, followed by Hilo in Hawai‘i County and Kahului in Maui County. The majority of community-support businesses in the extreme tsunami-inundation zone are retail and general services businesses.

Employees and local residents at community-support locations could be in danger if a tsunami were to occur during typical business hours (for example, from about 8 a.m. to 6 p.m.). In addition, patrons at these facilities may only be aware of tsunami threats from the perspective of their homes and therefore not fully aware of evacuation procedures or even tsunami potential when they are out running errands or attending a religious service. The high number of religious organizations in the extreme tsunami-inundation zone, however, presents an education/outreach opportunity for county and State emergency managers to work with religious leaders in disseminating tsunami-hazard and community-resilience education materials developed by the emergency-management community.

Results of the community-support businesses analysis should be considered preliminary for several reasons. First, although some remote, imagery-based verification of business locations was completed for this analysis, no fieldwork was conducted to verify the location accuracy of the businesses. Second, the results summarize the number of facilities, not the number of individuals in the facility, and no extra weighting is given to larger facilities. Third, in the Infogroup Employer Database, similar facilities may sometimes be coded differently. For example, a facility with the word “hospital” in its name was coded as a hospital in some cases but as an outpatient-care facility in other cases. Therefore, results should not be considered a definitive assessment of the distribution of facilities but instead should be considered preliminary for the purposes of initiating discussions and future analytical

Figure 8. Bar graph showing types of businesses in the extreme tsunami-inundation zone in the State of Hawaii, organized by North American Industry Classification code. %, percent.

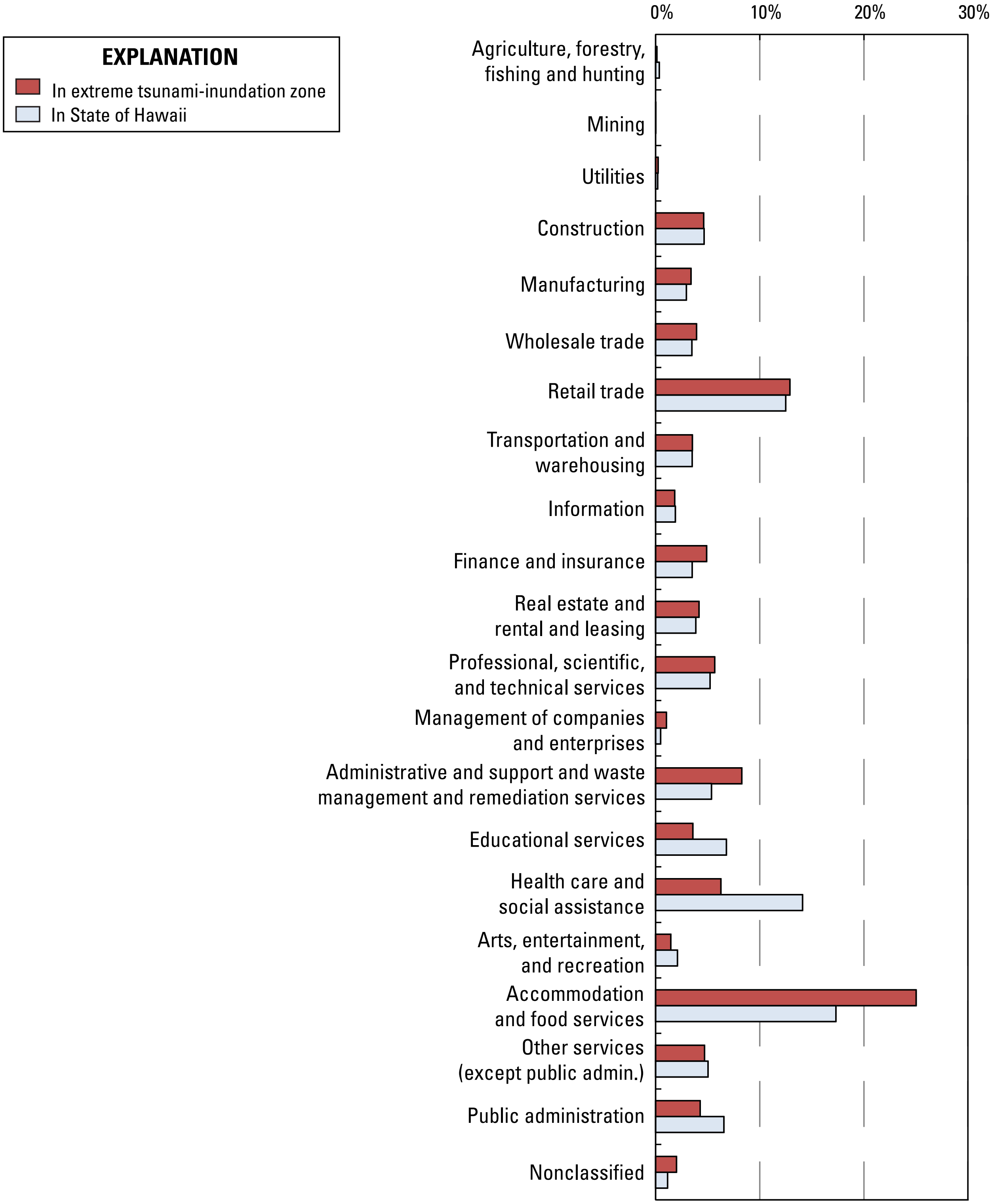

Table 2. Summary of the amount and percentage of community-support businesses in the extreme tsunami-inundation zone in the State of Hawaii.

[%, percent]

Community-support businesses	In extreme tsunami-inundation zone	State total	Percentage
Banks and credit unions	156	458	34%
Civil and social organizations	86	183	47%
Department stores	17	47	36%
Government offices	473	1,281	37%
Libraries	25	91	27%
Markets	156	421	37%
Religious organizations	279	1,052	27%
Retail	4,274	9,177	47%
Services (general)	2,171	5,255	41%
Shipping	120	294	41%
Shopping centers and malls	41	97	42%

efforts. On the basis of this preliminary study, and although we believe the Infogroup Employer Database in its raw form is effective at determining regional trends, field verification is necessary before the data can be used in an operational or tactical sense.

Dependent-Care Facilities

Dependent populations are defined here as individuals who temporarily reside in facilities where they would be dependent on external assistance to evacuate and recover. Facilities with such populations include:

- *Adult-assistance services*, such as assisted-living facilities for the elderly, continuing-care retirement communities, and skilled-nursing-care facilities;
- *Child services*, such as child day-care services and child and youth services;
- *Correctional facilities*;
- *Medical and health services*, such as family-planning centers, offices of dentists, offices of physicians, and psychiatric and substance-abuse hospitals;
- *Medical centers*; and
- *Schools*.

Results indicate that there may be significant numbers of dependent-population facilities in the extreme tsunami-inundation zone (table 3). The highest number of dependent-population facilities in the extreme tsunami-inundation zone were medical and health services (2,024), followed by schools (111), child services (95), and medical centers (37). Urban Honolulu has the highest number of dependent-care facilities in the extreme tsunami-inundation zone at 929, with the majority being medical and health services facilities. Kailua in Honolulu County and Hilo are the next highest communities at 308 and 303 respectively. The low number of exposed medical centers, but high number of exposed medical and health services (which includes physicians' offices), in some

Table 3. Summary of the amount and percentage of dependent-care facilities in the extreme tsunami-inundation zone in the State of Hawaii.

[%, percent]

Dependent-care facility	In extreme tsunami-inundation zone	State total	Percentage
Adult-assistance services	32	145	22%
Child services	95	333	29%
Correctional facilities	5	12	42%
Medical and health services	2,024	8,828	23%
Medical centers	37	161	23%
Schools	111	517	21%

Table 4. Summary of the amount and percentage of public venues in the extreme tsunami-inundation zone in the State of Hawaii.

[%, percent]

Public venue	In extreme tsunami-inundation zone	State total	Percentage
Colleges	23	98	23%
Entertainment facilities	633	1,447	44%
Overnight accommodations	267	500	53%

communities suggests that medical health centers in those communities may be able to handle casualties during the immediate response phase of a disaster; however, those communities may experience difficulties in maintaining medical services during the longer-term recovery phase. On the basis of these results, a follow-up study to confirm the location and determine the size of these dependent populations may be warranted.

Additional evacuation planning may be required in communities with high numbers of dependent-population facilities because of the limited mobility of certain groups at these facilities, such as those in schools and nursing homes. Also, parents may attempt to enter tsunami-prone areas to retrieve children from schools and day-care centers or adult children may attempt to enter tsunami-prone areas to retrieve their parents from elderly care facilities, which present additional evacuation issues for facility managers. In addition to unique evacuation and relief issues, many dependent-population facilities represent critical social services that, if lost, could slow community recovery following an extreme event. For example, the loss of day-care centers could keep parents at home, thereby slowing business recovery.

The Infogroup Employer Database has similar issues for dependent-care facilities as for community-support businesses. In addition, some categories may contain facilities that are not as much of a concern in a particular category as others are. For example, “schools” may include bus depots and other school facilities at which children would not be present along with traditional elementary and secondary schools.

Public Venues

Identifying public venues provides some insight on where significant numbers of tourists and local residents may congregate during the day and where significant evacuation issues may exist if a tsunami occurs. Although we cannot determine how many people visit these sites at a given time, knowing where public venues are provides emergency managers with some insight on community vulnerability hotspots. We focus on the following public-venue facilities for this analysis:

- *Colleges,* including colleges, universities, professional schools, and junior colleges;
- *Entertainment,* including amusement and theme parks, arcades, bowling centers, fitness and recreational sports centers, golf courses and country clubs, marinas, museums, nature parks, theaters (drive-in, live, and motion picture), and zoos and botanical gardens; and
- *Overnight accommodations,* including hotels and motels, bed and breakfasts, and room/board houses.

Results indicate that there are significant numbers of public venues in the extreme tsunami-inundation zone that likely attract high numbers of customers or tourists, including 23 colleges, 633 entertainment facilities, and 267 overnight-accommodation facilities (table 4). Urban Honolulu, as was also the case for community-support businesses and dependent-care facilities, has the highest number of public venues in the extreme tsunami-inundation zone (388). Lāhainā (Maui County), Hilo, and Kahului also have high numbers of public venues in the extreme tsunami-inundation zone (85, 58, and 43, respectively). Entertainment facilities make up the majority of the exposed public venues in the State.

Tourist populations can be difficult to estimate due to their transience and the general lack of data regarding their numbers. Hotel guest counts were not available for the 267 overnight accommodations facilities (which include hotels/motels, resorts, bed-and-breakfasts, and other facilities) in the State of Hawaii’s extreme tsunami-inundation zone; therefore, small motels are counted the same as large resorts. Another accommodation-related issue is that the overnight accommodations in the extreme tsunami-inundation zone represent 53 percent of all overnight accommodations facilities in the State; therefore, a tsunami could result in significant impacts to the tourism industry in terms of available lodging.

Large numbers of visitors could be in danger if a tsunami were to occur during a high-occupancy time (for example, holidays or weekends). Visitors may not be fully aware of evacuation procedures or even the potential for tsunamis if they are coming from areas with no history of tsunamis. The presence of public venues in the extreme tsunami-inundation zone, however, also presents an outreach opportunity for emergency managers to work with owners and employees of these public venues to educate local and tourist populations.

Similar concerns expressed previously on the use of the Infogroup Employer Database apply to public venues and overnight-accommodation facilities. For example, in working with the data, we realized that businesses classified as “colleges” may include not only 2- and 4-year colleges but also technical schools, trade schools, flight schools, and even dance academies. Therefore, the “colleges” category should not be

Table 5. Summary of the amount and percentage of critical facilities in the extreme tsunami-inundation zone in the State of Hawaii.

[%, percent]

Critical facility	In extreme tsunami-inundation zone	State total	Percentage
Emergency services			
Civil-defense facilities	6	11	55%
Fire stations	15	35	43%
National-security facilities	14	53	26%
Police stations	11	80	14%
Infrastructure			
Airline companies	22	60	37%
Airports	4	11	36%
Electric companies	5	12	42%
Gas companies	6	7	86%
Gas (wholesale)	34	66	52%
Public-works facilities	12	32	38%
Radio and television broadcasting	45	105	43%
Water and sewer facilities	2	9	22%

considered a summation of the traditional use of this term, namely 2- and 4-year colleges.

Critical Facilities

Certain facilities are important for short-term response and long-term recovery of a community following a tsunami. For the purposes of this study, critical facilities are those considered important for short-term response operations and are broken into two categories—emergency services and infrastructure. This list is not meant to be exhaustive of all facilities that will be important immediately after a tsunami strikes, merely beginning estimates of the need for certain facilities for further discussions within the State of Hawaii. The critical facilities identified for this study include:

- *Emergency services*, including civil-defense facilities, fire stations, national-security facilities; and police stations; and
- *Infrastructure*, including airline companies and airports, electric facilities, public-works facilities, gas facilities, radio and television stations, and water and sewer facilities.

Results indicate that there are several critical facilities in the extreme tsunami-inundation zone (table 5). Exposed emergency services are not particularly numerous in the extreme tsunami-inundation zone but are also not common in the State overall; civil-defense facilities and fire stations are most affected (55 percent and 43 percent of facilities are exposed, respectively). Infrastructure is also potentially vulnerable, with radio and television broadcasting (45), wholesale gas (34), and airline companies and airport facilities (26) being most common. Gas-company facilities are few in number (7) in the State, but 6 of these are exposed to the extreme tsunami-inundation zone. Due to the terms of use of the Infogroup Employer Database, we are unable to provide maps of critical facilities in relation to the extreme tsunami-inundation zone. Interested parties should contact HI-EMA for additional information related to issues regarding critical infrastructure.

In most cases, the relative percentages are low for most categories when comparing facilities in the extreme tsunami-inundation zone to State totals. A logical next step for analysis is to determine the locational accuracy of critical facilities that are highlighted as being in the extreme tsunami-inundation zone, due to concerns expressed previously on the accuracy of the Infogroup Employer Database. Another area for further investigation is the redundancy of facility functions in an area. For example, results presented here may indicate that a community's police stations are in the extreme tsunami-inundation zone. If a neighboring community also has the same issue, then the ability to maintain order for the region is compromised even more. However, if a neighboring town has similar facilities that are not in the extreme tsunami-inundation zone, resources could be shared between communities.

Composite Indices of Community Exposure

Emergency managers, especially those with State or Federal agencies, assess community vulnerability often in relative terms to prioritize limited resources. To facilitate comparisons for the communities presented in this report, we developed composite indices of amounts and percentages of community exposure to tsunami hazards in Hawai‘i. These indices are based on the amounts and percentages, respectively, of developed lands, residents, employees, community-support businesses, dependent-care facilities, and public venues in each of the 91 communities and in the unincorporated land of the 4 counties. Information on facilities was limited to counts for this analysis because the actual number of individuals at each site was not gathered. Critical infrastructure data were not included in the composite indices because of the shared nature of several of the facility types.

Composite indices of community exposure were developed for each of the 95 geographic units by first normalizing values in each category (developed land-cover area, residents, employees, community-support businesses, dependent-care facilities, and public venues) to the maximum value found within that category. Normalizing data to maximum values creates a common data range of 0 to 1 for all six categories and is a simple approach for enabling comparisons among disparate datasets. The six normalized values are then added together, resulting in one final score with a data range of 0 to 6 for each of the 95 geographic units. This is done for both amounts and percentages. The two unitless indices allow us to compare the relative exposure levels for the 95 geographic units at regional or State levels. Because they are relative metrics, the numbers do not provide much meaning for individual communities.

Table 6 summarizes the two composite index values (each with a range from 0 to 6), where higher values indicate higher amounts or percentages for the 91 communities and the unincorporated land of the 4 counties. Figure 9 provides the same results in a map-based format to better visualize spatial variations in composite scores across the State. Note, in figure 9, colored points near the county names represent the scores for the unincorporated land of each county. These scores are meaningless for individual communities and only provide insight on the relative exposure of communities to tsunamis in Hawai‘i. In general, the highest composite exposure score is found in Urban Honolulu (6.00), with the next-highest scores being for Kailua in Honolulu County and Hilo in Hawai‘i County (fig. 9) (1.30 and 1.28, respectively). No spatial trend is discernible for composite percentage scores, as low and high values are found in each county (fig. 9).

A frequency histogram illustrates the distribution of composite amount and percentage values (fig. 10), with the x-axis showing the sum of the six normalized values with a range of 0 to 6, summarized here in 0.5 increments, and the y-axis noting the number of communities for each category. Results portrayed in table 6, figure 9, and figure 10 indicate that most communities have low composite amount and percentage values. Composite amount values are skewed heavily to the lowest bin of 0.0 to 0.5, where 92 of the 95 geographic units have composite exposure values of 1.0 or less, demonstrated in figure 9 by the numerous green dots that represent scores less than 1.0. It is possible that a community in this lowest bin may have a high number of exposed assets in one category (for example, residents), but overall, a low composite amount score indicates that most of its assets are not in tsunami-prone areas. The highest composite amount value is 6.00, denoting Urban Honolulu in Honolulu County (fig. 9). The high skewness of the distribution to the lowest composite-score bins (less than 1.0) indicates that the community assets exposed to tsunamis are consistently and significantly higher in Urban Honolulu than in the other communities, expressed by the high number of green points in figure 9.

Unlike the composite exposure amount values, the composite percentage values do not skew as strongly to the lowest bin. The highest composite percentage value is 5.97 for the community of Hanalei, located on the northern coast of the Island of Kaua‘i (fig. 9). A score of 5.97 indicates that the percentage of community assets in the extreme tsunami-inundation zone is consistently high. Hanalei is a small community where 97 percent of its residents and 100 percent of its employees, developed land, community-support facilities, dependent-care facilities, and public venues are in the extreme tsunami-inundation zone. However, the larger number of communities with scores between 2.0 and 4.0 indicates that Hanalei is not as anomalous for composite percentage values as Urban Honolulu is for composite amount values.

As noted earlier, certain communities have high relative amount values and others have high relative percentages. Figure 11 illustrates the two composite indices for the 95 geographic units, where higher values indicate higher amounts or percentages. The bar graph representing the amount of assets is reversed on the vertical axis in figure 11 to facilitate easier comparisons of the two values in individual communities. Values for both indices increase as the bar extends away from the central line. As noted elsewhere in this report, some communities have high amounts but low percentages of assets in the extreme tsunami-inundation zone; for example, Urban Honolulu has the highest composite amount value (6.00) but one of the lower composite percentage values (2.37). In contrast, other communities have low composite amount values but high percentage values; for example, the community of Hanalei has the highest composite percentage value (5.97) but one of the lowest amount values (0.10). Other examples of this include the communities of Kekaha (Kaua‘i County), Hale‘iwa (Honolulu County), and Lā‘ie (Honolulu County). The few communities that have relatively high composite values in both amount and percentage categories include the communities of Urban Honolulu, Kailua (Honolulu County), and Hilo (Hawai‘i County).

To provide some insight on which communities have the highest combined exposure to tsunamis, we normalized the composite amount and percentage values to maximum values found in each category (6.00 for composite amounts and 5.97 for composite percentages), thereby creating a common data range of zero to one and minimizing any bias between categories. These normalized indices were then added together to produce a final index ranging between zero and two (fig. 12). The final index is, again, numerically meaningless for a given community but does offer a glimpse of relative exposure

Table 6. Range of composite amount and percentage index values for communities in the extreme tsunami-inundation zone in the State of Hawaii.

Range	Composite Amount Values		Composite Percentage Values	
5.0 to 6.0	Urban Honolulu		Hanalei	Kekaha
			Hale‘iwa	Lā‘ie
			Mā‘ili	Waialua
4.0 to 4.9			Mokulē‘ia	Kawela Bay
			Iroquois Point	Wai‘anae
			Wailua	Hanapēpē
			Kailua (O‘ahu)	Lāhainā
			Hau‘ula	Pūpūkea Beach Park
			Nānākuli	Waimānalo Beach
			Mākaha	Kaunakakai
			Kahuku	Waimea
3.0 to 3.9			Kā‘anapali	‘Ewa Beach
			Ka‘a‘awa	Ko Olina
			Kahului	Nāpili-Honokōwai
			Pā‘ia	Kīhei
			East Honolulu	Hilo
			Punalu‘u	
2.0 to 2.9			Kapa‘a	Mā‘alaea
			Anahola	Kāne‘ohe Station
			Urban Honolulu	
1.0 to 1.9	Kailua (O‘ahu)		‘Ualapu‘e	Unincorporated Kaua‘i County
	Hilo		Kalihi Wai	Puakō
			Po‘ipū	Kapalua
			Hā‘ena	Kahalu‘u
			Wainiha	Unincorporated Honolulu County
			Olowalu	
			Waikāne	
			Unincorporated Maui County	
0 to 0.9	Kahului	Unincorporated Honolulu County	Wailuku	Waimānalo
	East Honolulu	Lāhainā	Mākena	Unincorporated Hawai‘i County
	Kīhei	Wai‘anae	Hickam Housing	Mānele
	Unincorporated Kaua‘i County	Kāne‘ohe Station	Kailua (Hawai‘i)	Waihe‘e-Waiehu
	Nānākuli	Hale‘iwa	Kahalu‘u-Keauhou	Līhu‘e
	‘Ewa Beach	Lā‘ie	Ocean Pointe	Kāne‘ohe
	Kapa‘a	Mā‘ili	Waimalu	‘Ele‘ele
	Kā‘anapali	Mākaha	Hōlualoa	Hāna
	Hickam Housing	Nāpili-Honokōwai	He‘eia	

Table 6.—Continued

Range	Composite Amount Values		Composite Percentage Values	
	Wailuku	Waialua	Wailea	Launiupoko
	Kaunakakai	Kekaha	Mākaha Valley	Hanamāʻulu
	Pūpūkea Beach Park	Waimānalo Beach	Princeville	Kīlauea
	Hanalei	Hauʻula	Laupāhoehoe	West Loch Estate
	Kailua (Hawaiʻi)	Unincorporated Hawaiʻi County	Māhinahina	Paukaʻa
	Wailua	Iroquois Point	Kaumakani	ʻAiea
	Waimea	Puakō	Wainaku	Wailua Homesteads
	Poʻipū	Ko Olina	Pearl City	Hōnaunau-Nāpoʻopoʻo
	Kāneʻohe	Pāʻia	Kukuihaele	Waipahu
	Mokulēʻia	Līhuʻe	Āhuimanu	Pāpaʻikou
	Kahuku	Hanapēpē	Kualapuʻu	Kalaoa
	Unincorporated Maui County	Kahaluʻu	Haʻikū-Paʻuwela	Hawaiian Paradise Park
	Punaluʻu	Waimalu	Hawaiian Beaches	ʻEwa Gentry
	Māʻalaea	Ocean Pointe	Pākalā Village	
	Kawela Bay	Kapalua		
	Kaʻaʻawa	Waiheʻe-Waiehu		
	Waimānalo	Anahola		
	Kahaluʻu-Keauhou	Hāʻena		
	Wailea	Pearl City		
	Hōlualoa	Kalihi Wai		
	Heʻeia	Pākalā Village		
	Olowalu	Mākena		
	ʻUalapuʻe	Waikāne		
	Wainiha	Waipahu		
	Launiupoko	ʻAiea		
	Mānele	Hanamāʻulu		
	Princeville	West Loch Estate		
	Hāna	Kīlauea		
	ʻEleʻele	Wailua Homesteads		
	Mākaha Valley	Kalaoa		
	Āhuimanu	Māhinahina		
	Hōnaunau-Nāpoʻopoʻo	Laupāhoehoe		
	Wainaku	Kaumakani		
	Haʻikū-Paʻuwela	Kualapuʻu		
	Hawaiian Paradise Park	Paukaʻa		
	ʻEwa Gentry	Hawaiian Beaches		
	Pāpaʻikou	Kukuihaele		

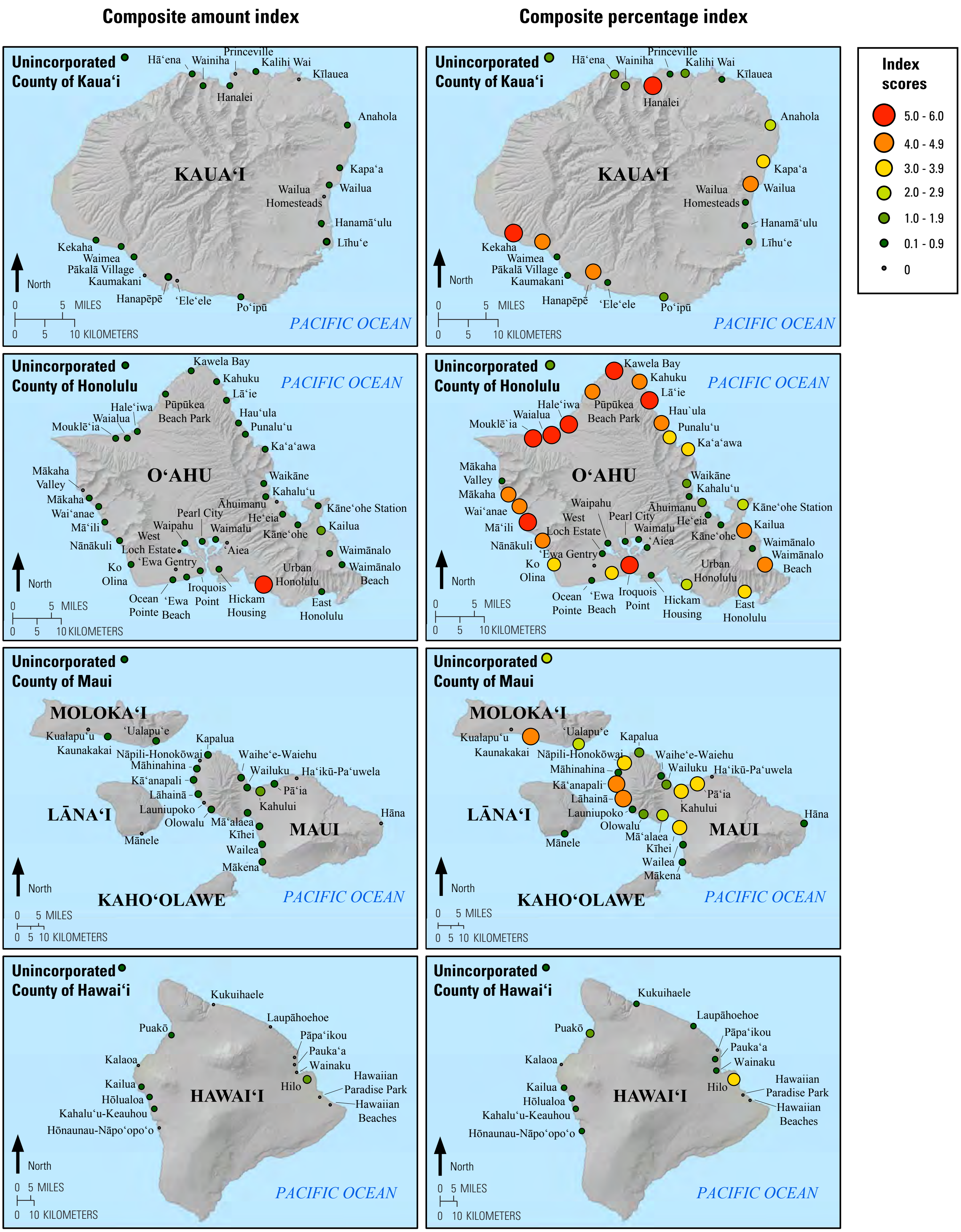
Composite amount index
Composite percentage index
Unincorporated County of Kaua‘i
KAUA‘I
Hā‘ena
Wainiha
Princeville
Kalihi Wai
Kīlauea
Hanalei
Anahola
Kapa‘a
Wailua
Wailua Homesteads
Hanamā‘ulu
Līhu‘e
Kekaha
Waimea
Pākalā Village
Kaumakani
Hanapēpē
‘Ele‘ele
Po‘ipū
North
0 5 MILES
0 5 10 KILOMETERS
PACIFIC OCEAN
Unincorporated County of Honolulu
O‘AHU
Kawela Bay
Kahuku
Lā‘ie
Hau‘ula
Punalu‘u
Ka‘a‘awa
Pūpūkea Beach Park
Hale‘iwa
Waialua
Mouklē‘ia
Mākaha Valley
Mākaha
Wai‘anae
Mā‘ili
Nānākuli
Ko Olina
Ocean Pointe
‘Ewa Beach
‘Ewa Gentry
Iroquois Point
West Loch Estate
Waipahu
Pearl City
Waimalu
‘Aiea
Āhuimanu
He‘eia
Kāne‘ohe
Kāne‘ohe Station
Kailua
Waikāne
Kahalu‘u
Waimānalo
Waimānalo Beach
Urban Honolulu
East Honolulu
Hickam Housing
Unincorporated County of Maui
MOLOKA‘I
LĀNA‘I
MAUI
KAHO‘OLAWE
Kualapu‘u
Kaunakakai
‘Ualapu‘e
Kapalua
Nāpili-Honokōwai
Māhinahina
Kā‘anapali
Lāhainā
Launiupoko
Olowalu
Mānele
Waihe‘e-Waiehu
Wailuku
Ha‘ikū-Pā‘uwela
Pā‘ia
Kahului
Mā‘alaea
Kīhei
Wailea
Mākena
Hāna
Unincorporated County of Hawai‘i
HAWAI‘I
Kukuihaele
Laupāhoehoe
Pāpa‘ikou
Pauka‘a
Wainaku
Hilo
Hawaiian Paradise Park
Hawaiian Beaches
Puakō
Kalaoa
Kailua
Hōlualoa
Kahalu‘u-Keauhou
Hōnaunau-Nāpo‘opo‘o
Index scores
5.0 - 6.0
4.0 - 4.9
3.0 - 3.9
2.0 - 2.9
1.0 - 1.9
0.1 - 0.9
0

Figure 9. County maps of composite normalized amount and percentage index values for communities in the extreme tsunami-inundation zone in the State of Hawaii. Values range from 0 (lowest) to 6 (highest) and are the sum of the normalized values (each from 0 to 1) of residents, employees, developed land, community-support businesses, dependent-care facilities, and public venues in each community. Note that colored points near each county name represent scores for the unincorporated land of each county. km, kilometer.

throughout the region. The communities with the highest combined values are Urban Honolulu, Hale‘iwa, Hanalei, Kekaha, and Lā‘ie. Some communities are primarily vulnerable to tsunamis due to the amount of their assets found in the extreme tsunami-inundation zone (for example, Urban Honolulu), whereas others are vulnerable due to having higher percentages of their assets in the extreme tsunami-inundation zone (for example, Hanalei and Lā‘ie).

There are several reasons that this relative assessment of vulnerability to tsunamis should only be considered a first approximation and not a final statement. First, these calculations focused only on a selection of variables—developed land, residents, employees, community-support businesses, dependent-care facilities, and public venues. Follow-up studies of community vulnerability should include additional community assets, such as cultural resources or natural resources. Second, the final index assumes an equal weighting of the amounts and percentages of exposed community assets. There is a dearth of current research on the relative importance of either in determining the overall vulnerability of a community; however, future research may suggest that a different weighting could be used. Third, these calculations do not include variations in community resilience, another key component of vulnerability. The ability of a community to withstand, absorb, adapt to, and recover from losses defines its resilience, and—with other conditions remaining the same—greater resilience lowers a community's vulnerability to extreme events. For example, if two communities have identical community assets in tsunami-prone land but one has a tsunami education program, a well-rehearsed evacuation plan, a coordinated response network, redundant critical infrastructure, and a holistic postdisaster recovery plan, then that community would probably have greater resilience. Despite their similar asset distributions, the same extreme natural event could mean a short-term crisis in the more resilient community and a longer-term disaster in the other community.

Summary

Data and graphs presented in this report are provided to support a collaboration of the Hawai‘i Emergency Management Agency, the State of Hawaii Office of Planning, the Pacific Disaster Center, and the USGS that focuses on improving understanding of community vulnerability to tsunamis in Hawai‘i. The purpose of the assessment was to update an earlier analysis that characterized the landscape in the tsunami-evacuation zone of the State of Hawaii and compared amounts and percentages of community assets exposed, based on various socioeconomic attributes, to tsunamis.

Results indicate that there are significant variations in amounts and percentages of community assets exposed to extreme tsunami hazards, with regards to the distribution of developed land cover, residents, employees, community-support businesses, dependent-care facilities, public venues, and critical facilities (emergency services and infrastructure). Some communities, such as Urban Honolulu and Kailua in

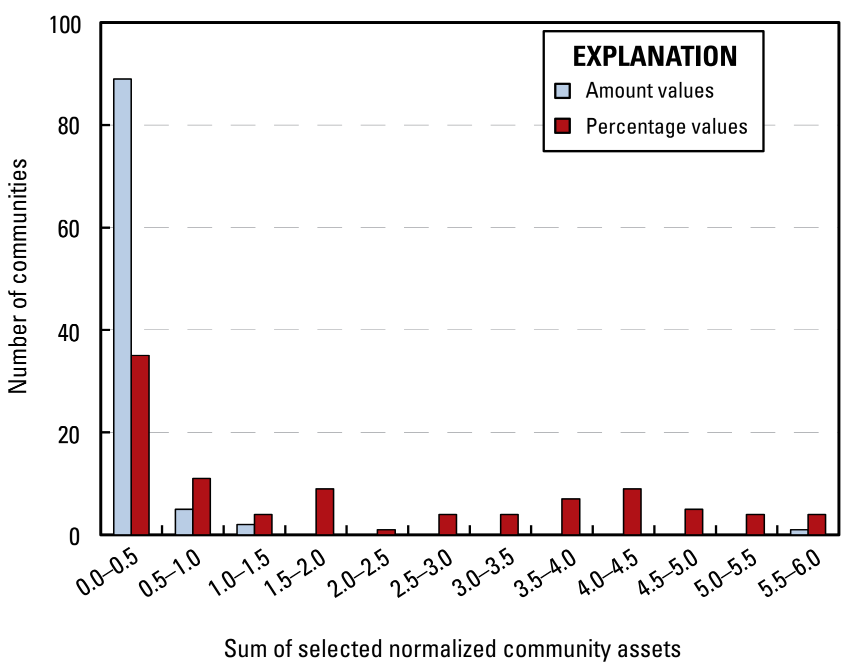

Figure 10. Frequency histogram showing the sum of normalized exposure indices for the extreme tsunami-inundation zone in the State of Hawaii.

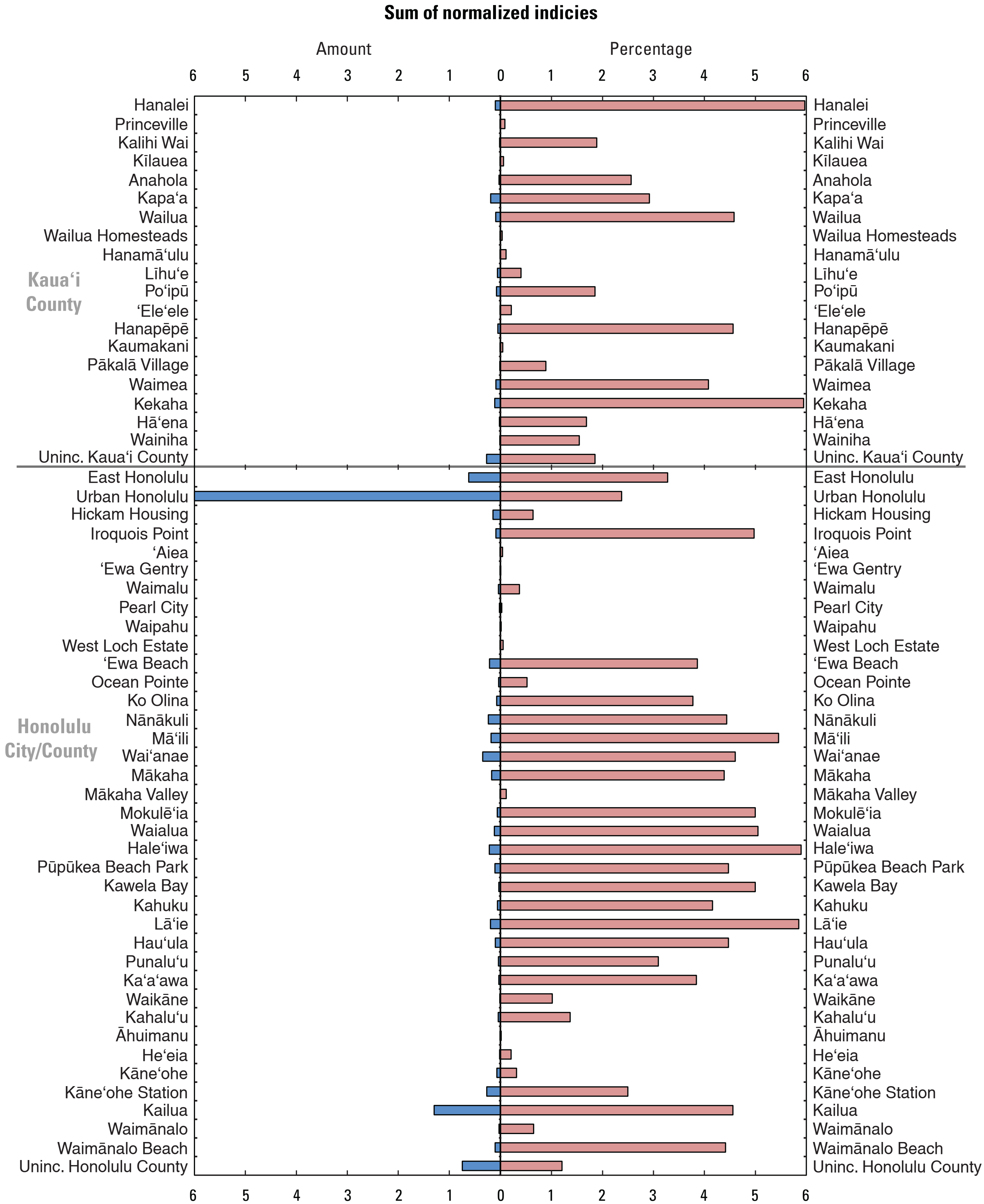

Figure 11. Bar graphs showing sum of normalized amount and percentage indices for communities in the extreme tsunami-inundation zone in the State of Hawaii. Uninc., unincorporated.

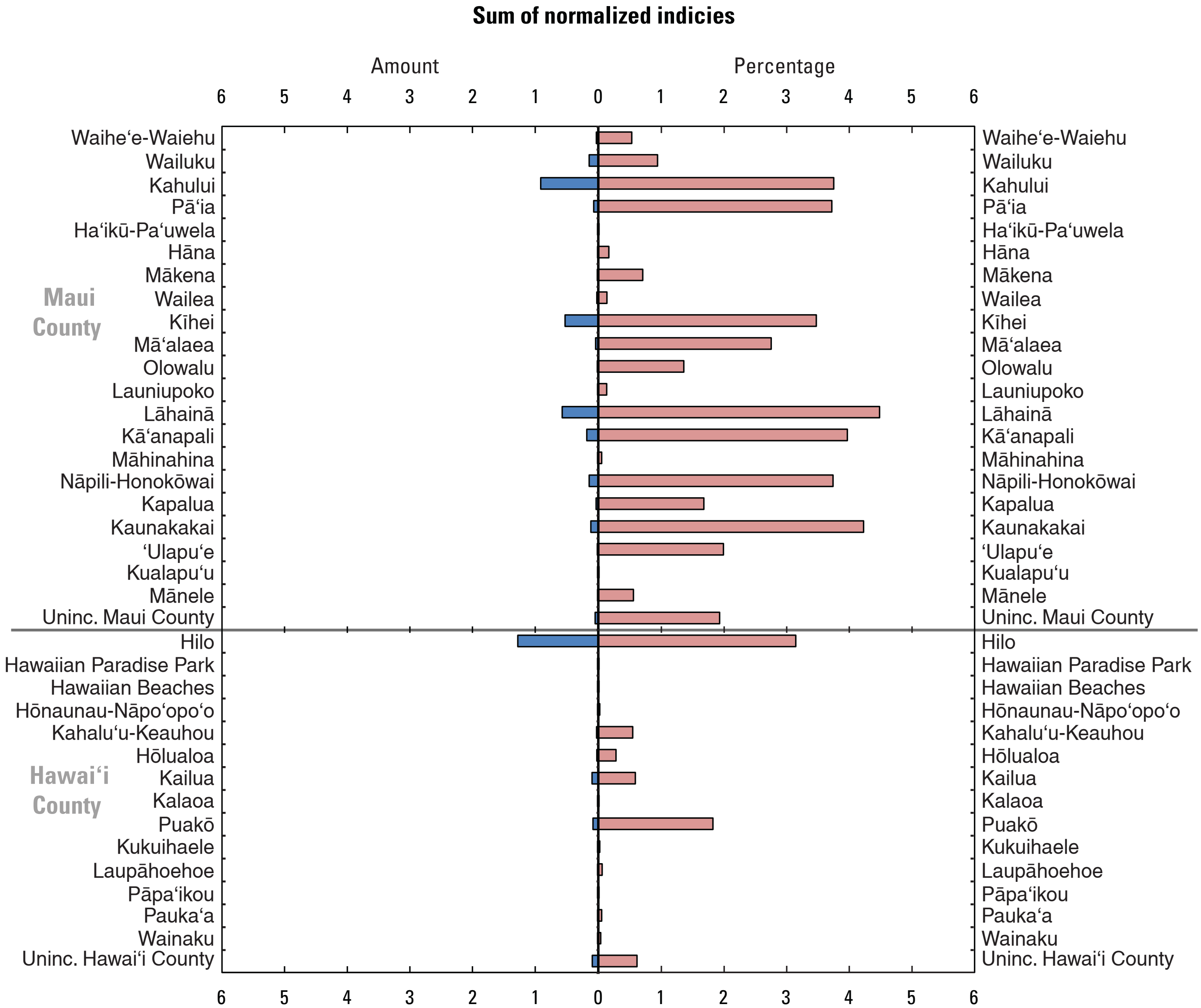

Figure 11.—Continued

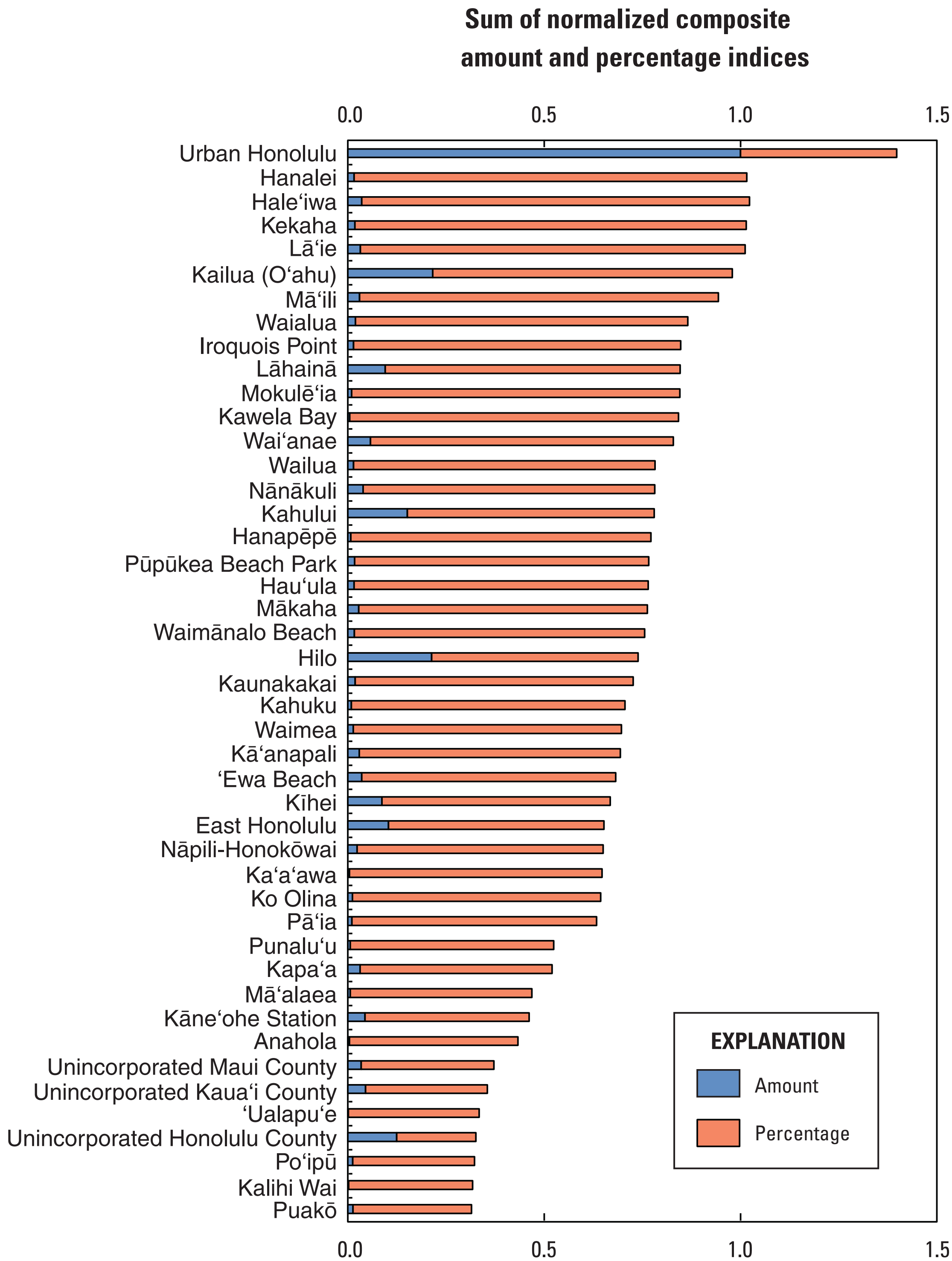

Figure 12. Bar graphs comparing sum of normalized composite amount and percentage indices for selected communities in the extreme tsunami-inundation zone in the State of Hawaii.

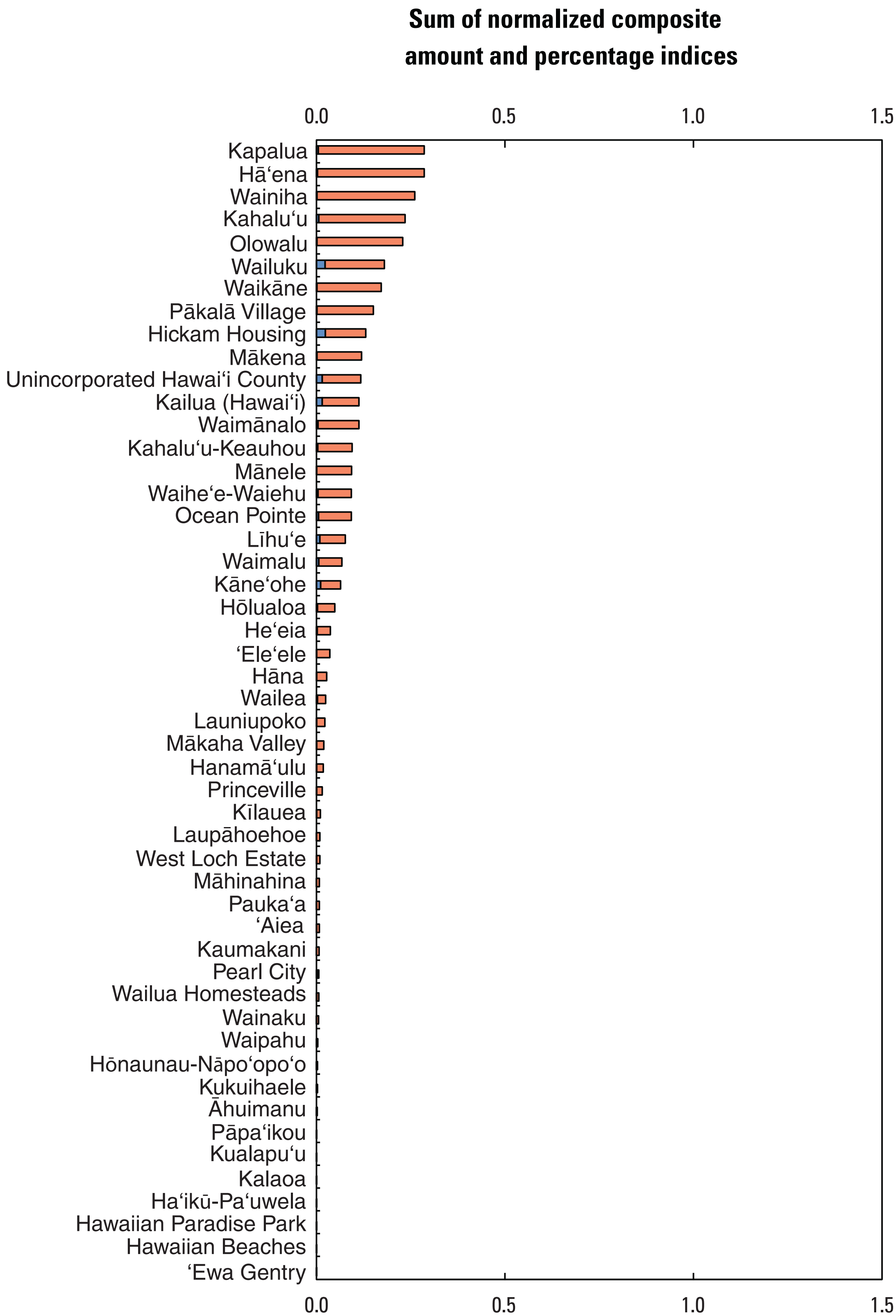

Figure 12.—Continued

Honolulu County, have high exposure to extreme tsunamis, because they have large amounts of their assets in tsunami-prone land; however, these large amounts represent a smaller percentage of the community. Other communities, such as Kawela Bay, Hanalei, and Mokulē‘ia, where small amounts of assets in tsunami-prone areas represent large percentages of a community's total assets, may experience greater relative impacts and social disruption and have fewer internal resources available during recovery. It is up to policymakers, land-use managers, emergency managers, nonprofit organizations, and private citizens to determine where to allocate limited risk-reduction resources and attention—to the communities with high loss potential, to communities that may be incapable of adapting to the loss of significant percentages of their assets, or to a specific demographic or economic sector.

Information presented in this report will further the dialogue on reducing risk to tsunami hazards in Hawai‘i and help identify future preparedness, mitigation, recovery planning, and outreach activities within the coastal communities and economic sectors of the State of Hawaii. Follow-up studies to document community resilience would complement this report and provide the State of Hawaii with a more complete picture of community vulnerability to tsunamis. In addition, results of this study may also help public officials determine where site-specific risk assessments and more-detailed tsunami-inundation modeling efforts may be warranted to further understand the threats posed by tsunamis to coastal communities in Hawai‘i.

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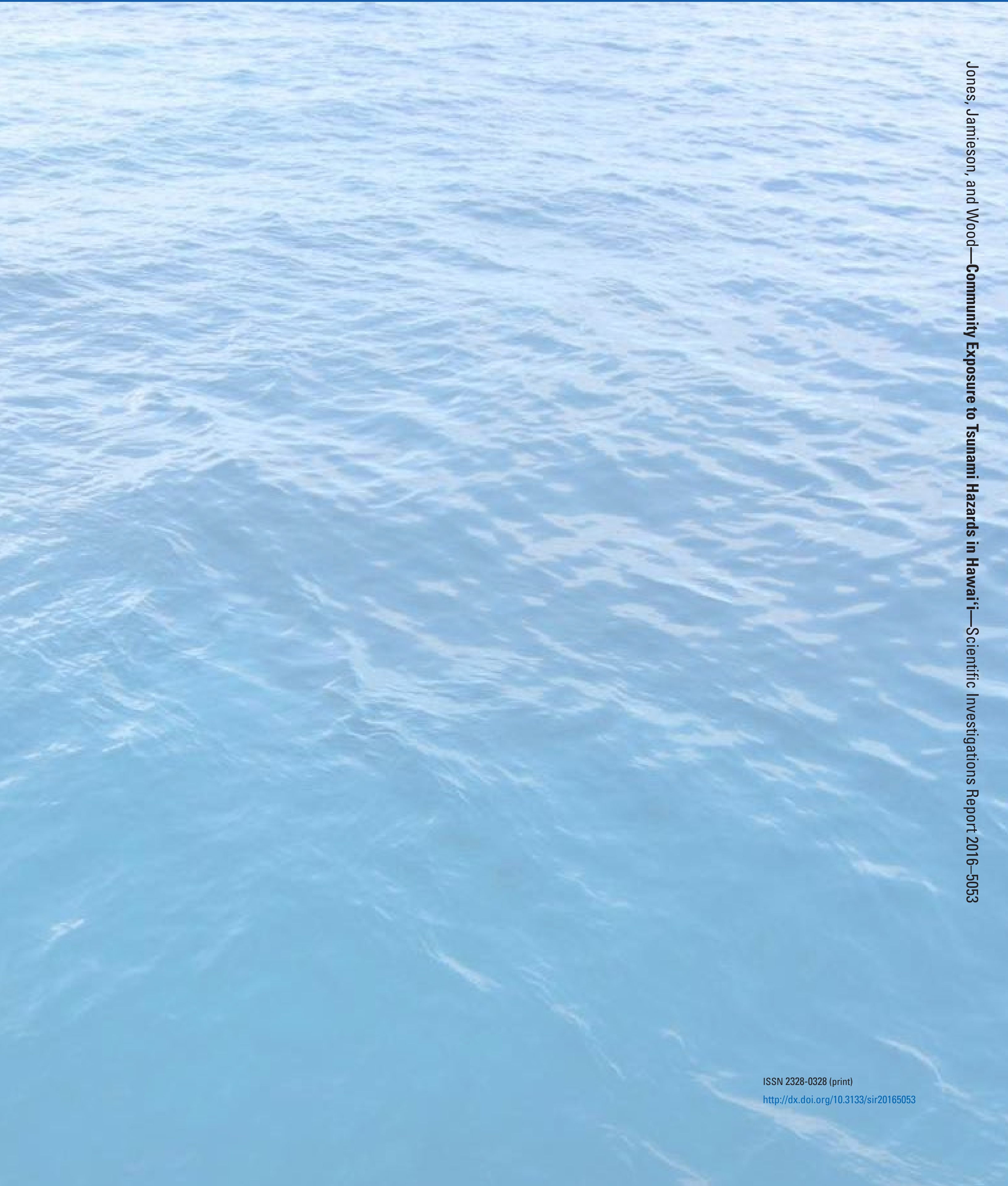

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