SEA-LEVEL RISE IN HAWAII: IMPLICATIONS FOR FUTURE SHORELINE LOCATIONS AND HAWAII COASTAL MANAGEMENT

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Introduction

Management of coastal development in Hawaii is based on the location of the certified shoreline, which is representative of the upper limit of marine inundation within the last several years. Though the certified shoreline location is significantly more variable than long-term erosion indicators, its migration will still follow the coastline's general trend. The long-term migration of Hawaii's coasts will be significantly controlled by rising sea level. However, land use decisions adjacent to the shoreline and the shape and nature of the nearshore environment are also important controls to coastal migration. Though each of the islands has experienced local sea-level rise over the course of the last century, there are still locations across the islands of Kauai, Oahu, and Maui, which show long-term accretion or anomalously high erosion rates relative to their regions. As a result, engineering rules of thumb such as the Brunn rule do not always predict coastal migration and beach profile equilibrium in Hawaii.

With coastlines facing all points of the compass rose, anthropogenic alteration of the coasts, complex coastal environments such as coral reefs, and the limited capacity to predict coastal change, Hawaii will require a more robust suite of proactive coastal management policies to weather future changes to its coastline. Continuing to use the current certified shoreline, adopting more stringent coastal setback rules similar to Kauai County, adding realistic sea-level rise components for all types of coastal planning, and developing regional beach management plans are some of the recommended adaptation strategies for Hawaii.

Certified Shoreline and Coastal Zone Management

Shoreline location in the Hawaiian archipelago is the foundation for coastal zone management regulations, jurisdictional demarcation, and resource management. Shoreline certification is the regulatory process that identifies and maps the landward limit of inundation along a section of coast. The shoreline, as identified in both statute (Hawaii Revised Statute Chapter 205A) and rule (Hawaii Administrative Rule Chapter 13-222) is the "upper reach of the wash of waves, at high tide, during the season of high surf, not to include tsunamis and storms, and usually evidenced by vegetation line or debris line." The meaning of this definition was clarified by the Hawaii Supreme Court in 2006, when they stated that the shoreline is the "highest wash of the highest wave," where highest means most landward, not highest elevation.

This one definition establishes the baseline for coastal setbacks, which effect development, subdivisions, and consolidations, and is also the referenced location for the landward limit of the State's submerged lands. Identification of the shoreline is based on recent evidence, and is typically a snapshot showing the landward most location of inundation for the previous several years, though is not an elaborate coastal analysis. Additionally, a certified shoreline is only valid for 12 months, further evidence of its temporary nature and the events it was intended to capture.

The ephemeral nature of a certified shoreline can create erroneous development practices in areas where land use decisions do not properly assess long-term trends and variability in the coastal environment. Additionally, areas with fixed shoreline setbacks may have structures threatened by coastal natural hazards early in their lifespan if their coastal erosion rates are high or there is high short-term variability in shoreline location. All of these coastal land use decisions and the resulting developments are potentially threatened by future sea-level rise. Even the more progressive county coastal zone setback and development regulations do not have the capacity to accommodate alterations in their calculated erosion rates, if they are beyond the variability of the current data.

Shoreline Controls Including Sea Level Rise

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The certified shoreline in Hawaii is the landward limit of inundation for the prior one to two years. Variability can be extreme in some areas when the coastal substrate, tidal extremes, and wave environment are highly dynamic. Though these factors provide the primary controls on inundation, there are numerous factors that play significant roles. Most controls on inundation can be segregated into several basic categories: Water Level, Wave Energy, and Coastal Landforms.

Water level is controlled by astronomical, meteorological, and oceanographic factors. Astronomical factors are primarily the gravitational attraction of the moon and sun, which produce the tides. Location on the planet, regional bathymetry, and local coastal morphology and shape provide key controls on the amplitude of the tidal range. Hawaii's coasts are subject to semi-diurnal microtides, of less than a meter in tidal range (Caldwell, *et al*, 2009). Meteorological controls on regional sea level include mesoscale eddies (Firing & Merrifield, 2004), anti-cyclonic surface currents that create local bulges in sea-level of up to 14 cm in elevation; storm surge; wave setup; and Ekman transport associated with winds and currents. Oceanographic controls include ocean currents, temperature, chemistry, and mass. Many of these factors contribute to the long-term rise of sea level and to regional variations in the rate and extent of sea-level rise. Though global average sea level is rising at a rate of ~3 mm/yr (Fletcher, 2009), locally sea-level rise ranges from rates as high as ~3.27 mm/yr at the Hilo tide gauge on the island of Hawaii to as low as ~1.50 mm/yr at the Honolulu tide gauge on the island of Oahu.

Wave energy in Hawaii (Vitousek and Fletcher, 2008) comes from four main sources: North Pacific Swell, Tradewind Waves, South Pacific Swell, and Kona Storm Waves. These inclement waves approach coastlines facing all points of the compass rose. Though wave energy for any given wave is related to its height and period, the total wave energy impacting a coastline is the combination of all waves reaching the coast at the same time. Thus multiple wave fronts, with different angles of attack, heights, and periods, will combine to potentially increase the extent of inundation.

Coastal landforms play a vital role in limiting both the wave energy reaching the coast, with the depth and breadth of the fringing reef (Vitousek, *et al*, 2008), and the extent of inundation, with the slope and substrate of the coast. Anthropogenic alterations to coastal landforms and sediment supply can have deleterious impacts (Rooney and Fletcher, 2005) to the coast's ability to respond to long-term or episodic changes. The relationship of these nearshore and sub-aerial landforms, combined with the effects of anthropogenic alterations, can create large variations in the extent of inundation across relatively short sections of coastline.

Typically, in Hawaii, the events that produce the highest extent of inundation on a regional level are a coincidence of high water levels and high wave energy, usually from multiple wave fronts (Caldwell, *et al*, 2009). These extreme inundation events are exacerbated in areas where the coastal dunes have been graded or the beaches sediment supply is diminished through artificial structures.

Shoreline and Long-Term Erosion and Accretion Trends

The majority of Hawaii's sandy coastlines have documented long-term erosion signals, with a significant portion of the eroding coasts showing accelerating erosion rates. Surprisingly perhaps, there is still a non-trivial percentage that has a long-term accretion signal (Coastal Geology Group website, 2010). These accreting coasts are of interest in that they contradict modern coastal engineering principals, such as the Brunn rule, which normally associate a landward migration of sandy shorelines under the influence of rising sea levels. Typically, these prograding coasts are assumed to have an excess of sediment, allowing them to maintain a healthy beach profile at higher elevations while extending the coastal plain seaward. Though these coasts are currently prograding, it is unknown how long the accretion will continue under rising sea levels. Many of these coastlines were located landward of the current coast during higher regional sea levels, so there is a distinct possibility that thresholds exist for specific environments to shift from accretional to erosional. Additionally, anthropogenic alterations of the coasts can reduce the sediment supply, causing a shift to erosion. The certified shoreline follows the general trend of the coastline, though its location is variable about the trend.

Recommended Strategies

With the silhouette of rising sea levels clearly on the horizon for the foreseeable future, it is imperative that coastal planners, regulatory agencies, and researchers focus their attention on the coming changes to the coastline. Several strategies are recommended, including improved coastal setback determinations and local beach management plans, developing land purchase programs, refining sea-level rise estimates and evaluating local risks and vulnerabilities, and incorporating future projections for demographic and development trends.

Currently, the County of Kauai has the most progressive coastal setback determinations in the State of Hawaii. They use the average annual coastal erosion rate, multiply it by 70 or 100 (70 years is the average lifespan of a coastal structure, and 100 years is used for stone or large structures), and add a 40-foot buffer. For coastlines that have static rates of erosion, this should adequately protect 50% of the structures, assuming that they are not remodeled in their existing footprint. For those areas where erosion is accelerating, or will accelerate in the lifetime of the structure, there may not be adequate setback to protect from erosion. For coasts that have highly variable shoreline locations, 40 feet may not be a sufficient buffer in the event of extreme erosion or inundation events. Additionally, as the shoreline migrates landward, so does the extent of all coastal natural hazards, placing the development increasingly in higher risk areas. There is only a standard 40-foot buffer for accreting shorelines.

Though these setback determinations are by far the most accommodating for the effects of coastal erosion, and go the farthest to protect individual and community health, welfare, and safety, acknowledging and planning for future rise in sea level would provide the most benefit. This could be accomplished by local beach and dune management plans that give a more careful consideration to the existing and future conditions of the coastline. In addition, the existing coastal erosion data contains information on the inherent variability of each section of coast; so improved buffers could be tailored for each area of the beach. Currently, a beach management plan is being developed for Kailua Beach, an accreting beach on Oahu, Hawaii. For prograding coasts, specific planning strategies should be developed to reduce individual and community coastal hazard exposure when accretion shifts to erosion. All of these could work in concert with the existing shoreline location methodology, incorporating the long-term planning components into the setback determinations.

At some point eroding coasts begin to threaten human development and a conflict between preserving the coastal resource versus preserving the developed coastal properties will emerge. One strategy is to begin creating local land trusts for each region or beach and identifying alignments between private and public land trusts for future land purchases. Creating land purchase programs that utilize tools such as willing seller buy out, condemnation, and reverse mortgages can create additional buffer space between development and migrating coastal hazards, and is a good fit for local beach and dune management plans.

Lastly, improved understanding and planning for local sea-level rise impacts are a necessity for reducing future individual and community exposure to coastal natural hazards. Research funding should be allocated toward establishing local sea-level rise curves that can be endorsed by State and county governments, agencies, academia, and public partners. These sea-level rise curves should be the baseline data for risk and vulnerability analysis for future inundation, flooding, storm wave, tsunami, and erosion hazards. Combined with projections of demographic and development trends, it will allow agencies to better allocate funding and resources for new projects and maintenance, as well as improve decision making for planning and permitting along the coast.

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