BRINGING SEA-LEVEL RISE INTO LONG RANGE PLANNING CONSIDERATIONS ON MAUI, HAWAII

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Abstract: Maui's coastal lands, along with many others worldwide, are under tremendous pressure from expanding development and accelerating coastal erosion. While it may be perceived by the public that the lands most at risk from sea-level rise are those immediately bordering the coastline, the threat to low-lying areas from a rising water table inland of the coast may also be great. Maui planning officials have begun to recognize that regardless of the uncertainty over projected rates of sea-level rise, threats associated with rising sea level should be identified and mitigated through a combination of modeling, mapping, and direct observation. This paper provides a review of current sea-level rise science and describes the scientific and management approaches being undertaken by Maui County to better understand potential risks associated with rising seas and account for these projections in long-range planning.

INTRODUCTION

In 2003, Maui County became the first county in the state of Hawaii to adopt a science-based approach to determining construction setbacks on coastal properties (Norcross-Nu'u and Abbott 2005). High-resolution annual erosion rate data spaced at

20 m intervals, produced by the University of Hawaii (UH) (Fletcher *et al.* 2003), are used to calculate the 50 year erosion-based setback plus a "25-foot" buffer. Following Maui's lead, the counties of Kauai and Honolulu are acquiring erosion rate data from UH to apply towards improving understanding of shoreline changes adjacent to permitted activities. Amendments to Kauai's setback rules have now been enacted into law requiring a 70 year erosion multiplier plus a "40 foot" buffer.

The use of erosion rate data and science-based setback rules has greatly improved the management of Maui's coastal lands (Norcross-Nu'u and Abbott 2005). Recently, however, the emerging concern of sea-level rise and the numerous associated implications of this issue have prompted Maui County to pursue further scientific and social/cultural studies to better anticipate sea-level related impacts and plan for their mitigation. As with improved setback rules resulting from erosion rate data, the intent of these studies is to provide a basis for developing new guidelines and regulations guiding coastal zone development.

EROSION DATA

The University of Hawaii Shoreline Study provides shoreline change data to the public and government partners to assist in decision-making in the coastal zone. Shorelines are highly variable environments characterized by a number of natural hazards. These include: tsunami, storm surge, high winds, coastal erosion, sea-level rise, and high wave overtopping. Building on eroding coasts increases vulnerability to all these hazards. A direct step to mitigating the impact of coastal hazards is to exercise avoidance (Hwang, 2005) by mapping high hazard zones designed, in part, on data such as historical shoreline movements.

A significant additional benefit to shoreline change data is to define zones of avoidance for the purpose of environmental conservation. When erosion threatens the built environment a common reaction is to armor the shoreline with a seawall or revetment (Fletcher et *al.*, 1997). Armoring may impound sand thereby impacting the sediment budget of a beach and exacerbating the erosion. Shoreline armoring also increases wave turbulence and reflection. It is common to find that the construction of one seawall on a beach leads to proliferation of additional seawalls. Armoring a chronically eroding coast leads to beach loss (Fletcher, et *al.*, 1997). In an era of accelerating sea-level rise (Church and White, 2006) the threat of chronic erosion and beach loss is growing and the use of shoreline data becomes a potentially significant coastal management tool in the effort to conserve beaches for future generations.

A website, http://www.soest.hawaii.edu/asp/coasts/index.asp, provides the UH data in the form of sets of historical maps and orthorectified air photo mosaics, modern vertical and oblique air photos, and maps depicting rates of shoreline change spaced every 20 m on the sandy beaches of Maui, Oahu, and Kauai.

THE PROBLEM OF RISING SEAS

Sea-Level Rise

Church and White (2006) document 20th Century acceleration in the rate of global sea-level rise. Studies (i.e., Emery and Aubrey, 1991) using tide gage data over the past 100 to 120 years generally propose a global rate between 1.0 and 2.0 mm/yr during the 20th Century compared today with satellite-based estimates exceeding 3.0 mm/yr (i.e., Cazenave and Nerem, 2004) and as high as ~3.7 mm/yr over the period 1999-2004 (http://membrane.com/sidd/sealevel.html). Because significant short-term variability in sea level can occur, extracting the global mean sea level information is complex. Also, the satellite data has a much shorter record than tidal gages, which have been found to require years of operation to extract trends.

Global sea-level rise is assumed to be caused by two principal sources: melting of the ice reservoirs on Greenland and Antarctica, as well as various alpine glaciers and ice sheets; and, thermal expansion of the upper ocean water column due to heating of the atmosphere.

Glaciers in southern Greenland are flowing 30 to 210 percent faster then they were ten years ago and the overall amount of ice discharged into the sea increased from 90 km^3 in 1996 to 224 km^3 in 2005, up 250 percent (BBC News, 2006). Greenland's contribution to average sea rise increased from 0.23 mm/year in 1996 to 0.57 mm/year in 2005, and melting accounts for between 20 and 38 percent of the observed yearly global sea level rise (Hansen et *al*., 2007). Notably, two-thirds of Greenland's contribution (0.38 mm/yr) is due to glacier dynamics (chunks of ice breaking off and melting), and one-third (0.19 mm/yr) is from direct melting of ice. As glacier acceleration and melting continue to spread northward, Greenland's contribution to global sea-level rise will continue to increase in coming years. In 2007 the number of melting days on Greenland set a new record (AGU, 2007).

Antarctica, potentially the largest trigger of global sea-level rise, presents a more enigmatic picture than Greenland. On average the globe has warmed about 1.1°F in the 50 years ending in 2005, while Antarctica has cooled about 10°C in October-November since 1985. Why has the air above Antarctica cooled over this period? The Antarctic ozone hole opened up about the same time as cooling began. Ozone absorbs UV radiation heating the atmosphere around it and absence of ozone has led to cooling in the stratosphere. Importantly, Antarctica is dominated by a strong band of westerly winds that tend to isolate the continent, keeping global warming from influencing Antarctic weather, and allowing the surface to cool. However, the Antarctic Peninsula lies at the outer reach of the vortex allowing the peninsula to warm significantly over the same time period (http://www.jsg.utexas.edu/walse/). Notably, the circumpolar vortex has strengthened in the past 25-30 years, forming an even stronger barrier than usual. However, climate modelers predict the circumpolar vortex will weaken as the ozone hole diminishes in coming decades. This will allow the Antarctic to warm with the rest of the globe, a process that has already begun. In their latest study (September 20, 2007) NASA researchers have confirmed that Antarctic snow is melting farther inland from the coast over time, melting at higher altitudes than ever and increasingly melting on Antarctica's largest ice shelf, the Ross Ice Shelf.

On the Antarctic Peninsula, the rate of atmospheric warming has reached 5 times the global average. Since 1945, the Antarctic Peninsula has experienced a warming of about 2.5° C and the annual melt season has increased by 2 to 3 weeks in just the past

20 years. Cook et *al*. (2005) document that 87 percent of glaciers on the Antarctic Peninsula are now retreating in a pattern that is spreading to the south annually. In the coastal region the 1,994 km^2 Larsen A ice shelf disintegrated suddenly in January 1995, and after 400 years of relative stability, nearly 2,978 km^2 of the Larson B and Wilkins ice shelves collapsed between March 1998 and March 1999. Additionally, the Southern Ocean surrounding the Antarctic continent has experienced a strong warming trend. Measurements from data recorders in waters around Antarctica show a (0.17° C) rise in ocean temperatures between the 1950's and the 1980's.

Thermal warming of the ocean surface is thought to account for about half of the current trend of global sea-level rise, while ice melt accounts for about 35 percent. The missing components are an indication of the high degree of uncertainty in the science of sea-level prediction. One way to circumvent this uncertainty is to model sea-level change on the basis of its relationship to atmospheric warming using historical records. Rahmstorf (2007) compared the record of global surface warming over the past 120 years and related it to the record of sea-level change over the same period. He found that the relationship predicted a global sea-level rise of 0.5 to 1.4 m by the end of this century under climate change scenarios projected by the IPCC (2007). In another paper, Rahmstorf et *al*. (2007) compared projections of climate change made in 1990 by the IPCC and found that observations in 2005 matched the upper limit of their projections.

A recent study in Nature (Rohling, et *al*., 2008) finds that average rates of sea-level rise of 1.6 m per century occurred during the last interglacial period. They conclude that because global temperatures during the last interglacial were comparable to modern projections of climate change this century under the influence of anthropogenic greenhouse-gas emissions, these rates of sea-level rise are relevant to the ongoing debate about high versus low rates of rise this century.

Coastal Erosion

As sea-level rises, shorelines experiencing a deficiency in sediment, or those at equilibrium with sediment availability, are likely to experience erosion (Bruun, 1983). As with most coastal communities nationwide, erosion has taken its toll on Maui's shores with over 8 km of beach lost since 1949 and 4.8 km of roadways threatened within the next 20 years (Fletcher et *al.* 2003). With an average rate of retreat of 0.3 m/yr for Maui's sandy shorelines and a recorded rise in local sea level averaging 2-2.5 mm/yr over the last half-century, the relationship between sea-level rise and sandy shoreline retreat has been, on average, 1:150 to 1:120. With global sea-level rise observed to have almost doubled over the last decade (Church and White 2006), the likelihood exists that erosion rates will also accelerate. For this reason, Maui County has committed to updating the erosion rate data at intervals of no longer than every 10 years. Given the inevitability of a time lag for data sets to reflect increased rates of erosion, Maui's 50-year construction setback may significantly underestimate the true 50-year safety margin under current and future erosional trends.

Improvements in the ability to model shoreline changes using the entire dataset for a littoral cell, and not only the data along a single transect, promise that the next update of Maui erosion trends will be characterized by reduced uncertainty, increased statistical significance, and improved ability to predict future shoreline positions (Genz et al., 2007; Frazer et *al*., in press, Genz et *al*., in press). It is vital to continually refine and improve models that provide statistically significant erosion hazard predictions. To further the goal of providing reliable erosion study results, UH researchers have developed the PX and PXT methods for calculating shoreline erosion rates. Recognition of a number of problems with the single transect (ST) method spurred this research. ST uses historical shoreline positions along a shore normal transect to calculate rates of shoreline change. Each transect calculates change independent of neighboring transects. This is unparsimonious. That is, it tends to over-fit the data by using more mathematical parameters than necessary to model the change at a beach because it assumes adjacent transects are independent. In theory, adjacent transects should tell a similar story about the change occurring at a beach because beach positions share sand along the shore. Instead, ST treats the beach as if it were a set of 20 m wide blocks that move independent of each other. ST also produces many rates that are not statistically significant, i.e., the rates are statistically indistinguishable from a rate of 0.0 m/yr. Importantly, short-term fluctuations in the beach due to seasonal and tidal changes (high complexity) and a lack of historical shoreline data (poor sampling) can mask long-term trends when attempting to calculate a change rate from a single transect.

To address these problems, UH has developed the PX methods (Polynomial in distance X) for calculating shoreline change rates to produce more meaningful, i.e., statistically significant and defensible, shoreline change rates. PX combines data from all transects along a beach and models shoreline change for the entire length of beach using polynomial regression. The resulting shoreline change models produce rates that vary continuously in the alongshore direction. These models employ information from the entire beach to model the rate at any one location. An advancement of the PX method, called PXT (Polynomial in distance X and Time) models shoreline change rates along the shore and with time. For sufficient data, PXT can find acceleration in the shoreline change rate – an important advance, as most beaches do not erode or accrete at a constant (linear) rate. See Romine et *al*., this volume, for applications of this methodology.

Inland Flooding

At least one community in Hawaii, Mapunapuna, located 2 km inland from the nearest shoreline, already experiences a debilitating inundation under extreme high tide conditions. During heavy rainfall events or high spring-tides, storm drains tied directly to the ocean back up with seawater, flooding streets with a mixture of ocean water and run-off forming a unique version of an urban estuary. Having entered through the seaward mouth of storm drain pipes, marine species of fish, and even hammer head shark pups are observed in these 1 m deep pools in the midst of the industrial region. In low-lying coastal areas on Maui, salt rinds and splash marks are seen surrounding urban storm drains over 200 m inland from the coast when high tides coincide with high surf events. As these harbingers indicate, inundation is likely to occur in low-lying coastal communities with increasing frequency as sea level continues to rise. The critical issue here is the hazard of marine flooding located in low-lying areas some distance from the shoreline.

Rising Water Table

Within coming decades, an increase in the elevation of the water table, associated with rising sea levels, will threaten low-lying lands on Hawaii coastal plains in several ways. Even before rising groundwater breaks the surface, aquifer contamination will occur, and subsurface drainage infrastructure such as leach fields, perforated pipes and retention basins will lose functionality as they are submerged by groundwater. While coastal groundwater is not used for human consumption, a significant portion of Maui's treated wastewater is disposed of via injection wells, and the potential impacts of a rising water table on the injection wells have not been considered, nor has the possibility of contaminated plumes making their way to the surface with the rising water table as it breaches the ground surface.

These impacts will not be limited to areas immediately adjacent to the ocean. Through the evaluation of methods to estimate hydraulic properties within the coastal plain on Maui, Rotzoll (2007) found that groundwater fluctuations as far as 5 km inland are tied to fluctuations in sea level. Water table levels were found to correlate with tide gauge data as well as with wave setup data from high surf events. For both tides and setup, propagation of the signal through the aquifer showed exponentially decreasing amplitudes and linearly increasing time lags. This research demonstrates that sea-level processes are directly connected to the position of the water table – there will be no time lag between sea-level rise and water-table rise.

MANAGEMENT APPROACHES

Currently, coastal erosion and management issues arise and are dealt with on a case-by-case, property-by-property basis. The outcome of this approach can be seen on most of Maui's sandy shorelines as a highly inconsistent patchwork of various erosion mitigation methods. There is a high degree of frustration among community members as they watch their favorite beaches disappear piece by piece, and as access to beaches becomes increasingly limited. Hazards such as sea-level rise and storm damage vulnerability are not included in the development review process and lead to increased vulnerability for coastal resources as well as coastal structures and their inhabitants.

Sea-level Rise Inundation Models

Much of Maui's critical infrastructure is located immediately adjacent to the coast, including the Central Maui Wastewater Treatment Facility, numerous state and county highways, and one of Maui's two electricity generation facilities (Figure 1). In 2004, analyses of options to provide needed improvements to the wastewater facility evaluated tsunami inundation potential, but did not consider the threat of rising sea levels. Because of recent advances in understanding potential threats related to sea-level rise, Maui County is starting to recognize the importance of identifying areas at risk of inundation for long range planning purposes. In early 2008, the Maui County General Plan is undergoing update, and advisory committees will be discussing designated sites for relocation of public infrastructure currently located in high-risk areas.

Fig. 1. Existing and proposed infrastructure threatened with rising sea level in Kahului, Maui

UH researchers have begun producing high resolution, lidar-based sea-level rise inundation maps for densely populated areas such as Waikiki and Honolulu. Despite the fact that impacts may not yet be seen for decades, the dramatic nature of the images depicting 1 m sea-level rise under high tide and heavy rainfall have prompted Maui officials to request inundation modeling for this island as well. Digital elevation models based on Lidar data have elevation accuracy in the range 0.25 – 0. 5 m, hence inundation maps serve as precise planning tools through the identification of specific areas where planning for inundation is prudent.

As an example, in a recent development application, sea-level rise was taken into consideration for the first time on Maui. The proposed project is a scrap metal and auto recycling facility to be located three blocks inland in the Kahului industrial area, and adjacent to a federally protected wetland (Figure 1). The drainage infrastructure, including underground retention basins, perforated drainage pipes and a leach field, was designed with multiple redundancies to significantly reduce the risk of spills and contamination to the wetland.

Upon closer analysis, it could be seen that the drainage infrastructure was designed to be located immediately above the existing water table. Additionally, preliminary inundation maps indicated this to be a high-risk area due to its low elevation and proximity to the wetland. As a result, the possibility of failure of the drainage infrastructure within the next several decades was high, particularly in light of the previously mentioned relationship between ground water levels and sea surface levels (Rotzoll 2007). Despite the fact that specific policy or regulations regarding sea-level rise do not yet exist, the developers agreed to raise the overall grade of the property by up to 0.6 m to accommodate the potential for rising ground water levels.

Storm Wave Inundation Models

Recent unpublished studies by UH model the relationship between inland incursions of storm waves and rising sea-levels. Preliminary results for the island of Oahu show significant increases in the area of land vulnerable to storm damage with a sea-level rise of less than 1m. As with the sea-level rise inundation models, storm wave inundation maps are critical for long range planning purposes, and will be created for Maui as part of the project described in the following subsection.

Shoreline Prioritization and Management Model

The Maui County Department of Planning is working under a collaborative grant with UH and the Maui Coastal Land Trust to develop a prioritization model for coastal resource management on Maui. The goal of this project is to combine scientific data with social/cultural input to identify acceptable approaches to shoreline management for individual shoreline segments, or littoral cells.

The scientific component will include data layers illustrating hazard levels for flooding, coastal erosion, sea-level rise and storm damage. The social/cultural component will include community input regarding the relative value of individual shoreline areas for cultural, recreational and economic pursuits. The overlay of all these factors will be used to establish priority areas for protection of the coastal lands, and priority areas for preservation of sandy beach resources.

Along with the priority outcomes, an analysis of allowable shore protection strategies will be produced for each shoreline segment. For regions where protection of coastal lands is a priority, such as areas with a high density of resort development, hard structures such as seawalls or revetments may be allowed. For areas where the priority for protection of beaches and coastal lands is roughly equal, such as areas with moderate development levels and healthy beaches, conditions may be established allowing soft forms of shore protection such as beach replenishment, possibly in conjunction with groins. For areas where protection of beach resources is a priority, such as pristine beach areas with limited or no existing development, conditions may be established prohibiting the use of any form of shore protection.

The model will be used to provide guidance to planners and decision makers, and for potential adoption of improved coastal management regulations. The anticipated outcome is to be able to better manage coastal resources through a comprehensive littoral cell-based approach rather than an ad-hoc, property-by-property approach.

Beach Management Plan

The Beach Management Plan for Maui (Mullane and Suzuki 1997) is a document intended to provide basic coastal processes educational information and recommendations for steps towards improving the management of Maui's coastal resources. A 2007 update of the plan (Norcross-Nu'u, Fletcher and Abbott *in review*) makes specific recommendations for identifying infrastructure, communities and developments at risk of sea-level rise and for the development of long-term plans to address the associated issues of a rising water table. Emphasis in the Beach Management Plan is also placed on the development of littoral-cell based coastal zone management as a more effective means of addressing coastal hazards and resource protection. While the first edition of the plan was adopted by the Maui County Council as a guiding policy document, the newly-revised second edition will go through the more rigorous process of adoption as an ordinance, so that it may be enforceable as a law.

CONCLUSION

Global sea-level rise is an ongoing and accelerating process with high likelihood of becoming a serious threat to coastal environments and development in coming decades. Recognizing that sea-level rise will cause significant changes to Maui's landscape in coming decades was a promising first step for Maui County governing officials. Assembling the framework for achieving an understanding of what these impacts may be has been an encouraging second step. The development of long-range plans incorporating community input, designs for high-hazard areas and resource protection objectives, is a challenging but achievable goal. Maui County hopes to be a leader both statewide and nationwide in addressing these emerging and critical issues.

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