A PRACTICAL APPROACH TO MAPPING EXTREME WAVE INUNDATION: CONSEQUENCES OF SEA-LEVEL RISE AND COASTAL EROSION.

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Abstract: This paper outlines a practical approach to mapping extreme wave inundation and the influence of sea-level rise and coastal erosion. The concept is presented for windward Oahu, Hawai'i. Statistical models of extreme wave height and recently developed empirical runup equations (Stockdon et al. 2006) provide extreme runup levels, which overlay geo-referenced aerial photos and high-resolution LIDAR elevation models. The alongshore wave height variability that contributes to alongshore runup variability is accounted for by the SWAN spectral wave model. Sea level is found to play a significant role in future inundation levels.

INTRODUCTION

Sea-level rise of 0.5-1.4 m (Rahmstorf 2007) is expected by the end of the 21st century. Previous work on the long-term impacts of sea-level rise has focused on flooding of low-lying coasts. Raising the static water level on a digital elevation model (i.e., passive flooding) displays the dramatic long-term effects of sea-level rise. The short-term effects of sea-level rise include increased frequency and severity of wave overtopping and wave attack, resulting in coastal inundation, erosion and morphological changes. The nature of these short-term impacts on coastal communities is still undetermined and may pose significant risk.

Managing the risk of coastal flooding is a balancing act between the base elevations of nearshore infrastructure and base flood elevations. Flood Insurance Rate Maps (FIRMs) are created to manage development siting.

To evaluate the risk of coastal flooding to nearshore communities, we use a practical approach to map extreme wave inundation and the influence of sea-level rise.

These methods are applied to a case study of Waimanalo, Hawai‘i, a low-lying coastal community protected by a fringing reef on the East Coast of Oahu, Figure 1.

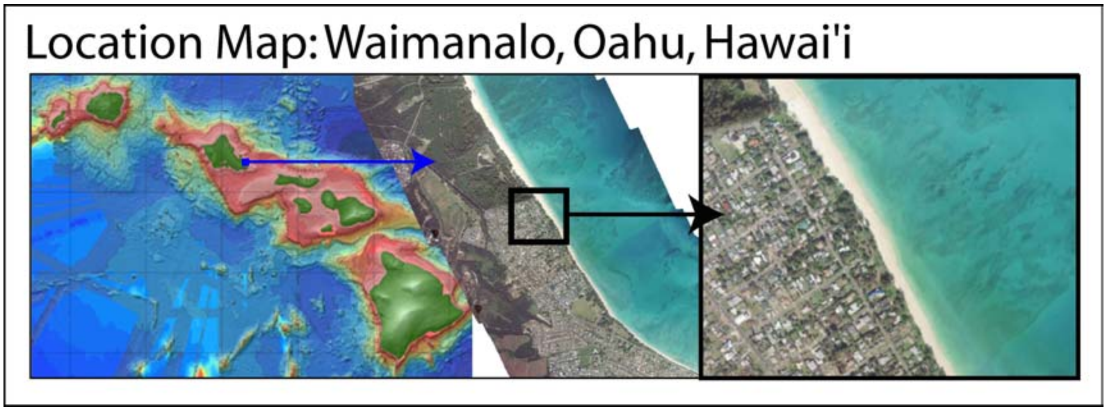

Figure 1 - Location Map of case study: Waimanalo, Oahu, Hawai'i

METHODS

We employ 3 approaches to map extreme runup and the influence of sea-level rise.

1) The 1st (*standard*) approach:
    a) Determine recurring wave height statistics.
    b) Translate the wave height to wave runup using empirical equations.
    c) Map the runup elevation spatially on a digital elevation model.
    d) Apply sea-level rise to assess risk.

2) The 2nd approach (*includes historical erosion analysis*):
    a) Determine recurring wave height statistics.
    b) Translate the wave height to wave runup using empirical equations.
    c) Map the runup elevation spatially on a digital elevation model.
    d) Apply sea-level rise and *an erosion rate* to assess risk.

3) The 3rd approach (*includes nearshore wave transformation*):
    a) Determine recurring wave height statistics.
    b) Model the nearshore wave transformation using the SWAN model.
    c) Translate the wave height to wave runup using empirical equations.
    d) Map the runup elevation spatially on a digital elevation model.
    e) Apply sea-level rise to assess risk.

As mentioned previously, managing the risk of coastal flooding is a balancing act between infrastructure elevations and total runup elevations. The key to evaluating the potential risk is estimating both of these elevations as accurately as possible.

To determine infrastructure and ground elevations, we use high-resolution aerial LIDAR surveys conducted by the NOAA Coastal Services Center Coastal Remote Sensing

Program in winter 2005, with 95% of the data having less than 31.8 cm horizontal error (Circular Error Envelope – CE_{95}) and a vertical accuracy of 1 cm.

The evaluation of runup elevations requires a statistical approach. Our approach follows Ruggiero et. al. (2001) who estimated extreme water levels (sum of extreme runup and extreme tides) to determine the frequency of dune impact and resulting morphology of the Oregon coast.

In this study, NOAA's wave-monitoring buoy (NDBC buoy 51001) provides data for statistical analyses of maximum return wave heights for Waimanalo. The Generalized Extreme Value (GEV) distribution gives the relationship between wave height and return period. The maximum return runup elevations are then derived from empirical relationships to the maximum return wave heights. In this approach, we apply the maximum return runup elevations at the Mean Higher High Water (MHHW) mark. Consideration of the joint probability of high waves and high tides may improve the total water level prediction; however, it is left to future work.

Our approach to determining the total runup juncture on a beach profile is analogous to FEMA's approach to determining FIRMs using their computer code RUNUP 2.0. Several shore-normal transects in the form of rectangular grid lines (5 m resolution) are cast on the shoreline of interest, and the analysis is performed on an individual transect basis. Beach profiles at each shore-normal grid line are extracted from high-resolution LIDAR elevation models (Figure 2). The LIDAR elevation model may be quite irregular or noisy, requiring smoothing of the elevation model or the alongshore inundation contours.

In approach #2, a historical shoreline analysis provides an erosion rate that is applied to the zero elevation contour. The historical shoreline analysis was performed using digitized shorelines extracted from historical aerial photographs and USGS T-sheets, following the method of Fletcher et. al. (2003). Annual Erosion Hazard Rates (AEHR) are determined using basis function methods following Frazer et. al. (accepted).

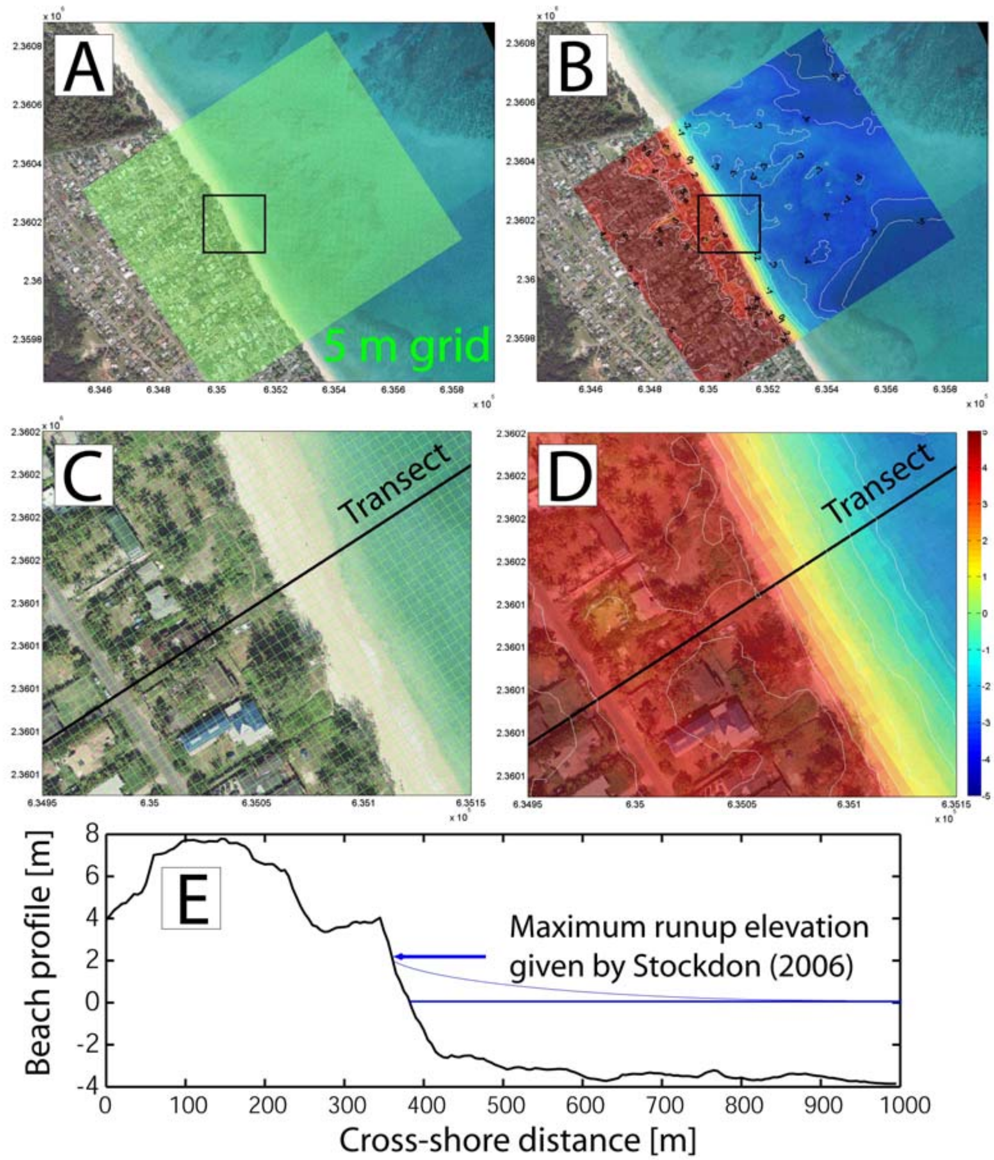

Figure 2 – The Waimanalo runup grid (A) and elevation (B) from a broad view. Beach profiles (E) are extracted from transects along shore-normal grid lines (C) where the elevation is given by a LIDAR survey (D).

In approach #3, a third generation spectral wave model, SWAN (Simulating WAves Nearshore – Booij et. al. 1999; Ris et. al. 1999), is run on nested grids (a 25 m grid extending to deep water and the 5 m nearshore grid – shown in Figure 3). The model is forced with parametric wave boundary conditions determined by the GEV distribution. Using SWAN, the spatial variability of the wave heights due to nearshore processes (including shoaling, refraction, convergence, divergence and breaking) can be resolved in the runup model.

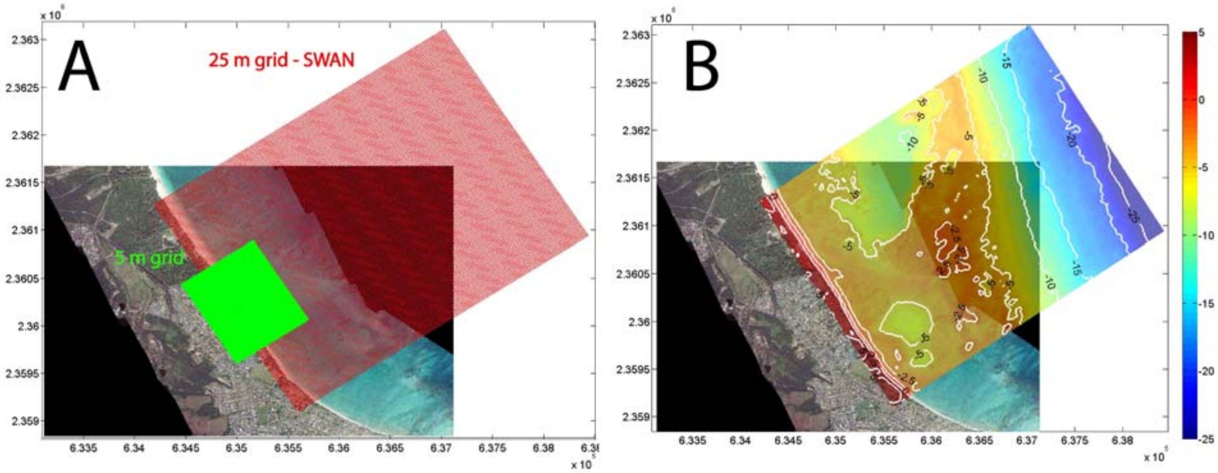

Figure 3 - A: the nearshore (5 m) and regional (25 m) SWAN grids for Waimanalo and B: the bathymetry

Once the return runup elevation and its spatial location is found for each grid line, the elevation model may be subject to static sea-level rise. The potential for increased flooding can be evaluated by observing the inland extension of the flooding contours.

RESULTS

Extreme wave statistics

Introduced by Jenkinson (1955), the Generalized Extreme Value (GEV) distribution uses Gumbel (type I), Frechet (type II), and Weibull (type III) distributions for different values of the shape parameter, $\kappa = 0$, $\kappa < 0$, $\kappa > 0$ respectively. Iterative maximum-likelihood estimates (MLE) fit the observed data to find the best estimates of the shape (κ), scale (σ) and location (μ) parameters of the GEV cumulative distribution function, $F(x)$, given by:

$$F(x) = \exp\left\{ -\left[1 + \kappa \left(\frac{x-\mu}{\sigma} \right) \right]^{-\frac{1}{\kappa}} \right\} \qquad \text{for } \kappa \neq 0$$

$$\exp\left\{ -\exp\left[-\frac{(x-\mu)}{\sigma} \right] \right\} \qquad \text{for } \kappa = 0$$

Based on given probability distributions and the return period probability equation $p_{T_R} = 1 - \frac{r.i.}{T_R}$, wave height for a return period of interest is found. Northeast swell poses the greatest hazard to Waimanalo. The largest wave heights in Hawai‘i are experienced during northwest and north swell. Thus, in the recurring wave height analysis, buoy data is windowed to northeast swell directions (35-75^{o}). The relationship between wave height and return period for Waimanalo is shown in Figure 4.

Extreme Runup

Empirical equations give runup elevation in both RUNUP 2.0 and our approach. RUNUP 2.0 uses different equations for different shorelines (sandy, riprap and impermeable), based on the surf similarity parameter: $\xi = \tan\theta / (H_o / L_o)^{1/2}$, where $\tan\theta$ is the beach slope, H_o is the deep-water significant wave height, and L_o is the deep-water wavelength. Our approach uses a recently developed equation (Stockdon et. al. 2006) for the 2% exceedance runup:

$$R_{2\%} = \ <\eta> + S$$

$$R_{2\%} = 1.1\left(0.35\beta_f\left(H_oL_o\right)^{1/2} + \frac{\left[H_oL_o\left(0.563\beta_f^2 + 0.004\right)\right]^{1/2}}{2}\right)$$

which similarly gives runup as a function of beach slope (foreshore slope β_f), deep-water wave height $\left(H_o\right)$, and deep-water wavelength $\left(L_o\right)$. We use the Stockdon formula because it is complete: it formulates runup as the sum of setup, $<\eta>$, and swash, S, due to both incident and infragravity energy. The relationship was derived from 10 datasets primarily from the continental US. To facilitate the comparison of each dataset, Stockdon computed reverse shoaling of wave heights measured in intermediate depths (~8 m) to back calculate the deep-water wave height. Reverse shoaling (using linear wave theory and assuming shore normal approach) is computed by dividing the nearshore wave height by the shoaling coefficient, $K_s = \sqrt{\dfrac{C_g(\text{nearshore})}{C_g(\text{deep water})}}$.

The previous relationship of wave height vs. return period is translated into runup vs. return period (shown in Figure 4), assuming a representative wave period of 16 sec. and a beach slope 1/24 (determined from a survey of Waimanalo).

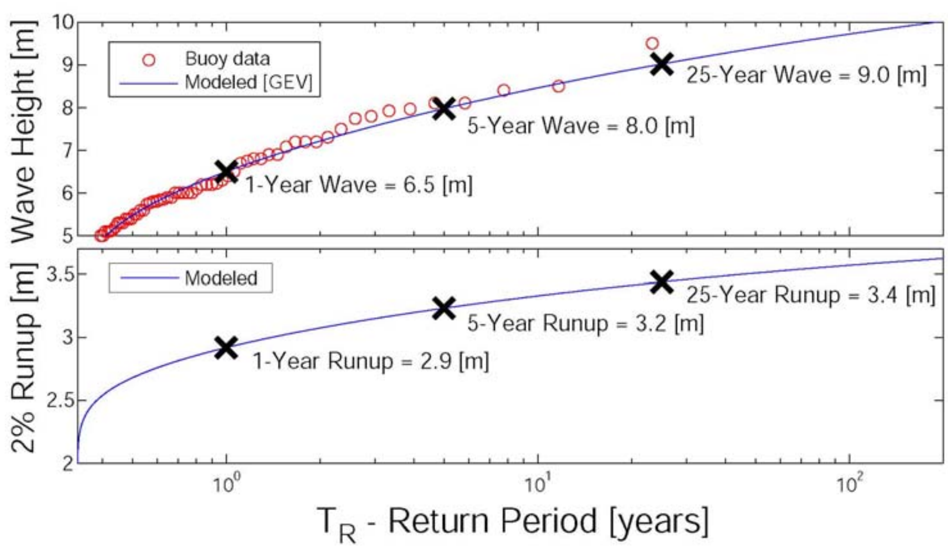

Figure 4 - Return significant wave height [m] and return period [years] for Waimanalo for the northeast swell window 75-35^o (Top) and corresponding return runup elevation [m] and return period [years] (Bottom) given by the Stockdon (2006) empirical runup relation using a nominal wave period of 16 sec. and a beach slope 1/24.

Mapping Extreme Runup (Approach #1)

From the known total runup level elevations, we can estimate the inundation contours for each return period and their inland migration due to sea-level rise (shown in Figure 5). It is important to keep in mind that approach #1 has no runup elevation variability. The inundation variability is only a function of the beach topography. The standard approach can be extended to account for runup variability as a function of a changing beach slope in the alongshore direction. However, when simply using the deep-water wave height in an empirical equation, the runup elevation is uniform in the alongshore direction. Using a wave transformation model will resolve this variability.

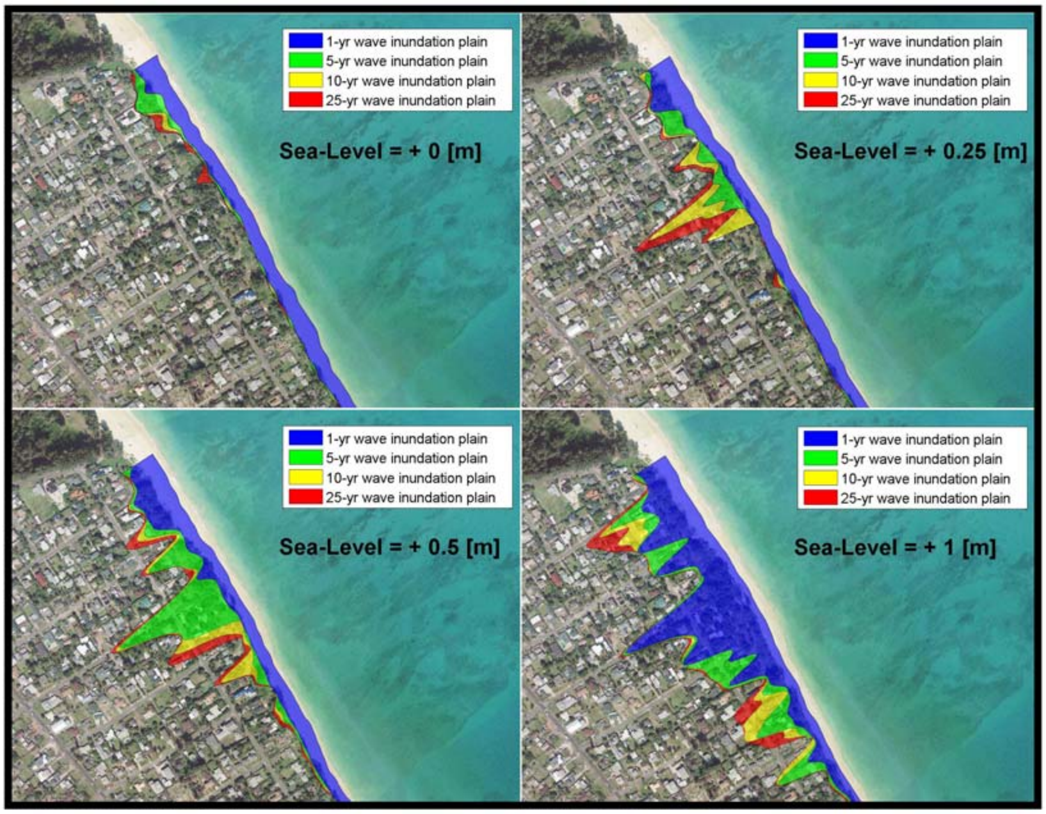

Figure 5 - Illustrating approach #1 - inundation contours for different scenarios of sea-level rise (0, +0.25, +0.5 ,+1.0 m).

Mapping Extreme Runup and shoreline change (Approach #2)

Depending on the dynamics of the shoreline, the inland migration of the return inundation levels rise may be considerably slower or be overtaken by recession of the shoreline due to erosional processes. In such a case, the erosion hazard will be greater than the inundation hazard to structures close to the coast. Waimanalo is not likely to have a significant erosion hazard, as it experiences very mild shoreline change rates (~1m/year accretion – 1m/year erosion). The case illustrated in Figure 6, shows the same inundation lines in approach #1 with a constant erosion rate of 0.6 m/yr to all transects.

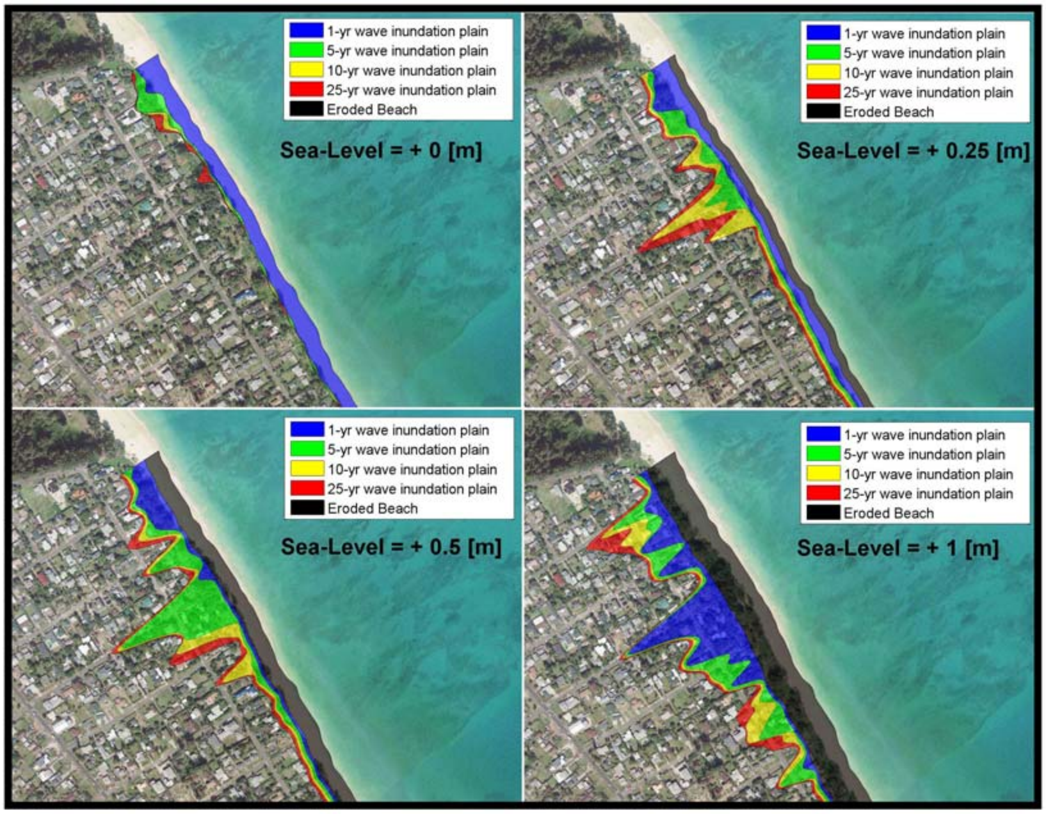

Figure 6 - Illustrating approach #2 - inundation contours for different scenarios of sea-level rise [0 (at present time), +0.25 (2025), +0.5 (2050), +1.0 m (2100)], and an eroded beach contour from a constant erosion rate of 0.6 m/yr.

Mapping Extreme Runup and nearshore wave processes (Approach #3)

Waimanalo is fronted by a fringing reef that dissipates a significant amount of energy during large swell events. SWAN accounts for the dissipation over the fringing reef due to friction and breaking. Default parameters of friction (JONSWAP coefficient 0.067 m^2/s^{-3}) and breaking parameters (α=1.0 & γ=0.85) are used.

The use of SWAN and reverse shoaling from intermediate depths on the reef (10, 15, 20 m) significantly reduces the projected wave heights and runup levels relative to the deep-water wave heights and runup levels. These results are illustrated in Figure 7 and quantified in Table 1.

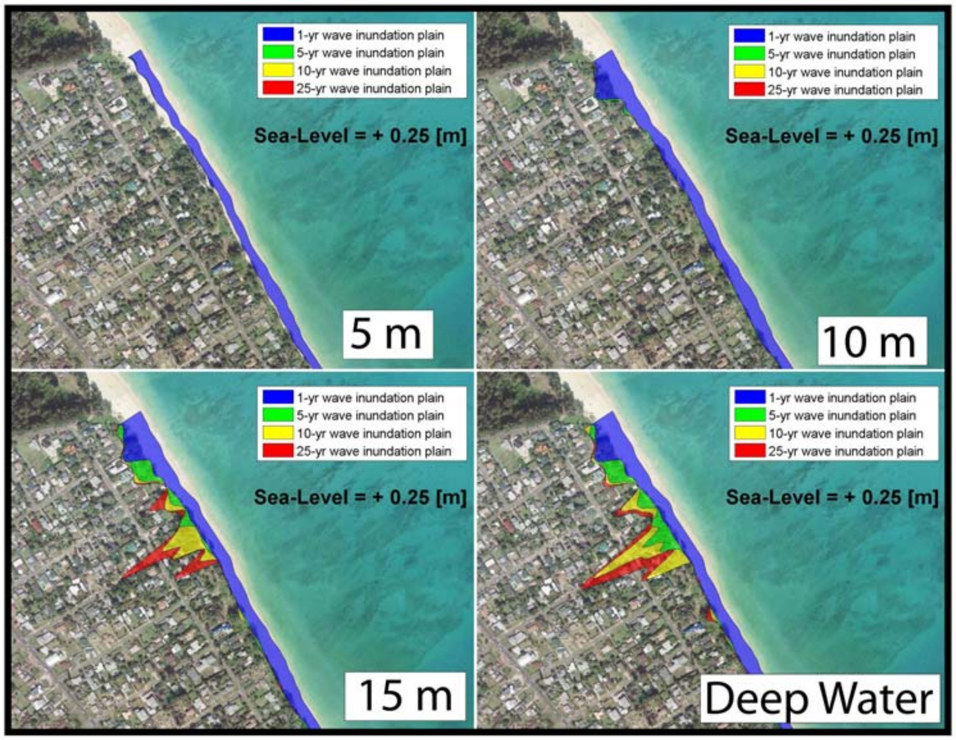

Figure 7 - Illustrating approach #3 - Projected inundation lines under a scenario of +0.25 m of sea-level rise with the runup computed from wave heights at different depths (5 m, 10 m, 15 m, and from deep water). The reverse shoaling and dissipation on the reef face is responsible for the significant reduction in runup and inundation at the coast.

Table 1 – Wave height and runup reduction over the fringing reef computed by SWAN and reverse shoaling.

Mean wave height [m] computed by SWAN at particular depth contours

	return period			
Depth	1 year	5 years	10 years	25 years
Deep-water	6.60	8.00	8.50	9.00
15 m	6.68	7.87	8.20	8.46
10 m	6.27	6.70	6.79	6.83
5 m	3.28	3.28	3.25	3.23
2 m	1.47	1.47	1.44	1.46

Mean runup [m] computed by Stockdon (2006) from wave heights (left) at particular depth contours

	return period			
Depth	1 year	5 years	10 years	25 years
Deep-water	2.82	3.10	3.20	3.29
15 m	2.83	3.08	3.14	3.19
10 m	2.75	2.84	2.86	2.87
5 m	1.99	1.98	1.98	1.97
2 m	1.33	1.33	1.32	1.32

% Reduction in wave height due to SWAN

	return period			
Depth	1 year	5 years	10 years	25 years
Deep-water	0.00%	0.00%	0.00%	0.00%
15 m	-1.20%	1.56%	3.53%	5.97%
10 m	4.96%	16.21%	20.07%	24.07%
5 m	50.25%	59.05%	61.75%	64.06%
2 m	77.79%	81.61%	83.04%	83.81%

% Reduction in wave height due to reverse shoaling

	return period			
Depth	1 year	5 years	10 years	25 years
Deep-water	0.00%	0.00%	0.00%	0.00%
15 m	6.82%	6.60%	6.49%	6.30%
10 m	13.98%	13.84%	13.77%	13.63%
5 m	26.76%	26.72%	26.78%	26.82%
2 m	48.92%	48.71%	49.22%	49.37%

% Reduction in runup

	return period			
Depth	1 year	5 years	10 years	25 years
Deep-water	0.00%	0.00%	0.00%	0.00%
15 m	-0.60%	0.78%	1.78%	3.03%
10 m	2.51%	8.46%	10.60%	12.86%
5 m	29.46%	36.01%	38.15%	40.05%
2 m	52.87%	57.12%	58.81%	59.77%

DISCUSSION

The major problem with our approach and RUNUP 2.0 (used in the FIRMS) is the improper use of empirical equations. The use of empirical equations facilitates the speed of computation and the ability to determine runup elevations on regional scales. However, there is a tradeoff between speed and scale of computation. Full process-based numerical modeling requires extensive computational time and thus cannot be readily applied to regional scales. Empirical models can be applied on regional scales at the expense of inaccuracies on local scales.

A major limitation of the application of empirical equations is the performance on a fringing reef. Empirical equations may perform quite well in predicting runup elevations in dynamically similar environments. On the other hand, they may perform quite poorly in dissimilar environments. One example of the potential problems that may result from use of empirical equations is the use of deep-water wave height to calculate runup. Using SWAN to predict the reduction in wave heights near or inside a fringing reef will account for the reduction in runup at the shoreline. Additionally, using SWAN rather than the individual transect method to compute the nearshore wave field, the spatial variability in wave height due to convergence and divergence is resolved. SWAN is able to compute wave setup inside a fringing reef. However, SWAN is not able to compute runup. Using a runup-resolving nearshore wave model would directly compute runup at the expense of computational speed and regional applicability. Nonetheless, the full process-based numerical modeling may be a considerably better approach.

The majority of the incident swell energy is reduced over dissipative beaches (mildly sloping beaches with wide surf zones) and fringing reefs, while infragravity motions dominate the sea level and runup signals at the shoreline (Guza & Thorton 1982; Ruessink 1998; Miles et. al. 2006; Kench & Brander 2006). Dissipation computed in SWAN and reverse shoaling significantly reduce the wave heights inside a fringing reef and corresponding runup elevations (as shown in Table 1). Outside the breaking point, reverse shoaling has a larger effect on reducing the wave height. Inside the breaking point, wave breaking is responsible for the largest reduction in wave height (50-83%), although reverse shoaling is responsible for an additional reduction (25-50%).

Our goal of mapping extreme runup levels on nearshore topography has encountered many limitations in the field of runup prediction. However, as empirical equations are developed for several different geologic settings and nearshore process-based numerical models improve, the ability to map the extreme runup levels and determine the influence of sea-level rise will also improve.

CONCLUSIONS

Practical approaches to mapping coastal inundation and the influence of sea-level rise can be quite informative, provided confident runup elevation estimates. The use of empirical equations in mapping runup elevations should be approached with caution, especially in fringing reef environments. The use of deep-water wave heights may significantly overestimate the runup at the shoreline. The use of nearshore wave models may improve the predictions of runup in fringing reef environments.

Following this approach we see that fringing reefs act as excellent natural breakwaters and may buffer adjacent coastlines against the short-term impacts of sea-level rise, particularly from the increase in frequency of wave-related inundation.

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