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DOI
10.1142/9789811204487_0086

Publication date
2019

Document Version
Final published version

Published in
Coastal Sediments 2019

Citation (APA)
Rueda, A., Cagigal, L., Anderson, D., Storlazzi, C., van Dongeren, A., Pearson, S., Marra, J., Ruggiero, P., & Mendez, F. J. (2019). Towards A Flood Risk Assessment On A Reef-lined Coastline. In *Coastal Sediments 2019* (pp. 991-997). World Scientific Publishing. https://doi.org/10.1142/9789811204487_0086

TOWARDS A FLOOD RISK ASSESSMENT ON A REEF-LINED COASTLINE

ANA RUEDA[1], LAURA CAGIGAL[1,2], DYLAN ANDERSON[6], CURT STORLAZZI[3], AP VAN DONGEREN[4], STUART PEARSON[4], JOHN MARRA[5], PETER RUGGIERO[6], FERNANDO MÉNDEZ[1]

1. *Surf and surge research group. E.T.S.C.C.P. Universidad de Cantabria. Av. Los Castros s/n 39005. Santander, Spain.* ruedaac@unican.es; mendezf@unican.es
2. *School of Environment, University of Auckland, 23 Symonds Street, Auckland, New Zealand.* lcag075@aucklanduni.ac.nz
3. *Pacific Coastal and Marine Science Center, United States Geological Survey, Santa Cruz, CA, USA.* cstorlazzi@usgs.gov
4. *Department of Applied Morphodynamics, Unit of Marine and Coastal Systems, Deltares, Delft, Netherlands.* Ap.vanDongeren@deltares.nl; Stuart.Pearson@deltares.nl
5. *NOAA NESDIS National Centers for Environmental Information (NCEI), 1845 WASP Blvd., Building 176, Honolulu, HI, USA.* john.marra@noaa.gov
6. *College of Earth, Oceanic, and Atmospheric Sciences, Oregon State Univ., Corvallis, OR 9733.* anderdyl@oregonstate.edu; pruggier@ceoas.oregonstate.edu

Abstract: The assessment of coastal flood risk on a reef-lined coastline presents several challenges. From the probabilistic side, we need to consider all possible events that could occur in the system, taking into account the different contributions of waves, storm surges, and tides that contribute to the total water level. To estimate reliable flood extents, we need to accurately model the complex wave processes that occur across the reef. To explore the multivariate nature of coastal flooding, we rely on a climate emulator that accounts for climate variability and simulates time series of all the variables involved. Due to the computational constraints to numerically simulate thousands of events, we explore the feasibility of using a recently developed tool, the HyCreWW (Hybrid Coral Reef Wave and Water level) meta-model to estimate wave run-up and flooding extents. Limitation of a 1D assessment are analyzed and results compared with 2D modeling.

Introduction

Wave-induced flooding is a major coastal hazard on tropical coasts fronted by coral reefs. In most of these locations, coastal flooding episodes can be caused either by tropical cyclone events or as a result of "sunny day" swell events generated by storms farther away (Hoeke *et al.*, 2013). To perform a robust flood risk assessment, it is necessary to account for all possible events that might occur in the system. However, sea level observations, from which the probability of the events can be assessed, are often limited. This leads to the need of performing stochastic simulation of multivariate events (Serafin *et al.*, 2016, Rueda *et al.*, 2017), to account for events that may be unrecorded, but are statistically possible. Once the statistics are well-captured, the synthetic and historic events need to be downscaled to obtain the associated flood extent and magnitude. The model XBeach (Roelvink *et al.*, 2009,2017) has been previously proved to accurately reproduce the hydrodynamics in reef environments, making it suitable for the purpose. However, it is computationally expensive for probabilistic assessments requiring thousands of simulations.

In this study we attempt to explore the feasibility of using a recently developed tool to estimate wave run-up in reef line shorelines, the HyCreWW (Hybrid Coral Reef Wave and Water level, Rueda *et al.* (under review)) metamodel to estimate flood extent. HyCreWW is defined for an idealized reef profile. Therefore, the limitations of a 1D assessment will be analyzed and the results compared with 2D modeling.

Hybrid Coral Reef Wave and Water level: HyCreWW

HyCReWW metamodel was developed for providing wave-driven run-up estimations along coral reef-lined shorelines under a wide range of fringing reef morphologies and offshore forcing characteristics. The metamodel is based on two models: (a) a full factorial design of recent XBeach Non-Hydrostatic simulations under different reef configurations and offshore wave and water level conditions (Pearson *et al.*, 2017); and (b) Radial Basis Functions (RBFs) for approximating the non-linear function of run-up for the set of multivariate parameters.

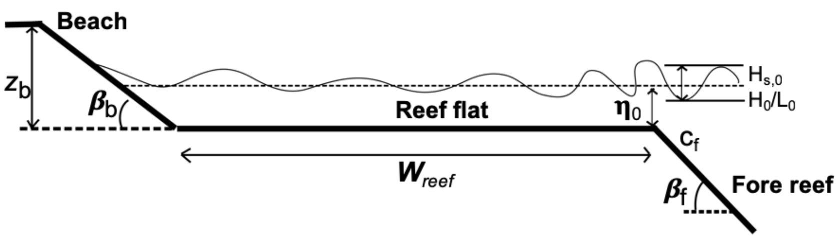

Fig. 1. Idealized reef (adapted from Pearson *et al.*, 2017).

The reef schematization is shown in Fig. 1. The hydrodynamic variables defined are offshore water level (η_0), significant wave height (H_0), and wave steepness (H_0/L_0); the reef morphologic parameters include fore reef slope (β_f), reef flat width (W_{reef}), beach slope (β_b), and seabed roughness (c_f). L_0 is the deep water wave length $L_0=gT_p^2/2\pi$, and T_p is the peak period. Beach crest elevation (z_b)

was fixed at a height of 30 m to focus on run-up as a proxy for coastal inundation. The parameter ranges are represented in Table 1.

Table 1. Primary XBNH model input parameters and their values.

Parameter	Symbol	Units	Values
Offshore water level	η_0	m	–1, 0, –0.5, 0, 0.5, 1, 1.5, 2, 2.5, 3
Offshore significant wave height	H_0	m	1, 2, 3, 4, 5
Offshore wave length	L_0	m	-
Offshore wave steepness	H_0/L_0	-	0.005, 0.001, 0.050
Fore reef slope	β_f	-	½, 1/10, 1/20
Reef flat width	W_{reef}	m	0, 50, 100, 150, 200, 250, 300, 350, 400, 500, 1000, 1500
Beach slope	β_b	-	1/5, 1/10, 1/20
Coefficient of friction	c_f	-	0.01, 0.05, 0.10

RBFs are a flexible interpolation technique originally developed by Hardi (1971). They have been previously used as a metamodel of SWAN for wave propagation problems (Camus *et al.*, 2011, Gouldby *et al.*, 2014) and recently with 2D surf beat Xbeach simulations on the coral coast of Fiji for coastal inundation forecasting (Bosserelle, personal communication) with successful results.

The validation of HyCReWW with existing field and laboratory (Fig. 2) demonstrates the ability to produce accurate run-up estimates along reef-lined shorelines over a large range of the parameter space.

Application

The location of study was Roi-Namur Island on Kwajalein Atoll in the Republic of Marshall Islands (Fig. 3). Its wave climate and reef morphology can be representative for many atolls and reef-lined coastlines in the Pacific, with the added value that it is a well-studied location with different field experiments and hydrodynamic simulations already performed there (Quataert *et al.*, 2015, Becker *et al.*, 2014, Cheriton *et al.*, 2016).

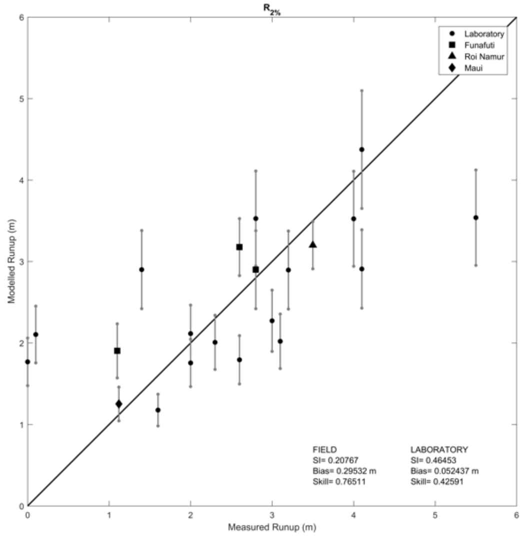

Fig. 2. HyCReWW validation, comparing measured and modeled run-up.

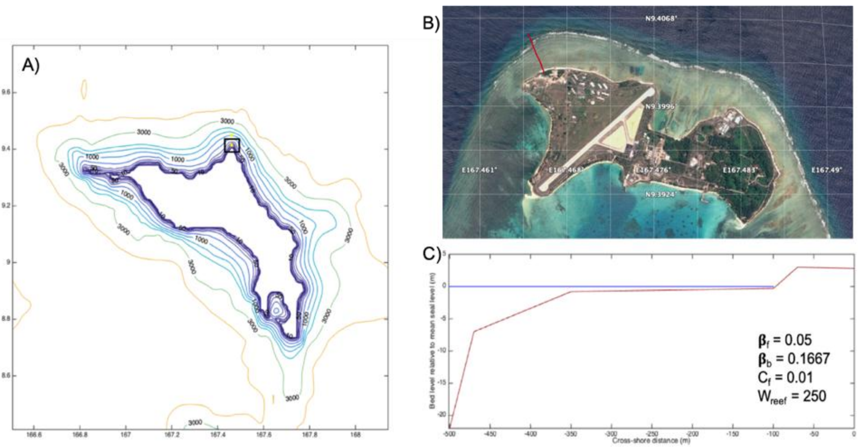

Fig. 3. Morphology of the study area. A) Kwajalain Atoll and bathymetric contours. B) Google Earth image of Roi-Namur, the northernmost part of the atoll, and the location of the cross-shore transect. C) Cross-shore transect (adapted from Quataert *et al.*, 2015)

After generating thousands of years of multivariate offshore conditions using the Time-varying Emulator for Short-and-Long-term Analysis of coastal flooding, TESLA-flood (Anderson *et al.*, in prep), a hybrid downscaling of wave conditions (using selection algorithms, SWAN, and non-linear interpolation techniques) was performed to account for the directional wave sheltering and obtain wave conditions closer to the reef. These results were validated with the measurements of a 600 kHz Nortek Acoustic Wave and Current Meter (AWAC) at a depth of 21m depth deployed during three previous campaigns in 2013–2015 (Cheriton *et al.*, 2016).

Due to the computational constraints of simulating thousands of events with XBeach, and recognizing 2D effects on the reef, we have selected a number of cases to simulate with a 2D XBeach Non-Hydrostatic. These form the basis of comparison with the run-up estimations provided by HyCReWW.

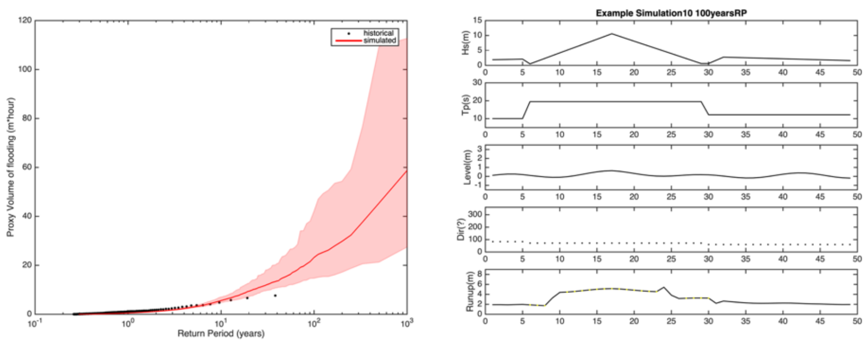

Fig. 4. Left: Return period analysis of a proxy of flooding. Black dots represent historical events, and red lines are simulated. Right: Example of one simulated hydrograph. The bottom panel gives the runup estimation from HyCReWW.

In this case, the selection of the events to simulate with a high resolution model, is based on a proxy of flooding volume (integrating through time the total water levels above the threshold that initiates overtopping). The left panel of Fig. 4 shows the historical events (black dots) and an ensemble of 10 realizations of 1000 years with TESLA-flood (red lines). The statistical model reproduces the flooding behavior, and is also capable of extrapolating the tail of the distribution for low occurrence probabilities (Fig. 4, left), indicating a dramatic change in the shape of the tail of the distribution (Frechet type). The right panel of Fig. 4 shows an example of a synthetic hydrograph with the associated values of significant wave height, wave period, wave direction, and water level, corresponding with a 100-year return period event. The bottom panel on the right side correspond to the run-up estimation with HyCReWW. These time-dependent hydraulic boundary conditions are essential for a correct estimation of the flooding extents with the 2D non-hydrostatic version of XBeach. Preliminary results show different behaviors in the flooding extents with similar occurrence probabilities of the multivariate boundary conditions.

Conclusion

Coastal flood risk assessment along reef-lined coastlines is a challenge involving different input data (bathymetry, topography, wave and sea level forcing), numerical models (wave transformation processes at regional-SWAN, and local-scale-XBeach), and statistical models. In this work we have combined the state-of-the-art of statistical and numerical models on a well-monitored island. The difficulties faced during the study emphasize the complexity of hydrodynamics in reef environments and open new research questions such as, what should be the optimal number of events to simulate with a high resolution model to perform a robust risk assessment? Will it be valid a single grid for 2D high resolution simulations in multimodal wave conditions? How can we validate extreme events, mostly associated with tropical cyclones?

Acknowledgements

This work was critically supported by the US Geological Survey under Grant/Cooperative Agreement G15AC00426 and from the US Department of Defense's Strategic Environmental Research and Development Program project RC-2644. AvD and SGP were partially funded by the Deltares Strategic Research Program "Quantifying Flood Hazards and Impacts".

References

Anderson, D., Rueda, A., Antolínez, J.A.A., Cagigal, L., Ruggiero, P., Méndez, F.J., "Time-varying Emulator for Short- and Long-term Analysis of coastal flooding: TESLA-flood" (in prep).

Becker, J.M., Merrifield, M.A., and Ford, M. (2014), "Water level effects on breaking wave setup for Pacific Island fringing reefs", *Journal of Geophysical Research: Oceans*, 119, 914-935.

Camus P., Mendez F.J. & Medina R. (2011), "A hybrid efficient method to downscale wave climate to coastal areas", *Coastal Engineering*, 58(9), 851-862.

Cheriton, O. M., C. D. Storlazzi, and K. J. Rosenberger (2016), "Observations of wave transformation over a fringing coral reef and the importance of lowfrequency waves and offshore water levels to runup, overwash, and coastal flooding", *Journal of Geophysical Research: Oceans*, 121, 3121-3140. doi:10.1002/ 2015JC011231.

Gouldby B., Méndez F.J., Guanche Y., Rueda A. and Mínguez R. (2014), "A methodology for deriving extreme nearshore sea conditions for structural design and flood risk analysis", *Coastal Engineering*, 88, 15-26.

Hardy, R.L. (1971), "Multiquadric equations of topography and other irregular surfaces", *Journal of Geophysical Research*, 76, 1905-1915.

Hoeke, R. K., McInnes, K. L., Kruger, J., McNaught, R., Hunter, J., and Smithers, S. (2013), "Widespread inundation of Pacific islands by distant-source wind-waves" *Global Environmental Change*, 108, 128-138. doi: 10.1016/j.gloplacha.2013.06.006.

Pearson, S.G., Storlazzi, C., van Dongeren, A.R., Tissier, M.F.S., Reniers, A.J.H.M. (2017), "A Bayesian-based system to assess wave-driven 1 flooding hazards on coral reef lined coasts", *Journal of Geophysical Research: Oceans*, 122, 10,099-10,117. doi:10.1002/2017JC013204.

Quataert, E., Storlazzi, C. D., van Rooijen, A., Cheriton, O. M., and van Dongeren, A. R. (2015), "The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines", *Geophysical Research Letters*, 1-9. doi:10.1002/2015GL064861.

Roelvink, J.A., Reniers, A, van Dongeren, A.R., van Thiel de Vries, J., McCall, R., Lenciski, J. (2009), "Modelling storm impacts on beaches, dunes and barrier islands", *Coastal Engineering*, 56, 1133-1152.

Roelvink, D., McCall, R., Mehvar, S., Nederhoff, K., Dastgheib, A. (2017), "Improving predictions of swash dynamics in XBeach: The role of groupiness and incident-band runup", *Coastal Engineering*, 134, April 2018, 103-123.

Rueda, A., Hegermiller, C.A., Antolinez, J.A.A., Camus, P., Vitousek, S., Ruggiero, P., Barnard, P.L., Erikson, L.H., Tomas, A., and Mendez, F.J. (2017), "Multi-scale climate emulator of multimodal wave spectra: MUSCLE-spectra", *Journal of Geophysical Research: Oceans*, 122, 1400-1415.

Rueda, A., Cagigal, L., Pearson, S., Antolínez, J.A.A., Storlazzi, C., van Dongeren, P., Camus, P., Méndez, F. (under review). "HyCreWW: A Hybrid Coral Reef Wave and Water level Metamodel", *Computer and Geosciences.*

Serafin, K., Ruggiero, P. (2014), "Simulating extreme total water levels using a time-dependent, extreme value approach", *Journal of Geophysical Research: Oceans*, 119, 6305-6329.