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Research paper

# HyCReWW: A Hybrid Coral Reef Wave and Water level metamodel

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ABSTRACT

Wave-induced flooding is a major coastal hazard on tropical islands fronted by coral reefs. The variability of shape, size, and physical characteristics of the reefs across the globe make it difficult to obtain a parameterization of wave run-up, which is needed for risk assessments. Therefore, we developed the HyCReWW metamodel to predict wave run-up under a wide range of reef morphometric and offshore forcing characteristics. Due to the complexity and high dimensionality of the problem, we assumed an idealized one-dimensional reef profile, characterized by seven primary parameters. XBeach Non-Hydrostatic was chosen to create the synthetic dataset, and Radial Basis Functions implemented in MATLAB® were chosen for interpolation. Results demonstrate the applicability of the metamodel to obtain fast and accurate results of wave run-up for a large range of intrinsic reef morphologic and extrinsic hydrodynamic forcing parameters, offering a useful tool for risk management and early warning systems.

## 1. Introduction

Coral reef-lined islands around the world, many of them belonging to Small Island Developing States, are subjected to coastal flooding episodes caused either by tropical cyclone events or as a result of "sunny day" swell events generated by storms farther away (Stephens and Ramsay, 2014; Hoeke et al., 2013). The variability of reef morphologies, offshore water level, and wave conditions makes our ability to evaluate and predict wave-driven flooding threats to these regions computationally expensive and site-specific (Bosserelle et al., 2015). However, the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) has indicated that there is a pressing need for developing new tools to improve access to early warning systems to help reduce risk exposure to these already vulnerable regions.

The aim of this effort is to make publicly available an easy-to-use tool to obtain fast and accurate run-up estimations, as a proxy to flood extent, on coral reef-lined shores. To accomplish this, we relied on an already simulated and validated dataset of wave run-up (maximum vertical extent of wave uprush on a beach) estimations for different reef morphologies and wave and water level conditions (Pearson et al., 2017). The novelty of this work is the utilization of Radial Basis Functions (RBFs) as an interpolation technique to obtain run-up estimations for infinite combinations of intrinsic coral reef morphologies and extrinsic physical oceanographic forcing. Validation with available laboratory and field studies reveals the good predictive skill of the developed metamodel (model-of-models). The paper is organized as follows. In section 2, we discuss the methods, where the schematization and numerical model used to create the synthetic dataset are reviewed, followed by the methodology and principal characteristics of the interpolation technique employed. Section 3 presents the results, where two kinds of validation are performed and discussed. In section 4, we provide our discussion of the findings and possible applications.

## 2. Methods

### 2.1. Hydrodynamic simulations

We developed the Hybrid Coral Reef Wave and Water level (HyCReWW) metamodel based on the already published synthetic database of waves, wave-driven water levels, and the resulting run-up

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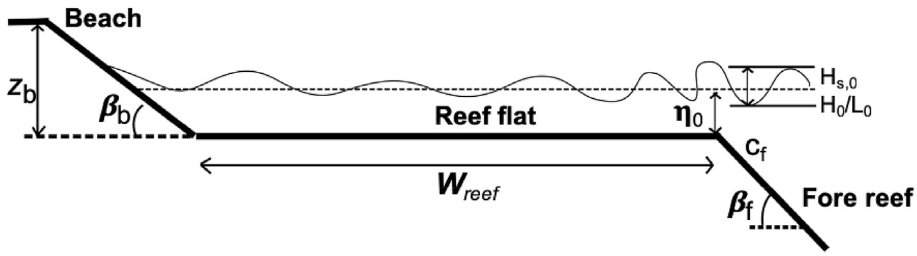


**Fig. 1.** Idealized reef profile and defined hydrodynamic and morphologic parameters, adapted from Pearson et al. (2017).

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

| Parameter | Symbol | Units | Values |
|---|---|---|---|
| Offshore water level | $\eta_0$ | 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 | $\beta_f$ | – | 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 | $\beta_b$ | – | 1/5, 1/10, 1/20 |
| Coefficient of friction | $c_f$ | – | 0.01, 0.05, 0.10 |

over coral reefs (Pearson et al., 2017). It made use of the process-based XBeach Non-Hydrostatic (XBNH) model (version 1.22.4867) with varying reef morphology and hydrodynamic forcing based on the schematization shown in Fig. 1. The hydrodynamic parameters defined are offshore water level ($\eta_0$), significant wave height ($H_0$), and wave steepness ($H_0/L_0$); the reef morphologic parameters include fore reef slope ($\beta_f$), reef flat width ($W_{reef}$), beach slope ($\beta_b$), 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 ($z_{beach}$) was fixed at a height of 30 m to focus on run-up as a proxy of coastal inundation. The parameters ranges are represented in Table 1. The original XBNH simulations of Pearson et al. (2017) considered a unimodal JONSWAP spectra applied shore-normal. For each combination of the input parameters, it was performed four 30-min simulation periods with random realizations of the surface elevation time series leading to 174372 XBNH simulations. Since, we are interested in an estimation of the top 2% of wave run-up ($R_{2\%}$), we obtained its average for the four simulations for each parameter combination, leading to 43593 XBNH design points following a full factorial distribution. XBNH is a depth-averaged, wave-resolving model that solves the shallow water equations, including non-hydrostatic pressure (McCall et al., 2014; Smit et al., 2014; Roelvink et al., 2015). Please refer to Pearson et al. (2017) for more information about XBNH model set up and validation.

### 2.2. Metamodel: Radial Basis Functions (RBFs)

The computational cost of running a process-based model such as XBNH in operational mode makes it worthwhile to explore other alternatives such as metamodels. If we consider our current simulation model where the input-output relationship is mathematically represented as follows:

$$z = f(\boldsymbol{X}) \tag{1}$$

where $\boldsymbol{X}$ is the vector of input parameters and $z$ is the output (in this case $R_{2\%}$), it can be rewritten as:

$$R_{2\%} = f(x_1, x_2, x_3, x_4, x_5, x_6, x_7) \tag{2}$$

where $\{x_i$, I = 1:7$\}$ are the normalized input parameters defined in section 2.1. For instance, $x_1$, the offshore water level, is defined as:

$$x_1 = \frac{\eta_0 - \min(\eta_0)}{\max(\eta_0) - \min(\eta_0)} \tag{3}$$

The task of the metamodel is to approximate the function, $f$, that relates the input vector $\boldsymbol{X}$ to the given output $z$. Following Hussain et al. (2001), the different methods to build metamodels can be classified into parametric and non-parametric techniques. The main difference between them is that parametric techniques approximate functions *a-priori* without prior knowledge about the underlying data; some examples of application of these models in coastal studies are polynomial models (Stockdon et al., 2006), or general linear (Camus et al., 2014a) and non-linear (Camus et al., 2014b) models. Non-parametric techniques instead use an *a-priori* method for constructing an approximating function based on observed responses; examples include neural networks (Kingston et al., 2011; Browne et al., 2007), Gaussian processes (Kennedy et al., 2006), splines (Minguez et al., 2011), and RBFs. RBFs were originally developed by Hardy (1971) and have proved to perform better than polynomial metamodels in high dimensional problems (Hussain et al., 2001). RBFs have also 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 et al. personal communication) with successful results. Therefore, we have chosen it as the interpolation technique to use in our current problem.

The RBF function takes the following general form:

$$z(\boldsymbol{X}) \approx RBF(\boldsymbol{X}) = p(\boldsymbol{X}) + \sum_{i=1}^{N} a_i \phi(\boldsymbol{X} - \boldsymbol{X}_i) \tag{4}$$

where $z(\boldsymbol{X})$ is the output of the metamodel (in this case 2% run-up), $p(\boldsymbol{X})$ is a monomial basis,

$$p(\boldsymbol{X}) = b_o + b_1 x_1 + b_2 x_2 ... + b_m x_m \tag{5}$$

where $m$ corresponds with the number of dimensions (7 in this case), and $b_{0,1,\ 2,..,m}$ are coefficients that need to be found together with the RBF coefficients $a_i$ by enforcing the interpolations constrains in the design points ($N$ = 43593). $\phi$ is the radial basis function, in this case defined by a Gaussian function of the form:

$$\phi(\boldsymbol{X} - \boldsymbol{X}_i) = \exp\left(-\frac{\boldsymbol{X} - \boldsymbol{X}_i^2}{2c^2}\right) \tag{6}$$

where $c$ is the shape parameter, which plays an important role on the accuracy of the interpolation technique. To obtain the value of this parameter $c$, we have followed the method defined by Rippa (1999), which is based on the idea of cross validation.

The large amount of defined design points ($N$ = 43593) makes the application of RBF to the entire dataset at once difficult because it would require inverting a matrix of 43593 × 43593, which involves several gigabytes of RAM memory. We therefore divided the problem in fifteen smaller sub-datasets for analyses. We fixed the values of $H_s$ (5 values) and $H_s/L_o$ (3 values), resulting in 15 problems in 5 dimensions ($\beta_f$, $W_{reef}$, $\beta_b$, $c_f$, and $\eta_0$), obtaining 15 RBFs in 5 dimensions for each combination of $H_s$ and $H_s/L_O$. Finally, we interpolated $z(\boldsymbol{X})$ in the space of $H_s$–$H_s/L_O$.

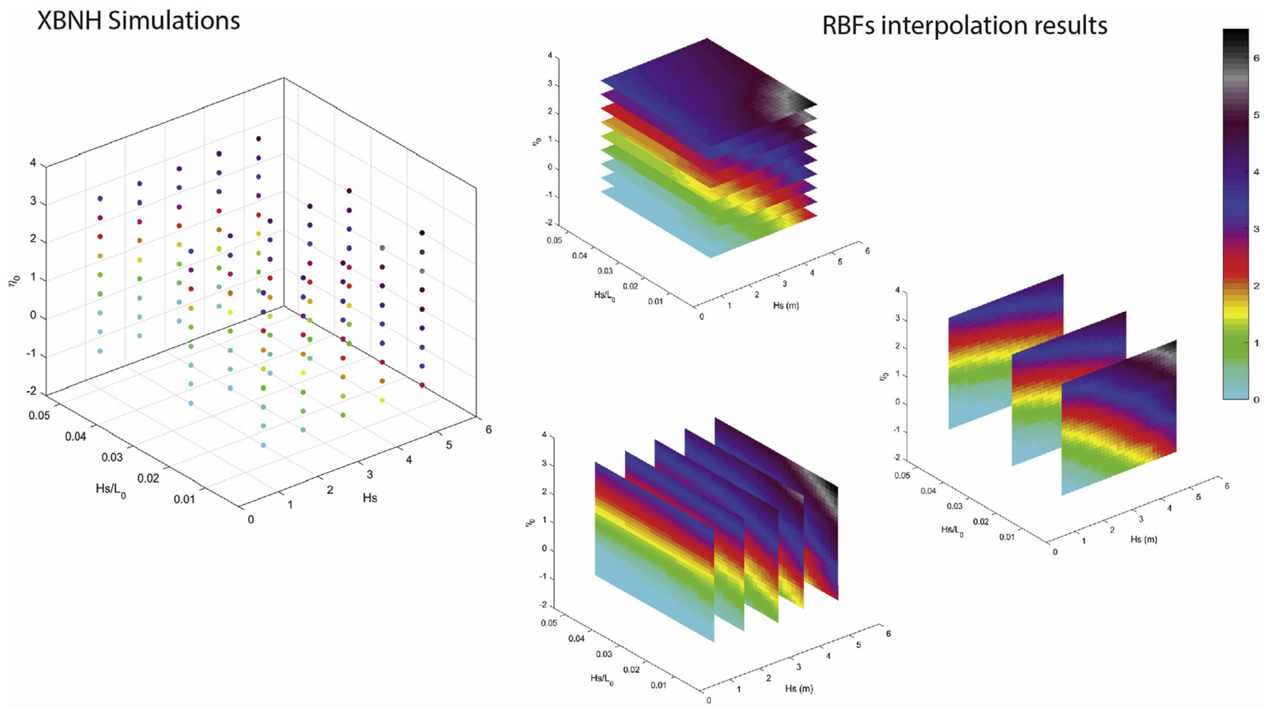


**Fig. 2.** Example fixing four of the parameters ($\beta_f$ = 0.1, $W_{reef}$ = 300 m, $\beta_b$ = 0.1, and $c_f$ = 0.05). The left panel shows the represents the three-dimensional matrix of XNBH simulations and the right panel shows three different slices of the response function fixing one of the variables in each plot ($R_{2\%}$ = f(Hs, Hs/Lo |η0), $R_{2\%}$ = f (Hs, η0,|Hs/Lo), and $R_{2\%}$ = f(Hs/Lo, η0 | Hs)).

## 3. Results

As an example, Fig. 2 demonstrates the performance of the metamodel where the values of four parameters ($\beta_f = 0.1$, $W_{reef} = 300$ m, $\beta_b = 0.1$, and $c_f = 0.05$) were fixed. In this case, the run-up is thus a function of the three oceanographic parameters, $R_{2\%} = f(H_s, H_s/L_o, \eta_0)$. Fig. 2 demonstrates the flexibility of the RBFs on the interpolation. As expected, larger run-up values are associated with larger wave heights, lower wave steepness, and with high water levels. This combination of $H_s$, $H_s/L_o$, and $\eta_0$ shows a slightly non-linear behavior.

### *3.1. Validation*

Because a metamodel is a model of models, the validation can be addressed at two levels: (1) validation of the mathematical model, and (2) validation of the numerical model (XBNH simulations) with field or lab measurements. The first point was accomplished by means of the *k*-fold validation method ($k = 20$), obtaining an average root mean square error (RMSE) of 0.28 m and a scatter index (SI) of 0.16 (Fig. 3). The behavior of the model is remarkable for all the large range of run-up values. The validation of XBNH simulations had already been carried out in previous works (Quataert et al., 2015; Pearson et al., 2017) for a reduced number of cases.

For practical purposes, it is highly desirable that the model is able to reproduce run-up on natural beaches protected by coral reefs to provide a predictive tool for risk management and early warning systems. Here we used existing field data (Quataert et al., 2015; Beetham et al., 2015; Cheriton et al., 2016), new field data (Appendix Table 1), and lab measurements (Demirbilek et al., 2007) to validate HyCReWW (Fig. 4). These model-data comparisons reinforce the ability of the metamodel as a predictive tool. Note that caution must be applied with the laboratory experiments, as they were carried out with $c_f = 0.001$, which is out of the range of the friction coefficient parameter space tested here. In this case, we assumed the minimum friction coefficient that has been

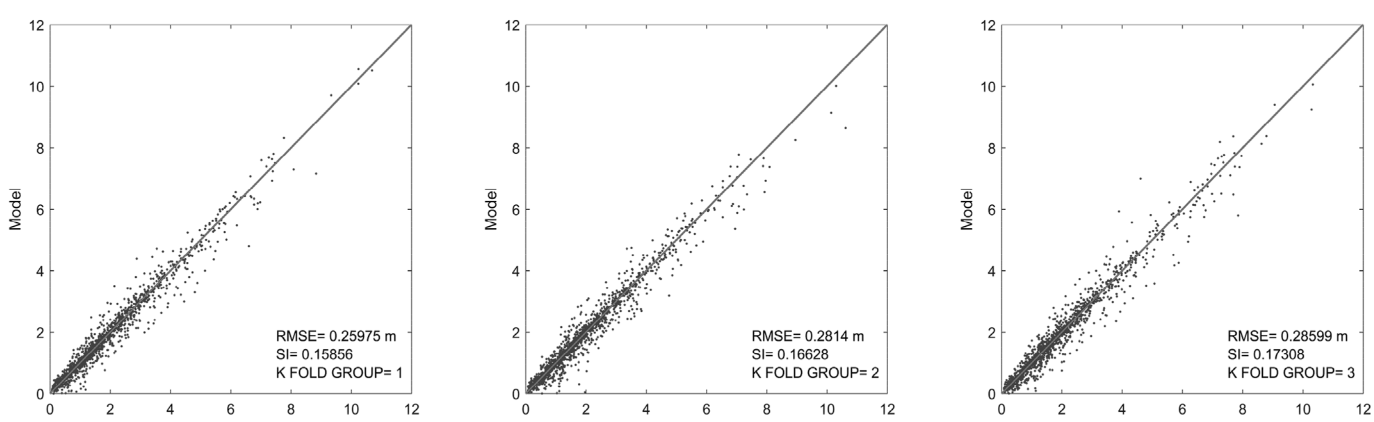


**Fig. 3.** Example k-fold model-data validation for the first three sub-datasets. Comparison between run-up values ($R_{2\%}$, in meters) from XBNH simulations (x-axis) and meta-model (y-axis).

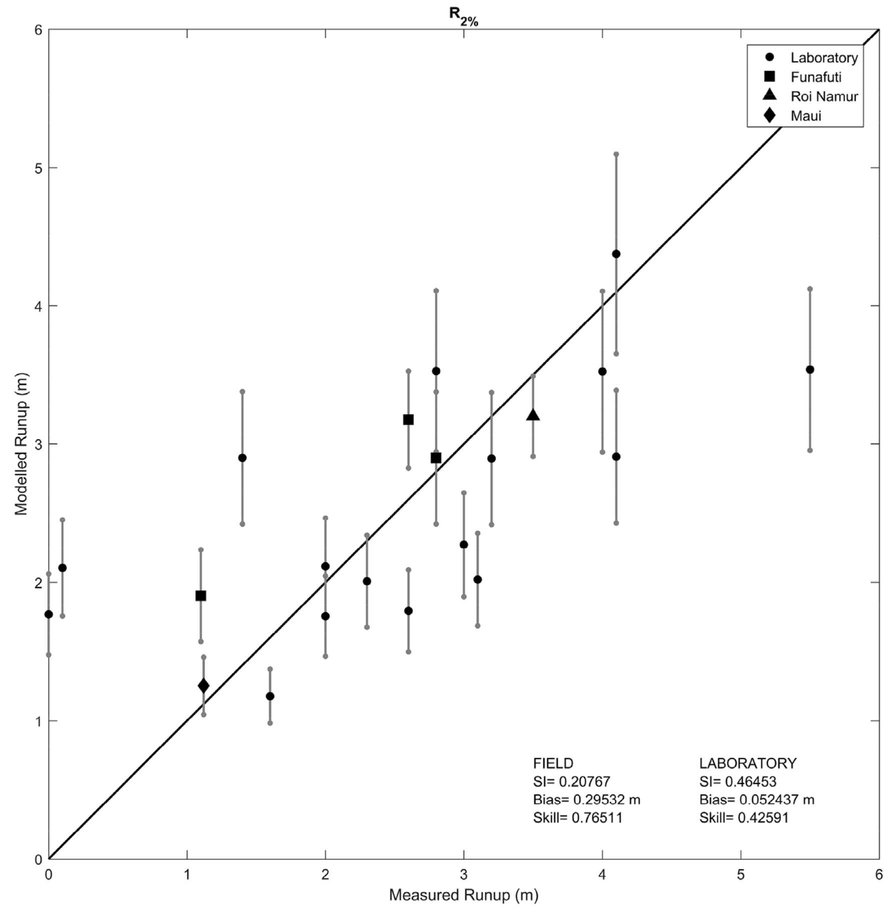


**Fig. 4.** Validation of HyCReWW model.

simulated ($c_f = 0.01$) as input of the metamodel, with their associated laboratory reef and wave characteristics. Nevertheless, more field and/or laboratory run-up data would be highly desirable to further validate the model.

### 3.2. MATLAB® implementation of HyCReWW

HyCReWW is implemented in MATLAB® to facilitate the application of the metamodel for run-up in coral reef environments (Fig. 5). Main.m is the script that runs the code. It reads a MATLAB® data file called Input_data.mat. This input file consists on an array with seven columns corresponding to the seven parameters ($\eta_0$, $H_0$, $H_0/L_0$, $\beta_f$, $W_{reef}$, $\beta_b$, and $c_f$) and a number of rows corresponding to the $N$ cases. The //RBF/ and //RBF_coefficients/ folders contain the functions and coefficients of the metamodel, respectively. Main.m returns a vector with the run-up values and the associated RMSE saving all the results in a MATLAB® data file called Output.mat. Therefore, the input/output equation is given by:

$$R_{2\%} = RBF\left(\eta_0^*, H_0^*, \frac{H_0^*}{L_0}, \beta_f^*, W_{reef}^*, \beta_b^*, c_f^*\right) \tag{7}$$

where, RBF represents the interpolation method based on RBFs coefficients and the asterisk is used to represent the normalized value of the seven input parameters (water level, significant wave height, wave steepness, fore reef slope, reef width, beach slope and coefficient of friction). The normalization however is performed in the Matlab script (Main.m). The output is R2%, an estimation of the top 2% of wave run-up, the root mean square error (RMSE) is also provided based on the scatter index (SI) obtained from the previous K-fold validation.

Interested users can download the software package (a single zip

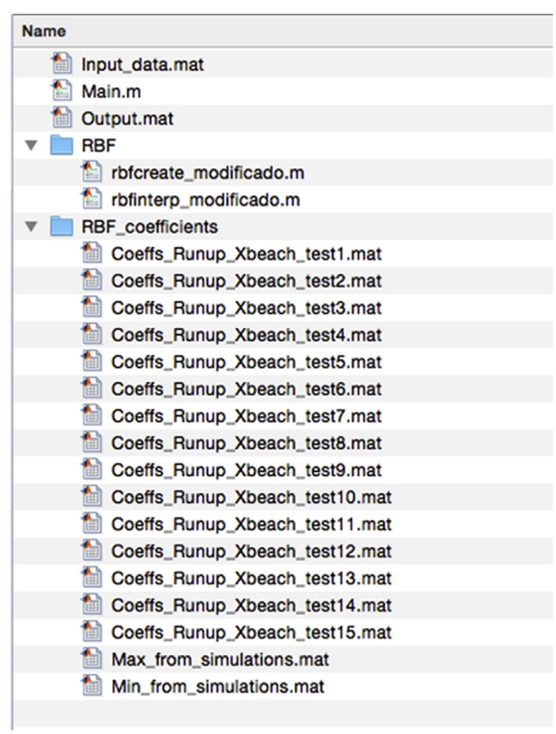


**Fig. 5.** Structure of HyCReWW files.

file) from the ScienceBase page, https://doi.org/10.5066/F7SX6CFQ. The zipped file includes all the files following the structure of Fig. 5.

## 4. Conclusions

The fast Hybrid Coral Reef Wave and Water level (HyCReWW) metamodel was developed for providing wave-driven run-up estimations along coral reef-lined shorelines under a wide range of reef and offshore forcing characteristics. The model is design to be used in coastal risk management as well as in early-warning systems.

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. The validation with existing field and laboratory demonstrates the ability to produce accurate run-up estimates along reef-lined shorelines over a large range of parameter spaces. However, more field and laboratory data are desirable to further validate the tool.

HyCReWW is envisaged to be used as a tool to obtain fast and accurate estimation of run-up as a proxy of potential inundation on early warning systems (EWS). The application of HyCReWW needs considerably less resources, experience and computation time (about 2000 time faster) than incorporating a wave transformation model such as XBNH into the EWS. For its application, it only requires the offshore wave conditions and water levels, that can be output of an offshore wave model, and the reef characteristics, such as reef width, and slope, that can be estimated from Google Earth or satellite images (e.g. Traganos et al., 2018). The validation indicates that the mean error introduced with the metamodel is less than 30 cm. Although other assumptions, such as the 1-D behavior, widely accepted by the scientific community due to the complexity involved on the 2-D simulations, might introduce larger errors on the run-up estimation.

To conclude, the metamodel presented here is an alternative to the Bayesian network developed by Pearson et al. (2017). For practical purposes, we have found that its main difference is a deterministic result (with its associated error bands) versus the probabilistic approach of the Bayesian networks, both with their associated benefits and drawbacks. HyCReWW therefore provides yet another tool to transfer coastal hazard information to stakeholders and the public in general; we thus highly encourage local stakeholders and coastal scientists to use these tools and provide feedback.

The metamodel is available to the scientific community by means of a open-source code developed in MATLAB® that compiles the algorithms and facilitate the use of the methodology.

## Authors contributions

F.J.M., C.S., P.C., and A.R. developed the concept for this study. S.P. and A.D., provided the XBeach numerical simulations. A.R. and L.C. performed the analysis. A.R., L.C., and F.J.M verified the analysis. A.R. wrote the original manuscript. All authors discussed the results and commented on the manuscript.

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## Computer code availability

Name of software: HyCReWW
Description: HyCReWW is a processed dataset of run-up estimations on a one-dimensional idealized reef profile for a finite number of X-Beach simulations for different reef morphologic configurations and offshore wave and water level conditions that has been parameterized based on Radial Basis Functions (RBFs). HyCReWW allows fast and accurate estimations of run-up along reef-lined shorelines
Source language: MATLAB®
Software availability: DOI: https://doi.org/10.5066/F7SX6CFQ

**Appendix Table 1. Reef and wave characteristic measured off Lahaina, Maui, Hawaii, on 2 September 2017. Coefficient of friction unknown and assumed to be $C_f = 0.03$**

| Parameter | Symbol | Value |
|---|---|---|
| Offshore water level (m) | $\eta_0$ | 1.35 |
| Offshore significant wave height (m) | $H_0$ | 1.5 |
| Offshore wave steepness (−) | $H_0/L_0$ | 0.005 |
| Fore reef slope (−) | $\beta_f$ | 0.05 |
| Reef flat width (m) | $W_{reef}$ | 220 |
| Beach slope (−) | $\beta_b$ | 0.0697 |
| Coefficient of friction (−) | $c_f$ | (0.03) |
| 2% Run-up (m) | $R_{2\%}$ | 1.12 |

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cageo.2019.03.004.

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