Runup Modeling in Low-Data Coral Reef Environments: Implications for Nesting Sea Turtles

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Abstract. Sea turtles are key species in many coastal ecosystems worldwide, particularly coral reef and seagrass habitats. Yet, six of seven species are endangered. Their nests, which incubate in beach sand and rely on specific climatic conditions for egg viability, face significant threats from inundation, for example through wave runup. This paper examines a method to rapidly predict wave runup in low-data coral reef environments, and the implications thereof on the inundation of sea turtle nests. The study uses two metamodels, BEWARE-2 and HyCReWW, to predict wave runup at Ras Baridi, Saudi Arabia, a key nesting site of the Red Sea green turtle population. The models were used to analyze runup events and inundation durations and provide a first estimate of a safe nesting elevation. Despite data limitations, the study provides valuable insights for coastal managers to protect sea turtle nests, suggesting that a 5-year return period runup elevation could serve as a threshold for nest relocation. However, the findings also highlight the importance of more accurate hydrodynamic predictions and the need for in-situ data to validate models and improve conservation strategies.

Keywords: Wave runup · coral reefs · metamodels · sea turtles · nest flooding

1 Introduction

Rising sea levels and increased storm activity due to climate change pose significant threats to coastal ecosystems. This is particularly problematic for endangered sea turtles, who rely on sandy beaches for nesting. Sea turtles lay numerous eggs due to the low survival rate of hatchlings, and specific climatic conditions are crucial for egg viability [1]. The salinity, moisture, and temperature of nests significantly influence hatchling development. Inundation of their nests due to heightened wave runup can lead to egg mortality and altered sex ratios of the hatchlings, potentially destabilizing turtle populations [2, 3]. The eggs cannot survive salt-water inundation for prolonged periods (>12 h), and even short durations (<1 h) can significantly decrease egg viability, particularly at either end of the incubation period (freshly laid or near hatching) [2].

C. Coelho et al. (Eds.): CD 2025, CRL 41, pp. 564–569, 2026.
https://doi.org/10.1007/978-3-032-15473-6_86

Mitigation strategies may include relocating nests to higher elevations or enhancing wave energy dissipation through reef preservation, restoration, or artificial reef creation. For example, defining safe nesting elevations ensures nests are moved out of high-frequency flood zones early in the incubation period without compromising the hatchlings' ability to reach the water. These strategies require a thorough understanding of local hydrodynamics, which is challenging in many of the data-scarce environments where sea turtles nest. Coastal managers need quantitative assessments of flooding likelihood along beach elevations to reduce flood risk, which benefits both coastal development and nest management [4].

This study explores the viability of wave runup modeling in data-limited coral reef environments by combining global datasets and metamodels. We aim to equip coastal managers with tools to assess and mitigate flood risks to sea turtle nests in low-data environments like our study area in Ras Baridi, Saudi Arabia.

2 Methods

Ras Baridi is a major green turtle nesting site on the central Saudi Arabian Red Sea coast (Fig. 1a) [5], where local coastal managers have reported flooding of nests. The beach features a fringing coral reef, ranging from 50–200 m in width and is bordered by a steep drop into deep water (Fig. 1b). It is a microtidal environment with a 0.2–0.3 m tidal range and consistent year-round waves of about 1 m.

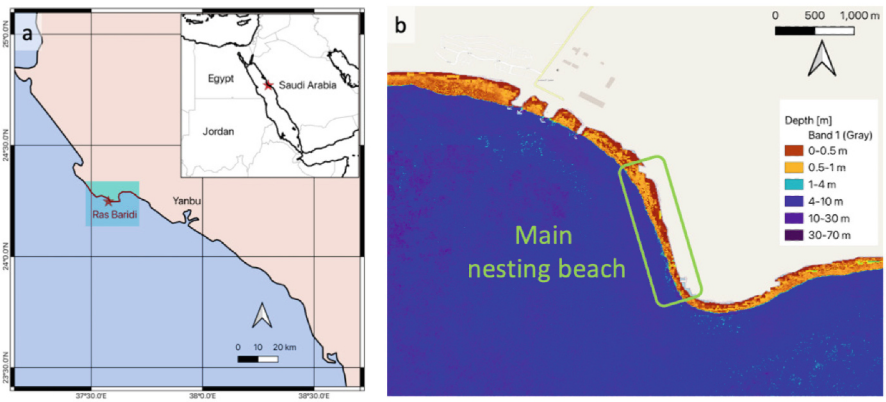

Fig. 1. **A** (a) Geographical overview of the study area, Ras Baridi, in Saudi Arabia and the Red Sea region; (b) bathymetry of the study area derived from the Allen Coral Atlas [10]

We used two different 1D metamodels, BEWARE-2 [6] and HyCReWW [7], to predict wave runup at low computational cost. HyCReWW parameterizes the input bathymetry profile, while BEWARE-2 uses a database of real bathymetry profiles (Fig. 2) to compute the 2% exceedance runup value ($R_{2\%}$). Because these two approaches differ significantly, their results are important to compare.

BEWARE-2 was developed using a training dataset of hydrodynamics and wave runup computed by the XBeach Non-Hydrostatic process-based hydrodynamic model for 440 combinations of water level, wave height, and wave period with 195 representative reef profiles that encompass the natural diversity in real-world fringing coral reef systems. The metamodel functions by matching input profiles to a database of 550 representative (measured) profiles with validated XBeach results and returns a weighted ensemble of the runup (Fig. 2). In the validation stage, the BEWARE-2 modeling system showed a 13% relative root mean square error and 5% relative bias compared to XBeach Non-Hydrostatic [6].

HyCReWW uses a schematic representation of fringing reef geometry through 7 parameters (Fig. 2): the water level, the offshore wave height, the offshore wave steepness, the fore-reef slope, the reef width, the beach slope, and the reef friction factor. The metamodel then interpolates the user input to a database of XBeach runup results through a radial basis function. HyCReWW has been validated with field and laboratory studies and predicts runup with an average root mean square error of 28 cm [7].

As model input, we used 1088 representative sea states, derived from 40-year large scale hindcasts of waves [8] and water levels from 1978–2018 [9] (Fig. 2). Allen Coral Atlas 10-m horizontal resolution bathymetry [10] was used for nearshore bathymetry (Fig. 1b), and ETOPO 2022 Global Relief Model with 15 arc-second resolution was used for offshore bathymetry [11].

The lack of accurate local data led to significant uncertainty in the input parameters for HyCReWW. A sensitivity analysis was therefore conducted to understand the influence of the input parameters on the model output. The sensitivity analysis was also used to screen the parameters to decrease the number of simulations that were run. Based on the sensitivity analysis results, the reef geometry parameters (beach slope, reef width, fore-reef slope and reef friction factor) were found to have a small influence on the results relative to the water level, wave steepness, and significant wave height. The reef geometry parameters were estimated using local data or from literature. We modeled wave runup for 4 different profiles, representing varying reef widths (80–170 m) along the beach, and computed runup values with return periods from 1 to 40 years to assess inundation risk.

The metamodel results provided timeseries data on wave runup, enabling the analysis of nest inundation duration. By examining the distributions of wave runup events exceeding a threshold value, we aimed to understand the flood risk to nests. Specifically, we investigated the duration of runup events and runup heights using HyCReWW and BEWARE-2 models.

The goal was to determine if inundation duration correlated with runup height, allowing nests to be relocated to safer elevations with little chance of being inundated for periods of time that can diminish egg viability. Runup event durations were defined by consecutive runup events with heights of at least 0.48 m and 0.61 m for HyCReWW and BEWARE-2, respectively. These were the minimum runup values modeled by each metamodel due to their input restrictions. Empirical probability density functions (PDFs) were created for inundation durations, and log-normal PDFs were fitted to extract statistical insights.

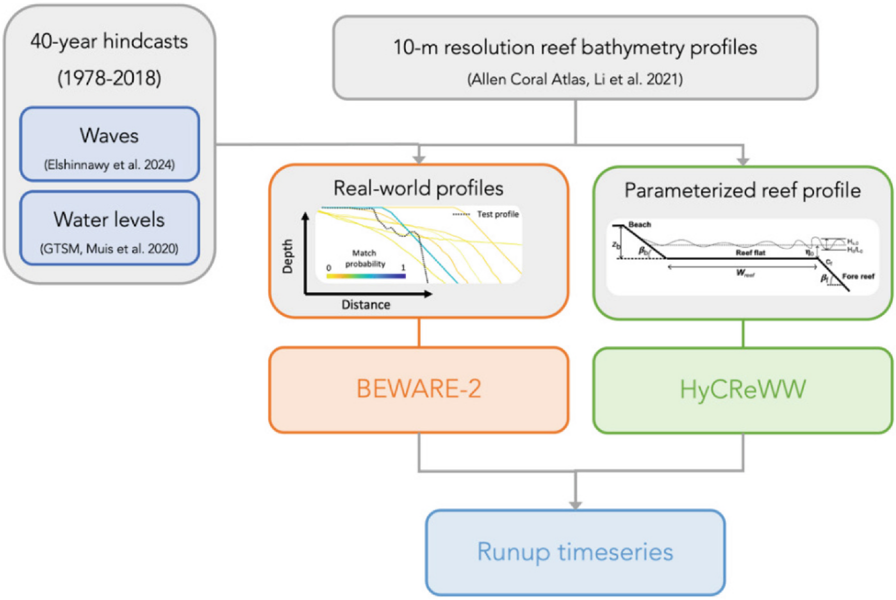

Fig. 2. Flowchart showing the methodology explored in this study. The input data (waves, water levels, and 10-m bathymetry) are used to force the BEWARE-2 and HyCReWW meta-models, which return timeseries of wave runup.

3 Results

The values of runup for different return periods and reef widths are shown in Table 1. They highlight the range of runup values across the beach for extreme events. BEWARE-2 showed a greater sensitivity to reef width than HyCReWW. This appeared to be due to the profile matching process for the reef with of 80 m, which was matched to a profile with a reef width of 50 m, resulting in an overestimation in runup there.

Table 1. Runup ($R_{2\%}$) return period values in meters from HyCReWW and BEWARE 2.0 for two different reef widths (W_r).

Return Period (yrs)	$W_r = 80$ m		$W_r = 170$ m	
	HyCReWW	BEWARE-2	HyCReWW	BEWARE-2
1	0.95	1.35	0.9	0.85
5	1.3	1.75	1.2	1.25
10	1.4	2	1.3	1.3
20	1.9	2.65	1.75	1.8
40	1.95	2.7	1.9	1.8

The HyCReWW results indicated that average $R_{2\%}$ was not well correlated with inundation duration. The median duration of a runup event was 7 h, and the lower and upper quartiles were 4 and 11 h, respectively (Fig. 3). Hence, every nest that gets inundated has a significant risk of reducing the viability its eggs.

A correlation between inundation duration and runup height was also not found in the BEWARE-2 results. Figure 3 shows that the lower quartile was 2 h, and the upper quartile was 10 h, which is apparent in the skew of the PDF towards the lower durations. The results show that the runup events have the ability to reduce the viability of eggs, to a lesser extent than the HyCReWW results.

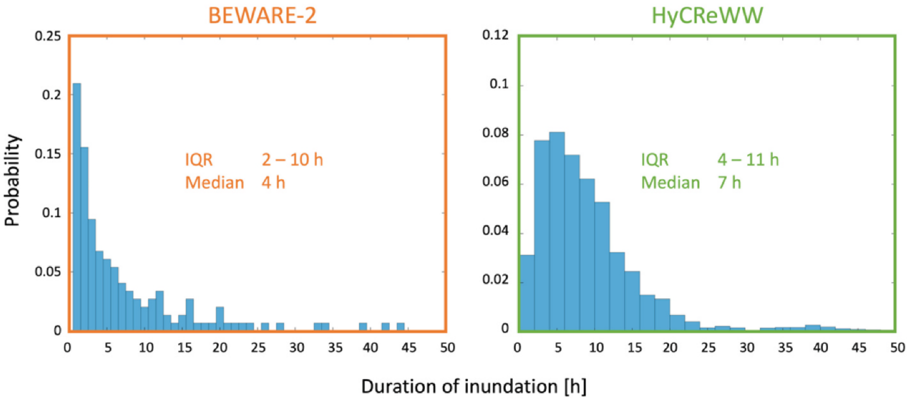

Fig. 3. Weighted histograms of the duration of the runup events modeled with BEWARE-2 (left, orange) and HyCReWW (right, green).

4 Discussion

The duration of the modeled runup events is important to deepening the understanding of flood risk to sea turtles as inundation for 6 h can decreases the viability of eggs by 30% [2]. The median durations of inundation were 4 and 7 h for BEWARE-2 and HyCReWW, respectively. The incubation period of green turtles is about 50–70 days [1], so nests should be placed at an elevation where it is unlikely that the nest will be inundated at all during the 2-month period.

As a conceptual exercise, the 5-year return period runup elevation at Ras Baridi was suggested as a ‘safe nesting elevation’ for sea turtles at Ras Baridi, with nests below this elevation deemed at risk. Such a threshold can be used in situ to determine which nests to relocate to higher elevations. This was at 1.25–1.75 m (BEWARE-2) and 1.2–1.3 m (HyCReWW) depending on the reef width. BEWARE-2 consistently predicted higher runup than HyCReWW, indicating it could be more suitable for conservative conservation strategies.

This study explored a methodology to estimate wave runup in data-limited coral reef environments using global, low-resolution data and low computational-cost meta-models. In regions where there is no alternative, such approaches may provide first estimates that can, for instance, help inform conservation strategies aimed at protecting vulnerable sea turtle nests from flooding.

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