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Assessment of runup predictions by empirical models on non-truncated beaches on the south-east Australian coast

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ABSTRACT

This paper assesses the accuracy of 11 existing runup models against field data collected under moderate wave conditions from 11 non-truncated beaches in New South Wales and Queensland, Australia. Beach types spanned the full range of intermediate beach types from low tide terrace to longshore bar and trough. Model predictions for both the 2% runup exceedance ($R_{2\%}$) and maximum runup (R_{max}) were highly variable between models, with predictions shown to vary by a factor of 1.5 for the same incident wave conditions. No single model provided the best predictions on all beaches in the dataset. Overall, model root mean square errors are of the order of 25% of the $R_{2\%}$ value. Models for $R_{2\%}$ derived from field data were shown to be more accurate for predicting runup in the field than those developed from laboratory data, which overestimate the field data significantly. The most accurate existing models for predicting $R_{2\%}$ were those developed by Holman [12] and Vousdoukas et al. [40], with mean RMSE errors of 0.30 m or 25%. A new *model-of-models* for $R_{2\%}$ was developed from a best fit to the predictions from six existing field and one large scale laboratory $R_{2\%}$ data-derived models. It uses the Hunt [17] scaling parameter $\tan\beta\sqrt{H_o L_o}$ and incorporates a setup parameterisation. This model is shown to be as accurate as the Holman and Vousdoukas et al. models across all tidal stages. It also yielded the smallest maximum error across the dataset. The most accurate predictions for R_{max} were given by Hunt [17] but this tended to under predict the observed maximum runup obtained for 15-min records. Mase's [22] model has larger errors but yielded more conservative estimates. Greater observed values of R_{max} are expected with increased record length, leading to greater differences in predicted values. Given the large variation in predictions across all models, however, it is clear that predictions by uncalibrated runup models on a given beach may be prone to significant error and this should be considered when using such models for coastal management purposes. It should be noted that in extreme events, which are lacking in the dataset, runup may truncated by beach scarps, cliffs, and dunes, or may overtop, and as a result, the probability density functions will have different tail shapes. The uncertainty already present in current models is likely to increase in such conditions.

1. Introduction

Runup is the final stage of a wave's landward propagation, and thus the determinant of the most landward position a wave can reach before receding seaward. Runup above the local ocean level outside the surf zone results from a combination of two processes: wave induced set up and swash (i.e., [12]. Past research has focussed on modelling maximum wave runup values, most commonly R_{max} [17,21,9] and $R_{2\%}$ [11,12,21,24,29,35,36,39–41]. R_{max} is the greatest elevation obtained by a single runup event within a given time period and is therefore a function of record length. $R_{2\%}$ is a statistical measure of the elevation exceeded by only 2% of all runup or swash events within a time period and, given constant wave conditions, should not vary with record length.

The importance of being able to predict maximum runup values for different wave and beach conditions is obvious with regard to hazard risk assessment. Typical applications include assessing overtopping swash flows [4,25], forecasting beach erosion with respect to climate change [7,19], or for design purposes, such as for beach nourishment or the positioning of temporary structures near the shoreline. A

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common goal has been to develop empirical models for predicting runup elevations that makes use of readily available or easily obtainable parameters. Models typically include a combination of (though not necessarily all of) wave height and length (H and L, respectively) and the beach (or swash zone) slope (β). Other important factors to take into account may be related to time-varying ocean water levels (i.e. tidal elevation), which can change the surf zone characteristics considerably.

Empirical runup models have been developed from both laboratory (e.g. [41,17,21]) and field data (e.g. [12,24,36]). Laboratory conditions are useful for separating the influence of different variables and excluding 3D effects. However, scale effects can be present in smaller scale models and often result in distorted dimensions of some variables; sediment size being a common example [14]), such that when scaled up to a prototype, a grain of sand may be more representative of gravel, which could result in different runup distributions. Field data on the other hand makes detection of the most influential variables more difficult and obtaining a wide variety of representative conditions is not always possible, such that the range of beaches and/or conditions used to create a model can be limited (e.g. [12,9,29,40]). Thus, individual models may not be applicable to beaches or wave conditions far beyond the parameter space initially used to develop the model. The method by which the runup is measured may also influence the recorded values. Recently, there has been a trend to measure runup through video analysis (e.g., [12,29,36]) and [40], while previous work used resistance wires (e.g., [21,11,39]) or counted the number of waves passing known locations up the beach [24]. Ref. [13] provide a discussion on the advantages and disadvantages between the resistance wire and image analysis techniques.

The use of large data sets and subsequent fitting to an empirical model by coefficients can result in reduced accuracy when considering specific parameter spaces [36,37]. Many other potential influences on runup have also been excluded because they are unknown or cannot be easily parameterised. For example, the nearshore bathymetric profiles of field sites used to develop runup models differ significantly, but this is not typically included as a model parameter. Variation in the nearshore bathymetric profile could lead to variable wave energy attenuation due to different shoreface slopes [42] and result in varying correlations between runup elevations and offshore wave conditions. Therefore, a model developed using data collected on the north-east coast of the United States (e.g. Duck, N.C., [12]) may provide less accurate runup predictions on Australian beaches compared with a model developed locally (e.g. [24]), or a model developed from planar laboratory beaches. As a result, runup models that have been developed using data from a specific site, or from a limited range of field data sites, may not be the best model for other locations. Shand et al. [32] obtained R_{max} field data by surveying debris lines following high energy events and compared their data with field and laboratory $R_{2\%}$ models. They found differences between laboratory- and field-data derived models and, perhaps unsurprisingly, found a tendency for the $R_{2\%}$ models to underestimate their measured R_{max} values.

Here, we investigate the performance of a range of available runup models applied to data from the southeast Australian coast. We determine model limitations and error margins that should be considered when using empirical models to forecast runup when no data for calibration is available.

Despite the absence of tidal water levels as a parameter in the runup models assessed below, the potential effect of tidal elevation on runup exceedance values is of interest because the surf zone conditions often differ between high and low tide [33,34]. Ref. [40] observed that runup models tended to over predict runup at low tidal stages and under predict during higher tidal stages, suggesting variability in wave energy dissipation at different stages of the tidal cycle. The south-east Australian coast is microtidal with a very steep lower shoreface, suggesting that the tidal influence may be less than in other regions [33]. Despite this, [27] observed differences in model performance depending on whether the tide was rising or falling; however, their observations were limited to only a few beaches, suggesting this is a factor worth investigating further with additional data from a wider range of beaches.

A caveat that must be noted for models derived from field data is that the most extreme runup events often occur in scenarios where the runup is truncated by a scarp or cliff, or overtopping occurs. None of the current empirical models are valid for these morphological conditions. After the 2011 Tohoku Tsunami, runup on coasts lined by 16 m cliffs had the highest watermarks of 21 m above mean sea level [31]. Callaghan et al. [8] reported extensive destruction of buildings due to wave impacts from waves overtopping 20 m high cliff faces. Runup data used for model calibration are, by necessity, obtained from conditions where the runup is not truncated and therefore may not include extreme events. This is also the case in the present study, where the existing and new models have been derived for runup on non-truncated largely planar beaches, with no impact on dunes or cliffs. Therefore, extreme conditions are typically, but not always (e.g. [10], outside the parameter space used to develop the empirical models, potentially limiting their use to less severe wave conditions. However, the widely observed and consistent scaling on H and L allows a degree of extrapolation and, therefore, application of such models to more extreme conditions.

The present paper addresses these issues and examines the accuracy of a suite of runup models, assessed for moderate wave conditions on 11 largely planar beaches along the south-east Australian coast. Beach states ranged from longshore bar and trough to low tide terrace [43] (Table 2). The geographically diverse dataset and range of wave and beach conditions allows for a comprehensive assessment of the accuracy and typical error margins of common empirical runup models applied to beaches falling within this range of beach states. A total of 11 runup models are assessed, viz.: [41,17,21,12,24,9,39,29,11,36,40]. These models have been developed using both laboratory and field data. Consistent differences in performance between the models developed from small scale laboratory data and those developed from field data are identified. Excluding small scale laboratory derived models, two different *model-of-models* are also developed by taking the best fit to predictions made by other models for a range wave and beach conditions, represented by the Iribarren number [18]. The *model-of-models* is then assessed in conjunction with the assessment of the existing empirical models. The paper is organised as follows. A brief outline of each of the models assessed follows in Section 2. Details of the field data sites, data collection, and analysis techniques are provided in Section 3. A comprehensive analysis of the results is presented in Section 4, followed by a discussion in Section 5. Concluding remarks are made in Section 6.

2. Selected runup models

Numerous empirical runup models are available which have been derived from laboratory or field data. A total of 11 models are described in this section, distinguished by the data type from which they were derived, i.e. laboratory data or field data. All of the field data derived $R_{2\%}$ models [12,23,24,29,36,40] and one large scale laboratory [39] $R_{2\%}$ model's predictions have been plotted over the range of Iribarren numbers experienced in the present data set (Fig. 1). For later reference in figure captions, each model is given an abbreviation (Table 1).

2.1. Runup models derived from laboratory data

The laboratory data used for model development consisted of regular (monochromatic) wave and random wave experiments. Ref. [41] used small scale flume data with combinations of waves with and without wind to assess wave runup distributions on an impermeable