How well can wave runup be predicted? Comment on Laudier et al. (2011) and Stockdon et al. (2006)

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Abstract

Laudier et al. (2011) suggested that there may be a systematic bias error in runup predictions using a model developed by Stockdon et al. (2006). They (Laudier et al.) tested cases which sampled beach and wave conditions that differed from those used to develop the Stockdon et al. model. Based on a re-analysis that we conducted, we found that in two of the three Laudier et al. cases observed overtopping was actually consistent with the Stockdon et al. predictions. In these cases, the revised predictions indicated substantial overtopping with, in one case, a freeboard deficit of 1 meter. In the third case, the revised prediction had a low likelihood of overtopping, which reflected a large uncertainty due to wave conditions that included a broad and bi-modal frequency distribution. The discrepancy between Laudier et al. results and our re-analysis appear to be due, in part, to simplifications made by Laudier et al. when they implemented a reduced version of the Stockdon et al. model.

Keywords

Beach, nearshore, field data, imagery, verification, uncertainty,

Introduction

Estimates of wave-driven overwash are valuable for making predictions of morphologic change [Sallenger, 2000], such as dune erosion and barrier island roll-over, ecological change associated with redistributions of sand and vegetation [e.g., Schupp et al., 2013], and saltwater fluxes into back-beach lagoons and estuaries [Laudier et al., 2011]. All of these overwash impacts can affect human safety, recreation, and economic well-being, either directly or indirectly. Estimating overwash requires estimates of both the total water level associated with tides, storm surge, and wave runup and the beach berm or dune elevation that may be overtopped by waves. Knowing the conditions under which overwash predictions are valid and understanding the source and magnitudes of uncertainties will influence how we use our knowledge to help society make decisions regarding the risks associated with inundation or severe erosion—and it can guide where future research efforts should be directed.

Here, we examine an evaluation of the wave runup parameterization initially presented by Stockdon et al. [2006] that has been the basis for a number of research studies, as well as operational predictions of overwash for nearly a decade [Stockdon et al., 2012]. The Stockdon et al. [2006, hereinafter referred to as S2006] parameterization is a best-fit linear model relating nearshore wave height and wave period and the swash zone beach slope to wave-runup levels:

$$R_2 = 1.1 \left(0.35\beta (H_0 L_0)^{1/2} + \frac{[H_0 L_0 (0.563\beta^2 + 0.004)]^{1/2}}{2} \right) \quad (1)$$

where R_2 is the level exceeded by only 2% of the runup levels, β is the foreshore slope, H_s is the significant wave height measured in 20 m water depth and L_0 is the wave length (computed from peak wave period, T_p , at 20 m depth). In total, the parameterization is the integration of three separate models that predict (1) wave-driven setup and swash motions due to both (2) incident-band and (3) infragravity-band frequencies. The role of swash zone slope is to reduce the contribution of setup and incident-band swash for gently-sloping, dissipative beaches [e.g., *Ruggiero et al.*, 2004]. Conversely, setup and incident-band swash will be more important on steeper, more reflective beaches. This suggests that runup on either very flat or very steep beaches could be predicted by neglecting certain processes using the S2006 parameterization at either of these end members. However, the full parameterization (equation 1) is easy to evaluate, and the inputs are not difficult to obtain. Additionally, the computational effort is not reduced if one or two of the three terms representing setup, incident swash, and infragravity swash are omitted. As such there is no reason to omit terms other than to assess the relative contributions of each process to the total runup, or overwash, estimate.

Thus, the most scientifically robust evaluations and applications of S2006 (or any overwash estimate using this parameterization) would include data that resolve each of the contributing processes, identify the relative importance of each to overwash, and quantify prediction errors associated with each term [e.g., as was done by *Stockdon et al.*, 2006]. However, observed water level or runup data required for such a demanding test are difficult to collect. Overwash estimates have been evaluated using proxies including observations of beach and dune erosion [*Stockdon et al.*, 2007; *Plant and Stockdon*, 2012] or of overtopping levels in back-beach lagoons [*Laudier et al.*, 2011; *Gallien et al.*, 2014]. Many of these studies (and even those that make direct measurements of runup) have concluded that the S2006 parameterization has meaningful predictive skill [*Senechal et al.*, 2011; *Guza and Feddersen*, 2012; *Matias et al.*, 2012]. The predictions are never perfect, which is to be expected since the S2006 parameterization was fit to a large number of field observations and includes uncertainty due to, for instance, short-scale alongshore variability and wave breaking variations related to different tide levels. Discrepancies between parameterized and observed runup can be attributed to a number of other factors, including uncertainty in nearshore wave height (nominally in 20 m water depth) and uncertainty in beach slope and beach topography, which should be measured synchronously with overwash events—but rarely are. Systematic uncertainty in the S2006 parameterization has been shown to be related, in part, to neglecting some details of wave-directional spectra [*Guza and Feddersen*, 2012] and morphological variations modulated by tides [*Guedes et al.*, 2011]. Some of these factors were analyzed by S2006.

Laudier et al. [2011, hereinafter L2011] investigate the performance of several overtopping models by comparing simulated overtopping to observed water level change in a closed lagoon. As part of a discussion, they conclude that the S2006 parameterization underestimates runup because when used in an overtopping model [*Hedges et al.*, 1998] no overtopping was predicted in cases where overtopping was observed. The prediction failure was hypothesized to be due to the fact that the S2006

parameterization included data from barred beaches, while L2011 studied a non-barred beach. L2011 speculate that, because wave heights used in the S2006 model development do not explicitly account for wave breaking over sand bars, the resulting parameterization must do so implicitly and the result will be a systematic under prediction of runup at non-barred sites. If this is the case, then runup at non-barred beaches will fall outside of the range of expected uncertainties (i.e., $rmse = 32\text{ cm}$) reported by S2006. A significant systematic error is concerning because it affects the interpretation of other studies that have utilized the S2006 parameterization (which has been cited over 200 times), and it affects future scientific studies and applications. Here, we find that the L2011 conclusions on the S2006 prediction errors are over stated; the S2006 predictions are actually generally consistent with the L2011 observations. We illustrate our findings with a re-analysis of L2011 and attempt to identify the source of our differing conclusions.

Re-analysis of L2011 runup predictions

The primary objective of L2011 was to test the accuracy of overtopping models by comparing predicted and observed overtopping rates. Changes in lagoon water levels were used as a proxy measurement of waves overtopping a beach berm. L2011 evaluate several overtopping models that require estimates of runup height due to wave-driven swash, which are added to measured tide level to get total water levels. Because wave processes are intrinsically stochastic and wave-by-wave processes are not resolved in their study, overtopping rates must be related to a statistical representation of runup heights, such as extreme value estimates (i.e., 1% or 2% exceedance levels). L2011 utilize several runup models, including Pullen et al. [2007], which they refer to as the European model. The European model is based on fitting parameters, analogous to the S2006 approach, but using laboratory data rather than field observations. It includes many of the same terms as S2006, with different dependencies for dissipative and reflective conditions. A disadvantage of the European model, acknowledged by L2011, is that it requires a measure of wave height immediately in front of the zone of wave runup. Consistent with the S2006 approach, L2011 replace this value with a nearshore significant wave height (H_s) measured in 15 m depth and correct for this by fitting calibration coefficients. L2011 then introduce the S2006 parameterization as a model developed using data from natural beaches. They note that the S2006 parameterization fit data based on conditions that were limited to offshore wave heights less than 2.5 m, which may limit its applicability to larger waves. (L2011 do not state whether the European model suffers from a similar limitation.) Both the European and S2006 parameterization predict the 2% exceedance level (R_2).

Because the main focus of L2011 is prediction of overtopping fluxes (of water) into the lagoon, they add an additional model to compute overtopping fluxes that is driven by R_2 estimates. Here, we do not discuss the overtopping models but, instead, focus on the implementation and accuracy of R_2 predictions. We are interested in determining whether the predicted occurrence of overtopping was likely or, as L2011 claimed, unlikely when the S2006 parameterization is used to estimate runup. The occurrence of overtopping is based solely on whether the freeboard deficit (i.e., R_c , the difference between total water levels and berm elevation [Baldock et al., 2012; Long et al., 2014]), exceeds 0. In this application, total water level includes the tide level, which is added to the runup level. L2011 point out

that the overtopping formulations define R_c values differently, such that exceedance statistics of runup maxima are required rather than statistics of the runup time series (e.g., R_2), which includes the entire swash trajectory from runup to rundown. However, if runup maxima are Raleigh distributed, then it is possible to relate statistics of maxima to statistics of runup time series. Using numerous assumptions, parameterized fitting of laboratory and field data sets, and ad hoc substitution of observable variables for experimental variables, L2011 develop overtopping predictions driven by oceanographic data relevant to their study site.

Calculating whether total water levels, including tide and S2006 parameterized wave runup, exceed the berm elevation is sufficient to determine whether there will be overtopping. To implement S2006, H_0 , T_p , beach slope, tide level, and berm elevation, as reported in L2011, are used to recompute R_c values. Figure 1 shows a re-analysis of L2011 runup Case 1 data digitized from L2011's figures 5 and 6. In contrast to the application of S2006 by L2011, overtopping is predicted during peak tide (1500-1600 hrs), particularly along the middle section of the beach (40-100 m alongshore), where overtopping was observed. L2011 do not show the R_2 estimates for any of their field cases, so a direct comparison of our runup height prediction to theirs is not possible. We re-evaluated the sensitivity analysis presented in L2011's Figure 9 and confirm that, under the assumption of negligible infragravity contribution and straight substitution of T_{m-1} for T_p , the results are identical to the reduced version of S2006 (L2011 equation 15).

We compare the L2011 conditions to the original S2006 data [Stockdon and Holman, 2011] to determine whether there is a systematic and statistically significant difference in the runup behavior for the conditions observed by L2011 compared to the data used to develop the S2006 parameterization. Because L2011 did not directly measure the runup elevations, we use the surveyed beach heights as a proxy for observed runup—assuming that, because overtopping was observed in each case, runup reached this level. Actual runup might be higher than what this approach would indicate—but, again, we are concerned with the fundamental issue of whether overwash would be predicted by S2006, and this is an objective way to address this concern. We included uncertainties in wave height, wave period, and beach elevations (reported in L2011 Table 1) by sampling these values from uniform distributions spanning the range of reported values. We find that overtopping ($R_c > 0$) was predicted by S2006 for L2011 case 1 and case 2 with extremely high probability, 50% and 70% likelihoods, respectively (Figure 2). In Case 3 the probability of predicted overtopping was just 7%. However, this is still high enough to expect an infrequent overwash event under these conditions.

Discussion and conclusions

Our reanalysis of L2011 demonstrates that, in two of three cases, the S2006 parameterization predicts overtopping over a wide range of possible variations in the input conditions associated with spatial variability (slope and beach height) and temporal variability (wave conditions). Specifically, Case 1 falls directly in line with predicted runup while Case 2 slightly over predicts runup (in contrast to the report of underprediction by L2011). The L2011 cases are indeed at the upper end or above the range of runup values used to develop the S2006 parameterization and, therefore, provide a valuable study to

contribute to predictive evaluations. In fact, many of the applications of the S2006 parameterization are aimed at extreme storms where it is expected that runup exceeds the values used in the S2006 development and where there are rarely observations to directly evaluate the prediction skill.

L2011 suggested that S2006 might systematically underestimate runup at their non-barred study site because the original parameterization relied on data largely from barred beaches. However, there is no evidence of a systematic error as (1) our re-analysis predicts overtopping (Figure 1) and (2) the prediction errors and uncertainties are consistent with the original S2006 analysis (Figure 2). In L2011, there were no examples of the S2006 runup predictions for the test cases, so it is difficult to determine the magnitude and cause of the discrepancies between our re-analysis and their result. But, we believe that L2011 under predict runup using S2006 due, in part, to unnecessary simplifications of the full S2006 parameterization. L2011 neglect the infragravity contribution (the third term in equation 1). Even under reflective conditions (L2011, Table 1: Iribarren number 0.7 to 2.8), infragravity processes can contribute to between 25% and 50% of the total runup variance (S2006, Figure 10). For the cases considered here, neglecting infragravity contributions may reduce the total runup magnitude by 15-35 cm. Using the full form of the S2006 parameterization, we find that for the flattest slopes (e.g., Case 3, slope = 0.08) that infragravity and incident swash contribute equally to runup. For the steepest slopes (e.g., 0.2), the infragravity contribution is about 20% of the incident swash contribution. Finally, another discrepancy is the use by L2011 of spectral period (T_{m-1}) rather than peak period in their implementation of S2006. (L2011 assume $T_p = 1.1 T_{m-1}$.) Using the spectral period may account for a 10% reduction in predicted R_2 , which amounts to a 40-50 cm loss in runup.

Considering the re-analysis of Case 3, the predicted runup does not exceed the likely distribution of beach elevations in 93% of our random samples from the input distributions. While this may indicate a systematic error in the S2006 formulation, the re-analysis of the first two cases indicates that this is unlikely. Case 3 is marked by several factors that may be linked to the underprediction. The range of input values is wider than in the other cases (Figure 2), indicating that the prediction error might result from input uncertainty. The chief factors in the input uncertainty are the estimate of the peak wave period, T_p , for conditions that are spectrally more broad banded compared to cases 1 and 2 (see L2011 Figure 4) and that the energy distribution is bi-modal. The range in T_p values results in estimates of R_2 that vary by 1 m (L2011, Figure 9). It is quite possible with mixed swell and sea that selection of the lower T_p associated with sea waves does not represent the waves that are driving runup. This is a weakness of the S2006 model (and other models as well), which don't explicitly accommodate broad-banded or multiple peaks in the frequency or direction of the wave spectra. These errors are not unique to the L2011 cases and were already captured in the stated 32 rms accuracy of the S2006 parameterization. In addition to the difference in wave-frequency spectrum for case 3, waves were reported as approaching from a more northerly direction compared to the other two cases. The geometry of the coastline at the study site is complex (L2011, Figure 2), and it is possible that this leads to systematic differences in wave transformation to the study site. Also, it has been shown that wave directional spreading can explain some of runup variability [Guza and Feddersen, 2012]. The S2006 parameterization cannot explicitly resolve dependence of runup on wave-direction or directional spreading.

There was also an inconsistency in how model-fitting was applied to the S2006 parameterization. The other runup parameterizations used by L2011 include additional multiplicative coefficients that can account for directional variations (and other factors) and were tuned by L2011 to obtain the best fit overtopping predictions, with a different correction factor for each case. Without this additional correction, overtopping was over predicted using the European model. This is analogous to the demonstration by S2006 that runup data from different field experiments could be better parameterized by choosing new coefficients for each case—and this problem of experiment-specific tuning has been identified in other models [Apotsos *et al.*, 2008]. This point is subtle, but extremely important: If one wants the best possible prediction with parameterizations based on existing data, additional tuning can improve predictions by absorbing unresolved processes. On the other hand, if it is not known a priori which unresolved processes are important, predictions are likely most robust if they fit a wide range of conditions, as was done in S2006.

Others have cited L2011 to indicate that little is understood about beach runup and overtopping events and have concluded that existing predictive understanding is inadequate as cases can be identified where overtopping is either overestimated or underestimated [Gallien *et al.*, 2014]. We conclude that S2006 captures a very broad range of conditions from field observations with a best-fit prediction of runup and characterization of the prediction errors that provides broadly applicable understanding that is useful for both research and societal applications. There are certainly a number of processes that have been neglected by the S2006 formulation (e.g., wave directional and frequency spectral variations), which could explain significant prediction uncertainty. New data needs to be collected, particularly higher runup values over a broad range of beach conditions, in order to test the efficacy of improved parameterizations. While L2011 has contributed to advancing our understanding of overtopping prediction capability, the conclusion that there are systematic errors in S2006 is not valid. We believe our reanalysis better illustrates both the predictive value of S2006 (primarily through use of the full parameterization) and where tractable research lies (e.g., explicitly resolving the messy details of frequency and directional spectra).

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Figure 1. Temporal and spatial variations in (A) freeboard deficit, calculated as the difference between total water level and berm elevation, for L2011 Case 1. Total water level includes the measured tide and wave runup (R_2) calculated using S2006 parameterization. Warm colors indicate where and when freeboard deficit is greater than 0 and overtopping is expected. Detailed views of water levels and berm elevation are presented for (B) a single alongshore location (75 m), and also for a (C) single time at high tide (16:00 hrs) and single alongshore locations.

Figure 2. Comparison of S2006 to L2011 runup cases 1 (top), 2 (middle), and 3 (bottom). For L2011 (red dots), the “observed” value is the range of maximum berm elevations given for each case. Blue dots are data from *Stockdon and Holman, 2011*.