Evaluation of empirical predictors of extreme run-up using field data

Roger D. Shand[1], Tom D. Shand[2], Peter J. McComb[3] and David L. Johnson[3]
[1]Coastal Systems Research Centre; Geography Program, Massey University
[2]Water Research Laboratory, School of Civil and Env. Eng., UNSW
[3]MetOcean Solutions Ltd. New Zealand

Abstract

Prediction of run-up elevation during extreme events is of particular importance in defining and managing coastal hazards and in the design of coastal structures. A theoretical approach has not yet been developed to predict run-up elevation. However, a range of empirical formula have been developed over the past 50 years based on field and laboratory studies. While these empirical models utilise similar primary variables, their precise form differs due to derivation methodology and intended use. The present study compares the various models with run-up elevation data collected during a series of recent extreme events in 2008 and 2010 at Otaki Beach on the south-west coast of the New Zealand North Island, and the historical August 1986 storm event at Narrabeen Beach, New South Wales. The sensitivity of predicted values to differing definitions of slope on two non-planer, natural beaches of low to moderate slope is assessed. Study results show significant variation between the individual models and between the modeled and observed values. Models based on irregular wave testing in laboratory facilities generally gave run-up magnitudes most similar to those at the field sites when slope was defined based on the upper beach/swash zone slope, although trend lines indicated that as the observed run-up becomes more extreme, the modelled run-up may become increasingly under-predicted. The application of these results to other coastal locations is discussed.

Keywords: wave run-up, storm event, coastal hazard, beach morphology

1. Introduction

Wave run-up occurs as waves travel across the surf zone and are then carried by momentum above the still water level until such forces are exceeded by gravity. Run-up comprises two dynamically different processes [15]; firstly time-averaged wave setup, where water level becomes elevated to balance the on-shore directed momentum flux or radiation stress which occurs following wave breaking, and secondly swash excursion, a ballistic-type phenomenon where a propagating wave-form intersects a solid structure, in this case the beach, and is directed upward and forward. Extreme swash motions may cause damage to structures or threaten personal safety.

Factors which may influence run-up include offshore wave characteristics, beach and surf-zone slope and morphology, as well as natural and artificial barriers. In addition, absolute elevation reached during extreme events is influenced by water-level components such as astronomical tide, storm surge and infragravity components within the surf zone. Swash motions on steep beaches are observed to typically occur at incident wave frequencies [8] implying a direct correlation between wave fronts and run-up. However, on flat, dissipative beaches swash motions at lower frequencies are often observed [17] indicating infragravity and/or far infragravity motions may dominate. This concept of lower frequency-dominated swash somewhat blurs the boundary between setup and run-up.

Difficulties inherent in run-up prediction include nonlinear wave transformation, wave reflection, three-dimensional wave and bathymetry effects, infragravity processes, porosity, roughness, permeability and groundwater elevation [18]. A theoretical approach has not yet been developed to predict run-up elevation. However, a range of empirical-based formula have been developed over the past 50 years using the results of field and laboratory studies. While many such expressions have been presented within the literature, a smaller number are commonly used within engineering design and hazard assessment; often without adequate justification of selection choice.

During 2008 and 2010 several significant storm events produced very high run-up elevations on the west coast of New Zealand's North Island. This paper describes these storm events and the associated run-up from the dissipative Otaki Beach field site. Run-up estimates using several commonly used empirical expressions are compared to those measured on-site. The sensitivity of these expressions to variation in the definition of slope is assessed. The expressions are also tested against a historic storm event at Narrabeen Beach, NSW to assess the effects of steeper morphology.

2. Existing Methods

Commonly used empirical run-up expressions are summarised within Table 1. Note that run-up is generally defined as corresponding to a certain percentage exceedance elevation, for example. the elevation exceeded by 10% of waves is termed $R_{10\%}$. For design wave run-up on beaches, $R_{2\%}$ is the most commonly used, this being is the run-up exceeded by two excursions out of 100.

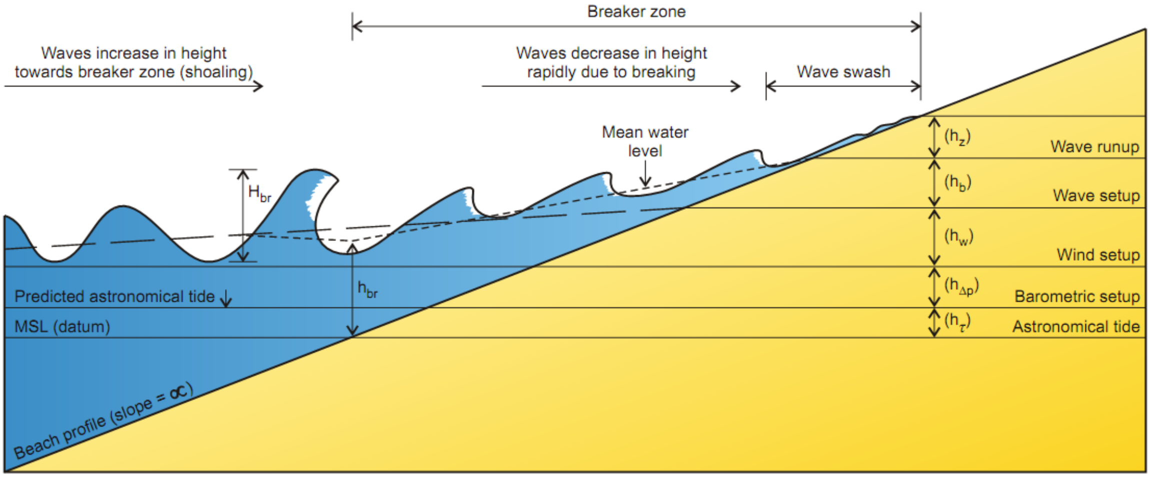


Figure 1: Schematic diagram of the run-up process.

Hunt (1959) [9] derived a simplistic model (model referred to hereafter as *Hunt59*) relating run-up (R) to offshore (deepwater) wave height and beach slope using a laboratory study of monochromatic waves on plane, impermeable beaches with slope steeper than 1(V):10(H) (Eqn. 1). This was adapted by Battjes (1974) [2] to incorporate wave steepness using the Iribarren number and was also fitted with an empirical coefficient derived from field data by Ahrens (1981) [1]. Mase (1989) [10] presented predictive equations for irregular run-up on plane, impermeable beaches (slopes 1:5 to 1:30) based on laboratory data (*Mase89*: Eqn. 2). These equations are also presented within the Coastal Engineering Manual [18] and modified by Hedges and Mase (2004) [4] to include wave setup, again for steep slopes only (1:5 to 1:30) (*H&M04*: Eqn. 3).

While laboratory experiments enable careful, quantified examination of the run-up process under varying wave and beach slope parameters, they are a simplistic representation of natural beaches. Holman (1986) [7] undertook field measurements of run-up at the CERC Field Research Facility at Duck, North Caroline, a generally reflective beach (slopes of 0.07 to 0.2) (*Hol86*: Eqn. 4). Run-up on this reflective beach was found to be dominated by swash motion at incident wave frequencies and the data best parameterised in terms of the Iribarren Number. By contrast, run-up on the very flat, dissipative beaches of Oregon was found to depend primarily on the deepwater, significant wave height Ruggiero *et al.* (2001) [13] with less dependence on beach slope and wave period. [13] combined the data obtained from the dissipative Oregon beaches with the [7] data from the reflective Duck site to derive a predictive expression which gave equal weighting to beach slope, deepwater wave height and deepwater wave length (*Rug01*: Eqn. 6).

Stockdon *et al.* (2006) [15] decomposed swash into incident and infragravity frequency bands. Incident swash was best parameterised using an Iribarren-based expression incorporating beach slope, in agreement with *Hol86*, and infragravity swash was best modelled using offshore wave height and wavelength only, and showed no statistical dependence on either foreshore of surf-zone slope. As such, [15] combined data from 10 field experiments in the USA, including the Duck and Oregon sites, and from field sites in the Netherlands to derive an expression incorporating setup and run-up components (*Sto06*: Eqn. 7). They also provided a simplified expression for extremely dissipative beaches where swash is dominated by infragravity motion.

Nielsen and Hanslow (1991) [12] had earlier evaluated run-up at 6 beaches on the New South Wales coast ranging from moderately dissipative (beach face slope of 0.026) to reflective (beach face slope of 0.19). They concluded that on steep beaches (> ~0.1), the vertical scale of best-fit run-up distributions is a function of both wave height and a surf similarity parameter, but that on flat, dissipative beaches (< 0.1), the vertical scale of distribution is independent of beach slope. Best fit length scales are presented for both cases and, under an assumption of Rayleigh distributed run-up, predictors for exceedance excursions were presented (*N&H91*: Eqn 5).

The expressions in Table 1 generally contain similar forcing parameters, although differ slightly in parameter emphasis and derived best-fit coefficients. All expressions have a beach slope parameter except for those given by *N&H91* and *Sto06* on dissipative beaches where slope is omitted. While the field studies generally used the intertidal beach slope, the definition is less clear when utilising laboratory-derived expressions where the entire bathymetry was a plane slope. While the Coastal Engineering Manual [18] suggests that the *beach face* should be used to define slope, alternative definitions including the upper beach/swash zone slope, or entire surf zone slope are possible and have been considered within the present study.

Table 1 Summary of commonly used empirical run-up expressions

	Laboratory, Regular Waves	
Hunt (1959)/ Battjes (1974)	$\frac{R}{H_0} = C\xi_0$ Empirical coefficient, C, is given as 1.61 (after Ahrens, 1981)	(1)
	Laboratory, Irregular Waves	
Mase (1989)	$\frac{R_{2\%}}{H_0} = 1.86\xi_0^{0.71}$	(2)
Hedges and Mase (2004)	$R_{2\%} = (0.34 + 1.49\xi_0)H_S$	(3)
	Field	
Holman (1986)	$R_{2\%} = (5.2\tan\beta + 0.2)H_S$	(4)
Nielsen and Hanslow (1991)	$R_{L\,2\%} = 1.98 \times L_{zwm}$ where $L_{zwm} = 0.6(H_{orms} \times L_o)^{0.5}\tan\beta$ for tan$\beta \geq 0.10$ $L_{zwm} = 0.05(H_{orms} \times L_o)^{0.5}$ for tan$\beta < 0.10$	(5)
Ruggiero et al (2001)	$R_{2\%} = 0.27(\tan\beta H_0 L_0)^{0.5}$	(6)
Stockdon et al (2006)	$R_{2\%} = 0.043(H_0 L_0)^{0.5}$ for $\xi_0 < 0.3$ $R_{2\%} = 1.1(0.35\tan\beta_f (H_0 L_0)^{0.5} + \left(\frac{[H_0 L_0(0.563\tan\beta_f^2 + 0.004)]^{0.5}}{2}\right)$ for $\xi_0 \geq 0.3$	(7)

Where R is run-up, H_0/H_s is deepwater significant wave height, L_0 is the deepwater wave period, ξ_0 is the deepwater Iribarren and tanβ is the beach slope.

3. Field Data

3.1 Kapiti Coast, New Zealand

The Kapiti Coast is approximately 40 km long, and characterised by a 3.5 km wide cuspate foreland which has developed in the lee of Kapiti Island. The run-up field site at Otaki Beach is located some 20 km north of the foreland (Figure 2). The inter-tidal beach is sandy and dissipative with a mean sediment diameter of D50 ≈0.16 mm. The mean beach width is ~100 m and the mean intertidal slope is 0.019 [3]. The beach is backed by a 5 m high foredune. The 300 to 500 m wide surf zone is characterised by 1 (possibly at times 2) sand bars and the average nearshore slope to 10 m depth is 0.010 (Figure 3).

The neap to spring tidal range is 0.4 to 1 m. The mean significant wave height is 1.1 m and the 1% exceedance significant wave height is 3.47 m [11]. Wave periods range between 3 and 17 s, with the peak period corresponding to the 1% exceedance significant wave height averaging 9.8 s. Seventy five percent of waves approach from the west-northwest, the window to the Tasman Sea.

Figure 2 Field site location at Otaki Beach, New Zealand with Kapiti Island in background. 21 September 2010.

A series of large storm events occurred during the winter of 2008 (24 June, 4 July and 23 July), and late winter 2010 (18 and 20-21 September). Run-up locations were identified either by the debris line, or by direct observation of the swash during the event. Note that wave-wave interactions, and topographic influence (dune irregularity and beach accessways) lead to longshore variation in run-up. Either during or immediately following each event, maximum run-up was marked along approximately 100 m of beach and later the positions and elevations surveyed with reference to NZMG and Wellington Vertical Datum 1953 (Mean Level of the Sea - 0.16 m). The resultant run-up data for each event were then averaged alongshore to provide a representative maximum run-up value for use in the subsequent analysis. Maximum run-up values for each event appear on Figure 4. Note, longshore variation in elevation of the maximum run-up line (for the 6 run-up episodes) ranged up to 0.9 m.

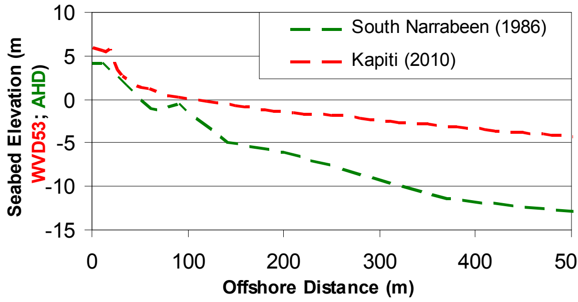


Figure 3 Typical cross-shore profiles for Otaki [3] and South Narrabeen [5] near the time of storm events

Wave and storm surge conditions during each run-up event were obtained from the Hindcast numerical model operated by Metocean Solutions Ltd. A high-resolution SWAN model is nested within regional and global Wavewatch III models which are driven by the GFS wind fields and include local wind data assimilation. Data was extracted at a position 6.7 km off the Otaki Coast, in approximately 45 m water depth. Tidal elevation was obtained from the NIWA tide model for the Otaki River mouth. Time-series of environmental conditions during the observed run-up episodes are presented in Figure 4, with the interval containing significant run-up peaks marked in red.

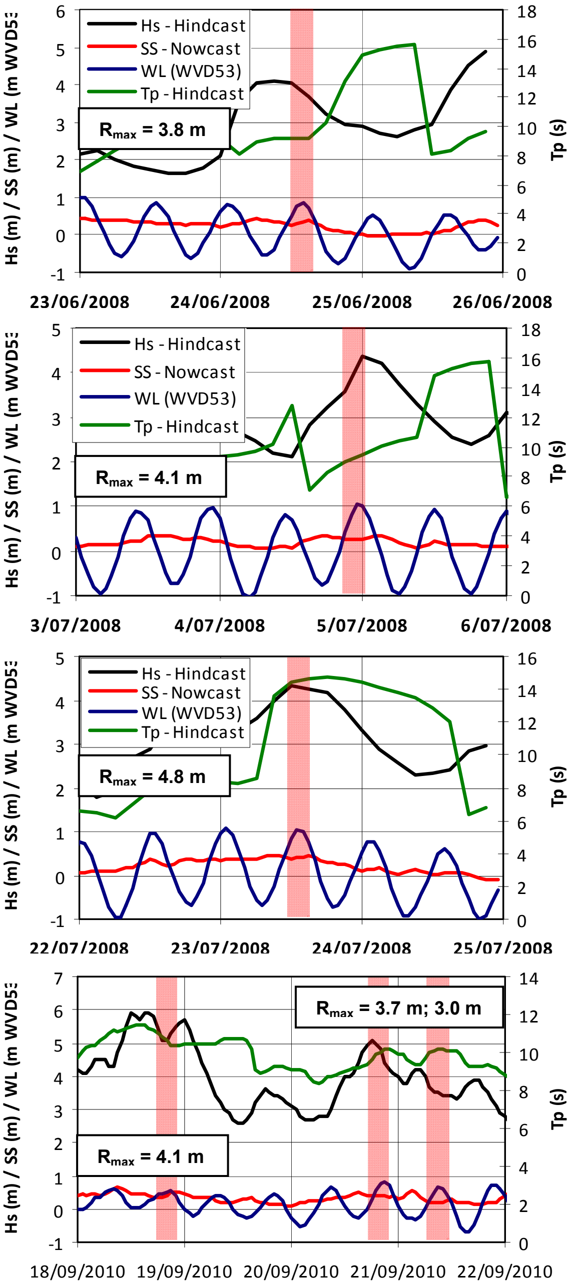


Figure 4 Time series of environmental conditions during the observed run-up period (marked in red) and maximum observed run-up elevations noted.

3.2 Narrabeen, New South Wales

While Otaki Beach is a relatively flat, dissipative beach with a steeper swash zone, many beaches such as the pocket beaches of the New South Wales Southeast Coast, exhibit a steeper cross-shore profile [16]. The Collaroy-Narrabeen embayment (Figure 5) is a 3.6 km long east facing reflective to intermediate type beach system [16] characterised by a steep offshore profile and single bar system (Figure 3). The beach has a mean sediment diameter of D_{50} ≈0.3 mm [6]. Wave run-up observed at South Narrabeen during a particularly severe storm event in August 1986 is compared to that predicted using the run-up expressions in Table 1 to determine whether the behaviour observed at Otaki Beach also applies to a steeper beach type.

Figure 5 Collaroy-Narrabeen Beach, NSW, March 1976. Photograph: A. Short

An intense low-pressure system off the New South Wales (NSW) coast in August 1986 produced offshore waves of over 7 m (Hs) which resulted in substantial beach erosion and extreme wave run-up. [5] give a comprehensive description of the storm event and resultant maximum run-up elevations and erosion volumes at beaches along the Sydney and Central Coasts. They provide detailed records of wind, water levels and wave conditions which occurred during the event. However, in summarising the environmental conditions and calculating theoretical run-up extents, they selected the maximum value for each parameter (including tide) that occurred over the 4th to 9th August 1986 storm period.

Offshore wave and water level conditions occurring over the 4th to 9th August 1986 are shown in Figure 6. Wave height peaked twice during the storm event, once on the 5th/6th and once on the 7th/8th. However, the coinciding high tide was larger during the first peak and peak period longer during the second peak. Maximum significant wave height reached over 7 m, which has a recurrence interval of around 7 years based on recent analysis of long-term buoy data [14]. While wave direction was not recorded by the wave buoy at Botany Bay, synoptic charts of the event indicate that wave direction during the peak on 5th/6th August was likely 110 to 120 degrees, increasing to 130 to 140 degrees during the second storm peak.

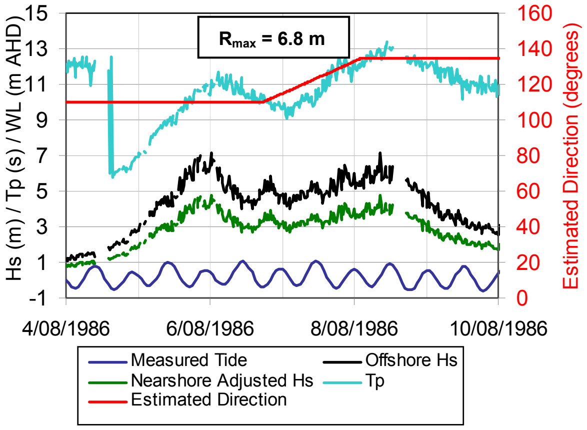


Figure 6 Wave and Water Level Conditions during the Storm Event of August, 1986 (source: MHL, MSB)

The sheltering effect afforded to South Narrabeen Beach by Long Reef Point has been assessed using results from a nearshore SWAN wave model investigation [6]. For waves with periods between 10 and 13 s and arriving from between 100 and 135 degrees, the reduction factor at South Narrabeen ranged between 0.65 and 0.7 of offshore wave height. Maximum observed runup along a 500 m stretch of beach at South Narrabeen ranged from 5.9 to 7.3 m, averaging 6.8 m.

Immediately prior to the 4th to 9th August 1986 storm, the upper beach/swash zone slope (tanβ) at South Narrabeen Beach was 0.10, the intertidal slope was 0.050 and the entire surf zone slope was 0.040 [5].

4. Evaluation of Empirical Expressions

The uncalibrated skill of each of the commonly used empirical run-up models was first tested using the Otaki storm data (Figure 7). The sensitivity of the models to three different slope definitions was tested; these slopes being the upper beach or swash zone slope between MSL and the vegetation line (tanβ = 0.044); intertidal slope between -1 and +1 m WVD53 (tanβ = 0.019); and the entire surf zone slope between approximate H_s breaking depth and vegetation line (tanβ = 0.012). The vegetation line was selected as it typically corresponds with storm run-up maxima.

Results show that best agreement is provided using the plane-slope, laboratory-based expressions of *Mase1989* and *H&M04* with the upper beach/swash zone slope. In these cases, run-up was predicted to within ±0.5 m (±15%) of the observed elevations with a mean difference (Table 2) of +4 to +5%. These expressions increasingly under-predict run-up when the intertidal or entire surf zone slopes are used. Of the field-derived expressions, *N&H91* provide the closest agreement, although as the beach slope (tan β) was always less than 0.1 regardless of definition, the *dissipative beach* version of the formula was used which excludes beach slope as a parameter. The *N&H91* expression predicted values 0.4 to 1.1 m lower than observed (12 to 30%). The remaining field-derived expressions under-predicted observed run-up, particularly when the intertidal or entire surf zone slopes were used. In these cases, under-predictions ranged between 24 and 66%.

The goodness-of-fit of the predictors was assessed by linear (least squares) regression modelling and Pearson correlation analysis between the modelled vs observed run-up data. Significant associations for n = 6 and the level of significance = 5%, occur when the correlation coefficient (r) is 0.811. All models, excepting *Hunt59* meet this requirement. Results show that the fitted line slope is, in all cases, less than one. This indicates that as the observed run-up becomes more extreme, the modelled run-up is increasingly under-predicted. The y-intercept of the laboratory-derived expressions is generally greater than zero, indicating that over-prediction likely occurs for lower run-up cases. The field-derived expressions of *N&H91*, *Rug01* and *Sto06* are, however, closer to zero indicating improved fit at lower run-up levels.

For the 4 to 9 August 1986 NSW storm, the time of maximum run-up was not known, so the temporal variation in run-up over this time has been assessed using the transformed local wave data and the previously-described run-up expressions (Table 1). All run-up equations predict maximum run-up at approximately 12 pm on 8th August. This maximum run-up elevation is marked on Figure 7.

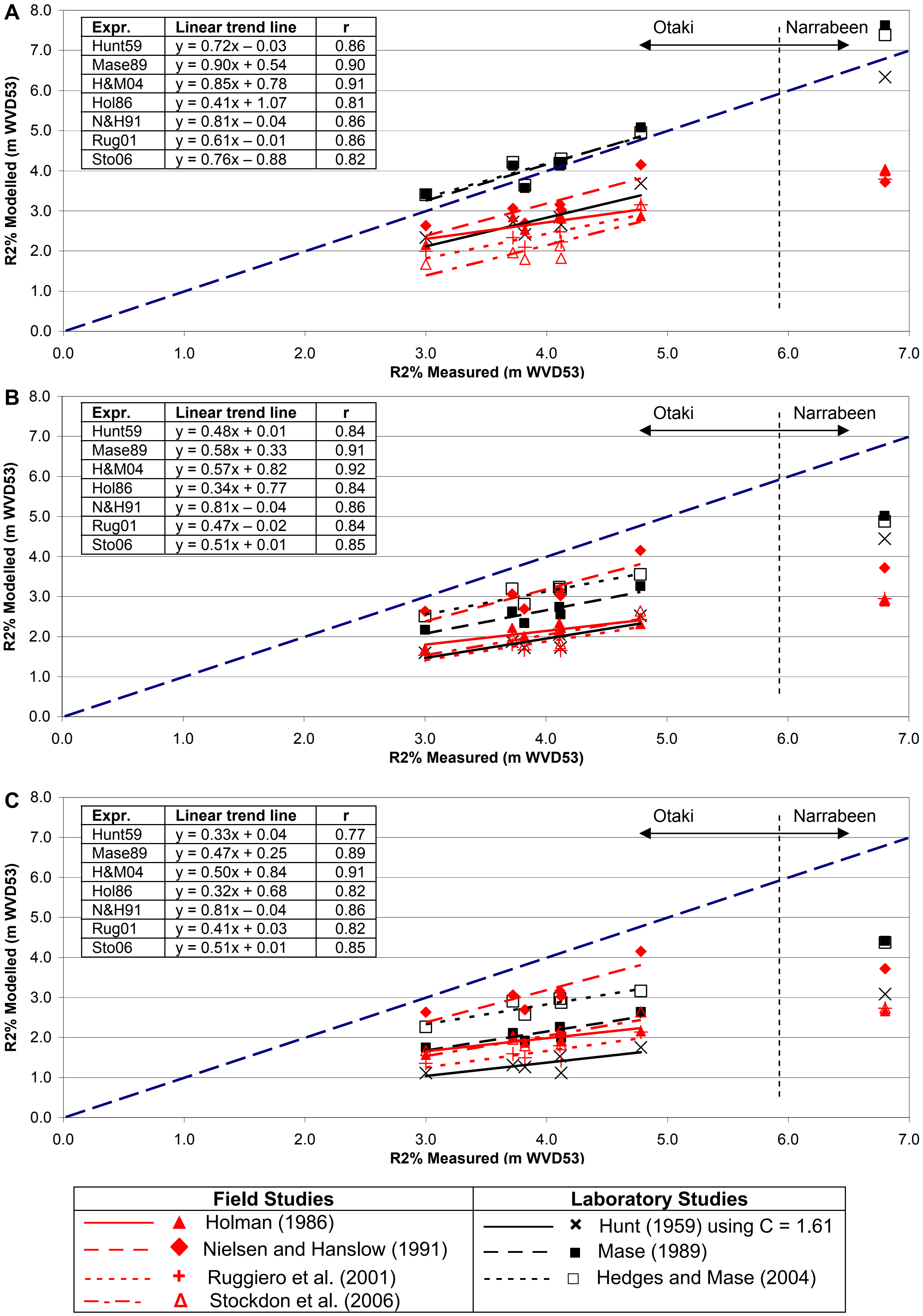
The steeper Narrabeen results are similar to the dissipative Otaki results. The Narabeen expressions derived from plane slope, laboratory data are in better agreement, or slightly over-predict observed values when the upper beach/swash zone slope is used (+9 to +12%). When the intertidal slope is used, laboratory derived equations under-predict observed run-up by -26 to -28% and, when the entire surf zone slope is used, by -35 to -36%. The expressions derived from field data again substantially under-predict run-up with the *N&H91* model providing best agreement (-45%). The remainder of the field-derived expressions under-predict run-up by up to 60% depending on slope definition.

Table 2 Summary of mean difference (%) between observed and modelled run-up for the Otaki storm data for each slope definition. Narrabeen difference indicated in brackets. Positive (over-predictions) indicated in **bold**.

Slope	Upper	Intertidal	Surfzone
Hunt59	-29% (-7%)	-51% (-35%)	-66% (-55%)
Hol86	-31% (-41%)	-46% (-58%)	-50% (-61%)
Mase89	**4% (12%)**	-33% (-26%)	-46% (-35%)
N&H91	-20% (-45%)	-20% (-45%)	-20% (-45%)
Rug01	-39% (-44%)	-53% (-57%	-58% (-60%)
H&M04	**5% (9%)**	-21% (-28%)	-28% (-36%)
Sto06	-47% (-41%)	-49% (-57%)	-49% (-60%)

5. Conclusion and Recommendations

Seven commonly used empirical run-up expressions are tested against field data obtained during several large storm events at Otaki Beach on the west coast of the New Zealand North Island. The sensitivity of the expressions to differing definitions of beach slope was also tested. These included the upper beach slope or swash zone slope, the intertidal slope and the entire surf zone slope. Results showed that expressions derived from laboratory testing using a plane slope and irregular waves [10; 4] provided better agreement with the observed extreme run-up values when the upper beach slope was used



A

Expr.	Linear trend line	r
Hunt59	y = 0.72x – 0.03	0.86
Mase89	y = 0.90x + 0.54	0.90
H&M04	y = 0.85x + 0.78	0.91
Hol86	y = 0.41x + 1.07	0.81
N&H91	y = 0.81x – 0.04	0.86
Rug01	y = 0.61x – 0.01	0.86
Sto06	y = 0.76x – 0.88	0.82

B

Expr.	Linear trend line	r
Hunt59	y = 0.48x + 0.01	0.84
Mase89	y = 0.58x + 0.33	0.91
H&M04	y = 0.57x + 0.82	0.92
Hol86	y = 0.34x + 0.77	0.84
N&H91	y = 0.81x – 0.04	0.86
Rug01	y = 0.47x – 0.02	0.84
Sto06	y = 0.51x + 0.01	0.85

C

Expr.	Linear trend line	r
Hunt59	y = 0.33x + 0.04	0.77
Mase89	y = 0.47x + 0.25	0.89
H&M04	y = 0.50x + 0.84	0.91
Hol86	y = 0.32x + 0.68	0.82
N&H91	y = 0.81x – 0.04	0.86
Rug01	y = 0.41x + 0.03	0.82
Sto06	y = 0.51x + 0.01	0.85

Figure 7 Predicted run-up elevation for the 2008 and 2010 Otaki storms and the 1986 event at Narrabeen, compared with observed run-up elevation (A) using an upper beach/swash zone slope (B), an intertidal slope, and (C) the entire surf zone slope.

(mean difference +4 to +5%) than when using the lower slope definitions (underestimated observed by up to 46%), or when using expressions derived from field studies (underestimated by up to 58%).

These results may be explained by the field-based expressions being derived from data collected during a range of wave and tidal conditions rather than just extreme events, with the final expressions based on overall least-error fitting. Resultant predictors are therefore weighted towards typical conditions. During extreme run-up events, water levels are generally substantially elevated with beaches adopting the classical equilibrium profile experiencing deeper water closer to the shoreline. In this situation, the dissipative component of the run-up process is less important than the ballistic swash component in determining the final run-up level. The laboratory-derived expressions use a plane bed so may better model the extreme run-up process.

Data collected on the steeper beach at South Narrabeen, NSW during an extreme storm event were also analysed using the run-up expression in Table 1. Findings are in close agreement with those from Otaki indicating these results may also apply to other beach types, although very steep beaches or reefs have yet to be tested.

Results of this study indicate that, as a first order approximation of extreme run-up on sandy beaches, the laboratory based models of *Mase89* and *H&M04* provide the most accurate estimation when the upper beach slope is used. However, for a site-specific evaluation, greater confidence may be achieved by collecting run-up data during extreme events and either optimising the slope definition for a selected model or calibrating a specific expression.

6. Acknowledgements

The authors thank the Kapiti Coast District Council and the Wellington Regional Council for funding, and Horizons Regional Council and Cuttriss Consultants Ltd for surveying run-up locations.

7. References

[1] Ahrens, J.P. (1981) Irregular Wave Run-up on Smooth Slopes. Coastal Engineering Technical Aid No. 81-17. Department of the Army, Coastal Engineering Research Centre. 26p.

[2] Battjes, J.A. (1974) Surf Similarity, Proceedings of the 14th Conference of Coastal Engineering, ASCE, pp. 466–480.

[3] Coastal Systems Ltd. (2008). Kapiti Coast Erosion Hazard Assessment: Part 1 Open Coast. Report prepared for the Kapiti Coast District Council by Coastal Systems Ltd., 79p.

[4] Hedges, T.S. and Mase, H. (2004) Modified Hunt's equation incorporating wave set-up, Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, Vol. 130, No. 3, pp. 109-113.

[5] Higgs, K. B. and Nittim, R (1988), Coastal Storms in NSW in August and November 1986, WRL Technical Report No 88/06, Water Research Laboratory, University of New South Wales.

[6] Harley, M. 2009. Daily to decadal embayed beach response to wave and climate forcing. PhD Thesis. School of Civil & Env. Eng, UNSW. 172p.

[7] Holman, R. A. (1986), Extreme Value Statistics for Wave Run-up on a Natural Beach, Coastal Engineering, Vol 9, No. 6, pp 527-544.

[8] Holman, R. A. and Sallenger, A.H. (1985). Set-up and swash on a natural beach. J. Geophys. Res., 90(C1): 945-953

[9] Hunt, I.A. (1959) Design of seawalls and breakwaters, Journal of Waterways and Harbours Division, ASCE 85 (1959) (WW3), pp. 123–152.

[10] Mase, H (1989), Random Wave Run-up Height on Gentle Slopes, Journal of the Waterway, Port, Coastal and Ocean Engineering Division, American Society of Civil Engineers, pp 593-609.

[11] MetOceans (2010) Design wave and water levels for the Kapiti Coast. Report prepared for the Kapiti Coast District Council by MetOceans Solutions Ltd. 30p.

[12] Nielsen, P, and Hanslow, D J (1991), Wave Run-up Distributions on Natural Beaches, Journal of Coastal Research, Vol 7, No. 4, pp 1139-1152.

[13] Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J. and Beach, R.A. (2001) Wave run-up, extreme water levels and the erosion of properties backing beaches, Journal of Coastal Research 17 (2), pp. 407–419.

[14] Shand, T.D., I D Goodwin, M A Mole, J T Carley, S Browning, I G Coghlan, M D Harley and W L Peirson. 2010B. NSW Coastal Inundation Hazard Study: Coastal Storms and Extreme Waves. WRL Technical Report 2010/16. Report for NSW Dept. of Env. Climate Change and Water. 41p + Appendices.

[15] Stockdon, H.F., Holman, R.A., Howd, P.A. and Sallenger, Jr., A.H. (2006) Empirical parameterization of setup, swash, and run-up. Coastal Eng. 53(7), pp 573-588

[16] Short, A.D. and Hesp, P.A. (1982). Wave, Beach and Dune Interactions in Southeastern Australia. Marine Geology, 48 (1982) 259-284.

[17] Thornton, E.B. and Guza, R.T. (1983). Transformation of Wave Height Distribution. J. Geophys. Res. 88(C10), 5925-5938.

[18] USACE (2006), EM 1110: Coastal Engineering Manual. US Army Corps of Engineers.