WAVE RUNUP AND WAVE RUNDOWN ESTIMATION BASED ON LONG-TERM VARIATION OF WIND STATISTICS

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Abstract

The paper presents a simple analytical method which can be used to estimate wave runup and wave rundown on shorelines and coastal structures for sea states based on long-term wind statistics. Nine different recently published wave runup formulae and one rundown formula are applied together with wind statistics from the Northern North Sea, the North Atlantic and the Northwest Shelf of Australia. Examples of results representing realistic field conditions are provided, demonstrating how global wind statistics can be used to make first-order estimates of wave runup and wave rundown.

Keywords: Wave runup; Wave rundown; Iribarren number; Wind statistics; Coastal protection work

1. Introduction.

The recent focus on climate change has generated interest in extreme phenomena; for example in the analysis of wave runup and wave rundown on shorelines and coastal structures like breakwaters, sand barriers, seawalls and artificial reefs; see the recent works by de la Pena et al. (2014), Blenkinsopp et al. (2016), Poate et al. (2016), Atkinson et al. (2017). For shorelines and coastal structures it is crucial to be able to make reliable assessments of the maximum runup and the maximum rundown in order to design safe and cost-efficient coastal protections.

The wave runup height is defined as the vertical difference between the highest point of wave runup and the still water level. Similarly, the wave rundown height is defined as the vertical difference between the lowest point of wave rundown and the still water level. The runup consists of two components; the wave setup and the swash. The wave setup is the mean water elevation level referring to the deep water level caused by the radiation stress (see Dean and Dalrymple (1984)). The swash motion oscillates from the wave setup corresponding to the interception between the water and the shoreline or structure; see de la Pena (2014) for more details. Due to the stochastic features of waves, most of the commonly used design formulae apply the 2% exceedance value of the runup maxima at the toe of the shoreline or structure, $R_{2\%}$, as well as the 2% exceedance value of the rundown maxima, $R_{d2\%}$. Most of these commonly used design formulae are given in terms of the surf (Iribarren) parameter defined in terms of the significant wave height H_s in deep water, the spectral peak period T_p in deep water, and the slope of the shoreline or the structure.

Some of the more recent works, which will be considered here and referred to in more detail in Section 2, are those of Vousdoukas et al. (2012), de la Pena et al. (2014), Blenkinsopp et al. (2016), Poate et al. (2017) and Atkinson et al. (2017), among which the latter gives a comprehensive literature review as well as a summary of wave runup formulae. Furthermore, Myrhaug (2015) and Myrhaug and Leira (2017) applied some of these recent wave runup formulae using long-term variation of wave conditions. Myrhaug (2015) used the de la Pena et al. (2014) wave runup formula, while Myrhaug and Leira (2017) used the Blenkinsopp et al. (2016) wave runup and wave rundown formulae by including a procedure demonstrating how the 100-years return period values for the wave runup and wave rundown and the corresponding value of significant wave height and surf parameter can be calculated.

The purpose of this paper is to demonstrate how long-term wind statistics in deep water can be used to provide first-order estimates of the wave runup and wave rundown on shorelines. Some recently published wave runup formulae and one wave rundown formula are adopted together with long-term distributions of the mean wind speed 10 m above the sea surface from the Northern North Sea, the North Atlantic and the Northwest Shelf of Australia. The present analytical method should represent a useful tool which can be used at an early stage in risk analysis.

2. Background

Several small and large scale laboratory, as well as field experiments, have been performed to study extreme wave runup and wave rundown events, resulting in empirical formulae for estimating the 2% exceedance values of runup and rundown maxima. The formulae used in this study are adopted from the recently published works briefly summarized in the following.

de la Pena et al. (2014) proposed a new formulation of maximum wave runup $R_{2\%}$ as

$$R_{2\%} = 4m^{0.3}H_s\xi_p \tag{1}$$

where $m = \tan\alpha$ is the slope with an angle α with the horizontal (see Fig. 1), and ξ_p is the surf parameter defined as

$$\xi_p = m\left(\frac{H_s}{\frac{g}{2\pi}T_p^2}\right)^{-1/2} \tag{2}$$

and g is the acceleration due to gravity. It should be noted that here, as well as in the other subsequent formulae, H_s and T_p represent one storm condition with a duration of e.g. 3 h and with a return period specified by the user. Eq. (1) is valid for $\xi_p < 0.6$ and based on physical small scale model experiments with a sand seabed using two grain sizes for the three beach slopes $m = 1/50, 1/30, 1/20$; see de la Pena et al. (2014) for more details.

Blenkinsopp et al. (2016) presented results on wave runup and overwash on a prototype-scale sand barrier using data from laboratory experiments and gave the following formulae of maximum wave runup

$$R_{2\%} = 1.165 H_s \xi_p^{0.77} \tag{3}$$

$$R_{2\%} = (0.39 + 0.795\xi_p) H_s \tag{4}$$

and maximum wave rundown

$$R_{d\%} = (0.21 - 0.44\xi_p) H_s \tag{5}$$

Here, Eqs. (3) to (5) are valid for m in the range 0.088 to 0.154 and ξ_p in the range 1 to 2.9, and were obtained by investigating the performance of existing formulae of extreme wave runup maxima and wave rundown maxima based on both laboratory and field data. They compared these formulae with their own data, finding that two of the formulae of extreme runup maxima based on the small scale laboratory data by Mase (1989) and Hedges and Mase (2004) performed best. Thus, Eqs. (3) and (4) are modified versions of the original Mase (1989) and Hedges and Mase (2004) formulae, respectively. Blenkinsopp et al. (2016) suggested that the linear model in ξ_p (Eq. (4)) is the most easy model to apply to runup data for the range of beach slopes they examined.

Poate et al. (2016) presented a new parameterization for runup on gravel beaches from field experiments as well as from numerical calculations:

$$R_{2\%} = C_1 m^{0.5} T_z H_s \ ; \ C_1 = 0.49 \tag{6}$$

where T_z is the mean zero-crossing wave period. The field data upon which this formula is based were collected during a period of 2 years covering storm conditions with H_s in the range 1 m to 8 m from gravel beaches and barriers composed of fine gravel to large pebbles. It was recommended to use Eq. (6) when spectral wave data is not available; see Poate et al. (2016) for more details. Atkinson et al. (2017) assessed wave runup predictions on beaches on the south-east Australian coast using 11 existing empirical models. The data they used for comparison represent *m* in the range 0.02 to 0.16, ξ_p in the range 0.32 to1.65, and the bottom sediments consisted of medium sand with d_{50} in the range 0.25 mm to 0.5 mm. Furthermore, the wave conditions that were assessed, covered a range with the averages of about H_s = 1.5 m and T_p = 8.9 s, which were slightly below the mean conditions typical of the region with about H_s = 1.6 m and T_p = 9.5 s. Thus, the testing of the models in Eqs. (9) and (10) has been limited to the near-average conditions. However, the models are also considered to cover higher wave conditions since the models that Eqs. (9) and (10) are based upon, cover a wider range up to about H_s = 5 m and T_p = 15 s. Among the models they considered were those by Holman (1986), Vousdoukas et al. (2012) and two models proposed by the authors. The Holman (1986) model is based on measured wave runup maxima from field data obtained at Duck, North Carolina given by

$$R_{2\%} = (0.2 + 0.83\xi_p)H_s \tag{7}$$

The Vousdoukas et al. (2013) model is based on manually selected runup maxima measured on the south coast Algarve, Portugal (representing the European Atlantic coast), given by

$$R_{2\%} = (0.58m + 0.53\xi_p)H_s + 0.45 \tag{8}$$

In this formula, it should be noted that it yields a finite value of 0.45 for the runup when the offshore value of H_s is zero. Moreover, they proposed the following two formulae based on the best fit to the 11 models they considered where one of them (Eq. (9)) is forced through the origin

$$M1 R_{2\%} = 0.99 H_s \xi_p \tag{9}$$

$$M2 R_{2\%} = (0.16 + 0.92\xi_p)H_s \tag{10}$$

As a summary, Eqs. (1), (3) – (5) and (7) – (10) can be represented as

$$R_2 = aH_s + bH_s \xi_p^c + d \tag{11}$$

3. Examples of results for a Phillips wave spectrum and long-term wind statistics

In the literature many standard spectral formulations are found where some contain the mean wind speed at a given elevation above the sea surface as the parameter, e.g. the Pierson-Moskowitz and the Phillips spectra (Tucker and Pitt, 2001). In this section some examples of results are given by choosing the Phillips deep water wave spectrum for long-crested wind-waves (Tucker and Pitt, 2001)

$$S(\omega) = \alpha \frac{g^2}{\omega^5} \; ; \; \omega \geq \omega_p = \frac{g}{U_{10}} \tag{12}$$

where $\alpha = 0.0081$ is the Phillips constant, $\omega_p = 2\pi / T_p$ is the spectral peak frequency, and U_{10} is the mean wind speed at the 10 m elevation above the sea surface. For a given wave spectrum, H_s and T_z are $H_s = 4\sqrt{m_0}$ and $T_z = 2\pi (m_0 / m_2)^{1/2}$, respectively, where the spectral moments m_n for long-crested waves are defined as

$$m_n = \int_0^\infty \omega^n S(\omega) d\omega \; ; \; n = 0,1,2,... \tag{13}$$

For long-crested deep water waves it follows from Eqs. (14) and (15) that

$$H_s = 4\sqrt{m_0} = \frac{2\sqrt{\alpha}}{g} U_{10}^2 \tag{14}$$

$$T_p = \frac{2\pi}{\omega_p} = \frac{2\pi}{g} U_{10} \tag{15}$$

$$T_z = 2\pi (\frac{m_0}{m_2})^{1/2} = \frac{\sqrt{2}\pi}{g} U_{10} \tag{16}$$

By using Eqs. (2), (14) and (15), Eq. (11) can be rearranged to

$$R_2 = C_2 U_{10}^2 + d \tag{17}$$

where

$$C_2 = a\frac{2\sqrt{\alpha}}{g} + bm^c\left(\frac{2\pi}{g}\right)^{\frac{c}{2}}\left(\frac{2\sqrt{\alpha}}{g}\right)^{1-\frac{c}{2}} \tag{18}$$

Furthermore, by using Eqs. (14) to (16), Eq. (6) can be arranged to

$$R_2 = C_3 U_{10}^3 \tag{19}$$

where

$$C_3 = 0.49\, m^{0.5}\frac{2\sqrt{2}\pi\sqrt{\alpha}}{g^2} \tag{20}$$

Thus, R_2 will depend only on U_{10} for given values of *m* and the coefficients *a*, *b*, *c*, *d*, and consequently R_2 can be obtained from known wind statistics.

Parametric models for the cumulative distribution function (*cdf*) (or the probability density function (*pdf*)) of $V \equiv U_{10}$ are given in the literature; see a recent review by Bitner-Gregersen (2015). In the present study the results are exemplified by using four *cdfs* of *V*; one from Johannessen et al. (2001), two from Mao and Rychlik (2016), and one from Bitner-Gregersen (2015). First, the *cdf* of *V* from Johannessen et al. (2001) is based on 1 hourly values of *V* from wind measurements covering the years 1973 - 1999 from the Northern North Sea (NNS). Second, the two *cdfs* of *V* from Mao and Rychlik (2016) represent the wind speed along ship routes in the North Atlantic (NA) fitted to 10 years of wind speed data. The results used here are from two locations in the North Atlantic; 20^{o}W 60^{o}N (South of Iceland); 10^{o}W 40^{o}N (outside the west coast of Portugal). These *cdfs* of *V* are given by the two-parameter Weibull model

$$P(V) = 1 - \exp\left[-\left(\frac{V}{\theta}\right)^{\beta}\right]\ ;\ V \geq 0 \tag{21}$$

with the Weibull parameters θ and β as

$$\text{NNS: } \theta = 8.426\,\text{m/s}, \ \beta = 1.708 \tag{22}$$

$$\text{NA}(20^{\text{o}}W, 60^{\text{o}}N): \theta = 10.99\,\text{m/s}, \beta = 2.46 \tag{23}$$

$$\text{NA}(10^{\text{o}}W, 40^{\text{o}}N): \theta = 7.11\,\text{m/s}, \beta = 2.30 \tag{24}$$

Third, the conditional *cdf* of V given H_s from Bitner-Gregersen (2015) based on wind data from hindcast analysis from the North-West Shelf of Australia (NWSA) is used. These data cover the years 1994 – 2005, representing a wide range of wind and wave conditions ranging up to about $H_s = 8\text{m}$ and $T_p = 20\text{s}$. This conditional *cdf*, which essentially is Eq. (21), is given by the two-parameter Weibull model

$$P(V \mid H_s) = 1 - \exp\left[-(\frac{V}{\theta})^{\beta} \right] ; \ V \geq 0 \tag{25}$$

with the Weibull parameters

$$\theta = 0.050 + 5.514\,H_s^{0.280} \tag{26}$$

$$\beta = 1.250 + 5.600\,H_s^{0.660} \tag{27}$$

Here, the dimension of H_s and θ are in metres and m/s, respectively.

In the following, the expected values and the variances of the wave runup and wave rundown are calculated based on the given formulae and wind statistics. This requires the calculation of $E\left[V^n\right]$ and $Var\left[V^n\right]$ for $n = 2$ and $n = 3$ according to Eqs. (17) and (19), respectively. As V is Weibull distributed this gives (Bury, 1975)

$$E\left[V^n\right] = \theta^n \Gamma(1+\frac{n}{\beta}) \quad (28)$$

$$\sigma^2\left[V^n\right] \equiv Var\left[V^n\right] = E\left[V^{2n}\right] - \left(E\left[V^n\right]\right)^2 \quad (29)$$

where Γ is the gamma funtion.

Thus, the present results are given for the average wind and wave conditions at the four sites, and Table 2 gives a summary of the results using the wind statistics from NNS, NA and NWSA. The corresponding values of $E[H_s]$ and $E[T_p]$ based on Eqs. (14) and (15), respectively, are also given in Table 2. It appears that $E[H_s]$ and $E[T_p]$ are in the ranges 0.9 m to 2.1 m and 4.0 s to 6.3 s, respectively. For NNS and NWSA the standard deviation (std. dev.) to the mean value (m.v) ratios are 1.2 and 0.2, respectively, and for the two NA locations these ratios are 0.8 and 0.9. By using these results together with the formulae in Eqs. (17) to (20) the mean value and the mean value $\pm$ one standard deviation for the models referred to as Nos. 1 to 9 (see Table 1) are given in Table 3, exemplified by using the slope $m = 0.1$. It should be noted, however, that this slope is strictly outside the validity range of model No.1 (see Table 1), but is included here for comparison. From Table 3 it appears that the large wave runup and wave rundown values are obtained for NA $(20^{\circ}W\,60^{\circ}N)$ followed by those for NNS, NWSA and NA $(10^{\circ}W\,40^{\circ}N)$. It should be noted that the small negative rundown values for model 4 demonstrate that the wave rundown is slightly below the still water level. The wave runup values are also depicted in Fig. 2. By comparing the wave runup formulae at each site and the corresponding mean value $\pm$ one standard deviation of the maximum wave runup, it appears from Table 3 and Fig. 2 that there is overlap between the values, except for NWSA model No. 1, which is outside the range of the values obtained by the other models; although there is a small overlap with model Nos. 2 and 3. However, it should be emphasized that these results are not general, since they are due to the single slope m = 0.1. It is also noted that the scatter in the NWSA results is significantly smaller than for the other sites, which is caused by the smaller scatter in the NSWA data.

An alternative to the stochastic method used here for estimating the wave runup and wave rundown is to use a deterministic method, which is to substitute $E[V]$ in Eqs. (17) and (19), i.e. to replace U_{10}^2 and U_{10}^3 with $(E[V])^2$ and $(E[V])^3$, respectively. By using this together with the results in Table 2, the deterministic to stochastic method ratios are given in Table 4. For the two NA locations and NNS the ratios are in the range 0.44 to 0.93, while the ratios are in the range 0.99 and 1.00 for NWSA. These different values of the ratios are due to the different statistical features of the long-term distributions of the wind speed. However, overall a stochastic method should be used as the stochastic features are taken into account consistently compared with what the deterministic method does.

4. Discussion

Here, the present method versus a commonly used practice in coastal engineering is briefly discussed. For calculating the maximum wave runup and wave rundown heights due to random waves, common practice would be to start from available data on joint statistics of H_s and T_p (or other characteristic wave periods) within directional sectors at a nearby offshore (deep water) location; then to transform these applying an appropriate wave simulation model yielding the joint statistics of H_s and T_p at the actual coastal site; and finally using this result as input for calculating the maximum wave runup and wave rundown. This procedure would also include shorelines exposed to mixed sea states with combined wind-waves and swell from different directions. Alternatively, this paper provides a simple analytical method giving first-order estimates of maximum heights of wave runup and wave rundown due to random waves from observed long-term wind statistics, with examples based on in-situ data obtained from four offshore sites together with a Phillips deep water wind-wave frequency spectrum. It is also assumed to be a smooth transition from deep water to the coastal site, excluding influences such as initial shoaling and wave energy dissipation across evolving bathymetry with varying shallow water depths. Thus, analytical estimates of the associated maximum wave runup and wave rundown on beaches and coastal structures are obtained. Such simple methods are useful to be able to quickly make estimates, which can be used to compare with more complete computational methods. It might also be useful under field conditions when there is limited time and access to computational resources. Although the present results are valid for the specifically chosen wave runup and wave rundown formulae, wave spectrum and long-term distributions of U_{10}, it gives an analytically based method which can be used for other formulations of wave runup and wave rundown, as well as for other deep water wave spectra and long-term distributions of U_{10} . However, the accuracy and the time savings of the first-order approximation versus common practice should be assessed, but this is only possible to quantify by comparing with such methods covering a wide parameter range, which is beyond the scope of the present work.

5. Summary and conclusions

A simple analytical method which can be used as first-order estimates of wave runup and wave rundown on shorelines and coastal structures for sea states based on long-term wind statistics is provided. This is achieved by applying eight different recently published wave runup formulae and one wave rundown formula together with wind statistics from the Northern North Sea, the North

Atlantic and the North-West Shelf of Australia. The expected values and the variances of the 2% exceedance value of the wave runup maxima and the wave rundown maxima are calculated. From the example calculations it appears that:

- by comparing the wave runup formulae at each site and the corresponding mean value ± one standard deviation of the maximum wave runup, there is overlap between all the eight models except for three of the models based on the North-West Shelf of Australia wind statistics;
- the stochastic method should be used since the stochastic features are taken into account consistently.

Overall, the method should represent a useful tool to give first-order estimates of wave runup and wave rundown on shorelines and coastal structures based on global wind statistics, with the assumptions and limitations as discussed in Section 4.

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Table 1. Wave runup (RU) and wave rundown (RD) formulae according to Eq. (11) for Model Nos.1 to 8, and Eq. (6) with C_1 = 0.49 for Model No. 9.

Model No.	Author(s)	a	b	c	d
1, RU	de la Pena et al. (2014)	0	$K=4m^{0.3}$	1	0
	Blenkinsopp et al. (2016)				
2, RU		0	1.165	0.77	0
3, RU		0.39	0.795	1	0
4, RD		0.21	-0.44	1	0
	Atkinson et al. (2017)				
5, RU	$M1R_2$	0	0.99	1	0
6, RU	$M2R_2$	0.16	0.92	1	0
7, RU	Holman (1989)	0.2	0.83	1	0
8, RU	Vousdoukas et al. (2012)	0.58m	0.53	1	0.45
9, RU	Poate et al. (2016)				

Table 2. Examples of results using wind statistics from NA, NNS and NWSA.

	NA		NNS	NWSA
	20°W 60°N	10°W 40°N		
$E[V]$(m/s)	9.8	6.3	7.5	7.3
$E[V^2](\mathrm{m}^2/\mathrm{s}^2)$	112.9	48.1	77.0	53.1
$E[H_s]$ (m)	2.1	0.9	1.4	1.0
$E[T_p]$(s)	6.3	4.0	4.8	4.7
$\frac{\text{st.dev}}{\text{m.v.}} = \frac{\sigma[V^2]}{E[V^2]}$ Model Nos. 1-8	0.8	0.9	1.2	0.2
$E[V^3](\mathrm{m}^3/\mathrm{s}^3)$	1478.1	420.5	967.7	391.6
$\frac{\text{st.dev}}{\text{m.v.}} = \frac{\sigma[V^3]}{E[V^3]}$ Model No. 9	1.2	1.3	1.9	0.3

Table 3. Expected values (line 1 for each model) and expected value ± one standard deviation (line 2 for each model); all dimensions are in metres.

Model No.	NA		NNS	NWSA
	20°W 60°N	10°W 40°N		
1	2.5 0.4, 4.5	1.1 0.1, 2.0	1.7 0, 3.7	1.2 1.0, 1.4
2	1.6 0.3, 2.9	0.7 0.1, 1.3	1.1 0, 2.4	0.8 0.6, 1.0
3	1.8 0.4, 3.2	0.8 0.1, 1.5	1.2 0, 2.6	0.8 0.6, 1.0
4	-0.10 -0.18, -0.02	-0.04 -0.08, 0	-0.07 -0.15, 0	-0.05 -0.06, -0.04
5	1.2 0.2, 2.2	0.5 0, 1.0	0.8 0, 1.8	0.6 0.5, 0.7
6	1.5 0.3, 2.7	0.6 0.1, 1.1	1.0 0, 2.2	0.7 0.6, 0.8
7	1.4 0.3, 2.5	0.6 0.1, 1.1	1.0 0, 2.2	0.7 0.6, 0.8
8	1.2 0.6, 1.8	0.8 0.5, 1.1	1.0 0.3, 1.6	0.8 0.7, 0.9
9	1.9 0, 4.2	0.5 0, 1.2	1.3 0, 3.8	0.5 0.3, 0.7

Table 4. Deterministic to stochastic method ratios.

	NA		NNS	NWSA
	20°W 60°N	10°W 40°N		
Model Nos. 1-7	0.85	0.83	0.73	1.00
Model No. 8	0.91	0.93	0.85	1.00
Model No. 9	0.64	0.59	0.44	0.99

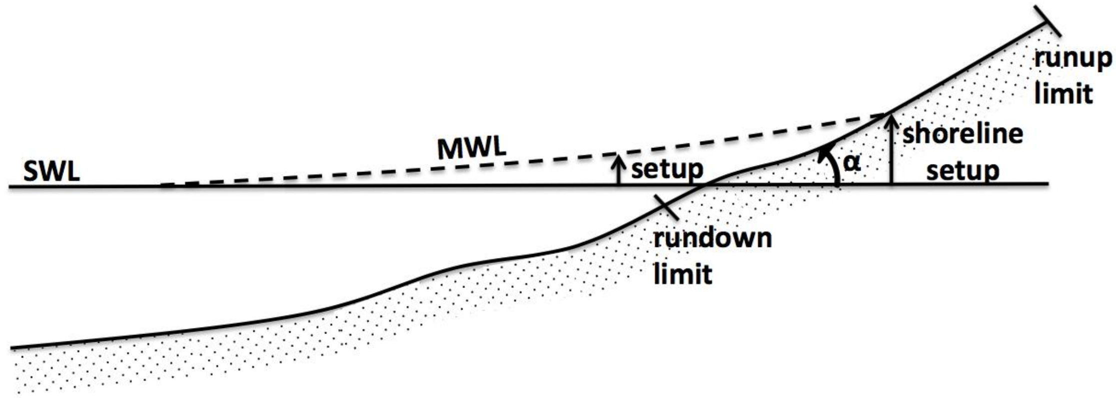

Figure 1. Definition sketch of wave runup and wave rundown.

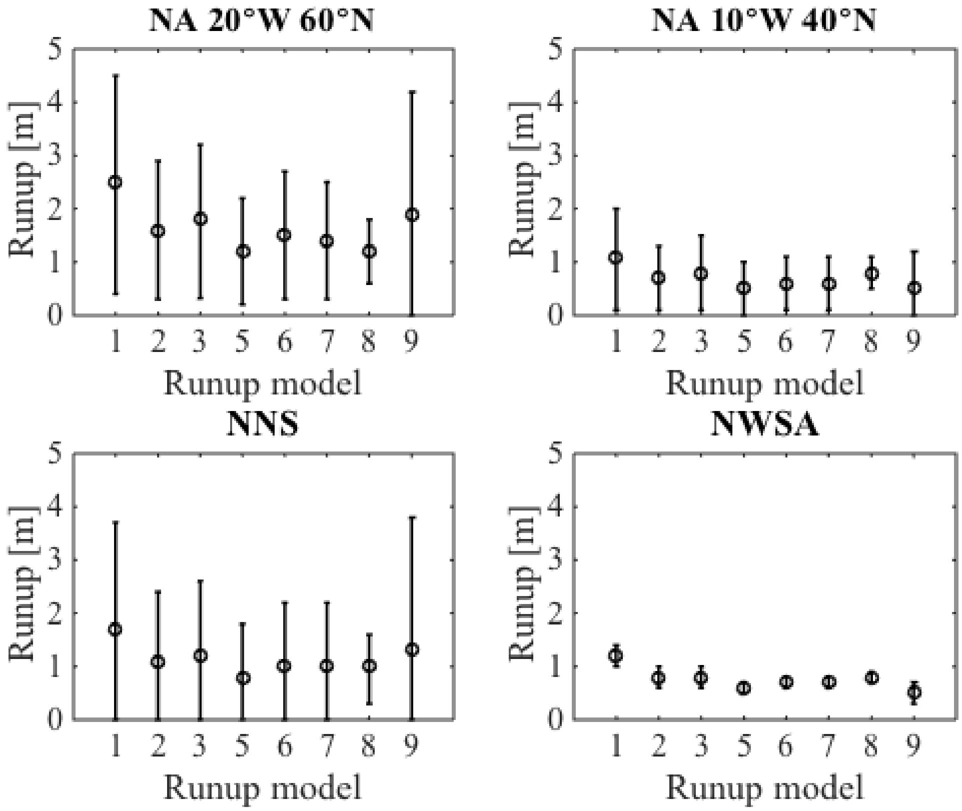

Figure 2. Wave runup for the models referred to in Table 1 corresponding to the results in Table 3 (mean value ± one standard deviation) for the two NA locations, NNS and NWSA.