https://studiumeditore.it/riviste/coastal-and-offshore-science-and-engineering/
https://doi.org/10.53256/COSE_220203

A new approach for wave chronology analysis and hindcast wave series synthesis

S. T. Canelas[a], F. Sancho[b,*] and A. Trigo-Teixeira[a]

[a] CERIS, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 LISBOA, Portugal
[b] Laboratório Nacional de Engenharia Civil, Avenida do Brasil 101, 1700-066 LISBOA, Portugal

* Corresponding author: fsancho@lnec.pt

ABSTRACT

The coastal zone is characterised by its high dynamism, which reflects on the shoreline position, indicating coastal erosion, stability or accretion. Predicting shoreline evolution is not only hampered by limitations of the modelling capacities but also by the intrinsic uncertainty of the future wave climate. The use of past wave series may not represent the future wave climate and therefore an envelope of shoreline positions should be considered, instead of a single one. The use of wave chronology analysis is a useful tool for obtaining these shorelines. This paper introduces a new method for synthesizing wave series randomly and for assessing the impact on long-term shoreline modelling, using a classical one-line modelling approach. This study was applied to Vagueira beach (Portugal), characterised by a strong dynamism. These results are compared with those obtained using rearranged wave series. Wave series synthetic construction methods that allow for this analysis are based on a multivariate statistical analysis of past wave series. For a long-term analysis, random synthetic series of wave height, period and direction are generated. The method considers the random generation of wave parameters respecting their statistical interdependence (height vs period and height vs direction). The shorelines resulting from the wave chronology analysis from several realizations of probable wave sequences are quite similar in areas far from the defence structures but have a great variability close to them. This phenomenon was reported in previous studies and can be justified by the physical processes that occur close to the structures that are not captured by the models.

KEYWORDS

Shoreline evolution, one-line numerical model, long-term wave series, multivariate statistical analysis, Monte-Carlo approach

1 INTRODUCTION

Sandy beaches have a dynamic nature being mostly shaped by sea waves that induce sediment transport, representing about 31% of the world's coastal areas (Luijendijk et al., 2018). The coastal morphology evolution presents a complex behaviour due to non-linear interactions between drivers, such as the prevailing currents and the wave orbital velocity, and the sediment response, such as the sediment transport function. These non-linearities influence the ability to predict the shoreline evolution in the medium (several weeks to few months) to long term (years to several decades) scales (Southgate, 1995).

Due to anthropogenic (e.g., coastal occupation and construction of dams, retaining sediments) or natural (e.g., natural extinction of sediment sources) effects, sandy beaches can enter into sediment unbalance and suffer from erosion problems, affecting the socio-economic value of the area and, conceivably, endangering people and goods (Mentashi et al., 2018, Vousdoukas, 2020). These problems can be aggravated by rising sea levels and climate change. Looking ahead to sandy beaches' coastline predictions for years 2050 and 2100, Vousdoukas et al. (2020) show a general erosive trend with average values of retreat in the order of tens of meters for the 2050 horizon (from -78.1 to -1.1 m for a greenhouse gas Representative Concentration Pathway (RCP) of 4.5, and -98.1 to 0.3 m for RCP 8.5 (IPCC 2013)) to hundreds of meters for the 2100 horizon (-164.2 to -14.8 m and -240 to -35.3 m for RCP 4.5 and RCP 8.5, respectively). To mitigate the erosion problems, coastal planning measures must be taken. The use of numerical models for predicting shoreline behaviour in the future is a widely used practice.

The one-line model has for the past few decades been frequently chosen for modelling the shoreline evolution for long-term forecasts (tens of years), capable of incorporating the entire shoreline of a sedimentary cell (up to tens of kilometres) (Hanson and Kraus, 1989). This model is applicable if there is a good knowledge of the local morphodynamic mechanisms (e.g., sediment transport, and boundary conditions) and of the wave regime (Hanson et al., 2003). The one-line shoreline model main assumptions are: 1) the longshore sediment transport carried out by wave action is the main modelling agent, where cross-shore currents, wind and tidal transports are not considered; 2) the total sediment transport rate occurs within the beach profile and is defined by the properties of breaking waves; 3) the shoreline is the line that describes the changes in the beach plan, being considered a fixed point in the profile; 4) the beach profile maintains its shape throughout the simulation, advancing and receding its position with the sediment transport variations (Hanson and Kraus, 1989). These assumptions imply a thorough characterization of the study area and the existence of long-term morphological data (e.g. shoreline position, grain size, beach profiles) and wave climate data, to achieve an adequate calibration and validation of the model. The exclusion of other physical processes that influence shoreline evolution, as well as the non-updating of the beach profiles, rewards faster computing, and less error accumulation in long-term runs, compared to process-based models. However, as in all types of forecasts, considering past data (e.g. wave regime series) as a reliable representation of the future entails some uncertainties.

Wave chronology (or wave event sequencing) is defined by Hanson *et al.* (2003) as "the effect on coastal morphology of different sequences of waves with the same overall statistical properties". In other words, it is the outcome morphology that results from different wave sequence scenarios. Although the future wave time series (or wave sequence) is unknown, its statistical properties can be assumed, with some accuracy, from the analysis of the past long-term datasets, resulting from both in-situ wave buoys and validated hindcast data. The wave chronology analysis method allows the calculation of an envelope of possible future shoreline positions, rather than the usual single (one shoreline) output (*e.g*. Southgate, 1995). The wave chronology effects cannot be validated since in nature a given morphology is only shaped by the exact wave sequence that occurred. Numerical modelling is a good alternative to wave chronology analysis, however, it can be time-consuming with high computational costs.

Due to the randomness of the wave conditions, the shoreline prediction accuracy is affected by the future wave climate. To quantify this uncertainty, the influence of the wave chronology on shoreline evolution is tested.

The purpose of this analysis is to create a procedure that allows the generation of several probable wave time series scenarios leading to several shoreline positions. By applying the existing methods (see section 2) and improving their gaps, such as the generation of long-term wave series with statistically dependent parameters, it was possible to evaluate various synthesizing wave series methods and their impact on long-term shoreline simulations.

Vagueira beach in Portugal was chosen to test this method, an area with high anthropogenic pressure, suffering from serious erosive problems, where several coastal protection interventions were carried out, including both hard coastal defences and artificial sand nourishments (Sancho, *et al,* 2020).

The influence of each method on the long-term shoreline evolution was tested considering rearranged wave series and synthetic storm episodes, within the Litmod (Vicente and Clímaco, 2003) one-line model framework. The Monte-Carlo approach was also tested making 100 shoreline simulations with the best-performing wave series synthesis method.

2 WAVE CHRONOLOGY STATE OF THE ART

There are essentially three methods to create a synthetic wave series: 1) using the past wave climate conditions with the highest probability of occurrence; 2) rearranging the past real wave time-series order; 3) generating a random wave-sequence synthetic series from wave parameters' statistical distributions.

Le Méhauté and Soldate (1983) assessed a method, based on the occurrence frequency of wave height (Hs), wave period (T) and wave direction (Dir) sets, for shoreline evolution outputs and proposed "ground rules" for its application on prediction methods. This study was performed on a sheltered beach (Miami beach) with a dominant wave direction for two years. The five most frequent Hs, T, and Dir sets were chosen to build an input wave series. The main conclusion drawn from this study was the importance of the wave sequence (even in the medium-term) and the advantage in applying this method for predicting the position of the future shoreline as it has associated an uncertainty measure.

Hanson and Kraus (1987) performed a sensitivity analysis of the GENESIS one-line shoreline model to varying wave conditions. They produced, from a basic wave series, different series where the order of the waves was changed using random criteria such as sorting wave height or simply shuffling the records, keeping unvaried the total wave energy characteristic of the series. The results of these simulations proved to be sensitive to wave chronology and mainly to the wave direction parameter.

Vrijling and Meyer (1992) applied the one-line model to perform Monte-Carlo simulations of the shoreline position near a port. The authors stressed that the existence of a correlation between coastal variables influences the results considerably.

Southgate (1995) approached the wave chronology impact on medium-term shoreline evolution using synthetic wave series generated from a rearranged real wave series. The following guidelines were suggested: 1) the wave sequences taken from the original series must be of similar length and; 2) the start and end of the segments must not contain a storm event, being the divisions made ideally in low wave height segments. The number of segments does not significantly change the outcome, suggesting 24 rearranged wave data series as the minimum simulations for a viable chronological analysis. This approach is restricted to the existing sequences within each division and may reduce the variability of oceanographic events.

Dong and Chen (1999) included random temporal variability in a Monte-Carlo study adapting the one-line model to account for cross-shore sediment exchanges. Later, Dong and Chen (2001), using the same model, analysed the chronology effect on critical shoreline erosion statistics. They concluded that as the evolution of the coastline is intrinsically non-linear, cumulative, and time-dependent, the chronology of the input was found to have some influence on the predictions of critical erosion; but that influence was relatively weak. Their results showed that the shoreline evolution was primarily a wave-climate-dependent process for both short and long terms.

More recently, Wang and Reeve (2010) and Reeve *et al.* (2014) randomly generated wave series using a statistical distribution of oceanographic parameters (Hs, T and Dir). Both works considered these parameters to have a statistically independent behaviour. Thus, the generated wave series statistical behaviour was compromised, not representing the original wave parameters' dependencies or correlations. The authors conducted a large number of long-term shoreline evolution simulations in the presence of breakwaters (Wang and Reeve, 2010) and groins (Reeve *et al.,* 2014). The Monte-Carlo approach was used to achieve large quantities of inputs to obtain several results. This method application improved the shoreline response analysis to different wave conditions. The computational cost and time consumption involved in the model make its application challenging.

Sena (2010) analyzed the wave chronology effect on long-term shoreline evolution simulations using the Le Méhauté and Soldate (1983) and Hanson (1987) methods. The author found that the long-term shoreline position is sensitive to the use of different synthetic wave series, especially in the vicinity of protective structures such as groins, and emphasized that the use of random wave series constructed from representative waves is preferable to the use of only representative waves, considering the characteristics of the study site (at the Portuguese northwest coast).

3 STUDY SITE FRAMEWORK

The present study area is located south of the Aveiro Lagoon inlet, along the northwest Portuguese coast, where several other studies have been conducted (e.g., Simões *et al*., 2013; Baptista *et al*., 2014). A 5.5 km region at Vagueira beach was chosen (Fig. 1).

Vagueira beach suffers from chronic erosion problems due to sediment supply reduction mainly as a consequence of the existence of several coastal structures which for years obstructed the littoral transport, being the jetties of the Ria de Aveiro the main contributors (Oliveira *et al*., 1982). Located on a sandspit between the Aveiro lagoon and the Atlantic Ocean, its high anthropogenic occupation near the shoreline contributes to complex coastal management. The Portuguese Environment Agency (A.P.A.) is currently studying the viability of placing a multifunctional submerged detached breakwater in front of Vagueira Beach town (Sancho *et al*., 2020).

A hindcast offshore wave series is used for the 20-year period from 01/01/1998 to 31/12/2017 (every 6 hours), from the ECMWF WAM forecast

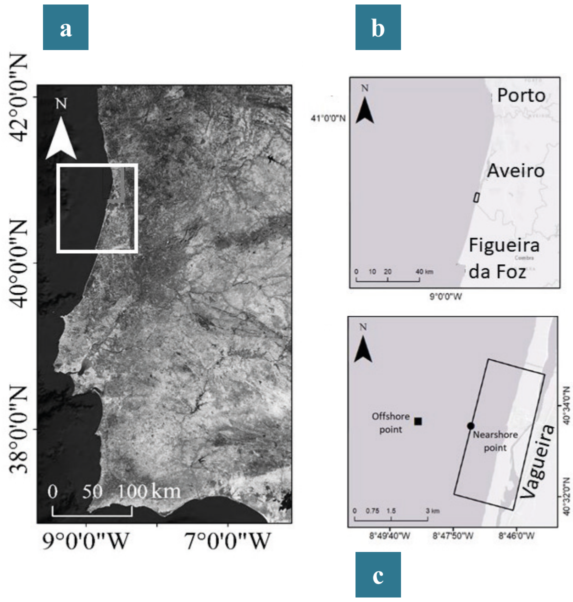

Figure 1. a) Portuguese coast; b) Domain location; c) Offshore and nearshore points. Basemap from ESRI © (2020).

model (Janssen *et al.,* 2002). This wave series was propagated until the 12-meter depth contour (Chart Datum) using the SWAN model (Booij *et al.,* 1997), henceforth referred to as nearshore wave series.

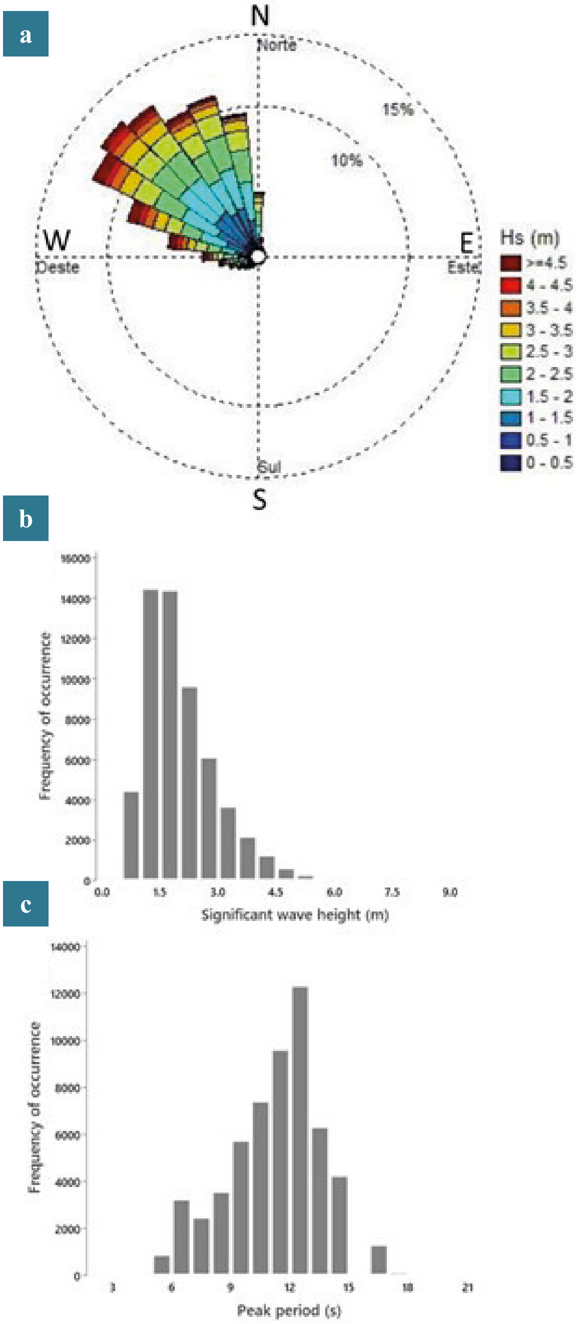

Figure 2. Wave regime offshore Vagueira beach in the period 1979 to 2018, sampled every 6 hours, ECMWF data. a) Wind rose with wave direction and significant wave height (Adapted from Freire et al., 2020); b) Frequency of occurrence of significant wave height; c) Frequency of occurrence of the peak period.

The offshore wave regime at Vagueira beach is, on average, characterized by a 2 m significant wave height, an 11.1 s peak period and a 291.5° mean wave direction (Freire *et al.,* 2020) (Figure 2). At 12 m of depth nearshore, the significant wave height is on average 1.8 m, the peak wave period varies from 3.5 s to 20.3 s, averaging 10.9 s, and the most frequent wave direction varies from 270° to 330° (Freire *et al.,* 2020).

4 METHODOLOGY

4.1 Shoreline model

Litmod is an one-line model for shoreline evolution that is based on two main assumptions (Vicente and Clímaco, 2003): 1) the beach profile does not change during erosion and accretion processes and, thus, the shoreline movement is simulated by the beach profile (from the closure depth to the berm crest height) moving parallel to itself; and 2) the longitudinal sediment transport is the determining factor in the evolution of the coast.

The Litmod model was applied to Vagueira beach, over a 7.5 km stretch discretized into 20 m cells, for a simulation period of 20 years with a time step of 1.2 hours. The Kamphuis (1991) sediment transport formula was used. According to Oliveira *et al.* (2020), values of 11 m MSL for closure depth, 4.5 m MSL for berm height and a 0.37 mm median sediment diameter were assumed. The initial shoreline corresponds to 2018 extracted from an orthophotomap with a 25 cm precision available by the Portuguese Territory Autority (DGT), using as shoreline indicator the dry-wet line.

4.2 Wave chronology and Monte-Carlo method

Several methods of producing synthetic wave series were tested, from the works of Le Méhauté and Soldate (1983), Hanson (1987), Southgate (1995) and Wang and Reeve (2010). The influence of each method on the long-term shoreline evolution was tested considering rearranged wave series and synthetic wave series. The Monte-Carlo approach is also tested with 100 shoreline simulations with the best-performing wave series synthesis method.

The wave chronology analysis based on synthetic wave climates would allow the creation of several (hypothetical, but plausible because they have the same statistical wave series behaviour) wave condition scenarios that lead to different shoreline positions. The result would be not a single shoreline, but a statistically representative shoreline of all scenarios generated (such as the mean shoreline position of all outcomes), and the associated uncertainty or space envelope.

The wave parameters' (e.g. wave height) statistics, from an annual or multi-annual series of daily averaged values, can be described by statistical distribution functions if the sample size is large enough to allow the construction of a histogram with statistical representativeness. The statistical distributions used in this study are presented below.

The two and three-parameter Weibull distribution (*W* (*x*), equation 1) can be applied, for instance, to the wave height parameter (*W* (*H*))

$$p(x) = \begin{cases} R(H) & H\varepsilon\left[0, H_i\right) \\ \mathrm{W}(\mathrm{H}) & H\varepsilon(H_i, +\infty) \end{cases} \tag{1}$$

where for the two-parameter equation,

$$W(H) = \frac{a}{b}\left(\frac{H}{b}\right)^{a-1} exp - \left(\frac{H}{b}\right)^{a} \tag{2}$$

and the three-parameter equation,

$$W(H) = \frac{a}{b}\left(\frac{H-\mu}{b}\right)^{a-1} exp - \left(\frac{H-\mu}{b}\right)^{a} \tag{3}$$

In the above, μ is the sample mean, is the scale calibration parameter and is the shape calibration parameter that can be calculated from the Maximum Likelihood Estimate method (MLE) (Muraleedharan *et al.,* 2007).

Other distributions, such as the lognormal (*LN*(*H*), equation 4, and the logistic (*Lg*(*H*), equation 5), can also present a good fit to the wave parameters' frequency of occurrence, due to their skewed behaviour (Raqab *et al.,* 2010).

$$LN(H) = \frac{e^{-\left(\frac{(ln ln\, x)^2}{2\sigma^2}\right)}}{H\sigma\sqrt{2\pi}} \tag{4}$$

$$Lg(H) = \frac{exp^{-\left(\frac{H-\mu}{a}\right)}}{a\left(1 + exp^{-\left(\frac{H-\mu}{a}\right)}\right)^2} \tag{5}$$

The use of independent statistical distributions of wave parameters for random extraction can lead to unrealistic wave parameters' combinations. The univariate analysis does not respect certain nature-observed correlations and events (such as offshore waves breaking due to excessive steepness), where there is a clear and almost universal relationship between wave height and wave period, and often a location-dependent relationship between wave height and wave direction (Holthuijsen, 2007).

4.3 Synthesizing the wave series

Initially, a multivariate exploratory analysis of the hindcast data was performed to describe the wave regime (Figure 3). The analysis included a simple univariate statistical description of the significant wave height (Hs), peak period (Tp) and mean wave direction (Dir), as well as the relationships between them (Hs vs. Tp and Hs vs. Dir). The latter allowed to find the Hs dependent statistical distributions of Tp and Dir.

Two synthetic wave series methods were assessed: 1) rearrangement of the 20-year order of the original wave series and 2) random generation from the Hs, Tp (as a function of Hs) and Dir (as a function of Hs) statistical distributions.

For the first method, thirty wave time series were generated from the rearrangement of the years' order in the original nearshore wave series. A complete wave series with the rearranged annual order was constructed by randomly choosing the sequence in which the years appear in the series. The absence of inter-annual storms was verified (as recommended by Southgate, 1995). These wave series were then used to simulate the 20-year shoreline evolution for the Vagueira beach coastal stretch.

In the second method, to generate synthetic wave series, the following steps were taken:

1. Hs bins with a 0.5 m range were created and, for each Hs bin, a statistical distribution for Tp and another for Dir was adjusted. Being Dir a circular parameter (0° to 360°) and considering that the study case faces approximately the 280° wave direction, it was added 360° to all values below 90° so that their distribution function is as continuous as possible.

2. The best fit two and three-parameter distribution functions were searched. The Weibull distribution yielded the best fit Tp (2-parameter distribution for the offshore series and 3-parameter distribution for the nearshore series), while for Dir it was the logistic distribution (2-parameter distribution). Using the location and scale (or shape, location and scale for the 3-parameter Weibull) parameters corresponding to the best fit distributions for each Hs bin, a simple linear regression model for Tp and a 2nd order polynomial regression model for Dir allowed to relate them with Hs. For the nearshore Tp, a 3rd-order polynomial regression presented a better fit for the 3-parameter Hs dependency, and for the nearshore Dir the choice of the 2nd-order regression was maintained, changing only the values of the regression curve.

Figure 4 shows the Hs-distribution from the synthetic wave series as well as the Hs-Tp and Hs-Dir scatter plots, allowing to conclude that the original data is well represented by the synthetic data.

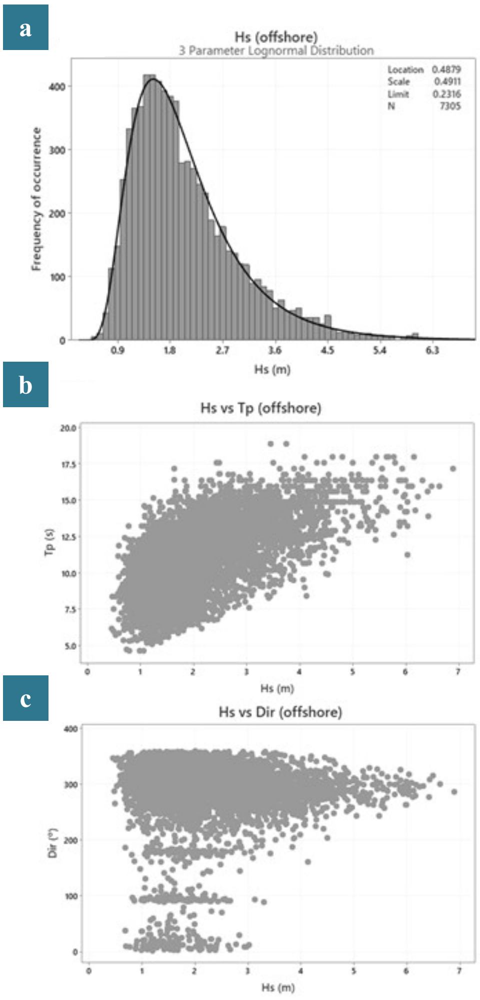

Figure 3. 20-year offshore wave series. a) Significant wave height (Hs), with 3-parameter lognormal distribution histogram; b) Hs and Tp relation scatter plot; c) Hs and Dir relation scatter plot.

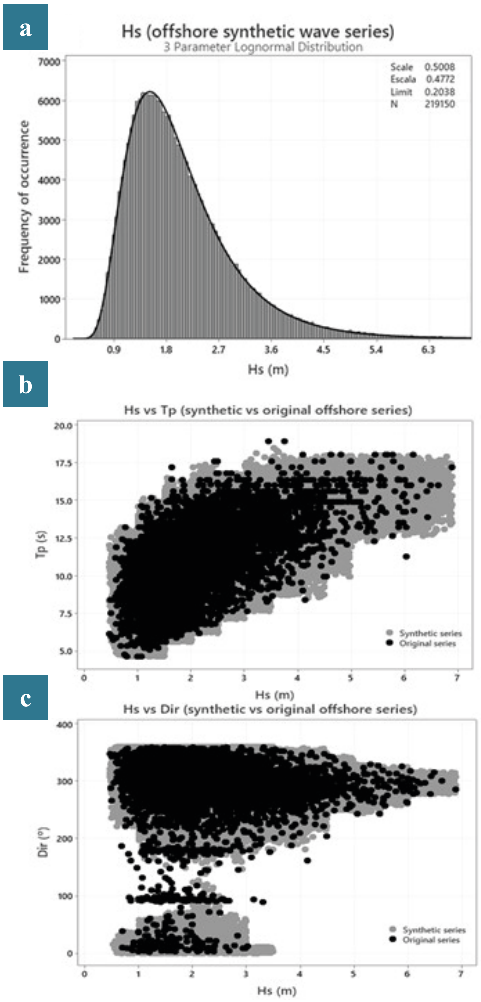

Figure 4. 230 Offshore synthetic wave series of 20 years each. a) Significant wave height (Hs), with 3-parameter lognormal distribution histogram; b) Hs and Tp relation scatter plot; c) Hs and Dir relation scatter plot.

5 RESULTS

5.1 Rearranged 1998-2017 wave time series

Figure 5 presents a close-up view of the domain area of interest of the final shoreline positions (after 20 years) of 30 simulations using rearranged wave series, as well as the reference simulation (black) which corresponds to the 20-year simulation using the original (1998-2017) wave series. The figure further shows the mean line obtained by averaging the positions of the 30 simulations (broad dashed), and the 95% (dot-dash) and 5% (dashed) percentiles.

One first notices that the original wave sequence originates a shoreline position near the ensemble extreme positions. Secondly, the rearranged wave series simulations present a large variability near the coastal protection structures. The physical processes that occur near the defence structures are complex and their description in models of reduced complexity are not described properly, which may be one of the explanations for the high variability of the shoreline position near the structures. Away from the coastal structures, the

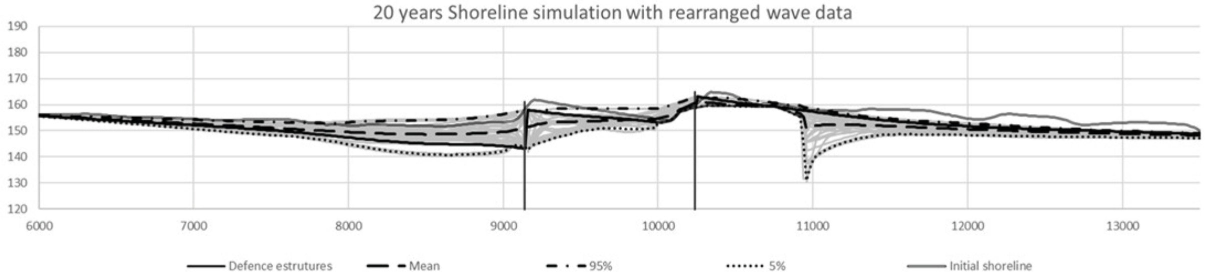

Figure 5. 20 years of shoreline evolution simulation using 30 series with rearranged real waves. Longitudinal distance (in meters) in the x-axis and cross-shore distance (in meters) in the vertical axis. Eixo vertical: cross-shore distance (m).

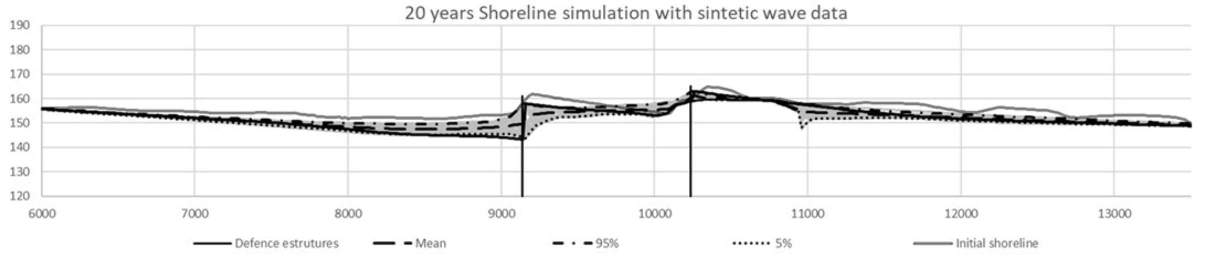

Figure 6. 20 years of shoreline evolution simulation using 30 series with synthetic waves series. Longitudinal distance (in meters) in the x-axis and cross-shore distance (in meters) in the vertical axis.

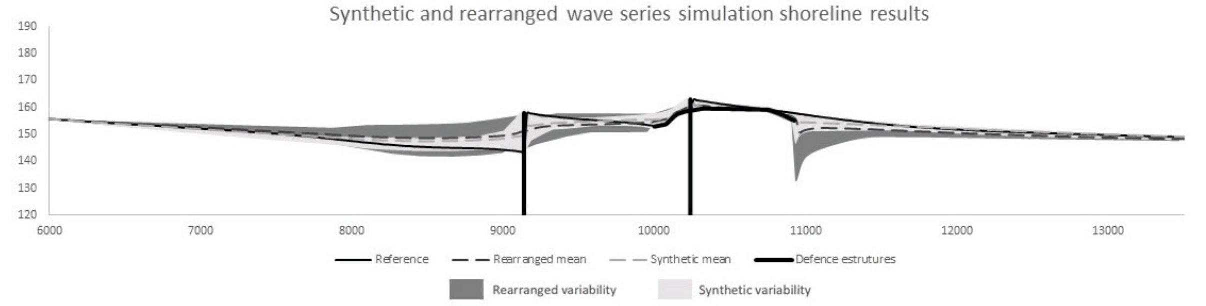

Figure 7. Rearranged (dark grey) and synthetic (light grey) shoreline position simulated variability and mean (dashed lines) compared with the simulated reference line with original wave series (black). Longitudinal distance (in meters) in the x-axis and cross-shore distance (in meters) in the vertical axis.

simulated shoreline positions are quite close to each other, which is in agreement with Sena's (2010) conclusions.

Regarding the initial shoreline position, the full set of simulations shows a general erosive trend of the study area.

The longitudinal sediment transport was calculated for three positions (or cross-sections) throughout the domain (at x=6500, 10000 and 13000 m). At those locations, the annual computed longitudinal sediment transport ranges between 650,000 and 700,000 m^3/year. At each position, the ensemble median sediment flux is slightly lower than that found for the reference simulation. This may explain why the reference shoreline position lies near the 5% percentile line in some areas of the domain.

5.2 Synthesized wave series from the statistical distribution of the 1998-2017 series

Using the parameters and statistical distributions determined in section 4.3 for the wave height, period and direction, thirty nearshore wave series were synthesized, each of a 20-year duration. Each wave series led to the corresponding shoreline evolution simulation (Figure 6). The shoreline positions from this method show a decrease in variability, compared to that computed in the rearranged waves simulations (Figure 7). This is particularly evident near the coastal structures. Also, the reference situation continues to show a position near the extremities (5% and 95% percentiles) of the envelope (Figure 6).

For these simulations, the computed ensemble sediment transport fluxes, at the above referred three positions, ranges also between 650,000 and 700,000 m^3/year, but shows a larger dispersion than the previous results.

6 DISCUSSION

The results from both wave time series generation methods show plausible individual shoreline evolution simulations and final (20-year) positions. For each method, the final shoreline positions lie within an envelope capturing the variability and unpredictability of the time sequence. This variability, mainly in the vicinity of the coastal defence structures, has been described in the literature (e.g. Sena, 2010). The calculated annual net alongshore sediment transport rate variation is within less than 5% of the reference sediment transport rate (from the original time series).

Using the statistical distributions that presented the best fit for the wave parameters, the shoreline

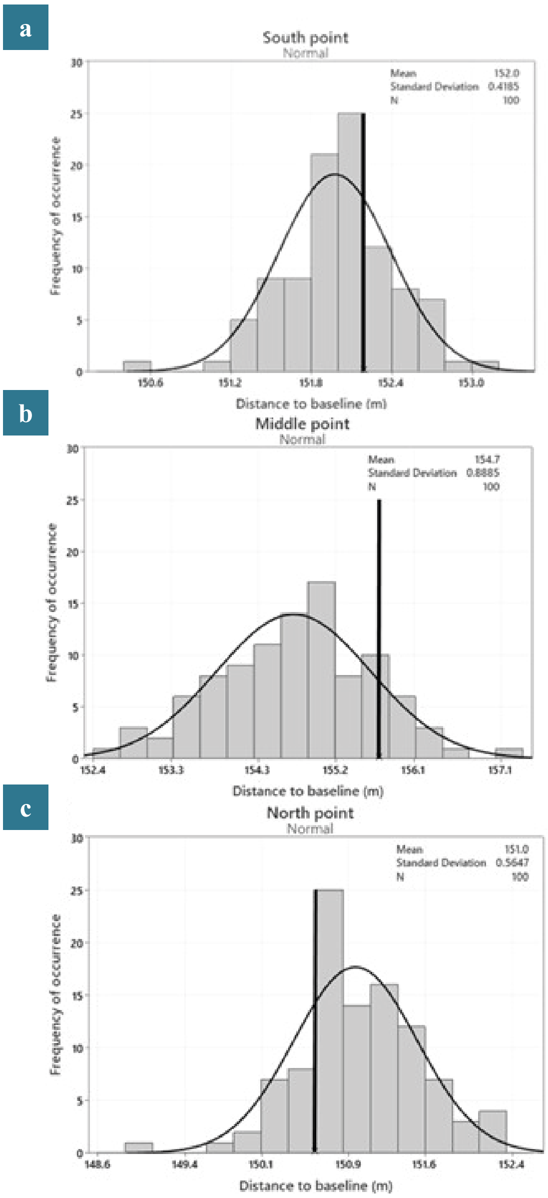

Figure 8. Shoreline position histograms for the south (a), middle (b) and north (c) points in the domain. The black line represents the initial shoreline position and the evolution can be either accretionary (value concentration to the right) or erosive (value concentration to the left). The Normal distribution was adjusted to each histogram.

position envelope showed a decreased variability compared to that of the rearranged wave series. However, the maximum distance between the envelopes of those simulations is 17 m (see the northern stretch, near the seawall, in Figure 7), whereas the distance between the mean lines has a maximum of 3.7 meters. For the model reliability at this scale, these values are considered negligible. Hence, the benefit of using the Monte-Carlo approach is the possibility of its application to an infinite number of simulations with little effort, it is only necessary to use the statistical distributions determined for each wave parameter to limit the values to the data-inferred range.

One further advantage of the Monte-Carlo method is its ability to accommodate climate change scenarios. That is, one can incorporate climate change predicted tendencies and relations into the statistical distributions of the wave parameters, and thus obtain corresponding synthesised wave series.

Additionally, the inclusion of synthetic storm events was tested (Teixeira-Canelas, 2021), using for the synthesis of the storm events the same method used for the synthesis of the wave series. These events were randomly distributed by the wave time series, respecting the frequency of occurrence and duration of the observed storms. In the shoreline simulations, it was found that adding the storms did not change the model output (the 20-year shoreline) considerably. Nevertheless, the storminess inclusion can impact in the order of 5% the predicted net annual sediment transport rates.

Finally, using the Monte-Carlo approach, the synthetic wave series generation was selected to perform 100 shoreline position simulations to obtain shoreline position histograms along with the domain (see examples in Figure 8). With the 100 shoreline simulations it is possible to construct histograms for each domain point with the occurrence probability of the shoreline position relative to the baseline. In each sub-figure, the shoreline positions to the right of the initial position are indicative of accretion, where the opposite occurs for those at the left. So, in the present case, the ensemble mean positions show an erosive trend at the south and middle cross-sections and an accretive trend at the north point. This kind of chart indicates the uncertainty in the shoreline position related to the wave series and helps to better understand it at various points throughout the domain and to assist coastal management decisions.

7 CONCLUSIONS

Wave chronology analysis is a tool to obtain a probabilistic envelope of possible shoreline positions rather than a deterministic result, to attempt to accommodate the future wave time-sequence unpredictability. Here, this methodology was used assuming that the future wave climate retains the statistical characteristics of the recent past one, and thus no other effects, such as climate changes, are addressed in this analysis. However, the method opens the possibility for including that effect.

Due to the predicted large shoreline position variability near coastal defence structures, it is considered that wave chronology analysis is especially important to understand the long-term impact of these structures.

Generating random wave series from statistical distributions that respect the interdependencies of the wave parameters has proven to be the most effective way in synthesizing wave series for this type of analysis. Due to their ease of creation, synthetic random wave series can be produced with the desired temporal range without depending on the existence of datasets other than for statistical analysis. However, the use of real rearranged wave series also showed consistent results, with a higher variability of the shoreline position near the structures, which can be used for the understanding of the influence of coastal defence works in the long term.

Comparing the results obtained with 30 versus 100 simulations of the shoreline position, it can be concluded that thirty simulations are recommended as a minimum to get a shoreline position envelope and about one-hundred simulations are necessary to obtain shoreline position distribution curves (possibly, one at each cell in the domain). It is advised to systematically use wave chronology analysis in future studies, and it is suggested to automate the whole process of synthetic random wave series production, the model set up and output organization, to make this method more practical for users.

ACKNOWLEDGEMENTS

This article was prepared within the PhD work of S. Teixeira Canelas, under a grant provided by the Portuguese Science and Technology Foundation (PD / BD / 128510/2017). The authors acknowledge the Portuguese Territorial General Directorate (DGT) for making available the orthophoto maps, the National Laboratory for Civil Engineering (LNEC) for supporting this study, and Dodet *et al.* (2010) for providing the hindcast offshore wave data.

REFERENCES

Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., & Cooke, R. M. (2019). Ice sheet contributions to future sea-level rise from structured expert judgment. Proceedings of the National Academy of Sciences, 116(23), 11195-11200. doi: 10.1073/pnas.1817205116

Baptista, P., Coelho, C., Pereira, C., Bernardes, C., and Veloso-Gomes, F. (2014). Beach morphology and shoreline evolution: Monitoring and modelling medium-term responses (Portuguese NW coast study site). Coastal Engineering, 84, 23-37. doi:10.1016/j.coastaleng.2013.11.002

Booij, N., Holthuijsen, L. H., & Ris, R. C. (19961997). The “swan” wave model for shallow water. In Coastal Engineering Proceedings 68-676. doi:10.1061/9780784402429.053(p. 1(25)).

Dong, P., and Chen, H (2001). Wave chronology effects on the long-term shoreline erosion predictions. Journal of Waterway, Port, Coastal, and Ocean Engineering, 12(3), 186-189. doi: 10.1061/(ASCE)0733-950X(2001)127.

Dong, P., and Chen, H. (1999). A probability method for predicting time-dependent long-term shoreline erosion, Coastal Engineering, 36, 243-261. doi: 10.1016/S0378-3839(99)00013-7

Freire, P., Capitão, R., Sancho, F. , Fortes, C. J., Neves, M. G., Pinheiro, L., … Baptista, P. R. (2020). Estudo de caracterização e viabilidade de um quebra-mar destacado multifuncional em frente à praia da vagueira: Caracterização da hidrodinâmica e da variabilidade morfo-sedimentar – Relatório 7 (61/2020 – DHA/NEC). Lisbon: LNEC (in Portuguese).

Hanson, H., Aarninkhof, S., Capobianco, M., Jiménez, J. A., Larson, L., Nichols, R. J., … Vriend, H. J. (2003). Modelling of coastal evolution on yearly to decadal time scales. Journal of Coastal Research, 19(4), 790-811. ISSN 07490208.

Hanson, H., and Kraus, N. C. (1989). Genesis: Generalized model for simulating shoreline change. Technical reference (1). U.S. Corp of Engineers.

Hanson, H., Kraus, N. C. (1987). Genesis: Generalized model for simulating shoreline change. Report 1. Technical Reference.

Holthuijsen, L. H. (2007). Waves in oceanic and coastal waters. Cambridge, U.K.: Cambridge University Press. ISBN-10 0-511-27021-6

Janssen, P. (2002). The wave model: Meteorological Training Course Lecture Series. ECMWF.

Jevrejeva, S., Jackson, L. P., Grinsted, A., Lincke, D., & Marzeion, B. (2018). Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C. Environmental Research Letters, 13(7), 1-15.

Kamphuis, J. W. (1991). Alongshore sediment transport rate. Journal of Waterway, Port, Coastal, and Ocean Engineering, 117(6), 624-640. doi:10.1061/(ASCE)0733-950X(1991)117:6(624)

Luijendijk, A., Hagenaars, G., Ranasinghe, R. et al. The State of the World’s Beaches. Sci Rep 8, 6641 (2018). doi: 10.1038/s41598-018-24630-6

Mehaute, B. L., Wang, J. D., and Lu, C. (1983). Wave data Discretization for shoreline processes. Journal of Waterway, Port, Coastal, and Ocean Engineering, 109(1), 63-78. doi: 10.1061/(ASCE)0733-950X(1983)109:1(63)

Mentaschi, L., Vousdoukas, M. I., Pekel, J., Voukouvalas, E., & Feyen, L. (2018). Global long-term observations of coastal erosion and accretion. Nature Scientific Reports, 8(1), 1-11. doi: 10.1038/s41598-018-30904-w

Muraleedharan, G., Rao, A., Kurup, P., Nair, N. U., and Sinha, M. (2007). Modified Weibull distribution for maximum and significant wave height simulation and prediction. Coastal Engineering, 54(8), 630-638. doi: 10.1016/j.coastaleng.2007.05.001

Oliveira, I. M., Valle, A., and Miranda, F. (1982). Littoral problems in the Portuguese West Coast. Coastal Engineering 1982. doi: 10.1061/9780872623736.117

Oliveira, F.S.B.F., Sancho, F., Neves, M.G, Pinheiro, L., Fortes, C.J., Teixeira, S., … Pombo, R. (2020). Estudo de caracterização e viabilidade de um quebra-mar destacado multifuncional em frente à praia da Vagueira. (T1) Estudos em modelo matemático: Alternativas de quebra-mar destacado para proteção contra galgamentos e erosão costeira – Relatório 8. (231/2020 – DHA/NEC). Lisbon: LNEC (in Portuguese).

Raqab, M. Z., Al-Awadhi, A., and Kundu, D. (n.d.). Discriminating among Weibull, log-normal, and log-logistic distributions. Communications in Statistics - Simulation and Computation, 47(5), 1397-1419. doi: 10.1080/03610918.2017.1315729

Reeve, D. E., Pedrozo-Acuña, A., and Spivack, M. (2014). Beach memory and ensemble prediction of shoreline evolution near a groyne. Coastal Engineering, 86, 77-87. doi: 10.1016/j.coastaleng.2013.11.010

Sancho, F., Oliveira, F.S.B.F., Fortes, C.J.E.M., Baptista, P., Roebeling, P. (2020). Estudo de caracterização e viabilidade de um quebra-mar destacado multifuncional em frente à Praia da Vagueira. Atas das 6.as Jornadas de Engenharia Hidrográfica / 1.as Jornadas Luso-Espanholas de Hidrografia, Lisbon, 3 pp. 231-234 (in Portuguese).

Sena, M. V. (2010). Modelação de Evolução da Linha de Costa Influência do Uso de Séries Sintéticas de Agitação (Master’s thesis, IST, Lisbon, Portugal) (in Portuguese).

Simões, S., Pereira, C., Coelho, C., Antunes-do-Carmo, J.S. (2013). Quebramares destacados: análises comparativas de eficiências de proteção na Praia da Vagueira. Revista Recursos Hídricos, Volume 34(2), pp 25-40 (in Portuguese). doi: 10.5894/rh34n2-3

Southgate, H. N. (1995). The effects of wave chronology on medium and long term coastal morphology. Coastal Engineering, 26(3-4), 251-270. doi: 10.1016/0378-3839(95)00028-3

Stripling, S., Panzeri, M., Blanco, B., Rossington, K., Sayers, P., and Borthwick, A. (2017). Regional-scale probabilistic shoreline evolution modelling for flood-risk assessment. Coastal Engineering, 121, 129-144. doi: 10.1016/j.coastaleng.2016.12.002

Teixeira-Canelas, S. (2021). Performance of shoreline evolution strategies: A perspective look and the use of one-line shoreline evolution modelling. PhD dissertation, Instituto Superior Técnico, Lisbon, Portugal.

Vicente, C., Clímaco, M. (2003). Evolução das linhas e costa – desenvolvimento e aplicação de um modelo numérico. Lisbon, Portugal: LNEC (in Portuguese).

Vousdoukas, M. I., Ranasinghe, R., Mentaschi, L., Plomaritis, T. A., Athanasiou, P., Luijendijk, A., & Feyen, L. (2020). Sandy coastlines under threat of erosion. Nature Climate Change, 10(3), 260-263. doi: 10.1038/s41558-020-0697-0

Vrijling, J.K., Meyer, G.J., (1992). Probabilistic coastline position computations. Coastal Engineering 17, 1 – 23. doi: 10.1016/0378-3839(92)90011-I

Wang, B., and Reeve, D. (2010). Probabilistic modelling of long-term beach evolution near segmented shore-parallel breakwaters. Coastal Engineering, 57(8), 732-744. doi: 10.1016/j.coastaleng.2010.03.004