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Representative Waves for Morphological Simulations

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ABSTRACT

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In the present study, a set of representative waves is derived for the coast adjacent to the *Ria de Aveiro*, such that it is morphologically equivalent to the complete wave regime. Different schematising methodologies are presented, based on the principles of conservation of wave energy and equivalent longshore sediment transport capacity over the beach profile. Firstly, the sediment transport capacities due to the whole set of waves is computed and then various sets of representative waves are proposed based on the principles above. The most suitable set is selected by taking into account the dominant sediment transport processes at the selected site. The representative waves can be used to significantly reduce computational time in morphological models, by reducing the number of different sea states that characterise the annual wave climate. This simplified nearshore wave regime shall provide the wave effects into the sediment transport formulae and the hydrodynamical model.

ADDITIONAL INDEX WORDS: *Representative wave, Longshore sediment transport*

INTRODUCTION

The *Ria de Aveiro* is a coastal lagoon located in the northwest of the Iberian Peninsula, connected with the Atlantic Ocean through an artificial channel and exchanges the most part of its water with the ocean across a narrow inlet (Figure 1). It is important to evaluate the sediment transport at the entrance and neighbouring areas in order to understand the evolution of the bottom, namely the existence of erosion and deposition areas.

The aim of this study is to find a simplified wave regime which induces a longitudinal sediment transport at a beach equivalent to that caused by the complete wave regime. With this purpose the methodology proposed by CHONWATTANA *et al.* (2005) was applied with the modifications described in the next section. This method is based on the principles of conservation of wave power and longshore sediment transport capacity between the two sets of wave regimes.

The first step is to calculate the longshore sediment transport due to the complete wave regime offshore Aveiro. After that, the regime is simplified using different formulae for the sediment transport and new estimates of the longshore transport are calculated. Comparing the results between these wave regimes with the complete one, the best simplification can be chosen.

METHODOLOGY

Wave regime

The complete wave regime was obtained based on data from two wave directional buoy located in *Figueira da Foz* (40º11'08"N – 9º8'44"W, depth 92m ZH) and *Leixões* (41º19'00"N – 8º59'00"W, depth 83m ZH) (CAPITÃO *et al.*, 1997; COSTA *et al.*, 2003). In spite of the different locations, the offshore regime for these two buoys can be considered the same (COLI, 2003), that is, these 2 buoys register the same wave climate and thus their records can be complemented with each other in case one buoy fails. After joining the available data from the buoys, we obtain a deep water wave time series of approximately 11 years long (1990-2001). This time series is used to calculate the wave regime by grouping the occurrences in classes of 0.5m for the significant wave height H, 2s for the wave period *T*, and 22.5° for the wave direction, α. The complete wave regime results in 282 distinct waves (of different classes).

Longshore transport

To calculate the longshore sediment transport due to these set of waves, a cross-shore section 1.5 km northward of *Ria the Aveiro* lagoon inlet was selected (Figure 1). The wave regime is computed along this section, considering wave refraction and shoaling, and assuming straight and parallel bottom contours.

The longshore sediment transport is calculated by means of six longshore sediment transport formulations. The first one was presented by VONGVISESSOMJAI *et al.* (1993) (CHONWATTANA *et al.*, 2005), which is adapted from the CERC (1984) formula. This one is based on the assumption that the longshore transport rate depends on the longshore component of wave energy flux in the surf zone:

$$Q_\ell = 0.064208\, f H_0^{5/2} F(\alpha_0) \quad (1)$$

$$F(\alpha_0) = \cos\alpha_0^{1/4} \sin 2\alpha_0 \quad (2)$$

where f is the wave frequency and the sub-index 0 denotes deepwater.

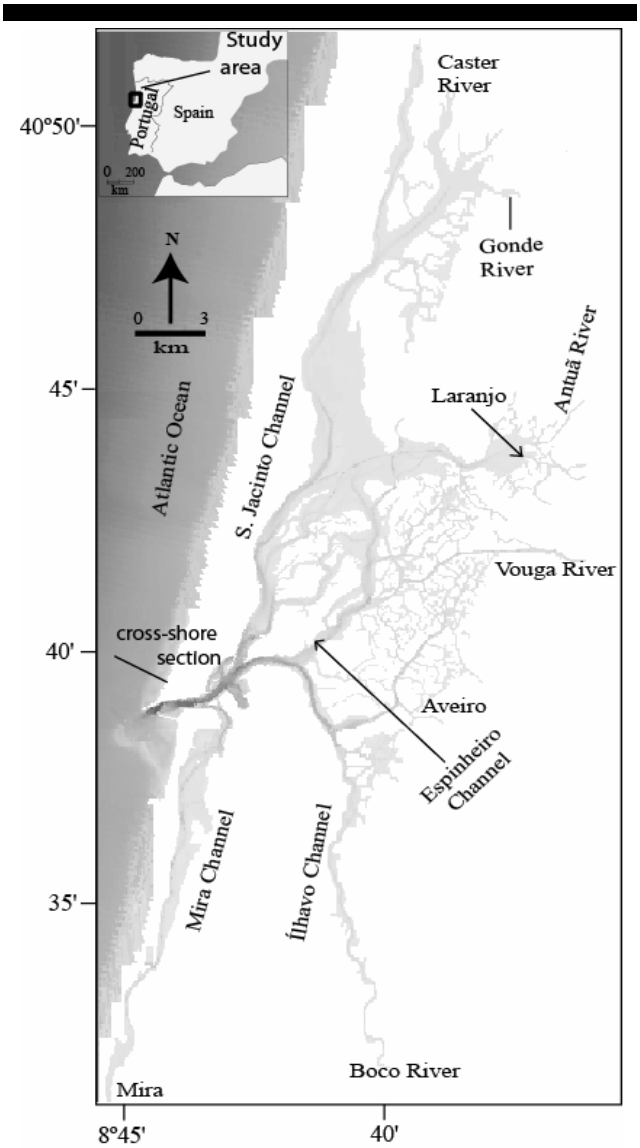

Figure 1. Localisation of the *Ria de Aveiro* lagoon.

Additionally to this formula, five more formulae were selected (LARANGEIRO and OLIVEIRA, 2003). In these formulae Q_ℓ is proportional to the wave characteristics in the breaker line having different dependences in wave breaker height, wave period and incident wave breaker angle. The selected formulations are presented in Table 1 (column 2), together with an abbreviation by which they will be referred subsequently (column 1). Column 3 highlights, for each formula, the dependency of the sediment transport flux on the wave height in the breaker line. It should be noted that all these formulae make use of significant wave height, except for the one of VALLE *et al.* (1993) which accounts for the root mean square wave height, H_{rms}.

The explanation of the column 4 of the Table 1 is in the end of the section below.

Simplifications of the wave regime

To calculate a simplified wave regime the method proposed by CHONWATTANA et al. (2005) is used. The wave power in the cross-shore and longshore directions are given by:

$$\text{Power in cross-shore direction} = H_0^2 T \cos\alpha_0 \quad (3)$$

$$\text{Power in longshore direction} = H_0^2 T \sin\alpha_0 \quad (4)$$

If the total longshore sediment transport is to be conserved among two different sets of wave regimes, then equation (1) yields,

$$H_0^{5/2} \cos\alpha_0^{1/4} \sin 2\alpha_0 = \text{constant} \quad (5)$$

Now if the wave energy and longshore sediment transport are to be conserved, equations (3), (4) and (5) are constants and form a non-linear system:

$$\begin{cases} H_0^2 T \cos\alpha_0 = C_1 \\ H_0^2 T \sin\alpha_0 = C_2 \\ H_0^{5/2} (\cos\alpha_0)^{1/4} \ \sin 2\alpha_0 = C_3 \end{cases} \quad (6)$$

The constants C_1, C_2 and C_3 are calculated for each wave of the wave regime, given H_0, T and α_0.

The simplified wave regime is calculated by dividing the complete regime in a few (usually less than 10) directional or wave height classes, each one corresponds to one equivalent wave. Each class has one trio $\left(C_{1,eq}, C_{2,eq}, C_{3,eq}\right)$ that is a function of the percentage of occurrence of all waves within that new class:

Table 1: Longshore sediment transport formulae Q_ℓ.

Longshore sediment transport formulae	$Q_\ell\,(\mathrm{m^3s^{-1}})$	C_3	$H_{b,eq}$ (m)
Valle *et al* (1993) **(C2)**	$K_1 H_b^{5/2} \sin(2\alpha_b)$	$H_{rms_b}^{5/2} \sin(2\alpha_b)$	$\frac{2}{\sqrt{2}}\left(\frac{C_{3,eq}}{\sin(2\alpha_{b,eq})}\right)^{2/5}$
Komar & Inman (1970) **(K&I)**	$K_2 H_b^{5/2} \cos(\alpha_b)\sin(2\alpha_b)$	$H_b^{5/2} \cos\alpha_b \sin(2\alpha_b)$	$\left(\frac{C_{3,eq}}{\cos\alpha_{b,eq}\sin(2\alpha_{b,eq})}\right)^{2/5}$
Kraus *et al* (1988) **(Kr88)**	$K_3 H_b^{3/2} \sin(2\alpha_b) W$	$H_b^{3/2} \sin(2\alpha_b) W$	$\left(\frac{C_{3,eq}}{\sin(2\alpha_{b,eq}) W}\right)^{2/3}$
Kamphuis *et al* (1986) **(K86)**	$K_4 H_b^{7/2} \sin(2\alpha_b)$	$H_b^{7/2} \sin(2\alpha_b)$	$\left(\frac{C_{3,eq}}{\sin(2\alpha_{b,eq})}\right)^{2/7}$
Kamphuis (1991) **(K91)**	$K_5 H_b^2 T_p^{1.5} \sin^{0.6}(2\alpha_b)$	$H_b^2 T_p^{1.5} \sin^{0.6}(2\alpha_b)$	$\left(\frac{C_{1,eq}}{\cos\alpha_{b,eq}}\right)^{2/5}$

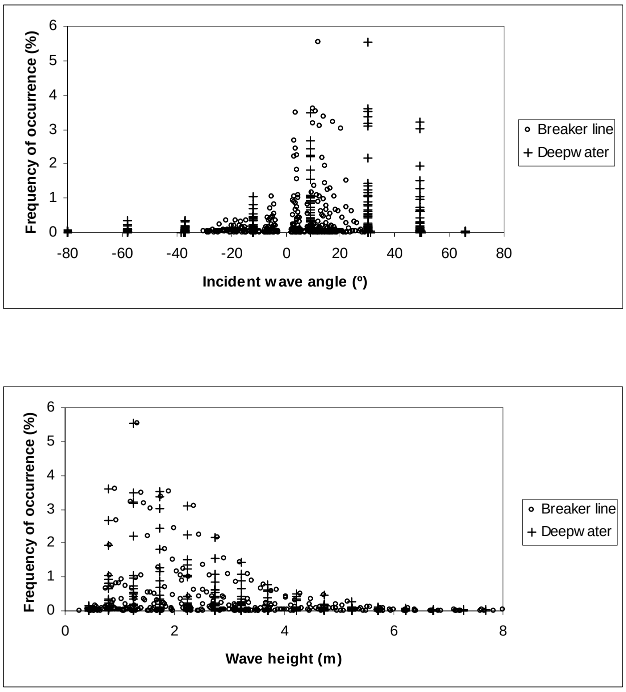

Figure 2. Frequency of occurrence of the (a) incident wave angles and (b) wave heights of the complete wave regime.

$$\left(C_{1,\,eq}, C_{3,\,eq}, C_{3,\,eq}\right) = \left(\frac{\Sigma\, p_i C_{1,i}}{\Sigma\, p_i}, \frac{\Sigma\, p_i C_{2,i}}{\Sigma\, p_i}, \frac{\Sigma\, p_i C_{3,i}}{\Sigma\, p_i}\right) \quad (7)$$

where p_i is the probability of occurrence of each wave of the selected class.

Once having computed $\left(C_{1,eq}, C_{2,eq}, C_{3,eq}\right)$ the system (6) is inverted to obtain $\left(H_{0,eq}, T_{eq}, \alpha_{0,eq}\right)$ of the equivalent wave, that is:

$$\begin{cases} \alpha_{0,eq} = \arctan \dfrac{C_{2,eq}}{C_{1,eq}} \\ H_{0,eq} = \left(\dfrac{C_{3,eq}}{\left(\cos\alpha_{0,eq}\right)^{1/4} \sin 2\alpha_{0,eq}}\right)^{2/5} \\ T_{eq} = \dfrac{C_{1,eq}}{H_{0,eq}^{2} \cos\alpha_{0,eq}} \end{cases} \quad (8)$$

The wave with these characteristics is representative of a certain directional or wave height class and their frequency of occurrence is the sum of the individual frequencies of occurrence within that class (from the complete wave regime).

An analogous computation was made for the other longitudinal transport formulae presented in Table 1, which depend on the wave characteristics at the breaker line.

For the breaker line, the energy flux in cross-shore and longitudinal directions, in the breaker line, are:

$$\mathrm{F_{b,cross\text{-}shore}} = \mathrm{const} H_b^{5/2} \cos\alpha_b \quad (9)$$

$$\mathrm{F_{b,longitudinal}} = \mathrm{const} H_b^{5/2} \sin\alpha_b \quad (10)$$

Assuming conservation of the wave energy, equations (9) and (10) will be equal to constants C_1 and C_2, respectively, which are now independent of the wave period (due to wave refraction by Snell's law). The additional equation depends on the sediment transport formula used, and is derived assuming longshore sediment transport conservation as in eq. (5), originating the new constants C_3 presented in Table 1 (column 3).

After grouping the complete wave regime in directional or wave height classes and calculating $\left(C_{1,eq}, C_{2,eq}, C_{3,eq}\right)$ we obtain the equations for $\alpha_{b,eq}$, $H_{b,eq}$ and T_{eq}. The equation for $H_{b,eq}$ is presented in Table 1 (column 4) for each formula, while for $\alpha_{b,eq}$ and T_{eq} are presented below:

$$\begin{cases} \alpha_{b,eq} = \arctan\left(\dfrac{C_{2,eq}}{C_{1,eq}}\right) \\ T_{eq} = \begin{cases} 0.99 H_{b,eq} + 5.35, & \text{if C2, K \& I, Kr88, K86} \\ 0.483\left(\dfrac{C_{3,eq}}{H_{b,eq}^{2} \sin^{0.6}\left(2\alpha_{b,eq}\right)}\right)^{2/3} + 3.08, & \text{if K91} \end{cases} \end{cases} \quad (9)$$

RESULTS

To analyse which method of simplification is the most adequate, several groupings of the waves, by directional and wave height classes, were made. Thus, one has the degree of freedom to, *a priori*, choose how many waves will have the simplified regime, and how are the individual waves (or contributions) from the complete set lumped together.

Considering a lumping of the waves by directional classes (that is, grouping together all waves within a certain range of α) we tested two simplifications: one based on the deepwater wave angle (simplification 1a), and the other based on the wave breaker angle (simplification 1b). In the case of grouping the wave regime by wave height classes, we also divided the groups by their deepwater wave height (simplification 2a) or the breaker wave height (simplifications 2b and 2c). In Figure 2 are illustrated the incident wave angles (Figure 2a) and wave heights (Figure 2b) in deepwater (+) and at the breaker line (◦) versus the frequency of occurrence.

With this process to simplify the complete wave regime we obtain several simplified wave regimes, one for each longshore sediment transport formula and simplification procedure (1a, 1b, 2a, 2b and 2c). Each simplified regime will thus consist of a small set of waves (typically less than 10) that yield the same annual total longshore sediment load and wave power as the averaged wave climate.

Table 2: Wave simplified regime computed through the K91 longshore sediment transport formula.

Wave number	Frequency (%)	$H_{b,eq}$ (m)	$\alpha_{b,eq}$ (º)	$T_{p,eq}$ (s)
1	14.29	0.87	20.52	8.65
2	45.74	1.56	22.10	9.28
3	24.75	2.50	20.76	10.75
4	9.71	3.42	19.41	11.50
5	3.87	4.40	20.22	12.19
6	1.19	5.39	22.73	13.76
7	0.23	6.35	18.87	14.06
8	0.13	7.48	15.25	14.88

Table 3: Longshore sediment transport results for wave regime simplification 1b. ($Q_\ell = \times 10^6\,\mathrm{m^3 year^{-1}}$).

	CERC	C2	K&I	Kr88	K86	K91
Complete wave regime	8.83	3.11	5.63	1.44	8.52	1.90
CERC	8.83	3.99	7.22	1.83	11.61	2.09
C2	8.83	3.99	7.23	1.71	8.68	2.02
K&I	8.83	3.98	7.22	1.71	8.66	2.02
Kr88	8.83	4.68	8.49	1.83	11.33	2.35
K86	8.83	4.91	8.91	1.94	11.61	2.48
K91	8.83	4.00	7.24	1.71	8.71	2.09

As an example, the simplified wave regime corresponding to "simplification 2b" and with Q_ℓ computed from K91 is composed of 8 waves, each of them chosen *a priori* to belong to a different wave height class (with 1m intervals). The characteristics of these waves as computed from the procedure outline above are presented in Table 2.

Longshore sediment transport results

For each simplified wave regime, it is calculated the longshore sediment transport through the several different longshore sediment transport formulae presented in Table 1. The results for the total annual alongshore transport are compared to the "reference" value for the Portuguese *Aveiro* west coast presented in bibliography: $Q_\ell = 1\times 10^6\,\mathrm{m^3}\,year^{-1}$ (LARANGEIRO and OLIVEIRA, 2003). Comparing this value with those obtained with the transport formulae presented above it is possible to conclude which formula performs better.

In Table 3 are presented the results of the total annual longshore sediment transport Q_ℓ for the simplification 1b. This simplification is made by grouping the waves of the complete wave regime in classes with an interval of incident wave breaker angle of 5 degrees each, resulting in 12 representative waves (Fig. 2a). Column 1 identifies the formula by which the simplified regime is calculated (see Table 1). Line 1 identifies the formula by which the total longshore transport is computed, for any given wave regime. The results under line 2 were obtained for the complete wave regime (282 waves). The results below line 2 correspond to those calculated for the simplified regimes. For instance, one observes that the formula that best predicts the reference value (1x10^6 m^3/yr) is Kr88. However, the simplified regimes yield values of Q_l somewhat larger (between 18% and 35%) than the value for the complete regime (1.44x10^6 m^3/yr).

Analysing Table 3 in detail we can conclude that, for simplification 1b, the longshore sediment transport computed for the complete wave regime by all transport formulae (1st line) are overestimated when compared with the reference value.

When we analyse the results obtained for the simplified wave regimes the conclusions are that using CERC formula the results are independent of the simplified wave regime that is used. The most sensitive formula to the (simplified) wave regime is the K86 formula due to its larger-power dependence of the breaker wave height $(H_b^{7/2})$. The formulae less sensitive to the wave regime are Kr88 $(H_b^{3/2})$ and K91 (H_b^2), which have the smallest wave height dependence.

To analyse which regime simplification performs better, the values of Q_ℓ were normalised taking the ratio between the transport values calculated by the simplified wave regimes and the values obtained by the complete regime: Q_{simp}/Q_{total}. The average and standard deviation of these normalised ratios have also been calculated.

An example of the normalised values computed from the results in Table 3 is presented in Table 4. Also in this table are presented the averages and standard deviations of the normalised values of the results of using different wave regimes (vertical averaging), and the averages of the results from the several longshore sediment transport formulae (vertical averaging) and the standard deviations of these. Thus, looking down a given column one can see how much a certain transport formula is sensitive to variations in computing the simplified wave regime, whereas looking across a given line one concludes how good a simplified wave regime (and methodology) is for all the transport formulae. For instance, column 2 shows that the CERC formula yields precisely the same results for any (properly) simplified wave regime as for the complete wave regime. However, lines 2 and 3 indicate that computing the simplified wave regime using the CERC formula gives rise, on average, to worse results for the total transport than using C2 to simplify the wave regime.

Analysing the results of the formulae that are a function of the wave characteristics at the breaker line, the K91 formula is the one that provides the most stable results $(\overline{Q_{\ell\,norm}} = 1.14, \sigma = 0.13)$.

Analysing the results of the horizontal averaging, we conclude that to compute simplified wave regimes, the formulae C2, K&I and K91 are those that provide the best results of the longshore sediment transport computed with simplified regimes, with $\overline{Q_{\ell\,norm}}$ equal to 1.14 for the first two formulae and 1.15 for the last one, and standard deviations for all three formulae equal to 0.13.

Average of Q_ℓ

To analyse the several simplifications that were made, all the averages of the longshore sediment transport for all the simplifications tested were joined in one single table (Table 5). That is, Table 5 contains all the horizontally averaged results of each simplification (in the second last column of Table 4 and similar ones). From it we can conclude which method to compute

Table 4: Longshore sediment transport normalised results for wave regime simplification 1b. ($Q_\ell = \times 10^6\,\mathrm{m^3 year^{-1}}$).

Form / Regime	CERC	C2	K&I	Kr88	K86	K91	$\overline{Q_{\ell\,norm}}$	σ
CERC	1.00	1.28	1.28	1.27	1.36	1.10	1.22	0.14
C2	1.00	1.28	1.28	1.19	1.02	1.07	1.14	0.13
K&I	1.00	1.28	1.28	1.18	1.02	1.06	1.14	0.13
Kr88	1.00	1.50	1.51	1.27	1.33	1.24	1.31	0.19
K86	1.00	1.58	1.58	1.35	1.36	1.30	1.36	0.21
K91	1.00	1.28	1.29	1.19	1.02	1.10	1.15	0.13
$\overline{Q_{\ell\,norm}}$	1.00	1.37	1.37	1.24	1.19	1.14		
σ	0.00	0.14	0.14	0.07	0.18	0.11		

Table 5: Longshore sediment transport normalised results for all wave regime simplifications tested. ($Q_\ell = \times 10^6 \, m^3 year^{-1}$).

Simp Regime	1a	1b	2a	2b	2c	M	σ
CERC	0.98	1.22	0.77	0.98	0.98	0.99	0.16
C2	0.93	1.14	0.78	1.00	0.98	0.96	0.13
K&I	0.93	1.14	0.77	0.98	0.96	0.96	0.13
Kr88	0.93	1.31	0.81	1.01	1.57	1.12	0.31
K86	1.14	1.36	0.82	1.01	0.99	1.06	0.20
K91	0.93	1.15	0.77	0.99	0.97	0.96	0.13
M	0.97	1.22	0.79	1.00	1.08		
σ	0.08	0.10	0.02	0.01	0.24		

a simplified wave regime is the best one and which of the computed simplified wave regimes produce longshore transports close to those obtained with the complete wave regime.

Thus, Table 5 shows us that the simplification that provides the best results is simplification 2b $(M = 1.00, \sigma = 0.01)$. This wave regime simplification consists in grouping the complete wave regime in wave breaker height classes with intervals of 1m, resulting in 8 representative waves. The second best tested simplification is 1a $(M = 0.97, \sigma = 0.08)$, which corresponds to divide the complete wave regime in directional classes of wave angles in deepwater, resulting in 8 equivalent waves.

Analysing the average and standard deviation of the simplified wave regimes (horizontal average), we conclude that those that are computed through C2, K&I and K91 are the ones that produce results more stable (smaller standard deviation) for longshore sediment transport. The results for all three simplified wave regimes are $M = 0.96, \sigma = 0.13$.

CONCLUSIONS

This paper dealt with simplifying a given deep-water wave regime for morphodynamic modelling computations, so that the annual alongshore sediment transport load is maintained. The method proposed by CHONWATTANA *et al.* (2005) was extended and applied to the longshore sediment transport formulae presented in Table 1, which are functions of the height, period and angle of incidence of the waves at the breaking point.

Our results indicate that the longshore sediment transport formulae of VALLE *et al.* (1993), KOMAR and INMAN (1970) and KAMPHUIS (1991) are more adequate and accurate to compute the simplified wave regime than the other formulae (KRAUS *et al*., 1988 and KAMPHUIS *et al*., 1986). In absolute terms, of the former 3 formulae, the one by KAMPHUIS (1999) seems to be more accurate for this coastal stretch.

To derive a simplified wave regime, among the 5 different alternatives that were tested, the best method is to divide the complete wave regime in wave height classes of intervals of 1m, resulting in 8 equivalent waves, for the wave regime used in this study.

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