ASSESSMENT OF THE LONGSHORE SEDIMENT TRANSPORT AT BUARCOS BEACH (WEST COAST OF PORTUGAL) THROUGH DIFFERENT FORMULATIONS

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Abstract

This study applies some of the most practical longshore sand transport formulations and evaluates their adequacy to estimate the total (suspended and bed load) longshore sediment transport rate (LSTR) at Buarcos Beach, in the West coast of Portugal. The straightforward methodology here present is simple to apply and therefore useful to quickly obtain a first estimate of the littoral transport in coastal engineering studies. A sensitive analysis to the variation of hydrodynamic and morphologic parameters was performed. The most accurate prediction of the LSTR at Buarcos coastal region was obtained by the Kamphuis formulation derived in the last decade, which is recommended to be applied in similar hydrodynamic and morphologic conditions in the West coast of Portugal.

Introduction

Predictions of the longshore sediment transport rate (LSTR) are essential in a broad range of coastal engineering studies. Until now the LSTR estimates have been largely based in predictive empirical formulations that were calibrated from field measurements or laboratory physical models. However, the derivation and application of those predictive formulations are enclosed in four major difficulties: (1) large variability on the environmental conditions at the nearshore zone; (2) complexity of the governing physical processes; (3) errors and uncertainties in the data used to calibrate the formulation; and (4) limit number of field data that reveal considerable scatter.

(1) The nearshore zone is a highly energetic region characterized by a complex interaction of physical processes dependent on a wide range of morphodynamic conditions characterized by seasonal and inter-annual variations. In these cases, empirical formulations have remained site-specific because it is difficult to drive reliable formulations for such a wide range of environment conditions.

(2) Efforts to quantify mechanisms have been centred on those that are less complex and easier to measure in detriment of others equally important. For example, suspended load transport has been subjected to further investigation than bead load transport because it is easier to measure. Transport mechanisms in the swash zone have received less attention than those in the surf zone due to their complexity and difficult quantification. Only recently the transport in highly energetic environments as storms events was quantified (Miller, 1999), even though for long its importance has been recognised. Such different degrees of knowledge about essential mechanisms obscure the selection of the governing processes to be included in the empirical formulations.

(3) Although measurement techniques for sediment transport have been improved, there are still many unresolved problems. Three standard techniques are worldwide used in field measurements: sediment tracer, long- and short-term impoundments and streamer sediment traps. Their methodologies differ in fundamental assumptions, key measurements, calculated algorithms and time scales, and may not be consistent with each other (Wang *et al.*, 1998). General discrepancies were found when measured values obtained from more recent streamer trap and short-term impoundments techniques were confronted with predictions from empirical formulations that were mainly calibrated by tracer measurements (Kraus *et al.*, 1988; Wang *et al.*, 1998). Errors associated with the field measurements and their propagation through data reduction and transport calculations have not been quantified (Wang, 1999). Laboratory physical models offer the advantage of controlled accurate measurements, but small scale and simplified hydrodynamic and morphodynamic conditions are limiting aspects to a more widely use.

(4) Empirical formulations are dependent on a limited number of field measurements that exhibit considerable scatter, which could be explained not only by the quality of the data itself as mentioned in (3), but also by a more difficult to deal high environmental variability as stated in (1).

Such scatter produces uncertainty in the evaluation of the proportionality coefficients found in many empirical formulations.

The formulations here applied were derived based on three methods of analysis: the energy flux method, the stream power method and the dimensional analysis method. The energy flux method is based on the most commonly used assumption in LSTR predictions, which states that the longshore immersed weight sediment transport rate, I_l, is proportional to the longshore wave power per unit length of beach, P_l. The stream power method (Bagnold, 1963) is based on a physical interpretation of the mechanism underlying sediment transport: the bottom shear stress induced by wave oscillatory movement sets sediment particles into suspension which are adverted in the direction of the flow by any superimposed steady current with no additional stresses. In dimensional analysis methods the physical parameters that govern the transport mechanism are grouped in dimensionless combinations. The resulting expressions were mainly developed from laboratory experiments and relate measured environmental parameters to volumetric transport rates.

This paper aims to examine some LSTR predictive formulations through the use of site-specific hydrodynamic and morphologic conditions in the West coast of Portugal. This analysis enables to identify the formulations that are expected to perform well in identical regional environmental conditions.

Study area

Buarcos Beach is an important seaside resort located in the Atlantic West coast of Portugal. It has a NW-SE general orientation and an extension of approximately 2.8 km (Figure 1a). Almost the total longshore extension of the beach is covered by hard rock outcrops, which have an onshore-offshore orientation and average development from 2 m depth above chart datum (CD) to 1 m depth below CD. The beach sediments are mainly medium and coarse sand ($D_{50} = 0.69$ mm). The mean tidal range is 2.2 m. The average annual wave climate (Figure 1b), at 10 m depth CD in front of Buarcos beach, was derived (Capitão *et al.*, 1997) at mean sea level (2 m above CD), based on a data series (from January 1984 to December 1996), recorded at a wave-rider station located offshore.

Buarcos coastal dynamics has been studied by several authors. Periodic surveys performed during the infilling process of Figueira da Foz beach (Figure 1a), after the construction of the jetties of Mondego estuary mouth, allowed to estimate the local LSTR as 1 000×10^3 m^{3}year^{-1} (Vicente and Clímaco, 1986). More recently, Larangeiro *et al.* (2003), based on the wave data series used in the present study and through the application of a profile type mathematical model, obtained an identical value.

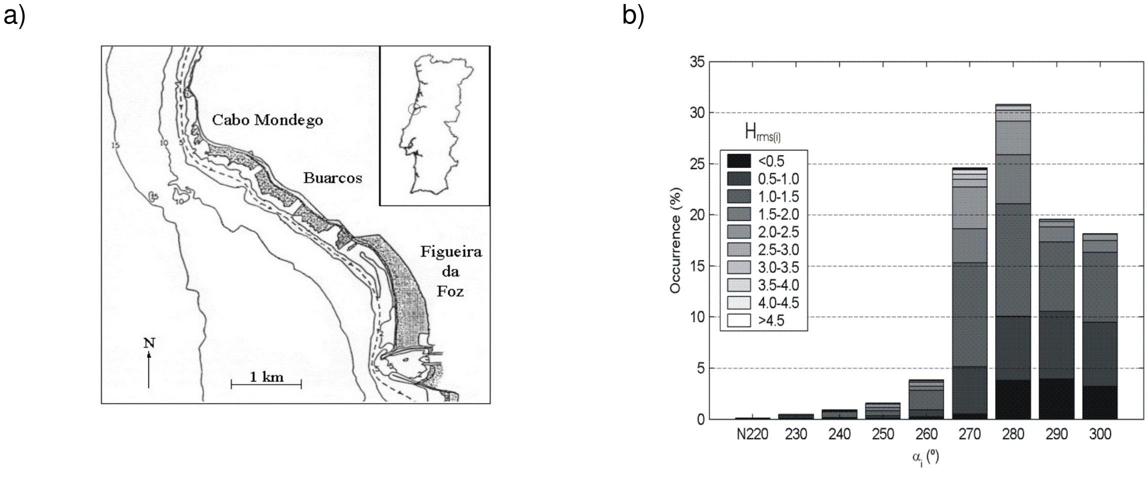

Figure 1 – Study area: a) Location of Buarcos Beach; b) Average Annual Wave Climate.
(i index indicates incident wave conditions)

Total longshore sediment transport formulations

The formulations applied are briefly characterized in this section. They are presented in Table 1 together with an abbreviation by which they will be referred subsequently.

Energy flux method. The most commonly used formula is Eq. (1), known as CERC equation (US Army Corps of Engineering, 1984), which states that I_l is proportional to the wave energy flux evaluated at the breaker position, P_{lb}, through an empirical dimensionless coefficient K. In this study, two values of K were experimented: the value derived by Komar and Inman (1970) based on their fluorescent sand tracer experiments at the Pacific Coast, $K = 0.77$, for use with the statistic wave height parameter H_{rms}; and the value proposed by Valle, Medina and Losada (1993) in the empirical Eq. (2), in which K has a decreasing trend with increasing sediment diameter. The last relation was found to be the best fit curve to a set of available databases relating sediment transport with median sediment grain size. This relation applied to Buarcos coastal sediments yields the value $K = 0.25$, also for use with H_{rms}.

Stream power method. Komar and Inman (1970) pointed out that Eq. (1) is largely empirical and that considerations about the mechanics of sand transport found in the model of Bagnold (1963) should give a more physically realistic relation. Thus, they proposed Eq. (3), where the dimensionless coefficient K', that relates I_l with wave and current parameters, was taken as 0.28, based on florescent sand tracer experiment data. Kraus *et al.* (1982), based on sand tracer field experiments performed in several locations at the East coast of Japan, developed simple linear expressions relating the tracer key measurements to wave and current conditions, Eqs. (4.2) and (4.3). Those relations were then introduced in Eq. (4.1) that together with the additional assumption of plane seabed slope, enable the computation of the LSTR from wave and current parameters, Eq. (4.4). More recently, Kraus *et al.* (1988) verified that the LSTR measured from streamer traps during DUCK85 and SUPERDUCK experiments was well correlated with a quantity defined as the discharge parameter, R, defined by Eq. (5.1). Assuming the existence of a linear dependence between I_l and R, the authors obtained an empirical relation through linear regression analysis, Eq. (5.2), in which the intercept $R_c = 3.9$ m^{3}s^{-1} is interpreted as the critical water discharge parameter. The model proposed by Walton (1980), in which P_l is calculated through Eq. (6.2), includes the Longuet-Higgins cross-shore current distribution model, Eq. (6.1).

Dimensional analysis method. Kamphuis *et al.* (1986) using an extensive laboratory and field data set and through dimensional analysis derived an empirical relation, Eq. (7), which takes into account the seabed slope and the sediment grain size. With additional laboratory study and further dimensional data analysis, Kamphuis (1991) modified Eq. (7), adding the influence of the wave period in Eq. (8).

Table 1 – LSTR formulations applied

Reference	Abbreviation	Mathematical expression	Eq. (number)
Komar & Inman (1970)	C1	$K = 0.77$ $Q_l = KP_{lb}/[(\rho_s - \rho)ga'] = K\Big/\left[16\gamma^{1/2}(\rho_s - \rho)a'\right]\rho g^{1/2} H_b^{5/2}\sin(2\alpha_b)$	 (1)
Valle *et al.* (1993)	C2	$K = 1.4e^{(-2.5D_{50})}$ $Q_l = K\Big/\left[16\gamma^{1/2}(\rho_s - \rho)a'\right]\rho g^{1/2} H_b^{5/2}\sin(2\alpha_b)$	(2)
Komar & Inman (1970)	K&I	$I_l = K'(EC_g)_b \cos\alpha_b \overline{V_l}/u_m$	(3)
Kraus *et al.* (1982)	KR82	$Q_l = V_a bW$; $b = 0.027H_b$; $V_a = 0.014\overline{V_l}$; $Q_l = 3.8\times10^{-4}/(\gamma\, i)H_b^2\, \overline{V_l}$	(4.1); (4.2); (4.3) (4.4)
Kraus *et al.* (1988)	KR88	$R = \overline{V_l}WH_b$ $I_l = 2.7(R - R_c)$; $R_c = 3.9m^3s^{-1}$	(5.1) (5.2)
Walton (1980)	WT	$(V/V_0)_{LH} = 0.2(X/W) - 0.714(X/W)\ln(X/W)$ $P_l = \rho g H_b WVC_f/[(5\pi/2)(V/V_0)_{LH}]$	(6.1) (6.2)
Kamphuis *et al.* (1986)	KP86	$Q_l = 1.28/[(\rho_s - \rho)a']H_b^{7/2}\, i\, D_{50}^{-1}\sin(2\alpha_b)$	(7)
Kamphuis (1991)	KP91	$Q_l = 2.27/[(\rho_s - \rho)a']H_b^2 T_p^{1.5}\, i^{0.75} D_{50}^{-0.25}\sin^{0.6}(2\alpha_b)$	(8)

Where: $Q_l =$ LSTR; $\rho_s =$ sediment density; $\rho =$ water density; $g =$ gravity acceleration; $a' =$ solid fraction of beach sediment ($a' = 1 - porosity$); $\gamma =$ breaker index; $H_b =$ breaking wave height; $\alpha_b =$ incident wave breaker angle; $(EC_g)_b =$ energy flux at the breaker line; $\overline{V}_l =$ mean longshore current velocity; $u_m =$ maximum oscillatory velocity magnitude under the breaking wave; $V_a =$ tracer advection velocity; $b =$ depth of mixing; $W =$ surf zone width; $i =$ seabed slope; $(V/V_0)_{LH} =$ Longuet-Higgins current distribution; $X =$ distance from the measured current to the shoreline; $V =$ longshore current at X; and $C_f = 0.01$, is the friction coefficient.

Table 2 – Other formulations applied in the methodology

Reference	Mathematical expression	Eq. (number)
US Army Corps of Engineers (1998)	$H_b = H_0^{4/5}\left(C_{g0}\cos(\alpha_0)\right)^{2/5}\left[g/\gamma - H_b g^2 \sin^2(\alpha_1)/\left(\gamma^2 C_0^2\right)\right]^{-1/5}$	(9)
US Army Corps of Engineers (1998)	$\sin\alpha_b = \left(g\, H_b/\gamma\right)^{1/2}\left(\sin\alpha_0/C_0\right)$	(10)
US Army Corps of Engineers (1984)	$H_b/h_b = 0.78$	(11)
US Army Corps of Engineers (1984)	$V_l = 20.7\, i\left(gH_b\right)^{1/2}\sin(2\alpha_b)$	(12)
US Army Corps of Engineers (1998)	$u_{mb} = \gamma/2(gh_b)^{1/2}$	(13)

Where: $H_0 =$ offshore wave height; $C_{g0} =$ offshore group velocity; $\alpha_0 =$ offshore wave angle with respect to the shore-normal; $C_0 =$ offshore wave celerity; $h_b =$ breaker depth; and $V_l =$ longshore current velocity.

Methodology

Using linear wave theory, assuming that the nearshore depth contours are straight and parallel the shoreline and that there is conservation of wave energy during the shoaling process, the breaking conditions in the surf zone of Buarcos were derived based on the transformation of the average annual wave climate known at 10 m depth CD in front of the beach (Figure 1b). The breaking wave height and correspondent angle were calculated through the application of Eqs. (9) and (10). The breaker depth was estimated from the breaking criteria defined in Eq. (11). The average longshore current velocity and maximum horizontal velocity at the bottom were estimated by Eqs. (12) and (13). For the Walton model, Eqs. (2) and (12) were applied to assess the relation coefficient between I_l and P_l and to estimate V, and it was assumed $X = W/2$ in Eq. (6.1).

Results and discussion

The LSTR for the average annual wave climate (Figure 1b) was estimated through all the formulations presented. The importance of the variation of the morphologic parameters grain size (1) and seabed slope (2) and of the hydrodynamic parameters wave height (3) and wave angle (4) was assessed.

(1) To acknowledge for the influence of the sediment grain size on the LSTR, computations were performed for D_{50} within the range 0.5-0.9 mm. The results are presented in Figures 2a-b. The same trend (LSTR decrease with D_{50} increase) was found in all formulae. Within the D_{50} range analysed, the formulations C2 and WT are the most sensitive to the grain size variation. They both decrease by a factor of 2.7. The formulation KP91 is the less variable with the grain size. It shows a decrease factor of 1.2. In between is KP86 formulation with a decrease factor of 1.8. However, because the highest values of the LSTR are obtained with KP86 and WT, these two formulations present the highest variation with the sediment grain size.

(2) Seabed slopes within the range 0.01-0.02 were used to assess the influence of the seabed slope on the LSTR. Figures 3a-b shows the results. As expected, when the seabed becomes steeper there is an increase in the LSTR given by all formulae. K&I and KP86 show a substantial dependence on the seabed slope. For these two formulae, the LSTR duplicates within the range of seabed slope analysed. The lower influence of the variation of this parameter was observed for KP91, with an increase factor of 1.7. As in the previous analysis, due to the magnitude of the LSTR obtained with KP86, its variation with the seabed slope is the most relevant.

(3) The variation of the LSTR with the wave height was analysed for the waves incident from the directional sector with longer duration, N265-275°, which accounts for waves with H_{rms} within the range 0.4-5.3 m. The results of the computations are shown in Figure 4a. The vertical axis presents

the ratio between the LSTR computed with the various formulae and the computed with the C1 formulation. The C2, KR82, KR88 and WT formulae have identical variation tendency to the C1 formula, since in all of them the breaker wave parameters (height and direction) are powered to the same factor. The lower values found by KR88 for waves with H_{rms} below 1.0 m are due to the parameter R_c, which effect becomes less important as the wave height increases. KP86 gives the highest variability due to the higher exponential of the wave height. For higher waves, KP91 increases faster than C1, due to the explicit dependence on the wave period. The decreasing trend obtained with K&I formulation is not due to the factor wave height directly, but instead, it is associated to the variation of the wave direction at breaking, which as can be seen in Eq. (10) depends on the breaker height.

(4) The variation of the LSTR with the incident wave direction was tested for each formulation, using the average wave height of the annual wave climate, $H_{rms} = 1.22$ m. The results of the computations are presented in Figure 4b. The most sensitive formulae to wave direction are C1, C2 and those having the same dependence on the parameters wave height and wave direction. Under lower values of breaker wave angle, KR88 has a different behaviour from C1, due to the effect of the parameter R_c. KP86 and KP91 present a rather different variation tendency from C1. KP86 is more sensitive to the reduction of the breaker wave height as the incident direction departs from the shore-normal (N216°), whereas the lower dependence of KP91 on the breaker wave height and direction induces a lower variability on the LSTR for the outer directional sectors of the wave climate. K&I formulation has an almost identical behaviour to C1 formulation, however, its lower dependence on the breaker wave angle becomes noticeable as the angle increases.

Larangeiro *et al.* (2003) concluded that the presence of the outcrops reduces by 33% the LSTR in Buarcos coastal region. Thus, in order to evaluate the adequacy of the formulations here applied to predict the LSTR at Buarcos coastal region, their results, affected by this reduction factor, were compared with the reference value of 1 000×10^3 m^{3}year^{-1} (Figure 5a). Considerable scatter was found in the predictions given by the different formulations. C1, KP86 and WT formulae unrealistically overpredict the reference value by a factor of 5.9, 6.0 and 4.5, respectively. C2, KR82 and KR88 formulae also revealed an overpredictive behaviour but of a lower order of magnitude (1.9, 2.5 and 1.8 times higher than the reference value). The best agreement with the reference value was found in KP91 and K&I formulations, for which the results were 1 062×10^3 m^{3}year^{-1} and 1 212×10^3 m^{3}year^{-1}. The LSTR distribution as function of the hydrodynamic parameters wave height and wave direction can be seen in Figure 5b, for the results obtained with KP91.

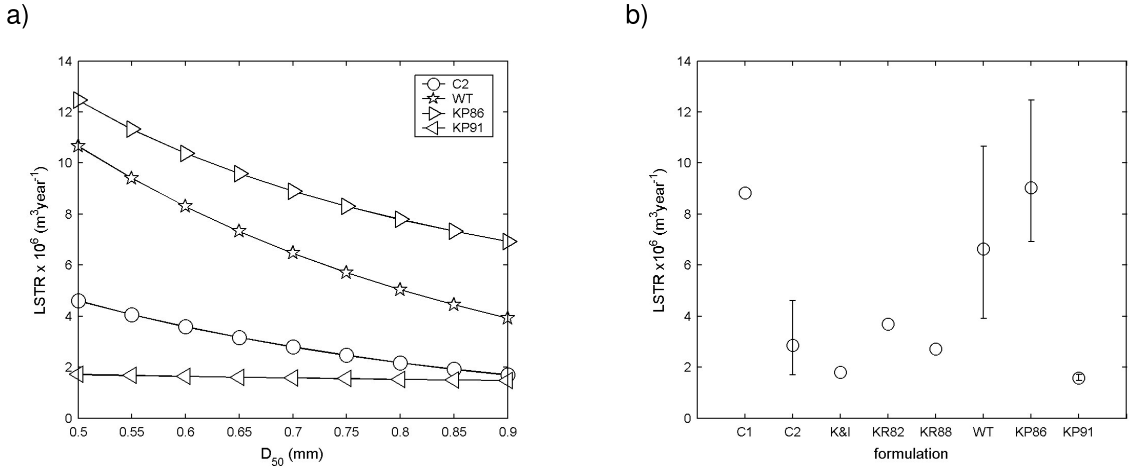

Figure 2 – LSTR variation with sediment diameter: a) Trend variation; b) Magnitude variation.

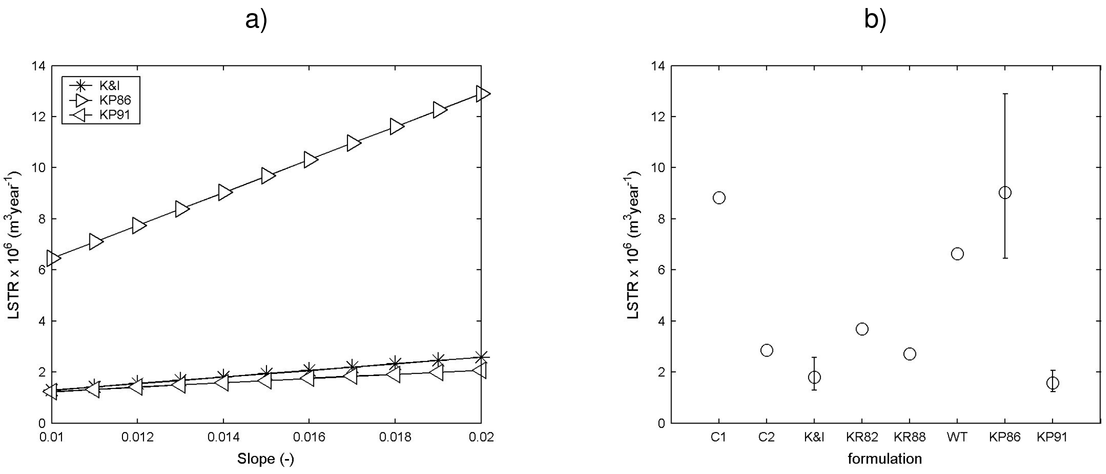

Figure 3 – LSTR variation with seabed slope: a) Trend variation; b) Magnitude variation.

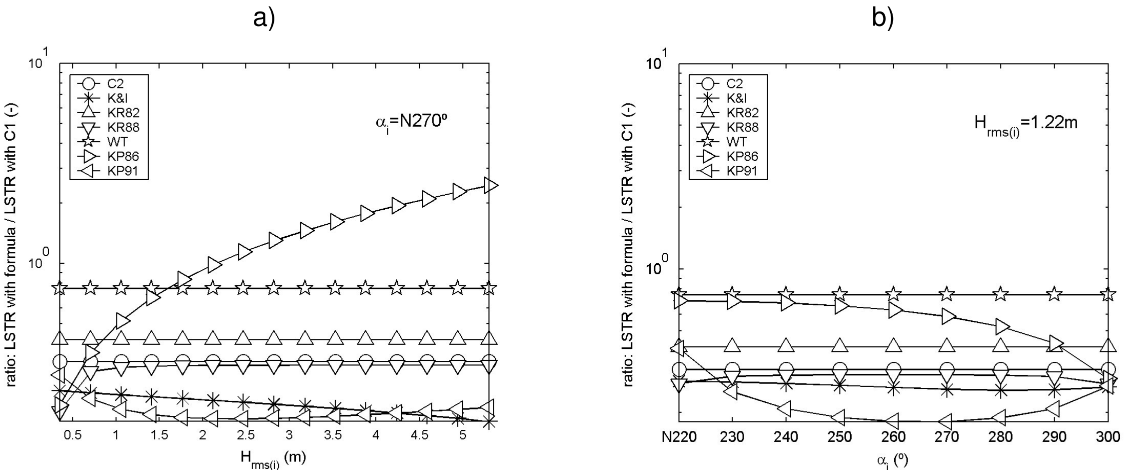

Figure 4 – LSTR variation with wave conditions: a) Wave height; b) Wave direction. (i index indicates incident wave conditions)

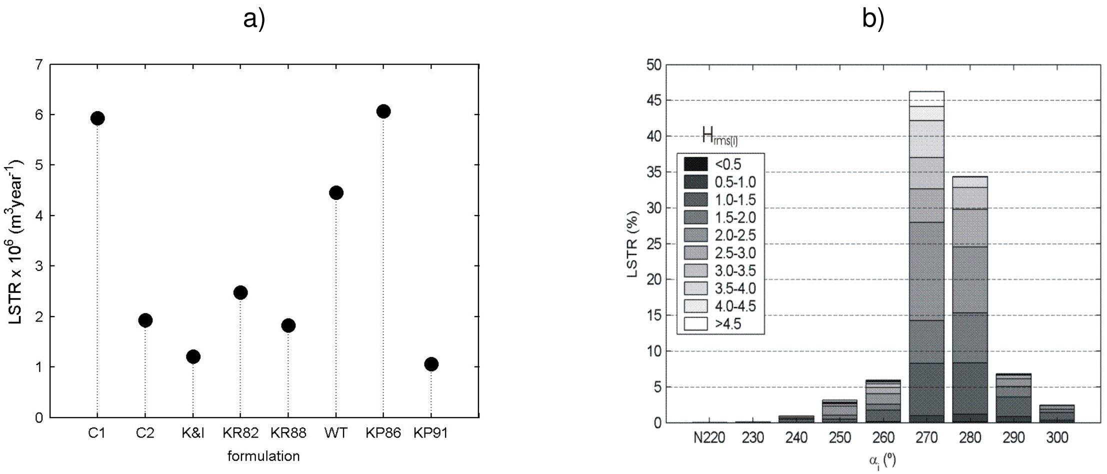

Figure 5 – LSTR at Buarcos coastal region: a) results of all formulae applied; b) distribution as function of wave parameters for KP91. (i index indicates incident wave conditions)

Conclusions

A comparative study between some of the most practical longshore sand transport formulae was done for the hydrodynamic and morphologic conditions at Buarcos Beach, West coast of Portugal. Calculations were performed using an average annual wave climate, based on a twelve-year time series of wave observations.

To understand the behaviour of the formulations under changing hydrodynamic and morphologic conditions, their sensitivity to the parameters wave height, wave direction, grain size and seabed slope was investigated. In comparison with the other formulations, KP91 is the less sensitive to sediment grain size and seabed slope variations. Therefore, when this formulation is applied, errors in the estimation of the LSTR due to uncertainties in the evaluation of those parameters are not expected to be important. In opposition to that, KP86 should be used with care because its sensitivity to the morphologic parameters is emphasised by its overpredictive behaviour.

The reference value $1\,000\times10^3\ \mathrm{m^3 year^{-1}}$ for the LSTR at Buarcos coastal region was used to assess the accuracy of the different formulae. The results can be used as guidelines in the selection of a simple empirical formulation to compute the LSTR in other locations of the Portuguese West coast. It is recommended the application of KP91 formulation, since it produced the most accurate result. K&I along with the current velocity Eq. (12) is also expected to perform well. Unrealistic high estimates misadvise the application of C1 and KP86 formulae. Alternatively, C1 might be applied considering a lower value for the K coefficient. Computations show that the K coefficient should be reduced to 0.13, which is much smaller than the value of 0.77 proposed by Komar and Inman (1970).

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