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Towards improving the prediction of longshore sediment transport

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Abstract Bulk formulae are often used in coastal studies to estimate the net longshore sediment transport (LST) rate. For the same hydrodynamic conditions at a given beach, rates of LST predicted by different bulk formula can vary by factors in a range between 2 and 10, and may not actually reflect the real LST rate. This can have serious economic consequences when designing, for example, beach nourishment schemes. The present paper attempts to reduce these errors and presents a more accurate, site-specific methodology to estimate LST. The study, from four contrasting locations, draws on existing theory and field measurements of hydrodynamics and suspended sediments in the surf zone to develop a new longshore transport model, *LT-MOD*. Case studies are used to compare the performance of *LT-MOD* against existing bulk LST formulae at daily time scales. This inter-comparison is then extended over much larger temporal and spatial scales by examining measured and predicted shoreline changes attributable to LST.

Key words longshore sediment transport; modelling; field measurements; suspended sediment concentration profile

INTRODUCTION

A range of engineering and beach management applications require estimates of longshore sediment transport (LST). In many cases investigators may not have access to specialist modelling software to simulate LST (e.g. LITPACK (http://www.dhigroup.com/Software/Marine/LITPACK.aspx). They may also lack equipment required to measure suspended sediment concentrations, water depth (*h*), breaker height (H_b), period (*T*), and shore approach angle (α_b), and the longshore current speed (*S*) required as input parameters in empirical formulae. Furthermore, most LST formulae make a number of simplifying assumptions and apply only to extensive and relatively straight littoral systems. There is a need therefore to develop a new method to estimate LST for local cases based on a few simple observations and on established knowledge of site-specific cross-shore distributions of sediment, wave properties, longshore current, and bed roughness.

The new LST model outlined here, *LT-MOD*, combines measured and predicted cross-shore and vertical profiles of the wave properties and the longshore current with an existing field-validated equation to predict the suspended sediment concentration profile (*C-Profile*) in the surf zone. In the model, *C-profiles* are predicted at defined time-steps and cross-shore locations and the total LST flux is obtained by integration. Although *LT-MOD* excludes some second-order physical processes, it can account for cross-shore variations in bed sediment grain size and for wave and/or current generated bedforms. Test-case results from *LT-MOD* at four different coastal sites are first compared with existing bulk LST formulae at diurnal time scales. The performance of *LT-MOD* is then examined over much larger spatial and temporal scales using a study of shoreline erosion and accretion in southern Brazil. This study aims to assess the ability *LT-MOD* and bulk formulae to accurately predict shoreline changes attributable to LST.

METHODS

LST bulk formulae

Many bulk LST formulae have been developed using field and laboratory data. All make simplifying assumptions regarding hydrodynamics and sediment processes, and do not consider factors such as barred topography and/or the cross-shore sediment exchanges. Here we only consider three well-known LST formulae. The CERC formula (USACE, 1984), with accuracy claimed to be ± 30% to 50% (Wang *et al.*, 2002), states:

$$Q_1 = \frac{K_1}{16(s-1)(1-p)}\sqrt{\frac{g}{\gamma_b}}H_b^{2.5}\sin(2\alpha_b) \tag{1}$$

where Q_1 is the volumetric LST rate (m^3/s) integrated across the width of the surf zone, K_1 is the CERC coefficient (typically = 0.39), s is the specific density of the sediment (2.65), p is the sediment porosity (0.32), g is the acceleration due to gravity, γ_b is a "*wave breaker*" index (0.78), H_b is the breaker height and α_b is the wave approach angle to the shoreline. The Kamphius (1991) formula also includes terms expressing the influence of median grain size, D_{50}, and beach slope, m, in the form:

$$Q_2 = K_2\left(\frac{1}{(1-p)}\right)\left(\frac{g}{2\pi}\right)H_b^2 T^{1.5} m^{0.75} D_{50}^{-0.25}\sin^{0.6}(\alpha_b) \tag{2}$$

where the constant $K_2 = 7.9 \times 10^{-4}$. Most recently, Bayram *et al.* (2007) have developed a new LST formula based upon a transport coefficient expressing sediment diffusivity (ε), in the form:

$$Q_3 = \frac{\varepsilon}{(\rho_s-\rho)(1-p)gw_s}F\overline{V} \tag{3}$$

where ρ_s is the sediment density, ρ is the water density, w_s is the sediment settling velocity, F is the flux of wave energy towards the shore and $\overline{V}$ is the mean longshore current velocity across the surf zone.

Field measurements

Measurements of *C-Profiles*, grain size distribution of bed and suspended sediments, bedforms and hydrodynamic conditions were obtained: along the southern shoreline of Rio Grande do Sul, Brazil (RS); Praia do Leste, Paraná, Brazil (PR); Skallingen, Denmark (SK); and Praia de Faro, Portugal (PF) (Fig. 1; Table 1). These sites were chosen to span a range of conditions between a dissipative fine-grained multiple-barred beach to a coarse-grained reflective beach. In all cases, wave heights were low to moderate and wave approach angles to the shore range from nearly normal to <5°. Photographs of the beaches in the study are shown in Fig. 2.

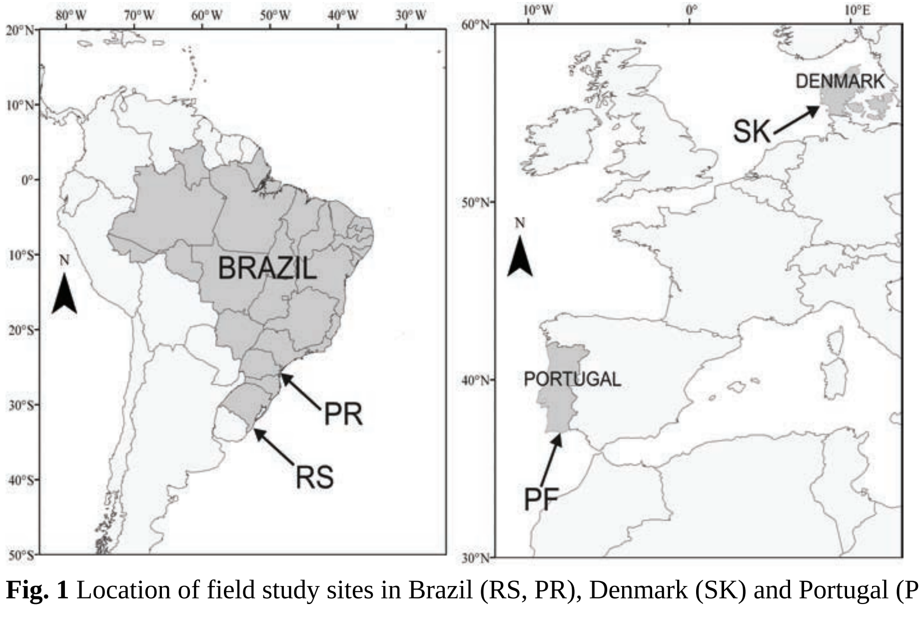

Fig. 1 Location of field study sites in Brazil (RS, PR), Denmark (SK) and Portugal (PF).

Table 1 Sediment and hydrodynamic characteristics of the study sites detailing: median grain size of suspended sediments (D_{50s}); median grain size of bed sediments (D_{50}); beach slope (m); average wave height (H); average wave period (T) and % time of offshore wave approach from stated directions.

Location	Description	D_{50s} (mm) suspension	D_{50} (mm) bed	m	H (m)	T (s)	ψ_S
RS	Very long, open ocean, dissipative, micro-tidal	0.15–0.21	0.18–0.22	1/13–1/30	1.4	7–9	SW (65%); NE (35%)
PR	Long, open ocean, intermediate, micro-tidal	0.08–0.42	0.12–0.64	1/10–1/30	1.5	6–14	SW (55%); NE (45%)
SK	Long, limited fetch, dissipative, meso-tidal	0.10–0.18	0.10–0.20	1/200	1.0	4–6	S (20%); SW (80%)
PF	Long, open ocean, reflective, meso-tidal	0.25–0.50	0.40–0.60	1/10–1/20	0.9	8–12	S-SW (90%); E (5%)

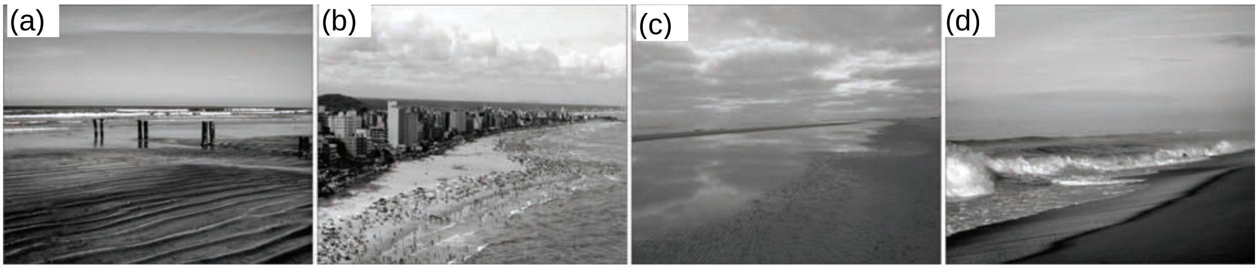

Fig. 2 Study sites: (a) Cassino, Rio Grande do Sul, Brazil (RS); (b) Praia de Leste, Paraná, Brazil (PR); (c) Skallingen, Denmark (SK) ; and (d) Praia de Faro, Portugal (PF).

Beach profiles were measured using a total station and samples of suspended sediment were collected using streamer traps (e.g. Kraus, 1987), Fig. 3. Streamer-trap data were then used to estimate the vertical *C-profile* by assuming the vertical current profile takes a logarithmic form. At RS and PR, the longshore current speed (S) was measured by timing a drogue float between two fixed points 200 m apart and the longshore current direction (ψ_S) and α_b were measured using a compass. Average values for H and T were estimated from approx. 150 incident waves by reference to a fixed marker close to the ST frame. Additionally, in some cases at RS, H, S, α_b and T were measured using PUV sensors at locations across the surf zone. At the SK and PF sites an electromagnetic current meter and a pressure sensor were used to measure directly S, ψ_S, H and T close to the streamer traps frames.

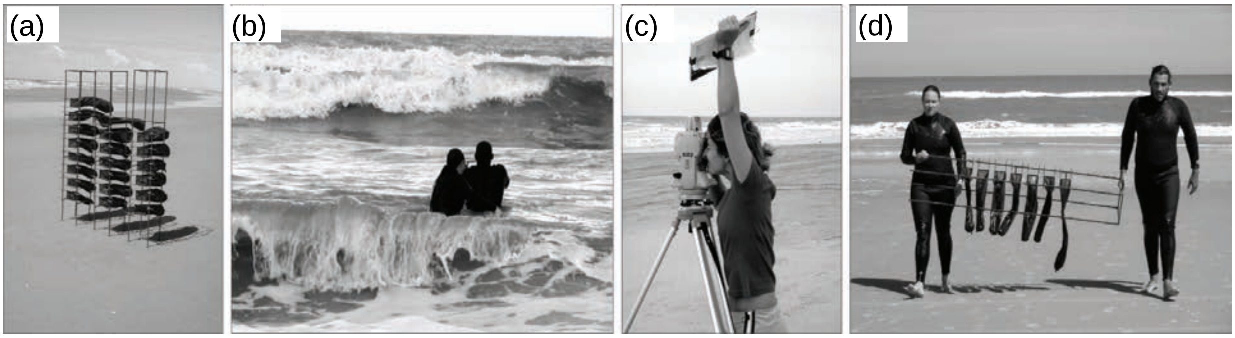

Fig. 3 LST fieldwork: (a) streamer traps ready for deployment; (b) streamer trap deployments in moderate wave conditions, RS; (c) beach profile measurements with a total station; and (d) streamer trap recovery, RS.

LT-MOD

Using measured hydrodynamic parameters, mean cross-shore profiles of the longshore current were computed in *LT-MOD* using a 1-D time- and depth-averaged longshore momentum balance approach between forcing terms (waves, wind and longshore slope), bottom stress and lateral mixing (cf. Ruessink *et al.*, 2001). Cross-shore changes in wave height were also obtained using the well-known wave energy balance and included the momentum equation for wave-induced set up (Van Rijn *et al.,* 2003). The model also included a simple roller parameterisation to represent the dissipation of energy by breaking waves. *C-Profiles* were computed across the surf zone using a single layer model (Williams *et al.*, 1999) expressed as:

$$C(z) = C(a)\left(\frac{z + L\alpha_{wc}}{a + L\alpha_{wc}}\right)^{-\alpha_{wc}} \tag{4}$$

where $C(a)$ is a "*reference*" C value at height a (e.g. Zyserman & Fredsøe, 1994), $\alpha_{wc} = w_s/\kappa(U_{*mean}+U_{*max})$, κ is von Kármáns constant (0.4) and U_{*mean} and U_{*max} are the wave period average and peak shear velocity in combined wave-current (*w-c*) conditions, respectively (cf. Soulsby *et al*., 1993). In computing the apparent bed roughness (k_s) required by the *w-c* model, *LT-MOD* accounts for measured and computed bedforms (Grant & Madsen, 1982; Van Rijn, 1984) and cross-shore grain size variations. It also accounts for apparent bed roughness attributable to bedload transport of sediment. In *LT-MOD*, cross-shore profiles of all the hydrodynamic and sediment parameters required to predict *C-Profiles* were obtained every 10 minutes at 5 m intervals over the cross-shore range 0.3 m < X < 500 m. The total LST flux for the simulation period was then calculated by integration of all *C-Profiles*.

RESULTS AND DISCUSSION

An example of a measured beach profile from the RS study showing streamer trap deployment locations is shown in Fig. 4(a). It shows a well-defined offshore bar at cross-shore position, X = 75 m. Figure 4(b) shows time series of: S at height above the bed, z = 0.38 m; and H and T values derived from the offshore PUV data using zero down-crossing methods, Fig. 5. During this time, T remains approximately constant and an increase in S around t = 2000 min. is associated with a corresponding increase in H. However, relatively high S values at the start of the record are associated with the lowest H values. In this case, wind plays a role in forcing the longshore current. The grey shading denotes the test period for the first example of an *LST-MOD* application discussed below. In this case, S was approx. 0.5 m/s, H was approx. 0.65 m, T was approx. 9 s and α_b was 12°. In this and other examples from RS, predicted cross-shore profiles of wave properties (H, T and α) and longshore current from *LT-MOD* were validated using data from the PUVs and the multi-PUV tower (not illustrated).

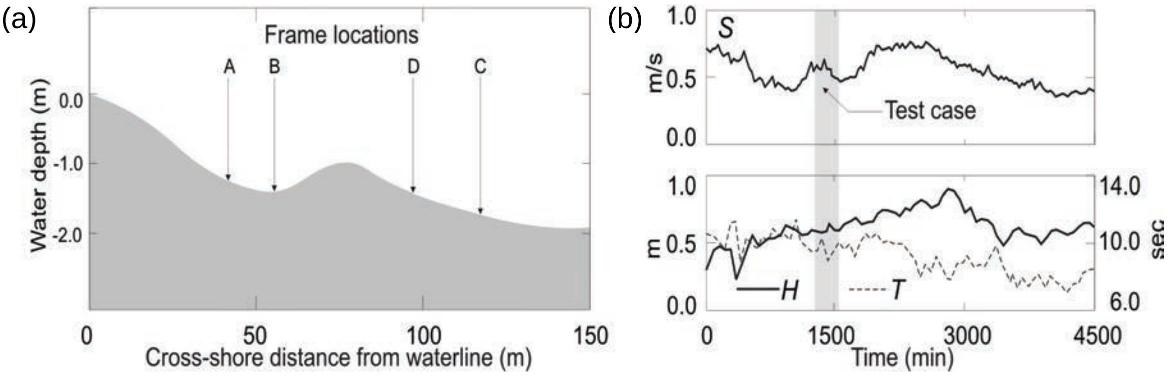

Fig. 4 Example beach profile (a), and hydrodynamic conditions (b), for the test case in RS.

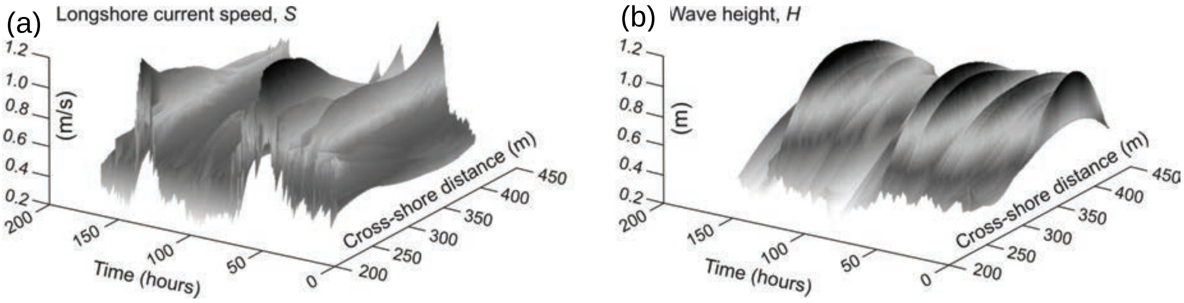

Fig. 5 Example of temporal variation in cross-shore profiles of longshore current speed (*S*) and wave height (*H*) derived from PUV data (RS).

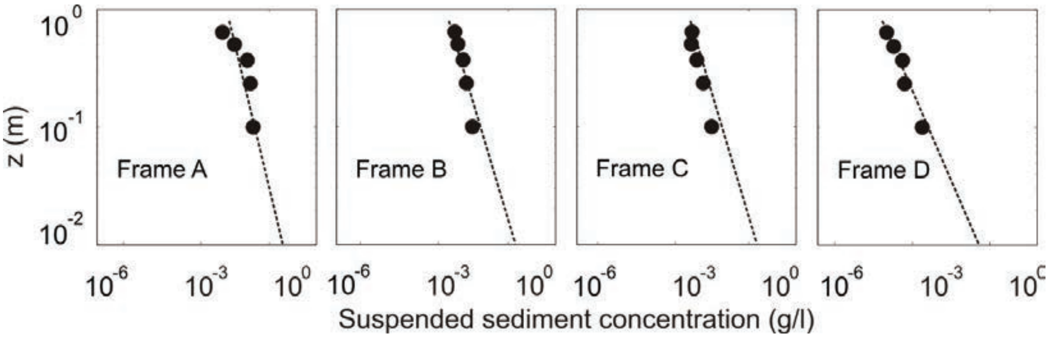

Fig. 6 Measured and predicted *C-Profiles* for frame locations shown in Fig. 4(a) for the test case in RS.

Examples of good agreement (typically $R^2 = 0.85$ or better) between measured and predicted *C-Profiles* (equation (4)) for frame locations indicated in Fig. 4(a) are shown in Fig. 6. The shape of all measured *C-Profiles* exhibit a good degree of consistency at locations across the surf zone and a reduction in predicted *C* values by around four orders of magnitude between *Ca* and *C* at z = 0.5 m is typical. When examining the whole data set, infrequent data outliers show no systematic trend and are thought to reflect both the inherent inaccuracy of the streamer traps and natural variability of suspended sediment in the surf zone. They also reflect departures from the normally observed exponential decay of sediment concentration with height above the bed noted at locations immediately behind bars (Williams *et al*., 2007). Although there is no objective way of verifying the validity of *Ca* values predicted by equation (4) in the field, the reduction of *C* with *z* is predicted independently of the measured *C-Profiles* and the good fit to data supports the view that predicted *Ca* values are realistic.

Selected *LT-MOD* results for the test case (Fig. 4(b)) are shown in Fig. 7. This shows cross-shore profiles of: (a) *H*, *S* and wave orbital speed, U_w; (b) U_{*mean} and U_{*max}; (c) predicted bedform height (η) and wavelength (λ); and (d) predicted rates of sediment transport from *LT-MOD* expressed in units of kg/s. For simplicity, the other terms used to derive the LST flux in the model are not illustrated. There are also a number of simplifying assumptions made in this demonstration simulation: (1) D_{50} is assumed to be invariant across the surf zone owing to lack of supporting field data; (2) D_{50s} is defined by the mean D_{50} of sediments in the streamer traps and takes no account of vertical changes in suspended sediment grain size; (3) a single α_w value is used to define wave-current interactions; (4) current-generated bedforms are not considered when defining the bed roughness. In this and other test cases, maximum LST is predicted in the trough behind bars.

Total LST from *LT-MOD* (Q_{MOD}), was obtained by integration across the computational domain. A comparison between Q_{MOD} and Q_1, Q_2 and Q_3, expressed in units of kg/s, by the bulk LST formulae for test cases at all the field sites are shown in Fig. 8. These span a range of approx. $2 < Q < 90$ kg/s. Predictions from the Bayram *et al.* (2007) formula have the highest correlation with Q_{MOD} ($R^2 = 0.95$). The predicted values Q_1 and Q_2 are higher than Q_{MOD}.

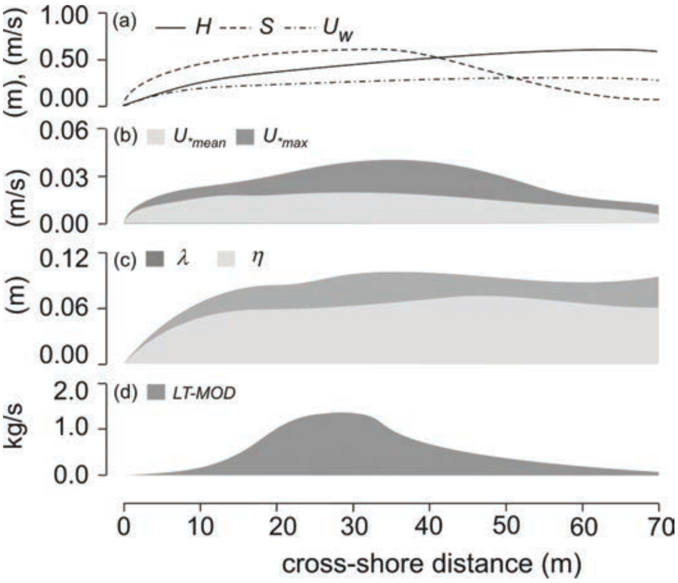

Fig. 7 Results from *LT-MOD* for the test case.

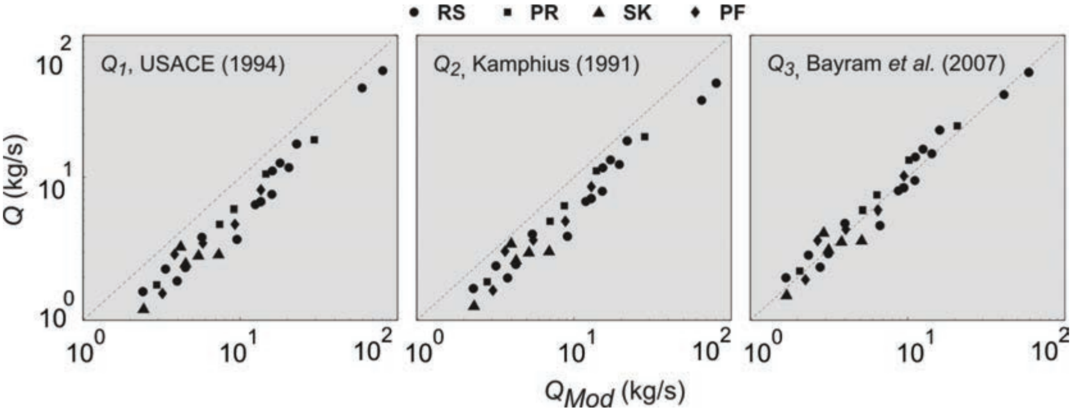

Fig. 8 Comparison between *LT-MOD* and bulk formulae for RS, PR, SK and PF experiments.

Although these tests indicated that *LT-MOD* gave predicted rates of instantaneous LST that matched approximately Q values predicted by the bulk formulae, the differences are sufficiently large to result in big discrepancies between predictions of total mass transport over extended periods of time, when both the magnitude and direction of LST is likely to be highly variable owing to variable wave conditions. Further, the test cases thus far do not consider *LT-MOD* and bulk LST formulae performance during storms when rates of LST can be orders of magnitude larger. To address this, the approach reported by Williams & Esteves (2005) was used to compare measured and predicted changes in shoreline position for the entire RS coastline that can be attributed to LST. Results from this study are summarised in Fig. 9 which shows changes in the shoreline position measured between the periods: (a) November 1999 to June 2000; and (b) June 2000 and April 2002. Model-derived wave data has been used in simulations of LST for these periods and the associated shoreline evolution has been calculated using a simple continuity relationship (cf. Williams & Esteves, 2005). The resulting predictions of change in the shoreline position using *LT-MOD* and Bayram *et al*. (2007) are also shown in Fig. 9 and show clearly that predictions from *LT-MOD* are in better agreement with the measurements.

There remain a number of uncertainties in the parameters used to define *LT-MOD*, each of which can significantly influence predicted Q_{MOD} values. These include: the suspended sediment grain size (affecting w_s), cross-shore variability in bed composition, affecting τ_{crit}, η, λ and z_o, and

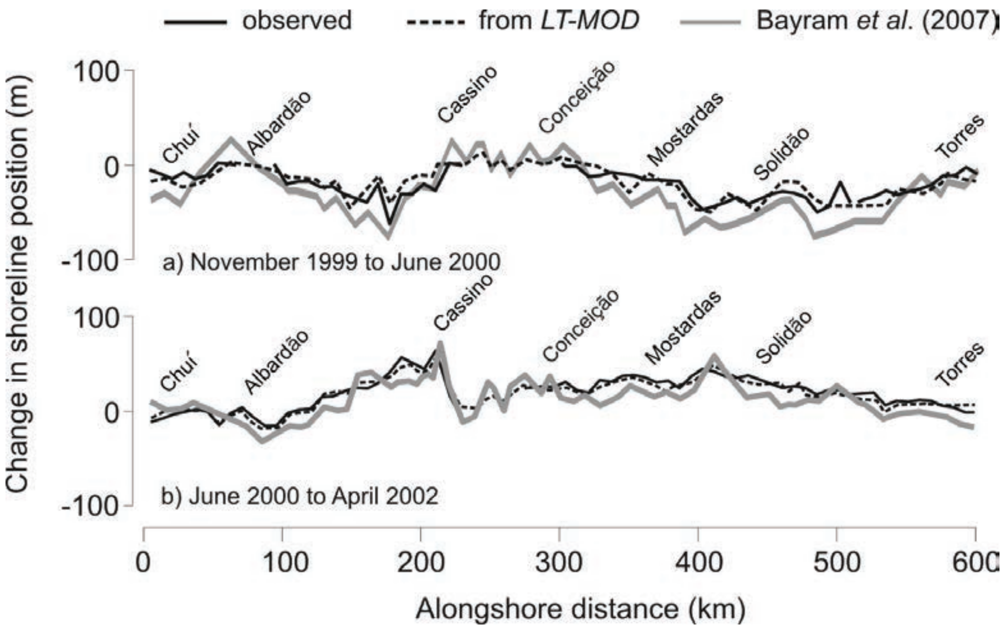

Fig. 9 Comparison between measured and predicted changes in RS shoreline position.

cross-shore hydrodynamic conditions, affecting wave-current induced bed shear stress. Although the field measurements and data proxies have defined as effectively as possible all the terms in *LT-MOD*, these errors cannot be eliminated entirely. In spite of these uncertainties, results in Fig. 9 show that *LT-MOD* offers a reasonably effective method to predict LST when site-specific information is provided.

CONCLUSIONS

High quality field measurements of hydrodynamic conditions and suspended sediments obtained in the surf zone at four contrasting locations characterised by different wave conditions, sediment types and beach profiles have been used to develop and validate the new model of longshore sediment transport, *LT-MOD*. The ability of *LT-MOD* to predict, with reasonable accuracy, *C-Profiles* at a number of different cross-shore locations has been verified. Although shear velocity values and bedform dimensions obtained from imposed hydrodynamic gradients across the model domain are at best approximations, and may not be accurate across the whole model domain, the use of more advanced approaches cannot be supported by the present sparse field data. *LT-MOD* is based on formulae developed primarily for wave-only, uni-directional flows or weakly interacting *w-c* situations. It is therefore interesting to find that even in the complex hydrodynamics of the surf zone, the relationships they define between the applied bed-shear stress and sediment mobility remain reasonably robust. Although predicted rates of instantaneous longshore sediment transport have been shown to be in fair agreement with some well-established bulk formulae, cumulative LST predicted by *LT-MOD* and by bulk formulae diverge significantly on longer time-scales. However, over extended spatial and temporal scales, *LT-MOD* has been shown to reproduce well measured changes in shoreline position attributed to LST along the coastline of RS. This demonstrates that for this case at least, *LT-MOD* has a capability of predicting net LST over spatial scales of approx. 100 km and temporal scales of approx. 2 years. *LT-MOD* has the advantage that most of the required input parameters can be acquired without recourse to sophisticated and costly equipment, and where data are missing, theory can be used to estimate with sufficient accuracy the required parameters. Input data can therefore be gathered relatively cheaply and quickly to provide a reliable prediction of LST that may out-perform other approaches in a range of situations. *LT-MOD* is therefore considered to have potential applications in situations where expert modelling and extensive field data sets are unavailable and/or where the time and space scales under consideration are large.

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