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LONG-TERM CROSS-SHOREFACE SEDIMENT FLUXES

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Abstract: There exists a large uncertainty about the importance of cross-shoreface sediment fluxes both in relation to the dynamic evolution of the shoreface profile and the potential role as a sink or source to the 'active' zone. The increasing availability of more reliable long-term observational data (direct and indirect) and of more detailed shoreface field observations seems to support earlier suggestions that the shoreface may be a potential source of coarser sediments to the nearshore. Here, this process is investigated by hindcasting and extrapolating long- and short-term observations available for the shoreface along the Ebro Delta. Analysis of the field data indicates that a structural onshore sediment flux is likely. Although a direct proof that this is also true on longer-term scales is not easy to substantiate, the careful conclusion is drawn that there exists circumstantial evidence that there is a net long-term feeding of coarser sediment towards the nearshore to an amount which is just about enough to compensate for 'losses' due to the present sea-level rise rate in the region.

INTRODUCTION

The increased attention for the impacts of climate change on coastal stability has put the long-term morphodynamic behaviour of the shoreface, being the interlink between the shelf and the nearshore, on the international research agenda. It is on these longer time scales that sediment fluxes to and from the nearshore need to be understood in order to mitigate climate change related coastal impacts. One of the objectives of the Fluxes Across Narrow Shelves (FANS) project is to assess the long-term cross-shore sediment exchange over the shoreface. The unique opportunity that the FANS project

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offers is the simultaneous retrieval of data over the whole of the shoreface including the nearshore and the shelf, domains which are commonly covered in isolation only. Further, the site chosen is of particular interest because of its narrow shelf, which may put a quite different boundary condition to the system than commonly encountered.

The present contribution centres around this question of long-term cross-shoreface sediment fluxes. While an important part of the project is devoted towards event-scale in-situ measurement of hydrodynamics and matter transport on the shoreface and shelf and the subsequent analysis and modelling thereof, our research approach aims to upscale these in-situ measurements to long-term sediment exchange fluxes. In order to achieve this we rely on process-based and data-based modelling using longer-term data, such as wave climate and historic shoreface evolution.

APPROACH

Our attention is focused on that part of the shoreface where the long-term, cross-shore sediment exchange between the nearshore and the inner shelf takes place. As shown furtheron, the historic shoreface evolution of the central Ebro Delta indicates that this concerns the middle shoreface. Sediment exchange rates at this part of the shoreface have previously only been estimated theoretically (Jiménez, 1996), using quasi-steady sediment transport models fed by wave data. Part of he FANS measuring campaigns was devoted to cover these depths by tripod in-situ measurements in the FANS field experiments on waterdepths of 8.5 m and 15 m.

With this region of the middle shoreface being central we have been performing research work along three lines:

(1) interpreting measurements of intra-wave flow variation and sediment concentration from the tripod measurements;

(2) making estimates of net cross-shore total sediment transports using the measured decadal wave mean hydrodynamic climate;

(3) modelling historic (800 AD-present) cross-shoreface sediment transports.

The above indicates that we are trying to integrate different scales of processes. This integration will be the focus in the discussion furtheron, after presenting results of the three research components first.

INTRA-WAVE FLOW VARIATION AND SEDIMENT CONCENTRATION

Through analysis of the flow and concentration measurements we have been searching for the importance of wave-asymmetry induced transport. Of all possible onshore directed flux mechanisms we would anticipate this mechanism to be the most likely and forcefully.

Figure 1 shows the co-spectral density of the near-bottom cross-shore velocity and suspended sediment at 0.1 m above the bottom during a recorded storm. Two observations can be made: (i) the net sediment flux, which is given by the integral of the co-spectrum over all the frequencies (e.g. Huntley and Hanes, 1987), is shorewards (in our reference system negative means onshore) and, (ii) the prime contribution to the sediment flux is centered around the frequency associated with the incident waves (which in this example is about 0.9 Hz). This behaviour is reproduced for most of the recorded conditions under energetic wave states, i.e. when the transport rates are significant, and stress the role of waves in feeding the upper shoreface due to this onshore transport (see e.g. Gracia et al., these proceedings).

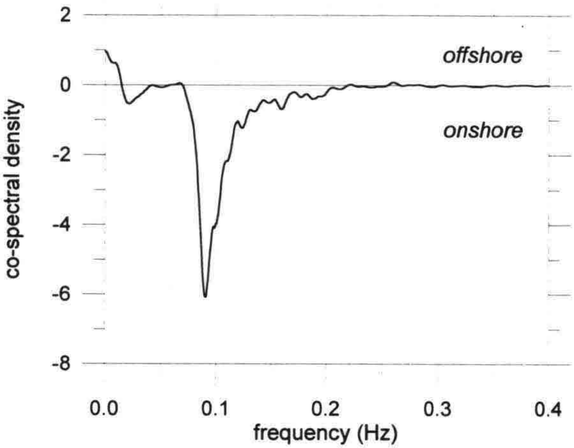

Fig. 1. Co-spectral density of cross-shore velocity and suspended sediment concentration at 0.10 m above the bottom (at 8.5 m depth).

In addition to this, we have started to investigate whether analytical approaches to estimate the concentration spectrum based on the near-bottom flow spectrum can explain the observed concentration spectra (Bosboom et al., 1998). We expect to present some results on the conference. In this context, we may mention that Jiménez et al. (1998) analysed the oscillatory component of the sediment transport and found that in most of the analysed cases there was a lag between the slowly-varying velocity variance and the sediment response, which was in the order of the incident wave period. This lagged response in which waves lead the sediment concentration was found to be reasonably well explained by taking into account the effects of wave groups (Jiménez et al., 1998).

NET CROSS-SHORE WAVE-INDUCED SEDIMENT TRANSPORT

Many steady and quasi-steady sediment transport models are based on the principle that the concentration is related to the third order velocity moment, i.e. when it concerns bed load transport. In order to analyse the contribution of the velocity to this moment, the velocity is divided into three components:

$$u(t) = \bar{u} + u_h(t) + u_l(t)$$

In which $\bar{u}$ is the mean velocity associated with the presence of currents, $u_h(t)$ is the high frequency oscillatory component and $u_l(t)$ is the low frequency part of the oscillatory component. If u_h is uncorrelated to $|u_l|^2$, the odd central moment does only exist of a contribution due to nonlinearity and those due to high frequency wave/low frequency wave and mean current interactions:

$$\langle u^3 \rangle = \bar{u}^3 + \langle u_h^3 \rangle + \langle u_l^3 \rangle + 3\bar{u}\langle u_h^2 \rangle + 3\bar{u}\langle u_l^2 \rangle + 3\langle u_h^2 u_l \rangle + 3\langle u_l^2 u_h \rangle + 6\bar{u}\langle u_h u_l \rangle$$

$\langle u_h^3 \rangle$ will be nonzero only for a horizontally asymmetric velocity field under non-linear waves (Bowen, 1980). The last term will be nonzero if there exists a correlation between the low frequency velocity component, u_l, and the high-frequency velocity variance u_h^2 (Roelvink and Stive, 1989).
In this context we study the high frequency wave contribution that corresponds to the skewness or horizontal asymmetry of the near-bottom velocity field. When, in the following, the term third order velocity moment is used, this means the contribution of the high frequency waves to the third order velocity moment.

The data used in this study were acquired on the Ebro delta inner shelf with tripod measurements on a waterdepth of 8.5 m (see for details Jiménez et al., 1999b). The maximum astronomical tidal range is 25 cm. Under Eastern storms the waves show longest periods, with T_p up to 12 s. (Jiménez et al., 1997). The time-series of near-bottom velocities and pressure were measured using a tripod with electromagnetic currentmeters. Sediment samples were taken at the tripod deployment. The mean grain diameter of local bottom sediment samples at the initiation of the experiments was 151 μm and 159 μm at the end of the experiments.

Table 1 lists the wave and velocity field parameters for bursts with the Ursell parameter U_r>0.8, obtained from observations of near-bottom third order velocity moments taken in the area of interest and analysed by Jiménez (1999a). They have been selected following the finding of (Jiménez et al. 1999b) that for wave states (bursts) with U_r values larger than 0.75, the near-bottom velocity field presented an horizontal asymmetry significantly different from zero. The Ursell number (U_r) has been calculated following Doering and Bowen (1995).

burst#	Ursell	T (s)	h (m)	L (m)	H (m)	$\langle u_h^3 \rangle_{ms}$ (m/s)
H161	1.15	8.79	8.5	71.6	0.14	0.0245
H160	0.92	8.77	8.5	71.3	0.11	0.0112
H97	0.88	9.04	8.5	73.8	0.10	0.0089
H79	0.87	9.27	8.5	76.7	0.10	0.0065
H96	0.84	8.99	8.5	72.8	0.10	0.0089
H163	0.84	9.22	8.5	76.2	0.09	0.0073
H98	0.81	8.27	8.5	66.4	0.11	0.0081

Table 1 Wave and orbital velocity field parameters (from Jiménez et al., 1999b).

Following Jiménez et al. (1999b) Figure 2 shows the relation between the Ursell number and the third order velocity moment for all bursts with U_r>0.5. Clearly, for increasing Ursell numbers, the velocity moment is increasing. Although this follows the expected behaviour, it has to be noted that velocity fields recorded during the field campaign, when non-linear, were very weakly non-linear, with few conditions giving an energy significantly different from zero in the bi-spectrum (Jiménez et al. 1999b). This is due to the characteristics of the study area, where long period waves (i.e. swell) are hard to be found (Jiménez et al. 1997), as along most of the Mediterranean coasts.

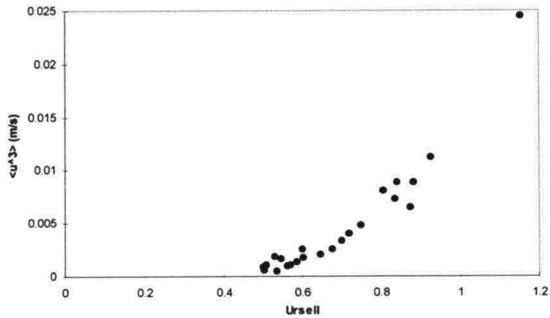

Fig. 2. Ursell number versus third order velocity moment

Although the measured data show nonlinearity as expected, the data are not representative for an assessment of the longer-term, say decadal, wave asymmetry-induced net onshore sediment transport flux since they only cover one month of data. Jiménez et al. (1997) constructed a longer term wave climate based on a variety of observational sources. An overview of the aggregated data is presented in Table 2. These data will be used to calculate the transport rates furtheron. An overview on sediment transport rates measured in the study area can be seen in Gracia et al. (these proceedings).

period sector	H (m)	T_m (s)	%
1	0.597	4.037	29.0
2	1.459	5.497	20.2
3	2.356	7.076	1.4
total			50.6

Table 2 Aggregated wave climate data

This wave climate data set, however, obviously does not include any details about orbital velocity moments. In order to calculate transport rates with different models, it is necessary to know more details about the velocity and velocity moments. Therefore, from the aggregated wave parameters we derived the time dependent velocity with the Fourier approximation method of Rienecker and Fenton (1981). In order to estimate the validity of this theoretical derivation the third-order velocity moment of this approximation is compared with the measured third-order velocity moments from the tripod measurements.

The relation between the Ursell parameter and the ratio of the calculated and the measured velocity moments is graphically shown in Figure 3. The ratio is increasing for decreasing Ursell parameters. For $U_r>0.8$ the ratio seems to be more or less constant with an average value of 1.6.

For waves with a smaller asymmetry, thus with a smaller Ursell number, the third-order velocity moments are increasingly overpredicted. We believe that this is caused by the fact that the waves are so small and directionally spread that for these very weakly non-linear and small waves a monochromatic non-linear theory will not be valid. Moreover, one should take into account that for small Ur values, the third-order velocity moment is very small, so that small inaccuracies in the calculated moment will give a large ratio since they are normalised by a small quantity. For the larger Ursell numbers, it seems that the approximation of the velocity with the method of Rienecker and Fenton gives a reasonably correct reproduction, especially in consideration of the rather small surface elevations.

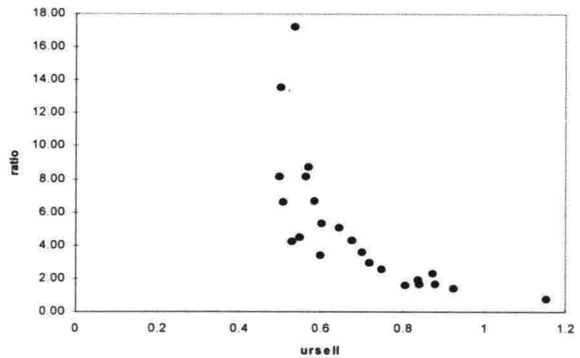

Fig. 3. Ursell versus ratio of computed and measured third-order velocity moment

Quasi-steady sediment transport models consist of a direct relationship between the time dependent sediment transport rate and the time dependent flow velocity, without a phase lag between the flow velocity and the concentration. These models are based on theoretical or analytical considerations or empirical data. In this paper four different models are used: Al Salem and Ribberink (1993); Bailard (1981); Ribberink (1997) and Dibajnia and Watanabe (1992). These models have been applied to estimate sediment transport rates, fed by the previously presented schematised yearly wave climate data (Table 2). The aggregated results in terms of yearly-integrated transport rate are collected in Table 3, and will be discussed below.

	Al Salem	Bailard	Ribberink	Dibajnia
period sector		(m^3/year/m)		
1	0.01	0.00	0.00	0.04
2	8.68	2.85	1.52	4.53
3	0.56	0.19	0.10	0.32
total	9.24	3.04	1.61	4.89

Table 3. Net onshore sediment transport rates based on aggregated wave data

In applying these models we have not included the influence of the presence of a sloping bed, which means that a potential fraction of sediment transport seawards has been neglected. Because the high frequency contribution of the third order velocity moment is directed shoreward, this would imply that the influence of the sloping bed makes transport rates smaller. Using the Bagnold approach to calculate this decrease in transport rate for typical bottom slopes in the study area showed that this influence is small (given the local bed slope Bagnold's slope parameter quantified the effect less than 0.2%).

LONG-TERM SHOREFACE MODELLING

While the FANS measurement campaign has lead to valuable observations of the instantaneous processes, it is our expectation that an important verification of the long-term fluxes can be done by hindcasting the long-term morphodynamic behaviour of the Ebro Delta shoreface. We have therefore concentrated on the application of shoreface evolution models, such as those developed by Niedoroda et al. (1996), Buijsman (1999), Steetzel et al. (1998), Stive and De Vriend (1996) and Stive et al. (1998).

While the sediment transport formulations of these shoreface models may be closely or only remotely connected to process-based formulations, their most prominent collective property is that their dynamic behaviour under variable forcing conditions is derived from a -known or assumed- shoreface state which is considered to be a static or dynamic equilibrium state under constant -or at most slowly varying- forcing conditions. The existence of such a state -at a generally subjective moment in time- is an essential assumption for these models. Here, we describe these concepts for the Niedoroda et al. (1996) model, which adopts an advection-diffusion concept for the sediment flux, hence known as the ADM-model.

The ADM-model maps the shoreface profile on a general exponential curve of the form:

$$h(x) = B(1 - e^{-\alpha x}) + Cx$$

Where x is the distance offshore, h(x) the water depth and B, C and α coefficients, allowing this function the fit most existing shoreface profiles. Along this profile the time-averaged sediment transport, Q, is described by two opposing terms:

$$Q = q_{ad} + q_{dif}$$

It should be noted that the time-averaging in this equation refers to a long-term average, implying that it is not a property easily derived from field evidence, since it represents an aggregated process.

The advective term represents the commonly onshore directed, wave-asymmetry-induced integrated sediment flux, in the form:

$$q_{ad} = -W \cdot e^{-\beta \cdot h}$$

The exponential form is chosen close to Bowen's second-order Stokes' derivation of the wave-asymmetry contribution:

$$\frac{1}{\sinh^{n}(kh)} \approx e^{-n \cdot k \cdot h} \sim e^{-\beta \cdot h}$$

with k being the wave number and n ranges from 3 to 6 for second-order waves.

Whether W is a proportionality constant or a function of depth is sofar left uncertain, but effectively in simulations it has been taken as a constant, which seems in agreement with the functional dependence derived by Bowen (1980).

The diffusive term represents the collection of commonly offshore-directed sediment transport mechanisms of the suspended concentration, c, due to undertow, downwelling and gravity-induced transport mechanisms in the functional form:

$$q_{dif} = -K_2 \cdot \overline{D}(x) \cdot \frac{\partial c}{\partial x}$$

While the proportionality constant is a free parameter in principle, but which sofar is captured in the diffusion coefficient. This coefficient has a functional form which makes it linearly varying with the distance from the shore, with D_0 as initial value at the shoreline:

$$\overline{D}(x) = \overline{D}_0 + \phi \cdot x$$

The core principle of this modelling approach, which is typical for all behaviour-oriented shoreface models mentioned, is that the dynamic properties of the model under variable forcing conditions is derived from a shoreface state which is known to be in static or dynamic equilibrium. The existence of such a state -at a generally subjective moment in time- is an essential assumption. This specific shoreface state then allows -in this particular model- for the derivation of the concentration dependence on h, since Q is assumed to be actually zero for the equilibrium shoreface state:

$$\frac{\partial c}{\partial x} = \frac{\partial c}{\partial h} \cdot \frac{\partial h}{\partial x} = -\frac{F_0 + W \cdot e^{-\beta \cdot h}}{\overline{D}(x)}$$

F_0 is a source or sink function, which may either represent a transversal source or sink, such as river sediment input or a lateral source or sink such as due to longshore sediment transport gradients.

Figure 4 Approximate configuration between VI and X th century

The above described modelling approach is applied to the historic evolution of an abandoned river lobe of the Ebro Delta. The Ebro Delta originated from sediment of the River Ebre about 3.5 million years ago (Jiménez, 1996). The conspicuous development of the present delta started as a consequence of the last sea-level stabilisation approximately 4,000 years ago. The present deltaic plane is essentially formed as a result of the three last deltaic lobes, of which the first two were abandoned. The oldest is the south-east one. About 1,200 years ago this lobe reached its maximum seaward extension (Figure 4). The river switched and since then the lobe became wave-dominated and started to erode. The present configuration of the Ebro delta is shown in Figure 4 with a dashed line.

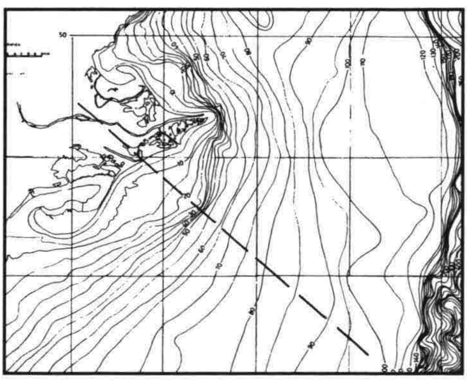

Figure 5 Map of present situation of the Ebro Delta

The evolution of the wave-dominated Ebro Delta region abandoned by the first-mentioned river lobe is simulated with the Advection-Diffusion model from the 8th century until nowadays (2,000 AD). The estimated final profile is obtained from Figure 5. The broken line indicates the cross-sectional area. The configuration of the delta between the VIth and Xth century in Figure 4 is fitted in Figure 5 to obtain the cross-sectional area of this period. It is supposed that the historic sea-level rise has a constant value of 0.005 m/year (Sánchez-Arcilla et al., 1996). The estimated measured profiles can be found in Figure 6; the schematisation of the initial profile is obtained from the estimated profile in 800 AD.

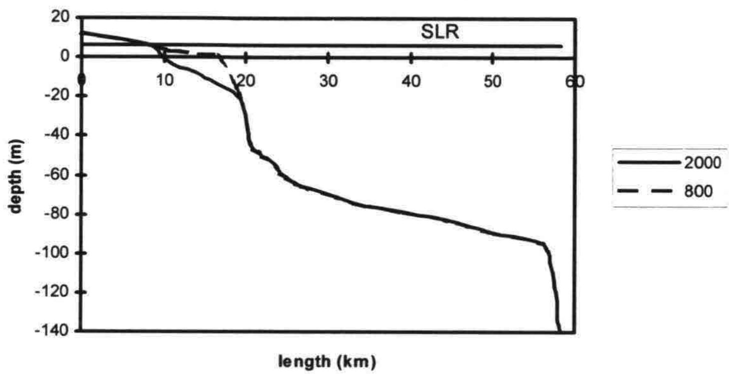

Figure 6 Equilibrium profile of Ebro delta

Following the approach described above, several modelling attempts with the ADM model were conducted. The basis of the simulations was to use default parameter settings and an externally derived value for the sink term. The term β was estimated from $\beta \sim nk$. An initial estimation for n is 2 and the estimated wave length is obtained from field data (Jiménez, 1988): L=70 m , gives β=0.18. The process of coastal erosion is assumed to occur because of a gradient in the southward longshore transport. The value of the sink term F_0, representing the gradient in the longshore transport, is estimated from the amount of sediment in the southern lobe nowadays: F_0=-70 m^3/year. The initial profile is assumed to be in equilibrium, therefore the term $F_0 = 0$ in the initial state and subsequently changed to its value during the calculations. As mentioned before, the historic sea level rise is assumed to have a constant rate of 0.005 m/year, which may be somewhat higher than recent estimates. All the other parameters in the transport terms are the same in the initial state as well as during the calculations, which for instance implies the assumption that the wave conditions do not change during the hindcast. Although using default parameter settings gave a reasonable hindcast, we obtained a best fit by making some slight modifications to the default values. We decreased the value of β to 0.12 and increased the value of W from 50 to 60 in the advective bed load term. The sink term, F_0 was changed to -60m^3/year. The calculated versus the measured profile is given in Figure 7, while the net total transport rate is given in Figure 8.

The transport rate is onshore directed near the coast; about 7 km outside the coastline, the transport rate is offshore directed until 12 km outside the coastline. From 12 km up to 30 km outside the coastline there is no net transport at all. The small wiggles in the transport rate along the profile are due to the discretization of the profile. These model results show that on the middle shoreface (waterdepths of 10 m) the net onshore sediment flux is of the order of 10 m^3/m/year. The transport rate at 8.5 m depth is determined to compare with field measurements; Q_{tot}=17.5 m^3/m/year in onshore direction (see Figure 8).

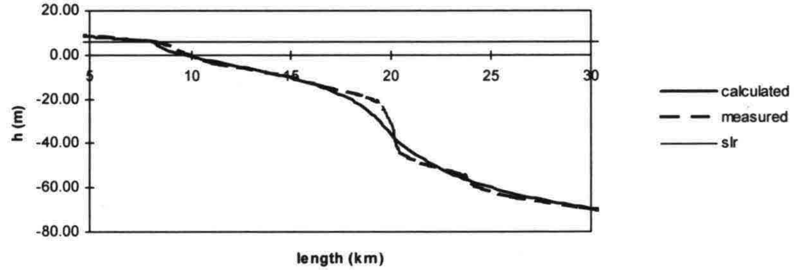

Figure 7 Calculated and measured profile 2000 AD, adjusted parameters

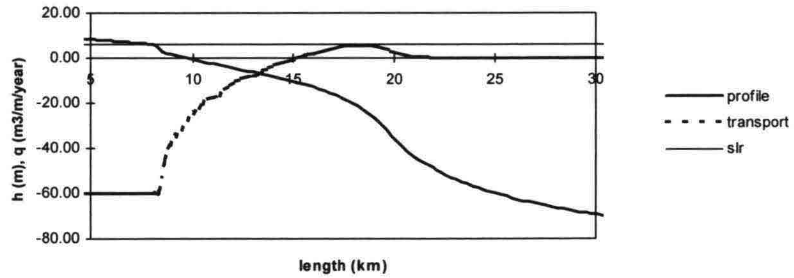

Figure 8 Total transport rate 2000 AD

DISCUSSION AND CONCLUSION

We have employed three research approaches to investigate the issue of a possible net exchange of sediment between the nearshore (or active zone) and the shoreface along the wave dominated region of the Ebro Delta.

First, we have explored the observations made with the tripod deployment at 8.5 m water depth, which is expected to have operated more or less exactly at the water depth where a possible exchange would take place. It appears that the observations consistently indicate that -although there exists a lag between the sediment response and the wave orbital stirring- a net onshore near-bottom sediment flux is present due to the dominance of the wave asymmetry effect. The indications are that this concerns the sediment size fractions at the tripod location, which were found to be approximately 150 μm. In contrast, sediment grain size distributions on the Ebro Delta shoreface indicate that the finer sediments (say below 80 μm) undergo a net flux towards the lower shoreface and inner shelf (see e.g. Jiménez et al. 1999a, Gracia et al. 1998).

Second, we have attempted to use various quasi-steady sediment transport formulae to derive the yearly net wave-induced flux from wave climate data. This requires the prediction of several higher-order velocity moments, which we have based on the nonlinear wave theory of Rienecker and Fenton. Comparison of the measured third order velocity moments for the most nonlinear bursts with this nonlinear wave model gave rise to optimism about the validity of the use of such a model to derive all the velocity information needed for sediment transport calculations with the various models. This approach was applied both to the tripod data and to a wave climate data set. The transports during the tripod deployment were found to be very small, which may indicate that one would need to be careful in making firm conclusions about the long-term representativeness of the field observations. The yearly net, asymmetry driven onshore transports for the 150 μm fraction according to the various transport formulations was found to be in the range of 2 to 10 $m^3/m/yr$. This seems consistent with the following indirect observation. The net increment of subaerial surface of the Ebro Delta lobe is found to be nearly nil (Jiménez and Sánchez-Arcilla, 1993), which gives rise to the interpretation that losses due to relative sea-level rise are compensated for by a feeding from the shoreface (see e.g. Jiménez, 1996). The estimate is in the range of 5 $m^3/m/yr$.

Third, we have applied a variety of shoreface models to an interpreted reconstruction of the historic shoreface evolution of this particular shoreface region. We believe these models to be applicable to the period from the moment on that the river mouth that build up this region was abandoned and the region became wave-dominated, which continues to be so until present. Although these models employ highly aggregated formulations for the sediment transport processes, their results should be considered at least qualitatively robust because of the long time integration involved. The various models gave a rather broad range of the present net onshore flux at 8.5 m water depth, viz. 1.5 to 17.5 $m^3/m/yr$. This wide range is expected to be the result of the above-mentioned behaviour-like sediment transport formulations, but also quantitatively they appear to confirm the order-of-magnitude of the more process-based estimates.

In conclusion, we would like to emphasise that the results derived in our study of the

Ebro Delta shoreface seem to support earlier suggestions that the shoreface may be a potential source of coarser sediments to the nearshore. Analysis of the field data indicates that a structural onshore sediment flux is likely. Although a direct proof that this is also true on longer-term scales is not easy to substantiate, the careful conclusion is drawn that there exists at least circumstantial evidence that there is a net long-term feeding of coarser sediment towards the nearshore to an amount which is just about enough to compensate for 'losses' due to the present sea-level rise rate in the region.

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