ABSTRACT

The aim of this study was to estimate longshore sediment transport on three sandy barred macrotidal beaches of Northern France using sediment traps. Measurements of longshore sediment transport were carried out at several locations across the intertidal zone during rising and falling tides in order to obtain estimates of longshore sediment flux from the lower to the upper beach and coupled with high-frequency (2 Hz) hydrodynamic data using a series of hydrodynamic instruments. Results showed that longshore sediment transport increased with both wave height and mean flow, but no relation was found with wave angle which is probably due to the influence of tidal currents that interact with wave-induced longshore currents. Although, limited variation of longshore sediment transport was observed, cross-shore variation showed that sediment fluxes were higher on the middle to lower beach, which can be explained by a decrease in tidal flow velocity towards the upper beach as well as wave-energy dissipation over the beach and intertidal bars. Longshore sediment transport direction appeared to be controlled by both incoming wave and tidal current direction, depending on the hydrodynamic zones, sediment transport being tidally-dominated in the shoaling zone and mostly wave-induced in the inner surf zone.

ADDITIONAL INDEX WORDS: Sediment traps, Hydrodynamics, Northern France

INTRODUCTION
Characterization of longshore sediment transport (LST) and its alongshore and cross-shore distribution across the beach are fundamental to the understanding of coastal morphodynamics and to the effective design of coastal engineering. Although longshore sediment transport processes have been extensively studied, most studies were conducted in micro- to meso-tidal environments, and comparatively only a few papers are specifically concerned with longshore sediment transport on macrotidal beaches (e.g., Davidson et al., 1993; Levoy et al., 1994; Masselink and Pattiaratchi, 2000). It has long been recognized from a large number of field and laboratory experiments that variation of longshore sediment transport is strongly controlled by longshore currents generated by waves breaking at an angle with the shoreline (e.g., Komar and Inman, 1970; Kamphuis, 1991). In macrotidal coastal environments, additional factors affect sediment transport, which also depends on the interactions of tidal currents with wave oscillatory flows and longshore currents generated by obliquely incident breaking waves (Davidson et al., 1993; Cartier and Héquette, 2011).

For a number of years, sediment transport studies were mostly focused on meso- to macroscale processes and estimated from beach volume change near coastal engineering structures such as jetties or groins that block littoral drift, for example, or from fluorescent tracer experiments (Voulgaris et al., 1998). During the last decades, with the development of high frequency sensors technology, sediment transport has also been determined using optical backscatter sensors (Davidson et al., 1993; Tonk and Masselink, 2005) or more recently, acoustic backscatter profiler instruments that can provide high resolution suspended sediment concentration estimates. Accurate calibration of acoustic or optical data is often problematic in natural environments, however, due to the presence of organic matter in the water column or to grain size variability (Battisto et al., 1999).

In this paper, we present the results of field measurements carried out on three macrotidal beaches of northern France for evaluating alongshore sediment transport in the intertidal zone under the action of wave and tidally-induced currents. In order to avoid the problems mentioned above in the turbid and organic-rich coastal waters of northern France (Vantrepotte et al., 2007), this study was based on sediment trap experiments. Wave and current measurements were also obtained during these experiments, using a series of hydrodynamic instruments deployed across the intertidal zone.

STUDY AREA
This study has been conducted on three sandy barred beaches of northern France from November 2008 to March 2010. The first field experiment site (Zuydcoote, ZY) is located near the Belgian border, facing the North Sea; the second site (Wissant Bay, WI) is on the shore of the Dover Strait, while the third study site (Hardelot, HA) is located on the coast of the eastern English Channel (Figure 1). Mean sediment size is 0.20 mm at Zuydcoote, 0.22 mm at Wissant and 0.23 mm at Hardelot. The field sites were selected based of their tidal range, which increases from approximately 5m at Zuydcoote to nearly 10m at Hardelot. The
northern coast of France is affected by semi-diurnal tides responsible for relatively strong tidal currents that flow almost parallel to the shoreline in the coastal zone. The dominant wave directions in the region are from southwest to west, originating from the English Channel, followed by waves from the northeast to north, generated in the North Sea. Wave energy is strongly reduced at the coast due to significant wave refraction and shoaling over the shallow sand banks of the eastern Channel and southern North Sea. Because of the flood-dominated asymmetry of the tidal currents, which may be reinforced by the prevailing southwesterly winds, the net regional sediment transport in the coastal zone is directed northward along the eastern Channel coast and toward the east-northeast along the southern North Sea coast (Sedrati and Anthony, 2007; Héquette et al., 2008).

**METHODOLOGY**

**Hydrodynamic instrumentation**

Three different hydrographic instruments were used during the field experiments. One Acoustic Doppler Current Profiler (ADCP), and two electromagnetic wave and current meters (Midas Valeport™, and InterOcean ADW S4) were deployed across the intertidal zone from the lower to the upper beach. The instruments were either deployed on the stoss side of intertidal bars (ridge) or in troughs (runnel) between the bars (Figure 2). All instruments operated during 9 minutes intervals every 15 min, providing almost continuous records of significant wave height ($H_s$), wave period and direction, longshore current velocity ($V_L$), and mean current velocity ($V_m$) and direction. Current velocity was measured at different elevations above the bed depending on each instrument. The ADW S4 and Valeport current meters recorded current velocity at 0.4 m and 0.2 m above seabed respectively, while the ADCP measured current velocity at intervals of 0.2 m through the water column from 0.4 m above the bed to the surface. Current velocity at 0.2 m above the bed was estimated using the ADCP data by applying a logarithmic regression curve to the measured velocities obtained at different elevations in the water column.

**Streamer Traps**

LST rates were estimated using streamer traps similar to the original design of Kraus (1987). The sediment traps consisted of a vertical array of five individual streamer traps with 63 µm mesh size sieve cloth that collected sand-size particles at different elevations above the bed, up to a height of approximately 1 m. These measurements were used to compute estimates of suspended sediment transport at discrete elevations above the bed as well as depth-integrated sediment flux. Calculations of the sediment flux from sand traps were carried out according to the procedure of Rosati and Kraus (1989) (Eq.1):

$$F = h \sum \limits_{i=1}^{N} F(i) + \sum \limits_{i=1}^{N-1} a(i) \times FE(i)$$  

Where $F$ is the depth integrated flux in kg.s$^{-1}$.m$^{-1}$, $h$ is the height of the streamer opening in meters, $F(i)$ is the sediment flux at a streamer $I$, $a(i)$ is the distance between neighboring streamers, $FE(i)$ is the sediment flux between neighboring streamers and $N$ is the total number of streamers.

The sediment traps were deployed along two shore-parallel transects with a spacing of about 100 m to investigate the alongshore variability in longshore transport rate. Measurements of longshore sediment transport were carried out at several locations across the intertidal zone (stoss side of intertidal bars and in the runnels) during rising and falling tides in order to obtain estimates of longshore sediment flux from the lower to the upper beach (Figure 2). Although the sediment traps were usually deployed in similar water depths, ranging from 0.8 to 1.4 m, sediment transport measurements took place in various hydrodynamic zones including shoaling, breaker and surf zones, depending on wave activity during sampling. For safety reasons, sand transport measurements were conducted only under low to moderate wave energy conditions ($H_s \text{max} \approx 0.70$ m).
RESULTS

Comparison of LST with hydrodynamic data

Two field experiments were conducted at each site between 2008 and 2010, involving more than 700 sediment samples that were used to compute 186 depth-integrated sediment fluxes. Among these, 79 depth-integrated sediment fluxes were computed using sediment trap measurements obtained close to the wave and current meters, allowing a comparison between LST and hydrodynamic parameters.

Our results showed a classical bottomward increase in sediment transport, with a high variability in total sediment flux depending on wave energy and mean current strength. In spite of some scatter in the data, comparison of measured sediment flux with hydrodynamic data obtained at the sediment collection sites showed that sediment transport increased with both significant wave height and mean current velocity (Figure 3A and 3B). High wave height values (>0.4 m) and strong current velocity values (>0.4 m.s\(^{-1}\)) were always associated with high transport rate (> 1 x 10\(^{-3}\) kg.s\(^{-1}\).m\(^{-1}\)) while the lowest sediment fluxes (<1 x 10\(^{-4}\) kg.s\(^{-1}\).m\(^{-1}\)) are exclusively related to low wave amplitude (<0.3 m) and weak mean flow (<0.2 m.s\(^{-1}\)). The range of sediment transport rates is particularly wide for \(V_m\) under 0.2 m.s\(^{-1}\), but with increasing current speed, the range of values is narrowed, especially above 0.4 m.s\(^{-1}\). This current speed may correspond to a threshold value above which the transport is dominated by the action of waves or mean current alone, but rather by a combination of these and/or by other forcing mechanisms. Least-square regression analyses nevertheless revealed a better relationship between longshore sediment flux and mean longshore current velocity, comparatively with wave height, showing that longshore transport strongly depends on the strength of the longshore current, which can be tidally induced but more commonly a combination of wave-generated and tidal flows. Results of multiple linear regression analyses using \(H_s\) and \(V_m\) at 0.2 m and 0.4 m above the bed showed that mean current velocity accounts for approximately 60% of the variance, while wave height can explain about 30%.

Although, LST commonly shows a relationship with the wave breaking angle (Komar and Inman, 1970; Kamphuis, 1991), no relation was found between LST and wave angle (\(R^2 = 0.20\)), which is probably due to the influence of tidal currents that interact with wave-induced longshore currents on these macrotidal beaches.

Alongshore variability of LST

A total of 60 depth-integrated sediment fluxes were sampled on two perpendicular beach profiles (P1 and P2) spaced 100 m apart. Our results show limited alongshore variation as revealed by high linear regression coefficients, except during one field experiment during which more variability was observed (Figure 4). The consistency in LST from one transect to the other can be explained by a high degree of alongshore uniformity of hydrodynamic processes as revealed by simultaneous measurements of waves and currents on both transects.

Although longshore sediment transport flux was generally equivalent alongshore, significant differences were observed in some occasions due to variations in beach morphology, which can result in a local increase in current velocity. This was notably observed during ebb when a sediment trap was located in the vicinity of a migrating intertidal channel in which flow canalization associated with runnel drainage locally increased sediment transport. In one of these occasions, the differences in sediment transport rates reached 2.4 x 10\(^{-3}\) kg.s\(^{-1}\).m\(^{-1}\) between the two transects.

Cross shore variation of LST

LST was measured during 28 days during which 103 sediment trap deployments were carried out during falling tide, while 83
deployments took place during rising tide. During each falling or rising tide, the higher sediment transport rates were generally obtained on the middle to the lower beach (R2 to R3), while the lower sediment transport rates were measured either on the upper beach (UB to R1) or on the lower beach (LB) (Figure 5), mostly during slack water conditions. Our cross-shore measurements also showed that more than 80% of the highest sediment fluxes were sampled on the intertidal bars and less than 20% were measured in inter-bar troughs.

Similarly to what was observed with sediment transport, current velocity generally increased from the upper to the lower beach. As shown on Figure 5, mean current velocity recorded during flood and part of the ebb was significantly higher on a bar located on the middle to lower part of the beach (R2) compared to velocities measured on a bar on the upper beach (R1) (Figure 5). This can be explained by a decrease in tidal flow velocity towards the upper beach. Simultaneous hydrodynamic measurements by different instruments deployed across the intertidal zone also show that significant wave height tends to decrease toward the upper beach (Figure 5) due to wave-energy dissipation over the beach and intertidal bars. Analyses of the influence of beach slope on sediment transport also suggest that the relatively steeper slopes associated with the stoss side of intertidal bars may cause a rapid increase in shoaling wave height and locally induce higher waves, which could also explain the high transport rates on the intertidal bars (Cartier and Héquette, 2011).

**Factors controlling the direction of LST**

In approximately 80% of cases, sediment transport was directed eastward on the beaches facing the North Sea (Zuydcoote) or the Dover Strait (Wissant) or northward on the beach located on the eastern Channel coast (Hardelot). This is to some degree due to the flood-dominated asymmetry of the tidal currents that is responsible for higher flood current velocities that are directed eastward on the northern coast and northward along the eastern Channel coast (e.g., Fig. 5). In addition, waves mostly originated from the NW during the field experiments conducted at Zuydcoote and Wissant and from the SW during the experiments carried out at Hardelot, which would also favor an eastward-directed transport at the northern sites and a northward transport at the east Channel site.

As shown on Figure 5, sediment transport directions are consistent with the direction of the mean flow that is either flowing northward or southward depending on the phase of the tide. Because wave agitation was limited during the HA09 experiment sediment transport was essentially tidally-induced, sediment being transported in the direction of the tidal current. In other circumstances, however, our data show that sediment can be transported in a different direction. Almost 60% of the sediment transport directions were consistent with expected tidal current directions, but about 40% appeared to be in the opposite direction. This can be partly explained by the fact that tidal current reversal does not occur at high or low tide, but typically after a delay of 2 to 3 hours due to the existence of stationary and progressive tidal waves in this region (Héquette et al., 2008), but also by variable wave influence on sediment transport processes depending on the wave energy level in the intertidal zone. During low wave energy conditions (<0.20m), streamer traps were not located in the surf zone, but rather in the shoaling zone where currents are only slightly generated by breaking waves. In this zone, sediment transport typically shows regularly reversing, tidally-induced, shore-parallel directions. Conversely, during higher wave energy conditions (>0.40m), sand trapping took place in or close to the breaker zone or in the surf zone, where the direction of residual sediment transport is strongly controlled by the direction of incoming waves. During such conditions, longshore sediment transport can be attenuated or strengthened by tidal currents, depending on the direction of the tidal flow.

**DISCUSSION AND CONCLUSION**

Evaluation of LST in the intertidal zone of macrotidal beaches appeared to be difficult to determine due to the complex interactions between several forcing parameters. In addition, several physical constraints (high organic content and fine-grained suspended sediments) did not allow us to measure sediment fluxes with high-resolution acoustic or optical sensors, but using...
streamer traps that can only provide time-averaged transport rates instead of high-frequency suspended sediment transport estimates.

Under the low to moderate hydrodynamic conditions that characterize our field measurements, LST proved to be controlled by both significant wave height and mean current velocity (Figures 3). Our data showed that sediment transport was mainly dependent on the mean flow, especially above a velocity threshold of approximately 0.4 m.s⁻¹. Although our results also show that wave action increases sediment remobilization, the absence of relationship between wave angle and sediment flux shows that the evaluation of LST rates based on longshore wave energy flux (e.g., Komar and Inman, 1970; Smith et al., 2009) is not suitable for estimating longshore sand transport on macrotidal beaches where tidal currents can modulate the magnitude of longshore sediment transport.

Although sediment transport rates showed a low alongshore variability, owing to a high degree of longshore hydrodynamic uniformity, longshore sediment flux were much more variable across the intertidal zone due to cross-shore variations in hydrodynamic processes and beach morphology. The higher sand transport rates were principally measured on the stoss side of hydrodynamic processes and beach morphology. The higher sand across the intertidal zone due to cross-shore variations in uniformity, longshore sediment flux were much more variable variability, owing to a high degree of longshore hydrodynamic

Dependence of total longshore sediment transport rates on incident energy and mean flow velocity, independently of rising or falling tide-dominated asymmetry, a tidal asymmetry in sediment transport could not be observed in our measurements. The variability in longshore sediment transport on the surveyed beaches appears to be essentially related to variations in wave energy and mean flow velocity, independently of rising or falling tide conditions.

**LITERATURE CITED**


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