Velocity Structure and Sea Bed Roughness Associated with Intertidal (Sand and Mud) Flats and Saltmarshes of the Wash, U.K.

Xiankun Ke† ‡, M.B. Collins† and S.E. Poulos†

†Department of Oceanography
The University
Southampton SO9 5NH, U.K.

‡State Pilot Laboratory of Coast
 & Island Exploitation
Nanjing University
Nanjing 210008, P. R. China

ABSTRACT ■

KE, X.; COLLINS, M.B., and POULOS, S.E., 1994. Velocity structure and sea bed roughness associated with intertidal (sand and mud) flats and saltmarshes of the Wash, U.K. *Journal of Coastal Research*, 10(3), 702–715. Fort Lauderdale (Florida), ISSN 0749-0208.

Velocity gradient rigs used to examine flow profiles across an intertidal zone within an essentially accretional embayment. Of the profiles measured, around 90% can be represented logarithmically. For comparison, associated bedforms were measured *in situ* using a bedform detector. Equivalent mean roughness lengths of 0.32–0.49 cm and 1.65 cm were established for the rippled Arenicola sandflat/lower sandflat, and lower mudflat of the intertidal zone, respectively,
  On the saltmarsh of the supratidal zone, however, the flow structure disappears: most of the observed profiles (75%) are structureless.
  Roughness lengths derived on the basis of the LETTAU (1969) and WOODING *et al.* (1973) equations and compared with the field observations demonstrate that empirical constants calculated for the sandflats must be multiplied by 5.4 and 3.1, respectively. In contrast, they represent adequately the flow resistance over the large-scale erosional features of the mudflats.
  Roughness lengths relate closely to the scale of the bedforms present with elements consisting of: particle grain size, ripples on the intertidal sandflats, and large-scale scour features associated with the mudflats.

ADDITIONAL INDEX WORDS: *Intertidal flat, saltmarsh, velocity gradient rig, logarithmic profile, roughness length, shear velocity, drag coefficient, bedform detector.*

INTRODUCTION

Field observations have shown that velocity profiles in the sea can be represented by the von Karman-Prandtl velocity equation:

$$u/u. = (1/\kappa)\ln(z/z_0) \qquad (1)$$

Where u is the velocity at a height z above the bed, u. is the shear velocity, κ is the von Karman constant (equal to 0.4 at sea (SOULSBY, 1983; DYER, 1986)) and z_0 is the roughness length.

The study of the logarithmic velocity profiles commenced as early as in the 1950's (LESSER, 1951). Since then, researchers have examined the properties of the velocity profile in continental shelf and coastal environments, such as embayments and tidal channels (CHARNOCK, 1959; STERNBERG, 1966; DYER, 1970; CHANNON and HAMILTON, 1971; McCAVE, 1973; HARVEY and

VINCENT, 1977; SOULSBY, 1983; HEATHERSHAW and LANGHORNE, 1988).

For intertidal flat areas which are some of the most active regions in terms of sediment transport and deposition the available information on the flow characteristics are somewhat limited. Early in the 1970's, however, velocity profiles on the intertidal flats of the Wash were observed to correlate reasonably well (*i.e.,* over 56% of the time) to the von Karman-Prandtl representation during the rising stages of the tide (COLLINS *et al.,* 1981). Later investigations within the Loughor Estuary (S. Wales) and the Wash showed similar trends in the data sets (HANDYSIDE, 1977; CARLING, 1978; CARLING, 1981; VAN SMIRREN, 1982).

The present investigation examines the characteristics of velocity profiles along a coastal profile at Freiston Shore, the Wash; this exemplifies an accretional embayment incorporating extensive intertidal flats and saltmarshes. The velocity structure within such an environment is charac-

terized here together with the associated bound-
ary layer parameters. These results are compared
with other data sets to examine differences in time-
scales and between the various sub-environments.
Such observations are critical to any regional
studies of sediment dynamics.

PHYSICAL SETTING

The Wash is uniquely rectangular in shape and
lies within the eastern coastline of England ad-
jacent to the North Sea (Figure 1). It is an area
where coastal sediment dynamic investigations
have continued over some 30 years, where the
coastal profile is steadily prograding (EVANS, 1965;
EVANS and COLLINS, 1975).

The mean tidal range over the region is 6.5 m
and 3.6 m on springs and neaps, respectively. The
maximum tidal current speeds at Freiston Shore
observed as part of the present investigation are
about 0.48 m/sec (Station 2) to 0.56 m/sec (Station
2) (KE, 1991)); these are consistent with the ear-
lier survey results showing a maximum current
speed of 0.41 m/sec (resolved into an onshore/
offshore component of 0.39 m/sec and longshore
component of 0.14 m/sec at Station 1 in 1972
(EVANS and COLLINS, 1975)) to 0.66 m/sec (the
maximum tidal current speed observed at Station
3 (VAN SMIRREN, 1982)). Most of the observed
current speeds lie within the range of 0.10 to 0.50
m/sec. For comparison, the typical accretional in-
tertidal flats of the Jiangsu coastline in China are
associated with a mean tidal range of less than 4
m but with maximum tidal current speeds of 0.55
m/sec (ebb) to 0.83 m/sec (flood) and mean tidal
current speeds of 0.18–0.28 m/sec (ebb) to 0.31–
0.57 m/sec (flood) over the intertidal flats accord-
ing to the Marine Geomorphology and Sedimen-
tology Laboratory (MGSL) in 1984. On this basis,
tidal processes operating over the intertidal flats
of the (macrotidal) Wash embayment are com-
paratively weak. At the same time, however, wave
action is superimposed upon the intertidal flats
of the Wash. Wave heights of 0.6 m are common
during windy days based upon field measure-
ments. For example, on 1 April 1991, a wave rider
buoy located in the central part of the Wash re-
corded average and maximum wave heights of
0.8–1.0 m and 1.6 m, respectively, while a south-
west gale passed over the region (SAVILL, *personal
communication*, 1992).

The coastal region of the Wash exhibits dis-
tinctive zonations from HW to LW (EVANS, 1965)
as follows: saltmarsh, higher mudflat (Plate 1A),

Arenicola sandflat, lower mudflat (Plate 1B), and
lower sandflat (Figure 2). The sediments of the
sandflats consist of well-sorted very fine sands,
with a mean grain diameter of 3.0–3.5 ϕ. On the
higher mudflat and saltmarshes, the clay and silt
contents increase to 25–50% (AMOS, 1978).

The tidally- and wave-induced processes on the
intertidal flats lead to the development of an
abundant variety of bedforms. Ripples, with a
wave height of 1–2 cm and wavelength of 10–20
cm, occur commonly on the sandflats (AMOS and
COLLINS, 1978). The higher and lower mudflats
are incised extensively by gullies and small creeks
(0.1–0.2 m deep and 0.2–04. m wide) with their
long (5–10 m) and short (0.5–1.0 m) axes lying
both perpendicular and parallel to the coastline,
respectively.

The present contribution describes velocity
profile measurements undertaken at 4 stations
during June 1992 and on a spring tide across the
intertidal flats and saltmarsh at Freiston Shore.
Stations 1 and 2 are located on the lower sandflat
and lower mudflat (Plate 1B), respectively. Sta-
tion 3 is located at the landward limit of the Areni-
cola sandflat (*i.e.,* virtually at the boundary be-
tween the Arenicola sandflat and the higher
mudflat), whilst Station 4 is located at the sea-
ward edge of the saltmarsh (Figure 2).

METHODS

Two Braystoke velocity gradient rigs (BFM 001
and BFM 004) constructed by Valeport Ltd.
(Devon, U.K.) were used to measure the vertical
current structure (Table 1). Rig BFM 001 was
located on the bed through the use of guide ropes.
It was connected then by a cable to a digital meter
on the inflatable boat anchored some 20 m away
from the sensors. In contrast, Rig BFM 004 was
lowered over the side of the boat at the time of
the measurements. Wave heights and periods were
measured using a vertical (graduated) rod and
stop watch every ½ hr. Wind and wave directions
which were onshore and mainly from the south-
west to northeast during the survey were observed
using a compass.

The bedform profile was measured throughout
a tidal cycle using a simple device referred to as
a 'bedform detector' consisting of a thin plate of
sheet steel with a wooden handle (Figure 3). Ep-
oxy (WRA system 4501) adhesive was smeared
onto the surface of the sheet for each of the mea-
surements. During the survey, the plate was in-
serted vertically into the sea bed parallel to the

Plate 1. The outlook of the mudflat in the Wash: (A) Upper mudflat; (B) Lower mudflat.
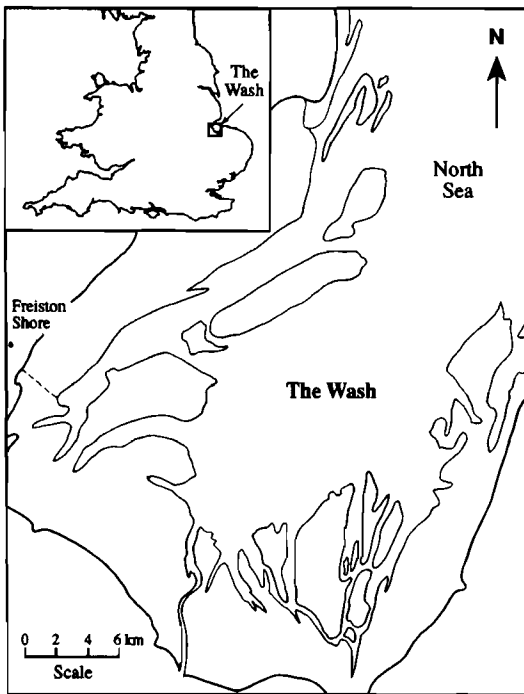
Figure 1. Location map of the Study Area: - - - - - intertidal area and the profile along which measurements were undertaken.

current direction and perpendicular to the crest-line orientation. The bedform profile was then measured on the basis of the upper surface of the sediment adhering to the resin to an accuracy of ±1 mm (Figure 3).

The velocity gradient rig data obtained in the field were processed using linear regression anal-ysis. Equation 1 is rewritten as:

$$\ln z = \ln z_0 + (\kappa/u_*)u \qquad (2)$$

Each set of observations was fitted to this log-arithmic profile with the corresponding correla-tion coefficients (r) and constants in the linear regression relationship being obtained. An 'ac-ceptable' logarithmic profile was regarded as that with correlation factors (r^2) greater than 0.8 (INMAN, 1963).

On the basis of Equation 2

$$z_0 = e^A \qquad (3)$$

$$u_* = 0.4/B \qquad (4)$$

Roughness lengths were calculated also on the basis of the observed bedforms applying the methods of LETTAU (1969) (Equation 5) and WOODING et al. (1973) (Equation 6) as follows:

$$z_0 = 2.0H(H/\lambda)^{1.4} \quad \text{for } 15 < \delta/z_0 < 1,000 \qquad (5)$$

where H is ripple height, λ is the ripple length and δ the boundary layer thickness, and

$$z_0 = 0.5HS/\xi \qquad (6)$$

where H is the average vertical extent or obstacle height, S is the cross-sectional area seen by the flow per horizontal area ξ and, for two-dimen-sional ripples, $S/\xi \approx H/\lambda$.

The drag coefficient (C_{100}) was calculated using a conventional method (DYER, 1986):

$$u_*^2 = C_{100}u^2_{100}$$

with

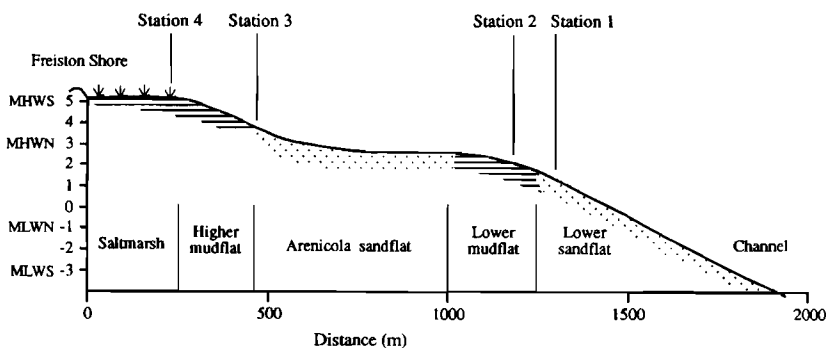$$C_{100} = u_*^2/[(u_*/\kappa)\ln(z/z_0)]^2 = [\kappa/\ln(100/z_0)]^2 \qquad (7)$$

Figure 2. Coastal profile and survey stations at Freiston Shore, the Wash.

Table 1. *Specification of velocity gradient rigs used in the investigation.*

Rig ID	Impellers		Velocity (m/sec)		Sensor Position, Above the Sea Bed									
	Nos.	Dia. (mm)	Range	Accuracy	z (cm)					ln z				
					M5	M4	M3	M2	M1	M5	M4	M3	M2	M1
BFM 001	5	125	0.025–10	±1.5%	7	21	41	82	152	1.9	3.0	3.7	4.4	5.0
BFM 004	5	28	0.035–2	±1.8–8.2%	2.7	7.4	20	37	55	1.0	2.0	3.0	3.6	4.0

RESULTS AND DISCUSSION

Logarithmic Profiles

Most of the velocity profiles observed over the intertidal flats of the Wash can be represented by a logarithmic form; *i.e.*, $r^2 > 0.8$ (Table 2 and Figures 4, 5, 6). The lowest frequency of occurrence (82%) of logarithmic profiles occurs at Station 2 during the ebb tide. However, if the readings of the M2 current meter are removed from the analysis (as there is some suspicion that the current meter failed), then all of the data sets would have been represented logarithmically (Table 2 and Figure 5b). The logarithmic character of velocity profiles has been observed elsewhere for this region and other U.K. estuaries (COLLINS and KE, *in preparation*); this implies, generally, that velocity profiles on intertidal flats can be represented by the Prandtl-von Karman logarithmic velocity curve.

The logarithmic characteristic of profiles measured over the intertidal flats of the Wash are consistent throughout the flood or ebb phases of the tide and over the upper and lower parts of

Figure 3. Sketch of the bedform detector.

the intertidal zone. Such an interpretation differs from that arising from earlier studies over the same area; these concluded that the frequency of occurrence of the logarithmic profile was higher on the flood than on the ebb phase of the tide. Likewise, it was higher over the upper part than over the lower part of the intertidal zone (VAN SMIRREN, 1982). Such differences indicate either seasonal variation in the velocity profiles over the intertidal flats, or may result from the recovery of velocity data from a coastal profile which were associated with extensive erosional processes between 1972 to 1982 (VAN SMIRREN and COLLINS, 1982). Thus, the higher frequency of occurrence of logarithmic profiles on intertidal flats *may* be interpreted as being accompanied by the accretional and progradational processes. A corresponding decrease in the occurrence of logarithmic profiles in an offshore direction may be indicative of erosion of the intertidal flat sediments.

The survey undertaken at Station 4 shows that tidal current speeds over the saltmarsh are low with mean flood and ebb speeds of 0.10 m/sec and 0.13 m/sec, respectively. The associated velocity profiles are not logarithmic in character with only 25% of the profiles with $r^2 > 0.8$; the remainder are highly irregular (Table 2 and Figure 7). Compared to the profiles obtained on the intertidal flats, in relation to the shallow water depths and the roughened surface of the saltmarsh formed by intensive incised gullies and creeks, the tidal current flow here may be vertically structureless. This interpretation is not fully verified by the present investigation, however, as the small velocity gradient rig used in the study may still be in need of further technical improvements.

Roughness Length (z_0)

The mean roughness lengths derived for the intertidal flats vary between 0.32 cm to 1.65 cm (Table 2 and Figures 4, 5, 6). Such a value is higher than would be expected for a flat very fine sand bed with a mean grain size of 3 to 3.5 ϕ (0.09 to
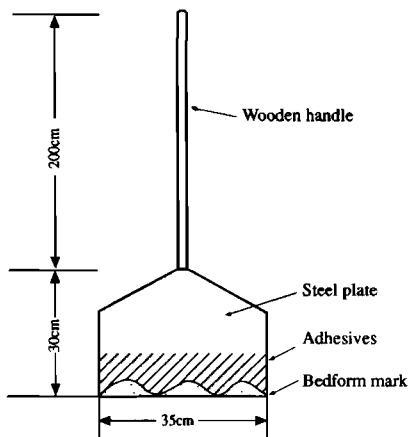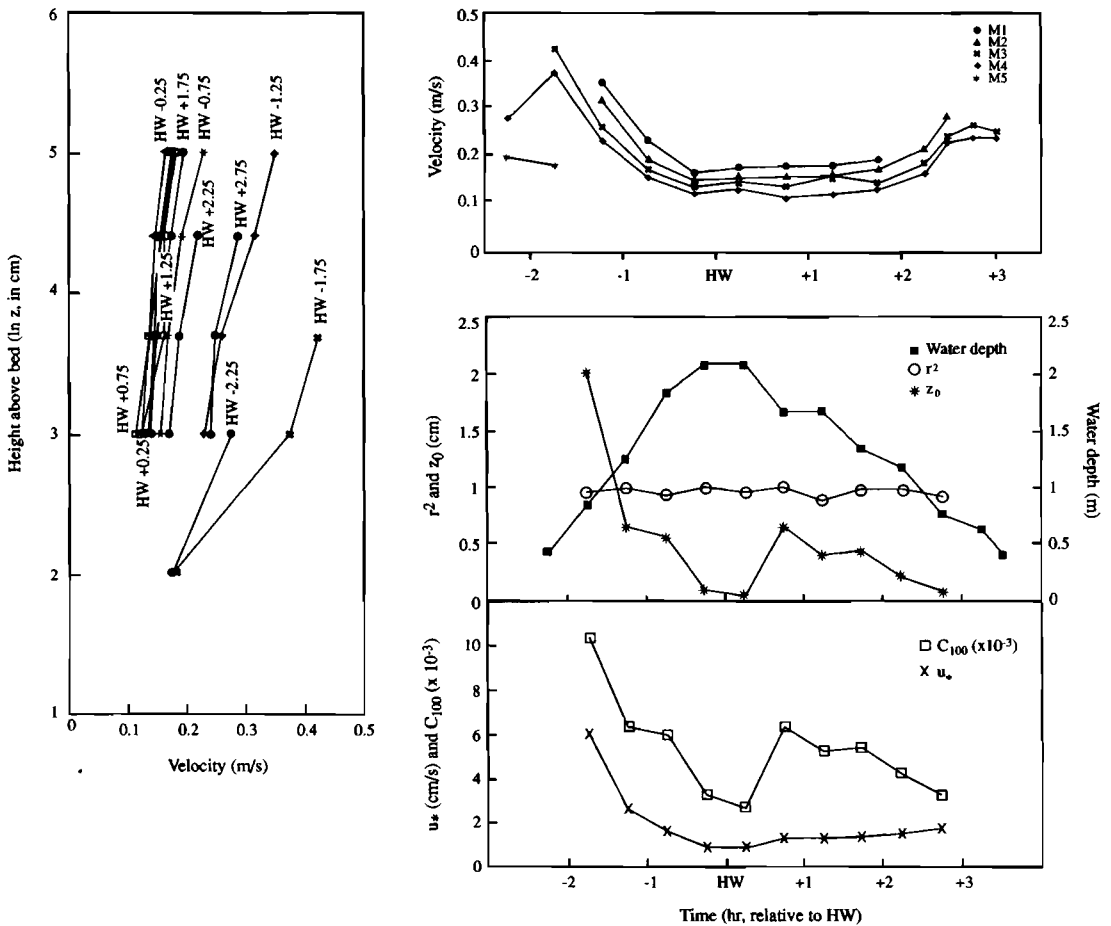
Figure 4. (Left, a) Velocity profiles (Rig BFM 001), (Right, b) z_0, u_* and C_{100}, Station 1.

0.13 mm), assuming that $z_0 = D/30$ (NIKURADSE, 1933); it is close, however, to the z_0 value derived for a rippled sand bed of 0.6 cm (SOULSBY, 1983).

Roughness lengths associated with the flood phase of the tide are usually lower than those observed during the ebb phase. Such a trend is enhanced from the outer to the inner part of the intertidal zone (Table 3): this may imply that sediment dynamics processes are stronger on the flood than on the ebb and over the inner part than over the outer part of the intertidal zone.

The temporal distribution of roughness lengths throughout a complete tidal cycle shows that it differs on the lower mudflat (Station 2) from that on the lower and Arenicola sandflats (Stations 1 and 3). On the sandflats, high roughness lengths occur at the beginning of the flood and immedi-

ately after HW: low values occur around HW and at the end of the ebb (Figures 4a and 6b). In contrast, high roughness lengths occur around HW and at the end of ebb on the lower mudflat with low values associated with the beginning of the flood and immediately after HW. Such trends are controlled mainly by changes in the tidal current direction and differences in the bedform orientation on the sandflats and mudflats, respectively,

On the sandflats, most of the ripples lie with their crestlines parallel (or at low oblique angle) to the coastline. On the mudflat, the large-scale scoured bedforms lie almost perpendicular to the coastline. As the flood currents approach the intertidal zone, from 300° to 40° relative to North (see Figure 1) (EVANS and COLLINS, 1975; KE, 1991), they flow obliquely across the ripples on

Table 2. *Logarithmic profile characteristics and boundary layer parameters associated with the intertidal (sand/mud) flats and saltmarshes of the Wash.*

Station	Environment	Flood		Ebb		Mean		z_0 (cm)			μ (cm/sec)			C_{100} ($\times 10^{-3}$)		
		r^2	log %	r^2	log %	r^2	log %	Flood	Ebb	Mean	Flood	Ebb	Mean	Flood	Ebb	Mean
1	Lower sandflat	0.96	100	0.97	100	0.96	100	0.82	0.29	0.49	2.77	1.31	1.84	6.48	4.48	5.21
2[a]	Lower mudflat															
	M12345	0.88	100	0.82	82	0.85	89	1.52	1.98	1.73	2.40	2.07	2.22	8.39	10.10	9.01
	M1345	0.96	100	0.96	100	0.96	100	1.42	1.98	1.56	2.54	2.38	2.32	8.55	9.60	8.98
	Mean	0.92	100	0.89	91	0.91	95	1.47	1.98	1.65	2.47	2.23	2.27	8.47	9.85	8.98
3	Arenicola sandflat	0.98	100	0.97	100	0.97	100	0.15	0.45	0.32	0.67	0.88	0.80	3.72	5.43	4.65
4[b]	Saltmarsh					0.91	25			3.88			1.79			25.94

[a] M12345 means that data sets from all current meters are used in the calculations, and M1345 means only meters 1, 3, 4, and 5 are used
[b] At station 4, only 3 of the 12 data sets fit the logarithmic profiles, and are used in the calculation

Table 3. *Ratio of the mean roughness length on the ebb and flood (from the outer to the inner part of the intertidal zone).*

Station No.:	Station 1	Station 2	Station 3
Environment:	Lower Sandflat	Lower Mudflat	Arenicola Sandflat
z_0(ebb)/z_0(flood)	0.35	1.35	3.00

the sandflats; it is parallel to the bedforms on the lower mudflat. Thus, during the flood tide, the influence of the bedforms on the velocity profiles is at a maximum on the sandflats, but is minimal on the lower mudflat as the result of current and bedform interaction. Around HW as the currents are still observable and flow towards 40° (N), such processes will be reversed. During the ebb, similar conditions as on the flood tide will occur.

Current speeds measured on the intertidal sandflats are <0.5 m/sec with the maximum during the survey of only 0.43 m/sec (Station 1). Hence, bedforms observed throughout the tidal cycle do not differ greatly from those measured during LW. This pattern has been verified by the bedform measurement over a tidal cycle and at LW (Table 4) together with the bedform-current speed relationships established previously by STRIDE (1982). In this sense, the bedforms measured on the intertidal flats during LW could represent average bedform conditions prevailing throughout a tidal cycle.

The roughness lengths derived using the equations of LETTAU (1969) and WOODING *et al.* (1973) using the measurements obtained from bedform detector and during LW are, however, much lower than those derived on the basis of analysis of the velocity profiles (Table 4). The former values are normally about 19% of those derived from the velocity profile, if Equation 5 is used; they are about 33%, if Equation 6 is applied. It is likely, therefore, that previously established aerodynamic models (LETTAU, 1969; WOODING *et al.,* 1973) cannot be applied simply to the flow over the intertidal flat environment. For such an application, the constants in Equations 5 and 6 should be multiplied by 5.4 and 3.1, respectively. The establishment of revised expressions between z_0 and H/λ, suitable for use on intertidal flats is in need of more simultaneous monitoring of vertical flow profiles and bedform changes in response to flow conditions.

The results obtained from Station 2, which is located on the lower mudflat, reveal higher z_0 val-

Table 4. z_0 calculated from measured velocity profiles and bedforms at Station 1.

Time (hr)	z_0 (u) (cm)	H	λ	H/λ	z_0(E5) (Lettau, 1969) (cm)	z_0(u) z_0(E5)	z_0(E6) (Wooding et al., 1973) (cm)	z_0(u) z_0(E6)
			(cm)					
HW − 1.5	0.66	1.5	9	0.17	0.13	5.1	0.24	2.8
HW − 0.3	0.09	1.5	18	0.08	0.06	1.5	0.09	1.0
HW + 1.0	0.52	1.0	12	0.08	0.04	13.0	0.06	8.7
Average	0.49*	1.3	13	0.10	0.08	6.1	0.13	3.8
LW**		1.2	10	0.13	0.08		0.13	
		1.0	6	0.17	0.08		0.16	
		2.0	16	0.13	0.13		0.22	
		1.3	8	0.17	0.11		0.21	
Average	0.49*	1.4	10	0.15	0.10	4.9	0.18	2.7
Mean	0.49*					0.09	5.4	0.16	3.1

*Mean value for the whole of the tidal cycle based upon the calculation of velocity profile
**Bedform measured at LW, on the sandflat at a number of different sites

ues than recorded at the other stations on the intertidal flats (although the sea bed sediments here are finer). Consequently, the critical control on roughness length would appear to be neither grain size, nor the scale of the small bedform (such as ripples on the surface of the flats), but rather the large-scale scoured morphology of the bed; *i.e.,* the densely-distributed gullies and creeks located between the depositional mud bodies (Plate 1B). The gullies and creeks are usually 0.1–0.2 m in depth and 0.2 m wide with the oval-shaped mud body being some 1.5 × 3 to 5 m in size; its long axis lies perpendicular to the coastline. Assuming that the scoured mudflats act as a kind of bedform, with H = 0.15 m and λ = 0.7 m, the z_0 values derived from the analyses undertaken by LETTAU (1963) and WOODING et al. (1973) would be 1.61 cm and 3.75 cm, respectively. These values are very close to the observed mean and maximum z_0 values of 1.65 cm and 4.02 cm, respectively, based upon the velocity profile observations. Hence, the creeks/gullies and muddy depositional bodies constitute, in themselves, a form of large-scale bedform; these, in turn, influence the structure of the velocity profiles and the z_0 values. The roughness length associated with such bedforms appears, therefore, to be represented reasonably by the experiential equations of LETTAU (1969) and WOODING et al. (1973).

The observed logarithmic velocity profiles over the saltmarsh (Station 4) relate to a mean roughness length of 3.88 cm; this is an order of magnitude higher than those derived for the intertidal sandflats; they are the same order of magnitude

as those of the lower mudflat on the intertidal zone. In terms of their geomorphological characteristics, the surface topographical features of the saltmarsh and the lower mudflat are quite similar. This similarity may have been implied by their same order of magnitude of roughness lengths derived from the velocity profile measurements. Hence, in terms of its hydrodynamics, the lower mudflat is more similar to the saltmarsh than to the intertidal sandflats.

Roughness lengths are considered also to be affected by wave processes (GRANT and MADSEN, 1979). Usually, the superimposed effect of waves upon velocity profiles causes an effective increase in z_0 (WRIGHT, 1989). The results of the present investigation have not identified such a trend. With increasing water depths, wave height and z_0 increase (Figure 6). There appears to be a time lag of approximately ¾ hr, however, between an increase in the wave height and that in z_0. Such observations infer that the roughness length is controlled here mainly by tidally-dominated processes.

Shear Velocity (u.)

The variation in shear velocity follows the trend of the changes in tidal current velocities throughout a tidal cycle. The mean u. varies between 0.80 and 2.27 cm/sec in such an environment (Table 2; Figures 4, 5, 6).

Generally, the u. associated with the flood tidal currents are one to two times higher than those on the ebb. This pattern implies that the flood
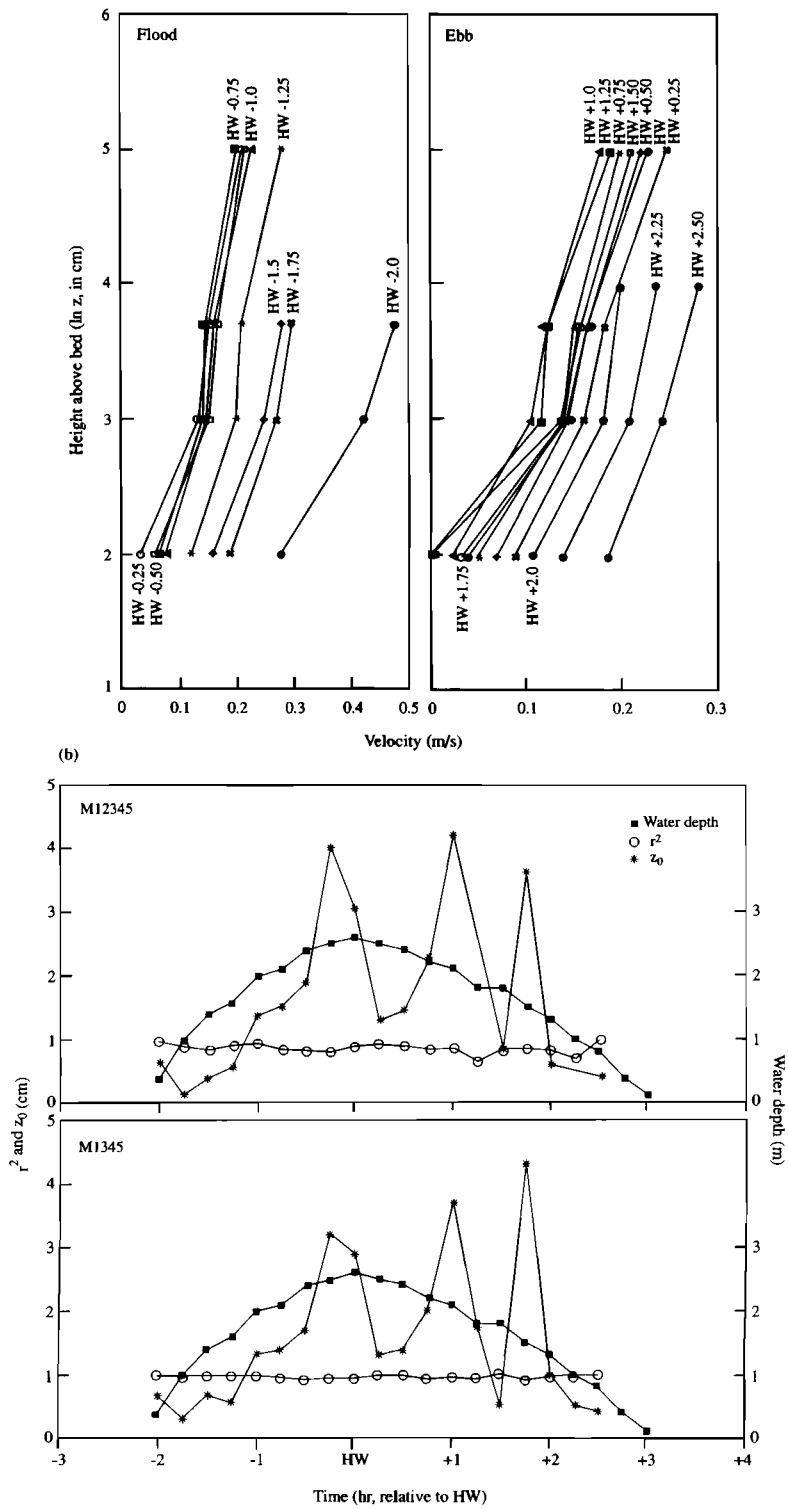
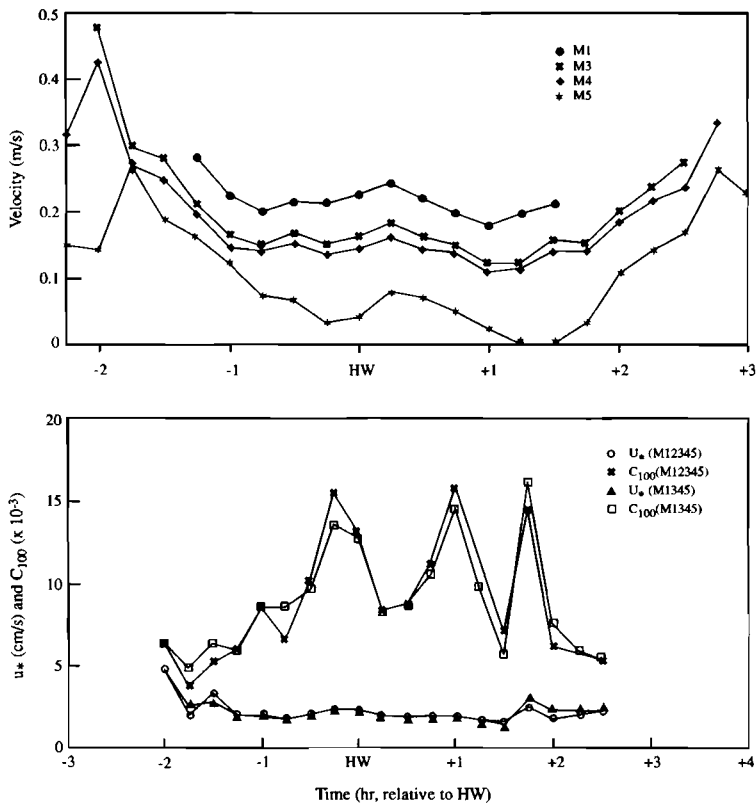Figure 5.   (Top, a) Velocity profiles (Rig BFM 001), (Bottom, b) r^2 and z_0, Station 2.

Figure 5. Continued. (c) uz, u$_*$, and C$_{100}$ Station 2.

currents exert a stronger influence on the sea bed and the associated sediments than the ebb flow.

Given: u. changes with location over the intertidal flats. There is an observed overall trend for u. to decrease from the outer to the inner parts of the intertidal flats. Likewise, there is a pronounced increase in u. over the lower mudflat; this coincides with topographical changes in the bed slope and relief (Figure 2 and Plate 1). Hence, the effectively rougher sea bed over the mudflats coincides with higher shear velocities and high boundary shear stresses over this area.

The derived u. on the intertidal (sand) flats is higher than that on the saltmarsh, implying high bed mobility; *i.e.*, tidal currents on the intertidal (sand/mud) flats especially over the lower mudflat are associated with more intensive sediment dynamic processes than on the saltmarsh. This interpretation is in agreement with the early qualitative interpretations of EVANS (1965). Indeed,

tidal current velocities over the saltmarsh are so low that it would appear that they cannot rework, move or transport bed sediments during most of the tidal cycle (Figure 7). The transportation and resuspension of deposited sediments over the saltmarsh surface appear to be negligible, therefore, with fine-grained material entering or leaving the saltmarsh only through small creek and gully systems within the marsh. Such processes are predominant at the beginning of the flood and at the end of the ebb phases of the tide. Accretion of the saltmarsh surface results mainly from the settling of suspended particulate matter (SPM) from the water column of unsteady tidally-induced flow over areas along the edges of (or between) the creeks and gullies.

Drag Coefficient (C$_{100}$)

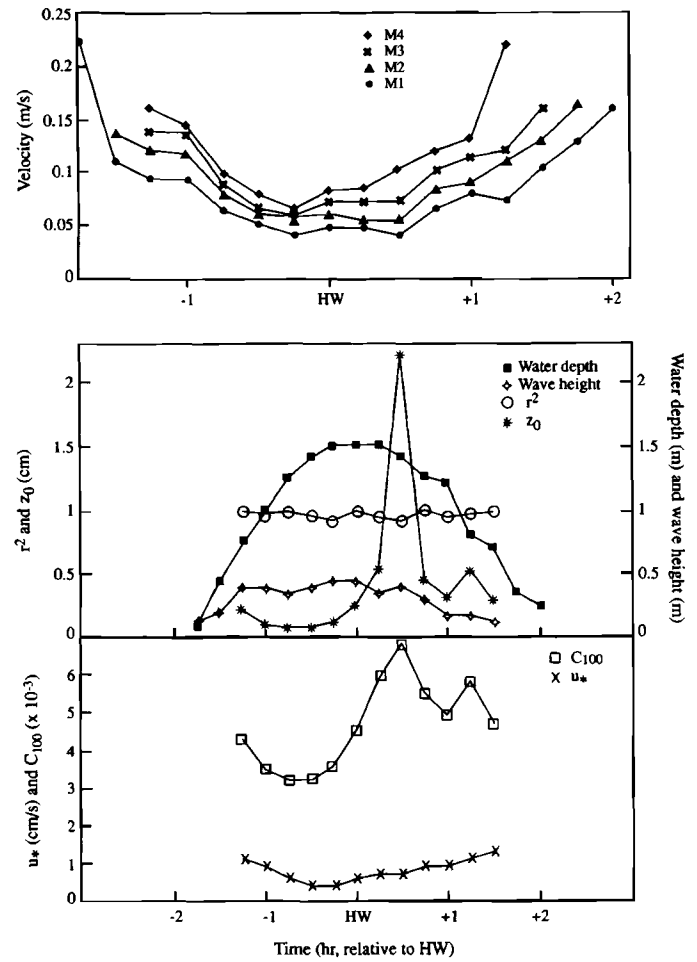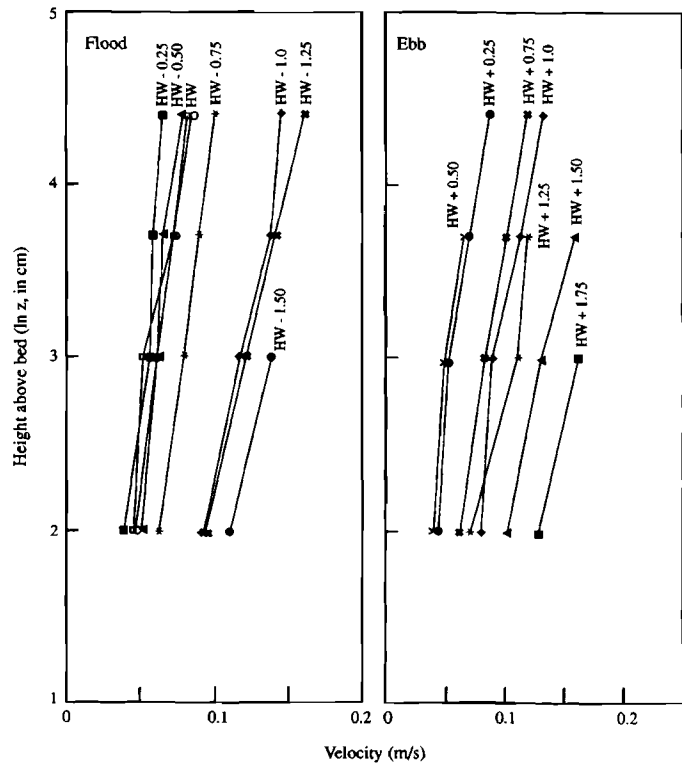The mean drag coefficient derived for the intertidal flats ranges from about 5×10^{-3} to $9 \times$

Ke, Collins and Poulos

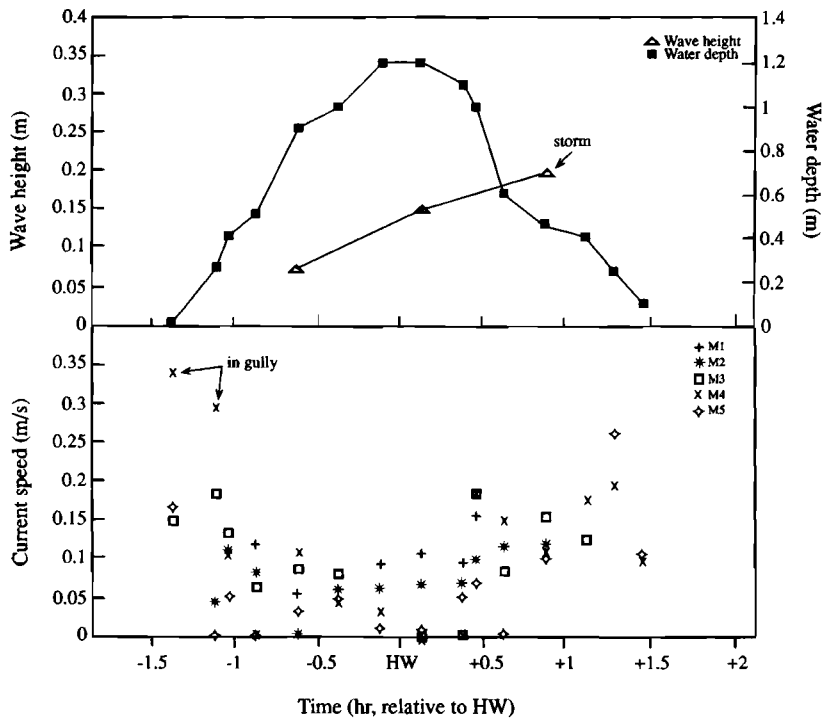Figure 6. (Left, a) Velocity profiles (Rig BFM 001), (Right, b) z_0, u. and C_{100}, Station 3.

Figure 7. Hydrographical survey (Rig BFM 004) at Station 4 on the saltmarsh of the Wash.

10^{-3}; this is the same order of magnitude as that derived for tidally-dominated environments elsewhere (i.e., 3×10^{-3} in STERNBERG, 1968). A higher derived value (8.98×10^{-3}) relates to the lower mudflats, which is an indication of a roughed sea bed over the area. The lower and Arenicola sandflats are associated with similar lower C_{100} values compared with those of the lower mudflat (Table 2 and Figures 4, 5, 6).

The order of magnitude difference between the drag coefficient associated with the intertidal sand flats and that of the saltmarsh (Table 2) appears to be related to the very roughened surface of the saltmarsh; it is covered by vegetation and is incised densely by a network of small creeks and gullies.

CONCLUSIONS

(1) For an accretional coastal embayment, tidal currents over the intertidal flats follow a logarithmic profile in the column with a frequency of occurrence of around 90%. The profiles are logarithmically stable over most of the intertidal zone; they vary only over the area between the intertidal and subtidal zones in response to the influence of topographically-induced flow.

(2) The greater part of the intertidal zone is associated with mean roughness lengths of 0.32 to 0.49 cm with u. values of 0.80 to 1.84 cm/sec. The derived C_{100} values are 4.48×10^{-3} and 5.43×10^{-3} for the lower sandflat and Arenicola sandflat, respectively. Corresponding values for the lower mudflat are 1.65 cm, 2.27 cm/sec, and 8.98×10^{-3}, respectively. Differences between the subenvironments are considered to be due mainly to the scale of the sea bed relief; i.e., a rippled bed for the former and scoured gullies and creeks for the latter.

(3) Currents on the saltmarsh are dominated by structureless rough turbulent flow conditions with only some 25% of the observed velocity profiles being logarithmic in character. The few observed logarithmic profiles observed on the saltmarsh were associated with mean roughness lengths of 3.88 cm together with a u. of 1.79 cm/sec and C_{100} of 25.94×10^{-3}. These values differ from those representing the intertidal flats implying that there is an essential difference be-

tween the sediment dynamics of the saltmarsh and the adjacent intertidal sandflats. Low current speeds and shear velocities together with high roughness lengths and drag coefficients show that the hydrodynamic regime over the surface of the saltmarsh is somewhat quiescent (at least, during most of the tidal cycle under (normal) calm weather conditions). In such an area, suspended particulate matter in the water column can settle easily to cause vertical accretion on the bed surface.

(4) Comparison between the roughness lengths derived from velocity profiles and on the basis of the equations of LETTAU (1963) and WOODING et al. (1973) using bedforms indices measured simultaneously with velocity profile measurements and during low water on the lower sandflats reveal an unproven representation of the equations for the large-scale topographical bedforms on the lower mudflat. For the rippled sandflats of the intertidal zone, the expressions need to be modified in order to obtain roughness lengths comparable to those derived from the velocity profiles. It would appear that constants in the equations should be multiplied by 5.4 and 3.1, respectively.

(5) The superimposed effect of low wave activity (with a maximum wave height of approximately 50 cm) on the velocity profiles does not lead to an increase in the apparent roughness length immediately. Rather, there is a time lag of some ¾ hr between the maximum wave height and such an increase. Such processes require further investigation in tidally-dominated areas.

ACKNOWLEDGEMENTS

LITERATURE CITED

AMOS, C.L., 1978. Intertidal flat sedimentation of the Wash. Unpublished Ph.D. Thesis, London: Imperial College, University of London, 404p.

AMOS, C.L. and COLLINS, M.B., 1978. The combined effects of wave motion and tidal currents on the morphology of intertidal ripple marks: The Wash, U.K. *Journal of Sedimentary Petrology*, 48, 849–856.

CALING, P.A., 1978. The influence of creek system on intertidal flat sedimentation. Unpublished Ph.D. Thesis, University of Wales, 258p.

CARLING, P.A. 1981. Sediment transport by tidal currents and waves: Observation from a sandy intertidal zone (Burry Inlet, South Wales). *Special Publication International Association of Sedimentologists*, 5, 65–80.

CHANNON, R.D. and HAMILTON, D., 1971. Sea bottom velocity on the continental shelf south-west of England. *Nature*, 231, 383-385.

CHARNOCK, H., 1959. Tidal friction from currents near the sea bed. *Geophysical Journal of the Royal Astronomical Society*, 2, 215–221.

COLLINS, M.B.; AMOS, C.L., and EVANS, G., 1981. Observation of some sediment transport processes over intertidal flats, the Wash, U.K. *Special Publication International Association of Sedimentologists*, 5, 81–98.

COLLINS, M.B. and KE, X., 1993. Tidally-induced flow structure over the intertidal flats. (in preparation).

DYER, K.R., 1970. Current velocity profiles in a tidal channel. *Geophysical Journal of the Royal Astronomical Society*, 22, 153–161.

DYER, K.R., 1986. *Coastal and Estuarine Sediment Dynamics*. Chickesta: Wiley, 324p.

EVANS, G., 1965. Intertidal flat sediments and their environments of deposition in the Wash. *Quarterly Journal of the Geological Society of London*, 121, 209-245.

EVANS, G. and COLLINS, M.B., 1975. The transport and deposition of suspended sediment over the intertidal flats of the Wash. *In:* HAILS, J. and CARR, A. (eds.), *Nearshore Sediment Dynamics and Sedimentation.* London: Wiley, pp. 237–306.

GRANT, W.D. and MADSEN, O.S., 1979. Combined wave and current interaction with a rough bottom. *Journal of Geophysical Research*, 84, 1797–1808.

HANDYSIDE, T.M., 1977. An investigation of hydrodynamic parameters of an intertidal sand flat in the Loughor Estuary using velocity profiles. Unpublished B.Sc. Thesis, University of Wales, Department of Oceanography, 56p.

HARVEY, J.G. and VINCENT, C.E., 1977. Observation of shear in near-bed currents in the southern North Sea. *Estuarine and Coastal Marine Science*, 5, 715-731.

HEATHERSHAW, A.D. and LANGHORNE, D.N., 1988. Observations of near bed velocity profiles and sea bed roughness in tidal currents flowing over sandy gravels. *Estuarine and Coastal Marine Science*, 26, 459–482.

INMAN, D.L., 1963. Sediments: Physical properties and mechanics of sedimentation. *In:* SHEPARD, F.L. (ed.), *Submarine Geology*. New York: Harper and Row, pp. 107–151.

KE, X., 1991. Report of Fieldwork on the Intertidal Flat

of Freiston Shore, the Wash. Department of Ocean-ography, University of Southampton, 7p.

LESSER, R.M., 1951. Some observations of the velocity profile near the sea floor. *Transactions of the American Geophysical Union*, 32, 207–211.

LETTAU, H., 1969. Note on aerodynamic roughness parameter estimation on the basis of roughness element description. *Journal of Applied Meteorology*, 8, 828–832.

McCAVE, J.N., 1973. Some boundary-layer characteristics of tidal currents bearing sand in suspension. *Memoires Societe Royale des Sciences de Liege*, 6e serie, Tome VI, 178–206.

MARINE GEOMORPHOLOGY AND SEDIMENTOLOGY LABORATORY, 1984. Report of Jiangsu Coast Studies, Department of Geography, University of Nanjing, China (in Chinese), 378p.

NIKURADSE, J., 1933. Stromungsgesetze in ratven Rehren. *Forschung Gebiete d. Ing.* Wesens Ser. B., Band 4 (Very. Deutsch. Forschungsheft), 361p.

SOULSBY, R.L., 1983. The bottom boundary layer of shelf seas. *In:* JOHNS, B. (ed.), *Physical Oceanography of Coastal and Shelf Seas*. Elsevier Sciences Publishers, pp. 189–266.

STERNBERG, R.W., 1968. Friction factors in tidal channels with different bed roughness. *Marine Geology*, 6, 243–263.

STRIDE, A.H. (ed.), 1982. *Offshore Tidal Sands: Processes and Deposits*. London: Chapman and Hall, 222p.

VAN SMIRREN, J.R., 1982. Hydrodynamic and sedimentary characteristics of a predominantly sandy intertidal zone: The Wash, Eastern England. Unpublished M.Sc. Thesis, University of Wales, 144p.

VAN SMIRREN, J.R. and COLLINS, M.B., 1982. Short-term changes in sedimentological and hydrographical characteristics over a sandy intertidal zone, the Wash, U.K. *Geo-Marine Letters*, 2, 55–60.

WOODING, R.A.; BRADLEY, E.F., and MARSHALL, J.K., 1973. Drag due to regular arrays of roughness elements of varying geometry, boundary layer. *Meteorology*, 5, 285–308.

WRIGHT, L.D., 1989. Benthic boundary layers of estuarine and coastal environments wave imposed on boundary layer. *Reviews in Aquatic Sciences*, 1, 75–95.