Experimental investigation of the impact of macroalgal mats on flow dynamics and sediment stability in shallow tidal areas

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A R T I C L E   I N F O

Article history:
Received 14 April 2011
Accepted 29 December 2011
Available online xxx

Keywords:
algae Ulva intestinalis
sediment bio-stabilization
tidal hydrodynamic
flow resistance

A B S T R A C T

This study aims to quantify the impact of macroalgal mats of Ulva intestinalis on flow dynamics and sediment stability. Such mats are becoming increasingly common in many coastal and estuarine intertidal habitats, thus it is important to determine whether they increase flow resistance, promote bed stability and therefore reduce the risk of erosion leading to tidal flooding or to degradation of coastal lagoons. The study has been carried out through a systematic series of experiments conducted in the large open-channel flume of the Total Environment Simulator (TES) facility, University of Hull, UK. The experimental facility was set up with a bed of fine sand, partially covered by strands of U. intestinalis; living individuals attached to large clasts were collected from Budle Bay, in the Lindisfarne National Nature Reserve, UK, and transplanted to the flume. The TES was equipped with acoustic doppler velocimetry (ADV) and acoustic backscatter (ABS) sensors, which measured current velocity, water level, bed level, and suspended sediment concentration. The experiments consisted of several unidirectional flow runs, firstly with a mobile sediment bed covered with U. intestinalis, then with a bare sediment surface, conducted at three different water depths. Under the investigated experimental range of velocities, typical of tidal environments, the macroalgal filaments were bent parallel to the sediment bed. The resulting velocity profile departed from the classical logarithmic trend, implying an increase of the overall roughness. This result reflects the different vertical Reynolds shear stress profiles and energy spectra features of the turbulent flow with respect to a bare sandy bed configuration. Macroalgae are also found to affect the morphological configuration of bedforms. The overall result is significant bio-stabilization, with increased flow resistance and reduced sediment transport.

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1. Introduction

The increase of green macroalgal populations, and concomitant loss of seagrasses, is becoming increasingly common in many coastal and estuarine intertidal habitats (Bolam et al., 2000; Silva et al., 2004). Macroalgal mats influence flow and sediment dynamics, as well as biochemical dynamics and, as a result, can cause major changes to coastal ecosystems. Therefore, detailed knowledge of the effect that macroalgal mats have on flow dynamics, sediment stability and water quality is required for improved understanding of their impact on the ecology of coastal and estuarine environments. Such knowledge is also important for improving numerical models used to predict tidal circulation and morphodynamic evolution. Generally, attached algal growth is restricted to relatively shallow tidal areas which dry at low water and are subject to tidal currents and waves capable of resuspending the sediments during the tidal cycle.

The impact of submerged vegetation on hydrodynamics and morphodynamics has been the objective of many studies in the last two decades. The attention, however, has focused mainly on rooted plants, in particular seagrasses. These plants are generally stiffer than macroalgae, their canopies can emerge and, when submerged, may stand nearly vertical generating two different flow layers, including a shear-layer at the top of the canopy (Nepf and Vivoni, 2000). When these vertical standing plants present a significant frontal area they cause a higher drag and generate larger vortices (Nepf and Ghisalberti, 2008). Studies of the effects of macroalgal mats on near-bed flow conditions and sediment dynamics are scarce Romano et al. (2003), even though macroalgae are known to...
play a significant role in stabilizing intertidal sediments (Silva et al., 2004). Algal mats exert a binding and baffling effect and create regions of diminished bed shear stress, thereby inhibiting erosion and maximising sedimentation from suspension (Frostick and McCave, 1979; Lopez and Garcia, 1998). For example, the experiments carried out by Romano et al. (2003) in circular flumes show that Enteromorpha intestinalis significantly increases overall flow resistance, causing a reduction in mean velocity in the range 18–56% and, at the same time, enhances the physical protection of the bed which reduces sediment erosion by 60% at 10% coverage and by 90% at 60% coverage.

Other filamentous branched green macroalgae, like some Cladophora species, form thick mats (tufts) in sheltered areas. Unlike Ulva intestinalis mats, in which the algae strands are less intertwined, these tufts keep currents compressed close to the bed. The flow through this thick mat has the characteristics of a pressure driven flow, with shear restricted to the upper and lower boundary conditions of Cladophora mat, as documented by Escartín and Aubrey (1995). The algal mats then behave as a hydrodynamically rough boundary, leading to a reduction of the effective water depth.

Using wooden cylinders to simulate plant stems Ghisalberti and Nepf (2004) observed that submerged vegetation modifies the near bed velocity profiles creating regions with diminished bed stress where turbulent kinetic energy production is balanced by drag dissipation. The penetration of the shear-scale turbulence generated at the top of the canopy is limited by the canopy drag, controlling the decay of the stress driven flow within the upper canopy. The significantly slower transport experienced by the lower canopy is associated with small scale turbulence generated within the canopy itself. The dynamics of the Kelvin-Helmholtz vortex generated at the top of the canopy is revealed by the waving motion observed in flexible canopies. However, Nepf and Ghisalberti (2008), reviewing the effect of vegetation on channel flow, point out that the effects of flexible canopies and of patches of vegetation are still poorly understood.

The present study aims at widening the knowledge of how the presence of macroalgal mats affects the flow field and the sediment dynamics in shallow tidal environments where the flow depth is continuously changing through time. In particular, we focus on the behaviour of a sandy sediment bed covered by patches with high densities of strands of Ulva intestinalis, a macroalga which is known to be highly tolerant of sedimentation (Eriksson and Johansson, 2005). A depth-limited submerged canopy configuration was reproduced at the real scale in a large laboratory flume by using a large number of natural strands collected in a tidal bay. Under a range of water depths typical of tidal environments and supporting the growth of macroalgae, we studied the flow field modifications that, in the presence of algal mats, promote bed stability and increase flow resistance, thus reducing the erosion of tidal landforms as well as the risk of tidal flooding. In particular, we show that the presence of U. intestinalis on a sediment bed causes an increase of the form drag; on the other hand, algal strands influence the structure and size of bedforms, also controlling their planimetric arrangements. The overall results of these different actions are a decrease of turbulence intensity near the bed and a change of velocity profile shapes that are much steeper near the bed. This information will be of benefit to numerical modellers, as well as to environmental engineers and managers who are faced with the problem of devising novel strategies to accommodate tidal inundation, to protect and restore tidal environments.

The body of the paper is organised as follows. In Section 2 we describe the experimental apparatus and the test configuration. Section 3 is devoted to the analysis of velocity data collected in the tests, with particular reference to the characteristics of turbulence observed with and without macroalgae. Finally, Section 4 is a discussion of the results and Section 5 reports some conclusions and suggestions for future research.

2. Materials and methods

2.1. Macroalgae species and sediment

The species selected for the present experiments was Ulva intestinalis, a common macroalga, which can be very abundant in nutrient enriched coastal systems. The area selected for collecting the specimens needed for the experiments was Budle Bay in the Lindisfarne National Nature Reserve, in north-east England. The bed of this bay is covered by a continuous mat of macroalgae close to a stream inlet and by a sparse cover in the intertidal flats located in the middle of the bay. For the present experiments a sparse coverage, typical of more exposed areas, was selected. The macroalgae were collected in the intertidal flats, by removing strands attached to pebbles in order to favour the transplant of macroalgae into the flume, as explained below. The strands collected had lengths ranging from 5 to 60 cm, mean length of 25 cm, mean width of 2.2 cm, mean weight of 49 g, and the clasts to which they were attached were typically 8 cm³ in volume.

The sediment chosen for the experiments was a non cohesive, well calibrated, fine sand, characterised by a median grain size, $d_{50} = 0.135$ mm. This choice was dictated by the grain size of the sediments covering the tidal flats of Budle Bay.

2.2. Experimental facility and measuring devices

The experiments were carried out in the Total Environment Simulator (TES) recirculating flume at the University of Hull, UK, allowing the study of hydraulic conditions, bed morphology and plant arrangement typical of natural field conditions. Real vegetation was planted in sediment representative of that found in estuaries and a range of flow depths that represent typical submergence depths was investigated. For these experiments the length and the width of the flume tank were set at 11 m and 2 m, respectively. A 20 cm deep, horizontal and flat sediment bed was created using the fine sand specified above. The TES is equipped with pumps to generate flow and paddles to generate waves. The pumps provided unidirectional flow conditions, and the discharge was set to produce mean flow velocities in the range of 0.20–0.25 m s⁻¹. A series of pit-type traps (each 25 cm wide and 50 cm long) were located across the downstream end of the flume in order to catch the sediment transported as bedload. These traps were removed at the end of each run and the collected sediment was weighed to determine the mean sediment transport rate. Suspended sediment bypassing the traps was collected in the recirculating tank located below the flume outlet.

Velocity, water and bed level measurements were collected in the 2 m wide and 2 m long sampling volume located approximately at the centre of the flume, corresponding to the acrylic window (see Fig. 1). This measuring area was located 6 m downstream of the flume inlet, to ensure fully developed, uniform flow conditions. The longitudinal, lateral and vertical velocity components, $(u_x, u_y, u_z)$, were measured at a set of selected points by means of four Nortek laboratory ADVs, denoted as ADV0, ADV1, ADV2, ADV3 in Fig. 1. These devices were located 1.2, 1.1, 1.0 and 0.9 m from the window wall and were moved longitudinally to monitor the along-flow positions $X_1, X_2, X_3, X_4$ located at $0.8, 1.0, 1.2$ and $1.4$ m from the upstream limit of the measuring area. About 10 different points, depending on the flow depth, were sampled along a given vertical. At each measuring point the velocity components were sampled at a frequency of 25 Hz for an acquisition time of 120 s. The ADV sampling volume was approximately 350 mm³.
Three Aquatec ABS sensors (denoted as ABS1, ABS2, ABS3 in Fig. 1) were located in fixed positions at the upstream end of the study area. These sensors operated at a frequency of 4 MHz, 2 MHz and 1 MHz, respectively, and recorded the bed surface position over time, also allowing measurements of bedform migration rate.

Finally, the total mass of sediment transported along the flume as bedload was measured at the end of each run by weighing sediment collected within the pit-type traps. Some water samples were also occasionally collected to measure the amount of suspended sediment.

### 2.2.1. Experimental Programme

The collected specimens of *U. intestinalis* were planted by burying the pebbles up to 10 cm in the sandy bed of the flume in a regular diamond pattern with lateral and longitudinal spacing equal to 20 cm and 40 cm, respectively, ensuring a density of 12 plants per m² (see Fig. 1). The large number of fronds attached to each pebble generated a fan shape covering up to 20 by 10 cm of the sandy bed (Fig. 1) and the pebbles remained always below the bed surface.

The experiments, summarised in Table 1, were carried out by initially filling the TES with a still water layer of depth $D$, and subsequently pumping a selected discharge $Q$ ensuring the required uniform unidirectional flow conditions. The water depth observed with flowing water, after equilibrium bedform configuration established, was on average 5 mm larger than $D$. A first series of experiments (hereinafter denoted as M) was conducted with the sandy bed covered with *Ulva intestinalis* and salt water ($\rho = 1027$ kg/m³). The macroalgae were then removed from the flume, the salt water was replaced with fresh water ($\rho = 999$ kg/m³) and, after scrading the bed flat, a second series of tests (hereinafter denoted as B) were carried out under the same initial hydraulic conditions of the M runs. The experiments were run for the minimum time needed to develop stable bedforms along the flume, before commencing measurements.

### 3. Data analysis

The Acustic Doppler Velocimeter (ADV) time series were firstly filtered, removing erroneous values and correcting for tilt and misalignment of the probes. In particular, the data removed consisted of i) measurements closer than 0.5 cm to the bed and ii) measurements containing more than 5% of bad data, namely points for which the mean and the minimum correlation were $<70$ and $<50$, while the mean and the minimum signal to noise ratio (SNR) were $<15$ and $<5$, respectively. A detection routine was used to remove high velocity ‘spikes’ from the time series. The corrections for probe tilt and misalignment involved rotating the velocity vectors in the horizontal and vertical planes such that the average lateral and vertical velocities within the entire fluid volume spanned by ADV measurements were zero (thus ensuring one dimensional bulk flow conditions). Generally, the tilt and misalignment correction angles were so small as to render the corresponding corrections negligible.

After these preliminary operations, the mean velocity vector $\bar{u}$ was calculated at each sampling point, by averaging over the acquisition time (120 s). Owing to the statistical steadiness of the flow field, the instantaneous velocity vector $u'$ was decomposed as:

$$ u' = \bar{u} + u' $$

### Table 1

Summary of the experimental conditions. Notations are as follows: $D$: depth of the still water initially filling the experimental apparatus; $Q$: water discharge used to obtain uniform flow conditions; $Q_b$: mean bedload discharge. Tests have been carried out with either algae covered (M tests) or bare (B tests) sandy bed.

<table>
<thead>
<tr>
<th>Run</th>
<th>$D$ (m)</th>
<th>$Q$ (l/s)</th>
<th>$Q_b$ (kg/mh)</th>
<th>$Q_a$ (kg/mh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.220</td>
<td>90</td>
<td>0.30</td>
<td>~0</td>
</tr>
<tr>
<td>2</td>
<td>0.255</td>
<td>102</td>
<td>0.27</td>
<td>~0</td>
</tr>
<tr>
<td>3</td>
<td>0.315</td>
<td>124</td>
<td>0.22</td>
<td>0.03</td>
</tr>
</tbody>
</table>
where \( \vec{u}' \) is the vector of the turbulent velocity fluctuations and the overline denotes the time average value.

Before analysing in detail the specific features emerging from the analysis of the distributions of \( \overline{u} \) and \( \vec{u}' \), it is worthwhile discussing the overall structure of the velocity field and sediment bed resulting from direct observations. In the case of bare sediment, the bed was rapidly covered by 1–2 cm high and 8–16 cm long bedforms, with sinuous crest-lines. In the presence of *Ulva intestinalis* the flow meandered around the algal strands, generating slightly smaller linguoid bedforms, migrating around the points of attachment of the algal strands. This overall picture is confirmed by operating a spatial interpolation of \( \overline{u} \) in a horizontal plane close to the bed. Geometrically correcting the photos taken during each experiment, we have reconstructed the spatial distribution of macroalgae and of bed topography in the measuring area. The location of the macroalgae, the bed topography and the velocity field shown in Fig. 2a suggests that the flow meanders around the lines of *Ulva intestinalis* strands. Water depths recorded by Acoustic Doppler Velocimeters over macroalgae were, on average, a few millimetres greater than depths over bare bed, indicating that *U. intestinalis* strands lay parallel to the bed within bedform troughs. In some cases bedform migration caused a partial burial of algal strands. Visual observations also highlighted that algal filaments oscillated sinusoidally both in the lateral and vertical directions, with the meandering in near bed flow. This behaviour is very different from that of the majority of plants analysed in laboratory experiments, in which the vegetation occupied a significant portion of the water column.

The first analysis carried out on the velocity data concerned the vertical distribution of the longitudinal mean velocity, \( \overline{u}_L \). It is well known that in fully developed turbulent flows occurring over

**Fig. 2.** a) Plan view of the flow field near a macroalgae covered bed. The areas occupied by macroalgae are depicted in light green. The contour fill represents the magnitude of the vertical velocity vector obtained by spatial interpolation of ADV measurements in a plane located 2 cm over the mean bed surface. All units are expressed in metres. Vertical distribution of the longitudinal velocity component, averaged over turbulence observed in the runs carried out with b) a bare sandy bed and c) a macroalgae covered bed. The verticals investigated are located just over a macroalgae stem. Circles refer to M1, B1 tests; squares denote M2, B2 tests; triangles denote M3, B3 tests. White symbols denote bare sandy bed data; black symbols denote macroalgae covered bed data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
a rough bed the vertical distribution of \( \bar{u}_x \) is well approximated by a logarithmic law of the form (Hinze, 1959):

\[
\frac{\bar{u}_x}{\bar{u}} = 5.75 \log \frac{z \epsilon_s}{\epsilon_s} + 8.5
\]  

where \( u \) is the friction velocity, \( \epsilon_s \) is the Nikuradse roughness parameter and \( z \) is the elevation over the mean bed surface. In order to analyse how this profile is modified by the presence of macroalgae, \( \bar{u}_x \) has been plotted versus \( z \) in a semi-log plot (Fig. 2b–c).

In the case of the bare bed, the velocity measurements are well represented by Eq. (2) and the experimental points fit a linear relationship as shown in Fig. 2b. Some deviations are observed for the points closer to the free surface, where wake effects affect the flow. In the case of the macroalgae covered bed, the vertical distribution of velocity has been analysed only in the upper water layer, i.e. outside the thin macroalgae layer covering the sediment bed. The presence of a macroalgae strand (Fig. 2c) leads to a significant departure of the velocity profile from the logarithmic one, especially in run M2. The profiles are in general characterised by a steeper growth induced by the lower velocities close to the bed.

In all the experiments, the vegetation filaments laid parallel to the bed and, hence, occupied a relatively restricted region near the bed. The velocity profile outside this region was found to follow a logarithmic law. This profile was used to estimate the overall shear stress that is applied to the bed. When plotting the vertical velocity profile of turbulent averaged velocities, data were removed from within the narrow region occupied by the macroalgae as well as from near to the water surface, where the measurements were affected by wake effects. This procedure is similar to that followed by Escarit and Aubrey (1995) for analysing the flow field establishing over a Cladophora covered bed. However, the mechanical behaviour of macroalgal mats in this study is very different from the canopies investigated by many other researchers (e.g., Nepf and co-workers), which allowed the study of the velocity profile within the vegetated layer.

In order to quantify the differences/similarities between the vertical distributions of \( \bar{u}_x \), we have determined \( m \) and \( \epsilon_s \) by plotting the quantity \( 5.75 \log \epsilon_s (z) \) as a function of \( \bar{u}_x \). A linear fitting of the experimental data obtained in the layer extending 15 cm from the top of the Ulva intestinalis canopy has been performed and the correlation coefficient measuring the reliability of the fitting has been estimated. The slope \( m \) and the intercept \( b \) of the straight fitting line allow us to estimate the friction velocity \( u_\tau = 1/m \) and the roughness coefficient \( \epsilon_s = 10^{(b+8.5)/5.75} \). For each run 16 fitting lines were calculated (one for each vertical measured by ADV) which can each be linked to a specific location of the monitored vertical: over sand, over the attachment points of a macroalgae, over macroalgae strands. A typical example of this analysis is shown in Fig. 3.

The 16 linear regression lines obtained for the measured velocity profiles have been statistically analysed using the Standard Error (SE) of \( m \) and \( \epsilon_s \), namely:

\[
SE_m = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y})^2 / (n - 2)}{\sum_{i=1}^{n} (x_i - \bar{x})^2}}
\]

\[
SE_\epsilon = \frac{1}{n - 2} \left( \frac{\sum_{i=1}^{n} (y_i - \hat{y})^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \right)^{1/2}
\]

where \( y_i = 5.75 \log \epsilon_s (x_i) \) is the independent variable, \( x_i = u_\tau \) is the dependent variable, \( y = mx + b \) and \( n \) is the number of data points.

The standard errors have been used to determine the 95% confidence intervals for \( m \) and \( \epsilon_s \), and, hence, for \( u_\tau \) and \( \epsilon_s \). Table 2 shows that the friction velocity generally attains larger values over macroalgae than over bare bed, even though the differences are very small. Indeed, the value of \( u_\tau \) obtained by averaging all the data corresponding to points over macroalgae is 0.03 m/s, while that referring to points over sand is 0.02 m/s. The influence of macroalgae is more marked in the case of the roughness parameter.

Table 2

<table>
<thead>
<tr>
<th>Run</th>
<th>( u_\tau ) (m/s)</th>
<th>( \epsilon_s ) (m)</th>
<th>( u_\tau ) (m/s)</th>
<th>( \epsilon_s ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Macroalgae</td>
<td>Bare bed</td>
<td>Macroalgae</td>
<td>Bare bed</td>
</tr>
<tr>
<td>1</td>
<td>0.02 ± 0.01</td>
<td>0.03 ± 0.01</td>
<td>0.05 ± 0.06</td>
<td>0.06 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>(0.01 ± 0.03)</td>
<td>(0.01 ± 0.06)</td>
<td>(0.00 ± 0.11)</td>
<td>(0.00 ± 0.32)</td>
</tr>
<tr>
<td>2</td>
<td>0.03 ± 0.01</td>
<td>0.02 ± 0.00</td>
<td>0.08 ± 0.08</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>(0.02 ± 0.05)</td>
<td>(0.02 ± 0.04)</td>
<td>(0.00 ± 0.26)</td>
<td>(0.00 ± 0.07)</td>
</tr>
<tr>
<td>3</td>
<td>0.03 ± 0.01</td>
<td>0.02 ± 0.01</td>
<td>0.08 ± 0.04</td>
<td>0.03 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>(0.02 ± 0.04)</td>
<td>(0.01 ± 0.15)</td>
<td>(0.00 ± 0.14)</td>
<td>(0.00 ± 0.14)</td>
</tr>
</tbody>
</table>

Please cite this article in press as: Venier, C., et al., Experimental investigation of the impact of macroalgal mats on flow dynamics and sediment stability in shallow tidal areas, Estuarine, Coastal and Shelf Science (2012), doi:10.1016/j.ecss.2011.12.035
As shown in Table 2 the values of $e_i$ over macroalgae are greater than those estimated over bare bed; the average values for selected points over macroalgae and bare sand being 0.09 m and 0.04 m, respectively. The statistical significance of these results have been evaluated by applying the t-test, the Wilcoxon rank sum test (U-test) and the two-sample Kolmogorov–Smirnov goodness of fit hypothesis test (NIST/SEMATECH, 2011) to the results of the M and B experiments. In all cases the null hypotheses that the two samples have the same mean or are taken from the same population can be rejected at a 0.05 significance level. Therefore, for the algal mat density considered in the present experiments, the global effect on the flow field consists of lower near bed velocities, a slight increase of the friction velocity characterising the water layer flowing over the macroalgae and a more significant increase in the corresponding roughness parameter. These effects are most clearly evident in velocity profiles collected above algal strands, where bedform morphology is markedly altered, as described above.

The vertical distributions of turbulent Reynolds stresses, $\tau_z = -\rho \bar{u} \bar{w}$, and turbulent intensity in the longitudinal direction $\sigma_{u_x}(= \langle \bar{u}^2 \rangle^{1/2})$ confirm the above observations.

Fig. 4 shows the vertical profiles of $\tau_z$ and $\sigma_{u_x}$, calculated for a macroalgae covered bed (run M) and a bare sandy bed (run B). Both $\tau_z$ and $\sigma_{u_x}$ attain a maximum about 5 cm from the bed, near the boundary of the roughness sublayer where drag, dispersive stresses, interactions between the flow, moving sediment particles and, in the case of M runs, algae mats, provide additional mechanisms for momentum extraction (Nikora and Goring, 2000).

The presence of macroalgae lying nearly parallel to the bed and oscillating slowly with the flow does not seem to significantly alter the distribution of turbulent Reynolds stresses close to the bed (Fig. 4a, b, c), even though a slight decrease of turbulent intensity is apparent in Fig. 4d, e, f alongside the near bed velocity deficit exhibited by velocity profiles. Clearly, the specific distribution along each monitored vertical of both $\tau_z$ and $\sigma_{u_x}$ is influenced by the location of individual strands, as well as by bedform geometry (Blom and Booij, 1995; Dimas et al., 2008). In particular, the vertical distribution of both $\tau_z$ and $\sigma_{u_x}$ tends to deviate significantly from a nearly triangular profile in the recirculating flow region that forms downstream from a bedform crest, exhibiting a maximum above the bed. A similar behaviour is likely to be triggered by macroalgae strands.

To obtain a macroscopic description of the flow features within the study area, the logarithmic law (Eq. (2)) and the shear stress profiles have been averaged in horizontal planes parallel to the bed. The results of the double averaging (over time and space) thus obtained are shown in Fig. 5. The plots confirm that the presence of Ulva intestinalis leads to velocity profiles that are much less steep near the bed, where the flow velocity is decreased, while the total bottom friction given by the sum of grain and form roughness increases. This global behaviour results from the interaction of two countering effects. The presence of U. intestinalis on the one hand enhances the form drag but, on the other hand, influences it indirectly, controlling the structure and size of bedforms, as well as their planimetric arrangements. The damping of bedforms promoted by algal cover clearly tends to decrease form drag. In the present experiments the overall result of these competing mechanisms is a decrease in both the near bed velocity and the corresponding fluctuations which, in turn, produces a lower effective bed shear stress (i.e. associated with grain roughness) and enhanced sediment stability. This result is confirmed by the values of the sediment mass mobilised in the different experiments. As reported in Table 1, the mean hourly bedload discharge observed in

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**Fig. 4.** Left panel: vertical profiles of turbulent Reynolds stresses, $\tau_z = -\rho \bar{u} \bar{w}$, for the ADV measurements carried out in: a) runs B1 and M1, b) runs M2 and B2, c) runs B3 and M3. Bare sandy bed data are denoted by white circles, while black circles denote macroalgae covered bed data. Right panel: vertical profiles of longitudinal turbulent intensity $\sigma_{u_x}$ for the ADV measurements carried out in: d) runs B1 and M1, e) runs M2 and B2, f) runs B3 and M3. Bare sandy bed data are denoted by white circles, while black circles denote macroalgae covered bed data.

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the presence of macroalgal mats is typically smaller than that measured with bare sandy bed conditions. Water samples collected during the experiments indicate a significant decrease of suspended sediment concentration by a factor four in the presence of algal cover (on average 0.12 g/l compared with 0.41 g/l). The overall picture emerging from Fig. 5 suggests an upward shift of the roughness sublayer when macroalgae are present. Ulva strands, lying parallel to the bed reduce the near bed velocity and turbulent intensity. As a consequence, the flow depth tends to increase in order to accommodate the same discharge, leading to the turbulent shear stress distribution shown in Fig. 5c. Indeed, ABS measurements indicate that certain variability in flow depth occurred not only along the channel, owing to the presence of bedforms, but also in the various experiments, with individual probes measuring a maximum change of about ~15 mm and the smallest change of ~3 mm. Average changes in depth ranged between 0 and 8 mm per experiment, with slightly greater changes for the experiments with algae.

Further information on the effects of macroalgae is given by the energy spectrum of turbulent fluctuations, $u'_v$, depicted in the log–log plot of Fig. 6. Although the density scatter is relatively high, the mean values obtained by binning the data on a logarithmic scale are reasonably well approximated with a straight line having a slope of $−5/3$. The deviations from this line occurring at larger frequencies are most probably due to the measurement noise (Nikora and Goring, 2000). The presence of algal mats appears to both slightly reduce the energy at high frequencies and to shift the energy of larger eddies and the inertial subrange towards lower frequencies. In contrast to the trend observed by Christiansen et al. (1999) and Leonard and Luther (1995) in tidal marsh canopies, algal mats lying parallel to the bed, appear to promote the production of larger turbulent eddies.

This scenario is confirmed by estimates of the temporal macro-scale (Hinze, 1959)

$$T_E = \int_0^{\infty} R_t(\tau)d\tau$$  \hspace{1cm} (5)

where $R_t$ is the Eulerian autocorrelations of the velocity fluctuations defined as:

$$R_t(\tau) = \langle u'_x(t)\cdot u'_x(t+\tau) \rangle$$  \hspace{1cm} (6)

$\tau$ being the time lag. As shown in Fig. 7, the macro-scale $T_E$ falls almost within the range 0.1–0.3 s. Applying Taylor’s frozen turbulence hypothesis, relating temporal to spatial turbulent fluctuations, in the presence of macroalgae the size of turbulent macro-eddies generally increases with respect to bare bed conditions.

4. Discussion

In the present experiments with Ulva intestinalis exposed to uniform flow conditions, it was observed that algal filaments aligned nearly horizontally in a narrow layer close to the bed, sheltering the sediment from direct flow drag. This dynamic behaviour has significant consequences even in the presence of a sparse algal mat cover. U. intestinalis strands caused the flow to meander around them, inducing changes in bedform morphology and reducing bedform amplitude. Sometimes bedform migration also led to partial burial of macroalgal strands and filaments. This interaction between macroalgae and bedforms provides a further mechanism for the organic enrichment of sediment, besides the increased sedimentation and retention of organic particles associated with algal mats. The capacity of U. intestinalis to promote the incorporation of organic material in the sediment, potentially leading to anaerobic conditions, is to be balanced by the reduction of water turbidity and nutrient concentration and by the increase in sediment stability as described by Madsen et al. (2001). The global result can be either positive or negative depending on the local conditions: in more exposed areas, such as that considered in the present study, the improvement in sediment stability will dominate, while in more sheltered areas oxygen deficiency may cause problems. In general, the overall bed shear stress acting just above the narrow layer occupied by macroalgae increases owing to the form drag associated with the presence of both vegetation and bedforms. However, the interaction between vegetation and bedforms results in damped bedform amplitude and, hence, in a smaller bed shear stress associated with grain roughness. This is the cause of the reduced intensity of sediment transport rate observed in the presence of algal cover.

In the present experiments, hydraulic conditions (flow depth and velocity) and macroalgal features (length and width of each individual) are typical of those encountered in tidal environments. Thus the observed flow resistance depends only on plant density and planar arrangement. We have in particular focused our attention on a typical sparse coverage, characterising more exposed areas and, hence, more prone to erosion. Nevertheless, during the experiments we have not changed macroalgal density and, hence, we are not able to derive a quantitative relation linking bed friction to percent algal cover. Despite the sparse coverage and independently of the considered flow depth, the presence of algal mats has been invariably found to exert a protecting action on the sediment bed. We argue that a further increase of the plant density would

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Please cite this article in press as: Venier, C., et al., Experimental investigation of the impact of macroalgal mats on flow dynamics and sediment stability in shallow tidal areas, Estuarine, Coastal and Shelf Science (2012), doi:10.1016/j.ecss.2011.12.035

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![Fig. 5. Average over planes parallel to the bed of: a) the turbulence averaged longitudinal velocity; b) the fluctuating velocity; and c) the total shear stresses. Spatial average over planes parallel to the bed is denoted by (…), while an overbar indicates time average. White and black symbols denote bare sandy bed data and macroalgae covered bed data, respectively. Circles refer to M1, B1 tests; squares denote M2, B2 tests; triangles denote M3, B3 tests.](image-url)
lead to a stronger stabilization of the bed, owing to the sheltering action produced by the algal cover. This is supported by Romano et al. (2003) who tested different bed densities in a relatively narrow (0.1 m wide) circular flume, focussing their attention on the relation between the speed of the rotating annular drive plate used to generate the flow and the mass of eroded sediment. They showed that increasing algal density implies a reduction of the flow velocity, and established density-dependent relationships for Ulva intestinalis densities showing a significant increase in friction drag with increasing percent algal cover: increasing bed cover from 10% to 60% resulted in a decrease in current velocities from 18% to 56%. As a result of increasing density, the bedform size, and hence the form resistance, would tend to be further reduced.

5. Conclusions

The present study provides an overview of how Ulva intestinalis affects the unidirectional flow over a sandy bed. The data collected under a range of flow depths typical of tidal environments suggest that macroalgae exert a significant stabilizing effect even when the algal cover is sparse. As documented by direct observations and bed elevation measurements, and unlike most of the plants used in other laboratory flume studies, this species of macroalgae tend to lie flat over the bed, moving sinusoidally with the current. The interaction of the macroalgae with the flow results in a decreased bedform amplitude, with small bedforms forming around the macroalgae strands. In other words, U. intestinalis exerts a sheltering action on the bed which changes the morphology and migration rate of bedforms. Moreover, the interaction of the fronds and bedforms results in an upward shift of the roughness sublayer, where shear stress is more intense. The resulting vertical distributions of the longitudinal velocity and of shear stress, suggest that macroalgae lead to a decrease of the mean flow velocity and an increase of the overall flow resistance close to the bed. The friction velocity is generally greater over macroalgae than over bare bed. The presence of macroalgae, however, also contributes to a reduction in the effective bed shear stress associated with grain roughness, responsible for sediment motion. The overall sediment mobility, and hence the amount of transported sediment, are thus reduced. The present study focused on macroalgal mat interactions with steady unidirectional flow conditions. Nevertheless, both temporal and spatial flow dynamics are key to fully understand the momentum transfer mechanisms and their influence on flow resistance (Nikora et al., 2001, 2004). Further study is presently ongoing to assess the influence of macroalgal mats on sediment transport in wave-current induced flows under the range of flow depths found in intertidal areas supporting macroalgae growth.

Fig. 6. Energy Spectrum of turbulent fluctuations $u'_x$ for a) bare sandy bed (run B3) and b) macroalgae covered bed (run M3) conditions. Black circles denote the mean values of the energy density computed by binning the data. The $-5/3$ fitting line predicted by Kolmogorov is also shown. The investigated vertical is that corresponding to ADV1 and location X1 of Fig. 1, while the measuring volume is 3 cm above the bed.

Fig. 7. a) Temporal macro-scale and b) spatial macro-scale of turbulent eddies resulting from Eulerian autocorrelation of longitudinal velocity fluctuations. The temporal macro-scale has been estimated integrating the autocorrelation function up to the first zero crossing. The spatial macro-scale has been derived assuming Taylor’s frozen turbulence hypothesis. White and black symbols denote bare sandy bed data and macroalgae covered bed data, respectively.
Acknowledgements

We gratefully acknowledge the important contribution of Brendan Murphy during the experimental stage of this project. This work has been supported by the European Community’s Sixth Framework Programme through the grant of the Integrated Infrastructure Initiative HYDRALAB III within the Transnational Access Activities, Contract no. 022441. Partial funding has also been provided by MIUR within the project PRIN 2008, “Eco-morphodynamics of tidal environments and climate change”.

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