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Measuring hydrodynamics and sediment transport processes in the Dee estuary

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Abstract

The capability of monitoring and predicting the marine environment leads to a more sustainable development of coastal and offshore regions. Therefore, the continuous measurement of environmental processes become an important source of information. The present paper shows data collected during 6 years, and in particular during 2008, in the Dee Estuary. The data aims to improve the observations of the mobile sediments in coastal areas and its forcing hydrodynamics and turbulence. Data involves the deployment of instrumented rigs measuring sediment in suspension, currents, waves, sea level, sediment size and bedforms as well as cruise work including grab sampling, CTD profiles and side-scan sonar. The data covers flood and ebb tides during spring and neap periods with moderate and mild wave events, thus, having a good coverage of the processes needed to improve knowledge of sediment transport and the parameterizations used in numerical modelling. The data, in raw and treated, is being banked at BODC (British Oceanographic Data Centre, http://www.bodc.ac.uk/) which is the formal British organization for looking after and distributing data concerning the marine environment.

1 Introduction

Coastal areas support many human activities of economic, industrial and leisure importance. Moreover, they represent a very important habitat for many marine and bird species. In order to manage properly such areas, knowledge of the physical, biological and chemical processes is necessary and therefore the observation, quantification and simulation of such processes are very important. Coastal ecosystems are experiencing changes affecting the dynamic boundary between the land and the sea. Coastal waves and currents are highly variable and can have a significant impact on human activities and structures. Therefore, the continuous research and improvement of environmental monitoring has become a vital issue for the safety and well-being of coastal society. The capability of monitoring and predicting the marine environment leads to a more sustainable development of coastal and offshore regions (Pinardi and Woods, 2002; GOOS, 2003).

In recent years, the scientific community has been paying more attention to several aspects of wave-current-bed-sediment interaction. Mastenbroek et al. (1993) showed how a wave-dependent bottom drag coefficient improved the results of a 2-D storm surge model in the North Sea. Baumert et al., 2000; Souza et al., 2001; and Bolaños et al., 2005, using a coupled wave-tidal-circulation model, showed the relevance of wave action over the stress at the sea bed and thereby the erosion and suspension of particulate matter. Brown and Wolf (2009) improved storm surge modelling by considering a wave dependent surface stress. Thus, simultaneous measurements of such processes are necessary, though not common, to understand and improve it's modelling. There is a pressing need for improved observations of the mobile sediments in coastal areas in order to upgrade modelling systems, ultimately allowing the appropriate management of nearshore and estuarine areas that are under increasing pressure.

The data presented in this paper aims to improve the observations of the mobile sediments in coastal areas, to advance research on observational techniques, especially using acoustic methods for measuring sediment concentrations, bed forms and transport. To advance understanding of critical aspects of the key processes, for example bedform evolution, modes of sediment entrainment and the impact of mixed sediments, in combined waves and currents; and to make a critical assessment of the extent to which the predictive capabilities related to sand transport remain valid in a mixed sediment environment. The data set represent a unique source of information due to the simultaneous measurements of the processes involved in sediment transport.

The Dee is a macrotidal estuary characterized by the presence of waves at its outer margins, strong tidal flows in its channels, and a mixed seabed usually muddy sands or sandy muds. The overall transport direction, in or out of the main outer channels of the estuary, is probably grain-size dependent. The Dee is, thus, a conveniently located “natural laboratory”.

The present paper shows data collected during 6 years, and in particular during 2008. First a detailed description of the Dee Estuary is given. Then details of rigs and instrumentations deployed are discussed together with an overview of the data and the environmental conditions during the recording period. Comprehensive data of the Dee Experiment is also summarized in Sect. 6. Finally the conclusions are presented outlining the key aspects that can be addressed with this data set.

2 The Dee estuary

The Dee is a macrotidal, funnel-shaped estuary situated in the eastern Irish Sea (Fig. 1). It has a length of about 30 km, with a maximum width of 8.5 km at the mouth of the estuary. The average tidal prism in the Dee is 4×10^8 m^3, annual mean river discharge is only of 31 m^3/s (with peak flows of the order of 300 m^3/s) making the Dee a tidal dominated estuary. Tidal range during mean spring at Hilbre Island is in the order of 10 m. A tidal bore has been reported to occur in the canalised upper part of the estuary (Simpson et al., 2004). Moore et al. (2009) report a sediment import into the estuary, but it is suggested that the Dee could be reaching a morphological equilibrium and that the rate of accretion may decrease in the future. The main channel bifurcates 12 km seaward from the canalised river at the head of the estuary, resulting in two deep channels extending into Liverpool Bay. The Dee Estuary presents a mixture of sediments containing a range of non-cohesive and cohesive sediments and, therefore, the threshold of motion of the bed might be a complex process dependent on several conditions. The estuary is a major wildlife area and is one of the most important estuaries in Britain and amongst the most important in Europe for its populations of waders and wildfowl. The two shorelines of the estuary show a marked contrast between the industrialised usage of the coastal belt in Wales and residential and recreational usage in England. The estuary has been subject of several man made modifications such as canalisations and training wall causing siltation and accretion on the eastern shore and colonisation of some areas by saltmarsh.

The estuary contains extensive areas of intertidal sand and mudflats which support a variable but characteristic benthic fauna depending on the nature of the substrate. Large areas of saltmarsh also occur at its head and along part of its north-eastern shore. The three sandstone islands which comprise the Hilbre Island complex represent the only natural hard rock coast within the estuary.

3 Instrumentation and deployments

The Dee Estuary has been subject of study and measurements by the Proudman Oceanographic Laboratory (POL) since 2004 when deployment of rigs and cruises in the area started to take place. Recently, within the NERC funded FORMOST (Field observation and modelling of the sediment triad) project (http://www.pol.ac.uk/home/research/formost/), measurements were carried out during 2008 and 2009.

The measurement program in the Dee during 2008 consisted of the deployment of 2 recent versions of STABLE (Sediment Transport and Boundary Layer Equipment) rigs. STABLE is a platform to Study Near-bed Turbulent Currents and Associated Sediment-Dynamics. The biggest and most complex structure designed and built by the Mechanical Engineering group at POL is the STABLE-III equipment (Fig. 2). STABLE-III is the third generation of this apparatus which was conceived originally in 1981. It measures the interactions between turbulent currents and sediments at the sea-bed. It is a tripod standing about 2.5 m high and the feet occupy a circle about 3.5 m in diameter, it weighs about 2500 kg (Williams et al., 2003). Mini-STABLE (Fig. 2) is a smaller version of STABLE-III. STABLE-III and mini-STABLE were deployed in the Hilbre Channel and Welsh Channel respectively (Fig. 1).

The period of deployments was from mid February to mid March, the first one to be deployed was mini-STABLE (12/02/2008) in the Welsh channel, and STABLE-III two days later in Hilbre channel. Rigs were equipped with different instruments to measure currents, waves, concentration of sediment in suspension, sediment size, salinity and temperature. Instruments used were ADVs (Acoustic Doppler Velocimeter) able to rapidly and accurately sample 3-D current component in a small sampling volume by using the pulse-coherent technique.

ABS (Acoustic Backscatter System) measures the strength of backscatter signal that can be inverted to obtain concentration and size of particles in suspension in the water column. The use of acoustic backscatter (ABS) techniques to measure suspended sediment dates back to the 1980s (Crawford and Hay, 1993; Young et al., 1982; Thorne and Campbell, 1992).

LISST (Laser In Situ Scattering and Transmissometry) designed to measure particle size based on the principle of laser diffraction. The standard processing software supplied with the LISST computes the volume concentration in units of microlitres per litre (ul/l). The LISST laser optics must be checked on a regular basis to ensure that they remain properly aligned (Styles, 2006) and background scatter calibration must be also performed.

ADCP (Acoustic Doppler Current Profiler), which measures the velocity of water using a physical principle similar to the ADVs. Traditionaly ADCP have been used to study current profiles with resolution of the order of 0.5 m but nowadays ADCP instruments can be used for resolution of up to 1 cm allowing the study of turbulence and sediments transport.

The rigs also contained ripple profilers, mini-STABLE had a line scan ripple profiler and STABLE-III a 3-D scanner which is a line scan ripple profiler that rotates to provide an area coverage. The transducer allows to find the bed position within a spatial resolution of about 5 mm and with an error of 0.01 m (Williams et al., 2004, 2005).

In order to measure turbidity (suspended particulate matter) a series of OBS were installed to the ADVs. OBS measure turbidity on NTU units, the instruments were set to a high turbidity range.

Pre-deployment instrument operations consisted of typical servicing, calibration and testing of instruments. Synchronization of clocks were performed and instruments were set to start the recording at 06:00 12/02/2008 for mini-STABLE and 06:00 14/02/2008 for STABLE-III.

In order to deploy and recover the rigs, an oceanographic research vessel (Prince Madog) was used. The deployment and recovery periods were used also to perform CTD profile and LISST station, grab sampling and side-scan sonar transects.

3.1 Welsh channel deployment

All parts for mini-STABLE were transported to Menai Bridge, UK, and loaded onto the Prince Madog and then deployed in the Welsh channel. Instruments on the rig were 2 ADVs, 1 ABS, a line scan ripple profiler, a sediment trap, a LISST and ADCP. Unfortunately the ADCP and ABS were damaged and data was lost. Figure 2 shows the rig before the deployment manoeuvres. Table 1 shows the summary of the instruments, their position on the frame and some sampling information. High frequency sampling was used in order to have turbulence and small/fast processes information.

3.2 Hilbre channel deployment

STABLE-III was constructed at POL's Vittoria Dock site (Birkenhead, UK) in the weeks prior to its deployment in the Hilbre Channel. The frame had 3 ADVs in horizontal position, 2 ADCPs, 3 OBS sensors linked to ADVs, an ABS, a LISST, a sensor for temperature and salinity and a Settling-tube sediment trap. However, two of the OBS did not record properly. Figure 2 shows the rig at the Prince Madog just before deployment. Table 2 shows a summary of the rig instrumentation with the sampling strategy used.

4 Data treatment and access

ADVs data has been cleaned and flagged for possible spikes that can appear in this kind of instruments. The approach taken was following Goring and Nikora (2002) and modified by Wahl (2003). The method is based in 3-D Poincare map in which each component of velocity and its first and second derivative are plotted against each other. The points located outside of the ellipsoid in the Poincare map are excluded or replaced by a polynomial interpolation. This method has been used by Mori et al. (2007) to clean ADV data in bubbly flows. Figure 3 shows an example of the despiking algorithm on the data. It can be seen that the method properly removes the spikes. It has to be noted that the data was very clean and only a few spikes were found in the raw data.

LISST data is treated directly with the manufacturer software using the calibration information of each instrument. ABS raw data has to be converted to obtain sediment concentration profile by an inversion algorithm (Betteridge et al., 2008). If the phase of the backscattered signal from a suspension of sediments is randomly distributed between 0–2π, the backscattered signal from a multi-frequency ABS can be converted to concentration and mean particle size (Sheng and Hay, 1988; Hay, 1991; Thorne and Campbell, 1992; Thorne and Hanes, 2002).

Although using multi-frequency can be used to obtain profiles of particle size and concentration, at this stage in the analysis, advantage has been taken of the sediment trap data located on the frames to obtain estimates for the suspended particle size, and the ABS inversion used these sizes to calculate suspended sediment concentration profiles.

Wave parameters can be obtained from ADCP or from combining ADV and pressure data. The PUV method has been used to obtain wave parameters from ADV and pressure. The method uses linear theory to convert velocity and pressure spectra to surface elevation spectra:

$$
\begin{aligned}
C_{\eta p} &= \left[\frac{\cosh(kh)}{\cosh(k(h+z))}\right]^2 \frac{C_p}{\rho^2 g^2} \\
C_{\eta u} &= \left[\frac{\sinh(kh)}{\cosh(k(h+z))}\right]^2 \frac{C_u}{\sigma^2}
\end{aligned}
\tag{1}
$$

where $C_{\eta p} C_{\eta u}$ are surface elevation spectra based on pressure and velocity, k is wave number, h is the mean water depth relative to the seabed, z is the vertical distance relative to the mean water level.

In order to take into account the background currents the surface wave dispersion relation has been modified:

$$\omega = \sqrt{gk\tanh kH} + kU\cos\alpha \qquad (2)$$

ω, is frequency
k, is the wave number
U, is the background velocity
α, angle between currents and waves

The wave direction is estimated by comparing the magnitude of the cross spectra at each frequency:

$$D = \tan^{-1}(C_{pu}(f)/C_{pv}(f)) \qquad (3)$$

C_{pu}, Cross spectra of pressure and u component
C_{pv}, Cross spectra of pressure and v component

The PUV method is very convenient because it only requires a single point velocity and pressure estimations, however it requires a weighted average of the background current over the full water column to properly transfer the measurements to the surface. Another limitation is that at any given frequency the PUV will estimate a single direction.

The data, in raw and treated, is being banked at BODC (British Oceanographic Data Centre, http://www.bodc.ac.uk/) which is the formal British organization for looking after and distributing data concerning the marine environment.

5 Environmental conditions during the 2008 deployment period

5.1 Hydrodynamics

Time series of hydrodynamic parameters at Hilbre channel and Welsh channel during the deployment period are shown in Fig. 4. Current speed is controlled by tides and it follows the spring/neap and flood/ebb cycle. Velocities at Hilbre channel are slightly larger during flood. Wave parameters are modulated by tide and the wave event during the second neap period, observed in the Welsh channel, is not present in the Hilbre channel due to a possible dissipation of energy when waves propagate in the estuary mouth. Current direction at the Hilbre channel location is aligned with N–S while at the Welsh channel is E–W. The ebbs at the Welsh channel produce a change in current direction that could be attributed to eddy formation due to curvature of channel, interaction with the fame and with the coastline ledge. Wave direction is predominantly from E and NE at the Welsh channel, however at the Hilbre predominant directions are from north, in agreement with the channel orientation.

5.2 Sediment in suspension

The LISST is used to provide an estimate of sediment size distribution in the area. Sediment size distributions during the first days of deployment at STABLE-III and mini-STABLE are shown in Fig. 5, the distributions correspond to times when the smallest particles dominate (to reduce possible shifting of the distribution due to flocculation). It shows a dominance of small particles with a diameter of around 70 microns which represent the limit between silt and very fine sand, there is also an important contribution of fine sand. Both locations show the same pattern in size distribution, but larger concentrations at the Welsh channel. The large concentration of cohesive particles could support the formation of flocs at some stage of the tidal cycle.

Figure 6 shows time series of integrated parameters from the LISST and the OBS at STABLE-III. The suspended sediment concentration from the LISST is not clearly related to flood and ebb but there is an evident signal that correlates with the spring-neap cycle. The peak size of the distribution shows that, in contrary to concentration, large particles are present for both spring and neap tides and this might be controlled by flood and ebb cycle. The turbidity data from the OBS shows a very similar pattern as the concentration from the LISST showing a large correlation and a strong neap/spring signal. The mild wave events have a slight effect on sediment concentration from the LISST. A rise of concentration and turbidity in the burst 380 that agrees with a wave event can be observed. The concentration presents large scatter when compared with velocities from ADVs. This shows that the concentration at 1.5 m above the bed is not a pure representation of bottom processes but it could also involve some flocculation and small particle processes that might need longer time to react to environmental conditions.

5.3 CTD stations

Even though the Dee Estuary is tidal dominated, the stratification can be important in turbulence and transport processes. CTD stations were performed taking advantage of the deployment and recovery manoeuvres of the rigs. Stations were performed every half hour during 24 h if the weather and timing for entering/exiting the channels allowed it. An example of the salinity and temperature profiles in the Hilbre Channel are presented in Fig. 7 where the tidal oscillation of surface stratification can be observed. Close to low tide, a surface low density layer is present, meanwhile near high tide the profiles become more monotonic and with larger salinity due to the entrance of the saline water.

6 Complementary data

Other field measurements have been performed in the Dee Estuary by POL, rig deployment and cruises have been taking place since 2004 to collect hydrodynamic, sediment in suspension and bedform data, measuring turbulence and intra-wave processes. Tables 3 to 7 summarize the data available that have been collected. 2004 was the year the Dee Estuary experiment started involving the deployment of STABLE and two bed frames. Similar deployments took place during 2005 and 2006. In 2007, the deployments were extended including Mini-STABLE and the addition of more instruments into the rigs.

Similar to the 2008 campaign, the 2009 was funded by the FORMOST NERC project and it involved the deployment of Mini-Stable and STABLE-III but also included the idea of looking at biological effects, hence it included chlorophyll sampling and two deployments (winter and spring).

7 Conclusions

This work has presented a data set that comprises measurements of the relevant bottom processes focused to significantly advance the understanding of critical aspects of the key sediment transport processes, for example, bedform evolution, modes of sediment entrainment and the impact of mixed sediments in combined waves and currents and contribute to the improvement of its modelling. The Dee Estuary presents very interesting features, making it an interesting site to study not only because of its local importance but because of the mixed processes taking place there involving tidal hydrodynamics, wave events, sand and cohesive sediment, biological activity and river influence.

Sediment transport data is usually sparse and the data available is normally under relatively narrow sediment size conditions (e.g. sandy beach or narrow distribution in laboratory). Data in mixed sediment conditions are less frequent and thus the sediment transport processes occurring in such environments are less understood. The presence of a fine fraction can modify the formation of steep ripple profiles, thereby modifying significantly the boundary layer flow structure that occurs above a bed of clean sand. Processes of flocculation and effects of biology in such environments are very important and difficult to reproduce in a laboratory, thus this data set is a very valuable source of information as it covers several years and winter-summer periods under mild and moderate wave events. Simultaneous measurements of hydrodynamics, bed features, turbulence and suspended sediment concentration were performed considering high frequency sampling in order to obtain information on fast processes such as intrawave sediment entrainment and breaking and formation of flocs. In the representation of quite complex coastal areas, sand transport and morphological models still tend to rely on rather rudimentary transport concepts that often do not include, even in a simplified parameterised form, such fundamental mechanisms as the "wave-related" component of the transport that arises from intra-wave processes.

This data set is ideal for testing hydrodynamic, turbulence and sediment transport models and critically assess the improvement in the transport predictions that arise from the inclusion of a range of detailed transport processes. These include improved bed roughness prediction, representation of the "wave-related" transport component, effects of a mixed sediment bed and the extent to which our predictive capabilities related to sand transport remain valid in a mixed sediment environment.

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Table 1. Instrumentation in mini-STABLE rig deployed in the Welsh Channel.

Mini-STABLE: Welsh Channel, 53°22.156′ N 3°19.577′W, 12/02/2008–13/03/2008		
Instrument	High above the bed (m)	Sampling
ADV G412+B331	0.63	16 Hz, 20 min burst every 1 h
ADV G250+B233	0.35	16 Hz, 20 min burst every 1 h
Line-scan Ripple profiler	1.04	1 scan every 5 min
Sediments trap	1.18	
LISST-100	1.56	0.025 Hz, 20 min every hour

Table 2. Instrumentation in STABLE-III rig deployed in Hilbre Channel.

STABLE-III: Hilbre Channel, 53°22.382′N 3°14.147′W, 14/02/2008–11/03/2008		
Instrument	High above the bed (m)	Sampling
ADV G496+B281	1	8 Hz, 20 min burst every 1 h
ADV G355+B285	0.7	8 Hz, 20 min burst every 1 h
ADV G358+B292	0.4	8 Hz, 20 min burst every 1 h
OBS T8193	100	8 Hz, 20 min burst every 1 h
ABS	1.2	128 vertical bins (cm), 20 min burst every hour
LISST100X	182	0.025 Hz, 20 min every hour
CT probe 7216	100	8 Hz, 20 min burst every hour
CT probe 7217	70	8 Hz, 20 min burst every hour
CT probe 7218	40	8 Hz, 20 min burst every hour
3-D ripple profiler	134	1 3-D image every hour
Settling tube sediment trap.	105	
ADCP 600 Hz	2.3	Bin size 0.5 m, 49 bins
ADCP 1200 Hz (Gimbal)	2.3	Bin size 0.5 m, 49 bins

Table 3. Summary of the March 2004 data.

Location	Rig/position	Instrumentation	Other data
Hilbre Channel	STABLE-II 53°23.422′ N 03°14.217′ W	Ripple profiler LISST ABS	CTD Grab sample
	Bed-frame 53°22.773′ N 03°14.113′ W	ADCP Current meter	
Welsh Channel	Bed-frame 53°22.156′ N 03°19.351′ W	ADCP 2 ADV LISST	CTD

Table 4. Summary of the February 2005 data.

Location	Rig/position	Instrumentation	Other data
Hilbre Channel	STABLE-II 53°22.340′ N 03°14.062′W	2 ADVs Ripple profiler LISST CT ABS	CTD Grab sample Side-scan sonar
	Bed-frame 53°22.629′N 03°4.213′W	ADCP	
Welsh Channel	Bed-frame 53°22.202′N 03°19.517′W	LISST ADCP	Side-scan sonar

Table 5. Summary of the February 2006 data.

Location	Rig/position	Instrumentation	Other data
Hilbre Channel	STABLE-II 53°22.231′ N 03°14.016′W	2 ADVs Ripple profiler LISST ABS CT	Side-scan sonar CTD SMP from water samples
	Bed-frame 53°22.944′N 03°14.216′ W	ADCP	
Welsh Channel	Bed-frame 53°22.196′ N 03°19.471′ W	ADCP	

Table 6. Summary of the March 2007 data.

Location	Rig/position	Instrumentation	Other data
Hilbre Channel	STABLE-III 53°23.151′ N 03°14.391′ W	ADCP LISST Ripple profiler ABS 3 ADV Pressure sensor 2 OBS CT	CTD Grab samples SMP from water samples Side-scan sonar
Welsh Channel	Mini-STABLE 53°22.047′ N 03°19.401′ W	ADCP 3 ADVs Ripple scanner ABS Sediment trap LISST	CTD Grab samples SPM from water samples Side-scan sonar

Table 7. Summary of the 2009 data.

Year and month	Location	Rig/position	Instrumentation	Other data
2009 February	Hilbre Channel	STABLE-III 53°22.529′ N 03°14.205′ W	3 ADVs ABS Ripple profiler 3 OBS Sediment trap ADCP MicroCAT LISST	Side-scan sonar CTD SPM-chlorophyll sampling Grabs
	Welsh Channel	Mini-STABLE 53°22.248′ N 03°19.571′ W	2 ADVs ABS Ripple scanner Sediment trap ADCP MicroCAT LISST	Side-scan sonar CTD SPM-chlorophyll sampling Grabs
2009 May	Hilbre Channel	STABLE-III 53°22.514′ N 03°14.156′ W	3 ADVs ABS Ripple profiler 3 OBS Sediment trap ADCP MicroCAT LISST	Side-scan sonar CTD SPM-chlorophyll sampling Grabs
	Welsh Channel	Mini-STABLE 53°22.138′ N 03°19.782′ W	2 ADVs ABS Ripple scanner Sediment trap ADCP MicroCAT LISST	Side-scan sonar CTD SPM-chlorophyll sampling Grabs

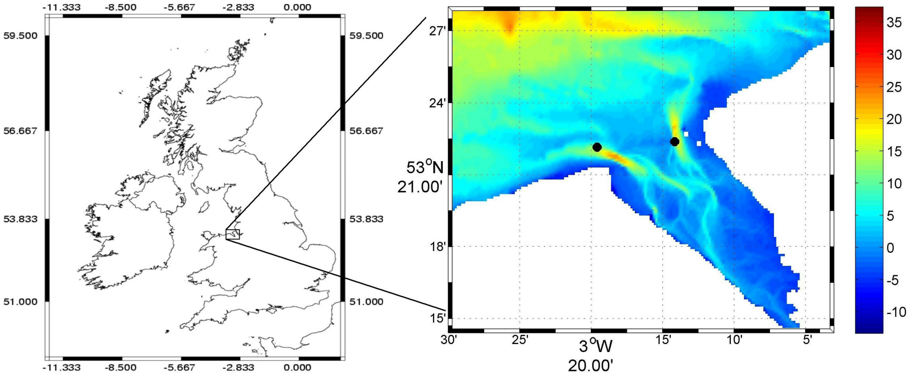

Fig. 1. Location of the Dee Estuary in the Irish Sea. Right figure shows the Dee bathymetry and location of rigs at the Welsh (West) and Hilbre (East) channels.

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Fig. 2. Mini-STABLE (left) and STABLE-III (right) during the deployment manoeuvres on the Prince Madog.

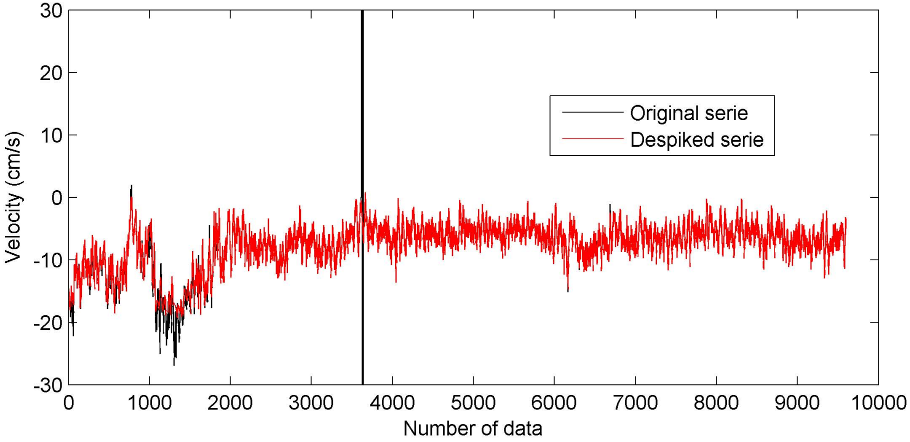

Fig. 3. Example of original and despiked ADV time series.

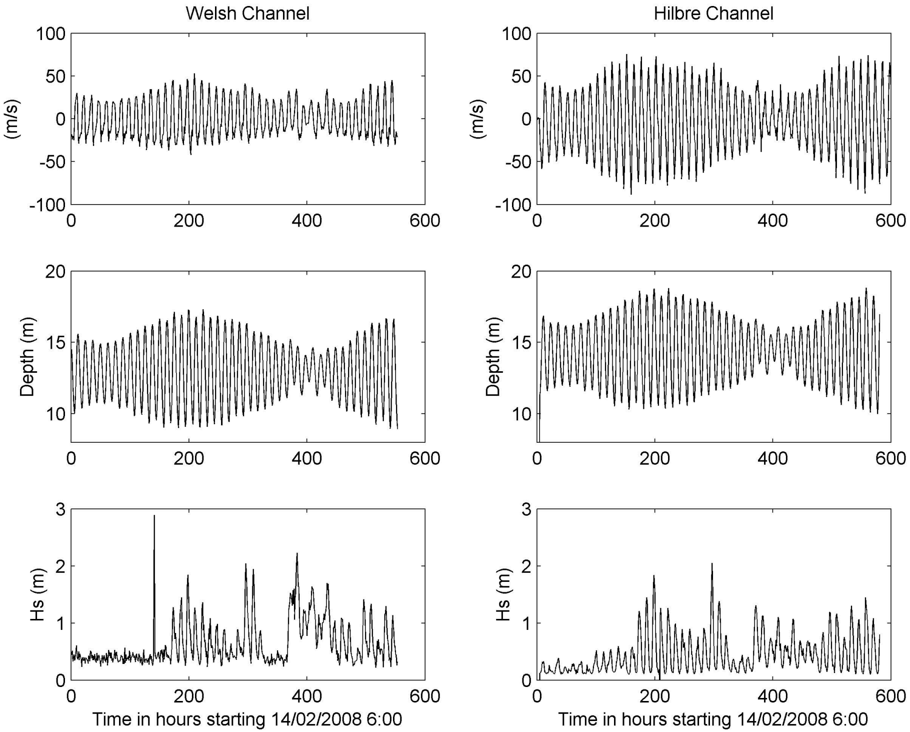

Fig. 4. Time series of current velocity (positive is flood and negative is ebb), water depth and significant wave height at the Welsh Channel (left) and at Hilbre Channel (right).

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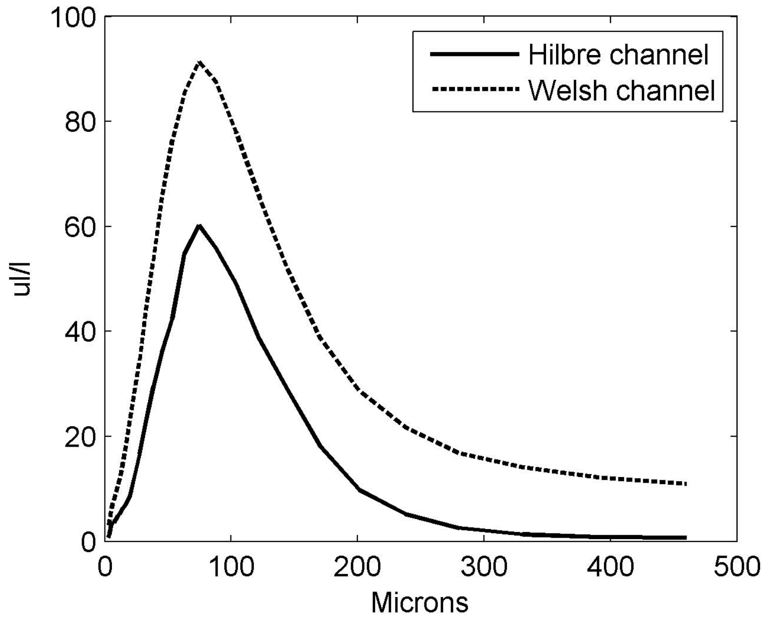

Fig. 5. Size distribution of suspended sediment during the first day of deployment.

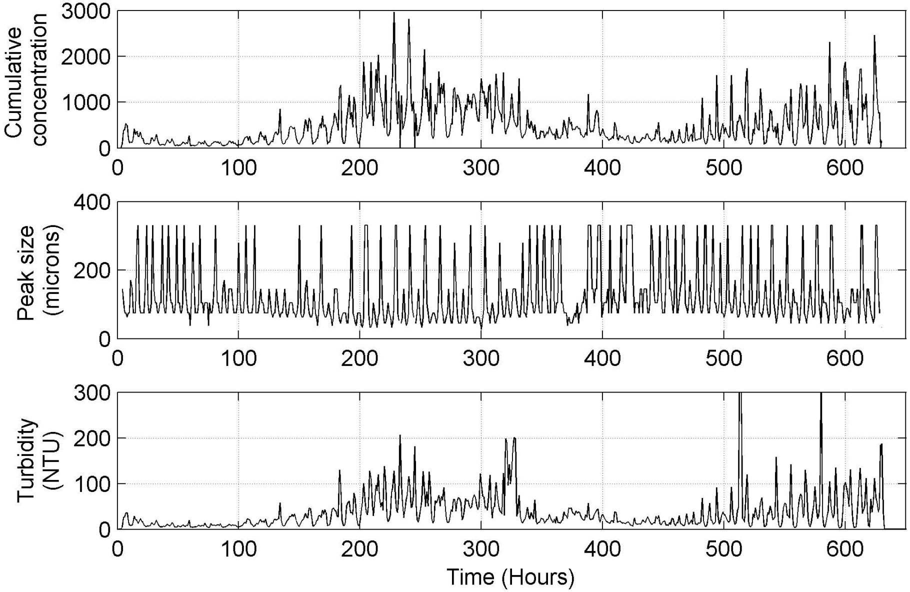

Fig. 6. Time series of integrated parameters from the LISST. Top panel is the concentration. Second panel is the peak size. Third panel is the turbidity from the OBS sensor.

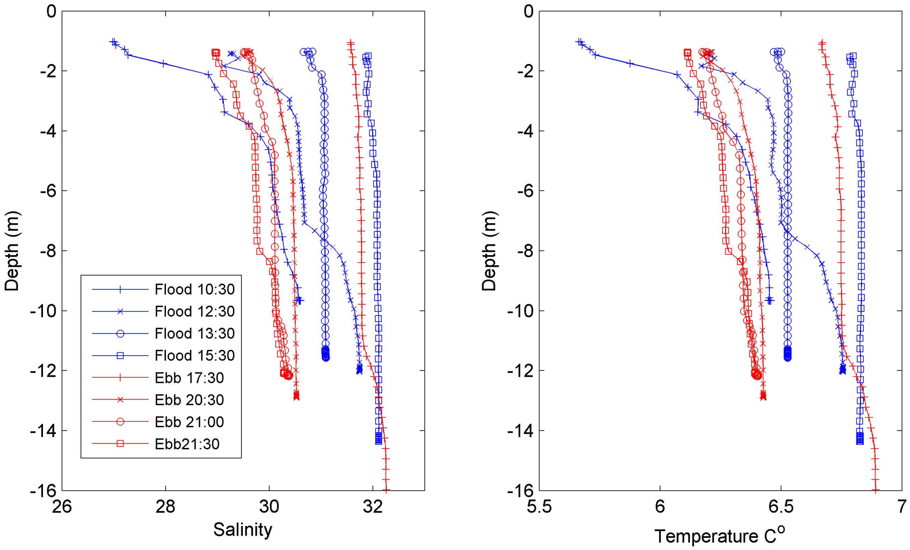

Fig. 7. Samples of salinity and temperature profiles in the Hilbre Channel during the 14 February 2008.