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Bathymetric sidescan investigation of sedimentary features in the Tay Estuary, Scotland

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Abstract. A comparison of results from mapping using a swath bathymetric sonar system in the Tay Estuary, Scotland, and remote sensing data on the position of frontal systems, indicates that the frontal systems are controlling the distribution of sedimentary features in the estuary. The boundaries between zones, defined by the advancing flood fronts and exiting fresh water, are sharply defined both by the front and the bottom bedforms. Static fronts, usually axial fronts, exist at well-defined bathymetric changes and result in relatively stable bedforms. However, measurements of current velocities at migrating fronts suggest that the vertical component of velocity accelerated at the front boundary will cause erosion at the bed and migrating bed features. Predictions of sediment movement and sediment feature migration rates across areas where these fronts migrate are confirmed by the bathymetric sidescan sonar results that show asymmetry of the sedimentary dune features. The use of new high-resolution sonar, together with its repeatable precision in locating sedimentary bedforms, has significant implications for long-term modelling of sediment transport in estuaries and other similar areas.

1. Introduction

During 2002, a wide-area habitat survey was made of the Firth of Tay, Eden Estuary and inner St Andrews Bay on the east coast of Scotland for Scottish Natural Heritage in support of a proposal to designate the area a marine Special Area of Conservation (SAC) under the EU Habitats Directive (European Community 1992). The site is proposed for the following (Annex 1) conditions: estuaries, mudflats and sandflats not covered by seawater at low tide (colonized by estuarine communities that display a transition from predominantly brackish to fully marine species), and sandbanks which are slightly covered by seawater all the time. In addition, the area also supports a nationally important breeding colony of the common seal, *Phoca vitulina*, with around 600 adult haul-outs at the site to rest, pup and moult.

As a first stage in any habitat classification, an appraisal of the physical and biological conditions must be made. The Tay Estuary forms part of the northern limits of the study and has been the focus of a number of important investigations over the last 30 years with extensive sediment analysis (Buller and McManus 1975), current modelling (Charlton *et al.* 1975), biological appraisal (Khayrallah and Jones

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1975) and more recently remote sensing studies (Anderson 1989). Many of the physical investigations have attempted to map aspects of the sedimentation patterns and relate these to physical processes within the estuary. Subsequent to a preliminary evaluation of the proposed SAC an intensive acoustic-based investigation using high-resolution swath bathymetric sidescan sonar was initiated. The focus of this paper is the result of the acoustic investigation in the Tay Estuary and the implication of the results for understanding the physical processes within the estuary.

2. Tay Estuary—environmental setting

The Tay Estuary is situated on the east coast of Scotland north of the Firth of Forth between the coastal towns of Dundee to the north, Tayport to the south, Newburgh to the west and Carnoustie to the east (figure 1). The site is an excellent example of a northern North Sea estuary with a coastline characterized by low cliffs cut into Carboniferous and Devonian Sandstones, wave-cut platforms on Pleistocene boulder clays, extensive sand dune complexes and low-lying marsh areas.

At the outer part of the estuary on the south shore, an extensive area of sand dune complexes occurs at Tentsmuir, which is one of the largest dune fields in Scotland. In the last 5000 years, approximately 4 km of seaward migration has been recorded at this site (McManus *et al.* 1980). The dunes of Tentsmuir merge into the coastline of the outer Tay Estuary with its foreshore of intertidal sand with some shingle and dunes. Further west, along the south shore of the estuary, cliffs and a small rock platform are cut into Devonian sandstone and basalts and are overlain by shingle and cobble beaches with sparsely distributed large glacial erratic boulders at the coast edge. Further west, thick mud sequences dominate the

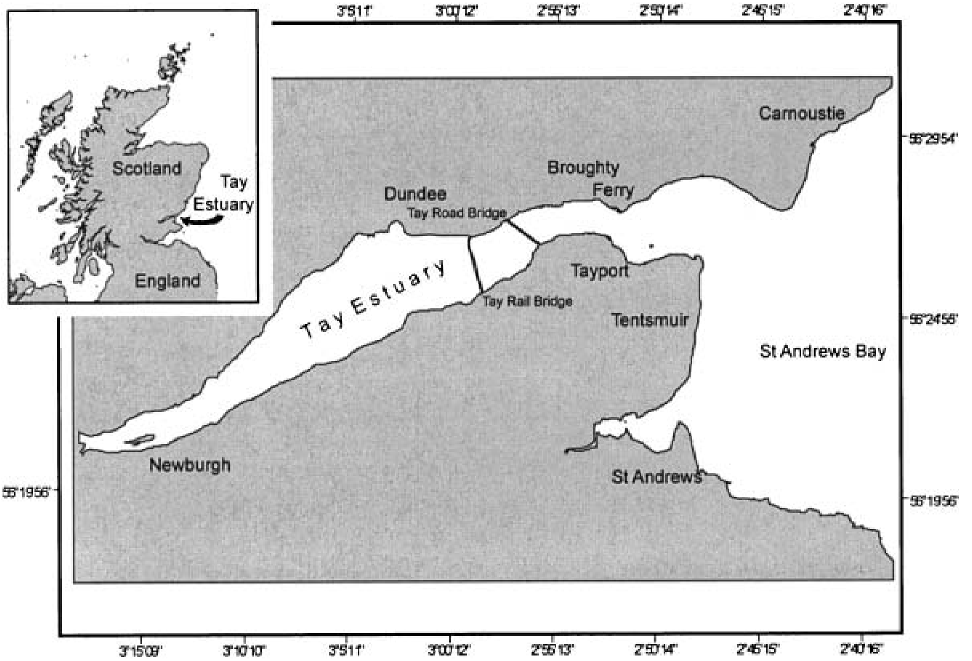

Figure 1. Location map of Tay Estuary.

coastline with shingle bars extending to the low water mark. Raised beach deposits with glacial sands and shingles occur around Newburgh. Marsh deposits stabilize the thick alluvial muds that have accumulated west of here and the north shore of the estuary has been further stabilized by the planting of extensive reed beds over the last 200 years. The shoreline along the north bank of the Tay has been protected from erosion between Invergowrie to the east and Broughty Ferry to the west. To the east, discontinuous mussel beds characterize the large expanse of shallow foreshore in Monifieth Bay. Another significant dune sequence at Buddon Ness compliments that at Tentsmuir. However, movement of these dunes has been restricted over the last 20 years by revetment protection schemes on the east shore.

The Tay Estuary is long and narrow and runs for approximately 42 km from the confluence of the rivers Tay and Earn in its south-west corner to the Tentsmuir sandbanks in the east. The estuary has been classified as a partially mixed type with moderate tidal range (Williams and West 1975). The Tay is Scotland's largest river, discharging an average daily flow rate of $198\,\mathrm{m}^3\,\mathrm{s}^{-1}$. The River Tay is the firth's main source of fresh water and is joined by the River Earn; between them they drain approximately $6500\,\mathrm{km}^2$ of land and account for 95% of the fresh water input into the firth. Large intertidal sediment flats with mid-channel sandbank complexes border the firth's channel for most of its length. At the mouth of the firth, two large sand flats and shoals extend to the east with the Abertay Sands on the south shore measuring approximately 6 km in length. The maximum depth of the channel is 32 m at Broughty Ferry. However, depths for most of the channel range from 2 to 20 m, and the water quality is good although with high turbidity. The inner parts of the Tay are largely sheltered from wave action; however, outer areas of this system are exposed to strong tidal currents and strong wave activity. The distribution of sediments within the site, together with the gradients of exposure and salinity, has a major influence on the biological communities associated within this high-quality estuarine habitat.

3. Current patterns and frontal systems

The main tidal influence in the Tay Estuary is produced by an amphidromic system centred off the south-west of Norway. The dominant anti-clockwise wave action in this system produces a southward moving tidal wave that travels south to meet with a secondary, and more southerly, system seaward of the Firth of Forth. The tidal systems, together with bathymetric and coastline profiles, cause a difference between offshore tidal currents and estuarine tidal currents in the Tay area that result in complex circulation patterns and variations in current strengths at different tidal states. The mean tidal ranges at Dundee are 3.5 m, 5 m and 6 m for neap, spring and equinoctial tides, respectively, with a tidal prism volume of $286\times10^6\,\mathrm{m}^3$ on spring tides (Charlton *et al.* 1975). The strength and direction of the tidal currents in the estuary are strongly controlled by the large shallow mud flats and sand banks. In addition, the maximum height of the tide levels can be increased by up to 2 m due to westerly winds between the outer Tay and Newburgh. Maximum tidal velocities of $1.9\,\mathrm{m\,s}^{-1}$ have been recorded on the spring ebb and flood in the channel narrows to the west of Broughty Ferry. It has been estimated that up to 60% of the volume of the Tay Estuary ebb flow is exchanged with the sea each tidal cycle and that full exchange would be achieved after five or six tides (Charlton 1980).

Numerous recent studies of the Tay Estuary noted the significant influence of tidal fronts in the mixing of waters over tidal cycles (Anderson and Ferrier 1997, Ferrier and Anderson 1997a, b, McManus *et al.* 1998, McManus 2000). Tidal fronts are created at the mixing boundary between fresh water and saline water. Not only are there salinity, density and temperature contrasts across the front, but also they are usually observed at the sea surface by a foam and debris trail. The foam and debris trail is typically located behind the advancing denser salt water flood, and the front can exhibit a significant angle with the salt water intruding beneath the fresh water. Alternatively, the foam and debris trail may be located directly above the water boundary where there is significant shear and where the water bodies are moving parallel to each other. Thus, fronts are controlled by the dimensions and shape of an estuary, the rate of inflow of fresh and saline water and the amount of turbulent stirring. Lateral shear is an important element in maintaining fronts where strong bathymetric changes, such as exist in the Tay Estuary around the many large sandbanks, have a significant control on the fronts. A number of significant fronts were first recognized in the Tay Estuary by Anderson and Callison (1987) using thermal radiometry from aircraft. Later, Anderson (1989) showed that typically five or more fronts could be recognized across the estuary. The dominant fronts that have been consistently noted include lateral axial convergent fronts, tailed axially convergent fronts and longitudinal fronts. Longitudinal fronts have been studied in some detail in the Tay Estuary and are thought to exist as a result of rapid bathymetric changes between deep channels and shallow sandbanks (Anderson and Ferrier 1997). Tailed axially convergent fronts form as the longitudinal fronts, which have developed from the marginal waters sweeping off the tidal flats on either side of the estuary, meet in the narrows and migrate up the estuary with the rising tide (Ferrier and Anderson 1997a). The influence of the bathymetry has been further confirmed by recent current and density data collected across fronts in the estuary that suggest that the fronts are mainly driven by inertia due to flow over the sandbanks rather than by buoyancy forces (Neill *et al.* 2000).

The significance of fronts as a control on bedform character in the estuary has been shown by Wewetzer *et al.* (1999b) who noted that the location of fronts can be correlated with different ripple and dune sizes identified by sidescan sonar surveys between the road and rail bridges. McManus (2000), however, noted that only longitudinal fronts give rise to sedimentation in the form of channel parallel sandbanks, but that cross-channel fronts associated with the migrating saline wedge were not believed to give rise to substantial deposition.

4. Acoustic mapping of bedform features

Acoustic methods for marine surveying have developed significantly since the 1940s (Fish and Carr 1990). However, significant progress in high-resolution near-shore surveying has only been made relatively recently with the increased power and decreased cost of personal computing (Bates and Byham 2001). In the Tay Estuary, acoustic techniques have been used since the 1960s to map bathymetry for navigation purposes and also to map sediment features, such as the sand dune systems and sand banks. Early studies using continuous trace echo sounders showed that over large parts of the estuary the bed was covered with ripples, sand waves and sand dunes of various dimensions (Buller and McManus 1975). However, information on the spatial distribution of these bedform features was limited until the use of side-looking (or sidescan) sonar became readily available. Although these sonars provided far more detail of sediment bedform distribution, they were of limited range, and it was difficult to precisely locate the images on the estuary bed. A number of very useful studies using sidescan sonar were conducted between the rail and road bridges, where the results from intense survey line spacings were used to recognize a number of small to large dune features with abrupt linear boundaries between different dune fields (Wewetzer 1997, Wewetzer *et al.* 1999a). Furthermore, whereas these studies were conducted at different stages of the tidal cycle, Wewetzer *et al.* (1999b) recognized areas where bedforms were asymmetric with either flood or ebb dominance throughout the tidal cycle and areas where the asymmetry changed with the tidal cycle. These studies also measured flow velocities within the estuary and concluded that the mean or maximum velocities were not the dominant factor controlling dune formation, rather the crucial factor was the length of time a flow was above a threshold for dune development, estimated by Dalrymple and Rhodes (1995) as $0.5\,\mathrm{m\,s^{-1}}$. In addition to studies of bedforms in the estuary, some early work also focused on the sub-bottom sequences using acoustic sparker records to show how the meandering early Tay River carved out the original valley. These findings were substantiated by McManus *et al.* (1980). Green (1975) used acoustic pinger data to show the internal structure of sand waves near the mouth of the estuary. Such sub-bottom information is critical when making an evaluation of sediment dynamics within the estuary, as knowledge of the sediment volume is necessary in all sediment bedform movement calculations.

Over the last five years, a new generation of digital sidescan sonar and swath bathymetric sidescan sonar have become available for near-shore surveying. These new sonars not only provide very detailed images of bedforms but can also provide quantitative information about the features and their locations. The use of these sonars to link bedform features to previous work on current and frontal systems was the focus of this research. The bathymetric sidescan is an extension of high-resolution digital sidescan that not only enables a picture of the seafloor to be produced across a swath sampled by the transducers along the boat track, but also measures the bathymetry across the swath through the use of multiple transducers (figure 2(*a*)). Each transducer, and its associated swath, contains many hundreds of reflection data points from the seabed. With pulse repetition rates of three to five times a second, this results in surveys with often millions of bathymetric data points. The method has found widespread application for mapping large swaths of gently undulating seafloor as the width of each swath is approximately seven times the depth of water to the transducers (Bates and Byham 2001).

5. Acoustic data acquisition and processing

The bathymetric sidescan system used for this survey was a Submetrix System 2000 (Bates and Byham 2001) with 117 kHz hull-mounted transducers (figure 2(*b*)). These were deployed together with a motion reference unit (0.05° TSS-DMS05 by TSS, Inc. Watford, Hertfordshire, UK) connected to a differential global positioning system (dGPS MAX by CSI Wireless Calgary, Alberta, Canada). This combination of instrumentation allows features on the seafloor to be mapped with 100% coverage at a vertical resolution of 30 cm or better. This is of particular relevance for habitat mapping and long term monitoring of sediments in dynamic environments such as the Tay Estuary. A further advantage of the technique is that the amplitudes of reflection strength or 'sidescan-like' images can be measured coincidently to the bathymetric data points. The amplitude data can then be used as an overlay to the bathymetry to map the position and spatial distribution of seafloor features with amplitude strength referenced to known features on the seafloor. In the field, the acoustic acquisition systems were also linked via a local area network to a separate computer for navigation charts

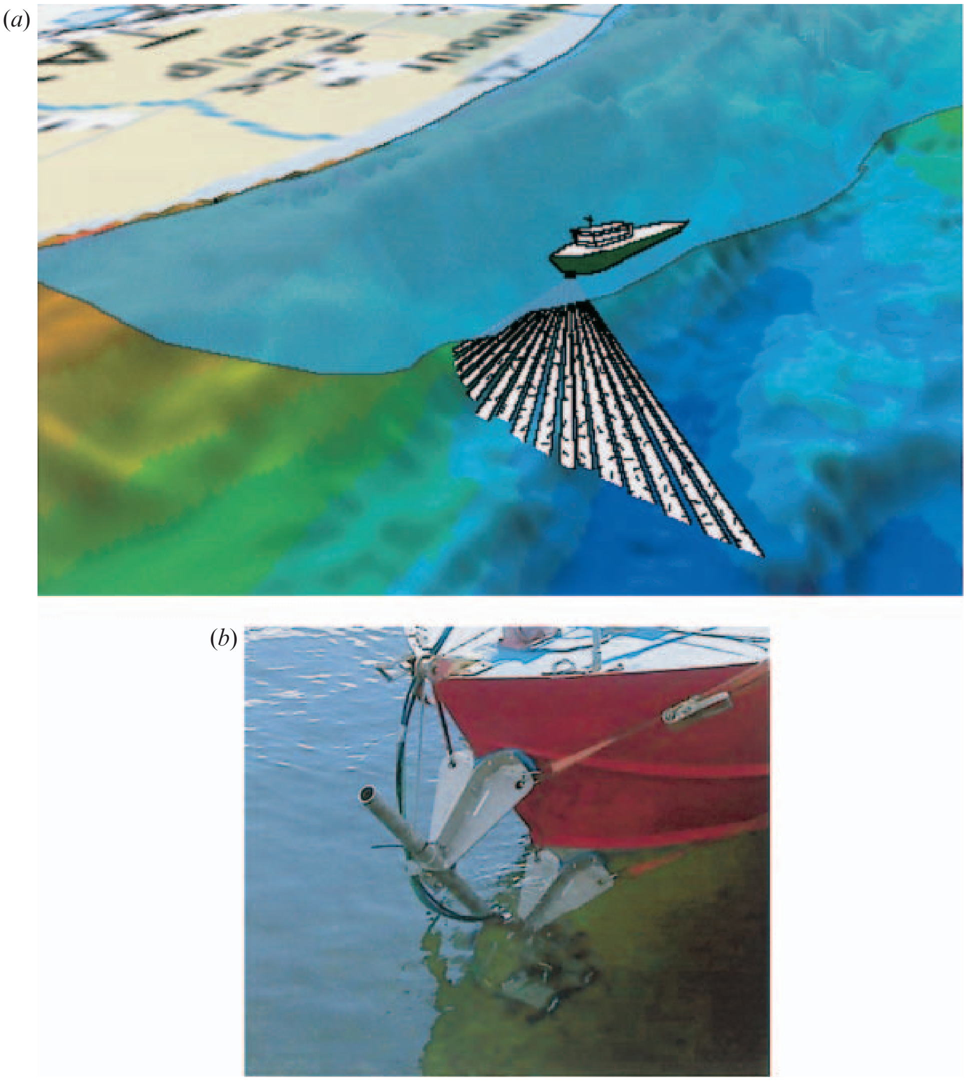

Figure 2. (*a*) Schematic representation of acoustic surveying using a bow-mounted swath bathymetric sidescan sonar. (*b*) Photograph of a bow-mounted bathymetric sidescan sonar.

provided through the HyPack navigation software (HyPack by Coastal Oceanographic, Inc., Middletown, CT, USA).

Acoustic survey work on the estuary was conducted during July and August 2002. Survey lines were spaced at 100–200 m intervals with additional infill lines along the coastlines, around moorings and near the bridges. Acoustic surveying was only accomplished where the water depths were greater than 3 m, as at depths shallower than this the accuracy of measurements diminishes and swath widths are greatly reduced. However, the results of the survey reported here are limited to the region between the rail bridge and the outer estuary along the main channel as this is the area that has received most previous attention and, thus, where most data for frontal movement and current velocities exist. The survey was conducted at all states of the tide with tidal corrections in the final bathymetric analysis provided by measurements from Dundee Port, Admiralty tables for 10-minute intervals and tidal predictions for different parts of the estuary from Buller and McManus (1975). Prior to surveying, the bathymetric sidescan system was calibrated for transducer offsets, roll, pitch, yaw and heave values on a relatively flat sea bed area. In the field, all survey data were recorded onto magneto-optic tape drives for subsequent playback and processing.

In addition to the bathymetric sidescan survey, a number of low frequency acoustic profiles were acquired through the major sand dune sequences using an ORE sub-bottom profiling system. This system used 3 kHz frequency transducers to penetrate approximately 15 m beneath the seabed. The analogue system was deployed in a towed configuration close to the survey vessel. A chart recorder was used to preserve the sub-bottom profiles on paper in the field.

Acoustic data processing first included separation of the bathymetric and sidescan signatures. The bathymetric data was processed using RTS2000 (SEA (Group) Ltd, Frome, Bath, UK) and included correction for water velocity variations and transducer configuration, editing of spurious data points outside of acceptable depth boundary limits (shallower than 3 m and deeper than 35 m) and final output to a gridding routine. Two grid resolutions were chosen for making general survey charts of the estuary and for analysing the sedimentary bedforms. The former grid bin size was set at 5 m while the latter bin size varied depending on the data density at specific places within the estuary. Processing of the sidescan information was accomplished using SonarWeb Pro (Chesapeake Technology Inc., Mountain View, CA, USA) and included geometrical correction and amplitude adjustment for offset angles from the transducers. In particular, SonarWeb Pro uses amplitude corrections to the amplitude time series, based on the work of the United States Geological Survey (USGS) (Danforth 1997). Nadir was removed using bottom tracking algorithms, with manual adjustment in areas of rapidly changing bathymetry. The final lines were projected onto the relevant datum (OSGB36) for individual analysis. An attempt was made to mosaic the sidescan data. However, this did not prove to be possible as it was found that the different angels, or views, of insonification from different passes with the sonar created shadows in contradictory positions between runs. This is a common problem with attempts to mosaic sidescan sonar records where it is necessary only to mosaic data that has been acquired in one direction. Final output for the sidescan data was in the form of geo-referenced images which were superimposed on the bathymetry.

Analysis of the acoustic survey results was made using the ArcView (ESRI) Geographical Information System (GIS). The use of a GIS facilitated comparison not only of new data but also with historical data. Further analysis of the bedforms was accomplished using Fledermaus (IVS) 3D visualization software.

6. Sediment sampling

During the acoustic survey, a number of sediment samples were taken using Van-Veen grabs and bottom trawls for comparison with the previous sediment studies by Buller and McManus (1975) and McManus *et al.* (1980). The sediment samples were subsequently processed in the laboratory using both manual sieving techniques for grain sizes greater than 2 mm and automated techniques using a laser diffraction particle analyser for grain sizes less than 2 mm. The combined results were statistically analysed to give values for median grain size, mean grain size, standard deviations and sorting.

7. Acoustic results

A 3D map of the bathymetry for the main estuary channel is shown in figure 3(*a*). The main channel follows the south shore from the outer Tay to Broughty Ferry where it swings to the north shore. Numerous shallow sand banks are shown, with many of these exposed or partially exposed at low tide. The narrows between Tayport and Broughty Ferry result in a deepening of the channel to a maximum depth of 32 m caused by increased flow velocities (Buller *et al*. 1972). Sediments in this area are dominated by coarser material and mussel beds with average flow velocities inferred to be too high for dune formation. Two areas of bathymetric detail, where significant bedforms have developed, are highlighted in figure 3(*a*). Where the main channel swings to the north, large sand dunes were mapped with amplitudes of up to 5 m and wavelengths of 50–200 m. An oblique view of these is shown in figure 3(*b*). A cross-section through these features, running from the road bridge towards Broughty Ferry, is shown in figure 4(*b*). In this figure, the asymmetric nature of the dunes is demonstrated with lee faces orientated to the west and stoss faces orientated to the east, indicating a flood tide dominance. In figure 4(*c*), an example record, from the sub-bottom profiler through the sand dune, shows the internal structure of a large dune (amplitude 5 m) and also shows smaller, less than 50 cm amplitude, dunes superimposed on the major dunes. A second area to the south of the main channel (figure 3(*c*)) shows smaller sand waves with

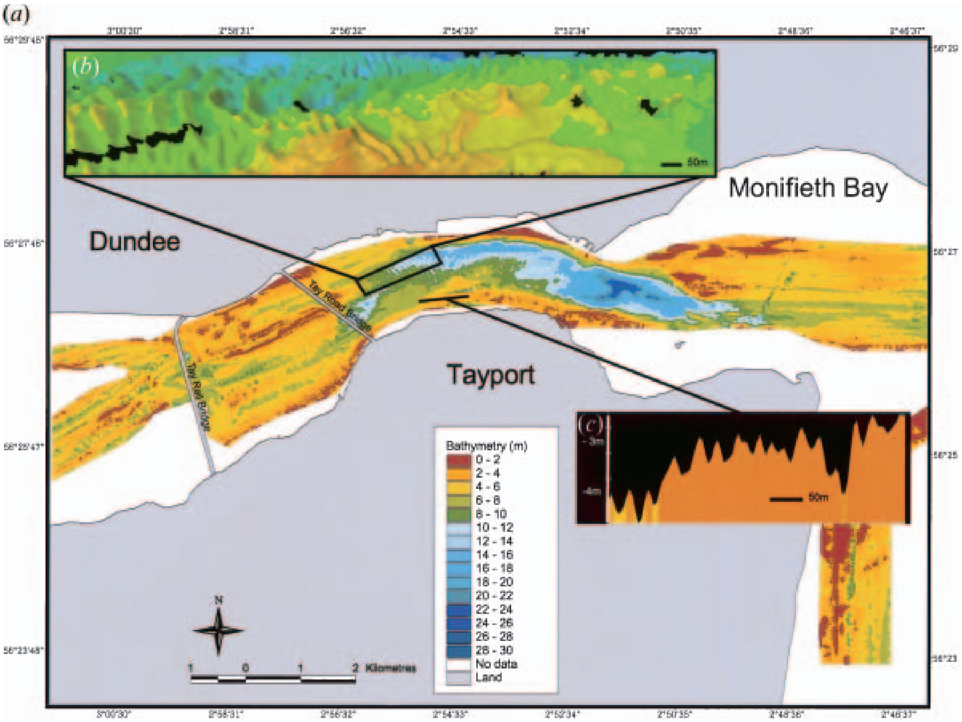

Figure 3. (*a*) Bathymetric map of middle Tay Estuary, showing the Tay road and rail bridges. (*b*) 3D view of large sand waves in the middle to north shore of the Tay Estuary south of Dundee. The black areas are those where no data were obtained due to obstructions in the channel. (*c*) Cross-section through sand waves on the south shore of the Tay Estuary near Tayport.

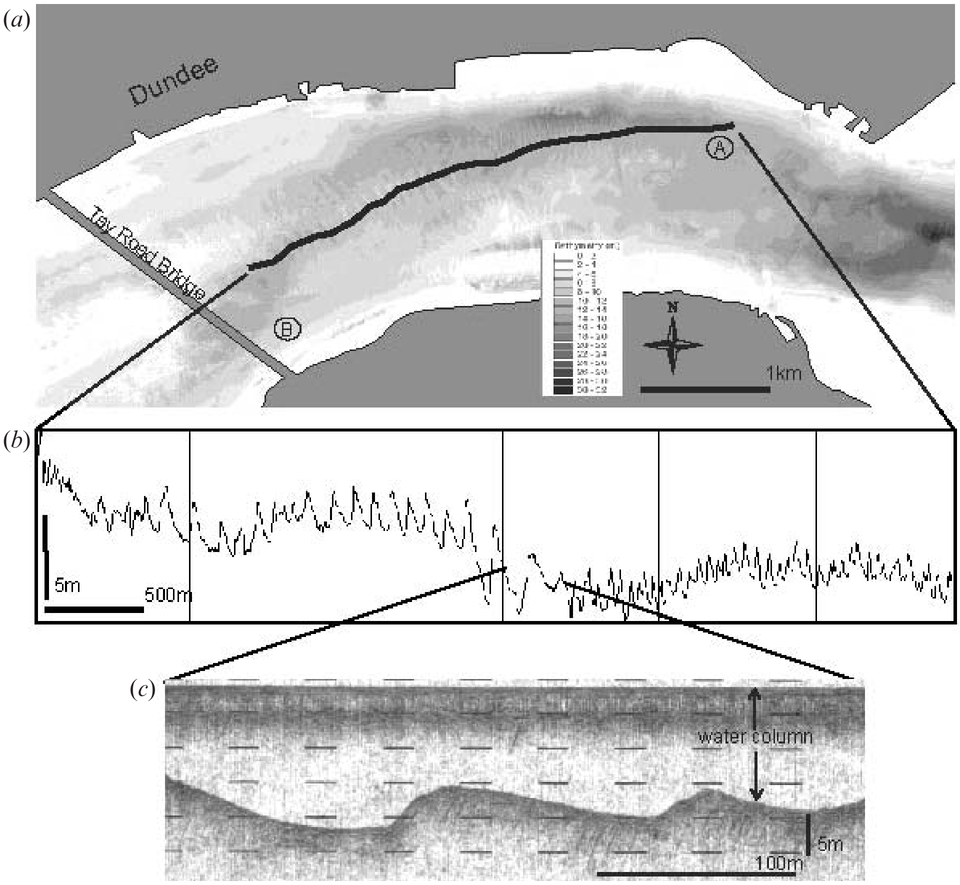

Figure 4. (*a*) Bathymetric map of sediment structures to the east of the Tay Road Bridge, showing locations of current velocity measurements, A and B. (*b*) Cross-section through sand waves along the central channel of the Tay Estuary showing asymmetry of flood dominated sandwaves. (*c*) Sub-bottom cross-section through the largest sandwaves.

amplitudes of 1–2 m and an asymmetric direction reversed to the dunes on the northern side of the estuary, indicating ebb tide or river flow dominance.

The results of the sedimentary grain size analysis were plotted together with the extensive datasets presented by McManus *et al.* (1980) and demonstrate that for the areas studied there has been little change in overall sediment distribution over the last two decades. The GIS was used to combine the results of grain size and bedform distribution into a map of sediment features (figure 5). Several different categories of bed type were identified based on grain size, bedform size and bedform orientation. Areas identified on this figure with 'sub-bathy resolution' refer to those locations where the scale of sedimentary bedforms was either too small to be mapped as individual features or the features were small enough to be moved on each tidal cycle.

8. Sediment analysis

The size of sedimentary features, such as sand waves, has been correlated with water depth by a number of researchers and much of this work is summarized by

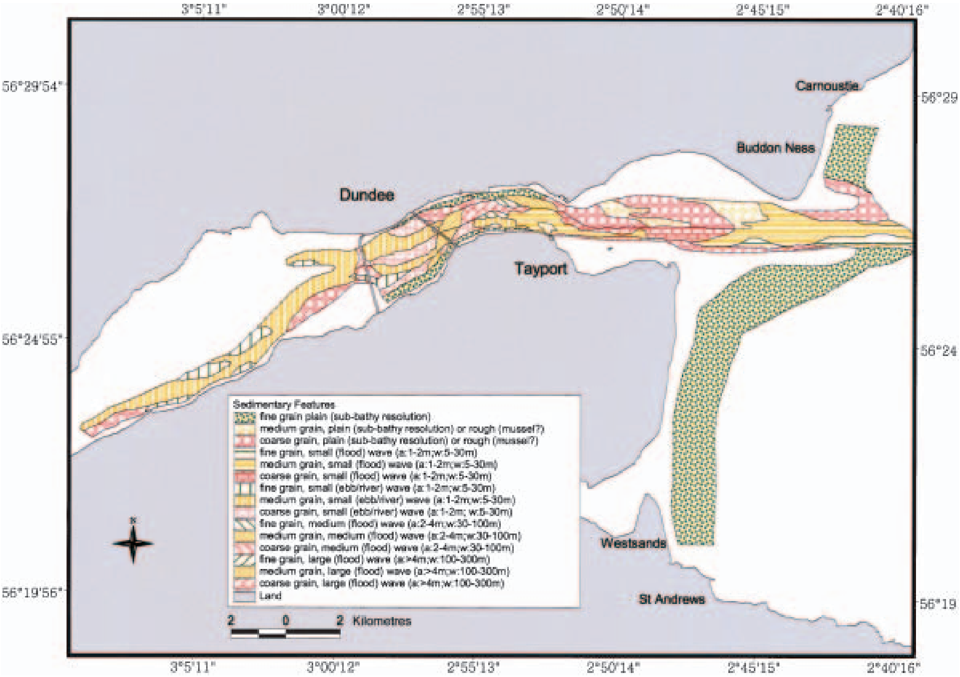

Figure 5. Classification of sedimentary structures and sediment grain size from the bathymetric sidescan sonar results.

Flemming (2000). His study demonstrated that the dimensional parameters of height and spacing of sub-aqueous flow-traverse bedforms, such as those found in the Tay Estuary, define a highly correlated exponential relationship for the global situation with variations based on prevailing local conditions. Local conditions that cause perturbations of the global trend were cited as changing flow depths, frontal systems and storm wave action. In depth-limiting flow conditions, dune height and water depth are inherently correlated. The results of over 260 measurements of sand wave height were calculated from the Tay Estuary bathymetric maps and plotted against the global curves derived by Flemming (2000). The resultant curve is shown in figure 6 together with those for Flemming (2000) and Allen (1968). A correlation coefficient for the Tay of 0.5 was calculated. Although this is not high, it compares favourably with many studies in the literature, where correlation coefficients are typically in the range 0.3–0.6.

Flemming (2000) also reported on the upper limit dune size as a function of grain size with respect to wavelength. For the Tay, most of the sedimentary features that were measured with the bathymetric sonar fall into the dune category of Flemming (2000); however, the results from this study show a clear relationship with large sand waves within coarser grain size sediments. Thereafter, as the sediment grain size increases to cobbles and boulders, the size of the sand waves does not increase because it becomes difficult for the average energy (velocity) of currents within the Tay to move this material.

9. Front movement

A number of studies have been made of the frontal systems in the Tay Estuary with the most recent work conducted using airborne imagery and mathematical

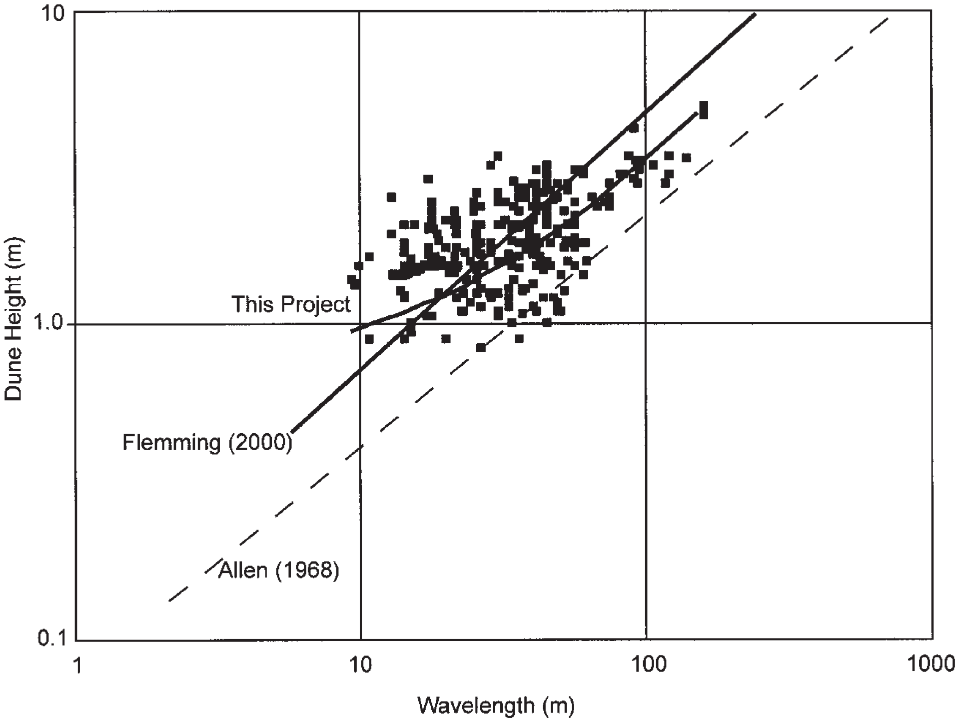

Figure 6. Relationship between dune height and wavelength for information taken from the bathymetric sidescan data together with results reported by Flemming (2000) and Allen (1968).

modelling by Ferrier and Anderson (1997a, b). Their work clearly demonstrated the complex tidal mixing within the estuary and throughout the tidal cycle. The orientation, location and relatively short timescale for the formation and decay of the fronts suggests an origin related to intratidal and lateral salinity balances. During the flood tide, saline water enters the estuary dominantly along the north side with floodwater cascading over the shallow flats of Monifieth Bay; along the southern shore, discharge of the fresh water from the Tay continues. As tidal flooding continues, the fronts move up the estuary with the contrast in waters between the incoming salt water and the freshwater discharge causing a series of ‘Y-shaped’ fronts on the rising tide. The progress of these fronts over the middle section of the Tay Estuary is shown in figure 7 at 5 h before high tide (from satellite images from this study), 2.5 h before high tide, 1 h before high tide and 10 min after high tide (from Ferrier and Anderson 1997a). The fronts marked on this figure represent the position of the surface foam lines that are usually some distance behind the denser saline wedge of bottom water travelling up the main channel. The front moves into the estuary at a velocity similar to the rising tide (1–1.5 $\mathrm{m\,s^{-1}}$). On a large spring tide, these fronts can reach beyond the Tay rail bridge; but on smaller neap tides, they more commonly turn between the bridges. In figure 8, the fronts are superimposed on a summary of the bedform features for this part of the estuary. In this figure, the sizes of bedforms are not shown, but the asymmetry is indicated. A correlation can be seen between the bedforms and the position of the fronts in the estuary. A major Y-shaped front sweeps along the main channel with the largest

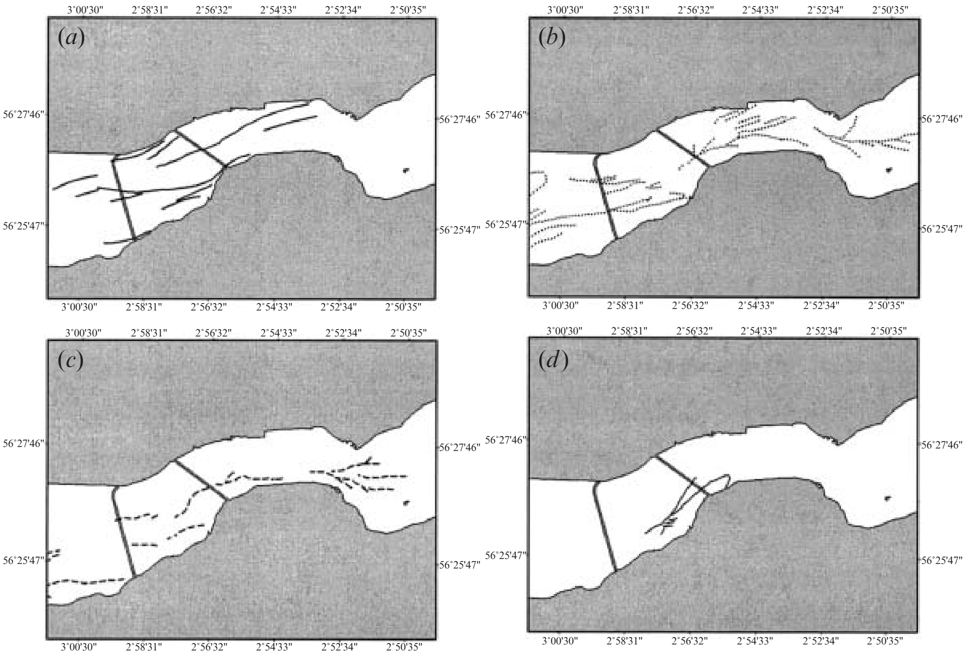

Figure 7. Frontal systems showing the progress of the intruding saline wedge into the Tay Estuary. (*a*) 5 hours before high water. (*b*) 2.5 hours before high water. (*c*) 1 hour before high water. (*d*) 10 minutes after high water (from Ferrier and Anderson 1997a, b).

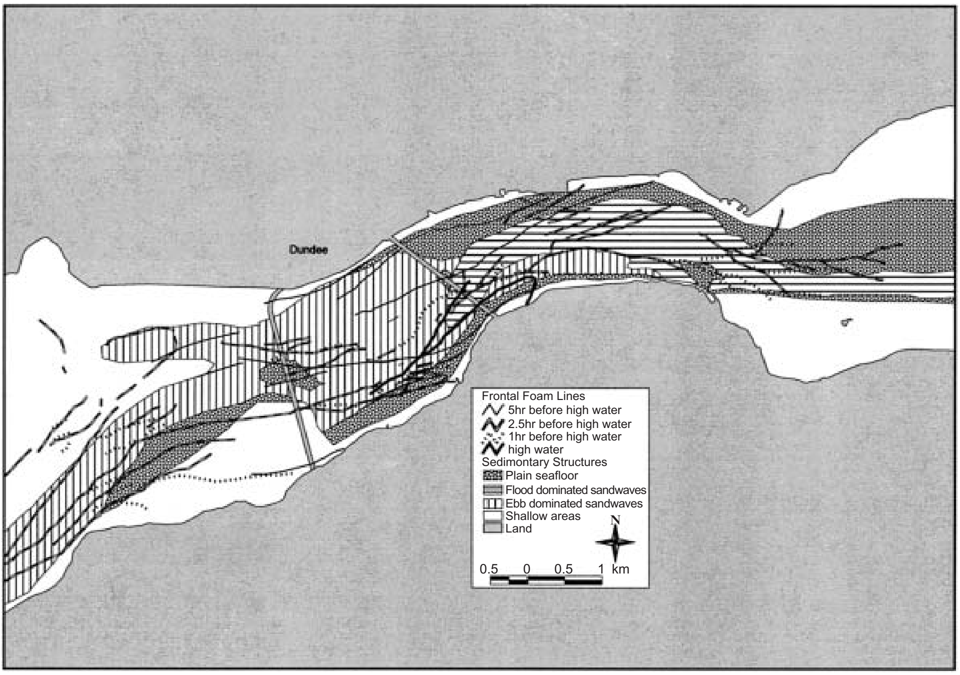

Figure 8. Sedimentary features summarized from the bathymetric sidescan survey superimposed with frontal systems taken from Ferrier and Anderson (1997a, b).

flood bedforms formed to the north side of the frontal system in the coarse to medium grain size sediment of the main channel. On the south side of the main front, the frontal foam line remains relatively stable throughout the flooding tide, and the river dominated bedforms persist over the shallow areas, where there is less mixing of the denser saline water with the fresh water. Between the bridges, the river water and ebb currents dominate over the medium grain sand, with flood sand waves only seen in the main channel. West of the rail bridge, no further flood waves are recorded with the bathymetric sidescan at this scale of resolution. It must be remembered, however, that the minimum repeatable, recordable feature with the bathymetric sidescan system in the current study was 50 cm, even though the resolution of the system is less than this. Features smaller than 50 cm were seen on the sidescan data, and information from individual bathymetric sidescan swaths showed that it will be possible, in the future, to measure these on a wider area survey. One goal of future work will be to map these smaller features. However, it is likely that these smaller features are more mobile and influenced by the flood/ebb state of the tide over much greater areas of the estuary than the larger sedimentary waves and dunes described here.

10. Discussion

Knowledge of the movement and distribution of sediments within a dynamic system such as the Tay Estuary is important for any sub-aqueous engineering work, habitat study or environmental assessment. In order to make estimates of sedimentary feature migration rates, information about the driving forces (currents and frontal systems), physical setting (bathymetry) and material properties (grain size and type) is necessary. This study has provided much of the vital information needed to make the migration estimates; however, it did not independently record current strengths in the estuary. Rather, these values were taken from the previous studies by Buller *et al.* (1972) and McManus *et al.* (1980). Current velocities over full tidal cycles at two specific sites (location A and location B, figure 4) in the central main channel are presented here. Velocities were extracted at 0.5 m above the bed surface, which is inferred to approximate the velocity at a grain size level, where bed load transport will be initiated (Middleton and Southard 1984). Following the method of Sternberg (1972), a critical flow velocity needed to initiate bed load transport of $0.44\,\mathrm{m\,s^{-1}}$ was calculated using the velocities and the measured median grain size. From the current velocity measurements, it was seen that at station A this velocity was attained for 5 h on the flooding tide but only 3.5 h on the ebbing tide, whereas at station B the velocity was attained for 4 h on the flood tide and 4.5 h on the ebbing tide.

In order to calculate sediment movement, following the work of Wewetzer (1997), a graphical method based on the modified Bagnold equation (Sternberg 1972) was used to estimate bed shear stress, volumetric sediment transport and critical shear stress. The results of the sediment transport calculations per tidal cycle for each area are shown in table 1. The celerity, or velocity, of sedimentary feature migration was calculated for site A alone, as it was only at this location that sufficient information was known on the sedimentary feature volumes (amount of sediment above glacial till) from cross-sections with the sub-bottom profiler (figure 4(*c*)).

The dynamics of current and sediment movement in complex estuaries, such as the Tay, are difficult properties to measure on a wide area basis. However, knowledge of these is vital for the management of sediment transport in the estuary,

Table 1. Migration rate and sediment transport per tidal cycle for locations A and B. Negative values indicate net transport in ebb direction.

Location	Tidal state	Dune migration rate (m yr^{-1})	Sediment transport per tidal cycle (kg m^{-1})
Area A	Flood	75.74	213.1
	Ebb	47.96	134.8
	Net	27.78	78.3
Area B	Flood		5.1
	Ebb		177.5
	Net		−172.4

in particular for maintaining the dredged port access channel. Sediment movement is also important to studies of certain types of pollution migration and habitat preservation. In the Tay Estuary, the influence of fronts has been shown to be of major importance in sculpting the physical setting. Along frontal systems, Brubaker and Simpson (1999) and Wewetzer *et al.* (1999a) have demonstrated that vertical current velocities in the vicinity of the front are accelerated compared to the horizontal components, thus enabling downward cutting scour of pre-existing bedforms where the bedforms contain sediment particles that are within the mobility range for the maximum current velocities. Where fronts are static, for example along the longitudinal frontal system separating the ebbing fresh water and advancing saline water that exists on the south side of the estuary where bathymetry rapidly shallows, the bedforms will be stable. In order to make a full evaluation of the influence of the increased velocities associated with migrating fronts, one would require the recording of current velocities on all states of the tide over the entire estuary in 3D. While the technology is available today to economically record 2D current profiles using Doppler current meters, the logistics and costs of doing this exercise in 3D is prohibitive. The new generation of bathymetric sidescan sonars have demonstrated their ability to quantitatively record small bathymetric changes and image very small bedform features with precise position fixing. Furthermore, the spatial resolution (both horizontal and vertical) of seafloor mapping systems is continually being improved upon with the latest multibeam sonar capable of measuring centimetre-size features. The utility of these technologies was demonstrated in this study by the confirmation of sediment bedform migration rates at locations where the bathymetric sidescan showed flood dominated or ebb dominated asymmetric bedforms. Thus, it is proposed that these techniques can be used to measure properties of a sedimentary system that results from front positions and front movement in an estuary, thereby aiding in our understanding of dynamics of frontal systems. The use of GIS for integrating data and comparing results from different types of measurements was also very valuable in this study.

In this survey, there appeared to be a lower limit of bedform size that could be imaged by the bathymetric sidescan system of approximately 30 cm amplitude. Whereas bathymetric sidescan, and certainly many of the highest resolution multibeam systems, are capable of mapping smaller bedform features, great care must be taken in mapping them as it is likely that features of this scale are moving in the Tay Estuary with each tidal cycle. It would be difficult, therefore, to produce a mosaic map of these features if this map were produced from individual surveys taken at many different states of the tide.

Our present understanding of bedform migration and physical changes during a tidal cycle, or longer time period, is still somewhat limited, either through constraints imposed by laboratory flume studies or by imprecise field investigations. The net sediment transport rates calculated in this study compare favourably to earlier studies in the Tay Estuary. For example, Wewetzer (1997) calculated an ebb-dominated sediment transport volume between the rail and road bridges at approximately $220\,\mathrm{kg\,m^{-1}}$, and this study found values of approximately $172\,\mathrm{kg\,m^{-1}}$. Numerous investigations have measured dune migration rates in various settings, and Dalrymple and Rhodes (1995) postulated a general inverse relationship between dune height and migration rates. The limited data for the larger westward migrating dunes calculated in this project would appear to follow this general relationship; however, more data are needed in order to calculate total sediment budgets for the estuary. Nonetheless, this study has shown the potential for using very high-resolution acoustic measurements to record bedform features that can be related to current and frontal movement. Thus, in the future, it may be possible, through repeat or time-lapse studies, to monitor the migration of the smaller bedforms, thereby increasing our understanding of the persistence of bed sediment transport pathways along which preferred sediment migration occurs. This type of information is vital for making pollution studies and for the long-term management and preservation of Special Areas of Conservation.

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