Monitoring the generation and evolution of the sediment plume behind towed fishing gears using a multibeam echosounder

F. G. O’Neill1*, S. M. Simmons2, D. R. Parsons2, J. L. Best3, P. J. Copland1, F. Armstrong1, M. Breen1, and K. Summerbell1

1Marine Scotland Science, Aberdeen AB11 9DB, UK
2Department of Geography, Environment and Earth Science, University of Hull, Hull HU6 7RX, UK
3Departments Geology, Geography and Geographic Information Science, Mechanical Science and Engineering, and Ven Te Chow Hydrosystems Laboratory, University of Illinois, 1301 West Green Street, Urbana, IL 61801, USA

*Corresponding author: tel: +44 1224 295343; fax: +44 1224 295511; e-mail: b.oneill@marlab.ac.uk


We compare optical and acoustic-based measurements of sediment concentration in plumes behind the otter door of a demersal trawl and behind the roller clump of a demersal twin trawl. Measurements were made using a LISST 100X and a RESON 7125 multibeam echosounder (MBES), and we demonstrate how the MBES can be used to reliably monitor and quantify the evolution of sediment plumes in the wake of towed demersal fishing gears. The MBES data detail the spatial and temporal decay of the plume size and the concentration behind the gear and also reveal significant differences in the behaviour of plumes in the wake of different fishing gear components. The results highlight the importance of being able to measure and understand the processes at work at the level of the individual gear components and also detail the range of conditions over which an acoustic-based MBES technique can be applied to monitor such dynamics and to assess the impact of fishing on the seabed and on the marine environment.

Keywords: multibeam echosounder, particle-size distribution, sediment mobilization, towed fishing gears.

Introduction

In recent years, concerns have been raised about the effects of towed demersal fishing gears and their impact on benthic organisms and habitats. Many studies have been conducted and a number of reviews have been published on the biological and environmental impacts of these gears (Jennings and Kaiser, 1998; Auster and Langton, 1999; Hall, 1999; Kaiser et al., 2002; Løkkeborg, 2005). An improved understanding has also been developed of the physical interaction of these gears with the seabed and the mechanical processes that can lead to the modification and alteration of the benthic environment. On soft sediments, these physical interactions can be classified broadly as being either geotechnical or hydrodynamic in nature: penetration and piercing of the substrate, lateral displacement of sediment, and the influence of the pressure field transmitted through the sediment can be considered geotechnical (e.g. Ivanović et al., 2011), whereas the mobilization of sediment into the water column can be considered hydrodynamic (e.g. O’Neill and Summerbell, 2011).

The mobilization of sediment by towed demersal fishing gears has been related to the release of nutrients, benthic infaunal mortality, and the resuspension of phytoplankton cysts and copepod eggs (O’Neill and Summerbell, 2011; Brown et al., 2013). At the fishery level, and in a range of environmental and ecological settings, the impact of towed demersal fishing gears remains poorly quantified and, as a result, poorly controlled. Hence, to gain a more in-depth understanding of the broader environmental and ecological implications of demersal fishing, it is important to be able to estimate accurately the amount of sediment put into the water column by these gears. The mechanisms of sediment suspension produced by gears are discussed by O’Neill and Summerbell (2011) who describe how the interaction between towed fishing gears, the seabed, and the ambient water produces regions of sediments...
high velocity, high shear-bed stress, and high turbulence, all of which contribute to the mobilization of sediment around and behind the gear components close to the seabed. As described by Ivanovic et al. (2011), the demersal otter door is designed to hydrodynamically spread the mouth of a trawl and to have sufficient weight to ensure that the trawl gear maintains contact with the seabed. The roller clump of a demersal twin trawl is designed to distribute the towing force of the central warp between the two gears of a twin trawl and again have sufficient weight to ensure that the gears maintain contact with the seabed. O’Neill and Summerbell (2011) have recently shown how the mass of sediment entrained in the wake of a specific gear component is related to the hydrodynamic drag of the component and the type of sediment over which it is towed. Further investigations, however, are required to examine in detail the processes and extent of sediment mobilization behind such gears.

A number of authors has made measurements of the sediment in the wake of towed gears using a range of optical, acoustic, and direct sampling techniques. Black and Parry (1999) used optical backscatter sensors to measure turbidity, and electric water pumps to collect time-integrated plume samples, behind “Peninsula” scallop dredges in southeastern Australia. O’Neill et al. (2008) measured particle-size distribution and concentration in the wake of scallop dredges in the west of Scotland using a LISST 100X (where LISST stands for laser in situ scattering and transmissometry). Pranovi et al. (2004) used a submerged pump to sample the wake of a clam harvesting gear called the “rusca” in the Venice Lagoon. The sediment put into suspension behind commercial and survey demersal trawls has also been investigated by Dounas (2006) and Dounas et al. (2007) in Greek waters, using 2 l water sampler bottles, by Dellapenna et al. (2006) in Galveston Bay, TX, USA, using transmissometers deployed from a smaller vessel behind the trawler, and by Durrieu de Madron et al. (2005) in the NW Mediterranean using a transmissimeter, a LISST 100X, and the acoustic backscatter signal from an acoustic Doppler current profiler (ADCP).

Winter et al. (2007) review some of these sampling methods and find that those that use backscatter from acoustic devices, such as ADCPs and acoustic Doppler velocimeters, are non-intrusive and are much less susceptible to biological fouling (Downing, 2006). Indeed, significant advances have been made in the use of the calibrated backscatter from acoustic devices to monitor sediment dynamics in a range of environments, including large river channels (Lane et al., 2008; Shugar et al., 2010), lakes (Czuba et al., 2011), and coastal systems (Merckelbach, 2006; Thorne et al., 2007). Essentially, acoustic methods relate the echo intensity of the high-frequency sound to the properties of the particles in suspension, although single-frequency acoustic devices are not capable of differentiating between changes in sediment concentration and changes in the particle-size distribution (Thorne and Hanes, 2002; Shugar et al., 2010). The application of these techniques thus requires repeated calibration with water-sediment samples, and most acoustic devices provide single-point data or one-dimensional profiles. Recent developments in multibeam echosounding, however, permit the collection and recording of data from within the water column, which can provide a holistic view of suspended sediment dynamics and sediment plume evolution across a two-dimensional area through time. The evolution of the multibeam echosounder (MBES) technology to collect data not only from the strongest acoustic return (e.g. the seabed), but also full digital returns from the path of the acoustic pulse through the water column, has enabled two-dimensional imaging of water column objects and opened up many exciting new research opportunities. These include estimating fish abundance (e.g. Trenkel et al., 2008), imaging bubble-plume structures (Schneider von Deimling and Papenberg, 2011; Weber et al., 2011), and measuring black smoker flow velocities (Jackson et al., 2003). The application of MBES for the quantification of suspended sediment concentrations and flow velocities has also recently been demonstrated (Best et al., 2010; Simmons et al., 2010), enabling the imaging of sediment dynamics across a two-dimensional swath within the flowfield.

In the present paper, we deploy a RESON 7125 MBES to quantify sediment concentrations and the sediment load that are mobilized into the water column in the wake of towed demersal fishing gears. Specifically, we detail the extent and concentrations of sediment mobilized by the otter door of a demersal trawl and the roller clump of a demersal twin trawl and examine the evolution and decay of the sediment plume behind each gear component. Additionally, the grain-size trends within the sediment plumes are also analysed and discussed.

**Material and methods**

Experimental trials were conducted with the RV “Alba na Mara” on grounds close to Burghead in the Moray Firth, Scotland, during September 2009 to measure the concentrations and particle-size distribution of sediment mobilized by two different fishing gear components, namely: (i) the otter doors of a demersal trawl and (ii) the roller clump of a demersal twin-trawl. The otter doors were 2.36 m² Morgère WS otter doors that weighed 450 kg and were 1.95 m long and 1.3 m high (Figure 1a). They were used to spread a 300-hp Jackson whitefish trawl with a rock-hopper groundgear with 55 m double bridles, which was towed at depths of ~20–25 m using warp lengths of between 60 and 75 m. The roller clump, which was towed directly from the vessel and not attached to a net, weighed 1.2 t and comprised ten circular disks and a rectangular plate (Figure 1b). The plate had dimensions of 1.02 × 0.94 m and supported a 0.1-m diameter axle, onto which the disks were mounted. The disks had inner and outer diameters of 0.11 and 0.58 m respectively, and were between 0.04 and 0.05 m in width. Measurements of the sediment plume were made optically, using a LISST 100X, and acoustically, using the acoustic backscatter from a RESON SeaBat 7125.

In addition, to classify and characterize the seabed sediment type, 15 grab samples were taken with a modified Day grab and the top 2.5 cm was subsequently sampled and frozen. These samples were later defrosted and dried, and the particle-size distribution of each sample analysed in the laboratory using a Malvern Instruments Mastersizer E Particle Size Analyser.

**LISST 100X**

The LISST 100X is an in situ particle sizer that uses the principle of laser diffraction to estimate the size distribution of an ensemble of particles and presents the resulting volume concentration (measured in µL⁻¹) in 32 logarithmically increasing size ranges between 2.5 and 500 µm.

Divers in a towed underwater vehicle (TUV; Figure 2) positioned the LISST 100X in the plume of the gear components. The TUV, which was also towed by the RV “Alba na Mara”, provides a safe working platform for divers to work in proximity to towed fishing gears (Main and Sangster, 1983). The pilot has direct control over the vertical and lateral movements of the
TUV, whereas the movement in the direction of tow is governed by the towing cable and controlled by the pilot via hardwire communications to the towing vessel. The LISST 100X was attached to a "wing" on the starboard side of the TUV that allowed the divers to position it within the sediment plume. The LISST 100X was configured to measure the particle-size distribution and volume concentration every second, and during each tow, measurements were made over approximately a 2-min period. These were at distances of 10, 20, 30, 50, 70, and 90 m when the plume behind the otter door was being investigated and at distances of 10, 20, 30, and 50 m when behind the roller clump.

Multibeam echosounder

The RESON 7125 is an MBES capable of recording backscatter amplitude across a 128° swath using either 256 or 512 contiguous beams at a frequency of either 200 or 396 kHz. The angular spacing between successive beams can be set to either equi-angle or equi-distant where, in the latter case, the angular beam widths are adjusted to provide the same azimuthal sampling distance. The RESON 7125 was mounted on the MV "Solstice", a 11.5-m long, 5.5 m beam catamaran workboat, which was chartered to work in conjunction with the RV "Alba na Mara". The data are sampled at intervals of ~2.15 cm along the beams, generating large volumes of high-resolution, water column data at ping (sample) rates of up to 50 Hz.

After each set of optical measurements, and when the divers and the TUV were out of the water, the backscattered acoustic return from the water column was recorded at distances of 10, 20, 30, 50, 70, and 90 m behind the port otter door (and at distances of 10, 20, 30, and 50 m behind the roller clump). The appropriate distance was maintained with the aid of a measured float line deployed from the Alba na Mara. In general, three 1-min readings were taken at each station.

Data analysis

The concentration, $M$ (μL$^{-1}$), of sediment in suspension is related to the mean square of the recorded MBES backscatter amplitude, $B$ (counts), by (Thorne and Hanes, 2002):

$$M = \frac{B^2}{\rho} \cdot \frac{1000}{\psi} \left( \frac{r}{SK_b K_s} \right)^2 e^{(\alpha_w + \alpha_s) r}.$$

(1)

The remaining terms on the right hand side of this equation, except $K_b$ (counts m$^{-3/2}$), the sensitivity constant for the $b$th beam (which is assumed to be equal for all beams), can be estimated or evaluated from the properties of the water, the sediment in suspension, and the MBES settings. $\rho$ is the relative density of the sediment to water and assumed to be 2.65 for quartz sands (Blyth and de Freitas, 1974), $r$ the distance from the MBES transducer, $\psi$ a correction for the MBES nearfield (approximated to unity), and $\alpha_w$ the water attenuation (Np m$^{-1}$) that can be derived from the standard equations (Fisher and Simmons, 1977). $\alpha_s$ is the sediment attenuation due to scattering and viscous absorption (Np m$^{-1}$) and is a function of the
concentration, *M*. It can be evaluated iteratively, however, given that it was estimated to affect the value of *M* by less than 1% it is set to zero. *S* is a function of the Sonar system settings and given by:

\[ S = \frac{r^2}{10} \exp\left(1 + G_T + G_R + TVG \log_2(K_{range}) + 2G_a \right), \]

(2)

where *r* is the pulse length (m), *P* the transmit power (dB re 1 μPa @1 m range), *G_R* the system gain (dB), *G_{TVG}* the time-varying gain (TVG) spreading coefficient, *K_{range}* a constant (estimated at 0.094 using measurements obtained by Simmons, pers. comm.), and *G_a* the TVG attenuation coefficient (dB km⁻¹).

In Equation (1), *K_s* (m kg⁻¹/²) is a function of the sediment grain-size distribution and is given by:

\[ K_s = \frac{f_e}{\sqrt{ap}}, \]

(3)

where *f_e* is the ensemble form function for a particular grain-size distribution (by the number of particles per fraction rather than volume per fraction) derived using the distribution obtained with the LISST 100X, the heuristic expressions for *f_e* described by Thorne and Meral (2008) and *a* the mean radius of the distribution.

The backscatter readings are Rayleigh-distributed as a result of the random and constantly changing positions of the sediment particles within the sampling volume (Thorne et al., 1993). The standard error of the mean-square value of *B* in Equation (1) reduces with the number of samples. The 1-min set of backscatter readings taken at each station were hence averaged temporally and spatially across the two-dimensional swathe following the method described by Simmons et al. (2010). Furthermore, the sampling volumes are unlikely to be spatially independent as successive beams can overlap, with the degree of overlap being determined by the selection of either the equi-angle or the equi-distant mode, the acoustic frequency and the number of beams in the swathe. The greater the overlap between the beams, the higher the expected error of the sample average. Additional overlaps may occur in the radial direction originating from the transducers, as the pulse length can be varied to a maximum of 300 μs, while the sampling interval is fixed at 29 μs (corresponding to a sample distance of 2.15 cm for a sound velocity of 1480 m s⁻¹). Larger pulse lengths will, however, improve the backscatter-to-noise ratio. The data presented here were all obtained with a pulse length of 80 μs with the 256 beam equi-angle mode employed.

Hence, it is possible to evaluate *K_s* by re-arranging Equation (1) to give:

\[ MK_s^2 = \frac{1000}{\rho B^2} \left( \frac{r}{SK_s} \right)^2 e^{4a_e r}. \]

(4)

and calculating the gradient of the regression between the LISST 100X concentration values of *M* and the MBES values of *MK_s^2*.

**Results**

**LISST 100X**

In all, nine individual tows took place with the divers in the TUV positioning the LISST 100X in the sediment plume of the otter door. This yielded between six and eight measurements of 2-min duration at each station (except at 90 m, where only one set of measurements was made). Four additional tows took place where the divers measured the sediment concentration in the wake of the roller clump using the LISST 100X, providing between two and four sets of measurements at each of the stations. Since the LISST 100X measures the volume concentration in each particle size bin at 1 Hz, there were ~120 measurements for each 2-min sample at each station behind the gear components. For each time-series, these were averaged to yield the mean volume concentration in each bin at the station then summed to give the total mean volume concentration of the sediment in the plume at that point. By assuming spherical grains, it was also possible to estimate the mean particle size in the water column and these were again averaged to yield an average particle size (*d_{50}* =) estimate at each station. Figure 3 presents a typical set of measurements of mean volume concentration in each of the particle size bins at each station behind the otter door during one of the tows and demonstrates how the concentration of the sediment in the plume decreases with distance from the door. The measurements also showed that there were differences between the particle-size distributions of the sediment in the plumes behind the components and on the seabed. Behind the door the average *d_{50}* was 0.180 mm, whereas behind the clump it was 0.170 mm. The average *d_{50}* of the grab samples (using the Malvern Analyser) was 0.201 mm.

**Multibeam echosounder**

Five tows were conducted with the MBES, providing between 8 and 18 1-min periods of readings at each of the sampling stations. Three tows with the MBES positioned behind the roller clump were also conducted, giving between 6 and 12 sets of readings at each sampling station. A set of raw backscatter data from a ping recorded 10 m from the otter door is shown in Figure 4. The backscatter from the suspended sediment is clearly visible in the volume near the seabed. Useful water column data are limited to the sector bounded by the arc of the sidelobe interference within the MBES swathe. The system noise includes a strong radial artefact around the nadir beams that can be clearly seen at the centre of the swathe. Interference is also generated through a combination of strong acoustic reflectors and both the surface and the seabed reverberation from the previous ping. This problem is more pronounced for the recordings made in the wake of the otter door,
as the cable sweeps pulling the groundgear passed through the MBES swathe. However, this effect was mitigated by averaging across the larger volume of the plume and by the careful screening of large deviations related to this effect.

Data analysis

The MBES data were processed using Equations (2)–(4) and the grain-size distributions obtained with the LISST 100X. The mean of the LISST 100X grain-size distributions measured in the plume yielded a value of $K_S = 0.0870 \, \text{m kg}^{-1/2}$ for the door and $K_S = 0.0859 \, \text{m kg}^{-1/2}$ for the clump. The data were averaged temporally over series of pings, which were selected based on the s.d. of the seabed depth varying less than 5 cm. The data were then interpolated to a Cartesian coordinate system in the region of interest near the seabed as shown in Figure 5. To relate the value of $MK^2_b$ to the LISST 100X measurements, it was necessary to devise a method of locating the dominant area of the plume and to ensure that the processed backscatter was not compromised by a poor signal-to-noise ratio and the reverberation effects present in the swathe. An amplitude threshold value of $8 \times 10^{-11} \, \text{(}\mu\text{l}1^{-1}) \text{ counts}^2 \text{ m}^3$ was found to lie above the typical values of noise present in the centre of the swathe and to generally yield a good definition of the plume shape. The locations of the threshold values for the averaged backscatter over 150 successive pings, collected at a single station at 20 m behind the otter door, are indicated by the dotted and solid contour lines in Figure 5.

To derive a value of $MK^2_b$ for the clump plumes, the data above the threshold was averaged over a volume between 0.25 and 0.75 m from the seabed. These boundaries are shown in Figure 5 and coincide with where the divers estimated that had positioned the LISST 100X. The sampling position of the LISST 100X for the door plumes is less certain. The divers estimated that it was at a height of $\sim 1.0$ m from the seabed; however, the horizontal position is more difficult to determine. The uncertainty derives from the fact that the door plumes are wider than those of the clump and that the divers, to maintain good visibility, position the TUV so that the divers in the cockpit are at the visible edge of the plume. As the visible dimensions of the plume are thought to be larger than those defined by the acoustic backscatter threshold, three mean distances from the acoustic edge of the plume were examined: 0–0.5, 0.25–0.75, and 0.5–1.0 m. The 0.25–0.75-m boundaries are shown as an example in Figure 5.

Table 1 contains the calibration constants, $K_b$, derived from a linear regression between the processed MBES backscatter and LISST 100X concentrations. The otter door measurements were taken from tows at stations of 10, 20, 30, 50, and 70 m from the door, and the roller clump measurements were taken from tows at 10, 20, 30, and 50 m from the clump. The door plume $K_b$ value, calculated from the data obtained at a horizontal distance

Figure 4. Raw MBES Echogram for a single ping showing the suspended sediment backscatter and difficulties associated with measuring the suspended sediment plume behind the towed gear. The backscatter, $B$, is plotted on a log scale to improve the contrast between the features.

Figure 5. MBES backscatter recorded 20 m behind the otter door after correction for acoustic losses, averaging and interpolation to Cartesian coordinates. The dotted line represents a threshold value and the solid lines represent the boundaries of areas of data used in the calibration regression.
of 0–0.5 m from the acoustic threshold, is closest to that of the clump. Therefore, these data were used to derive a calibration constant for the combined door and clump plume data. The data and regression fits for the door, the clump and the combined data are shown in Figure 6. The horizontal and vertical error bars represent the s.d. of the measurements obtained at the same distance behind the gear by the LISST 100X and the MBES, respectively. The regression lines represent the minimum mean square error for the expected linear relationship passing through the origin and yield a calibration constant value of $K_b = 1.51 \times 10^{-2}$ counts m$^{-3/2}$ ($r^2 = 0.86$, $p = 0.0241$) for the combined data from the door and clump plumes. The mean LISST 100X ($\mu$L$^{-1}$) and MBES ($MK_b^2$) values for each station are given in Table 2.

The mean concentrations measured at each of the stations behind the otter door are presented in Figure 7a (MBES) and Figure 7b (LISST 100X). The corresponding data for the
measurements made in the plume of the roller clump are presented in Figure 8a and b. In both cases, the fitted power-law curves show how the concentration of the sediment in the water column decreases with distance from the gear component. Figures 9a and b and 10a and b show the mean heights and widths of the plume threshold boundaries for the otter door and the clump. The sediment loads (Figures 9c and 10c) are derived by integrating the calibrated backscatter across the area of the plume and show that for the door, the sediment continues to be entrained up to 20 m behind it, whereas for the clump, the amount of the sediment put into the water column has already begun to decrease at 10 m. Assuming a relative density of 2.65, the maximum of the average sediment loads corresponds to 6.2 and 1.2 kg of the sediment per metre towed being mobilized by the door and the clump, respectively.

Figure 11a shows data representing the calibrated MBES backscatter over a series of 50 consecutive pings recorded at 20-m distance behind the otter door. The collected backscatter time-series was processed in a manner similar to that reported in Simmons et al. (2010) with a circular two-dimensional averaging window of radius 43 cm applied across the swathe for each ping. The outer edge (coloured grey) represents the concentration (34 \( \mu l^{-1} \)) corresponding to the threshold used to define the boundary of the plume. A similar series of 50 consecutive pings (Figure 11b) was recorded at 20 m distance behind the roller clump. These plots illustrate the smaller plume volume behind

<table>
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<tr>
<th></th>
<th>Door (m)</th>
<th>Clump (m)</th>
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<tbody>
<tr>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>LISST 100X conc. ( (\mu l^{-1}) )</td>
<td>123.3</td>
<td>80.4</td>
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<tr>
<td>( MK_c ) from MBES ( (10^{-10} (\mu l^{-1}) \text{ counts}^2 \text{ m}^2) )</td>
<td>2.81</td>
<td>1.53</td>
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Table 2. Mean values of the LISST 100X volume concentration measurements and processed MBES backscatter for five distances behind the trawl door and four distances behind the roller clump.
the roller clump compared with the otter door (typically around 70% smaller across the entire dataset) and that the concentrations are significantly higher close to the seabed. Artefacts can be seen as sharp angles on the grey surface in both plots where attempts were made to screen out areas of reverberation.

Quantifying MBES effective range
Using the data presented above, a model of the backscatter, $B$, based on a re-arrangement of Equation (1), was implemented to estimate the effective range from the transducers over which the backscatter amplitude is greater than the system noise level. This effectively quantifies the range of conditions over which an acoustic, MBES-based, monitoring technique could be used to quantify plume dynamics behind towed gears. A contour plot of the depths at which the backscatter signal from a sediment plume can be distinguished from the signal noise for a range of mean grain sizes and sediment concentrations is presented in Figure 12. The estimates were derived for a setting of 396 kHz using the calibration constant, $K_b = 1.51 \times 10^{-6}$ counts m$^{-3/2}$ and a value of $K_S$ calculated using lognormal grain-size distributions with a relative standard deviation of 0.3. The noise level at 83 dB gain was estimated at 142.5 counts using a model developed from noise measurements obtained separately (Simmons, pers. comm.). Attenuation in the water column above the plume was assumed to be solely due to the chemical and physical properties of the water. The signal-to-noise ratio of the modelled backscatter was maximized by setting the power and system gain to the highest levels of 220 and 83 dB, respectively. Likewise, the pulse length was set to the maximum of 300 μm, which leads to a ~90% overlap between successive samples along the beam. The reduction in signal to noise is therefore offset by a loss of independence of the samples, resulting in higher sample average standard errors. The plot demonstrates how the effective range increases with both mean grain size and volume concentration.

Discussion and conclusion
We have demonstrated how acoustic backscatter from an MBES can be used to monitor and quantify the evolution of sediment plumes in the wake of towed demersal fishing gears and explored the possibility of remotely monitoring the amount of the sediment that is suspended into the water column during commercial fishing operations. Such a capacity, combined with spatially and temporally refined fishing effort data and spatially refined data on the seabed sediment type, would permit the assessment, at
the fishery level, of the impact of towed demersal fishing gears on a range of environmental and ecological factors such as nutrient release and benthic faunal mortality. The extent to which this can be achieved will depend on the range of conditions over which this MBES technique can be applied, which is limited by the concentration and mean grain size of the sediment in suspension. The backscatter modelling suggests that sediment concentration and grain size combinations similar to those measured here would be discernible at ranges of greater than 100 m. This is more representative of typical commercial trawling depths and highlights the potential for using MBESs more widely in monitoring the environmental impact of towed demersal commercial fisheries.

Processing of the acquired MBES data has, however, demonstrated the care needed in selecting the sonar system settings. Acoustic reverberation, combined with the presence of strong acoustic reflectors in the swathe (tow cables, etc.), resulted in unwanted interference in the region of interest near the seabed. Decreasing the ping repetition frequency would help mitigate such effects and re-orientation of the MBES transducers to a forward-looking angle may also reduce the reverberation time. The acoustic scattering from the suspended sediment is a function of the grain-size distribution as well as concentration. Calibration of the backscatter to the suspended sediment concentration requires a reasonable estimate of the grain-size distribution (from seabed or water column sample analysis) and either a previously derived calibration constant or a knowledge of concentration levels (from the analysis of water column samples). Hence, it is necessary that the suspended material properties do not vary significantly in space or time during monitoring. The single frequency of the MBES ensures that information from other instruments will always be necessary to derive concentration values.

The present findings also highlight that additional sources of acoustic backscatter and attenuation in the water column may also need to be accounted for. The wake bubbles from the trawler were visible in the higher part of the swathe and were separated spatially from the near-bed sediment plumes under study. However, the acoustic attenuation caused by the bubble plumes has not been quantified herein. Backscatter from fish passing through the swathe can also be screened manually, although plankton and micro-turbulent flow structures associated with temperature and salinity (Goodman, 1990; Ross and Luec, 2003)
or density (e.g. Lavery et al., 2003) are more difficult to remove from the signal. These are possible sources of additional backscatter that could be hard to distinguish from the suspended sediment, particularly in the turbulent wake of the towed gear. An additional source of error, as discussed by Merckelbach (2006), could arise if the concentration of the sediment in the sample volumes is non-homogeneous, particularly at greater distances from the transducers where the volumes are larger. However, the good agreement between the LISST 100X and seabed grain-size distributions, and between the decay of the LISST 100X and MBES concentrations, suggests that these potential sources of error were limited for the results presented here.

Finally, Figures 9 and 10 demonstrate the (acoustically measured) growth and decay of the plume with distance behind the gear components. Visual observations of sediment plumes have shown that their dimensions are still increasing over this range (O’Neill et al., 2008). These observations, however, will have included the finer sediment that is diluted by the turbulent mixing in the expanding wake and should provide good estimates of the wake dimensions. The acoustic measurements, on the other hand, are of the position of a boundary corresponding to a sediment concentration of 34 μl l⁻¹, the dimensions of which will reduce as the heavier particles fall out from suspension and the finer grains are diluted as the wake expands. We have also shown that the volume concentration, the sediment load, and the particle-size distribution of the mobilized sediment differ behind the trawl door and the roller clump. This highlights the need to measure and understand the processes at work at the level of the individual gear components, since, in general, the nature of the plume will depend both on the character of the wake turbulence and on the sediment that is available for mobilization (O’Neill and Summerbell, 2011). Such an understanding would permit an improved and more accurate assessment of the impact of towed gears and provide the means to develop fishing gears of reduced impact. Furthermore, metrics such as “kg of sediment mobilized per metre towed” will contribute to the evaluation of the Good Environmental Status descriptors, such as that pertaining to seabed integrity, of the Marine Strategy Framework Directive (EC, 2008).

Figure 10. MBES-derived data showing the variation in (a) the mean plume height, (b) the mean plume width, and (c) the suspended sediment load, for the roller clump plume data above a threshold value. The suspended sediment load is derived by integrating the calibrated backscatter across the area of the plume and shows that the sediment load behind the clump has begun to decrease 10 m behind it.
Best, J., Simmons, S., Parsons, D., Oberg, K., Czuba, J., and Malzone, Auster, P. J., and Langton, R. W. 1999. The effects of fishing on fish grain-size distributions (lognormally distributed, with a relative standard deviation of 0.3 and median size, \(d_{50}\)) and volume sediment concentrations.


![Figure 11](image1.png)

**Figure 11.** Representation of the evolution of the plume over time at a threshold boundary at 14 \(\mu l^{-1}\), at a distance of 20 m behind (a) the otter door, plotted over 50 successive pings (4.3 s at a mean ping rate of 11.4 Hz) and (b) the towed clump, plotted over 50 successive pings (4.0 s at a mean ping rate of 12.3 Hz) obtained at a distance of 20 m behind.

![Figure 12](image2.png)

**Figure 12.** Estimate of the range over which the backscatter signal from a suspension of near-bed sediment will retain a signal of 0 dB relative to the expected level of system noise, for a range of different grain-size distributions (lognormally distributed, with a relative standard deviation of 0.3 and median size, \(d_{50}\)) and volume sediment concentrations.

**References**


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