Geol. Bull. Univ. Peshawar, 1988, Vol. 21, pp. 105–116

ACOUSTIC MEASUREMENT OF SUSPENDED SEDIMENTS IN THE EASTERN IRISH SEA

SYED SHAFIQUR REHMAN* AND C.E. VINCENT

School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, U.K.

ABSTRACT

An Acoustic Backscatter Meter of 2.7 MHz frequency and a working range of 64 cm has been used for measuring profiles of suspended sediments in the eastern Irish Sea. The ABM was running in burst mode, pinging at 4 Hz with a burst length of 160 seconds and a burst interval of 60 minutes. Data from the first two field deployments, each lasting up to 29 days, is presented here.

The data suggests that most of the suspended load was fine silt/clay sized material showing strong modulation at the semi-diurnal and spring-neap tidal periods. Throughout the tidal cycle the concentrations remained very low except during flood currents of the spring tide when they reach up to 150 mg/1. A mild storm was also recorded during the first deployment which resulted in high suspended load concentration rising up to about 50 cm above the seabed. Marked difference was also noticed between the suspended load concentration before and after the storm, suggesting that fine material had been advected out of the area by the storm. This is considered important in the dispersion of pollutants in shallow seas.

INTRODUCTION

The Irish Sea is a semi-landlocked body of the Atlantic Ocean between Great Britain and Ireland. It is about 330 km long and 185 km wide with a total area of about 47,000 km.^{2} Water depth on southern and western side is 100–120 m, while on the eastern side the depth is less than 50 m (Bowden, 1980).

Owing to a continuous discharge of low level effluent nuclear waste from the Sellafield reprocessing plant since 1952, the Irish Sea has become the most radioactively polluted sea in the world. These effluents are disposed in the northeastern Irish Sea through a 2.5 km long twin pipeline in 20 m deep water. The source of nuclear waste is pond water, which flows continuously and where spent fuel elements are stored before reprocessing, and sea tanks which are discharged twice a day and contain waste arising from the reprocessing (Kershaw et al., 1986; Hain, 1986).

---

* *On study leave from Department of Geology, University of Peshawar, Peshawar, Pakistan*

There are two components of this discharge, the soluble water-borne radio nuclides of $^{134/137}Cs$ and ^{90}Sr and the insoluble sediment-bound nuclides like ^{106}Ru, ^{144}Ce, $^{238, 239, 240, 241}Pu$ and ^{241}Am (Howarth, 1984). The soluble component of the activity is immediately diluted and washed away from the outfall but it stays in solution and either moves with currents or becomes trapped in the interstitial water of the substrate. The insoluble components, on the other hand, rapidly stick to the surface of fine sediments and are then transported and dispersed. Some of the fine particles form colloids which descend to the seafloor and are burried in the course of time. The importance of sediments in rapid and effective removal of pollutants has been observed by Hetherington (1976), who showed that about 95% of the total activity discharged into the seawater is lost through the sediments phase immediately. It has also been observed that the seabed in northeastern Irish Sea is being bioturbated to a depth of about 1 m (Kershaw et al., 1983; Sills and Edge, 1987) which eventually renders the bed more easily erodible than by currents alone.

Over the period of nearly four decades, these pollutants have concentrated in the Irish Sea to such an extent that they are posing a serious threat to the environment of the region in general and to marine and human life in particular. One direct and major health hazard to human life arising from this waste disposal is the consumption of diseased/contaminated fish and other sea food obtained in large quantities from the Irish Sea. Whereas, the other cause of concern is the onshore transport of insoluble radio nuclides which adhere to fine sediments and are deposited on the beaches around the sea. These polluted particles, if and when, blown inland by strong onshore winds could prove potentially dangerous for coastal population and may cause serious illnesses.

To analyse the problem, a series of experiments was jointly undertaken by the Fisheries Directorate of the British Ministry of Agriculture, Fisheries and Food (MAFF) and the University of East Anglia, Norwich. It was decided to study the circulation pattern of the eastern Irish Sea through tides, waves and storms and also to measure the subsequent sediment transport using underwater acoustic technique. The objective was to develop the technique of acoustic measurement of suspended sediments, and also to explain why the pollutant have not been removed from the vicinity of the out fall.

For this purpose the MAFF laboratories designed a large metallic tetrapod (about 2 m high) which could be lowered to the sea bed and pulled back by a metallic rope. This bottom-mounted autonomous system is capable of measuring oceanographic parameters close to the sea bed in continental shelf environments (Fig. 1). The instruments attached to the tetrapod included an Acoustic Backscatter Meter (ABM), an optical transmissometer, a vertical array of five electromagnetic current meters, an altimeter (to fix the height above the sea bed), a thermistor, a pressure sensor, compass and a tilt meter (for orientation of the tetrapod) and a battery for the power supply to these instruments. Two Seadata loggers were used to record the data, one for the ABM and the second for other sensors. The loggers and the battery packs were mounted on a platform 2 m above the base of the tetrapod.

ACOUSTICS

Theory

The basic theory involved in acoustic measurement of suspended particles in water column is that a pulse of sound is transmitted underwater from a transducer which is scattered

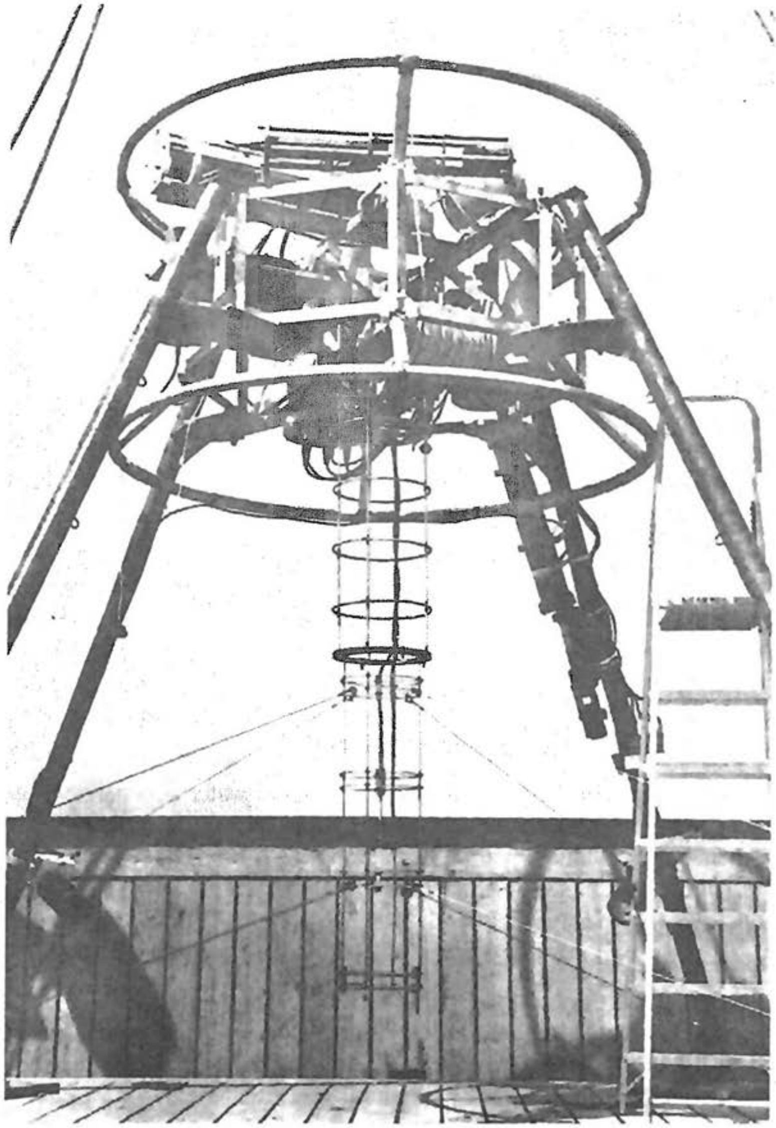

Fig. 1. MAFF tetrapod equipped with the ABM, electromagnetic current meters, optical transmissometer, and other instruments ready for deployment.

back by particles that come in the path of the beam and is recorded by a receiver. In some devices the transmitter and receiver is the same and id regarded as a transceiver (monostatic SONAR). A transceiver is a block of piezoelectric ceramic material covered by a thin layer of conducting electrode which physically changes its size and thickness when fluctuating electrical voltage is applied to it. The expansion and contraction of the transceiver causes condensation and rarefaction which produces ultrasonic signals when the element is underwater. Reciprocally, when the echo returns the alternating acoustic pressure creates an alternating voltage across the electrodes which is amplified, digitized and recorded.

Instrumentation

The device used for this purpose is called the Acoustic Backscatter Meter (ABM) which has two main components namely, the Transceiver Unit and Data Acquisition Unit. The former comprises of a pressure container, A 2.7 MHz transceiver with 12 mm diameter, analog-to-digital (A/D) converter, a small 8-bit computer, an oscillator, an internal clock and a 12 volt battery to supply power to these items. The data acquisition unit contains a cassette recorder, 140 m long tape and batteries, all housed in a pressure case which is connected by a cable to the other unit. The ABM has a working range of 64 cm, therefore, it is deployed vertically looking down, with its transceiver not more than 64 cm above the seabed.

The system is designed to send a burst of high-frequency sound signals (using 2.7 MHz frequency) at a rate of 4 Hz (4 pings per second) for 160 seconds, at a burst interval of 60 minutes. At the time of measurement, an electric pulse of 10 ms duration is generated and applied to the transceiver which converts it into ultrasound and radiates it into the water column in a narrow beam.

The backscattered pressure (P_b) from an aggregate of particles is received by the same transceiver and converted into electrical signal which is amplified and eventually digitized by the A/D converter. The output is range-gated every 12.5 ms to produce a complete profile of 64 digitized P_b values from successive range cells of about 1 cm height. One such profile is recorded for every ping emitted during a burst and is placed in the buffer memory. Due to a limited recording capacity of the logger, on-board processing takes place prior to recording and thus 8 profiles are averaged temporally and adjacent pairs of two 1 cm range-cells vertically to produce a single profile with 2 cm resolution every 2 seconds.

The acoustic measurement of suspended particles in water is dependent upon the characteristics of the Sonar system namely, intensity of the incident signal, range of the ABM, attenuation of beam due to absorption and scattering, and the size, shape and density of the target material. These parameters are combined mathematically in the Sonar equation and expressed in decibles (Lynch, 1985);

$$S + NL = SL - 2TL + TS + DI$$

where S + NL = total output from the device including signal plus the noise level (generated by the instrument itself). SL = source level i.e., the intensity of the incident signal, while 2TL = two-way transmission loss of the beam by spreading and attenuation. TS = target strength (size and density of the scatterer) and DI = directivity index which includes beam pattern and shape of the transducer.

Prior to its first deployment in the Irish Sea the ABM was calibrated using a recirculating tank of the type described by Vincent et al. (1986) against 100 mg/1 of 125 mm fine sand. The choice of sediment size used for calibration was based on grab samples taken during an earlier cruise and the problem of beam attenuation by suspended material was ignored as the concentration was quite low. Based on the results of first calibration exercise, following equation was derived to convert the digital value of P_b into suspended sediment concentration in milligrams per litre:

$$\text{Conc (mg/l)} = (P_b^2 * 100/126^2) * (11.3\ j) \ldots\ldots\ldots\ldots\ldots (1)$$

where P_b^2 = digital value of backscattered pressure measured at the transceiver's face, and j = distance between the transceiver's face and respective range cell (in cm).

Before its second field deployment, the ABM was slightly retuned to make it sensitive for sediments finer than 125 mm. Therefore, it was recalibrated against 50 mg/1 of 37 mm silt. The equation derived from this exercise is as follows:

$$\text{Conc (mg/l)} = (P_b^2 * 50/169^2) * \exp(0.143\ j) \ldots\ldots\ldots\ldots (2)$$

LOCATIONS

The first field deployment of the ABM took place between 17th July and 15th August 1986 at about 10 km due west from Workington harbour in the northeastern Irish Sea (station A, Fig. 2). Station A lies at 54° 39' N and 3° 44' W in 17 m deep water and is situated in a region where the bottom surficial sediments were between sand and muddy-sand suggesting a sand: mud ratio of about 9:1. The clay content of the mud was around 60%, the remainder being silt, whereas, the sand fraction had a median grain size of 0.25 mm.

The second deployment of the ABM, with increased tuning, took place at station B between 17th September and 15th October, 1986. This locality lies about 15 km due west of the Whitehaven harbour (54° 34' N and 3° 50' W) at 27 m water depth. Though this station lies a little further offshore, still the sediments were sand/muddy-sand. The clay content was higher at around 80% and the median sand size was smaller i.e., 0.177 mm.

RESULTS AND DISCUSSION

Complete profiles of suspended sediment concentration for stations A and B were produced by substituting the respective digitized P_b values in equation 1 and 2, respectively. All final profiles were characterised by a strong bottom echo registered in the 29th or 30th range-cell (representing a distance of 58 to 62 cm from the transceiver). Close to the device, however, the first 3 cells (about 6–8 cm) consistently showed anomalous values, which were attributed to electronic head ringing and were, therefore, ignored in further analyses.

Sediment concentrations at two levels (range-cell 12 and 26) were selected from each profile as representative values. They were analysed and correlated by plotting on a time series plot (Fig. 3). Data from cell 12 represents the so-called "mid-water" concentration at approximately 40 cm above the bed. Whereas, cell 26 shows the "near-bed" concentration at nearly 10 cm above the bed. The concentrations are minimum at the time of slack water, but as the tidal currents reach their maximum speed in about 3 hours time, the concentrations also increase accordingly. This indicates that the suspended load concentrations at both levels show a clear modulation with both semi-diurnal (12.4 hours) and spring-neap tidal cycles (over a fortnight).

The circulation of water in the Irish Sea is strongly controlled by tides. The tidal range for the eastern Irish Sea is very high (8.4 m mean spring and 4.5 m mean neap at Liverpool). Hence, during spring tides, the current velocities are relatively high enough to cause significant erosion and resuspension of the bed sediments. This is clearly demonstrated by comparing the times of high/little suspension (Fig. 3) with the times of high/low tidal range for the area (Fig. 4).

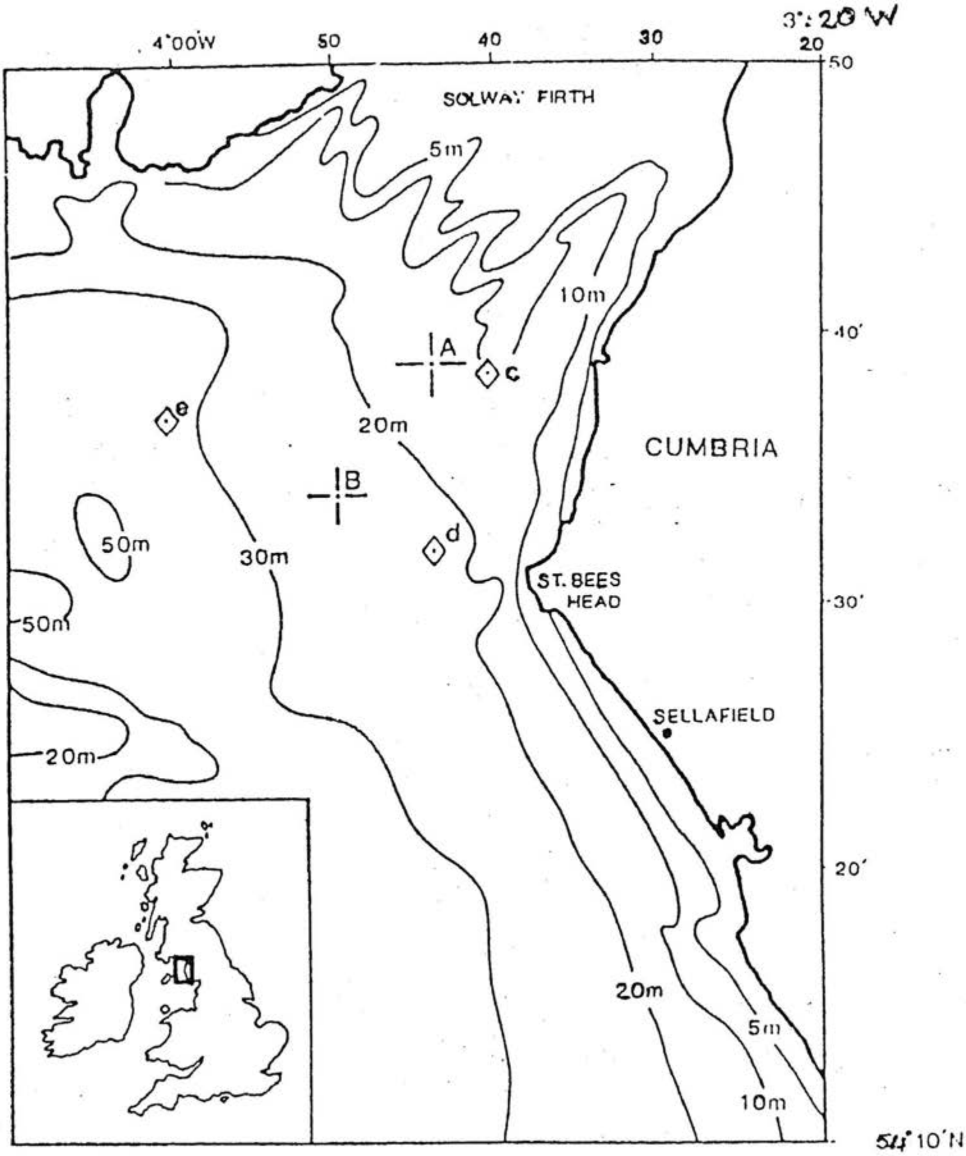

Fig. 2. Location map of the eastern Irish Sea (from British Admiralty Chart 1826). Capital letters with a cross show locations of the ABM stations A and B; small letters with diamonds represent positions of tidal current measuring stations.

Despite differences in their respective tidal current velocities (1.1 and 0.6 m/s), the concentrations measured during fastest spring currents are similar (about 105 mg/1) for stations A and B, respectively. During neap tides, however, they usually remain less than 20 mg/1 when the current velocities are of the order of 0.6 and 0.4 m/s for the two stations. It is, therefore, suggested that during neap currents enough stresses can not be generated at the seabed to resuspend bed sediments in the presence of a significant mud component.

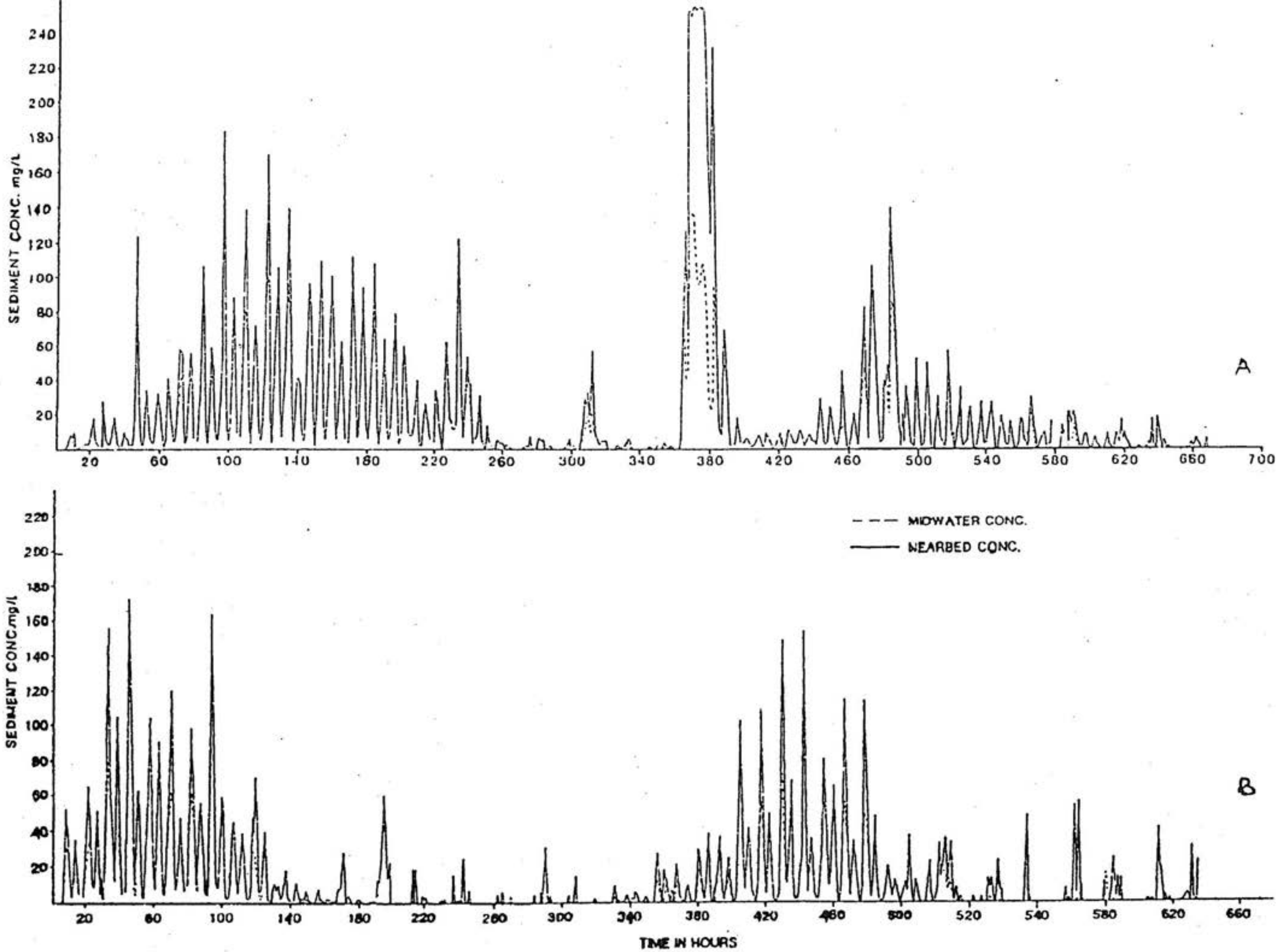

Fig. 3. Time series profiles of the suspended load concentration at (a) station "A" and, (b) station "B". Midwater level represents 40 cm above the bed and the nearbed at 10 cm above the bed. The unusually high peak in (a) around hour 380 represents a high suspension event due to gale force winds during neap tides.

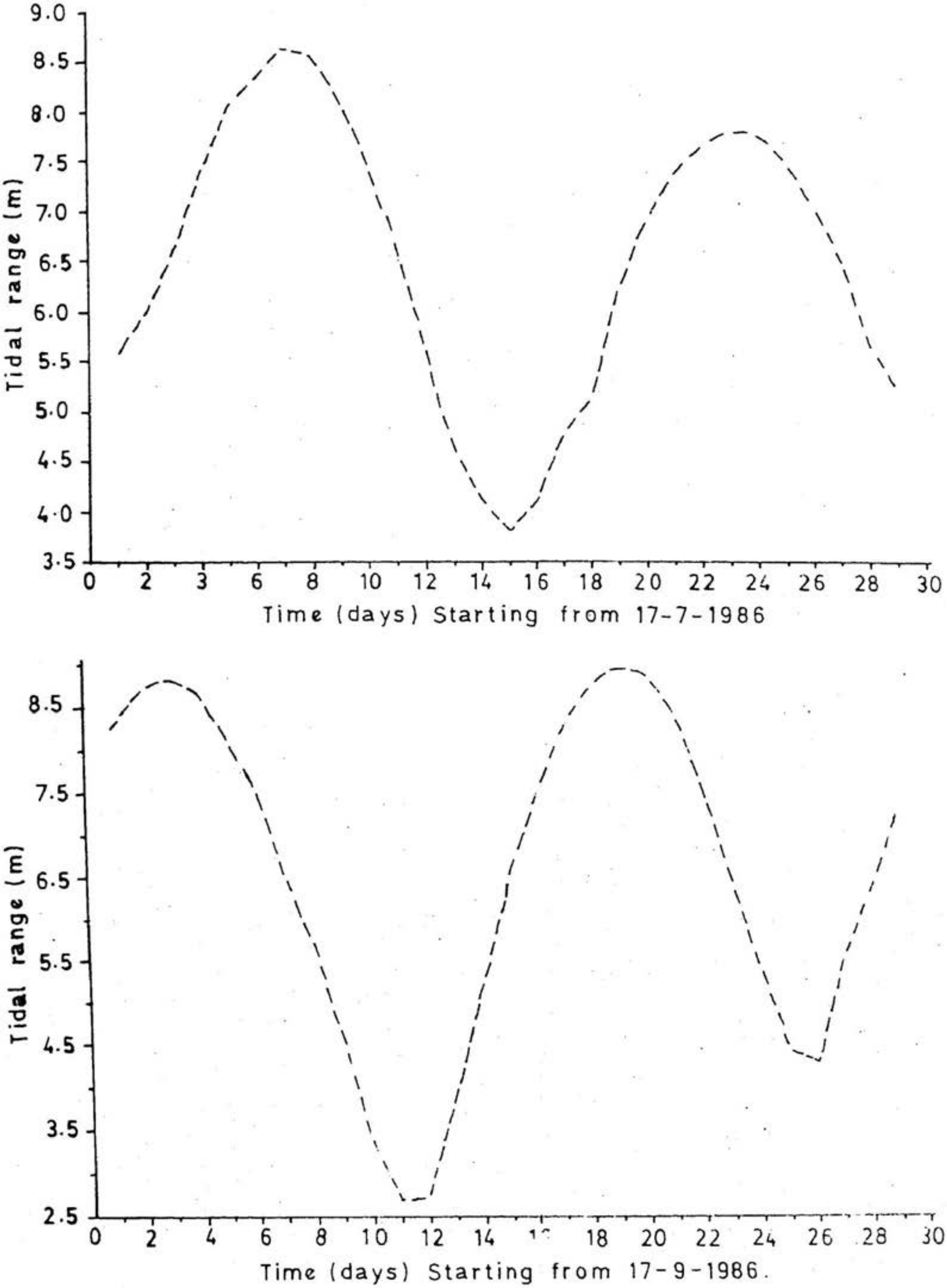

Fig. 4. The tidal range (m) for Liverpool Bay area corresponding to the time of ABM deployments at stations A and B, respectively. Mean daily range from (a) 17–7–1986 to 15–8–1986. (b) from 17–9–1986 to 16–10–1986.

The time series plot of station A (Fig. 3) also shows an anomaly where and event of very high suspension was recorded from 360–400 hours after the initial deployment, which falls in the neap tide period. Inspections of the meteorological charts of the region revealed that around the beginning of August, 1986 a mild cyclone was tracking across the northern Britain and bringing winds of 12–15 m/s to the Irish Sea. Hence on 2nd August, these winds have been slowing across the Irish Sea for more than 12 hours over a fetch of nearly 300 km. Significant wave height of 2 m and wave period of 6 seconds are expected from such fetch-limited winds (Carter, 1982). The effect of such waves on the seabed, in 17 m of water, is wave orbital currents of about 10 cm/s. Whereas, shear stress on the bed, due to a combined effect of currents and waves, can be considerable (Grant & Madsen, 1979). Thus the concentrations became very high during that period which would otherwise have been very low.

During the storm it is clear that the amount of sediment in suspension increases considerably and that the coarser fraction of the bed also starts to become mobile. In addition to the mainly oscillatory movement by tidal currents (which give little net transport), during storms the wind-driven currents also play an important role as these currents are often not oscillatory in nature. This combination of high suspension and wind-driven circulation suggests an important role for storms even in regions where tidal currents are strong.

Another important aspect of the storm at station A is related to the sediments dispersal. There is a marked difference in the suspended load concentrations before and after the storm (Fig. 5). Before the storm, the usual peak spring concentrations were around 120-140 mg/1 which dropped subsequently to nearly one third of this value (40 mg/1) under similar tidal conditions after the storm. Since much of the fine sediment in this region come from the Solway Firth and is then redistributed by currents, the finer material accumulated in the vicinity

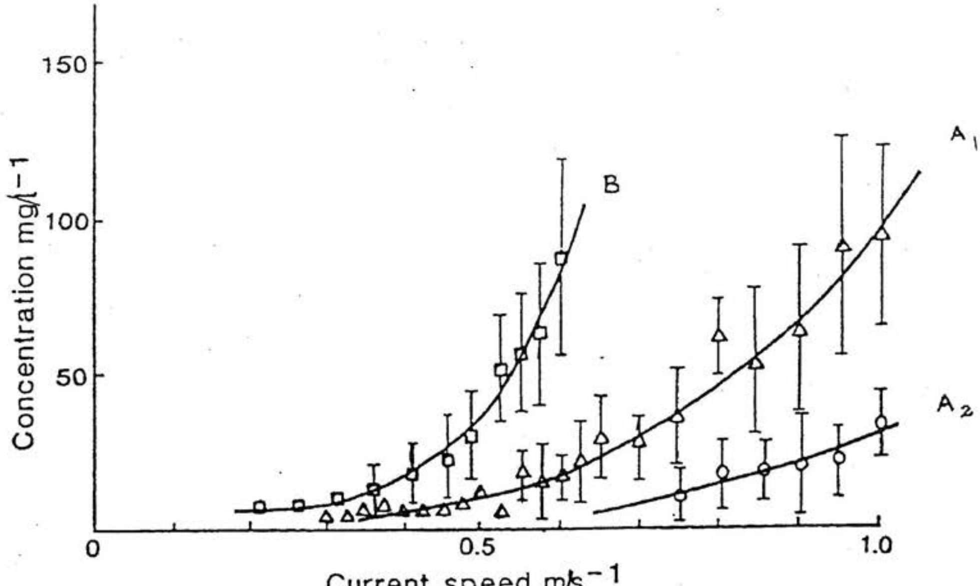

Fig. 5. Relationship between current velocity and suspended load concentration. Concentrations are nearly equal at A and B despite difference in current velocity, suggesting the presence of mud at A. A_1 and A_2 are pre- and post-storm concentrations at site A. Bars are 1 standard deviation.

of station A during the relatively quiscent period was advected away during the storm. Hence the difference in the pre- and post-storm conditions reflect also upon the changes in the availability of sediment in the area.

The distribution of particles as a function of height from the bed (Fig. 6) suggest that for velocities < 55 cm/s, the concentrations are low and uniform. However, when the currents achieve a velocity of about 1 m/s, the concentration increases rapidly, especially up to 10 cm above the bed. Whereas, under the storm conditions when sand particles are also temporarily lifted into suspension, the size distribution is less uniform.

CURRENTS

Ironically no current velocity measurements could be recorded for the first two deployments of the tetrapod in the Irish Sea due to an electronic problem in the second data-logger. Both deployments produced a good quality ABM data but without the corresponding current velocities it was of limited use. In order to compare the measured concentrations with current velocities of the region, the latter were interpolated from the published data. British Admiralty Chart 1826 was used for this purpose which is a bathymetric map of the eastern Irish Sea. This map also has a set of current velocities for typical spring and neap semi-diurnal (13 hours) tidal cycles. These data represent long-term averages of the surface tidal streams at those particular stations and may be expected to vary both with time and height above the bed.

Current velocity data for stations A and B were produced by interpolating the data of the nearest tidal diamonds and thus may be far from real. Nevertheless, in the absence of true data it substituted well and shows a good relationship with variations in the suspended load flux of the area (Fig. 7). The data show a positive correlation between speed and concentration, and also a gradual variation in the suspended load flux with various stages within a single cycle.

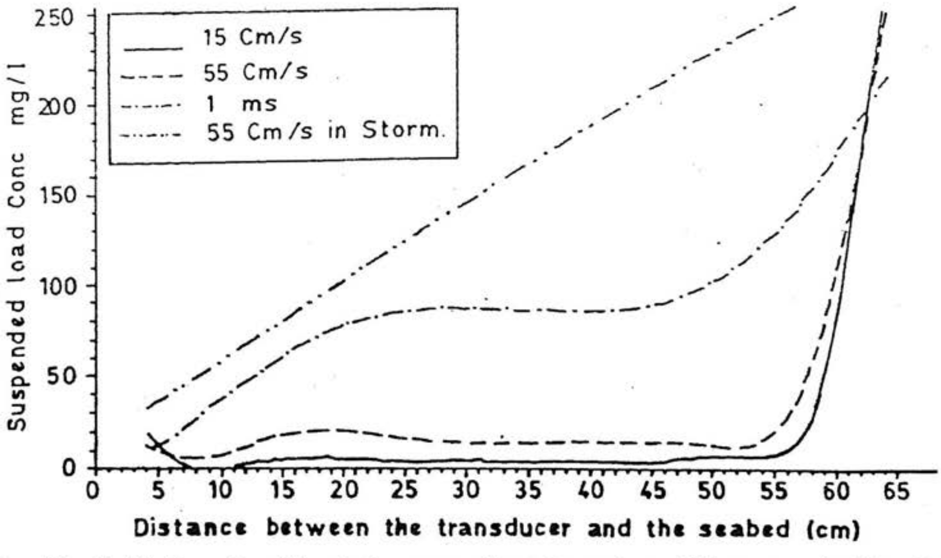

Fig. 6. The distribution of particles in the water column for various tidal current velocities. At low velocities the particle size is fine and uniformly distributed but as the coarser fraction of the bed sediments start to move at higher velocities the water becomes stratified.

Once again, a certain speed threshold (about 40 cm/s) is noticeable below which little sediment is resuspended. This indicates towards the presence of a mud component and higher yield strength of the bed sediments.

CONCLUSIONS

The circulation of water in the eastern Irish Sea is predominantly controlled by semi-diurnal tides of a significantly high tidal range (8.5 m average spring). The data suggests initial resuspension of sediments from the bed and beginning of transport at a current velocity of about 1 m/s. Under normal tidal flow the suspended material is relatively fine silt and its dispersal is gradual and diffusive in nature. The net sediment transport, resulting from residual drift, is small compared to any advection due to storms.

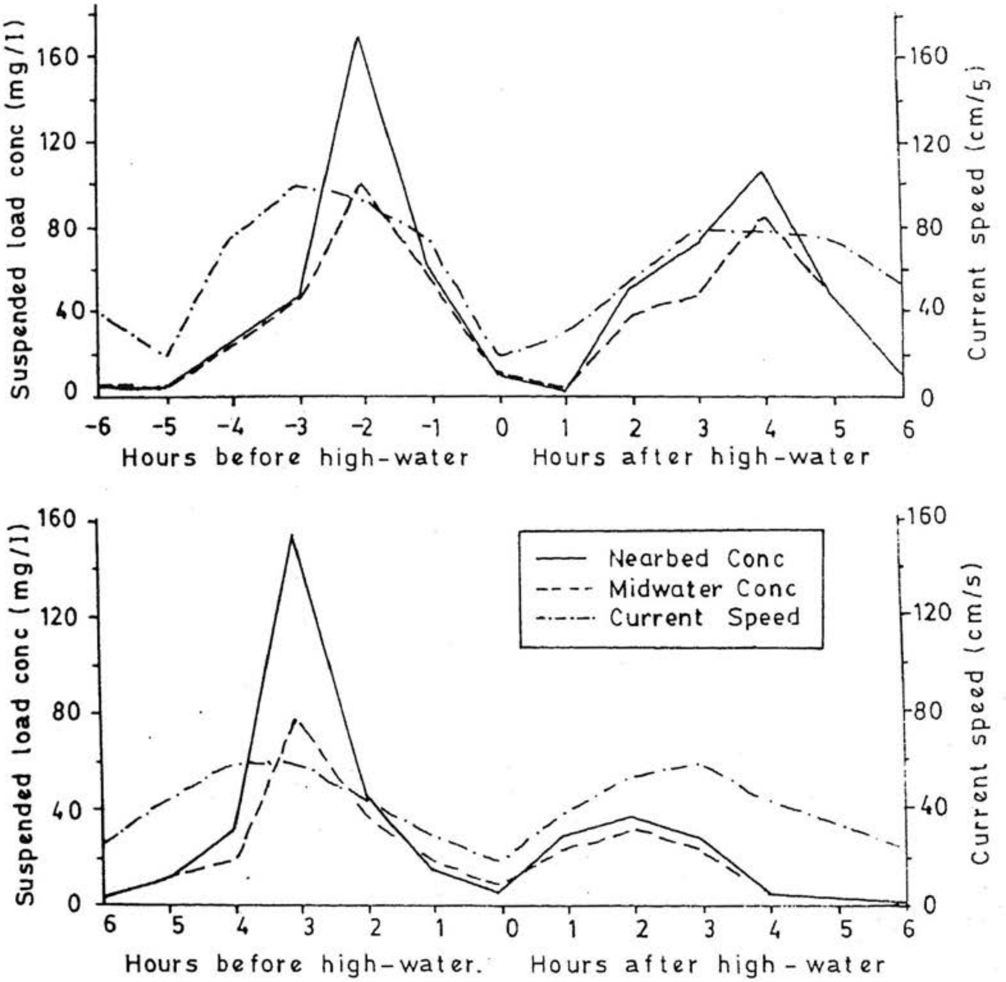

Fig. 7. Variation in the suspended load flux during a 13 hour semi-diurnal tidal cycle for spring tides; (a) station A, (b) station B. At both stations the fastest currents are experienced around 3 hours before the high water.

The significance of storms in net sediment transport in the Irish Sea is reflected by the abnormally high suspended load profiles, measured during that period. The sediment concentration in the area is controlled by the availability of the fine particles which are advected away during a storm and require a long quiscent period to re-accmulate in the region. The coarser fraction of the bed sediments moves only during storms, apparently as a result of enhanced bed shear stresses, due to a combined action of tides, waves and wind-driven currents.

A multi-frequency system was developed and then deployed in the Irish Sea to avoid the bias in result arising from the size selected for calibration. The results of the subsequent deployment will be published later.

Acknowledgements: We would like to thank Nick Pearson and Mike Thomas of MAFF for the development of both hardware and software of the ABM. Ministry of Science and Technology, Government of Pakistan is thanked for supporting the research.

REFERENCES

Bowden, K.F., 1980. Physical and dynamical oceanography of the Irish Sea. In: The north-west European shelf seas: the seabed and the sea in motion. II Physical and Chemical Oceanography and Physical Resources (F.T. Banner, M.B. Collins and K.S. Massie, Eds.). Elsevier, Amsterdam, 391–414.

Carter, D.J.T., 1982. Prediction of wave height and period for a constant wind velocity, using the JONSWAP results. Ocean Engineering 9, 17–35.

Grant, W.D. & Madsen, O.S., 1979. Combined wave and current interaction with a rough bottom. J. Geophys. Res. 84, 1797–1808.

Hain, J.H.W., 1986. Low-level radioactivity in the Irish Sea. Oceanus 29, 16–27.

Hetherington, J.A., 1976. Radioactivity in surface and coastal waters of the British Isles. Ministry of Agr. Fisheries and Food, Radiobiol. Lab. Lowestoft, FRL. 11, 1–34.

Howarth, M.J., 1984. Currents in the eastern Irish Sea. Oceanogr. Mar. Biol. Ann. Rev. 22, 11–53.

Kershaw, P.J., Swift, D.J., Pentreath, R.J. & Lovett, M.B., 1983. Plutonium redistribution by biological activity in the Irish Sea sediments. Nature 306, 774–775.

_______, Breale, J.H., Woodhead, D.S. & Lovett, M.B., 1986. Alpha-emitting hot particles in the Irish Sea sediments. Sci. Tot. Envir. 53, 77–87.

Lynch, J.F., 1985. Theoretical analysis of ABSS data for HEBBLE. Mar. Geol. 66, 277–290.

Sills, G.C. & Edge, M.J., 1987. Sediment behaviour in the Irish Sea. Unpublished report No. OUEL 1698/87, Deptt. Engg. Sci. University of Oxford. 20. pp.

Vincent, C.E., Hanes, D., Tamura, T. & Clarke, T.L., 1986. The acoustic measurement of suspended sand in the surfzone. In: Proc. Inter. Confr. Measuring Techniques of hydralulic phenomena in offshore coastal and inland waters. London, 9–11 April, 1986, Paper K3, 443–451.