I.O.S.

IMPLICATIONS OF SEDIMENTOLOGICAL AND HYDROLOGICAL PROCESSES ON THE DISTRIBUTION OF RADIONUCLIDES IN A SALT MARSH NEAR SELLAFIELD, CUMBRIA

BY
A.P. CARR AND M.W.L. BLACKLEY

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TAUNTON

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ABSTRACT

The report examines sedimentological and hydrological processes affecting a salt marsh in the Ravenglass estuary, which is situated S of the Sellafield nuclear fuel reprocessing plant. The results are discussed in the context of the distribution of low-level radioactive effluent at the site.

Detailed elevational measurements on sections across a subsidiary creek show mainly seasonal variations attributed to expansion of clay minerals. Transducers deployed at a range of depths in the marsh sediment point to rapid changes in pore water pressure in response to the tidal cycle and suggest infiltration of both water and radionuclides from the coarse sediments below, especially during neap tides. Desiccation cracking of the marsh clays provides preferential pathways from the surface. These, and other factors, imply distribution of radionuclides by other mechanisms than simply accretion and emphasize the environmental diversity at this location.

KEYWORDS 103 Coastal sites 111 Hydrogeology 124 Field experiments
131 Soils/sediments 299 DOE sponsored research

This work has been commissioned by the Department of the Environment as part of its radioactive waste management research programme. The results will be used in the formulation of Government policy, but at this stage they do not necessarily represent Government policy.

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SUMMARY

Over the past decade or so considerable research has been carried out into the fate of the low-level radioactive effluent from the BNFL reprocessing facility at Sellafield, Cumbria. This report focusses attention on related sedimentological and hydrological aspects at a salt marsh site on the N bank of the R Esk near Ravenglass where activity levels reach a maximum.

A range of techniques has been used including electromagnetic distance measurement (EDM) and pore water pressure studies. The results show that:

i) Over a two-year period at the specific site studied there were no significant changes in salt marsh creek level, although seasonal fluctuations, of the order of 2 cm, occurred. These were probably due to expansion of clay particles during the winter months. Nearby, however, there was vertical erosion of ∿ 1 m.

ii) Pore water pressures indicated a dynamic situation with very rapid responses both to tidal fluctuations and to rainfall. During neap tides there was clear evidence for water seeping upwards from the underlying clay/sand interface. Shortlived radionuclides ($^{95}Zr/^{95}Nb$ and ^{106}Ru) were detected in this zone.

iii) Additionally, it has been observed that soil polygons, once initiated by desiccation, thereafter provide preferential paths for water and radionuclides to reach the sub-surface sediment.

These, and other results are discussed in relation to the existing literature. It is concluded that the estuarine environmental situation is far more complex than early workers had assumed.

1. INTRODUCTION

It had been assumed initially that radioactive effluent from the nuclear processing facility at Windscale (now Sellafield) would either be carried out of the Irish Sea and rapidly diluted or locked-up indefinitely within the sediments of the sea bed nearby. Over time the permanence of sea bed disposal came into question (eg Smith et al, 1980). The research described in this report re-examines, in the light of new evidence, some of the conclusions reached by earlier workers concerning inter-tidal estuarial deposits because, in the event, it was in such locations that levels of radioactivity proved to be highest.

Although there is a substantial body of literature which examines the impact of radionuclide releases into the environment, the vast majority of these studies approach the problem from an unrelated standpoint. Sholkovitz (1983, p 153) summarised the situation as follows:

> '...... a major deficiency in many studies of artificial radionuclides is that the interpretation of the data lack supporting ancillary geochemical, biological, hydrological and sedimentological information which would help to elucidate those processes responsible ...... Cases in point include .... investigations in the Irish Sea region receiving Windscale discharges ......'

Although Sholkovitz was specifically concerned with plutonium, his strictures are more widely applicable. This report attempts to redress the balance to some extent by examining certain hydrological and sedimentological aspects affecting the salt marsh site subject to the highest levels of radioactivity occurring in the Sellafields area even if, as he wrote (p 144): 'studying a tidally dynamic estuary is wrought with complexities'.

The results described here strictly apply only to the specific location where the work has been carried out, and over the timespan over which the data were collected. Nevertheless, they serve as a cautionary warning as to the dangers of inferring and extrapolating aspects, such as accretion rates, from one area to another; a notable feature hitherto. Further studies at other inter-tidal locations are presently under way to assess the generality of the conclusions reached thus far.

1.1 Description of the area

The Ravenglass estuary is situated some 15 km south of the Sellafield (formerly Windscale) reprocessing plant of British Nuclear Fuels PLC (Figure 1a). It consists of the lower courses of the rivers Irt, Mite and Esk. While the immediate coastline is composed largely of sand-dunes the estuary itself is more complex. Although the bulk of the sediment consists of sands and gravels, underlain by a coherent till, there are areas of silt and clay particularly along the banks of the estuary. Upon these areas a series of salt marshes has developed. They are reputed to be as much as 1000 years old (Hamilton and Clarke, 1984). However, cartographic evidence suggests that they have developed, at least partially, as a consequence of the railway viaducts constructed during the mid-nineteenth century. The marsh discussed in the present report is located immediately northeast of the Eskmeals viaduct (Figure 1b, c) and is an example of such post-railway development. This ungrazed marsh extends over an area of some 300 x 175 m and contains a full range of plant communities distributed broadly in accordance with surface height. Over the principal vegetated area of interest an upper zone of *Halimione portulacoides* and a lower one of *Puccinellia maritima*, *Suaeda maritima* and *Salicornia spp* dominate. Total gamma radiation levels are between 2 and 3 times those occurring on the Newbiggin marshes on the south side of the estuary (Horrill, 1983), even although the Newbiggin ones were themselves at one time regarded as maxima (Stanners, 1980).

While the amphipod *Corophium voltutator* is prominent during the summer months and reworks the upper 1-3 cm of the muddy silt deposits (Hamilton and Clarke, 1984), the estuary in-fauna is very limited in general. Both Hetherington (1978) and Stanners (1980) in this estuary, and Stumpf (1983) in a contrasting North American marsh (Delaware, USA), regarded biological processes as a minor factor.

Offshore the tidal range varies from about 6.5 m on springs to 3.5 m on neap tides and each tide is essentially sinusoidal in form. However, at the viaduct site in the River Esk the pattern becomes highly asymmetric. The inflowing tide is restricted to between 2-2½ hours and, while it reaches approximately 3.5-4.0 m OD on springs and 2.5 m OD on neap tides, the water level does not drop much below +1 m OD so that the ebb flows for about 10 hours per tide (Figure 4). The asymmetry is also reflected in the salinity values. Hamilton and Clarke (1984) quote values for high tide of ∿ 31‰ falling to ∿ 4‰ for much of the low water period. Assinder *et al* (1984) and Eakins *et al* (1984) give values of the order of 1‰ and

and 0.2‰, respectively, as a minimum. Even on a representative neap high water IOS obtained 32.5‰, very close to typical sea-water values, at Ravenglass. Both water (and salinity) levels may be modified by precipitation in the immediate area or within the Esk basin. At low water most of the river bed is exposed, showing the complex relation of ebb and flood channels and local bed forms. The situation at high water varies between conditions where the ground level of the lower salt marsh is not quite reached to one where, on equinoctial springs, even the highest marsh is inundated.

2. TECHNIQUES

A range of methods has been employed to try to access the significance of different processes affecting the salt marsh on the north bank of the R Esk near Eskmeals. The two principal methods were:

a) The use of an electromagnetic distance measurer (EDM) and acrylic reflectors to determine the level of the ground surface along a series of profiles at monthly (or bimonthly) intervals.

b) The deployment of pressure transducers, one to determine the water level in the river and a further 5 to measure the pore water pressure at a series of depths within the sediment at a specific location in the lower salt marsh.

In addition other techniques were used on a limited scale and with varying degrees of success. These included the evaluation of the significance of desiccation cracks in the mud surface; the measurement of shear strength at different depths using a Pilcon direct-reading shear vane; and conventional topographic survey to record the eroding river edge of the salt marsh. Maps, plans and air photographs were examined in order to obtain details about the construction of Eskmeals viaduct and the development and changes in the outline of the salt marsh of the neighbouring area. Aspects of the work programme necessitated the taking of both box and conventional cores. These cores were x-rayed; analysed for organic and water content, and for particle size, as appropriate. Some 35 of the sub-samples from two of the cores were analysed for gamma-emissions.

2.1.1 Use of electromagnetic distance measurer (EDM) and acrylic reflectors

The method devised involves the use of an electro-optical system, with the EDM mounted upon a theodolite. The instruments used were an AGA 112 EDM, and a Wild T1 theodolite capable of estimation to 3 seconds of arc (= ±0.29 cm at 200 m). In general observations were taken onto a series of acrylic reflectors, which were threaded on a cord and aligned on the marsh surface at rightangles to the line of sight. However, near the ends of profiles where the ground surface was obscured by vegetation, reflectors, attached to thin rods, were positioned at a known height above ground level.

Slope distances were obtained from the EDM and these, together with vertical and horizontal angles measured by the theodolite were translated into horizontal distances, vertical changes in height, and spacing between targets using an HP-41C programmable calculator. From these data it is possible to obtain surface heights to an accuracy of ±0.5 cm at 200 m (and pro rata) while avoiding any direct disturbance of the site under investigation. In order to facilitate comparisons between surveys a computer program was used to interpolate heights at 0.5 m spacing along the lines of section and to calculate means and standard deviations for each of these points over the total number of surveys. Another program enabled comparisons to be made between specific surveys.

The EDM technique is described in more detail in Carr (1983).

2.1.2 Changes in creek surface height

For this investigation 5 lines of section were chosen (Figure 1b) varying between approximately 32 and 210 m away from a survey position at the base of the railway embankment. This position was marked by a concrete block and checks on the block's height were made regularly using datum marks on the stonework of the nearby viaduct, and from an Ordnance Survey benchmark in the vicinity. As can be seen from the map and Figure 3, the sections become longer and the profiles less steep as the distance from the embankment increases.

Between May 1982 and May 1984 19 surveys were carried out, at monthly intervals between January 1983 and January 1984, but bimonthly otherwise. As far as possible surveys were timed to take place just prior to the minimum range ('neapest') tides in the respective lunar cycle.

The results are summarised in Figures 2-3 and Tables 1-4 and A1a-e. Two features are notable. These are, firstly, the very limited extent of the elevational changes and, secondly, their apparent seasonal nature. Figure 2 shows the percentage of interpolated data points indicating 'accretion' between consecutive surveys (continuous line). Because random events (such as the incidence of rainfall at low water when the marsh is exposed to the atmosphere) may complicate the picture an element of smoothing has also been applied (pecked lines). The actual values for the respective sections are given in Table 1. The magnitude of the changes is apparent from Figure 3, Table 2-4 and Appendix 1 (Tables A1a-e). Table 3, in particular, demonstrates the aspect of 'seasonality' while Table 2 shows that the net change for each section, A to I, over the two-year period May 1982 to May 1984 was only about 1 cm. This change is of the order of the accuracy of the method. It is clear from Figure 3 and Tables A1a-e that such changes as do occur are mainly concentrated at the edges of the creek. This is even true of Section A where, because there is greater relief, results are somewhat more variable. Taken overall, in spite of the seasonal changes in height which are of the order of 2-3 cm, and irrespective of whether the surface is bare as in the creek, or vegetated as is the case of the section ends, only 32 of the 253 interpolated data points had standard deviations exceeding ±2 cm and only 2 approached ±10 cm.

2.1.3 Discussion

Because of its importance in respect of the fate of that fraction of the radioactive effluent which returns to the shore, various workers have attempted to calculate accretion rates for the marsh sediments of the R Esk (eg Hetherington, 1976; Aston and Stanners, 1979) relying primarily on geochemical methods. The results of their curve-matching techniques will be discussed more fully in Section 4 of this report. However, while the varying proportions of the different radioisotopes occurring in the effluent discharge from Sellafield could be matched plausibly on an annual basis with those found in the marsh sediment cores, this relationship often appeared to show substantial accretion rates. (See Section 4.4 of this Report). It is in this context that the seasonal variability recorded on the 5 profiles surveyed by the EDM technique need to be considered.

Kelly, Aston and Assinder (1982) describe the composition of a sample from the coastal sediment at Newbiggin. This gives values of 69% illite, 10% chlorite; 13% kaolinite and 8% illite-montmorillonite. Hetherington and Jefferies (1974) also found the same minerals present in the clay fraction from Eskmeals. Montmorillonite is highly expansive in conditions of high moisture content. Such expansion is almost completely reversible (Ravina, 1983, p 151). Chlorite is moderately expansive (Gillott, 1968, p 109). Thorne (1978, p 66) observed that there is no linear relationship between percentage content of expansive clay and the amount of expansion, small fractions being sufficient to effect substantial movement. However Driscoll (1983, p 94) noted that the expansion of montmorillonite may be inhibited by the presence of illite. Although there appears to be a widespread view that contraction during the summer months is primarily due to transpiration by vegetation (Ward, 1953; Reeve et al, 1980; Driscoll, 1983) there are nevertheless a number of other relevant factors. These include composition and concentration of pore fluid - in the present case free Na^+ ions are of significance -; dry bulk density and soil structure; the enhanced permeability due to cracking; and the effect of fluctuating and shallow water tables (Johnson and Snethen, 1978, p 118). In addition, the organic content and the time and rate of water withdrawal is important (Ravina, 1983). While the soil properties determine the potential for swelling it is the environmental conditions which determine the amount. Thus in Britain's normally mild, damp climate potential volume changes are rarely realised. For the southeast of England soil moisture deficits at freshwater sites usually reach a maximum during September and reduce to zero towards the end of December (Driscoll, 1983). Clayey soils take 2-3 months to swell fully after a return to field capacity (Reeve et al, 1980, p 430).

It is a little difficult to determine the sum of these various factors in the context of the Ravenglass estuary especially since the general picture for northwest England would be less acute than that for the southeast of the country. However Figure 2 does suggest a pronounced seasonal effect with the greatest percentage change in direction occurring in about September ('accretion') and January/March ('erosion'), the latter depending upon the year in question. This picture is slightly obscured by the varying survey interval (which also could have the effect of magnifying absolute amounts when bimonthly measurements were taken depending upon the nature of the intervening trend). It is important not to confuse direction of trend with magnitude. For example, while between December 1983 and January 1984 78.6% of surface elevations appear to have fallen, net change on sections A and C was minimal. This is shown even more clearly in comparisons between the January and March 1984 data where, while 59.8% of all surface elevations appeared to fall, 72 out of 253 calculated heights differed by $\leq \pm 0.2$ cm, well under the limit of accuracy for the technique. The seasonality aspect is complicated still further by the tendency towards decreasing salinity and, hence, pH during the winter months as local rainfall at the site and more extensive runoff from the drainage basin become more prominent. Finally, the periods of inundation of the marsh vary from month to month with highest tides (and hence longest duration of submergence by saline water) occurring in February, March, August and September.

It would seem, therefore, that while there are systematic changes of elevation throughout the year the timing suggests that the causes for these are more complex than the simple evapo-transpirational explanation for deficit recorded in more stable, freshwater, environments. It is interesting, too, to note that the order of change is comparable for both the vegetated section ends and the bare creek. This is not what would be expected if transpiration from the salt marsh vegetation was important nor is it what would be anticipated if foliar trapping of sediment, as suggested by Chapman (1960, p 36) and Hamilton and Clarke (1984, p 329) was a significant process.

Other workers in the Eskmeals area have commented on the apparent low level of biological activity. While, on occasions, some surface disturbance by in-fauna may occur at the EDM site, the evidence from cores suggests that the effect of this is very limited. Localised mats of Enteromorpha have also been found to develop on the creek surface and these may result in transient aberrations of surface level.

Throughout this discussion the words 'erosion' and accretion' have been placed in quotation marks since they have been used to convey negative or positive changes in elevational level rather than the manifestation of a sedimentological process. The arguments for the height changes encountered on Sections A-I being a response to chemical and physical processes in the soil have already been given. The reasons against straight deposition and erosion of silt and clay are in many ways the simple converse. That is:-

i) There is a seasonal periodicity in surface level with little net change.

ii) Except for the creek edges, where 'real' changes occur, the amount of altitudinal variation is quite similar throughout the whole section (and to a lesser extent between the sections also). In the short time available for sediment to settle out at the top of the tide it seems improbable that a uniform blanket would be deposited, especially since submergence times could vary both between the creek centre and the vegetated marsh, and between one section and another. It also seems impossible that such a process would completely dominate lateral changes of sediment deposition and erosion.

The effect of greater tidal currents and runoff, and of the prevalence of small waves in the estuary during the winter is not clear. Although more sediment is likely to be taken into suspension it is not obvious as to the extent that it will be deposited in relatively sheltered environments, such as the one surveyed, over the short period of submergence. This period is of the order of 2 to 3.5 hr at spring tides (Figure 4); the duration of slack water is rarely as much as 0.4 hr.

It is interesting to note that Frostick and McCave (1979) found that erosion resulted in the lowering of the muddy inter-tidal flats of the R Deben, Suffolk, during the winter; accretion predominated during the summer. This is the converse of the experience described here for the R Esk and may be attributable to greater exposure and, possibly, a smaller proportion of expansive clay minerals at the East Coast site.

2.2.1 Deployment of pore water pressure transducers

Six Druck PTX gauge pressure transducers were used, one to record water level height in the R Esk at Eskmeals viaduct and the remainder located at depths between 25 and 85 cm below the ground surface of a site in the lower salt marsh (Figure 1b). At this site the marsh surface is at ∿ +3.0 m OD and the junction between the underlying sands and the silt and clay of the marsh at ∿ +2.0 m OD. The marsh transducers were installed on 23 September 1982 and the river sensor on 21 January 1983.

The specification of the transducers was as follows:

i) Non-linearity and hysteresis : less that ±0.1% max. This gave short-term repeatability of better than ±0.35 cm water, assuming constant temperature.

ii) Temperature effects : less than ±0.3% total error from -2°C to +30°C.

The Druck transducers converted pressures (0-350 mbars) gauge to currents (4 to 20 mA). The measurable maximum pressure was equivalent to a depth of ∿ 350 cm of sea water. Since the river transducer was at approximately +1.0 m OD this means that water levels over ∿ 4.5 m OD may be attenuated. However, in subsequent calibration tests, transducer response proved essentually linear to 27 mA (= 5.0 m sea water), ie to 6.0 m OD. The gauge outlets were vented to the atmosphere via small bore tubes integral to the cable construction. This provided greater resolution and accuracy than would otherwise be possible and obviated the need for correction for atmospheric pressure. The transducers had small porous pots mounted on the pressure input to keep the pressure diaphragm uncontaminated by sediment; they were de-aired before installation. The porous pot was surrounded by sand while the rear of the transducers was sealed with bentonite and the hole backfilled. According to Vaughan (1974) backfill material is unlikely to present a problem since it can be some ten times more permeable than the surrounding soil before the influence on pore pressure is significant.

The data recording system converted the transducer currents to frequency and totalled this frequency on counters over a 40 second period. The final count was logged on EPROMs. (Eraseable Programmable Read Only Memory). Logging took place every 12 minutes. On those occasions where identical values for a transducer occurred on 2 successive 12 minute sampling intervals it was assumed that high water fell midway between hence giving an effective 6-minute sampling period. During quiescent periods no power was supplied to the transducers. The resolution of the logging system was ∿ 0.43 cm water. The EPROM capacity was 4096 records which gave a maximum interval of 34 days between EPROM changes. Car-type batteries were changed at the same interval. For test purposes the logging system also displayed the currents drawn by each transducer. EPROMs were returned to IOS (Taunton) for reading, and data from them was recorded onto magnetic tape and a quick-look printout made.

Throughout the duration of the experiment calibrations were made from time to time between river water level as recorded by Transducer #6 and as surveyed by topographic levelling. Agreement was consistently good irrespective of the level of the tide and hence the percentage salinity. This is because the maximum head coincided with the maximum salinity, and the transducers were calibrated in terms of sea water.

The same relationship between milliamps and centimetres was used for the marsh transducers (Transducers #1-5) to produce an apparent water level height for each sensor. Partly because of likelihood of initial equilisation problems due to the drilling of the boreholes and because of the evident necessity of a river transducer to clarify interpretation problems no data were used until 21 January 1983.

It is possible that there is some conflict from the marsh transducers between the measurement of pore pressures varying due to drainage, and changes attributable to undrained loading (ie falling and rising/high tides, respectively). While drainage effects are likely to be valid, pore pressure changes due to undrained loading may be rapid. The deformability of the piezometer is likely to be different from that of the surrounding soil so that total pressure, and pressure changes, could be atypical (Vaughan, 1974). In spite of these qualifications the calculated apparent water level heights appear to give plausible values.

2.2.2 Evidence from pressure transducer records

Table 5 lists the availability of data for the 6 transducers. Complete records are available for 408 tides between 21 January and 15 December 1983. [Missing records are due to storm damage, operational error or, at the end of the period, progressive instrument failure attributable to condensation entering the vented cables.]

The data may be looked at in 2 ways:

a) The actual or apparent height of the water level for each high tide as given by Transducer #6 and Transducers #1-5, respectively.

b) The phase difference between the peak water level in the river and the corresponding peak pore water pressure as recorded by the transducers in the marsh sediments. Although this relationship is primarily tidal, sometimes it may be influenced by such factors as rainfall.

The results are given in Figures 4-8 and Tables 6-9.

2.2.3 Real and apparent changes in water level

Figures 4a, b and 5 give an indication of the changes in river water level as recorded by Transducer #6; 4a, b for a representative range of spring and neap tides, respectively, while Figure 5 shows the complete record for the month of January 1983. Figure 5 includes the two prominent surges which affected the North-west coast of England between 30 January and 1 February. The smaller of these is also included in Figure 4a as a comparison. It has been chosen in preference to the other which, while probably correct, is technically out of range. The bigger surge may represent at least the 1 in 50 year event.

Figure 4 shows how short is the period during which the tide can affect the surface of even the lowest marsh areas. This time varies between barely 3 hours at springs to zero at extreme neaps. Over much of the tidal cycle the water level is constant at about +1 m OD and the river flow continues to ebb. A similar tidal asymmetry is described by Dankers et al (1984) for Delfzijl, Netherlands. The R Esk 'low water' level is partly the effect of the viaduct which impedes drainage at the recording site.

Figures 6-8 give the actual river water level as recorded at the top of each tide and the corresponding maximum apparent water levels for the marsh transducers in relation to OD. Figure 6 covers parts of January, February and March; Figure 7 parts of May and June; and Figure 8 the balance of June and part of July. Taking the figures as a whole there is a tendency for the apparent water levels of the marsh to converge with the actual river water level (drawn as a thin continuous line) as the tides progress from neaps to springs; the higher the spring tide the closer the agreement. In addition, there is the suggestion of a seasonal effect with a closer correspondence of river and marsh transducers during the later summer period (Figure 6, (and 7), contrasted with Figure 8). The neap data vary between those occasions where the river high water level is consistently above the apparent water levels of the marsh transducers (Figure 6a; Figure 7 first neap period) to those where it is consistently below and the marsh transducers show draining (Figure 6b). The smooth draining curve apparent from time to time for Transducers 1 and 2 in Figures 6b and 8 is not wholly real, the plateau being determined by the threshold current consumption of the transducer rather than the pore water pressure.

2.2.4 Phase lag between river and marsh pressure sensors

The closer height agreement on a seasonal basis of Transducer #6 with, especially, Transducer #1 is probably linked with the shorter lag time between about July and September. This feature is well shown in Table 6 (See also Table B1). For the period 18 July-15 August there were 35 tides where the river water level exceeded 2.75 m OD (ie the approximate sensor height of Transducer #1) and pore pressure was positive on Transducer #1. The average delay time between high water in the river and maximum apparent height for the same tide at the top transducer was 6.17 minutes; comparable figures for 21 January-2 February and 10 November-11 December were 15.23 and 17.35 minutes respectively. Further data on lag times are given in Tables 7-9. Table 7 summarizes the month-by-month information of Table 6. By contrast Table 8 lists all the occasions where the river level at high water was ≦ 2.75 m OD and Transducer #1 recorded negative pore pressure. This condition is typical of neap tides where there had been no substantial rainfall to complicate the picture; as a result progressive drying-out of the marsh surface zone occurred. Under these conditions, delay times for Transducer #1 (and often Transducer #2 also) could not be resolved, but values for Transducer #5, and nearly always Transducers #3 and 4, could be calculated. It is apparent that although the records from all 3 bottom marsh transducers show long delays, they were least for the lowest sensor. Table 9 gives mean delay duration for Transducers #3-5 for the total number of tides within each 'monthly' sampling period. While differences may not be great the lowest transducer (#5) invariably has a shorter lag than Transducer #4 and there is - with one marginal exception - a similar relationship between Transducers #4 and 3.

2.2.5 Discussion

The shorter lag times of summer and early autumn may be attributed either to the cracking of the marsh surface, so providing a rapid water pathway downwards, or to the reduced viscosity of water, or both. Viscosity of fresh (and sea) water is reduced by ∿ 20 per cent between 8° and 16° C and ∿ 44 per cent between 0° and 20° C. Vertical cracking of the vegetated marsh, such as that where the transducers were installed, is never very conspicuous. Nevertheless, the fact that lag time, vis-a-vis the river high water, is proportionately less between the air/marsh interface and the top transducer(s) than between the underlying sand/marsh interface and the bottom transducer(s) points to the predominance of this factor. Ravina (1983) cites Ritchie, Kissel and Burnett (1972) who 'have shown that wet field clay soils, where water movement may occur in invisible cracks and slickensides, have hydraulic conductivities 25 times greater than the same soil which has been repacked in the laboratory'. Macroscopic cracking would be far more effective still. Water transport in the immediate surface zone could also be enhanced to some extent by the preferred pathways provided by plant roots (Bouma and Dekker, 1978). This effect is likely to be more widespread than vertical cracking. Although much of the vegetation at the transducer site is perennial, both root growth and the tendency to surface desiccation would likely be at a maximum over the summer period. Most roots occur within the top 30 cm (Table 10).

Reference was made in the previous section to the lowest marsh transducer having the least mean delay time overall, as well as at neap tides when the top transducers were often merely subject to a prolonged drying cycle. This, coupled with the fact that Transducer #5 always responded to tidal fluctuations in the river, lends support to the argument that water circulates upwards from the underlying silt/sand interface. Hamilton and Clarke (1984, p 329) also believed that 'for most areas' of the estuary of the R Esk there was upward and lateral seepage but they thought that this was freshwater from land drainage. The importance of vertical water movement will vary between spring and neap tides and in relation to the incidence of precipitation. The situation is summarized in Figure 9.

In research at a site adjacent to the R Severn,Thorne (1978, p 219) found that groundwater levels responded rapidly to drawdown in the neighbouring channel. He attributed this to the high permeability of the underlying deposits although even in the silt and clay above permeabilities of 2 m hr^{-1} were measured. Thorne believed vertical flow was dominant over lateral at the site.

Both the preferred water pathway via vertical cracks, and the lag/tidal cycle relationship, are relevant factors in the distribution of short-lived radionuclides, and possibly those having a longer half-life also. This aspect will be examined in more detail later in this report.

2.2.6 The rainfall effect

Figures 10 and 11 record the effects of 2 periods of rain between 31 August and 18 September 1983. Both occurrences correspond to neap tides. In neither instance did the high water level of the river (quite) reach the surface height of the marsh (∿ 3.0 m) although it sometimes exceeded the OD height of the uppermost transducer (Transducer #1 = 2.73 m). Rainfall figures were those observed on an hourly basis at the nearby meteorological station at Eskmeals. (It is to be noted that in order to emphasise the similarities in the shape of the profiles different scales are used in the diagrams not only for rainfall but for each of the transducers).

Figure 10 shows, firstly, that the apparent water level of Transducer #1 is strongly influenced by the incidence of rainfall with the trace being almost the mirror image of the water level in the river. Secondly, that the rainfall was sufficient to raise the water level in the river by up to 28 cm immediately prior to the morning high tide of 18 September. This probably reflected the earlier precipitation in the basin of the R Esk.

Figure 11 depicts data for the rather longer period between 31 August and 3 September and includes Transducer #2 in addition to those shown in Figure 10. There were 2 substantial incidences of rainfall, that early on 1 September and again around noon on 2 September, with smaller quantities thereafter. Until the second incidence the water level of the river was little affected but on that occasion there was some elevation at low water, of the same magnitude as that of 18 September (Figure 10). The much smaller rainfall event at mid-day 3 September not only produced inflexions in the water level curve but the whole of that low water period can be seen to be atypically high.

The uppermost marsh transducer (#1) showed a complex picture. It responded substantially to the first rainfall event and, except for very minor 'kicks' related to the tidal cycle, proceeded to drain from that time until the next major event. There was then again a substantial response with rapidly increasing apparent water level. Thereafter, even small quantities of rain caused wildly fluctuating changes in pore water pressure. The small finger-like peak in the afternoon of 2 September may be a reflection of the near-simultaneous high tide in the river; this high tide is apparent on the record from the underlying Transducer #2. Transducer #2 is interesting because, inspite of being only 27 cm below #1, the form of the profile is more closely comparable to that of the river even if the magnitude is both different and varies within the sampling period. Following the rainfall event of 2 September apparent water level values for Transducer #2 are far closer to actual values of Transducer #6 than they were before that event. However, like Transducer #1, #2 has become much more susceptible to the effect of small periods of rainfall later on in the sampling period. Transducer #3 (not shown) is virtually unaffected by rainfall events at any time during the August-September example described.

2.2.7 Discussion

The data described above show that the effect of precipitation upon pore water pressures, water circulation, and water levels - both apparent and real - depends largely upon the pre-existing moisture content of the marsh sediments and the incidence of precipitation. For example, rain falling at high water spring tides would have only an indirect effect, such as marginal changes in pH and salinity and perhaps some eventual increase in water flow and water level at the subsequent river low water(s). However, rainfall corresponding in time with low water neap tides can produce substantial modifications to the normal neap-spring tidal picture, as Figures 10 and 11 indicate. Furthermore such effects are decidedly cumulative and non-linear. It is not surprising therefore that there is sometimes an element of variability in the actual/apparent water level and lag relationships both between between individual marsh transducers and between the marsh transducers and the transducer recording river water level. Gillham (1984, p 307) has commented upon the 'highly disproportionate manner' in which shallow watertables may be affected by precipitation events. He noted both the large and rapid response to the incidence of rainfall and observed that the legacy of past events could be significant in this context (p 311).

2.3 Other techniques and observations

2.3.1.1 Desiccation cracks and soil polygons

Some reference has already been made to vertical cracking in salt marsh sediments and of the preferential paths which such cracks provide for the passage of water (and, by inference, of radionuclides). Soil polygons may occur at any level of the marsh. However, all the best developed structures are on areas of bare sediment whether this is in salt pans, shallow creeks, or other unvegetated (or seasonally vegetated) places. This sub-section describes an investigation into a well-defined area of such features, and their associated vertical cracks, located in the upper salt marsh at the northwest corner of the site. Figure 12 shows the polygons at the time they were exhumed (July 1982) following a prolonged drying-out period. They broke up roughly into cuboids of some 20 cm in size. In order to determine how far the vertical cracks might extend below this level fissures bounding nearby polygons were seeded with barium sulphate. The site was box-cored down to a depth of 60 cm in June 1983, a time when seasonal cracking was still minimal. X-rays of the core showed barium sulphate filling cracks down to at least 23 cm below the surface and potential pathways with possible sulphate deposits to about double this depth. Analysis of the radioactivity of the corresponding core samples indicated the presence of short-lived ^{95}Nb ($\frac{t}{2}$ = 35 days) at a depth of 52.5 ± 2.5 cm in quantities just above the minimum detectable amount (MDA) (See later).

2.3.1.2 Discussion

Figure 13, taken at a site in the lower marsh, shows how surplus sediment can be extruded at ground level once the soil moisture deficit disappears and visual cracks close up. This implies deposition of material within the gap prior to that time. Hamilton and Clarke (1984, p 347) have also observed this phenomenon in the Eskmeals area. Thus it would appear that cracks may provide a preferential pathway for sediment as well as water. Bypassing effects have been recorded in other environments (eg Kneale and White, 1984), as has sediment particle transport even within the soil matrix (Pilgrim and Huff, 1983).

The fact that cracking may occur in areas of marsh which have been covered during the previous high tide lends support to the view of Ravina (1984, p 171) who wrote: 'It is noteworthy that cracking is strongly dependent ..... upon the rate of moisture change and not only its magnitude'. Ravina (1983) also commented upon the tendency of cracks to reappear in the same place. He attributed this to the reorientated clay platelets on the sheared surfaces which thereafter formed a plane of weakness.

Graham and Houlsby (1983) found that lightly overconsolidated natural clays are often anisotropic because of their mode of deposition. In their example the clay was ∿ 1.8 times stiffer in the horizontal than the vertical direction. It seems probable that a similar situation would exist in the Eskmeals area. The implications are that, firstly, vertical cracking would be relatively easy to develop and, secondly, that expansion and contraction horizontally would be likely to be larger and more rapid than that observed in a vertical direction with the EDM. This view is supported by the work of Johnson and Snethen (1978, p 118) who suggested that 'fissures may reduce lateral pressures and limit swell in the vertical direction to about one third of the volumetric swell'.

The need to discover the likely potential depth of cracks within the marsh was the result of the wide diversity of views and observations in the sedimentological literature (Allen, 1982). Allen tried to summarize these when he wrote (p 552): 'A useful rule of thumb is that polygon size is 3-8 times the crack depth ......'. In general the experience of soil scientists seems to differ from that of sedimentologists. For example, Reeve et al (1980, p 440) found that the 'magnitude of cracking varies according to soil type and soil moisture deficit but in extreme years can involve surface cracks 5 cm across and 1 m deep' in Britain. The features measured at the Eskmeals viaduct site are substantially deeper than the 'rule of thumb' and approach the size recorded by Reeve et al. It will be seen subsequently that a depth of 60 cm is a substantial proportion of the thickness of the marsh sediments.

2.3.2 Shear strength measurements and augering

A Pilcon direct-reading shear-vane was used to try and determine the nature of accretion of salt marsh sediments on the basis that steady deposition would correspond to progressive increases in shear strength as sediment compacted with depth. Initial trials, on the Newbiggin side of the R Esk, were encouraging with a marked change in shear strength of the silts corresponding to a visible discontinuity in the marsh sediments. However, when the technique was tried on the marsh northeast of the Eskmeals viaduct, results were less satisfactory. Measurements were taken at a depth of 18.5 cm using a 25 m grid which had been laid out by staff from the Institute of Terrestrial Ecology (ITE). The values obtained bore a close relationship to the drainage network of the marsh, but little else. When measurements were taken at greater depths there was no systematic pattern from one survey point to the next. This was attributed to the intermittent, and highly localised, presence of bands or lenses of sand within the more typical silt deposits. It was therefore decided to examine the nature of the interface between the silts and clays of the salt marsh and the underlying sands and gravels. Eleven sites were investigated by augering while cores were taken at 2 others. In the lower marsh the depth of transition varied from 0.4 m to > 1.2 m, with most values ∿ 1.0 m. In the upper marsh depths varied between 1.2 and 1.7 m with 3 out of the 4 showing narrow bands of sand above these levels. Three of the 11 augering sites were located in the creek system and hence boring was carried out from a lower surface height. Perhaps surprisingly, the OD level of the interface between marsh silt and underlying sands and gravels was little different from that obtained in adjacent auger holes taken from the vegetated marsh surface.

There are thus two points of note:

a) the thinness of the marsh silt and clay deposits.
b) the tendency to both lateral and vertical variations within those deposits.

2.3.3 Core analysis at transducer site

The main source of sedimentological information comes from a core collected close to the pressure transducer site in the lower salt marsh (Figure 1b). The core evidence was intended to shed light on the changes in pore water pressure and to provide samples for the analysis of radioisotopes levels by ITE. Mechanical analysis of the sediment was by sieving or pipette, as appropriate. A quarter-phi (ϕ) interval, (where $\phi = \log_{-2}$ mm) was used to 4ϕ and a 1ϕ interval thereafter to 10ϕ. Water and organic content were measured. Table 10 summarizes much of the data and analysis. It will be seen that the organic content drops progressively from the surface layer, where it is of the order of 10 per cent, to zero at 65 cm depth. It is the water contained within the plant roots that largely explains the very high water content of the upper samples in the profile (notably between 0-30 cm), although the higher proportion of clay there is also a factor. The next two columns of Table 10 show, firstly, how the transducer positions relate to the samples and, secondly, place the radioisotope data, which is examined more extensively hereafter, in context. The remainder of the table is given over to a breakdown of the particle size analysis. Almost all samples are bimodal, albeit the three lowest ones only 'vaguely' so; three samples are trimodal (40-45; 45-50; 55-60 cm). Because of the importance of the relation between fine grained material and radioactivity the final two columns record the percentage of sediment $< 6\phi$ (ie < 15.6 μm) and $< 7\phi$, (ie < 7.8 μm), respectively. Further detail, principally in the context of between-sample variability, is provided under the heading Distributions.

The data in Table 10 will be drawn upon in subsequent discussion.

2.3.4 Changes in the position of the river bank

Conventional topographic survey techniques were used to measure the position of the marsh 'cliff' face in July 1982, May 1983 and March 1984. During this period one of the main river channels has been directed close to the north shore of the estuary immediately E of the viaduct. Rates of erosion varied widely both over time (1982-83 compared with 1983-84) and along the length of the 250 m measured. In the first year the maximum retreat of the marsh cliff was approximately 2 m and recession was concentrated at the western (viaduct) end of the marsh. In the following year maximum erosion reached some 4 m and was almost entirely along the eastern length, although even here it could be minimal in places (eg in line with Section I (Figure 1b)). Much of the material that was eroded simply slumped down as an apron in front of the cliff and was sufficiently stable for abundant *Salicornia spp* to develop during the 1984 summer period.

Thus in this context, as in many others, it is the variability - even within a small compass - that is the striking feature of the River Esk salt marsh environment.

2.3.5 Evidence from cartographic sources and air photography

One approach to the calculation of sedimentation rates and the age of the salt marsh is by means of longer-term documentary records. Table C1 lists those maps which provide relevant information, together with the total vertical photographic coverage of the Eskmeals site.

2.3.5.1 Cartographic evidence

There were no Ordnance Survey maps and plans before the large scale mapping of the area in 1860. However there were the usual small scale surveys by, in this case Donald and Hodskinson in 1770-1, the Greenwoods in 1821-2 and, additionally, a large number of 'railway maps'. The first pertinent one of these was that of 1850; from 1854 onwards they were published almost on an annual basis until about the turn of the century. Railway maps showed lines in existence, under construction, and proposed. It is therefore possible to date the Eskmeals viaduct to between 1850 and 1854. The first large scale Ordnance Survey mapping in 1860 recorded some rudimentary salt marsh along the north shore of the estuary in the viaduct area; nevertheless the high water mark was drawn hard against the 'solid' land rather than across the stylised representation of vegetation between there and the river. By the survey revision of 1897 the salt marsh had substantially evolved so that high water mark was drawn close to its present position.

The record therefore suggests a dramatic change in the marsh boundaries between 1860 and 1897: the inescapable conclusion is that this is likely to have been caused by the building of the viaduct and the associated embankment. (An embankment which itself appears to have undergone some modification during that period presumably due to the double-tracking of the railway but possibly because of the initial need for protection from scour).

2.3.5.2 Air photography

Vertical cover exists for 1946, 1966, 1973 and 1980. That of 1946 is on an approximate scale of 1:10200, the other 3 flights are all at about 1:7500. Unfortunately, little information can be obtained from the 1946 flight because this coincides with high tide. The other surveys show only very slight changes in the outline of the upper salt marsh on the northern shore of the estuary; this stability also applies to the lower marsh east of the main N-S drainage creek (Figure 1b). However, there is evidence of detailed change in the area of that part of the lower salt marsh immediately south of Sections A to I. Much of the apparent difference is likely to be simply the effect of the covering of annual vegetation, the 1980 survey being taken at the end of the growing season while both earlier flights were taken much earlier in the year. Two real changes are nevertheless possible.

a) an increase in the density of vegetation mainly between 1966 and 1973, and -

b) the change in position of a major channel of the River Esk towards the north between 1973 and 1980. This appears to have resulted in erosion of the riverwards edge of the marsh over the intervening period, and indeed, thereafter (See above).

3. ANALYSIS OF RADIOACTIVITY IN SALT MARSH CORES

Incidental reference has been made already to the analysis of 2 cores from the salt marsh immediately northeast of the Eskmeals railway viaduct and embankment. These cores were taken near the transducer site in the lower marsh (Figure 1b) on 19 May, and in an area of soil polygons in the upper marsh on 17 June 1983, respectively.

The samples were taken at 5 cm intervals throughout the length of the cores. Any substantial fragments of root were removed prior to oven-drying in the laboratory at 90°C. The c 60 g samples were then ground and placed in plastic containers for gamma counting, which was carried out by the Institute of Terrestrial Ecology at their Merlewood, Cumbria, laboratory.

A complete gamma spectrum was obtained for each sample using a Ge(Li) detector shielded by 10 cm of lead. Counting times were a compromise between time available and sensitivity; 60 K second counts enabled nearly all the commonly occurring radionuclides to be quantified for at least part of the vertical depth of the cores. These radionuclides include ^{60}Co, ^{95}Nb, ^{95}Zr, ^{106}Ru, ^{125}Sb, ^{134}Cs, ^{137}Cs, ^{144}Ce, ^{154}Eu, ^{155}Eu and ^{241}Am. The gamma spectra were analysed by the Canberra Spectran-F system. It is, of course, impracticable to detect plutonium isotopes using gamma measurement techniques.

Table 11 lists the positive results together with those values below the minimal detectable amount (MDA) where they are relevant to the overall picture. Some of these data are shown in diagrammatic form in Figure 14. A comparable analysis for the soil polygon site forms Table 12.

It is clear from Tables 11 and 12 that only the naturally-occurring isotope ^{40}K and the caesium isotope ^{137}Cs exceed MDA throughout the whole profile. What is particularly interesting is the existence of detectable amounts of short-lived isotopes at depth. This applies to ^{95}Nb at the polygon site where, as has already been noted, its presence appears to be linked to residual vertical cracks in the soil.

It also applies at the transducer site. In the latter instance ^{95}Zr exceeds MDA in the sample centred on 82.5 cm below ground level, ^{106}Ru exceeds MDA in the samples centred on 82.5 and 87.5 cm, and ^{95}Nb exceeds MDA in samples centred at 72.5; 82.5 to 92.5, and again at 107.5 and 112.5 cm. The latter position corresponds to the base of the core. The profile for ^{137}Cs also suggests minor increases at comparable depths to those where positive values of ^{95}Nb were observed.

Figure 15 provides a comparison of the level of activity of the transducer site core with Hamilton and Clarke's (1984, p 358) Core 'A' from the south side of the estuary. For the present purpose the detailed 1 cm analyses of Core 'A' have been aggregated into units spaced at 5 cm intervals. While there are generally higher activity values recorded from the IOS/ITE (transducer) core there are only minor differences in the shape of the activity profile. However this similarity is restricted to the half-metre immediately below ground level and shown in the figure. Peaks, such as those recorded at greater depths in the transducer site core, do not appear to have been observed elsewhere. The fact that they are all from radioisotopes with short half-lives is significant. It implies a pathway from below (or, just possibly, laterally). Such a pathway has already been inferred from the pore water pressure data. Surface accretion is not a viable explanation.

Figure 16 examines the ^{137}Cs data at the transducer site. Not only does it show a close relationship with particle size but, more importantly, it demonstrates that the ^{137}Cs content is strongly correlated with the proportion of fines at each level of the core. The 'bulges' in the profile, as shown in Figure 17, correspond with the amount of clay within the respective sample (Table 10). Figure 16 also shows that, while there is a plausible correlation between water content and ^{137}Cs activity, this is not as good as that between particle size and ^{137}Cs. Since there is a relationship between water content and the finer sediment fraction some correlation between water and activity would be expected in any case. Good correlations also occur between the amount of ^{241}Am and the percentage of fine sediment present. However, other radionuclides either have too few samples exceeding MDA or, in the case of those with short half-lives, secondary peaks at greater depths complicate the issue.

4. RADIONUCLIDE CONTENT IN THE ESTUARIAL SEDIMENTS OF THE RIVER ESK AND MECHANISMS FOR DISTRIBUTION

4.1 Background

It is not the intention to attempt a review of the extensive body of literature already available concerning radionuclides, whether in the Irish Sea in general or specifically along its eastern coastline. However, it is necessary to set the data described earlier in this report in context.

The Windscale/Sellafield manufacturing and reprocessing plants have now been operating for over 30 years. Radioactive effluent discharges from the site commenced in 1952 (Mauchline, 1980) or 1953 (Assinder et al, 1984). Figures are available for discharges from 1957 onwards, although these data are not always complete (Table 13). The MAFF commenced a monitoring role in 1965 (Jefferies, 1970) and a substantial proportion of the reports and papers since that time have been produced under the aegis of that body. Other major reference sources have been the Institute of Marine Environmental Research (IMER); UKAEA; and the University of Lancaster. Papers fall broadly into those exclusively concerned with inter-tidal sites and those which treat such sites as part of a broader Irish Sea problem. They may also be divided into those which concentrate on the transuranics (especially plutonium) and others which discuss a wider range of fission products. Because of the relatively high proportions of caesium in the outfall effluent, and because caesium is present as both ^{134}Cs and ^{137}Cs isotopes, with apparently the same chemistry but with different half-lives (Hetherington and Jefferies, 1974, p 325), this element, along with the actinides, has been examined in particular detail.

It is difficult to calculate the proportion of radionuclides which have returned to the coast from offshore, partly because of the different behaviour of different elements, and of different chemical states of the same element, but also because of the absence of any form of total inventory for the environmental distribution of radioactivity. However, Hetherington et al (1975, p 200) have suggested that, in the case of plutonium, 'at least' 96% of that discharged from the BNFL site remains locked-up in the fine-grained seabed sediment nearby. Furthermore, Eakins et al (1984) have provided tentative estimates of the quantity of plutonium and americium in sediments of the estuary of the R Esk. Extrapolating from these figures it seems unlikely that as much as 1% of the transuranics have returned to the land so far. This proportion may well apply to other radionuclides, particularly non-conservative ones, such as ^{144}Ce. For conservative elements such as caesium where the residence time in the Irish Sea is relatively limited (Jefferies et al, 1982), or those where the half-life is short, the fraction eventually returning to the shore must be substantially less.

4.2 Lag time between discharge of radionuclides from Sellafield and incorporation into sediments in the Ravenglass estuary

Jefferies (1970) compared the ^{95}Zr + ^{95}Nb and ^{106}Ru radioactivity discharged from the (then) Windscale outfalls with the gamma dose rates over the mud flats and sandy beaches in the Ravenglass estuary. He concluded (p 207) that for ^{95}Zr + ^{95}Nb there was a delay of about 2 months. Hetherington and Jefferies (1974, p 323) used a serial correlation technique to estimate the length of time taken between the discharge of pulses of specific radionuclides from Windscale and their detection on the surface of the estuarine sediment of the River Esk. They concluded that in the case of ^{106}Ru, ^{144}Ce and ^{95}Zr + ^{95}Nb the best correlations were with lags of 1, 1, and 2-3 months, respectively ($p = 0.05$; $p > 0.5$; $p = 0.001$). They attributed the different lags to the varying times of injection and the ensuing environmental conditions. From this 'known' fact Hetherington (1976, p 101) argued that since the ^{239}Pu/^{238}Pu ratio of contemporary surface sediments and sea water were the same 'it is concluded that the ^{239}Pu/^{238}Pu ratios in the deeper sediment profiles in this area relate to the period during which they were deposited', ie the sedimentation rate is reflected in the activity profile. More recently, however, Stanners and Aston (1981, p 106) have suggested that the best fit between sedimentation rates and ^{137}Cs activity would be obtained by assuming a lag of 1.5 years between effluent discharge and incorporation within the sediments of the Esk estuary. This 'lag time .... is confirmed by other radionuclides and other Ravenglass cores ....'.

For plutonium Aston and Stanners (1981, p 581-2) believed there was a finite time lag of 2-3 years between discharge from Sellafield and deposition in the Ravenglass estuary. This longer period was attributed to a slower transit time, or to the 'clearance time', for sediments in the Irish Sea basin. Aston et al (in press) have described the within-estuary variability both of plutonium activity levels and of the ^{239}Pu/^{238}Pu ratio for contemporary sediment. They concluded that it was 'unlikely' that the annual sequence of plutonium isotope ratios from the surface sediments at Newbiggin could closely reflect the annual sequence or ratios in the Sellafield discharges.

Nevertheless, in general, the concept of the classic BNFL radionuclide profile as a measure of accretion remains (eg Hamilton and Clarke, 1984).

4.3 Diffusion and leaching

The concept that the annual effluent pattern from BNFL is reflected in cores taken through inter-tidal estuarine sediments is only credible if subsequent mobility of radionuclides and re-working of sediment can be shown to be insignificant.

Hetherington and Jefferies (1974, p 325) used the chemical similarity of ^{134}Cs and ^{137}Cs to calculate an apparent diffusion rate - ie a diffusion rate which allowed for such factors as bioturbation and sorption - for Ravenglass sediments. They estimated a figure of 4.2 cm yr^{-1}, and an apparent vertical diffusion coefficient of $\sim 10^{-6}$cm s^{-1} (= 31.5 cm yr^{-1}). Duursma and Gross (1971, p 154) noted that the apparent diffusion rate for ^{106}Ru in Windscale sediments was considerably higher than for Mediterranean ones. They attributed this to a higher level of biological activity. Hetherington and Jefferies (1974) thought the same explanation might apply to ^{137}Cs. However, Section 1.1 of this report indicated that various authors (including Hetherington, 1978) regarded biological processes as comparatively unimportant both in this type of environment and at this specific site. In the case of plutonium, Hetherington (1978) recognized that interstitial activity was reaching deeper sediment layers. He (p 264-5) dismissed diffusion as a mechanism because of the absence of a concentration gradient but thought that the other conceivable alternative, that of biological activity, was not very likely either. Stanners (1980, p 28) agreed that diffusion of ^{235}Pu, ^{239}Pu and ^{137}Cs was of 'negligible importance'.

One of the major difficulties is the question of sorption and desorption of radionuclides. Coughtrey and Thorne (1983) have reviewed the literature for the fission products. This helps to emphasise the differences between one radionuclide and another, for example in response to pH, salinity, and anoxic conditions. Ruthenium seems to exist in a number of different valency states and forms numerous complexes; Caesium and its radioisotopes appear to be associated with sediments to a far greater extent in fresh, as distinct from saline, water. This binding is related primarily to illite content. Kelly et al (1982) analysed a marsh clay sample from Newbiggin and found $\sim$ 70% illite (see Section 2.1.3).

Tamura (1964) discussed the highly-retentive nature that minerals, such as illite displayed for certain radionuclides in fresh water environments. In the case of

Chalk River, Canada, (p 262), ^{137}Cs moved some 84 m in 6 years, reducing to 2.1 to 2.3 m yr^{-1} by 1964. The movement of groundwater was $\sim$ 0.6 m d^{-1} (ie $\sim$ 225 m yr^{-1}). Although Tamura commented on the smallness of the dispersion of ^{137}Cs over time relative to the water movement, this distance is substantially greater than that calculated by Hetherington and Jefferies (1974) for diffusion in the Ravenglass area. There appears to be some evidence for the desorption of caesium as pH and salinity increases (eg Nishita et al, 1956; Patel et al, 1978) although Hetherington and Jefferies (1974) thought fission radionuclides were generally tightly bound to sediment.

Both Assinder et al (1984) and Eakins et al (1979; 1984) have noted that, under low salinities, water in the Ravenglass estuary appears to be enriched by plutonium (and americium). Eakins et al (1984) suggested that actinides may be leached from sediments in the estuary by fresh river water at low tide and by brackish water backed up on the incoming tide. (Offshore Pu mobility is thought to reflect a higher oxidation state (Livingston et al, 1982)). On the basis of evidence from a number of different locations Sholkovitz (1983, p 139) stated that 'evidence against Pu remobilisation is indirect and not convincing'. As Assinder et al (1984, p 30) said: 'The existence of a mechanism for release of plutonium from particulates at low salinities has wide implications, in that it suggests the possibility of mobilisation of plutonium stored in estuarine, and intertidal sediments generally by freshwater flushing, eg by percolating rainwater, groundwater ....'. Santschi et al (1983, p 201) have written: 'Many recent geochemical studies have employed radioisotopes .... to estimate rates of accumulation and/or bioturbation of coastal marine sediments. The underlying assumption is that these radionuclides are irreversibly attached to solid particles'. In experiments Santschi et al found that ^{134}Cs, ^{236}Pu, ^{241}Am and other radioiosotopes were removed from the water column more rapidly in the summer than during the winter; they attributed this mainly to biotic effects, although for ^{134}Cs they considered diffusion through the sediment-water interface was important.

Hetherington (1978, p 239) thought that there was no evidence for remobilisation of plutonium in the estuarine sediments; Aston and Stanners (1981, p 581) believed vertical redistribution of plutonium was 'exceedingly small'. Hamilton and Clarke (1984, p 379) wrote: 'Once transported and deposited in the sediments' .... ('non-conservative phases') .... 'do not appear to be remobilised'.

4.4 Accretion rates for salt marsh environments

Chapman (1960) discussed the general concept of measurement of rates of marsh accretion. She noted that the data tended to refer to 'isolated spots' on salt marshes. Most measurements relied on placing a layer of 'distinctive sand' on or near the marsh surface and subsequently coring down to this level. Chapman concluded that the rate of accretion was principally affected by the density and type of vegetation; the height of the marsh relative to sea level; and the distance from creeks. Stumpf (1983) cited examples of modern salt marshes having 'high' rates of sedimentation, ie between 0.15 cm yr^{-1} and 0.6 cm yr^{-1}. This was frequently from influx of inorganic sediment, not peat formation. Accretion was attributed to attempts by the marsh to maintain equilibrium with relatively rising sea level. Stumpf reported that areas with higher tidal ranges tended to have higher accretion rates. Again, as with the data reported by Chapman, these were largely the result of measurements above marker horizons. Thus no allowance was made for compaction of underlying sediment. Hence net accretion, relative to an absolute datum, is likely to have been overestimated. Dankers et al (1984) gave estimated accretion rates up to 1.7 cm yr^{-1} for the Dollard-Ems area of the Netherlands. Such high figures are primarily a response to reclamation works and reflect adjustments to the latter. Similar rates probably occurred in the Ravenglass estuary after the Eskmeals (and other) viaducts were constructed in the mid 19th century. As will be seen below much greater rates have been suggested for the Eskmeals-Newbiggin area.

Aston and Stanners (1982, p 169) suggested that 0.5 cm of sediment could have been deposited over one tidal cycle at their inter-tidal creek site at Eskmeals Pool on the Newbiggin shore of the River Esk. Hamilton and Clarke (1984, p 359) described the use of jute mats to measure short-term (2-3 days) accretion. On the basis of 6 'periods of tidal submergences' during September 1983 they calculated a mean annual deposition rate of 0.3 cm for the northern bank of the Esk and 0.5 cm for the southern; the mean density of the wet sediment was 1.3 gm ml^{-1}. Although Hetherington (1976, p 101-2) reports direct measurements at Newbiggin, which showed an accretion rate of $\sim$ 20 mm yr^{-1} ± 50% during 1972-74, most other calculations for sedimentation rely on the 'fingerprints' created by the unique combinations of radionuclides at any specific time as discharged from Windscale/Sellafield.

Apart from the prima facie evidence for the relationship between these 'fingerprints' and radionuclide profiles in cores there are other arguments which support an interpretation based upon sedimentation. Hetherington et al (1975, p 205) felt that, in the case of both offshore and inter-tidal core sites, only accretion could explain how 2 nuclides, plutonium and caesium, which had such different chemical properties, produced such similar depth profiles. They cited similar results in Buzzard's Bay (Noshkin, 1972). Unfortunately, Sholkovitz (1983) along with other workers interpret the Buzzard's Bay data differently, ie as preferential scavenging of Pu and the relative mobility of caesium. Hamilton (1983, p 181) considered that the laminae which were often present in the marsh deposits reflected annual sedimentation, analogous to varves (see Figure 18).

Hetherington (1976, p 101) suggested that the best agreement between activity profiles and accretion rates would be obtained by assuming an average deposition at Newbiggin of the order of 1.4 cm yr^{-1}. Already by 1978, Nunny (p 40) regarded as 'suspect' Hetherington's conclusion that the variation of plutonium (and by inference other radionuclides) with depth in offshore cores was primarily a function of sediment accumulation.

Aston and Stanners (1979, p 532) looked at the distribution of a range of radionuclides from their core NB-1. They concluded that the best match would correspond to a sedimentation rate of 67 mm yr^{-1} while 'any rate < 45 mm yr^{-1} is unreasonable'. In a later paper, concentrating mainly on plutonium in the Ravenglass estuary, Aston and Stanners (1981) calculated accretion for 3 cores as 13-16; 10-16 and 62-65 mm yr^{-1}. Sholkovitz (1983, p 142) has criticised these results on various grounds, ranging from disagreement as to the position of plutonium maxima in the cores to the absence of figures both for organic and water content and to demonstrate vertical homogeneity of the sediments. Stanners and Aston (1981) examined 7 cores in the Ravenglass estuary. Sedimentation rates determined by ^{137}Cs and $^{134}:^{137}Cs$ ranged between 0.25 and 71 mm yr^{-1}. Their method assumed a constant net sedimentation rate (p 101).

A series of papers by Clifton and Hamilton, 1982; Hamilton, 1983; Hamilton and Clarke, 1984, provide an indication of the variability which may occur; calculated sedimentation rates varying between 2 ± 1 mm yr^{-1} and 64 ± 22 mm yr^{-1}. Clifton and Hamilton (1982) suggested that the amount of annual deposition might vary within a profile. Hamilton and Clarke (1984) noted that erosion was possible.

4.5 Relationship of radioactivity to particle size and water content

The fact that radioactivity levels are higher in the salt marsh along the north bank of the River Esk than on the Newbiggin side may simply reflect the higher proportion of fine sediment in the former (see Table 10 of this report and eg Hetherington and Jefferies, 1974). Various workers (eg Hetherington and Jefferies, 1974; Hetherington et al, 1975; Hetherington, 1976; James et al, 1978; Aston and Stanners, 1982; Aston et al (in press); Assinder, 1983; Sholkovitz, 1983; Hamilton and Clarke, 1984) have commented upon the link between sediment particle size and the levels of radioactivity, and also between water content and activity (eg Jefferies, 1970; Hetherington and Jefferies, 1974; Stanners, 1980; Aston and Stanners, 1982). To some extent these relationships may reflect the responses of non-conservative and conservative radionuclides, respectively. However, the situation is rendered more complex because there is also a correlation between water content and particle size (Stanners, 1980, Aston and Stanners, 1982), bulk samples of fine sediment (clay and silt) containing higher percentages of water than sandier deposits. Water content is enhanced where organics are present in the marsh clayey-silts; percentage of water as a proportion of dry weight is then at a maximum. A further complication is the within-estuary variability referred to above (Aston et al, in press). Thus, at least in the case of plutonium, highest activity levels appear to be associated with the turbidity maximum in the estuary, not necessarily particle size.

The majority of the papers describing the relationship between radioactivity and particle size restrict the discussion to the surface or near-surface sediment (eg Aston and Stanners, 1982) and/or report their findings in a somewhat generalised way (eg that, for ^{241}Am, 'the finely divided silt' (sic) '(< 1 μm) has the highest specific activity which is only twice that of the coarser silt' (James et al, 1978, p 138)). However, Hetherington and Jefferies (1974); Hetherington et al (1975); Hetherington (1976, 1978); Stanners (1980); Clifton and Hamilton (1982); Assinder (1983); Hamilton and Clarke (1984); Aston et al (in press), amongst others, have examined cores through the sediment at their respective sampling sites. Hetherington and Jefferies (1974, p 324) cored down to depths of 25 cm and concluded that at their location there was no change in the proportions of particle sizes for samples taken within that depth range. This view was re-iterated for Newbiggin cores by Stanners (1980, p 345). Other researchers either give only the percentage of sediment less than a specific size for each depth sample (eg % < 63 μm (Assinder, 1983)) or publish no particle size data at all. For their core NB-1, Aston and Stanners

(1979) sampled down to a depth of 42 cm and carried out a grain-size determination for nine fractions, the smallest of which was 53 µm. Since most of the activity is contained in or on sediment < 63 µm (eg 99% of the plutonium is found on sediment < 63 µm (Aston et al, in press)) this classification is not particularly rewarding. Hamilton and Clarke (1984) appear to have cored to depths of a metre or more but detailed particle size data are lacking for their published results.

Assinder (1983, p 194) has made the interesting observation that the radioactivity-grain size correlations hold irrespective of the particular isotope involved. Using Assinder's data for core NB-1 it is possible to obtain significance levels of $p = 0.001$ for ^{144}Ce; and $p = 0.01$ for ^{106}Ru, ^{137}Cs, ^{238}Pu and ^{239,240}Pu. These result from taking $\log_n$ of the activity for each of 11 depths between 0-2 and 40-42 cm and the percentage of sediment < 63 µm.

For the transducer site core described in Section 3 of this report the best correlations are also found with $\log_n$ (rather than linear or exponential relationships) of the ^{137}Cs and ^{241}Am activity against the particle size. This would appear to provide useful support that ^{241}Am is not adsorbed onto the sediment surface but is ion-exchanged (James et al, 1978, p 138). It also supports the view that caesium may be preferentially absorbed into the illite lattice (Duursma and Bosch, 1970; Duursma and Eisma, 1973; Aston and Duursma, 1973). Hetherington and Jefferies (1974, p 331) assumed that particles were spherical, and plotted the log of the specific activity of the sediment against the log of the particle mean diameter. They interpreted the results as showing that the uptake of activity was a surface process; this held specifically for ^{95}Zr + ^{95}Nb, ^{106}Ru, ^{137}Cs and ^{144}Ce. Hetherington (1978, p 245) believed that both fission products and plutonium were adsorbed onto the surface of the sediment. Hamilton and Clarke (1984, p 377) also thought that plutonium and americium were adsorbed onto the surface, although hot-spot particles - fragments of reprocessed fuel rods containing plutonium, americium and curium - were also present (Hamilton, 1981). Correlations between $\log_n$ activity v particle size imply either a relation between volume (rather than surface area) and activity or that sediment particles are not spherical.

5. CONCLUSIONS

The previous Section of this report focussed attention on the diversity of view regarding such aspects as lag times, leaching, accretion rates, and the relation of radioactivity to particle size and to water content. While most of the references were directly relevant to the inter-tidal area of the Ravenglass estuary, some covered other sites and ranges of experience. Even those concepts which appeared to be widely accepted - such as the relationship between Windscale effluent nuclides and sedimentation profiles in the River Esk - seem suspect. Indeed, in discussing the matching of effluent and ^{239}Pu in cores Hetherington (1978) wrote that the 'evidence, although persuasive, remains circumstantial'.

Much of the difficulty would appear to centre around the spatial variability not only within the Esk as a whole (Aston et al, in press) but even within a space of 10^2m on the Newbiggin shore (Aston and Stanners, 1982). Horrill (1983, p 214) found that for just the surface of the marsh on the opposite, northern, bank: 'Variability within even a small area can be large ....'. The Esk estuary is not unique, as is clear from Nixon's review of coastal marsh research (Nixon, 1980, p 495). Although Nixon was writing at that point specifically about nitrogen his comment is more widely applicable: '.... field studies have shown that .... marsh .... is itself a complex metabolic mosaic, where not only the magnitude, but even the direction of net .... fluxes may vary widely over distances of a few metres'.

The data in Section 2 of this report for processes within the salt marsh area northeast of the Eskmeals viaduct give further evidence for variations within a short distance, whether horizontal or vertical. The minor seasonal elevational changes of creek sections A-I during 1982-84 contrast with horizontal and vertical erosion of $\sim$ 6 m and 1 m respectively for the river bank nearby. Similarly, the pore water pressures and apparent flow regime within the lower marsh varies markedly between spring and neap tides, and is subject to aberrations such as that due to precipitation coincident with low water on neap tides. The regime would be expected to be different in the higher marsh where water level at high tide on extreme neaps would not reach the interface between the underlying sands and gravels and the superimposed silts and clays. Horrill (1983) found a similar difference with respect to surface radioactivity. Highest levels of short-lived radionuclides were found on the lower marsh where tidal inundation was most frequent; highest levels of ^{241}Am, a long-lived isotope, were found on the upper marsh.

Soil polygons and associated vertical cracking provide local bypassing mechanisms for radionuclides - in this case specifically ^{95}Nb - to reach sub-surface levels rapidly. ^{95}Zr, ^{95}Nb and ^{106}Ru were all detected at depth in a core from near the transducer site (Figure 1b) and are thought to reflect infiltration upwards.

(Quantities are, however, much smaller than near the top of the profile.) The experience here varies from that of Hamilton and Clarke (1984) who invariably found short-lived radionuclides restricted to the surface sediment.

The relatively short time since the railway viaducts of the Ravenglass estuary were constructed; the changing channels of the River Esk; the erosion of banks of fringing marshes; and the general reworking of the sedimentary deposits all add emphasis to Nunny's (Nunny, 1978, p 32) belief that salt marshes are not efficient as long-term sinks. Hamilton (1983, p 178) believed it was necessary to predict the fate of radionuclides over timespans of 500-1000 years. Hunt and Jefferies (1981, p 535) used a truncation period of 10,000 years. During the past 10,000 years eustatic rise in sea level is thought to have been about 25 m (Flemming, 1982) or more (West, 1977).

There are other problems. Calles (1983, p 165) has observed that the settling behaviour of a resuspended sediment is very different from 'first time' settling behaviour. Duursma and Bosch (1970, p 466) stated: 'Drying irreversibly decreases the capacity of re-wetted sediment to absorb radionuclides'.

Another aspect causing difficulty is site specific. Although Assinder (1983) found sites in the Esk estuary where plutonium levels exceeded by more that 4 times those of the Newbiggin site in 1977 it appears that these values may be exceptional. If so it is difficult to explain how plutonium effluent from Windscale, with its very long half-life, could increase (again by 4 times) without any increase in the percentage in the sediments (Hetherington, 1976, p 94) or with a disproportionately small increase (Woodhead, 1984, p 1184).

While it may not be necessary to invoke 'yet unknown mechanisms' (Kautsky and Murray, 1981, p 85) it is apparent that, in the case of the inter-tidal sediments of the Ravenglass estuary, increasing research has diminished, rather than confirmed, the apparent concensus of opinion of a decade ago. There is therefore a parallel with the situation offshore (Smith et al, 1980; Kirby et al, 1983) where the picture has also proven to be more complex than assumed initially.

Further research is essential if only to establish the relative importance of the multiplicity of factors operative within the estuary of the River Esk and other similar locations.

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Table 1 : Trends in changes in height of marsh surface (direction only, not magnitude) between surveys.

Survey Nos:	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	9/10	10/11	11/12	12/13	13/14	14/15	15/16	16/17	17/18	18/19
1982	May-July	July-Sept	Sept-Nov	Nov-Jan	Jan-Feb	Feb-Mar	Mar-Apr	Apr-May	May-June	June-July	July-Aug	Aug-Sept	Sept-Oct	Oct-Nov	Nov-Dec	Dec-Jan	Jan-Mar	Mar-May 1984
Section	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -	+ -
A	10 10	7 20 (+1)	25 3	21 7	19 9	12 16	15 13	5 23	12 16	5 23	14 14	14 14	21 7	21 7	18 10	13 15	16 12	12 15 (+1)
C	10 20 (+1)	9 34	41 2	22 21	16 27	29 14	28 15	11 32	9 34	8 35	17 23	18 22	19 24	25 17 (+1)	35 7 (+1)	17 24 (+2)	19 19 (+5)	12 27 (+4)
E	16 24	3 41	44 0	33 11	29 15	32 12	26 18	4 40	11 33	8 36	15 29	26 17 (+1)	31 12 (+1)	28 16	41 3	6 37 (+1)	21 18 (+5)	3 41
G	12 44	10 50	59 4	56 7	51 11 (+1)	8 54 (+1)	59 4	58 5	2 61	12 50 (+1)	43 20	26 37	52 11	45 18	62 1	11 50 (+2)	12 46 (+5)	0 63
I	3 61	23 50	73 0	66 9	70 4	6 68	40 35	15 60	5 69 (+1)	33 42	45 28 (+2)	39 36	39 36	61 13 (+1)	67 6 (+2)	6 69	26 45 (+4)	6 69
Totals:	51 159	52 195	242 9	198 55	186 66	87 164	168 85	93 160	39 213	66 186	134 114	123 126	162 90	180 71	203 27	53 195	94 140	33 215
% accretion =	24.3	20.1	96.4	78.3	73.8	34.5	66.4	36.8	15.5	26.2	54.0	49.3	64.3	71.7	88.3	21.4	40.2*	13.3

Data abstracted from interpolated values. Figures shown as (+2) = number of data points showing no change between successive surveys.

Where totals ≠ 253 means field data points missing (especially on earliest surveys where banks not surveyed).

[* 72 out of 253 values are marginal (ie ± 0.2 cm)].

TABLE 2

RAVENGLASS : CHANGES BETWEEN SURVEYS (cm)

	SECTION (complete)						SECTION (excluding parts* of banks)				
SURVEY**	A	C	E	G	I		A	C	E	G	I
1-2	+1.2	-0.9	-0.1	-0.8	-0.9		+0.6	-0.9	-0.1	-0.5	-0.9
2-3	-1.1	-0.6	-1.7	-0.5	-0.3		-0.5	-1.2	-1.3	-0.5	-0.3
3-4	+1.9	+2.6	+3.5	+1.7	+2.9	Limit of full profiles	+2.4	+2.3	+2.8	+2.4	+2.9
4-5	+0.7	0.0	0.0	+1.2	+0.7		+0.3	+0.3	0.0	+0.9	+0.9
5-6	-0.2	+0.2	+0.7	+1.0	+1.3		+0.4	+0.2	+0.4	+0.6	+1.1
6-7	-1.3	+0.1	-0.1	-0.7	-1.0		-0.2	+0.3	-0.1	-0.6	-1.0
7-8	+1.8	-0.2	+0.3	+0.9	+0.1		-0.2	0.0	+0.3	+0.8	+0.1
8-9	-1.5	-0.8	-1.4	-0.9	-1.0		-1.1	-0.8	-1.4	-0.9	-0.6
9-10	-0.6	-0.1	0.0	-1.1	-0.8		-0.1	-0.1	0.0	-1.1	-1.2
10-11	-1.0	-0.8	-0.9	-0.5	-0.2		-1.0	-0.4	-0.6	-0.5	-0.2
11-12	+0.2	+0.3	0.0	+0.3	+0.4		-0.1	-0.1	0.0	+0.3	+0.4
12-13	0.0	-0.3	0.0	-0.2	0.0		0.0	-0.1	0.0	-0.2	0.0
13-14	+0.5	0.0	+0.5	+0.5	+0.1		0.0	-0.2	+0.5	+0.5	+0.1
14-15	+0.1	+0.1	+0.3	+0.2	+0.3		-0.2	+0.1	+0.3	+0.2	+0.5
15-16	+0.6	+0.7	+1.5	+1.4	+1.8		+0.6	+0.7	+1.3	+1.2	+1.7
16-17	0.0	-0.1	-1.1	-0.8	-1.0		0.0	-0.1	-0.8	-0.6	-1.2
17-18	-0.8	-0.2	0.0	-0.6	-0.6		-0.4	-0.2	0.0	-0.3	-0.3
18-19	+0.1	-0.2	-1.0	-0.6	-1.2		+0.1	-0.2	-1.0	-0.9	-1.0
a)net change	+0.6	-0.2	+0.5	+0.5	+0.6						
b)net change as calculated by survey (19-1)	+0.5[ø]	-0.5[ø]	+0.4[ø]	+0.9[ø]	+0.8[ø]						

*variable

[ø] differences between (a) and (b) are due mainly to vegetated ends of profiles not being measured on early surveys.

** for dates see Tables 1 or 3

Changes between Surveys 1 and 2; 2 and 3; 3 and 4; 4 and 5; 17 and 18; 18 and 19 cover bimonthly periods and therefore should be double the magnitude of other (monthly) variations assuming continuous trends within comparison periods.

TABLE 3

RAVENGLASS : BIMONTHLY AND 'SEASONAL' ANALYSIS OF CHANGE : WHOLE SECTIONS (cm)

	Section						Section				
	A	C	E	G	I		A	C	E	G	I
Survey											
1-2	+1.2	-0.9	-0.1	-0.8	-0.9	May-July 1982	+0.1	-1.5	-1.8	-1.3	-1.2
2-3	-1.1	-0.6	-1.7	-0.5	-0.3	July - Sept					
3-4	+1.9	+2.6	+3.5	+1.7	+2.9	Sept - Nov	+1.0	+2.9	+4.0	+3.2	+3.9
4-5	+0.7	0.0	0.0	+1.2	+0.7	Nov - Jan					
5-7	-1.6	+0.3	+0.5	+0.3	+0.3	Jan-March 1983					
7-9	+0.2	-1.0	-1.1	0.0	-1.1	March - May	-1.4	-1.9	-2.0	-1.6	-2.1
9-11	-1.6	-0.9	-0.9	-1.6	-1.0	May - July					
11-13	0.0	+0.1	0.0	+0.1	+0.4	July - Sept	+1.3	+0.8	+1.1	+1.3	+1.6
13-15	+0.6	+0.1	+0.7	+0.6	+0.4	Sept - Nov					
15-17	+0.7	+0.6	+0.4	+0.6	+0.8	Nov - Jan					
17-18	-0.8	-0.2	0.0	-0.6	-0.6	Jan-March 1984	-0.7	-0.4	-1.0	-1.2	-1.8
18-19	+0.1	-0.2	-1.0	-0.6	-1.2	Mar - May					

TABLE 4

RAVENGLASS : CHANGES PER SECTION BETWEEN DESIGNATED SURVEYS (cm)

	SECTION					
SURVEY	A	C	E	G	I	
July 82 - July 83	-1.3*	+0.3	+0.3	+1.1	+1.7	
Sept 82 - Sept 83	-0.1	+0.9	+2.1	+1.7	+2.4	Sept 82 profiles abnormally low
Nov 82 - Nov 83	-1.4	-1.5*	-0.7	+0.6	-0.2	*Substantial areas of change on N Bank
Jan 83 - Jan 84	-1.4	-0.9	-0.4	0.0	-0.2	
March 83 - March 84	-0.6	-1.4	-0.9	-0.9	-1.1	
May 83 - May 84	-0.8	-0.5	-0.7	-1.5	-1.3	
May 82 - May 84	+0.5	-0.5	+0.4	+0.9	+0.8	Values for C, G and I appear greater than net (bi)-monthly change because of different end limits on different surveys.

Table 5 Ravenglass : pore water pressures - data availability

		Transducer No:						
		1	2	3	4	5	6	Notes
Date (1983)	n =	2.73	2.56	2.42	2.27	2.13	0.96	m OD
21 Jan pm -1 Feb am	21	x	x	x	x	x	x	Transducer #6 installed in river
								Cables for 1-5 cut. Data for transducer #6 available over intermediate period
6 March pm -21 Mar pm	30		x	x	x	x	x	Cables restored
22 Mar am -18 Apr pm	54	x		x	x	x	x	
19 Apr am -18 May am	57		x	x	x	x	x	
18 May pm -16 June am	56	x	x	x	x	x	x	
16 June pm -18 July am	61	x	x	x	x	x	x	
18 July pm -15 Aug am	54	x	x	x	x	x	x	
15 Aug am -13 Sept am	56	x	x	x	x	x	x	
13 Sept pm -10 Oct pm	53	x	x	x	x	x	x	
11 Oct am -9 Nov pm	58	x	x	x	x	x	x	
10 Nov am -11 Dec am	61	x	x	x	x	x	x	
11 Dec pm -11 Jan am (1984)	60	1-29	x	1-9; 45-60(?)	1-29	1-20	1-45	

n = no. of high waters

In addition data are available for Transducers 1-5 over most of the period from 27 October 1982 to 21 January 1983

TABLE 6 Mean delay times in minutes for transducers #1-5 relative to river high water. Positive pore pressure on Transducer #1, and water level at Transducer #6 > 2.75 m OD

Dates 1983	n =	Transducer #:				
		1	2	3	4	5
21 Jan-2 Feb	13	15.23	17.54	16.62	15.23	14.31
18 May-16 June	38	11.84	20.37	14.53	15.63	14.68
16 June-18 July	44	7.64	21.27	17.32	17.73	16.77
18 July-15 Aug	35	6.17	12.17	11.49	14.74	14.06
15 Aug-13 Sept	40	9.30	18.90	16.65	17.55	17.10
13 Sept-10 Oct	38	12.00	21.79	16.26	15.79	15.32
11 Oct-9 Nov	47	16.32	25.40	18.26	19.79	19.02
10 Nov-11 Dec	46	17.35	29.96	20.61	18.39	17.09

This table is a simplified version of that which appears as Appendix Table B1 of this report. Detailed explanatory notes will be found there.

Table 7 Delay times for transducers relative to river high water. Positive pore pressure on Transducer #1 and Transducer #6 > 2.75 m O.D water level.

Totals to 11 December 1983

	n =	Transducer No: 1	2	3	4	5	
a)	338(336)	365(319½)	-	491(466)	492½(474½)	472(455)	All records incl 22 Mar - 18 Apr
b)		12.96(11.41)	-	17.43(16.64)	17.49(16.95)	16.75(16.25)	Values in () exclude events [2 & 26]
a)	301	279½	522	418½	430½	410)	All data excl 22 Mar - 18 Apr
b)		9.29	20.81	16.68	17.16	16.35)	
a)	277	199	376	349½	368½	352)	Excludes 18 abnormal delay times (ie results are 'typical')
b)		8.62	16.29	15.14	15.96	15.25)	
a)	24	100½	146	69	62	58)	Abnormal delay times as listed in Table B1
b)		50.25	73.00	34.50	31.00	29.00)	

Rows a) Total delay time in 12 minute sampling units; (total excluding 'long' delays).

b) Mean time in minutes for total no. of units; (mean time excluding 'long' delays).

Table 8

Delay times for those occasions where Transducer 1 has negative pore pressure and river transducer height ≤ 2.75 m OD.

Date (1983)		Transducer No:				
	n =	2	3	4	5	
21 Jan-1 Feb	5	29	16½	15	13	
		69.60	39.60	36.00	31.20	
6 Mar-21 Mar	10	>>>16	47½	45½	43½	Provisional - no data on #1
		-	57.00	54.60	52.20	
22 Mar-18 Apr	15	-	68½	60	57	No data on #2
		-	54.80	48.00	45.60	
19 Apr-18 May	14	>>72	59	53	48½	Provisional - no data on #1
		-	50.57	45.42	41.57	
18 May-16 Jun	13	>>32½	>54	>46½	48½	1 event indeterminate on #'s 3 and 4
		-	>49.85	>42.92	44.77	
16 Jun-18 Jul	12	>>36	46½	42½	37½	
		-	46.50	42.50	37.50	
18 Jul-15 Aug	16	>>30½	58½	52	49½	
		-	43.88	39.00	37.125	
15 Aug-13 Sept	14	>62	49	40	36	Includes 2 '+ve' rainfall events on #1
		-	42.00	34.29	30.86	
13 Sept-10 Oct	11	63½	42½	37½	36	
		69.27	46.36	40.91	39.27	
11 Oct-9 Nov	7	38½	24½	21	20	
		66.00	42.00	36.00	34.27	
10 Nov-11 Dec	12	>>>27	>>36½	>>33.0	50½	
		-	-	-	50.5	
Totals to 11 Dec.	129	-	>>503	>>446	440	units
$\bar{x}$ delay =		-	>>46.8	>>41.5	40.9	minutes

Upper row for each period lists total delay time in 12 minute sampling periods.
Lower row for each period lists mean delay time in minutes.

Compare these values with the Abnormal Delay Times for Positive Pore Pressure for Transducer #1 in Table 7.

Table 9

Delay times for all available data between 21 January and 11 December 1983 for transducers 3 to 5 (Minutes)

Date (1983)		Transducer No:			
	n =	3	4	5	
21 Jan-1 Feb	21	25.1	22.0	19.7	
6 Mar-21 Mar	30	34.0	31.0	29.4	
22 Mar-18 Apr	54	32.4	28.4	27.4	
19 Apr-18 May	57	30.3	26.2	24.2	
18 May-16 Jun	55	24.9*	22.9*	21.6	*+1 event indeterminable ∴ omitted for all
				(22.3)	(includes all 56 data points for #5)
16 Jun-18 Jul	61	24.7	23.6	21.6	
18 Jul-15 Aug	54	23.4	23.3	22.1	
15 Aug-13 Sept	56	22.8	21.8	20.0	
13 Sept-10 Oct	53	23.5	21.7	20.9	
11 Oct-9 Nov	58	22.8°	23.0	21.2	°result of 1 anomalously low reading
10 Nov-11 Dec	58	25.3^{+}	22.8^{+}	21.4	$^{+}$3 events undeterminable ∴ omitted for all
				(23.9)	(includes all 61 data points for #5)
Totals	557	26.0	24.1	22.5	

On all occasions the delay is least on #5 and where data are available it is greater still on #2 (see eg Table 6)

Table 10 Ravenglass : Core at transducer site

Ground level = 2.985 m OD

Sample depth (cm)	Centred on (m OD)	% organic	Water content as % dry wt	Transducer hts (m OD)	Radioisotope data	Particle size data Modes (φ)	Distributions (φ)		% a	% b
0-5	2.96	10	52		Ru^{106} max. All detectable amounts of isotopes begin at surface except Sb^{125} and Cs^{134}=10-15 cm.	6.0; 10.0	5-7=51%; 10=29% 5-10=92%; 3.75-10=98%		52	41
5-10	2.91	8	55			5/6.0; 10.0	5-7=51%; 10=27% 5-10=92%; 3.75-10=98%		52	41
10-15	2.86	7	53		Lower limit Ce^{144}	5/6.0; 10.0	5-7=42%; 10=35% 3.75-10=97%		60	48
15-20	2.81	8	51		Cs^{137} peak (present throughout core)	5/6.0; 10.0	5-7=49%; 10=30% 5-10=93%; 3.75-10=97%	Bimodal	56	43
20-25	2.76	6	55	←#1=2.73	Am^{241} peak (present 0-55 cm). Lower limit Sb^{125}	5/6.0; 10.0	5-7=50%; 10=31% 5-10=95%; 3.75-10=98%		61	45
25-30	2.71	5	50		Lower limit Co^{60}; limit top zone Ru^{106}	5/6.0; 10.0	5-7=44%; 10=33% 5-10=93%; 3.75-10=98%		61	49
30-35	2.66	5	43		Lower limit Eu^{154}; limit top zone Nb^{95}, Zr^{95}	5.0; 10.0	5-7=52%; 10=27% 5-10=88%; 3.75-10=94%		48	36
35-40	2.61	4	33		Lower limit Eu^{155}	5/6.0; 10.0	5-6=29%; 10=22% 2.75-10=<100%		42	33
40-45	2.56	4	40	←#2=2.56		2.75; 5.0; 10.0	2.75=12%; 5.0=18%; 10=17%; 2.75-7.0=77%; 2.75-10=99%	Trimodal	29	22
45-50	2.51	3	30			3.0-3.50; 6.0; 10.0	2.75-3.75=52%; 6.0=12%; 10=17%; 2.75-10.0=99%		27	23
50-55	2.46	2	31		Lower limit Cs^{134} (intermittent above)	2.75-3.25; 10.0	2.75-3.75=67%; 10=12%; 2.75-10.0=97%	Bimodal	19	16
55-60	2.41	2	30	←#3=2.42		3.0-3.25; 5.0; 10.0	2.75-3.75=53%;4.0-6.0=23% 10=12%; 2.75-7.0=81% 2.75-10=98%	Trimodal	21	17
60-65	2.36	1	27		General minimum for activity (except Cs^{137})	3.25; 10.0	2.75-4.0=76%;10=8% 2.75-10=97%		14	12
65-70	2.31		24			2.75; 10.0	2.50-3.50=67%;10=6% 2.50-5.0=87%;2.50-10=98%		10	8
70-75	2.26		26	←#4=2.27	Nb^{95}	2.75; 10.0	2.50-3.25=75%;10=6% 2.50-4.0=87%;2.5-10=98%		9	7
75-80	2.21		27			2.75; 10.0	2.50-3.25=76%;10=5% 2.50-4.0=88%;2.50-10=98%	Bimodal	8	7
80-85	2.16		24	←#5=2.13	Ru^{106} secondary) Nb^{95} Zr^{95} peaks)	2.75; 10.0	2.50-3.25=77%;2.50-4.0=86% 10=7%;2.50-10=97%		11	9
85-90	2.11		26		Ru^{106}, Nb^{95}	2.75; 10.0	2.25-3.25=86%; 10=4% 2.0-10.0=99%		5	4
90-95	2.06		28		Nb^{95}	2.75; 10.0	2.25-3.0=74%; 10=4% 2.0-10.0=99%		5	4
95-100	2.01		29		Nb^{95} Lower zone	2.75; 10.0	2.25-3.0=79%; 10=3% 2.0-10.0=99%		3	3
100-105	1.96		27			2.75;10.0	2.25-3.0=84%; 10=2% 2.0-10.0=98%	Vaguely bimodal	2	2
105-110	1.91		24		Nb^{95}	2.75; 10.0	2.25-3.0=82%; 10=2% 2.0-10.0=97%		2	2
110-115	-		-		Nb^{95}	-	-			

a = % < 15.6μm
b = % < 7.8 μm

Notes
1. Radioactivity - Radioisotopes listed exceed Minimum Detectable Amount (MDA).
2. Sediments - phi (Ø) grades refer to sieve (etc) trapping sediment of that size and up to next coarsest category. Quarter-phi units to 4 Ø; whole phi units from 4 to 10 Ø. (1 Ø = 0.500 mm; 2 Ø = 0.250 mm; 3 Ø = 0.125 mm; 4 Ø = 0.0625 mm; 5 Ø = 0.0313 mm; 6 Ø = 0.0156 mm; 7 Ø = 0.0078 mm; 8 Ø = 0.0039 mm; 9 Ø = 0.0020 mm; 10 Ø = 0.0010 mm; ie Ø = $\log_{-2}$ mm).

Table 11 : Ravenglass : radioactivity for core near transducer site

t/2 =	458 yr	285 d	5.26 yr	30.23 yr	16 yr	1.81 yr	1.28 x 10^7 yr	35 d	1.0 yr	65 d	2.7 yr	2.05 yr
Sample depth	AM-241	CE-144	CO-60	CS-137	EU-154	EU-155	K-40	NB-95	RU-106	ZR-95	SB-125	CS-134
0-5 cm	2.23E-04	2.85E-05	3.91E-06	4.42E-04	2.44E-05	1.33E-05	2.32E-05	3.58E-06	5.01E-04	1.93E-06		<3.94E-07
	8.25	1.05	0.14	16.35	0.90	0.49	0.86	0.13	18.54	0.07		<0.01
5-10	2.98E-04	2.00E-05	4.88E-06	5.12E-04	2.46E-05	1.86E-05	2.25E-05	4.71E-07	3.15E-04	5.90E-07		<3.90E-07
	11.03	0.74	0.18	18.94	0.91	0.69	0.83	0.02	11.66	0.02		<0.01
10-15	2.91E-04	6.62E-06	6.27E-06	5.54E-04	2.36E-05	1.78E-05	2.30E-05	<2.63E-07	8.85E-05	1.88E-06	1.07E-05	9.32E-06
	10.77	0.24	0.23	20.50	0.87	0.66	0.85	<0.01	3.27	0.07	0.40	0.34
15-20	5.02E-04	<2.31E-06	9.31E-06	7.08E-04	2.03E-05	1.55E-05	2.25E-05	<2.62E-07	2.96E-05	1.67E-06	8.46E-06	1.06E-05
	18.57	<0.09	0.34	26.20	0.75	0.57	0.83	<0.01	1.10	0.06	0.31	0.39
20-25	9.53E-04	<2.16E-06	9.14E-06	6.04E-04	2.36E-05	1.73E-05	2.40E-05	3.98E-07	1.19E-05	1.01E-06	7.01E-06	8.33E-06
	35.26	<0.08	0.34	22.35	0.87	0.64	0.89	0.01	0.44	0.04	0.26	0.31
25-30	5.75E-04	<1.89E-06	1.80E-06	4.37E-04	1.79E-05	1.27E-05	2.51E-05	4.49E-07	4.14E-06	9.09E-07	<1.28E-06	8.82E-06
	21.28	<0.07	0.07	16.17	0.66	0.47	0.93	0.02	0.15	0.03	<0.05	0.33
30-35	2.66E-04	<1.56E-06	9.09E-07	2.55E-04	4.07E-06	2.23E-06	2.30E-05	5.00E-07	<2.15E-06	2.57E-07	<9.83E-07	2.71E-06
	9.84	<0.06	0.03	9.44	0.15	0.08	0.85	0.02	<0.08	0.01	<0.04	0.10
35-40	7.37E-05	<1.34E-06	<1.81E-07	1.40E-04	<1.40E-06	9.79E-07	2.29E-05	<1.90E-07	<1.78E-06	<2.75E-07	<7.74E-07	1.26E-06
	2.73	<0.05	<0.01	5.18	<0.03	0.04	0.85	<0.01	<0.07	<0.01	<0.03	0.05
40-45	4.51E-05			1.02E-04		<8.34E-07	2.21E-05					8.61E-07
	1.67			3.77		<0.03	0.82					0.03
45-50	8.05E-06			3.55E-05			1.93E-05					<1.94E-07
	0.30			1.31			0.71					<0.01
50-55	1.52E-05			4.36E-05			1.86E-05					4.83E-07
	0.56			1.61			0.69					0.02
55-60	<1.87E-06			1.45E-05			1.76E-05					<1.74E-07
	<0.07			0.54			0.65					<0.01
60-65				1.15E-05			1.74E-05					
				0.43			0.64					
65-70				9.95E-06			1.53E-05	<2.09E-07				
				0.37			0.57	<0.01				
70-75				8.39E-06			1.61E-05	4.74E-07				
				0.31			0.60	0.02				
75-80				6.02E-06			1.71E-05	<1.97E-07	<1.11E-06	<2.69E-07		
				0.22			0.63	<0.01	<0.04	<0.01		
80-85				6.57E-06			1.75E-05	4.30E-06	5.59E-06	1.45E-06		
				0.24			0.65	0.16	0.21	0.05		
85-90				3.69E-06			1.52E-05	1.36E-06	1.46E-06	<3.00E-07		
				0.14			0.56	0.05	0.05	<0.01		
90-95				2.19E-06			1.35E-05	6.24E-07	<1.12E-06	<2.95E-07		
				0.08			0.50	0.02	<0.04	<0.01		
95-100				2.24E-06			1.39E-05	<2.54E-07	<1.20E-06	<3.28E-07		
				0.08			0.51	<0.01	<0.04	<0.01		
100-105				1.66E-06			1.27E-05	<2.25E-07	<1.06E-06	<2.95E-07		
				0.06			0.47	<0.01	<0.04	<0.01		
105-110				1.65E-06			1.43E-05	4.57E-07	1.10E-06	<3.04E-07		
				0.06			0.53	0.02	<0.04	<0.01		
110-115				2.74E-06			1.58E-05	8.12E-07	1.07E-06	<2.98E-07		
				0.10			0.58	0.03	<0.04	<0.01		

Activity is given in µC gm^{-1} and Bq.gm^{-1} for upper and lower row for each sample depth respectively.

Table 12 : Ravenglass : radioactivity for core near polygon site

Sample depth	AM-241	CE-144	CO-60	CS-137	EU-154	EU-155	K-40	NB-95	RU-106	ZR-95	SB-125	CS-134
0-5	2.90E-04	7.99E-06	4.11E-06	5.40E-04	1.63E-05	1.09E-05	2.01E-05	2.63E-06	9.45E-06	1.41E-06	6.04E-06	1.01E-05
	10.73	0.30	0.15	19.98	0.60	0.40	0.74	0.10	3.50	0.05	0.22	0.37
5-10	2.27E-04	<1.52E-06	1.62E-06	3.67E-04	7.32E-06	4.61E-06	1.91E-05	6.00E-07	9.70E-06	3.10E-07	<1.04E-06	5.19E-06
	8.40	<0.06	0.06	13.58	0.27	0.17	0.71	0.02	0.36	0.01	<0.04	0.19
10-15	2.67E-05	<1.01E-06	3.85E-07	1.15E-04	<9.62E-07	<6.32E-07	1.91E-05	<1.33E-07	<1.37E-06	<1.88E-07	<6.03E-07	1.60E-06
	0.99	<0.04	0.01	4.26	<0.04	<0.02	0.71	<0.005	<0.05	<0.01	<0.02	0.06
15-20	1.09E-05		3.06E-07	8.13E-05			2.19E-05	5.43E-07	2.29E-06			1.25E-06
	0.40		0.01	3.01			0.81	0.02	0.08			0.05
20-25	2.79E-06		<1.09E-07	2.36E-05			1.98E-05	<1.31E-07	<9.37E-07			3.49E-07
	0.10		<0.005	0.87			0.73	<0.005	<0.03			0.01
25-30	1.34E-06			9.38E-06			1.77E-05					1.10E-07
	0.05			0.35			0.65					0.005
30-35	<1.17E-06			3.94E-06			1.96E-05					<1.20E-07
	<0.04			0.15			0.73					<0.005
35-40				2.00E-06			1.96E-05					
				0.07			0.73					
40-45				1.03E-06			1.98E-05					
				0.04			0.73					
45-50				1.29E-06			2.05E-05	<1.67E-07				
				0.05			0.76	<0.01				
50-55				1.22E-06			1.83E-05	4.14E-07				
				0.05			0.68	0.02				
55-60				1.19E-06			2.03E-05	<1.97E-07				
				0.04			0.75	<0.01				

Activity is given in $\mu C.gm^{-1}$ and in $Bq.gm^{-1}$ for upper and lower row for each sample depth respectively.

Year	Annual Discharge (Curies)												
	^{90}Sr	^{95}Zr	^{95}Nb	^{103}Ru	^{106}Ru	^{134}Cs	^{137}Cs	^{144}Ce	$^{238+239+240}Pu$	^{241}Pu	^{241}Am	Total α	Total β*
1957	1644	708	6420	3600	26616	NA	3720	2580	NA	NA	NA	57.6	64392
1958	2520	2520	6120	5904	42264	NA	6192	5964	NA	NA	NA	62.4	82152
1959	1548	4980	10140	8952	35472	NA	1980	6996	NA	NA	NA	67.2	91908
1960	516	2352	6276	11568	39624	NA	912	768	96	NA	NA	81.6	77532
1961	492	1680	7896	3180	25140	NA	1092	2160	144	NA	NA	133.2	47772
1962	1020	936	4272	1836	22992	NA	1104	2400	192	NA	NA	186.0	44904
1963	552	564	3264	9600	33372	NA	372	1392	240	NA	NA	228.0	48240
1964	972	21560	20880	1200	24504	NA	2800	3216	288	NA	NA	282.0	60660
1965	1512	17480	32200	1800	20148	NA	2960	3888	300	NA	NA	405.6	54720
1966	912	14080	23360	NA	24924	NA	4890	6852	300	NA	NA	NA	NA
1967	1392	18800	25720	NA	17232	NA	4050	13704	492	NA	NA	NA	NA
1968	1356	28080	37160	NA	24204	NA	10040	9960	828	NA	576	1416	NA
1969	2940	31560	30120	NA	22896	NA	12060	13536	816	NA	396	1356	NA
1970	6276	9080	9920	NA	27660	6775	31170	12480	936	NA	540	1656	NA
1971	12332	17380	18120	NA	36468	6372	35820	17252	1128	NA	1020	2688	NA
1972	15160	25624	23520	NA	30500	5815	34840	13564	1548	NA	2172	4380	NA
1973	7444	14900	28100	NA	37800	4481	20770	14548	1776	NA	2952	4380	NA
1974	10648	2560	6996	NA	29160	26993	109770	6532	1248	NA	3192	4560	NA
1975	12636	2629	5924	NA	20556	29211	141377	5608	NA	NA	NA	NA	NA
1976	10344	3099	5980	NA	20698	19953	115926	3996	1266	35048	323	1613	183482
1977	11534	2482	5480	NA	22053	16066	121032	4114	981	26517	99	1241	192768
1978	16160	2210	3995	231	21897	10909	110483	2819	1567	47928	214	1837	192550
									238 + 239 + 240				
1979	6810	1610	2651	157	10615	6363	69255	2250	323 + 1012 = 1335	40383	212	1675	109678
1980	9506	1610	2713	124	9295	6464	80163	992	186 + 550 = 736	19684	223	1045	116391
1981	7498	3429	5309	296	14330	4530	63695	467	134 + 414 = 548	16127	237	803	103543
1982	8628	5730	8223	458	11316	3736	54060	589	127 + 434 = 561	13105	173	769	95352
1983	5500	5715	10408	500	14948	2412	32438	657	78 + 236 = 314	8944	60	378	67202

Table 13 Recorded annual discharge of fission products from the Sellafield (Windscale) outfall(s). Updated from Smith, Parker and Kirby (1980) using values in British Nuclear Fuels' Annual Report on Radioactive Discharges and Monitoring of the Environment for years 1980-1983. (Published 1981-1984 respectively). For terabecquerels (10^{12}Bq) x 0.037 Ci

* Excludes low energy β emitters

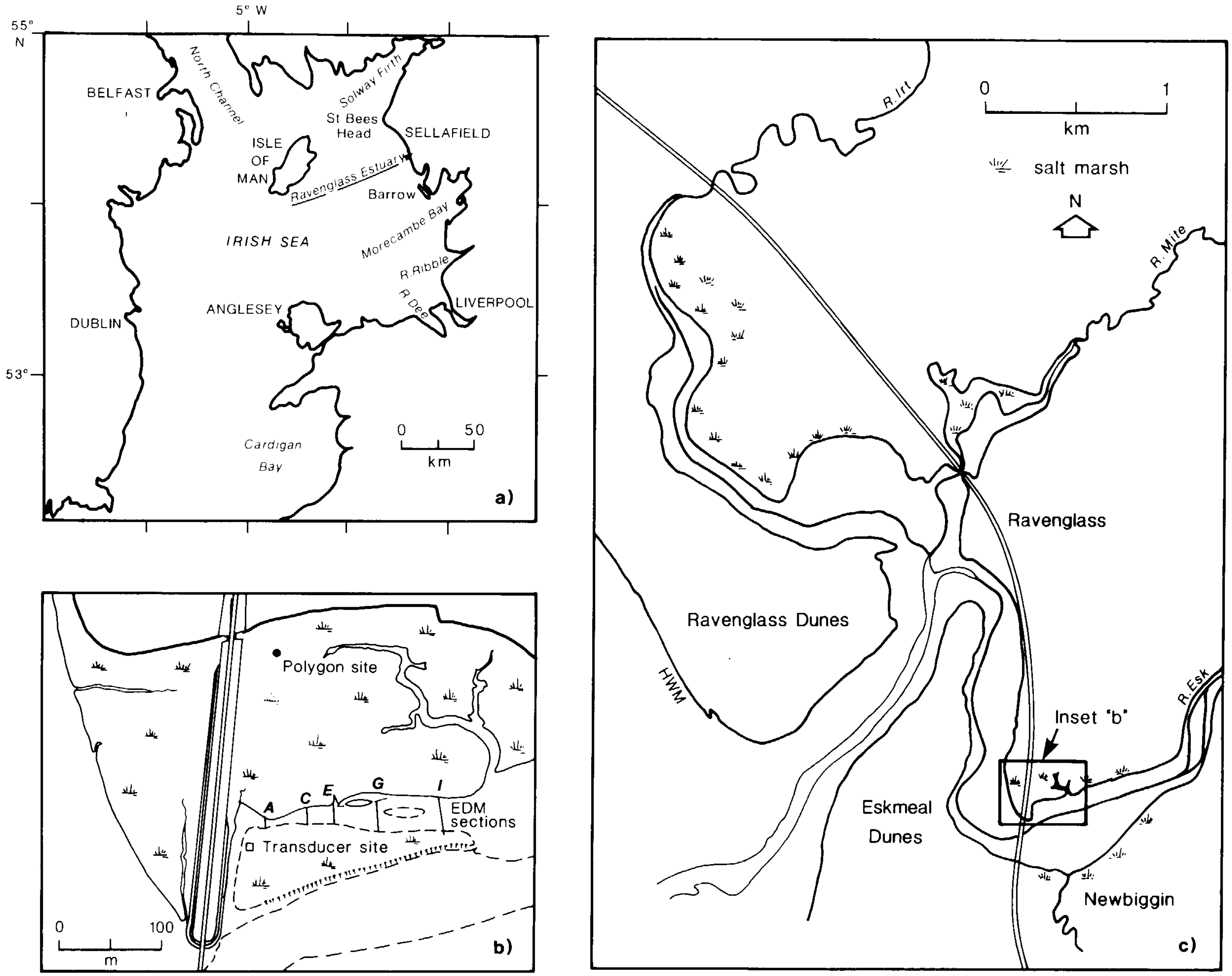


Figure 1: Site Map

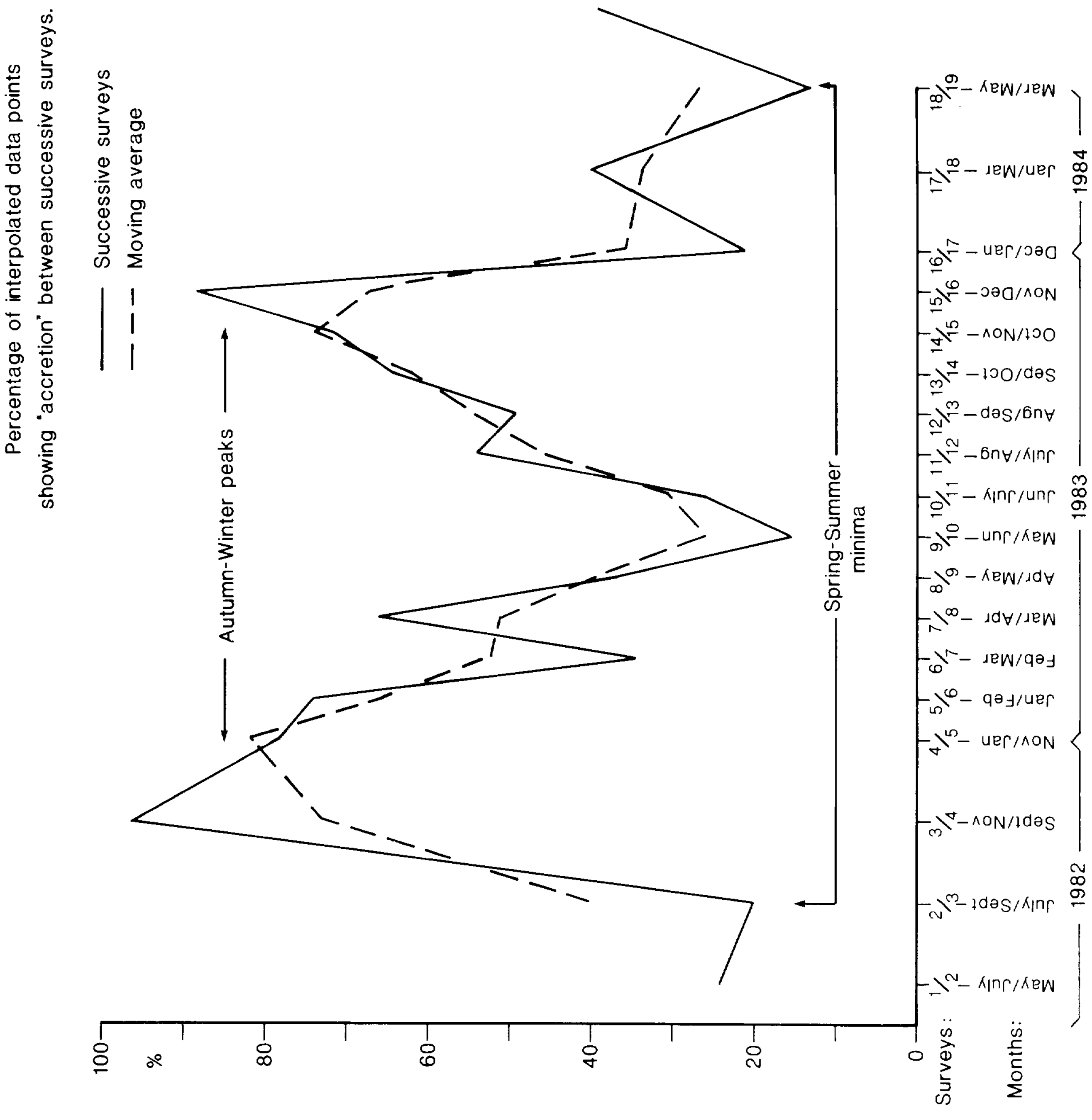


Figure 2: Sections A to I. Proportion of data points (n = 253) showing 'accretion' between successive surveys. Moving average: Position b = $[\frac{a}{2} + b + \frac{c}{2}]/2$.

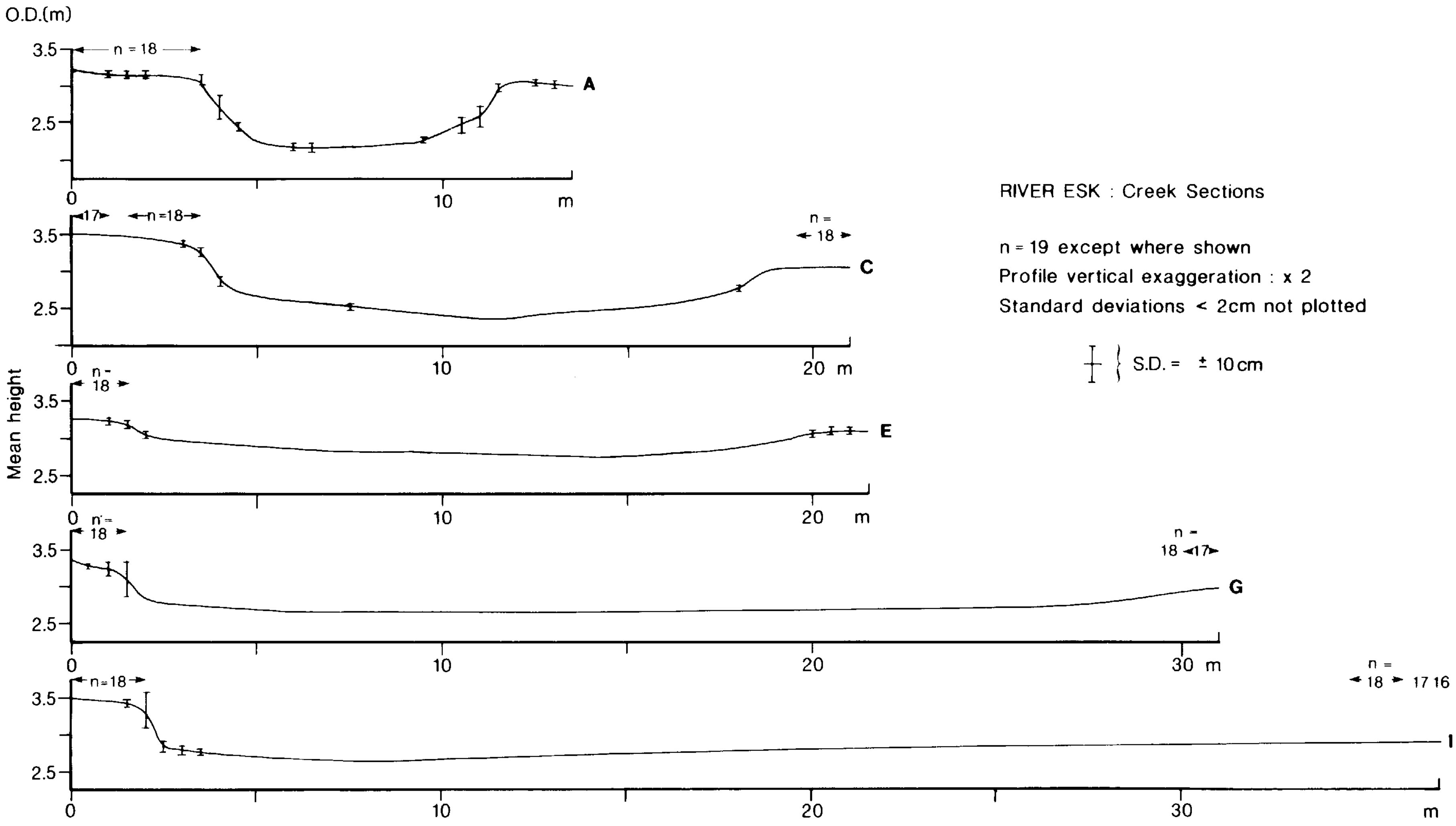


Figure 3: Sections A to I. Mean profile, and standard deviation for each interpolated data point where SD ≧ 2 cm. Only 33 out of 253 survey positions fall in this catagory.

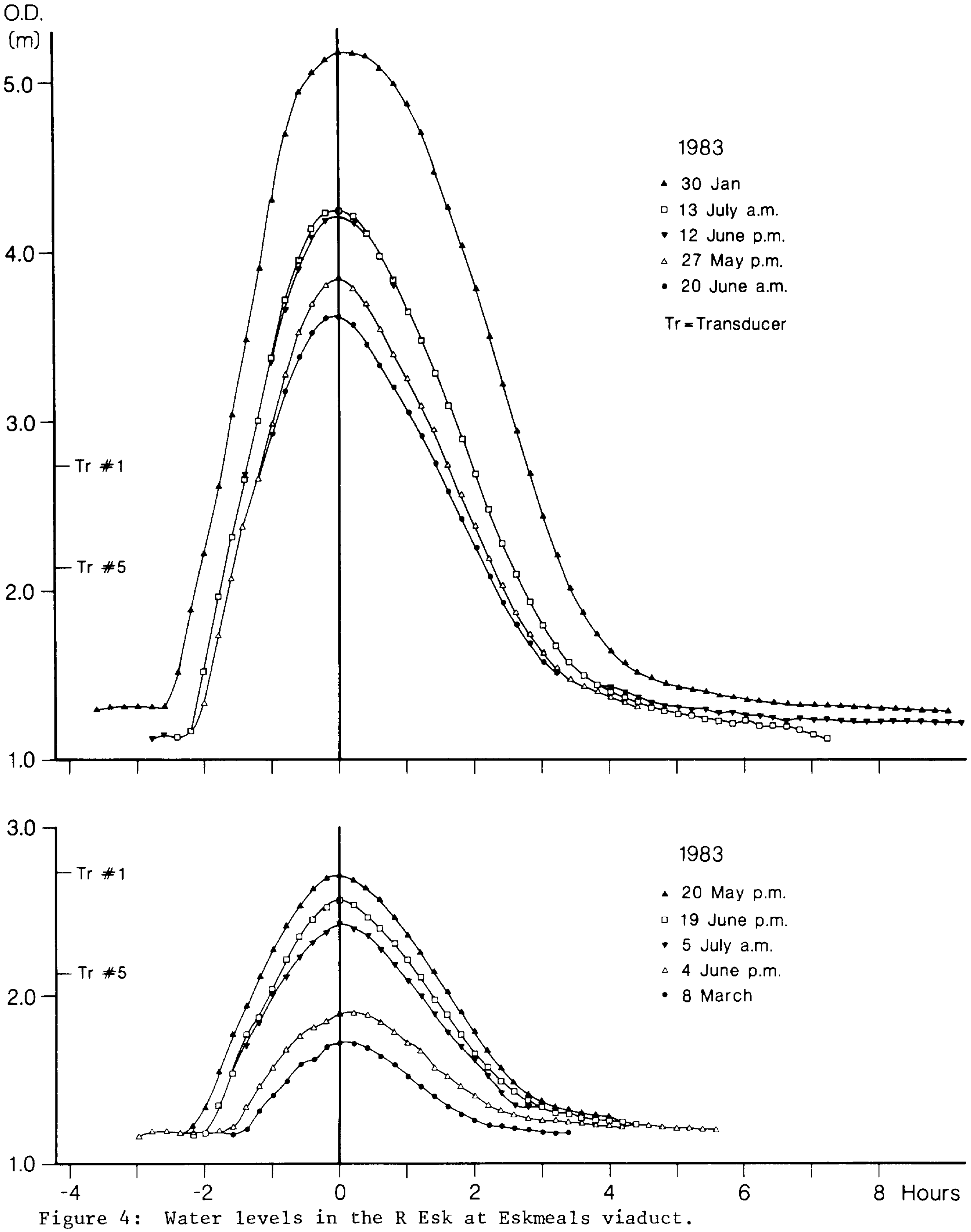


Figure 4: Water levels in the R Esk at Eskmeals viaduct.
a) Spring tides. Note surge component in tide at 30 January.
b) Neap tides.
The difference in level at low water reflects the discharge from the Esk basin.

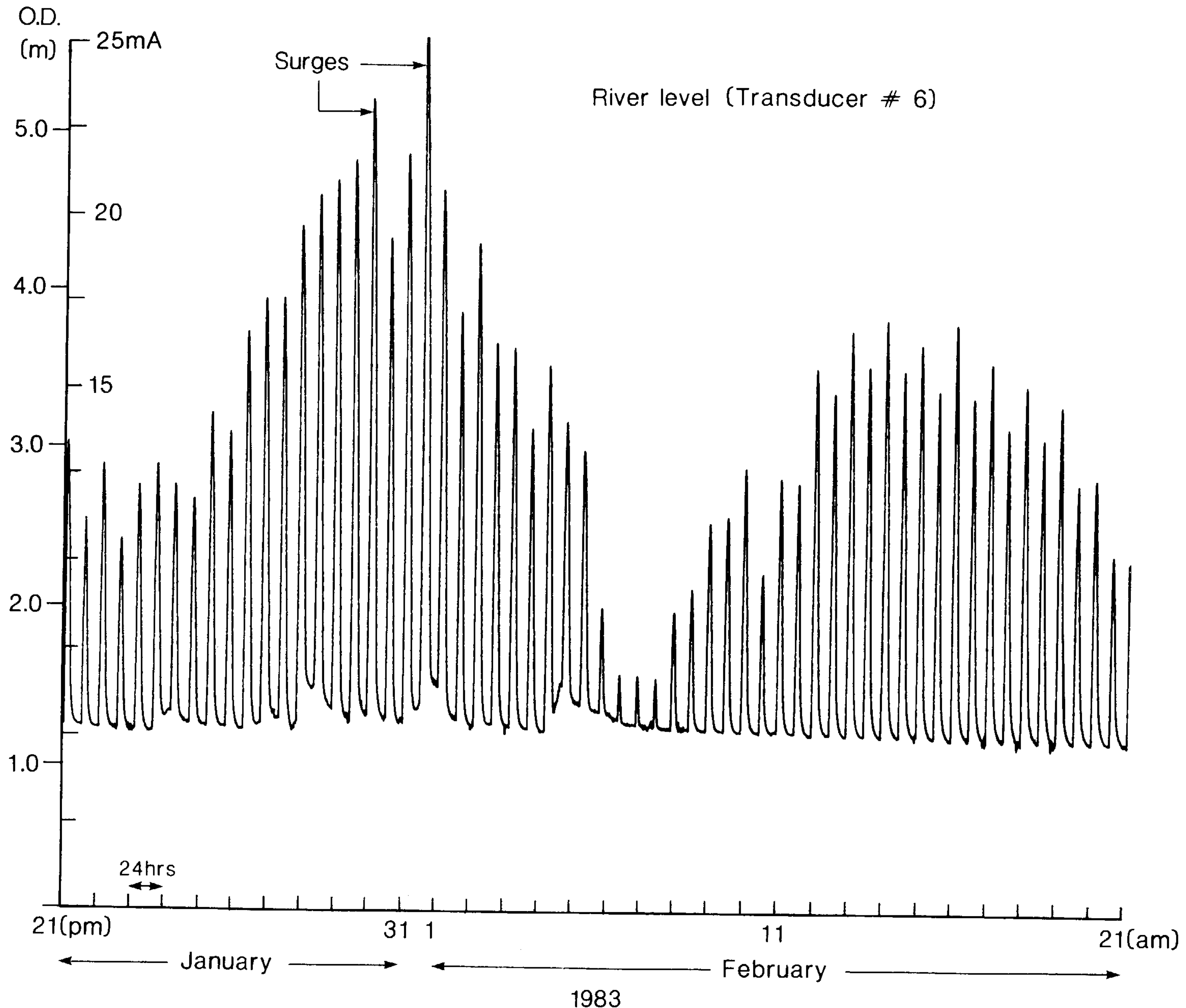


Figure 5: Water levels in the R Esk at Eskmeals viaduct for the period 21 January to 21 February 1983. The highest tides correspond to 2 major surges which affected the northwest coast of Britain during the period.

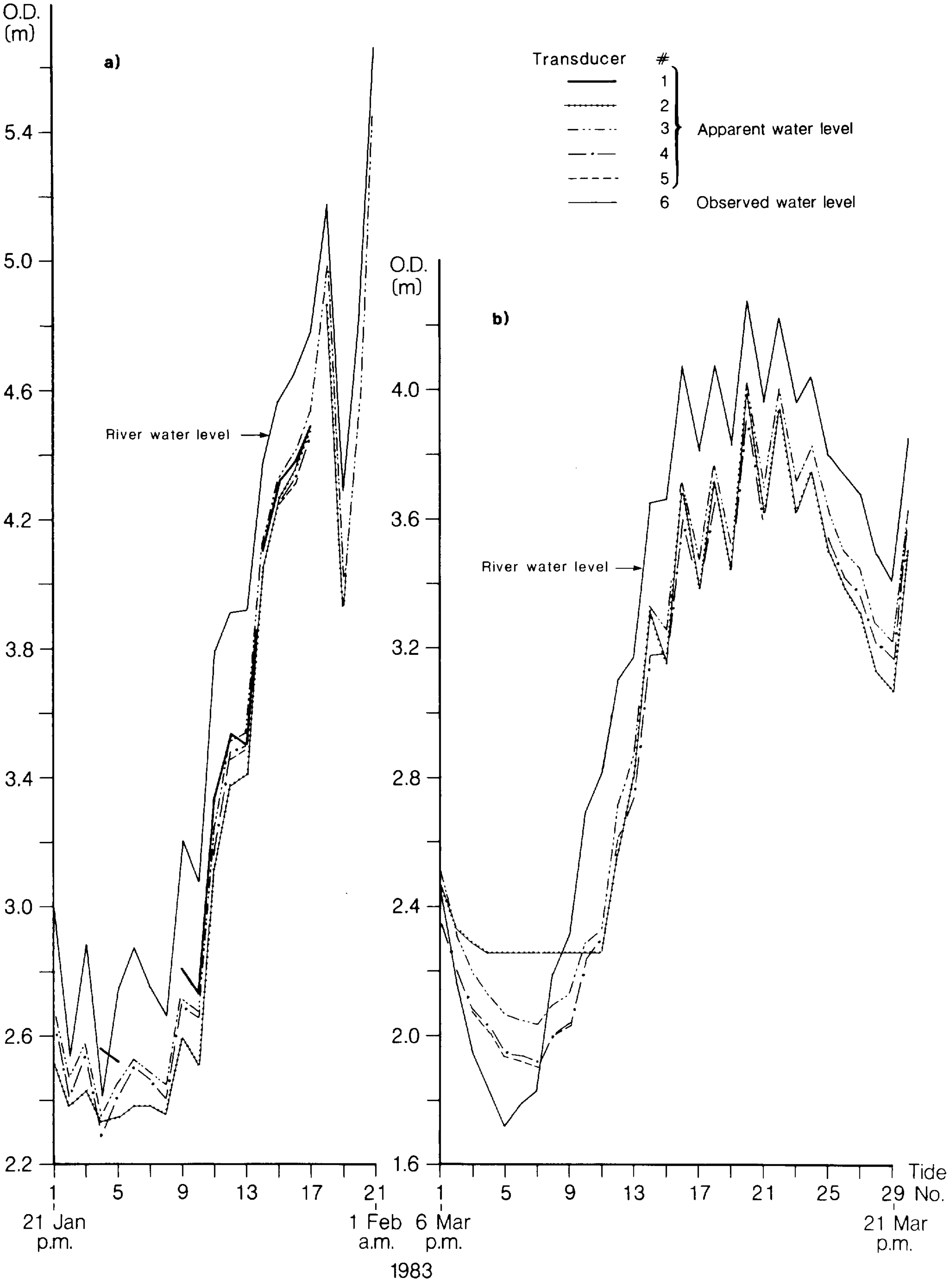


Figure 6: Apparent water level in relation to actual river water level at successive high tides. Winter.

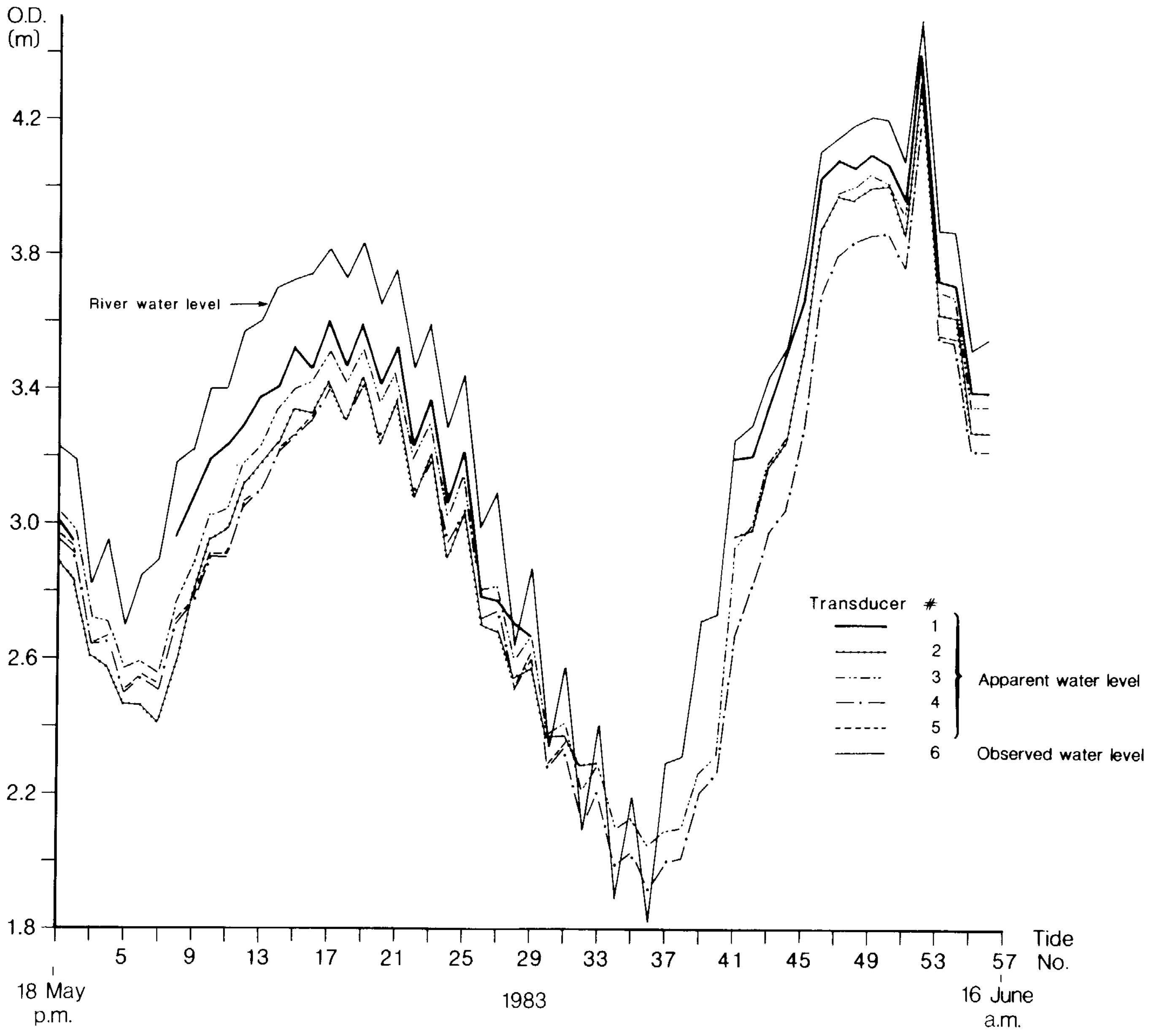


Figure 7: Apparent water level in relation to actual river water level at successive high tides. Spring. Note the convergence of Transducers #1 and 6 during the second group of spring tides as compared with the first.

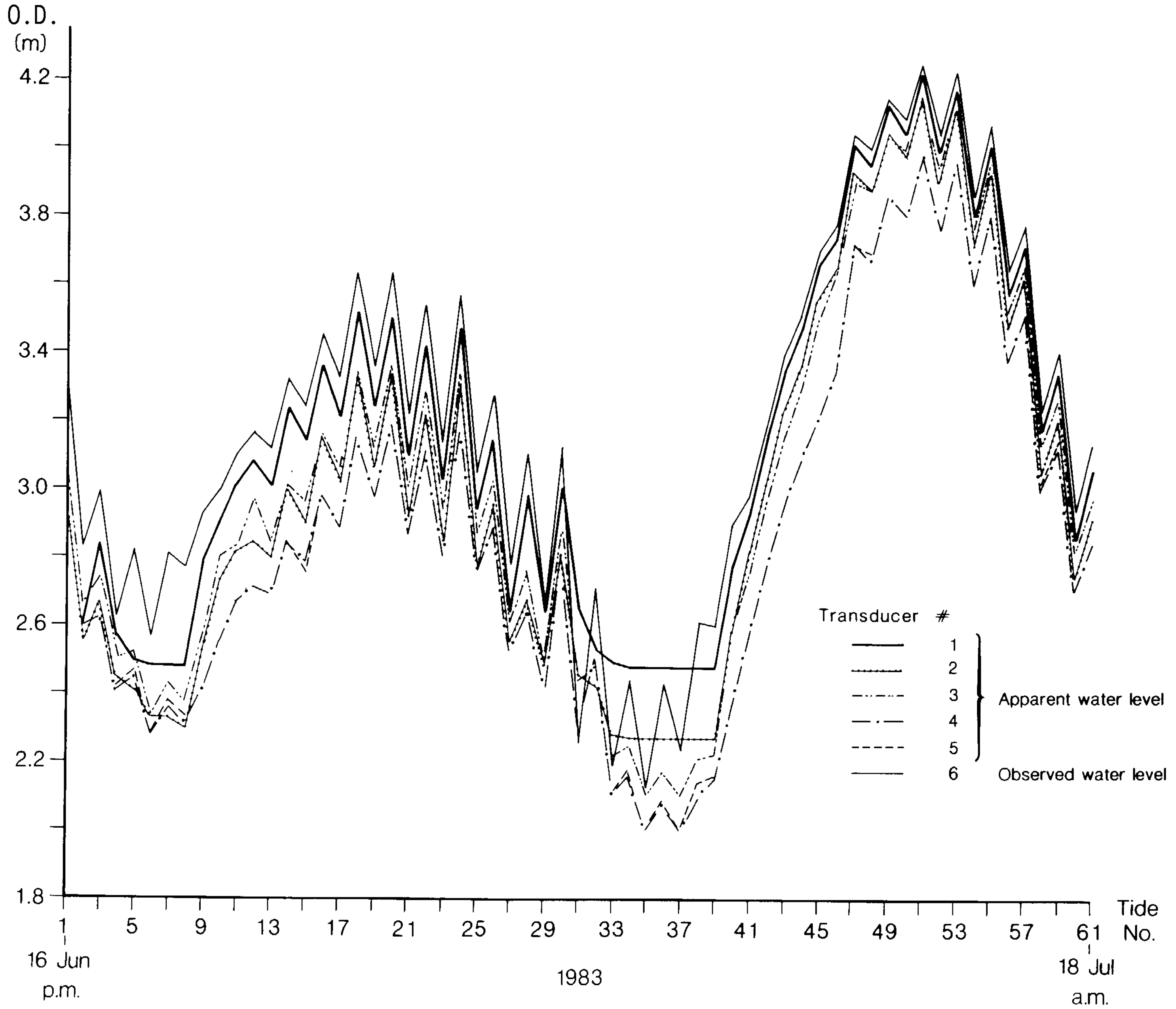
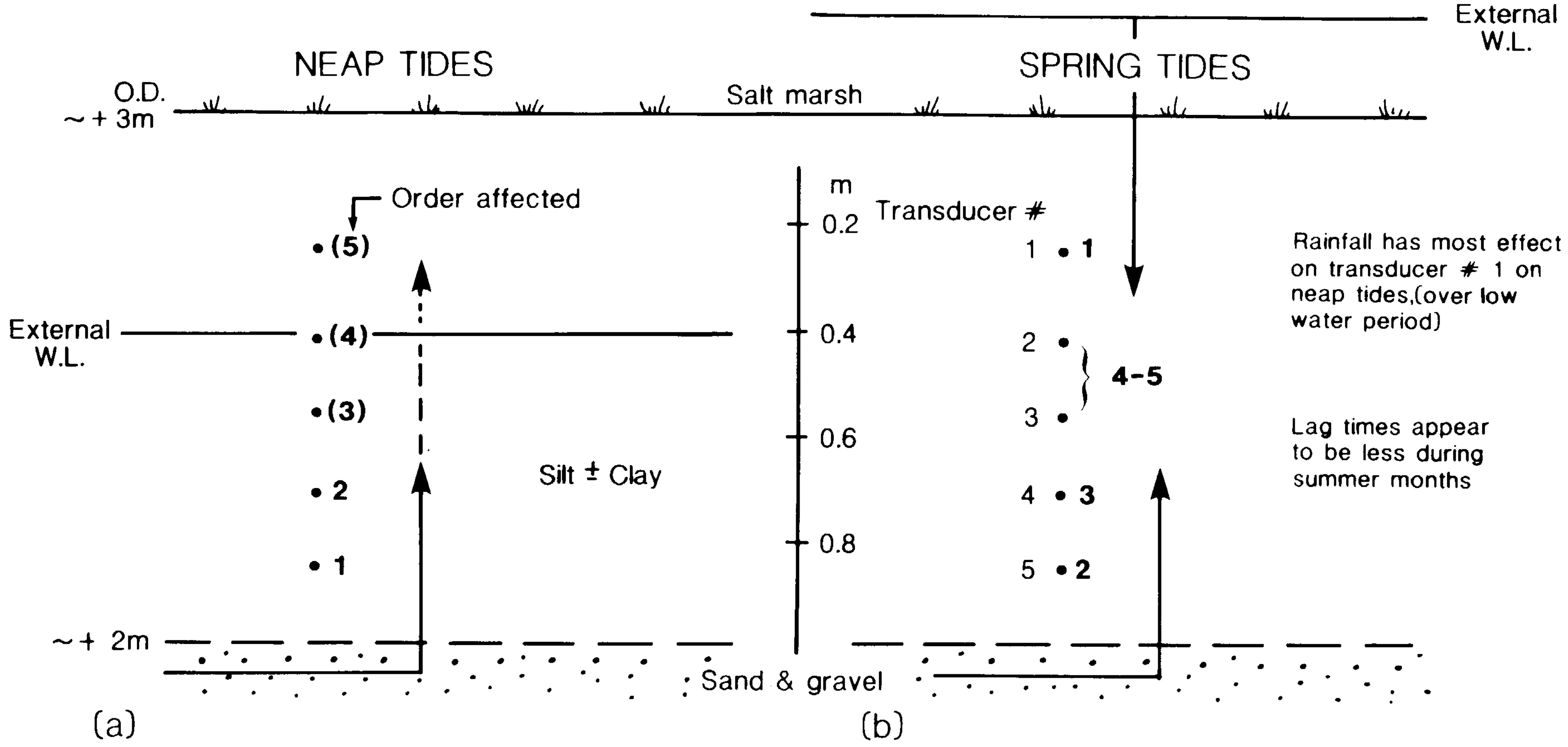


Figure 8: Apparent water level in relation to actual river water level at successive high tides. Early summer. Note the convergence of Transducers #1 and 6 compared with Figure 6. The draining curve of the upper transducers (Transducer #1 (first neaps); Transducers #1 and 2 (second neap period)) is partly an artifact of the instrumentation used.



Rainfall has most effect on transducer # 1 on neap tides,(over low water period)

Lag times appear to be less during summer months

Figure 9: Diagram of basic flow pattern : Ravenglass

(a)Although in example water level reaches transducer at 42cm lag effects prevent water from reaching this height before river level falls. Some capillary effects above.

(b) Fate of intermediate transducers depends on external water levels, duration, etc. Marsh may or may not become fully saturated in time available.

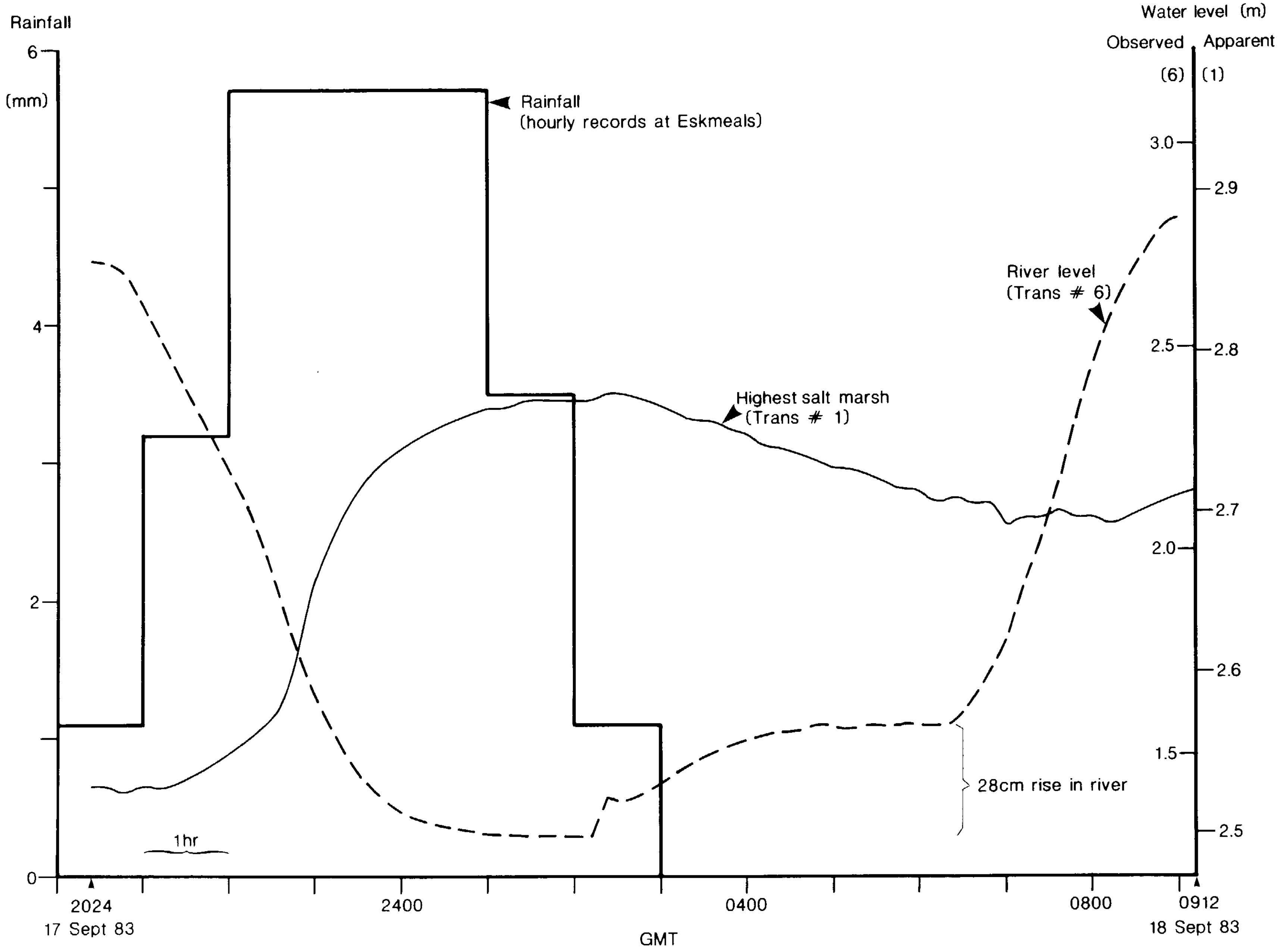


Figure 10: The effect of rainfall on the highest salt marsh transducer (Transducer #1) and its relation to river level (Transducer #6) over a neap low water.

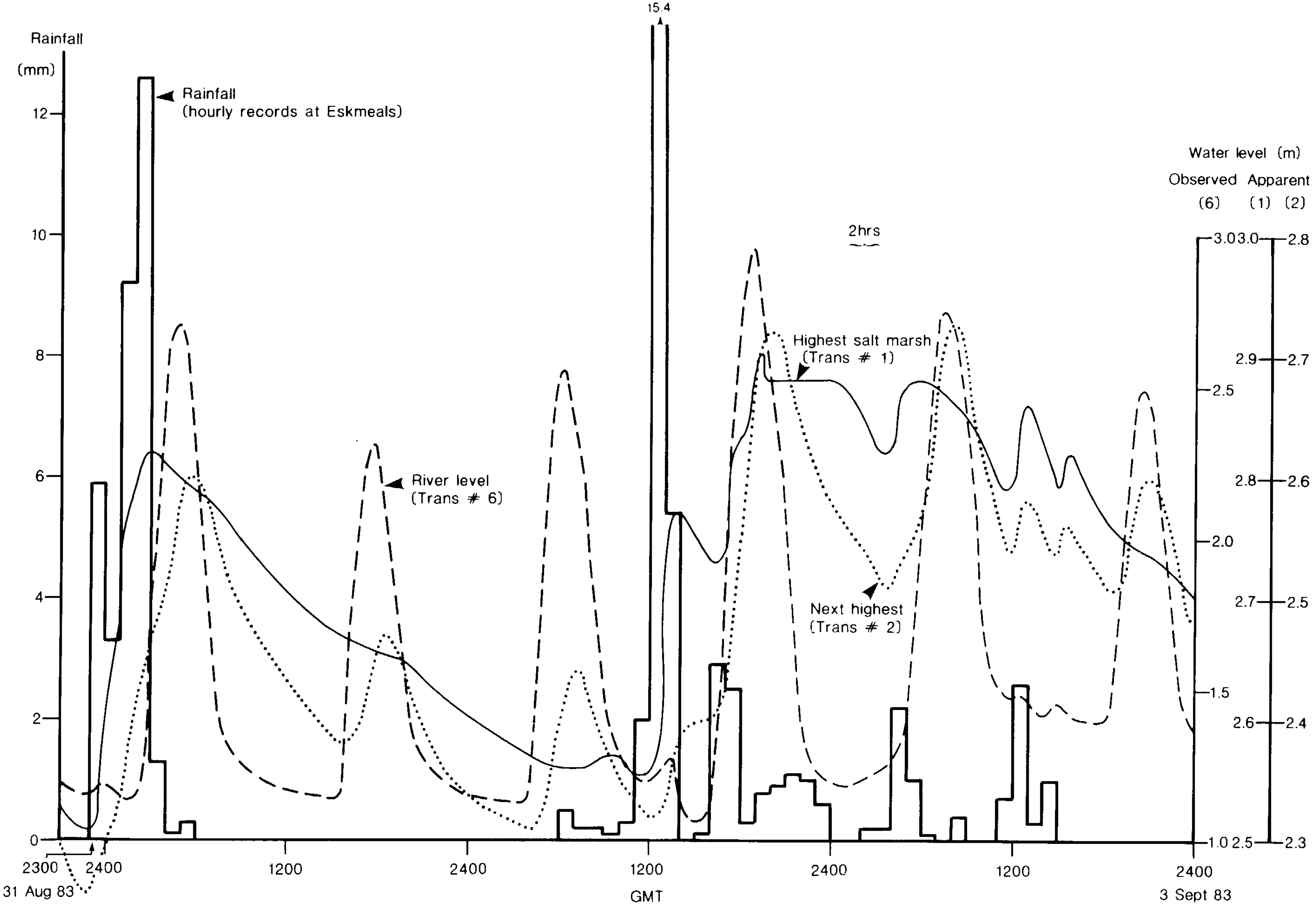


Figure 11: The effect of rainfall on the highest two salt marsh transducers (Transducers #1 and 2) during neap tides. The tidal cycle in the river also affects the marsh transducers and is itself affected by rainfall.

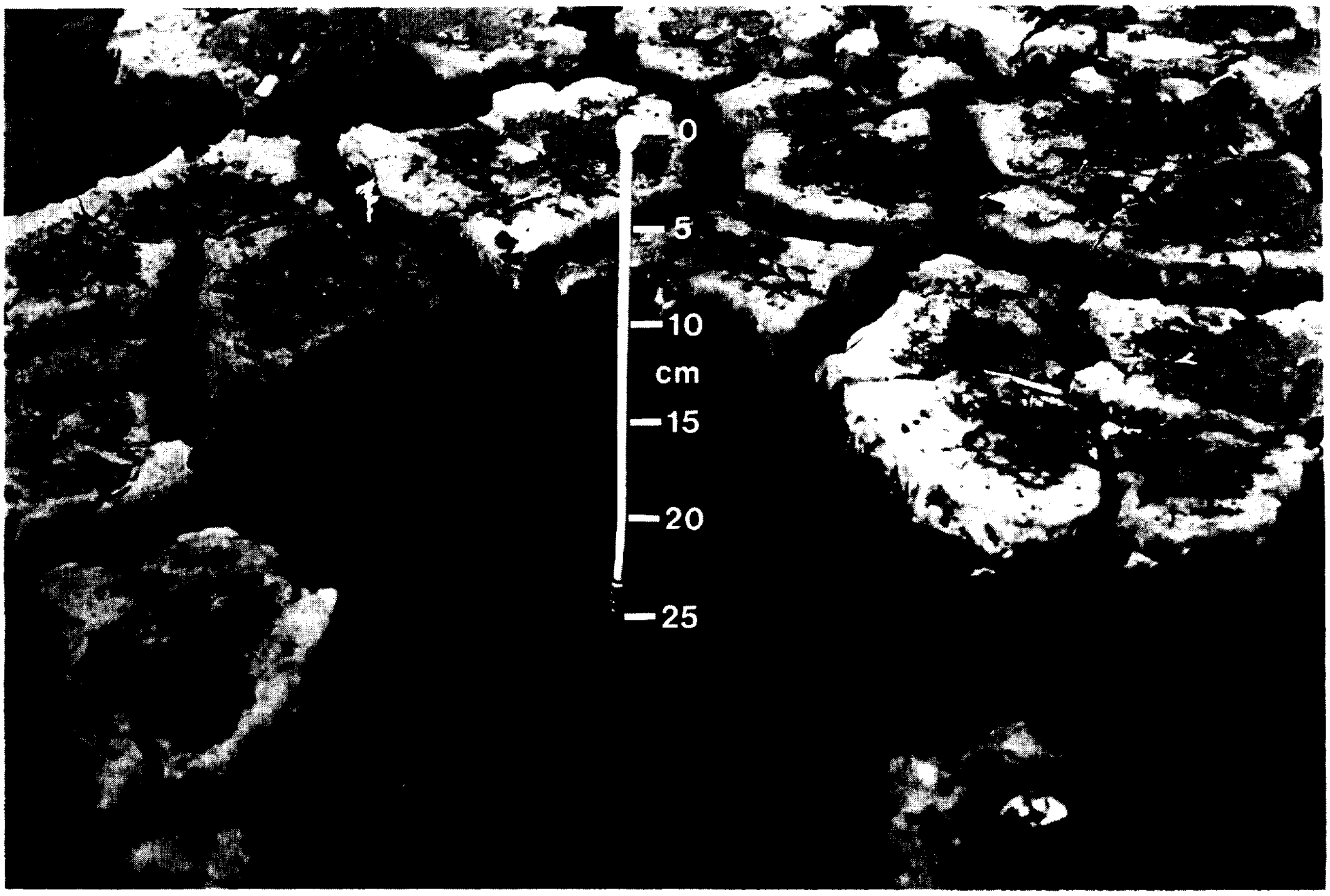


Figure 12: Soil polygons. July 1982.

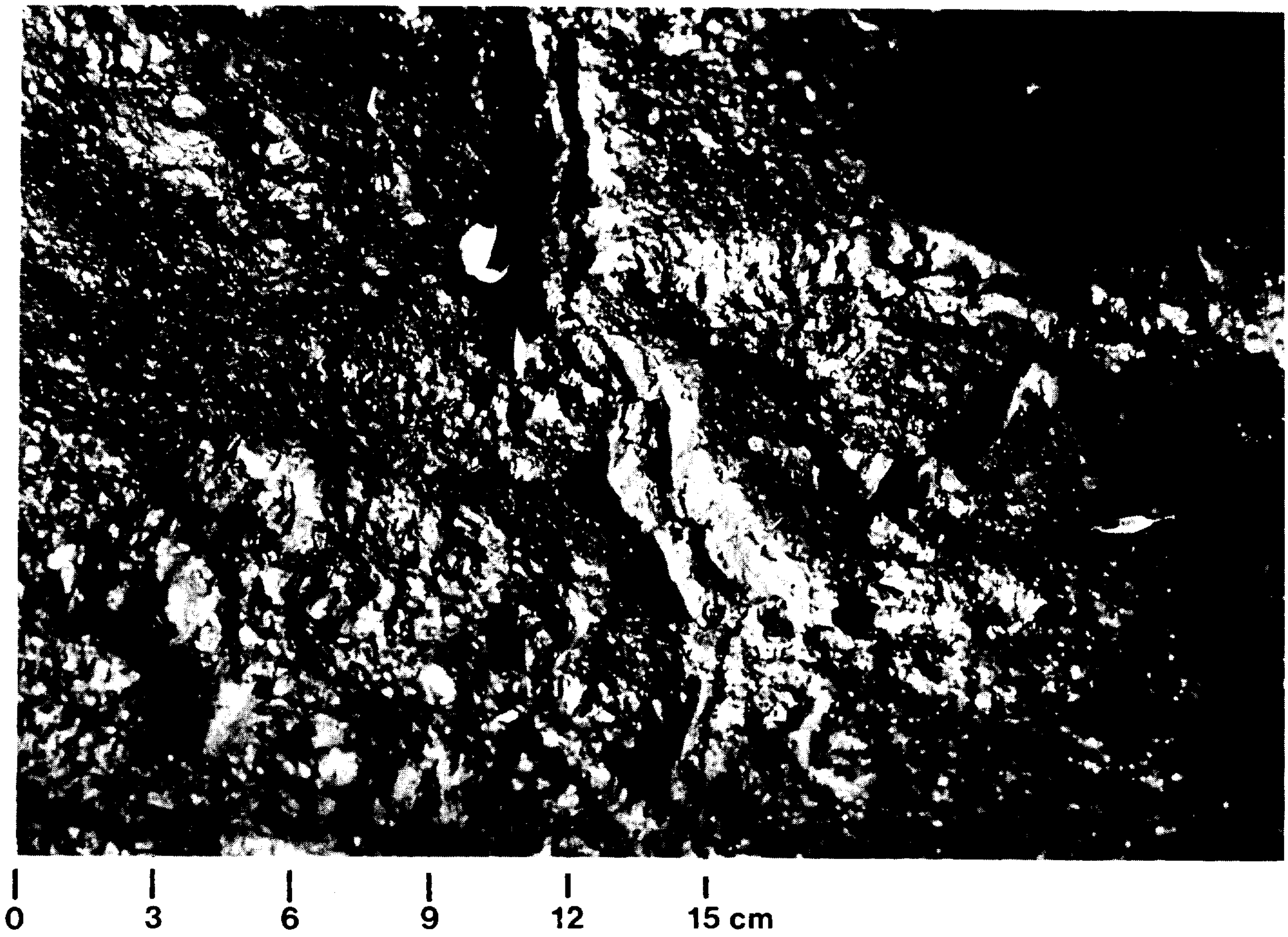


Figure 13: Extruded material from infilled vertical crack.

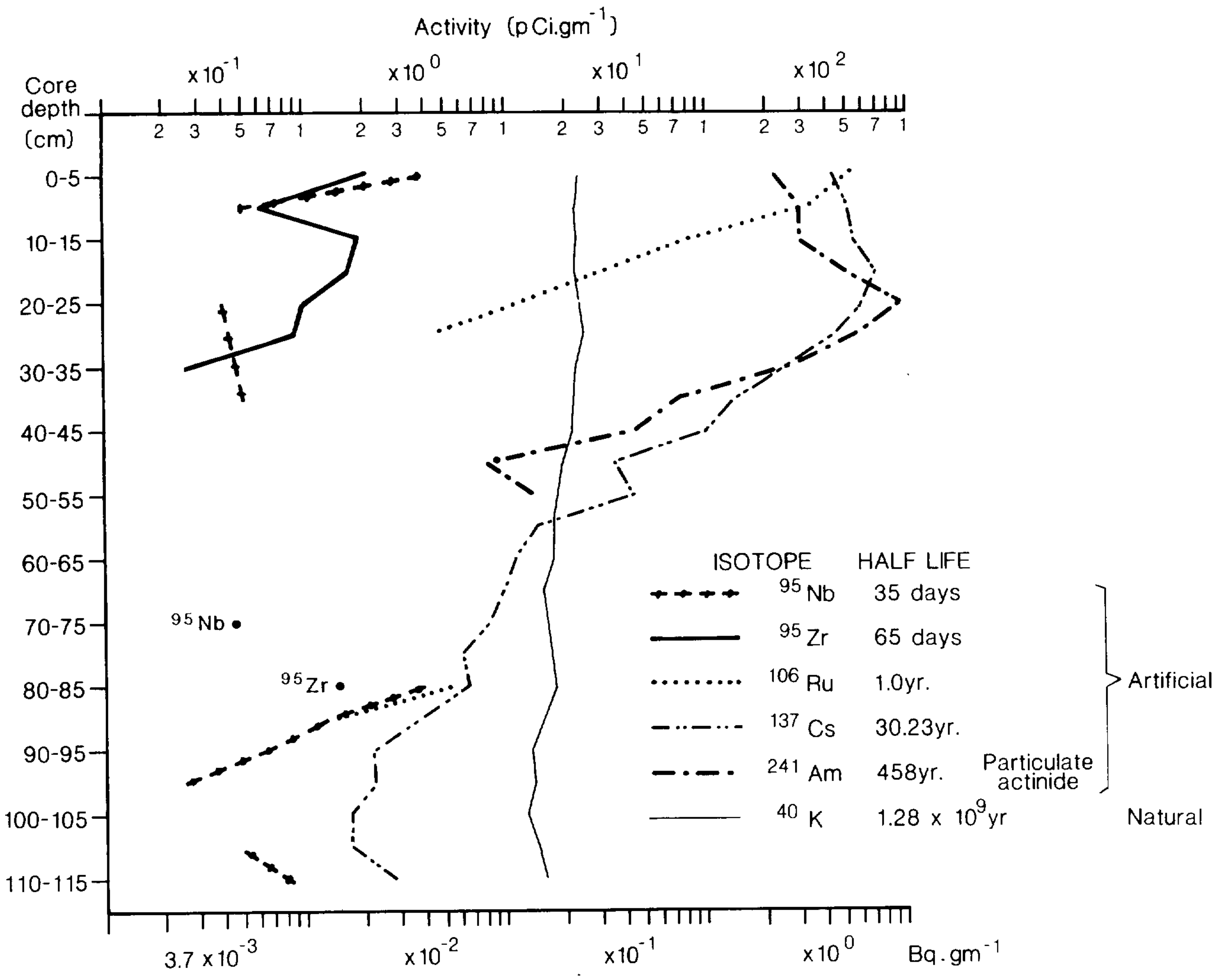


Figure 14: Activity profiles of artificial radionuclides ^{95}Nb, ^{95}Zr, ^{106}Ru, ^{137}Cs and ^{241}Am for the core (Core '1') taken near the transducer site (Figure 1b). ^{40}K is shown for completeness.

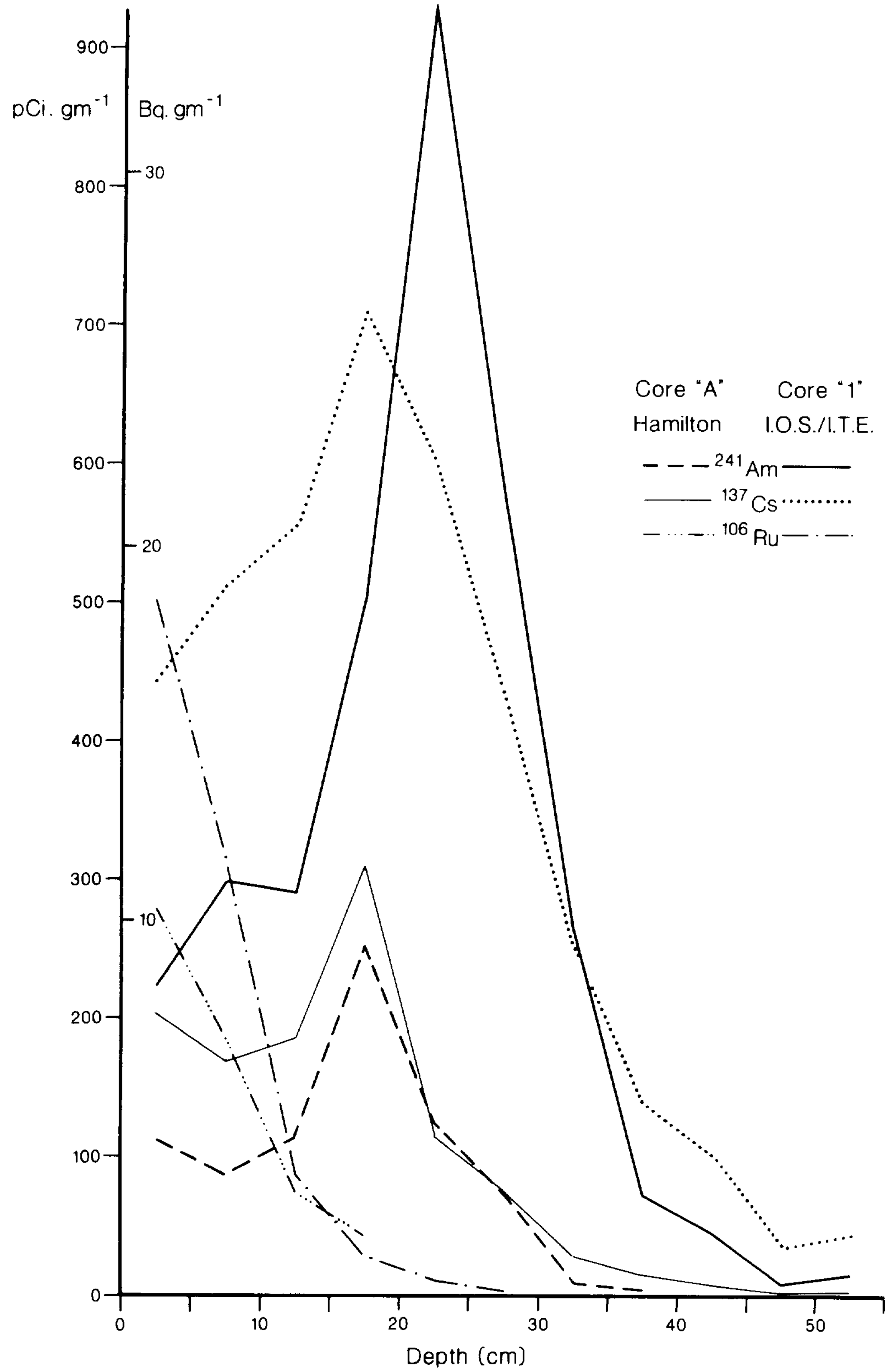


Figure 15: Comparison of radioactivity profiles between Core 'A' (Hamilton and Clarke, 1984) and IOS/ITE Core '1', ie the core taken near the transducer site. Note the similar profiles over this depth although Core '1' activity levels tend to be higher. For this comparison Core 'A' data was aggregated from its original 1 cm sampling interval to the 5 cm spacing of Core '1'.

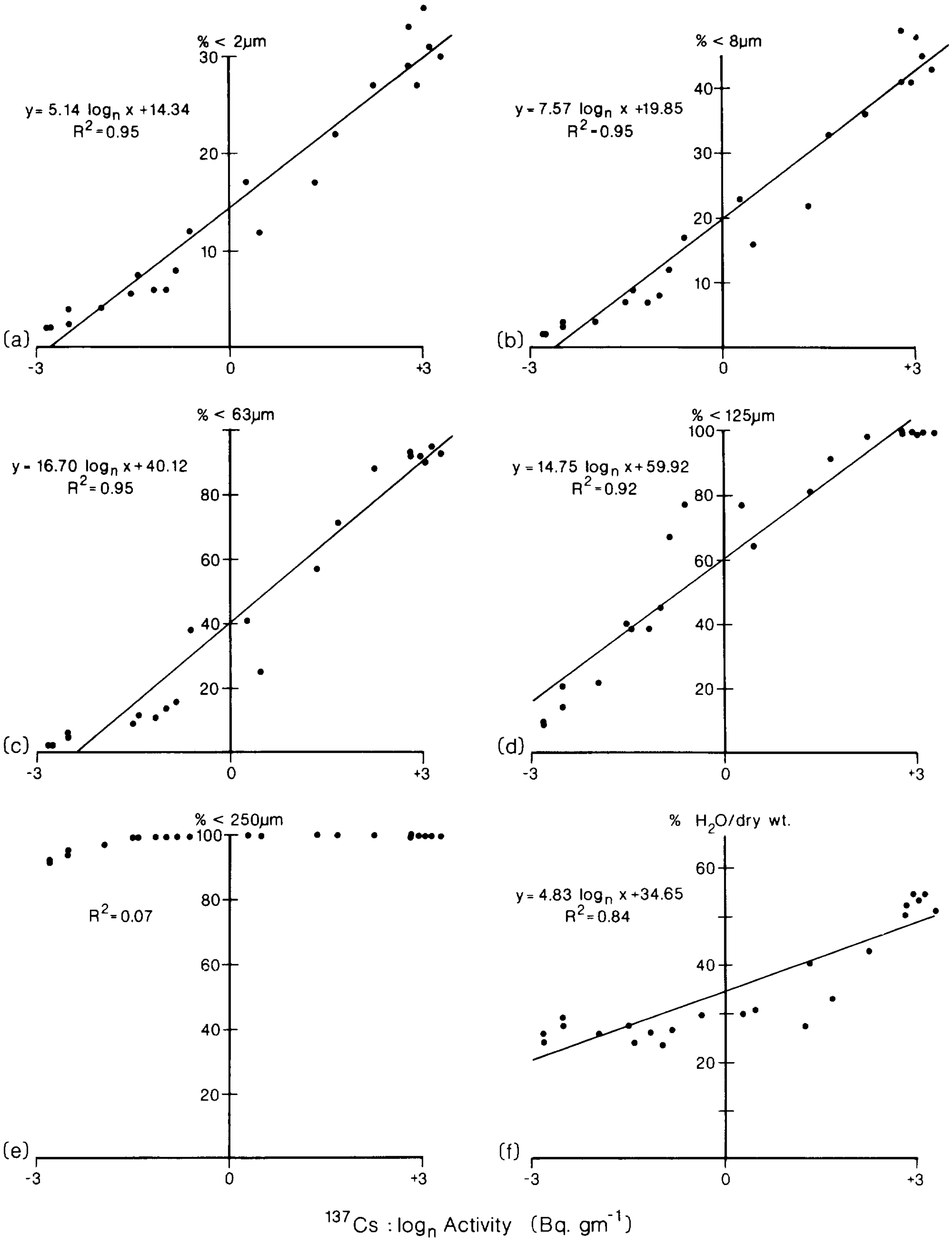


Figure 16: The relationship between ^{137}Cs activity and particle size (a-e) or water content (f) for Core '1'. Note how the relationship is very close for (a-c) but falls away rapidly when sediment > 63 µm is included.

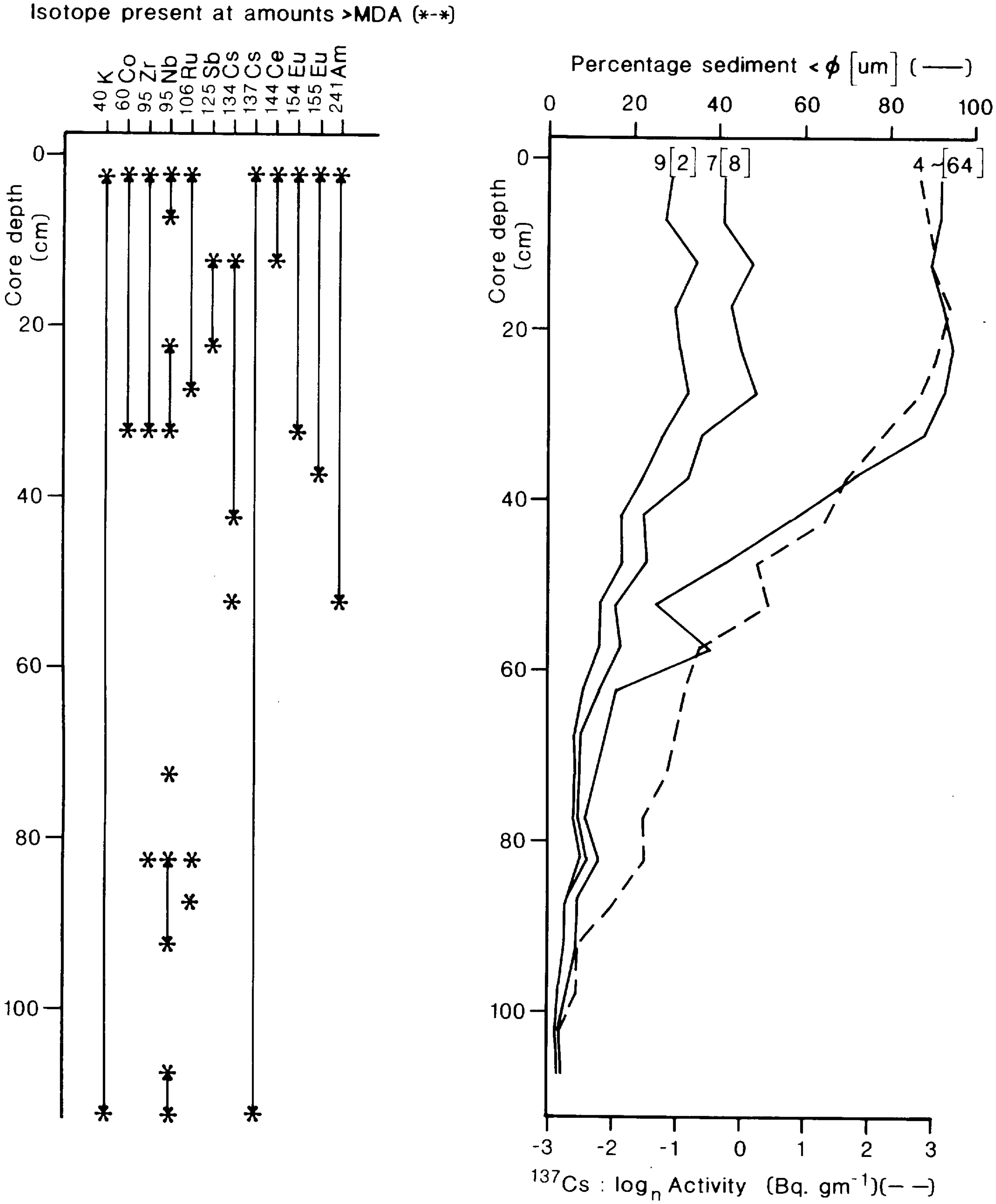


Figure 17: The presence of radionuclides in quantities > MDA and their relation to the percentage of fine sediment: Core '1'. The curve for ^{137}Cs, in the same units as Figure 16, is also shown. Note the similarity of form to that for sediment < 4ϕ(∿ 64 μm).

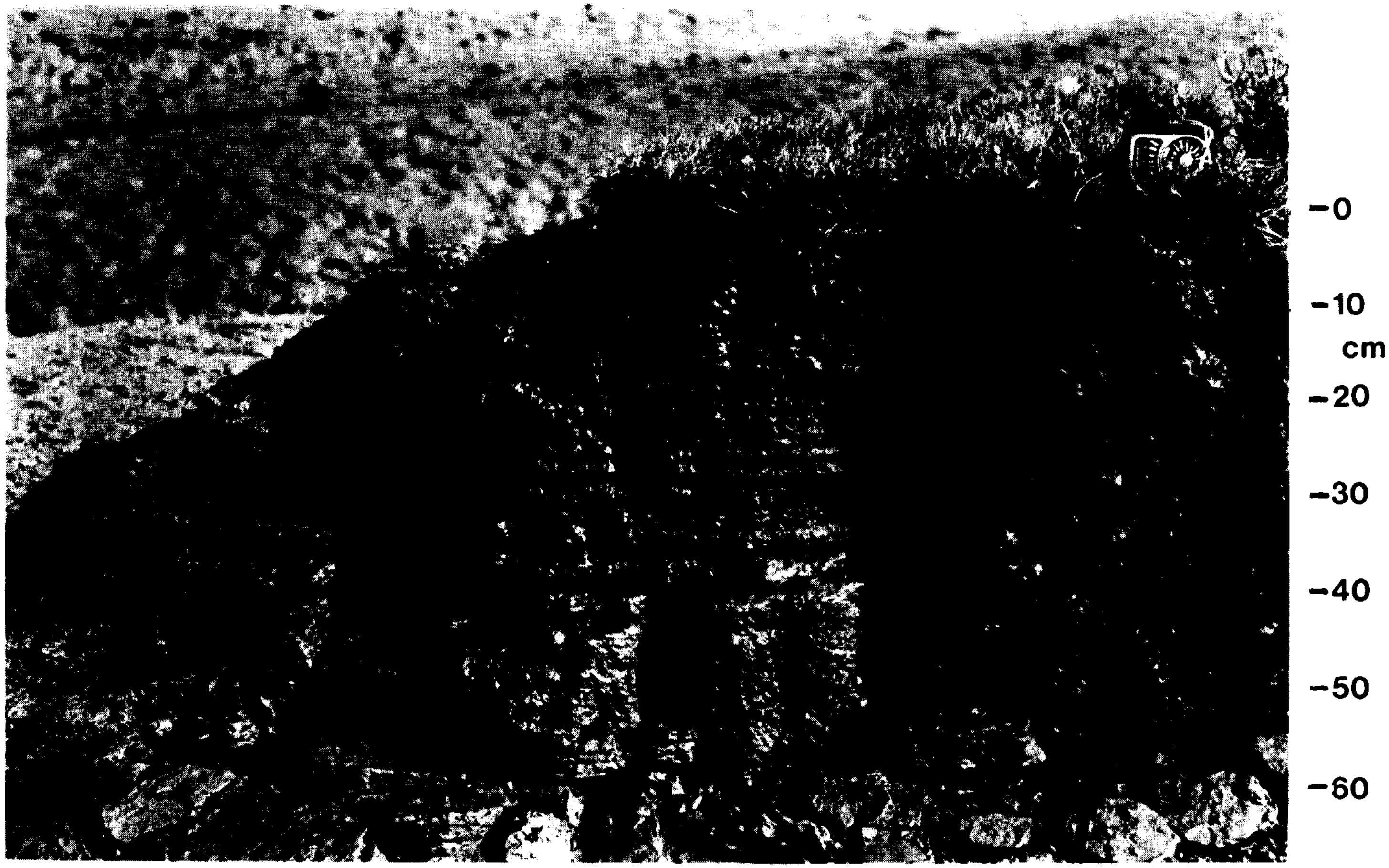


Figure 18: Varve-like features in eroding marsh cliff face.

Ravenglass Estuary   Section A

No of surveys - 19

Distance (metres)	no. of points	mean height (metres)	standard deviation	range (metres) min	max
0	18	3.2269	0.0112	3.2080	3.2510
0.5	18	3.2050	0.0162	3.1835	3.2380
1.0	18	3.1831	0.0237	3.1526	3.2266
1.5	18	3.1754	0.0229	3.1426	3.2194
2.0	18	3.1706	0.0243	3.1152	3.2099
2.5	18	3.1608	0.0191	3.1169	3.1819
3.0	18	3.1388	0.0150	3.1043	3.1603
3.5	18	3.0921	0.0281	3.0238	3.1358
4.0	19	2.6982	0.0655	2.6330	2.8812
4.5	19	2.4641	0.0240	2.4164	2.4966
5.0	19	2.2822	0.0184	2.2591	2.3346
5.5	19	2.2162	0.0148	2.1763	2.2337
6.0	19	2.1899	0.0210	2.1310	2.2094
6.5	19	2.1819	0.0211	2.1378	2.2087
7.0	19	2.1663	0.0132	2.1455	2.1964
7.5	19	2.1715	0.0169	2.1445	2.1994
8.0	19	2.1899	0.0134	2.1708	2.2139
8.5	19	2.2038	0.0131	2.1780	2.2204
9.0	19	2.2225	0.0104	2.1991	2.2380
9.5	19	2.2443	0.0201	2.1711	2.2615
10.0	19	2.2929	0.0126	2.2566	2.3069
10.5	19	2.3875	0.0397	2.3640	2.5438
11.0	19	2.5923	0.0548	2.5302	2.7181
11.5	19	3.0071	0.0245	2.9236	3.0385
12.0	19	3.0739	0.0129	3.0509	3.1079
12.5	19	3.0665	0.0226	2.9826	3.0885
13.0	19	3.0426	0.0278	2.9377	3.0647
13.5	19	3.0206	0.0152	2.9835	3.0390

Table A1a : Computed values at 0.5 m intervals for electromagnetic distance meter (EDM) surveyed profiles. May 1982 - May 1984

Ravenglass Estuary

Section C

No of surveys - 19

Distance (metres)	no. of points	mean height (metres)	standard deviation	range (metres) min	max
0	17	3.5013	0.0139	3.4830	3.5410
0.5	17	3.4931	0.0120	3.4784	3.5203
1.0	17	3.4850	0.0138	3.4578	3.5040
1.5	18	3.4725	0.0150	3.4362	3.4945
2.0	18	3.4455	0.0134	3.4147	3.4703
2.5	18	3.4126	0.0168	3.3710	3.3983
3.0	18	3.3642	0.0266	3.3023	3.3983
3.5	18	3.2529	0.0313	3.2000	3.2981
4.0	19	2.8552	0.0332	2.8163	2.9575
4.5	19	2.7051	0.0113	2.6895	2.7374
5.0	19	2.6518	0.0135	2.6136	2.6731
5.5	19	2.6224	0.0117	2.5913	2.6425
6.0	19	2.5968	0.0098	2.5774	2.6119
6.5	19	2.5732	0.0098	2.5536	2.5908
7.0	19	2.5447	0.0187	2.4776	2.5676
7.5	19	2.5206	0.0200	2.4477	2.5432
8.0	19	2.5024	0.0095	2.4796	2.5193
8.5	19	2.4779	0.0090	2.4544	2.4932
9.0	19	2.4541	0.0098	2.4324	2.4709
9.5	19	2.4326	0.0096	2.4112	2.4508
10.0	19	2.4114	0.0097	2.3920	2.4278
10.5	19	2.3922	0.0108	2.3698	2.4084
11.0	19	2.3648	0.0168	2.3246	2.3847
11.5	19	2.3537	0.0175	2.3294	2.3870
12.0	19	2.3867	0.0156	2.3582	2.4150
12.5	19	2.4134	0.0143	2.3854	2.4378
13.0	19	2.4342	0.0135	2.4083	2.4688
13.5	19	2.4560	0.0100	2.4335	2.4701
14.0	19	2.4769	0.0113	2.4571	2.4970
14.5	19	2.4994	0.0095	2.4779	2.5147
15.0	19	2.5214	0.0093	2.5029	2.5369
15.5	19	2.5441	0.0109	2.5140	2.5603
16.0	19	2.5729	0.0094	2.5483	2.5869
16.5	19	2.6057	0.0138	2.5605	2.6218
17.0	19	2.6696	0.0098	2.6534	2.6904
17.5	19	2.7322	0.0092	2.7092	2.7459
18.0	19	2.7861	0.0212	2.7600	2.8617
18.5	19	3.0006	0.0127	2.9746	3.0316
19.0	19	3.0497	0.0154	3.0152	3.0733
19.5	18	3.0730	0.0129	3.0363	3.0922
20.0	18	3.0775	0.0101	3.0562	3.0939
20.5	18	3.0765	0.0125	3.0541	3.1014
21.0	18	3.0668	0.0113	3.0431	3.0838

Table A1 b

Ravenglass Estuary

Section E

No of surveys - 19

Distance (metres)	no. of points	mean height (metres)	standard deviation	range (metres)	
				min	max
0	18	3.2527	0.0102	3.2290	3.2680
0.5	18	3.2467	0.0111	3.2303	3.2659
1.0	18	3.2232	0.0242	3.1514	3.2566
1.5	18	3.1733	0.0286	3.1180	3.2375
2.0	19	2.7776	0.0219	2.7464	2.8267
2.5	19	2.7345	0.0131	2.7171	2.7647
3.0	19	2.7073	0.0101	2.6923	2.7244
3.5	19	2.6844	0.0099	2.6691	2.7017
4.0	19	2.6638	0.0097	2.6456	2.6794
4.5	19	2.6488	0.0099	2.6264	2.6626
5.0	19	2.6301	0.0109	2.6081	2.6468
5.5	19	2.6139	0.0103	2.5932	2.6296
6.0	19	2.6029	0.0108	2.5775	2.6175
6.5	19	2.5918	0.0106	2.5664	2.6070
7.0	19	2.5815	0.0101	2.5560	2.5983
7.5	19	2.5752	0.0103	2.5482	2.5930
8.0	19	2.5709	0.0111	2.5409	2.5860
8.5	19	2.5653	0.0112	2.5368	2.5803
9.0	19	2.5604	0.0107	2.5342	2.5753
9.5	19	2.5553	0.0105	2.5317	2.5713
10.0	19	2.5508	0.0102	2.5273	2.5658
10.5	19	2.5446	0.0104	2.5232	2.5614
11.0	19	2.5399	0.0104	2.5207	2.5560
11.5	19	2.5358	0.0101	2.5164	2.5517
12.0	19	2.5305	0.0119	2.4950	2.5455
12.5	19	2.5243	0.0103	2.4992	2.5391
13.0	19	2.5198	0.0108	2.4994	2.5367
13.5	19	2.5133	0.0111	2.4920	2.5303
14.0	19	2.5006	0.0120	2.4765	2.5247
14.5	19	2.4934	0.0139	2.4655	2.5145
15.0	19	2.5244	0.0104	2.5074	2.5444
15.5	19	2.5400	0.0096	2.5182	2.5592
16.0	19	2.5553	0.0103	2.5301	2.5730
16.5	19	2.5740	0.0116	2.5439	2.5911
17.0	19	2.5912	0.0124	2.5606	2.6130
17.5	19	2.6111	0.0147	2.5788	2.6520
18.0	19	2.6376	0.0128	2.6067	2.6689
18.5	19	2.6678	0.0120	2.6402	2.6891
19.0	19	2.7033	0.0120	2.6842	2.7325
19.5	19	2.7577	0.0182	2.7192	2.7965
20.0	19	2.8269	0.0296	2.7401	2.8613
20.5	19	2.8560	0.0284	2.7610	2.8935
21.0	19	2.8567	0.0240	2.7819	2.8879
21.5	19	2.8541	0.0199	2.8029	2.8823

Table A1c :

Ravenglass Estuary Section G

No of surveys - 19

Distance (metres)	no. of points	mean height (metres)	standard deviation	range (metres)	
				min	max
0	18	3.3275	0.0113	3.3120	3.3510
0.5	18	3.2843	0.0204	3.2150	3.3159
1.0	18	3.2341	0.0379	3.0921	3.2683
1.5	18	3.1095	0.0974	2.8366	3.2016
2.0	19	2.8119	0.0102	2.7975	2.8284
2.5	19	2.7781	0.0091	2.7668	2.7944
3.0	19	2.7516	0.0087	2.7385	2.7700
3.5	19	2.7284	0.0080	2.7167	2.7445
4.0	19	2.7100	0.0107	2.6803	2.7291
4.5	19	2.6963	0.0109	2.6681	2.7138
5.0	19	2.6847	0.0106	2.6594	2.7020
5.5	19	2.6752	0.0110	2.6506	2.6945
6.0	19	2.6676	0.0131	2.6418	2.6884
6.5	19	2.6626	0.0132	2.6387	2.6844
7.0	19	2.6592	0.0129	2.6361	2.6816
7.5	19	2.6573	0.0127	2.6346	2.6806
8.0	19	2.6561	0.0127	2.6331	2.6791
8.5	19	2.6554	0.0136	2.6287	2.6771
9.0	19	2.6553	0.0138	2.6242	2.6751
9.5	19	2.6561	0.0130	2.6278	2.6751
10.0	19	2,6571	0.0120	2.6319	2.6754
10.5	19	2.6581	0.0127	2.6330	2.6834
11.0	19	2.6593	0.0133	2.6330	2.6865
11.5	19	2.6605	0.0126	2.6335	2.6830
12.0	19	2.6616	0.0122	2.6340	2.6819
12.5	19	2.6623	0.0121	2.6369	2.6825
13.0	19	2.6626	0.0127	2.6399	2.6843
13.5	19	2.6635	0.0132	2.6395	2.6873
14.0	19	2.6660	0.0125	2.6390	2.6888
14.5	19	2,6691	0.0119	2.6444	2.6883
15.0	19	2.6716	0.0120	2.6498	2.6922
15.5	19	2.6729	0.0119	2.6495	2.6930
16.0	19	2.6747	0.0116	2.6490	2.6952
16.5	19	2.6776	0.0120	2.6509	2.6957
17.0	19	2.6806	0.0120	2.6529	2.6966
17.5	19	2.6831	0.0117	2.6549	2.6986
18.0	19	2.6851	0.0118	2.6569	2.7017
18.5	19	2.6875	0.0125	2.6598	2.7047
19.0	19	2.6909	0.0127	2.6627	2.7102
19.5	19	2.6947	0.0119	2.6671	2.7113
20.0	19	2.6975	0.0114	2.6716	2.7128
20.5	19	2.6995	0.0136	2.6621	2.7219
21.0	19	2.7011	0.0161	2.6513	2.7257
21.5	19	2.7044	0.0136	2.6690	2.7227
22.0	19	2.7088	0.0119	2.6861	2.7268
22.5	19	2.7127	0.0125	2.6870	2.7311
23.0	19	2.7166	0.0137	2.6860	2.7361
23.5	19	2.7211	0.0143	2.6919	2.7450
24.0	19	2.7253	0.0136	2.6979	2.7505
24.5	19	2.7303	0.0129	2.7031	2.7516
25.0	19	2.7368	0.0127	2.7083	2.7560
25.5	19	2.7431	0.0127	2.7139	2.7625
26.0	19	2.7504	0.0135	2.7205	2.7693
26.5	19	2.7608	0.0132	2.7322	2.7800
27.0	19	2.7747	0.0142	2.7489	2.8017
27.5	19	2.7876	0.0160	2.7405	2.8070
28.0	19	2.8037	0.0179	2.7505	2.8226
28.5	19	2.8332	0.0146	2.7972	2.8516
29.0	19	2.8688	0.0129	2.8413	2.8909
29.5	18	2.9031	0.0099	2.8791	2.9233
30.0	17	2.9300	0.0095	2.9147	2.9482
30.5	17	2.9587	0.0141	2.9397	2.9800
31.0	17	2.9981	0.0140	2.9743	3.0204

Table A1d

Ravenglass Estuary Section I

No. of surveys - 19

Distance (metres)	no. of points	mean height (metres)	standard deviation	range (metres) min	max
0	18	3.4609	0.0139	3.4400	3.4950
0.5	18	3.4576	0.0148	3.4324	3.4855
1.0	18	3.4472	0.0180	3.4165	3.4734
1.5	18	3.4169	0.0202	3.3723	3.4490
2.0	18	3.3225	0.0965	3.0020	3.4170
2.5	19	2.8233	0.0300	2.7674	2.9012
3.0	19	2.7818	0.0268	2.7046	2.8140
3.5	19	2.7566	0.0226	2.6997	2.7893
4.0	19	2.7335	0.0199	2.6947	2.7648
4.5	19	2.7138	0.0175	2.6792	2.7434
5.0	19	2.6971	0.0163	2.6572	2.7241
5.5	19	2.6829	0.0151	2.6438	2.7089
6.0	19	2.6703	0.0138	2.6393	2.6957
6.5	19	2.6591	0.0132	2.6353	2.6861
7.0	19	2.6499	0.0131	2.6256	2.6756
7.5	19	2.6409	0.0139	2.6163	2.6728
8.0	19	2.6382	0.0159	2.6083	2.6734
8.5	19	2.6425	0.0175	2.6057	2.6739
9.0	19	2.6501	0.0147	2.6199	2.6731
9.5	19	2.6562	0.0125	2.6289	2.6791
10.0	19	2.6638	0.0132	2.6380	2.6890
10.5	19	2.6730	0.0150	2.6473	2.7038
11.0	19	2.6820	0.0147	2.6561	2.7114
11.5	19	2.6905	0.0138	2.6629	2.7169
12.0	19	2.6990	0.0141	2.6674	2.7228
12.5	19	2.7077	0.0148	2.6733	2.7325
13.0	19	2.7163	0.0143	2.6839	2.7389
13.5	19	2.7246	0.0140	2.6938	2.7423
14.0	19	2.7324	0.0148	2.7009	2.7495
14.5	19	2.7398	0.0166	2.7030	2.7617
15.0	19	2.7460	0.0176	2.7055	2.7674
15.5	19	2.7522	0.0173	2.7113	2.7752
16.0	19	2.7587	0.0161	2.7215	2.7832
16.5	19	2.7648	0.0155	2.7316	2.7915
17.0	19	2.7710	0.0150	2.7417	2.7947
17.5	19	2.7769	0.0141	2.7490	2.7978
18.0	19	2.7822	0.0127	2.7563	2.8010
18.5	19	2.7871	0.0120	2.7613	2.8079
19.0	19	2.7921	0.0133	2.7643	2.8135
19.5	19	2.7973	0.0149	2.7684	2.8238
20.0	19	2.8025	0.0150	2.7709	2.8290
20.5	19	2.8075	0.0148	2.7742	2.8335
21.0	19	2.8117	0.0140	2.7814	2.8372
21.5	19	2.8156	0.0143	2.7876	2.8408
22.0	19	2.8194	0.0143	2.7907	2.8414
22.5	19	2.8233	0.0141	2.7941	2.8422
23.0	19	2.8263	0.0128	2.7984	2.8444
23.5	19	2.8285	0.0133	2.8028	2.8524
24.0	19	2.8316	0.0139	2.8036	2.8571
24.5	19	2.8352	0.0137	2.8050	2.8591
25.0	19	2.8384	0.0136	2.8095	2.8617
25.5	19	2.8406	0.0139	2.8143	2.8647
26.0	19	2.8421	0.0134	2.8181	2.8668
26.5	19	2.8434	0.0130	2.8186	2.8682
27.0	19	2.8456	0.0130	2.8192	2.8692
27.5	19	2.8484	0.0137	2.8202	2.8703
28.0	19	2.8516	0.0146	2.8191	2.8719
28.5	19	2.8526	0.0158	2.8155	2.8751
29.0	19	2.8548	0.0172	2.8120	2.8746
29.5	19	2.8570	0.0179	2.8150	2.8763
30.0	19	2.8587	0.0164	2.8183	2.8765
30.5	19	2.8602	0.0142	2.8243	2.8785
31.0	19	2.8613	0.0127	2.8299	2.8773
31.5	19	2.8630	0.0119	2.8339	2.8792
32.0	19	2.8648	0.0119	2.8370	2.8807
32.5	19	2.8670	0.0140	2.8370	2.8926
33.0	19	2.8682	0.0140	2.8376	2.8868
33.5	19	2.8696	0.0144	2.8402	2.8953
34.0	19	2.8721	0.0145	2.8428	2.9041
34.5	18	2.8751	0.0151	2.8462	2.9043
35.0	18	2.8780	0.0145	2.8543	2.9034
35.5	18	2.8791	0.0134	2.8580	2.9029
36.0	18	2.8781	0.0126	2.8580	2.9018
36.5	17	2.8790	0.0132	2.8564	2.9009
37.0	16	2.8788	0.0152	2.8465	2.9001

Table A1 e

Table B1 Delay times[Ø] for transducers relative to river high water. Positive pore pressure on Transducer #1, and Transducer #6 > 2.75 m OD water level.*

Ø Times in 12 minute units
* Leaves 1 dubious value during rainfall period of 3 August which has been omitted
N.D = no data
pps = pore pressures

Dates 1983	n=	Transducer No: 1	2	3	4	5	
21 Jan - 2 Feb	13	16½	19	18	16½	15½	
		15.23	17.54	16.62	15.23	14.31	
23 Mar - 18 April	[37]	[65½](46)	N.D	[72½](68)	[62](58)	[62](58)	Long delays on neaps. Event 2=7 and event 26=12½ on #1.
		[21.24](15.77)]		[23.51(23.31)]	[20.11(19.89)]	[20.11(19.89)]	
18 May - 16 June	38	37½(26½)	59½(50)	46(42)	49½(46½)	46½(43½)	Long delays at beginning of 2nd neaps. Event 26=5 and event 27=6 on #1.
		11.84(8.83)	18.79(15.79)	14.53(14.00)	15.63(15.50)	14.68(14.50)	
16 June - 18 July	44	28(18½)	78⁺(52)	63½(47½)	65(49)	61½(46½)	⁺Long recovery period following neaps. Transducer #2; 9=6½, 10=4½, 28=4½, 30=2½, 40=5, 41=3.
		7.64(5.84)	21.27(16.42)	17.32(15.00)	17.73(15.47)	16.77(14.68)	
18 July - 15 Aug	35	18	35½	33½	43	41	
		6.17	12.17	11.49	14.74	14.06	
15 Aug - 13 Sept	40	31(22)	63(48½)	55½(48½)	58½(53½)	57(52)	1 long delay during surrounding -pps ie Event 31=9 on transducer #1. 2 long delays during surrounding -pps in #2: Event 31=7½; event 36=7.
		9.30(6.95)	18.90(15.32)	16.65(15.32)	17.55(16.89)	17.10(16.42)	
13 Sept - 10 Oct	38	38(21½)	69(47½)	51½(41½)	50(42)	48½(41)	Long delays: #1 event 1=6½ beginning 1st neaps; events 30 and 37=5 each (beginning and end of 2nd neaps). Corresponding delays on #2=4½, 5 and 12.
		12.00(7.37)	21.79(16.29)	16.26(14.23)	15.79(14.40)	15.32(14.06)	
11 Oct - 9 Nov	47	64(43½)	99½(66)	71½(59)	77½(61½)	74½(60)	Consp. delays during 1st neaps and at beginning and end of 2nd neaps. Trans #1 12=8½, 14=7, 34=7, 41=~4. Trans #2: 6=5, 10=9½, 12=6, 34=4½, 41=8½. For event 10 #3=3; #4=8½, #5=8.
		16.34(12.73)	25.40(19.32)	18.26(17.27)	19.79(18.00)	19.02(17.56)	
10 Nov - 11 Dec	46	66½(32½)	111(70)	79(59½)	70½(56½)	65½(52½)	Includes 2 f. long delays at end of 1st neaps; 4 delays (#36-39) during 2nd neaps but having +pps.
		17.35(8.1)	29.96(21.00)	20.61(17.85)	18.39(16.95)	17.09(15.75)	
11 Dec - 11 Jan 1984	-	- - - - - - - - Not analysed in detail - - - - - - - - - - - - - - - - - - →					

Upper row for each data period gives total delay time in 12 minute sampling periods.

Lower row mean time in minutes. Figures in brackets exclude 'long' delays.

TABLE C1 List of relevant cartographic material consulted

1860	Ordnance Survey	1:10560	Sheet 82	1st edition,	Published 1867(?)
1897	" "	"	" 82SE	2nd edition,	Published 1900
1970	" "	1:2500	" 0894-0994,		Published 1971

(and derived 1:10000 SD 09NE; SD 09SE)

Other sources

1774 County of Cumberland 1770-71 by T Donald engraved J Hodskinson. BM Maps 183.0.2.(1)

1825 " " " 1821-22 by C & I Greenwood. BM 1945(29)

1850 Cumberland with its railways. H G Collins. BM Maps 1 aa 103

1854 Collins' railway and telegraph map of Cumberland. BM 1945(34)

1864 Cumberland shewing all the railways and stations. Smith and Sons BM 1945(10)

1877 Crutchley's road and railway map of Co of Cumberland. BM 1945(12).

Other surveys examined gave no useful additional details on the construction of the viaduct; the outline of the salt marsh; or the position of high water mark.

List of aerial photographs consulted

			Approx scale	Notes
16 January 1946	RAF flight reference	106G/UK/1127	1:10200	High water
28 May 1966	Ordnance Survey	66-101-119/120	1:7500	
23 June 1973	Hunting Surveys	HSL UK 7386 5578/9	1:8300	
4 October 1980	University of Cambridge	RC8-DQ 170/1	1:7300	Some cloud