

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD
DIRECTORATE OF FISHERIES RESEARCH

FISHERIES RESEARCH TECHNICAL REPORT

No. 59

The field assessment of effects of dumping
wastes at sea: 7 Sewage sludge and
industrial waste disposal in the
Bristol Channel

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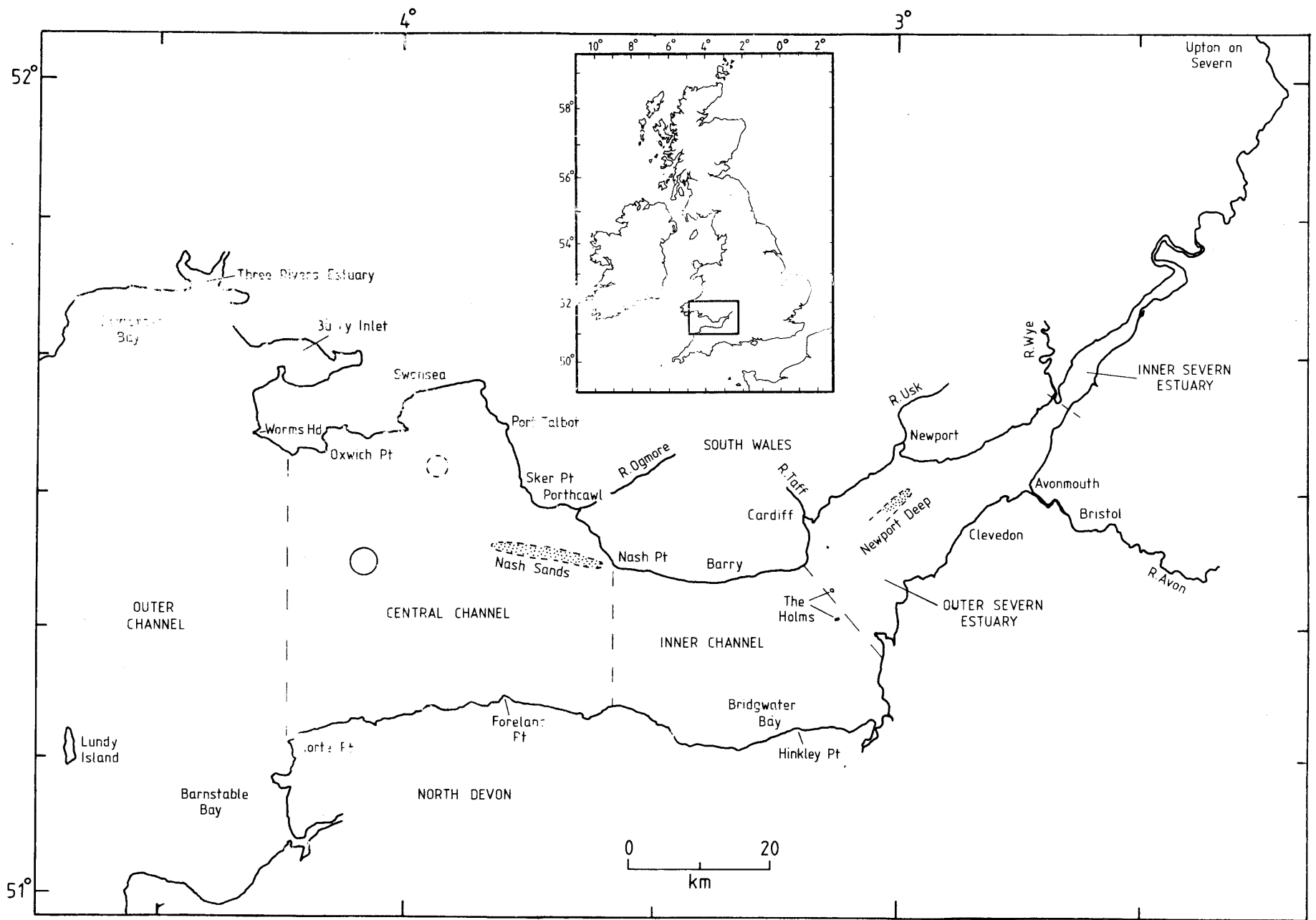


Figure 1 The Bristol Channel and Severn Estuary.

1 Introduction

1.1 Purposes of the study

The Bristol Channel has been used for the disposal of wastes by dumping from vessels for a number of years. Dumping of sewage sludge started from the City of Bristol's sewage treatment works in 1969 at a position 51°20'N, 04°04'W. In 1974 the dumping site was moved to its present location at 51°24.5'N, 04°04'W (Figure 1). Some industrial wastes have been included in the sewage sludge and since 1974 sewage sludges from South Wales have been dumped in the same area.

Since the enactment of the Dumping at Sea (DAS) Act in June 1974 (Gt. Britain-Parliament, 1974), disposal of waste by dumping in this sea area has been regulated under licences issued to the Wessex and Welsh Water Authorities by the Ministry of Agriculture, Fisheries and Food (MAFF). As an important part of its responsibilities under the DAS Act, MAFF monitors the environmental impact of waste disposal by dumping; this is to determine in particular the dispersal pathways of dumped waste and any effects on fisheries and marine life generally. The Ministry's policy and approach to the monitoring of dumping grounds has been described earlier in this series of reports (Norton and Rolfe, 1978) and details of the methods used have also been published (Eagle *et al.*, 1978a).

This report presents the results of specific surveys which have been carried out in the vicinity of the Bristol Channel dumping ground to: (i) characterise the area in physical, chemical and biological terms so as to provide a reference point against which the results of future surveys can be compared; (ii) identify the dispersal pathways and fate of the dumped waste and its persistent components; (iii) identify effects on the physical and chemical characteristics of the area attributable to dumping and to define any resulting biological effects.

In addition to the surveys carried out by MAFF, use has also been made of the published results of investigations made by other organisations. In particular, the general area of the Severn Estuary and the Bristol Channel has been under study for several years by the Institute of Marine Environmental Research (IMER) at Plymouth and by the relevant Regional Water Authorities under the auspices of the Severn Estuary Joint Committee and its Technical Working Party.

1.2 General background and uses of the area

The Severn Estuary and the Bristol Channel together form a roughly horn-shaped area, the tidal limits of which extend over 240 km from Upton-on-Severn to Lundy Island. For the purposes of this study only the part of the Severn Estuary west of the River Wye has been considered in any detail; and most attention has been given to the Central Bristol Channel in which dumping takes place (Figure 1).

Tides in the region have the largest diurnal range (13 m) found in Britain but the exchange of water between the Bristol Channel and the open sea is limited, the flushing time for the system as a whole being of the order of 300 d (Hamilton, 1973). The effective dispersion of material within the Estuary has contributed to its ability to receive large quantities of industrial and domestic effluent from a number of conurbations and industrial complexes, and has thus played an important role in their development.

Commercial sea fishing takes place mainly to the west of a line drawn between Worm's Head and Morte Point (4°20'W) in the outer Channel, but is less important in the central and inner Channel, although several rivers entering the Severn Estuary are important for salmon. The main shellfisheries are for cockles in the Burry Inlet, lobsters near Barnstaple, shrimps in the Severn Estuary and mussels in the Burry Inlet and Three Rivers Estuary. Some fish farming of shrimps, oysters and flatfish takes place at Hinkley Point nuclear power station and sea angling is a popular sport throughout the Channel and outer Severn Estuary. The Channel is used extensively for amenity purposes, having bathing beaches on the English side south from Clevedon and on the Welsh side west from Barry, and providing a large sea area for boating and yachting. Several bird sanctuaries exist in the Severn Estuary and large populations of birds overwinter in the area.

Large quantities of sand and gravel are extracted from several areas of the Severn Estuary under licence from the Crown Estate Commissioners; in 1976 over 2 million tonnes were taken from areas between Bristol and Swansea. Some of the quantities are taken from the Nash Sands close to the dumping area in the central Channel but the majority is from the Severn Estuary itself.

The use of the Channel for the dumping of wastes must therefore avoid conflict with several interests in the area and regulations are framed with this objective. Although the present study will concentrate on the sewage sludge and industrial waste dumping in the central Channel, the influence of dredged spoil dumping in the adjacent Swansea Bay will also be considered. Further quantities of dredged spoils from Bristol, Newport and Cardiff are dumped upstream in the Severn Estuary close to the ports of origin and will not be considered in detail in this report.

1.3 Composition and quantity of dumped wastes

The quantity and composition of the sewage sludges and industrial wastes licensed to be dumped during 1977 and 1978 are given in Table 1. Amounts totalling 482 000 t of sewage sludge and 10 085 t of industrial waste were licensed for disposal but the actual quantities dumped were lower; Table 2 shows the estimated quantities of the waste and its components dumped in each of the three years 1976, 77 and 78.

The quantities of dredged spoil dumped in 1977, together with the estimated quantities of certain trace elements contained therein, are shown in Table 3. For the reason already specified, the figures are separated into the spoils dumped in Swansea Bay and those in the Severn Estuary.

Table 1 Quantity and composition of sewage sludges and industrial wastes licensed for dumping in the Bristol Channel, 1977 and 1978.

Component	Sewage sludge* mg l ⁻¹ wet wt unless stated		Industrial wastes† mg l ⁻¹ wet wt unless stated	
	Range	Average	Range	Average
Suspended solids	2.0 - 7.0%	3.3%	0 - 10%	4.8%
Particulate organics	1.5 - 5.5%	2.2%	<0.1%	<0.1%
Particulate inorganics	0.5 - 1.5%	1.1%	0 - 10%	4.8%
Nitrogen (as N)	0.08 - 0.12%	0.1%	ND	ND
Phosphorus (as P)	0.036- 0.048%	0.04%	ND	ND
Cadmium	0.4 - 1.4	0.8	0 - 10	1
Chromium	3 -30	23	0 -2070	570
Copper	12 -35	15	0 - 310	110
Lead	10 -30	17	0 - 100	20
Mercury	<0.1 - 0.3	0.1	0 - <0.1	<0.1
Nickel	1 - 9	3	0 -1270	110
Zinc	20 - 55	40	0 - 130	57

* Includes primary, secondary (biological) and digested sludge from four different sewage works (Bristol, Newport, Abergavenny and Nash); total quantity licensed is 482 000 t a⁻¹.

† Includes waste from 13 production sites totalling 10 085 t a⁻¹. Industries include metal finishing, aerospace, carpets and paints.

ND = not determined.

Table 2 Quantities (tonnes) of sewage sludge and industrial wastes dumped during 1976-8 in the Bristol Channel

Year	Waste	Quantity dumped	Suspended solids	Cd	Cr	Cu	Ni	Pb	Zn	Hg	N	P
1978	Sewage sludge	393 600	9 513	0.3	7.8	4.9	0.4	7.8	16.3	<0.1	328	152
	Industrial waste	5 020	306	<0.1	4.4	0.6	2.3	0.1	0.4	<0.1	ND	ND
1977	Sewage sludge	330 680	8 767	0.4	6.1	4.0	1.3	3.8	11.2	<0.1	284	127
	Industrial waste	5 272	275	<0.1	3.0	0.6	0.8	0.1	0.3	<0.1	ND	ND
1976	Sewage sludge	308 160	8 566	0.5	7.4	4.3	2.3	3.4	13.0	<0.1	260	120
	Industrial waste	6 665	232	<0.1	4.9	0.9	0.8	0.1	1.0	<0.1	ND	ND

ND = not determined.

Table 3 Quantities of dredged spoil dumped in 1977 (tonnes) in the Bristol Channel

Dumping area	Quantity dumped	Solids	Quantity of materials contained						
			Cd	Cu	Cr	Ni	Pb	Zn	Hg
Swansea Bay	3 350 000	1 775 000	<7.1*	128	83	100	400	666	1.6
Severn Estuary	5 100 000	2 552 000	<2.8*	95	94	105	233	602	1.3

* Some determinations below detection limit of analytical method employed for Cd (2 mg kg⁻¹).

The current level of sewage sludge dumping has increased substantially from 1976 to 1978 due to diversion of sludge from land tipping in South Wales, the contribution of a new works in South Wales and the expansion of sewage treatment in the Bristol area. On the other hand the quantity of industrial waste dumped has decreased slightly since the introduction of the DAS Act in 1974.

1.4 Scope of surveys and methods

The area in the vicinity of the dumping site has been monitored by MAFF research vessels on several occasions. The surveys on which this report is based were conducted in 1975, 1976, 1977 and 1978. In October 1975 an extensive grid of stations in the central Channel (Figure 2) was

sampled from RV CORELLA using a 0.1 m² Day grab in an attempt to collect three samples at each station. Where the grab failed to collect a sample on rock or gravel substrate, an anchor dredge was used to provide a single bulk sample. In July 1976 a more limited grid of stations was surveyed from RV CLIONE, sampling with a Day grab. On the latter survey a side-scan sonar survey of the area was also conducted, using an EG and G model 259 dual channel system at 125 m range. In 1977 a further grid of stations was sampled in the region of the dumping area and in Swansea Bay.

Where more than one sample was successfully collected, one was used to provide a sample of the upper 1-2 cm of sediment for particle-size, organic carbon, metal (and in 1976 and 1977, microbiological) analysis, and the others

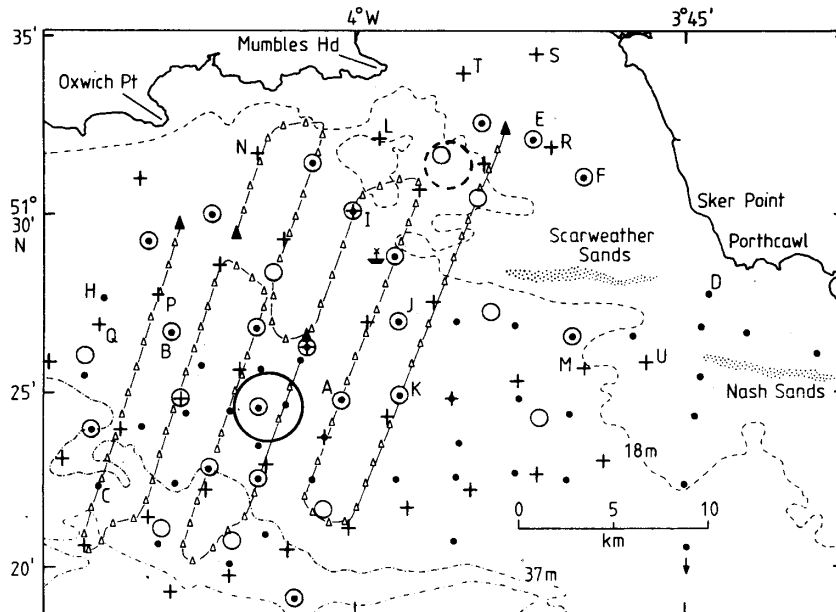


Figure 2 Sampling and sonar surveys carried out during 1975, 1976 and 1977.

- + 1977 grab station (CLIONE 11/77)
- 1976 grab station (CLIONE 11/76)
- 1975 grab station (CORELLA 16/75)
- ↓ 2 further stations, 2 and 4 miles south, not shown, from which no samples were obtained.
- △ - △ - △ track of side-scan sonar survey (1977).
- sewage sludge dumping ground.
- dredged spoil ground.
- A-F : location of samples referred to in Figure 14 and Section 5.1.3;
- G: location of core shown in Figure 15; H-U: locations of stations in Figure 12.

were sieved through a 1 mm sieve to collect the macrobenthos. In many cases where sampling was difficult, only one sample was retained, in which case the sediment and benthos evaluations were carried out on the single sample. Samples of biota were preserved in 5% formalin and returned to the laboratory for identification. Details of the methods employed for the analysis of sediment and the identification of fauna have been published (Eagle *et al.*, 1978a).

In October 1978, RV CORELLA was used to record current velocity and direction at different depths over a 25 h period using direct reading current meters (DRCM) to provide data on local tidal currents. For the purpose of determining the longer term residual bottom water movements in the area, a series of eleven drops (each of 100) of seabed drifters was carried out between October 1975 and February 1978 from the Wessex Water Authority's dumping vessel MV GLEN AVON and MAFF research vessels.

1.5 Report structure

The dumping area is in a part of the Channel subject to inputs of potential pollutants from several sources (river discharges, sewage and industrial effluents, etc.); thus any assessment of the effects of dumping will be assisted by knowledge of the inputs of these substances from other sources. These are estimated in Section 2 of this report.

The hydrography of the area allows predictions to be made concerning the dispersion and the fate of dumped waste: it is described in Section 3. The results of the microbiological analyses also identify initial transport paths and are discussed in Section 4. The results of the sediment surveys allow a description of the nature, distribution and dynamics of the natural sediments of the area and reveal the extent to which dumping has affected the chemical characteristics of the sediment (with respect to the organic carbon and metal contents of the sediment); these are considered in Section 5. The difficulties of sampling the benthos quantitatively rule out a detailed assessment of biological effects, but a qualitative description of the benthos is provided in Section 6. The overall conclusions on the fate of dumped material and its effects are given in Section 7.

2 Inputs to the Severn Estuary and Bristol Channel

Because of the enclosed nature of the central Channel where dumping takes place, the quantities of organic substances, metals, etc., reaching this area from the dumping of wastes are supplemented with material from other sources, e.g., from the rivers entering the Estuary and Channel, from direct discharges and from atmospheric deposition. In order to facilitate consideration of the relative importance of these sources it is necessary to consider first the relative magnitude of these inputs to the survey area. To this end a survey of inputs to the Estuary and Channel was conducted in 1975-76 by MAFF and by the Severn Estuary Technical Working Party (SETWP, 1977). Since that time, a programme of monitoring the flows and composition of discharges in greater detail has

been undertaken by the Regional Water Authorities through the Severn Estuary Technical Working Party and more accurate estimates of inputs from rivers, sewage and industrial discharges have been prepared (SETWP, 1980) and results of these studies for Swansea Bay (Chubb *et al.*, 1980) published.

In the discussion of relative inputs five main sources of material have been considered:

- (1) river discharges;
- (2) sewage outfalls discharging to the Estuary and Channel;
- (3) industrial outfalls discharging directly to the Estuary and Channel;
- (4) atmospheric deposition;
- (5) dumping of waste.

The dumping of dredged spoils also takes place (Table 3). Although the dumping of these large quantities of spoil may have an influence in specific areas, it would be unrealistic to regard dredged spoil as a fresh input to the system since much of the material dredged is comprised of sediment originating from within the Estuary and Channel. For this reason the input of dredged spoil has not been included in the comparison of inputs in the remaining part of this section.

The results of the most recent survey (1977-9) for the Estuary and Channel are summarised in Table 4. River discharges account for over 90% of the volume flow into the Estuary and for a significant proportion of organic, suspended solids and metals (particularly nickel and copper) inputs. Sewage and industrial discharges are major sources of the metals, mercury, cadmium and chromium, while atmospheric deposition is most important for lead and zinc. Sewage outfalls are the major source of BOD. Dumping contributes only a few percent of most inputs to the whole Estuary and Channel, except for the BOD contribution which was estimated at 10.6%. From the viewpoint of the whole system therefore, dumping is shown to be only a minor contributor to organic and metal inputs.

Because the dumping site is a long way from the major freshwater inputs and the larger sewage and industrial discharges, it may be unrealistic to consider the relative importance of inputs to the central Channel on the basis of a simple numerical comparison of inputs to the whole system. For instance, much of the BOD in effluents discharged in the Severn Estuary will have been satisfied by the time the waters reach the central Channel; some of the metals will also remain within the Estuary associated with sediments. Atmospheric deposition was also shown to be less significant in the central Channel than in the Estuary near to the main industrial centres (SETWP, 1980).

A more realistic, but still crude, upper estimate of the relative importance of dumping inputs to the central Channel may be made by comparing inputs into the central Channel only. A comparison of these based on detailed measurements of flows and concentrations from 1977 to 1979 (Chubb *et al.*, 1980) is shown in Table 5. On this basis, dumping in 1978 contributed 28% or less of local metal inputs. The BOD input appears most significant at 51% but the authors of the survey suggested that the particulate organic matter estimates were more reliable due to doubts on the measurement of BOD in industrial effluents. If this is assumed to be the case, then dumping

is estimated to contribute only 27% of local organic inputs. Dumping inputs for 1976 would have been relatively less important because of the smaller quantity dumped (20% less than in 1978).

Although the absolute figures quoted in Table 5 may still be of limited significance due to the number of approximations made, they do reveal what are believed to be real differences in the relative importance of dumping as a source of each waste component. This is relevant to the effects of dumping on the sediment composition which are discussed in Section 5.

Table 4 Comparison of inputs to the Severn Estuary and Bristol Channel (1977-9)

Source	Flow ($\text{m}^3 \text{ s}^{-1}$)	Total inputs (kg d^{-1})							
		BOD	Suspended solids	Ni	Cd	Cr	Cu	Pb	Zn
Rivers	337.4	75 700	1 800 000	352	20	ND	337	195	1 560
Sewage outfalls	9.55	102 000	112 000	33.8	7.7	46.7	53.5	51.9	456
Industrial discharges	3.15	51 500	429 000	15.3	20.1	123	97.9	213	919
Atmospheric deposition	24	ND	ND	55	12.9	21	118	665	2 180
Dumping	0.01	27 100	26 100	7.4	0.8	33.4	15.1	21.6	45.8
Total	374	256 000	2 370 000	464	61.6	224	621	1 150	5 160

Source: Severn Estuary Technical Working Party, 1980

Table 5 Comparison of dumping inputs to Central Channel (kg d^{-1}) in 1977-79 with other inputs to Swansea Bay

Source	BOD	POM*	Suspended solids	N	P	Ni	Cd	Cr	Cu	Pb	Zn	Hg
Dumping	25 300	17 000	26 100	899	416	7.4	0.82	33.4	15.1	21.6	45.8	0.16
Domestic sewage	13 500	10 245	13 300	2 150	399	4.0	0.13	3.9	7.6	4.5	26.5	0.04
Industrial effluent	4 600	9 770	30 400	4 930	12	3.9	0.31	66.8	83.1	74.7	269.0	6.05
Rivers and streams	6 200	24 900	111 000	2 660	318	181.0	3.77	10.8	61.1	18.1	412.0	0.75
Atmospheric inputs	ND	ND	ND	ND	ND	15	0.8	4	13	34	170	ND
Total	49 600	61 915	180 800	10 639	1 145	211.3	5.83	118.9	179.9	152.9	923.3	7.00
Dumping as % of local inputs	51	27.4	14.4	8.5	36.3	3.5	14.1	28.1	8.4	14.1	4.9	2.3

*POM = particulate organic matter
Source: Chubb *et al.* (1980)

3 Hydrographic characteristics of the receiving area and implications for the dispersal of dumped wastes

3.1 General characteristics

The Bristol Channel/Severn Estuary system (Figure 1) is characterised by the largest tidal range around the U.K., a large freshwater input and a semi-enclosed nature. This combination of features produces a water body that is vertically well mixed as a result of the high energy of tidal movements but which has a restricted exchange with waters outside the Channel; the latter leads to pronounced variations in salinity along the length of the Estuary and Channel.

The tidal range increases eastwards along the Channel, from 7 m on spring tides at Lundy through 8.5 m near the dumping ground to 12.2 m on spring tides at Avonmouth. The strength of tidal currents increases correspondingly, maximum near-surface velocities ranging from 2 knots ($\approx 100 \text{ cm s}^{-1}$) in the west to 5 knots ($\approx 250 \text{ cm s}^{-1}$) in the

constricted upstream reaches. The orientation and magnitude of these flows in the central Channel are shown in Figure 3; maximum velocities in open waters lie in the range 2-3 knots ($100\text{-}150 \text{ cm s}^{-1}$) but flows are faster off headlands and in shoal areas, and slower in bays. The predominant east-west alignment of these currents is modified in the northern part of the Channel by the set of the tide into and out of Swansea Bay.

The average freshwater input into the Severn Estuary/Bristol Channel is of the order of $300\text{-}400 \text{ m}^3 \text{ s}^{-1}$ but varies seasonally; e.g., the input of the River Severn varies between $20 \text{ m}^3 \text{ s}^{-1}$ (June) and $150 \text{ m}^3 \text{ s}^{-1}$ (February) in a typical year. These large variations lead to significant differences in the form of the summer and winter near-surface salinity distributions, examples of which are given in Figure 4 for July 1973 and February 1974 (IMER, 1974). Waters throughout the Channel are well mixed during normal river flows, the difference between surface and bottom water salinity rarely exceeding $0.1^{\circ}/\text{oo}$ (Hamilton, 1973). However, slight stratification has been

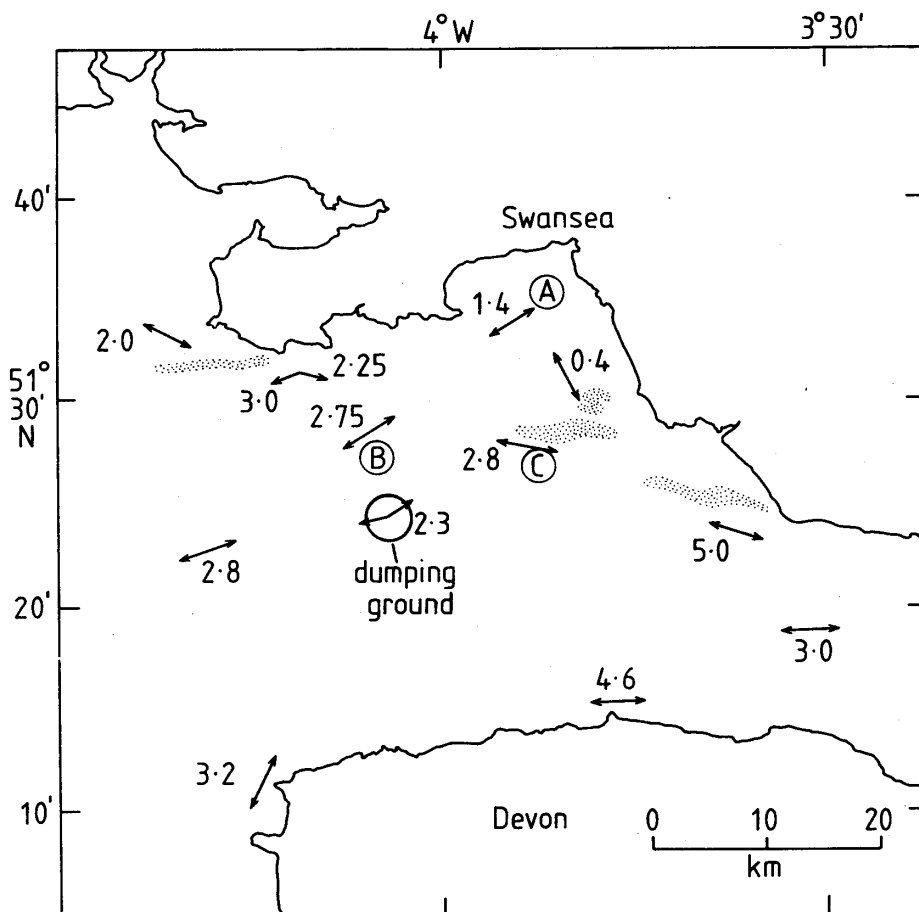


Figure 3 Tidal flows showing direction and maximum near-surface velocities in knots from Admiralty Chart No. 1165 and MAFF observations. **A**: position of C. M. Davies' observations in 1971 (Collins *et al.*, 1979). **B** & **C**: positions of IOS observations (Heathershaw and Hammond, 1980a).

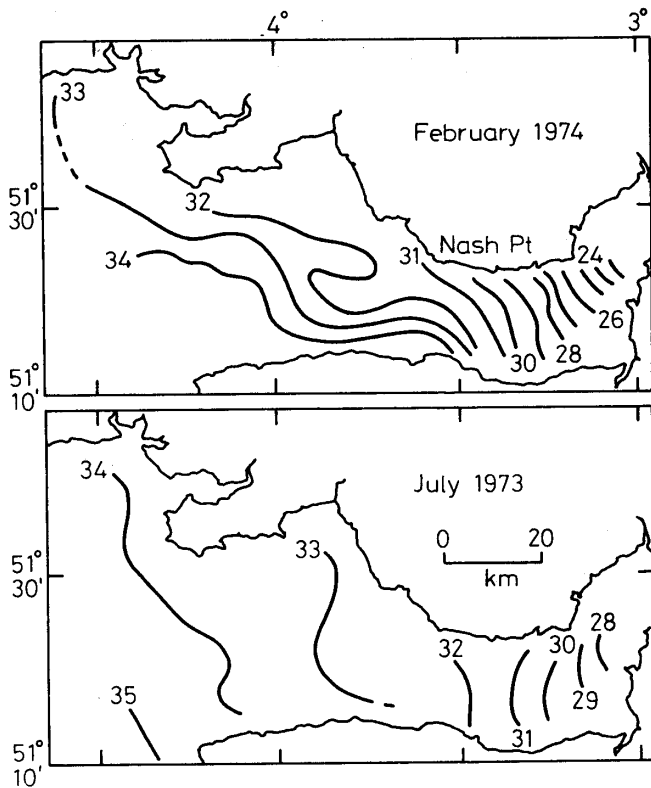


Figure 4 Salinity ($^{\circ}/\text{oo}$) during a winter (February 1974) and a summer (July 1973) month at a depth of 10 m. From IMER (1974).

observed as far west as the central Channel during periods of high runoff (IMER, 1974). Observations from RV CORELLA at the dumping ground in October 1978 showed a slight semi-diurnal variation in surface salinity of $0.5^{\circ}/\text{oo}$.

The isohalines in the central and outer Channel commonly show a tongue of more saline water extending eastwards along the north Devon coast (Figure 4), from which it has been deduced that the water circulation in this region takes the form of a large anti-clockwise gyre (Lee, 1965; Hamilton, 1973). It is thought that this feature restricts the exchange of water between the inner and central Channel areas, since it confines water escaping downstream of Nash Point to the area close to the Welsh coast. The high retention time of water in the inner Channel area that results from this circulation has been estimated by IMER from river flow and salinity data and is shown in Figure 5. Water entering the inner Estuary was shown to take between 150 and 300 d to leave the Channel in May 1973 to January 1974, but seawards of Nash Point the flushing rate increased, and the fresh water rapidly mixed into the Celtic Sea.

3.2 Tidal and wave-induced currents at the dumping ground

Tidal currents were measured using a DRCM over a 25 h period from RV CORELLA anchored at the dumping

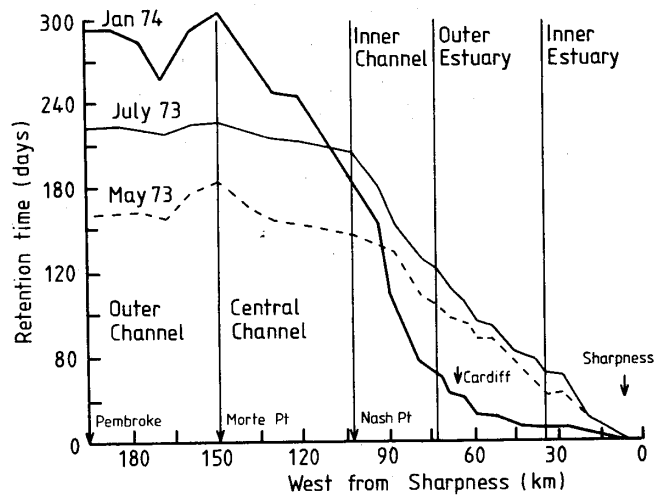


Figure 5 Retention time, in days, for river run-off in the compartments of the Bristol Channel shown in Figure 1. From IMER (1975).

ground in October 1978. Although these measurements are the only ones to have been conducted in the dumping area itself, other workers have carried out investigations of water movements in the Estuary and Channel (IMER) and in the central Channel and Swansea Bay (University College of Swansea and Institute of Oceanographic Sciences (IOS), Taunton). While published findings of these programmes of work have been used and referred to in the text, a review of their findings is beyond the scope of this paper and thus detailed descriptions will only be provided of the hitherto unpublished MAFF observations.

The variation in velocity with depth during the period of MAFF's observations is shown in Figure 6 and progressive vector plots for observations at 1 m above the bed and 10 m below the surface are shown in Figure 7. The observation period was mid-way between spring and neap tides; thus the maximum observed velocities are approximately 0.75 of spring tide and 1.5 times neap tide values. It can be seen from Figure 6 that the tidal incursion takes the form of a standing wave. The period of slack water was more pronounced at high than at low water; during the latter the current 1 m above the bed was not observed to drop below 5 cm s^{-1} , whereas at high water velocities were in the order of $3\text{-}5 \text{ cm s}^{-1}$ for up to one hour.

Maximum currents observed 10 m below the surface were 90 cm s^{-1} , suggesting a spring tide maximum velocity of 120 cm s^{-1} (2.3 knots). The corresponding value at 1 m above the sea bed (\bar{U}_{100}) was 50 cm s^{-1} (67 cm s^{-1} springs, 1.3 knots). Using the quadratic stress law (Komar, 1976), which would appear to be applicable on sandy gravel substrates (Sternberg, 1968) such as are found at the dumping ground (see Section 5.1.2), the friction velocity can be calculated as:

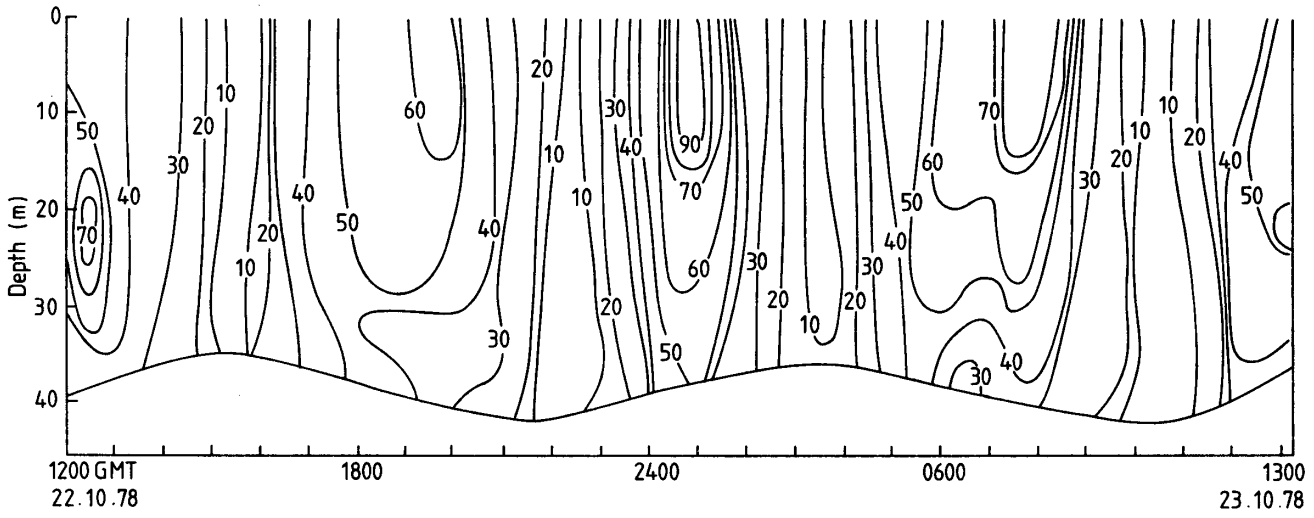


Figure 6 Variations in current velocity with time and water depth over 25 h at the dumping ground in October 1978. Velocities in cm s^{-1} .
 (Weather conditions: wind from N to W, 0-12 knots; swell from W, 0.3-0.7 metres).

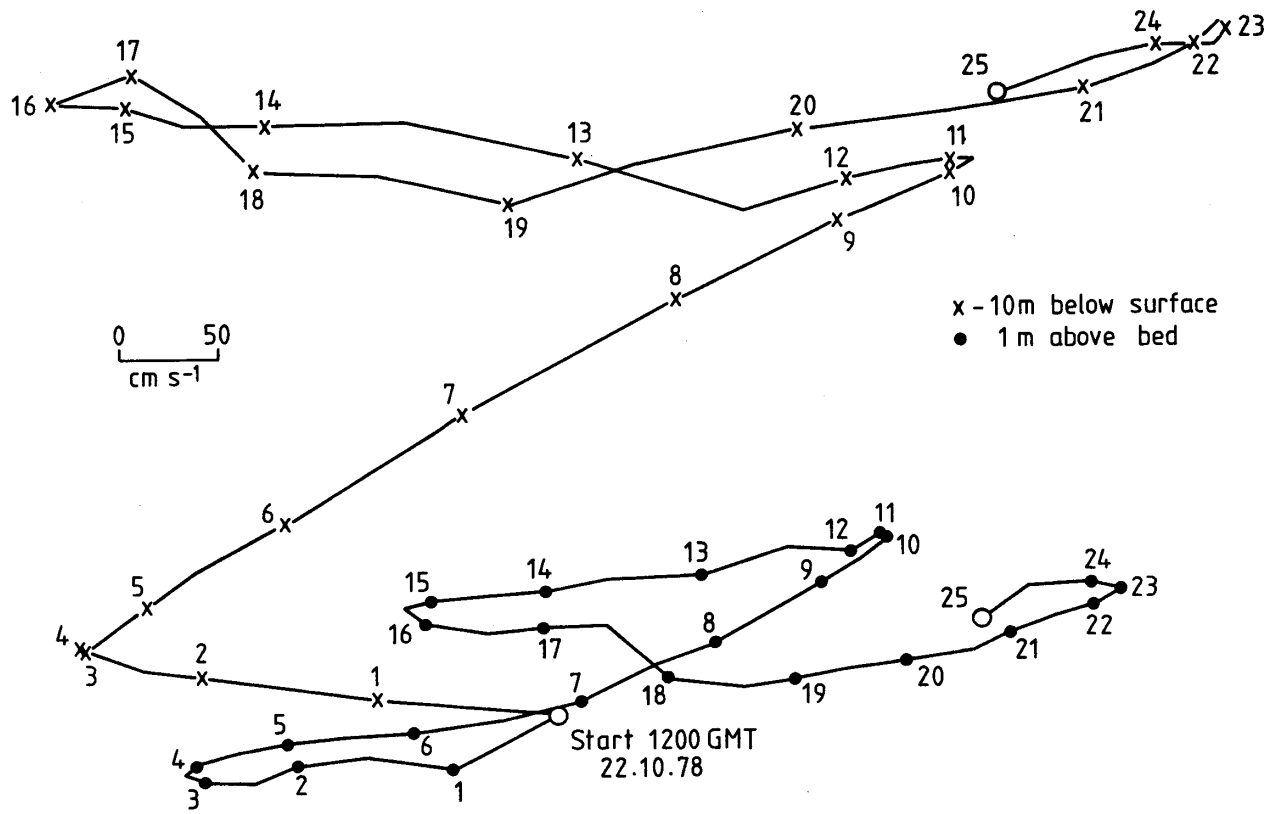


Figure 7 Progressive vector plots from observations over 25 h at the dumping ground in October 1978, 10 m below surface and 1 m above bed.

$$U_* = .0547 \bar{U}_{100}$$

which yields a maximum (spring tide) value of 3.66 cm s^{-1} in the region of the dumping ground. The progressive vector plots of currents at the dumping ground shown in Figure 7 show that the strongest near-surface and near-bed tidal flows are aligned along approximately an ENE/WSW axis. There appeared to be a greater northward component in the residual currents near the surface (7 cm s^{-1} in a direction 7° true compared with those near the sea bed (4 cm s^{-1} in a direction 55° true)).

Measurements of \bar{U}_{100} have also been made in Swansea Bay by C M Davies in 1971 (Collins *et al.*, 1979) at the position (A) marked in Figure 3. The maximum (spring tide) value of \bar{U}_{100} was between 19 and 21 cm s^{-1} during a 2-week period in July 1971, reflecting the lower surface tidal velocities (Figure 3) in the inner Bay. More recent work in 1975-7 by IOS, Taunton (Heathershaw and Hammond, 1980a) on the tidal currents and residual circulation of Swansea Bay and the adjacent area of the Channel included the collection of current meter data from a site 5 km north of the dumping ground (at $51^\circ 27' \text{N}$ $04^\circ 05' \text{W}$, Station (B) in Figure 3). This site exhibited a mean westerly residual over a 50-day observation period of 0.6 cm s^{-1} . A site near the Scarweather Sands (Station (C) in Figure 3) displayed a north-easterly near-bottom residual of 2.3 cm s^{-1} but the mid-depth residual was 2.8 cm s^{-1} in a south-westerly direction.

The low steadiness factor in the current meter results from the station nearest the dumping ground (Station (B) in Figure 3) suggests that caution should be exercised in deducing long-term residual drift trends at the dumping ground from the single 25 h period of observation. Taken together with the IOS observations, however, they do suggest a consistent east to north-easterly component in near-bottom residual currents in the region of the dumping ground. Midwater and surface residuals appear to be more variable in this section of the Channel.

The wave climate in the central Bristol Channel has been continuously recorded since October 1974 by a 'Waverider' buoy moored close to the Scarweather Light Vessel, 11 km north-east of the dumping ground (Carr *et al.*, 1976). Analysis of records between October 1974 and September 1975 shows that for most of the year waves are less than 1 m in height and have a period between 5 and 10 s. The maximum observed values for height and period were 3.9 m and 17 s respectively. These data on the frequency of occurrence of the various combinations of wave period and significant wave height have been used to estimate the range of near-bed wave-induced velocities, using the procedure of Komar and Miller (1975). The percentage of the year when given values of near-bed velocity (U_m) are exceeded close to the Scarweather Light Vessel at water depths of 10 m, 20 m and 36 m is shown in Figure 8. Assuming that the wave climate at the dumping ground (36 m depth) is similar to that at the Scarweather Light Vessel, it is predicted that values of U_m do not exceed 5 cm s^{-1} for 50% of the year, but that during rare storm periods velocities can attain $40\text{-}50 \text{ cm s}^{-1}$.

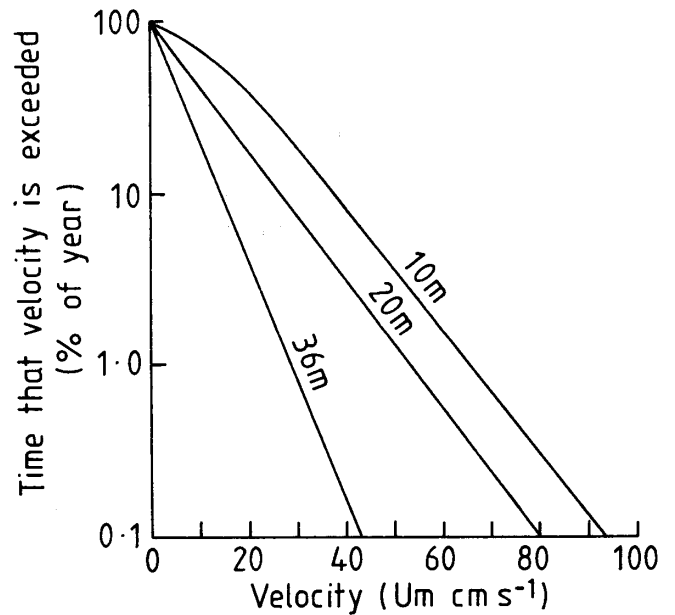


Figure 8 Percentage of the time that maximum near-bed oscillatory flows (U_m) exceed a given velocity at depths of 10, 20 and 36 m. Based on data from IOS Waverider buoy sited close by the Scarweather Light Vessel (Carr *et al.*, 1976).

3.3 Long-term bottom water movements

Woodhead seabed drifters (Woodhead and Lee, 1960) have been used in many areas to provide data on bottom residual currents, in some cases in connection with the dispersion paths of wastes dumped at sea. The transport of drifters is believed to reflect near-bottom water movements accurately where the tidal current at mid-water depth is less than 2 knots, but in more dynamic systems drifters are prone to glide in mid-water for extended periods of time (Harden Jones *et al.*, 1973; Dickson, 1976). With tidal currents exceeding 3 knots at springs and 1.5 knots at neaps in the study area the net transport of drifters will undoubtedly include periods of mid water drift. However, sewage sludge particles may be similarly transported and the use of seabed drifters in dispersion studies is not necessarily invalidated. Indeed, in Liverpool Bay a good general agreement was found between the ultimate distribution of labelled sludge and the recovery pattern for seabed drifters, suggesting similar behaviour during dispersion (Crickmore, 1972).

Batches of 100 seabed drifters were dropped at the dumping ground on eleven occasions between October 1975 and February 1978. The returns from this experiment show that bottom waters have a complex residual circulation which is subject to variation induced by differing conditions of tide, weather and freshwater runoff. This experiment will be reported in full elsewhere (Riley and Rolfe, in preparation), but the main results are summarised here.

The percentage of the drifters returned from each release (32-53%, see Table 6 and Figure 9) is high compared with returns from releases in the western English Channel and Celtic Sea (Jones, 1974) where only 25% were recovered. Riley and Ramster (1972) showed that even when drifters were placed along a popular and accessible stretch of the East Anglian coast, only 81-89% were returned. When the greater problems of access to some stretches of the Bristol Channel coastline are considered, the returns suggest that bottom water movements from the Bristol Channel dumping area are primarily landward. Of the drifters returned, most were recovered from the Bridgwater Bay area (46% of returns) and the Swansea Bay area (29% of returns). Other recovery sites, in order of importance, were the north shores of the inner Channel/outer estuary, Barnstaple Bay, the inner Severn estuary and the north Devon coast (Figures 1 and 9, Table 6).

there was a marked tendency for drifters to come ashore in Swansea Bay in the winter and spring and in Bridgwater Bay during the summer and autumn, the periodicity being slightly less well defined in the latter area.

Studies involving seabed drifters have also been carried out by Collins and Ferentinos (1979) from release points north and south of the dumping site. These also exhibited a landward movement towards the same regions of the Channel as in our study. However, the position of release influenced the site of recovery, for releases north of the dumping ground resulted in most drifters being recovered from Swansea Bay while from releases south of the dumping ground they were found in both Swansea and Bridgwater Bays.

The shortest time taken for a drifter to come ashore was 8 d, the recovery area being just north of Nash Point. Three percent of the released drifters were returned from the Nash Point area within 25 d of being dropped; the direction and magnitude of residual drift indicated by them were in general agreement with the short-term current meter data (Section 3.2) which showed that residual movements from the dumping ground exhibited a north-easterly component. Most of the drifters recovered from each drop, however, came ashore over an extended period of time, normally in the order of one year. The precise timing of the beachings appeared to depend upon factors other than the number of days since release. It is evident from Figure 9 that, irrespective of the length of time since the drifters were released,

On the basis of these results it is not possible to derive a detailed model for long-term bottom water movements. Clearly seasonal factors are involved and long periods elapse when the net landward motion is absent or very slow. Nevertheless, the general pattern of recovery is broadly consistent with the circulation model described in Section 3.1. During low river flows in summer the gyre in the central and outer Channel is less well developed, permitting saline water to penetrate further upstream (Figure 4), probably facilitating upstream movement of drifters into Bridgwater Bay. Under winter river discharge conditions, however, the gyre is best developed, and it appears that drifters become entrained in the outflow of water close into the Welsh coast and carried into Swansea Bay.

Table 6 Summary of seabed drifter returns, November 1975–November 1978

Date of release	% returned	Returns by area* (%)									
		A	B	C	D	E	F	G	H	J	
2 November 1975	52		1	9	1	1	20	1	18	1	
18 May 1976	40			18	1	2	16	1	1		
25 January 1977	42			7	10	4	21				
9 February 1977	53			11	9	3	30				
4 March 1977	45			32	6		7				
19 May 1977	32			9	1	3	13	1	5		
3 June 1977	32			5	3		20	2	2		
26 July 1977	52			14	2	2	29	2	3		
22 August 1977	35			10	1	2	16	1	5		
8 December 1977	36			13	6		17				
14 February 1978	41			5	8	5	22	1			

*See Figure 9 for location of areas

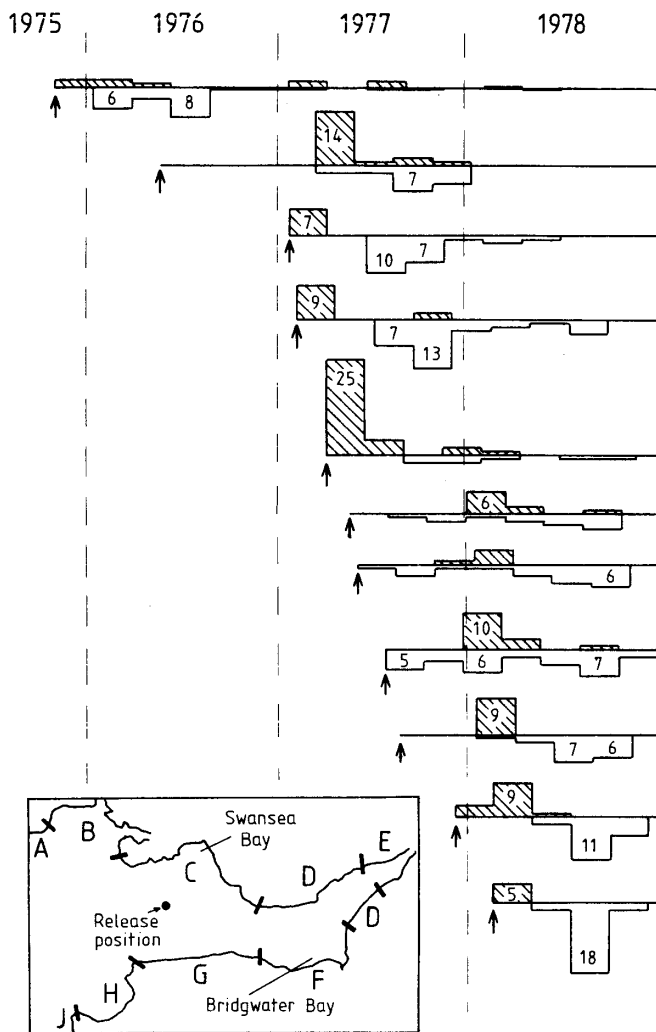
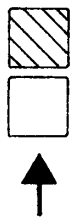


Figure 9 Return rates for seabed drifters for the Swansea Bay and Bridgwater Bay areas, in 75-day intervals.



Swansea Bay (Area C)

Bridgwater Bay (Area F)

time of release of 100 drifters.

(Note: numerical values given for peaks).

3.4 The dispersion of dumped waste

3.4.1 Dumping practice

Sewage sludges arising from Wessex and Welsh Water Authority treatment plants, and industrial wastes from the Bristol area, are discharged to the Bristol Channel dumping ground from two vessels. The MV GLEN AVON carries about 7-8 loads per week of 950 t of sludge from Bristol; this is discharged through valves in the ship's bottom over a period of approximately 25 min at a vessel speed of about 5 knots. The other dumping vessel operates from

Newport and discharges into the wake at a rate of 3-500 t h⁻¹ whilst steaming over the dumping ground at a speed of about 3 knots. Due to the need to steam down channel on the ebb and return on the flood tide, discharge takes place shortly (1-2 h) before low water.

3.4.2 Initial dispersion of the waste

The initial dilution of waste in the wake of MV GLEN AVON, as estimated from the general formulae of Tromp (1976), is likely to exceed 100:1 within the first minute. The slower rate of discharge from the Newport based dumping vessels results in a higher dilution rate. Dilution of similar sludges with sea water at ratios greater than 100:1 has been shown to inhibit widespread flocculation of the sludge particles (Eagle *et al.*, 1978b and in preparation; Crickmore, 1972). Particles will thus tend to settle at the settling rates of mixed and digested sludge particles: these rates are of the order of 0.05-0.005 mm s⁻¹ (Crickmore, 1972; Hydraulics Research Station, 1968) for the median sized particles, and in the range 5-10 mm s⁻¹ for the coarsest particles. The latter are therefore likely to settle sufficiently rapidly to reach the sea bed within the first 1-2 h of discharge, i.e., at or just to the west of the dumping ground.

The remainder of the sludge particles are likely to be more effectively dispersed through the water column by eddy diffusion processes which are dependent upon the strength of wave and tidally induced turbulence, and upon the degree of density stratification present. Observations of the behaviour of dumped sludge have identified vertical mixing rates of between 0.1 and 3 mm s⁻¹ in an area with a vertical density gradient and slow currents (New York Bight-Callaway *et al.*, 1976), and rates of at least 5 mm s⁻¹ in a region of very slight stratification and moderate currents (Liverpool Bay-Crickmore, 1972). The stronger tidal currents and lack of vertical stratification in the Bristol Channel suggest that the rate of vertical mixing may exceed 5 mm s⁻¹ during the periods of fastest currents and this would result in the waste being dispersed throughout the water column over a period as short as 1-2 h. As a result of subsequent advective water movements at the dumping ground (Section 3.2) waste would be expected to move within a sector between east and north-east of the dumping site during the tidal cycle following disposal at low water.

3.4.3 Sites of initial deposition

Both coarse and fine particles are likely to reach the sea bed within a few hours of discharge, through either eddy diffusion or settlement. During periods when the friction velocity falls below approximately 1.5 cm s⁻¹ fine material held in suspension above the sea bed can pass into the interstitial spaces of sand and gravel deposits and thus accumulate

(McCave, 1970). Similarly, fine suspended particles may adhere to exposed surfaces of settled muds during periods of slackened currents. These processes are reversed, however, when the friction velocity exceeds a critical value and fine material may be resuspended.

A second mechanism whereby sludge particles may become incorporated in the sediment arises from interaction with coarse natural sediments in suspension in the water column which are continually settling out and being resuspended. The inevitable collision of fine sludge particles with this seston leads to the incorporation of the sludge into more rapidly settling sediment/organic matter agglomerates, especially in winter when suspended sediment levels are at their highest. These mechanisms are discussed further in Section 5.2.3.

3.4.4 *The long-term fate of particulate waste*

From the above paragraphs it would appear that waste particles are likely to become incorporated within the suspended sediment load that is circulating within the central Channel, part of which may undergo periods of temporary accumulation within sand and gravel interstices of the sea bed locally. The ultimate fate of dumped material will thus be determined by the movement and fate of the natural sediments in the area. This is discussed in Section 5, together with the evidence of sites of accumulation of the major persistent components of the waste.

4 **Distribution of faecal bacteria on the sea bed**

Sediment samples were examined for the presence of faecal bacteria during the 1976 and 1977 surveys in order to determine the distribution of these organisms on the sea bed as a means of identifying areas of initial settlement of sewage sludge particles. Samples of sediment to a depth of 1 cm were taken from Day grab samples and placed in sterile jars using aseptic techniques. These samples were resuspended in measured volumes of sterile water and volumes equivalent to 0.1 and 1.0 g of sediment were filtered through a 0.45 μm membrane filter. The membranes were incubated on pads impregnated with 4% Teepol lactose broth (Halls and Ayres, 1974) at 37°C and 44°C for approximately 18 h. Yellow lactose-fermenting colonies, which were assumed to be coliforms and *E. coli* respectively at the two temperatures were counted and used to calculate the numbers of organisms/g sediment. Further details of the techniques used have been described by Eagle *et al.* (1978a).

The numbers of *E. coli* and bacteria found in 1976 during a period of daily sewage sludge dumping are shown in Figure 10. Both types of bacteria were found in increased numbers in the region of the dumping ground. The zone of detectably increased numbers of *E. coli* was restricted to this area but the more abundant coliforms could be detected over a wider area with the highest numbers found in one sample near the Swansea Bay spoil site. Due to the

difficulty of collecting suitable samples for microbiological analysis, bacteria levels were not determined at several stations at the eastward end of the sampling grid. Nevertheless the results are consistent both with the initial settlement of sludge particles along the east-west tidal axis and, from the coliform results, with a residual movement to the north-east from the dumping ground; i.e., in the direction of initial movement predicted in Section 3.4. The high concentrations in the north of the survey area probably arose from coastal discharges or from the recent dumping of dredged spoil. The 1977 survey which took place following a break in dumping activity of over four days has not been reproduced here. Coliforms were distributed widely throughout the survey area, a distribution consistent with rapid dispersal from the dumping ground.

5 **The sediments**

5.1 **The distribution of natural sediment types**

5.1.1 *General description*

The sediments in the vicinity of the dumping ground have been sampled on three occasions by MAFF (Section 1.4) and a side-scan sonar survey has been carried out. The sampling positions and the track of the sonar survey are shown in Figure 2. The samples of surface sediment were analysed for particle size, organic carbon and trace metal content. The general distribution of sediment types in the central and outer Bristol Channel is shown in Figure 11 which has been compiled from the results of these surveys and from side-scan sonar surveys conducted by IOS, Wormley, together with data from IOS, Taunton, and IMER, Plymouth. A detailed map of the results of the MAFF 1976 side-scan sonar survey is presented in Figure 12.

The side-scan sonar surveys show that within the area surveyed east of Morte Point much of the sea bed is free of superficial sediments, and that rock outcrops and coarse lag gravel deposits predominate. The two major exceptions to this pattern are the topographically featureless accumulations of muddy sands in the Swansea Bay area and the elongate zone of sand shoal complexes that extends westwards from the vicinity of Nash and Sker Points and coalesces with the extensive region of continuous sand cover that occupies the deeper water areas west of Morte Point. Bedforms are well developed in most of the sand deposits of this area. A zone of thin sand deposits often lies between the regions of continuous sand cover and the exposed rock floor areas, the sands typically taking the form of ribbons (Kenyon, 1970). Ribbons of mobile gravels are found off the north Devon coast where tidal currents are strongest (Figure 3).

5.1.2 *Bedrock outcrops and gravel deposits*

Extensive bedrock outcrops were identified only in the south-eastern corner of the area covered by the

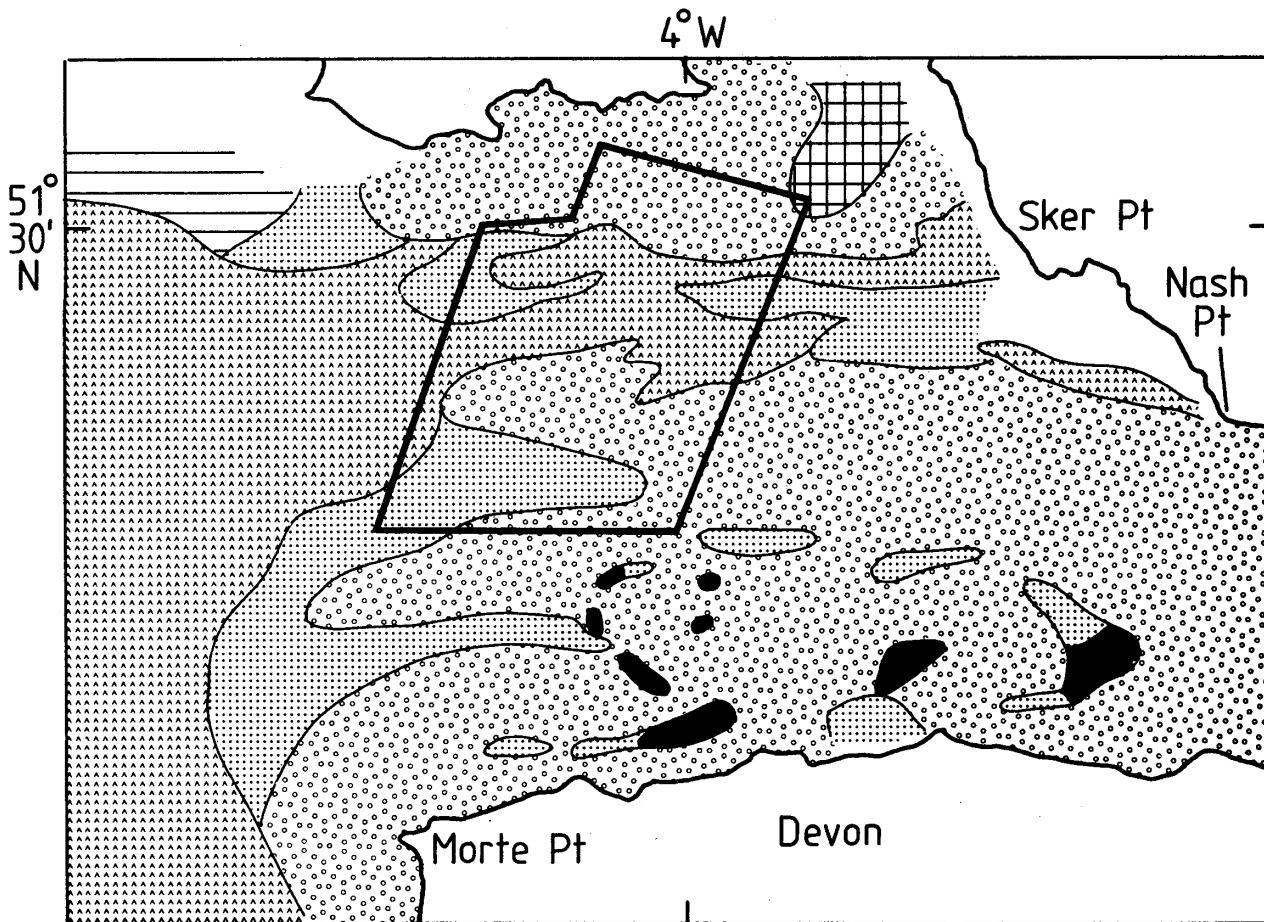
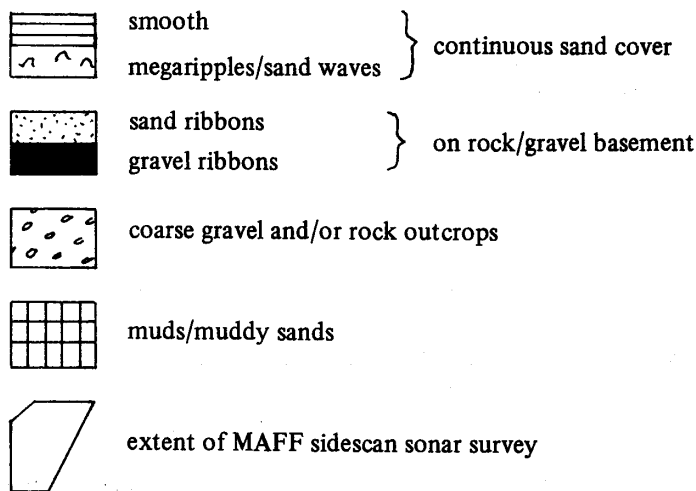


Figure 11 Seabed sediments of the Bristol Channel from side-scan sonar surveys



sonar survey (Figure 12). The echo-sounder records from the 1975 survey show that these outcrops are part of a much wider area of exposed bedrock which lies to the south and east of the dumping ground. At most of the grab stations worked, however, it was possible to obtain a sample of a coarse lag gravel deposit which mantles the rock surface, if rather patchily. The nature of this deposit appeared to be similar throughout the survey area and was comprised of a heterogeneous mixture of gravels, cobbles and boulders. Material in the latter two size grades

was always rounded, well encrusted and of a wide variety of lithologies (sandstones, limestones, shales, granites, flints). Some of the finer gravels were of a more polished appearance suggesting mobility, with little broken shell present.

The percentage of material coarser than 4 mm in the sampled sediment (excluding material larger than about 5 cm diameter) is shown in Figure 13. The gravel deposits, which were most extensive in the southern part of the survey area, also contained grit

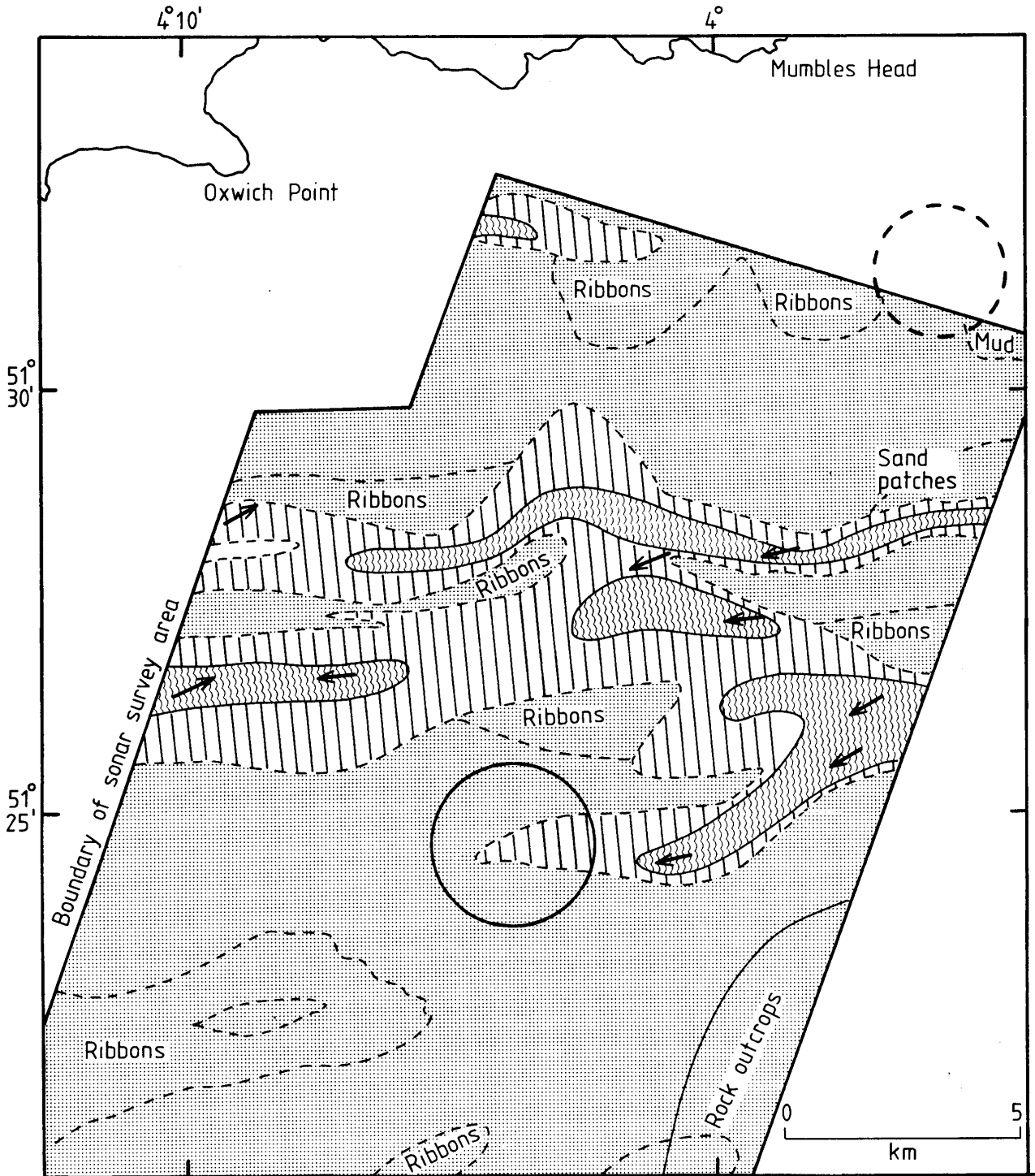







Figure 12 Major variations in sediment types in the vicinity of the sludge dumping ground, as indicated by MAFF side-scan sonar survey.

- ← direction of bedform movement
-  areas of sandwaves and sand ridges
-  sheets of megarippled sand
-  coarse lag gravels, sometimes in association with sand ribbons, sand patches or rock outcrops.
-  sludge dumping ground
-  dredged spoil dumping ground

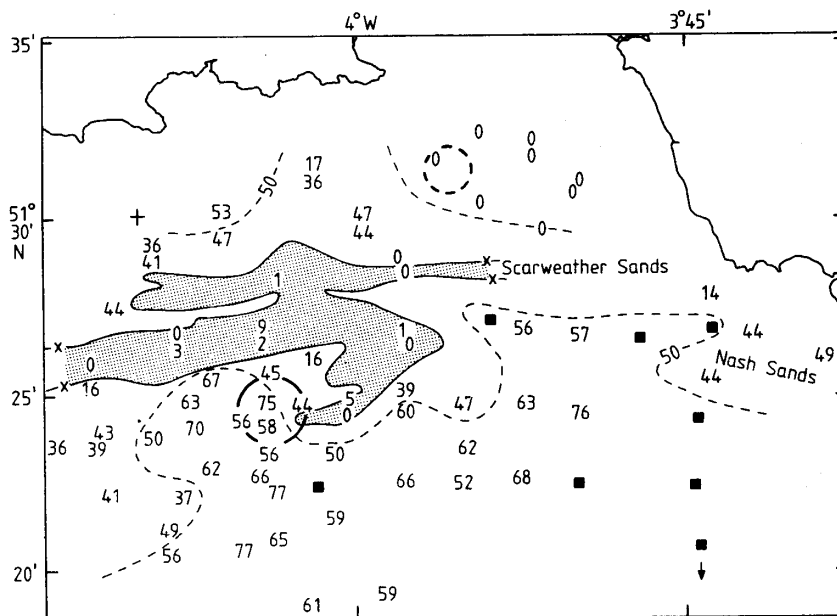
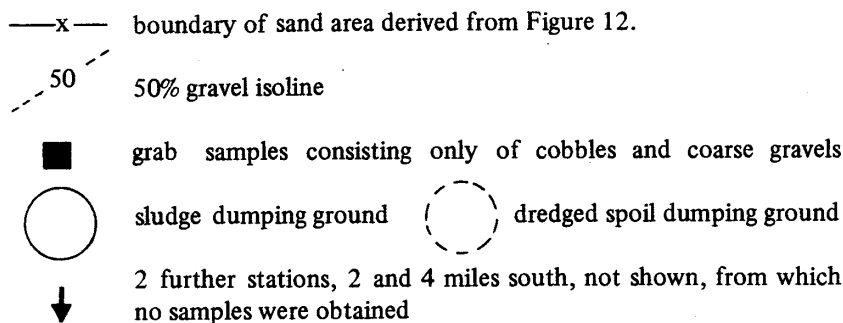


Figure 13 Gravel (>4 mm) in sediment samples



and coarse sand with some mud in the vicinity of the dumping ground and south of Oxwich Point (see Section 5.1.4). Gravels to the east of the survey area (shown in Figure 13 as stations where no particle-size analysis was conducted) contained very little matrix material, i.e. they included over 75% coarser than 4 mm.

5.1.3 Sand deposits

Three types of sand deposit were identified within the survey area (Figure 12): (1) areas of continuous sand cover with complex bedforms; (2) sand as thin ribbons and matrix material in gravel areas; (3) sand associated with mud deposits. Mineralogically the sands were similar, consisting of roughly equal proportions of quartz grains and rock fragments. Shell and other biogenic material was normally present but only in small quantities. All grains were well polished and rounded.

The area of continuous sand cover consisted of a system of east-west elongated shoals and sand sheets extending westwards into an area of extensive sand

deposits (Figure 11) and eastwards into the linear sand bodies associated with Nash and Sker Points. The sheets of sand contained megaripples with wavelengths of between 2 and 5 m and height of less than 1 m. These sheets surrounded shoals of thicker sand deposits which exhibited a wide variety of bedforms with sandwaves present in many areas, having heights between 3 and 9 m and wavelengths between 50 and 300 m. Both symmetrical and asymmetrical forms have been identified, with both simple and bifurcating crestlines. Sand ridges of similar dimensions, with their crests parallel to the sand transport direction, also occurred. At two localities ridges showing sigmoidal crest plans (Caston, 1972) were observed. Megaripples were present upon the limbs of most of these larger bedforms. Particle-size analyses of these sands showed that they contained negligible amounts of material finer than $125 \mu\text{m}$ or coarser than 2 mm, and that they were composed either of a well defined bimodal grain size distribution, with a dominant mode at $250\text{-}350 \mu\text{m}$ and a subsidiary mode at $500\text{-}700 \mu\text{m}$, or a well sorted lognormal grain population with a mode in the range $350\text{-}700 \mu\text{m}$. Examples of these distributions are given in Figure 14 (A and B).

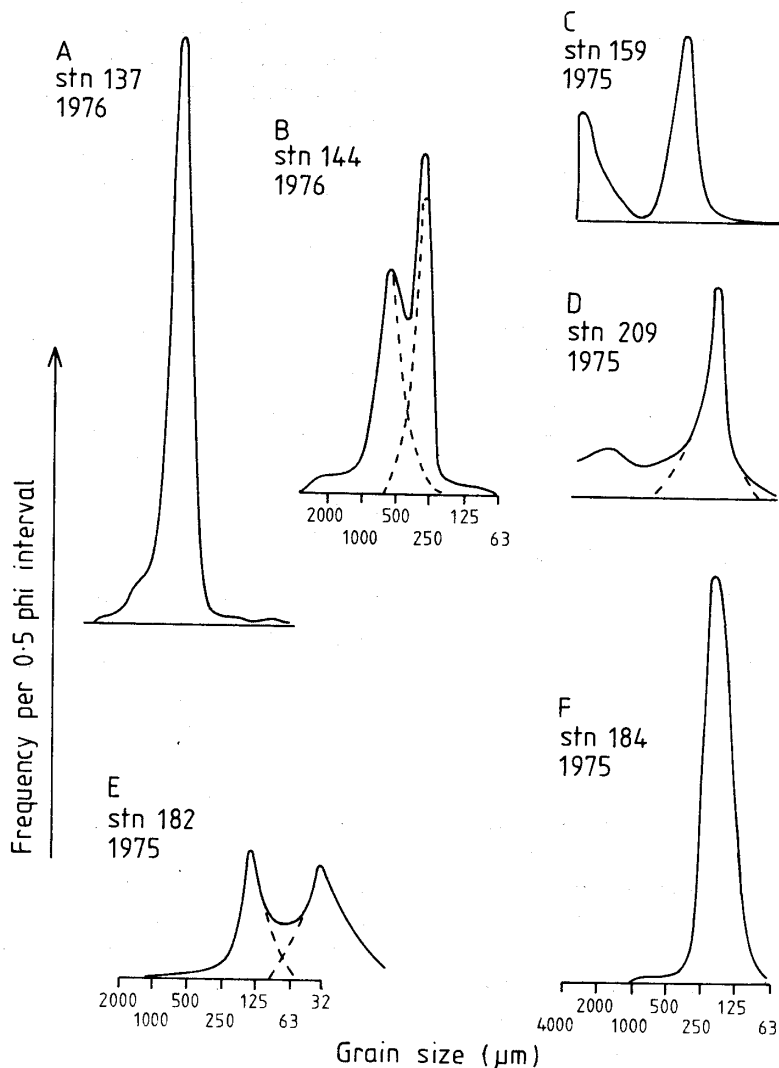


Figure 14 Particle-size distribution of the sand fraction of typical samples from the survey area, showing component lognormal populations (see Figure 2 for sampling location).

The zones of sand ribbons occurred either in the transitional zones between continuous sand cover and gravel areas or at isolated localities on the gravel substrates, generally within depressions or in association with submarine scarps. The ribbons were of type 'B' as described by Kenyon (1970): narrow deposits of sand elongated parallel to the direction of strongest tidal flows. Although often only a few centimetres thick and consequently exhibiting no surface features, some ribbons did contain enough sand to allow the development of megaripples. Samples of the gravel substrate in areas where sand ribbons occurred always contained a component lognormal grain population with a mean lying in the range 350-700 μm , which is in agreement with Kenyon's observations on the size of sands composing ribbons. In some areas these medium/coarse sands formed the bulk of the matrix material within the basal gravel deposits, e.g., Figure 14 (C), but in the southern half of the surveyed area a second sand population was found having a mean in the fine sand range, 125-250 μm ,

e.g., Figure 14 (D). These fine sands were more common close to the shoreline; in the pocket of slightly muddier gravels inshore of Nash Sands they replaced coarse/medium sand populations entirely.

The third type of sand deposit, sand associated with muds, occurred in Swansea Bay. The limited side-scan sonar and echo-sounder records from this area showed a flat, featureless sea bed with a patchy variation in acoustic properties. Cores taken from grab samples showed either a homogenous compacted sandy mud, e.g., Figure 14 (E), or a similar deposit overlain by a few centimetres of well washed fine sand, e.g., Figure 14 (F). A vertical section of the latter core is illustrated in Figure 15 and is consistent with the mobile sands of the area having moved over a deposit of dredged spoil (see Section 5.1.4). The patchy distribution of this surface veneer of sand probably accounted for the variability in reflector type observed on the side-scan sonar records.

Sediment/water interface

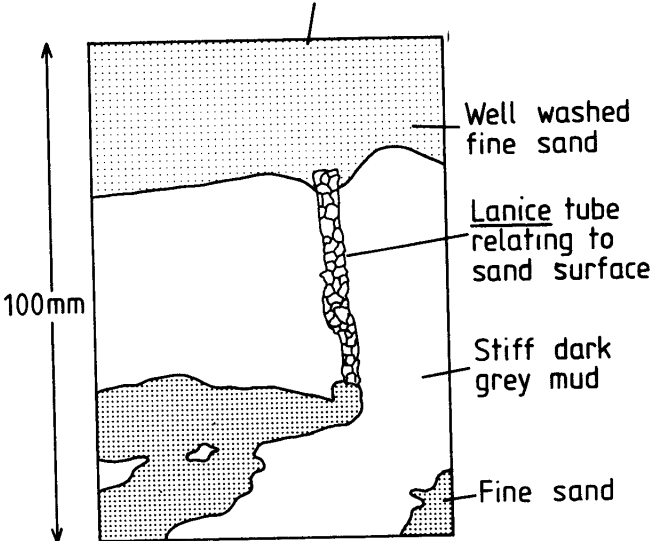


Figure 15 Diagrammatic vertical section of a short core taken from Swansea Bay (station G in Figure 2).

5.1.4 Mud deposits

The distribution of silt and clay (material less than $63 \mu\text{m}$) is plotted in Figure 16. It followed the broad variation in sediment types described in Section 5.1.1. The elongated zone of continuous sand cover was devoid of mud; the gravel basement areas contained up to 15% fine material, and within a restricted area inside Swansea Bay the silt and clay content of the sediment reached 40%. The latter deposits varied from dewatered grey sandy muds to black thixotropic material. This mud deposit encompassed the outer Swansea Bay spoil ground, which receives $ca. 2 \times 10^6$ t of dredgings each year. Furthermore, 9.5×10^6 t of spoil were also dumped at this site between 1967 and 1969 during the construction of Port Talbot harbour. These factors suggest that the area of mud accumulation was not natural, and that the distribution of muds observed was the result of slow reworking of the dumped maintenance and capital dredgings. The mud balls and thin mud layers found in several of the samples from the northern part of the survey area may have been derived from this source. However, the inner part of Swansea Bay is generally a muddier sedimentary environment than further offshore (Davies, 1974) as a result of local mud inputs (largely the reworking of estuarine silt and clay deposits from Swansea and Port Talbot) and due to the general decrease in tidal energies within the bay. These factors allow deposition of silt-sized material to take place in the area (Collins *et al.*, 1979).

Several of the samples collected from the muddy gravel areas to the south of the zone of continuous sand cover contained small lumps of tenacious brown, grey or blue clay, implying that there are restricted

seabed exposures of relict (Pleistocene or Flandrian) clay deposits. This suggests that the gravels and cobbles that form the sea bed in this region are a lag deposit, perhaps composed of the coarser elements of an eroding mantle of boulder clay. The reworking of this underlying clay material may be one source of the muds caught up within the gravels.

5.2 Sediment dynamics

5.2.1 Gravel disturbance

Field and flume experiments (Komar, 1976) have established reasonably well the relationship between near-bed water flows and the threshold of sediment movement for cohesionless sediments. Figure 17 shows the relationship for both wave and tidally-induced flows.

Using these graphs in conjunction with the available data on maximum near-bed velocities (Section 3.2), it becomes evident that gravel disturbance is minimal at the dumping ground since peak tidal and wave-induced currents ($U_* = 3.7 \text{ cm s}^{-1}$, $U_m = 45 \text{ cm s}^{-1}$, respectively) are only just capable of initiating motion in fine gravels of 2 mm diameter. The movement of gravel material by storm waves is enhanced in shallower waters but, even in the shallower parts of the survey area at 20 m depth, grains of up to 2 mm diameter may be in motion for only up to 5 days per year, with particles of up to 8 mm diameter being disturbed only during periods of extreme wave activity. Although the movement of gravels occurs more frequently through the inevitable coincidence of tidal and wave-induced flows, gravel disturbance is very unlikely to be a significant process within the surveyed area; this is consistent with the observations that the coarser gravel particles were generally well encrusted.

5.2.2 Bedload (sand) transport

The distribution of sand deposits and the dynamics of sand transport in this area are very complex. The origins of the large sand bodies, the sources of their material, the interactions between the varying sand populations and present day water movements, and the resulting residual transport of sand are only partly understood. However, the results of research at the Institute of Oceanographic Sciences (Carr *et al.*, 1976; Heathershaw and Hammond, 1980b) and at University College Swansea (Collins *et al.*, 1979; Collins and Ferentinos, 1979), together with the data from the MAFF surveys allow the following brief description to be made of sand transport mechanisms in the vicinity of the dumping ground.

The abundance of bedforms arising from sand movement (e.g., ribbons, megaripples, sandwaves and ridges) and the wide occurrence of well-sorted sand

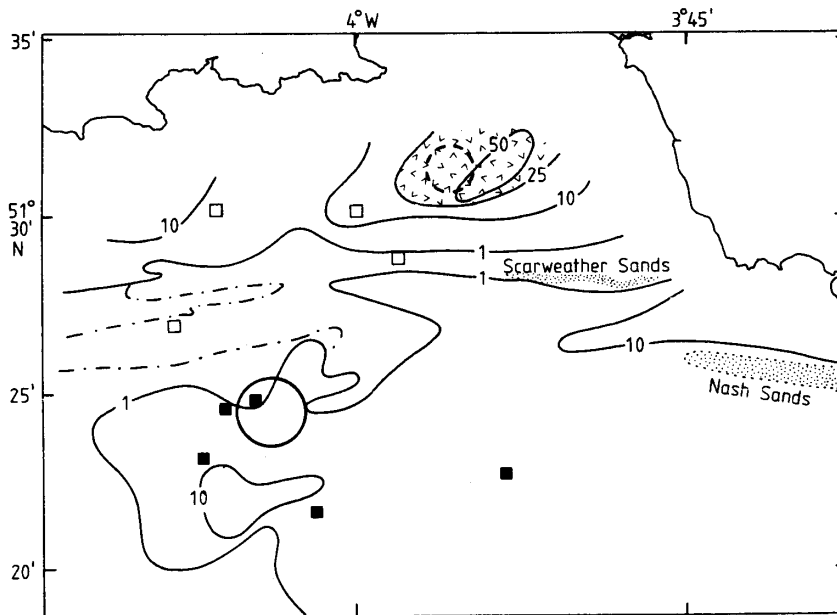
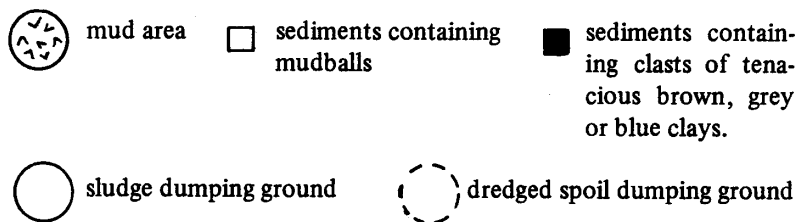


Figure 16 Mud (<63 μm) in sediment samples; 1, 10, 25 and 50% isopleths are shown.



particle populations (Figure 14) show that the area is one of active sand transport, as would be expected according to the hydrographic data. Movement occurs in mud-free sands when the tidal friction velocity exceeds approximately 1.5 cm s^{-1} and when wave-induced near-bed currents attain $10\text{-}15 \text{ cm s}^{-1}$ (Figure 17). Flows of this magnitude occur at the dumping ground during mid flood and mid ebb currents throughout the spring/neap cycle, and as a result of wave-induced currents for 10-15% of the year. The mobility of sand decreases into Swansea Bay due to the reduced strengths of the tidal currents (see Figure 3). The magnitude of wave-induced near-bed currents increases, however, in shallower water (Figure 8), thus enhancing sand movement particularly in exposed shoal areas.

The directions of transport of medium and coarse sands can be inferred from the alignment of bedforms; side-scan sonar records show features indicating that the axis of sand movement lies between north-east/south-west and east/west coincident with the direction of the strongest tidal flows (see Figures 3 and 12). The direction of residual sand transport along this axis can be identified where

the larger transverse bedforms exhibit an asymmetrical profile. The directions identified from such profiles within the zone of sandwaves reveal a predominantly westward direction of movement, in agreement with observations made in the zone of sandwaves lying to the west of the survey area (Kenyon and Stride, 1970) and in the part of the survey area north of $51^\circ 25' \text{N}$ by Collins *et al.* (1979) and Heathershaw and Hammond (1980b). There are, however, variations in this predominant westward movement near the Scarweather Sands and towards the western extremity of the survey area. This description is broadly consistent with the model of sand movement proposed by Collins and Ferentinos (1979) and Heathershaw and Hammond (1980b) in which south of a line from Porthcawl to Mumbles Head (Figure 2), sand movement is westwards except in the vicinity of the major sand bodies such as Nash and Scarweather sands where movement around the banks occurs. To the north of this line and into Swansea Bay, sand movements are less uniform with easterly and north-easterly components into Swansea Bay. The easterly to north-easterly movement of sediment from the outer Swansea Bay dredged spoil disposal area has been confirmed by radioactive tracer studies (BTDB, 1975).

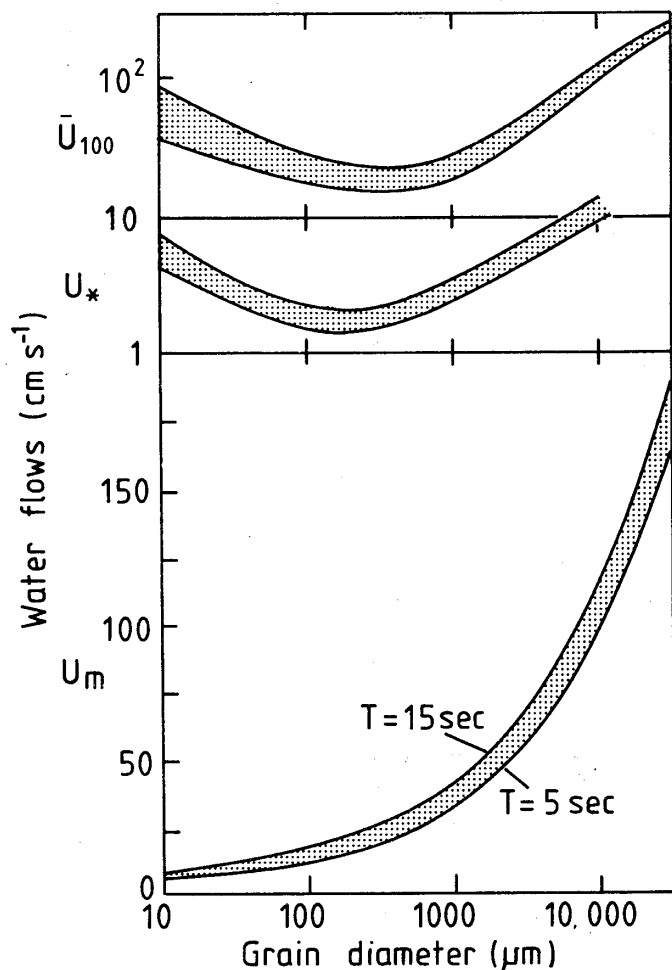


Figure 17 Relationship between water flow and the threshold of grain movement (from Komar, 1976). U_m = maximum wave-induced near-bed velocity (oscillatory); T = wave period; \bar{U}_{100} = velocity of unidirectional flow 1 m above sea bed; U_* = friction velocity of unidirectional flow.

The movement of sand in the immediate vicinity of the dumping area can be predicted from the tidal flows, assuming different threshold velocities for the transport of sands of different particle size. Analysis of residual movements derived from the DRCM data (Section 3.2) suggests that the coarsest particles having a threshold of 50 cm s^{-1} ($U_* = 2.75 \text{ cm s}^{-1}$) had a residual movement to the south-west of about 1 cm s^{-1} . The residual movement of medium sands having a threshold of 40 cm s^{-1} ($U_* = 2.2 \text{ cm s}^{-1}$) was effectively zero, but finer particles having a threshold of 25 cm s^{-1} ($U_* = 1.4 \text{ cm s}^{-1}$) had a residual transport rate of 3 cm s^{-1} in a direction 070° (true). If the asymmetry of the peak tidal flows observed near the dumping area over a 25 h period is typical, a slight south-westerly residual movement of coarse to medium sands is to be expected; this is supported by the observed extension of a sand wave field in this direction (Figure 12). On the other hand, particles finer than about $150 \mu\text{m}$ are capable of

movement over much of the tidal cycle and would move with the overall residual movement of bottom waters in an east-north-easterly direction towards the sheets of sand which connect the dumping area to the coarser sands to the east.

5.2.3 Suspended sediment dynamics

In terms of its suspended regime the central region of the Bristol Channel is very much a transitional zone between the essentially marine outer Channel, where very low seston levels are found, and the highly turbid Severn Estuary. Typical near-surface suspended sediment concentrations measured by IMER in the outer, central and inner Channel and the Severn Estuary are, respectively, in the ranges 1-10, 10-25, 25-250 and $250-1\ 000 \text{ mg l}^{-1}$ (Figure 18).

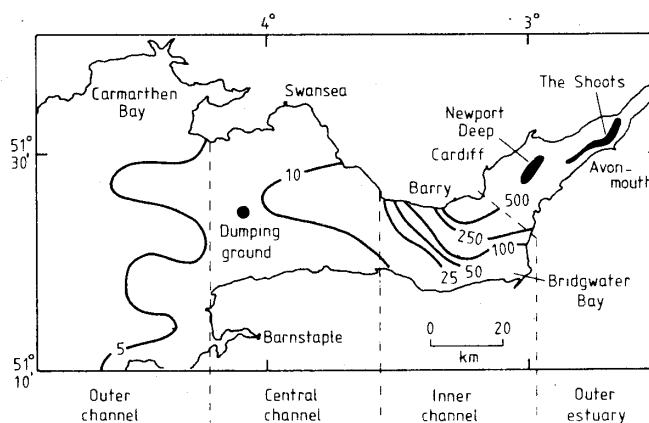



Figure 18 Typical mid-water seston concentration (mg l^{-1}) over a summer neap-tide period. Data supplied by IMER.

 Fluid mud areas (from Kirby and Parker, 1973)

The Severn Estuary system is a very effective trap for fine sediments. It has been estimated that the annual riverborne input of mud accounts for only 5-10% at most of the total mud load currently in circulation within the Estuary. Thus the residence time of fine particulate material may be in the order of many tens of years (Kirby and Parker, 1977). Fine sediment dynamics within the Estuary are influenced by the high tidal energy of the system which can keep large volumes of mud constantly in suspension, resulting in the occurrence of comparatively small areas of settled mud; Bridgwater Bay and the Newport Deep (Figure 2) are the only areas of extensive mud accumulation (Kirby and Parker, 1973). The concentration of material in suspension varies over the lunar cycle, maximum spring tide concentrations in excess of $5\ 000 \text{ mg l}^{-1}$ being observed off Avonmouth. The lower velocities of the neap tides result in the periodic formation of extensive fluid mud deposits in several channel floor areas (Figure 18; Kirby and Parker, 1973 and 1977).

Repeated surveys conducted by IMER in the central Channel have demonstrated seasonal variations in suspended sediment concentrations, with the highest levels occurring during the winter months. This variability may be due to changes in the pattern of exchange of suspended sediments within the Estuary, the increased particulate contribution from winter run-off, and localised resuspension by storm waves, particularly over shallow water mud deposits such as occur in Swansea Bay (Davies, 1974). Observations in October 1978 showed that a semidiurnal variation in seston concentrations occurred at the dumping ground, and presumably at many other localities within the central Channel. This is shown in Figure 19. It is evident that material was eroded from the sea bed during periods of peak bottom flow and dispersed throughout the water column until the decrease in tidal energy allowed the material to re-settle on the bed. Coulter counter analyses of water samples collected 2 m above the bed showed the seston to be composed almost exclusively of silt and clay-sized particles, with a ubiquitous mode in the 5-15 μm diameter particle range and a subsidiary mode between 40 and 50 μm during periods of active resuspension. This material may include sewage sludge particles, the majority of which are in the size range 5-50 μm , as well as other silts in 'transit'. The evidence in Section 5.1.4 that limited exposures of

relict clays occur within the substrate suggests that local erosion may also contribute to increased seston concentrations.

The long-term fate of fine particulate material originating within the central Channel region may be to: (a) settle out and accumulate in any sheltered environments within the central Channel; (b) move upstream to become entrapped within the Severn Estuary system; (c) diffuse seawards. Undoubtedly all three processes occur to some extent; evidence for the effectiveness of each will now be briefly discussed.

Interstitial mud deposits associated with gravels are present in the vicinity of the dumping area and it is possible that suspended particulate matter could become entrained in these deposits during periods of slack water (Section 3.4.3). These gravels are likely to be of limited capacity, and liable to occasional re-working. Side-scan sonar and grabbing surveys have shown that there are no other extensive areas of mud accumulation in the central Channel area outside of Swansea Bay. Furthermore, much of the mud encountered in the outer part of Swansea Bay may be derived from spoil dumping activities and thus not be indicative of hydrographic conditions conducive to mud accumulation. Further inshore in Swansea Bay a

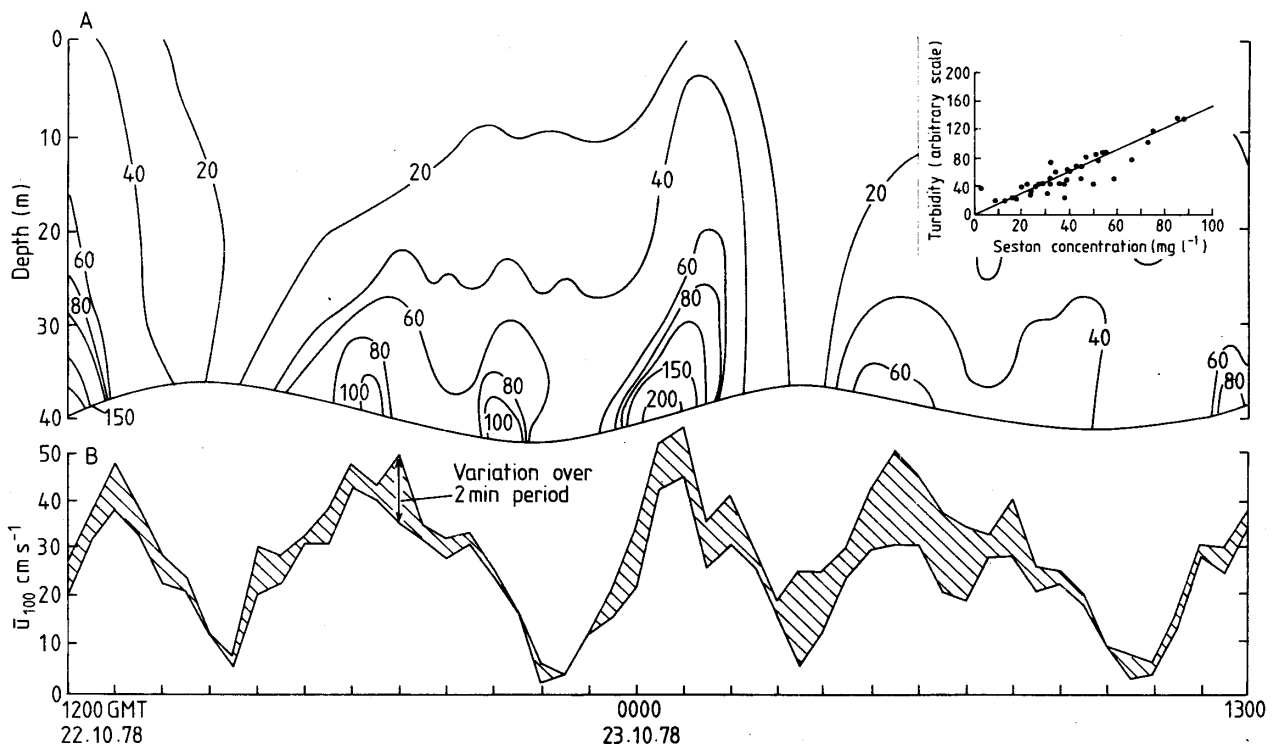


Figure 19 The variation in seston concentration (A) and current velocity 1 m above the bed (B) during a 25 h period at the dumping ground in October 1978. Seston concentration was as defined by light transmittance isopleths on an arbitrary turbidity scale, with gravimetric calibration shown in insert.

depositional environment exists (Collins *et al.*, 1979) which accounts for the formation of littoral and estuarine deposits of silt and clay within the Swansea Bay area. Seabed drifter and current meter data suggest that these may receive fine material generated in offshore areas including the dumping area, particularly during the winter months. These fine sediments are unlikely to form permanent deposits because many are spasmodically reworked during periods of high river discharge and storms. This cyclic movement of material is enhanced by continuous maintenance dredging at Swansea and Port Talbot.

Many of the seabed drifters released at the dumping ground were recovered from the Bridgwater Bay area (see Section 3.3) indicating an effective up-estuary movement of material transported as near-bed suspended load, particularly during the summer months. Thus a proportion of the large reservoir of fine sediments within the Severn Estuary may be derived from offshore sources. The marked increase in the levels of suspended solids that occurs in the central Channel during the winter period suggests that this movement up channel is reversed at intervals. This is also suggested by the apparent estuarine origin of much of the particulate organic matter of the Bristol Channel (Section 5.3).

Thus it would appear that fine sediments generated within the Bristol Channel area eventually become caught up in the fine sediment systems of the Swansea Bay and the inner Bristol Channel/Severn Estuary. Mud deposits within such areas tend to be ephemeral, however, and fine material within these systems is likely to undergo frequent reworking, with associated alternating periods of seaward and landward transport. Over long periods of such recycling the finest, clay-sized components of the sediments may tend to become separated from the bulk of the sediments, remaining in suspension in the water mass over very long periods of time and ultimately being transported out into open shelf waters.

5.3 Organic matter in sediments

Three particle-size fractions (4000-500 μm , 500-90 μm , <90 μm) of each sediment sample were analysed for organic content. The approximate organic content of the two coarser fractions was measured by loss on ignition at 550°C for 8 h; the organic carbon and total nitrogen content of the <90 μm fraction was measured on a Carlo Erba CHN analyser, after previously removing carbonates by treatment with sulphurous acid (Eagle *et al.*, 1978a). The carbon content of the total sediment was estimated by multiplying the ignition loss figures by a correction factor of 0.6 (Olausson, 1975) and combining the resulting percentages in the ratios that their respective fractions contributed to the total sediment.

5.3.1 Spatial variations in organic matter

The organic carbon contents of the surface sediments found during the various surveys in 1975-7 are shown together in Figure 20 since there were only minor differences between concentrations in samples collected at the same sites on the three surveys. The highest concentrations were 2-3% organic carbon found in the sediments of the outer Swansea Bay area and to the south-west of the dumping ground. In general, concentrations were higher in the northern and southern extremities of the survey area, contrasting with the low concentrations of 0.3-0.5% found in the zone of mobile sand deposits. A comparison of the distribution of organic carbon (Figure 20) with that of silt and clay in the sediments (Figure 16) shows that the zone of highest carbon content towards Swansea Bay was associated with a higher mud content. This is due to the similar hydro-dynamic behaviour of fine mineral particles and light organic debris and to the association of degrading organic matter with grain surfaces and clay lattices.

In order to separate significant spatial variations from those caused by different sediment particle sizes, the organic content of specific size fractions should be considered. The distribution of organic carbon in the finest of the fractions analysed (<90 μm) has been plotted in Figure 21. The percentage of clay in the <90 μm fraction (as an index of specific surface area) was found not to be correlated with the organic carbon concentration in the <90 μm fraction; thus the spatial variation of organic carbon in Figure 21 is believed to reflect the effects of local inputs, transport pathways and sinks of organic matter.

The concentration of organic carbon in the fine sediment fraction appears similar in the three surveys, varying between 1.6 and 5.0%. This is higher than in the vicinity of other offshore sewage dumping grounds where concentrations do not normally exceed 2.5% (Eagle *et al.*, 1978b, 1979, in preparation; Murray *et al.*, 1980; Kiff and Nunny, in press). The high concentrations are consistent with earlier observations (Stoner, 1974) which indicated that levels of organic matter in the <63 μm fraction of the sediments in this area varied between 8 and 12% in 1971. The widespread distribution of concentrations of up to 3.5% organic carbon (\approx 8% organic matter in Stoner's data) without an obvious point source suggests that such levels may be partly natural or the result of long-term anthropogenic inputs from a wide variety of sources. Levels of organic detritus tend to be higher in estuaries than in the coastal zone (Darnell, 1967), thus the generally high levels of organic matter in the sediments of the central Bristol Channel may reflect the proximity of the Severn Estuary system.

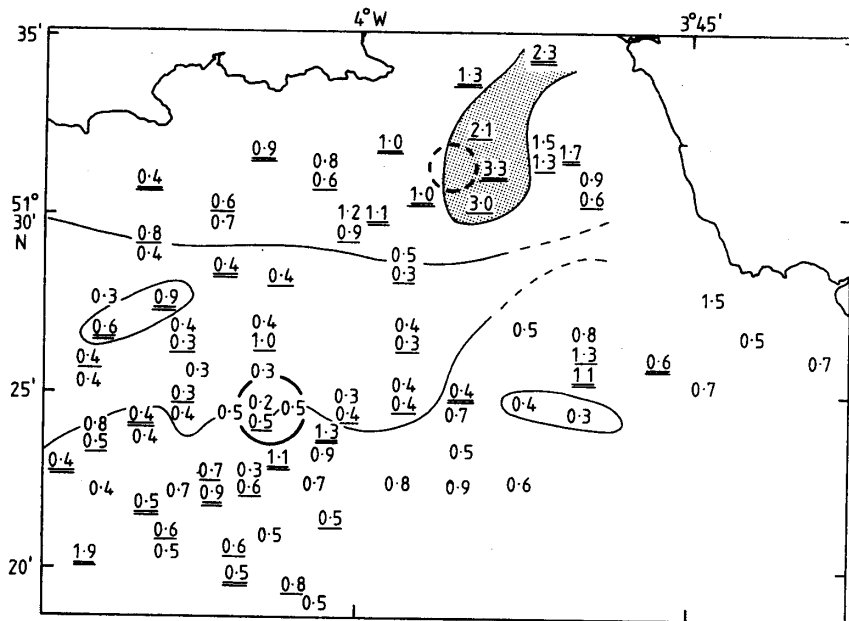


Figure 20 Concentrations of organic carbon (%) in sediment samples (1975, 1976 and 1977 figures)

- sludge dumping ground
- dredged spoil dumping ground
- >2% organic carbon in samples.

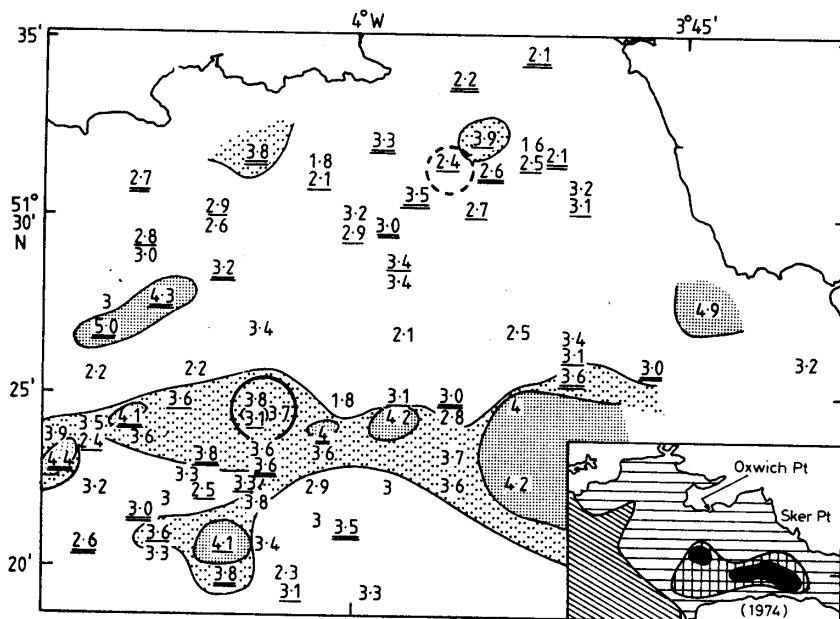


Figure 21 Concentrations of organic carbon (%) in the $<90 \mu\text{m}$ fraction of sediment samples (1975, 1976 and 1977 figures).

- sludge dumping ground
 - dredged spoil dumping ground
 - >3.5% organic carbon in samples
 - >4% organic carbon in samples.
- Inset shows concentration of organic matter in $<63 \mu\text{m}$ fraction of the sediments (from Stoner, 1974)
- >12%
 - 10-12%
 - 8-10%
 - <8%

The area where organic carbon concentrations exceeded 3.0% coincides with an area where dumped material was expected initially to reach the sea bed (Section 3.4). This suggests that sludge particles are capable of accumulating locally in the gravel interstices of the sea bed, elevating carbon levels by up to 40% of the background level. Further localised elevations in organic carbon concentrations occurred within Swansea Bay and inshore of Nash Sands; although these may have included a contribution from sludge dumping, they are more likely to have arisen from coastal discharges and dredged spoil dumping.

The observed distribution of organic compounds is consistent with the estimates of local inputs (Section 2) which suggested that the amount of particulate organic substances from sludge dumping was only 27% of local inputs and even smaller relative to that from discharges entering the Severn Estuary and Bristol Channel. If it is assumed that these other inputs become widely distributed, then local elevations in the organic carbon concentrations of sediment from sludge dumping would be expected to be

over and above a general enrichment of organic concentrations from these other sources. A further point to be noted is that, despite the quantities dumped having increased from 1975 to 1977, there is no evidence of a corresponding increase in carbon concentrations in the fine sediments (Section 5.4.3). This provides further evidence that the deposition of dumped material in the muddy interstices of gravel is likely to be only temporary.

5.3.2 Carbon/nitrogen ratios

In Figure 22 the total nitrogen concentration within the $<90 \mu\text{m}$ fraction of the sediment samples is plotted against the organic carbon content for each of the three annual surveys. Most of the samples have a C/N ratio in the range 11:1 to 18:1. These ratios are high compared with sediments from off-shore areas, which normally possess ratios similar to those found in plankton (7:1-10:1, Degens and Mopper, 1976; Eagle *et al.*, in preparation). High ratios are typical of terrigenous debris (Arrhenius, 1949), saltmarsh detritus (Haines *et al.*, 1976) and anaerobic estuarine silts (Murray *et al.*, 1980), or may

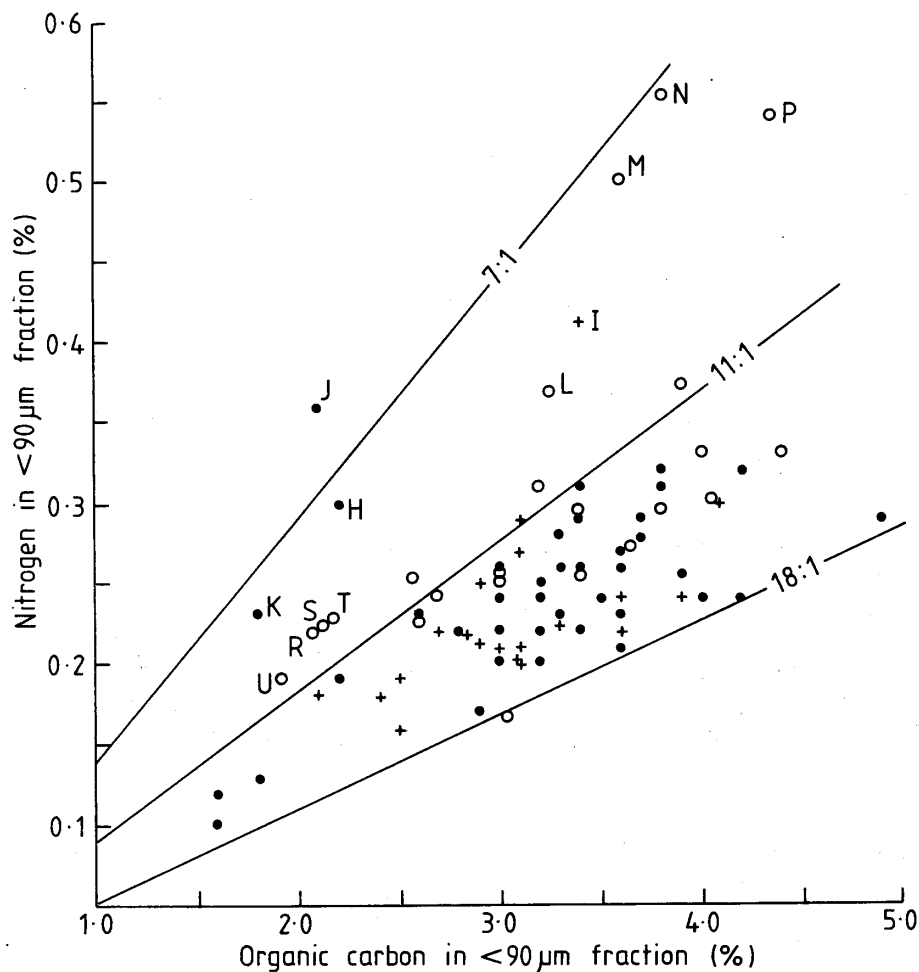


Figure 22 Organic carbon/total nitrogen ratios in $<90 \mu\text{m}$ fraction of the sediments.

● 1975 + 1976 ○ 1977. See Figure 2 for location of stations H-U.

reflect the presence of coal dust which is known to contaminate Severn Estuary/Bristol Channel sediments derived from the Barry/Newport area (IMER, 1975). This implies that much of the fine organic detritus in the central Bristol Channel area had a landward rather than a seaward source, as is also suggested by total C/N ratios in seston determined by IMER in 1973 (A. W. Morris, personal communication) (Table 7). The seasonal reduction of the C/N ratio caused by the growth of phytoplankton occurred in offshore waters in the spring/summer but not off Nash Point, nor in the outer Severn Estuary where the higher estuarine ratios prevailed throughout the year.

Digested sludge particulates which form the bulk of the sewage dumped in the Bristol Channel have a C/N ratio of approximately 8:1. Assuming a 'natural' C/N ratio of 15:1, elevation of the carbon content of the sediments by 40% (such as is postulated to occur in the vicinity of the dumping ground) would produce a ratio of 13:1, indistinguishable from background values. The location of the samples exhibiting C/N ratios of less than 10:1 are shown as stations H to T in Figure 2. Some of these were found within the area of mobile sand whose relatively low organic content may have allowed the effects of temporary deposition of nitrogen rich material (perhaps sewage sludge) to be more apparent. Other samples were from stations closer inshore where sewage-derived organic matter having a low C/N ratio would also be present.

The C/N ratios of samples taken in 1977 tended to be lower than in the preceding years. There is no evidence that seasonal changes in the abundance of plankton may have influenced these C/N ratios, the 1975, 1976 and 1977 surveys having been made in October, July and September respectively. The 1977 ratios would thus be consistent with the presence of a higher proportion of organic matter of planktonic or sewage origin. The increased quantity of sewage sludge dumped from 1975 to 1977 may be one cause of reduced C/N ratios at stations in the central part of the survey area.

5.4 Trace metals in sediments

The concentrations of mercury, copper, zinc, lead, nickel and chromium were measured in the sediment samples collected in 1975, 1976 and 1977. The metals were extracted from two specific fractions of the sediment (<90 μm , 90-500 μm) by employing a rigorous acid leaching technique and the concentrations were determined by atomic absorption spectrophotometry (Eagle *et al.*, 1978a). The spatial variation in trace metals has been plotted in Figures 23-34; since the three sets of data were generally consistent they have been grouped together in each figure except in the case of mercury in the coarse sediment fraction where results were available only for 1977. The concentration of cadmium in both size fractions of the sediment was below the detection limit of the method employed (0.2 mg kg^{-1}) at all stations except that furthest into Swansea Bay.

The concentrations of metals in a number of potential sources are given in Table 8. The major catchments draining into the Bristol Channel/Severn Estuary system are not significantly mineralised and the minerogenic component of these sediments has been taken from Stoner (1974). However, levels of trace metals in the aqueous phase are elevated probably as a result of inputs from coastal outfalls and the high water retention capacity of the system (Section 2); thus concentrations of metals associated with particle surfaces are likely to be higher where adsorption or complexing can take place with organic matter. This probably occurs in the organic muds of the Swansea and Port Talbot areas which are dredged and dumped into the outer Swansea Bay area and in Severn Estuary muds. The metal concentrations of dumped sewage sludge and industrial wastes are given in Table 1.

5.4.1 Spatial variation in metal concentrations

The concentrations of all metals analysed in the <90 μm fraction showed similar distributions (Figures 23-28) with a zone of slightly elevated concentrations running east-west through the sludge dumping ground. The highest levels of metals (2.8-3.1 mg kg^{-1} mercury, 430 mg kg^{-1} zinc,

Table 7 Total Carbon : total nitrogen ratios; Bristol Channel seston samples*

1973	The Holms ¹	Nash Point ²	Barnstaple Bay ³	Carmarthen Bay ³
April	17	18	15	15
May	22	20	—	8
June	27	22	10	6
July	18	15	7	6
November	17	25	17	15

* Source : IMER

1 Outer Severn Estuary

2 Central Channel

3 Outer Channel

Table 8 Trace metal concentrations in natural sediments and Swansea Bay sediments (mg kg^{-1})

	Hg	Cd	Zn	Pb	Cu	Cr	Ni
Non-organic (Minerogenic) phase of Bristol Channel sediments-average (Stoner, 1974)	—	—	88	26	22	60	24
Swansea Bay intertidal muds-range (Bloxham <i>et al.</i> , 1972)	0.04-0.76	11-60	80-1650	110-2850	55-2215	—	—
Swansea/Port Talbot dredgings-range (Murray and Norton, 1979)	0.3-1.4	1.8-18	250-1100	120-650	50-150	28-63	55-60
Severn Estuary muds-average (Kirby and Parker, 1973)	—	2.5	340	133	45	—	—

130 mg kg^{-1} lead, 53 mg kg^{-1} copper, 77 mg kg^{-1} nickel and 60 mg kg^{-1} chromium) were found at or just west of the disposal ground where initial settlement of the sludge was expected (Section 3.4). A second zone of elevated concentrations occurred within the outer Swansea Bay area in the vicinity of the spoil dumping ground. The geographical association of these two zones of elevation with the dumping grounds of the area suggests that the former was attributable to the accumulation of sludge solids within sand and gravel interstices, the latter to the dumping and dispersion of contaminated maintenance dredgings. A further area of slight elevation occurred at the eastern extremity of the survey area inshore of Nash Sands and may have been due to the discharge of effluents from coastal outfalls. In Swansea Bay, to the north of the survey area, there appeared to be a further significant source of mercury contamination, presumably associated with the chlor-alkali plant discharge to the bay.

The concentrations of metals in the 90-500 μm fraction (Figures 29-34) showed similar distributions, with a general zone of slightly elevated concentrations running east-west through the southern part of the sludge dumping area. Concentrations were also elevated at the Swansea Bay spoil dumping ground. Analysis of the coarse fraction showed that the highest concentrations of most metals were well inside the bay, probably due to large coastal industrial discharges (Section 2). In the case of mercury, the highest concentration was found at the station located near the end of an outfall from a chlor-alkali plant (Clifton and Vivien, 1975).

Differences in the spatial distributions encountered throughout the survey area for different metals may reflect the importance of different sources. In the case of lead in the fine fraction (Figure 26) it can be

seen that increased concentrations either near the dumping ground or inshore are only a factor of 2-3 higher than the lowest in the survey area. This is consistent with the findings of Section 2 which would suggest that the large diffuse atmospheric input of lead (from vehicle exhausts and smelter discharges; Olausson, 1972; Hetherington, 1976) could result in an overall enrichment tending to mask the effects of local point source inputs.

Spatial variations in the nickel concentration in the fine fraction were also slight (Figure 27). This may be attributable to the low level of nickel in dredge spoil, and to the small contribution from sewage sludge relative to river run-off (Table 5). The tendency for nickel to be partially lost from the particulate phase of sewage sludges to solution (Rohatgi and Chen, 1975) may also reduce the apparent contribution due to sludge dumping.

Although a zone of elevated zinc and copper concentrations was found in the fine fraction of the sediments near to the dumping ground (Figures 24 and 25), the degree of enrichment was also small and consistent with the finding that inputs of these metals from sludge were much less than those from other sources (Section 2). The relative importance of dumping inputs for chromium (28% of local inputs) was estimated in Section 2 as being greater than for the metals so far described. This appears to be reflected in a greater difference between the elevated concentrations of this metal in the sediments near to the dumping ground and the lower concentrations immediately to the north and south.

Mercury showed the greatest spatial variations in both sediment fractions (Figures 23 and 29) with the highest concentrations inshore confirming the estimates of Section 2 that local discharges were the dominant sources of particulate mercury in this area.

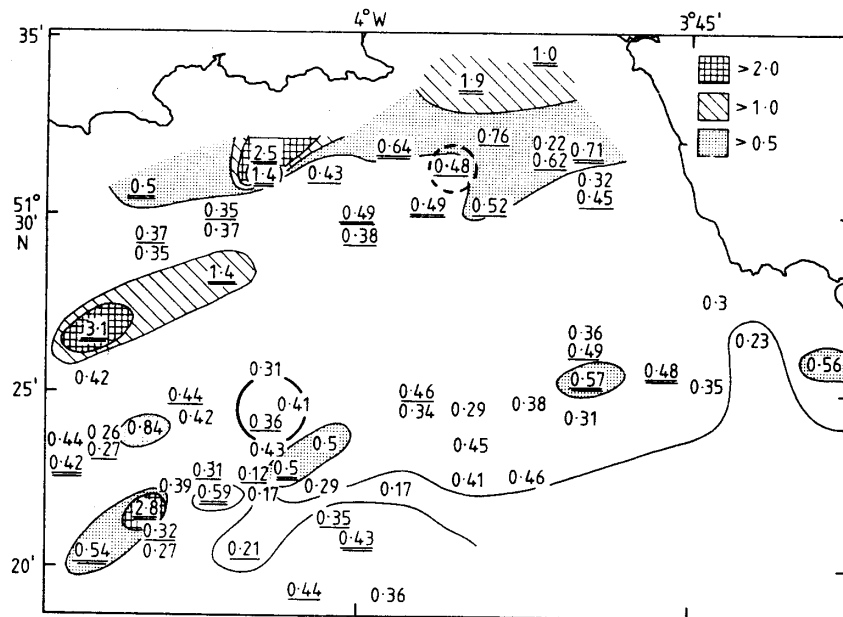


Figure 23 Concentration of mercury in the $<90 \mu\text{m}$ fraction of the sediments (mg kg^{-1}); 1975, 1976 and 1977 figures.

- sludge dumping ground
- ⊖ dredged spoil dumping ground

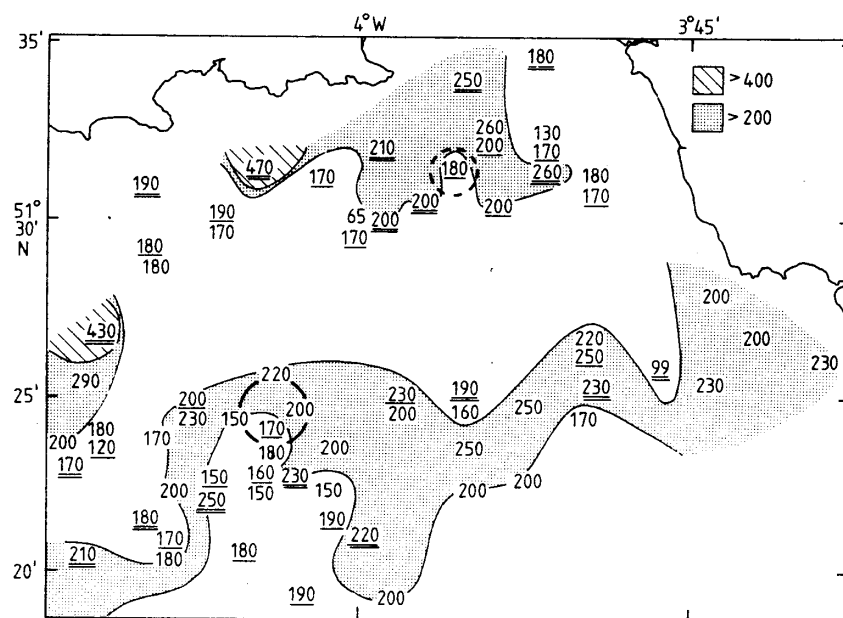


Figure 24 Concentration of zinc in the $<90 \mu\text{m}$ fraction of the sediments (mg kg^{-1}); 1975, 1976 and 1977 figures.

- sludge dumping ground
- ⊖ dredged spoil dumping ground

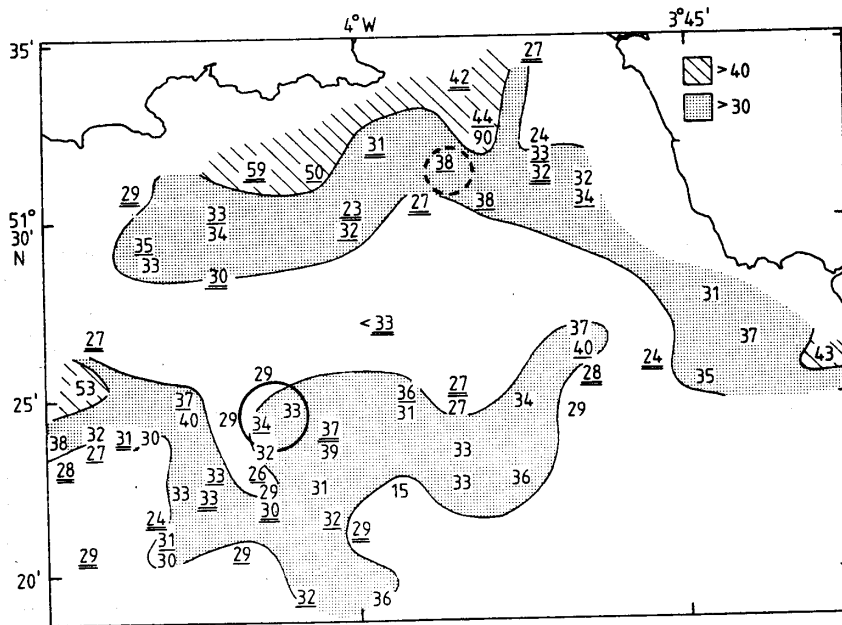


Figure 25 Concentration of copper in the $<90 \mu\text{m}$ fraction of the sediments (mg kg^{-1}); 1975, 1976 and 1977 figures.

- sludge dumping ground
- dredged spoil dumping ground

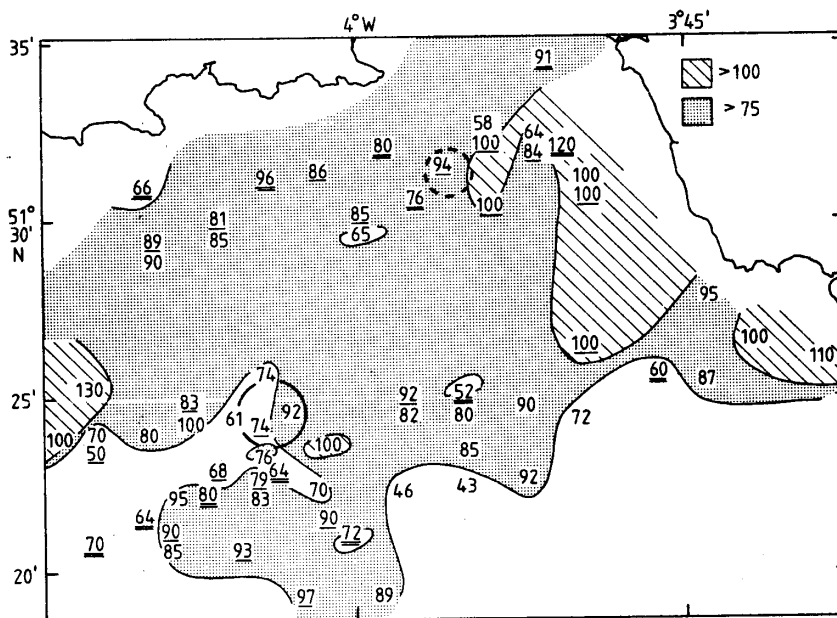


Figure 26 Concentration of lead in the $<90 \mu\text{m}$ fraction of the sediments (mg kg^{-1}); 1975, 1976 and 1977 figures.

- sludge dumping ground
- dredged spoil dumping ground

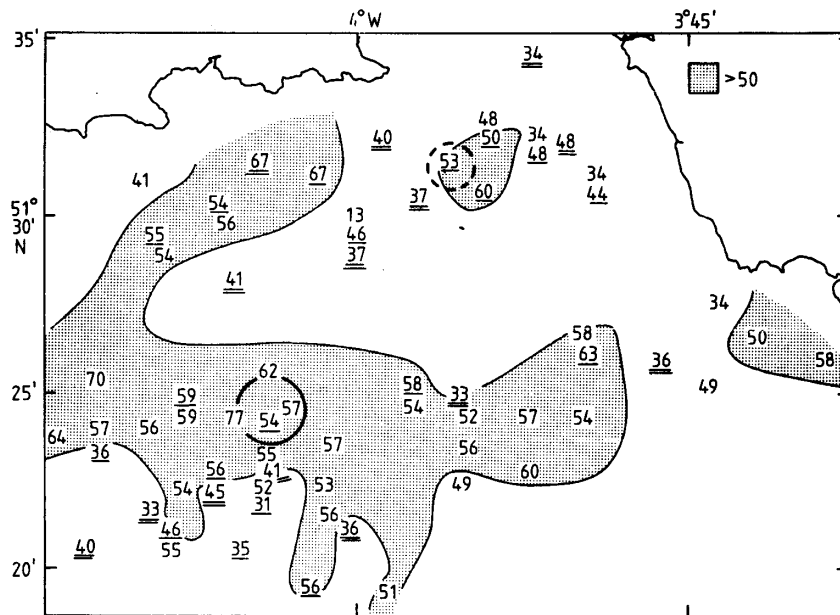


Figure 27 Concentration of nickel in the <math><90 \mu\text{m}</math> fraction of the sediments (mg kg^{-1}); 1975, 1976 and 1977 figures.

- sludge dumping ground
- ⊖ dredged spoil dumping ground

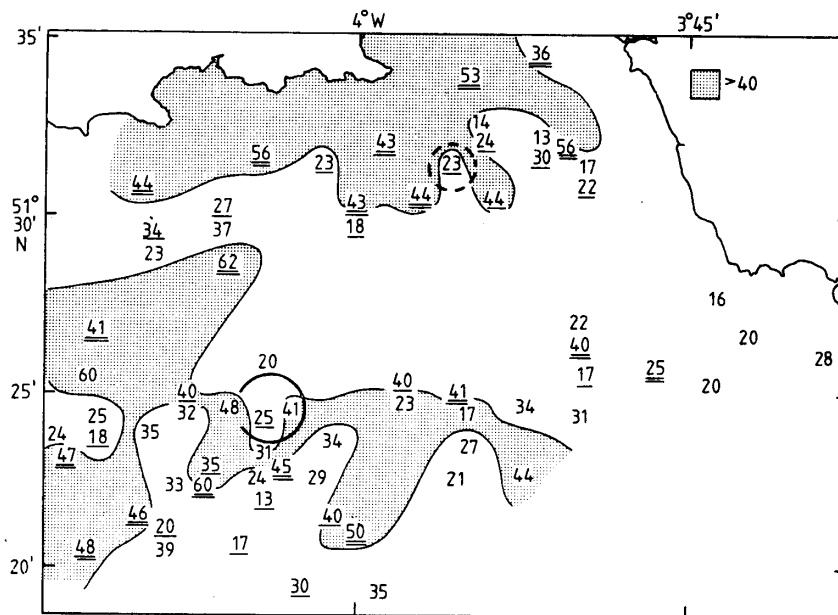


Figure 28 Concentration of chromium in the <math><90 \mu\text{m}</math> fraction of the sediments (mg kg^{-1}); 1975, 1976 and 1977 figures.

- sludge dumping ground
- ⊖ dredged spoil dumping ground

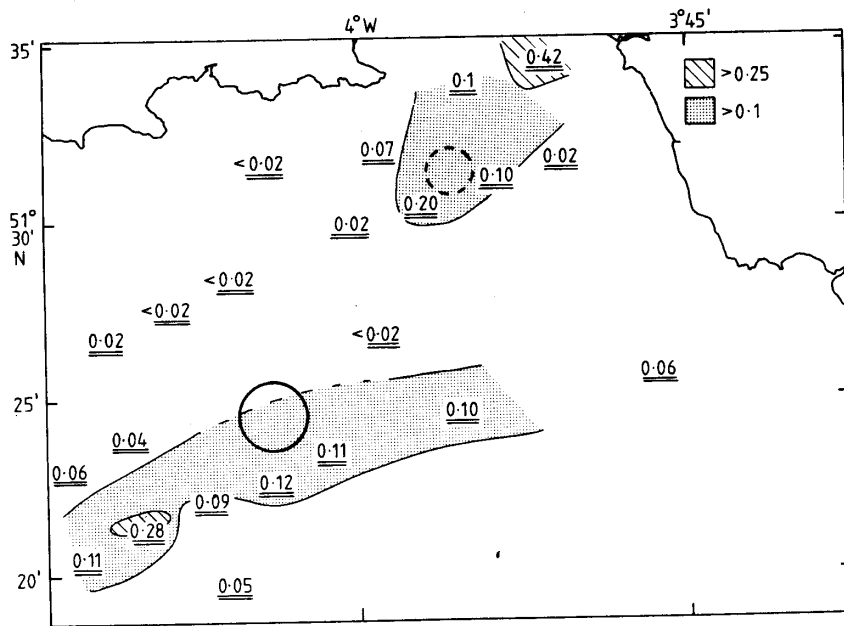


Figure 29 Concentration of mercury in the 90-500 μm fraction of the sediments (mg kg^{-1}).

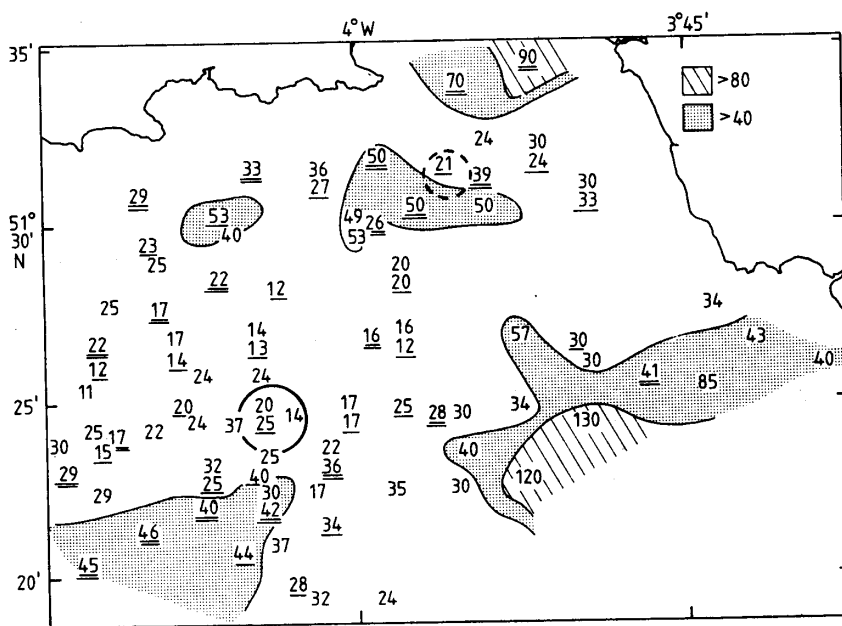


Figure 30 Concentration of zinc in the 90-500 μm fraction of the sediments (mg kg^{-1}).

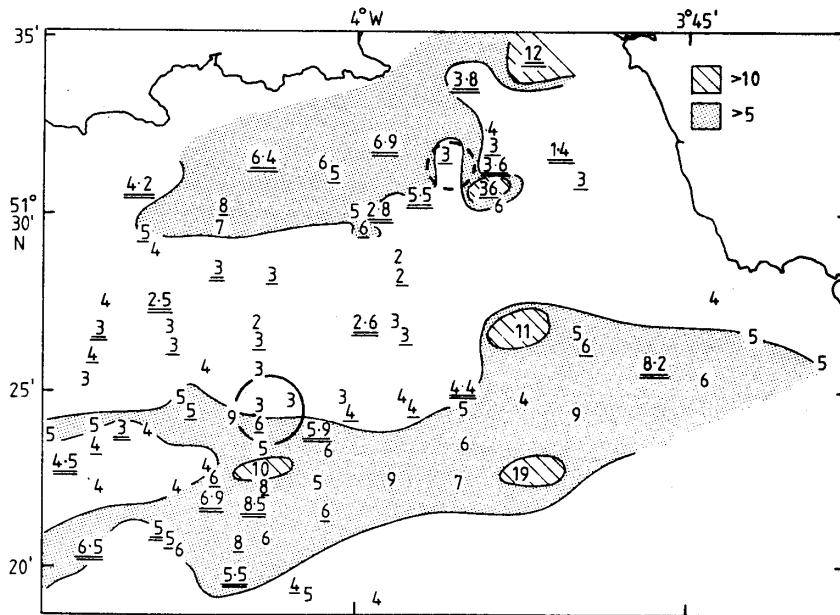


Figure 31 Concentration of copper in the 90-500 μm fraction of the sediments (mg kg^{-1}).

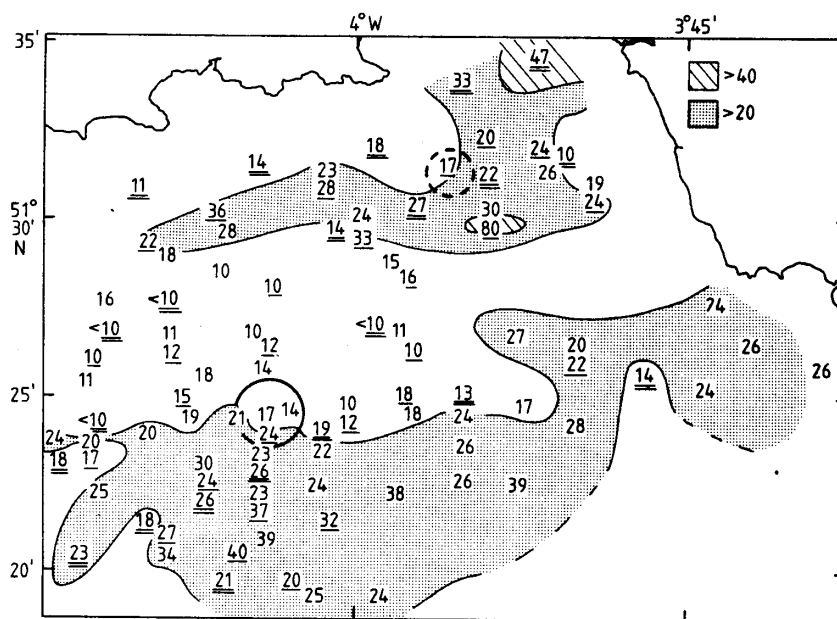


Figure 32 Concentration of lead in the 90-500 μm fraction of the sediments (mg kg^{-1}).

Cadmium concentrations were all below the detection limit of 0.2 mg kg^{-1} except at the station located near an industrial outfall in Swansea Bay where the coarse fraction contained 0.7 mg kg^{-1} . These findings are consistent with the view that cadmium is rapidly lost from the particulate phase of sewage and sewage sludge (Rohatgi and Chen, 1975).

5.4.2 Organic carbon/metal correlations

The degree to which the organic carbon content was correlated with the metals mercury, zinc and lead in the fine ($<90 \mu\text{m}$) fraction of the sediment is shown in Figure 35 and the correlation coefficients for all the metals analysed are given in Table 9. The distribution of lead and zinc was significantly correlated with

Table 9 Correlation coefficients between trace metal content (mg kg^{-1}) and organic carbon content (%) of fine ($<90 \mu\text{m}$) fraction

Metal	Correlation coefficient
Mercury	0.29
Copper	0.21
Zinc	0.53
Lead	0.50
Chromium	0.00
Nickel	-0.22
n = 50	
P 0.001 = 0.443	
P 0.01 = 0.354	
P 0.05 = 0.273	

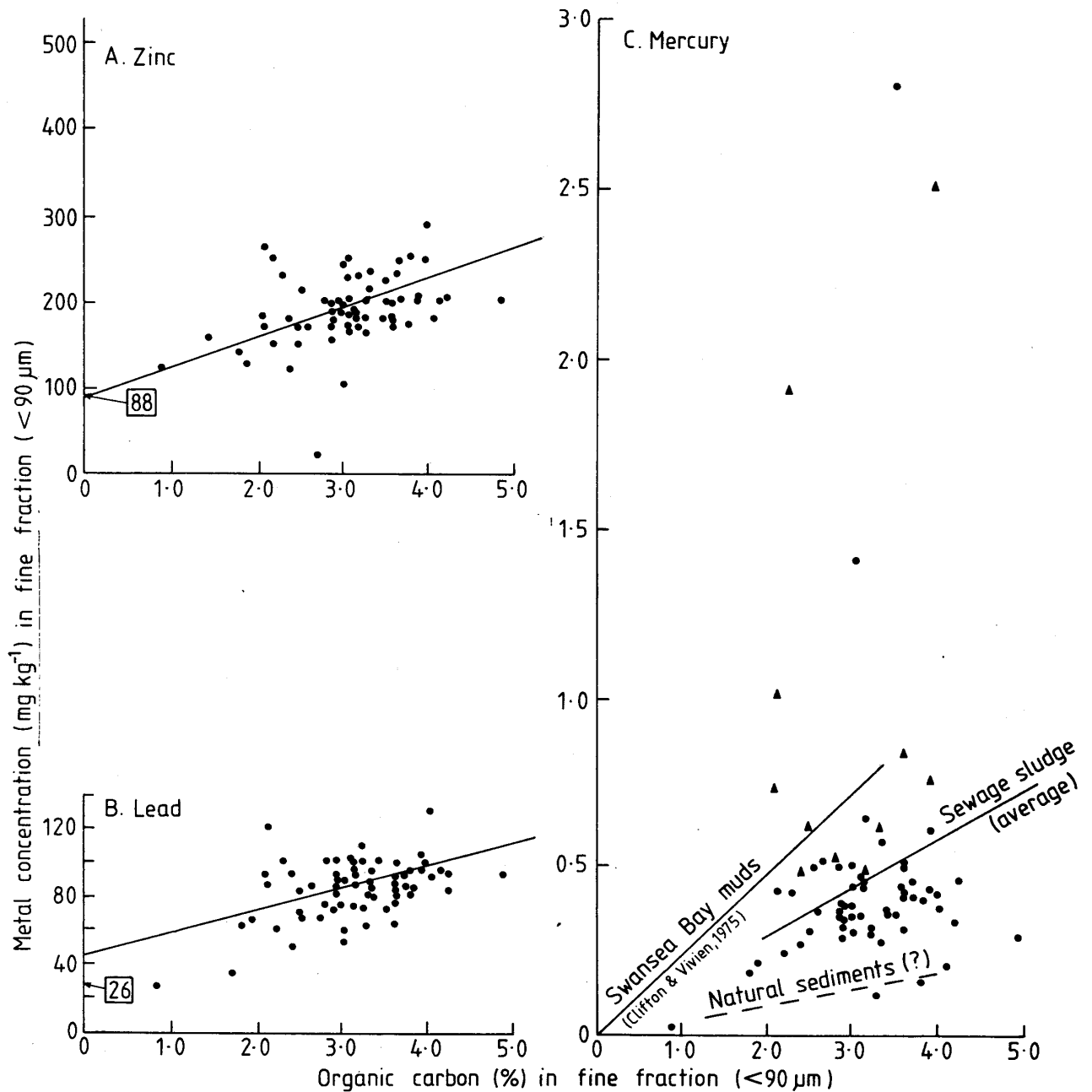


Figure 35 Trace metal/organic carbon relationships in the fine ($<90 \mu\text{m}$) sediment fractions (1975-7 surveys). **88** — average concentration in the minerogenic phase of the sediments (Stoner, 1974). Regression analysis performed on data from all three surveys combined. Swansea Bay sediments distinguished (\blacktriangle) in C.

the distribution of organic material. The relative amounts of these two metals associated with the organic and inorganic phases of the sediment can be estimated by extrapolating the regression line to cut the ordinate in Figure 35. The values so identified (88 and 46 mg kg⁻¹ for zinc and lead respectively), theoretically the mean concentrations of these metals in the inorganic fraction of the fine sediment, correspond reasonably well to the average zinc and lead concentrations found previously (88 and 26 mg kg⁻¹) in the 'mineral' fraction of Bristol Channel sediments (Stoner, 1974). Chromium and nickel exhibited no significant correlation with the organic carbon content of the <90 µm fraction of the sediment. This is also in agreement with Stoner's findings that 85 and 67% respectively of these metals were associated with the mineral phase of the fine sediments. Copper and mercury exhibited a low degree of correlation with organic carbon concentrations, which may be attributable to the existence of differing metal/carbon ratios in particulate matter from different sources. The poor correlation between the mercury and carbon content is shown in Figure 35C. The majority of sediments contained Hg/C ratios greater than those expected for 'natural' sediments but within the range encountered in sewage sludges. However, in the northern part of the survey area and particularly in Swansea Bay the mercury concentrations were substantially higher. This is consistent with the findings of Clifton and Vivien (1975) who demonstrated the existence of mercury-enriched sediments from the inner part of Swansea Bay.

5.4.3 Temporal variations in metal concentrations

In the surveys conducted in 1975, 1976 and 1977, owing to the difficulties of sampling, only six stations were common to all three surveys, two in the vicinity of the dredged spoil area and four around the sewage sludge dumping area. The concentrations of carbon and metals at these stations from 1975 to 1977 are compared in Figure 36. An increase in the organic carbon content of the whole sediment occurred during the period of the study at two stations, but this was mainly due to an increased fine fraction of the sediment, because the concentration of organic carbon in this fraction remained constant.

In the case of the metal concentrations in the fine fraction near the dredged spoil dumping area, and also to a lesser extent in the sewage sludge area, concentrations of some metals appear to have increased from 1975 to 1977. These trends were not found in the coarse fraction where reductions in concentration occurred. The latter may reflect conditions immediately prior to the survey, whereas the fine material accumulated in the sediment could reflect the longer term effects of dumping which, for sewage sludge, has increased from 1975 to 1977. However, in view of the uncertainties in relocation of sampling

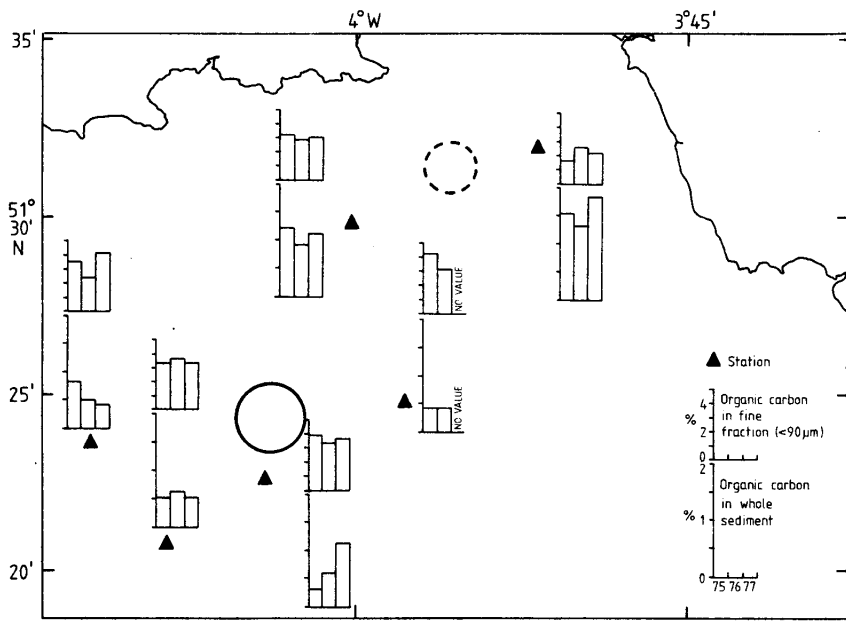
stations from one survey to another, the significance of these temporal changes is difficult to assess.

6 The benthos

During the 1975 survey an attempt was made to collect two 0.1 m² Day grab samples from each of 60 stations for precise identification of benthos. In 1976 fewer stations were sampled and in 1977 only a description from a first visual inspection was recorded on the vessel. During the 1975 and 1976 surveys it proved impossible to sample quantitatively at most stations owing to the failure of the grab to effectively sample fauna on the hard ground encountered over much of the survey area. The samples of fauna which were retained on a 1 mm sieve were inspected at sea before preservation in formalin. A detailed laboratory examination of samples from the 43 stations effectively sampled in 1975 supplemented by an on-board examination of the contents of grab samples from the remaining stations, the 17 anchor dredge hauls and one Agassiz trawl tow, allowed a qualitative description to be made of the benthos within the survey area. The location of stations worked by grab, dredge and Agassiz trawl are shown in Figure 37. Because of the difficulty of sampling, a more comprehensive assessment of the benthos would require direct observation using underwater photography and/or scuba diving.

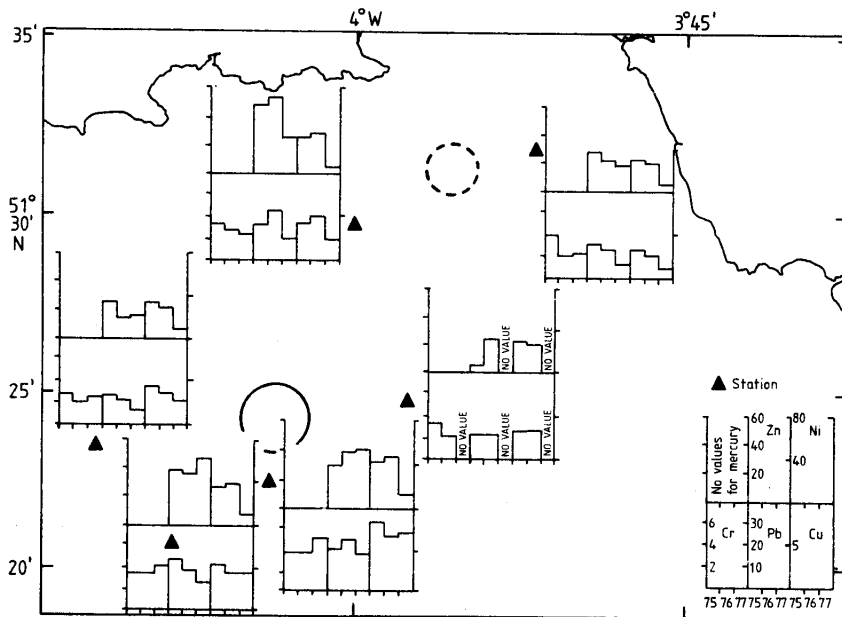
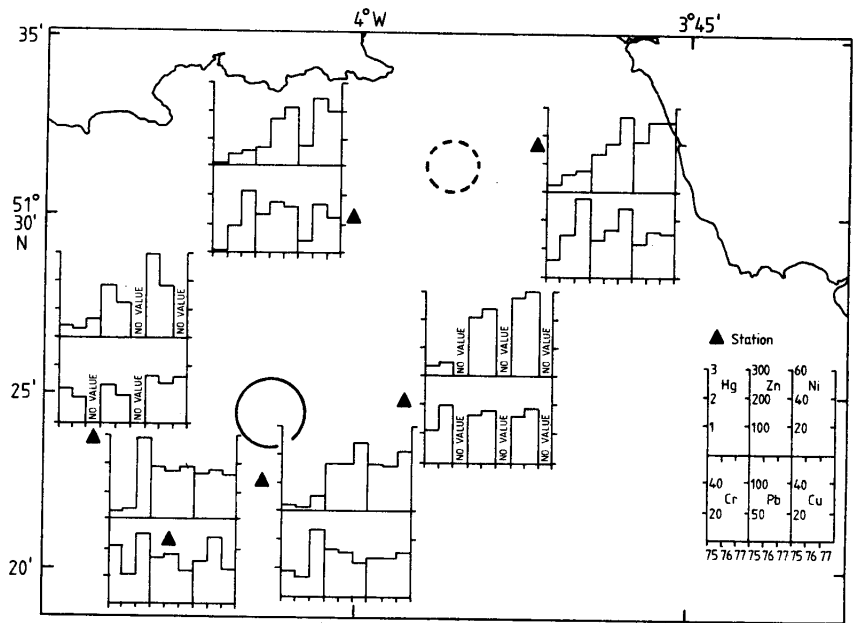
Studies have also been made by Warwick and Davies (1977) of IMER who collected their samples with a naturalist's dredge supplemented by grabbing where the bottom was sufficiently soft. They applied objective analysis to their data, modified to overcome sampling inadequacies (a practice which was not considered valid in the present study on account of the larger percentage of stations from which no satisfactory samples could be obtained by either grab or dredge). They found that a division of stations into major faunal communities could be achieved using the classification technique of Field (1971) and the Bray Curtis index of similarity (Bray and Curtis, 1957) but distinguishable at a similarity level of only 18% owing to the variability and paucity of the fauna. Because of this only a superficial comparison of the Warwick and Davies and the MAFF surveys has been made. Although both studies employed wide station spacing, within the study area several benthic community types were identified reflecting the characteristics of the sediments (Figure 37).

Warwick and Davies suggested that the area surrounding the dredged spoil ground was characterised by an *Abra* community (Petersen, 1913) dominated by the bivalve *Nucula turgida*. This community is typical of muddy sands in sheltered locations often rich in organic material. They found that this gave way to a sand fauna characterised by *Spisula elliptica* (typical of loose sands) and other *Venus* community species. The fauna in two of our 1975 stations to the east of the dredged spoil ground (Area A in Figure 37) were dominated by many *Nucula turgida* and accompanied by *Goniada maculata*, *Nephtys hombergi*, *N. longosetosa* and *N. cirrosa*, but other stations in the



A: organic carbon of whole sediment and $<90 \mu\text{m}$ fraction.

B: metal concentration of $<90 \mu\text{m}$ fraction (mg/kg dry weight).



C: metal concentration of $90-500 \mu\text{m}$ fraction (mg/kg dry weight).

Figure 36 Temporal variations in organic carbon and metal concentrations at six station locations sampled in 1975, 1976 and 1977.

Note: no values for mercury (coarse) for 1975, 1976 and 1977.

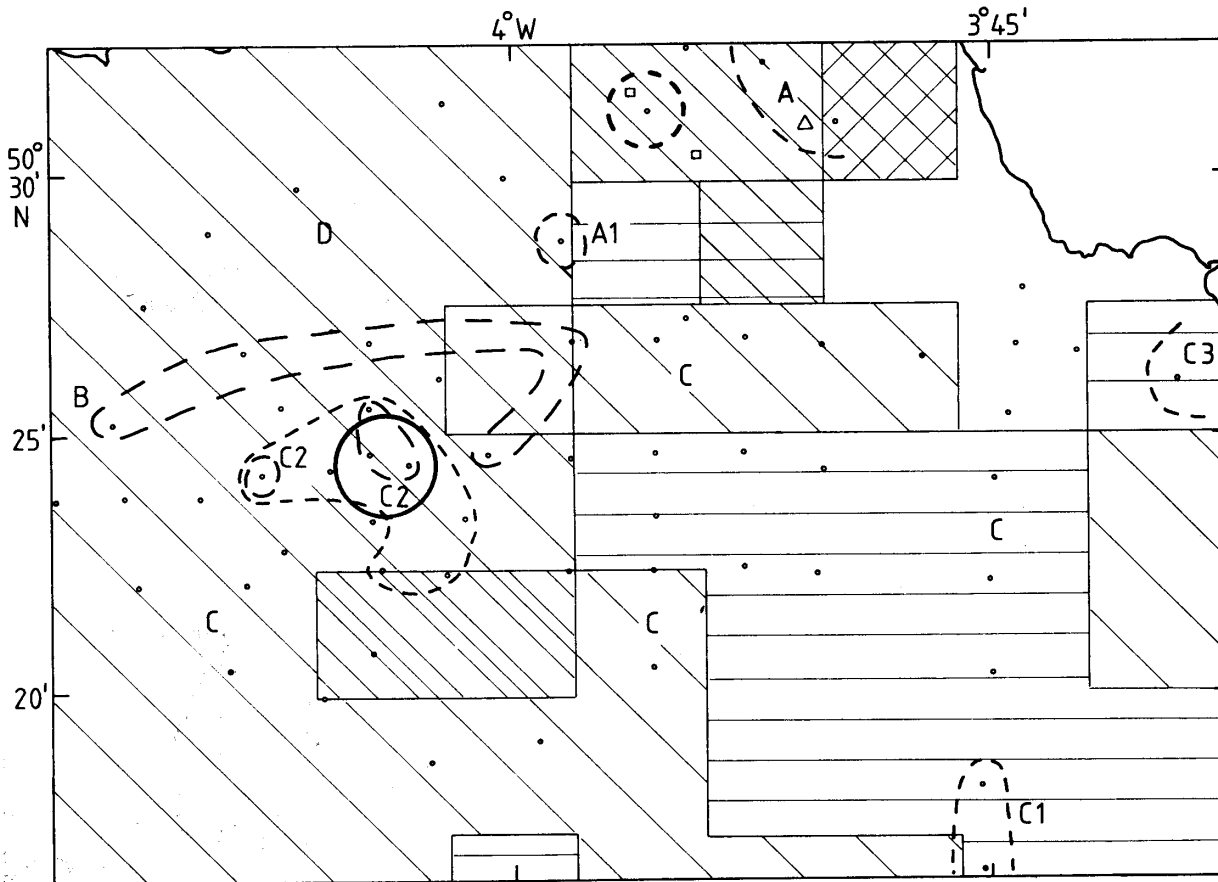


Figure 37 Benthic fauna communities:

- 1975 grab and dredge stations; fauna examined on board.
- △ Agassiz trawl haul.
- 1976 grab stations.

Faunal associations from Warwick and Davies (1977).

- ⊠ *Venus* association.
- ▨ *Abra* association.
- ▤ *Modiolus* association.
- ▧ Reduced hard bottom fauna.

A, etc., faunal associations identified in MAFF surveys (Section 6)

vicinity, sampled in 1975, 1976 and 1977, and also the Agassiz trawl station contained many *Spisula elliptica* with *Nucula turgida* indicating the presence of a mixed *Abra/Venus* community. Two stations worked in 1976, one on and the other just to the south-west of the spoil ground where the muddy sediment was noticeably thicker and tenacious, appeared on superficial inspection to be devoid of fauna possibly due to smothering from the dumping of dredged spoil. The presence of biota at a station sampled in 1975 a little to the north of the dumping ground suggests that these effects are localised to the area of dumping. At only one station (A1), situated between the two dumping grounds, was a classical *Abra* community found in which the tube-dwelling polychaete, *Pectinaria koreni*, was abundant in fine sand at a density of up to 72 per 0.1 m².

In the area lying within the boundary of continuous sand cover (shown in Figure 12) to the north of the sludge dumping ground (Area B, in Figure 37) the fauna was extremely sparse or totally absent. The amphipod, *Ampelisca* sp., and the polychaete, *Nephtys cirrosa*, both of which exhibit some tolerance of mobile sediments, were sometimes present in small numbers.

The third and most widespread benthic association (Area C) was located to the south and east of Area B. The fauna was restricted mainly to a poorly developed epifauna of various erect hydroids, *Alcyonium digitatum*, small anemones, *Flustra* spp., sea mats, sponges, solitary tunicates, barnacles (e.g., *Balanus crenatus* and *Verruca stroemia*), *Pomatoceros triqueter*, *Anomia ephippium* and chitons, often in

association with rock-boring bivalves such as *Zirfaea crispata* and *Hiatella* sp. Any unattached fauna was sparse and generally limited to the offshore gravel community of Jones (1950), dominated by crustaceans and echinoderms such as *Porcellana longicornis*, *Macropodia rostrata*, *Eupagurus* sp., *Pandalina brevisrostris*, *Ophiothrix flagilis*, *Psammechinus miliaris*. True infauna was either extremely sparse or absent.

Within this large Area C three minor variations were found. Firstly, epifauna at the two stations to the extreme south-east (C1) was noticeably well developed, possibly due to the presence of clearer waters from offshore (Section 3.1): the infauna, however, was poor on account of the strong currents and lack of superficial sediments. Secondly, at four of the stations on or near the dumping ground (C2) small numbers of up to 14 species of sedentary polychaetes were found, together with the epifauna typical of Area C, indicating the presence of settled superficial deposits, probably in sheltered pockets among the rocky ground. The numbers of species and individuals averaged 32 and 106 per 0.1 m² respectively at these four stations and a further four stations in the vicinity showed above average numbers of species and individuals. This is the area subject to organic enrichment from sludge dumping (Figure 21) which may be a factor in promoting growth especially of the detritus-feeding polychaetes. The third variation (C3) occurred at the eastern edge of the surveyed area. The fauna was basically similar to that at C2 except for the presence of up to 78 *Nucula nucleus* per 0.1 m² at one station, which may be indicative of the greater quantity of mud present in this otherwise coarse gravel substrate. *N. nucleus* was also present in small numbers at two in-shore stations nearby.

To the north of the mobile sands in Area D, the benthos was sparse and very mixed. Some stations here resembled those in Area C but others were characterised by small numbers of *Lanice conchilega*, *Pectinaria koreni* and *Scalibregma inflatum* due to the presence of more muddy gravels; however, the presence of *Nephtys cirrosa* at a few stations indicated the presence of sand interspersed with the gravels.

The faunal associations identified were broadly consistent with those reported by Warwick and Davies (1977). They found that most of the area outside Swansea Bay was characterised by a poorly defined *Modiolus* community or a reduced hard bottom community. In places these tended to merge with each other and, to the south of the dumping ground, also with an *Abra* community. This latter association is compatible with the variation C2 identified in our surveys. The sandy area (B) was not specifically distinguished by Warwick and Davies but the presence of *Ampelisca*, questionably a characteristic species in this mobile sand area, was noted to the north-east of the dumping ground in the vicinity of Area B. The major difference between the surveys was in Area D where Warwick and Davies designated the fauna as a *Modiolus* community, and therefore did not suggest the presence of the muds found in our surveys. The wide spacing of both IMER and MAFF stations over patchy ground probably accounted for these differences.

If the results of the IMER and our studies are considered together there is some evidence that the faunal communities of most of the area were typical of the natural substrates. As would be expected, the dredged spoil dumping in Swansea Bay had caused depletion of the benthos in the immediate vicinity of the dumping ground. In the central part of the Channel around the sewage sludge dumping ground the area is subject to fast currents, resulting in a gravelly or sandy substrate and generally very sparse fauna. There were, however, indications of slight enrichment in the sludge dumping area. The present scale of dumping would thus appear to be having only a marginal effect on the benthos owing to the effectiveness of the dispersion in the area.

7 Conclusions

The dumping of approximately 400 000 t a⁻¹ of sewage sludges (wet weight) and small quantities of industrial waste into the central Bristol Channel represents only one of a number of inputs of material to that area. Large amounts of organic substances and some metals are also discharged to the Severn Estuary and Bristol Channel from sewage and industrial outfalls; others enter from rivers, atmospheric deposition and the dumping of dredged spoil. Estimates of the relative magnitude of these inputs during the period of these surveys (1975-7) have been made and suggest that sewage sludge dumping is mainly of local significance, amounting to up to 51% of the direct inputs of organics and trace metals to the central Channel.

The dumping area and the central Channel are characterised by strong tidal flows and also, during westerly storms, by strong wave-induced near-bed movements. Initial residual water movements from the dumping ground appear to be to the north-east. Under some conditions this movement, as deduced from seabed drifter releases, would appear to be maintained in bottom waters into Swansea Bay and towards Nash Point. Under other conditions, however, landward movement may be slow, with movement upstream suggested, particularly to Bridgwater Bay. Dumped waste would thus be expected to be dispersed along the tidal axis with some residual movement to the north-east. In the longer term, however, particulate matter would become widely dispersed within the central and inner Channel. Limited confirmation of the short-term movements of dumped sludge particles was obtained from the measurement of faecal bacteria in the sediment.

A study of the natural sediment distribution and dynamics showed the dumping area to be in a region of muddy gravels. To the north and east, mobile sands predominated while into Swansea Bay finer sands and silts were found. Sites of deposition of suspended sediment, whether of sewage or other origins, were identified in the interstices of the gravels near the dumping area, in Swansea Bay and further upstream in Bridgwater Bay. The areas of accumulation locally were considered to be of limited capacity and subject to reworking during storms.

Analysis of the organic carbon and trace metal concentrations in the sediment showed that elevated concentrations of these substances occurred in several zones. One, arising from dumping of sewage sludge, was located along an east-west transect through the dumping area. The orientation of this main area of enrichment was slightly different from that expected from the north-easterly residual bottom currents measured at the dumping ground. Although this may indicate that the observations of currents at the dumping ground may not accurately reflect those in the general area, the presence of mobile sands to the north-east would make movement in this direction difficult to detect. Other zones of enrichment were identified as arising from the dumping of dredged spoil in outer Swansea Bay and from industrial discharges to the bay.

Because of the difficulty of sampling the gravelly substrate quantitatively for benthos, it has not been possible to describe the macrobenthos in other than qualitative terms. No gross effects of sewage sludge dumping have been identified; the fauna was relatively sparse and consistent with the substrate type. In the immediate vicinity of the dumping area, however, the increased organic content of the sediments may have resulted in slight changes in species composition. Dredged spoil dumping on the other hand does appear to have depleted the bottom fauna locally in the disposal area in Swansea Bay.

8 References

- ARRHENIUS, G., 1949. Carbon and nitrogen in sub-aquatic sediments. *Geochim cosmochim. Acta*, 1: 15-21.
- BLOXAM, T.W., AURORA, S.N., LEACH, L. and REES, T.L., 1972. Heavy metals in some river and bay sediments near Swansea. *Nature Phys. Sci.*, 239: 158-9.
- BRAY, J.R. and CURTIS, J.T., 1957. An ordination of the upland forest communities of Southern Wisconsin. *Ecol. Monogr.*, 27: 325-349.
- BTDB, 1975. British Transport Docks Board. Report on Research, 1974, 8-9.
- CALLAWAY, R., TEETER, A.M., BROWNE, D.W. and DITSWORTH, G.R., 1976. Preliminary analysis of the dispersion of sewage sludge discharged from vessels to New York Bight waters. In "Middle Atlantic, Continental Shelf and the New York Bight ..." (ed.) Gross, M. Grant. *Spec. Symp. Am. Soc. Limnol. Oceanogr.*, 2: 199-211.
- CARR, A.P., HEATHERSHAW, A.D. and BLACKLEY, M.W.L., 1976. Swansea Bay (Sker) Project-Progress report for the period August 1975 to July 1976. *Scient. Rep. Inst. Oceanogr. Sci, Taunton* (26), 28 pp.
- CASTON, V.N.D., 1972. Linear sandbanks in the southern North Sea. *Sedimentology*, 18: 63-78.
- CHUBB, C.J., DALE, R.P. and STONER, J.H., 1980. Inputs to Swansea Bay. pp. 307-326. In "Industrialised Embayments and their Environment Problems - a Case Study of Swansea Bay". (eds.) Collins, M.B., Banner, F.T., Tyler, P.A., Wakefield, S.J. and James, A.E., Pergamon Press, Oxford, 616 pp.
- CLIFTON, A.P. and VIVIEN, C.M.G., 1975. Retention of mercury from an industrial source in Swansea Bay sediments. *Nature, Lond.*, 253: 621-622.
- CRICKMORE, M.J., 1972. Initial behaviour of sludge. pp. 45-58. In "Out of Sight, Out of Mind" - Report of Working Party on the Disposal of Sludge in Liverpool Bay. Her Majesty's Stationery Office, London, 483 pp.
- COLLINS, M., FERENTINOS, G. and BANNER, F.T., 1979. The hydrodynamics and sedimentology of a high (tidal and wave) energy embayment (Swansea Bay, northern Bristol Channel). *Estuar. & Coast. Mar. Sci.*, 8: 49-74.
- COLLINS, M. and FERENTINOS, G., 1979. Sediment transport through the area south of Eastern Gower as related to the sediment budget of Swansea Bay. Final Report to IOS (Taunton), 111 pp.
- DARNELL, R.M., 1967. Organic detritus in relation to the estuarine ecosystem. pp. 376-382. In 'Estuaries' (ed.) Lauff, G.H., *Am. Assoc. Advanc. Sci. Publ.* (83), Washington DC, 757 pp.
- DAVIES, C.M., 1974. Location of spoil grounds in sedimentary systems. *Dock Harb. Auth.*, 55: 120-124.
- DEGENS, E. and MOPPER, K., 1976. Factors controlling the distribution and early diagenesis of organic material in marine sediments. pp. 60-110. In "Chemical Oceanography Vol. 6." (eds.) Riley, J.P. and Chester, R., Academic Press, London, 414 pp.
- DICKSON, R.R., 1976. Field tests of seabed drifters, using sector-scanning sonar techniques. *J. Cons. int. Explor. Mer.*, 37: 3-15.
- EAGLE, R.A., NORTON, M.G., NUNNY, R.S. and ROLFE, M.S., 1978a. The field assessment of effects of dumping wastes at sea. 2: Methods. *Fish. Res. Tech. Rep., MAFF. Direct. Fish. Res., Lowestoft*, (47), 24 pp.
- EAGLE, R.A., HARDIMAN, P.A., NORTON, M.G. and NUNNY, R.S., 1978b. The field assessment of effects of dumping wastes at sea. 3: A survey of the sewage sludge disposal area in Lyme Bay. *Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft*, (49), 22 pp.

- EAGLE, R.A., HARDIMAN, P.A., NORTON, M.G. and NUNNY, R.S., 1979. The field assessment of effects of dumping wastes at sea. 4: A survey of the sewage sludge disposal area off Plymouth. Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft, (50), 24 pp.
- EAGLE, R.A., HARDIMAN, P.A., NORTON, M.G. and NUNNY, R.S., in preparation. The field assessment of effects of dumping wastes at sea. 8: Sewage sludge dumping in the Outer Thames Estuary. Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft.
- FIELD, J.G., 1971. A numerical analysis of changes in the soft bottom fauna along a transect across False Bay, South Africa. J. exp. Mar. Biol. Ecol., 7: 215-253.
- GREAT BRITAIN-PARLIAMENT, 1974. Dumping at Sea Act 1974. Her Majesty's Stationery Office, London, 13 pp.
- HAINES, E., CHALMERS, A., HANSON, R. and SHERR, B., 1976. Nitrogen pools and fluxes in a Georgia saltmarsh. pp. 241-254. In 'Estuarine Processes vol II'. (ed.) Wiley, M. Academic Press, New York and London, 428 pp.
- HAMILTON, P., 1973. The circulation of the Bristol Channel. Geophys. J. R. astr. Soc., 32: 409-422.
- HALLS, S. and AYRES, P.A., 1974. A membrane filtration technique for the enumeration of *Escherichia coli* in seawater. J. appl. Bact., 37: 105-109.
- HARDEN JONES, F.R., GREER WALKER, M. and ARNOLD, G.P., 1973. The movements of a Woodhead seabed drifter tracked by sector scanning sonar. J. Cons. int. Explor. Mer, 35: 87-92.
- HEATHERSHAW, A.D. and HAMMOND, F.D.C., 1980a. Tidal currents and residual circulation in the Swansea Bay area of the Bristol Channel. pp. 123-156. In "Industrialised Embayments and their Environment Problems - a Case Study of Swansea Bay." (eds.) Collins, M.B., Banner, F.T., Tyler, A.E., Wakefield, S.J. and James, A.E. Pergamon Press, Oxford, 616 pp.
- HEATHERSHAW, A.D. and HAMMOND, F.D.C., 1980b. Transport and deposition of non-cohesive sediments in Swansea Bay. pp. 215-248. In "Industrialised Embayments and their Environment Problems - a Case Study of Swansea Bay." (eds.) Collins, M.B., Banner, F.T., Tyler, A.E., Wakefield, S.J. and James, A.E. Pergamon Press, Oxford, 616 pp.
- HETHERINGTON, J.A., 1976. Some measurements of the uptake of radioactivity by marine sediments and the implications for the monitoring of other pollutants. ICES CM 1976/E:47, 8 pp (mimeo).
- HYDRAULICS RESEARCH STATION, 1968. Sludge out-fall for London. Report Ex 388, Hydraulics Research Station, Wallingford, 60 pp. & figures.
- IMER, 1974. Report 1973-74. NERC Institute for Marine Environmental Research, Plymouth, 71 pp.
- IMER, 1975. Report 1974-75. NERC Institute for Marine Environmental Research, Plymouth, 85 pp.
- JONES, N.S., 1950. Marine bottom communities. Biol. Revs. 25: 283-313.
- JONES, S.R., 1974. Some results from Woodhead seabed drifter releases in the Western English Channel and Celtic Sea. Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft, (10), 21 pp.
- KENYON, N.H., 1970. Sand ribbons of European tidal seas. Mar. Geol., 9: 25-39.
- KENYON, N.H. and STRIDE, A.H., 1970. The tide-swept continental shelf sediments between the Shetland Isles and France. Sedimentology, 14: 159-173.
- KIFF, P.R. and NUNNY, R.S., in press. Bed sediment surveys. In "Report of the Liverpool Bay Working Group". Department of the Environment, London.
- KIRBY, R. and PARKER, W.R., 1973. Fluid mud in the Severn Estuary and Bristol Channel and its relevance to pollution studies. Ann. Symp. Inst. Chem. Eng., Graduates and Students Sect., Paper A4., 14 pp.
- KIRBY, R. and PARKER, W.R., 1977. Sediment dynamics in the Severn Estuary: background for the study of the effects of a barrage. pp. 41-52. In "An environmental Appraisal of the Severn Barrage" (ed.) Shaw, T.L. The University, Bristol, 41-52.
- KOMAR, P.D. and MILLER, M.D., 1975. On the comparison between the threshold of sediment motion under waves and unidirectional currents with a discussion of the practical evaluation of the threshold. J. sediment. Petrol., 45: 362-367.
- KOMAR, P.D., 1976. Boundary layer flow under steady, unidirectional currents. pp. 91-106. In 'Marine Sediment Transport and Environmental Management' (eds.) Stanley, D.J. and Swift, D.J.P., Wiley-Interscience, New York and London, 602 pp.
- LEE, A.J. 1965. Hydrographical observations in the Irish Sea. Fishery. Invest., Lond., Ser. II, 23 (2), 1-25.
- McCAYE, I.N., 1970. The deposition of fine-grained sediment from tidal currents. J. Geophys. Res., 75: 4151-4159.

- MURRAY, L.A. and NORTON, M.G., 1979. The composition of dredged spoils dumped at sea from England and Wales. Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft, (52), 10 pp.
- MURRAY, L.A., NORTON, M.G., NUNNY, R.S. and ROLFE, M.S., 1980. The field assessment of effects of dumping wastes at sea. 6: The disposal of sewage sludge and industrial waste off the River Humber. Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft, (55) 35 pp.
- NORTON, M.G. and ROLFE, M.S., 1978. The field assessment of effects of dumping wastes at sea. 1: An introduction. Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft, (45), 9 pp.
- OLAUSSEN, E., 1972. Water sediment exchange and recycling of pollutants through biogeochemical processes. pp. 158-161. In "Marine Pollution and sea life" (ed.) Ruivo, M. Fishing News (Books) West Byfleet and London, 624 pp.
- OLAUSSEN, E., 1975. Manual of methods in aquatic environmental research. I. Methods for the detection, measurement and monitoring of water pollution, Section 20. F.A.O. Fish. Tech. Pap., (137), 201.
- PETERSEN, C.G.J., 1913. Valuation of the sea. II. The animal communities of the sea bottom and their importance for marine zoogeography. Rep. Dan. biol. Stn., 21: 1-44.
- RILEY, J.D. and RAMSTER, J.W., 1972. Woodhead seabed drifter recoveries and the influence of human, tidal and wind factors. J. Cons. int. Explor. Mer., 34 (3), 389-415.
- RILEY, J.D. and ROLFE, M.S. (in preparation). Seabed drifter releases in the Bristol Channel. Fish. Res. Tech. Rep., MAFF Direct. Fish. Res., Lowestoft.
- ROHATGI, N. and CHEN, K.Y., 1975. Transport of trace metals by suspended particulates on mixing with seawater. J. Wat. Pollut. Control Fed., 47 (9), 2298-2316.
- SEVERN ESTUARY TECHNICAL WORKING PARTY, 1977. Severn Estuary survey and systems panel: first report to the Technical Working Party of the Severn Estuary Joint Committee, 136 pp. (Restricted circulation).
- SEVERN ESTUARY TECHNICAL WORKING PARTY, 1980. Second report of the systems and surveys panel of the Severn Estuary Technical Working Party. A: Inputs to the Severn Estuary, 22 pp. (Restricted circulation).
- STERNBERG, R.W., 1968. Friction factors in tidal channels with differing bed roughness. Mar. Geol., 61: 243-260.
- STONER, J.H., 1974. Trace element geochemistry of particulates and waters from the marine environment. Ph. D. thesis, University of Liverpool, 336 pp.
- TROMP, D., 1976. Aspects of the concentration of discharged noxious substances in the wake of a ship. IMCO Symposium on the prevention of pollution from ships. Acapulco, Mexico, 26 pp.
- WARWICK, R.M. and DAVIES, J.R., 1977. The distribution of sublittoral macrofauna communities in the Bristol Channel in relation to the substrate. Estuar. & Coast. Mar. Sci., 5: 267-288.
- WOODHEAD, P.M.J. and LEE, A.J., 1960. A new instrument for measuring residual currents near the sea bed. ICES CM 1960/12 Hydrogr. Comm. 6 pp. (mimeo).