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Sea Disposal: Modelling Studies of Waste Field Dilution

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Mathematical models have been set up to describe the dispersing plume formed when liquid effluent is discharged to a ship's wake and the susbequent dilution of the waste field after it has spread over the disposal area. Comparisons were made between the dilution obtainable at the disposal site off the River Tees with that at a site off the Humber. On the basis of the rather limited oceanographic data available, the models indicate that the waste would mix throughout depth more quickly at the Humber site than at the Tees but the shallowness of the water at the Humber would limit the rate of subsequent dilution. Within 48 h of the waste becoming spread over the disposal area, the dilution at the Humber ground was predicted to be 2.2×10^6 times; in the same period the waste discharged off the Tees would be 9.7×10^6 times dilution. Under the stratified conditions which can occur at the Tees disposal area in summer, the estimated dilution would be reduced to 3.7×10^6 times.

With steady and relatively weak residual currents, it was predicted that diluted effluent would not be completely cleared from either disposal area in the 2–3 days between successive discharges. However, the estimated dilution of the effluent in this interval is several orders higher than concentrations known to be toxic to sensitive marine species and stronger residual flows than those assumed are known to occur intermittently, so that significant build-up is unlikely and the waste would not have any long term adverse effects on marine life.

The seas around the British Isles may be regarded as a resource in that they provide rich fishing grounds and regions where strong tidal currents ensure that wastes are rapidly reduced in concentration. Particular concern has been expressed recently that undue harm may be being caused to fish stocks by the direct discharge from ships of sewage sludge and industrial effluents. To assess whether a particular disposal operation is having an adverse effect, studies have to be undertaken of the physical, chemical and biological features of the discharge area, taking into account the method of discharge and the load involved.

Currently by-product acid from the manufacture of methyl methacrylate is discharged to the North Sea in an approved disposal area some 16 km off the mouth of the River Tees. This waste is released into the wake of the disposal vessel, resulting in the formation of a diluting plume. To ensure that the effluent is widely spread, the ship traverses the disposal zone in a series of zigzag tracks so that, shortly after completion of the discharge operation, the plume has dispersed to form a patch of diluted waste of similar size to the disposal area. Subsequently, this patch is advected by the local currents and further diluted by turbulent mixing in the sea.

Various studies have been made of the initial dilution stage of discharge to the wake of a moving vessel (Tromp, 1976; Lewis, 1985; Byrne *et al.*, 1987), resulting in predictive formulae which can be used to assess the immediate impact of the waste discharge. On a much broader scale, models covering the southern North Sea have been used to predict the long term fate of pollutants resulting from estuary outflows and marine outfalls (van Pagee *et al.*, 1986). A major study of North Sea pollution which involves modelling and extensive field observations commenced in 1988 (Huthnance, 1987). However, to date very little attention has been paid to the intermediate scale dispersion of wastes (i.e. on a time scale of hours to days), processes which are particularly relevant to an assessment of the environmental impact of sea disposal operations.

This paper describes the development of mathematical models to simulate this intermediate scale dispersion and uses the results to assess the impact of the sea disposal operation off the Tees; comparisons are made between this disposal site and an alternative site off the Humber estuary.

Structure of the models

Model of the dispersing plume

The initial mixing of effluent with the sea in the wake of a discharging tanker is greatly aided by turbulence generated by the drag of the ship and the stirring of the propellor. Subsequent mixing is due to wind and tidally generated turbulence and, for a continuous discharge, the waste forms an expanding plume behind the ship.

Dilution of any element of this plume is caused by mixing transversely or vertically downwards but is not assisted by longitudinal mixing as that process mixes diluted waste with itself.

The first stage in the study was to develop a plume model which would describe the transverse and vertical mixing of an element of waste released at a particular time during the disposal operation. This model used the IMO formula (Tromp, 1976) to compute dilution in the immediate wake of a disposal vessel. For a single discharge orifice, the IMO formula indicates that the dilution, D_1, due to wake mixing is given by,

$$D_1 = \frac{0.0030\, U_v^{1.4} L^{1.6} t^{0.4}}{Q} \quad (1)$$

where U_v is the ship's speed (m s^{-1}),
L is the ship's length (m),
t is the time from discharge (s)
and Q is the volume discharge rate ($m^3\ s^{-1}$).

Subsequent to the wake mixing, the transverse and downwards spreading of the plume was described by a plume model with an assumed Gaussian distribution in the horizontal plane and a semi-bounded Gaussian distribution in the vertical. Thus, the dilution, D_2, along the plume axis is given by,

$$D_2 = \frac{\Pi\, S_y S_z}{Q\, U_v} \quad (2)$$

where S_y, S_z are the standard deviations of the concentration distributions across the plume and vertically downwards.

The standard deviations can be related to mixing coefficients, which include the effects of turbulent motions and the dispersive influence of current shear, by the expressions,

$$S_y^2 = 2K_y\, t \quad (3)$$

$$S_z^2 = 2K_z\, t \quad (4)$$

where K_y, K_z are transverse and vertical turbulent mixing coefficients
and t is the time after the wake dilution stage.
Vertical mixing is assumed to be complete (Pasquill & Smith, 1983, p. 328) when,

$$S_z = 0.8\, h \quad (5)$$

where h is the total depth.

To set up each plume model, details of the hydrographic characteristics of the study region are required at mesh points on a grid covering the area. The model tracks the movement of a plume element, using the stored values at the corners of the grid in which the element lies to derive interpolated values for the current and depth. These values are employed by the model to compute the movement and dilution of the element at a series of time steps from completion of the wake dilution stage. Values for the mixing coefficients are read in from separate computer data files. The model uses equation (1) to calculate the starting dilution and equations (2) to (4) to compute the dilution of the waste element at each time step thereafter. The output from the model shows the movement of the waste relative to the coastline and the corresponding dilution with time on a VDU display.

Random walk model of spreading patch

Once an individual disposal operation has been completed, the trail of diluted waste continues to expand and merges to form a spreading field (Fig. 1). For the second stage in the study a random walk model was set up to describe the advection and dispersion of this field. This model, which has the same data bases as the plume model, also allows for dilution by mixing of the waste along the direction of the mean flow. The starting size for the waste field was assumed to have a total area equal to that of the disposal zone. The starting depth of each field was assumed to be that to which the effluent would mix in 4 h, this period being the average time available for vertical mixing in an 8 h disposal operation.

The minimum dilution for the dispersing patch was determined by computing the consecutive positions of a cluster of particles as they move away from the disposal area. Each particle was assumed to be displaced by turbulence by an amount, D_j, in the time interval, dt,

$$D_j = (6K_j\, dt)^{0.5} R_j \quad (6)$$

where K_j are mixing coefficients in the x direction (east–west), the y direction (north–south) and the z direction (vertically downwards),
and R_j are random numbers in the range −1 to +1 (Webb, 1982).

If tidal and turbulent displacement take the particle outside the bounds of the model grid then it is lost to the calculation and the overall number of particles is reduced by one. This assumption is justified for discharges which are not close to the edge of the model (i.e. particles can only be taken out of the area by the residual drift current, not directly by the tidal current). If the displacement takes the particle onto the land, then the diffusion is recalculated with different random numbers since it is impossible for material to be diffused across the shoreline. Similarly, if the vertical diffusion step takes the particle above the water surface or below the seabed, then the diffusion is recalculated using a new random number.

The effect of shear in the direction of the mean flow was simulated by introducing a variation in the tidal and wind induced current using the following formula:

$$U = U_s\,(1-(z/h)^n) \quad (7)$$

where U is the tidal current at depth z down from the sea surface,

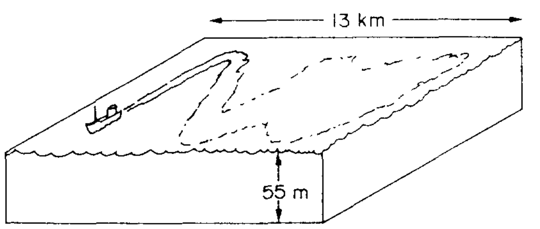

Fig. 1 Formation of a diluted waste field from the spreading wake plume.

U_s is the surface tidal current,
and n is a power coefficient determined from current measurements in the area.

Hydrographic characteristics of the disposal areas

The essential requirements for setting up a model are data on the local bathymetry, tidal currents, non-tidal residual drift and the mixing conditions. Bathymetric data for the Tees and Humber areas were derived from Admiralty Charts. Tidal current data were obtained from tidal stream records (Admiralty, 1975/1976). The principal data on the residual drift were derived from the MAFF recording current meter which was anchored in the disposal area over a twelve month period spanning 1978 and 1979 (S. R. Jones, pers. comm.). Additional estimates of the magnitude and variation of the residual drift were obtained from studies by MAFF (Durance & Jones, 1976; Medler, 1977), Institute of Oceanographic Sciences (Davies, A. M., 1983) and the ICI Brixham Laboratory (Lewis, 1984).

The selection of appropriate mixing coefficients depends on whether they are required for the small scale eddies involved in plume dispersion or for the large scale turbulence which controls the spreading of the overall waste patch. The most important hydrographic differences between the two disposal areas are the total depth and tidal current speeds; the Tees area has a mean depth of some 55 m compared with about 15 m off the Humber, and the tidal current amplitude on a spring tide has a magnitude of 0.5 m s^{-1} in the Tees area compared with 1.0 m s^{-1} off the Humber. Stratification developing at a depth of 10 to 15 m has been reported to occur in summer to the north of Flamborough Head (Ramster, 1977) and density measurements on 11 July, 1984 confirmed the presence of such layering within the Tees disposal area (Fig. 2).

On the basis of dye dispersion experiments at a variety of coastal sites (Talbot & Talbot, 1974; Bowden & Lewis, 1973), the following approximate relationship was established for the small scale mixing:

$$K_y = A.U_m^2 \tag{8}$$

where K_y is the coefficient of mixing across the mean current
A is a constant of proportionality, value 1.4 s
and U_m is the peak depth mean tidal current speed.

To estimate the larger scale horizontal mixing coefficients in the Tees and Humber disposal areas, use was made of the four-thirds power law relation between dispersion coefficients and eddy scale (Okubo, 1971). Okubo showed that many of the large scale dye tracing experiments undertaken in the North Sea under exercise RHENO supported the four-thirds law. The size of the Tees disposal area is appreciably greater than that at the Humber (Table 1) and on the basis of Okubo's definition of length scale, l, values for l were estimated to be 15.5 and 8.4 km for the Tees and Humber disposal areas respectively. From the four-thirds law, the corresponding horizontal mixing coefficients were estimated to be 16.0 and 6.0 $m^2 s^{-1}$.

Values for the vertical mixing coefficients were derived from the results of various dye experiments in the North Sea (Talbot & Talbot, 1974). Typical values under mixed conditions appear to be about 0.0020 $m^2 s^{-1}$ and this rate was assumed for both the Tees and Humber areas. In practice, the strong tidal flows off the Humber are likely to result in a higher mixing rate than this.

A summary of the mixing coefficients used in the plume and patch models is given in Table 2.

Results

Predictions of the plume dispersal stage

For the disposal of by-product waste from the manufacture of methyl methacrylate, a particular vessel, volume discharge rate and speed are employed (Table

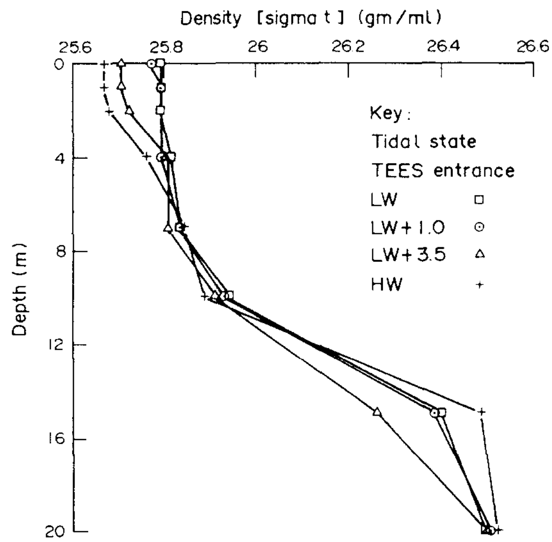

Fig. 2 Vertical density structure in the Tees disposal area, 11 July, 1984.

TABLE 1
Approximate dimensions of disposal area.

	East–West (km)	North–South (km)	Depth (m)
Tees	13	13	55
Humber	5.4	9.2	15

TABLE 2
Mixing coefficients assumed in modelling studies.

	Tees	Humber
	($m^2 s^{-1}$)	
Small scale mixing coefficients		
Vertical (homogeneous conditions)	0.0020	0.0020
Horizontal	0.3500	1.4000
Large scale mixing coefficients		
Vertical (homogeneous conditions)	0.0020	0.0020
Horizontal	16.0000	6.0000
Shear rate, n,	4.0	

TABLE 3
Discharge conditions for methyl methacrylate by-product waste disposal operation.

Total discharge in one disposal operation (t)	1000
Effluent discharge rate (t h^{-1})	120
Effluent density (kg m^{-3})	1400
Length of vessel (M.V. *Yarrow*) (m)	65
Speed during discharge (m s^{-1})	4.0

3). It has been estimated from experimental studies (Delvigne, 1983) that the wake energy due to the ship is sufficiently dissipated for the energy of natural turbulence to dominate dilution some 12 min. after discharge. Considering the first 12 min. after discharge, the IMO formula for wake mixing predicts that a dilution of 9600 times is achievable in this time. Recent studies suggest that the IMO formula provides a rather conservative estimate of the dilution obtainable in the wake (Byrne *et al.,* 1987). The plume model assumes that there are no interactions with waste discharged earlier and, therefore, the model ceases to be valid when the ship's track crosses the diluting plume formed on the previous traverse of the disposal area. It is estimated that no interactions are likely to occur over at least the first hour of dispersion and this period was used to compute the dilution change along the axis of the discharge plume. Values for the plume dilutions attained in this time in the Tees and Humber areas are given in Table 4. These results show that over the first hour after discharge the surface dilution at the Humber was predicted to be approximately double that at the Tees disposal ground.

However, the near-bed dilution at the Humber indicates that the waste was beginning to become mixed to the seabed because the waters are so shallow; once mixed through depth further dilution would depend on horizontal mixing alone. At this stage of the dilution process, vertical mixing is still a significant factor at the Tees disposal area.

Predictions of the patch dispersal stage

As stated earlier, by the end of an 8 h disposal operation, the mean time for mixing would be 4 h. Using the vertical diffusion coefficient of 0.0020 $m^2\ s^{-1}$ (Table 2), the estimated mean field depth was calculated to be 15 m. This is the approximate depth of the thermocline which develops in summer at the Tees area and equals the average water depth at the Humber.

The random walk model was run to simulate the movement and dilution of the waste field over a period of 5 days under well mixed conditions at each of the disposal areas. Figure 3 shows the displacement and spread of particles released at the Tees disposal area after 2, 3, and 5 days. The results of these runs are shown as plots in Fig. 4. Table 4 gives dilution estimates at the start of the formation of the waste field and after 48 h.

Effect of stratification

The plume and patch models were also run to show the effect of the summer stratification at the Tees area on plume and patch mixing. Predicted dilutions at the surface and immediately above the density interface are shown in Table 4. The change in surface concentration of the patch at the Tees under stratified conditions is also plotted in Fig. 4.

Discussion

Studies of the toxicity of methyl methacrylate by-

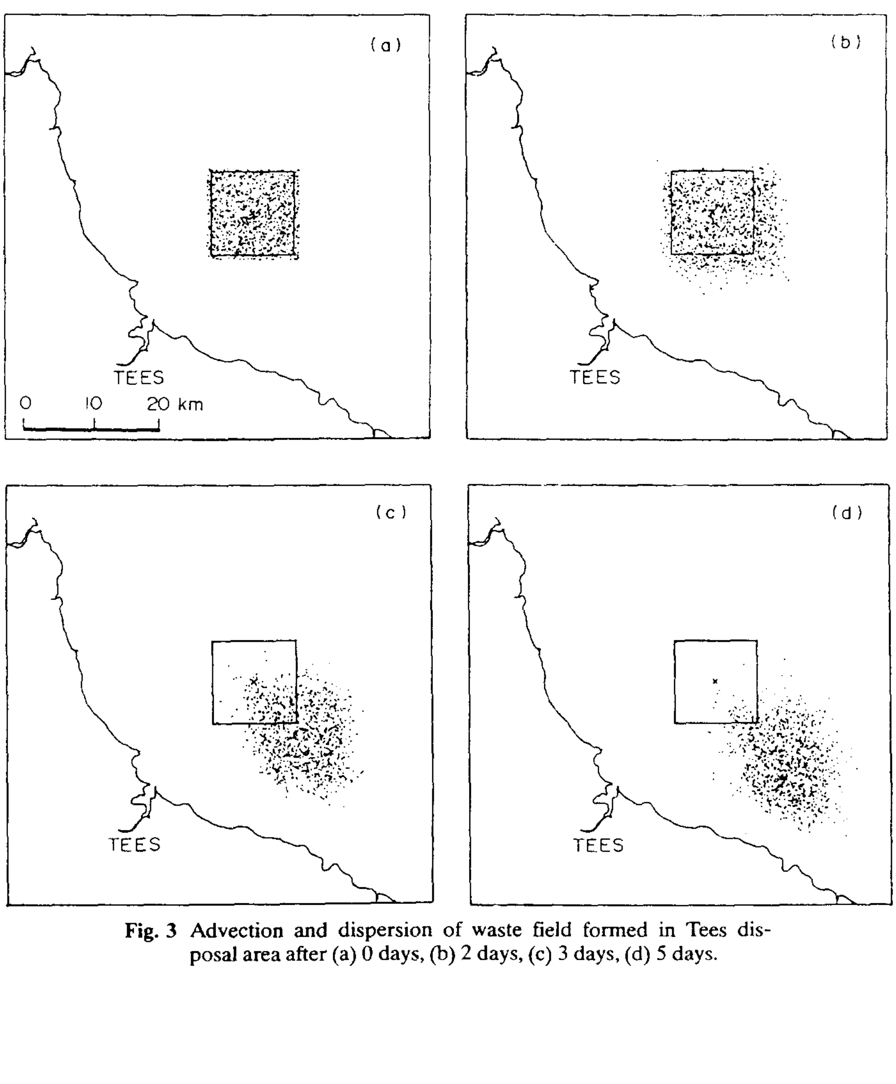

Fig. 3 Advection and dispersion of waste field formed in Tees disposal area after (a) 0 days, (b) 2 days, (c) 3 days, (d) 5 days.

product acid to zooplankton indicate that a dilution of 1.5×10^4 would render the waste safe for an exposure period of 48 h. As can be seen from Table 4, the effluent would be diluted well above this level within the first hour after discharge at the Tees or Humber areas. Thus, apart from species exposed to the acidic effluent in the immediate wake of the vessel, acutely toxic effects to marine life are unlikely to occur.

The relative merits of the Tees and Humber disposal areas were assessed using the plume and random walk model predictions. Once the waste had become spread over the disposal area, corresponding to time, $t=0$ in the patch stage, the minimum dilution off the Humber was estimated to be about one-third that off the Tees. As can be seen from Fig. 3, the dilution in the Tees area was predicted to increase much more rapidly than at the Humber and after 48 h the Tees dilution reaches 9.7×10^6 times whilst the Humber is 2.2×10^6. Under stratified conditions at the Tees disposal area, vertical mixing is limited and after 48 h there would be only a marginal increase on the starting dilution of 3.6×10^6 times. Thus, the Tees disposal area generally offers more favourable conditions for diluting waste than the Humber area; however, this advantage would be far smaller under the stratified conditions which have been observed to occur in summer.

It should be noted that the above predictions apply

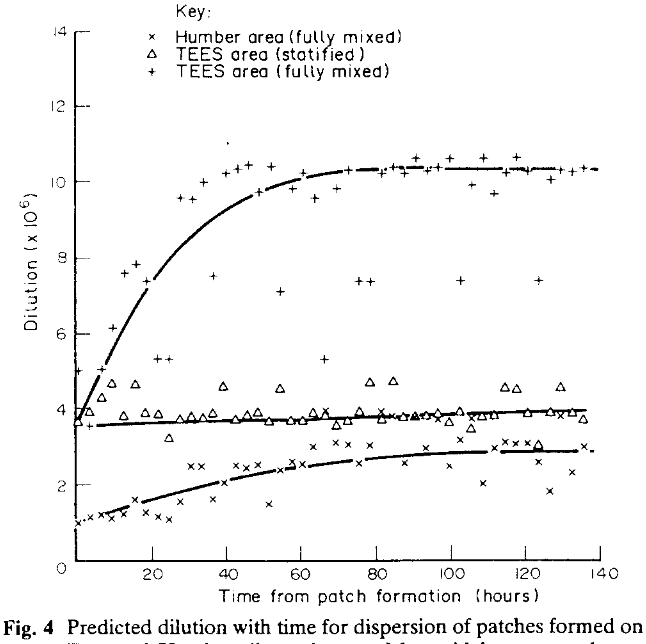

Fig. 4 Predicted dilution with time for dispersion of patches formed on Tees and Humber disposal areas. Mean tidal ranges and zero wind stress assumed.

TABLE 4
Predicted dilutions at different stages of dispersion.

		Plume		Patch	
Dispersion time (h)		0.1	1.0	0	48
Tees area					
Homogenous	Surface	9.6×10^3	2.1×10^5	3.6×10^6	9.7×10^6
	Seabed	inf	inf	inf	4.4×10^7
Stratified	Surface	9.6×10^3	2.1×10^5	3.6×10^6	3.7×10^6
(15 m)	Above interface	inf	1.4×10^8	3.6×10^6	3.7×10^6
Humber area					
Homogenous	Surface	9.6×10^3	4.3×10^5	1.0×10^6	2.2×10^6
	Seabed	inf	4.7×10^8	1.0×10^6	2.2×10^6

to the existing licensed areas. If the Humber disposal area were made equal to that at the Tees, the patch model would predict similar dilutions at the Humber and at the Tees under stratified conditions. This conclusion rests on the assumptions that the depth of the density interface at the Tees is similar to the mean depth at the Humber and that the mixing coefficients would increase with scale according to the four-thirds law. In practice, the stronger currents at the Humber could make the rate of dilution of the waste field exceed that at the Tees disposal area.

The model was also used to assess the possibility that a concentration build-up could occur in each disposal area due to the superimposition of wastes from successive disposal operations. In the Tees and Humber areas, the usual time between successive discharges of 2–3 days may be insufficient for either area to be completely clear of waste before the next discharge (Fig. 3). This suggestion rests on the assumed values of 0.04 and 0.05 m s^{-1} for the residual flow through the Tees and Humber disposal regions respectively. The results of long term recording current meter observations indicate that residual currents along the east coast of England display a considerable variation. Measurements to the north of Flamborough Head and in the Tees disposal area have revealed a marked difference between summer and winter flows (Ramster, 1977). In winter there appears to be a clockwise gyral, which follows the same pattern at all depths, whereas in summer, a two layer system develops with a tendency for the surface waters to move offshore, countering a near-bed shorewards drift. Overall, the strength of the residual current shows a considerable variability and other observations suggest that the longshore flow intermittently strengthens and reverses direction (Lewis, 1984). It seems, therefore, that the chances of waste being introduced into a disposal area which already contains materials from an earlier disposal operation are relatively small. Even if this situation were to arise, the predictions indicate that the waste from the previous discharge would have been well diluted, so that chronic effects on plankton, fish and benthic fauna would be unlikely.

Conclusions

The modelling study of the dispersion of wastes discharged to the wake of a moving ship suggested that:

1. Waste would dilute more rapidly during the first hour after release in the Humber disposal area than in the Tees area due to the vigorous turbulence generated by the strong tidal currents in the former region. The shallowness of the Humber site would, however, limit the rate of subsequent dilution whereas dilution by vertical mixing in the Tees area would not be so restricted.

2. Under homogeneous conditions, the rate of dilution of the overall waste field formed at the Tees site would be markedly faster than that for the Humber and after 48 h the predicted dilution at the Tees would be at least 9.7×10^6 times as compared with 2.2×10^6 at the Humber. However, under the stratified conditions which are known to occur in the Tees disposal area in summer, the rate of dilution would be much slower and the dilution attained after 48 h would be 3.7×10^6 times. This is still appreciably greater than the dilution achievable in the same time in the same smaller disposal area off the Humber.

3. If the residual drift along the coast is steady and small, it is predicted that the usual time between successive discharges of 2–3 days would be insufficient for either the Tees or Humber areas to be completely cleared of waste before the next discharge. However, the known variability of the residual flows along the east coast of England and the high dilutions predicted by the models suggest that concentrations would not build up to levels which would cause chronically toxic effects to the marine life.

Admiralty. (1975/76). Tidal stream atlas: North Sea–Northern portion NP 252 & Southern portion NP 251.
Bowden, K. F. & Lewis, R. E. (1973). Dispersion in flow from a continuous source at sea. *Water Res.* **7**, 1705–1722.
Byrne, C. D., Law, R. J., Hudson, P. M., Thain, J. E. & Fileman, T. W. (1989). Measurements of the dispersion of liquid industrial waste discharged into the wake of a dumping vessel off the River Tees. *Water Res.* (In press.)
Davies, A. M. (1983). In *Flushing times of the North Sea.* ICES 1983/CRR: 123.
Delvigne, G. A. L. (1987). Experiments on the dilution capacity of wakes from dumping tankers in the North Sea. In *Oceanic Processes in Marine Pollution,* Vol. 2 (T. P. O'Connor, W. V. Burt & I. W. Duedall, eds), pp. 000–000. Robert E. Krieger Publishing Co., Malabar, Florida.
Durance, J. A. & Jones, S. R. (1976). Spatial variability of residual drift off the east coast of England in 1975. ICES CM 1976/C:3.
Huthnance, J. (1987). NERC North Sea Project. NERC News, October, 1987.
Lewis, R. E. (1985). Dilution of waste in the wake of a ship. *Water Res.* **18**, 941–945.
Lewis, R. E. (1984). Circulation and mixing in estuary outflows. *Cont. Shelf Res.* **3**, 201–214.
Medler, K. J. (1977). Residual drift regimes in the west central North Sea during JONSDAP 76. ICES 1977/C:5.
Okubo, A. (1971). Oceanic diffusion diagrams. *Deep Sea Res.* **18**, 789–802.
Pasquill, F. & Smith, F. B. (1983). *Atmospheric Diffusion.* Third edition. Ellis Horwood Ltd., Chichester.
Ramster, J. W. (1977). Residual drift regimes off the north-east coast of England. ICES CM 1977/C:8.
Talbot, J. W. & Talbot, G. A. (1974). Diffusion in shallow seas and in English coastal and estuarine waters. *Rapp. P.-v. Réun. Cons. int. Explor. Mer.* **167**, 93–110.
van Pagee, J. A., Gerritsen, H. & de Ruijter, W. P. M. (1986). Transport and water quality modelling in the southern North Sea in relation to coastal pollution research and control. *Water Sci. Tech.* **18**, 245–256.
Webb, A. J. (1982). A random walk model of the dispersion of caesium-137 in the Irish Sea. M.Sc. thesis. University of Wales.

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An Analytical Method for Butyltin Species in Shellfish

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A method for analysing tributyltin (TBT) and dibutyltin (DBT) in shellfish is presented that places modest requirements on equipment and supplies. It is based on capillary gas chromatographic analysis of hexyl derivatives of any extractable organotin species present. Two internal standards are used. Data are presented showing that the precision and accuracy of the method are generally better than ±20%.

Tributyltin (TBT) containing marine antifoulants have seen widespread use for over 20 years. Concern about the adverse effects on marine life of TBT leaching from treated surfaces has resulted in strict controls of its use in France, the United Kingdom, the United States, and other jurisidictions (see Champ & Pugh, 1987; Waldock *et al.,* 1987a; Clark *et al.,* 1988). Current concern about the adverse effects of TBT on shellfish began with the identification of TBT-leachate from antifouling paints as being responsible for the collapse of the oyster fishery around Arcachon, France in 1980 (see Alzieu, 1986). It is now recognized that water concentrations of TBT in the 10–50 ng l^{-1} range can exert lethal and sublethal effects on a wide variety of marine organisms particularly for the case of sensitive juvenile life forms (Waldock *et al.,* 1987b; Cardwell & Sheldon, 1986).

Microbial degradation is probably the dominant process for the breakdown of TBT in nearshore waters (Seligman *et al.,* 1986; Lee *et al.,* 1987) with dibutyltin (DBT) the major degradation product (Lee *et al.,* 1987). While DBT appears to be at least an order of magnitude less toxic to marine animals (Laughlin & Linden, 1985; Thain *et al.,* 1987), its widespread use as a stabiliser for PVC plastics (Blunden *et al.,* 1985) and its relationship to TBT as a degradation product makes