Residual circulation in the Bristol Channel, as suggested by Woodhead sea-bed drifter recovery patterns

Bristol Channel
Sea-bed drifter
Water circulation
Numerical model
Sediment transport

Canal de Bristol
Flotteur dérivant
Circulation
Modèle numérique
Transport de sédiment

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ABSTRACT

Woodhead sea-bed drifters were released from 11 stations in the Bristol Channel. Recoveries ranged between 51 and 68% of those released at each station. Drifter transport paths are inferred on the basis of geographical recoveries and elapsed times. The suggested near-bed residual water circulation pattern represents seaward and landward transport in mid-channel and along the coastal zones, respectively; it is consistent with numerically predicted frictionally-driven tidal current residuals. Landward transport of water in the coastal zone of the Bristol Channel provides a possible explanation for upstream transfer of fine-grained sediments. Such a mechanism might be more generally applicable to other estuarine systems.

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RÉSUMÉ

Circulation résiduelle sur le fond du canal de Bristol d'après les flotteurs dérivants de Woodhead

Des flotteurs dérivants de Woodhead, largués en 11 stations dans le canal de Bristol, ont été récupérés dans une proportion de 51 à 68%. Leurs trajectoires sont déduites des coordonnées géographiques à la récupération ainsi que des durées de dérive. Le modèle suggéré de circulation résiduelle de l'eau au voisinage du fond représente le transport vers le large et vers la terre au milieu du canal et le long des zones côtières, respectivement; il est en accord avec la prévision numérique des courants résiduels dus au frottement de la marée. Le transport d'eau vers la terre dans la zone côtière du canal de Bristol pourrait expliquer le transport vers l'amont des sédiments fins. Ce mécanisme s'appliquerait plus généralement à d'autres systèmes estuariens.

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INTRODUCTION

Residual water movements in the Bristol Channel are caused by the complex interaction of currents generated by tides, density gradients, windstress and waves. Such movements have been investigated using temperature, salinity and chemical data (Hamilton, 1973; Abdullah *et al.*, 1973; IMER, 1974), sea-bed drifter releases from a sludge dumping ground (Murray *et al.*, 1980) or numerical models. Subsequent comparisons have been made between predictions from the models and hydrographic observations (Owen, 1980; Uncles, 1982). Analyses of individual contributions to the Eulerian residual current have been carried out, from a qualitative standpoint, and have demonstrated the relative magnitudes of currents due to density gradients, non-linear advection, friction and continuity (Uncles, *op. cit.*).

This investigation deduces bottom residual water circulation in the Bristol Channel, based upon the recovery patterns from sea-bed (Woodhead) drifter releases. The Woodhead drifter (Woodhead, Lee, 1960) has been used extensively to interpret the near-bed movements of waters and sediments in continental shelf, coastal and estuarine environments (Robinson, 1964;

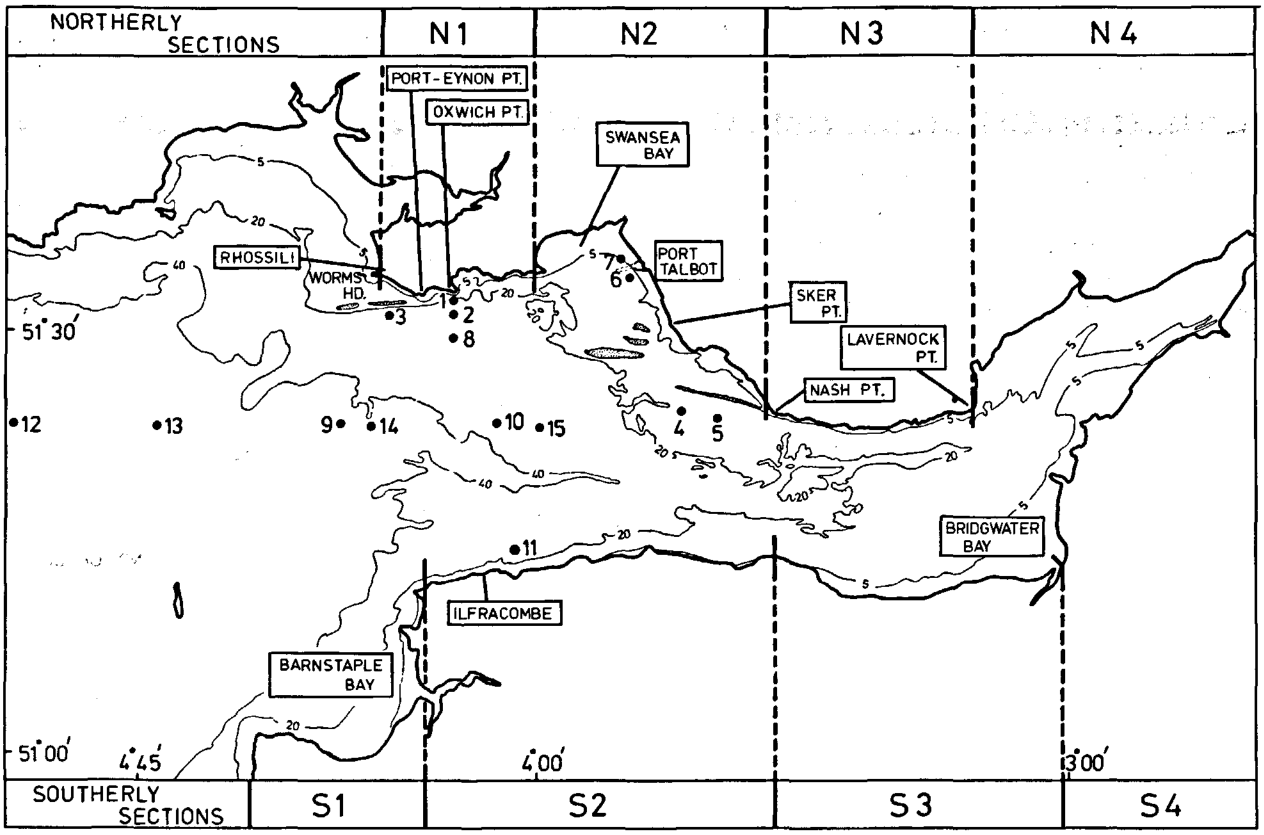

Figure 1

The study area showing locations referred to in the text. Stations 1 to 15 represent the sea-bed drifter release positions. The division of the northerly and southerly coastlines into Sections (N_1 to N_4 and S_1 to S_4, respectively) is to simplify the discussion of drifter recovery patterns. Bathymetry is in metres; stippled areas represent sandbanks.

Ramster, 1965; Morse *et al.*, 1968; Harvey, 1968; Phillips, 1968; Gross *et al.*, 1969; Halliwell, 1973; Robinson, 1973; Jones, 1974; Bartolini, Pranzini, 1977; Ramster, Jones, 1978; Murrey *et al.*, 1980). The Woodhead drifter is obtainable from Nields Patents Ltd., Penarth Road, Cardiff, Wales, UK.

Drifters were released in November 1976 and October/November 1977 at 11 stations in the Bristol Channel. Of these, 1 000 were released at stations along the northern coastline of the Channel, between Worms Head and Nash Point (stations 1 to 7, Fig. 1). In this area, detailed sedimentological and hydrographical investigations have been undertaken (Ferentinos, Collins, 1978; Collins *et al.*, 1979; Collins *et al.*, 1980; Collins, Banner, 1980) providing an extensive data base for the meaningful interpretation of the recovery patterns. A further 350 drifters were released at stations along a N-S cross channel transect from Oxwich Point to Ilfracombe (stations 8, 10 and 11, Fig. 1) and at a more westerly central Channel station (station 9). Of late, predictions and measurements of currents in the vicinity of these releases have become available (Uncles, 1982).

Short-term and long-term recovery patterns from the drifter releases are described in this contribution and discussed within the context of a suggested near-bed residual water circulation pattern for the Bristol Channel. The pattern is considered with reference to: 1) currents predicted from numerical models; and 2) its significance in relation to sediment transport paths.

METHODS AND ANALYSIS

The Woodhead drifters used were weighted with 7 gm of copper tubing at their lower end. A similar weighting was used on drifters used to determine the near-bed residual drift in Liverpool Bay (Halliwell, 1973) and should result in drifter speeds being near to those at the waters, for currents >17 cm/sec. (Woodhead, Lee, 1960).

Details of the releases at the various stations, using R. V. *Ocean Crest*, are listed in the Table. In general, between 60 and 200 drifters were released at each of the stations. At stations 6 and 7, however, batches of 50 drifters were released on ebb and flood phases of neap and spring tides. The release positions were to the north and south of the dredged approach channel to Port Talbot Harbour (Fig. 1), and were made to investigate its effect on near-bed movement. Recovery patterns from these releases have been discussed elsewhere (Ferentinos, Collins, 1978) and are summarised in the Table and in subsequent discussions.

Recoveries are reported in terms of both short-term (as of 1 July 1978) and long-term (1 June 1982) patterns; these correspond with times since release of approximately 600 days and 2 000 days, respectively.

In order to simplify the presentation and interpretation of temporal and spatial variability in drifter recovery patterns, the northern and southern coastlines of the Channel are described in terms of sections, N_1 to N_4

and S_1 to S_4 (Fig. 1). The adoption of this procedure and various other methods of data presentation are used to both clarify and enhance recovery information. Hence, Figure 2 represents temporal variability in recovery from stations 1 to 5 from the various sections of the Channel, at the same time scale. Figure 3 presents the locations of the long-term recoveries. Figure 4 summarises the overall recoveries from stations 6 and 7 within section N_2; and, finally, Figure 5 divides recoveries from stations 8 to 11 into various time increments (0-100 days, 100-300 days, and >300 days) and sections.

RESULTS

Station locations are shown in Figure 1. Stations 1 to 11 relate to the present investigation. Stations 12, 13, 14 and 15 are release points for similar studies carried out by MAFF (Ministry of Agriculture, Fisheries and Food), whose results are used in the final overall interpretation.

The percentage of the drifters returned from each of the releases in the present investigation is high (51 to 68 %, *see* Table), also the recovery time considered is much longer than in most exercises. Such an overall recovery can be compared with rates of 18 to 34 % for the Irish Sea (Harvey, 1968), 26 to 48 % for the northern coastline of England (Ramster, Jones, 1978), 25 % for the western English Channel and Celtic Sea (Jones, 1974), 36 % for Morecambe Bay (Phillips, 1968), 52 % for the Humber Estuary (Robinson, 1964), and 18 to 26 % (stations 12 to 14) and 32 to 53 % (station 15) for the MAFF investigations in the Bristol Channel.

The main areas of drifter recovery were Swansea Bay, in the short-term, and Bridgwater Bay in both the short- and long-term.

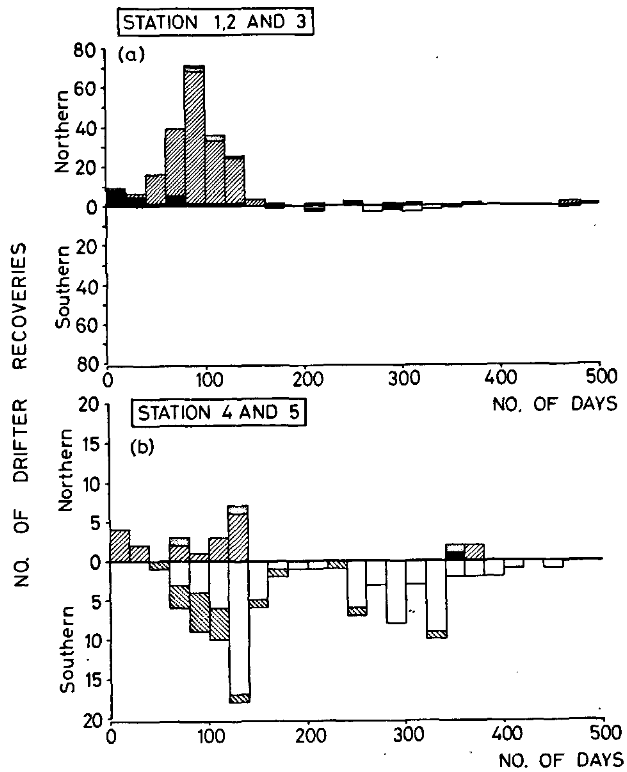

Figure 2

Drifter recoveries, against time, for releases from stations 1, 2 and 3 [Fig. 2 (a)] and from stations 4 and 5 [Fig. 2 (b)]. Key: ▬ *Section* N_1; ▨ *Section* N_2; ▩ *Section* N_3; ▥ *Section* N_4; ▭ *Section* S_3; ▧ *Section* S_4.

Table

Summary of sea-bed drifter returns, November 1976-May 1982.

Station	Date of release	No. of drifters released	% returned: Short-term (July, 1978)	% returned: Long-term (June, 1982)
1	17 November 1976	100	65	68
2	17 November 1976	100	64	67
3	17 November 1976	200	50	56
4	3 November 1976	100	61	68
5	3 November 1976	100		
6*	14 November 1976 and	400*	48	51
7*	23 November 1976			
		1,000		
8	19 October 1977	86	32	55
9	19 October 1977	92	21	55
10	19 October 1977	83	9	60
11	21 November 1977	66	28	58
		347		

* *See* Ferentinos and Collins (1978) for details of releases, between flood and ebb phases of neaps and springs.
Note: stations 12 to 15 are MAFF release positions; recoveries from these are referred to in the text.

Stations 1, 2 and 3

The short-term recovery patterns from the three stations, representing the western portion of the northern coastline, are relatively similar (Fig. 2*a*). The figure summarises all drifter recoveries in relation to coastal sections (N_1, N_2, N_3, N_4, S_3 and S_4), apart from 3 releases from Station 1 which went to the west.

The pattern illustrated reflects an immediate and high recovery rate within N_1, which decreases with time. This is followed by a large and normally-distributed recovery within N_2 with an optimum at between 80 to 100 days. After approximately 300 days, there is a minor peak in recoveries in S_3.

Most of the drifters recovered from these stations were returned within the first 4 months after release, *i.e.*, 60, 51 and 50% from stations 1, 2 and 3, respectively. The time lapse between release and recovery from the stations is, in general, proportional to distance. Hence, recoveries were earlier along the more westerly stretches of coastline. Long-term drifter recoveries are indicative of an accumulation within Bridgwater Bay (Fig. 3).

Stations 4 and 5

The short-term recovery patterns from stations 4 and 5 differ from stations 1, 2 and 3 in that many more recoveries are associated with the southern coastline (Fig. 2). Recoveries along the northern coastline are concentrated within N_2 and N_3, with both an initial peak within the first 20 days, another after 120 to 140 days and a final peak in recovery between 340 to 360 days. Along the southern coastline, recoveries are strongly bimodal within S_3; here, the maxima occur after 300 to 320 days respectively, *i.e.*, there is an approximate 200 day delay between initial and secondary recoveries. Hence, the net movement of the majority of the drifters (71% of the total) was towards the east; the remainder (29%) were recovered between Sker Point and Nash Point (Fig. 1).

Long-term recovery patterns (Fig. 3) are indicative of accumulation within Bridgwater Bay; they also show two drifters recovered from Croyde Bay, to the north of Barnstaple Bay after a time-period in excess of 600 days.

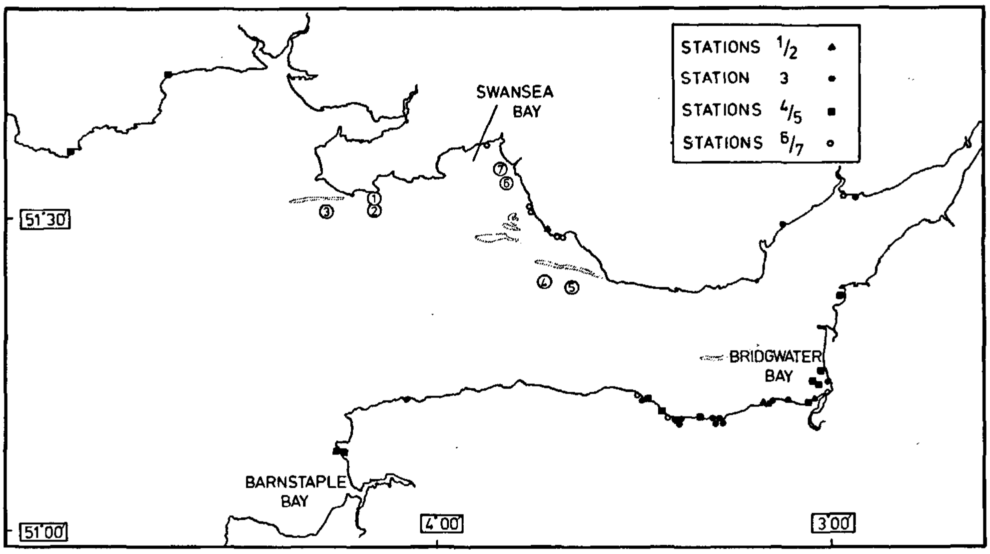

Figure 3
Long-term (>600 days) drifter recoveries. Key to recoveries (see inset). ▲ Stations 1/2; ● Station 3; ■ Stations 4/5; ○ Stations 6/7. Station locations are repeated from Figure 1.

In terms of releases from each of the stations, the initial net easterly movement can be summarised, as an overall percentage return, as follows:

Station 1: 14% from between Oxwich Point and Mumbles, 27% from Swansea Bay and 54% from between Port Talbot and Nash Point.

Station 2: 20% from Swansea Bay, 67% from Port Talbot to Nash Point.

Station 3: 88% from between Swansea and Port Talbot, 12% between Rhossili and Port Eynon Point.

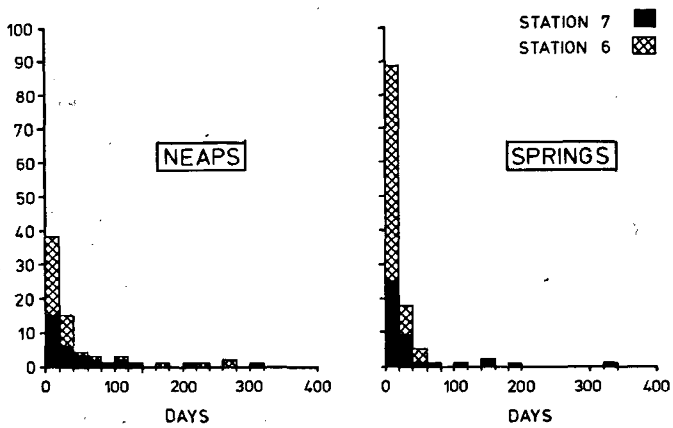

Figure 4
Number of drifter recoveries at stations 6 and 7, with time.

Stations 6 and 7

Recovery patterns from releases at these stations have been described in detail elsewhere (Ferentinos, Collins, 1978). Within the context of the present investigation, it is of interest to note that: 1) all recoveries took place within section N_1, with the majority coming ashore within the first 25 days after release; 2) transport was both to the northwest and southeast from releases at both stations, with the highest overall recovery after spring tides (Fig. 4).

Most of the long-term recoveries were still from within N_1 (Fig. 3), but with some up-channel beachings.

Stations 8, 9, 10 and 11

Station 8 is close against the northern coastline and station 11 is within 5 km of the southern coastline: stations 9 and 10 are approximately mid-channel, with station 9 further to the west (Fig. 1). Recoveries from all stations are summarised in Figure 5.

The recovery patterns from station 8 show high initial recoveries within sections N_1 and N_2, with the majority within N_2. The recovery rates decrease gradually with time. After 100 to 300 days, drifters were returned from sections S_3 and, after >300 days, from S_2 and S_3.

Recoveries from stations 9 and 10 are essentially similar, but with early recoveries on the northern coastline within section N_2 for station 9 and N_1 for station 10. The peaks in recovery along these sections of the coastline occur between 100 to 300 days (Fig. 5). Recoveries from the southern coastline are concentrated within section S_3, for time periods in excess of 100 days, but also are found within S_2 and S_4 (station 10). It is of interest to note that an individual drifter from station 9 was recovered from Hells Mouth, Rhiw, North Wales on 25 May 1979; similarly, a single recovery from station 10 was from Morecambe Bay on 5 October 1980. No evidence is available to suggest that transport to these extreme locations was other than by natural processes.

Drifter recoveries from station 11 show some concentration in section N_2 within the first 300 days. Other

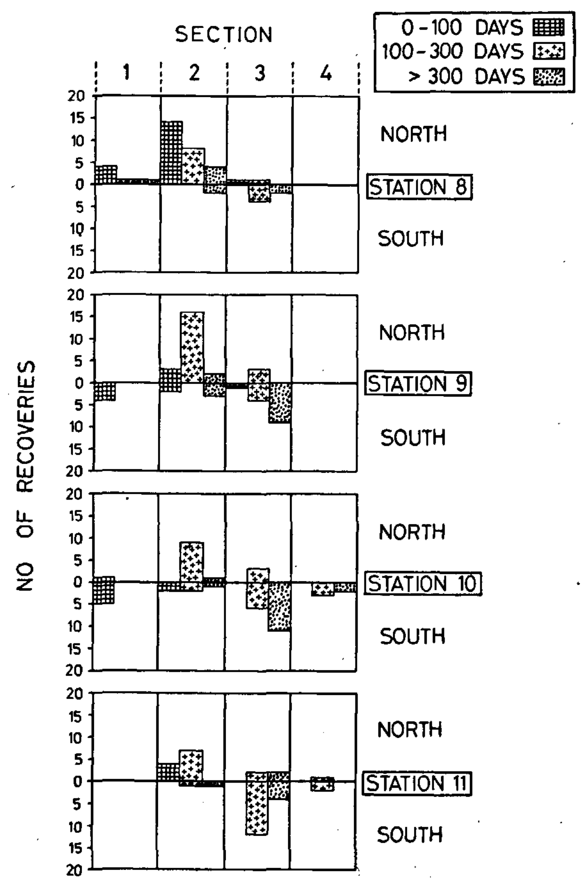

Figure 5

Drifter recoveries from stations 8, 9, 10 and 11 within various time intervals after release: 0 to 100 days; 100 to 300 days; and >300 days.

recoveries took place in N_3 and N_4 after periods in excess of 100 days. Similarly, recoveries in S_2, S_3 and S_4 occurred after 100 days had elapsed.

INTERPRETATION OF RECOVERY PATTERNS

Drifter recovery patterns are used to interpret net drift or "residual water circulation" patterns. Within the Bristol Channel, such patterns are induced by the complex superimposition of currents generated by density differences, tides, winds and waves. Irrespective, for the time being, of the dominant mechanism, a conjectural drift pattern for the Bristol Channel is presented as Figure 6. The method of presentation is a compromise between inferred "direct" and "indirect" paths, based upon the recovery times of the various drifter sets. The basic assumption made in comparing results from releases in various parts of the network in different years is that, with the relatively long periods of recapture being considered, short period variability in regime, associated with the time of release, will have been filtered out.

The paths indicated by (A) represent release and recovery from stations 1, 2 and 3. In particular, one branch of the path indicates transfer in a clockwise direction around the Helwick Sands (*see* also Britton, 1977). The main path progresses eastwards along the south Gower coastline, then into Swansea Bay and towards Southeast *via* Hutchwns Point to Nash Point. Cross-channel transfer is then indicated to Bridgwater Bay, with a recovery time difference of approx. 100 days between the northern and southern coastlines of the Channel (*see* also Fig. 2, Parker, Kirby, 1982).

Paths (B) represent release and recovery from stations 4 and 5 to the south of the Nash Sands. Once again, clockwise transfer around the sandbank is indicated by early recoveries (<40 days); this circulation pattern (*see* also Ferentinos, Collins, 1979 and 1980) has been modelled recently, in terms of Eulerian residual tidal currents (Owen, 1980, Fig. 8). A subsidiary downstream transport path, with subsequent transfer to the coastline between Hutchwns and Nash Points, is indicated by the later arrivals over this section (60-140 days). A similar recovery period appears to represent direct cross-channel transfer into Bridgwater Bay, with movement both to the west (S_3) and east (S_4). Bimodality in the recovery times in Bridgwater Bay indicates also downstream transport and subsequent upstream recovery (after 240 to 400 days). Long-term recovery path (B) is important in that it demonstrates considerable downstream transport, prior to recovery along the northern coastline of Barnstaple Bay.

Path (C) is limited in its extent and represents release from stations 6 and 7 in an area of low currents and tidal current divergence to the north and south (Collins *et al.*, 1979): the immediate (5 day) recovery of drifters from releases here indicate the importance of wave-action in onshore transport. The long-term recovery patterns demonstrate that the current system here is semi-enclosed and that drifters only rarely find their way to other stretches of the coastline.

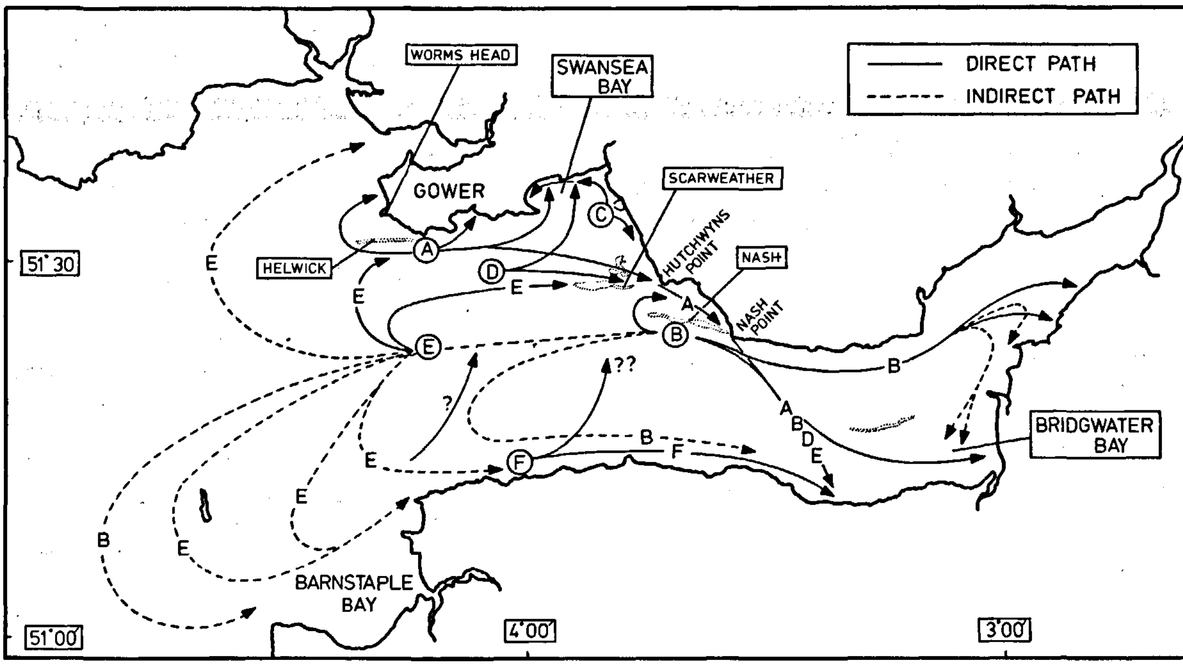

Figure 6

Residual water movement as indicated by the interpretation of drifter recovery patterns. Key: path A, release and recovery from stations 1, 2 *and* 3; *path B, from stations* 4 *and* 5; *path C, from stations* 6 *and* 7; *path D, from station* 8; *path E, from stations* 9 *and* 10 (*note: path* E_1, *derived partly from MAFF releases*); *path E, from station* 11.

Path (D) represents release and recovery from station 8, just offshore from stations 1, 2 and 3. Transport paths are similar to the easterly portion of Path (A).

Path (E) represents stations 9 and 10 and shows both direct transfer to the northerly coastline and then across to Bridgwater Bay. Significantly, recoveries in Barnstaple Bay and along the central southern coastline indicate downstream mid-channel transfer and subsequent upstream coastal transport. Mid-channel releases by MAFF, at stations 12, 13, 14 and 15 (Fig. 1) have not yet been published in full apart from a summary diagram relating to recoveries in Swansea and Bridgwater Bays from releases from station 15 (Murray *et al.*, 1980; Fig. 9; *see* below). However, data kindly made available to the authors indicate: 1) early and long-term recoveries from all stations at sites along the northern coastline, in Carmarthen Bay and to the East as far as Nash Point (Murray, pers. comm.); and 2) some recoveries within Barnstaple Bay, prior to recoveries from Swansea Bay and the peak of recoveries from Bridgwater Bay.

Releases from station 11, path (F), provide confirmation of upstream movement along the southern coastline, but also a somewhat anomalous early recovery from the northern coastline. No detailed explanation of this latter transport path can be put forward by the authors, which seems to be contrary to the other rather well-established patterns. It can be suggested tentatively that a period of easterly winds during December 1977, followed by westerlies in January (meteorological data from Puckey House, Port Talbot Harbour), might account for the abrupt transfer to the northerly part of the system. For comparative purposes, releases by MAFF, in 1972/1973, at a station just to the west of station 11 of the present investigation indicated net upstream transport and transfer into Barnstaple Bay (Riley, pers. comm.). These data confirm transport path (E) and extend the system further to the west along the northern coastline (E1, Fig. 6).

DISCUSSION

Problems of interpretation in relation to water circulation

Sea-bed drifter recovery patterns undoubtedly represent some kind of residual water movement (*see*, for example, Ramster, Jones, 1978). Certainly, the drifters are susceptible to the action of waves, particularly in shallow water areas (Collins, Barrie, 1979). Similarly, it has been suggested that at high mid-water current velocities (50 to 95 cm/sec.) saltation of the drifter occurs, although it tends to remain within 3.5 m of the sea bed. At velocities >95 cm/sec., the drifter lifts from the near-bottom layer to glide for extended periods in mid-water (Dickson, 1976). Such movements are considered to represent the scale of turbulence near the sea bed and have a bearing on the interpretation of sea bed drifter returns (Harden Jones *et al.*, 1973). An additional complication is the rate of movement of the drifter in relation to that of the ambient mass (Woodhead, Lee, 1960; Collins, Barrie, 1979).

In terms of near-bed wave action, maximum orbital velocities of the order of 1 m/sec. have been predicted from some of the shallower water areas of Swansea Bay (Collins *et al.*, 1979; Fig. 8 *b*). This value is far in excess of the "threshold" velocity for the drifter under waves (Collins, Barrie, 1979) or, indeed, under the combined action of waves and tidal currents. Such considerations should be taken into account during the interpretation of results from the northern coastline, which is affected directly by long-period swell waves from the southwest. From a MAFF investigation in the Bristol Channel (station 15, Fig. 1), it was deduced that the tidal currents were sufficient to cause drifters to glide in mid-water over extended periods (Murray *et al.*, 1980). Predicted depth-averaged spring tidal currents, which can be assumed to be similar to mid-water velocities, are in excess of 100 cm/sec. over the majority of the area under investigation (Owen, 1980; Fig. 6) and even reach 200 cm/sec. in a zone between Nash Point and Lavernock Point, in an area of high tidal energy dissipation (Owen, *op. cit.*; Fig. 10).

Notwithstanding the problems of interpretation, the drifter recovery patterns nevertheless appear to represent a consistent pattern of water movement. It is now of interest to consider the relationship of this pattern to predicted residual current patterns produced from other techniques and to assess its implications in terms of sediment transport processes.

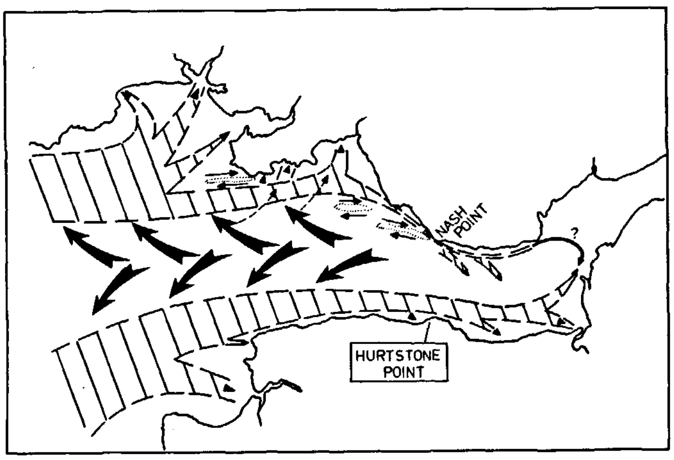

Figure 7
Conjectural near-bottom drift pattern for the Bristol Channel. The shaded areas represent upstream coastal boundary transfer.

A generalised model

The drifter recovery pattern (Fig. 6) is summarised as a conjectural model in Figure 7. In this, seaward movement takes place along the longitudinal axis of the channel while the northern and southern coastal zones are dominated by landward movement. Some tidal current and wave-induced transfer occurs between the central and coastal regions. In particular, southwesterly swell causes transfer into the central northerly section of the coastline (Fig. 7).

Wave action along each section of the coastline is suggested in the drifter recovery patterns by the instantaneous landward transfer of releases from stations 6 and 7. Other evidence is provided by the results of MAFF (Murray *et al.*, 1980), where summer and autumn releases from station 15 (Fig. 1) were recovered in Swansea Bay. Such recoveries along the northern coastline probably represented periods of high wave energy. Similarly, the somewhat bimodal nature of the recoveries in Bridgwater Bay, in the MAFF investigations (Murray *et al., op. cit.,* Fig. 9), is consistent with the proposed model (Fig. 7).

Comparison between the proposed drifter pattern and various predicted residual currents for the Bristol Channel, originating from density gradients, non-linear advection, friction and continuity, respectively (Uncles, 1982) demonstrates that only the frictional-driven residuals meet the requirements of mid-channel downstream movement, upstream coastal movement and cross-channel transfer (Fig. 8). These currents, ranging from 2 ± 2 mm/sec. in the west to 6 ± 5 mm/sec. in the east, represent upchannel flows in the shallow water regions, with return flow in the deeper channels. The upchannel flow in the vicinity of Bridgwater Bay is enhanced by Stokes drift (Uncles, *op. cit.*).

The forcing mechanism for the frictional residuals is given as:

$$V_F = \frac{4 D E_{M_2}}{3 \pi h}[2 u_s - E_{M_4} \cos \varphi_p]$$

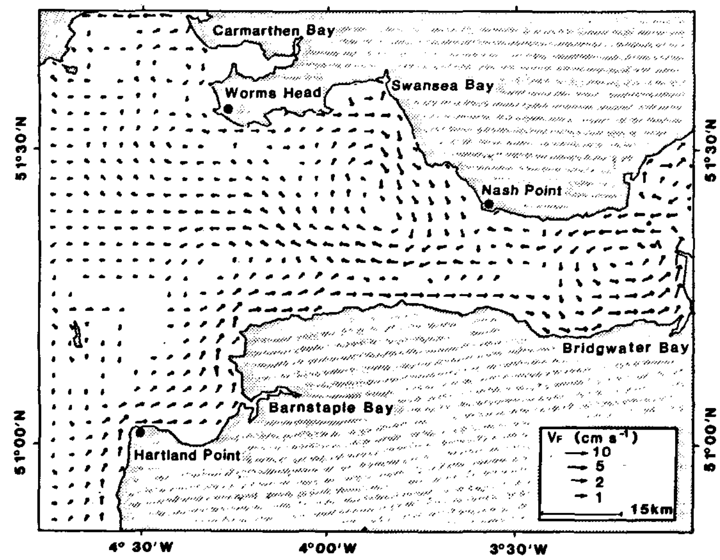

Figure 8
Frictional-driven residual currents from the Bristol Channel, derived from a depth-integrated numerical model (from Uncles, 1982).

Where D is the friction parameter (2.5×10^{-3}), h is water depth, u_s is the Stokes drift and E_{M2} and E_{M4} are the maximum tidal currents associated with the main semidiurnal and first (shallow water) harmonic, respectively. Φ_p is a function of the phase difference between the M_2 and M_4 tidal currents. Interaction between the amplitudes and phases of the M_2 and M_4 tidal currents constituents has been used elsewhere to predict sand transport paths and to demonstrate their correlation with zones of "bed-load parting" (Pingree, Griffiths, 1979).

The integrated residual currents along specific transport paths, derived from the numerical model results (Fig. 8), can be compared with drifter recovery times. For example, an individual water particle would take 8, 20 and 50 days, to reach sections N_1, N_2 and S_3, respectively, from stations 1, 2 and 3; comparable drifter recovery times are around 30, 100 and 200 days. Similarly, the direct and indirect paths into Bridgwater Bay from stations 4 and 5 are, on average, 100 and 300 days based upon the predicted currents; drifter recovery times are 17 and 50 days, respectively. Both sets of data infer a relatively constant ratio between predicted frictionally-driven residual currents and the rate of drifter movement; this ranges from 0.20 to 0.26 for stations 1, 2 and 3 and is 0.32 and 0.34 for combined releases from stations 4 and 5. These ratios, between residual water and drifter movements, compare with a value of 0.5 for instantaneous water and drifter velocities derived experimentally (Fig. 1, Collins, Barrie, 1979).

The significance of frictionally-driven residual currents in defining sea-bed recovery patterns in the Bristol Channel can be compared with the interpretation of similar studies in the Humber Estuary, Northeast England. Recovery patterns in this smaller estuarine system indicated complex water circulation patterns, with an ebb-dominated main axial flow and upstream drift at the margins (Robinson, 1964 and 1973). In other sea-bed drifter experiments, investigators have considered residual movement to be caused by tidal streams (Morecambe Bay, Phillips, 1968) or the combined effect of tidal currents and longitudinal density gradients (Liverpool Bay, Halliwell, 1973). Interestingly, in a recent attempt to explain variability in residual currents in Liverpool Bay, based on Eulerian and Lagrangian techniques, it was pointed out that theoretical analyses had demonstrated that "conditions in the Bay are intermediate... between those in an estuary where friction forces predominate, and those in the deep sea" (Ramster, 1973).

Sediment transport considerations

The main problems in interpreting water circulation from sea-bed drifter studies have been reviewed above (first section). In terms of their representation of the movement of particulate matter, it would appear that Woodhead drifters respond in a similar manner to fine-grained sludge (Crickmore, 1972) or, at least, to particles smaller than fine sand (Collins, Barrie, 1979). Some confirmation of this association is provided by this investigation, in that the main areas of drifter accumulation, Swansea and Bridgwater Bays, are also areas of extensive mud accumulation (Collins *et al.*, 1979; Parker, Kirby, 1981). Assuming, therefore, that the conjectural bottom drift (Fig. 7) is also representative of fine-grained sediment transport, comparisons can now be made with predicted and inferred transport paths resulting from other techniques.

The effective isolation of the Swansea Bay section of the northern coastline, for example, is consistent with the conclusion that this area is semi-enclosed in terms of sediment circulation (Collins *et al.*, 1979). Predicted bedload transport rates also show a major westward-moving path in the main Channel, with rates in the Bay being two orders of magnitude less than in the offshore region (Heathershaw, 1981; Fig. 11). Wave-induced transfer across the boundary has been predicted, as has transfer of material through the Nash Passage, adjacent to Nash Point (Ferentinos, Collins, 1978; Fig. 66; Collins, Banner, 1980). Furthermore, the landward transport of material of the size of fine-sand along the southern coastal boundary is confirmed by the results of a heavy mineral investigation. Analyses of samples from both the littoral and shallow offshore coastal zone have demonstrated the presence of a distinctive suite of minerals, derived from localised input from the rivers draining into Barnstaple Bay. This assemblage has been found to extend along the coastline as far as Somerset (Barrie, 1980).

Landward transport of fine-grained material through shallow water coastal boundary zones, as opposed to seaward transport in the deeper waters, leads to two exceptionally important sedimentological conditions. Firstly, landward transfer along the coastal boundary zones of the Bristol Channel provides a feeder mechanism for the bed-load parting zone, which is prevalent in the area of high tidal energy dissipation (*see* above) between Nash Point and Lavernock Point (*see* also Culver, 1980; p. M41). It has been predicted, both in terms of side-scan sonar data (Stride, 1963) and from numerical modelling (Pingree, Griffiths, 1979), that sand transport paths are upchannel to landward and down-channel to seaward of this zone. Secondly, the transport path, described above, could account for: a) the presence of fine sands in the Severn Estuary, which are considered to have their origin in the Celtic Sea (Hamilton *et al.*, 1980); and b) for the net landward transport of fine material which has taken place over the past 8 000 to 9 000 years (Murray, Hawkins, 1976), which has found support in the work of Culver and Banner (1978).

This model of lateral inhomogeneity in net transport paths differs from that proposed by Culver (1980), which assumes vertical two-way differentiation; it is consistent, however, with the explanation proposed by Robinson (1973) for the seaward origin of the mud deposits of the inner Humber Estuary.

CONCLUSIONS

a) High percentage returns from Woodhead sea-bed drifter releases have been interpreted in terms of an ebb-dominated main channel system, with flood-dominated coastal boundary zones to either side. Lateral transfer takes place towards the boundaries in the tidal current system; this is supplemented along the northern coastline by superimposed southwesterly wave action.

b) The proposed circulation model is consistent with predicted frictionally-derived residual tidal flows, based on interaction between the main semidiurnal (M_2) and shallow water (M_4) tidal current harmonics.

c) Assuming that the sea-bed drifters represent the saltation/suspension transport at fine-grained sediment particles, the landward coastal transfer of material could provide: 1) the feeder mechanism to a "bed-load parting zone"; and 2) explain the long-term landward movement of both biogenic and clastic particles. Such processes are likely to be widely applicable to other estuarine and coastal systems.

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