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# Sediment dynamics of the Severn Estuary and inner Bristol Channel

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**Abstract:** Net sediment transport pathways have been determined in many environments by studying grain size trends. This approach is extended here to an inner shelf environment, with improved statistical techniques.

Patterns of net surficial sediment transport are proposed, indicating that the area is dominated by up-estuary transport. Exceptions exist in the form of radial mud transport at the river mouths and (clockwise) sand circulation around linear sandbanks.

Six different sedimentary environments are defined on the basis of the shape of the 'transfer function' and its relationship to the grain size distributions. Erosion takes place along the axis of the estuary. Dynamic equilibrium is reached around the linear sandbanks, whilst accretion occurs at the head of the estuary and where there are riverine inputs.

The results are compared with numerical model outputs, representing water movement and sediment transport. Over the seaward part of the study area, there is agreement between the two approaches; contradictions increase, however, towards the upper reaches of the estuary. The discrepancies can be attributed to: (1) inherent differences between patterns of water and sediment movement; (2) difficulties in modelling intertidal boundary conditions; (3) inadequate representation of river influences in the models; and (4) time-scale differences, associated with sediment transport processes.

Marine sediment transport investigations are concerned mainly with: (1) determination of the direction of net sediment transport; (2) estimation of sediment transport rates; and (3) identifying the location of accretional or erosional conditions.

Mechanics-orientated approaches are based upon empirical equations for transport rates, related to tidally- and wave-induced near-bed shear stresses. The validity of such solutions is variable (Heathershaw 1981; Pattiaratchi & Collins 1985).

Transport pathways can be determined qualitatively from the deposits themselves. For example, progressive improvements in sorting or decreases in mean grain size have been considered as indicating net sediment transport. Recently, net transport paths have been related to grain size trends; this is based upon the concept that grain size distributions are the result of erosion, transport and accumulation processes, rather than the sedimentary environment (e.g. beaches and rivers) alone (McLaren & Bowles 1985).

The present contribution applies this new technique to the macrotidal Severn Estuary and Bristol Channel (Fig. 1) to: (1) determine net sediment transport patterns; (2) define sediment transport environments on the basis of grain size and dynamic stability (i.e. erosion, accretion or equilibrium); and (3) undertake preliminary comparisons between the derived results and observations based upon other methods.

## Study area

### *Geology and geomorphology*

The Bristol Channel is 50–60 m deep at its seaward end, with extensive shallow water areas (10–20 m) up-channel (Fig. 1). The coastline is characterized by cliffs, with low coastal plains near the outlets of the tributary rivers (Harris & Collins 1988). The Severn Estuary is bordered by extensive mud flats and wetlands, currently being eroded (Allen & Rae 1987; Allen 1990).

The surficial sediment cover is thin (generally less than 10 m) over most of the Channel, with large areas of bedrock (Mesozoic and older strata) exposed (Lloyd *et al.* 1973; Brooks & James 1975). Large amounts of sediments are deposited within the linear sandbanks, such as the Nash, Holm and Culver Sands (Fig. 1); these are formed by residual circulations in the estuarine waters. The areas sampled for the grain size trend analysis lie mainly in the inner part of the Channel and Severn Estuary, where the cover of loosely-consolidated sediments is almost continuous, together with the Nash Sands.

### *Waves and tides*

The Channel receives high wave energy being exposed to the Atlantic Ocean, with a fetch of up to 6000 km (Collins 1987). Storm waves over 10 m in height have been recorded

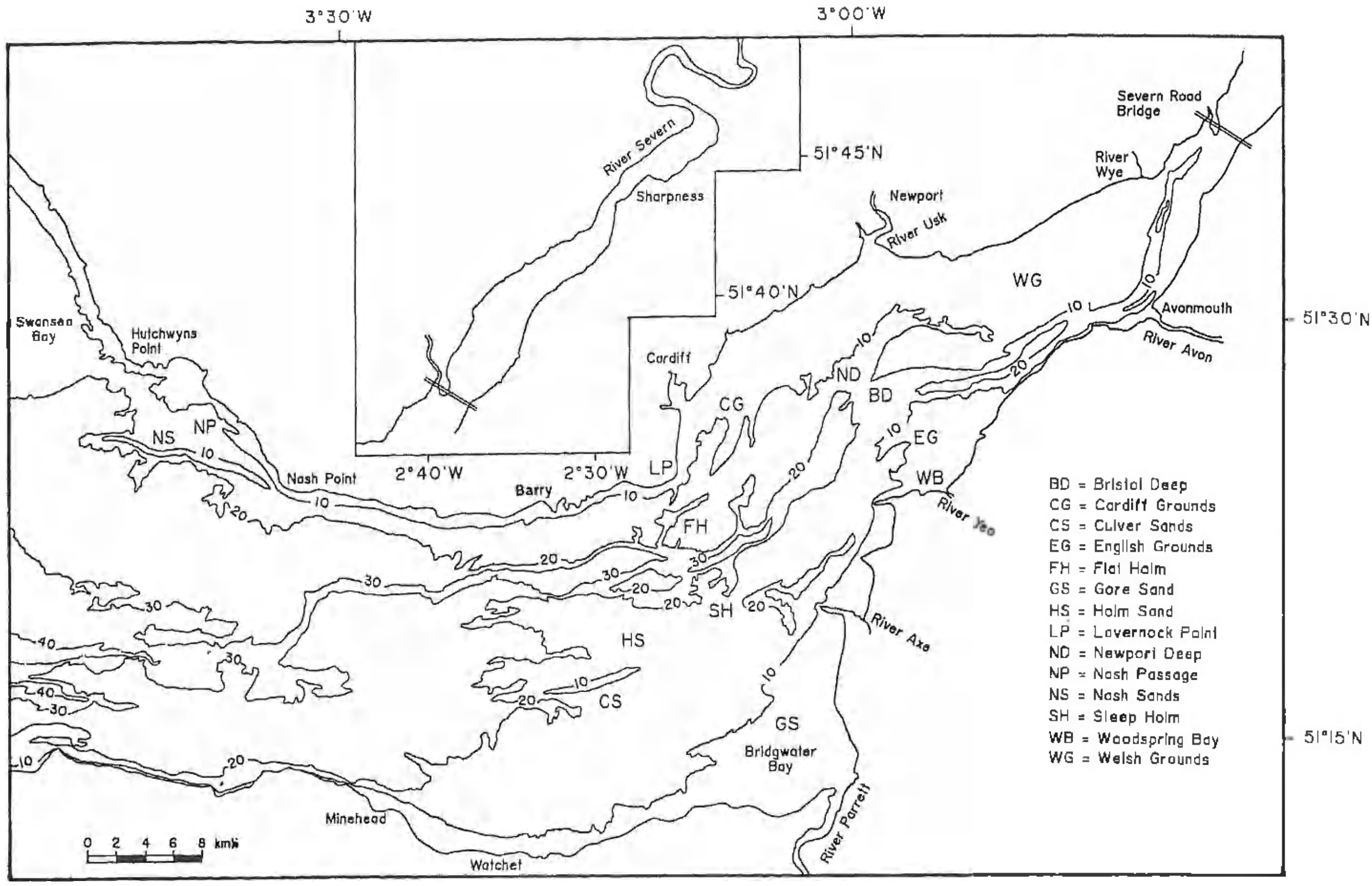


**Fig. 1.** Location map, with water depth in metres. The areas to landward and seaward of Flat Holm are referred to as the Severn Estuary and Bristol Channel, respectively.

for the outer Bristol Channel. Wave heights with a 50 year return period reach 4.7 m near Nash Point, but reduce to 3.5 m towards the east of Flat Holm.

Semi-diurnal tides predominate over the region, with the $M_2$ (lunar semidiurnal) component accounting for 72% of the overall tidal amplitude in Swansea Bay (Wilding & Collins 1980). Mean spring tidal ranges increase from 5.0 m at the mouth of the Channel (Harris & Collins 1988) to over 14 m at the head of the estuary (Kirby 1986), in response to the 'funnelling effect' of the bathymetry and reduction in channel width. Neap tidal ranges are around half that of the spring tides.

The macrotidal regime results in strong and essentially rectilinear tidal currents, which range between 1.0 m $s^{-1}$ and 2.0 m $s^{-1}$ on spring tides. In some sub-tidal channels, they reach, however, 2.5 m $s^{-1}$ on spring tides and 1.5 m $s^{-1}$ on neap tides (Kirby 1986).

### *Sediment supply and transport paths*

Surficial sediments in the Bristol Channel/Severn Estuary are supplied, at least partially, by the rivers. The total freshwater drainage basin area is $2.5 \times 10^4$ $km^2$ (Collins 1983), with a mean water discharge ranging from $9.5 \times 10^9$ to $15.8 \times 10^9$ $m^3$ $a^{-1}$ (Murray *et al.* 1980). Annually, around $1.6 \times 10^6$ tonnes of fine-grained sediments are discharged from the basin; a large proportion ($1.25 \times 10^6$ tonnes) of this is supplied by the Rivers Wye, Avon and Severn. The presence of fine-grained material causes the formation of extensive peripheral salt marshes (140 $km^2$ in area) and high suspended sediment concentrations in the water column (i.e. 20 g $l^{-1}$, during spring tides; Kirby 1986) of the Severn Estuary. Overall, it has been estimated that between $4.5 \times 10^6$ (on neap tides) and $13.4 \times 10^6$ (on spring tides) tonnes of suspended sediment are present in the overlying waters (Collins 1983).

Other sediment sources are sea-bed and coastal erosion (Harris & Collins 1988), reworking of the glacial tills (Culver & Banner 1979; Ferentinos & Collins 1985) and input from the Celtic Sea (Sollas 1883; Murray & Hawkins 1976; Culver & Banner 1979).

Numerous investigations have been undertaken to understand sediment transport in the Bristol Channel and Severn Estuary over the past 25 years (for reviews see Parker & Kirby 1982; Collins 1983, 1987, 1989; Dyer 1984). Within this context, controversy has arisen recently between the use of 'bedload parting' (Stride & Belderson 1990, 1991) and 'mutually evasive transport' models (Harris & Collins 1991) to explain sand movement within the system. Nevertheless, it has been concluded that 'in general terms the bed-load parting and the mutually evasive sand transport systems are not exclusive of one another. The bed-load partings exist mainly offshore and the mutually evasive paths mainly in sand-choked estuaries' (Stride & Belderson 1991). Notwithstanding this observation, the present state of knowledge is still insufficient to understand fully sediment supply and transport within such a complex system.

## Methods

### *Data acquisition and analysis*

Sea-bed sampling was carried out, during April/May 1988, using a Day grab for the sub-tidal areas. During June 1988, the intertidal zone was sampled from a small hovercraft. The sampling strategy was based upon a grid coverage of the area, from the Severn Road Bridge to a line of 3°54′W longitude (Fig. 1). The sampling interval was approximately 1.5 km, with a reduced density over rocky sea-bed areas. Conversely, sampling density was increased within the coastal zone and over bathymetric features, such as sandbanks and subtidal channels.

Sediment was collected at 901 of the stations, whilst 247 others were characterized by 'hard ground' (or exposed bedrock; Fig. 2). Grain size analysis was carried out using a Malvern 26001 Laser Particle Sizer, for both the sand- and mud-sized material. Where necessary, dry sieving was used for the gravel fractions.

Grain size parameters (mean, $\mu$; sorting coefficient, $\sigma^2$; and skewness, Sk) were derived using the moment formulae, as follows:

$$\mu = \int_{-\infty}^{\infty} s\, \mathrm{d}(s)\, \mathrm{d}s \qquad (1)$$

$$\sigma^2 = \int_{-\infty}^{\infty} (s-\mu)^2\, \mathrm{d}(s)\, \mathrm{d}s \qquad (2)$$

$$Sk = \frac{1}{(\sigma^2)^{3/2}} \int_{-\infty}^{\infty} (s-\mu)^3\, \mathrm{d}(s)\, \mathrm{d}s \qquad (3)$$

where $s$ is the grain size (in $\phi$ units) and $\mathrm{d}(s)$ is the frequency distribution function.

### *Identification of net transport pathways*

Net sediment transport pathways can be inferred from grain size trends. For sampling sites $D_1$ and $D_2$, $d_1(s)$ and $d_2(s)$ are assumed to be the grain size distributions, respectively. Along a transport pathway from $D_1$ to $D_2$, $d_2(s)$ is related to $d_1(s)$ through a 'transfer function' $X(s)$, defined by:

$$d_2(s) = kX(s)\, d_1(s) \qquad (4)$$

where $k$ is a scaling coefficient. $X(s)$ provides the statistical relationship between the two deposits. The shape of $X(s)$ depends upon the energy gradient along the transport paths; it can be negatively or positively skewed (but with a lower frequency). If $X(s)$ is negatively skewed, then sediment will become finer and more negatively skewed in the direction of transport; if $X(s)$ is positively skewed, then sediment will become coarser and more positively skewed (McLaren & Bowles 1985). Hence, from $D_1$ to $D_2$, at least one of the following two cases (Cases B and C; Case A is associated with the grain-size changes for the source area; McLaren & Bowles 1985) will dominate:

Case B: $\sigma_1^2 < \sigma_2^2$, $\mu_2 > \mu_1$ and $Sk_2 < Sk_1$

Case C: $\sigma_1^2 < \sigma_2^2$, $\mu_2 < \mu_1$ and $Sk_2 > Sk_1$

where subscripts 1 and 2 represent sampling sites $D_1$ and $D_2$, respectively. If no sediment exchange takes place between the two sites, however, the probability of occurrence of

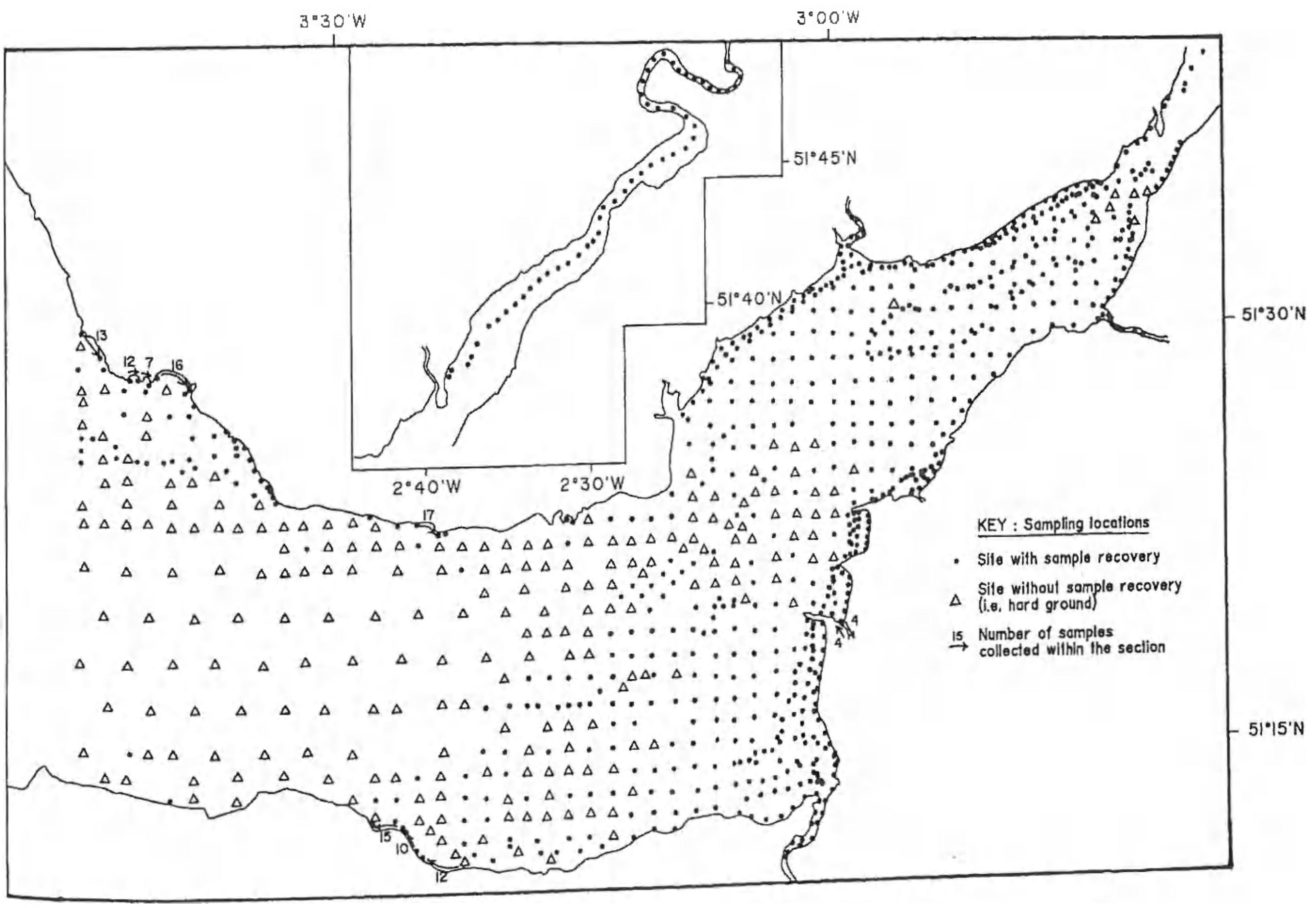


**Fig. 2.** Surficial sediment sampling sites.

either Case B or C is very low. If the probability is high, then the most probable transport direction can be identified.

A procedure for calculating the probabilities of Case B and C occurrences, together with a significance test to determine if the probability is high enough for such transport, has been proposed (McLaren & Bowles 1985). For $n$ samples along a survey line, $N = (n^2 - n)/2$ possible pairs are formed. For each direction, $N_x$ (the observed numbers of pairs representing Case B or C) is then established. Finally, a $Z$-score for each case and each direction is calculated, using the formula:

$$Z = \frac{N_x - pN}{[Np(1-p)]^{1/2}} \qquad (5)$$

where $p$ is the background probability. A $Z$-score which exceeds a certain level indicates that transport in a preferred direction is highly probable. The 95% and 99% levels of significance are $Z = 1.645$ and $Z = 2.330$, respectively.

Equation (5) can be rewritten as:

$$[p(1-p)]^{1/2} Z/N^{1/2} - N_x/N + p = 0 \qquad (6)$$

The relationship between $Z/N^{1/2}$ and $N_x/N$ with various values of $p$ is shown on Fig. 3 by the solid lines, under the condition $Z = 2.330$. The lower limit of $N_x/N$ exceeding the significance level is defined by the intersection of a solid line (representing influence from $p$) and a dashed line (representing influence from $N$). For example, if 100 sediment samples are collected along a line and $p = 1/8$ is used, then $N_x/N$ must exceed 0.22 in order to define the transport direction.

McLaren & Bowles (1985) used $p = 1/8$ for the determination of the $Z$-score. Gao & Collins (1991) have suggested recently, however, that higher values should be used. Figure 3 shows that if $p$ is too low, then the $Z$-scores for both directions may be above the 99% significance level, as reported by McLaren & Collins (1989). In order to avoid the ambiguity, $Z$-scores for the assumptions that $p = 1/5$, $p = 1/6$, $p = 1/7$ and $p = 1/8$ have been calculated.

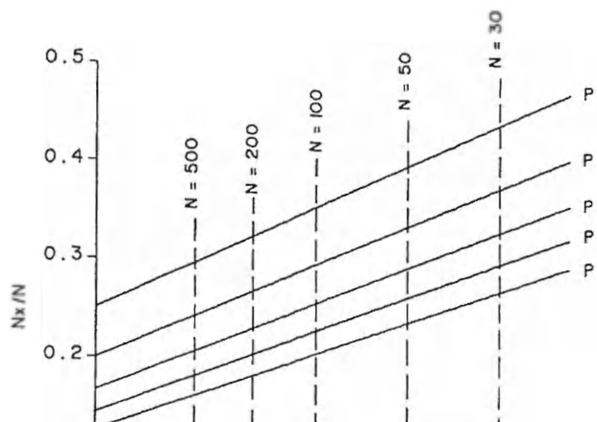


**Fig. 3.** Influence of the background probability upon the 99% significance level.

$Z$-scores, based upon a particular background probability and without any ambiguity, are used in the significance test.

It is more difficult to establish lines of samples for detailed investigation over an inner shelf area, than along a river channel. A possible method is to contour one of the grain-size parameters, so that lines associated with the largest gradient of the parameter can be selected. In practice, however, this is inappropriate because various grain-size parameters are involved and the transport paths are not necessarily associated with the largest gradient. For the present study, therefore, around 500 lines associated with a gradient in the three parameters and with various directions were examined. All of the lines with their $Z$-scores exceeding the 95% significance level (with $p = 1/8$) were then selected for further analyses.

## *Sediment stability*

Equation (4) implies also that $X(s)$ defines the relative probability of each particular grain size fraction being eroded, transported and deposited. Consequently, upon the successful derivation of a transport trend, the shape of transfer functions may be used to assess the 'status' of the transport regime. Four shapes of $X(s)$ can be related to the $D_1$ and $D_2$ grain size distributions (Fig. 4; McLaren & Collins 1989), as outlined below.

(a) The shape of $X(s)$ resembles those of $d_1(s)$ and $d_2(s)$, with similar modes (Fig. 4a). The relative probability of grains being transported produces a grain size distribution similar to that of the actual deposits, suggesting that the environment is in *dynamic equilibrium*. As a consequence, for every grain within the deposit, there is an equal probability that it will be transported and re-deposited.

(b) The shapes of the three distributions are similar, but the mode of $X(s)$ is finer than the modes of $d_1(s)$ and $d_2(s)$ (Fig. 4b). In this situation, more fine grains are being deposited than are being eroded and transported; thus, the environment is *accreting*.

(c) The shapes of the three distributions are similar, but the mode of $X(s)$ is coarser than those of $d_1(s)$ and $d_2(s)$ (Fig. 4c). More grains are being eroded than deposited and the environment is *eroding*.

(d) Regardless of the shapes of $d_1(s)$ and $d_2(s)$, $X(s)$

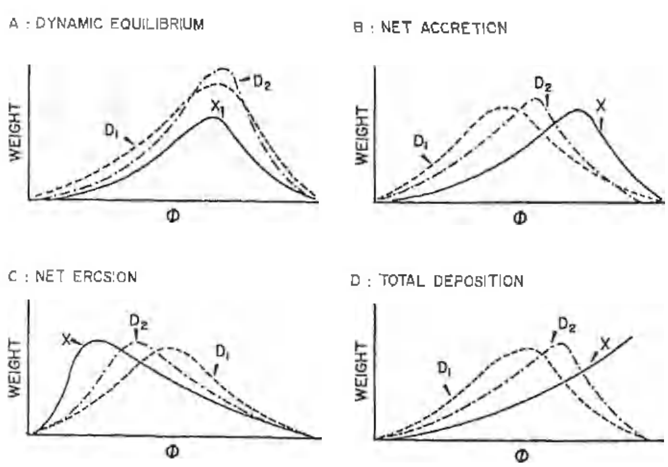


**Fig. 4.** Status of sediment transport regime, on the basis of the relationship between the transfer function and the distributions of deposits at $D_1$ and $D_2$ (from McLaren & Collins 1989). Weight values increase upwards and $\Phi$ values increase to the right.

increase monotonically over the complete size range (Fig. 4d). This pattern occurs when sediment, once deposited, undergoes no further transport (i.e. *total deposition*).

The shapes of the transfer functions are examined below, for areas where the trend of sediment transport is shown to be statistically significant. Typical transfer functions are used then to illustrate the status of the transport regime. Based upon the status, as well as the sediment facies and the case of sediment transport (Case B or C), various transport environments are identified.

## Results

### *Net transport pathways*

Altogether, 78 lines were identified as having their Z-scores exceeding 95% significance level on the basis of $p = 1/8$, as summarized in Table 1 and Fig. 5. Within the data set, some Z-scores exceed the acceptable significance level for both directions, when only a low background probability (i.e. $p = 1/8$) criteria is applied (e.g. Lines 5 and 7). This ambiguity almost disappears, however, when a high background probability ($p = 1/6$) is applied. Therefore, only lines with a Z-score exceeding the 95% significance level, at $p = 1/6$, are used hereafter to infer net sediment transport. Hence, Lines 2, 26, 35, and 37 are rejected because of their low Z-scores. Likewise, one of the directions of Lines 5, 7, 34, 70, 71, 72 and 77 is rejected for being under the 95% significance level (Table 1). The inferred transport pathways are shown on Fig. 6.

### *Identification of 'transport' environments*

Parts of the study area where loosely-consolidated sediments occur can be classified into six different 'transport environments' (see Fig. 7 and Table 2), based upon:

**Table 1.** *Sediment trend statistics for the survey lines, with the significant Z-scores*

| Line | Case | Direction | $N$ | $N_x$ | $Z_{1/8}$ | $Z_{1/7}$ | $Z_{1/6}$ | $Z_{1/5}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | B | Up | 91 | 34 | 7.17 | 6.29 | 5.30 | 4.14 |
| 2 | C | Up | 91 | 21 | 3.05 | 2.40 | 1.64 | 0.73 |
| 3 | B | Up | 36 | 11 | 3.28 | 2.80 | 2.24 | 1.58 |
| 4 | B | Up | 325 | 86 | 7.61 | 6.27 | 4.74 | 2.91 |
| 5 | B | Down | 105 | 21 | 2.32 | 1.67 | 0.92 | 0.00 |
| 5 | B | Up | 105 | 41 | 8.23 | 7.25 | 6.15 | 4.88 |
| 6 | B | Up | 28 | 11 | 4.29 | 3.78 | 3.21 | 2.55 |
| 6 | C | Up | 28 | 8 | 2.57 | 2.16 | 1.69 | 1.13 |
| 7 | B | Up | 253 | 78 | 8.82 | 7.52 | 6.05 | 4.31 |
| 7 | C | Down | 253 | 48 | 3.11 | 2.13 | 0.98 | −0.41 |
| 8 | B | Up | 28 | 8 | 2.57 | 2.16 | 1.69 | 1.13 |
| 9 | B | Up | 15 | 10 | 6.34 | 5.80 | 5.20 | 4.58 |
| 10 | C | CW | 78 | 24 | 4.88 | 4.16 | 3.34 | 2.38 |
| 11 | B | CCW | 210 | 101 | 15.60 | 14.00 | 12.22 | 10.18 |
| 12 | C | CCW | 45 | 21 | 6.93 | 6.21 | 5.40 | 4.47 |
| 13 | B | CCW | 55 | 15 | 3.31 | 2.75 | 2.11 | 1.35 |
| 14 | B | Up | 78 | 33 | 7.96 | 7.07 | 6.08 | 4.93 |
| 15 | B | Up | 45 | 19 | 6.03 | 5.36 | 4.60 | 3.73 |
| 16 | B | Up | 120 | 36 | 5.80 | 4.92 | 3.92 | 2.74 |
| 17 | B | Up | 55 | 24 | 6.98 | 6.22 | 5.37 | 4.38 |
| 18 | B | Up | 78 | 42 | 11.04 | 9.99 | 8.81 | 7.47 |
| 19 | B | Up | 45 | 15 | 4.23 | 3.65 | 3.00 | 2.24 |
| 20 | B | Up | 45 | 21 | 6.93 | 6.21 | 5.40 | 4.47 |
| 21 | B | Up | 21 | 9 | 4.21 | 3.74 | 3.22 | 2.62 |
| 22 | B | Up | 36 | 20 | 7.81 | 7.08 | 6.26 | 5.33 |
| 23 | C | Up | 36 | 14 | 4.79 | 4.22 | 3.58 | 2.83 |
| 24 | B | Up | 171 | 87 | 15.17 | 13.67 | 12.00 | 10.09 |
| 25 | B | Up | 35 | 22 | 8.82 | 8.21 | 7.33 | 6.34 |
| 26 | B | Up | 36 | 9 | 2.27 | 1.84 | 1.34 | 0.75 |
| 27 | B | Up | 45 | 23 | 7.83 | 7.06 | 6.20 | 5.22 |
| 28 | B | Up | 105 | 57 | 12.95 | 11.71 | 10.34 | 8.78 |
| 29 | B | Down | 15 | 5 | 2.44 | 2.11 | 1.73 | 1.29 |
| 30 | B | Down | 10 | 7 | 5.50 | 5.04 | 4.53 | 3.95 |
| 31 | B | Down | 55 | 15 | 3.31 | 2.75 | 2.11 | 1.35 |
| 32 | B | Down | 55 | 15 | 3.31 | 2.75 | 2.11 | 1.35 |
| 33 | B | Down | 91 | 31 | 6.22 | 5.39 | 4.45 | 3.36 |
| 34 | B | Down | 91 | 23 | 3.69 | 3.00 | 2.20 | 1.26 |
| 34 | B | Up | 91 | 19 | 2.42 | 1.80 | 1.08 | 0.21 |
| 35 | C | Up | 55 | 13 | 2.50 | 1.98 | 1.39 | 0.67 |
| 36 | C | Down | 351 | 103 | 9.54 | 8.06 | 6.37 | 4.38 |
| 37 | B | Up | 136 | 24 | 1.82 | 1.12 | 0.31 | −0.69 |
| 38 | C | Down | 15 | 8 | 4.78 | 4.32 | 3.81 | 3.23 |
| 39 | B | Down | 15 | 4 | 1.66 | 1.37 | 1.04 | 0.65 |

**Table 1**—(*Continued*)

| Line | Case | Direction | $N$ | $N_x$ | $Z_{1/8}$ | $Z_{1/7}$ | $Z_{1/6}$ | $Z_{1/5}$ |
|---|---|---|---|---|---|---|---|---|
| 39 | C | Down | 15 | 8 | 4.78 | 4.32 | 3.81 | 3.23 |
| 40 | C | Down | 21 | 17 | 9.49 | 8.73 | 7.91 | 6.98 |
| 41 | C | Down | 21 | 11 | 5.53 | 4.99 | 4.39 | 3.71 |
| 42 | C | Down | 15 | 6 | 3.22 | 2.85 | 2.43 | 1.94 |
| 43 | C | Down | 36 | 10 | 2.77 | 2.31 | 1.79 | 1.17 |
| 44 | B | Seaward | 66 | 28 | 7.35 | 6.53 | 5.62 | 4.55 |
| 45 | B | Seaward | 78 | 25 | 5.22 | 4.48 | 3.65 | 2.66 |
| 46 | B | Seaward | 55 | 26 | 7.80 | 6.99 | 6.09 | 5.06 |
| 47 | B | Seaward | 28 | 14 | 6.00 | 5.40 | 4.73 | 3.97 |
| 48 | B | Seaward | 28 | 15 | 6.57 | 5.94 | 5.24 | 4.44 |
| 49 | B | Seaward | 36 | 22 | 8.82 | 8.03 | 7.16 | 6.17 |
| 50 | B | Seaward | 28 | 14 | 6.00 | 5.40 | 4.73 | 3.97 |
| 51 | B | Seaward | 28 | 14 | 6.00 | 5.40 | 4.73 | 3.97 |
| 52 | B | Seaward | 28 | 13 | 5.43 | 4.86 | 4.23 | 3.50 |
| 53 | B | Seaward | 28 | 14 | 6.00 | 5.40 | 4.73 | 3.97 |
| 54 | B | Seaward | 28 | 14 | 6.00 | 5.40 | 4.73 | 3.97 |
| 55 | B | Seaward | 45 | 23 | 7.83 | 7.06 | 6.20 | 5.22 |
| 56 | B | Seaward | 45 | 19 | 6.03 | 5.36 | 4.60 | 3.73 |
| 57 | B | Seaward | 55 | 24 | 6.98 | 6.22 | 5.37 | 4.38 |
| 58 | B | Seaward | 78 | 24 | 4.88 | 4.16 | 3.34 | 2.38 |
| 59 | B | Seaward | 91 | 31 | 6.22 | 5.39 | 4.45 | 3.36 |
| 60 | B | Seaward | 28 | 15 | 6.57 | 5.94 | 5.24 | 4.44 |
| 61 | B | Seaward | 55 | 26 | 7.80 | 6.99 | 6.09 | 5.06 |
| 62 | C | Down | 36 | 29 | 12.35 | 11.36 | 10.29 | 9.08 |
| 63 | C | Down | 55 | 40 | 13.51 | 12.39 | 11.16 | 9.78 |
| 64 | C | Down | 36 | 15 | 5.29 | 4.70 | 4.03 | 3.25 |
| 65 | B | Seaward | 28 | 8 | 2.57 | 2.16 | 1.69 | 1.13 |
| 66 | B | Up | 66 | 31 | 8.47 | 7.59 | 6.61 | 5.48 |
| 67 | B | Up | 55 | 23 | 6.57 | 5.84 | 5.01 | 4.05 |
| 68 | B | Up | 21 | 9 | 4.21 | 3.74 | 3.22 | 2.62 |
| 69 | C | Up | 55 | 26 | 7.80 | 6.99 | 6.09 | 5.06 |
| 70 | C | Down | 36 | 8 | 1.76 | 1.36 | 0.89 | 0.33 |
| 70 | C | Up | 36 | 20 | 7.81 | 7.08 | 6.26 | 5.33 |
| 71 | C | Down | 36 | 8 | 1.76 | 1.36 | 0.89 | 0.33 |
| 71 | C | Up | 36 | 19 | 7.31 | 6.60 | 5.81 | 4.92 |
| 72 | C | Down | 28 | 8 | 2.57 | 2.16 | 1.69 | 1.13 |
| 72 | C | Up | 28 | 14 | 6.00 | 5.40 | 4.73 | 3.97 |
| 73 | B | Up | 36 | 13 | 4.28 | 3.74 | 3.13 | 2.42 |
| 74 | B | Up | 15 | 9 | 5.56 | 5.06 | 4.50 | 3.87 |
| 75 | B | Seaward | 78 | 35 | 8.65 | 7.72 | 6.68 | 5.49 |
| 76 | B | Seaward | 21 | 12 | 6.19 | 5.61 | 4.98 | 4.26 |
| 77 | B | Down | 153 | 31 | 2.90 | 2.11 | 1.19 | 0.08 |
| 77 | B | Up | 153 | 63 | 10.73 | 9.51 | 8.14 | 6.55 |
| 78 | B | Up | 36 | 19 | 7.31 | 6.60 | 5.81 | 4.92 |

$N$, number of possible pairs along the line of samples.

$N_x$, number of pairs indicating a particular trend.

$Z_{1/8}$, $Z_{1/7}$, $Z_{1/6}$ and $Z_{1/5}$, $Z$-scores for $p = 1/8$, $p = 1/7$, $p = 1/6$ and $p = 1/5$, respectively ($Z = 1.645$ for 90% significance level and $Z = 2.330$ for 95% significance level).

Direction of transport: Down, down-estuary; Up, up-estuary; CW, clockwise; CCW, counterclockwise; Seaward, dispersion away from a river mouth.

(i) sediment facies (sand, sand and mud admixtures, or mud); (ii) sediment transport characteristics (Case B or C); and (iii) dynamic stability (i.e. accretion, dynamic equilibrium, or erosion), in terms of the relationship between the X-function and the grain size distributions (see above). Average grain-size parameters for the environments identified are lised in Table 3. Based upon the information presented in Tables 1–3 and Figs 5–7, the characteristics of each of the environments are now described.

*Environment I.* This includes the beach and nearshore sands of eastern Bridgwater Bay, as the only environment where net sand erosion occurs. Exceptionally strong trends (Lines 62–64, Table 1) indicate down-estuary transport. Fine sands (2.5$\phi$) occur typically here, with a coarser mode of the X-function (Fig. 8a).

*Environment II.* This environment (i.e. sand, Case C transport, and in 'dynamic equilibrium') includes: the Nash Sands (IIa); the Culver Sands (IIb); Cardiff Grounds (IIc); and the upper Severn Estuary (IId). The sediments become

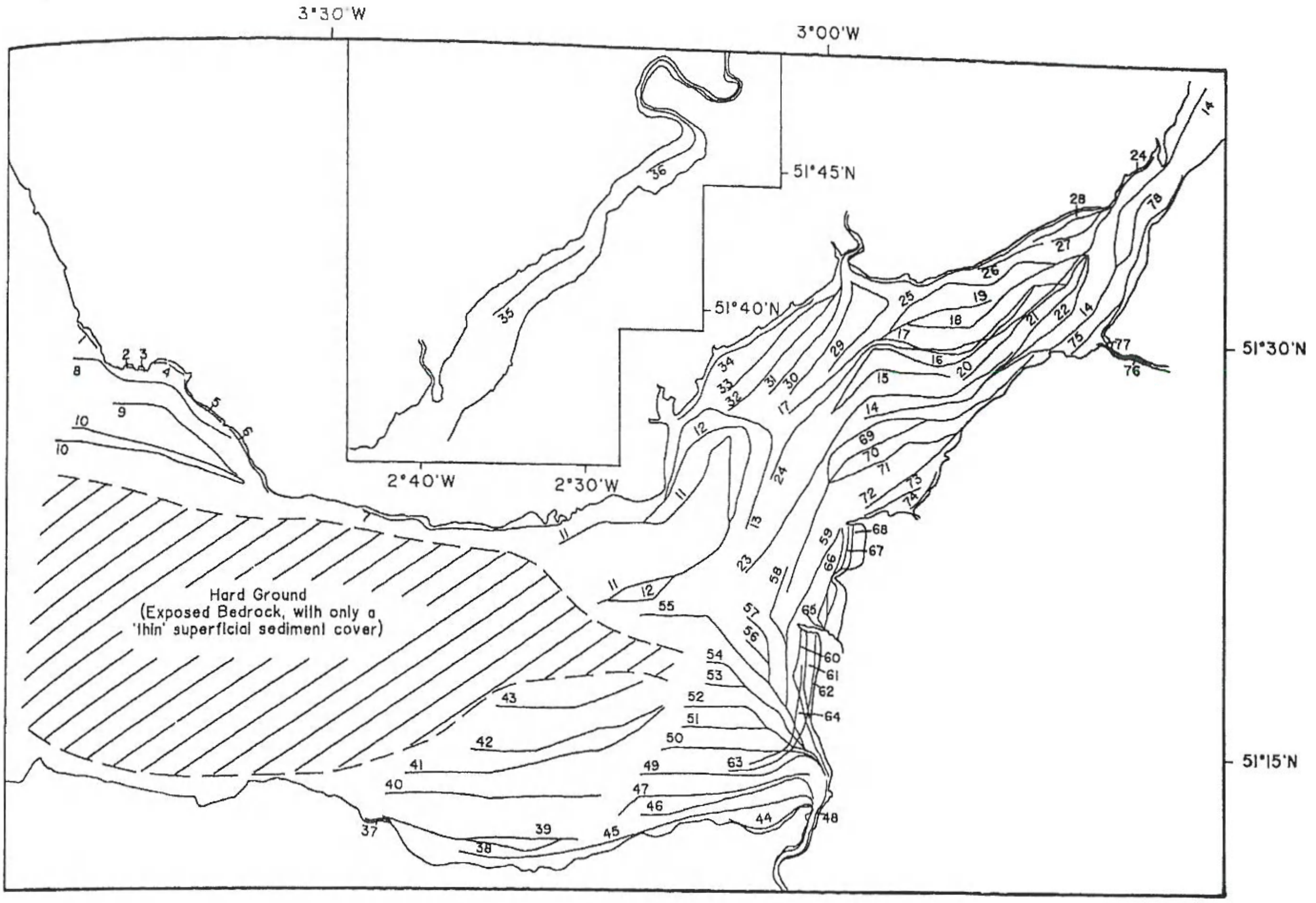


**Fig. 5.** Sample lines used to determine sediment transport paths.

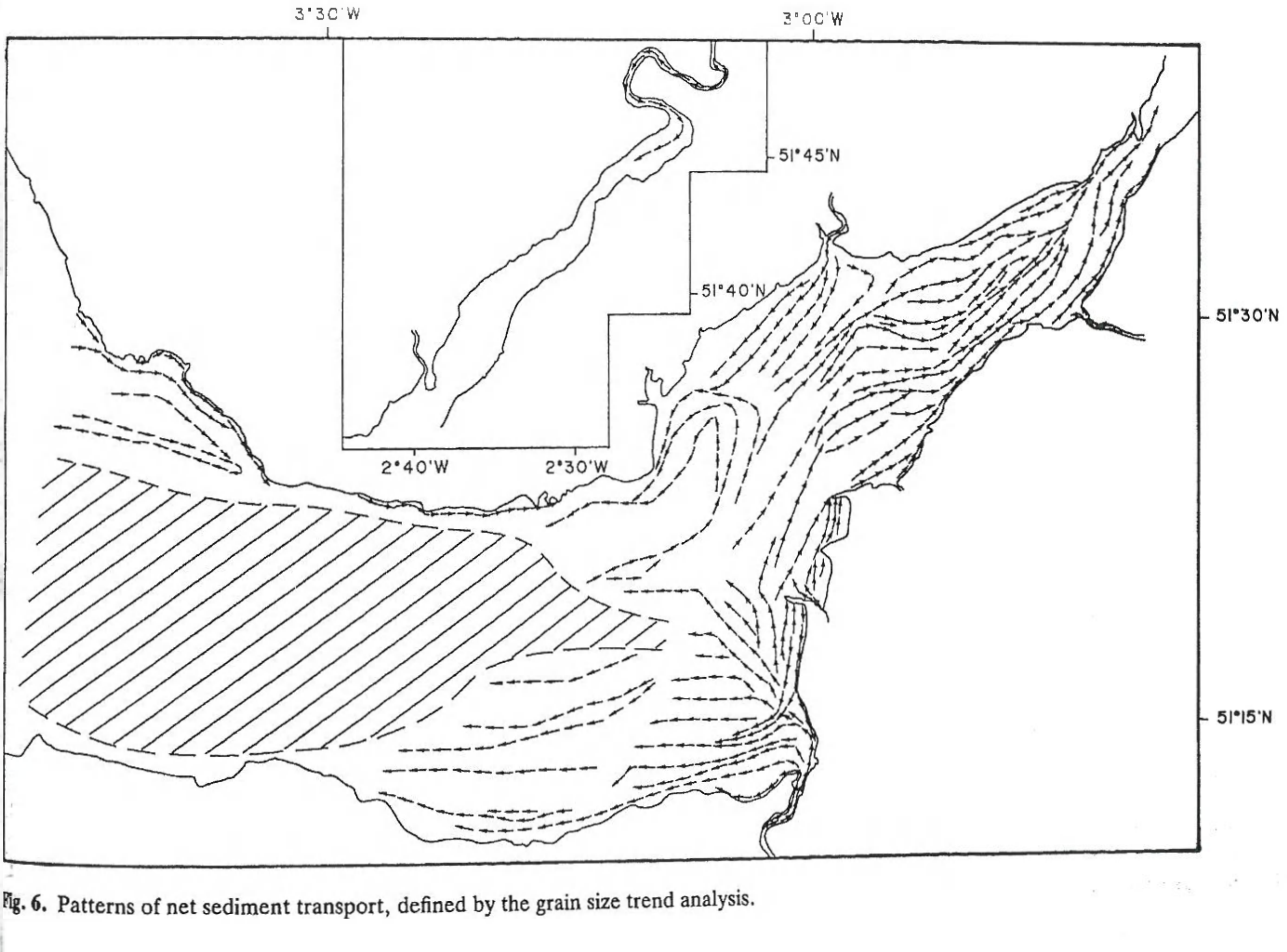


**Fig. 6.** Patterns of net sediment transport, defined by the grain size trend analysis.

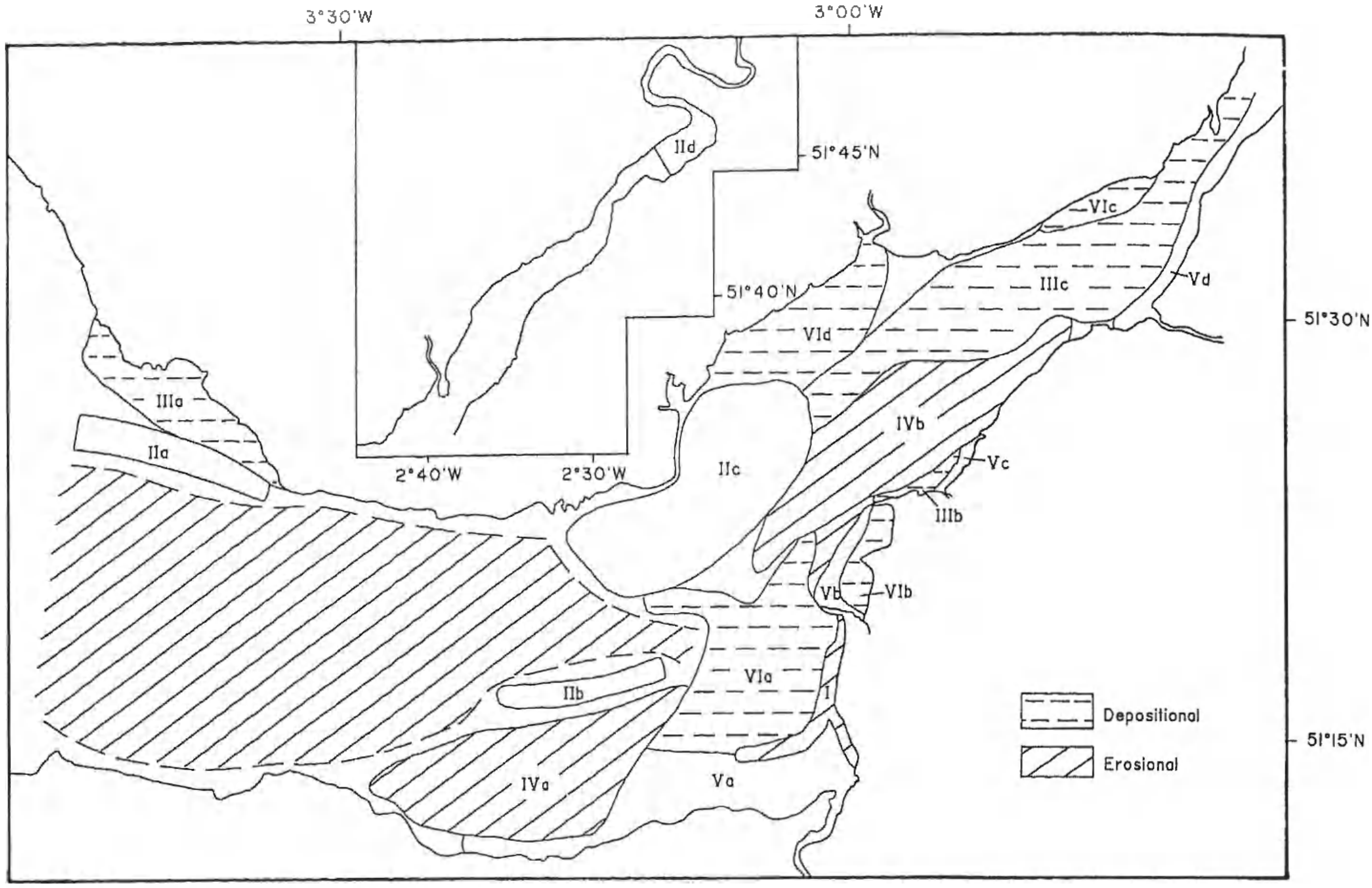


**Fig. 7.** Sediment transport environments, on the basis of dynamic status, sediment provinces and the Case B and C conditions.

steadily finer, from the Nash Sands to the upper Severn Estuary, ranging from medium (1.34$\phi$) to fine sands 2.90($\phi$) (Table 3).

Transport around the Nash Sands is represented by Line 10, as (clockwise) sand circulation around a linear sandback (cf. Pattiaratchi & Collins 1988). The X-function mode lies at 1.0$\phi$, showing that coarse sand is the dominant size fraction in transit.

To the south of the Culver Sands, the trend analysis of Line 43 indicated westerly (down-estuary) transport. The

**Table 2.** *Sediment transport environments in the Severn Estuary and Bristol Channel*

| Environment* | Sample lines | Sediment type | Case | Status |
|---|---|---|---|---|
| I | 62–64 | sand | C | net erosion |
| IIa | 10 | sand | C | equilibrium |
| IIb | 43 | sand | C | equilibrium |
| IIc | 11–13 | sand | C | equilibrium |
| IId | 36 | sand | C | equilibrium |
| IIIa | 1, 3–9 | sand | B | net accretion |
| IIIb | 73 | sand | B | net accretion |
| IIIc | 14–22, 25, 78 | sand | B | net accretion |
| IVa | 38–42 | mixed | C | net erosion |
| IVb | 23, 69–72 | mixed | C | net erosion |
| Va | 44–49 | mud | B | equilibrium |
| Vb | 59, 65 | mud | B | equilibrium |
| Vc | 74 | mud | B | equilibrium |
| Vd | 75–77 | mud | B | equilibrium |
| VIa | 50–58, 60–61 | mud | B | net accretion |
| VIb | 66–68 | mud | B | net accretion |
| VIc | 27–28 | mud | B | net accretion |
| VId | 30–33 | mud | B | net accretion |

* Locations given in Fig. 8.

**Table 3.** *Average grain-size characteristics in each of the transport environments (defined in Table 2 and on Fig. 9)*

| Environment* | Grain-size parameters ($\phi$) | | | Number of samples |
|---|---|---|---|---|
| | $\mu$ | $\sigma^2$ | $S_k$ | |
| I | 2.69 | 1.00 | 3.17 | 22 |
| IIa | 1.34 | 0.71 | 1.79 | 13 |
| IIb | 1.87 | 0.88 | 1.97 | 9 |
| IIc | 2.13 | 1.93 | 1.64 | 34 |
| IId | 2.90 | 1.06 | 2.63 | 27 |
| IIIa | 1.85 | 1.02 | 0.55 | 14 |
| IIIb | 2.43 | 0.77 | 3.59 | 10 |
| IIIc | 2.59 | 1.69 | 1.90 | 106 |
| IVa | 2.44 | 2.37 | 1.11 | 29 |
| IVb | 3.87 | 2.53 | 0.51 | 29 |
| Va | 6.80 | 1.51 | −0.61 | 60 |
| Vb | 6.45 | 1.85 | −1.37 | 11 |
| Vc | 6.73 | 1.38 | −0.14 | 8 |
| Vd | 6.75 | 1.49 | −0.53 | 28 |
| VIa | 6.59 | 1.69 | −0.76 | 57 |
| VIb | 6.66 | 1.48 | −0.54 | 26 |
| VIc | 6.94 | 1.44 | −0.85 | 56 |
| VId | 6.38 | 1.78 | −0.98 | 23 |

* Locations given in Fig. 8

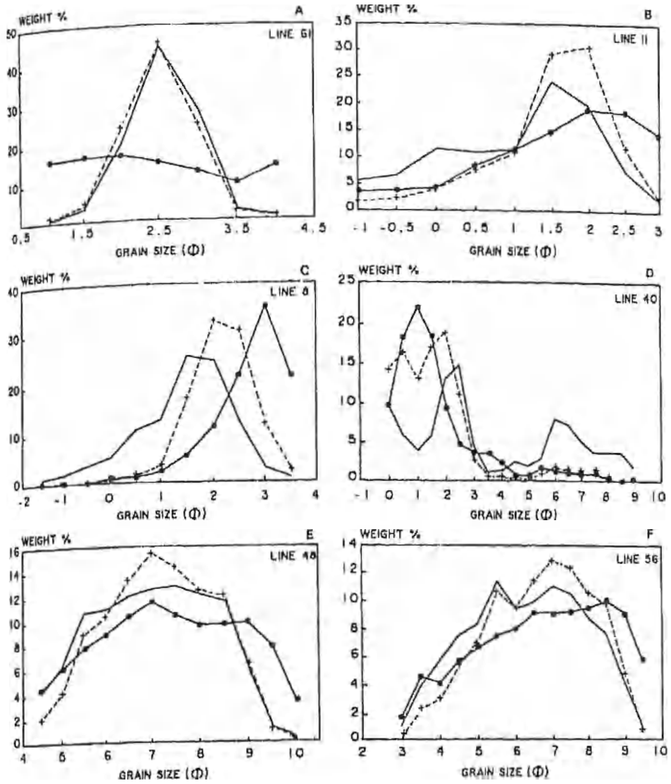


**Fig. 8.** Distribution functions of $d_1(s)$ (solid line), $d_2(s)$ (dashed line and plus signs) and $X(s)$ (solid line and dots), averaged along the survey line, for: (**A**) Environment I; (**B**) Environment IIc; (**C**) Environment IIIa; (**D**) Environment IVa; (**E**) Environment Va; and (**F**) Environment VIa.

sands are finer than at the Nash, with the X-function mode indicating that medium sand (1.5$\phi$) is the size most easily transported.

Lines 11–13 were used to establish the presence of counterclockwise circulatory transport around the Cardiff Grounds. The trends are well defined, whilst the X-function indicates that medium to fine sand (1.5–2.0$\phi$) is the dominant size of material being transported (Fig. 8b).

Analysis of samples up-channel in the Severn Estuary has revealed a downstream transport above Sharpness (Line 36, for IId). Fine sand (2.5$\phi$) is the dominant size being moved.

*Environment III.* This is characterized by sandy material, Case B transport and net accretion; it includes the area to the north of the Nash Sands (IIIa), the outer part of Woodspring Bay (IIIb), and the Welsh Grounds and Bristol Deep (IIIc).

In IIIa, Lines 1 and 3–9 indicate net up-estuary transport, suggesting sand accretion between the Nash Sands and the coastline at Nash Point. The sands are finer than those circulating around the Nash Sands, whilst the X-function is indicative of fine sand (3.0$\phi$) transport (Fig. 8c).

Outer Woodspring Bay is represented by Line 73, where the trend statistics indicate up-estuary transport and that fine sand (3.0$\phi$) is the size of material undergoing maximum transport rates.

The Welsh Grounds and Bristol Deeps incorporate 11 lines occupying the northern side of the main estuarine channel. Lines 23 and 24 include samples consisting of sand and mud admixtures. As they are located within the dominantly sand transport regime and their (up-estuary) transport conforms with other lines, however, they have not been identified as a 'separate' sub-environment. Overall, IIIc exhibits marked trends, supporting up-estuary transport and net accretion. Along all the lines, fine sand (3.0$\phi$) is the material most easily transported, apart from Line 78 (2.5$\phi$) located over the shoaling ground near the Severn Road Bridge.

*Environment IV.* This incorporates mixed bottom sediments, Case C transport and net erosion within two areas: between the Culver Sands and the English coastline (IVa); and the Bristol Deep/English Grounds (IVb).

IVa contains Lines 38–42, indicating westerly transport of sand and mud admixtures. The X-distribution shows coarse sand (1.0$\phi$) to be the dominant size in transport; its modal position indicates erosion (Fig. 8d).

Five lines define IVb, located in the central portion of the Severn Estuary and along its southern side. Similar to IIIb, the trends are dominantly up-estuary. Medium sand (1.5$\phi$) is the dominant size fraction undergoing transport.

*Environment V.* This is identified by its muddy surficial sediments, Case B transport and dynamic equilibrium, this environment includes southern Bridgwater Bay (Va), the area offshore from the River Axe (Vb), inner Woodspring Bay (Vc), and the coastal zone to the north of the River Avon (Vd). Unlike the sand and the mixed transport environments, the mean grain size here does not decrease in an up-estuary direction. The finest mud occurs in southern Bridgwater Bay (6.80$\phi$), whilst the coarsest is offshore and is associated with sub-environment Vb (6.45$\phi$). The mean grain size is everywhere medium to fine silt, with no significant differences in size associated with the sub-environments (Table 3).

In southern Bridgwater Bay, the trends are highly significant, indicating transport from the River Parret. The mode of the X-function lies between 7.0 and 8.0$\phi$ (Fig. 8e). Trends of Lines 59 and 65 in Vb indicate seaward transport associated with the outflow from River Axe; the X-function shows that fine silt (7.0$\phi$) is the dominant material in transport. In Vc (inner Woodspring Bay), mud appears to be associated with the River Yeo. The trend is significant (Line 74; Table 1) and indicates transport in an up-estuary direction.

Lines 75–77 (Vd) show strong trends of transport out of River Avon and up the Severn Estuary. Similar to other mud sub-environments, the mode of the X-function for the three lines is at 7.5$\phi$.

*Environment VI.* This environment VI (i.e. mud, Case B transport, and net accretion) incorporates northern Bridgwater Bay (VIa), the inner River Axe (VIb), the northern coastal zone (VIc); and the area off the River Usk (VId).

Similar to Va, the sample sequences in northern Bridgwater Bay originate near the mouth of the River Parret and fan outwards across the embayment. The X-distributions show that very fine silt and clay are the predominant mobile sizes (8.0 to 9.0$\phi$; Fig. 8f).

Lines 66–68 in VIb suggest an association with the River Axe, whilst fine silt and clay transport dominates.

In VIc, Lines 27 and 28 indicate mud deposition near the narrows (Severn Road Bridge), along the northern side of the Severn Estuary. Transport is up-estuary, consistent with the directions in the nearby sub-environments.

Lines 30–33 indicate a transport regime emanating from the River Usk, trending down-estuary. The X-function is indicative of net accretion.

*Summary.* The distribution of sedimentary environments (described above) compared to areas of outcropping pre-Quaternary rocks (indicative of erosion) represents, in general, dynamic stability. Hence, along the main channel of the Severn estuary and most of the longitudinal axis of the Bristol Channel, erosion is taking place. Accretion is associated generally with the head of the estuary and areas adjacent to the tributary rivers, such as the Parret and Usk. Linear sandbanks, such as the Nash, Culver and Holm Sands, are considered to be in a state of dynamic equilibrium.

## Discussion: comparison with previous investigations

### *Patterns of water movement*

Investigations into residual water circulation and maximum near-bed shear stresses (or speeds) for the Bristol Channel have been undertaken on the basis of current meter observations and seabed drifter recovery patterns (Collins & Ferentinos 1984; Harris & Collins 1985) and numerical modelling (Hamilton 1973; Robinson 1978; Pingree & Griffiths 1979; Owen 1980*a*, *b*; Uncles 1982*a*, *b*, 1984; Uncles *et al.* 1985; Stephens 1986; Wolf 1987). Representative results obtained from the higher resolution (2-D and 3-D) numerical modelling approaches are compared now with transport patterns defined using sediment trends, as follows: (1) residual currents (Owen 1980*a*); (2) residual currents (Uncles 1982*a*); (3) near-bed and mid-depth Eulerian residual water circulation (Wolf 1987 and pers. comm.); and (4) tidally-induced maximum stresses on the sea-bed, resulting from $M_2$–$M_4$ and residual current interaction (Uncles 1984).

A 2-D numerical model to simulate residual currents in the Channel, driven by the $M_2$ tides and combined $M_2$–$S_2$ tides, was developed by Owen (1980*a*). The model used a grid spacing of 1.29 km (east) by 1.37 km (north), with a time step of 30 lunar seconds. Residual currents, due to $M_2$ tides (Fig. 9a), agree with the sediment trends (Fig. 8) in sub-environments IIa, IIc, IIIa and IVa). Poor correlation exists, however, for sub-environments I, IIb, IIIc and Vd, most of which lie close to the river systems.

Eulerian residual currents for the Channel, between 2°37.0'W and 4°58.4'W and using a grid spacing of 3.1 × 3.1 km, have been simulated by Uncles (1982*a*). The model incorporated $M_2$ tides and a typical salinity distribution. Residual water circulation patterns predicted by the model are similar to the sediment trends in IIa, IIc, IIIa and Va. Contradictions exist for I and IIb (Fig. 9b).

A 3-D numerical model, with a grid size of around 1 km, has been used to investigate flows throughout the water column and near the bed (Wolf 1987, and pers. comm.). In comparison to the near-bed flows (Fig. 9c), there is good correlation between the model and the trends in IIa, IIb, IIc, IIIa and IVa. The correlation is poor for sub-environments I, IIIb, IIIc, IVb, Va, Vb, Vc, VIa, VIb and VIc which again are mainly the areas receiving river inputs.

A 2-D model has been used to derive maximum near-bed stresses, due to $M_2$–$M_4$ interaction and other currents (Uncles 1984; Fig. 9d). The model shows the stress to be directed down-estuary over the central (longitudinal) part of the Channel and up-estuary along both the sides. The up-estuary flood-dominated zone increases in width towards the head of the estuary. Such a pattern is similar to that of the sediment trends derived for Bridgwater Bay (IVa, Va and VIa), but is contradictory to those in IIIa, IIc and VId.

All the model results representing water movement include some areas of similarity and some of contradiction with the grain size trends. The inconsistencies are associated mainly with non-linear relationships between the current speeds and sediment transport rates, as described below.

Suspended sediment transport rates can be expressed in terms of current speed multiplied by the concentration of suspended matter, integrated over the water depth. Averaged over a period of time, however, the rate can be decomposed into advective and dispersive terms (Dyer 1974; Su & Wang 1986). Studies in estuarine environments have shown, for example, that some dispersive terms are not small compared with the advective terms (Su & Wang 1986). Hence, the net transport of suspended matter is not controlled, in many cases, by residual water movement or maximum stresses (for example, see Gao *et al.* 1990).

Bedload transport is controlled, primarily, by sediment properties (particle density, size and shape) and superimposed current speeds (tidally- and wave-induced motion and other forms of water movement). This results in a non-linear relationship, such that transport rates are proportional to the $n$th power ($n \geq 3$) of current speed. When averaged over time, the rate is controlled by a combination of advective and dispersive effects. Some deviation between bedload transport and water movement is, therefore, likely. For example, bed-load transport directions have been observed to reverse under the superimposed influence of waves in Swansea Bay (Pattiatrachi & Collins 1984). The same wave action would not cause, however, a comparable reversal in residual water movement.

The Bristol Channel and Severn Estuary combine to create a complicated estuarine system in which, inevitably, sediment transport is influenced strongly by dispersive (non-linear) effects. Apparent contradictions which exist near Bridgwater Bay and the Avon and Usk Rivers appear to represent such an influence; this results from freshwater discharges associated with the tributary river systems, which have not been incorporated into the modelling approaches.

### *Sediment transport pathways*

Various investigations have been undertaken to examine sediment movement in the Bristol Channel, using a variety of techniques (Table 4). Transport pathways defined by previous studies are compared here with the results obtained from the trend analysis, in terms of sand transport and cohesive sediment movement.

(i) *Sand (bed-load) transport.* Sand is present within the system in the form of linear sandbanks, or as thin sand sheets. The Nash Sands (IIa) has been identified previously as a sand ridge associated with tidally-induced (clockwise)

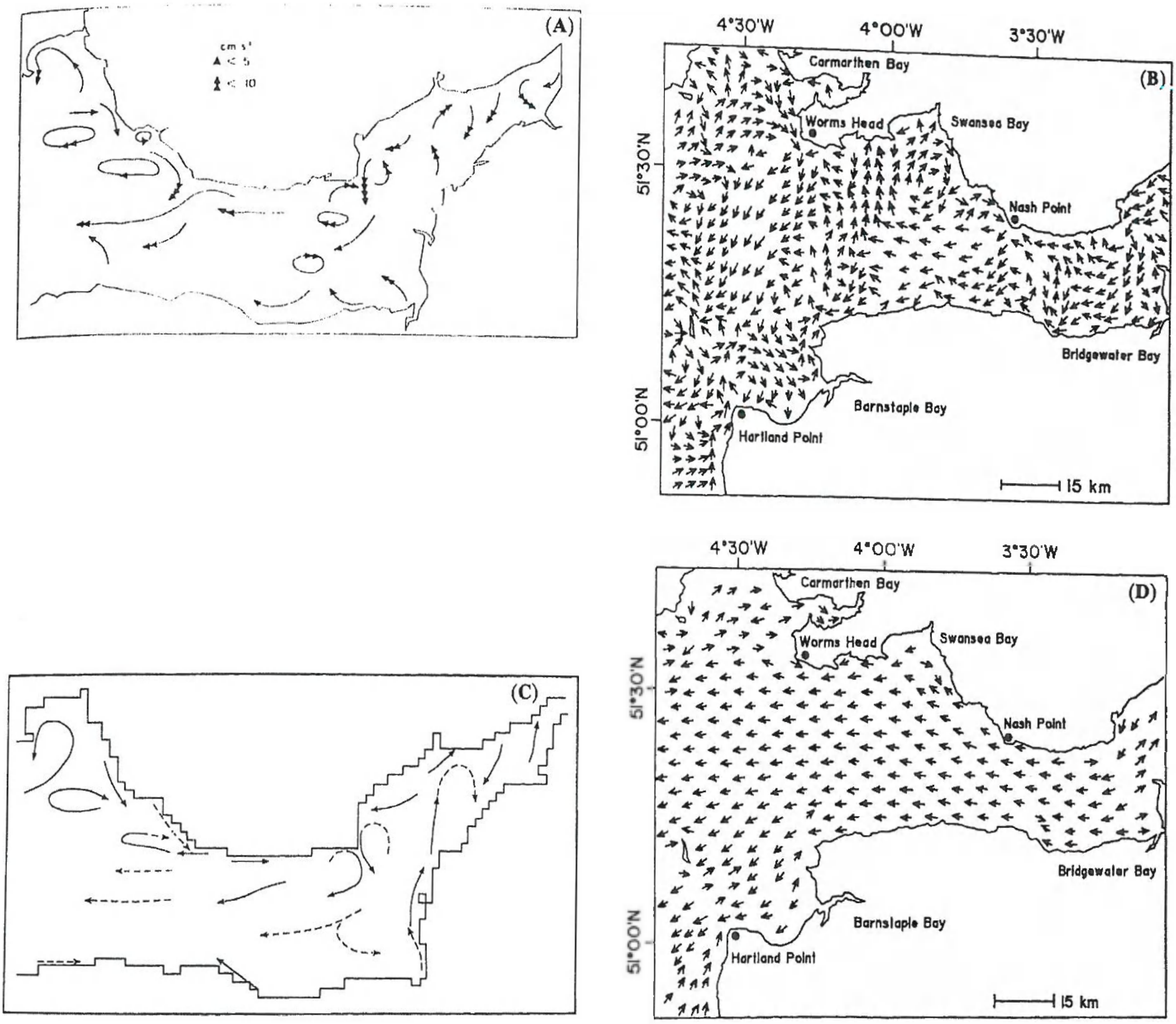


Fig. 9. Schematic summary of numerical model results of water movement in the Bristol Channel and Severn Estuary: (A) 2-D model of residual circulation (Owen 1980*a*); (B) 2-D model of residual currents due to density and non-linear tidal effects (Uncles 1982*a*); (C) the Wolf (pers. comm.) 3-D model of residual circulation (solid arrows represent water movements more clearly defined than those with dashed arrows), based upon a generalized integration of surface, mid-depth and near-bed currents; and (D) 2-D model of maximum bed tidal stress (Uncles 1984).

eddies (Ferentinos & Collins 1980); hence, net transport is to the west along the south, but to the east along the northern flank. Such as a pattern is exactly the same as that identified from the trend analysis.

On Holm Sands (Davies 1980) and Cardiff Grounds (Harris & Collins 1985), clockwise sand circulation is indicated by bedform asymmetries. The trend analysis shows, in contrast, westerly transport to the north of the Holm Sands and anticlockwise sand circulation around the Cardiff Grounds. Such contradictions may result from differences in the spatial scales of the investigations. For example, the lengths of the Holm Sands and Cardiff Grounds are only 1/5 of those of Lines 10, 11 and 12 (Fig. 5). Hence, localized patterns of sediment movement were not identified within samples from the lines representing the spatial scale adopted for this study.

Two models have been proposed to account for Holocene bedload transport patterns: the 'Bedload Parting' (Stride & Belderson 1990, 1991) model and the 'Mutually Evasive Transport' (Harris & Collins 1988, 1991) model.

A bedload parting zone shown by the dotted line on Fig. 10 is believed to extend from Barry towards Bridgwater Bay, along a curved line across the Channel. Associated with this 'feature', net transport of bedload is towards the west in the Bristol Channel and towards the east in the Severn Estuary. Where comparison is possible between this conceptional model and Fig. 6 (Environments V and VI are not comparable, because of the presence of muddy sediments), agreement exists for the upper Severn Estuary and most of the southern part of the area. Contradictions are present in the north, from Hutchwns Point to River Usk. The grain size trends are indicative of up-channel transport along the shoreline, extending from Hutchwns Point to Barry; down-channel transport occurs between Barry and River Usk.

The mutually evasive transport model (Fig. 10) defines

**Table 4.** *Sediment transport investigations relating to the Bristol Channel and Severn Estuary*

| Type of evidence | Author(s) |
|---|---|
| Current measurements | Kirby & Parker (1975); Collins *et al.* (1980); Parker & Kirby (1982); Pattiaratchi & Collins (1984); Parker (1987); Harris & Collins (1988) |
| General water movement | Hamilton (1973); Pingree & Griffiths (1979) |
| Numerical model | Odd (1982) |
| Seabed drifter recoveries | Collins & Ferentinos (1984) |
| Bedform orientations | Stride (1963); Belderson & Stride (1966); Kenyon & Stride (1970); Davies (1980); Ferentinos & Collins (1980); Harris & Collins (1985); Pattiaratchi & Collins (1987); Harris (1988) |
| Sediment distributions | Sollas (1883); Belderson & Stride (1966); Collins *et al.* (1980); Davies (1980); Evans (1982) |
| Heavy mineral distributions | Barrie (1990) |
| Movement of foraminiferal tests | Murray & Hawkins (1976); Culver & Banner (1979); Culver (1980) |
| Trace element fluxes | Chester & Stoner (1975) |
| Geomorphological changes | Mantz & Wakeling (1982) |
| Remote sensing data | Collins (1983); Kenyon (1983) |
| Magnetic fabric analysis | Imienwanrin (1988) |
| Literature reviews | Parker & Kirby (1982); Collins (1983, 1987, 1989); Dyer (1984); McLaren & Collins (1989); |
| Bed load transport pathways | Stride & Belderson (1990; 1991); Harris & Collins (1991) |

ebb- and flood-dominant zones, in terms of net sediment transport. It is essentially similar to the trend analysis results (Fig. 6) for the Nash Sands, along the southern coastline of the Severn Estuary and near Holm Sands. Model and trend analyses contradict, however, in the central part of the Severn Estuary (i.e. over some of IIIc and IVb) and some areas around Culver Sand (IIb) and near Watchet (part of IVa).

(ii) *Suspended sediment transport.* Schematized circulation patterns for fine-grained sediments have been studied and proposed by Parker & Kirby (1982) and by Collins (1983). In the schematic model of Parker & Kirby (Fig. 11a), suspended material is transported up-channel along the northern side of the Severn Estuary, whilst Bridgwater Bay appears to be a sink for fine-grained material. The sediment trend analyses demonstrate (Fig. 6), however, seaward transport within VIc (River Usk) and radial movement from the River Parret (Va and VIa).

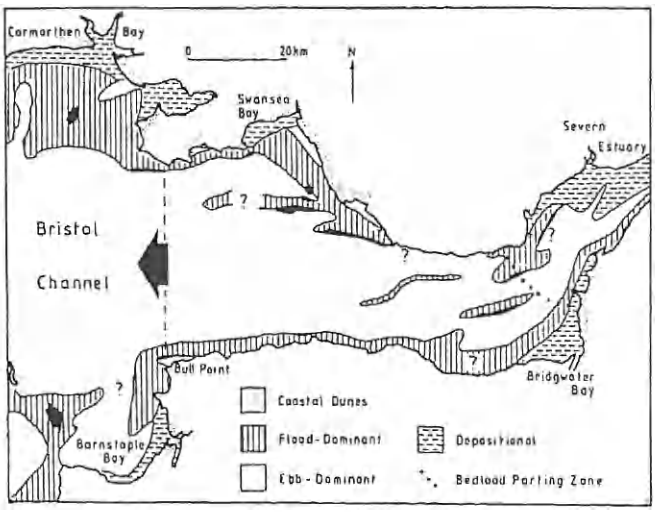


**Fig. 10.** Conceptual models for sand transport in the Severn Estuary and Bristol Channel showing 'bedload parting' and 'mutually evasive transport' patterns (after Harris & Collins 1991).

The model of Collins (Fig. 11b) represents suspended sediment transport in the surface waters. This interpretation agrees with the trend analysis for Va, VIa and VIc, but ambiguities exist in eastern Bridgwater Bay.

Interestingly, in both models, the influence of tributary river inputs is not as marked as indicated by the grain size trends. The latter analysis demonstrates that these rivers (Parret and Usk, in particular) control the net transport paths of fine-grained sediments (Fig. 6). It is worth noticing that such radial transport was not observed at the mouths of Rivers Avon and Wye. This limitation is probably because these rivers are located in the bay-head area, where the relative importance of tidal currents is enhanced and the influence of the freshwater plumes weakened.

In another approach to the problem, magnetic anisotropy data from eight short cores from outer Bridgwater Bay and off Newport and Avonmouth have been used to represent principal and subsidiary grain orientations (Imienwanrin 1988). Long grain axis orientations appear to be influenced not only by the dominant flood-ebb tidal currents in the main channel, but also by the outflows from the Rivers Parret, Usk and Avon.

(iii) *Transport implications.* The contradictions identified above do not necessarily invalidate any particular approach, because of the wide range of time-scales applied. For example, tidal current and wave measurements provide data on a time-scale of $10^{-2}$–$10^{0}$ a, whilst geomorphological investigations relate to time-scales of the order of $10^{3}$ a. Likewise, the two models ('bedload parting' and 'mutually evasive transport') are hypotheses to account for long-term material balance within the system. Both approaches incorporate a wide variety of evidence, representing different time-scales.

Interpretation of grain size trends can, in itself, represent various time-scales; this depends upon sampling depth and technique and accumulation rates. Hence, the time-scale is shorter for an area with high accumulation rates, than for one experiencing minimal accretion or undergoing erosion.

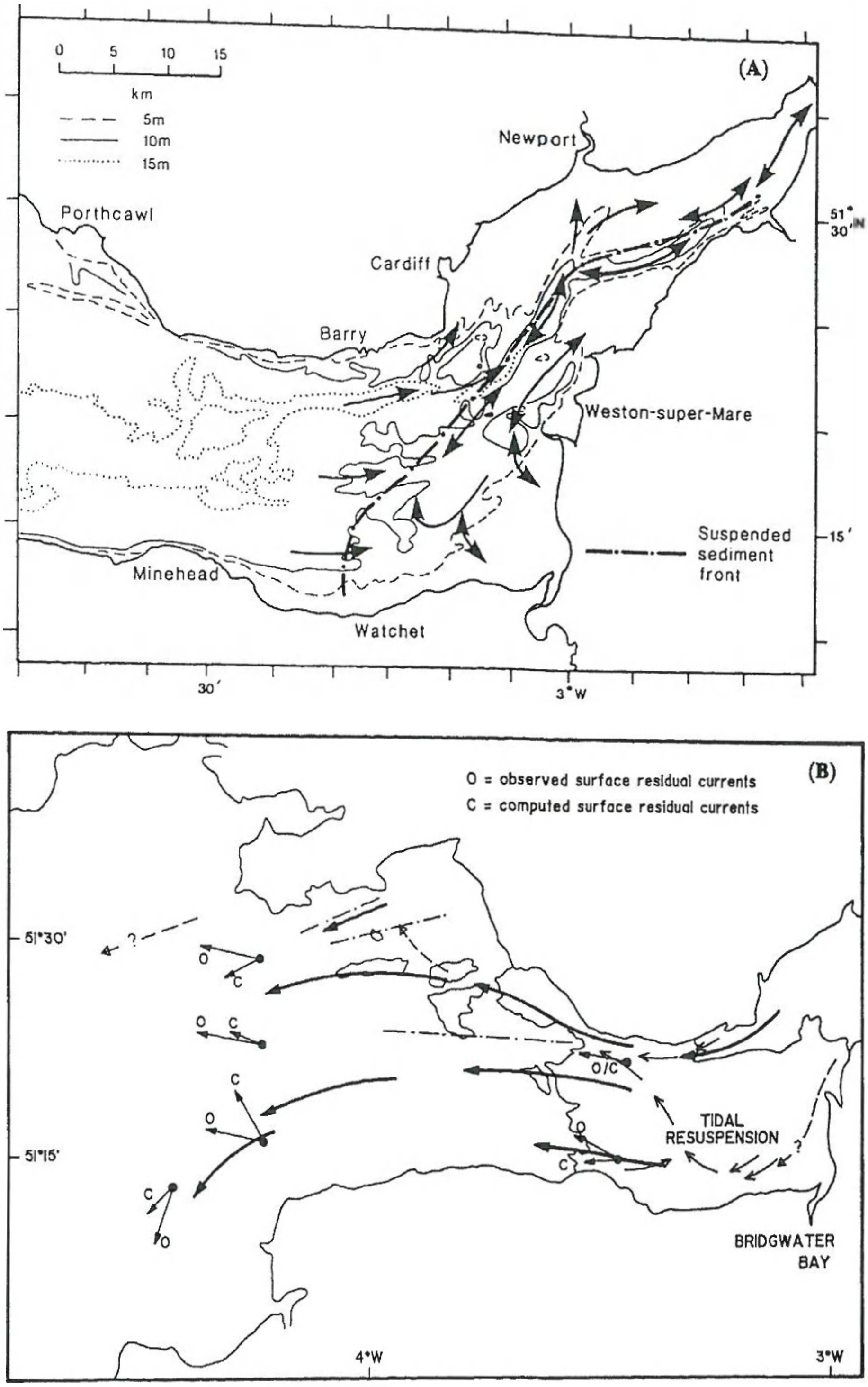


**Fig. 11.** Conceptual models for fine-grained sediment transport in the Severn Estuary and Bristol Channel: (**A**) suspended sediment circulation (from Parker & Kirby 1982); and (**B**) suspended sediment movement in the surface water (thick solid arrows represent transport directions, arrows with dashed line possible directions, and thin solid arrows schematized residual surface water circulation (after Collins 1983).

## *Erosional/accretional patterns*

Major regional depositional areas have been recognized as: (i) inner Bridgwater Bay (Kirby & Parker 1983); (ii) a sub-tidal area within Swansea Bay (Collins *et al.* 1980); and (iii) off the River Usk and inner Severn Estuary (Harris & Collins 1985). These areas are identified also in the grain size trend analysis.

Present deposition rates (over a period of $10^3$ a) in Swansea Bay (near IIIa), Bridgwater Bay (VIa) and in the Newport Deep (VIc) have been measured, using the $^{210}$Pb dating technique (Clifton & Hamilton, 1979). In Swansea Bay, the measured rate was 0.14–0.19 cm a$^{-1}$. There was poor correlation in Bridgwater Bay and Newport Deep between the $^{210}$Pb specific activity and depth within the deposits. Deposits in these areas appear either to be accumulating rapidly or constitute part of an 'unstable' sedimentary system. Other surveys have suggested that areas of Bridgwater Bay are eroding under the present hydrodynamic conditions (Mantz & Wakeling 1982; Kirby 1986). Such localized variations have not been identified in the trend analysis. In summary, there is a consistent pattern between the radionuclide and trend analysis data in two of the sub-environments.

## Conclusions

(1) Net sediment transport pathways for the Severn Estuary and inner Bristol Channel have been defined on the

basis of grain size trend analyses. Ambiguities in the significance test used in the analyses disappear when $p = 1/6$ is used, as a background probability for Case B or C conditions. Hence, the following patterns have been identified: clockwise movement around the Nash Sands; radial transport from the River Parret, to seawards, in Bridgwater Bay; down-estuary transport characterizing the coastal zone, from Barry to Newport, with up-estuary transport dominant over other parts of the Severn Estuary.

(2) Based upon the relationship between the grain size distributions and the transfer function, the dynamic status (i.e. erosional, equilibrium or accretional environments) of areas have been analysed. Combined with facies and transport observations (i.e. Case B or C), this has led to 6 environments being identified: (i) the Nash Passage, Bridgwater Bay and inner Severn Estuary as the main accretional areas (in agreement with previous investigations); (ii) erosion around the Bristol Deep, between the Culver Sands and the English coastline; and (iii) sandbanks mostly in a state of (dynamic) equilibrium.

(3) Areas of poor correlation between the results of previous investigations and the trend analysis are associated mainly with the tributary rivers. Such discrepancies can be caused by non-linear effects between water and sediment movements. Some of the differences can be ascribed to variations in time-scales, but further investigations should address this particular issue.

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