English Channel
Dover Strait
Sediment dynamics
Modelling
Sandbanks

Manche
Pas-de-Calais
Dynamique sédimentaire
Modélisation
Bancs sableux

Sediment transport pathways in the Eastern English Channel

Nicolas T.L. GROCHOWSKI [a] [b], Michael B. COLLINS [a], Simon R. BOXALL [a], Jean-Claude SALOMON [c], Marguerite BRETON [c] and Robert LAFITE [a] [d]

[a] Department of Oceanography, the University, Southampton SO9 5NH, U.K.

[b] Groupe de Recherche Manche, Centre National de la Recherche Scientifique, France.

[c] Institut Français de Recherche pour l'Exploitation de la Mer, Centre de Brest, B.P. 70, 29280 Plouzané, France.

[d] Département de Géologie, Université de Rouen, B.P. 118, 76134 Mont-Saint-Aignan Cedex, France.

ABSTRACT

Sand transport pathways are predicted, by combining outputs from an hydrodynamic numerical model with empirical sediment transport formulae. Tidal simulations, combined with various wind conditions, are compared with patterns presented in the literature. Results show that tides determine the long-term transport pattern in the area; this consists mainly of an ebb-dominated (North Sea towards Channel) mid-Strait region and flood-dominated pathways along the coastlines, which narrow towards the (Dover) Strait. Localised transport paths are identified; these are believed to be responsible partially for the presence of large sandbanks. Superimposed SW and NE wind activity overwhelms the tidally-induced pattern; this occurs infrequently and long-term pattern is not affected. The superimposed effect of surface waves is investigated (but not presented in detailed here); it is shown to be of limited importance.

Oceanologica Acta, 1993. **16**, 5-6, 531-537.

RÉSUMÉ

Transits sédimentaires en Manche orientale

Les directions de transits de sables sont déterminées en combinant des équations empiriques de transport de sédiment aux résultats d'un modèle hydrodynamique numérique. Pour différentes conditions de vent, les directions de transits simulées sur un cycle de marée sont comparées aux schémas connus. Les résultats révèlent que la marée est le facteur dominant de la dynamique sédimentaire régionale, avec un transit dominé par le jusant au centre du détroit du Pas-de-Calais (de la Mer du Nord vers la Manche) et un transit dominé par le flot le long de la côte. Le domaine de transit côtier se rétrécit à l'approche du détroit. Des transits localisés sont aussi identifiés et pourraient être, en partie, responsables de la présence de larges bancs sableux. Les vents de Sud-Ouest et Nord-Est modifient les directions de transits induites par la marée; ceci est peu fréquent et le transit à long terme ne se trouve pas affecté. L'effet surimposé de la houle sur la dynamique régionale est examiné (mais non présenté en détail) et apparaît négligeable.

Oceanologica Acta, 1993. **16**, 5-6, 531-537.

INTRODUCTION

Sediment movement cannot yet be predicted with any precision; this is due mainly to the complexity of the physical processes governing flow-sediment interaction, and the need to monitor all of the parameters involved, at the required frequency (Dyer and Soulsby, 1988). Hence, accurate forecasts of bedload, suspended load (or total load) are difficult to establish. Transport models can be derived on the basis of outputs from hydrodynamic numerical models (*e. g.* Amos and Judge, 1991); they can provide a valuable approach to the simulation or indication of sediment transport directions over a large area, which can be relatively accurate (Mauvais, 1991). Such high spatial and temporal resolution cannot be achieved using traditional geological, geomorphological, or sedimentological indicators (grain size trends, bedform orientation, internal structure of the surficial sediment, *etc.*), visual observations, or direct measurements (Amos and Judge, 1991). Such transport regimes may be investigated also for a variety of hydrodynamic conditions.

The present investigation attempts to delineate long-term transport patterns in the eastern Channel and southernmost part of the North Sea (Fig. 1), and examine the effect of wind and surface waves on tidally-induced transport directions. A series of short-term (*i. e.* single tidal cycle) predictions of bedload transport only are presented here.

Water movement, over the region, is controlled largely by tides (*see* Dyer, 1986): surface streams reach 1.8 m s^{-1}, on spring tides in the Dover Strait. Surficial sediments at the seabed are believed to be relict in response to the Flandrian transgression, consisting mainly of non-cohesive sand, sandy gravel, and gravel material (Larsonneur *et al.*, 1982); these have been formed into large interfingering linear sandbanks, separated by lag gravels (Fig. 1).

METHODS

The general methodology used in the present study, including the sensitivity analysis, has been presented and described elsewhere (Grochowski *et al.*, 1993). Briefly, it consists of combining the instantaneous velocity output of an hydrodynamic numerical model with various sediment transport equations, to calculate transport at each grid point of the model (for each time step). Instantaneous transport rates are vectorially-averaged over a tidal cycle.

Current flow

The 2-D hydrodynamic model used covers the entire English Channel, on a one nautical mile (1,855 m) grid; it is described in detail elsewhere (Salomon, 1991; Salomon and Breton, 1991). The model's outputs are in terms of water levels and instantaneous depth-integrated velocities ($\hat{U}$), for various combinations of wind and tides; this consists of 62 velocity fields over a tidal cycle of 12.4 hours (*i. e.* time step of 12 mn).

To derive current speed near the seabed and the bottom shear stress (τ), from $\hat{U}$, the vertical distribution of currents must be assumed. Here, vertical flow structure up to 2 m above the bed is considered logarithmic, described by the von Karman-Prandtl equation:

$$u_z = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \qquad (1)$$

where u_z is the velocity at a distance z from the bed, κ is the experimentally derived von Karman constant (0.4), z_0 is the seabed roughness length at which u = 0, and u_* is the friction velocity ($u_* = (\tau/\rho)^{1/2}$). Above this logarithmic layer, the velocity distribution is described by a power law:

$$\left(\frac{u_1}{u_2}\right) = \left(\frac{z_1}{z_2}\right)^{1/n} \qquad (2)$$

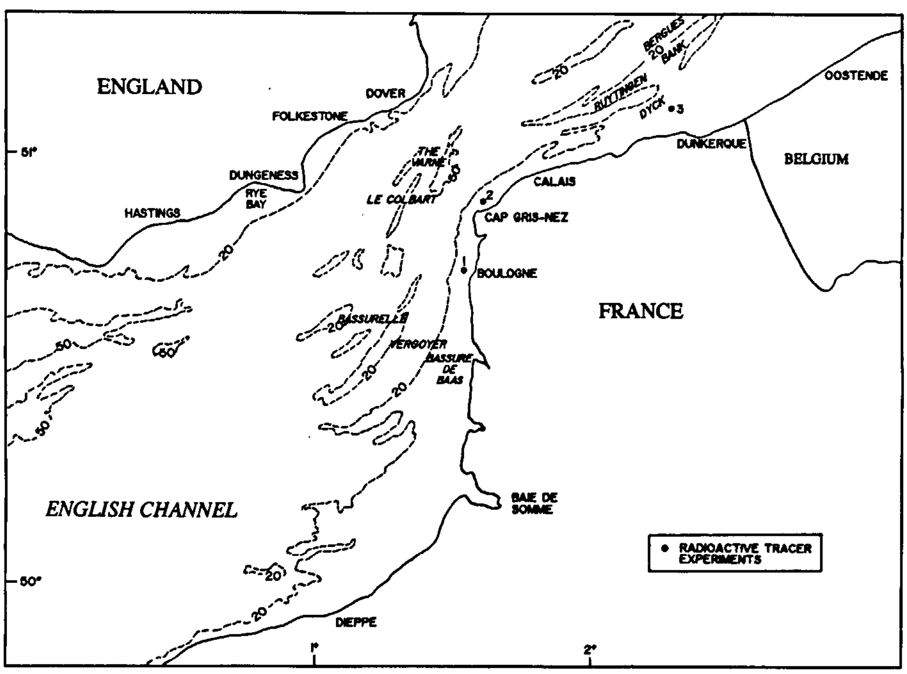

Figure 1

Location map showing major sandbanks and the radioactive tracer experimental sites.

where n = 5 to 10 (Dyer, 1986). van Veen (1938), for instance, has shown that n = 5.2 from more than 500 profiles from the Dover Strait; this is adopted here.

Matching these two distributions at the top of the logarithmic layer (z_1 = 2 m) and writing the friction velocity in terms of z_1, gives

$$u_* = \hat{U}\kappa \left(\frac{n+1}{n}\right)\left(\frac{z_1}{h}\right)^{1/n}\left(\ln\frac{z}{z_0}\right)^{-1} \quad (3)$$

equation (3) was used to obtain friction velocity, u_* and bottom shear stress ($\tau = \rho\,|u_*|u_*$). z_0 is derived from C_{100}, the drag coefficient at 1 m above the bed, using the logarithmic profile *i. e.* $C_{100} = [\kappa/\ln(1/z_0)]^2$. Sternberg (1972) has shown that C_{100} approaches a value near 0.003 for naturally-sorted sand and gravel sediments, regardless of bed configuration (including bedforms of H < 20 cm *i. e.* ripples).

Finally, it should be noted that veering of current along the vertical (due to Coriolis) is not taken into account in the analysis since it is likely to be influenced unpredictably by the presence of sandbanks (*cf.* Soulsby, 1981; Lees, 1983) in shallow waters.

Sediment transport computations

Four transport equations have been selected for use, on the basis of reported results when compared with *in situ* measurements (*see* Heathershaw, 1981; Lees, 1983; van Rijn, 1986). Results of these equations are compared, in places, with those inferred from radioactive tracer experiments (*see* below). It must be emphasised, however, that the aim is not to compare equations, but to establish whether predictions can be used with relative confidence, for the whole area. The formulae of Yalin (1963), Engelund and Hansen (1967), and Gadd *et al.* (1978) were used and described in Grochowski *et al.* (1993), but an additional equation (van Rijn, 1986) is introduced here: it is based on a semi-empirical pick-up function (*E*) and an expression for the jump or saltation length (λ), so that bedload transport is given by:

$$q_b = E\lambda \,;\ \tau > \tau_c \quad (4)$$

$$\lambda = 3\, d_{50}\, D_*^{0.6}\, T_*^{0.9} \quad (5)$$

$$E = 0.00033\, \rho_s \left[\left(\frac{\rho_s - \rho}{\rho}\right) g d_{50}\right]^{0.5} D_*^{0.3}\, T_*^{1.5} \quad (6)$$

where ρ and ρ_s are the water and sediment densities respectively, g is the acceleration due to gravity, d_{50} is the median sediment grain size, T_* is the non-dimensional excess shear stress ($T_* = (\tau - \tau_T)/\tau_T$) and D_* is the dimensionless particle parameter:

$$D_* = d_{50}\left[\left(\frac{\rho_s - \rho}{\rho}\right)\frac{g}{\upsilon^2}\right]^{1/3} \quad (7)$$

The threshold shear stress, τ_T is obtained from Yalin's (1972) modification of Shields' curve.

Superimposed effect of waves

The Strait of Dover is the area least exposed to wave activity around the British Isles: energy is dissipated due to sea-bed friction, when waves propagate through the English Channel and the North Sea. Wave conditions (*see* Table) for the this study have been abstracted from observations made at the Varne Light Vessel (Draper and Graves, 1968), the Bassurelle Light Vessel (Despeyroux, 1985), and offshore of Boulogne (*see* Dewez, 1988) and Folkestone (Hydraulics Research, 1991).

Table

Wave conditions used in the sediment transport computations.

	Wave period (s)	Significant wave height (m)
"Average" wave	5.5	0.75
"Stormy" wave	6.5	2.4
"Annual" wave	7.0	4.2

In the presence of tidally-induced steady current, the superimposed effects of wave can be responsible for a large increase in sediment transport rates. The basic mechanism of transport, under combined currents and waves, is the enhanced mobilization of particles by the stirring action of the waves and transport by the current (van Rijn, 1991). In the present study, the well-documented Bijker (1967) model is used to derive and examine the enhanced bed shear stress due to currents and waves (*see* Heathershaw (1981) and Lees (1983) for a full description of the enhancement factor). The assumption made was that the transport formulae under unidirectional flow conditions remained valid under combined action (van Rijn, 1991). The threshold for sediment movement under combined flows was obtained from Komar and Miller's (1974) expression. Although the detailed results are not presented in this contribution, a generalised interpretation is presented below ("Results").

Sediment grain size

It is accepted that most of the surficial sediment of the English Channel is in dynamical equilibrium with the tidal regime (Curry, 1989), as has been demonstrated by both sedimentological and geomorphological studies (Johnson *et al.*, 1982) and numerical modelling (Pingree and Griffiths, 1979; Salomon, 1991). The area is highly dynamic, however, in terms of particle movement *i. e.* sand, d < 2 mm (Grochowski *et al.*, 1993). As the present study is interested primarily in determining regional transport patterns, a uniform grain size (d_{50} = 250 µm) has been selected for the computations; this is considered as being representative of the sand fraction of the lag deposit (Larsonneur *et al.*, 1982; Barbier, 1986; Augris *et al.*, 1990). Predictions represent, therefore, potential transport rates.

RESULTS AND DISCUSSION

Model calibration

Measured bedload transport rates from radioactive sand tracer experiments (Dewez *et al.*, 1989; Augris *et al.*, 1990;

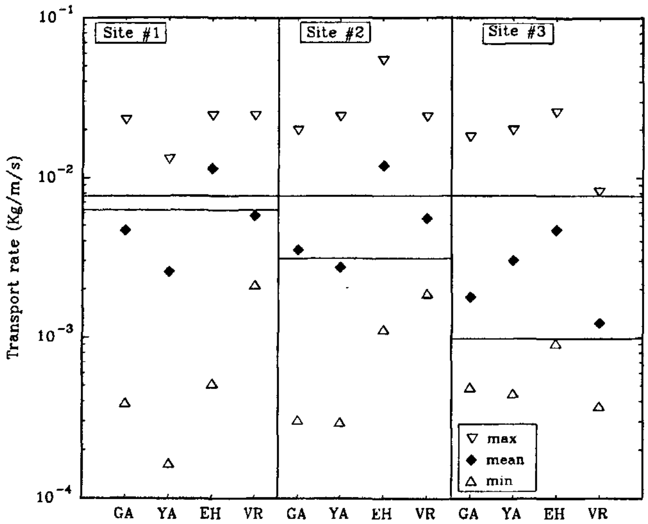

Figure 2

Comparison of maximum and minimum measured (horizontal lines) and predicted "local" transport rates [Key: GA (Gadd et al.*, 1978); YA (Yalin, 1963); EH (Engelund and Hansen, 1967); VR (van Rijn, 1986)]. Both the field experimental and numerical predictions are based upon sediment grain size of between 200 and 315 µm.*

Beck *et al.*, 1991) have been compared with computed rates for the same period. These experiments were carried out along the French coastline, at three sites in water depth of 5-20 m (Fig. 1). Predictions represent a "local" transport rate, around the tracer sites (3 x 5, 3 x 3, and 5 x 7 miles grid for sites # 1, # 2, and # 3, respectively); they include the superimposed effect of "average" wave conditions. The predictions, over these areas, spread typically over one to two orders of magnitude, which is larger than for the experiments (Fig. 2). It appears that Gadd *et al.*'s (1978) and van Rijn's (1986) equations provide the best results, although only marginally. van Rijn's expression is preferred here, on the basis of its theoretical approach and use of a sediment "pick-up" function (*see* Dyer and Soulsby, 1988). Hence, the predictions presented below are based on the applications of this equation.

Tidally-induced transport

It must be emphasised firstly that only single tidal cycle predictions are presented here, so that they apply only for a fraction of the time.

A typical and relatively simple pattern is shown as Figure 3 with a large ebb-dominated mid-strait region, flood-dominated paths along the coastlines which narrow towards the Strait and a bedload convergence along a line running from Hastings to the baie de Somme. These results indicate that sand enters the Channel, from the North Sea, through the central and deepest part of the Strait; this would converge then with sand originating from the central English Channel. The predicted transport pathway along the French coastline will be responsible for some sand being (re)exported towards the North Sea; this is supported by the tracer experiments and may be considered as along-term process. The existence of the ebb- or flood dominated zones are due to inequalities between ebb and flood current speeds (Pingree and Griffiths, 1979): such inequalities, due to higher harmonics in the tidal currents, are enhanced further by non-linear sediment transport processes.

The tidally-induced pattern may be regarded as representing long-term conditions for a number of reasons. The most apparent of these is that, although modulated on a time scale of fourteen-day intervals, the tide is reinforcing constantly its action. Indeed, similar results (not presented here) have been obtained for mean and neap tides: although the pattern is maintained, the magnitude of transport decreases with tidal current strength. Moreover, as the weather/wind conditions can be considered calm over about 50 % of the year, the tidally-induced pattern should not be disturbed over this period. The derived pattern agrees well with regional information inferred from geological indicators and tracer studies, as compiled and redefined recently by Dewez *et al.* (1989).

In comparison with previous interpretations, the results presented here provide an increased resolution which shows features not described before, *i.e.* the narrow flood-dominated pathway along the English coastline (suspected by Dewez *et al.*, 1989), and a number of localised paths or gyres associated generally with sandbanks (Fig. 1). There appears to be a genetic relationship between most of the sandbanks and the gyres, with the banks being the consequence of rotatory motion. This relationship has been demonstrated elsewhere by Owen (1980), using numerical modelling for the Bristol Channel. The primary cause of such eddies could be due to interaction between the rectilinear tidal currents and abrupt changes in seabed topography (*i.e.* gyres and associated sandbanks in the middle of the Strait are on the edge of central trough, Fig. 1); or coastal irregularities and constrictions [*e.g.* the Dover Strait (Ferentinos and Collins, 1979; 1980)]. The

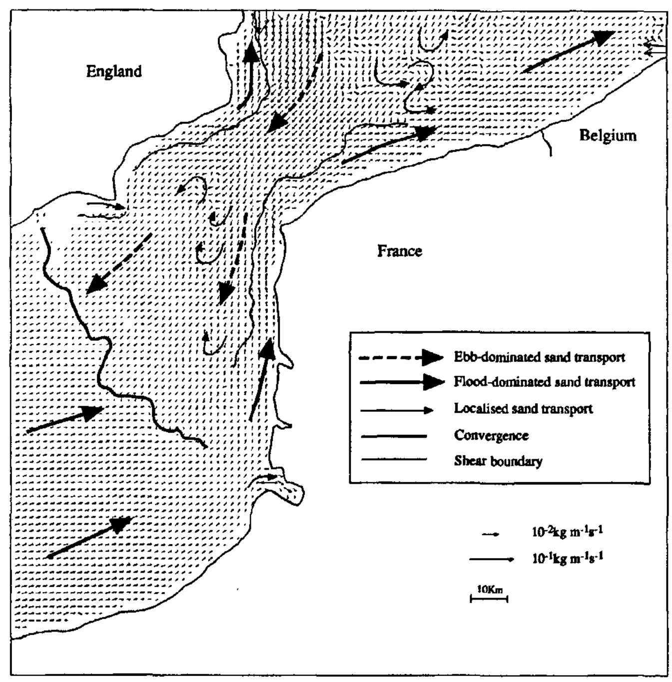

Figure 3

Predicted sediment transport vectors (250 µm) for a mean tide, with no wind, using van Rijn's (1986) equation.

sedimentary characteristics of the sandbanks represent also the continuous eddy mechanism, which sort and concentrate the dispersed sands. The sandbanks are composed generally of well to very well sorted sands, while the surrounding seabed consists of a coarse lag deposit (*see* Hamblin, 1989). Deposition occurs within the central part of the gyres, due to a reduction in the magnitude of current speeds and bed shear stresses. The permanence of the sandbanks here suggests also that waves have a limited destructional effect and that the predictions are consistent with observations. The existence of sand ridges imply also that there must be an adequate sediment supply. In this case, the availability of sand could be met by the presence of the bedload convergence zone.

Wind effects

Long-term records of wind speed and direction show that SW and NE winds dominate throughout the whole year. The strongest wind are from SW, but NE winds may be important during spring (Barbier, 1986; Clique and Lepetit, 1986). Likewise, the homogenous mean wind-stress field and the steady-state approximations have been shown to be satisfactory for the region (Oerlemans, 1978).

The main effect of the SW wind (Fig. 4) is to reinforce the general residual movement towards the North Sea (*cf.* Postma, 1990; Salomon and Breton, 1991); at the same time, the localised features described above have disappeared. In contrast, a NE wind is predicted to enhance transport in the ebb-dominated central region and to narrow the coastal flood-dominated pathways, especially along the English coastline (Fig. 5). The bedload convergence still occurs and is only slightly shifted towards the south. The pathway along the French coastline has almost disappeared but has been established as permanent by the tracer experiments; the influence of the NE wind (occurring only 10 % of the time) must be limited.

Interpretation of sidescan sonar and seismic surveys (Hamblin, 1989) indicates that to the southwest of Dover Strait, net bedload transport is towards the North Sea. SW winds (occurring ~ 20 %) appear to have, therefore, a noticeable impact on the long-term transport pattern i.e. the bedload convergence would be mobile, between Dungeness and its (tidal) location shown on Figure 3, depending upon wind conditions. This interpretation does not agree with the location provided by Dewez *et al.* (1989) and Beck *et al.* (1991), which is based upon current meter data alone.

Some of the transport paths or areas persist, however, throughout all the simulations; these are in the southern part of the eastern Channel and in the area along the French and Belgian coastlines. As wind conditions for which predictions have been obtained occur over about 30 % of the time, changes in transport pattern imply important activity at the seabed; this includes resuspension events, erosion, and the mobility of the sandbanks. The sandbanks do not disappear, however, during such events; rather, the region can been seen as transient, for the transport or transfer of material. In this case, sedimentary material is available from the bedload convergence zone, but heterogenous material will be brought to (and mixed with) the well-sorted sands of the banks; these will be (re)sorted by repeated tidal action.

Surface wave effects

The predictions (not presented here) indicate that "average" waves have virtually no effect on the regional transport pat-

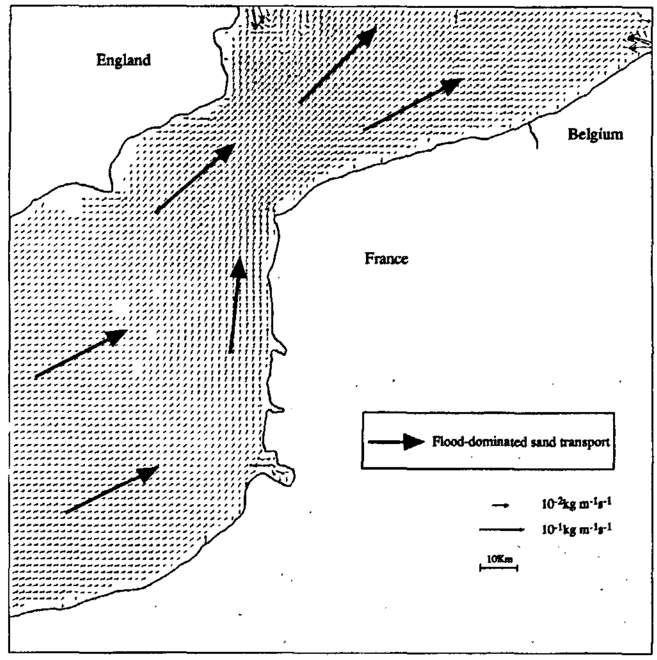

Figure 4

Predicted sediment transport vectors (250 μm) for a mean tide, with SW wind (5 ms^{-1}), using van Rijn's (1986) equation.

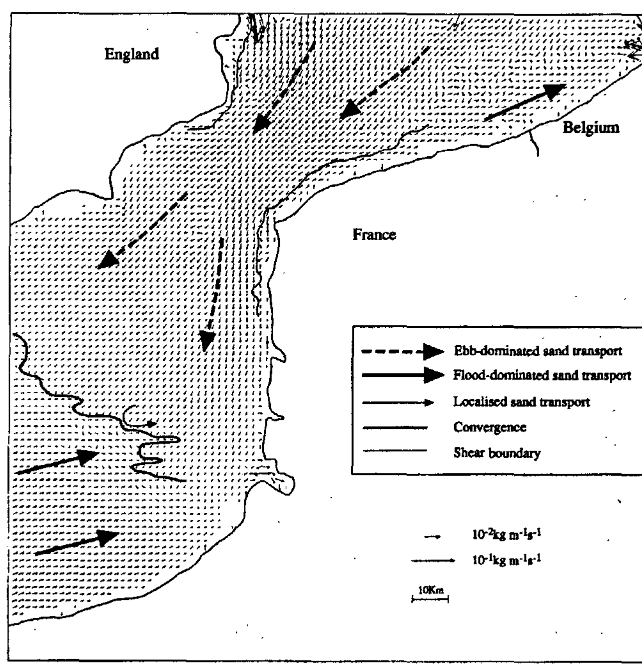

Figure 5

Predicted sediment transport vectors (250 μm) for a mean tide, with NE wind (5 ms^{-1}), using van Rijn's (1986) equation.

tern. The superimposed effect of "stormy" waves is predicted to perturb the pattern, whilst the "annual" wave destroys the tidally-induced pattern. Transport directions are changed significantly only very close to the shoreline (~ 5 m isobath). Overall, the effect of surface waves on regional transport directions can be considered as only of limited importance; their effect essentially increases transport rates with increasing wave energy (*cf.* Pattiaratchi and Collins, 1985) and decreasing water depth.

CONCLUSIONS

1) Tidal action determines largely the long-term transport pattern in the area, this includes a large ebb-dominated mid-Strait region and flood-dominated narrow coastal zones.

2) The main SW and NE winds occasionally overwhelm the tidally-induced pattern, with only the SW influencing long-term patterns (by reinforcing the mean movement and shifting the bedload convergence towards the North Sea).

3) There appears to be a genetic relationship between the presence of localised eddying transport paths and the presence of large sandbanks; this requires further investigation, with a model of finer spatial resolution (in preparation).

4) The superimposed effect of wind-generated surface waves, on the general transport pattern, is negligible.

Acknowledgement

This research was undertaken within the framework of the European Communities MAST (Marine Science and Technology) programme (MAST 0053C, *Fluxmanche*).

REFERENCES

Amos C.J. and J.T. Judge (1991). Sediment transport on the eastern Canadian shelf. *Continent. Shelf Res.*, **11**, 1037-1068.

Augris C., P. Clabaut and O. Vicaire (1990). Le domaine marin du Nord-Pas de Calais (nature, morphologie et mobilité des fonds). IFREMER (France), 96 pp.

Barbier G. (1986). Le littoral de la Région Nord-Pas de Calais: qualité du milieu marin. Report IFREMER/Région Nord-Pas de Calais Conseil Régional, 152 pp.

Beck C., P. Clabaut, S. Dewez, O. Vicaire, H. Chamley, C. Augris, R. Hoslin and A. Caillot (1991). Sand bodies and sand transport paths at the English Channel-North Sea border: morphology, hydrodynamics and radioactive tracing. *Proceedings of the International Colloquium on the environment of the epicontinental seas, Lille, 20-22 March, 1990, Oceanologica Acta*, **vol. sp. 11**, 111-121.

Bijker E.W. (1967) The increase of bed shear in a current due to wave motion. *A.S.C.E. Proceedings of the 10th International Conference on coastal engineering*, **1**, 746-765.

Clique P-M. and J-P. Lepetit (1986). Catalogue sédimentologique des côtes françaises: de la frontière belge à la baie de Somme. E.D.F., Eyrolles, Paris, 11-133.

Curry C. (1989). The rock floor of the English Channel and its significance for the interpretation of marine unconformities. *Proc. Geol. Ass.*, **100**, 339-359.

Despeyroux Y. (1985). Étude hydrosédimentaire de l'estuaire de la Canche. *unpublished PhD. thesis, Université de Lille, France*, 188 pp.

Dewez S. (1988). Sédimentation et dynamique en Manche orientale (de la baie d'Authie au cap d'Alprech). *unpublished Ph.D. thesis, Université de Lille, France*, 276 pp.

Dewez S., P. Clabaut, O. Vicaire, C. Beck, H. Chamley and C. Augris (1989). Transits sédimentaires résultants aux confins Manche-Mer du Nord. *Bull. Soc. géol. Fr.*, **5**, 1043-1053.

Draper L. and R. Graves (1968). Waves at Varne Light Vessel. NIO. internal report A34, 18 pp.

Dyer K.R. (1986). *Coastal and Estuarine Sediment Dynamics.* Wiley-Interscience, 342 pp.

Dyer K.R. and R.L. Soulsby (1988). Sand transport on the continental shelf. *A. Rev. Fluid Mech.*, **20**, 295-324.

Engelund F. and E. Hansen (1967). A monograph on sediment transport in alluvial streams. Technisk Vorlag. Copenhagen, 62 pp.

Ferentinos G. and M.B. Collins (1979). Tidally-induced secondary circulations and their associated sedimentation processes. *J. oceanogr. Soc. Japan*, **35**, 65-74.

Ferentinos G. and M.B. Collins (1980). Effect of shoreline irregularities on a rectilinear tidal current and their significance in sedimentation processes. *J. sedim. Petrology*, **50**, 1081-1094.

Gadd P.E., J.W. Lavelle and D.J.P. Swift (1978). Estimates of sand transport on the New York shelf using near-bottom current-meter observations. *J. sedim. Petrology*, **48**, 239-252.

Grochowski N.T.L., M.B. Collins,J S.R. Boxal and J.-C. Salomon (1993). Sediment transport predictions for the English Channel, using numerical models. *J. geol. Soc., Lond.* (in press).

Hamblin R.J.O. (1989). Dungeness-Boulogne. Sea bed sediments and Quaternary geology (1:250,000 chart, sheet 50°N-00°). British Geological Survey.

Heathershaw A.D. (1981). Comparison of measured and predicted sediment transport rates in tidal currents. *Mar. Geol.*, **56**, 75-105.

Hydraulics Research Ltd. (1991). Coastal defence studies Hyte to Folkestone. Wave recordings October 1990-May 1991. Report EX 2379, 48 pp.

Johnson M.A., N.H. Kenyon, R.H. Belderson and A.H. Stride (1982). Sand transport. in: *Offshore Tidal Sands. Processes and Deposits*, A.H. Stride, editor. Chapman and Hall, London, 58-94.

Komar P.D. and M.C. Miller (1974). Sediment threshold under oscillatory waves. *Proceedings of the 14th Coastal Engineering Conference, Copenhagen*, 765-775.

Larsonneur C., P. Bouysse and J.-P. Auffret (1982). The superficial sediments of the English Channel and its Western Approaches. *Sedimentology*, **29**, 851-864.

Lees B.J. (1983). The relationship of sediment transport rates and paths to sandbanks in a tidally dominated area off the coast of East Anglia, UK. *Sedimentology*, **30**, 461-483.

Mauvais J.-L. (1991). The role of hydrodynamics in environmental studies: the case of tidal seas. *Proceedings of the International Colloquium on the environment of the epicontinental seas, Lille, 20-22 March, 1990, Oceanologica Acta*, **vol. sp. 11**, 29-45.

Oerlemans J. (1978). Some results of a numerical experiment concerning the wind-driven flow through the Straits of Dover. *Dt. hydrogr. Z.*, **31**, 182-189.

Owen A. (1980). The tidal regime of the Bristol Channel: a numerical modelling approach. *Geophys. Jl R. astr. Soc.*, **62**, 59-75.

Pattiaratchi C.B. and M.B. Collins (1985). Sand transport under the combined influence of waves and tidal currents: an assessment of available formulae. *Mar. Geol.*, **67**, 83-100.

Pingree R.D. and D.K. Griffiths (1979). Sand transport paths around the British Isles resulting from M_2 and M_4 tidal interactions. *J. mar. biol. Ass. U.K.*, **59**, 497-513.

Postma H. (1990). Transport of water and sediment in the Strait of Dover. in: *Facets of modern biochemistry*, Ittekot *et al.*, editors. Springer Verlag, 147-154.

Salomon J.-C. (1991). Hydrodynamic action on benthic macrofauna in tidal coastal zones. *ICES Mar. Sci. Symp.*, **192**, 15-23.

Salomon J.-C. and M. Breton (1991). Courants résiduels de marée dans la Manche. *Proceedings of the International Colloquium on the environment of the epicontinental seas, Lille, 20-22 March, 1990, Oceanologica Acta*, **vol. sp. 11**, 47-53.

Soulsby R.L. (1981). Measurements of the Reynolds stress components close to a marine sand bank. *Mar. Geol.*, **42**, 35-47.

Sternberg R.W. (1972). Predicting initial motion and bedload transport of sediment particles in the shallow marine environment. in: *Shelf Sediment Transport*, D.J.P. Swift, D.B. Duane and O.H. Pilkey, editors. 61-82.

van Rijn L.C. (1986). Applications of sediment pick-up function. *J. hydraul. Engng, Am. Soc. civ. Engrs*, **112**, 867-874.

van Rijn L.C. (1991). Sediment transport in combined currents and waves. in: *Sand transport in Rivers, Estuaries and the Sea*, R. Soulsby and R. Bettess, editors. Euromech 262, Balkema, Rotterdam, 3-15.

van Veen J. (1938). Water movements in the Straits of Dover. *J. Cons. int. Explor. Mer*, **13**, 7-36.

Yalin M.S. (1963). An expression for bedload transportation. *J. hydraul. Engng, Am. Soc. civ. Engrs*, **90**, HY5, 105-119.

Yalin M.S. (1972). *Mechanics of Sediment Transport*. Pergamon, Oxford, 248 pp.