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Sediment exchanges between the Seine estuary and its adjacent shelf

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Abstract: The study of sediment dynamics within the Seine estuary and its adjacent shelf permits some conclusions regarding sediment exchanges in this coastal zone. On the shelf, sediment transport is directed toward the Seine estuary and contributes to the infilling of the estuary by marine sands and muds; these were originally derived from land carried to the shelf at times of lower sea level, and subsequently transported shoreward by dominant tidal and wave-induced currents. In the estuarine section, tidal processes form a turbidity maximum both by inducing strong bed resuspension and by trapping fluvial and marine sediments due to flood current predominance. Occasionally this turbid zone extends seaward during periods of river floods, and sediment is redispersed onto the shelf. This phenomenon has been amplified by man-made modifications of the estuarine morphology. However, currents patterns tend to retard the natural seaward escape of fluvial material, mainly due to dredging operations at the present time. Thus, man has changed the natural role of the estuary from a sink to a source of fluvial sediments for the shelf. A tentative sedimentary budget is proposed, taking into account the various sources of material and the complexity of sediment dynamics.

Among the most important sedimentological functions of estuaries is that they provide a natural basin for the storage of sediments supplied from both the land and the sea. The adjacent coastal embayments also constitute sediment traps in a few cases, but are mainly transitional sedimentary areas, subjected to the combined action of waves and tidal currents which control erosion, transport and deposition. The understanding of estuary–shelf interrelationships is often an intricate problem which must take into account the different sources and transport patterns of sediments.

The Bay of Seine is the largest embayment along the southern coastline of the English Channel receiving the largest river in this area (Fig. 1). In the Seine estuary, previous studies indicate deposition of sediments from both fluvial and marine origin since about 8500 BP, due to the Flandrian transgression (Lefebvre *et al.* 1974; Lefebvre 1977). At the present time, the estuary is almost entirely filled in. The mechanisms controlling the accumulation of sediments in the recent years have been studied by Rajcevic (1957), Vigarié (1965), Germaneau (1968, 1969, 1971) and recently by Avoine and colleagues (Avoine 1981; Avoine *et al.* 1981, 1986*b*). In this part of the English Channel, the combination of tidal currents and wave action resulting in the mobility of offshore sands and, on the other hand, the significant river inputs, contribute together to create high rates of sedimentation within the estuary. Man-made modifications have amplified this phenomenon by producing large geometric changes (Avoine *et al.* 1981).

The objectives of this paper are (1) to review our present knowledge on the sources and transport pathways of suspended and bedload sediment in the Seine estuary and adjacent shelf, (2) to attempt to develop a sediment budget in the coastal margin taking into consideration the sedimentary dynamics of the entire area and estuary–shelf exchanges.

Regional setting

Bathymetry and morphology

In the Seine estuary, the present morphology is entirely artificial. The estuary is funnel-shaped, and width and cross-sections decrease exponentially upstream from the mouth (Fig. 2B). The main channel is surrounded by jetties which separate it from the adjacent shoals. The channel depth is generally constant and maintained by dredging at −5 m below MLWS. Extensive tidal flats and marshes have developed behind the jetty north of the channel.

The main stages of the estuarine-training, described in detail by Avoine *et al.* (1981), have accelerated sedimentation rates in the estuary, and provoked a seaward migration of the zones of high sedimentation as the upper parts of the estuary were filled. At the present time, tidal flats and marshes have accreted almost to the high tide level. These modifications have caused spectacular effects, for example in the reduction of the volume of the estuary. In 1834, between the mouth and Tancarville, 30 km upstream, the total volume was $1.6 \times 10^9\,m^3$ (below high spring tide). By 1978, this volume had been reduced by almost 50% to $0.84 \times 10^9\,m^3$. Filling, at the rate of $5.3 \times 10^6\,m^3$ per year since 1834, still occurs in the lower part of the estuary. Between 1959 and 1980, the average volume reduction was $4.5 \times 10^6\,m^3$ per year. If this rate is maintained, the estuary outside the trained channel might be entirely filled within 50 years.

The estuary debouches into the Bay of Seine, a $4000\,km^2$ rectangular embayment along the southern coast of the English Channel (Fig. 2A). The Bay of Seine is <45 m deep. From the mouth of the estuary, the sea floor falls away gradually ($1\,m\,km^{-1}$) northwards. The main bathymetric features are a submarine trough (Le Parfond)

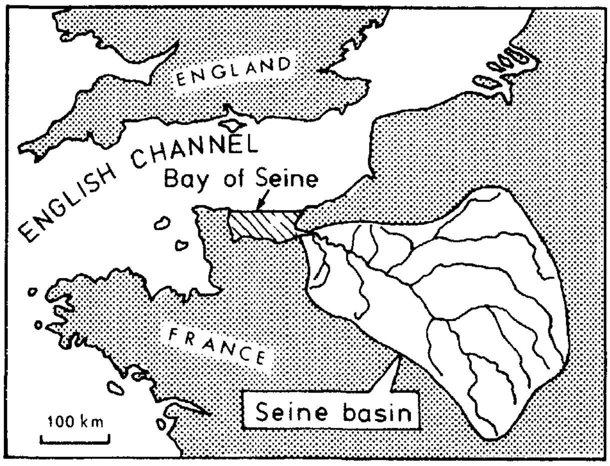

Fig. 1. Location of the study area.

oriented NW–SE which is incised up to 15 m below the adjacent shelf and corresponds to the palaeo-Seine valley (Auffret *et al.* 1980), and a few isolated linear sand banks: for example the Banc de Seine situated adjacent to the Parfond trough and several sandbanks in the western bay.

River inputs

In the Bay, the present supply of fluvial sediment is dominated by that from the Seine River, which has a mean annual discharge of $435\,m^3\,s^{-1}$. River flow varies seasonally, with a well-defined flood season between December and May, and a low flow period from June to November. Instantaneous flow values vary from a maximum of $2000\,m^3\,s^{-1}$ during extreme floods to a minimum of $100\,m^3\,s^{-1}$ in summer.

The Seine River supplies a large quantity of suspended silt and clay to the estuary. Suspended sediment concentrations determined monthly during the past 10 years from samples collected at Poses, 160 km upstream of the mouth, show a mean annual influx of 5×10^5 t (dry weight). It attains 1×10^6 t during wet years and can fall as low as 2×10^5 t during dry years. A daily sampling programme has shown that the influx of fluvial suspended sediment varies closely with river discharge (Avoine 1986); 75% of the total annual suspended load is carried during river floods. In contrast, transport of sediment as bedload is poorly documented, but can be considered as negligible (Vigarié 1965).

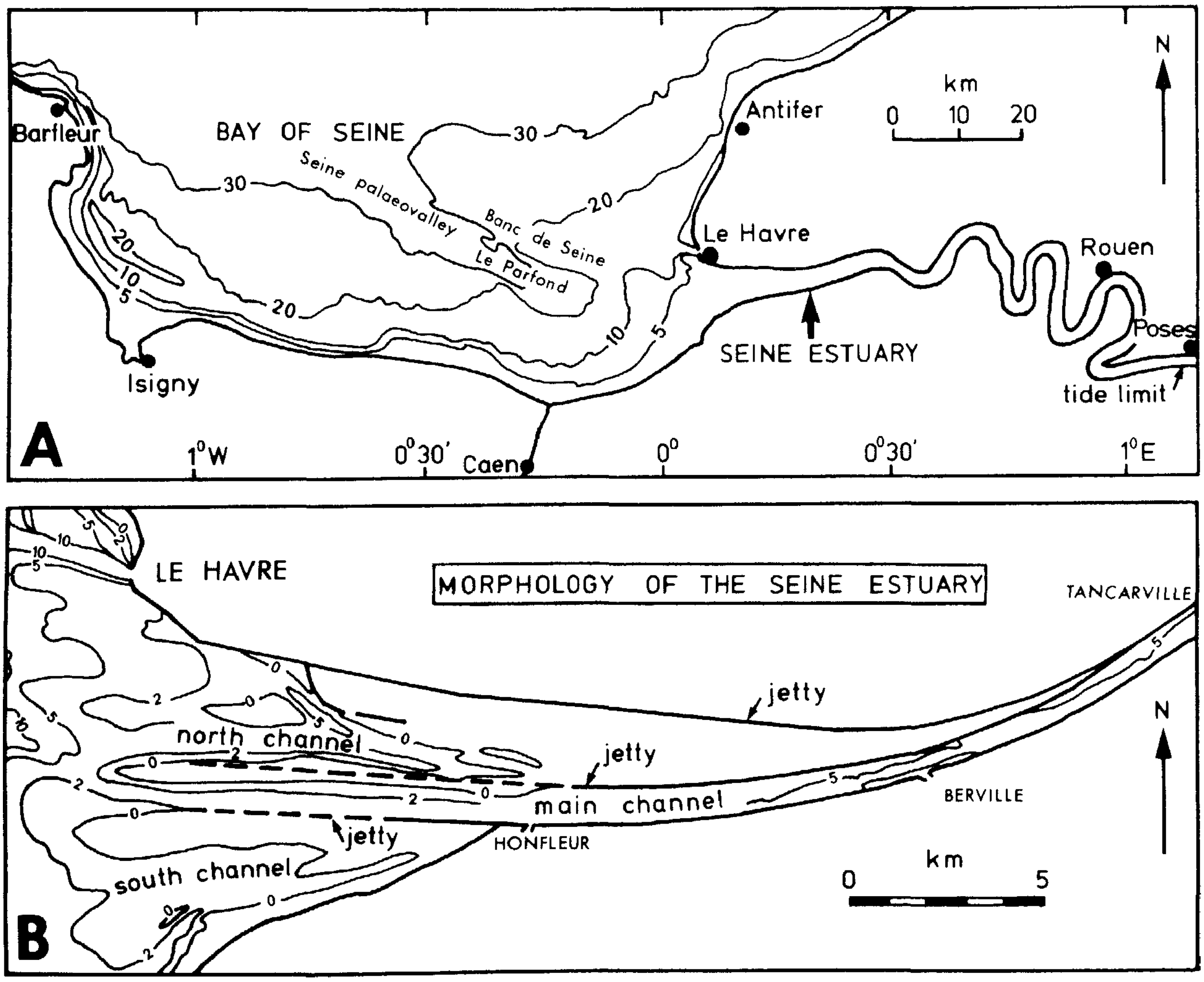

Fig. 2. A General bathymetry of the Bay of Seine; **B** Morphology and bathymetry of the Seine estuary. (Contours intervals in metres below MLWS.)

Physical oceanography

Salinity characteristics

Salinity distributions permit the division of the Bay of Seine into two distinct areas: the western part, which is dominated by strong penetration of saline waters from the English Channel along a NW–SE axis, and the eastern part, which is greatly influenced by river runoff (Avoine *et al.* 1984*a*; Le Hir *et al.* 1986). Seasonal variations in salinity seaward of the Seine estuary are related to the annual cycle of river flow. During floods, fresh water passes across the bay in two predominant directions, westward and northward, as far as the northern limit (Fig. 3). Strong vertical salinity gradients have been measured in the estuary mouth and on the shelf. From numerical model data, it has been shown that such floods are responsible for a density-induced circulation of estuarine-type with a two-layer flow (Le Hir *et al.* 1986 and Fig. 5).

Within the Seine estuary, the salt intrusion extends up to 40 km from the mouth during periods of low river discharge, and 20 km during floods (Avoine 1981). It must be noted that during the past decades, the upstream limit of the salinity intrusion has migrated seawards in response to the seaward extension of the training jetties (Avoine *et al.* 1981). This downstream migration is probably due to the increase in flow velocity associated with a volumetric reduction of the estuary. Within the jettied channel, the estuary is generally partially to well-mixed, according to the river discharge fluctuations and the neap-spring tidal cycles as shown in other macrotidal estuaries by Allen *et al.* (1980).

Tides and tidal-induced currents

General characteristics of tides in the English Channel are given by Chabert d'Hières & Le Provost (1978). As it propagates from West to East, the tidal wave becomes asymmetrical in very shallow coastal waters, and the duration of the flood tide is markedly shorter than that of the ebb. At the same time, a slack-water period of about 2 h duration occurs at high tide.

The Bay of Seine is macrotidal with tidal range varying from 3 m at neap tide to 7.5 m at spring tide. In the Seine estuary, this large tidal range, in comparison with the relatively shallow depths, maintains and amplifies the friction asymmetry of the tidal wave as it propagates upstream. The Seine estuary is tidally hypersynchronous (Le Floch 1961), that is, the tide range attains a maximum within the estuary (8 m in spring tides). The tide extends upstream to Poses, where it is stopped by a weir.

Tidal currents are strong in the Bay of Seine and Seine estuary. The general characteristics of the water circulation have been described by several authors on the basis of hydrological measurements, self-recording current meters, drifter releases and numerical models (Le Hir *et al.* 1986; Salomon 1981, 1986; Salomon & Le Hir 1981; Thouvenin & Salomon 1984).

In the bay, the tidal current system, influenced by the general movements of water in the English Channel, is deflected toward the coasts and the Seine estuary. Current velocities decrease gradually from the West to the East. In the western part, currents are strongly rectilinear, with mean velocities attaining 1 m s^{-1}, and tidal excursions of the order of 20 km on spring tides. In the eastern part,

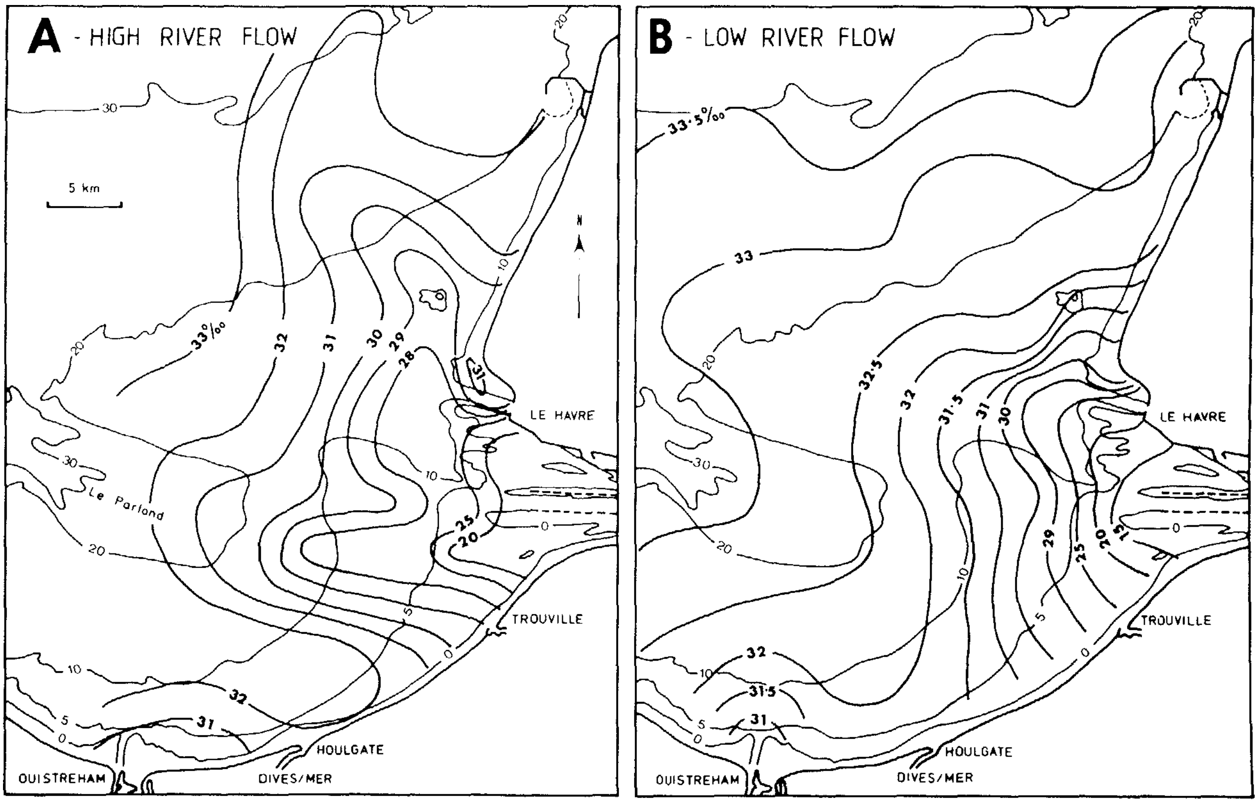

Fig. 3. Eastern part of the Bay of Seine: surface salinity distribution (‰) at low tide, during high river flow (A) and low river flow (B).

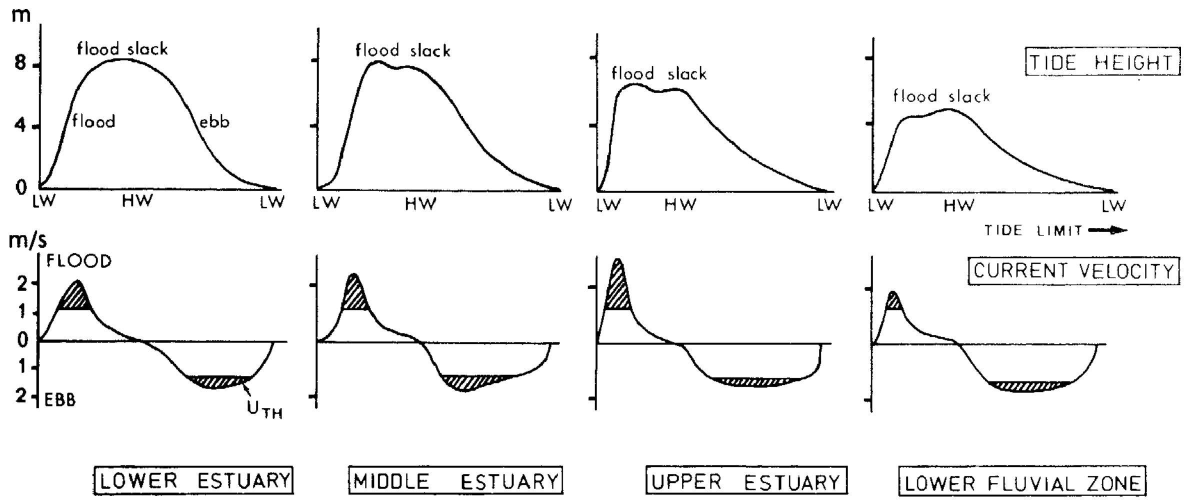

Fig. 4. Schematic diagram of time–height and time–velocity asymmetry in the Seine estuary.

directions rotate about an ellipse oriented E–W, and tidal excursions are only 6 to 8 km, with current velocities decreasing from 0.75 down to 0.50 m s^{-1}. Towards the shoreline, the ellipses flatten, the currents are bidirectional and run parallel to the southern and eastern coasts. In the entire bay, an asymmetry in peak tidal flows occurs, corresponding to the asymmetrical tidal wave, with flood currents being of shorter duration but stronger than the ebb currents.

Within the estuary, this asymmetry is further amplified and the distribution of the tidal wave results in a short, but rapid flood, followed by a longer lasting ebb with lower current velocities (Fig. 4). The predominance of flood currents, which can attain 2.5 m s^{-1}, is particularly marked during spring tides when the deformation of the tide wave is maximal. During neap tides, there is less deformation, and flood and ebb currents are of approximately equal strength.

The entraining of the main flow into a narrow slot-like channel has had a considerable effect on the current velocity distribution. As the tide propagates upstream, the marked reduction in cross-section brings about a local amplification of current velocities (Avoine *et al.* 1981). By contrast, currents on the other side of the jetties are much weaker, and form large gyres during a tidal period (Salomon & Le Hir 1981).

Ebb and flood flow patterns within the estuary also reflect the impact of the training jetties. The marked time–velocity and time–height asymmetry (Fig. 4) brings about maximum flood currents at a higher water elevation than the ebb. Therefore, the maximum ebb discharge occurs when most of the flow is concentrated in the entrained channel, in contrast to the maximum flood discharge, which occurs when part of the adjacent shoal areas are submerged. This effect, described in detail for tidal channels of the Dutch Wadden Sea by Postma (1961), concentrates the ebb flow in the trained channel, and the flood on the shoals and adjacent channels.

Residual water movements

The residual water circulation has been calculated from current data and numerical models of the bay (Le Hir *et al.* 1986; Salomon 1986) and within the estuary (Avoine *et al.* 1981; Salomon 1981; Salomon & Le Hir 1981). In the bay, the residual circulation is influenced simultaneously by three phenomena: tides, salinity gradients and winds. Le Hir *et al.* (1986) have summarized the dominant aspects of the residual movements. Several clockwise eddy systems develop in different parts of the bay. One of these gyres, situated in the NE part, provokes a NW outflow of the Seine River waters towards the English Channel. A two-layer density circulation occurs immediately seaward of the estuary mouth, where salinity gradients are responsible for an estuarine-type net water movement with residual currents oriented landward near the bottom and seaward in surface waters (Fig. 5). This schematic circulation may be strongly disturbed by wind action.

In the Seine estuary, residual water movements have also been affected by the training jetties in addition to the concentration of both the ebb-flow and river discharge in the main channel (Fig. 5). These combined effects provoke a net seaward movement of water in the trained channel at all depths, despite the salinity gradients (Avoine *et al.* 1981;

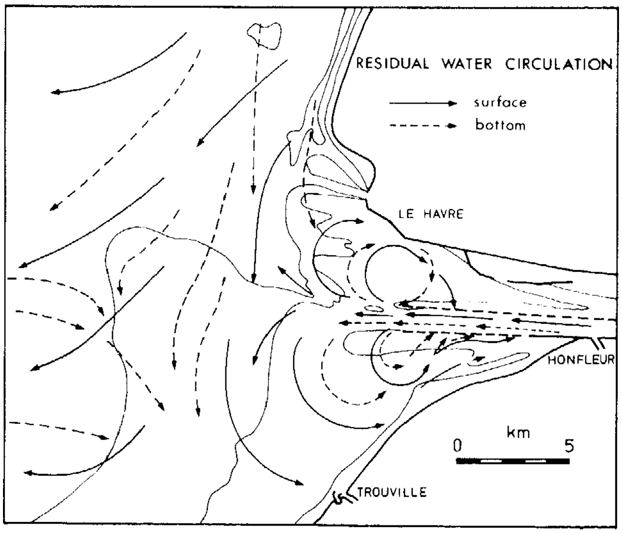

Fig. 5. Schematic diagram of the residual circulation in the Seine estuary mouth, based on current data and numerical models (modified after Salomon & Le Hir 1981).

Salomon 1981). By contrast, circular gyres develop within the estuary mouth to either side of the jetties, and a net landward flow takes place in the adjacent channels (Fig. 5).

Wave characteristics

The Bay of Seine is partly sheltered from the action of the prevailing swells which come from the Western Channel. On the other hand, local wind-induced waves are predominant, from the W to NW sector in the eastern part of the bay, and from the NE in the western part. There is only a little wave data, except seaward of the estuary mouth and near Antifer. In these areas, wave periods range between 4 and 5 s. Statistical studies have shown that the decennial maximum significant wave height is about 5 m, the maximum wave height about 9 m (Laboratoire Central d'Hydraulique de France 1973).

Most of the time, wave action affects the coastal area down to a few metres depth, below which tidal currents generally become predominant (Larsonneur 1971, 1972; Larsonneur *et al.* 1982). During storm events, the effects of waves is much deeper, and the combined action of tidal currents and waves are responsible for most sediment transport processes on the continental shelf (Aloïsi *et al.* 1977).

Sediment distribution

The grain size of bottom sediments decreases from the English Channel toward the Bay of Seine, this being due to a process of reworking and redistribution of pre-Flandrian deposits over the last 7000 years (Larsonneur 1972; Larsonneur *et al.* 1982). Within the bay, sediments are derived from both the eroded Quaternary deposits and from biological production. Their general distribution parallels the decrease of tidal current velocities from the centre of the bay to the coast. The gravelly deposits, which are widely represented, are largely immobile under present wave and current conditions. By contrast, sand and mud are still mobile and are continually readjusting to the fluctuations of the modern hydrodynamic regime, as shown bv a recent survey using side-scan sonar imagery (Auffret & d'Ozouville 1986*a*).

Many aspects of the sediment distribution have been studied in the Seine estuary and the eastern part of the bay (Fig. 6 and Avoine 1981). Within the main estuary channel,

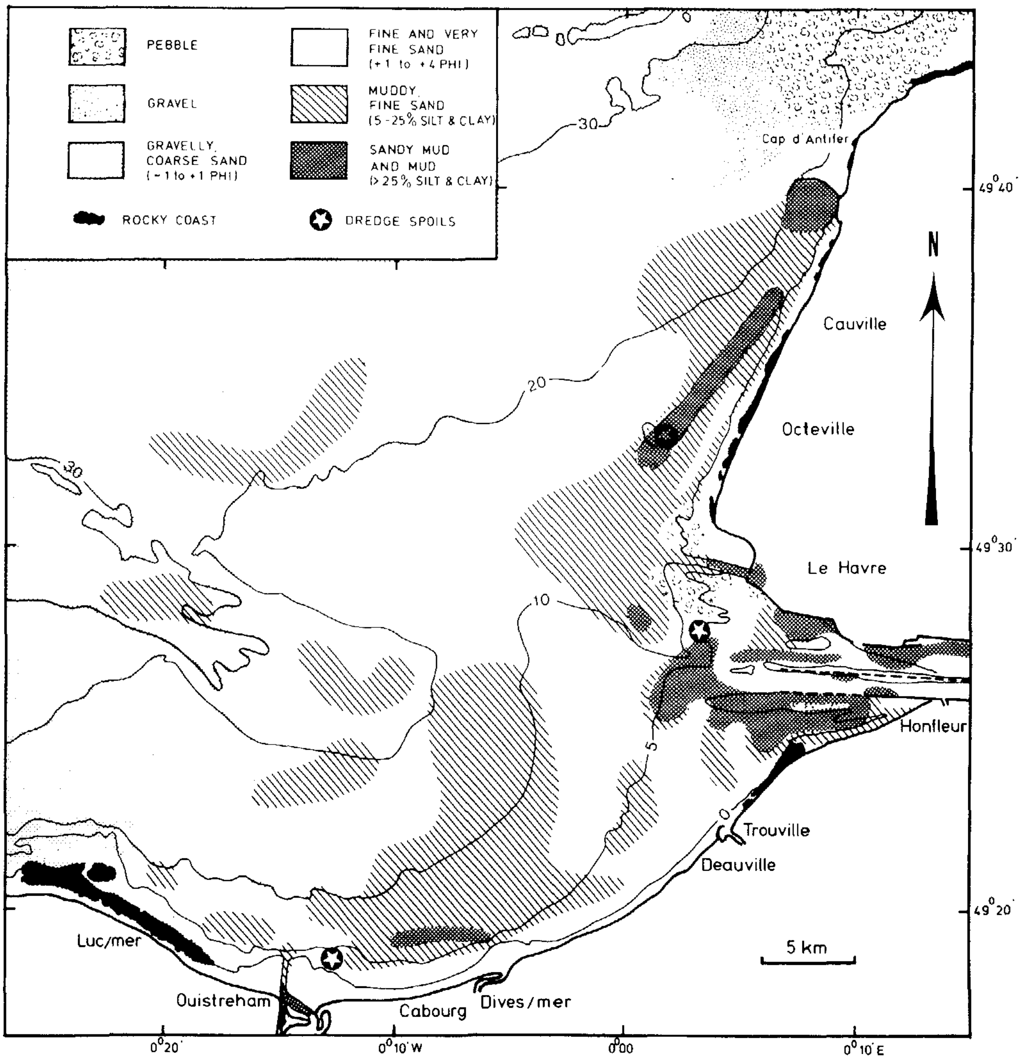

Fig. 6. Distribution of superficial sediments in the eastern part of the bay and estuary mouth.

the deposits are clean fine sand of marine origin (Germaneau 1968, 1971; Lefebvre *et al.* 1974), whilst on the tidal flats and marshes along the northern side, the sediments are mainly thinly bedded silts and clays. In the estuary mouth, sediment patterns are more heterogeneous and patchy. Several mud zones have developed on either side of the channel jetties and seaward of the downstream extremity of the jetties (Fig. 6), showing coarsely interbedded sand–mud sequences.

On the shelf, with the sedimentary pattern corresponding to the decreasing of tidal current velocities toward the Seine estuary, the coarser fraction is represented by gravelly sand, whilst side-scan sonar imagery has shown numerous sand ribbons oriented NW-SE covering a gravelly floor (Auffret & d'Ozouville 1986*a*). The Bance de Seine, a large sand bank situated adjacent to the Parfond trough, represents an accumulation of mobile coarse sand. Fine and very fine sand are found toward the estuary, with several mud zones on either side of the Seine mouth (Fig. 6). It has been noted that the mud zone situated to the SW of the estuary is mainly the result of the present erosion of relict deposits of Holocene age, off Dives/mer (Avoine 1981; Avoine *et al.* 1984*a*). These consolidated silty clays may be eroded by currents and wave action, then redistributed and incorporated in modern deposits. To the N of the Seine mouth, near Octeville, an extensive mud zone has formed, produced by the northward dispersion of dredge spoil from Le Havre harbour.

Sediment dynamics within the estuary

In macrotidal estuaries, tides play a significant role in controlling sedimentological processes (Allen *et al.* 1980). This role is particularly marked in the Seine estuary where the spring tide range reaches 8 m and where a turbidity maximum forms by tidal-current resuspension of sediments from the bed. On every semidiurnal tidal cycle, large quantities of material are resuspended during peak current periods and settle at slack water of the flood tide (Fig. 7). In the main channel, during spring tide and low river flow, the amount of suspended sediment varies from a minimum of 30 000 t to a maximum of 400 000 t with concentrations of 0.1 g l^{-1} and 1 g l^{-1} respectively (Avoine 1981). Thus, the turbidity maximum appears as a transient phenomenon related to tidal currents. Besides the semidiurnal fluctuation of this maximum, there is an up and down estuary movement which reaches 20 km on spring tides (Fig. 7).

Grain-size analysis of material carried in suspension shows three distinct fractions, the nature of which has been determined using a scanning electron microscope. The fine-grained fraction, with a mean size of about 3–5 μm, is formed by individual particles of various sources. The medium sized fraction, from 8–20 μm is composed of aggregated finer particles, whilst the coarser fraction (more than 100 μm) consists of fine sand of marine origin, the aboundance of which is closely-correlated with current velocities. This latter is derived from the marine sands in the estuary, carried as bedload from the shelf and resuspended within the estuary, as shown by a radioactive tracer experiment (Avoine *et al.* 1984*c*).

This tidal resuspension varies with tide range during the neap-spring tidal cycles (Fig. 7). Large-scale erosion and resuspension occurring during spring tides, when current velocities are high, whilst on neap tides, when currents are weaker the turbidity maximum is less developed (Fig. 7). The amount of sediment in suspension between spring and neap tides varies from 2000 000 t to 20 000 t (mean values). In macrotidal estuaries such as the Gironde, recent studies have shown that neap-spring cycles control sedimentation and the seaward escape of suspended sediment (Allen *et al.* 1977, 1980; Castaing & Allen 1981). During periods of decreasing tidal amplitude, the ratio of sedimentation to

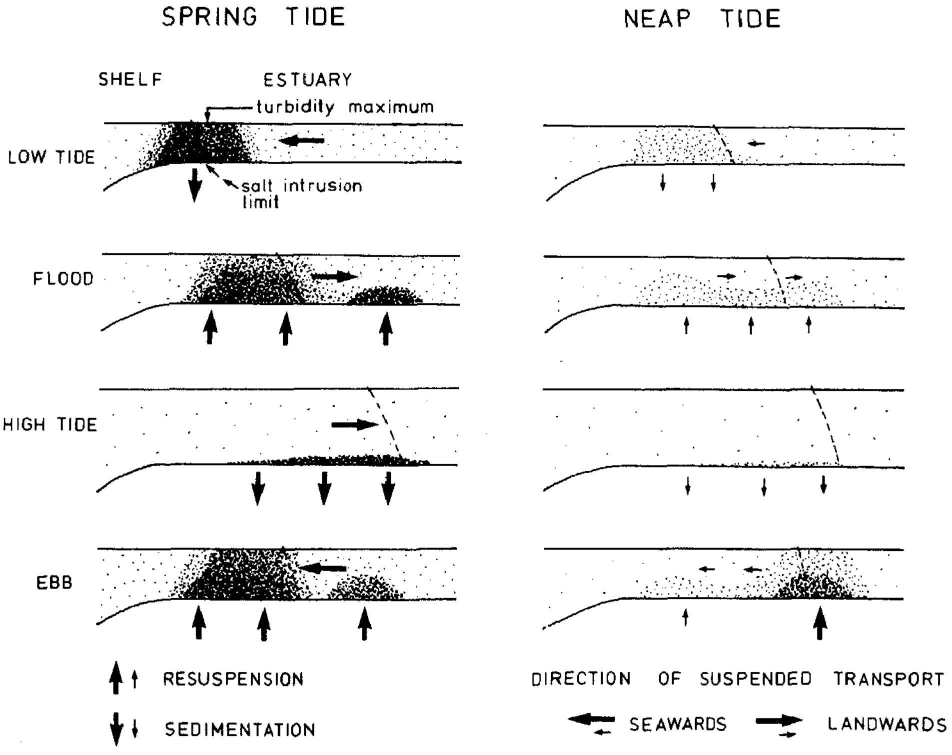

Fig. 7. Schematic evolution of the turbidity maximum along the Seine estuary during a semi-diurnal tidal cycle, at spring tide and neap tide.

erosion increases. Fluid mud forms during neap tides, which then is partly re-eroded when tidal range and velocities increase again. However, in the Seine estuary, fluid mud has not been observed, probably because the suspended sediments are mainly composed of fine sand and silt. A field study using sand labelled with a radioactive tracer has permitted the threshold of grain motion and the beginning of resuspension to be determined in comparison with tidal current velocities. During neap tides, the tracers, with mean sizes of $175\,\mu m$ and $260\,\mu m$, were carried upstream as bedload. During periods of increasing tidal amplitude, these radioactive tracers were easily resuspended when current velocities attained $0.90\,m\,s^{-1}$. Thus, sand appears to be of significant importance in the development of the turbidity maximum. It may be a characteristic feature of macrotidal estuaries in which sediment inputs of marine origin are dominant, as is the Seine estuary.

Within the marginal N and S channels (Fig. 2), current velocities are weaker than in the main ebb channel and resuspension of bottom deposits is less important. The understanding of net sediment transport patterns within the estuary is based mainly on flux measurements in the axis of the different channels (Avoine 1981): seaward transport dominates in the ebb channel, and landward transport prevails in the marginal flood channels (see Fig. 10). This scheme characterizes ebb-tidal deltas (Hayes 1980). No data are available on the residual transport over the shoals but, according to the marked time–velocity and time–height asymmetry (Fig. 4), landward transport must occur over the channel-margin shoals and upper part of the channels, as shown in embayments of similar configuration (Postma 1961; Hubbard & Barwis 1976; Gallivan & Davis 1981). On the whole, the net sediment movement can be considered as directed upstream. This is corroborated by a two-dimensional model (Salomon 1981), indicating that the ebb-flood asymmetry causes an upstream transport of suspended material, creating a tidal sediment trap which maintains the turbidity maximum within the estuary. This phenomenon, independant of the density circulation due to the density gradients between fresh and salt water, has been described in other macrotidal estuaries by Allen *et al.* (1980). It is particularly marked during spring tides and low river flow, when tidal asymmetry is at its maximum. The turbidity maximum appears therefore as a tidally-induced phenomenon which controls sediment movement and sedimentation within the estuary.

It must be noted that over the past 30 years, the turbidity maximum has migrated seaward in response to the seaward extension of the training jetties on either side of the main channel (Avoine *et al.* 1981). This migration, of over 40 km accompanied by the decline in extent of the salt intrusion, has resulted in increasing the seaward escape of fluvially suspended sediment.

Seaward escape of suspended sediment from the estuary

Whilst the development of the turbidity maximum as a sediment trap for suspended sediment is mainly controlled by tidal processes, its location in the estuary also varies seasonally with river discharge (Fig. 8). During periods of low river flow, the turbid zone is maintained within the estuary the amount of sediment in suspension is at a maximum and sediment has a long residence time of up to several months (Avoine 1981). During river floods, the concentration of both ebb flow and strong river discharge in the main channel is responsible for a downstream migration of the turbidity maximum. When the longitudinal to and fro movement within the estuary is large enough, i.e. only at spring tides, the downstream limit of the turbidity maximum is seaward beyond the estuary. Then a turbid plume forms with an offshore gradient of suspended matter concentrations, reaching the Parfond trough, 30 km seaward of the estuary mouth (as shown in a longitudinal section in Fig. 8). Large amounts of material are then carried from the river basin and can be expelled seaward in the upper part of the water column without a temporary stay in the estuary. Under these conditions, the residence time of suspended sediment is very short, less than a week (Avoine 1981).

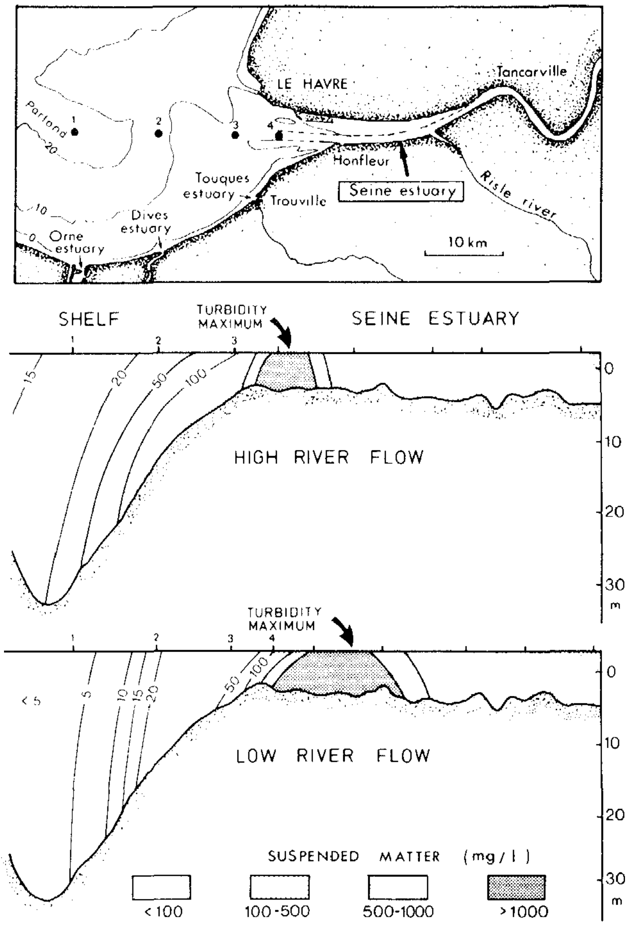

Fig. 8. Longitudinal sections of the turbidity maximum in the estuary mouth and adjacent shelf at low tide, during spring tide, at high river flow and low river flow.

The geometry of the seaward dispersion of suspended sediment from the Seine estuary has been examined on a 50-station grid at different tidal and river flow conditions. Conventional water sampling was employed in order to study the total distribution and the characteristics of suspended sediment throughout the water column. Due to the high turbulence occurring in the bay, vertical suspended sediment concentration profiles were found to be relatively homogeneous. Figure 9 summarizes the basic seasonal variability in spatial distribution of particulate matter in the surface waters at low tide. It appears that during a river

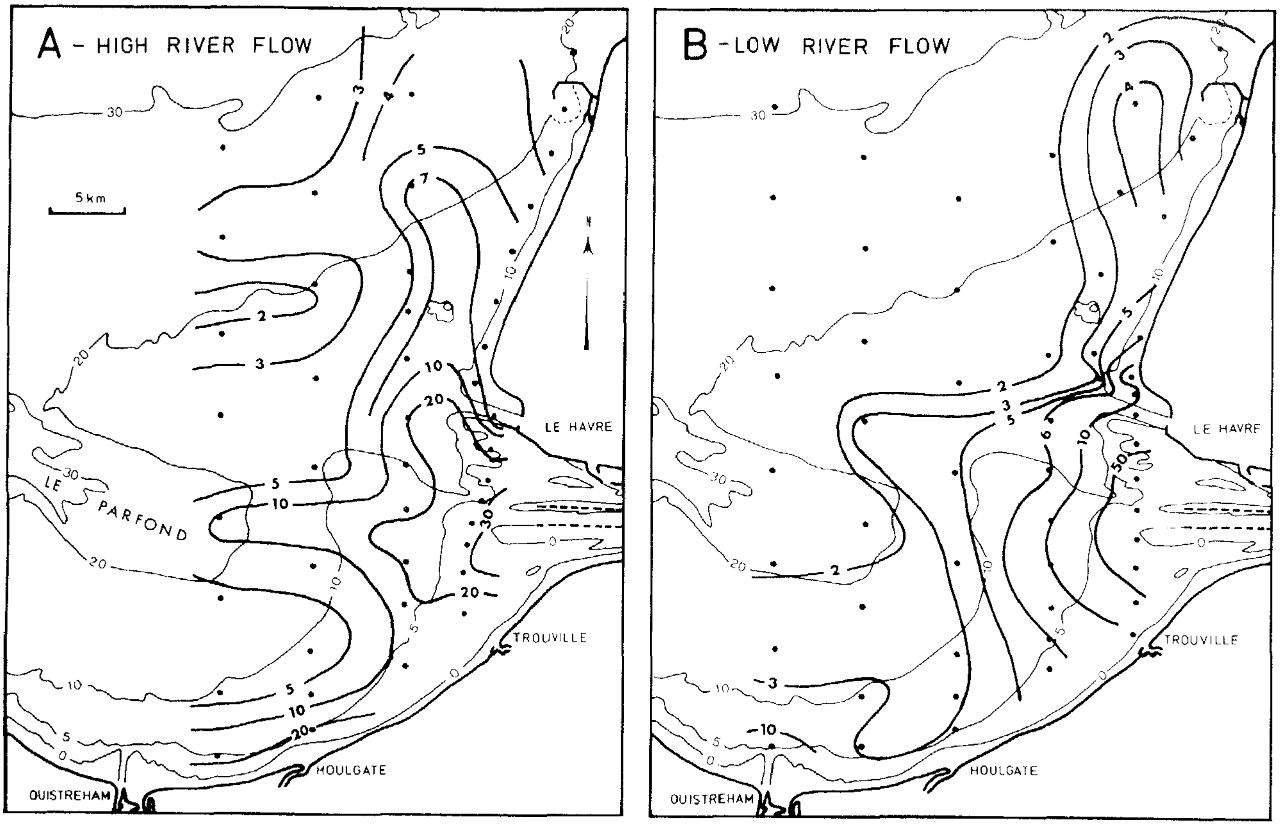

Fig. 9. Total suspended matter concentrations (in mg l^{-1}) in surface waters, at low tide, during spring tide, at high river flow (A) and low river flow (B).

flood, the turbid plume extends W and N along two separate pathways (Fig. 9A), similar to those shown in salinity distribution patterns during the mixing of fresh and salt water (Fig. 3). During low river flow, suspended sediment concentrations are much lower and the turbid plume is limited to immediately seaward of the estuary mouth (Fig. 9B). It must be noted that the prolongation of turbidity N along the coast under low flow conditions is due to the resuspension of mud deposits during the storm event that occurred in this area just before water sampling. The formation of the turbid plume in the bay does not result in the seaward escape of the whole of the suspended load of the estuary during a single tide. Several consecutive tides are required to evacuate the system, a mechanism also described in the Gironde estuary (Allen *et al.* 1974; Castaing & Allen 1981). At every spring ebb tide, the downstream end of the turbidity maximum extends out to the Bay of Seine and turbid waters are dispersed to the N and W by the tidal currents (Fig. 9). At every flood tide, the turbidity maximum re-enters the estuary but has lost a part of the suspended sediment load which has been added to the turbid plume.

In order to determine the suspended sediment transport paths, sediment flux measurements were obtained at different anchor stations located in the estuary mouth and the bay, according to the method of Inglis & Allen (1957). These investigations will be described in another publication and only the main results are summarized in Fig. 10. As shown above, it appears that the amount of suspended material contribution to the coastal shelf zone depends strongly on seasonal variations of the river flow. During periods of high river flow, in spite of a net landward transport in the southern flood channel, the overall depth and width integrated result is a net seaward transport of suspended sediment out of the estuary onto the Bay of Seine, and thence a westward and northward transport path according to the observed turbid plume geometry (Fig. 10A). Large amounts of material are thereby deposited within Le Havre harbour during this period. It must be noted that this natural net northward transport is probably strongly amplified by the continual disposal of dredge spoils (Fig. 11) from Le Havre harbour which in turn are dispersed northward as shown by a radioactive tracer experiment (Tola 1984). Investigation of near-surface suspended sediment concentrations using satellite imagery shows that, during strong river floods, an extensive turbid plume is entrained northward by the net current drift which occurs along the eastern coast, and this diffuses into the Eastern English Channel. (Thomas 1986). Nevertneless, little is known about the total amount of material which bypasses the northern limit of the bay. However, it is probably entrained within the residual water movement dominated in this area by the clockwise eddy system which was first predicted from a numerical model (Le Hir *et al.* 1985).

During periods of low river flow (Fig. 10B), the vertical profile of the residual suspended sediment flux within the estuary mouth shows a strong landward-directed flux near the bottom and a little seaward transport in surface waters, except in the southern flood channel, similar to that of the residual current velocity (Salomon & Le Hir 1981; Le Hir *et al.* 1986. Then, little sediment escapes northward of the estuary and the overall result is a net landward transport

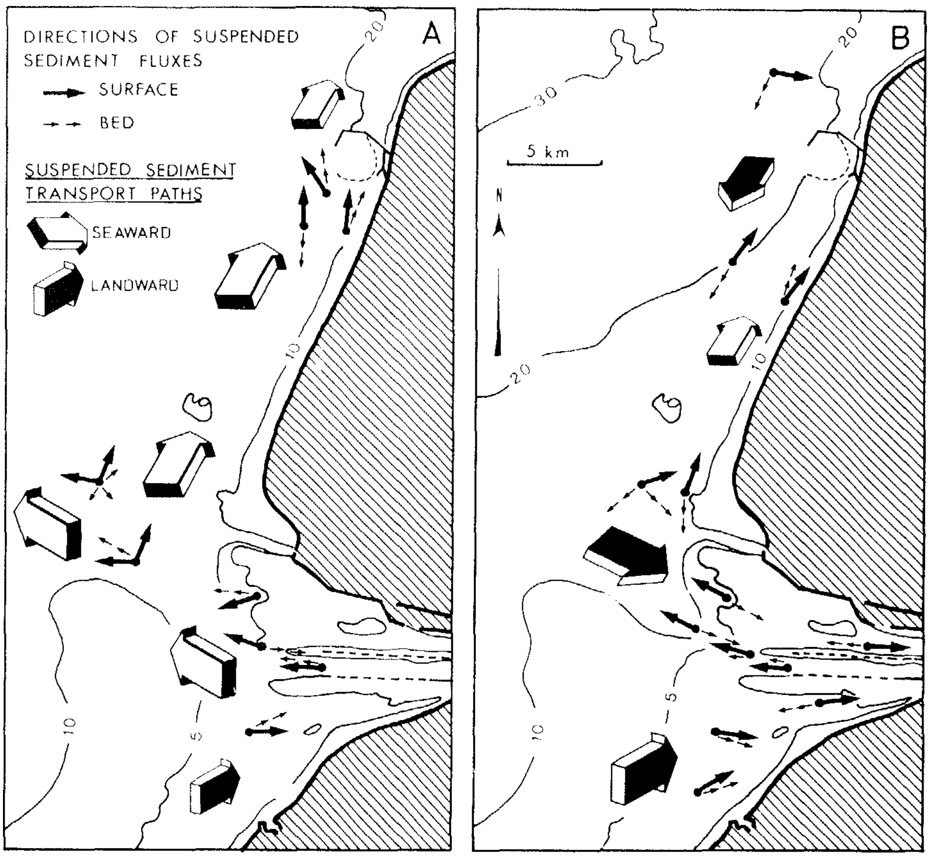

Fig. 10. Suspended sediment transport paths in the eastern part of the bay and estuary mouth, based on flux measurements during spring tide, at high river flow (A) and low river flow (B). (Note: the length of arrows is not representative of the Magnitude of calculated fluxes.)

of suspended sediment from the bay into the estuary, particularly within the southern flood channel.

Heavy metals issuing from polluted river basins are mainly carried by the finer sediment particles, and can be considered as tracers of fluvial influence. Their concentrations have been measured extensively in bottom deposits of the study area in order of appreciate the role of fine-grained sediments supplied from the estuary in shelf sedimentation (Boust 1981). Taking into account heavy metal concentrations both in marine sediments considered as little influenced by man's activities, and in strongly-polluted estuarine deposits on the northern tidal flats, it is possible to calculate the fluvial contribution to mud deposition on the shelf and the estuary mouth (Fig. 11). It appears that the zone of influence is limited to a narrow, nearshore band. This represents the full extend of recent sedimentation from fluvial origins on the shelf, and is therefore more confined than the turbid plume observed throughout the water column.

Within the estuary mouth, the mud zones situated on either side of the trained channel are formed by the deposition of silt and clay derived from the turbidity maximum which extends seaward at ebb tide and is partly reintroduced into the marginal flood channels during flood tides. These deposits are strongly influenced by the Seine river inputs and exhibit spatial and density variations caused by the combined action of currents and waves (Avoine *et al.* 1984*a*). Suspended sediments which are not reintroduced are dispersed onto the shelf. There they can settle in less turbulent zones near the estuary mouth, e.g. Le Havre harbour in which the annual entrapment has been estimated to be 1 × 10^6 t, an increase from that observed during the preceding decades, that is, before the extensive seaward jettying of the main channel and resultant downstream migration of the turbidity maximum (Avoine *et al.* 1981). A small amount of sediment escapes from the turbid plume and follows the net current drift, both westward to the Parfond trough in which they settle during the slack water periods, and northward along the eastern coast of the bay where dredge spoil strongly amplifies the natural dispersal and sedimentation patterns. Elsewhere, submarine television investigations have shown a near-bottom turbid zone occurring above clean sand shelf sediments. This phenomenon, similar to the nepheloïd layer observed in the deep sea, has been described on other continental shelves (Drake 1976). This turbid layer is supplied by sediments of fluvial origin and also probably by erosion now prevailing in the extensive mud patch situated along the S coast, off Dives/mer (Fig. 6). The latter represents silt and clay relict deposits of Holocene age, with heavy metal concentrations below the background level (Boust 1981).

Sediment transport on the shelf

Bed-load transport

The general distribution of bottom sediments reflects the tidal current velocities (Fig. 6), and is largely the result of the reworking of Quaternary deposits, described in the English Channel by Larsonneur *et al.* (1982). Hamilton *et al.* (1980) have suggested that the reworking is still in progress to the SW of Britian. In the case of the Bay of Seine, a similar conclusion can be proposed resulting from the role

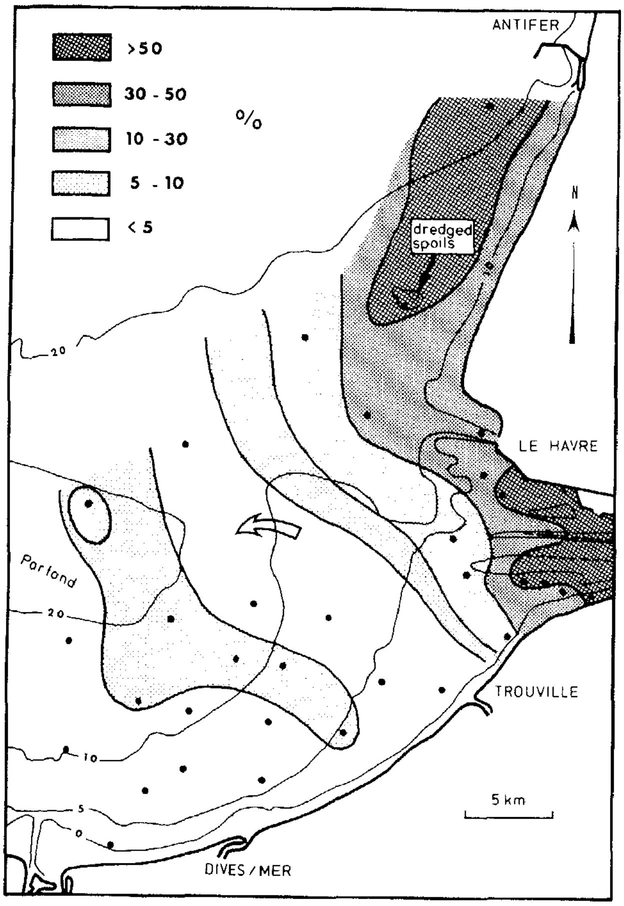

Fig. 11. Percentage of fluvial contribution to mud deposition on the shelf and estuary mouth (after Avoine *et al.* 1986*a*).

played at the present time by tidal currents and, additionally, by waves. The present patterns of sand transport have been extensively studied in the eastern part of the bay using several techniques, such as radioactive tracer experiments, grain-size analysis, self-recording current meter measurements, side-scan sonar and other geophysical methods. All the data tend to show that the dominant bed-load transport is oriented from offshore to onshore, toward the Seine estuary.

Tidal currents are responsible for the development of sedimentary bedforms which can be used to postulate regional patterns of sediment transport (Belderson *et al.* 1982). In the Bay of Seine, numerous longitudinal bedforms have been described by Auffret & d'Ozouville (1986*a*) following a side-scan sonar survey. The most important feature is a zone of sub-parallel sand ribbons directed NW–SE, which develops in the middle part of the bay. These sand ribbons, similar to those described by Kenyon (1970), are separated by floors of coarser sand gravel. They are elongated along the direction of tidal currents calculated from a numerical model by Salomon (1985), that is, along the direction of dominant sand transport. According to McLean (1981), sand ribbons occur in areas of low sediment supply and relatively low transport rates, but the presence of asymmetrical sand waves facing the SE, developing along the ribbons, suggests a net sand transport directed toward the eastern bay which must be taken into account in the sediment budget.

Towards the Seine estuary, where there are lower current velocities and the nature of bottom deposits is heterogeneous and patchy, large-scale bedforms do not develop. Nevertheless, underwater television observations have shown the presence of small-scale ripples in this area. Estimates of directions of net sand transport and drift rates were made at different locations using radioactive tracer techniques. These field studies, which have been described in detail elsewhere (Avoine *et al.* 1984*b*), show that the observed tracer dispersion patterns are elongated according to the rectilinear nature of the tidal currents which run parallel to the southern and eastern coasts of the bay, except at a station situated northward of the Banc de Seine (Fig. 12) where currents rotate about an ellipse with two dominant directions. The net transport vector directions are strongly correlated with the asymmetry in peak tidal flows, i.e. in the direction of the dominant flood currents, a

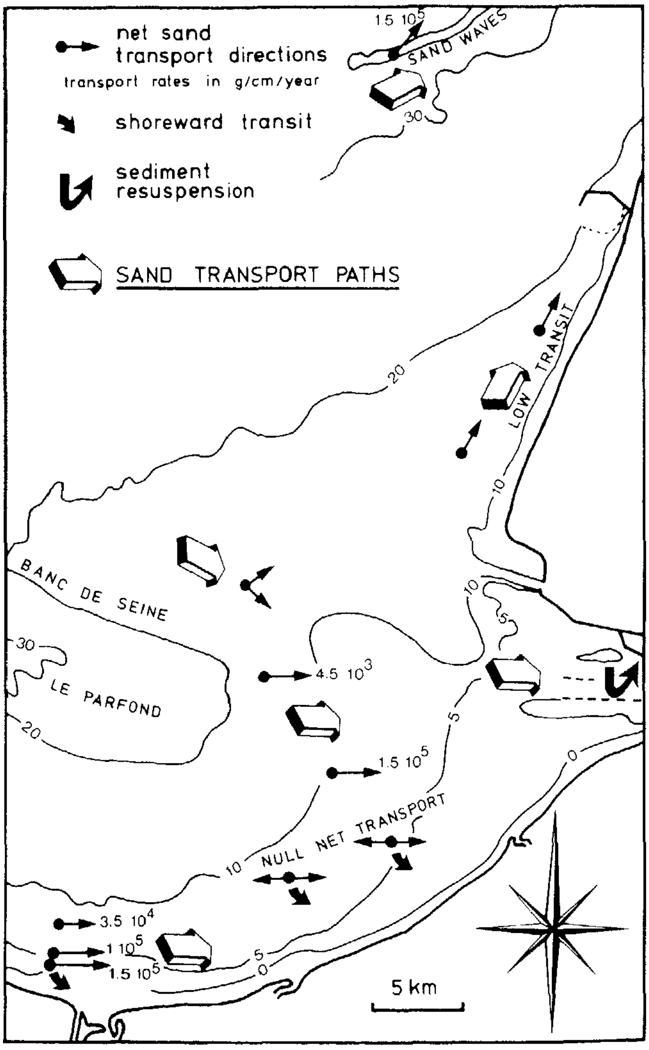

Fig. 12. Sand transport paths in the eastern part of the bay, based upon radioactive tracer experiments (black arrows). (Note: the length of arrows is not representative of the transport rates which are indicated in g cm^{-1} year when calculated.)

classical phenomenon observed on macrotidal continental shelves (Johnson *et al.* 1982). Along the S coast, the long term pattern of sand movement is an eastward transport under the action of flood currents, whilst in waters shallower than 6–8 m deep, the influence of storm waves provoke a shoreward transport from the subtidal part of the bay to the littoral zone (Fig. 12). However, off Dives/mer, the alternating eastward and westward movements of the radioactive tracers have been found to be of equal length (Fig. 12), that is, this area appears as a zone of apparent null net transport, except for shoreward migration. Along the eastern coast of the bay, radioactive sand deposited offshore on the dredge spoil ground moves toward the NNE, under the action of tidal currents. In addition, wave activity is responsible for a net longshore drift directed eastward along the S coast and southward along the E coast, due to the dominant action of waves from the W to NW sector (Fig. 13).

Sediment transport rates have been calculated using the tracer balance method proposed by Courtois & Monaco (1969). The highest value of net bed-load transport rate is shown in Fig. 12 for each station. The maximum obtained is $1.5 \times 10^5\,\mathrm{g\,cm^{-1}\,year^{-1}}$, an order of magnitude below the mean values calculated in similar hydrodynamic conditions by Heathershaw (1981) in Swansea Bay.

Suspended sediment transport

Little is known about the resuspension and transport of fine-grained sediments in the bay. On different continental shelves, several recent studies have shown that temporal variability of suspended sediment concentrations in the water column is mainly controlled by wave activity (Lavelle *et al.* 1978; Drake *et al.* 1980; Bothner *et al.* 1981; Young *et al.* 1981). In the Bay of Seine, water sampling carried out in different weather conditions showed higher concentrations occurring after a storm than during a calm period (Avoine *et al.* 1984*a*). On the other hand, a radioactive tracer experiment using fluid mud of different concentrations has shown that these non-consolidated deposits are easily eroded and resuspended by tidal currents (Avoine *et al.* 1984*b*). The conclusion is that the movement of suspended sediment on the shelf is controlled by the combined action of tidal and wave-induced currents and that optimum conditions for transport probably occur during storm periods. The incessant alternation of periods of mud resuspension and deposition explains the high variability of fine-grained deposits observed over a very short time-scale (Avoine *et al.* 1984*a*). Nevertheless, when erosion is offset by strong suspended sediment inputs, mud deposition does occur in certain shallow areas (McCave 1971). This is the case in the Seine estuary mouth during river flood periods.

The general pattern of suspended sediment transport on the shelf is probably directed toward the Seine estuary in the bottom waters, resulting from the two-layer density circulation which occurs seaward of the estuary mouth (Fig. 5). This interpretation, however, is complicated by several mechanisms, such as the erosion of relict deposits exposed on the sea-bed, the turbid plume extruded seaward of the estuary, the artificial input from dumping of dredged spoil and its dispersal, and the presence of an occasional near-bottom turbid layer. Similar problems can be found in other areas, such as Swansea Bay (Collins *et al.* 1979), showing the real difficulties encountered in studying all the aspects of sediment transport on a shelf area.

Discussion

Figure 13 summarizes data available on sediment circulation. On the inner shelf, the general sand movement is towards the Seine estuary. An estuary mouth shoal has developed, which is up to 20 m thick (Auffret & d'Ozouville 1986*b*). It largely results from an accumulation of sand during the last Holocene rise of sea level. At present time, the Seine estuary is almost entirely filled in, and the estuary mouth shoal forms an exterior arc, which differentiates it from estuaries which are only slowly filled, such as the Thames (d'Olier 1974). When sand from the shelf reaches the estuary mouth, it is redistributed in different circulation cells by alternating tidal currents. A bidirectional sediment circulation parallel to the direction of river flow forms linear sand banks separated by ebb and flood dominated channels, a characteristic feature of tidally-influenced estuaries (Wright 1977; Hayes 1980). Over several decades, this situation has been completely controlled by the building of the training walls. Wave activity at the estuary mouth probably reinforces flood currents in causing an upstream transport of sand, as shown in other exposed macrotidal environments (Jago 1980; Wright *et al.* 1980).

Fluvial mud transported seaward on ebb tides is partly reintroduced on either side of the trained channel by flood currents (Fig. 13), resulting in only a relatively small net mud loss to the sea, as shown in similar conditions by Terwindt (1967). With the exception of Le Havre harbour and the estuary mouth, the total amount of fluvially suspended sediment which by-passes the estuary is not sufficient to induce a significant accumulation of mud on the shelf. The other natural sources of fine-grained material comprise (1) erosion of offshore relict deposits which occurs probably during periods of stormy weather, (2) cliff erosion which comprises only a small fraction of total budget of suspended sediment in the study area, and (3) the poorly documented introduction of particulate matter from the western English Channel, as shown using artificial radioisotopes discharged from La Hague nuclear fuel reprocessing plant as tracers (Jeandel *et al.* 1980). These radioactive tracers reveal that during periods of low river flow, a certain amount of suspended material is carried from offshore and introduced into the Seine estuary, as far as 30 km upstream of the mouth. This material may be derived from various offshore sources as well as from fluvial sediments dispersed onto the shelf in winter and subsequently reintroduced in summer. The last assumption is supported by other recent geochemical evidence (Gueguenait *et al.* 1986).

Dredging activities constitute an important anthropogenic source of fine material for the shelf. Amongst the different dredged spoils of the study area (Fig. 13), only the one which is situated north of Le Havre is of any regional significance (see Fig. 6 and Fig 11). It is remarkable to note that a large part of the Seine river input is not directly deposited in the Bay of Seine, but is deposited first in Le Havre outer-harbour and only then dredged and dispersed on to the shelf. So, dredging operations must be given more attention in studies of estuary–shelf exchanges, as shown in

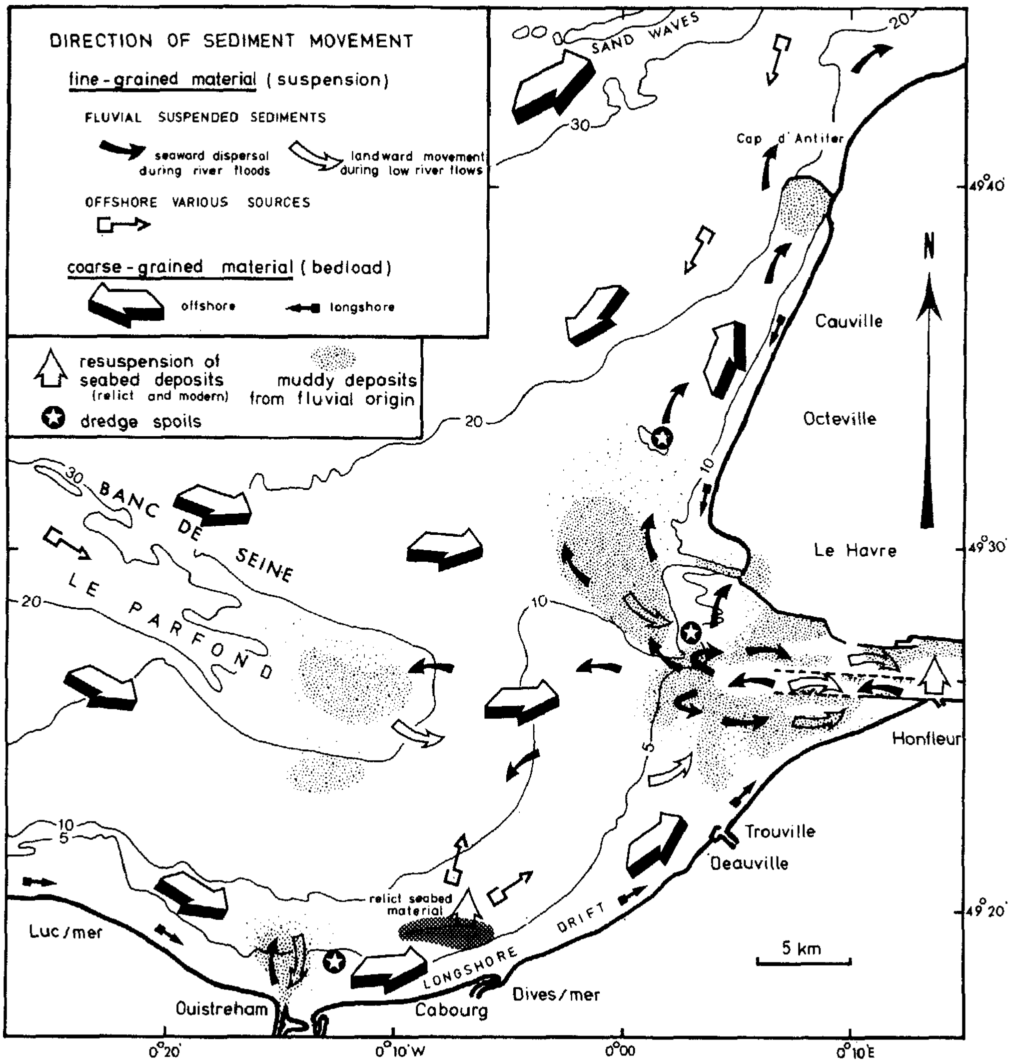

Fig. 13. Schematic summary of the sediment circulation pattern in the estuary mouth and its adjacent shelf, based on sedimentological data, radioactive tracer experiments, flux measurements, sidescan sonar records, near-bottom current data and geochemical analysis.

other areas, such as the US East Coast estuaries (Nichols 1986).

Sediment budget

In spite of the fact that some data are not available, attempts can be made to calculate a tentative budget for the input, deposition and loss of sand and mud in the Seine estuary and its adjacent coastal zone. The estuary is at present filling with sediment at the rate of $4.5 \times 10^6\,m^3$ a year. Mud represents about one third ($1.5 \times 10^6\,m^3$) to which must be added $1.5 \times 10^6\,m^3$ deposited yearly in Le Havre outer-harbour. The annual amount of sediments trapped in the coastal margin is approximatively $3 \times 10^6\,m^3$ of sand and $3 \times 10^6\,m^3$ of mud. As the river inputs contribute a maximum of $1.5 \times 10^6\,m^3$ of fine-grained material, the largest part of the deposits must be of marine origin, i.e. a good half of the mud and all the sand.

The origin of the sand can be found easily on the shelf. The comparison of hydrodynamics surveys in the Bay of Seine between 1874 and 1913 has shown a mean increase depth of 0.68 m from Le Havre to Dives/mer, corresponding to a mean erosion of $1.7 \times 10^6\,m^3$ a year (Volmat, *in* Vigarié 1965). An extension of that erosion of the sea-floor to a larger area between Le Havre and Ouistreham would permit the estimated $3 \times 10^6\,m^3$ a year to be attained. On the other hand, the longshore drift directed toward the estuary supplies about $2 \times 10^5\,m^3$ a year from both the E and S coast (Laboratoire Central d'Hydraulique de France 1973). It may also be possible that sand ribbons situated in the central part of the bay supply a significant amount of sand into the estuary, but data are not available.

In contrast, the origin of mud is more difficult to ascertain. The Seine river supplies a maximum of $1.5 \times 10^6\,m^3$ a year but a part of this material is most probably dispersed seaward out of the Bay of Seine. Consequently, offshore sources must supply more than half of the mud accumulation in the coastal zone. As shown in other areas of mud accumulation, the erosion of relict clay deposits may represent the most important offshore source, but its real contribution is incalculable (see McCave 1973). Data on other possible sources are not available.

Conclusion

In spite of the numerous processes which affect in the coastal zone, the present study of sedimentary interactions between the Seine estuary and its adjacent shelf permit some conclusions regarding the sediment budget. Two major sources of material have been recognized: (1) a marine source of relict sand and mud originally derived from landward, carried to the shelf at times of lower sea level, then transported shoreward to fill the Seine estuary, (2) a present clay fluvial source of fine-grained sediments. In natural conditions, prior to the intervention of man, the estuary could be considered as a sink for all marine and fluvial sediments. At the present time, the entraining of the main channel accompanied by a natural infilling is responsible for the seaward escape of a part of the fluvial material. The dispersal of these fine-grained sediments depends on variations in the physical dynamic processes. Patterns of advective currents tend to retard the seaward escape. Most of the suspended sediment deposited on the inner shelf are in fact deposited close to the estuary mouth, particularly in Le Havre harbour. Dredging operations appears to be the main cause of the seaward dispersal of fluvial sediments in the Bay of Seine and probably outside. Thus, man has changed the natural function of the estuary from a sink to a source of fluvial sediment for the sea. However, sediment moved out of the coastal zone during river floods is compensated by large amounts of material moved from the shelf in periods of low river flow, and the tendency is still for a sediment trap, only partially perturbed by man's activity.

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