Hydrological and dynamical characteristics of the River Louros plume, western Greece

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(Received July 19, 1993; accepted June 1, 1995)

Abstract. Most sediments delivered to the oceans are associated with sediment-laden river outflows. Consequently, oceanographic and sedimentation processes in the receiving basins are influenced by the presence and dispersion of the river plumes. The physical characteristics (temperature, salinity, density, and suspended sediment) and velocity regime of the plume of the River Louros are examined here, in association with deposition of the suspended material. During high freshwater discharges (approx. 50 m^3/s), the plume has a thickness of 2 m near to the river mouth; it spreads then as a thin layer (< 0.5 m) of fresher water, extending southwards over distances of several kilometres. Velocities along its main axis reduce rapidly in the shallow waters (< 2 m) of the river mouth area due to bottom friction. Further offshore, river outflow spreads as a buoyant plume, decelerating due to the upwards entrainment of the ambient water. Hence, coarser suspended sediment are deposited near the river mouth, whilst finer-grained material is dispersed seaward. The later is deposited either as individual particles according to their size, or by the action of biophysicochemical processes (i.e., flocculation, pelletization).

1. Introduction

River mouths and their nearshore areas are regions where sediment-laden river discharges meet and mix with the ambient receiving marine waters. Here, spreading and deceleration of the outflow is followed by relatively rapid deposition of the sediment load. Bates (1953) has distinguished three types of river outflow, with respect to density differences between the inflows and basin waters, relating them to delta formation. These types are defined as homopycnal, hyperpyc-

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nal and hypopycnal flows.

Homopycnal flows occur when the sediment-laden fluid enters a basin filled with fluid of similar density; this happens primarily when a stream enters a freshwater lake. Mixing takes place readily in three dimensions, with the developing deltaic sequence having the classical "Gilbert-type" structure.

Hyperpycnal flows occur when the density of the discharging effluent is higher than the density of the basin waters. Outflows from hypersaline lagoons or from rivers with exceptionally high suspended sediment concentrations (e.g., the Yellow River, China) fall into this category. In this case, sediment-laden fluid flows down the side of the basin and then along the bottom as a turbidity (density) current. Deltas at the mouth of submarine canyons might be formed by such hyperpycnal flows.

Any hypopycnal flow is characterized as having a lower density than the ambient waters, with the sediment-laden outflow moving over the denser ambient fluid as a buoyant surface plume. As the world's major rivers discharge into saltwater basins, they are characterized by such flows.

Freshwater has an average density of $\rho_f = 1$ g/cm^3, in the absence of suspended material; in comparison, seawater has a density of $\rho_s = 1.028$ g/cm^3. In most rivers, the outflow density is increased by the presence of the suspended load; however, this is small in comparison to that created by the salt content of the marine waters. For example, an increase of 100 mg/l in the suspended load concentration will increase the density by only 0.0001 g/cm^3 (Wright, 1985a). Thus, river waters can be expected to be generally lighter than the ambient seawater. An exception is the Yellow River in China, where hyperpycnal flows have been identified (Wright, 1989); this means that suspended sediment concentrations (SSC) of > 30 g/l are present, in order to make up the difference of 0.028 g/cm^3 between the fresh and saline waters. As an SSC < 1 g/l is the most common situation when a river discharges into a saltwater body, hypopycnal flows are formed; these are known as river plumes.

River plumes are of interest in the study of oceanographic processes, including: (i) physical aspects of the mixing between the river inflow and the seawater; (ii) sedimentation processes, depending upon the hydrodynamical characteristics of the plume and its mixing processes with the surrounding fluid; (iii) biological processes, due to the introduction of nutrients by the river waters; and (iv) pollution problems of the nearshore zones, influenced by the pollutant-laden river plumes.

Many studies on the plumes of major river systems have been carried out during the last few decades, involving different aspects of the mixing and sedimentation. Scruton and Moore (1953), for example, carried out aerial and surface observations around the Mississippi delta; the amount of material in suspension was found to be determined mainly by the river discharge and distance from the mouth, whilst turbid waters were identified as extending seaward for distances of at least 100 km. Further, Coleman and Wright (1971) have studied the mechanisms of effluent expansion and interfacial mixing at the mouth of the South Pass of the Mississippi. Stefanson and Richards (1963) and Park (1966) investigated dispersion processes controlling the nutrient concentrations of phosphate and nitrate supplied by the Columbia River plume. Elsewhere, Gibbs (1970) and Curtin and Legeckis (1986) have found that the river plume reaches distance of 185 km and 230 km offshore, during low and high river discharges, respectively. Maldonado

(1975) found that the average plume thickness of the River Ebro (Spain) was about 3 m, extending about 2 km offshore; this was highly variable and depended primarily upon the wind and surface sea waves. The dispersal processes associated with freshwater from the Po River (Italy) into the coastal waters have been studied by Grancini and Cescon (1973). Garvine and Monk (1974) and Garvine (1975) studied the frontal structure of the Connecticut River plume in Long Island Sound and, later, Garvine (1977) observed the field of motion within the plume using drogues and drifters combined with an airborne camera. Eisma et al. (1978) investigated the suspended matter within the estuary and adjacent Atlantic Ocean region of the Zaire River. These investigators found the outer limit of the Zaire River plume (salinity of 35) to be at about 700 km offshore from the river mouth. Wright et al. (1980) described water and sediment dispersion of the Jaba River inflow (New Guinea). Ingram (1981) observed the field of motion and dilution effects associated with the plume of the Great Whale River (Hudson Bay). Stronach (1981), describing the Fraser River plume in the Strait of Georgia, stated that the thickness of the plume varies up to 10 m in water depth, whilst the water circulation within the Strait presents a salt-wedge type of stratification. The temporal and spatial variations in the Fraser River plume and their relationship to forcing processes induced by tides, waves and discharge regime was investigated by Royer and Emery (1982).

The primary forces governing the formation and diffusion of any given river plume are (Wright, 1985a): (i) inertia of the issuing river water and the associated turbulent diffusion; (ii) friction between the effluent and the bed immediately to seaward of the river mouths; and (iii) buoyancy, resulting from density differences between the issuing and the ambient fluid. Subsequent broadening and thinning of the plume is caused by the action of marine forces, with wind being the most important.

River plume investigations in Greek waters are somewhat limited, with the exception of those referring to the rivers Axios and Aliakmon (Robles et al.,1983; Balopoulos and James, 1984; Balopoulos et al., 1986). Some observations on the plumes of the rivers Arachthos and Louros were made by Piper et al. (1982) and Papayiannis (1985). Likewise, an attempt to relate velocity variations and suspended sediment concentrations to a mathematical model of plume and sediment dispersion has been described recently (Poulos and Collins, 1994), whilst the relative significance of river outflow and wave energy on delta formation associated with Greek rivers was presented by Poulos et al.(1993).

The present investigation examines the characteristics of the plume of the River Louros during high water discharge in February 1986, in terms of temperature, salinity, density and suspended matter. The velocity field of the plume is investigated, whilst processes governing its formation and dispersion are discussed. Sedimentological implications of the extent and change in position of the plume are considered, in terms of fine-grained sediment dispersion on the inner continental shelf. Finally, such observations are viewed within the context of other Greek river systems.

2. The study area

The study area is Salaora Bay, which is located in the northwestern part of the Amvrakikos

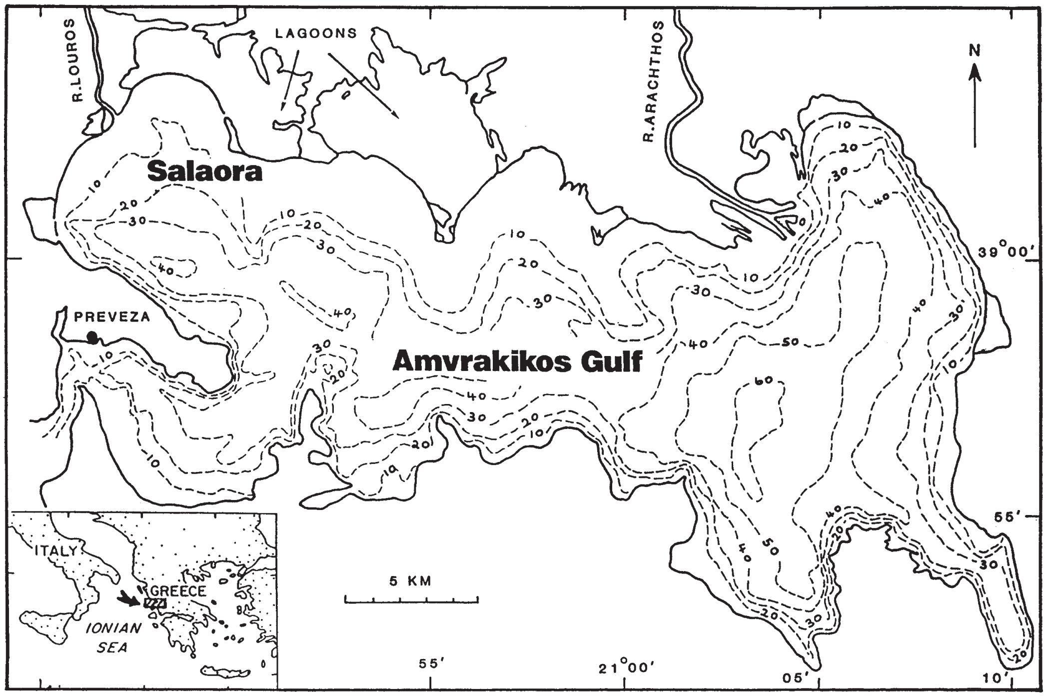

Fig. 1 - Amvrakikos Gulf: bathymetry based upon a chart (1:50,000) prepared by the Hellenic Hydrographic Service (1983) (depth in metres).

Gulf (Fig. 1), where the R. Louros discharges its sediment-laden freshwaters. The Bay of Salaora is open to Amvrakikos Gulf, in the south, with water depths of up to 40 m.

Amvrakikos Gulf is a semi-enclosed basin with a maximum depth of 65 m in its eastern part; it is separated from the open Ionian Sea by a beach barrier complex (Piper et al., 1982). The connection between the Gulf and the open sea is through a narrow channel, 600 m wide and 4 to 10 m deep, which includes an artificially dredged channel of about 8.5 m in depth. The whole northern Gulf shoreline consists of the deltaic plains of the rivers Arachthos and Louros. The River Arachthos discharges into the northeastern part of the Gulf.

Tides are minimal, ranging from 5 cm up to 25 cm (Tsimplis, 1994). Generally, moderate winds blowing over Amvrakikos Gulf combine with a limited fetch of about 10 km to create a rather calm wave climate. Amvrakikos Gulf has a positive water balance, in the sense that it receives more freshwater (i.e., rainfall and river inputs) than it loses through evaporation (Papayiannis, 1985). This balance results in the formation of a surficial layer of fresher water, of about 2 m in thickness, throughout the year. Beneath this layer, whose appearance is more intense within the northern part of the Gulf where the rivers discharge, there are another two main water masses. There is an intermediate layer, extending to a depth of about 20 m, which is warmer and less saline than the deep layer which lies below it (Papayiannis, 1985). The surficial freshwater layer has salinities of 20-22 ppt, reducing towards the mouths of the rivers (Piper et al., 1982); its surface water temperatures vary seasonally. The intermediate water mass has salinities of 30- 35, with temperatures varying from 17 to 18 °C. The deep water mass has salinities in excess of 36 ppt, approaching values of about 38 ppt, and with temperatures which are general-

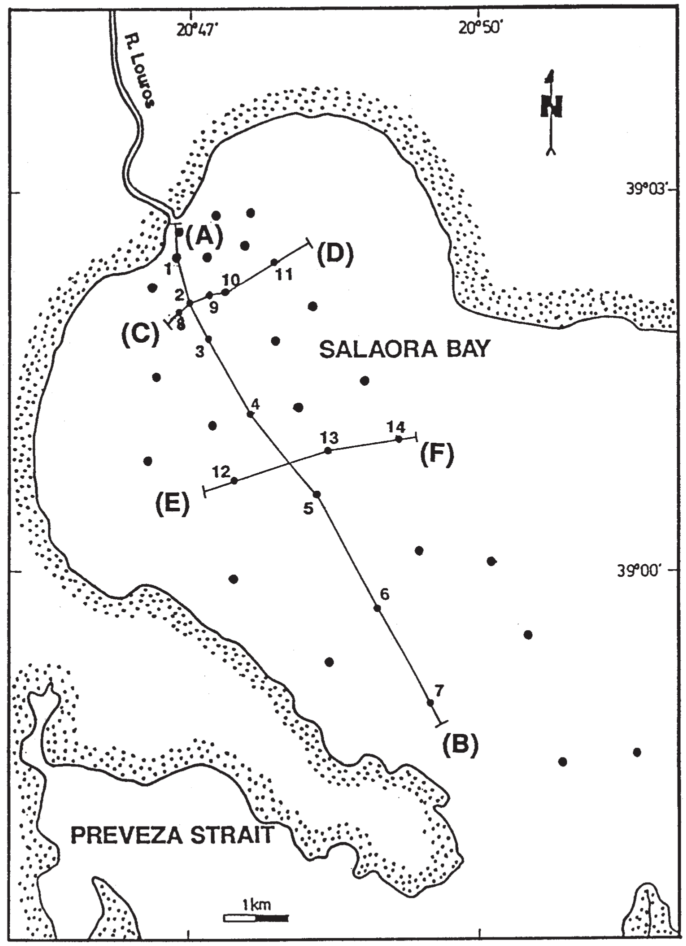

Fig. 2 - Salaora Bay: map showing sampling positions for the hydrological measurements and the collection of water samples. The sections A-B, C-D and E-F used in the subsequent analysis are also presented.

ly less than 16.5 °C.

The River Louros drains a catchment area of 785 km^2 with a mean annual discharge of 17.1 m^3/s, a minimum monthly value of 11 m^3/s (in August) and a maximum of 26.6 m^3/s (in February) (Therianos, 1974). During sampling for the present investigation, a water discharge of about 50 m^3/s at the river mouth was estimated; this was related to heavy rains which had fallen over the previous two days, as it was the intention of the study to monitor nearshore and offshore plume conditions after such a period of intensive rainfall.

3. Data collection and methodology

In February 1986, field data were collected in Salaora Bay, from the mouth of the River Louros and its adjacent offshore area. For data collection, a local fishing boat (M/V Ag. Vasilios, 11 m long) was hired, whilst a smaller boat was used for sampling in the shallow waters. The

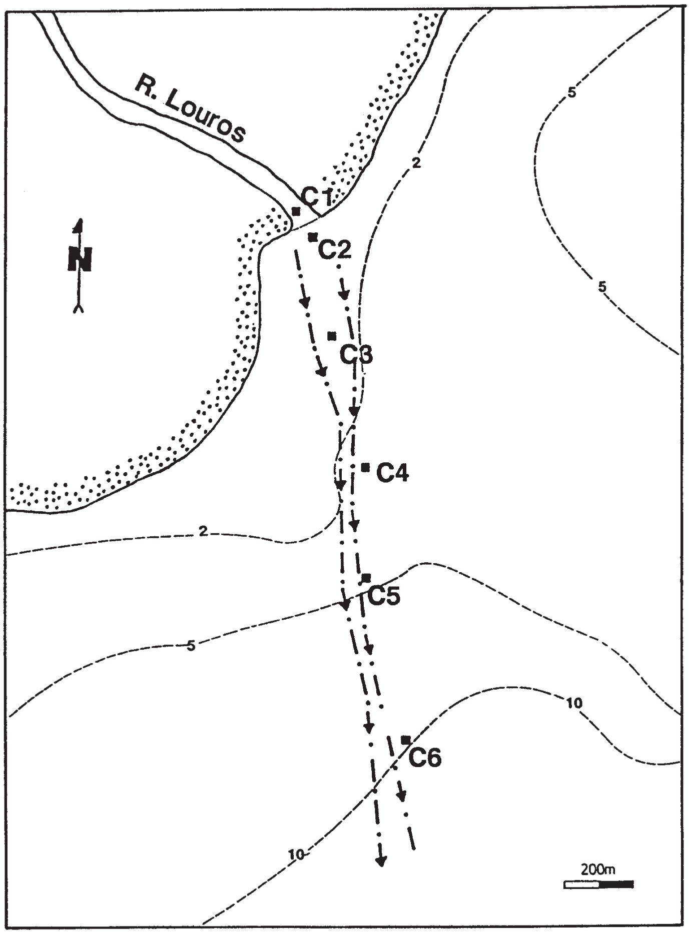

Fig. 3 - River Louros: map of the river mouth area, showing current meter stations (C1-C6) and the course followed by the drift cards (- • -) (depth in metres).

positions of all the sampling stations were fixed by reference to established locations on the adjacent shoreline, using an Embeco Monocular compass. The accuracy of position fixing can be assumed to be within ±20 m, because of the proximity to the shoreline and the prevailing "fair" weather conditions during sampling. It should be noted also that the wooden construction of the survey vessel used should result in only minimal errors in the monocular compass readings.

Temperature/salinity measurements were obtained, together with water samples from the surface and at different depths throughout the water column, at 35 stations (for locations, see Fig. 2). Current observations were made and drift cards were released within a distance of 2 km from the mouth of the River Louros. The location of stations and the course taken by the drift cards are shown in Fig. 3.

The temperature and salinity measurements were made using an EIl MC5 (Mk 2) thermosalinometer, calibrated prior to and after the field trips using standard seawater. Instrument specifications are as follows: for salinity between 0.5 and 32.5 ppt, an accuracy of ±0.1, and between 32.5 and 38.2 ±0.05 ppt. The temperature accuracy is 0.1 °C, for the range from 1.4 °C up to 30 °C. Current data were collected using a Braystoke Flow Meter (BFM 008 Mk 2), which measu-

Table 1 - River Louros plume: measured current velocities (V, in m/s) and directions (D, in N °). Depth is in m. For station locations see Fig. 3

Depth	Stations											
	C1		C2		C3		C4		C5		C6	
	V	D	V	D	V	D	V	D	V	D	V	D
0.0	1.250	140°	0.93	150°	0.36	160°	0.280	160°	0.250	170°	0.180	170°
1.0	1.100	140°	0.85	150°	0.22	160°	0.130	160°	0.100	170°	0.080	180°
1.5					0.10	160°						
2.0							0.025	170°	0.020	180°	0.015	190°
2.5							0.010	180°				
5.0									0.006	230°	0.007	200°

red speed and direction; for this, the threshold condition was n < 0.07 (i.e., a speed of 0.03 m/s), where n = revolutions per second on the meter (Table 1). Sub-surface water/suspended sediment samples were pumped on board vesel, using an ordinary petrol-driven water pump, into plastic containers of 2 to 6 l capacity. In order that the weight of the suspended sediment could be estimated, the water/sediment samples were filtered (using a vacuum pump) through pre-weighed and dried Sartorius (Nuclepore) 47 mm diameter polycarbonate membrane filters with an aperture size of 45 μm. The quantity of seawater filtered was between 0.5 and 4 l, depending on the suspended sediment concentrations present. The filters were dried and weighed to ±0.001 g, before and after filtration.

The density values were expressed in terms of σ_t ($\sigma_t = \rho$-1000), where ρ is the actual density of seawater expressed in g/cm^3 and is function of salinity and temperature. In this study, the density (ρ) values were calculated from the temperature and salinity data sets using the polynominal expression proposed by UNESCO (1983).

4. Results

4.1. Physical properties of the water column of Salaora Bay

Vertical profiles of temperature (T °C), salinity (S ppt) and density (σ_t) at selected oceanographic stations adjacent to and offshore from the mouth of the R. Louros are presented in Fig. 4.

As shown in this figure, the seawater temperature decreases with depth from 12.5 °C at the surface to 10.5 °C at 4 m; it then increases down to a depth of 14 m, reaching 15.8 °C. From there, the temperature increases slowly down to a depth of 20 m, where it is 16.4 °C. Below this depth, the temperature decreases very slowly, and is 15.0 °C just above the bottom.

The salinity is very low near the surface, at about 17 ppt; it increases gradually with depth, reaching 22 ppt at a depth of 2.5 m (Station 4) or 3.5 m (Station 6). Below these depths, it increases rapidly up to 14 m, where it is 35 ppt. Lower in the water column, it increases very slowly to 37 ppt near the seabed.

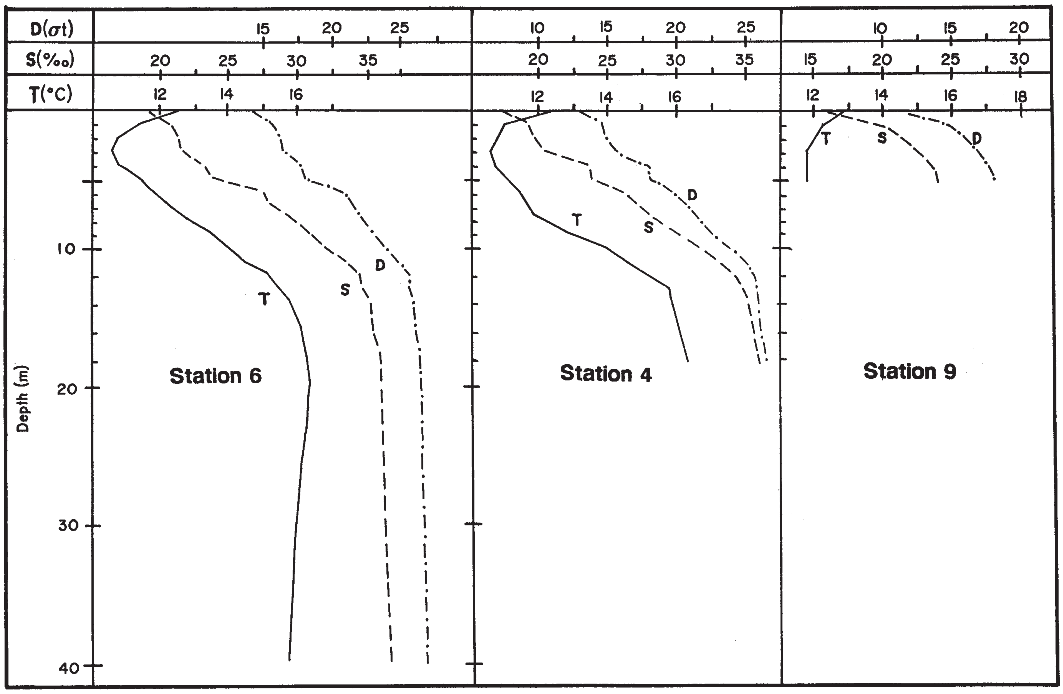

Fig. 4 - Salaora Bay (18-20/2/86): temperature (°C), salinity and density (σ_t) profiles (for station locations, see Fig. 2).

Below the surface layer, which is about 3 m in thickness and is characterised by high temperature (due to air-sea interaction) and low salinity (related to freshwater river inputs), a thermocline and halocline are present between 3 and 14 m. Below 14 m, there is a bottom water mass of rather constant temperature and salinity. The water density profiles, which are indicative of the stability of the water masses, present: a surface layer with density ranging between 14 and 17.5, and increasing down to a depth of 3 m; a pycnocline with rapid increases in density, from 17.5 to 27 (σ_t), between the depths 3 and 14 m; and a relatively constant density layer (σ_t ~ 26.5) below 14 m.

4.2. River plume characteristics

The plume of the River Louros has been identified, and its features, in terms of salinity (S) and suspended sediment concentrations (SSC), are presented in Fig. 5.

The River Louros plume was observed to be elongate in shape; its surface expression extended towards the SSE, for a distance of several kilometres, almost reaching Preveza Straits. A secondary and shorter branch of the plume, adjacent to the mouth of the river, extended towards the east. At a 2 m water depth, the aerial extent of the plume is almost the same as that at the surface; at 5 m, only a slight change in the properties between the river outflow and the ambient waters can be identified. As shown in Fig. 5, the isopleths of SSC follow generally the same trend as the isohalines, especially at the surface and at 2 m depth; between these depths, the plume is more distinctive.

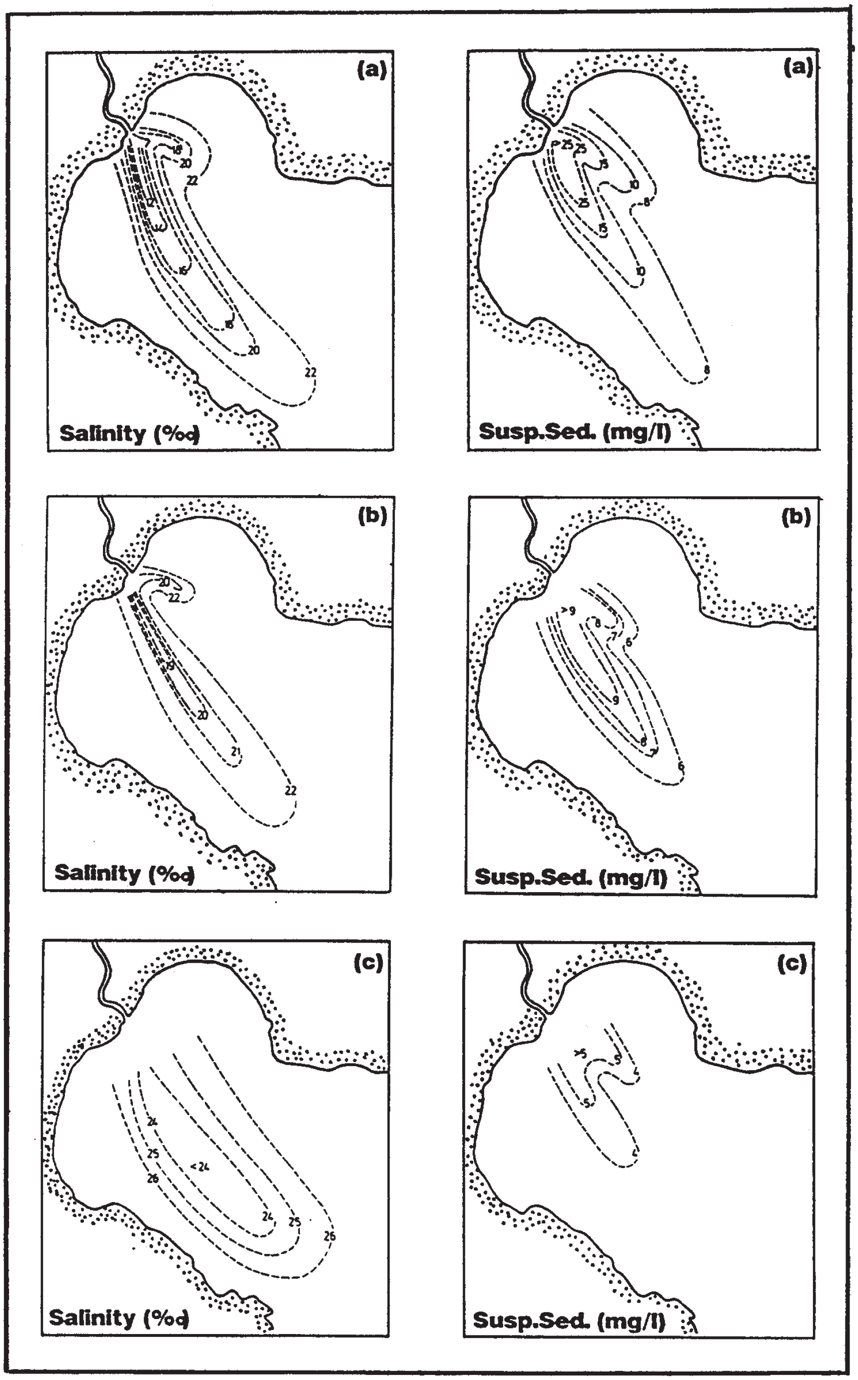

Fig. 5 - River Louros (18-20/2/86): lateral distribution of salinity and suspended sediment concentrations (mg/l) at (a) surface, (b) 2 m depth and (c) 5 m depth.

Three sections across the plume are shown in Figs. 6, 7 and 8: A-B, which lies along the longitudinal axis of the plume; C-D and E-F which lie perpendicular to A-B but at different distances from the mouth of the river (see Fig. 2). Over these sections, the distributions of salinity (Fig.

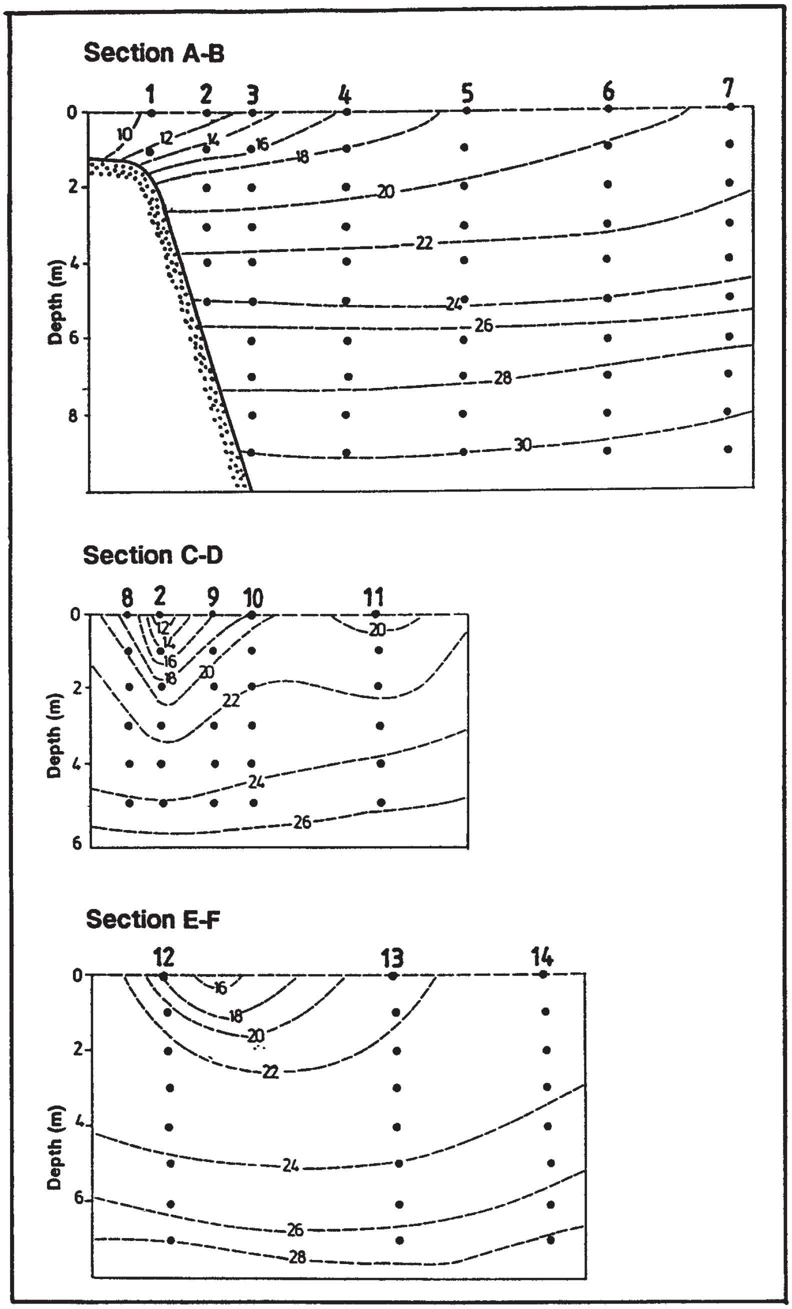

Fig. 6 - River Louros (18-20/2/86): salinity contours across sections A-B, C-D and E-F (for locations, see Fig. 2).

6), density (Fig. 7) and SSC (Fig. 8) are shown for the upper 10 m of the water column.

On Section A-B, the 10 ppt - salinity contour is present in the surface waters at the river mouth. The salinity increases steadily offshore, reaching a value in excess of 20 ppt at a distance of 5 km. Deeper down in the water column, the salinity increases to 20-22 between 2 and 4 m. There is then a rapid increase in salinity (i.e., a halocline) from 24 to 26 ppt between 4.5 and

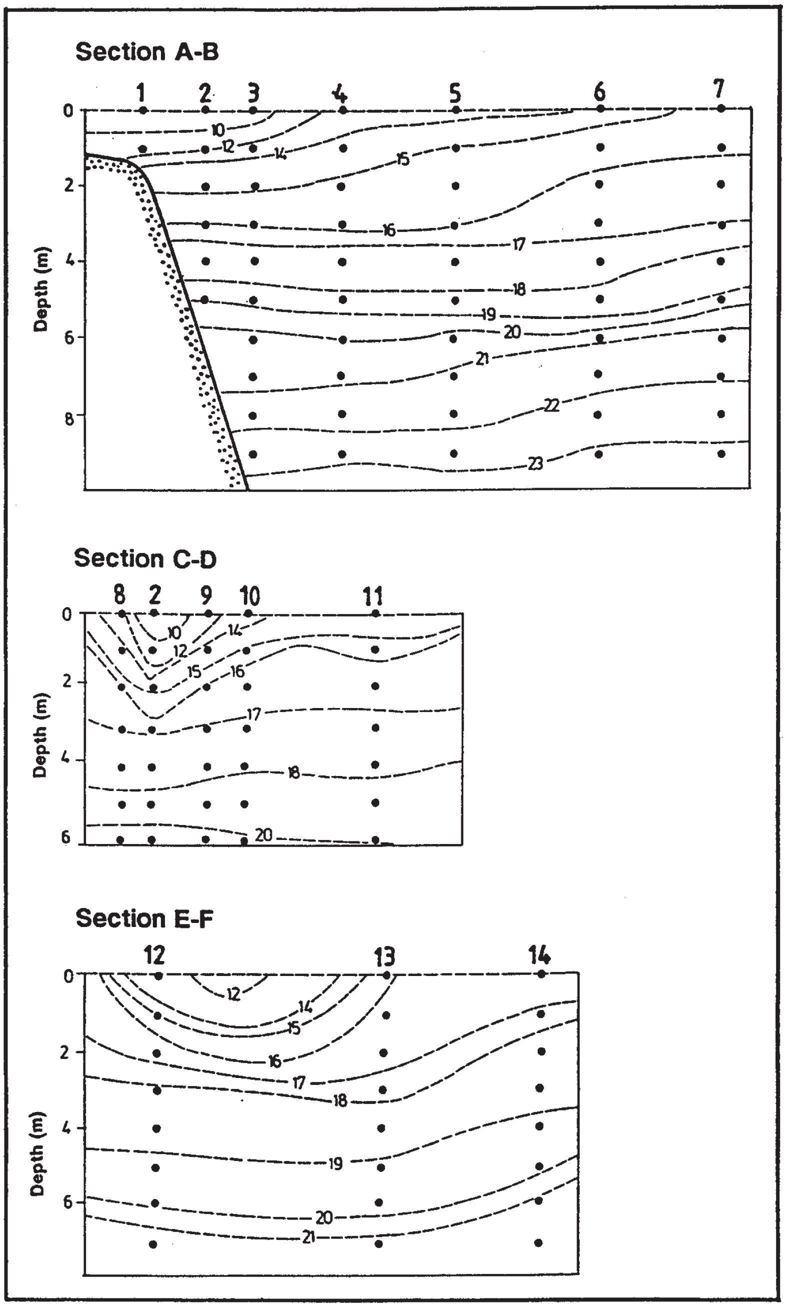

Fig. 7 - River Louros (18-20/2/86): density (σ_t) contours across sections A-B, C-D and E-F (for locations see Fig. 2).

6 m. Beneath the halocline, the salinity increases gradually to about 30 at 10 m. Along section C-D, the main branch of the plume is present below Station 2, with salinities of 12 ppt at the surface and 20 ppt at 2.5 m. The secondary branch, beneath Station 11, is restricted to salinities of 20 ppt in the upper 0.5 m. The deepest influence of the plume within the water column is represented by the 22 ppt isohaline, at a depth of about 3 m. On section E-F, which is located farther

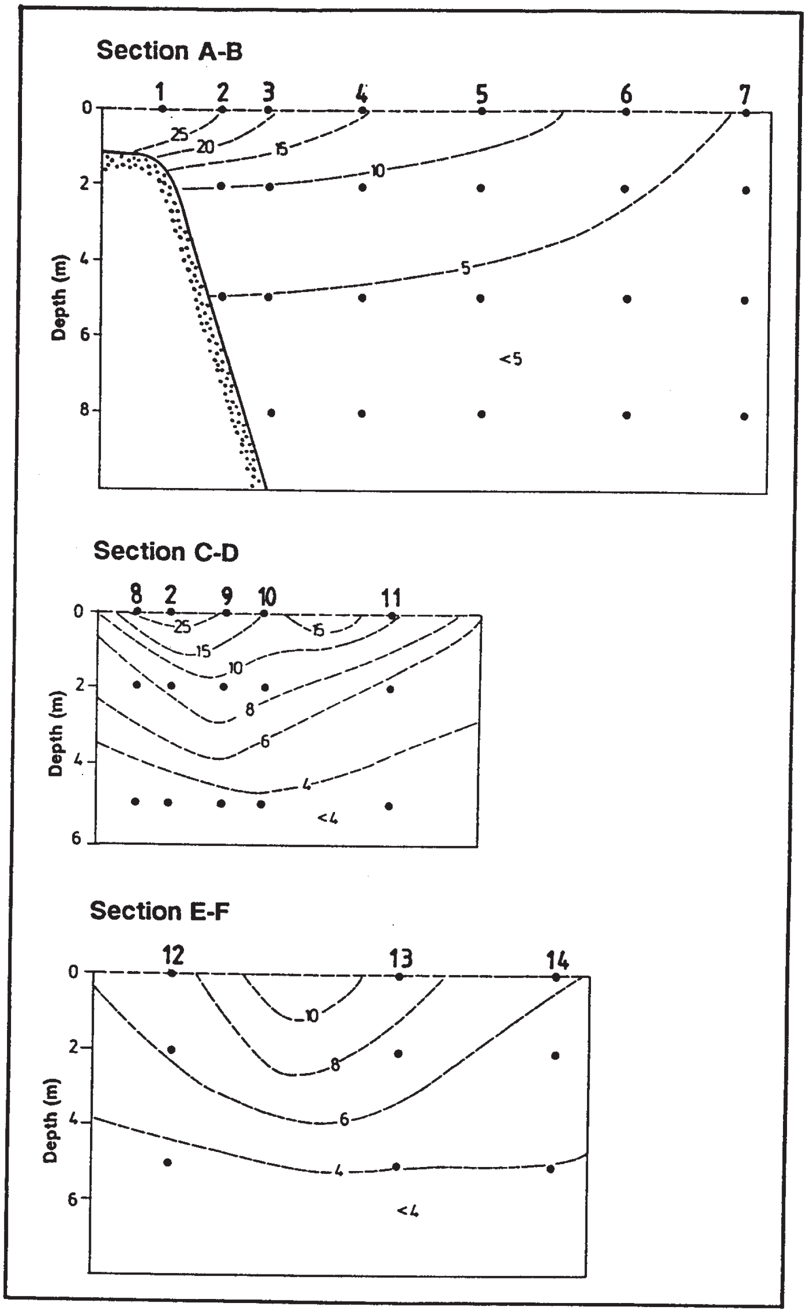

Fig. 8 - River Louros (18-20/2/86): suspended sediment (mg/l) contours across sections A-B, C-D and E-F (for locations see Fig. 2).

offshore than C-D, the main branch of the plume has broadened and shallowed, with salinities of between 16 and 22. The secondary branch is not present at this location.

Density profiles over the three sections (Fig. 7) are very similar to those described for the salinity. Densities range from about 10.0 (σ_t) near the river mouth, increasing offshore to > 15.0 (σ_t) beyond Station 6. The density also increases with depth, from 16.0 (σ_t) between 2 and 3 m

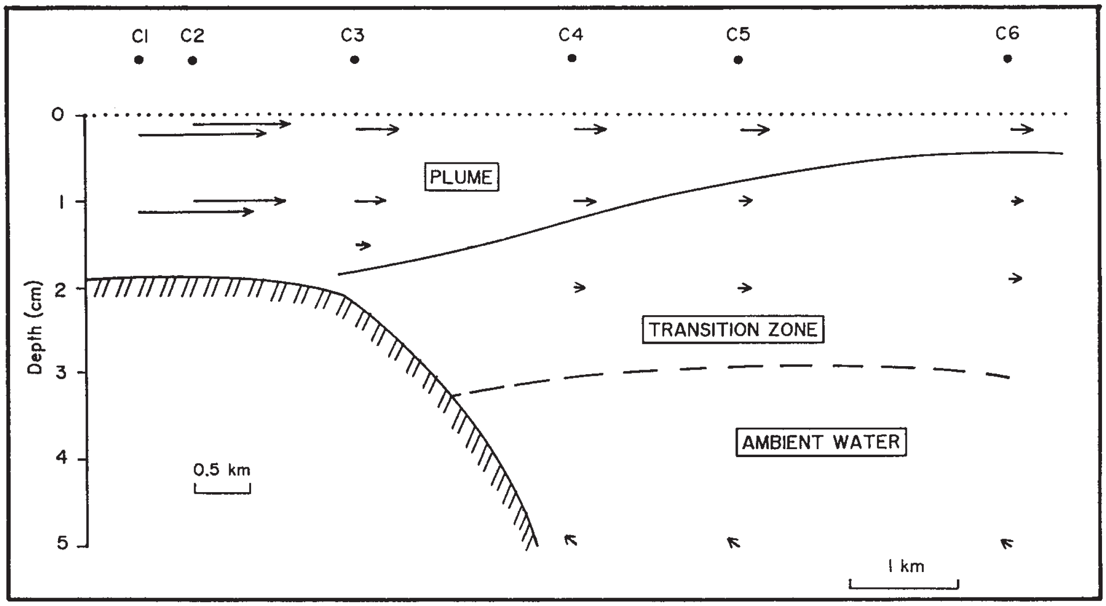

Fig. 9 - River Louros (21/2/86): current meter velocities presented schematically at the river mouth area (for station locations, see Fig. 3). Arrows are vectorial and their lengths represent the magnitude of the current speeds presented in Table 1.

up to 18-20.0 (σ_t) between 4.5 and 6 m; it reaches values in excess of 23.0 (σ_t) at 10 m. The gradual increase in density with depth provides evidence that the water column is stable. Also, the plume at the surface can be separated into two zones: the 'actual' plume, restricted within the 15.0 (σ_t) contour; and a transition zone between the plume and the ambient water, which lies between 15.0 and 16.0 (σ_t). A pycnocline is present between the 18.0 and 20.0 (σ_t) contours.

The behaviour of the SSC is the inverse of that for salinity and density. The highest levels are near the river mouth (> 25 mg/l), reducing to 15 mg/l and 10 mg/l at 3 and 6 km offshore, respectively (Fig. 8). The quantity of SSC also decreases rapidly down through the water column, and is 10 mg/l at 2 m depth, and < 5 mg/l beneath the pycnocline (i.e., between 4.5 and 6 m depth). On Sections C-D and E-F, there is the same decreasing trend in SSC down through the water column. Thus, on section C-D, the near-surface levels of 25 mg/l decrease to 10 mg/l at 1.5 m; they reduce to < 4 mg/l below the pycnocline. In section E-F, the suspended sediment levels are weaker, with concentrations of 10 mg/l near the surface, decreasing to 8 mg/l between 2 and 3 m depth, and 4-5 mg/l within the pycnocline.

4.3. Velocity of the river plume dispersion

Current profiles were obtained from 6 oceanographic stations along the main axis of plume dispersion, as indicated primarily by the movement of surface driftcards. The position of the current meter stations, together with the tracks followed by driftcards, are shown in Fig. 3. The current data obtained are presented in Table 1 (see chapter 3) and are illustrated schematically in Fig. 9. The main direction of plume dispersion was southwards, with velocities within the river plume reducing with distance from the river mouth and depth below the water surface. Outflow velocities, near the surface, are > 1 m/s at the river mouth; these reduce down to 0.3 m/s at a distance of 500 m, to become eventually < 0.2 m/s at 1500 m from the mouth. As shown in Fig. 9, strong deceleration occurs near the river mouth; farther to seawards, the outflow decelerates much more slowly.

5. Discussion

The general structure of the water column at Salaora Bay consists of: a surface layer; an intermediate layer, between 4 and 10 ±0 2 m, which is the pycnocline region; and a bottom layer, with nearly constant physical properties. Such a structure, with the surficial fresher water layer separated by a pycnocline from the bottom (denser) water mass, is likely to be a persistent feature throughout the year over the whole of Amvrakikos Gulf (Piper et al., 1982b; Papayiannis, 1985).

The surface layer is likely to have been formed by freshwater inputs from the two main rivers (Louros and Arachthos), from other smaller streams and from direct rainfall inputs. This layer is characterised by its low salinity, whilst its temperature varies seasonally in response to fluctuations in the air temperature. The intermediate layer (pycnocline), between 4 and 10 m, seems to be related to the presence of a sill (at approx. 10 m), in Preveza Straits; from here, the more saline and warmer waters of the Ionian Sea enter Amvrakikos Gulf. This water mass, upon mixing with the fresher upper layer, becomes cooler; as it was initially more saline, it also becomes denser and eventually sinks to form the bottom water mass. This water mass, especially in its lower parts, is likely to be deoxidised (Papayiannis, 1985) as mixing is restricted by: the presence of a shallow sill; the absence of high waves, due to the limited fetches; and the exceptionally low tidal ranges (< 0.5 m).

The size of the plumes and their areal extent over the receiving basin, together with their depth, depends primarily on the river discharge; their general shape is the result of the prevailing meteorological and oceanographic conditions. The River Louros plume, due to the absence of strong winds, waves or surface currents, tends to be elongate in shape; its long axis forms the seaward extension of the major distributary channel. Generally, plumes are deflected towards the right in the northern hemisphere (cf. to the left in the south), due to the action of the Coriolis force (McClimans and Sagrov,1982). However, it is usually the circulation induced by the wind, wave or tidal activity which governs the shape and the main direction of the plume dispersion. In the case of the Greek rivers, this movement is enhanced by their relatively low and strongly fluctuating discharges; these form shallow plumes, which are more susceptible to wind-induced water circulation patterns (Koutitas and O'Connor, 1980; Balopoulos et al., 1986).

The surface expression of the R. Louros plume, similarly to those formed offshore from other Greek rivers (i.e., River Axios, River Aliakmon; after Robles et al. (1983)) cannot be compared with the plumes established offshore from the mouths of the Mississippi (Scruton and Moore, 1953; Coleman and Wright, 1971), Amazon (Gibbs, 1970; Legeckis, 1986) and Zaire (Eisma, 1978), which extend > 100 km offshore; they can be compared, however, with smaller

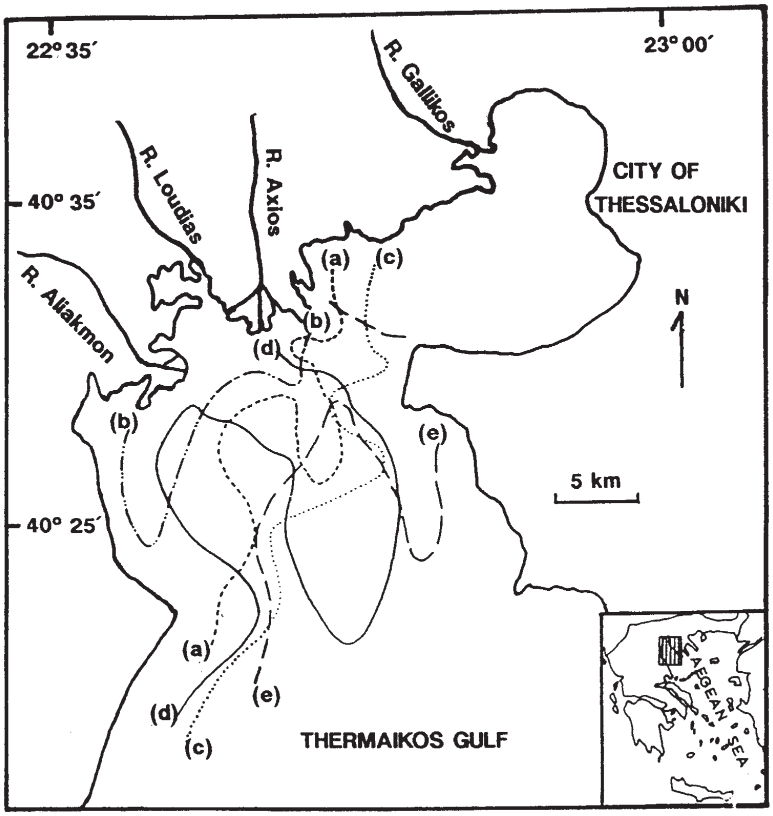

Fig. 10 - Seasonal dispersion patterns of river plumes over inner Thermaikos Gulf, as indicated by the surface isohaline 34 contour during: (a) August 1975; (b) September 1975; (c) November 1975; (d) February 1976; and (e) April 1976 (data abstracted from Robles et al., 1983).

Mediterranean river systems, such as those of the Ebro (Maldonado, 1975), Po (Grancini and Cescon, 1973) and Rhone (Ookmans, 1975), which are characterised by comparable discharge levels (Milliman and Syvitski, 1992). On the other hand, the plumes formed offshore from the river mouths of the Greek rivers, during moderate and high river discharge levels, might be expected to extend over most of the relatively small receiving basins; thus, they supply sediments not only to the area near their mouth and delta front areas, but also over most of their prodelta areas. Fig. 10, for example, shows annual variation in the freshwater outflows (salinity represented by the < 34 isohaline) of rivers discharging into Thermaikos Gulf. The plumes may be seen to be dispersed over the whole of the inner shallow water (depths < 35 m) embayment of the gulf; this is in response to periodic fluctuations in the wind-induced water circulation, as discussed previously. Moreover, terrigenous sediment inputs, from rivers draining into Thermaikos Gulf, have been identified not only within the inner parts of the Gulf but also farther to the south; these eventually reach the deep waters (> 1000 m) of Sporades basin (Lykousis et al., 1981).

The amount of suspended sediment contained within the river discharge depends upon many parameters relating to the catchment area, such as relief, lithology, and type of weathering pro-

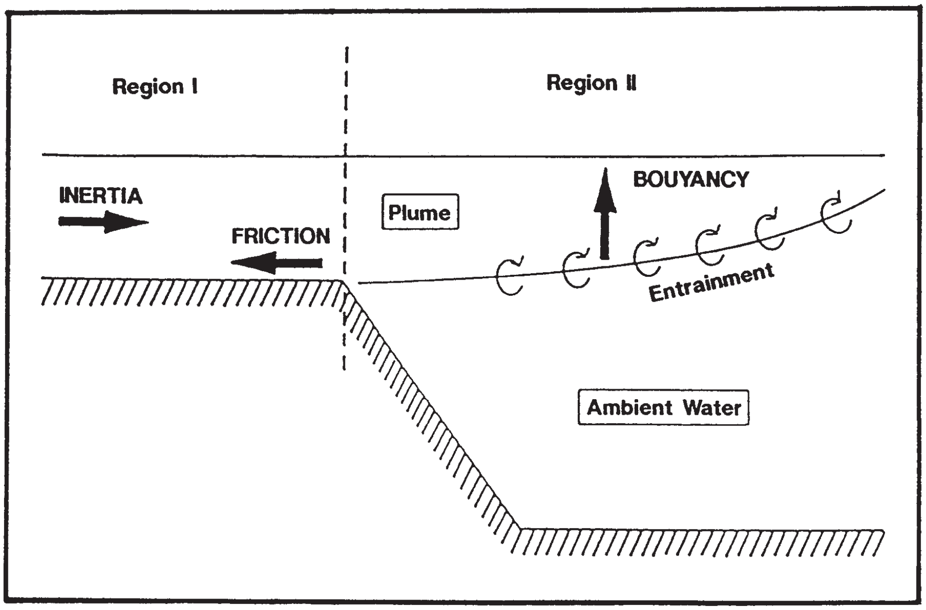

Fig. 11 - Schematic representation of plume dispersion with the different forces and processes operating within Regions I and II shown.

cesses. Furthermore, the sediment discharges fluctuate seasonally and are generally associated with flood events (Poulos et al., 1996). During the flood stage of the River Louros, the surface SSC varied from > 40 mg/l near the river mouth, to 25 mg/l above the delta front area, and < 10 mg/l farther offshore. These concentrations are reduced rapidly towards the lower boundary of the plume, as shown in Figs. 5 and 8. As deduced from the above, SSC's carried by the river plume reduce with distance from the river mouth, and with depth within the plume, as the plume loses its transporting ability. Below the surface layer of the water column in the receiving basin, which is influenced by the presence of the river plume, the waters are characterised by low (< 3 mg/l) and uniform concentrations of suspended material.

In summary, the river outflow undergoes rapid deceleration near its mouth, due to interaction with the distributary mouth bar (when present) and bottom friction. From the delta front and progressively in an offshore direction, the plume spreads as a buoyant feature; this decelerates gradually, in response to upwards entrainment of the ambient seawater (Wright, 1985b). Hence, energy characteristics of the River Louros plume are divided into two regions as is shown in Fig. 11: (I) where there is direct contact between the outflow and the sea bottom, wherein the dominant forces are the outflow inertia and the frictional force between the outflow and the bed; (II) where there is 'salt- wedge' type circulation and the dominant forces are the seaward inertia and buoyancy of the fresher water plume, and where the process of entrainment takes place (at the boundary between the overlying lighter and fresher layer and the more saline and heavier ambient seawater).

Within the region characterised by rapid deceleration and very low salinities, the coarser and, consequently, heavier fraction of the suspended sediment (coarse and medium grained sand) settles; this contributes, as well, to the formation of the river mouth bar. To seawards of the bar crest, the finer material (fine sand, coarse to medium silt) settles according its size/weight (Gibbs, 1977) or through the formation of flocs (Whitehouse et al., 1964); this is due to increasing salinities, in response to upwards entrainment of the more saline ambient waters. Even farther offshore, above the prodelta area where the salinity differences between the plume and the surrounding water are only very small, the very fine particles remaining in suspension (fine silt, clay), are expected to settle either as individual particles, as flocs or by the action of biophysicochemical processes such as that of pelletization (Weaver, 1989).

6. Conclusions

The plume of the River Louros, during the period of data collection (February, 1986) when the river was in a flood stage with a discharge of about 50 m^3/s (compared with an average discharge for February of 24.6 m^3/s (Therianos,1974)), dominated the upper 2 m of the water column near the river mouth. The plume extended up to 5 km seawards as a thin (< 0.5 m) surface layer, towards the south and covering almost the total area of Salaora Bay. The general structure of the water column of Salaora Bay is similar to that of the Amvrakikos Gulf, having: a surface fresher layer (2-3 m), with salinities < 22 ppt and temperatures varying seasonally and following fluctuations in the air temperature; an intermediate layer (3-15 m), a pycnocline region where salinity increases rapidly up to 35 with temperatures decreasing from 10 °C to 16 °C; and the bottom layer with near-bed salinity of 37 ppt and a temperature of 15 °C.

Suspended sediment concentrations, from > 25 mg/l at the river mouth, decrease rapidly seawards and with depth as the river outflow decelerates (losing, therefore, its transporting ability). This deceleration is more rapid near the river mouth as the river outflow interacts with the sea bed, whilst farther offshore, due to the greater water depths, it spreads as a buoyant effluent plume decelerating more slowly due to the upward entrainment of the ambient water.

The deposition of sediments within Salaora Bay is governed by the sediment-laden outflows of the River Louros. The buoyant plume, together with the water circulation, is capable of spreading fine-grained material all over the embayment. The rapid deceleration of the river outflow near the river mouth is accompanied by deposition of coarser grained material (sand), whilst farther offshore the mud fraction is deposited according to its particle size or by forming flocs, as salinity increases, and by biophysicochemical processes such as pelletization.

Acknowledgements. The authors would like to thank the staff of the Marine Geology Laboratory at Patras University and, especially, Prof. G. Ferentinos and Drs Papatheodorou and Achiliopoulos, for their help with the fieldwork and for their scientific discussions. Thanks are extended also to Mrs K. Davis for her help in drafting the figures. During preparation of the manuscript, one of the authors (S. Poulos) was supported by the EC "Human Capital and Mobility" Programme (Contract No. 920197).

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