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Circulation and suspended matter distribution in a microtidal deltaic system: the Isonzo river mouth (northern Adriatic Sea)

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ABSTRACT

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Two field investigations, under low river flow regime, were conducted in the Isonzo River mouth, Gulf of Trieste, to examine effluent dynamics and suspended sediment characteristics through the water column. The well-marked stratification influences particle size distribution. Multivariate statistical analysis was successfully utilized to define the characteristics and mutual relationships of the water masses in the estuarine zone. The results allow the Isonzo River mouth to be identified as a microtidal, low-energy, fine-grained deltaic system. The highly stratified water column and related hypopycnal flux prevail in the dynamic regime within the lower reach of the distributary mouth. This type of circulation is interrupted during extreme river floods, when the salt-wedge is pushed out of the river mouth.

ADDITIONAL INDEX WORDS: *salt-wedge, mixing zone, statistical analysis*

INTRODUCTION

The evolution of river mouths depends on several factors acting on sediment dispersal and accumulation pattern at different time and space scales. The most important are hydrodynamic parameters, such as tidal motion, river discharge and wave motion. Estuaries develop in coastal areas drowned by postglacial sea-level rise, subjected to daily tidal action, and where the fluvial sedimentary load is relatively small in relation to the dynamic forces that redistribute the terrigenous material. Deltas, on the contrary, are located in areas where these conditions are reversed, although single distributary channels may behave as estuaries themselves (PERILLO, 1995). Several studies have been conducted on river-mouth processes (e.g. WRIGHT and COLEMAN, 1974; WRIGHT, 1977) and focused on modelling the dynamics of river plumes (POULOS and COLLINS, 1994) and water circulation, sediment transport and deposition in estuaries (MEADE, 1972; PAULSON et al. 1989; DYER, 1991; BOLDRIN et al., 1992; KOSTASHUCK et al. 1992; SONDI et al., 1995). River mouths, especially estuaries, are sedimentary traps due to the rapid decrease in flow velocities and fine particle aggregation as consequence of sharp changes in physico-chemical conditions (MENON et al. 1998). Trace metals and contaminants are generally associated with fluvial suspended matter. An understanding of the dynamics of an estuarine system is thus important in the identification of the factors determining accumulation/desorption and to the prediction of the fate of contaminants in these environments (VERLAAN et al. 1998; ZWOLSMAN and VAN ECK, 1999). Following recent investigations into mercury contamination in the Gulf of Trieste (COVELLI et al. 2001; FAGANELI et al. 2003), the Isonzo River has been recognized as the main source of dissolved and particulate heavy metals in this area. However, information on estuarine physico-chemical processes affecting the Isonzo River suspended matter is still scarce.

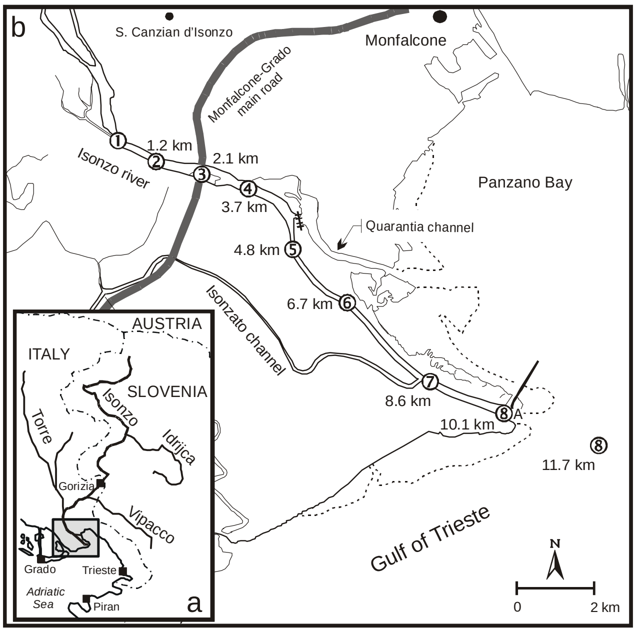

Figure 1: a): The Isonzo River drainage basin; b) the lower river course and location of sampling stations with related distances from the first sampling point.

The aim of this paper is to describe the physico-chemical characteristics of water masses within the Isonzo River channel, and outflow dynamics under relatively low water discharge, in order to identify the presence and extent of the salt-wedge and its influence on suspended matter concentration and grain-size distribution.

ENVIRONMENTAL SETTING

The Isonzo River is the main freshwater input to the Gulf of Trieste, a semi-enclosed marine basin located in the north-eastern Adriatic Sea (Fig. 1a). The surface area of the Gulf is about 600 km^2 and the water depth is generally shallow, reaching a maximum of about 25 m only in the central part of the Gulf. The catchment area of the Isonzo River covers about 3300 km^2, of which 2235 km^2 are located in Slovenia (where its name is Soča River) and the remainder in Italy.

The total river discharge depends in part on the water supply from its major tributaries (Idrijca, Torre-Natisone and Vipacco) and from the spring line located about 15 km upstream of the mouth. The average annual flow rate at the river mouth was estimated to be 80-110 m^3 s^{-1} (or 3.9 x 10^8 m^3 month^{-1}) by OLIVOTTI et al. (1986), 170 m^3 s^{-1} by ŠIRCA et al. (1999) and 196.8 m^3 s^{-1} (43.1-665.9 m^3 s^{-1}) based on more recent daily data (INTERREG II, 2001; Fig. 2). The river discharge shows significant seasonal variations, with two typical flood events governed by snowmelt and rainfall: a relatively long spring maximum (March-May) and a shorter, but more intensive, early autumn maximum (September-November), when the rate of flow can exceed 2500 m^3 s^{-1} (RAFVG, 1986). According to MOSETTI (1983), the mean annual solid discharge is 150 g m^3, with peaks of 1000 g m^3 during extreme events. Construction of artificial reservoirs for hydroelectric purposes is presumed to have reduced the sediment supply to the delta in the last eighty years. The estimated average sedimentation rate obtained by ^{210}Pb determination amounts to 1.84 mm yr^{-1} in the mid-Gulf (COVELLI et al., 2001), and 2.5 mm yr^{-1} in the coastal area in front of the river mouth (OGORELEC et al., 1991). Fluvial inputs appear to control primary production throughout the coastal marine system, as high contents of nutrients, especially nitrate, which determine phytoplankton blooms, are associated with the highest river discharges (MALEJ et al., 1995; SALVI et al., 1998).

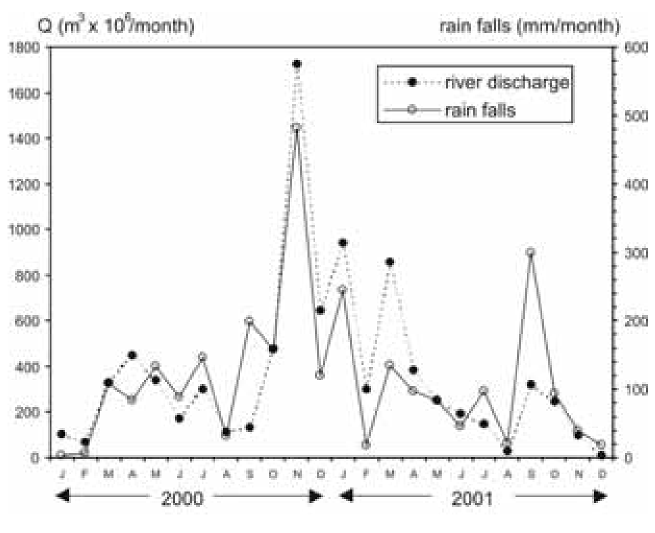

Figure 2: Comparison between average monthly rate of flow estimated at 15 km from the river mouth (INTERREG II, 2001) and mean monthly rainfall near Gorizia (data from ARPA FVG).

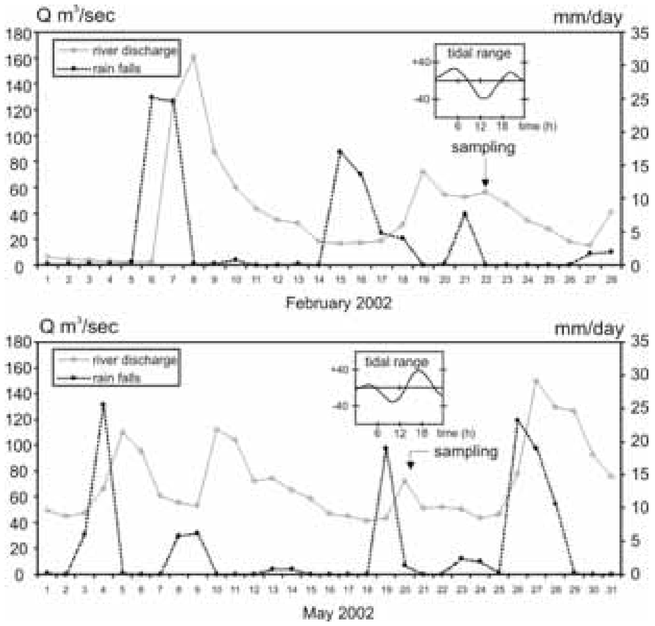

Figure 3. Comparison between average daily river discharge estimated at 15 km from the river mouth (data from RFVG, pers. comm.) and daily rainfall near Gorizia (data from ARPA FVG) in the sampling periods.

Currently, the Isonzo River mouth can be considered a stable straight and finger-like river-dominated delta (BRAMBATI, 1970) with river banks built up to prevent floods in the surrounding reclaimed areas. A delta bar crest faces the main distributary channel, which extends into the shallow waters of the Gulf of Trieste. A secondary river branch, the Quarantia channel, was active from the beginning of the 20th century until 1937, when a barrage was built to avoid transport and settling of sediments in Panzano Bay and, especially, into the navigation channel towards Monfalcone harbour. Medium to fine sands and pelitic sands prevail along the littoral zone on both sides of the river delta. The distribution pattern of fine deposits in the prodelta zone is related to the expansion of the fluvial plume in the Gulf and is characterized by grain-size decrease, from very sandy pelites near the river mouth, to pelites in the mid-Gulf and at depths greater than 6-7 m in Panzano Bay (BRAMBATI et al., 1983). The prodeltaic sediments are primarily carbonates, originating from Mesozoic limestone and dolomite, with secondary quartzo-feldspathic material derived from Eocene flysch, all of which are exposed in the Isonzo river drainage basin (STEFANINI, 1968). The water circulation system in the Gulf is affected by the action of winds (E-NE) and tides (average and spring ranges of 0.5 and 1 m, respectively).

The main circulation is anticlockwise and affects the whole northern Adriatic, acting on deep water layers flowing permanently at 2-3 cm s^{-1}. Wind-driven superficial currents characterize the uppermost water mass, to a depth of about 5 m, flowing anticlockwise with easterly winds and clockwise with westerly winds (STRAVISI, 1983; MALACIC, 1991).

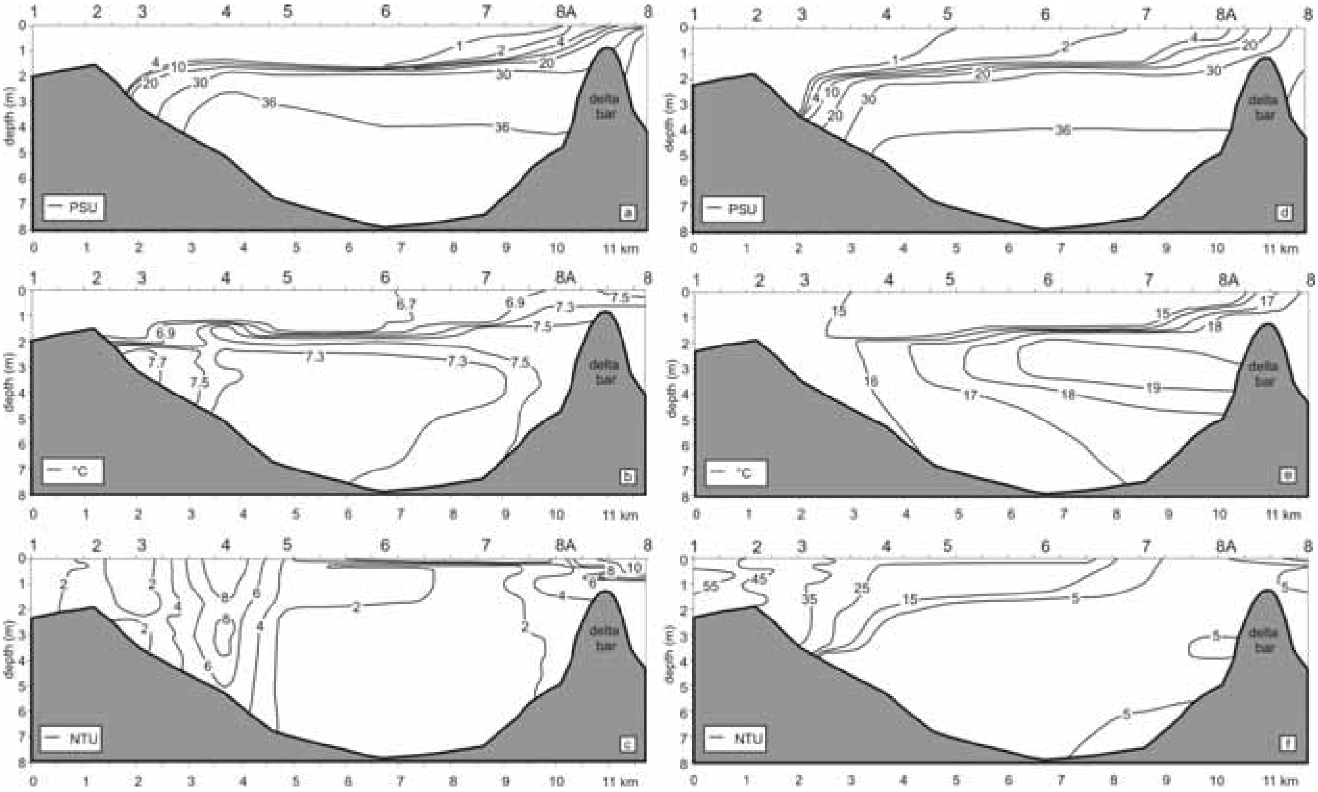

Figure 4. Schematic representation of salinity (PSU, Practical Salinity Unit), temperature (°C) and turbidity (NTU, Nephelometric Turbidity Units) in the lower river course in February (a, b, c) and in May (d, e, f) 2002.

EXPERIMENTAL METHODS

Field activities were carried out in two campaigns, both of them under low hydrodynamic flow regime (Fig. 3): the first one following a period of lower water discharge in February 2002 (56 $m^3 s^{-1}$ during the sampling day) and the second, during a period of relatively higher water discharge (73 $m^3 s^{-1}$ during the sampling day), in May 2002, after one day of heavy rains. Nine sampling stations were selected along the lower Isonzo river course (Fig. 1b), the first one about 11 km upstream from the mouth. Sampling was conducted from a boat along the main axis of the river channel starting from the sea (station 8), in both cases during neap flood-tide conditions. It is important to point out that in May, river flood flow reached station 6 while sampling operations were still in progress. Basic hydrographic parameters (pressure, temperature, salinity, turbidity) were recorded by CTD Hydrolab H_2O Multiprobe with a 0.1 dbar pressure step. Water samples were collected by means of a Niskin bottle (5 liters capacity) at the surface (i.e. 5-s; s=surface), at the bottom (i.e. 5-b; b=bottom) and at variable depths, according to the salinity profiles (i.e. 5-m; m=intermediate). Oxygen concentrations in water samples were determined using the Winkler method (GRASSHOFF et al., 1983). Along with salinity profiles reported in PSU (Practical Salinity Unit), the salinity was also measured (in ‰) on Niskin bottle samples using the Mohr-Knudsen titrimetrical method (STRICKLAND and PARSONS, 1972). To determine total suspended matter (TSM) concentrations, water samples were filtered on Whatman fibreglass GF/F (diameter 47 mm, 0.8 µm pore size) filters, pre-treated at 450 °C (STRICKLAND and PARSONS, 1972). Particulate organic carbon (POC) and total nitrogen (PN) contents, expressed as percentage of total solid and concentration (mg l^{-1}) in filtered water samples, were determined after acidification with 1 N HCl (HEDGES and STERN, 1984), using a Perkin Elmer CHN Elemental Analyser. Particle size analysis in the range 9-4 phi (1.95-62.5 µm) was performed by using a Coulter Multisizer II (Coulter Electronics Ltd., 1972). The Accucomp programme was used to acquire and process grain-size spectra.

RESULTS AND DISCUSSION

Hydrography and suspended matter

Spatial variability for salinity, temperature and turbidity in the river mouth section is shown schematically in Fig. 4a-e for lower (February) and higher (May) river discharges. At stations 1, 2 and 3 the temperature (averaging 6 and 15 °C, respectively) and salinity (< 1 ‰, < 2 PSU) values are homogenous through the water column and typical of riverine waters. Only in February, at the bottom of station 3, were intermediate salinity waters (16 ‰) detected (Fig. 5). These are formed by mixing of riverine and marine waters at the salt-wedge tip, always present in the river during low river discharge and shifting its position landward according to tidal range (RAFVG, 1995). In the central sector of the river mouth (stations 4, 5, 6 and 7), vertical salinity profiles allow a very sharp halocline between the surficial freshwaters and the bottom saltwaters to be distinguished. At station 8A, just before the delta bar, the trend of the vertical salinity profile

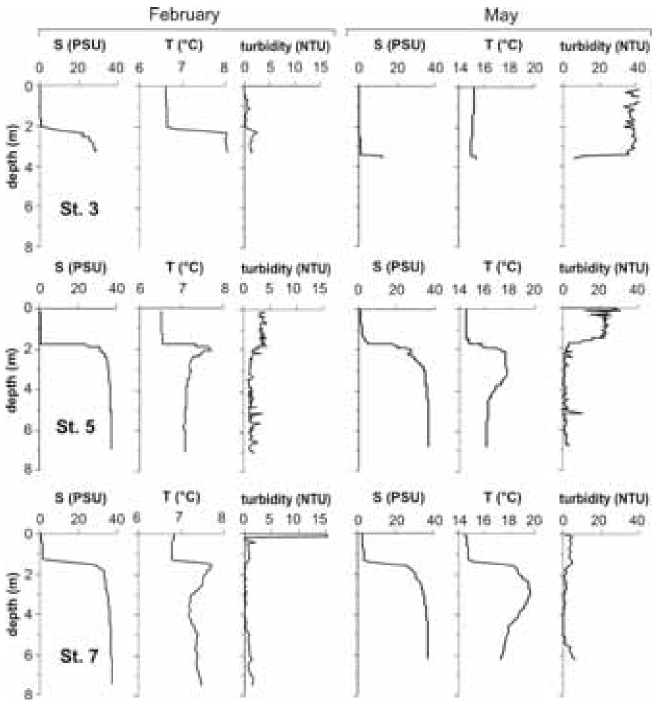

Figure 5. Vertical profiles of salinity (PSU, Practical Salinity Unit), temperature (°C) and turbidity (NTU, Nephelometric Turbidity Units) in sampling stations 3, 5 and 7 (February and May 2002).

suggests an increase in mixing between the fresh and salt water layers as the delta bar is approached. This intensified vertical mixing and entrainment can be explained in terms of breaking of internal waves (WRIGHT and COLEMAN, 1974; DYER, 1991), which also causes turbulence and an increase in turbidity values (Fig. 4c).

Temperature variability in the water column is small in winter (6.5-8.3 °C), whereas in spring, the range is much larger (14.3-19.6 °C). In comparison with February, the May data show a clear thermal stratification in the saline water mass, with a warmer layer at the top of the salt-wedge, just below the freshwater interface. Such a layer is restricted to a maximum of 30-40 cm vertical thickness (Fig. 5).

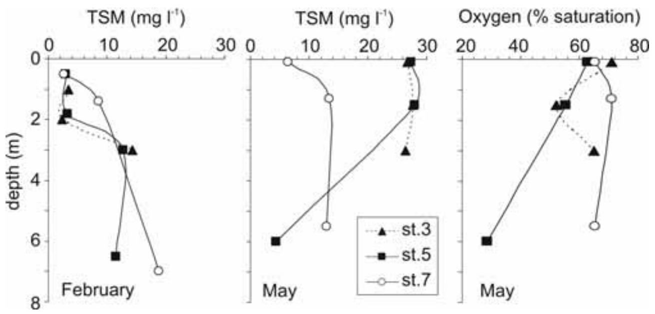

Figure 6. Vertical profiles of suspended load (TSM, mg l^{-1}) and dissolved Oxygen (% saturation) in stations 3, 5 and 7 (February and May 2002).

Turbidity values are generally very low in February (2-4 NTU, Nephelometric Turbidity Units), although maxima at sampling points 4 and 5 (6-8 NTU) characterize the interaction between fluvial and salt waters (Fig. 5). In May, this parameter is clearly related to the moderate flood event, showing the highest values (up to 55 NTU) in stations 1 and 2.

Dissolved oxygen concentration, measured only in May, exhibits a general decrease from the surface throughout the water column (Fig. 6). Undersaturated values at the bottom decrease from the sea (81.3 %, station 8) upstream to the salt-wedge tip (24.5 %, station 4). Oxygen depletion is due to respiration processes and consequent mineralization of organic matter in the salt-wedge. The low rate of exchange across the halocline implies that the residence time of the saline bottom water in the fluvial channel is probably long. The water can be renewed during the spring tide period of high current velocities or following intense floods which completely flush the sea water from the river mouth (DYER, 1991).

In February, TSM concentrations show a rapid increase from the surface to the riverbed (Fig. 6). The freshwaters layer is characterized by low TSM values (2 mg l^{-1}) in comparison with the intermediate depths (3-12 mg l^{-1}) and the saline bottom layer, where values are at a maximum (about 19 mg l^{-1}). An opposite vertical trend can be recognized in the data from the May sampling campaign, between station 4 and 6, where flood waters flow over the salt-wedge. Suspended loads at the surface reach up to 28 mg l^{-1}.

In February, particulate organic carbon (POC) and nitrogen (PN) varied within the ranges 0.7-14.6 % and 0.1-2.2 %, respectively. A general decrease of these parameters from the surface to the bottom layer was observed. In May, the corresponding POC and PN ranges were 1.1 %-11.8 % and 0.2-2.5 % respectively and intermediate depth samples showed higher percentages than both surface and bottom samples. The values for the Isonzo River are very close to the results obtained for the Adige (BOLDRIN et al., 1992) and Po (PETTINE et al., 1998) Rivers, the main water courses draining into the Adriatic Sea. POC and PN values are highly correlated (Fig. 7a), confirming that organically bound nitrogen was dominant in the estuarine suspended matter.

Significant inverse relationships between percentage values of POC and PN and suspended matter load were observed (Fig. 7b), similar to those reported for the Po River by PETTINE et al. (1998), and for most rivers in the world by MYBECK (1982). According to the last author, this is because autochthonous particulate matter is mixed with land-derived particles poor in organic content. This theory is supported by the marked positive linear relationship between carbonate contents and TSM (Fig. 7c). The distribution of POC (Fig. 7d) and PN (mg l^{-1} and %) as a function of salinity show similar relationships, thus indicating that physical processes such as advection and turbulent mixing control organic matter concentration. The POC/PN ratios varied between 4.4 and 8.7 in February, and between 5.1 and 7.3 in May. These values denote a freshwater and/or marine phytoplankton contribution (WAFAR et al., 1989; SULLIVAN et al., 2001).

The well marked stratification also affects particle size distributions of suspended matter along the river course and, vertically, in the water column in low discharge conditions (Fig 8). Grain-size spectra in the freshwater layer are usually skewed, poorly sorted and dominated by fine particles, with the mode ranging from 6.6 to 14.7 μm. In the mixing zone, particle size distributions show an abrupt increase in the fine fraction when compared with surface samples.

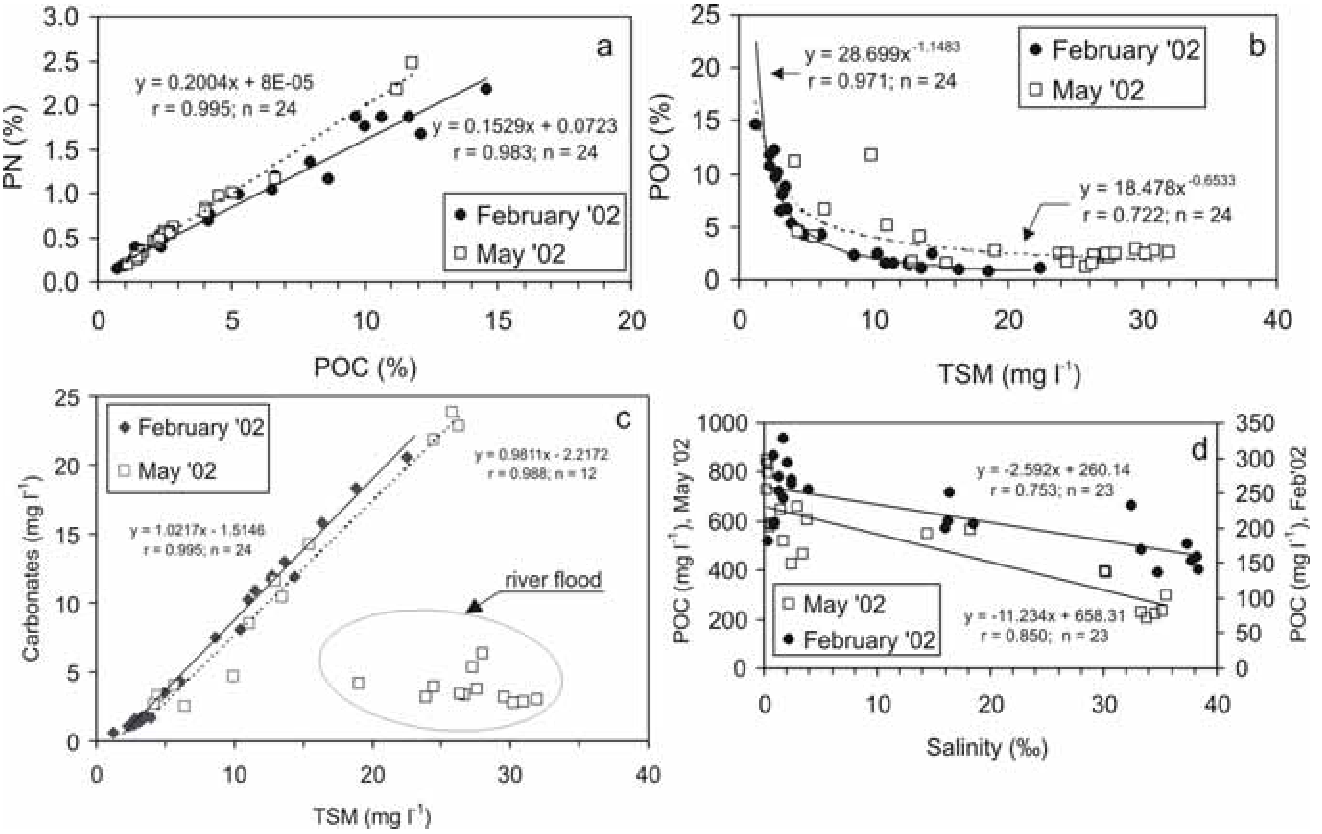

Figure 7. Relationship between POC and PN (a), POC and TSM (b), carbonate content and TSM (c) and POC and salinity (d) in the two sampling periods.

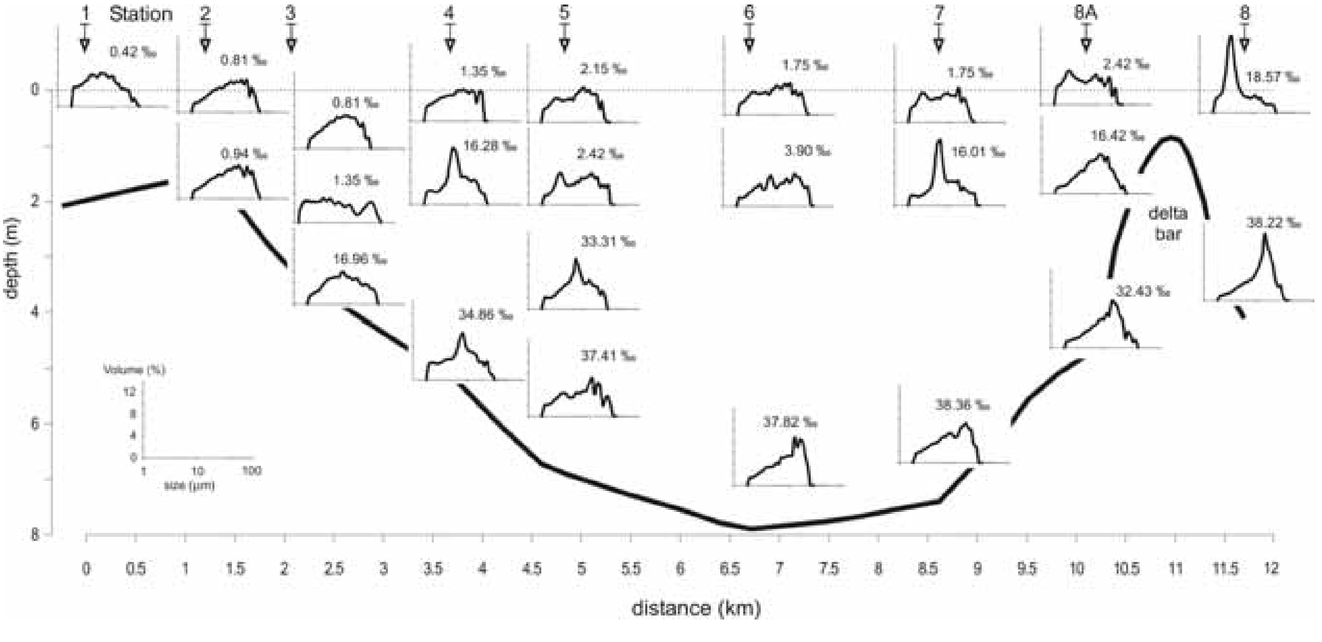

Figure 8. Grain-size spectra (volume %) of suspended matter in the Isonzo river mouth at low stage (February 2002). Salinity values (‰) for each sample are reported.

This typical sharp peak could be due to phytoplankton predominance and, particularly, to the aggregation of diatom cells influenced by low salinities (EISMA, 1993), water column stratification, low rainfall and nutrient availability (JONES et al. 1998, ORIVE et al., 1998).

Microscopic analyses confirmed the abundance of phytoplankton (mainly *Thalassionema nitzschioides, Pseudo-nitzschia seriata, Chaetoceros affinis*) in the mixing layer.

In this layer, the relative abundance is four times higher than at the surface and twice higher than at the river bottom, respectively (CABRINI, pers. comm.). In the bottom layer of the salt-wedge, the size spectra are positively skewed with coarser modal class between 12.8 and 16.0 µm. This particle size distribution is also evident in front of the river mouth (station 8), thus indicating that the source of particles does not seem to be the fresh layer across the halocline, but a slow inflow of seawater intruding the lower river course at the bottom.

Statistical analysis

The variability of the two data sets has been systematically examined using factor analysis, in order to provide information on the dynamics of particulate matter and water bodies in the river mouth. This multivariate statistical technique has been widely and successfully utilized in studies of coastal (IMBRIE and VAN ANDEL, 1964; KLOVAN, 1966) and estuarine (VASCONCELOS et al., 1995; VERLAAN et al., 1998) environments. Q-mode factor analysis was applied to suspended matter (grain-size, TSM, POC and PN) and physico-chemical parameters (T and S) in order to discriminate the main sample populations for each sampling. Varimax rotation was used as a best-fit procedure on the original data matrix. For the February sampling, factor loadings along with communalities, Eigenvalues, and percent of total variance accounted for are reported in Table 1a. Two factors account for the 95.69 % of the total variance. The first rotated factor, contributing 58.16 % of total variance, is related to freshwater samples, whereas the second factor is associated with seawater samples. The surficial sample of station 1 (1-s) and the bottom sample of station 7 (7-b) are the two end-members (Fig. 9a). Three main groups of samples are clearly distinguished from the binary relationship of the two factor loadings (Fig 9b). They reflect the characteristics of the main water bodies and their vertical stratification in the river mouth. The first group identifies fluvial samples (0.42-2.42, 1.84 ‰ avg salinity), collected at the surface along the whole river course from station 1 to station 8A, just before the river bar, and at the depth between 1.5-2 m at sampling points 2, 3, 5 and 6.

Table 1a: Q-mode Varimax rotated factor matrix for samples from February 2002

Variables	Factor 1	Factor 2	Communality
1-s (0.2m)	0.993	0.091	0.994
3-m (2.0m)	0.993	0.091	0.994
4-s (0.5m)	0.992	0.105	0.995
7-s (0.5m)	0.992	0.107	0.996
6-s (0.5m)	0.992	0.110	0.996
5-s (0.5m)	0.992	0.112	0.997
3-s (1.0m)	0.992	0.113	0.997
8A-s (0.2m)	0.991	0.104	0.993
5-ms (1.8m)	0.991	0.115	0.995
2-b (1.5m)	0.990	0.111	0.992
2-s (0.2m)	0.987	0.115	0.987
6-m (1.8m)	0.969	0.169	0.968
8-s (0.2m)	0.810	0.400	0.816
8A-m (1.0m)	0.670	0.710	0.953
3-b (3.0m)	0.653	0.726	0.953
7-m (1.4m)	0.639	0.656	0.839
4-m (1.5m)	0.447	0.780	0.808
5-b (6.5m)	0.159	0.956	0.939
5-mb (3.0m)	0.143	0.976	0.973
8-b (3.5m)	0.131	0.949	0.918
4-b (5.0m)	0.035	0.981	0.964
8A-b (4.0m)	0.028	0.969	0.940
6-b (7.0m)	-0.006	0.987	0.974
7-b (7.0m)	-0.061	0.990	0.984
Eigenvalues	*13.957*	*9.007*	
Total Variance	*58.16%*	*37.53%*	

Table 1b: Q-mode Varimax rotated factor matrix for samples from May 2002

Variables	Factor 1	Factor 21	Factor 3	Comm.
3-m (1.5m)	0.946	0.237	0.214	0.997
2-s (0.1m)	0.945	0.226	0.235	0.999
3-s (0.1m)	0.944	0.228	0.231	0.996
2-b (2.0m)	0.942	0.230	0.236	0.996
3-b (3.0m)	0.937	0.229	0.257	0.996
5-s (0.1m)	0.926	0.249	0.270	0.992
5-m (1.5m)	0.919	0.287	0.259	0.994
1-b (0.5m)	0.915	0.216	0.299	0.973
4-s (0.1m)	0.908	0.203	0.335	0.978
1-s (0.1m)	0.896	0.204	0.357	0.972
4-m (1.8m)	0.877	0.296	0.367	0.991
6-s (0.1m)	0.839	0.206	0.486	0.983
6-b (6.5m)	0.141	0.950	0.251	0.985
8-b (3.0m)	0.344	0.933	0.051	0.991
7-b (5.5m)	0.138	0.931	0.321	0.989
8A-b (3.0m)	0.45	0.880	0.120	0.991
8-s (0.1m)	0.442	0.877	0.164	0.991
4-b (4.0m)	0.144	0.631	0.758	0.993
5-b (6.0m)	0.156	0.580	0.797	0.996
7-m (1.3m)	0.523	0.383	0.758	0.995
8A-m (0.5m)	0.432	0.363	0.819	0.989
6-m (1.5m)	0.344	0.168	0.916	0.986
7-s (0.1m)	0.457	0.044	0.886	0.996
8A-s (0.2m)	0.381	0.012	0.923	0.997
Eigenvalues	*11.613*	*5.896*	*6.256*	
Total Variance	*48.39%*	*24.57%*	*26.07%*	

These samples (Table 2a) show, on average, low contents of TSM (3.16 mg l^{-1}) and low T (6.82 °C), whereas high contents of POC (90.07 µg mg^{-1}), PN (14.63 µg mg^{-1}) and high POC/PN ratios (7.17) were observed in comparison with bottom samples recovered from station 4 to station 8, and belonging to the third "saltwater" group (32.43-38.36, 36.06 ‰ avg salinity). In fact, for this group, the minimum POC and PN contents (11.48 and 2.19 µg mg^{-1}, respectively) and POC/PN ratio (6.35) are associated to maximum TSM values (15.21 mg l^{-1}) and higher temperature (7.30 °C), although the highest value for this parameter affects the mixing layer (7.68 °C). Only five samples, belonging to the second group, show intermediate salinity values (16.01-18.57, 16.85 ‰ avg), thus representing the freshwater-seawater mixing zone. Interfacial shear stress causes some entrainment of saltwater in the river water and an upward exchange of mass from the salt layer to the fresh layer (WRIGHT and COLEMAN, 1974). However, because of the stable density gradient, outlined by the sharp halocline revealed from CTD profiles and due to the relatively low velocity of the river current, mixing and turbulence are considerably reduced at the interface between the two water masses.

The Q-mode procedure, applied to the data matrix of late spring sampling, gave three factors accounting for 99.03 % of the total variance (Table 1b). The "end-member" samples are 3-m, 6-b and 8A-s, respectively, corresponding to three distinct groups of samples (Fig. 10a): freshwater samples, which belong to the moderate flood event, falling close to Factor 1; saltwater samples occurring near Factor 2; and freshwater and moderately salty samples identifying Factor 3. The last are found within the lower river course, which had not been reached by the flood event while sampling was in progress. Table 2b summarizes the average values of single parameters for each group. At the beginning of the flood event, fresh waters tend to be highly stratified and limited to the surface, filling the whole channel as river discharge increases. In May, flood waters had reached station 6 at the surface while the salt-wedge was still present upstream, at the bottom of station 4. During flood events, it was estimated, through in situ current-meter measurements, that freshwater takes from four to eight hours to reach the river bed (RAFVG, 1995). The same study showed that the value of the surface current speed (more than 120 cm sec^{-1}) is twice that recorded at the bottom. The salt wedge can be pushed completely seaward, to a position just outside the bar crest, during peak fluvial discharges. After a flood event, marine waters enter the river and move upstream depending on river flow and tidal fluxes. Tidal current speed is approximately 10-15 cm sec^{-1} in flood tide conditions (RAFVG, 1995).

For the May flood event, three distinct water masses interact along the estuarine section, as shown schematically in Fig. 10b.

Table 2a: Mean values (±std) of hydrographical parameters, TSM and the main compositional parameters for the three groups of samples recognised by factor analysis (February 2002).

parameter	unit	freshwaters (n=12)		mixing zone (n=5)		saltwaters (n=7)	
TSM	mg l^{-1}	3.16	±1.17	10.19	±3.68	15.21	±4.23
POC	µg mg^{-1}	90.07	±30.58	25.96	±9.51	11.48	±2.93
PN	µg mg^{-1}	14.63	±4.55	4.77	±1.60	2.19	±0.84
POC	µg l^{-1}	255.79	±42.49	242.08	±60.72	166.78	±32.26
PN	µg l^{-1}	41.91	±6.86	44.91	±11.26	31.09	±6.68
C/N		7.17	±0.84	6.31	±0.63	6.35	±0.92
T	°C	6.82	±0.35	7.68	±0.32	7.30	±0.12
S	‰	1.67	±0.96	16.85	±1.02	36.06	±2.49
turbidity	NTU	2.43	±2.55	8.72	±11.22	2.81	±2.09

Table 2b: Mean values (±std) of hydrographical parameters, TSM and the main compositional parameters for the four groups of samples recognised by factor analysis (May 2002).

parameter	unit	river flood n=12		saltwedge-upper limit n=2		fluvial waters n=5		saltwaters n=5	
TSM	mg l^{-1}	27.17	±3.54	5.01	±0.87	9.02	±3.73	20.99	±6.29
POC	µg mg^{-1}	24.46	±2.29	43.28	±3.61	77.49	±35.36	14.87	±2.11
PN	µg mg^{-1}	5.12	±0.56	8.96	±1.10	15.22	±7.51	2.65	±0.49
POC	µg l^{-1}	665	±111	215	±20	634	±305	306	±83
PN	µg l^{-1}	139	±27	44	±2	126	±69	54	±15
C/N		5.59	±0.22	5.65	±0.22	6.02	±0.41	6.60	±0.51
T	°C	15.07	±0.48	16.14	±0.03	15.24	±0.86	18.11	±0.99
S	‰	1.15	±1.17	33.53	±0.34	12.07	±8.71	33.15	±2.73
turbidity	NTU	36.35	±13.37	1.00	0.00	4.31	±1.69	5.24	±6.35
O_2	µmol l^{-1}	203.10	±29.91	66.38	±6.65	198.18	±10.69	163.03	±31.11
O_2	%	65.13	±9.69	26.52	±2.79	68.22	±3.76	67.58	±13.46

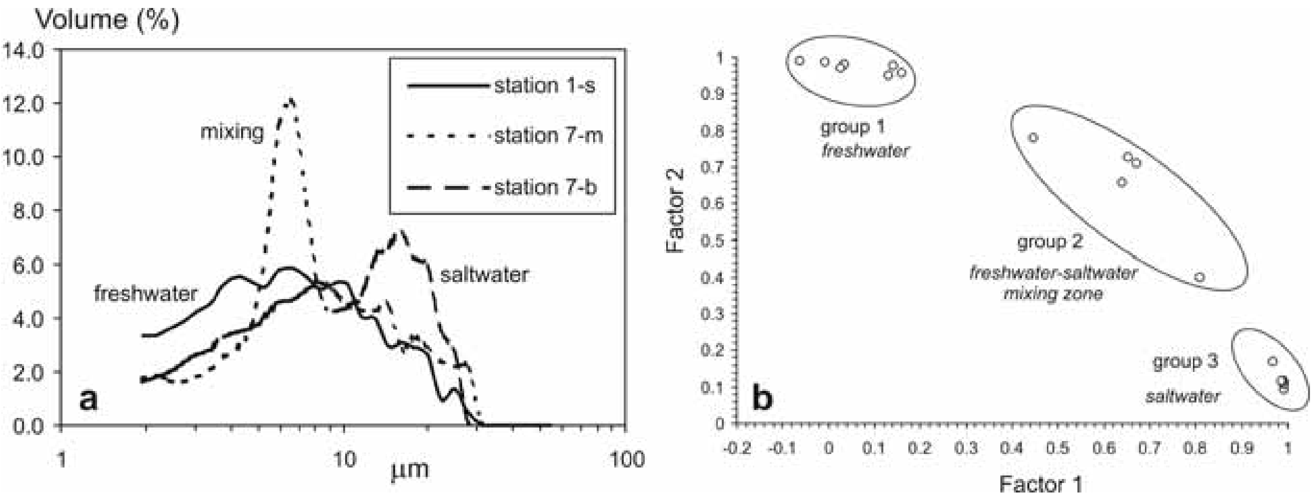

Figure 9. a) Typical grain-size spectra of suspended matter in freshwater (station 1-s), saltwater (station 7-b) and the mixing layer (station 7-m) in February 2002. b) Plot of factor loadings on the two factor axes for samples collected during the February 2002 campaign.

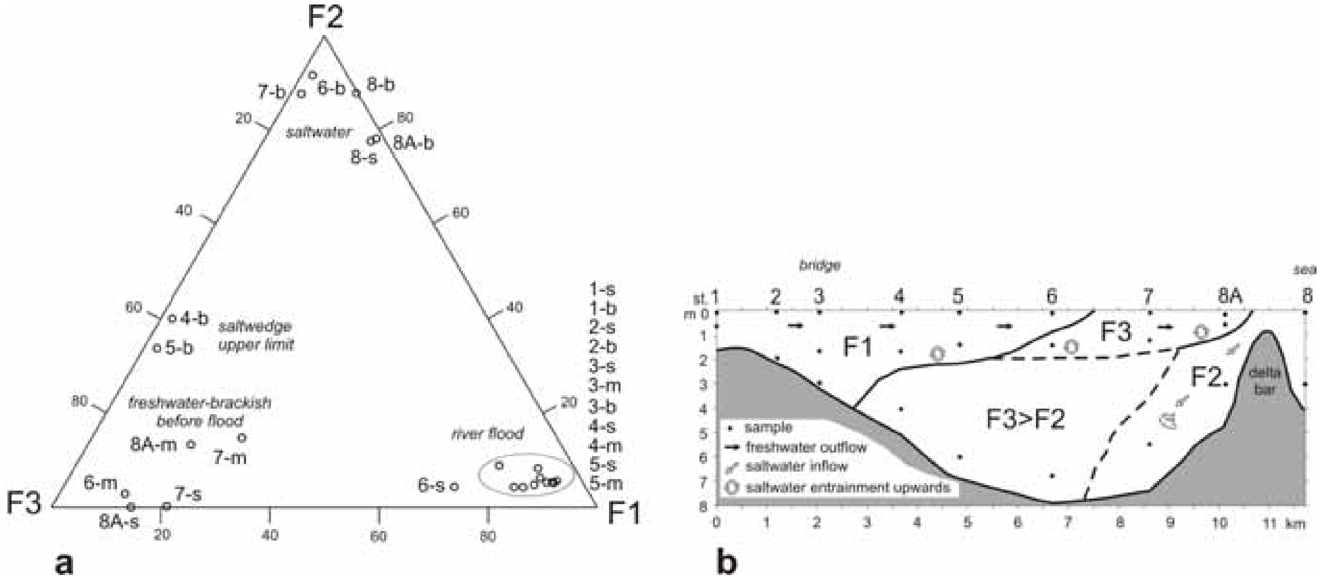

Figure 10. a) Plot of normalized factor components for samples collected during the May 2002 campaign. b) Schematic representation of the relationship between water masses and the three main factors in the lower river course (May 2002).

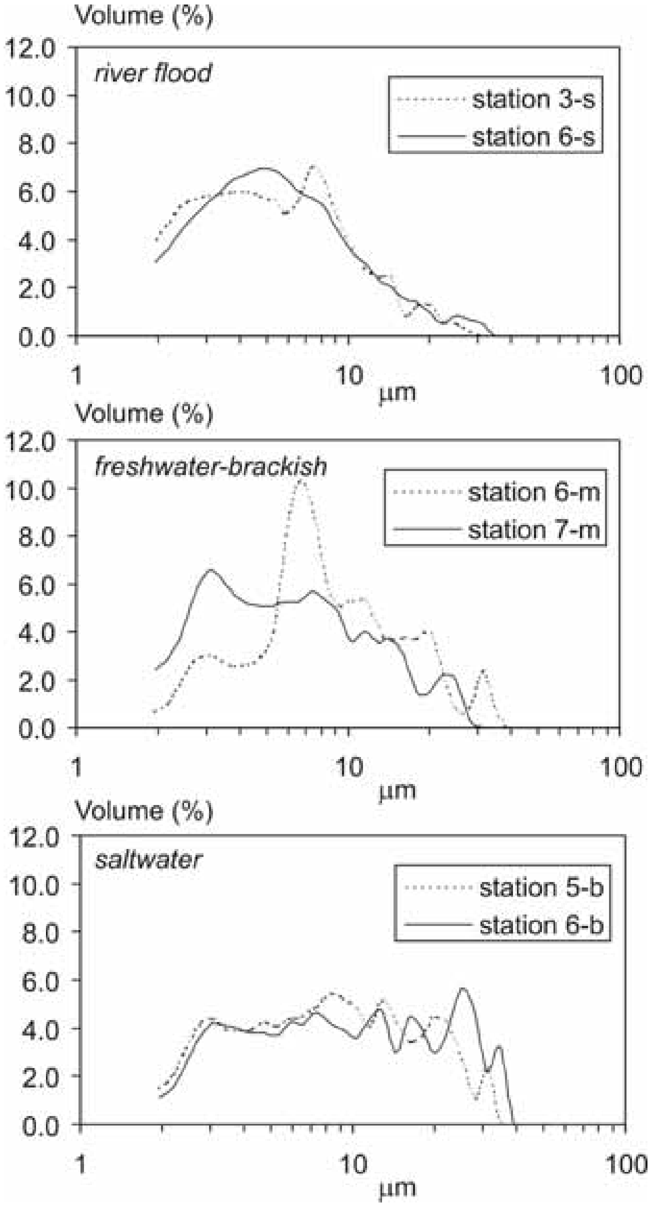

Figure 11. Representative grain-size spectra of suspended matter samples collected during the May 2002 campaign.

Grain-size spectra of TSM along the estuary (Fig. 11) are marked by two main sources, very fine river-borne and coarser marine particles. Particle size distributions are similar through the water column (mode 7.4 μm) in stations 1, 2 and 3, indicating homogenous transport conditions.

At low stage, although fluvial particles are partly affected by aggregation/flocculation in the mixing layer, it seems that fluvial suspended sediments do not settle in the channel. Because of the higher surficial river flow and the stratification, they are transported seaward of the mouth bar to the prodelta area and over even longer distances during flood periods (WRIGHT and COLEMAN, 1974). As demonstrated by the similarity of particle spectra of TSM above the bottom in front of the river mouth and in the channel, wave energy would contribute to resuspension of particles in the water column and tidal flux would provide the necessary energy for transporting suspended material in the salt-wedge.

CONCLUSIONS

The Isonzo River mouth is a microtidal, low-energy and fine-grained deltaic system. It is affected by long periods of low-medium discharges and short peaks of intense riverine flow, associated with high suspended sediment load, following heavy rainfall.

Systematic measurements of physico-chemical parameters along the water column in the lower course of the river allowed a salt-wedge intrusion to be distinguished, its extension in neap tide conditions to be defined, and the recognition of the freshwater-seawater mixing layer. The thickness of the freshwater layer above the saline intrusion decreases with distance seaward of the salt wedge tip whereas salinity increases. Suspended matter concentrations during low river discharge are higher at the bottom of the salt-wedge, the reverse being observed during a moderate flood event. In addition, grain-size spectra at the salt-wedge bottom are similar to those found outside the bar crest, suggesting a common marine source. Suspended particles are prevalently inorganic, and this component increases with high TSM concentrations. The organic fraction is bound to the finest particles and low POC/PN values indicate a contribution from freshwater and/or seawater phytoplankton. Multivariate statistical analyses helped to define the characteristics of the water masses in the estuarine zone, especially during moderate flood events, and their mutual relationships.

The Isonzo River mouth is rather deep in relation to fluvial discharge rate, and it is fronted by moderately deep water. Most of the year, the highly stratified water column and related hypopycnal flux prevail in the dynamic regime within the lower reach of the distributary mouth. This type of circulation, and the consequent buoyancy-dominated depositional pattern, is interrupted during extreme river floods. The salt-wedge is pushed out of the river mouth, turbulent bed friction becomes dominant and the coarser bed load is transported to the bar crest, where it accumulates following the rapid deceleration of the flow. The outflow spreads as a plume above the underlying marine water, transporting fine river borne material seaward to the prodelta zone. Further research should focus on sediment transport and deposition in front of the river mouth during real flood events and in the river channel during spring tide conditions.

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