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Nutrient fluxes from the Ebro River and subsequent across-shelf dispersion

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Abstract

Coastal areas receive significant amounts of nutrients (nitrogen, phosphorus, silicon) mostly from land-based sources, which contribute to increased biological productivity often exceeding that naturally found in coastal and marine environments. Most coastal zones of southern Europe are naturally oligotrophic with relatively small freshwater discharges. Studies of circulation and mixing processes over the continental shelf off the Ebro River delta are motivated by the need to understand transport pathways of natural and anthropogenic discharges affecting the adjacent marine environment. This paper investigates the characteristics of the last 45 km of the Ebro River in NE Spain, in terms of physiographic conditions, river discharges and hydrochemical and biological environment at three different periods in the annual cycle.

In spite of the high variability in water flow and ecological conditions, the study provides a reasonably good estimate of the overall amounts of nutrients discharged to the coastal environment. The largest nutrient load corresponds to nitrogen of which more than $10^4\,\mathrm{tm\,yr^{-1}}$ are discharged. Nitrogen regeneration took place in the lower river waters during fall and spring and nitrogen uptake prevailed at all stations in summer.

Phosphorus annual load of just $87\,\mathrm{tm\,yr^{-1}}$ does not contribute in a significant way to the fertilization of the coastal zone unlike other rivers draining highly developed watersheds. This is due to the trapping effect of the dams existing in the middle course of the river. The sudden phosphorus contribution due to the wash out of the salt-water wedge whenever the river flow increases to pre-flood conditions ($>400\,\mathrm{m^3\,s^{-1}}$) may be significant ($\sim 1.5$ tm or 2% of the overall P load).

The area coverage to which the Ebro River would add a surplus primary production of about $50\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$ (over a background of about $100\,\mathrm{g\,C\,m^{-2}\,d^{-1}}$), may be estimated in terms of nitrogen, at about $1200\,\mathrm{km^2}$ ($40\,\mathrm{km} \times 30\,\mathrm{km}$). If, however, the figures were based on phosphorus, the limiting nutrient in the freshwater system, then this increase in fertility would only affect an area of about $68\,\mathrm{km^2}$.

1. Introduction

River discharges are a prime source of nutrients for the coastal seas and also serve as a major conduit for the introduction of pollutants into the ocean. Maintaining or changing the quantity or

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quality of river discharge, therefore, becomes critically important as society tries to cope with present and future environmental changes. Predicting changes in estuarine processes and their impacts, however, requires knowledge of river flow, transport and discharge to the sea as well as definition of the fate of the discharged products in the estuarine, coastal and marine environments.

Coastal and shelf areas, all around the world, receive important amounts of chemical substances, mostly from land-based sources, which contribute to an increased biological productivity and, eventually, to undesirable levels of pollution. Rivers discharge, among other important substances, nutrients (nitrogen, phosphorus, and silicon) in amounts often exceeding those naturally found in coastal and marine environments. Nutrients are dispersed in estuarine and coastal areas often subject to restricted circulation with limited oxygenation. Whether they are in inorganic or organic form, dissolved or particulate, the nutrients accumulate in the bottom sediments and make estuarine areas prone to the development of eutrophication phenomena (English Channel, North Sea, Baltic Sea, Adriatic Sea, etc.).

Coastal areas affected by freshwater discharges are, at one time or another, invaded by plankton blooms (cyanobacteria, phaeocystis, etc.) that cause water discoloration (red tides) and some times produce large amounts of extracellular products. Atmospheric nutrient inputs, although not properly assessed (Alarcón et al., 1996), are also considered to have a significant contribution to the overall nutrient budgets in various coastal zones to the point of being considered responsible for the triggering of abnormal plankton blooms (Lancelot et al., 1990).

Estuarine areas are unequally affected by continental discharges depending on the physiographic conditions of the estuary and adjacent coastal zone, the hydrological regime and the oceanographic setup in the open seas. Estuaries in the relatively narrow southern European shelves with small or nearly absent tides, form relatively simple delta plains endangered by erosion as the rivers have all been subject to water control for irrigation and power production. They differ from the complex estuaries typical of the wide shelves of northern and western Europe, with large tidal ranges.

The coastal zones of southern Europe are naturally oligotrophic, since only small freshwater discharges caused by episodic stormy rain flow through otherwise dry rivers. Very often, long stretches of coastline are fertilized only by the discharge of mostly treated but nutrient-rich urban and industrial effluents, which may cause local eutrophic phenomena. Exceptions to this rule are estuarine areas receiving the discharges of the large rivers Po, Rhône and Ebro collecting the runoff from snow-covered mountain ranges (Alps, Pyrenees) and wastewater from large cities and intensive agricultural and industrial activities.

In the wide shelf coastal areas, internal nutrient fluxes are often controlled by biological regeneration, mostly in surface sediments. Conversely, in the narrow-shelf coastal environments the relatively strong longshore currents and density fronts control the internal nutrient fluxes mainly by interaction of currents with bottom topography (see various authors in this issue). Longshore currents in which the water flow leaves the coast to the right (left in the southern hemisphere) such as in the NW Mediterranean give rise to rather poor nutrient supply due to the cross-sectional circulation that brings nutrient depleted surface water onto the shelf. Productivity in these coastal waters is lower than that of the offshore areas (the so-called *Mediterranean Paradox*) where the general cyclonic circulation promotes fertilization (Sournia, 1973; Jacques and Treguer, 1986; Estrada et al., 1999).

An estuary is a semi-enclosed coastal body of water with free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage (Pritchard, 1955). River flow, tidally induced movements, precipitation and evaporation, wind stress and the distribution of sediments continuously fluctuate. Human activities such as dredging, land reclamation, bridge and sea wall construction and flood control measures impose further perturbation. Generalized interpretations of non-steady-state estuarine behavior in time-averaged terms should therefore include an indication of the degree of variability involved and, if possible, the relevant values of the more important controlling parameters (Morris, 1985).

There are numerous studies reported in the literature of the circulation and exchange processes in estuaries. As classified by Hansen and Rattray (1966), estuaries are generally influenced, to varying degrees, by tidal mixing and by gravitationally induced circulation resulting from longitudinal density variations caused by river input or high evaporation. Tidally driven estuaries such as the Mersey Estuary in the UK (Bowden, 1965) and the Bay of Fundy on eastern Canada (Holloway, 1981) tend to have vertically homogeneous water so that exchanges along the estuary are dependent on longitudinal dispersion. In contrast, weak tidal estuaries, e.g. the Mississippi River (Officer, 1976), often form a salt wedge with strong vertical salinity gradients so that circulation is primarily controlled by density-driven flows.

The Ebro River, with very weak tidal amplitudes and relatively small water flows most of the time, belongs to the salt wedge type of estuaries. Current studies of circulation and mixing processes over the continental shelf off the Ebro River delta, NE Spain, are motivated by the need to understand transport pathways of natural and anthropogenic wastes discharged to the nearshore marine environment in order to assess the long-term ecological effects of these discharges (Sanchez-Arcilla and Simpson, this issue).

This paper investigates the hydrography and transport characteristics of the Ebro River waters during a study that took place in November 1996, February–April 1997 and June–July 1997. Measurements and sampling were carried out from an outboard boat in the river channel between the sea and *Tortosa,* about 48 km upstream. Complementary investigations described elsewhere in this issue cover studies of the plume behavior carried out from the *N/O Tethys II* (Naudin et al., this issue) and open-sea oceanographic conditions carried out from the *B/O García del Cid* (Salat et al., this issue).

2. The Ebro River

The Ebro River (Fig. 1) discharges into the western Mediterranean Sea after a 928 km long parcours. The catchment area of 85,835 km^2 includes the mountains bordering the northernmost parts of the Iberian Peninsula (Cantabrian, Pyrenees and Iberian mountain ranges) and parts of the upper Castillian meseta. Most of the tributaries and the Ebro River itself are subject to intense water control by means of a network of dams and canals mostly built between the 1920s and 1980s with the dual purpose of irrigation and hydroelectric power generation (http://www.chebro.es/cuenca/cuenca.htm).

The last of these dams in *Ribarroja* (75 km from the sea) controls the water flow entering the lower Ebro River. This flow (Fig. 2) may vary from less than 100 m^3 s^{-1} in summer to more than 900 m^3 s^{-1} in winter, with an average flow that, in the absence of regulation, used to be close to 500 m^3 s^{-1}. A general decreasing trend in the mean annual discharge has been observed between 1914 and 1990 much steeper since 1960 (Guillén and Palanques, 1992). Peak discharges above 2500 m^3 s^{-1} may also take place causing floods of diverse consideration. One such flow was caused during the second half of January 1997, when the water authorities released as much water as they could safely do after heavy rains were forecast at the head of the Ebro tributaries. An *operational* flow of about 150 m^3 s^{-1} is required by the *Ascó* nuclear plant in order to keep the river water temperature raised within the stated limits. At present, under strict control mainly by the hydropower industry, lower flow rates are common all through the year, particularly in the drier months of April through November.

Mora d'Ebre, *Tortosa*, *Amposta* and the delta towns of *Deltebre* and *Sant Jaume d'Enveja*, with a total population of about 100,000, discharge partly treated sewage to the lower Ebro River. Chemical industries and the *Ascó* nuclear power plant, in the upper parts of this zone, are the major non-agricultural users of the Ebro water, returning their effluents to the river. Modest water transfers to other basins take place, particularly to the Northeast (*Tarragona*), but governmental plans

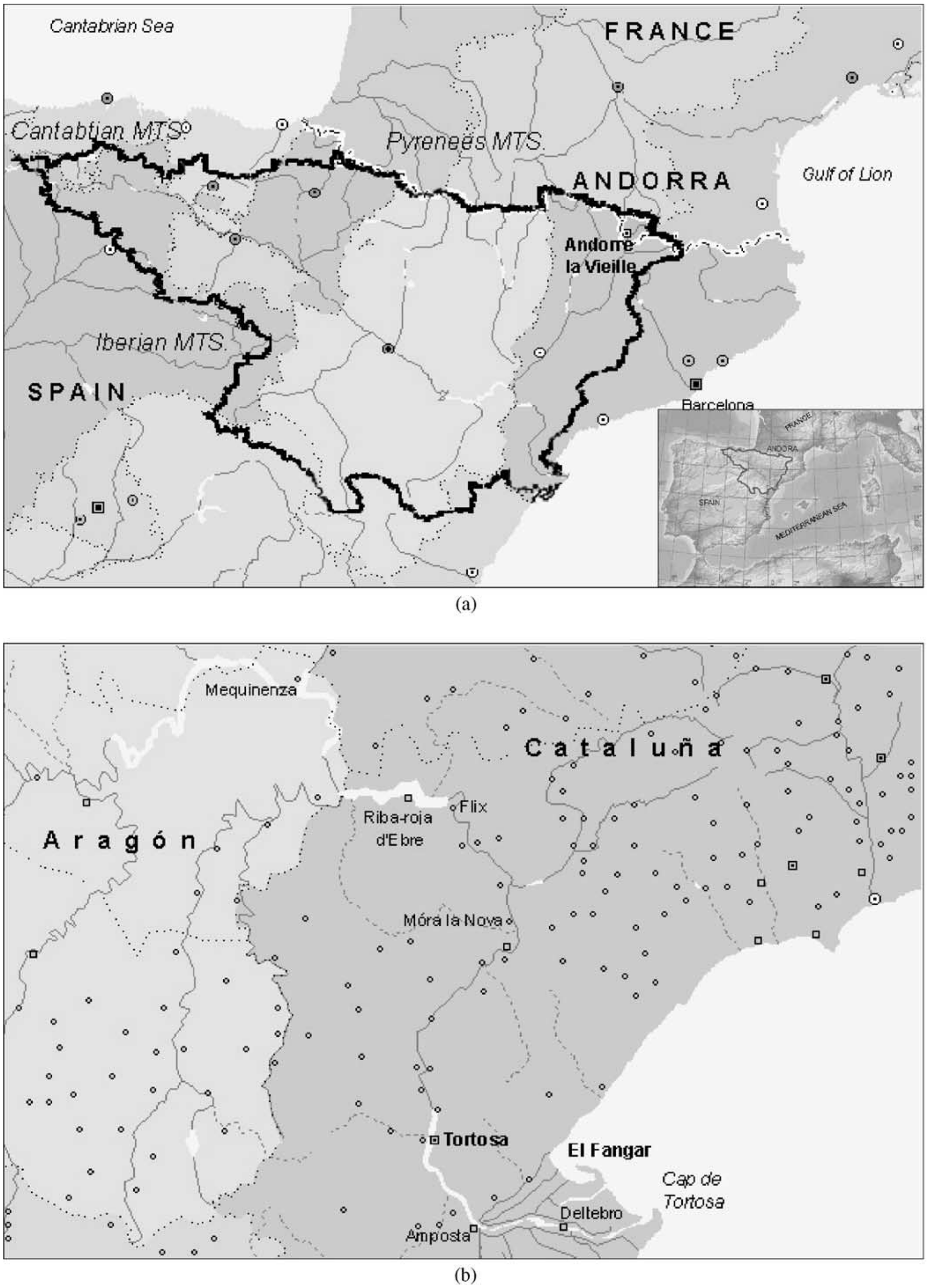

Fig. 1. (a) The Ebro River watershed and (b) the lower Ebro River with indication of the Mequinensa and Riba-roja dams.

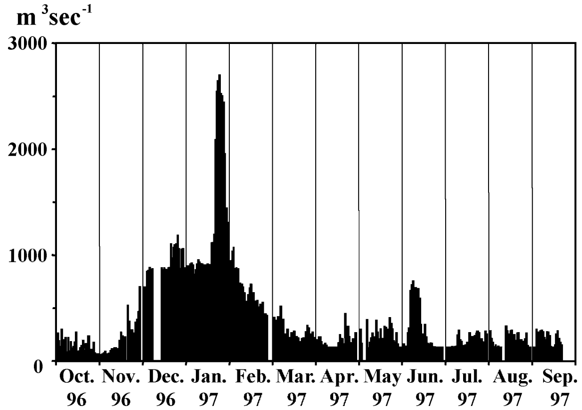

Fig. 2. River flow at the *Tortosa* gaging station during the year beginning October 1996 (Data kindly supplied by the *Confederación Hidrográfica del Ebro*).

are at present set that foresee transfers of more than $10^9\,m^3\,yr^{-1}$ to the agricultural and tourist areas of SE Spain (*Valencia*, *Alicante*, *Murcia*, *Almeria*).

The subaerial Ebro River delta, $325\,km^2$ at near sea level, is a beautiful river-dominated delta plain partly considered Natural Park. Known to have evolved during the last few centuries, mostly due to deforestation of the upper catchment areas (Guillén and Palanques, 1992), the delta reached a maximum area in the past not too different from the present one. The shoreline, mostly in the neighborhood of the river mouth, is at present rapidly retreating due to wave erosion and scarcity of river-born suspended sediments.

The present river channel (Fig. 3) is the result of a secular interaction between nature and humans who have been using both the water and the land gained by the river for cultivation of orange trees (in the higher lands) and rice (in the lower lands). These crops are still the main activities of the population of *Amposta*, *Deltebre* and *Sant Jaume d'Enveja*, between about 15 and 30 km from the sea. The rice pads are periodically flooded, mostly to avoid salinization and, upon draining, may discharge non-negligible amounts of fertilizers and pesticides into the coastal lagoons and the bays of *Els Alfacs* and *El Fangar*.

The river channel has a mean width of about 200 m although there are various locations in which the width reaches near 1 km. The lower-river bottom morphology is known from sonographs and bathymetric profiles. The channel depths observed during our study were always greater than 2 m and, particularly in the *Amposta* and *Riumar* areas, depths greater than 6 m were common. Various islands (*Gràcia*, *Sapinya* and *Vinallop*) split the channel forming the narrowest parts of the river. Shallow areas are periodically dredged between *Amposta* and *Tortosa* and the sand bar at the mouth to facilitate mostly leisure navigation.

3. Results

3.1. The freshwater

The upstream half of the section studied, at distances greater than 26 km from the sea with water depths between 2 and 5 m, always contained freshwater (salinity <1 psu) in the entire water column. In the lower part of the river (below about 25 km from the sea), two layers were always well defined:

(i) A freshwater surface layer, with salinity ranging from 0.5 to 5.0 psu increasing downstream and with the depth and a thickness of 1–2 m decreasing near the mouth.
(ii) A high-salinity bottom layer, with salinity ranging from 25 to 37.5 psu and a thickness up to 7 m depending on bottom topography.

The average nutrient concentrations in the freshwater between *Tortosa* and the salt-water wedge (salinity <1 psu), for the three surveys carried out are given in Table 1 together with an estimate of their variability (standard error).

The temperature distribution in the river (Fig. 4) was always quite homogeneous with a general cooling trend towards the sea, probably due to the progressive loss of heat introduced by the *Ascó* nuclear power plant further upstream. Some fluctuations in the surface temperature could also be due to the day/night warming/cooling cycle. Depending on the season, the bottom temperature was higher than that of the surface water. This was

Fig. 3. Area of study in the lower Ebro River channel.

Table 1
Average nutrient concentrations and standard error in freshwater (units in mmol m^{-1})

		(*n*)	NO_2+NO_3	NO_2	PO_4	SiO_4
Ebro I	07/11/96	7	149.04±0.01	1.33±0.10	1.12±0.06	36.66±0.84
Ebro II	27/03/97	26	120.64±0.27	1.40±0.03	0.34±0.02	64.27±0.36
Ebro III	04/07/97	8	208.06±3.61	0.61±0.02	0.53±0.09	50.92±1.48

particularly evident in November when the deep salt water had a maximum temperature at the central part of the section decreasing towards the river mouth, evidence of the time the salt-water wedge entered the river channel (Fig. 5).

The nitrate distribution (NO_3+NO_2) in the visited longitudinal section (Fig. 6) showed surface concentrations between 100 and 220 μmol l^{-1} with only a small decrease between *Tortosa* and the river mouth. The concentrations in the lower layer

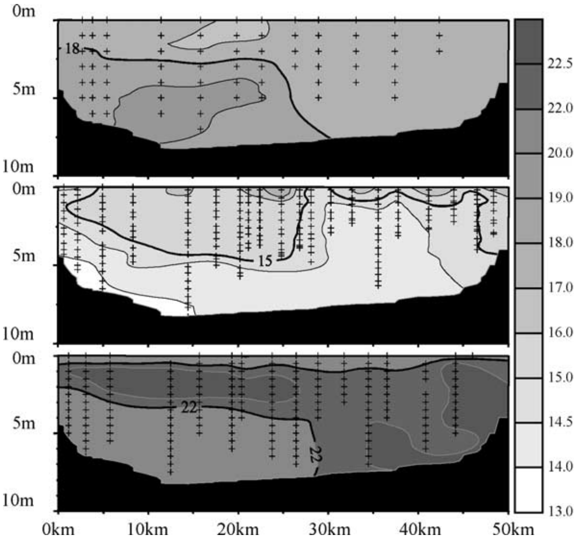

Fig. 4. Vertical distribution of *Temperature* (°C) along the lower Ebro River with indication of sampling stations: (a) Fans I (November 96); (b) Fans II (April 97) and (c) Fans III (July 97).

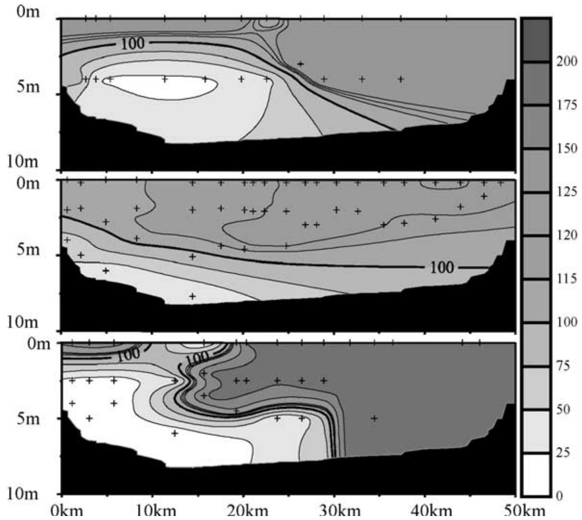

Fig. 6. Vertical distribution of *Nitrate* ($\mu mol\,l^{-1}$) along the lower Ebro River: (a) Fans I (November 96); (b) Fans II (April 97) and (c) Fans III (July 97).

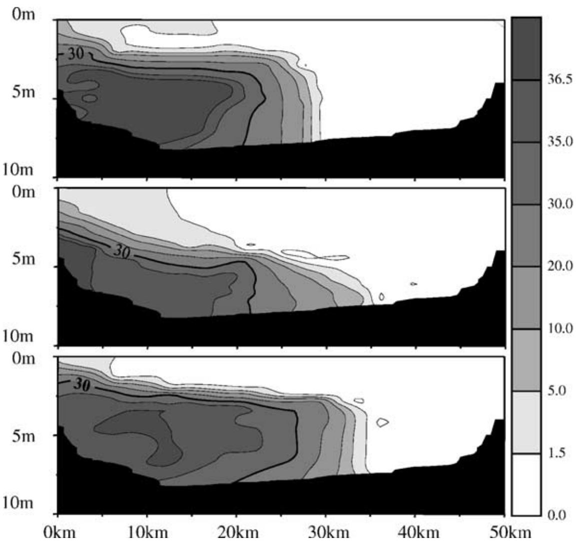

Fig. 5. Vertical distribution of *Salinity* (psu) along the lower Ebro River: (a) Fans I (November 96); (b) Fans II (April 97) and (c) Fans III (July 97).

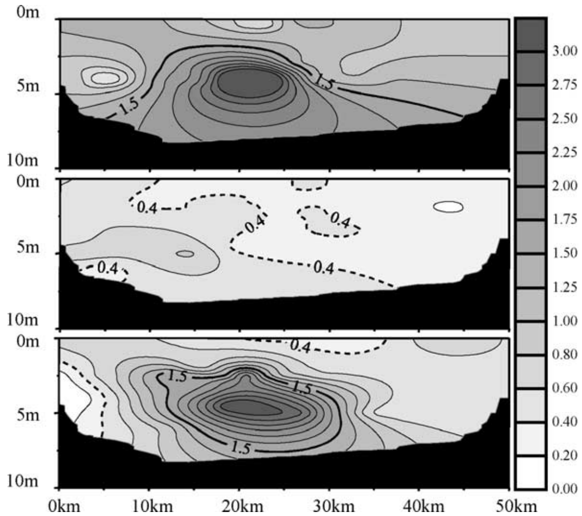

Fig. 7. Vertical distribution of *Phosphate* ($\mu mol\,l^{-1}$) along the lower Ebro River: (a) Fans I (November 96); (b) Fans II (April 97) and (c) Fans III (July 97).

(4 m depth) ranged between nearly zero and $40\,\mu mol\,l^{-1}$, reaching values below $10\,\mu mol\,l^{-1}$ in various stations. Although with much lower concentrations, nitrite showed a trend similar to that of nitrate ($<1.5\,\mu mol\,l^{-1}$) in most of the section. Only the upper layer, in the vicinity of the sea, showed concentrations as high as $3.5\,\mu mol\,l^{-1}$.

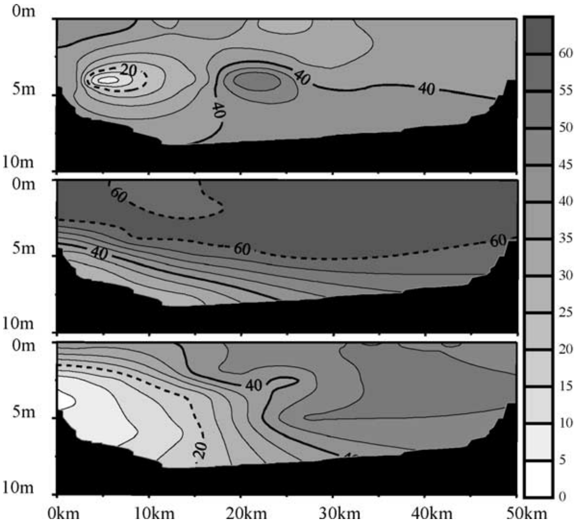

Fig. 8. Vertical distribution of *Silicic Acid* ($\mu mol\,l^{-1}$) along the lower Ebro River: (a) Fans I (November 96); (b) Fans II (April 97) and (c) Fans III (July 97).

The concentrations of orthophosphate (Fig. 7) in the freshwater layer varied between 0.2 and $1.2\,\mu mol\,l^{-1}$ with a slight increase in the downstream direction. The lower high-salinity layer showed concentrations between 0 and $4\,\mu mol\,l^{-1}$. Near the mouth, very low values typical of seawater were found while the salt-water wedge, near the upstream boundary showed the highest values.

The orthosilicic acid concentrations (Fig. 8) showed a trend similar to that shown by orthophosphate, varying between 20 and $70\,\mu mol\,l^{-1}$ in the freshwater layer, slightly decreases towards the sea. In the high-salinity water layer, the concentrations ranged between 4 and $55\,\mu mol\,l^{-1}$.

Percent oxygen saturation levels (Fig. 9) were rather constant in the upper layer, with values just above saturation (about 120%), showing a healthy phytoplankton-dominated environment. In the bottom layer, saturation levels were above or around 100% except in the salt-water wedge. In this part of the section, the oxygen saturation levels dropped to near 10% during the summer survey although they remained relatively high (>90%) during the spring survey after the wash-out caused by the high flow rates ($>2500\,m^3\,s^{-1}$) maintained for more than a week in January 1997.

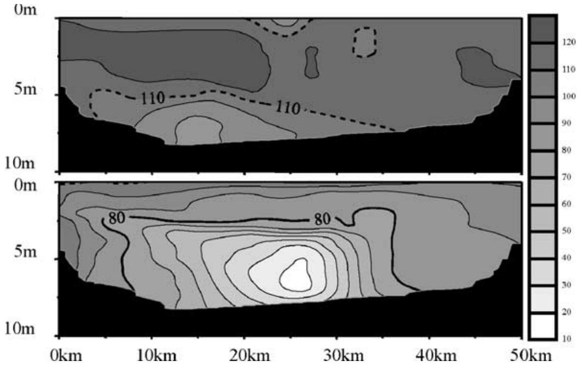

Fig. 9. Vertical distribution of *Dissolved Oxygen* (% Saturation) along the lower Ebro River: (a) Fans II (April 97) and (b) Fans III (July 97).

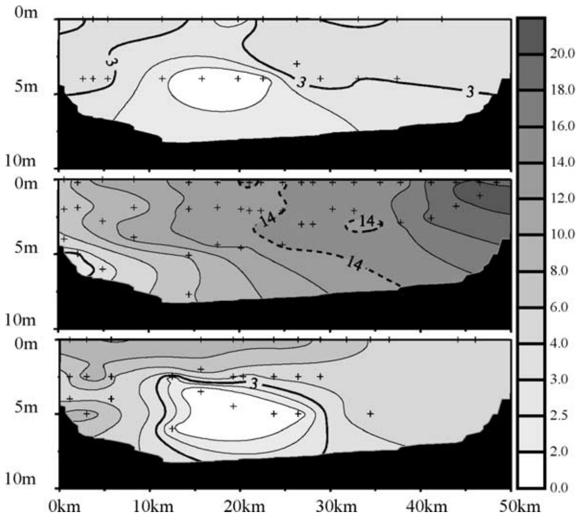

Fig. 10. Vertical distribution of Chlorophyll *a* ($\mu g\,l^{-1}$) along the lower Ebro River: (a) Fans I (November 96); (b) Fans II (April 97) and (c) Fans III (July 97).

The lack of oxygen sensor for the winter survey did not allow the likely anoxic environment to be observed at the head of the salt-water wedge.

The distribution of Chlorophyll *a* (Fig. 10) shows strong seasonal variations in the freshwater layer between about 2 and $20\,\mu g\,l^{-1}$. Also, the trend changed with the season. While the concentrations of Chlorophyll *a* were rather constant all along the section during the winter survey, they strongly decreased downstream in the spring survey when maximum concentrations were found

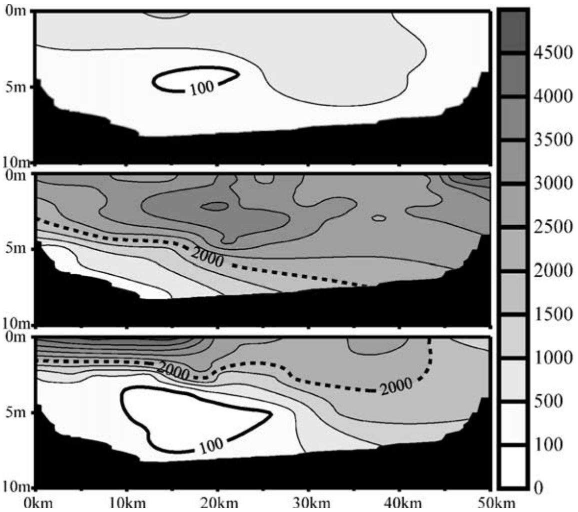

Fig. 11. Vertical distribution of *Phytoplankton cells* (cells ml^{-1}) along the lower Ebro River: (a) Fans I (November 96); (b) Fans II (April 97) and (c) Fans III (July 97).

in both layers and they increased downstream during the summer survey. In the lower layer, with high-salinity water, the very low Chlorophyll *a* concentrations, always less than $2\,\mu g\,l^{-1}$, increased towards the sea.

Total phytoplankton cells (Fig. 11) also vary seasonally, in the freshwater layer, between about $500\,cell\,ml^{-1}$ in winter and above $5000\,cell\,ml^{-1}$ in summer. In the high-salinity water layer, they were always in smaller numbers.

At the time of the surveys (Table 2), the mean flow of water was $110\,m^3\,s^{-1}$ in November 1996, $202\,m^3\,s^{-1}$ in March 1997 and $141\,m^3\,s^{-1}$ in July 1997. Both in November and July, the salt water in the lower layer showed very high orthophosphate concentrations and low nitrate concentrations and oxygen saturation levels (only in the latter survey) in the interior of the salt-water wedge. On the contrary, in March, only about two months after the large flood of January, the orthophosphate concentration was relatively low and the nitrate concentration and oxygen saturation high. The deep salt water receives important amounts of particulate organic matter from the upper freshwater layer which is digested by heterotrophic organisms leading to great increases in the concentrations of orthophosphate, orthosilicic acid and ammonium, and a decrease in the concentration of nitrate due to denitrification.

3.2. Assessment of fluxes

The flux of a particular constituent C through the river channel or any section within it is governed by the general equation

$$\Phi_C = \int Q(t) X_C(t)\,dt,$$

where $Q(t)$ is the time-dependent freshwater flow and $X_C(t)$ the time-dependent (vertically and horizontally averaged) concentration of constituent C.

Table 2
Nutrient fluxes within the freshwater layer

FANS	Ebro I (November 96)	Ebro II (April 97)	Ebro III (July 97)	Average	Var. Coef.
Flow ($m^3\,s^{-1}$)	110	202	141	151	31.0
Fluxes ($mol\,s^{-1}$)					
Nitrate	16.394	24.369	29.336	23.367	0.03
Nitrite	0.146	0.283	0.086	0.172	0.06
Orthophosphate	0.123	0.069	0.075	0.089	0.03
Orthosilicic	4.033	12.983	7.180	8.065	0.06
Fluxes ($tm\,yr^{-1}$)					
Nitrogen	7304	10,884	12,990	10,392	30.6
Phosphorus	120	67	73	87	33.6
Silica (SiO_2)	10,900	35,047	19,382	21,776	120.5

Table 3
Capacity of the reservoirs in the lower Ebro River

Dam	Capacity (Hm^3)	Average residence time (d)	Minimum residence time (d)	Maximum residence time (d)
Mequinensa	153	44	18	282
Ribarroja	291	8	3	52
Flix	11.7	0.3	0.1	2.1

The flux of any component F_C may be computed by multiplying the nominal water discharge Q times a *typical* (estimated) concentration X_C or $F_C = QX_C$.

When applied to the Ebro River, considering the freshwater flow averaged over the month before the survey and the concentrations measured during this study, the discharge of nutrients is given in Table 2. The total Chlorophyll flux was between 213 and 396 $\mathrm{kg\,d^{-1}}$ and the total number of phytoplankton organisms was of the order of $10^{17}\,\mathrm{cell\,d^{-1}}$.

Very small changes were observed in the various constituents along the river channel other than a slight decrease in nutrient concentrations due to the phytoplankton uptake more than compensated by the nutrients introduced with the sewage from the urban agglomerations existing along the banks. Since the water runs the distance between the *Mequinensa–Ribarroja* dams (Table 3) and *Tortosa* in less than one day, the chemical and ecological conditions in the freshwater along the lower Ebro River channel are those prevailing in these dams. The phytoplankton concentrations in this water are much lower than what the nutrient concentrations would allow for if they were not limited by some factor other than nutrients. The dams being relatively deep must have a light-limited plankton community and the water flushed, probably taken from the hypolymnion, is rich in nutrients and rather poor in phytoplankton.

3.3. The salt-water wedge

The increasing salinity observed at the lowest parts of the Ebro River are proof of the mixing of the upper freshwater layer with sea water entering at the river mouth and extending over the bottom forming a salt-water wedge, typical of non-tidal estuaries. For a well-mixed estuary (Stommel and Coleman, 1952), the net seaward flux of a dissolved constituent through any section is given by

$$\Phi_C = QX_C - AK_l\frac{\mathrm{d}X_C}{\mathrm{d}l},$$

where K_l is the longitudinal diffusion coefficient, l the longitudinal dimension, and A the cross-sectional area normal to the flow.

The diffusive flux term is negative because dissolved/dispersed constituents diffuse from high concentrations to low concentrations. Combining the above equation with a similar one describing the salt flux to eliminate the terms K_l and A, the net flux of salt Φ_S through any section of an estuary being zero under steady state conditions, gives Φ_C in terms of Q, X_C and S (Officer, 1976)

$$\Phi_C = Q\left(X_C - S\frac{\mathrm{d}X_C}{\mathrm{d}S}\right),$$

Where S is the salinity at the point of measure and $\mathrm{d}X_C/\mathrm{d}S$ the slope of the dilution curve (plot of X_C against S) computed with the values of these two properties corresponding to the two end-members (freshwater and pure seawater).

With the above equation, the net seaward nitrogen fluxes were computed (Table 4). The term within brackets in the above equation corresponds to the concentration of the constituent in the freshwater flow only if there are no gains or losses of the constituent during its passage through the estuary. However, if gains or losses occur, a higher or lower value will be obtained. The gains (+) and/or losses (–) of nitrogen after correction for the dilution with seawater were calculated at stations located along the lower river channel with concentration and salinity data available

Table 4
Nitrogen fluxes computed taking into account mixing with seawater

Flow = 120 $m^3 s^{-2}$		Ebro I						
Station		20	19	18	17	16	15	
Salinity		3.40	2.90	2.77	1.76	1.76	1.06	
Nitrate + Nitrite	(mmol m^{-3})	149.84	149.74	149.64	149.54	149.44	149.86	
Flux	(mol s^{-1})	16.67	1.64	6.40	15.97	15.96	15.72	
Gains/losses	(mmol s^{-1})	1482	1266	1203	777	767	523	
Flow = 120 $m^3 s^{-2}$		Ebro II						
Station		20	19	18	17	16		
Salinity		4.55	3.68	2.98	2.39	0.95		
Nitrate + Nitrite	(mmol m^{-3})	109.09	110.89	112.05	114.21	118.32		
Flux	(mol s^{-1})	26.50	26.28	26.04	26.09	25.97		
Gains/losses	(mmol s^{-1})	727	507	267	318	193		
Flow = 120 $m^3 s^{-2}$		Ebro III						
Station		16	15	14	13	12	11	10
Salinity		3.16	2.18	1.91	1.46	1.32	1.22	1.26
Nitrate + Nitrite	(mmol m^{-3})	163.44	167.53	170.14	164.63	164.63	136.11	185.93
Flux	(mol s^{-1})	26.40	26.20	26.36	25.19	25.08	20.83	28.13
Gains/losses	(mmol s^{-1})	−3666	−3867	−3704	−4874	−4988	−9229	−1931

(Table 4). Nitrogen regeneration took place during fall and spring and nitrogen uptake prevailed at all stations in summer.

3.4. Residence time and fate of the salt-water wedge

An estimate of the sea water flux into the salt wedge may be achieved by considering the amount of salt being entrained by the upper outflowing water layer making the salinity of the outgoing freshwater up to 5 psu, the highest we could observe within the near plume. For an average river flow regime of 200 $m^3 s^{-1}$, the flux of 37 psu seawater required to replenish the salt wedge would be of the order of 27 $m^3 s^{-1}$. Considering the volume of the salt wedge in the order $25 \times 10^6 m^3$, the residence time of this seawater would be of the order of 11 days. For a river flow regime of 65 $m^3 s^{-1}$, the residence time would increase to about 33 days.

When the river flow is above 400 $m^3 s^{-1}$, the salt wedge is pushed out to the sea (Muñoz and Prat, 1989). High-salinity water, poor in nitrate and rich in orthophosphate, ammonium and orthosilicic acid may cause a fertilization of the coastal area very different from that caused by the flow of freshwater. The nutrient concentration in this deep outflow does not follow any obvious mixing correlation with salinity and has a lower N/P ratio than that of the surrounding seawater (0–20). Observations made during the offshore survey on board the *N/O Tethys II* suggested that the river-wedge seawater might have been present in the surroundings of the Ebro River mouth.

4. Conclusions

In spite of the high variability in water flow and ecological conditions, the study carried out at the lower Ebro River provides a reasonably good estimate of the overall amounts of nutrients discharged to the coastal environment.

The largest nutrient load corresponds to Nitrogen of which more than 10^4 tm yr^{-1} are discharged. Phosphorus is discharged at relatively low concentrations that give rise to an annual load of only 87 tm yr^{-1}.

Nitrogen regeneration took place in the lower Ebro River waters during fall and spring and Nitrogen uptake prevailed at all stations in summer.

Unlike other rivers draining highly developed watersheds, the Ebro River does not contribute to the fertilization of the coastal zone with large phosphorus loads. This is due to the trapping of phosphorus onto organic matter by the phytoplankton developing and settling mostly within the various dams existing in the middle course of the river.

In addition to the inorganic nutrients discharged with the freshwater, nutrients from the salt-water wedge, particularly phosphorus, are also flushed out to the sea whenever the river flow increases above $400\,m^3\,s^{-1}$.

The area coverage to which the Ebro River would add a surplus primary production of about $50\,g\,C\,m^{-2}\,d^{-1}$ (over a background of about $100\,g\,C\,m^{-2}\,d^{-1}$), may be estimated in terms of nitrogen, at about $1200\,km^2$ ($40\,km \times 30\,km$).

If, however, the figures were based on phosphorus, the limiting nutrient in the freshwater system, then this increase in fertility would only affect an area of about $68\,km^2$.

The sudden phosphorus contribution produced in the coastal area by the pre-flood conditions when the river flow increases above $400\,m^3\,s^{-1}$ due to the wash out of the salt wedge, may be significant (~ 1.5 tm or 2% of the overall P load).

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