Acta Bot. Croat. 58, 105–125, 1999
CODEN: ABCRA 25
ISSN 0365–0588

Dedicated to Prof. dr. MERCEDES WRISCHER
on the occasion of her 70th birthday.

UDC 574.58(262.3)

PATCHY DISTRIBUTION OF PHYTOPLANKTON IN A HIGHLY STRATIFIED ESTUARY (THE ZRMANJA ESTUARY, OCTOBER 1998)

DAMIR VILIČIĆ[1]*, MIRKO ORLIĆ[2], ZRINKA BURIĆ[1], MARINA CARIĆ[3], NENAD JASPRICA[3], FRANO KRŠINIĆ[3], ANTE SMIRČIĆ[4], ZVONKO GRŽETIĆ[4]

[1] University of Zagreb, Faculty of Science, Dept. Botany, Rooseveltov trg 6, 10000 Zagreb, Croatia

[2] University of Zagreb, Faculty of Science, Dept. Geophysics, Horvatovac bb., 10000 Zagreb, Croatia

[3] Institute of Oceanography and Fisheries, Lab. Plankton Research, 20000 Dubrovnik, Croatia

[4] State Hydrographic Institute, Zrinsko-Frankopanska bb., 21000 Split, Croatia

The abundance, biomass and species composition of phytoplankton were determined in relation to hydrographic conditions in the highly stratified Zrmanja Estuary, eastern Adriatic coast, Croatia, during the October 1998 episode of strong river outflow. Phytoplankton accumulated around the halocline in the middle portion of the estuary, where nanoplankton provided the dominant autotrophic constituent. Marine phytoplankton accumulated there due to more favorable light and nutrient conditions along the outflow plume, as well as reduced zooplankton grazing. Orthophosphate was detected as a limiting growth factor in the estuary. The phytoplankton species assemblages at the seaward and riverine ends of the estuary were made up of taxa with corresponding salinity preferences. A subsurface temperature maximum was detected in the middle portion of the estuary, due to the combined effect of radiative heating and reduced heat exchange at the halocline level, as well as the accumulation of suspended matter close to the halocline and selective absorption of solar radiation.

Key words: Phytoplankton, microzooplankton, estuary, halocline, river discharge, nutrients, Adriatic Sea

---

* Corresponding author: E-mail: dvilici@zg.biol.pmf.hr

Introduction

Estuaries are highly productive habitats, providing ecologically and economically valuable fish-larvae and shellfish refugia, nurseries (Steele 1974), and dynamic nutrient transformation zones at the interface between freshwater and marine environments (Nixon 1995). The increased primary production in estuaries is influenced by nutrients brought by the river discharge (Malone et al. 1988). Microscale patchiness of plankton within a sharp pycnocline has been indicated by Tiselius et al. (1994).

Highly stratified estuaries are maintained in areas where a high volume of river discharge is combined with low tides (Dyer 1991). Such phenomena are well known all around the Mediterranean and along the eastern Adriatic coast. In the highly stratified Krka Estuary, dissolved organic matter and detritic particles (Žutić and Legović 1987, Cauwet 1991), microphytoplankton (Viličić et al. 1989), nanophytoplankton (Denant et al. 1991, Ahel et al. 1996), bacteria (Fuks et al. 1991) and pollutants (Mikac et al. 1989) accumulate along the sharp halocline.

Physico-chemical and ecological processes at the contact between karstic waters and the sea are generally unknown and represent an attractive area of investigation. There are scarce and old data on the hydrography of the Zrmanja Estuary (Petrik 1969, Buljan 1969), and adjecent coastal sea (Škrivanić and Barić 1979). Some data on the seasonal distribution of phytoplankton and microzooplankton in the lower reach of the estuary and in the Velebit Channel have been published (Kršinić 1980a, 1987; Viličić 1989).

The scope of this paper is to present for the first time thermohaline conditions and phytoplankton distribution along the upper and lower reach of the karstic Zrmanja Estuary during the October 1998 case study.

Investigated area

The Zrmanja River catchment is located in the central part of the Dinaric karst region of Croatia. The total length of the River Zrmanja from the source to its mouth in the Adriatic Sea is 69 km. Measurements of the Zrmanja River discharge at the Jankovića buk station, carried out between 1953 and 1990, show that average outflow equals 38 m^3/s, but may be as high as 456 m^3/s (December 1959) and as low as 0.09 m^3/s (June 1986). There is a complex water circulation in the karst system in the Zrmanja River catchment area (Bonacci 1999). The numerous permanent and temprary springs along the river are connected with swallow holes ("ponors") in the hinterland. Underwater springs ("vruljas") in the estuary discharge water during rainy (October–December) and snow melting periods (March–May). The estuary and the adjacent coastal sea is westerly oriented between the Velebit Mountain ridge on the north, and large North-Dalmatian plateau to the south and east (Friganović 1961). The surrounding area is scarcely inhabited, and without considerable anthropogenic influence. The lower reach of the Zrmanja estuary and adjacent coastal sea is an area of an exceptionally indented coastline. The estuary consists of the 14 km long upper reach (Fig. 1), from the Jankovića buk waterfalls to the wider portion of the estuary – Novigrad Sea, and the lower reach, which is 8 km long and consists of

Novigrad Sea (including the highly isolated Karin Sea) and the Novsko ždrilo connecting the Novigrad Sea with the adjacent coastal sea – the Velebit Channel. The upper reach of the estuary is mostly about 5 m deep, while the lower reach is up to 40 m deep. In the Novsko ždrilo strait there is a 19-m deep sill. The steep banks of the upper portion of the estuary are strongly eroded, making the estuarine bed relatively shallow.

The tides in the area are rather weak: M2 amplitudes are below 10 cm, and K1 amplitudes are close to 13 cm (e. g. KASUMOVIĆ 1960).

Materials and methods

Water samples for the analyses of phytoplankton were collected at seven stations along the thermohaline gradient from the Vinjerac (V1) marine station in the Velebit Channel, to Station Z5, the freshwater reservoir of Velebit Hydroelectric Power Plant" (Fig. 1), on 10 and 11 October 1998. Phytoplankton was sampled using 5-liter Niskin bottles at one-meter intervals in the upper reach of the estuary (at stations Z1, Z2, Z4), and at 0, 2, 4, 10 (and 30) m in the Novigrad Sea (N1) and Velebit Channel (V1, V2). Samples were preserved in a 2 per cent (final concentration) neutralized formaldehyde solution. The cell counts were obtained by the inverted microscope method (UTERMÖHL 1958). Subsamples of 50 mL were analyzed microscopically, after a sedimentation time of 24 h, within one month after the cruise. Cells longer than 20 µm were designated as microphytoplankton (MICRO). Cells were counted at a magnification of 400 × (1 to 2 transects) and 200 × (transects along the rest of the counting chamber base plate). Recognizable nanoplankton (NANO) cells (2 to 20 µm long) were counted in 20

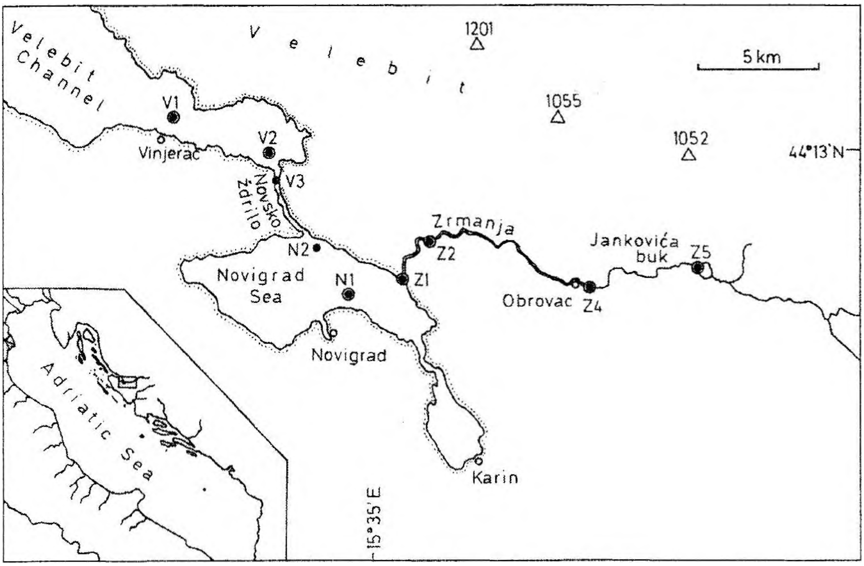

Fig. 1. Position of stations in the Zrmanja River estuary (stations V3, N1, N2 –lower reach, Z1, Z2, Z4 –upper reach) and the adjacent coastal sea (V1, V2). Station Z5 is in the reservoir of the hydroelectric power plant "Velebit".

randomly selected fields of vision along the counting chamber base plate, at a magnification of 400 ×. The precision of the counting method is ±10 %.

Chlorophyll *a* (Chl a) concentrations were estimated using a 112 Turner design fluorometer, following the method of PARSONS et al. (1984). For this purpose, subsamples (500 mL) were filtered using Whatman GF/C filters (1.2 µm mean pore size).

Samples for the analysis of microzooplankton were collected using 5-liter Niskin bottle samplers, fixed in 2.5 per cent neutralized formaldehyde and allowed to settle twice for 24 hours in plastic containers and glass cylinders, reducing the original volume of 5 L to a few milliliters. Counts were done at a magnification of 100 × (water immersion objective) using a self-designed chamber (75 × 45 mm, bottom glass 1 mm thick) (KRŠINIĆ 1980b).

Nutrient concentrations were measured using standard methods (STRICKLAND and PARSONS 1972, IVANČIĆ and DEGOBBIS 1984). The inorganic nitrogen/phosphorus ratio was calculated according to REDFIELD et al. (1963).

Fine vertical distribution of salinity and temperature was determined using a conductivity, temperature and depth profiler (SEA Bird Electronics Inc., USA). A white Secchi disc (30 cm in diameter) was used for estimating transparency.

Results

Rainfall and river water discharge determine thermohaline characteristics in the estuaries. High rainfall (300 mm) detected at Obrovac meteorological station in September 1998 (Fig. 2) resulted in high river discharge and a relatively thick

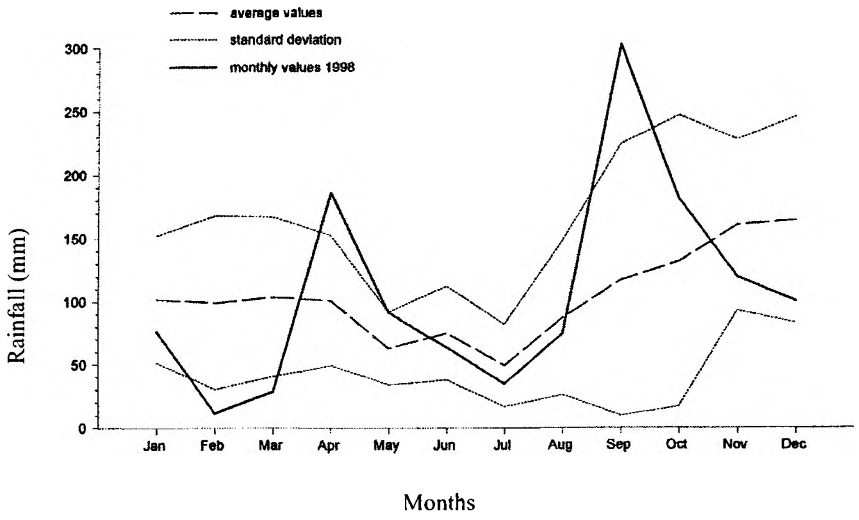

Fig. 2. Monthly rainfall values measured at the Obrovac station in 1998 (full line) compared with the average values for the 1958–1970 interval (dashed line) and corresponding standard deviations (dotted lines).

surface layer of low salinity in the Zrmanja Estuary in October 1998. Vertical profiles of temperature, salinity and sigma-t value, measured at Vinjerac station (V1) on 11 October 1998, are compared with the profiles measured at the same station on 7 September 1998 (Fig. 3). Secchi disc transparency and euphotic layer ceased to the bottom (mostly about 5 m deep) in the upper reach of the estuary.

In October 1998, a sharp halocline delimited the low-salinity surface layer and the saline bottom layer (Fig. 4). At the innermost station Z2, a vertical salinity gradient amounting to 26 m^{-1} was registered at a depth of 3 m. Vertical profiles taken at the stations positioned further seawards show that the upper layer was of virtually constant thickness, that the salinity of the surface layer increased in an outward direction, and that the salinity of the bottom layer was almost constant along the estuary. Obviously, the salty bottom water was entrained into the surface layer; consequently, it may be supposed that discharge increased seawards, and that a slight compensating landward flow occurred in the bottom layer.

In the lower reach of the estuary, i.e. at stations N1, N2 and V3, a subsurface temperature maximum was detected in the 3–5 m layer.

Concentrations of orthophosphate were low, reaching a maximum value of 0.14 $\mu mol\ L^{-1}$ in the lower boundary of the halocline, at station Z2 (Fig. 5). Above and below the halocline, values were lower than 0.1 $\mu mol\ L^{-1}$ (Tab. 1). Low concentrations of nitrate (0.44 to 2 $\mu mol\ L^{-1}$) were detected in the marine layers, in the lower reach of the estuary, while increasing concentrations (up to 14.78 $\mu mol\ L^{-1}$) were found above the halocline, in the upper reach of the estuary. Concentration of silicates was lower than 10 $\mu mol\ L^{-1}$ in the middle and seaward portion of the estuary, with increasing values above the halocline in the upper reach of the estuary (up to 39.58 $\mu mol\ L^{-1}$ at Z2). Concentrations of ammonia ranged from 0.17 to 1.94 $\mu mol\ L^{-1}$. Values higher than 1.2 $\mu mol\ L^{-1}$ were determined above the halocline in the upper reach of the estuary, and gradually decreased in the seaward direction. A patch of lower concentration nutrients was found at stations N1 and Z1, below the halocline, in the 2–4 m layer. The Redfield ratio ranged from 19 in the marine layers to extremely high values of several hundreds in the brackish layer of the inner portion of the estuary.

The water column was well oxygenated. The oxygen saturation ranged from 93 % near the bottom in the upper reach of the estuary to 108 % at the surface in Novigrad Sea.

Vertical stratification of freshwater and marine phytoplankton indirectly indicated the position of the halocline (Tab. 2). A sharp halocline divided two phytoplankton communities. Freshwater phytoplankton above the halocline was transported to the estuary by the riverine water from the small freshwater accumulation in front of the estuary, while marine phytoplankton was found below the halocline.

Phytoplankton exhibited patchy distribution along the estuary and the adjacent coastal sea. Phytoplankton accumulated in the middle portion of the estuary, at stations N1 and Z1, compared with the seaward and landward ends (Fig. 6).

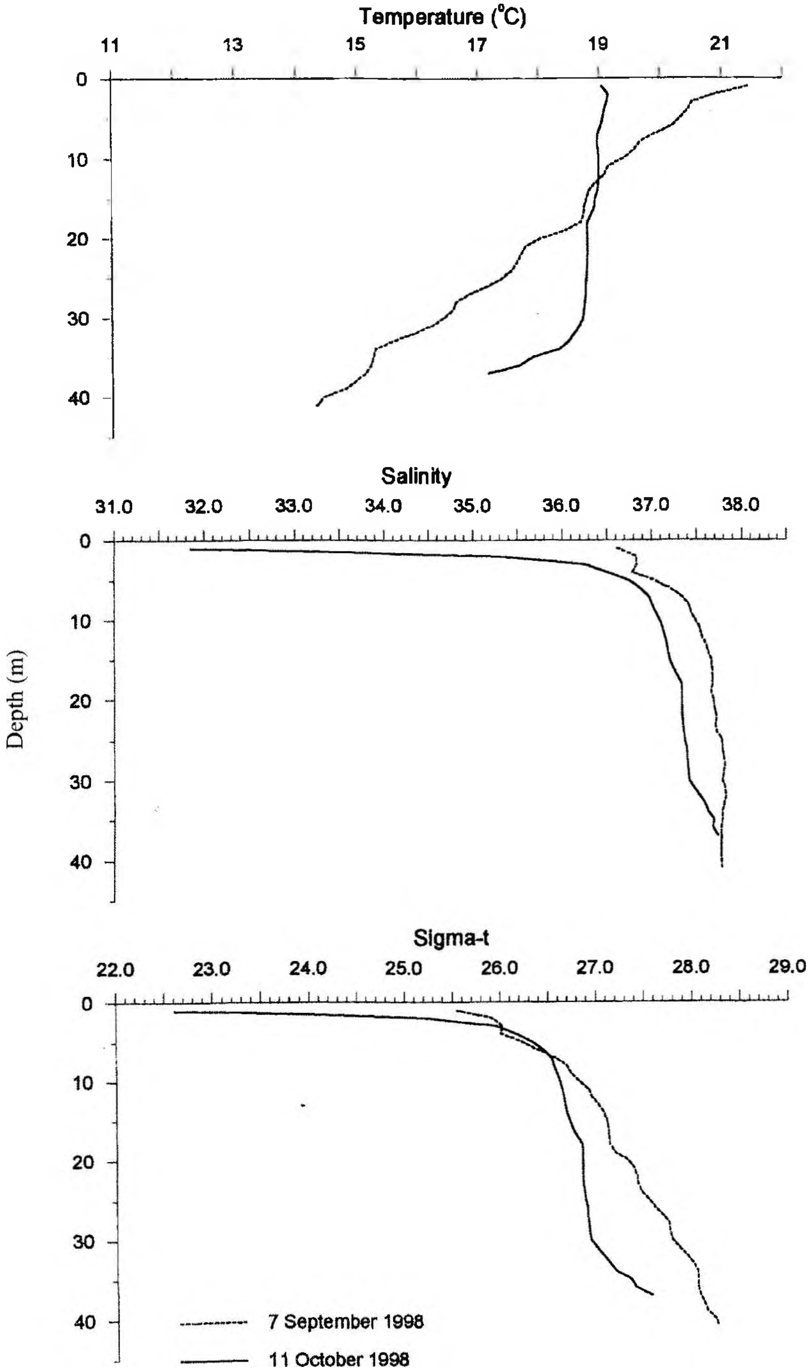

Fig. 3. Vertical profiles of temperature, salinity and sigma-t value measured at the Vinjerac station (V1) on 7 September (dotted lines) and 11 October (full lines) 1998.

Tab. 1. Range (min-max), average (AVG) and standard deviation (STD) of ortophosphate, nitrate, silicate concentrations (µmol L^{-1}), chlorophyll concentrations (Chl *a*, µg L^{-1}), microphytoplankton cell density (MICRO, cells L^{-1}), nanoplankton cell density (NANO, cells L^{-1}), and naupliar density values (ind. L^{-1}) in the Zrmanja estuary and the adjecent coastal sea, in October 1998. a = brackish layer, b = marine layer.

Stations/layers			Parametres						
			PO_4	NO_3	SiO_4	Chl *a*	MICRO	NANO	Nauplii
V1, V2, N1	a	Min-max	0.05 – 0.07	3.41 –15.75	6.3 –27.83	0.04 – 0.06	12400 – 43200	74370 – 116870	0 – 480
		AVG (STD)	0.06 (0.01)	11.04 (6.67)	18.09 (10.91)	0.05 (0.01)	27360 (15420)	98200 (21700)	208 (246)
	b	Min-max	0.02 – 0.07	0.64 –10.09	1.96 – 19.91	0.04 – 0.82	14400 – 603400	58790 – 170900	40 – 498
		AVG (STD)	0.05 (0.01)	2.44 (3.77)	7.77 (6.70)	0.25 (0.32)	118000 (237840)	100890 (40800)	212 (193)
Z1, Z2, Z4	a	Min-max	0.03 – 0.09	9.52 –14.78	18.82 –39.58	0.05 – 0.23	50600 – 127200	67900 – 244350	1 – 120
		AVG (STD)	0.06 (0.02)	11.64 (2.42)	30.89 (7.67)	0.13 (0.08)	68900 (32480)	156140 (61500)	16 (15)
	b	Min-max	0.07 – 0.14	2.23 – 2.92	10.44 – 14.86	0.49 – 0.56	45400 – 161200	27200 – 382000	152 – 180
		AVG (STD)	0.08 (0.03)	2.46 (0.30)	12.28 (2.09)	0.52 (0.04)	112500 (50600)	207700(147500)	166 (20)

Tab. 2. Vertical distribution of freshwater and marine phytoplankton taxa (cells L^{-1}) in the Zrmanja river estuary (Station Z2), October 1998.

Depth (m)	Dino	FW BACI	NANO 2–10 µm	NANO 10–20 µm	DINO <20 µm	Gymno	Pr mic	Pseudon	Lep med	Syraco	Dict oct
0	6400	38400	132400	1200	200	0	0	0	0	0	0
1	60800	65600	229200	0	0	0	0	0	0	0	0
2	13600	24000	110800	1600	1600	0	800	0	0	0	400
3	0	9600	244300	17600	8000	800	800	1400	8700	4800	2400
4	0	8000	177400	8800	8000	400	400	1600	0	1600	1200

Abbreviations:

Dino	*Dinobryon* sp.	Dino <20 µm	Dinoflagellates, cells <20 µm
FW BACI	Freshwater penatae diatoms	Pseudon	*Pseudonitzschia* spp.
NANO 2–10 µm	Nanoplankton, cells 2–10 µm	Lep med	*Leptocylindrus mediterraneus*
NANO 10–20 µm	Nanoplankton, cells 10–20 µm	Syraco	*Syracosphaera pulchra*
Gymnod	Small gymnodinoid cells	Dict oct	*Dictyocha octonaria*
Pr mic	*Prorocentrum micans*		

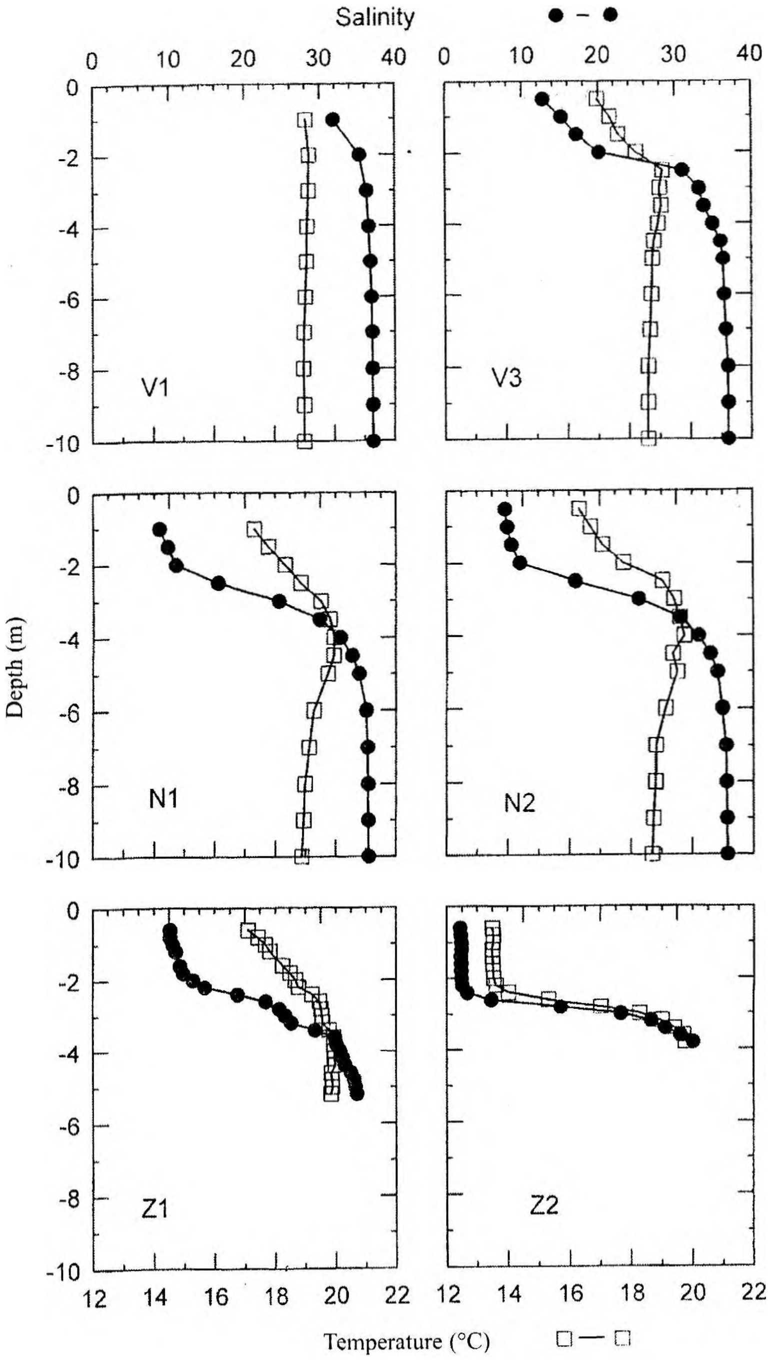

Fig. 4. Vertical profiles of temperature (squares) and salinity (circles) measured at six stations distributed along the Zrmanja Estuary and the adjacent sea on 11 October 1998. For station locations see Fig. 1.

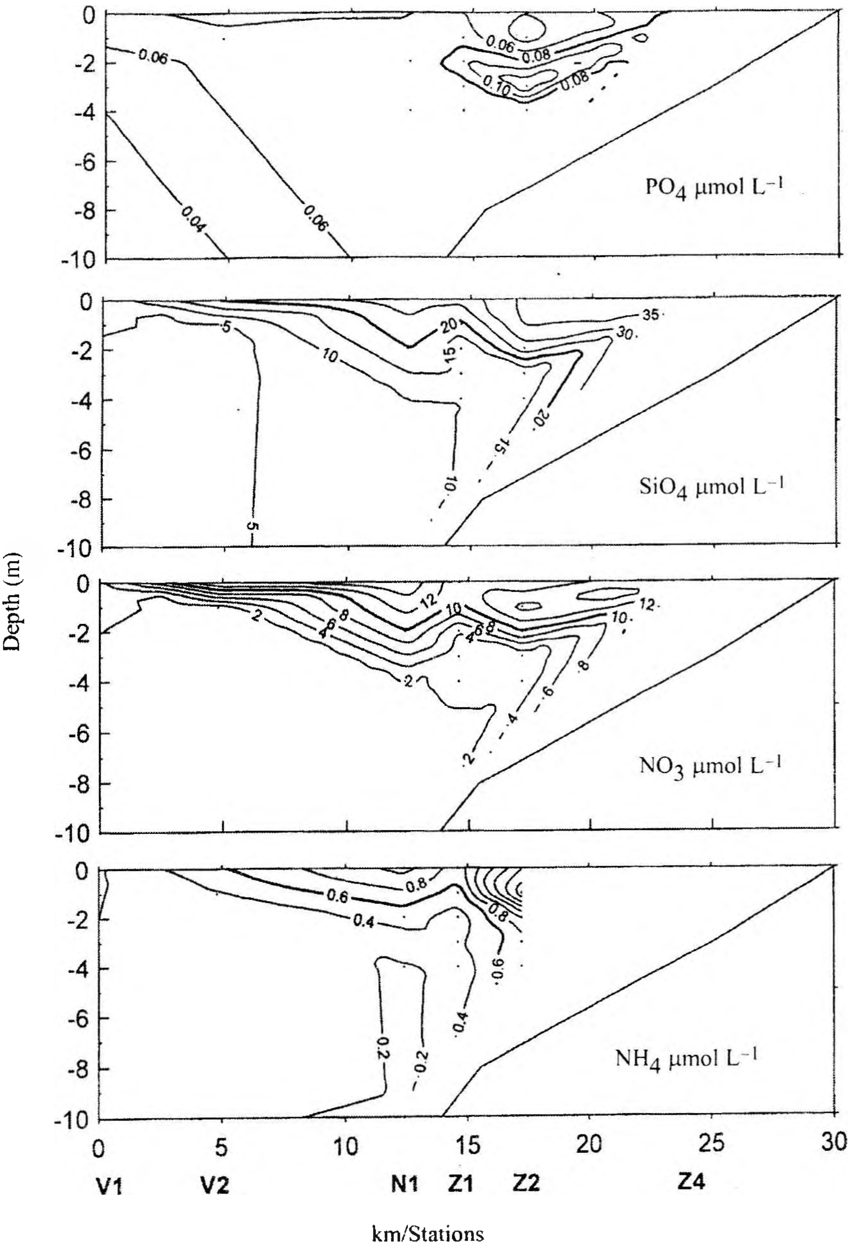

Fig. 5. Distribution of ortophosphates, silicates, nitrates and ammonia along the investigated profile, in October 1998.

Maximum abundances of diatoms and nanoplankton were detected at Z1, while dinoflagellates accumulated at N1 (Fig. 7). Marine microphytoplankton was dominated by diatoms at Z1. The maximum microphytoplankton and nanoplankton abundances were detected between the upper and lower boundary of the

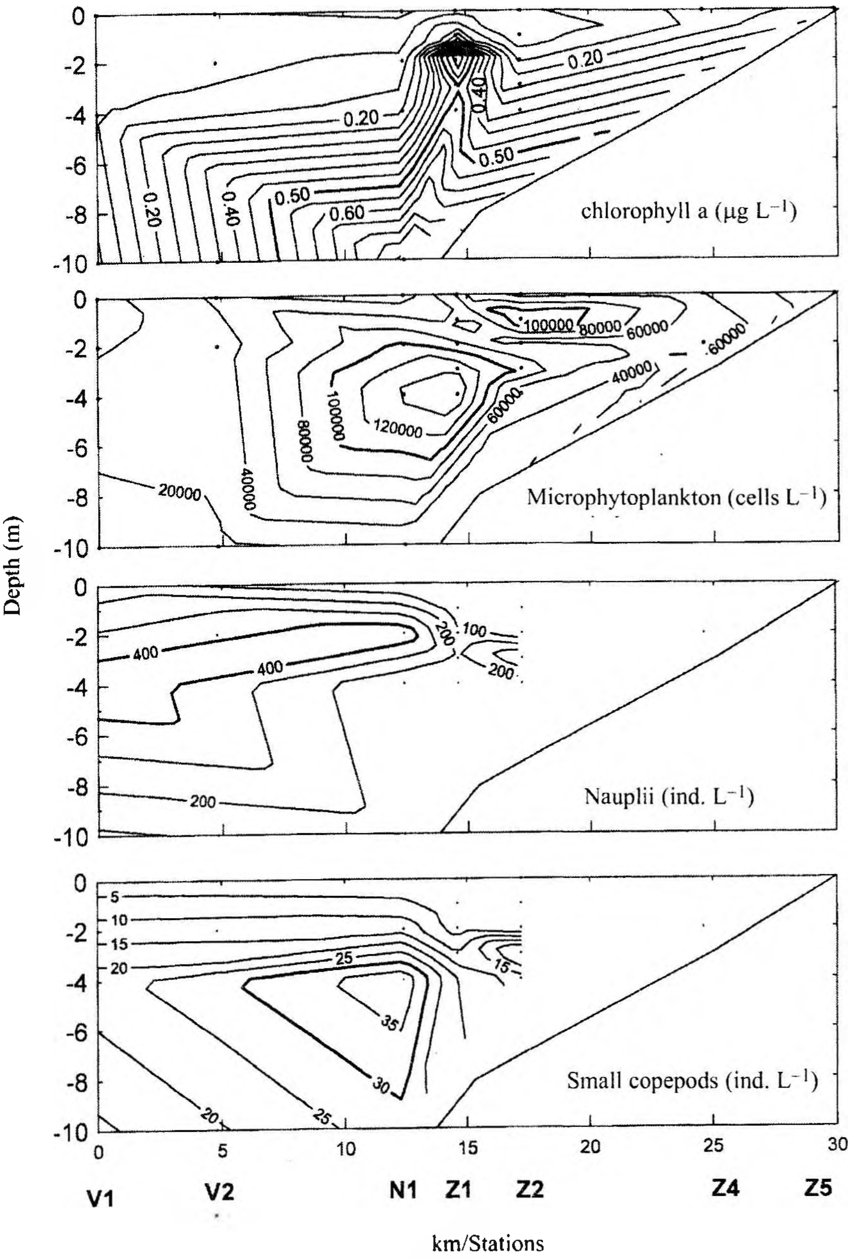

Fig. 6. Distribution of phytoplankton biomass, microphytoplankton cell density and microzooplankton populations (larval stages – nauplii, and small copepods) along the investigated profile, in October 1998.

halocline (2–4 m layer). Maximum biomass (chlorophyll a concentration) was determined at station Z1, along the upper boundary of the halocline (Fig. 6). The coincident maxima of nanoplankton abundance and chlorophyll a concentration

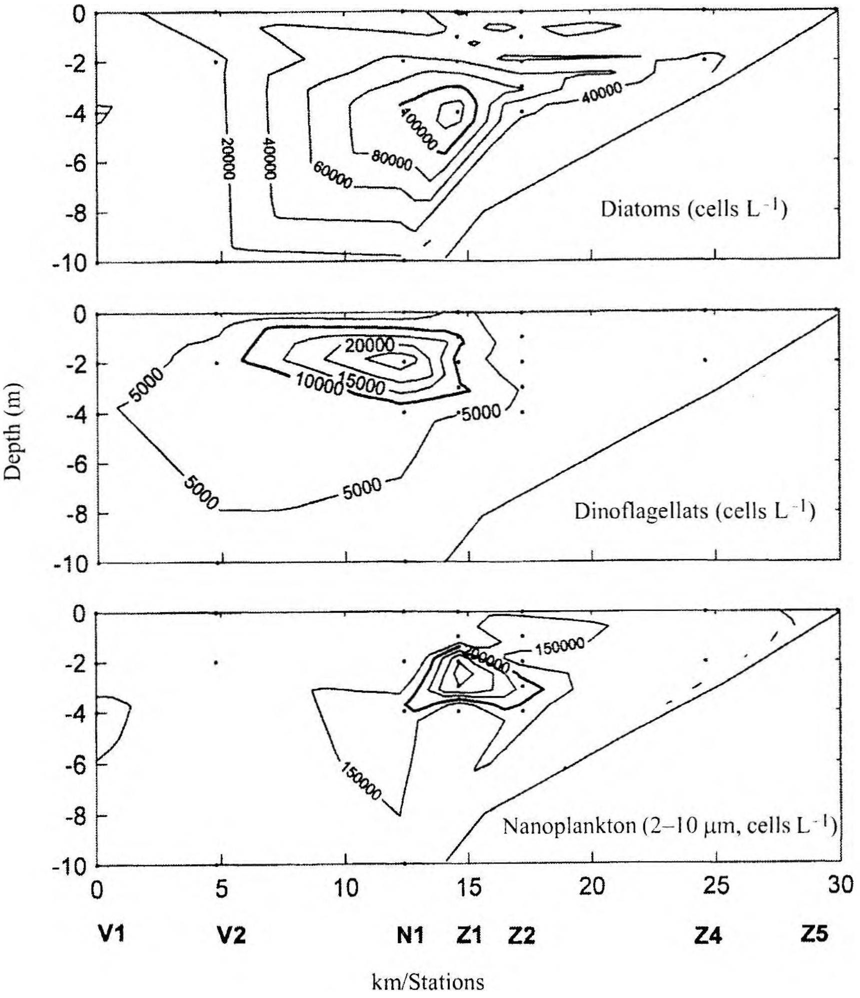

Fig. 7. Distribution of diatoms, dinoflagellates, and small nanoplankton along the investigated profile, in October 1998.

were determined at Z1, indicating small sized phytoplankton as being the dominant autotrophic constituent at this station.

Larval stages of copepods (nauplii) accumulated in and below the halocline, mostly in the lower portion of the estuary (Fig. 6). Small copepods were mostly distributed below the halocline, and accumulated in the Novigrad Sea (N1).

Marine phytoplankton species were distributed under the halocline, with a seaward increase of cell density. Exceptionally, the most abundant species of larger dinoflagellates *Prorocentrum minimum* (size about 20 µm), was detected above the upper boundary of the halocline (Fig. 7). The diatom *Leptocylindrus danicus* was mainly distributed in the Velebit Channel and in the Novigrad Sea (Fig. 8). Bigger nanoplankton cells (10–20 µm), mostly composed of dinofla-

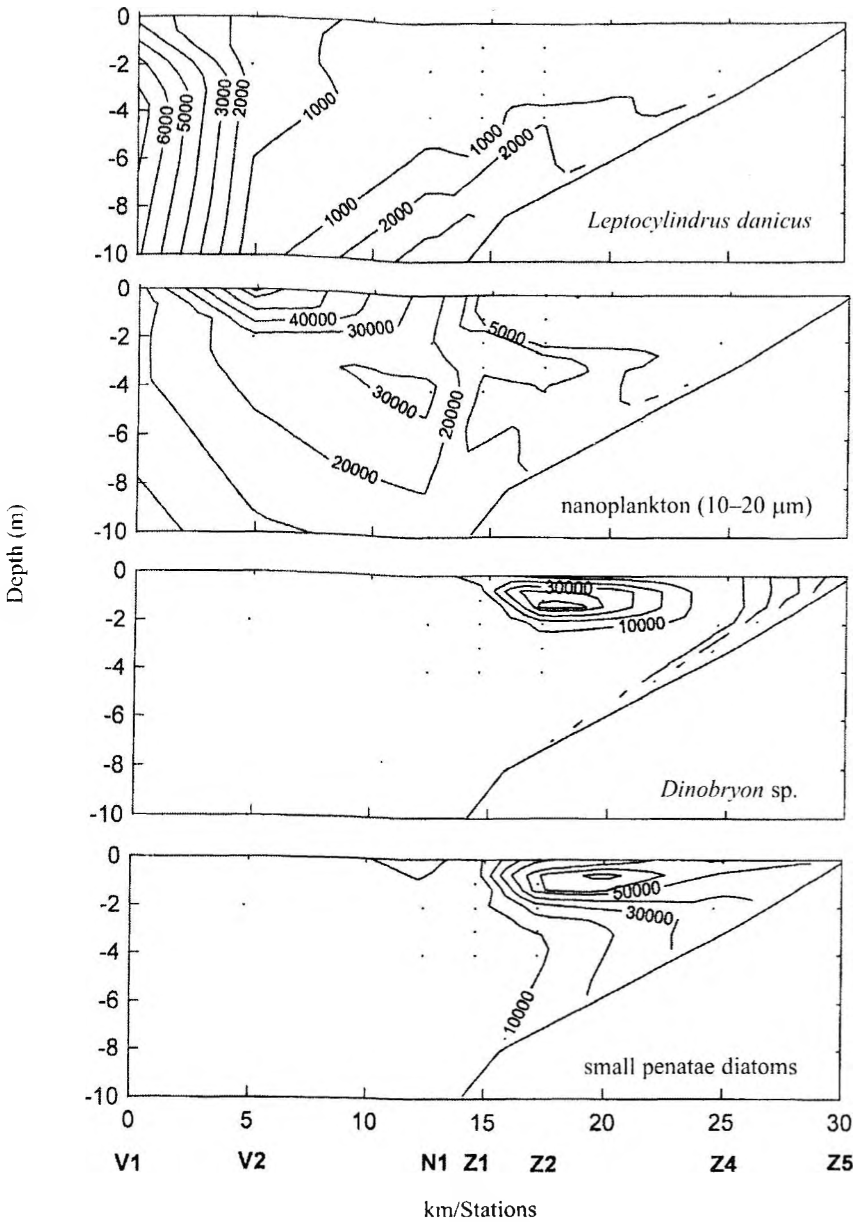

Fig. 8. Distribution of the marine diatom (*Leptocylindrus danicus*) and larger nanoplankton (upper two figures), as well as two freshwater taxa (two lower figures), along the investigated profile, in October 1998.

gellates, provided seaward distribution as well. On the other hand, the freshwater chrysophyte *Dinobryon* sp. and small freshwater pennatae diatoms were found above the halocline, with cell density values decreasing seaward. The marine phytoplankton community in the Novigrad Sea (N1) was dominated by the diatom *Thalassionema nitzschioides*, as well as nanoplanktonic dinoflagel-

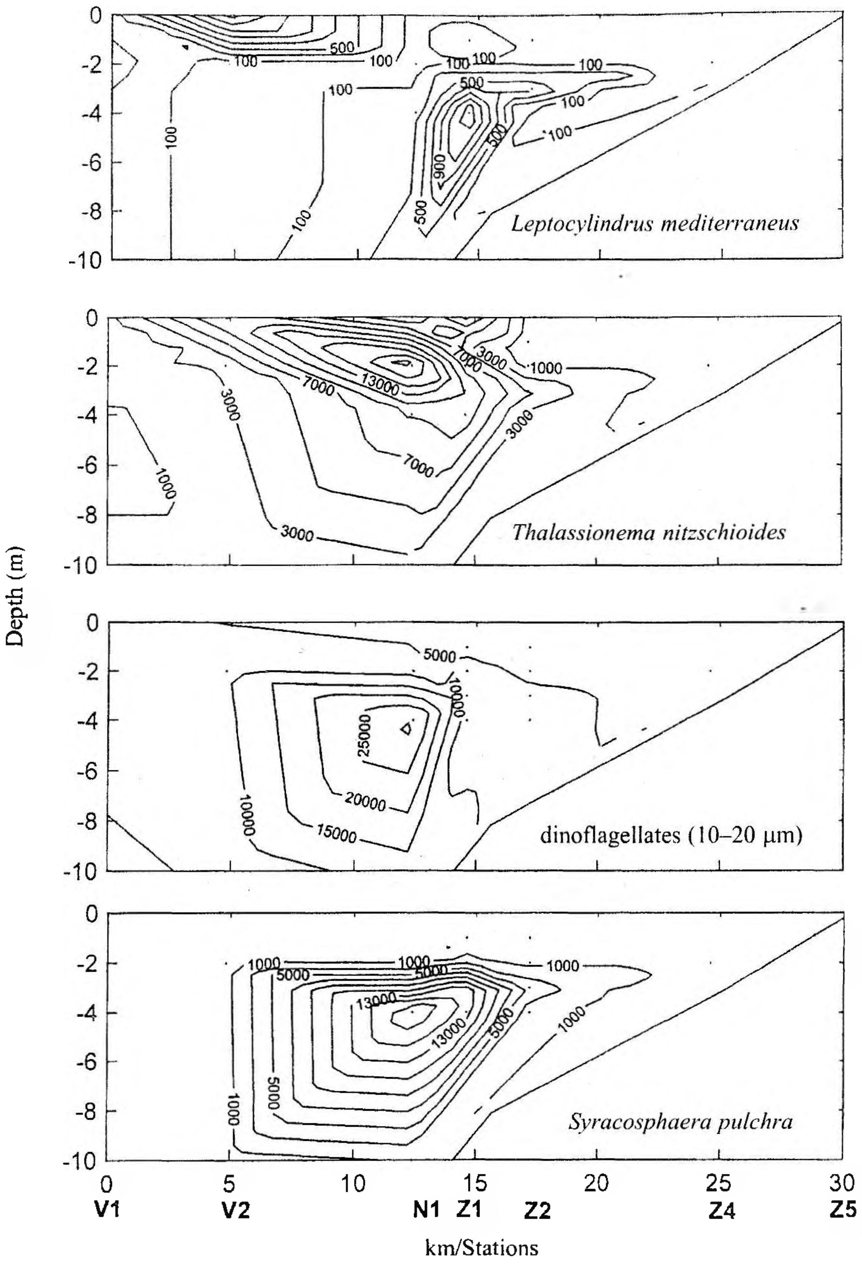

Fig. 9. Distribution of two marine diatoms (upper two figures), larger nanoplanctonic dinoflagellates and coccolithophorid *Syracosphaera pulchra* along the investigated profile, in October 1998.

lates and the coccolithophorid *Syracosphaera pulchra* (Fig. 9). The marine diatom *Leptocylindrus mediterraneus* provided a bimodal distribution of population with a maximum abundance at Z1 just below the halocline.

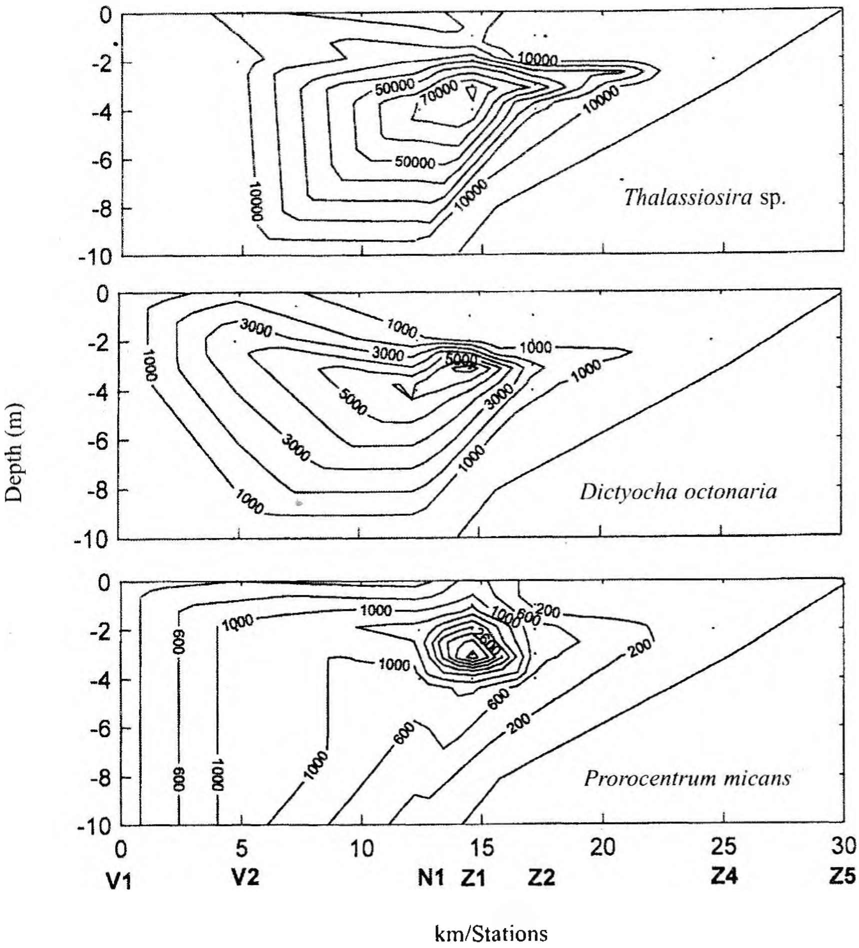

Fig. 10. Distribution of the marine diatom *Thalassiosira* sp., silicoflagellate *Dictyocha octonaria* and dinoflagellate *Prorocentrum micans* along the investigated profile, in October 1998.

Three marine species provided maximum cell density in the halocline at Z1: the centric diatom *Thalassiosira* sp., the chrysophyte *Dictyocha octonaria* and the dinoflagellate *Prorocentrum micans* (Fig. 10).

Discussion

Due to the rather weak tides in the area, the Zrmanja River may be expected to create a highly stratified estuary, at least during episodes of strong river outflow. The measurements performed in the Zrmanja Estuary in October 1998 could not be compared with the simultaneous discharge measurements: the latter had been discontinued in 1991 due to military events in the region, and had not restarted by the time the present experiment was carried out. Meteorological measurements, however, were renewed at the Obrovac station in 1997. They confirm the finding of the NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (1998), according to which during September 1998 the circulation over the North Atlantic reflected a strong negative phase of the North Atlantic Oscillation, bringing above-normal rainfall to most of southern Europe with area-averaged totals reaching the 99th percentile (Fig. 2). The effect of this anomaly and the supposed river discharge anomaly on the sea is documented in Fig. 3, in which vertical profiles of temperature, salinity and sigma-t value, measured at Vinjerac station (V1) on 11 October 1998 are compared with the profiles measured at the same station on 7 September 1998, in the framework of another experiment. It may be seen that during September 1998 salinity was considerably reduced, particularly in the surface layer, and that the vertical temperature distribution was rendered uniform, probably as a result of mixing. Consequently, sigma-t value decreased, not only close to the sea surface but in the bottom layer as well. The data clearly show that in October 1998 the Zrmanja River influenced the stratification and dynamics not only of the Novigrad Sea but of the Velebit Channel as well.

Having thus documented the meteorological and oceanographic conditions that preceded the October 1998 experiment, we may turn our attention to the spatial distribution of temperature and salinity observed on 11 October 1998. This is illustrated in Fig. 4 by vertical profiles taken at six stations in the Zrmanja Estuary and the adjacent sea. Due to the climatic anomaly just discussed, the Zrmanja River supported a highly stratified estuary at the time.

Vertical temperature profiles are also of interest (Fig. 4). The temperature of the surface layer was low in October 1998, the smallest value being recorded at station Z2. This might partly be due to the surface heat flux, which on average is directed upwards in September (SUPIĆ and ORLIĆ, 1999). Probably even more important was advection of the cold Zrmanja River waters: according to data collected at the Žegar station between 1948 and 1991, the average October river temperature equals 11.2 °C, which is about 5 °C lower than the concurrent sea temperature in the Velebit Channel (SUPIĆ and ORLIĆ, 1992). At most stations a thermocline was observed close to the halocline. At some stations, in particular N1, N2 and V3, a subsurface temperature maximum was detected as well. It could be interpreted in terms of a combined effect of radiative heating and reduced heat exchange at the halocline level. Moreover, accumulation of suspended matter close to the halocline and selective absorption of solar radiation might contribute to its occurrence. The same phenomena have previously been observed in some other east Adriatic estuaries – the Krka Estuary (LEGOVIĆ et al., 1991; ORLIĆ et al., 1991) and the Ombla Estuary (VILIČIĆ et al., 1995). Below the subsurface temperature maximum, the bottom layer temperature of the Zrmanja Estuary was fairly uniform in October 1998.

Freshwater species in the Zrmanja Estuary were scarce, in contrast to the estuary of the River Krka, where freshwater phytoplankton develops in the relatively large freshwater accumulation in front of the estuary (VILIČIĆ et al. 1989). Freshwater phytoplankton is more common in estuaries of bigger rivers (JACKSON et al. 1987). In reviewing the salinity tolerance of aquatic organisms, KINNE (1971) identified a critical salinity boundary at 4–7 PSU as a region of great physiological stress. Thus, the vertical composition of freshwater and marine taxa strictly detects the position of the halocline in a highly stratified estuary. The freshwater and marine phytoplankton mostly accumulates around the halocline. The freshwater chrysophyte *Dinobryon* and unidentified freshwater diatoms sink to the halocline and die due to the osmotic shock, resulting in the decrease of cell density in the seaward direction.

The marine phytoplankton species assemblages at the seaward and riverine ends of the estuary were made up of taxa with corresponding salinity preferences. Further seasonal research would indicate if some particular assemblages of species might be characteristic of the estuary. The distribution of species assemblages has been determined in partially mixed estuaries (i.e. REVELANTE and GILMARTIN 1978, WILDERMAN 1987), or some shallow estuaries with minimal tidal influence along the Atlantic coast of the USA (PINCKNEY et al. 1997), but no similar research for highly stratified estuaries in the Mediterranean has been published.

The fact that marine phytoplankton accumulates just below the halocline is due to the more favorable nutritive and light conditions, as well as the more stable conditions below the outflowing surface brackish layer. Maximum cell density and biomass were detected in the area where marine influences abruptly increase. Productivity greatly depends upon turbidity and light conditions (CLOERN 1987, JICKELLS et al. 1991); however, light was not limiting growth factor along the outflow plume in October 1998, because the euphotic layer was at least about 10 m thick (calculated according to Secchi disc visibility). In addition, the marine layer is a more favorable source of microconstituents for phytoplankton growth, since the concentration of trace metals in the Adriatic karstic rivers is low (M. BRANICA pers. communic.).

Phytoplankton accumulated below the halocline in the middle portion of the estuary is attractive food for herbivores. According to RUIZ et al. (1998) microzooplankton grazing is more responsible for phytoplankton distribution along the salinity gradient in the outer than in inner zone of estuaries. In other estuaries zooplankton accumulations were detected around the halocline and fronts (EGGLESTON et al. 1998). Reduced abundance of herbivores at station Z1 resulted in the development of the patch of diatoms and nanoplankton in the 2–4 m layer (Fig. 7). Coincidently, reduced concentration of nutrients appeared in the same microhabitat (Fig. 5).

Nanoplankton accumulation around the halocline is also due to the accumulation of organic matter (ŽUTIĆ and LEGOVIĆ 1987), and physico-chemical transformations of organic matter (EISMA et al. 1991) along the halocline. Many nanoplankton cells (2–10 µm in size) are mixotrophs participating in the processes of microbial transformation and the degradation of organic matter (HAGSTRÖM et al. 1988, LAUREILLARD and SALIOT 1993).

Low nitrate concentrations in the marine layer of the lower reach of the estuary and the Velebit channel (less than 2 µmol L^{-1}) are due to the isolation from the open Adriatic Sea, since the deeper layers of the open Adriatic are a reservoir of nitrates (ARTEGIANI et al. 1993). In addition, the absence of strong winds reduced resuspension of the sediments. Reduction of phosphates in the estuary may be due to precipitation in the small freshwater reservoir of the hydroelectric power plant in front of the estuary (station Z5), as already known from the literature (STRASKRABA et al. 1995).

The physical, chemical and biological conditions are highly variable in estuaries (MØHLENBERG 1995). However, the 11 October 1998 measurements were performed in the period from 9 a.m. to 3 a.m., during sunny, calm weather, where only slight tidal mixing could impact the water-column stratification.

Since the surrounding area is sparsely inhabited, it may be supposed that concentration of nutrients is not much higher throughout the year. Low concentrations of orthophosphate and a high Redfield ratio, as well as low phytoplankton cell density and biomass, indicate phosphorus as a strong limiting growth factor in the brackish layer of the estuary. The nuisance phytoplankton blooms cannot probably be expected in the estuary, at this moment.

The research should be continued in the direction of defining the budget of nutrients and allochtonous organic matter, current system, limiting growth factors, as well as the seasonal production and regeneration processes in the estuary.

Acknowledgements

We are indebted to Ms Janja Milković of the State Hydrometeorological Institute for providing the Obrovac rainfall data, and to Dr Dušan Trninić of the same institute for supplying us with the Zrmanja River discharge and temperature data. This research was supported by the Ministry of Science and Technology of the Republic of Croatia, under the projects 119121 and 119299.

References

AHEL, M., BARLOW, R.G., MANTOURA R.F.C., 1996: Effect of salinity gradients on the distribution of phytoplankton pigments. Mar. Ecol. Prog. Ser. 143, 289–295.

ARTEGIANI, A., GAČIĆ, M., MICHELATO, A., KOVAČEVIĆ, V., RUSSO, A., PASCHINI, E., SCARZZATO, P., SMIRČIĆ, A., 1993: The Adriatic Sea hydrography and circulation in spring and autumn (1985–1987). Deep-Sea Res. 40, 1143–1180.

BONACCI, O., 1999: Water circulation in karst and determination of catchment areas: example of the River Zrmanja. Hidrol. Sci. 44, 373–386.

BULJAN, M., 1969: Neka hidrografska svojstva estuarnih područja rijeke Krke i Zrmanje. Krš Jugoslávije 6, 303–331.

CAUWET, G., 1991: Carbon inputs and biogeochemical processes at the halocline in a stratified estuary: Krka river. Mar. Chem. 32, 269–283.

CLOERN, J.E., 1987: Turbidity as a control on phytoplankton biomass and productivity in estuaries. Cont. Shelf Res. 7, 1367–1381.

DENANT, V. SALIOT, A., MANTOURA, R.F.C., 1991: Distribution of algal chlorophyll and carotenoid pigments in a stratified estuary: the Krka river, Adriatic Sea. Mar. Chem. 32, 285–297.

DYER, K.R., 1991: Circulation and mixing in stratified estuaries. Mar. Chem. 32, 111–120.

EGGLESTON, D.B., ARMSTRONG, D.A., ELIS, W.E., PATTON, W.S., 1998: Estuarine fronts as conduits for larval transport: hydrodynamics and spatial distribution of Dungeness crab postlarvae. Mar. Ecol. Progr. Ser. 164, 73–82.

EISMA, D., BERNARD, P., CADEE, G.C., ITTEKKOT, V., KALF, J., LAANE, R., MARTIN, J.M., MOOK, W.G., VAN PUT, A., SCHUHMACHER, T., 1991: Suspended-matter particle size in some west-european estuaries; Part II: A review on floc formation and break-out. Neth. J. Sea Res. 28, 215–220.

FRIGANOVIĆ, M., 1961: Polja gornje Krke. Radovi Geogr. inst. Sveuč. Zagreb, sv.3.

FUKS, D., DEVESCOVI, M., PRECALI, R., KRSTULOVIĆ, N, ŠOLIĆ, M., 1991: Bacterial abundance and activity in the highly stratified estuary of the Krka river. Mar. Chem. 32, 333–346.

HAGSTRÖM, A., AZAM, F., ANDERSSON, A., WIKNER, J., RASSOULZADEGAN, F., 1988: Microbial loop in an oligotrophic pelagic marine ecosystem: possible roles of cyanobacteria and nanoflagfellates in the organic fluxes. Mar. Ecol. Prog. Ser. 49, 171–178.

IVANČIĆ, I., DEGOBBIS, D., 1984: An optimal mannual procedure for ammonia analysis in natural waters by the indophenol blue method. Wat. Res. 18, 1143–1147.

JACKSON, R.H., WILLIAMS, P.J.B., JOINT, I.R., 1987: Freshwater phytoplankton in the low salinity region of the river Tamar estuary. Estuar. Coast. Shelf Sci. 25, 299–311.

JICKELLS, T.D., LISS, P.S., MACKENZIE, F.T., O'KANE, J.P., 1991: What determines the fate of materials within ocean margins? In: MANTOURA R F C, MARTIN J-M, WOLLAST R (eds) Ocean margin processes in global change. Willey & Sons, Chichester, 211–234.

KASUMOVIĆ, M., 1960: Prilog hidrodinamičkoj teoriji morskih doba Jadranskog mora. Rasprave Odjela za matematičke, fizičke i tehničke nauke JAZU, II/2, 49–82.

KINNE, O., 1971: Marine ecology 1(2). Inter-Research, Lüneburg.

KRŠINIĆ, F., 1980a: Kvalitativna i kvantitativna istraživanja tintinida uz istočnu obalu Jadranskog mora. Acta Adriat. 21, 19–104.

KRŠINIĆ, F., 1980b: Comparison of methods used in microzooplankton research in neritic waters of the eastern Adriatic. Nova Thalassia 4, 91–106.

KRŠINIĆ, F., 1987: Tintinnines (*Ciliophora, Oligotrichida, Tintinnina*) in eastern Adriatic bays. Estuar. Coast. Shelf Sci. 24, 527–538.

LAUREILLARD, J., SALIOT, A., 1993: Biomarkers in organic matter produced in estuaries: a case study of the Krka estuary (Adriatic Sea) using the sterol marker series. Mar. Chem. 43: 247–261.

LEGOVIĆ, T., GRŽETIĆ, Z., ŽUTIĆ, V., 1991: Subsurface temperature maximum in a stratified estuary. Mar. Chem. 32, 163–170.

MALONE, T.C., CROCKER, L.H., PIKE, S.E., WENDLER, B.W., 1988: Influences of river flow on the dynamics of phytoplankton production in a partially stratified estuary. Mar. Ecol. Prog. Ser. 48, 235–249.

MIKAC, N., KWOKAL, Ž., MAY, K., BRANICA, M., 1989: Mercury distribution in the Krka River estuary (east Adriatic coast). Mar. Chem. 28, 109–126.

MØHLENBERG, F., 1995: Regulating mechanisms of phytoplankton growth and biomass in a shallow estuary. Ophelia 42, 239–256.

National Oceanic and Atmospheric Administration (1998): Climate Diagnostics Bulletin 98/9, Washington.

NIXON, S.W., 1995: Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia 41, 199–219.

ORLIĆ M., FERENČAK, M., GRŽETIĆ, Z., LIMIĆ, N., PASARIĆ, Z., SMIRČIĆ, A., 1991: High-frequency oscillations observed in the Krka Estuary. Mar. Chem. 32, 137–151.

PARSONS, T.R., MAITA, Y., LALLI, C.M., 1984: A manual of chemical and biological methods for seawater analysis. Pergamon Press, Oxford.

PETRIK, M., 1969: Karakteristike voda na dinarskom kršu. Krš Jugoslavije 6, 563–581.

PINCKNEY, J.L., MILLIE, D.F., VINYARD, B.T., PEARL, H.W., 1997: Environmental controls of phytoplankton bloom dynamics in the Neuse River estuary, North Carolina, U.S.A. Can. J. Fish. Aquat. Sci. 54, 2491–2501.

REDFIELD, J.L., KETCHUM, B.H., RICHARDS, F.A., 1963: The influence of organisms on the composition of seawater. In: HILL, M.N. (ed.) The Sea, Willey, New York, 26–77.

REVELANTE, N., GILMARTIN, M., 1978: Characteristics of the microplankton and nanoplankton communities of an australian coastal plain estuary. Aust. J. Mar. Freshw. Res. 29, 9–18.

RUIZ, A., FRANCO, J., VILLATE, F., 1998: Microzooplankton grazing in the estuary of Mundaka, Spain, and its impact on phytoplankton distribution along the salinity gradient. Aquat. Microb. Ecol. 14, 281–288.

STEEL, J.H., 1974: The structure of marine ecosystems. Harvard Univ. Press, Cambridge.

STRASKRABA, M., DOSTALKOVA, I., HEJZLAR, J., VYHNALEK, V., 1995: The effect of reservoirs on phosphorus concentration. Int. Revue Ges. Hydrobiol. 80, 403–413.

STRICKLAND, J.D.H., PARSONS, T.R., 1972: A practical handbook of seawater analyses. Fish. Res. Bd. Can. Bull. 167, 1–310.

SUPIĆ, N., ORLIĆ, M., 1992: Annual cycle of sea surface temperature along the east Adriatic coast. Geofizika 9, 79–97.

SUPIĆ, N., ORLIĆ, M., 1999: Seasonal and interannual variability of the northern Adriatic surface fluxes. J. Mar. Syst. 20, 205–229.

ŠKRIVANIĆ, A., BARIĆ, A., 1979: Cruises of the research vessel "Vila Velebita" in the Kvarner region of the Adriatic Sea. IV. Distribution of the primary nutrients. Thalassia Jugosl. 15, 61–88.

TISELIUS, P., NIELSEN, G., NIELSEN, T.G., 1994: Microscale patchiness of plankton within a sharp pycnocline. J. Plankton Res. 16, 543–554.

UTERMÖHL, H., 1958: Zur Vervollkommnung der quantitativen Phytoplankton Methodik. Mitt. Int. Ver. Theor. Angew. Limnol. 9, 1–38.

VILIČIĆ, D., 1989: Phytoplankton population density and volume as indicators of eutrophication in the eastern part of the Adriatic Sea. Hydrobiologia 174, 117–132.

VILIČIĆ, D., LEGOVIĆ, T., ŽUTIĆ, V., 1989: Vertical distribution of phytoplankton in a stratified estuary. Aquat. Sci. 51, 31–46

VILIČIĆ, D., JASPRICA, N., CARIĆ, M., 1995: Estuarij rijeke Omble: "cvjetanje fitoplanktona, eutrofikacija i zaštita. Proc. 1st Croatian Water Conference, Dubrovnik, 497–506.

WILDERMAN, C.C., 1987: Patterns of distribution of diatom assemblages along environmental gradients in the Severn river estuary, Chesapeake Bay, Maryland. J. Phycol. 23, 209–217.

ŽUTIĆ, V., LEGOVIĆ, T., 1987: A film of organic matter at the freshwater/seawater interface of an estuary. Nature 328, 612–614.