ISSN: 0001-5113 AADRAY	ACTA ADRIAT., 52(1): 29 - 44, 2011	UDC: 574.583(262.3)57.063

The phytoplankton composition and spatial distribution in the north-eastern Adriatic Channel in autumn 2008

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The Velebit and Pag Channels form a 40 km long and 4-14 km wide system running parallel to the northeastern Adriatic coast. The aim of this study was to investigate phytoplankton abundance, composition and distribution along the system in the autumn period. Sampling was carried out at 8 stations in November 2008. The spatial distribution of physico-chemical parameters indicated the existence of a pronounced horizontal thermohaline and trophic gradient. From the inner part of the Velebit Channel, which is an extension of the karstic Zrmanja River estuary, to the outer end of the Pag Channel, which communicates with the open sea, the temperature and salinity ranged from 11.0 to 16.0 °C and from 23.4 to 38.2, respectively. Nutrient concentrations ranged from 0.001 to 0.1 µmol L^{-1} for orthophosphates, from 0.85 to 7.0 µmol L^{-1} for total inorganic nitrogen and from 0.3 to 15.4 µmol L^{-1} for silicates. Total abundance of phytoplankton decreased from 5.5 x 105 cells L^{-1} to 8.5 x 104 cells L^{-1} along the trophic gradient. Diatoms dominated the phytoplankton with maximum abundances from 7.3 x 104 cells L^{-1} (85% of total phytoplankton) at the most oligotrophic stations up to 9.6 x 105 cells L^{-1} (96% of total phytoplankton) at the nutrient enriched stations. Statistical analysis on the basis of environmental and biological parameters clustered the stations in three main groups. The first group represented the southern Velebit Channel with higher nutrient levels and phytoplankton dominated by Thalassionema nitzschioides. *The second group included stations from the middle Velebit Channel with significantly lower levels of nutrients, and phytoplankton mostly dominated by* Bacteriastrum *sp. with a contribution by various diatom species. The third group represented the stations from the Pag Channel, and associated with the exclusive domination of* Bacteriastrum *sp. and a greater contribution of coccolithophorids. This paper also gives the first checklist of species present in the extremely oligotrophic area of the Velebit and Pag Channels. 148 taxa were identified: 91 diatoms, 47 dinoflagellates and 10 other flagellate morphotypes. Detailed electron microscopy analysis revealed three potentially toxic diatoms of Pseudo-nitzschia genus:* P. calliantha, P. pseudodelicatissima *and* P. manii. *The results of this work represent a valuable contribution to the knowledge of phytoplankton species composition and distribution relative to prevailing physico-chemical conditions in this poorly investigated transition zone.*

Key words: phytoplankton, taxonomy, trophic gradient, Adriatic Sea

INTRODUCTION

The longest channel in the northern part of the eastern Adriatic is the Velebit Channel, positioned between the northern Adriatic islands and the mainland. Velebit and the adjacent Pag Channel form a 40 km long and 4-14 km wide system running parallel to the coast between the island of Pag and the mainland. It communicates with the open sea through the Kvarnerić strait, and at the southern end is connected with the Zrmanja River estuary through the Novigrad Sea (Fig. 1). It represents a transition zone from the brackish and cold waters of the Zrmanja River estuary to the saline and warm waters of the Kvarnerić strait. Hydrographic characteristics of the area are defined by Zrmanja River inflow and numerous freshwater springs („vruljas“) which transport freshwater from the mainland through karstic underground channels (NOVOSEL *et al.*, 2002). The effect of river and „vruljas“ inflow is especially important during the rainy season, from October to December, and the period of snow melting from March to May (BONACCI, 2001). Bora wind is another phenomenon that highly influences hydrography of this area (ORLIĆ *et al.*, 2000). It reaches speeds of $40^{m/s}$, and is the strongest wind on the eastern Adriatic coast. Both bora wind and freshwater input reduce the salinity and temperature of surface waters in the Velebit and Pag Channels in comparison to the area outside the Channels. Salinity reaches its lowest values during autumn, as a result of maximal precipitation (PENZAR *et al.*, 2001).

Fig. 1. Location of sampling stations: Novigrad Sea (N1), Velebit Channel (V1 – V4) and Pag Channel (P1 – P3)

Previous phytoplankton studies in this transition zone showed that the thermohaline gradient between the southern and northern part of the Channel drives variations of phytoplankton biomass and community composition along the system (VILIČIĆ *et al.*, 2008, 2009). The influence of the karstic Zrmanja River is strongest in the Novigrad Sea area (BURIĆ *et al.*, 2005, BURIĆ *et al.*, 2007) and it almost reaches the middle part of the Velebit Channel. Despite the freshwater influence, the area is considered extremely oligotrophic, with low levels of nutrients and a deep chlorophyll maximum forming during the summer as a result of picoplankton production (VILIČIĆ *et al.*, 2008). The aim of this study was to investigate the abundance distribution and taxonomic composition of phytoplankton assemblages in relation to the thermohaline gradient and the increasing nutrient concentrations.

MATERIALS AND METHODS

The sampling was carried out in November 2008 along a deep-to-shallow water transect, from the Pag Channel (stations P3, P2, P1) to the Velebit Channel (stations V4, V3, V2, V1) and the Zrmanja estuary (station N1) (Fig. 1). 48 water samples were collected using 5 L Niskin bottles at five depths at stations N1 and V1 (surface, 2m, 4m, 10m, 20m) and at six sampling depths (surface, 4m, 10m, 20m, 40m, 60m) at the other stations. At each station, the fine-scale vertical distribution of salinity, temperature and density was determined using a CTD probe (Seabird Electronics Inc., USA). A white Secchi disk (30 cm diameter) was used to estimate transparency. Subsamples (1 L) for the determination of chlorophyll *a* (chl *a*) were filtered on Whatman GF/F filters and determined by the method of high performance liquid chromatography (HPLC). Nutrient concentrations were measured by standard methods (STRICKLAND & PARSONS, 1972, IVANČIĆ & DEGOBBIS, 1984). Phytoplankton samples were preserved with hexamine buffered formaldehyde (1.4% final concentration), as well as net samples (mesh size 20 µm) taken at each station for additional taxonomic analysis. Cells counts were performed by inverted microscope (Zeiss Axiovert 200) in sub-samples of 50 ml after 24 h of sedimentation (LUND *et al.*, 1958, UTERMÖHL, 1958). One transect along the counting chamber bottom was scanned at 400x magnification for larger nanoplankton (>5 µm) and abundant microphytoplankton, two transects were conducted at 200x magnification and a total bottom count was completed for taxa greater than 30 µm at 100x magnification. The minimum concentration that can be detected by this method is 20 cells L^{-1}. For selected species the identification was checked with 1000x magnification. A detailed taxonomic study was performed on the net samples which were analyzed with an Olympus BX51 microscope. Both microscopes used were operating with phase contrast and brightfield optics. For the study of selected diatom species, permanent slides were prepared from acid cleaned samples (HNO_3 and H_2SO_4) mounted in Zrax and observed by light microscope. Transmission electron microscope (TEM) observations were made by deposition of cleaned material onto formvar-carbon coated grids and examination with a Zeiss EM10A microscope. We used the following references for microalgae identification: (HUSTEDT, 1959, RICARD, 1987, HASLE *et al.*, 1996, HASLE & SYVERTSEN, 1997, BÉRARD-THERRIAULT *et al.*, 1999, AMATO & MONTRESOR, 2008).

The statistical package Primer 6 (CLARKE & GORLEY, 2006) was used for multivariate data analysis and to calculate the Shannon-Wiener diversity index. Hierarchical cluster analysis (average linkage) was used to distinguish the relationships between stations, applied to the Bray-Curtis similarities and Euclidean distances computed on abundance and environmental data, respectively. On the basis of Bray-Curtis similarities, the similarity percentages analysis (SIMPER) was applied to abundance data in order to identify dominant phytoplankton taxa in groups defined by cluster analysis. The program Statistica, version 8.0 (Statsoft, Tulsa, USA) was used for statistical procedures. The data were analyzed by multivariate analysis of variance (MANOVA) and one-way ANOVAs with post-hoc Bonferroni tests to differentiate among stations on the basis of particular environmental and biological parameters (salinity, temperature, nutrients, chlorophyll *a*). A logarithmic transformation $[\log_{10}(x+1)]$ was used on the data prior to statistical analyses in order to obtain normal distribution and homogeneity of variances (confirmed by Cochran's C test for MANOVA and Levene's test for ANOVA). The program Grapher 7.0 (Golden Software) was used for the preparation of figures.

RESULTS

Environmental parameters

The analysis of temperature and salinity along the Velebit and Pag Channel system revealed a distinct horizontal thermohaline gradient which was created by Zrmanja River freshwater inflow. The gradient was especially pronounced considering the surface temperature and salinity, which increased considerably between the Zrmanja River outer estuary (N1 station) and the Pag Channel (stations P1 - P3) (Fig. 2). Furthermore, the area could be divided into three sections according to their different thermohaline characteristics. The first area was a transition zone between the Novigrad Sea and the southern Velebit Channel (stations N1 – V1) with the most pronounced horizonal thermohaline gradient ($\Delta T = + 3.9$ °C , $\Delta S = + 13.2$). Throughout the middle Velebit Channel (stations V1 to P1) the difference between thermohaline surface values ($\Delta T = + 1.3$°C, $\Delta S = +1.6$) marked the farthest reach of river influence. The Pag Channel area (stations P1 – P3) showed the most stable thermohaline conditions along the whole transect. Vertically, the structure of the water column followed the changes in the surface layer. Therefore, the strongest stratification was detected in the Novigrad Sea (station N1), with the low salinity layer reaching 4 m depth, and reducing gradually towards station V1. In the water column of the south Velebit Channel and Pag Channel stations (V1 – P3) a slight decrease

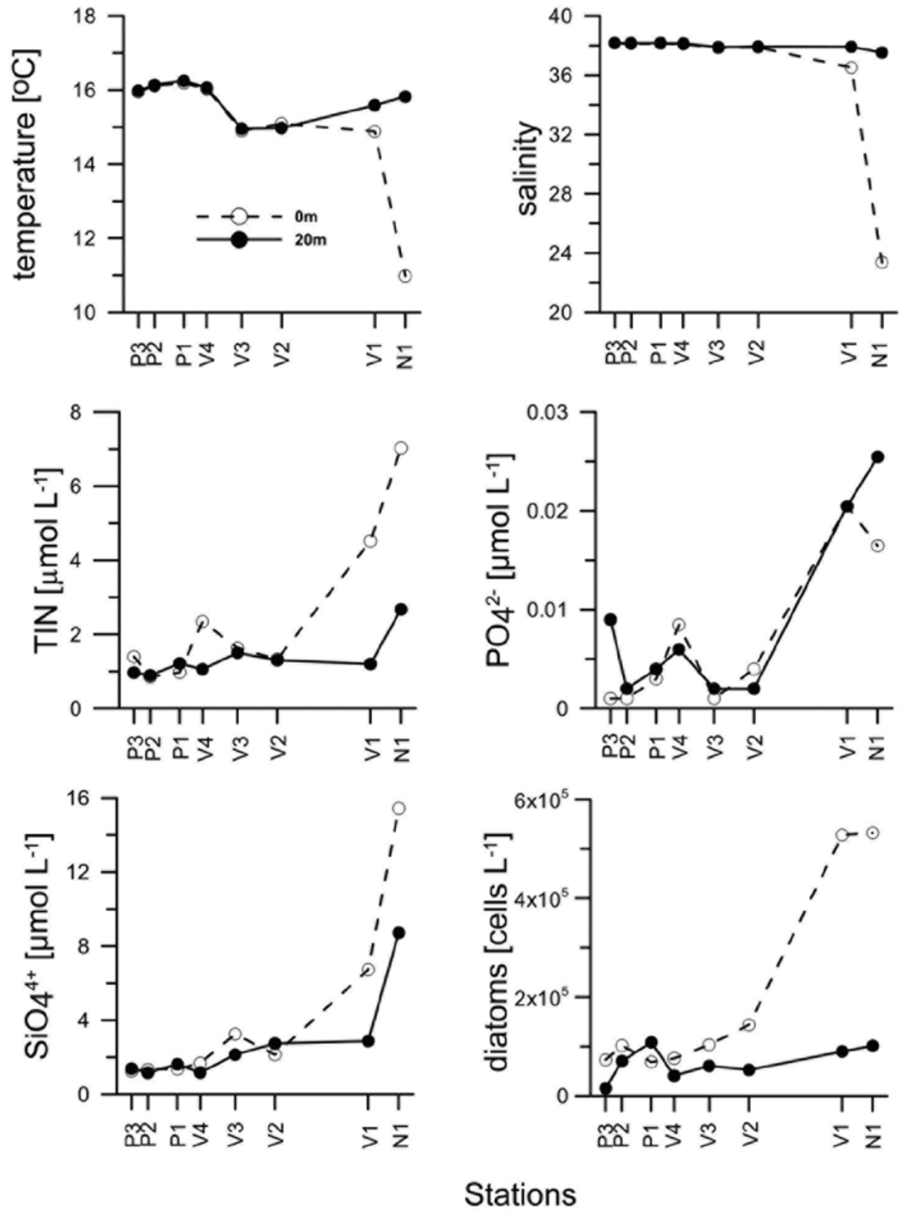

Fig. 2. Horizontal distribution of temperature, salinity, total inorganic nitrogen (TIN), orthophosphates (PO_4^{2-}), orthosilicates (SiO_4^{4+}) and diatom abundances along the Pag Channel – Velebit Channel – Novigrad Sea transect as recorded in November 2008. For the locations of sampling stations, see Fig. 1.

of temperature in the deepest layer (40 – 60 m) was observed, possibly because of the influence of underwater springs.

Concentrations of total inorganic nitrogen (TIN), orthophosphates (PO_4) and silicates (SiO_4) in the surface layer (0 – 20 m) decreased along the trophic gradient (Fig. 2). The nutrient concentrations were significantly negatively correlated with both temperature and salinity (Tab. 1) confirming their freshwater origin. High Redfield ratio (TIN/PO_4) values in the water column ranged from 31.6 (Station N1) up to 1403 (Station P3), indicating phosphorous limitation along the entire investigated area.

Multivariate analysis grouped stations in three different sections according to the physicochemical conditions (Fig. 3): 1) The Novigrad Sea (N1 station) as the least oligotrophic, with the strong influence of the Zrmanja River, 2) middle Velebit Channel where nutrient concen-

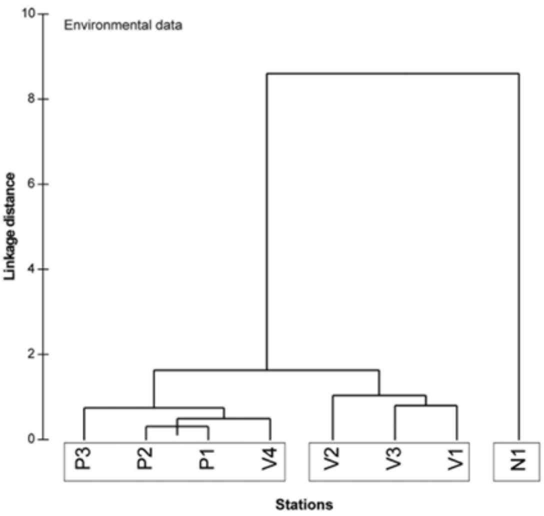

Fig. 3. Cluster dendrogram of the eight stations on the basis of Euclidean distance from the logarithmic transformed values of salinity, temperature, TIN, SiO_4 and PO_4 concentration data clustered and averaged for the whole water column. See Fig. 1. for station locations

trations were generally lower but the influence of freshwater underwater springs could still be detected and 3) the Pag Channel (stations P1 – P3) with the adjacent V4 station as the most oligotrophic area. The significant difference between stations was confirmed with MANOVA (Wilk's F test = 5.00, $p<0.001$). Station N1 differed significantly from other stations based on temperature (ANOVA F test=3.06, $p<0.05$), salinity (F=5.00, $p<0.001$), and nutrient data (TIN; F=3.25, $p<0.05$). For the other stations, with the exception of V1 (for PO_4; F= 25.3 $p<0.001$), no statistically significant difference was found.

Phytoplankton biomass, abundance and taxonomic composition

The spatial distribution of chlorophyll *a*, as an approximation of phytoplankton biomass, showed high patchiness with various depths of chlorophyll maxima along the transect (Fig. 4A). The highest concentration of chlorophyll *a* was detected in the Novigrad sea at station N1 (0.7 μg L^{-1}) in the surface layer. That maximum was caused by the bloom of planktonic diatom *Thalassionema nitzschioides*.

In the southern Velebit Channel (stations V1 – V3) maxima were found somewhat deeper, between 4 and 20 m. They were contributed mainly by various diatoms and nanophytoplankton (coccolithophorids). Further north, at stations V4 – P3, chlorophyll maxima were found deeper, between 20 and 40 m, corresponding to greater abundances of the chain forming diatom *Bacteriastrum* sp. and coccolithophorids.

Total abundance of phytoplankton decreased 6.5 times from the Novigrad Sea (Station N1, 5.5×10^5 cells L^{-1}) to the Pag Channel (Stations P3 – P1, 8.5×10^4 cells L^{-1}) (Fig.4B). Diatoms contributed up to 96% of the total phytoplankton abundance. Their contribution to total phytoplankton was greatest at Station N1 (5.3×10^5 cells L^{-1}, 96% of phytoplankton) and decreased

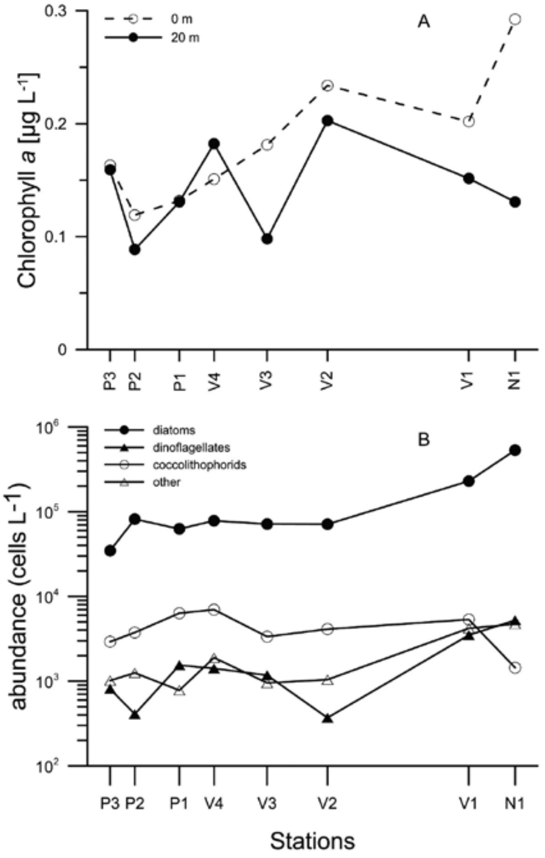

Fig. 4. (A) Chlorophyll a concentration and (B) phytoplankton group abundances (logarithmic scale) along the Pag Channel – Velebit Channel – Novigrad Sea transect in November 2008. For the locations of sampling stations, see Fig. 1.

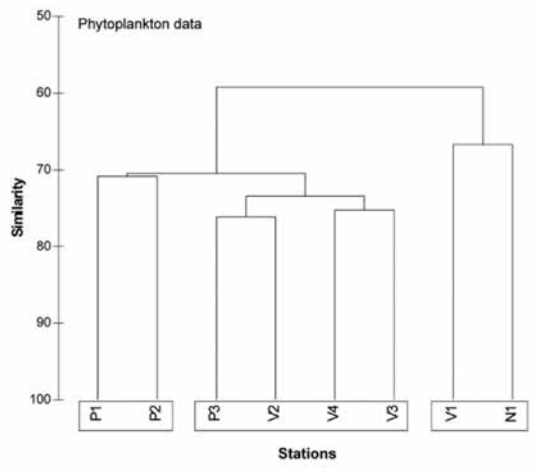

Fig. 5. Cluster dendrogram of the eight stations on the basis of Bray–Curtis similarities from the logarithmic transformed values of phytoplankton abundance data clustered and averaged for the whole water column. See Fig. 1. for station locations

towards the oligotrophic outer stations (P3, 7.3 x 10^4 cells L^{-1}, 85% of total phytoplankton). The abundance of coccolithophorids followed the opposite pattern. Their abundance and contribution was lowest at the eutrophic N1 station (1.4 x 10^3 cells L^{-1}, 0.2% of total phytoplankton), and much higher at the oligotrophic stations (P2, 1.2 x 10^4 cells L^{-1}, 12% of phytoplankton). The greatest abundance of dinoflagellates was detected at station N1 (8.6 x 10^3 cellsl^{-1}) and their contribution to total phytoplankton was negligible. Other phytoplankton groups, such as prasinophytes and chrysophytes (*Dinobryon* sp.) were present only at the nutrient enriched and riverine influenced N1 and V1 stations (maximum abundance 2 x 10^3 cells L^{-1}). The abundance of cryptophytes was generally low and did not exceed 7 x 10^3 cells L^{-1}, as recorded at station N1.

The cluster analysis based on phytoplankton composition and abundance (Fig. 5) identified three principal groups of stations, which reflect the distribution of dominant species (Tab. 2). The stations in the Novigrad Sea and adjacent part of the Velebit Channel (N1 and V1) constitute a group separated at the similarity level of 59.2%. SIMPER analysis identified dominant species *Thalassionema nitzschioides*, *Pseudo-nitzschia pseudodelicatissima* "sensu lato", *Leptocylindrus danicus*, *Chaetoceros curvisetus* and *C. compressus* collectively contributing to 24.23% within group similarity.

The rest of the stations were further subdivided at the 70.5% similarity level in two groups. The second group encompasses the middle Velebit Channel stations (V2 - V4) and the outer station of the Pag Channel (P3). Phytoplankton assemblage was characterised by the increase in dominance of chain forming diatom *Bacteriastrum* sp. (contribution of 6.85%) accompanied by diatoms (*L. danicus*, *Nitzschia longissima*, *C. compressus, P. pseudodelicatissima* "sensu lato") and coccolithophorids (32.58% of overall contribution).

The third group includes the stations from the middle part of the Pag Channel (P1 and P2). In this group *Bacteriastrum* sp. was also the dominant species but with a larger contribution to within group similarity (8.09%). The rest of the dominant taxa comprised coccolithophorids, *L. danicus*, *N .longissima* and cryptophytes contributing with 30.58% to within group similarity.

Table 1. Correlation matrix for physico-chemical parameters (N=45). All correlations are found significant at p<0.05

	Temp	Sal	TIN	PO_4^{2-}	SiO_4^{4+}
Temperature (°C)	1.00				
Salinity	0.82	1.00			
TIN µmol L^{-1}	- 0.77	- 0.69	1.00		
PO_4^{2-} µmol L^{-1}	- 0.31	- 0.54	0.45	1.00	
SiO_4^{4+} µmol L^{-1}	- 0.76	- 0.56	0.87	0.37	1.00

Table 2. *Mean values of dominant species abundances (>10^4 cells L^{-1}) for the upper 20 m of the water column (x 10^3 cells L^{-1}). Abbreviations: Thal.nitz – Thalassionema nitzschioides, P. pseudodel – Pseudo – nitzschia pseudodelicatissima „sensu lato“, Chaet. curvis – Chaetoceros curvisetus, Lept. dan – Leptocylindrus danicus, Nitz. long – Nitzschia longissima, Chaet. comp – Chaetoceros compressus, Bact. sp. – Bacteriastrum sp., Cocco. – coccolithophorids.*

	N1		**V1**		**V2**		**V3**		**V4**		**P1**		**P2**		**P3**	
	AVG	±SD	AVG	±SD	AVG	±SD	AVG	±SD	AVG	±SD	AVG	±SD	AVG	±SD	AVG	±SD
Thal. nitz	236.4	157.1	38.7	49.1	1.4	0.8	1.5	0.8	0.5	0.2	0.2	0.2	0.3	0.2	0.3	0.4
P. pseudodel	110.4	69.4	52.7	55.6	3.8	2.1	1.3	1.5	0.7	0.4	0.6	0.4	1.7	3.0	3.9	5.7
Ch. curv	104.9	102.6	23.0	33.2	3.0	1.4	1.3	1.2	0.0	0.2	0.2	0.2	1.1	1.2	0.0	0.0
Lept. dan	42.1	30.6	35.2	50.5	5.9	3.8	3.8	2.6	7.3	1.6	3.0	1.6	2.3	0.6	1.6	1.4
Nit. long	0.4	0.4	6.1	1.8	8.6	2.1	8.3	5.0	6.4	1.0	2.9	1.0	4.3	1.5	4.0	1.4
Ch. comp	6.0	6.3	9.2	5.0	5.5	6.7	3.6	3.8	2.2	0.4	0.4	0.4	4.7	8.1	0.8	1.5
Bact. sp.	1.9	2.5	48.4	26.6	57.1	30.1	42.0	17.8	59.8	23.1	72.4	23.1	74.7	16.7	25.1	24.4
cocco	0.3	0.6	4.3	5.0	6.0	1.8	4.3	4.1	7.8	3.1	5.0	3.1	4.3	4.4	3.5	4.4

The Shannon diversity index values varied from 0.51 to 2.21 at all stations (Fig. 6), the average being slightly lower at stations P1 (1.12) and P2 (1.04) than at the other stations (i.e. 1.94, 1.59, 1.54 for V1, V3, and P3, respectively).

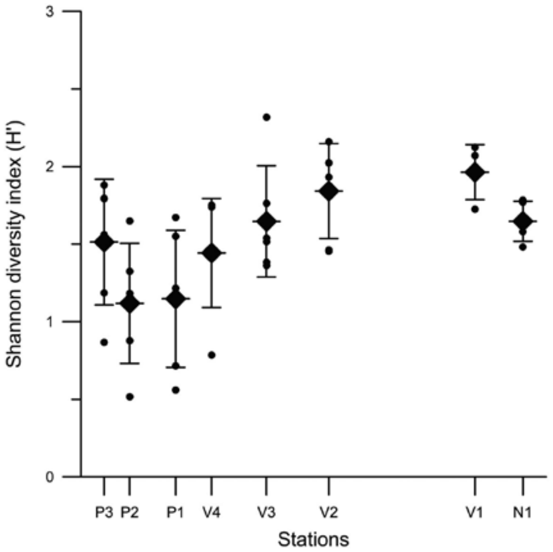

Fig. 6. Spatial changes of phytoplankton diversity (H') along the investigated profile

Light micrographs of most abundant species are given in Figure 7. A detailed taxonomic investigation of net samples identified 80 taxa which, together with 66 taxa enumerated in the water samples, comprised the list of 146 taxa (Tab. 3). The most species–rich group were diatoms, with 91 species (46 centrics and 45 pennates). The *Pseudo-nitzschia* species enumerated with light microscopy was identified as a member of P. *pseudodelicatissima* species complex based on the valve width (<3 µm) and pointed and elongated cell ends in girdle view. Based on the ultrastructural features visible in TEM, as seen in Figure 8, P. *pseudodelicatissima*-like specimens were attributed to three distinct morphotypes: P. *pseudodelicatissima*, P. *mannii* and P. *calliantha*. No observable difference in the distribution of three morphotypes between stations was found. Dinoflagellates were the second largest group with 45 species. Other recorded taxa belonged to coccolithophorids (5 species), silicoflagellates (2 species), chrysophytes (1 species) and two species of uncertain taxonomic affiliation.

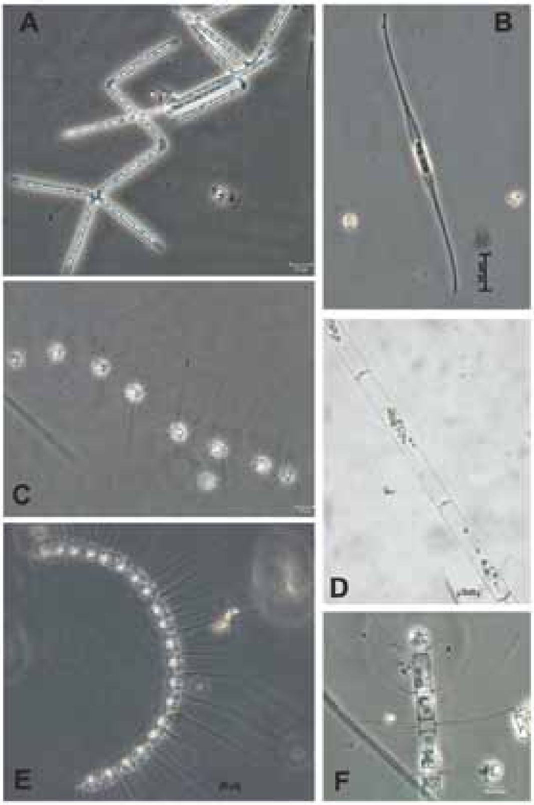

Fig. 7. Light micrographs of the most abundant diatoms along the Pag Channel – Velebit Channel – Novigrad Sea transect in November 2008. (A) Thalassionema nitzschioides (phase contrast), (B) Nitzschia longissima (phase contrast) (C) Bacteriastrum sp. (phase contrast), (D) Leptocylindrus danicus (differential interference), (E) Chaetoceros curvisetus (phase contrast) and (F) C. compressus (phase contrast)

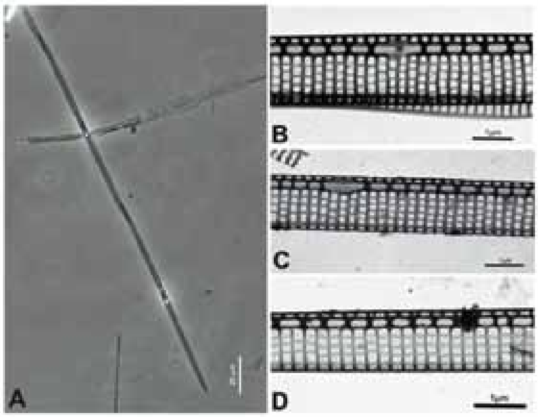

Fig. 8. Light and electron micrographs of Pseudo-nitzschia pseudodelicatissima "sensu lato" (A) chain colony (phase contrast LM), (B) P. calliantha central part of valve showing central nodule and stria structure (TEM), (D) P. pseudodelicatissima central part of valve showing central nodule and stria structure (TEM), (C) P. mannii part of valve showing stria structure (TEM)

Table 3. List of phytoplankton taxa found in the water (marked with asterisks) and net samples from November 2008 in the Velebit and Pag Channels. Diatoms usually occurring in benthic communities are marked with ^{b}. MAX is for maximum abundance of cells L^{-1} and Fr is frequency of appearance (45 samples is 100%).

Taxa	MAX	Fr (%)
BACILLARIOPHYCAE		
Achnanthes sp. ^{b}		
Amphiprora sulcata O'Meara ^{b}		
Amphora sp. ^{b}		
Asteromphallus flabellatus (Brébisson) Greville		
Auricula sp. ^{b}		
Bacillaria paxillifera (Müller) Hendey *	40	2.2
Bacteriastrum biconicum Pavillard		
Bacteriastrum Bacteriastrum furcatum Shadbolt		
Bacteriastrum hyalinum Lauder		
Bacteriastrum mediterraneum Pavillard *	9 500	46.7
Bacteriastrum sp. *	98 420	95.6
Ceratoneis closterium Ehrenberg * ^{b}	1 140	6.7
Cerataulina pelagica (Cleve) Hendey *	3 800	51.1
Chaetoceros affinis Lauder *	3 420	22.2
Chaetoceros anastomosans Grunow *	7 980	13.3
Chaetoceros borealis Lauder		
Chaetoceros brevis Schütt		
Chaetoceros coarctatus Lauder		
Chaetoceros compressus Lauder *	18 620	51.1
Chaetoceros curvisetus Cleve *	279 812	60.0
Chaetoceros danicus Cleve *	80	2.2
Chaetoceros decipiens Cleve *	7 220	55.6
Chaetoceros didymus Ehrenberg *	760	2.2
Chaetoceros diversus Cleve *	7 980	22.2
Chaetoceros laciniosus Schütt *	3 040	6.7
Chaetoceros lauderi Ralfs *	360	6.7
Chaetoceros lorenzianus Grunow		
Chaetoceros messanense Castracane		
Chaetoceros peruvianus Brightwell *	380	11.1
Chaetoceros rostratus Lauder *	1140	6.7
Chaetoceros simplex Ostenfeld *	1 140	11.1
Chaetoceros sp. *	12 540	6.7
Chaetoceros throndsenii Marino, Montresor & Zingone *	1 420	6.7
Cocconeis scutellum Ehrenberg * ^{b}	760	2.2
Coscinodiscus spp. *^{b}	380	15.6
Cyclotella choctawhatcheeana Prasad *	1 520	6.7

Dactyliosolen blavyanus (Peragallo) Hasle		
Dactyliosolen fragilissimus (Bergon) Hasle *	9 120	28.9
Dactyliosolen phuketensis (Sundström) Hasle		
Diploneis bombus Ehrenberg [b]		
Diploneis mediterranea (Grunow) Cleve [b]		
Diploneis smithii (Brébisson) Cleve [b]		
Entomoneis sp. [b]		
Eucampia cornuta (Cleve) Grunow *	380	6.7
Fragilaria sp. [b]		
Fragilariopsis kerguelensis (O'Meara) Hustedt		
Gomphonema angustatum (Kützing) Rabenhorst [b]		
Guinardia flaccida (Castracane) Peragallo *	1 520	60.0
Guinardia striata (Stolterfoth) Hasle *	3 800	82.2
Haslea wawrikae (Husedt) Simonsen *	40	6.7
Hemiaulus hauckii Grunow ex Van Heurck *	3 040	31.1
Hemiaulus sinensis Greville *	760	13.3
Leptocylindrus danicus Cleve *	122 532	88.9
Leptocylindrus mediterraneus (Peragallo) Hasle *	7 980	37.8
Leptocylindrus minimus Gran		
Licmosphenia clevei Mereschkowsky [b]		
Lioloma pacificum (Cupp) Hasle		
Lyrella lyra (Ehrenberg) Karajeva [b]		
Lyrella spp. [b]		
Mastogloia spp. [b]		
Mastogloia splendida (Gregory) Cleve [b]		
Navicula spp. * [b]	380	4.4
Neocalyptrella robusta (Norman ex Ralfs) Hernández-Becerril & Meave del Castillo *	380	4.4
Nitzschia amphibia Grunow [b]		
Nitzschia capitellata Hustedt [b]		
Nitzschia fasciculata Grunow [b]		
Nitzschia incerta Grunow * [b]	380	11.1
Nitzschia obtusa Smith [b]		
Nitzschia sigma (Kützing) Smith [b]		
Nitzschia longissima (Brébisson in Kützing) Ralfs * [b]	19 760	93.3
Nitzschia sp. * [b]	380	6.7
Plagiodiscus sp. * [b]		
Pleurosigma spp.	760	31.1
Proboscia alata (Brightwell) Sundström *	3 040	84.4
Proboscia indica (Peragallo) Hernández-Becerril *	380	15.6
Psammodictyon panduriforme (Gregory) Mann [b]		

Pseudo-nitzschia pseudodelicatissima “sensu lato” *	168 253	68.9
Pseudo-nitzschia calliantha Lundholm, Moestrup & Hasle		
pseudodelicatissima (Hasle) Hasle		
Pseudo-nitzschia mannii Amato & Montresor		
Pseudosolenia calcar-avis (Schultze) Sundström *	80	4.4
Raphoneis spp. [b]		
Rhizosolenia castracanei Cleve		
Rhizosolenia imbricata Brightwell *	2 660	48.9
Striatella unipunctata (Lyngbye) Agardh [b]		
Surirella ovalis Brébisson [b]		
Surirella spp. [b]		
Synedra ulna (Nitzsch) Ehrenberg		
Thalassionema nitzschioides (Grunow) Mereschkowsky *	438 920	77.8
Thalassiosira rotula Meunier *	1 140	2.2
Thalassiosira sp.		
Toxarium undulatum Bailey [b]		
		17.8
DINOPHYCEAE		
Alexandrium sp.		
Amphidoma caudata Halldal		
Ceratium candelabrum (Ehrenberg) Stein		
Ceratium extensum (Gourret) Cleve *	40	2.2
Ceratium furca (Ehrenberg) Claparéde & Lachmann *	190	6.7
Ceratium fusus (Ehrenberg) Dujardin *	380	15.6
Ceratium hexacanthum Gourret		
Ceratium horridum (Cleve) Gran		
Ceratium massiliense (Gourret) Jørgensen *	380	6.7
Ceratium pentagonum Gourret *	120	2.2
Ceratium symmetricum Pavillard		
Ceratium teres Kofoid		
Ceratium trichoceros (Ehrenberg) Kofoid *	40	4.4
Ceratium tripos (Müller) Nitzsch *	40	2.2
Ceratocorys gourettii Paulsen		
Corythodinium tesselatum (Stein) Loeblich Jr. & Loeblich III		
Dinophysis acuminata Claparède & Lachmann		
Dinophysis caudata Saville-Kent		
Diplopsalis „complex“ *	190	2.2
Gymnodinium cucumis Schütt		
Gymnodinium sp. *	1 520	6.7
Gyrodinium sp. *	760	13.3

Goniodoma polyedricum (Pouchet) Jorgensen		
Gonyaulax sp.		
Ornithocercus magnificus Stein		
Oxytoxum caudatum Schiller *	380	2.2
Oxytoxum sceptrum (Stein) Schröder *	380	2.2
Oxytoxum sp. *	380	13.3
Phalacroma rotundata (Claparède & Lachmann) Kofoid & Michener		
Podolampas elegans Schütt		
Podolampas palmipes Stein		
Prorocentrum compressum (Bailey) Abé ex Dodge		
Prorocentrum micans Ehrenberg *	1 140	8.9
Prorocentrum scutellum Schröder *	380	2.2
Protoperidinium bipes (Paulsen) Balech *	380	2.2
Protoperidinium conicum (Gran) Balech *	190	2.2
Protoperidinium curtipes (Jorgensen) Balech *	380	2.2
Protoperidinium diabolus (Cleve) Balech *	190	2.2
Protoperidinium divergens (Ehrenberg) Balech *	40	2.2
Protoperidinium globulum (Stein) Balech		
Protoperidinium oblongum (Aurivillius) Parke & Dodge *	190	2.2
Protoperidinium oceanicum (VanHöffen) Balech		
Protoperidinium pyriforme (Paulsen) Balech		
Protoperidinium steinii (Jorgensen) Balech		
Protoperidinium sp.*	40	2.2
Scripsiella sp. *	380	6.7
PRYMNESIOPHYCEAE		
Calciosolenia brasiliensis (Lohmann) Young *	380	6.7
Emiliania huxleyi (Lohmann) Hay & Mohler		
Ophiaster sp. *	760	6.7
Syracosphaera pulchra Lohman *	4 260	11.1
Rhabdosphaera clavigera Murray & Blackman	1 420	33.3
DICTYOCHOPHYCEAE		
Dictyocha fibula Ehrenberg *	380	11.1
Octactis octonaria (Ehrenberg) Hovasse *	380	6.7
CHRYSOPHYCEAE		
Dinobryon sp.*	2 090	6.7
UNCERTAIN		
Hermesinum adriaticum Zacharias *	40	2.2
Meringosphaera mediterranea Lohmann *	1 420	2.2

DISCUSSION

The Pag and Velebit Channel system was regulated mainly by Zrmanja River inflow, showing a distinctive gradient of biological and physico–chemical parameters along the transect. The vertical distributions of temperature and salinity showed that the water from the Novigrad Sea was entering the Velebit Channel, reaching all the way to the V2 station. From there on, river influence was low and the water column was homogenous with regard to its thermohaline properties. Compared to winter conditions in February 2008 in the same area, presented by VILIČIĆ *et al.* (2009), river influence was less intensive, especially in the middle Velebit Channel and Pag Channel. We can speculate that it could be the consequence of lower precipitation in November 2008 compared to February 2008 which would result in decreased freshwater inflow. The depths of the halocline and thermocline were similar as in winter, between 2 and 4 meters in the Novigrad Sea, twice as deep compared to summer conditions (VILIČIĆ *et al.*, 2008). All measured nutrients followed a similar pattern, decreasing gradually along the transect, which can be ascribed to the freshwater influence. The Novigrad Sea station and southern Velebit Channel were more nutrient–enriched, while the northern Velebit Channel and Pag Channel were extremely oligotrophic.

The cluster analysis of environmental parameters resulted in a somewhat different grouping of stations compared to the cluster analysis of phytoplankton species abundance at the same stations. These differences are probably the result of the discrepancy between the dynamic physico-chemical conditions and the response time that dominant phytoplankton species need to adapt to the current environmental conditions. Phytoplankton abundance followed the gradient regarding the amount of nutrients, with the highest abundances noted for the Novigrad Sea area, and the lowest in the Pag Channel. The same pattern was detected in winter investigations (VILIČIĆ *et al.*, 2009). Variations in phytoplankton assemblages can be explained by the different trophic preferences of certain species. Nutrient-enriched areas in the lower Zrmanja River estuary were dominated by various diatoms that normally proliferate in more eutrophic conditions (PUCHER-PETKOVIĆ & MARASOVIĆ, 1980; REVELANTE & GILMARTIN, 1980; BERNARDI AUBRY *et al.*, 2004; CETINIĆ *et al.*, 2006). These were *Thalasionema nitzschioides, Pseudo-nitzschia pseudodelicatissima* „sensu lato“, *Nitzschia longissima*, *Chaetoceros curvisetus*, *C. compressus* and *Leptocylindrus danicus*. On the other hand, phytoplankton communities of the oligotrophic middle Velebit Channel and Pag Channel were dominated by the chain forming diatom *Bacteriastrum* sp. and coccolithophorids. Additional analysis of *Bacteriastrum* sp. revealed that it is weakly silificied, indicating its ability to proliferate even if silicates are scarse. Values of the Shannon diversity index show a decrease of species diversity along the trophic gradient, with the lowest values in the most oligotrophic area. In the winter, the phytoplankton distribution (VILIČIĆ *et al.*, 2009) in the most eutrophic area of the transect was dominated by chain forming *Chaetoceros* and *Bacteriastrum* species, while coccolithophorids were the most abundant group in the oligotrophic Pag Channel. It is interesting that the autumnal phytoplankton community of the Novigrad Sea presented in this paper resembles the „winter group“ of dominant species in the same area (BURIĆ *et al.*, 2007). Since the work of BURIĆ *et al.* (2007) encompassed seven years of sampling in the Zrmanja River estuary (1998 – 2005), it can be assumed that the conditions detected in autumn 2008 regarding species compositions were an exception rather than normal autumnal species composition.

While the detailed taxonomic composition of phytoplankton from the eastern Adriatic Sea has been published by VILIČIĆ *et al.* (2002) and the list of species present in the Zrmanja River estuary, including the Novigrad Sea, was published by BURIĆ *et al.* (2005), this paper gives the first checklist of species present in the extremely oligotrophic Velebit and Pag Channels. Detailed analysis of acid - cleaned diatom frustules revealed a significant contribution of benthic diatoms to the total number of diatom species and may be viewed as evidence of high physical forcing in the area. TEM analysis of the *Pseudo-*

nitzschia frustules confirmed the former findings of potential toxin producer *P. calliantha* in the Novigrad Sea (BURIĆ *et al.*, 2008) and recorded its presence far more north, even in the oligotrophic waters of the Pag Channel. The results of the phytoplankton composition analyses in this extremely oligotrophic area call for an in depth analysis of the traits of occurring species as they have implications on the food web processes in this marine system.

ACKNOWLEDGEMENTS

This research was supported by the MINISTRY OF SCIENCE, EDUCATION AND SPORTS OF THE REPUBLIC OF CROATIA (project number: 111-1191189-1228). We wish to thank Marijan AHEL, Ruđer Bošković Institute, Zagreb who kindly provided HPLC instrumentation and helped in chlorophyll *a* analysis, and two anonymous referees for their valuable suggestions.

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Received: 12 July 2010
Accepted: 9 March 2011

Sastav i prostorna raspodjela fitoplanktona u sjeveroistočnom kanalu Jadranskog mora u jesen 2008. godine

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SAŽETAK

Velebitski i Paški kanal čine 40 km dug i 4-14 km širok sustav koji se proteže usporedno sa sjeveroistočnom obalom Jadranskog mora. Cilj ovog istraživanja je bio istražiti abundanciju, sastav i raspodjelu fitoplanktona duž sustava u jesenskom razdoblju. Uzorkovanje je obavljeno na 8 postaja u studenom 2008. Prostorna raspodjela fizikalno kemijskih parametara upućivala je na postojanje izrazitog horizontalnog termohalinog i trofičkog gradijenta. Od unutrašnjeg dijela Velebitskog kanala, koji je produžetak estuarija krške rijeke Zrmanje do vanjskog dijela Paškog kanala koji se spaja s otvorenim morem, raspon površinske temperature mora iznosio je 11.0 do 16.0 °C, a saliniteta 23.4 do 38.2. Koncentracije nutrijenata kretale su se u rasponu 0.001 - 0.1 μmol L^{-1} za fosfate, 0.85 - 7.0 μmol L^{-1} za otopljeni anorganski dušik i 0.3 - 15.4 μmol L^{-1} za silikate. Dijatomeje su prevladavale u fitoplanktonu s maksimalnom abundancijom u rasponu od 7.3 x 10^4 stanica L^{-1} (85% ukupnog fitoplanktona) na najviše oligotrofnim do 9.6 x 10^5 stanica L^{-1} (96% ukupnog fitoplanktona) na postajama s većom koncentracijom nutrijenata. Statistička analiza na osnovi bioloških i fizikalno kemijskih parametara podijelila je postaje u tri glavne grupe. Prva grupa predstavljala je južni dio Velebitskog kanala s većom koncentracijom nutrijenata i prevladavajućom vrstom *Thalassionema nitzschioides*. Druga grupa uključila je postaje iz središnjeg dijela Velebitskog kanala s nižim razinama nutrijenata i s prevladavajućom dijatomejom *Bacteriastrum* sp.. Treća grupa uključila je postaje u Paškom kanalu u kojima gotovo isključivo prevladava *Bacteriastrum mannii* sp. i prisutan je veći udio kokolitoforida. Ovaj rad također donosi prvi popis vrsta fitoplanktona prisutnih u ekstremno oligotrofnom području Velebitskog i Paškog kanala. Identificirano je 148 taksona od čega 91 dijatomeja, 47 dinoflagelata i 10 taksona raznih flagelata. Detaljna analiza pomoću elektronskog mikroskopa otkrila je tri vrste iz potencijalno toksičnog dijatomejskog roda *Pseudo-nitzschia*: *P-n. calliantha, P-n. pseudodelicatissima* i *P-n. mannii.* Rezultati ovog rada predstavljaju značajan doprinos poznavanju sastava i raspodjele fitoplanktona u odnosu na prevladavajuće fizikalno kemijske uvjete u ovom slabo istraženom tranzitnom području.

Ključne riječi: fitoplankton, taksonomija, trofički gradijent, Jadransko more