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EFFECTS OF THERMAL POLLUTION AND NUTRIENT DISCHARGES ON A SPRING PHYTOPLANKTON BLOOM IN THE INDUSTRIAL AREA OF THE LAGOON OF VENICE*

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LAGUNE DE VENISE
SELS NUTRITIFS
FLORAISON DE PHYTOPLANCTON
POLLUTION THERMIQUE
SKELETONEMA COSTATUM

RÉSUMÉ. – Dans le but de suivre une floraison printanière de phytoplancton dans une zone touchée par les eaux de refroidissement d'une centrale thermique, les variations temporelles des paramètres hydrochimiques et du phytoplancton ont été étudiées dans la partie centrale de la lagune de Venise. Des échantillons ont été prélevés une fois par semaine, dans dix stations, du début à la fin de la floraison, de février à mai 1986. L'algue responsable de la floraison était la Diatomée *Skeletonema costatum* (Grév.) Cl. qui présentait des densités très élevées (jusqu'à 6×10^7 cellules dm^{-3}) ; la communauté était ensuite principalement représentée par des phytoflagellés et des Diatomées pennées. A la fin du mois de mai, on a enregistré, dans cette même zone, une croissance progressive des différentes classes. Des analyses statistiques ont été appliquées pour mettre en évidence les effets thermiques : les résultats ont montré que les variations quantitatives du phytoplancton étaient seulement transitoires. Aucun effet permanent sur la composition des espèces n'a été observé, probablement en raison des caractéristiques hydrodynamiques du canal Malamocco-Marghera. Les données suggèrent aussi la superposition de deux formes de pollution différentes : la pollution thermique (engendrée par la centrale thermique) et la pollution chimique (due aux nombreuses industries dans la zone étudiée).

LAGOON OF VENICE
NUTRIENTS
PHYTOPLANKTON BLOOM
THERMAL PERTURBATION
SKELETONEMA COSTATUM

ABSTRACT. – In order to follow a spring phytoplankton bloom in an area affected by cooling waters discharged from a thermoelectric power plant as well as by high dissolved nutrient concentrations, hydrochemistry and phytoplankton time trends were studied in the industrial area of the Venice lagoon. Samples were collected weekly from the beginning of the bloom until it ended, from February to May 1986, in 10 stations. The centric diatom *Skeletonema costatum* (Grév.) Cl. (abundances up to 6×10^7 cells dm^{-3}) was responsible for the bloom ; afterwards, the community was mainly represented by phytoflagellates and pennate diatoms. At the end of May, slow growth of various taxa was recorded in the area. Statistical analyses were performed to highlight thermal and chemical effects : results showed that modifications in phytoplankton abundances due to thermal perturbation were only transient. Permanent effects on species composition were not observed, probably because of the strong hydrodynamics of the Malamocco-Marghera channel. The data also showed that thermal pollution was partly masked by pollutant inputs from industrial plant in the study area.

INTRODUCTION

Several studies regarding biological effects on primary production and phytoplankton communities, caused by discharge of cooling waters from nuclear and thermoelectric power plants, have been carried out in the Baltic (Ilus & Keskitalo 1987, Keskitalo 1987, Edler *et al.* 1980) and Western North Atlantic (Carpenter 1973). In the Mediterranean coastal area, data from French waters near Marseilles (Gulf of Fos, Minas 1977), Northern and Central Tyrrhenian (Innamorati *et al.* 1980, Ioannilli *et al.* 1980, Crema *et al.* 1980) and Northern Sardinian waters (Arru *et al.* 1989) are available. Observations from the Po Delta also concern nearby areas of the Adriatic (Solazzi *et al.* 1990).

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* The data presented here were collected with funds from the Ente Nazionale per l'Energia Elettrica (ENEL), Venice.

Some authors have demonstrated that cooling water outputs may become a source of thermal pollution, depressing phytoplankton primary production (Morgan & Stross 1969) or changing the succession of species composition (Bourgade 1977, Innamorati *et al.* 1980, Ilus & Keskitalo 1987, Solazzi *et al.* 1990). Other authors state that the effects of thermal discharges are largely overestimated, considering that legal limits imposed on power plants (at least for Italy) are stricter than necessary, in order to protect the biological resources of coastal sites (Cironi *et al.* 1993). The debate is therefore still open.

In the lagoon of Venice, a thermoelectric power plant belonging to the "Ente Nazionale per l'Energia Elettrica" (ENEL) is located in the central basin, close to the industrial area of Fusina. When working at full power (960 MWatts), its cooling wastes increase the water temperature by 10 °C so that, in summer, the lagoonal waters may reach very high temperatures. For this reason, the plant was restricted to working at two-thirds of its maximum power, according to laws fixing the upper temperature limit of the lagoonal waters, close to the outflow, at 30 °C. In 1979, the Italian Ministry for Industry allowed the plant to work at full power for a limited period of time, during which a series of experimental studies on evaluating the effects of cooling waters on the surrounding biological communities was to be performed.

For this purpose, a technical-scientific commission was set up and one of the subjects to be studied was phytoplankton. Since spring phytoplankton blooms usually occur in the central basin of the lagoon of Venice (Voltolina 1970, 1973), this study aimed at : i) describing the space/time evolution of a phytoplankton bloom from beginning to end, in relation to the hydrological and chemical features of the waters close to the power plant ; ii) highlighting phytoplankton species composition and abundance trends, according to distance from the thermal output, in order to ascertain whether modifications in the communities are caused by the thermal plume.

These topics are discussed in the present paper.

MATERIALS AND METHODS

Sampling area : The central basin of the lagoon of Venice is connected with the sea through the Malamocco-Marghera channel, which introduces salt water from the Northern Adriatic with tides. The morphology of this basin has been greatly modified. Over the last 40 years, the main operations have been :

— enclosure of marshes for aquaculture, limiting tidal spread (Avanzi *et al.* 1980) ;

— excavation of the Malamocco-Marghera channel to a depth of 14 m, changing the hydrodynamics of the area, with northward displacement of the sill (Cavazzoni 1977) ;

— setting up of heavy industry at Marghera, which caused evident pollution (Tiso 1966 ; Giordani Soika & Perin 1974 ; Perin 1975 ; Moretti *et al.* 1976 ; Campesan *et al.* 1981).

Lastly, the city of Venice adds its own anthropic pollution to the system. Cooling waters from the ENEL power plant at Fusina, about 1 km before immission into the Malamocco-Marghera channel, are discharged into this very complex ecosystem.

Samplings : Samplings were performed in spring 1986 : ten stations were selected, representing a series of gradual and/or different situations (Fig. 1). One station was located close to agricultural inputs (Tessera, st. 1) and another near the urban waste dump of Mestre (S. Giuliano, st. 2), both characterized by frequent phytoplankton blooms (Voltolina 1973). Near the ENEL power plant, stations were located at the water intake point (st. 3), close to the thermal waste outflow point (st. 5, at the confluence between the mouth of the Naviglio del Brenta and the Malamocco-Marghera channel) and in an intermediate position (st. 4). Other stations were set along the main channels through which thermal advection with the central basin takes place : the Malamocco-Marghera channel (st. 6 and 7) and the Fusina New Channel (st. 8, 9 and 10).

Samples were taken at the surface from February 27 to May 29 1986, in order to follow the phytoplankton bloom from beginning to end : they were collected during the last period of ebb tide, to observe the maximum effects of effluent on the system. Measurements were made weekly at stations 1, 2, 3 and 5, as these were considered the most representative points, and fortnightly at the other stations.

Transparency was estimated by a Secchi disc, temperature and salinity by a RS-5 inductive salinometer. Dissolved oxygen concentrations were determined by the Winkler method, as reported by Strickland & Parsons (1972) ; percent saturation values were calculated according to Weiss (1970). pH was measured on a Beckman pH-meter ; readings were corrected for *in-situ* temperature, following Gieskes (1969).

Samples for determination of dissolved nutrients, filtered on to Whatman GF/C glass fiber filters (1 µm pore size), were cooled with dry ice and stored at – 25 °C until analysis, which was performed using a Technicon Autoanalyzer for nitrites, nitrates and orthosilicates (Strickland & Parsons 1972). Ammonia and orthophosphates were analysed manually, according respectively to Solorzano (1969) and Strickland & Parsons (1972). All samples that exceeded the upper limit of the analytical range were diluted with synthetic sea water.

Chlorophyll *a* determinations were made on Whatman GF/C filters, disgregated with a homogenizer and extracted following Strickland & Parsons (1972) ; chlorophyll *a* and pheopigment concentrations were calculated according to Lorenzen (1967).

Samples for phytoplankton counting and species composition analysis were fixed in hexamethylene-tetramine-buffered formalin. Samples were counted after settling in chambers varying from 2 to 25 ml on an ICM405 Zeiss inverted microscope, according to Utermöhl (1958). About 200 cells were counted for each

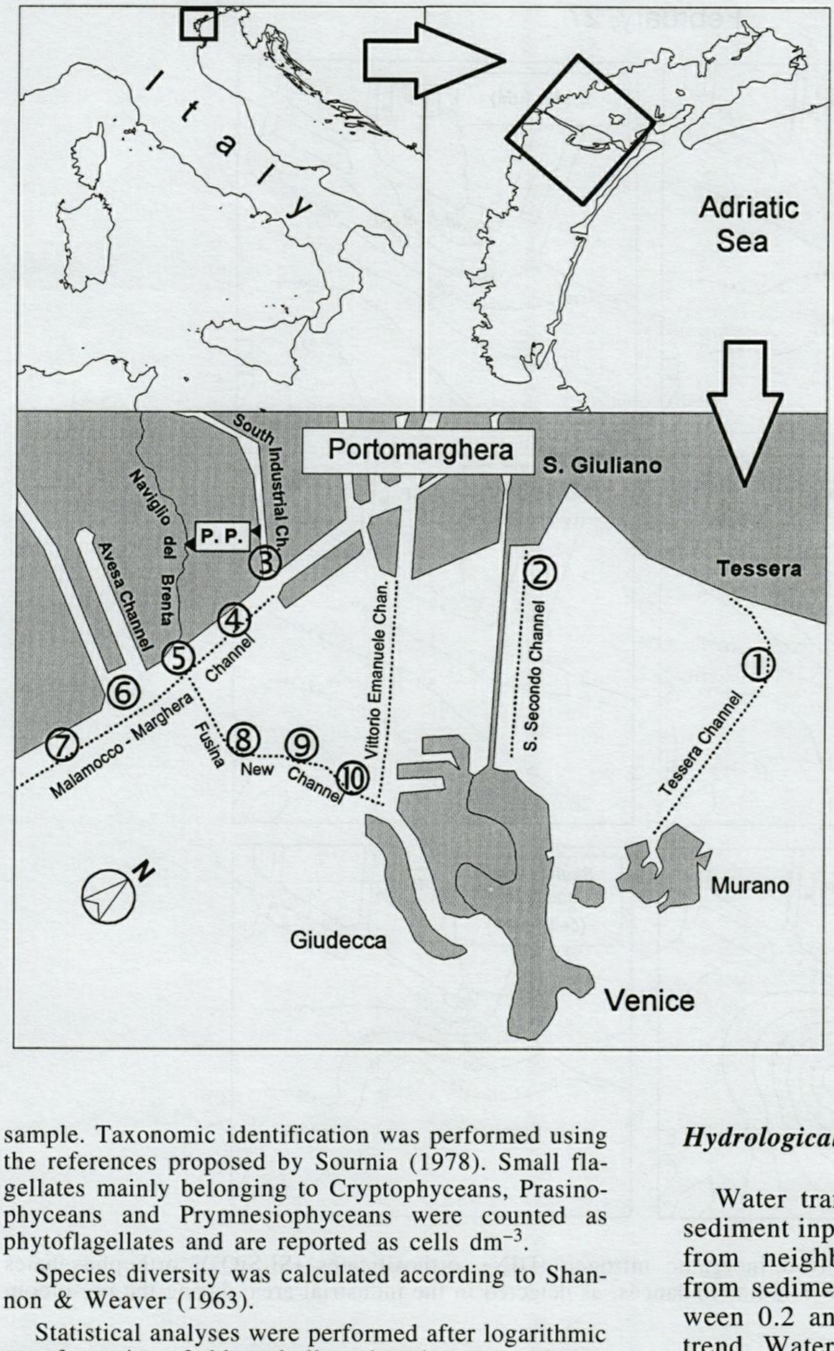

Fig. 1. – Sampling area (P.P. = power plant).

sample. Taxonomic identification was performed using the references proposed by Sournia (1978). Small flagellates mainly belonging to Cryptophyceans, Prasinophyceans and Prymnesiophyceans were counted as phytoflagellates and are reported as cells dm^{-3}.

Species diversity was calculated according to Shannon & Weaver (1963).

Statistical analyses were performed after logarithmic transformation of chlorophyll *a*, pheopigments and phytoplankton data, following Sokal & Rohlf (1981).

Results are discussed together with observations from data collected the following year (1987), in the same period and area (Socal *et al.* 1989, Alberighi *et al.* 1992).

RESULTS

Figures 2, 3 and 4 show, as synoptic pictures, the gradual changes in the main variables occurring before (February 27), during (March 27) and after (May 16) the phytoplankton bloom in the industrial area.

Hydrological features and nutrients

Water transparency was very low, because of sediment inputs from the hinterland, tidal drainage from neighbouring channels and resuspension from sediments. Secchi disc readings ranged between 0.2 and 1.2 m, with an irregular temporal trend. Water temperatures showed a minimum of 1.2 °C (st. 1, February 27) and a maximum of 27.8 °C (st. 5, May 22). The pattern of the Fusina thermal plume was evident during all samplings and was revealed by the gradient encountered proceeding along the Malamocco-Marghera and Fusina New Channels (Figs. 2, 3 and 4). Stations 9 and 10, the farthest from the plant, showed similar values to those located in the northern basin (st. 1 and 2; Table I). Salinity showed average values of about 30 PSU in most stations; freshwater outputs of little importance were evident at stations 1, 2 and 5. pH ranged from 7.89 to 9.07. Dissolved oxygen ranged between a maximum of 13.0 and a minimum of 2.4 cm^3 dm^{-3}, respectively at the beginning and end of spring

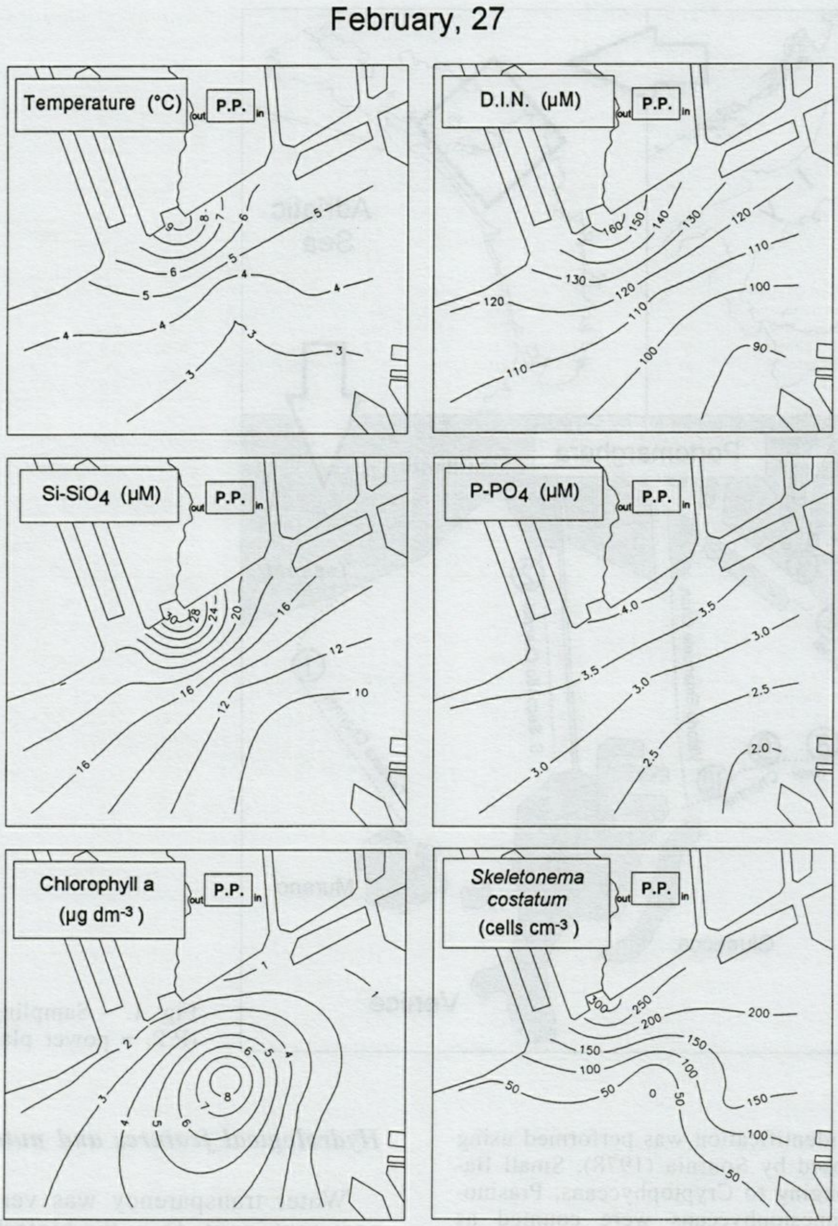

Fig. 2. – Isolines of temperature, dissolved inorganic nitrogen (DIN), orthosilicates (Si-SiO$_4$), orthophosphates (P-PO$_4$), chlorophyll *a* and *Skeletonema costatum* abundances, as detected in the industrial area, during the pre-bloom situation (February 27).

(st. 9, March 27 ; st. 2, May 29). Oxygen saturation values showed a broad range (46-211 %), because of production and respiration processes. Values exceeded 100 % during the first sampling period and became progressively undersaturated as spring proceeded. Only at stations 1 and 2 was no regular trend observed throughout the period.

Among nutrients, dissolved inorganic nitrogen (DIN) ranged between 2.9 (st. 9, April 2) and 194.3 µM (st. 2, March 12), showing mean values of up to 130 µM in stations 3 and 4, close to the industrial area (Table I). High concentrations were found along the Malamocco-Marghera channel, moving with the tidal wave (Figs. 2, 3 and 4). Nitrates represented the prevalent oxidation form of nitrogen, with wide variations from 0.9 to 142.5 µM. The main nitrate fraction was very high at stations 3, 4, 5 and 6, near the industrial zone and the Naviglio del Brenta (Fig. 5A). In stations 3, 4 and 5, nitrate concentrations showed no significant depletion in time, probably because of frequent pollution, while a decreasing trend during the first sampling period was evident in the other stations. Ammonia concentrations were lower than those of nitrates, showing higher percentages only in stations 1 and 2, less influenced by industrial

Table I. – Averages and standard deviations for each parameter in the sampled stations during 1986 (n = number of observations).

	stations	1 (n = 15)		2 (n = 15)		3 (n = 15)		4 (n = 8)		5 (n = 15)	
parameters	*units*	avg	*sd*	avg	*sd*	avg	*sd*	avg	*sd*	avg	*sd*
Transparency	m	0.8	*0.2*	0.7	*0.3*	0.8	*0.2*	0.8	*0.2*	0.8	*0.2*
Temperature	°C	14.6	*6.8*	14.7	*6.3*	16.0	*6.1*	15.8	*6.2*	19.9	*5.0*
Salinity	PSU	26.4	*2.0*	26.5	2.2	30.1	*1.2*	29.7	*1.5*	27.7	*1.6*
pH		8.57	*0.29*	8.27	*0.24*	8.11	*0.11*	8.13	*0.12*	8.06	*0.10*
Dissolved Oxygen	cm^3 dm^{-3}	7.5	*2.0*	6.0	*2.3*	5.7	*1.2*	5.8	*1.4*	5.5	*1.3*
Oxygen Saturation	%	122.5	*29.6*	96.0	*30.7*	97.8	*12.6*	98.0	*15.7*	99.3	*17.1*
Diss. Inorg. Nitrogen	µM	31.2	*28.2*	62.9	*36.3*	133.2	*24.7*	136.6	*37.9*	94.5	*29.4*
Orthophosphate	µM	4.3	*4.1*	9.4	*5.2*	7.0	*2.5*	10.5	*6.8*	5.1	*1.4*
Orthosilicate	µM	23.3	*13.0*	23.2	*10.2*	16.3	*4.3*	17.9	*3.7*	19.9	*6.7*
N/P	molar	26.8	*45.7*	9.0	*9.0*	21.8	*10.0*	16.8	*9.9*	20.7	*11.2*
Chlorophyll a	µg dm^{-3}	5.3	*3.9*	20.7	*26.6*	8.9	*10.2*	7.7	*7.2*	4.8	*4.1*
Pheopigments	µg dm^{-3}	0.8	*1.1*	5.6	*6.4*	2.3	*2.3*	1.8	*1.6*	2.4	*2.1*
Total Phytoplankton	cells cm^{-3}	3459	*5799*	10017	*16328*	3236	*4464*	5094	*7746*	3491	*5265*

	stations	6 (n = 8)		7 (n = 8)		8 (n = 8)		9 (n = 8)		10 (n = 8)	
parameters	*units*	avg	*sd*	avg	*sd*	avg	*sd*	avg	*sd*	avg	*sd*
Transparency	m	0.8	*0.2*	0.8	*0.2*	0.6	*0.1*	0.7	*0.1*	0.8	*0.2*
Temperature	°C	17.1	*6.2*	15.7	*6.2*	15.6	*7.4*	14.6	*6.3*	14.0	*6.5*
Salinity	PSU	29.6	*1.8*	30.3	*1.5*	30.0	*1.1*	30.1	*1.0*	30.8	*1.0*
pH		8.14	*0.11*	8.20	*0.14*	8.26	*0.19*	8.38	*0.20*	8.34	*0.18*
Dissolved Oxygen	cm^3 dm^{-3}	5.8	*1.4*	6.1	*1.6*	7.1	*2.6*	8.1	*2.8*	7.4	*3.1*
Oxygen Saturation	%	100.4	*17.3*	104.1	*23.2*	118.2	*30.6*	133.7	*39.4*	119.1	*41.9*
Diss. Inorg. Nitrogen	µM	95.5	*33.3*	67.7	*31.3*	61.6	*32.8*	42.2	*25.7*	37.4	*22.3*
Orthophosphate	µM	6.1	2.2	4.6	*1.5*	5.4	*1.8*	4.6	*2.1*	3.7	*2.0*
Orthosilicate	µM	15.3	*5.4*	12.7	*5.3*	12.3	*5.6*	12.2	*5.5*	10.9	*4.6*
N/P	molar	17.6	*10.5*	16.3	*10.8*	13.7	*12.4*	11.8	*12.5*	13.9	*15.2*
Chlorophyll a	µg dm^{-3}	6.3	*4.5*	9.0	*8.2*	9.8	*11.5*	10.5	*11.3*	9.3	*87.8*
Pheopigments	µg dm^{-3}	1.9	*2.6*	2.8	*4.2*	3.7	*5.5*	2.2	*2.5*	2.0	*2.5*
Total Phytoplankton	cells cm^{-3}	4787	*7609*	5366	*9200*	5775	*9362*	7926	*13157*	5558	*8856*

nitrate wastes : averages were 12.2 and 26.9 µM (Fig. 5A, respectively 39 and 42 % of DIN), with a maximum in station 4 (average = 39.4 µM). Nitrites varied between 1 and 2 µM. Orthophosphate concentrations were high on average, ranging from 3.7 to 10.5 µM, with a trend increasing over the sampling period (Figs. 2, 3 and 4) and decreasing both from the inner industrial area and from the Naviglio del Brenta towards the discharge channels, as detected for DIN. The high P-PO$_4$ levels measured at station 2 (average = 9.4 µM) are to be ascribed to the urban waste dump of Mestre : in fact, the lowest mean N/P ratios were obtained here (average = 9), while at Tessera, the low P-PO$_4$ levels measured at the beginning of the sampling period led to N/P ratios of up to 160. In the other stations, this ratio showed means of 15-20 (Table I). Orthosilicates showed a regular pattern in almost all stations, indicating the weak relation of this nutrient to industrial waste (Figs. 2, 3 and 4) ; the highest values were found at stations 1, 2 and 5 (averages = 20-23 µM).

Phytoplankton biomass, numerical abundance and species composition

Chlorophyll *a* averages ranged between 5 (st. 5) and 21 µg dm^{-3} (st. 2), showing a bimodal time distribution, common to almost all stations, and indicating that phytoplankton growth occurred in two distinct periods : the first (end of March – beginning of April) took place over the entire area, with a peak of up to 50 µg dm^{-3} ; the second (during May) showed a very pronounced but local peak at S. Giuliano (about 100 µg dm^{-3}). Between these periods, the biomass decreased considerably. Chlorophyll horizontal distribution in the industrial area revealed higher concentrations in the Fusina New Channel, with a tendency to spread to the other areas as the season proceeded (Figs. 2, 3 and 4). Pheopigments were low during the first sampling period (values very close to 0 µg dm^{-3}), but increased with increasing biomass. Peaks were found at the end of the growth period, during which cell senescence took place.

Phytoplankton counting data showed a similar trend, with peaks respectively on April 2 (6.5 × 10^7 cells dm^{-3}) and May 22 (1.1 × 10^7 cells dm^{-3}), both off Mestre (st. 2 ; Fig. 6A).

Phytoplankton communities were mainly dominated by diatoms (86-94 % of the total ; Fig. 5B), with the exception of station 1, where phytoflagellates (cryptophyceans) were abundant ; however, phytoflagellates were found throughout the sampling period.

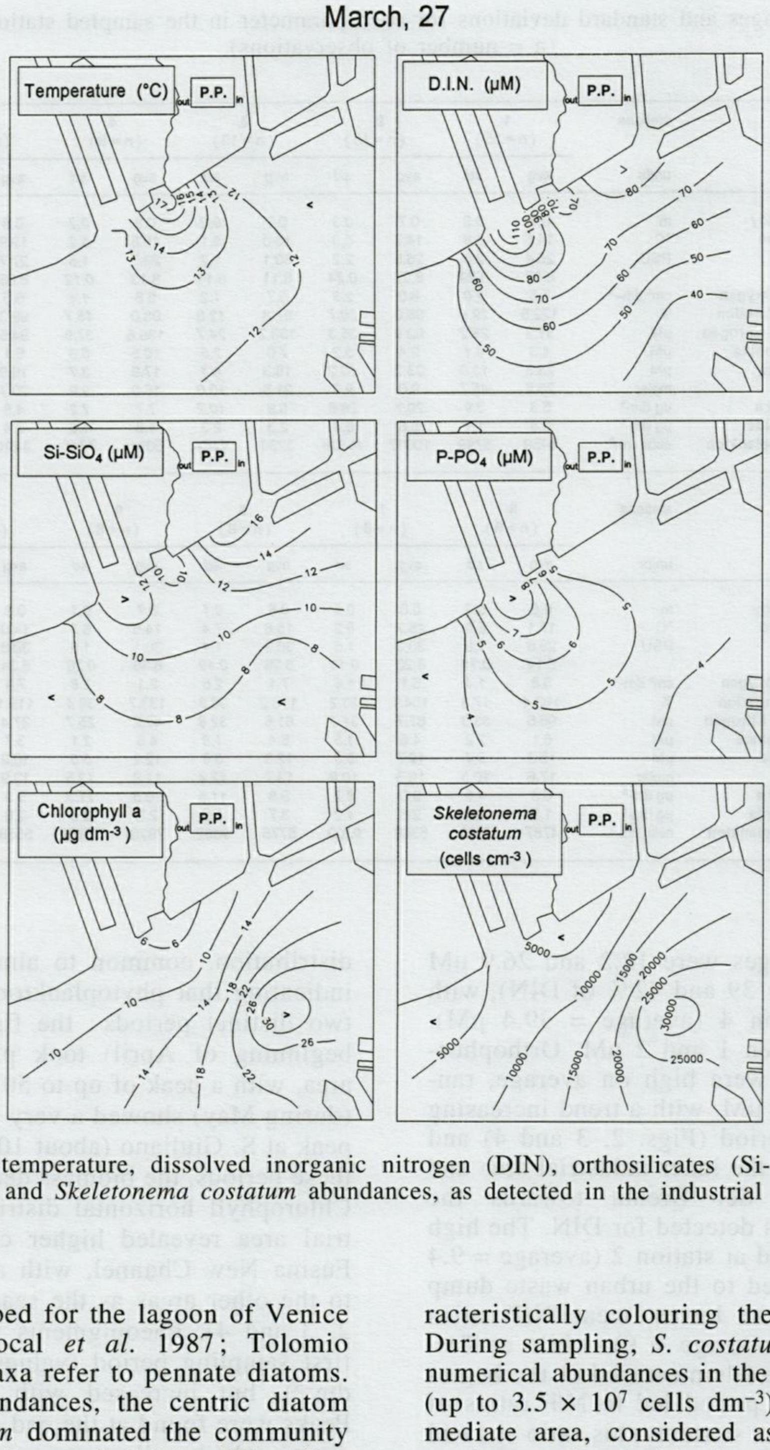

Fig. 3. – Isolines of temperature, dissolved inorganic nitrogen (DIN), orthosilicates (Si-SiO$_4$), orthophosphates (P-PO$_4$), chlorophyll *a* and *Skeletonema costatum* abundances, as detected in the industrial area, during the bloom situation (March 27).

As already described for the lagoon of Venice (Voltolina 1975 ; Socal *et al.* 1987 ; Tolomio 1993), most of the taxa refer to pennate diatoms. As regards cell abundances, the centric diatom *Skeletonema costatum* dominated the community for most of the sampling period (Fig. 5B). Afirst bloom peak (> 10^7 cells dm^{-3}) was recorded at the power plant outflow on March 18 (water temperature = 17.4 °C), about two weeks before the other stations (arrow in Fig. 6A) ; this growth lasted only a few days. In the surrounding area, the bloom started at the end of March and peaked on March 27 and April 2 (Fig. 6A). *S. costatum* reached peaks of 6 × 10^7 cells dm^{-3} (94 % of the total) at S. Giuliano, an area affected by human wastes (Fig. 6A). It spread over the whole central basin and the canals in the city of Venice, characteristically colouring the water dark brown. During sampling, *S. costatum* also reached high numerical abundances in the Fusina New Channel (up to 3.5 × 10^7 cells dm^{-3}), mainly in an intermediate area, considered as a sill between the northern and central basins, where hydrodynamics are very weak (Figs. 2, 3 and 4). Conversely, *S. costatum* was less abundant at station 1 (northern basin, Fig. 5B).

The apparent discrepancy between chlorophyll concentration and *S. costatum* abundances, as shown in Figs. 2 and 4, is due to the presence of other taxa in the community on February 27 and May 16.

The remaining phytocoenosis was regularly represented by benthic diatoms such as *Navicula cryptocephala, N. ramosissima, Amphora exigua* and *Nitzschia longissima*, most of them resuspen-

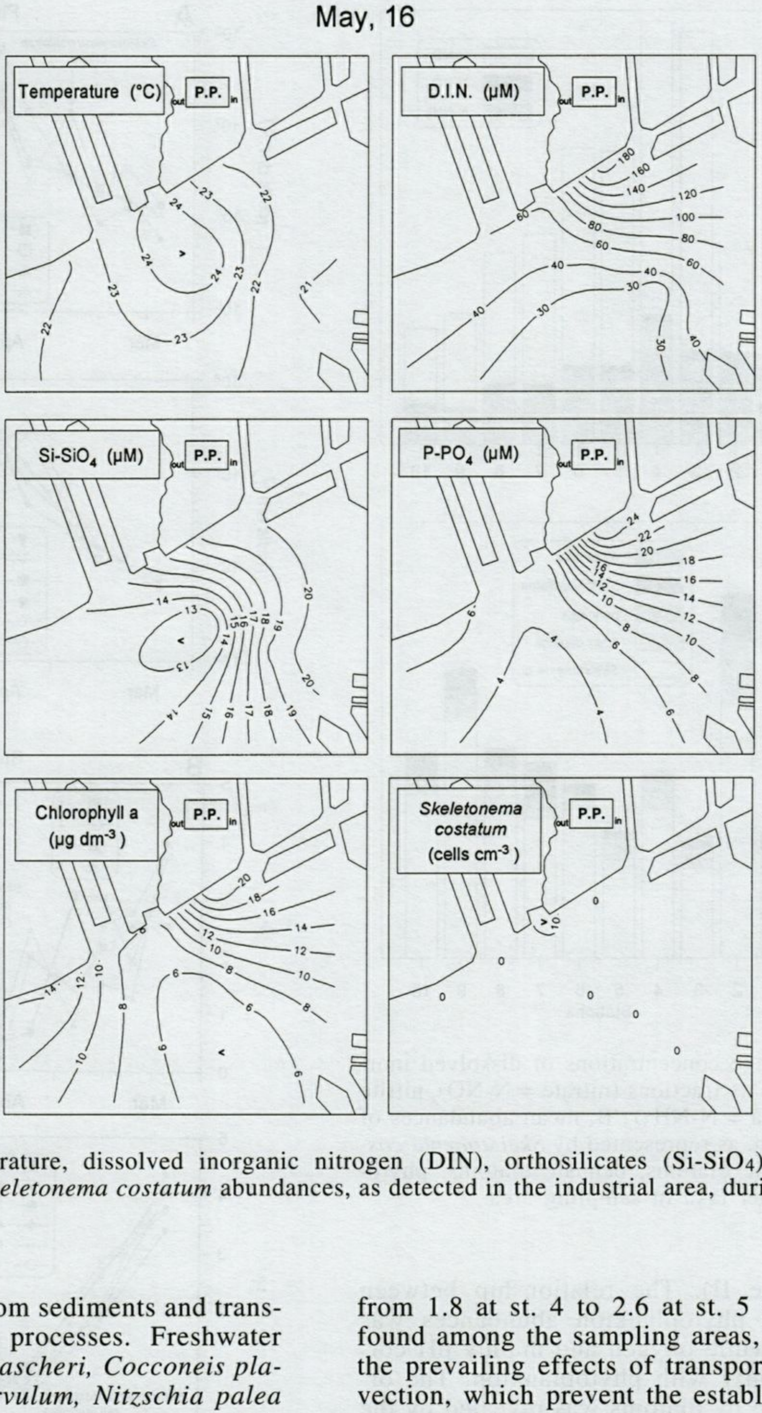

Fig. 4. – Isolines of temperature, dissolved inorganic nitrogen (DIN), orthosilicates (Si-SiO$_4$), orthophosphates (P-PO$_4$), chlorophyll *a* and *Skeletonema costatum* abundances, as detected in the industrial area, during the post-bloom situation (May 16).

ded in the water column from sediments and transported by hydrodynamic processes. Freshwater taxa such as *Eutreptiella pascheri, Cocconeis placentula, Gomphonema parvulum, Nitzschia palea* and Chlorophyceans were irregularly found, while neritic species (mainly *Pseudonitzschia delicatissima*) only occurred in stations influenced by coastal inputs (st. 6 and 7).

The diversity index showed an inverse trend when compared to phytoplankton biomass, due to the dominance of *S. costatum* on the phytoplankton community. Shannon values, close to 4 at the beginning of the sampling period (February 27), fell to less than 1 when *S. costatum* was at its peak (Fig. 6B). Some other very low values were observed coinciding with occasional phytoplankton peaks. Important differences (averages from 1.8 at st. 4 to 2.6 at st. 5 and 8) were not found among the sampling areas, probably due to the prevailing effects of transport and lateral advection, which prevent the establishment of local and autochthonous assemblages.

Statistical analyses

To follow the relationships between environmental and biological parameters, the data set concerned 15 variables (transparency, temperature, salinity, pH, dissolved oxygen, ammonia, nitrites, nitrates, orthosilicates, orthophosphates, chlorophyll *a*, pheopigments, diatom, phytoflagellate and total phytoplankton abundances), for a total of 108 samples, and a correlation matrix was

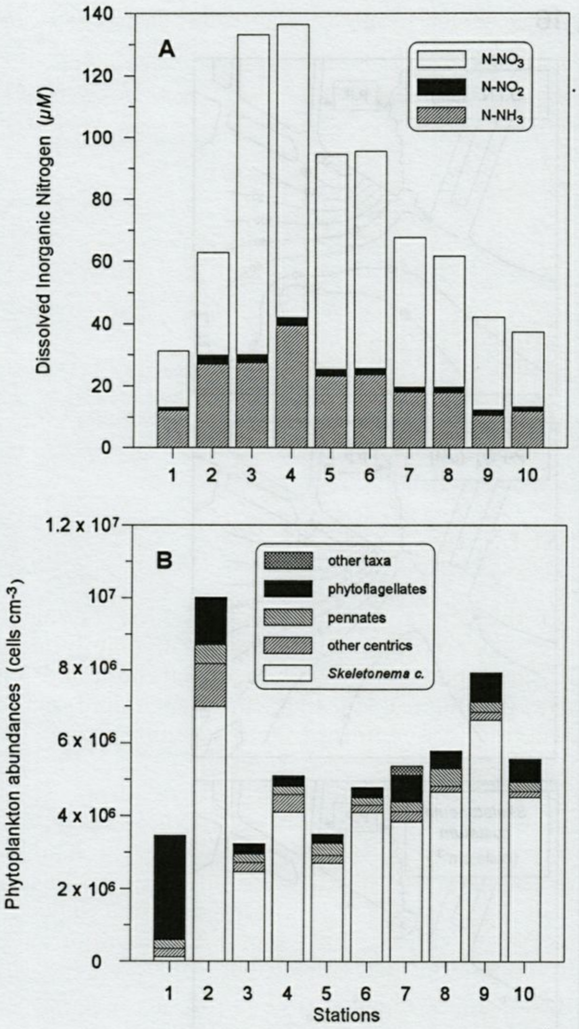

Fig. 5. – A, Average concentrations of dissolved inorganic nitrogen and its fractions (nitrate = N-NO_3, nitrite = N-NO_2, ammonia = N-NH_3); B, mean abundances of total phytoplankton, as represented by *Skeletonema costatum*, other centric diatoms, pennate diatoms, phytoflagellates and other taxa in sampling area.

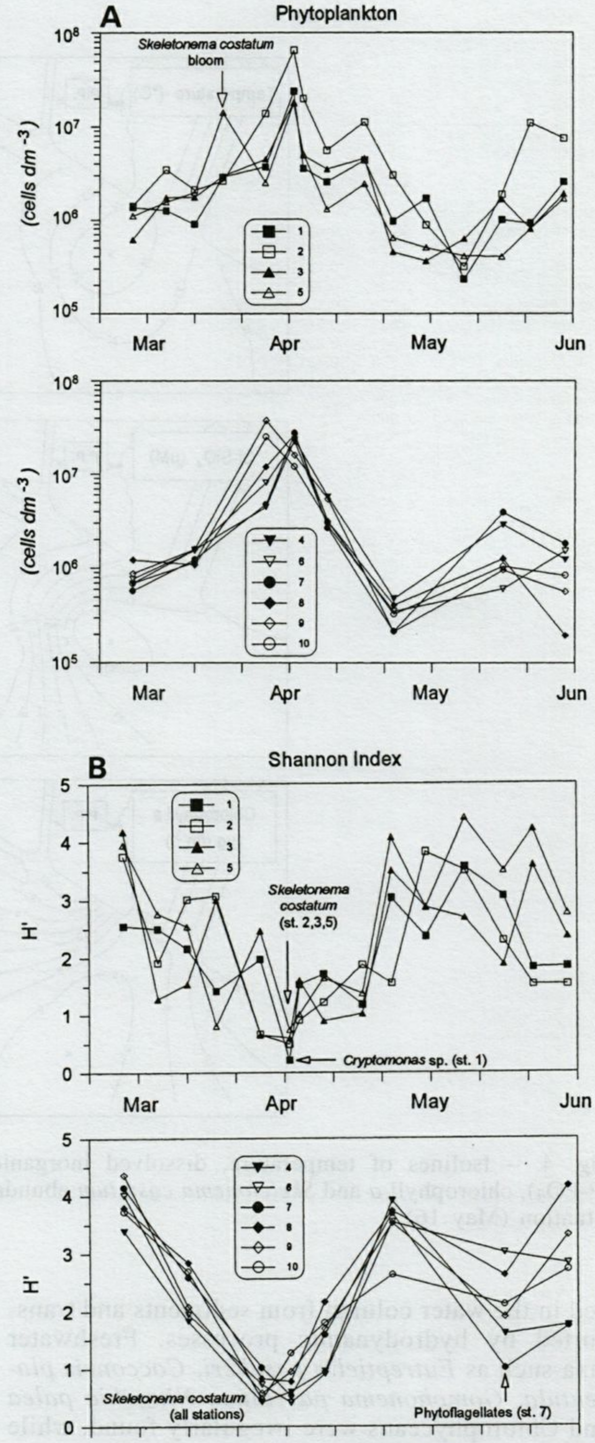

Fig. 6. – Time trends of total phytoplankton (A) and of diversity index (B) in sampling area. Dominant taxa are indicated at minima.

calculated (Table II). The relationship between temperature and phytoplankton abundances was not significant, while oxygen and mainly pH correlated significantly with phytoplankton. The orthosilicate uptake by diatoms was revealed by the negative correlation coefficient.

A multiple regression among phytoplankton abundance, as dependent variable, and temperature, salinity, ammonia, nitrites, nitrates, orthosilicates, orthophosphates, as independent ones, was calculated in order to highlight the main environmental features which influenced phytoplankton. R-squared adjusted was 0.22 (F-test = 5.35; $p < 0.05$); dissolved nutrients were the most influent variables. To avoid problems caused by highly collinear independent variables, a ridge-regression procedure was applied (Draper and Smith 1981). As theta increases slightly from zero, all the coefficients change rapidly, except that for orthosilicates. This suggests that the original least-squares estimates did not represent the true relationships between phytoplankton abundance

Table II. – Correlation matrix (degrees of freedom = 106). Bold numbers with °: significance at $p < 0.01$.

parameters	Tran.	Temp.	Sal.	pH	Oxyg.	-NH3	-NO2	-NO3	-SiO4	-PO4	Chl. a	Pheo.	Diato.	Phyto.	Total P.
Transparency	1														
Temperature	0.125	1													
Salinity	0.024	-0.120	1												
pH	0.018	-0.013	-0.184	1											
Dissolved Oxygen	-0.081	**-0.688** °	0.061	**0.448** °	1										
Ammonia	0.004	-0.033	-0.195	**-0.570** °	**-0.373** °	1									
Nitrites	-0.157	0.112	-0.183	**-0.659** °	**-0.347** °	**0.679** °	1								
Nitrates	-0.005	-0.236	0.137	**-0.604** °	-0.009	**0.534** °	**0.506** °	1							
Orthosilicate	0.029	0.151	**-0.497** °	-0.035	**-0.337** °	**0.459** °	0.240	-0.024	1						
Orthophosphate	-0.039	**0.517** °	-0.221	-0.131	**-0.529** °	**0.532** °	**0.519** °	0.053	**0.349** °	1					
Chlorophyll a	**-0.344** °	**0.270** °	-0.054	**0.384** °	0.003	-0.238	0.022	**-0.310** °	-0.242	**0.328** °	1				
Pheopigments	**-0.366** °	**0.431** °	0.024	0.217	-0.214	-0.208	0.063	**-0.247** °	-0.226	**0.358** °	**0.832** °	1			
Diatoms	**-0.323** °	-0.118	0.195	0.134	**0.253** °	-0.079	0.085	0.110	**-0.398** °	0.103	**0.623** °	**0.582** °	1		
Phytoflagellates	0.027	-0.145	-0.224	**0.558** °	**0.263** °	**-0.278** °	**-0.342** °	-0.403	-0.005	-0.048	**0.437** °	**0.266** °	0.190	1	
Total phytoplankton	**-0.269** °	-0.134	0.054	**0.395** °	**0.324** °	**-0.254** °	-0.138	-0.113	**-0.307** °	0.032	**0.723** °	**0.595** °	**0.852** °	**0.604** °	1

Table III. – Two-way Anova without replications. Comparisons: A, between station 3 (intake) and station 5 (discharge); B, among samples in the time (Sokal & Rohlf 1981).

parameters	**A** *F-test (df = 1)*	*p*	**B** *F-test (df = 14)*	*p*
Transparency	0.58	*ns*	17.2	*< 0.001*
Temperature	81.2	*< 0.001*	44.3	*< 0.001*
Salinity	24.8	*< 0.001*	1.2	*ns*
pH	12.4	*< 0.01*	14.7	*< 0.001*
Apparent Oxygen Utilization	0.8	*ns*	9.8	*< 0.001*
Ammonia	5.7	*< 0.05*	4.9	*< 0.01*
Nitrites	5.9	*< 0.05*	2.4	*ns*
Nitrates	28.5	*< 0.001*	2.5	*< 0.05*
Orthosilicate	6.7	*< 0.05*	3.4	*< 0.05*
Orthophosphate	17.8	*< 0.001*	4.3	*< 0.01*
Chlorophyll a	5.9	*< 0.05*	7.5	*< 0.001*
Pheopigments	0.4	*ns*	11.6	*< 0.001*
Total Phytoplankton	0.2	*ns*	9.3	*< 0.001*

and the individual variables. This leads us to confirm mainly an inverse relationship between phytoplankton and orthosilicates.

In order to highlight the possible influences of the cooling waters on both hydrochemical and biological variables, data related to intake (st. 3) and outflow (st. 5) were compared and submitted to a two-way ANOVA. Table III indicates that some hydrochemical variables, such as temperature, pH and nutrients, and chlorophyll were different both in time and between the two stations. Salinity showed significant differences between stations. At the end, phytoplankton abundance, transparency and dissolved oxygen (as Apparent Oxygen Utilization) varied only over the time.

As regards the two-way ANOVA applied to taxa abundances, a few pennate diatoms (undetermined pennates and *Navicula cryptocephala*) turned out to be more abundant at the outflow waters respect to the intake ones, while *S. costatum* showed differences in the time.

DISCUSSION

In the central lagoon of Venice, hydrodynamic processes are quite active and occur mainly along the deep channels (Malamocco-Marghera and Vittorio Emanuele), so that turbulence and lateral advection are forcing factors transporting and mixing dissolved and suspended matter. In addition, winds and storms can increase current speed and water-sediment exchange. Conversely, shallow areas, sometimes very close to the channels, are characterized by low hydrodynamics and high sedimentation rates: this particular heterogeneity greatly influences the geographic distribution of phytoplankton and macroalgae.

From the biological point of view, over the last ten years an increasing proliferation of macroalgae, mainly Ulvales, has been observed in shallow areas characterized by poor hydrodynamics (Sfriso *et al.* 1992). These benthic producers, which in some conditions reach biomass values of over 10 kg wet-weight m^{-2}, grow in competition with phytoplankton. Sfriso & Pavoni (1994) demonstrated that this competition is due to settling and resuspension, together with grazing pressure and not only to light and nutrients. At the end of spring, hypertrophic conditions are often observed, which lead to anoxic and reductive processes in sediments and water (Marcomini *et al.* 1995).

The narrow salinity range measured in spring 1986 confirms that the central lagoon has lost its original estuarine features (Avanzi *et al.* 1980). This means that the conservative behaviour of nutrients in this area is not detectable, partly due to unpredictable discharges of urban, agricultural and mainly industrial pollutants.

Several attempts have been made to calculate the general budgets of nutrient loads from industrial sources (Bellucco 1975, Perin 1975, Pavoni *et al.* 1992). The metabolism of macroalgae plays a fundamental role in these budgets: according to Marcomini *et al.* (1993), in 1987 the net biomass produced by macroalgae recycled respectively 136 % and 87 % of the nitrogen and phosphorus entering the central lagoon. For this reason, nutrient concentrations in the area are not very easy to predict, partly because they are subject to biological events. Studies have also been carried out on sediment-water exchange (e.g., Degobbis *et al.* 1986) : in pore water, nutrient variations are closely linked to macroalgal decay (mainly ammonia and orthophosphates ; Sfriso *et al.* in press, Sfriso & Marcomini 1994). Moreover, sediments represent a nutrient supply for the water column, mainly in cases of nutrient depletion by autotrophs.

During the first sampling period, favourable conditions for macroalgal growth were not present in the considered area, so that their influence on phytoplankton development was very low.

Mean nutrient concentrations during sampling were very high in stations close to the industrial zone, both as regards nitrogen and orthophosphates, which were diluted proceeding towards the two main diffusion channels (Malamocco-Marghera and Fusina New Channel). The inverse relationship between nutrients and distance from industrial plant has already been demonstrated (Bianchi *et al.* 1990, Sfriso *et al.* in press). In the northern basin, the source of nutrients is more influenced by agricultural activity : during 1986, the N/P ratios measured here were the highest and similar to previous values (Zingales *et al.* 1980, Bianchi *et al.* 1987a, 1987b). Moreover, this sampling area was the only one to show peculiar species composition, with a predominance of phytoflagellates (*Cryptomonas* sp, Fig. 7A).

As regards phytoplankton, a more extensive bloom was observed the following year (1987), showing a similar trend. In both years, *Skeletonema costatum* dominated the community at S. Giuliano (st. 2), with growth which peaked on 2 April (6-7 × 10^7 cells dm^{-3}, Alberighi *et al.* 1992). This extraordinary coincidence of abundances, dates and area in both samplings may provide clues to environmental conditions favourable to the growth of *S. costatum.*

In winter, the whole area is characterized by high nutrient concentrations and low algal growth. In spring, with the first sunny days, the temperature exceeds 10 °C giving rise to exponential growth of *S. costatum*, when small young cells (cell size = about 6 × 10 μm), attached in long colonies, duplicate very fast. Nutrients, mainly nitrates and silicates, are depleted with dramatic speed : at S. Giuliano, in the our case, nitrates and orthosilicates decreased respectively by about 100 and 5 times, in 33 days (Fig. 7B). When the temperature exceeds 15 °C, *S. costatum* abundances fall and senescent cells and chlorophyll degradation products appear. A scatterplot of *S. costatum* versus temperature was obtained using 1986 and 1987 data : a trend with maximum abun-

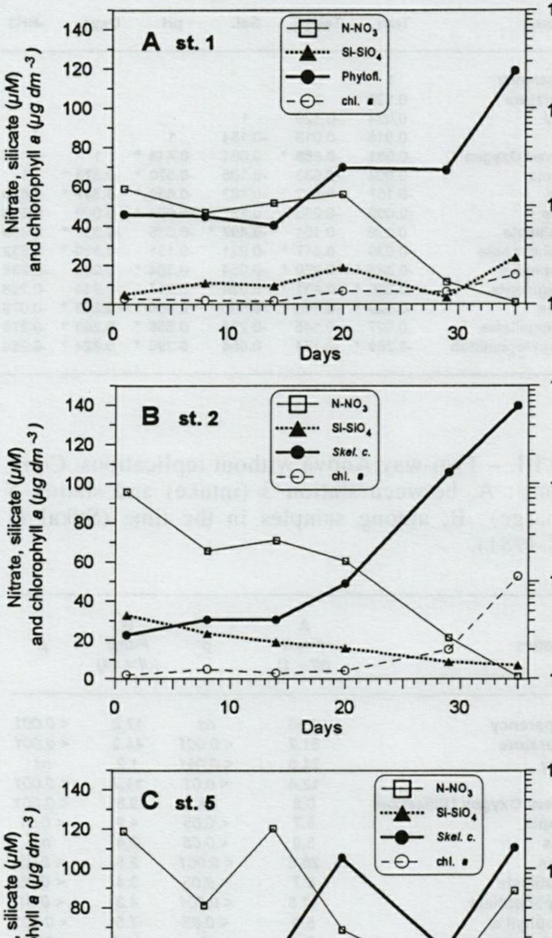

Fig. 7. – Time trends of nitrates, silicates, chlorophyll *a* and phytoflagellates during exponential growth at station 1 (A) ; nitrates, silicates, chlorophyll *a* and *Skeletonema costatum* at station 2 (B) and 5 (C). Scatterplot between *Skeletonema costatum* abundances and temperature (D) during 1986 and 1987 : best-fit curve is shown.

dances corresponding to optimal temperatures between 10 and 15 °C, together with the best interpolating curve, is shown in figure 7D. This temperature range clearly fits those described in the central and southern basins (Marchesoni 1954; Voltolina 1970, 1973; Socal *et al.* 1985, 1986).

Similar high abundances of *Skeletonema costatum* were observed in other estuarine systems (Blanc & Leveau 1970), where a significant inverse correlation between *S. costatum* and salinity was found. Conversely, our data didn't reveal a significant correlation, due to the narrow salinity range detected in the area.

In the post-bloom period, at the end of April 1986, mostly benthic pennate diatoms represented the community. In May, when the second growth peaked again in station 2, other centric diatoms dominated : of these, *Detonula* sp. reached abundances about one order of magnitude lower than the *S. costatum* peaks found in April. This contradiction (i.e., the last chlorophyll peak does not match the abundance peak) was only apparent, being due to the greater plasma volume (and consequent biomass) of *Detonula*.

In 1986 and 1987 the spatial variability of phytoplankton blooms showed that growth is favoured in areas of low hydrodynamics; water speed in the Malamocco-Marghera Channel is too high and micro- and macrolgae growth is disturbed by water currents.

The complex ecosystem of the central Venice lagoon is affected by the thermal output from the Fusina thermoelectric plant, which discharges 28 $m^3 sec^{-1}$ of water at a temperature 10 °C higher than that of the intake, water which then takes about 15 minutes to flow into the Malamocco-Marghera Channel. Significant and reproducible measurements of thermal perturbation were carried out by Nyffeler (1976) and Battaglia *et al.* (1983). Our temperature data indicate a mean increase of 3.8 Δt °C in 1986 and 5.1 Δt °C in 1987 between stations 3 and 5. Primary production experiments (Battaglia *et al.* 1983) showed a wide field of variability over the year (from 0.6 to 580 $mg\ C\ m^{-3}\ h^{-1}$). The above authors emphasize that no correlation between production and temperature was found, and conclude that thermal perturbation is too weak to cause significant changes in the ecosystem. Our results confirm this conclusion. Although statistical analyses demonstrated that thermal variations between st. 3 and 5 were significant, time trend of phytoplankton abundance seemed to be more important than spatial distribution. Correlation coefficient obtained between phytoplankton abundance and temperature was not significant, because the regression was not-linear (Fig. 7D).

Furthermore as Battaglia *et al.* (1983) found production minima in the industrial area and maxima in typically lagoonal waters, they concluded that the low primary production values measured in the "industrial stations" may be related to the presence of some compounds inhibiting phytoplankton metabolism, such as ammonia, high concentrations of which were detected in the area. In spring 1986, we measured ammonia concentrations of about 40 µM at the confluence of the Malamocco-Marghera and South Industrial Channels, and the lowest average chlorophyll and phytoplankton abundances were observed in both 1986 and 1987. These results may support our hypothesis (Bianchi *et al.* 1996), i.e. phytoplankton inhibition is due to the toxic effects of chemical compounds.

Attention must also be focused on local events, sometimes occurring suddenly. For example, during our samplings, although nitrates and phosphates were present at higher concentrations at the power plant intake and no significant differences were detected in phytoplankton biomass and abundance, a *Skeletonema costatum* log-phase occurred at the outflow station two weeks earlier than at the other stations (Fig. 6A, Fig. 7C); in this case, temperature played a more important role than nutrients, because in early spring Δt favoured the growth of *S. costatum* at the outflow water respect to the remaining part of the sampling area. However, this occurrence was transient, since the bloom was soon removed and scattered by tides.

A final consideration regards variations in hydrochemical parameters, depending partly on algal activity. It is a widespread opinion that dissolved oxygen as well as pH variations must be studied by following the day-night cycle with short-term samplings (Lara Lara *et al.* 1980, Bianchi *et al.* in press); this was done in our area during previous samplings (Battaglia *et al.* 1983) and after the present study (Alberighi *et al.* 1988, Bianchi *et al.* 1996). The close relationship between these environmental variables and phytoplankton communities was confirmed by our 1986 and 1987 data, demonstrating the validity of mid-term samplings too in order to follow the trend of hydrochemical variables.

CONCLUSIONS

Our results show that no permanent modifications in phytoplankton communities are caused by the thermal plume from the power plant of Fusina. Here, some local and transient blooms were observed, but tidal advection prevented the establishment of any "altered" autochthonous community.

Temperature effects on phytoplankton seasonal cycle were evidenced in the studied basin. Therefore, the thermal perturbation was somehow masked by hydrodynamic and chemical events, such as tidal advection and input of pollutants from industry. Thus, these factors, together with seasonality, dominate the environmental conditions which control the phytoplankton life-cycle in the central basin of the lagoon of Venice.

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