Spatial and Temporal Distribution of Phytoplankton in a Mediterranean Estuarine Canal System†

M. Puigserver, G. Ramon and G. Moyà

Dept. Biologia (Ecologia)
Universitat Illes Balears
Ctra. Valldemossa km 7.5
E-07071 Palma (Mallorca) Spain
e-mail: dbamps4@clust.uib.es

ABSTRACT

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Phytoplankton composition and distribution in a Mediterranean coastal drainage canal is discussed. The study includes the end portion of the Albufera of Majorca Gran Canal and it was studied from December 1992 to November 1994. Physical and chemical gradients are affected by fresh and marine water fluxes, which are responsible for phytoplankton heterogeneity. There is a gradual reduction in phytoplankton abundance (chlorophyll *a* and cells) from the inland sites to the outer (marine) ones. The phytoplankton is dominated by small-sized forms, mostly under 5 μm. Along with the high cell abundance, this indicates the eutrophic character of this system. The studied system shows the two phytoplankton dynamic models described for temperate estuaries. The innermost part of the canal shows two bloom periods throughout the annual cycle, one in the spring and the other in the autumn, both associated with water input from the Albufera. Nearest the sea, the phytoplankton dynamics, characterised by summer bloom, is tied up with mineralization processes of the organic matter and mainly with phosphorus recycling from the sediment. The filter role of these coastal wetlands is also confirmed.

ADDITIONAL INDEX WORDS: *Dynamics, biomass, nutrients, eutrophy, wetland, management, Western Mediterranean Sea.*

INTRODUCTION

Coastal wetlands are disappearing as a consequence of human activities. Their importance has been proven on numerous occasions and they have thus been studied to enable their protection and preservation (VÉLEZ, 1979; ALLEN and PYE, 1992). The Mediterranean wetlands are particularly interesting because they are subject to highly fluctuating seasonal climatic conditions, which influence their dynamics (CARRADA et al., 1983).

The Albufera of Majorca is a coastal marsh in the NE of Majorca island. With a surface of near 24 km² is separated from the sea by a sandbank 8 km long and 300 to 500 m wide. The Albufera has been severely affected by human activities since the second half of the nineteenth century (BARCELÓ and MAYOL, 1980). This has resulted in an artificial system. Waters are quickly led to the sea by means of an extensive net of drainage canals and all the lagoons have been in some way modified (MARTÍNEZ-TABERNER et al., 1990). In 1988, 1708 ha were declared a Natural Park (SECONA, 1990).

The general limnological characteristics of the Albufera have been published in various studies (MARTÍNEZ-TABERNER et al., 1990 and 1991; MARTÍNEZ-TABERNER and MAYOL,

1995; among others). Water replenishment in the Albufera occurs during torrential inputs as well as to semicontinuous intakes from springs, to infiltrations from wastewater and seawater (MARTÍNEZ-TABERNER et al., 1991). The Gran Canal constitutes the main drainage outlet into the sea (Figure 1). The Gran Canal is thus comparable to an estuary with a salt wedge regime as described by IBAÑEZ et al. (1997). Limitations are imposed by its small size, by being subject to a torrential and stationary regime of water inputs, by the low incidence of tides and by the regulation imposed by the park management. There is a dual circulation of waters of different characteristics: fresh waters on top and seawater below (MARTÍNEZ-TABERNER et al., 1995b).

The interaction zone between the Albufera and the Alcudia Bay has been studied from December 1992 to November 1994. Nutrient dynamics between the water column and the sediment and its effect on phytoplankton primary production and composition were the main study subjects (SINTES, 1993; MOYÀ et al., 1995; PUIGSERVER, 1996).

This contribution identifies the components of the phytoplankton community in the Albufera of Majorca Gran Canal and characterises its dynamics along an annual cycle. Differences along the inland-sea interaction axis are also shown.

MATERIALS AND METHODS

Mallorca's Albufera is affected by a typically Mediterranean climate. GUIJARRO and JANSÀ (1980) report an annual
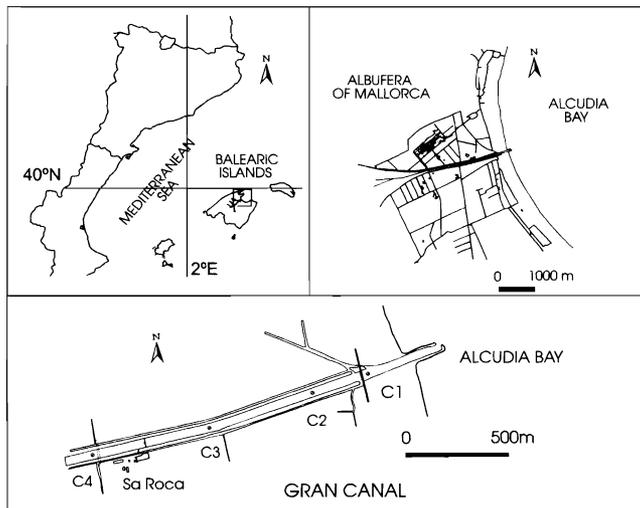
Figure 1. Study area showing sampling sites.

rainfall of 600 to 650 mm, 43 % of which occurs in autumn, 28–30 % in winter, 20–21 % in spring and 7–8 % in summer. During our monitoring period, annual rainfalls from 426 to 534 mm, mean seasonal temperatures from 9.3 to 24 °C and sunshine averages from 100 to 356 hours per month were reported (CENTRO METEOROLÓGICO TERRITORIAL DE BALEARES, 1992–1994).

The study area is the middle-to-lower portion of the Gran Canal (Figure 1), approximately 1400 m long and 50 m wide. It is artificially regulated by means of sluices at Sa Roca and at the junctions with adjacent canals. The park management sustains a gentle and continuous runoff through the year. Only in heavy rainfall periods water overflows and increases for short times the runoff flux.

Four sampling sites were selected (Figure 1). C4 is in the middle portion upstream from the sluice and it was selected as a reference point of conditions in the inner Albufera. The other three sites are at the end of the canal, downstream from the sluice. C2 and C3 are ahead of the junction of two adjacent canals, while C1 is found after this junction.

Sampling was carried out on a near monthly frequency from December 1992 to June 1994. A last sample was taken in November 1994 to seek possible changes in the phytoplankton community caused by a massive *plena* (local term applied to a rise in water level due to torrential rains which caused flooding) which took place in the Albufera.

Water level in C4 was about 20 cm, it was higher only in heavy rainfall periods, and a bridge enables access to the centre of the canal bed. Samples here were taken directly just below the surface. The remaining sites were sampled taken from a rubber dinghy in order to reach the centre of the canal and with a peristaltic pump, which enabled precise sampling at different depths. Two samples were taken per site, one just below the surface and the other near the bottom (about 1 m).

Salinity and temperature were measuring using a Microprocessor Conductivity meter WTW LF196. Oxygen concen-

tration using a Microprocessor Oxymeter WTW OXI196. Light intensity using a Phywe Luxometer. *In situ* pH was measuring using a WTW 196T pH-meter. Alkalinity was determined following GOLTERMAN *et al.* (1978) and STRICKLAND and PARSONS (1972). Nitrates, nitrites, silicates and phosphates were determined with a Technicon Autoanalyzer II following GRASSHOF (1969) for the first three and TREGUER and LE CORRE (1975) for the last. Ammonium (NH_4^+) was not measured in the present study. Pigment concentration was determined by filtration through Whatman GF/C, extraction in 90% acetone and measurement of absorbance with a Hitachi 2000 spectrophotometer. Chlorophyll *a* (Chl *a*) concentration was calculated after JEFFREY and HUMPHREY (1975).

Phytoplankton was studied from water samples fixed and stained with Lugol and shut airtight in 125 ml glass bottles (SCHWOERBEL, 1975). Sedimentation was in 10 or 25 ml columns, depending on the plankton concentration. Samples were observed with an inverted microscope OLYMPUS IM and following the classical methodology (UTERMÖHL, 1931; LUND *et al.*, 1958; MARGALEF, 1974).

The smallest algae were counted under 400 × and the larger ones under 100 or 200 ×. For some of the larger forms, the entire surface was scanned. For the remaining ones, an area was scanned which enabled counting between 100 and 400 specimens of the most abundant species in each sample (ALVEAL *et al.*, 1995). As remarked in other papers (ESTRADA and SALAT, 1989), in this type of study, generic or specific determinations are often impossible and they must thus remain less accurate. For instance, we have included as ultraplankton the flagellates smaller than 5 μm.

RESULTS

Physico Chemical Parameters, Chlorophyll *a* and Phytoplankton Cell Abundance

Water temperature patterns followed yearly solar cycles with winter minima, 8.4 °C, and summer maxima, 31.7 °C (Figure 2). A weak temperature increase at the water surface was observed in the direction Albufera-Alcudia Bay during the winter, which was inverted in the summer. These gradients are because water temperature in the inner Albufera is more affected by solar radiation, mainly due to the water being shallower. In the intervening seasons water temperature showed a higher horizontal uniformity. Water temperature in the deeper samples was not significantly different.

Light intensity was measured at C3, C2 and C1. At surface levels it also followed yearly solar cycles with winter minima, 8000 lux, and summer maxima, 120000 lux. Light intensity in bottom levels always surpassed 13 % of surface light intensity. Values went from 2000 to 62000 lux in winter and summer respectively. Light extinction coefficient (K) varied between 0.31 m^{-1} and 3.89 m^{-1} both measured at C1. K average from the different sites were 1.41 m^{-1} at C3, 1.16 m^{-1} at C2 and 1.49 m^{-1} at C1.

Two salinity gradients were detected in the studied area, one horizontal and the other vertical (Figure 3). These had been previously observed by MARTÍNEZ-TABERNER *et al.* (1995b). Salinity increases in an outward direction towards

SURFACE TEMPERATURE (°C)

BOTTOM TEMPERATURE (°C)
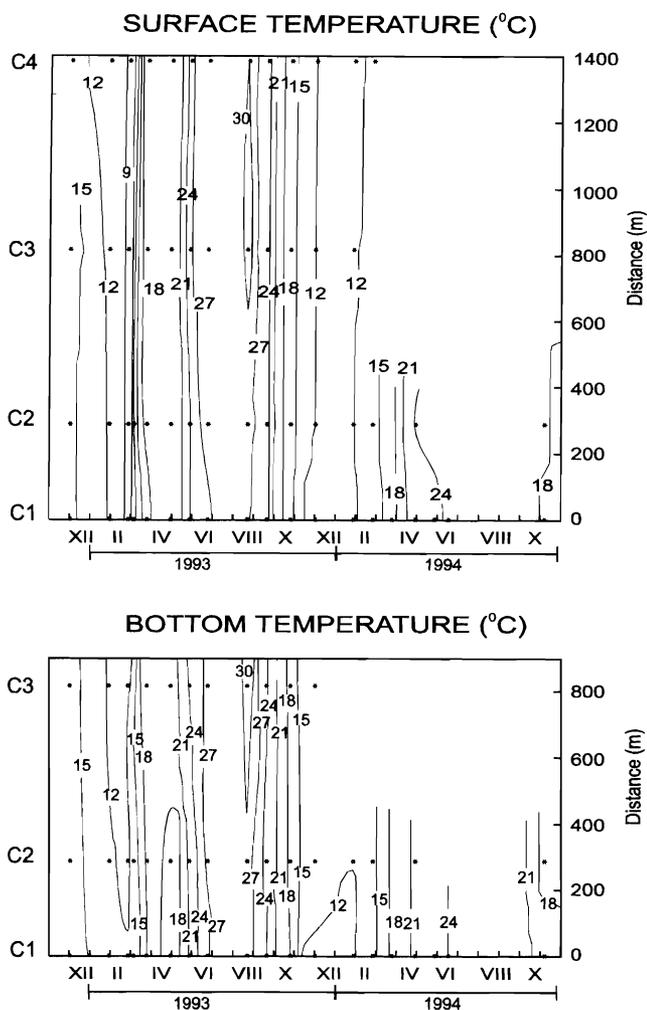
Figure 2. Horizontal change of temperature (°C).

SURFACE SALINITY (g kg⁻¹)

BOTTOM SALINITY (g kg⁻¹)
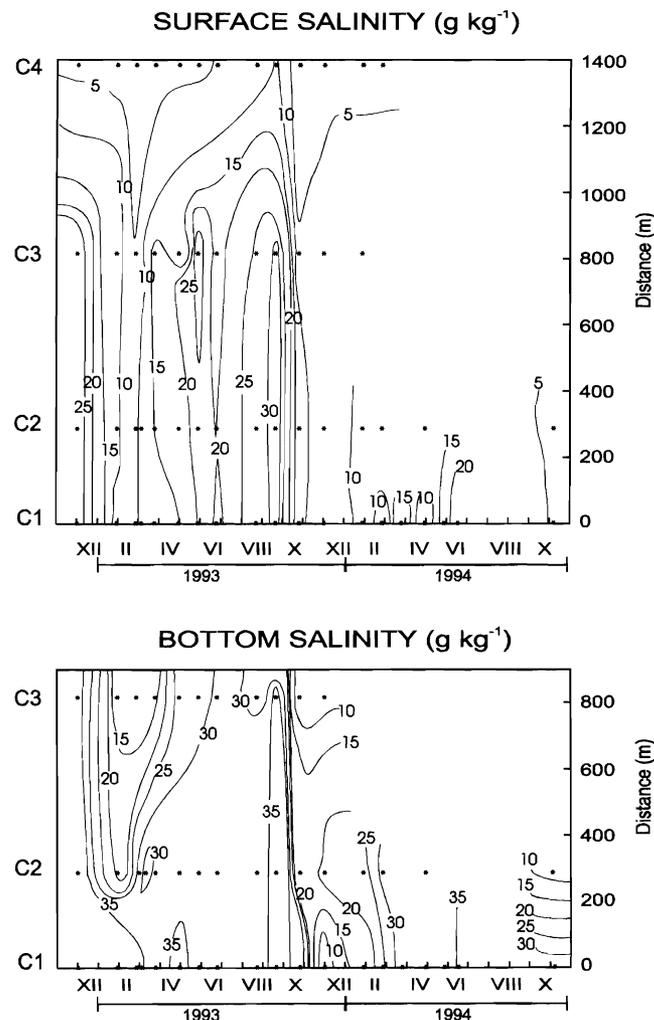
Figure 3. Horizontal change of salinity (g kg⁻¹).

the bay and in bottom samples. At C4 salinity remained at a more or less constant 5 g kg⁻¹ throughout the yearly cycle. These low values reflect the inland character of the waters in the inner Albufera. At C3, C2 and C1 salinity varied between 6 g kg⁻¹ and 37 g kg⁻¹, reflecting different degrees of fresh and marine waters influence. A greater influence from fresh waters was observed between February and April 1993. Surface waters were low in salinity (between 7 and 16 g kg⁻¹). At the end of spring and during summer surface salinity increased gradually (up to 33 g kg⁻¹), caused by the mixture with bottom water of higher salinity coming in from the sea. During the following autumn and winter salinity reverted to values similar to those of winter 1993 (up to 6 g kg⁻¹). In November 1994 very low salinities were present in C2 (2 and 10 g kg⁻¹ at the surface and the bottom respectively) and at the surface of C1 (4 g kg⁻¹). The latter is the result of the unusual heavy rainfall in the previous month (277 mm), which was almost eight times higher than the mean monthly

rainfall during the rest of our study (CENTRO METEOROLÓGICO TERRITORIAL DE BALEARES, 1992–1994).

A gradient of alkalinity has been recorded in the opposite direction of salinity. Higher values in surface than in bottom samples, and higher in the inner part than in the outer part of the canal were detected. Values ranged from 2.69 to 5.92 meq l⁻¹.

The highest nitrate values (1164 μM) were found at C4 (Figure 4). Values were smaller along the canal although at C1 they again increased at the surface (up to 585 μM). Concentrations were generally higher at the surface, with winter maxima and summer minima. DIN is mainly found as nitrates. Nitrite concentrations are not shown here due to their low values, which were a result of rapid mobilisation. Although ammonium (NH_4^+) was not measured in the present study; the low ammonium values measured in the interstitial waters on the upper part of the sediments at the same sites (LÓPEZ, pers. comm.) suggests that its concentration in the water column cannot be high.
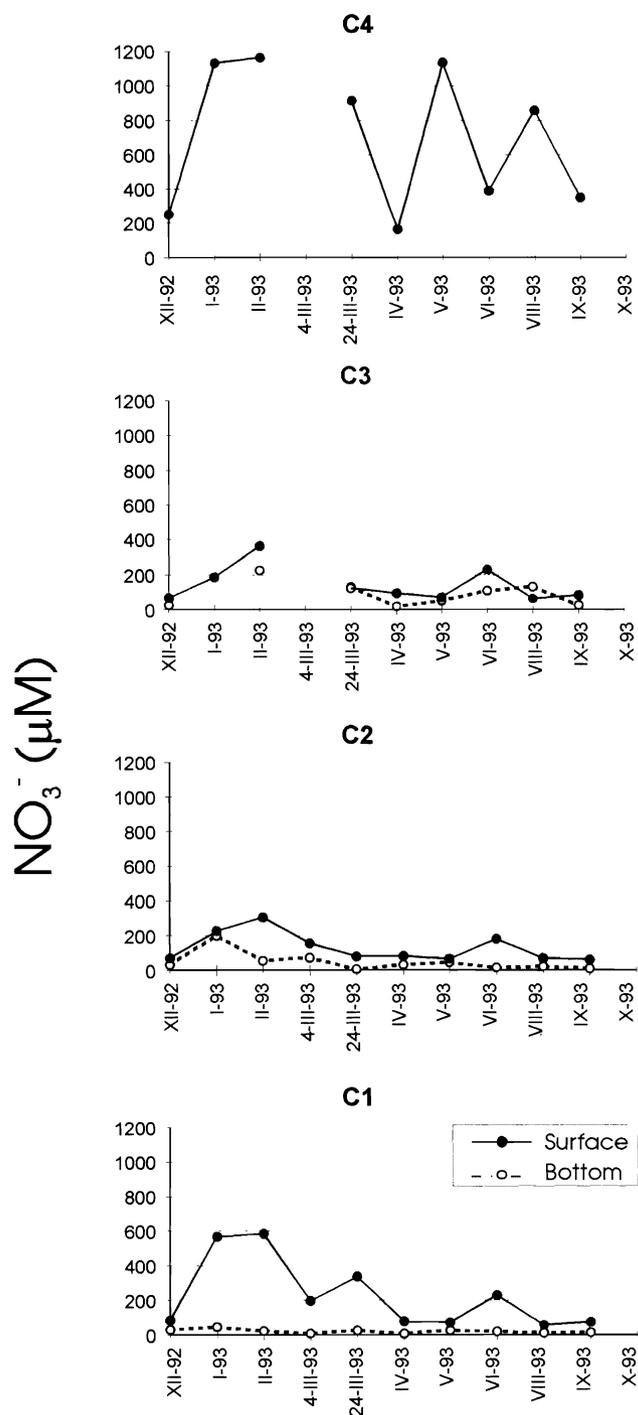
Figure 4. Changes in nitrate (μM).
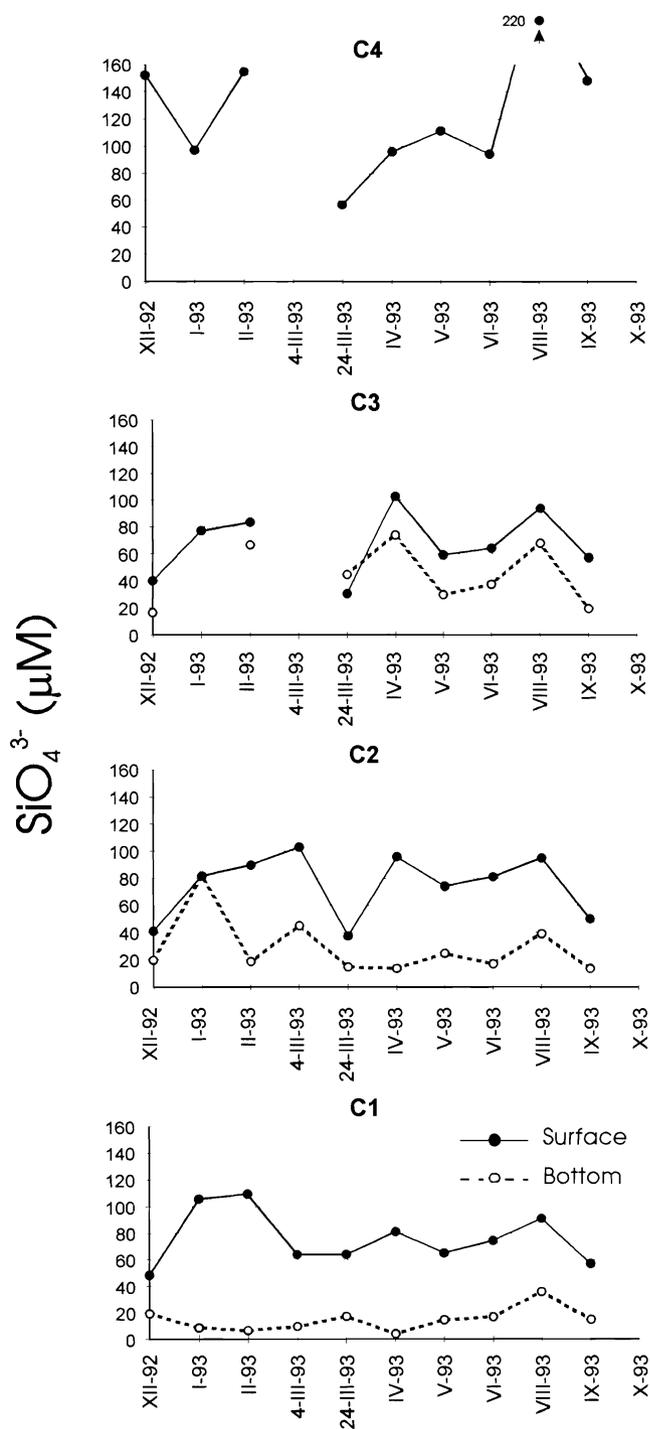
Figure 5. Changes in silicate (μM).

Silicate concentration patterns (Figure 5) followed those of nitrates, values dropping from C4 to C1 (from 220 to 4 μM). Concentrations were higher at the surface than at the bottom, differences within the water column being greater towards the sea.

Low phosphate concentrations were detected throughout the canal (Figure 6), though with abrupt increases (such as the 0.37 μM at C3 and C1 in February of 1993). Values were higher in the bottom samples of the outer part of the canal, although they were quite irregular. Concentrations were min-
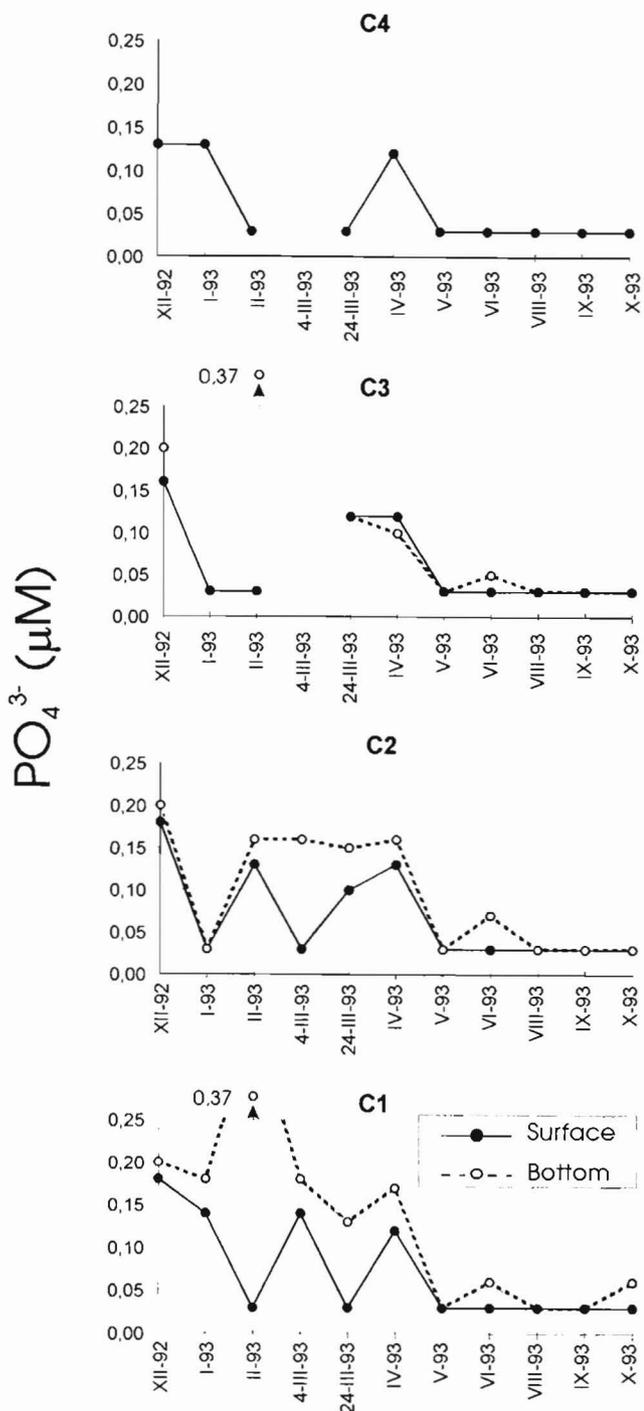
Figure 6.   Changes in phosphate (μM).

imal from May to October of 1993 (between 0.03 and 0.07 μM).

Chlorophyll a (Chl a) concentration varied from 0.6 to 29 mg m^{-3}, the values dropping from C4 to C1 (Figure 7). Concentrations increased at C4 during two periods, i.e. from the end of winter to the onset of spring (between 12.3 and 8.6 mg
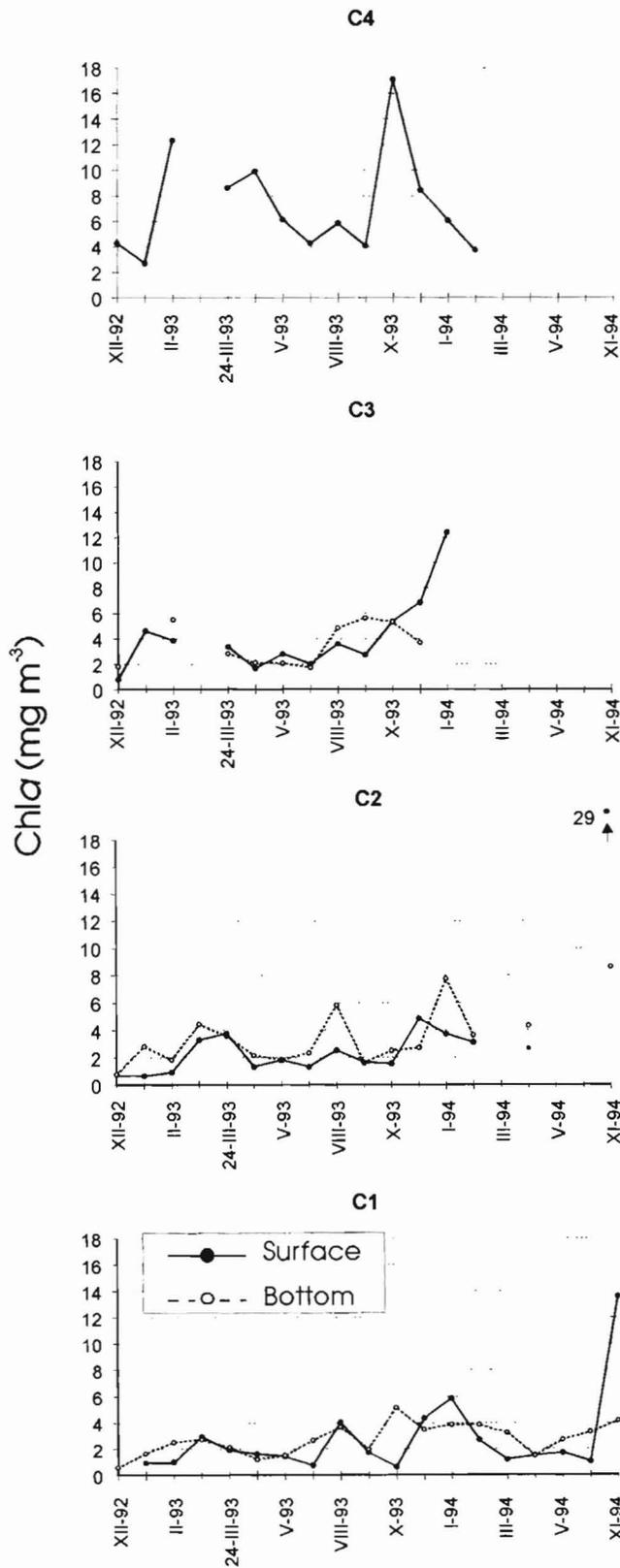
Figure 7.   Change in time of chlorophyll a concentration (mg m^{-3}).

Figure 9. Position of physico, chemical and biological parameters in the space defined by Principal Components I and II.

Figure 8. Change in time of phytoplankton abundance (cells ml⁻¹).

m^{-3}) and in the autumn (17.1 mg m⁻³). Chl *a* concentration at the other sites was less regular through the study and a yearly cycle cannot be readily observed. Concentrations were generally higher throughout the column in winter and early spring, and in the bottom waters in summer and early autumn. At C2 and C1 very high concentrations were detected in November 1994 (up to 29 mg m⁻³) mainly at the surface.

Total phytoplankton cell abundance was very high during the entire period of study, ranging from 64137 cells ml⁻¹ in April 93 at C4 to 1103 cells ml⁻¹ in February 93 in the surface sample of C2. Its most important changes are related to seasonal variability. With regard to total cell numbers, the Gran Canal phytoplankton community is characterised by a dual spatial heterogeneity, horizontal and vertical (Figure 8). Cell concentration decreased going seaward along the canal. Vertical heterogeneity is less pronounced and higher cell concentrations were in deeper layers. At certain instances Chl *a* and cell concentrations showed a similar evolution, although this has not been the general case.

The dynamics of the phytoplankton community shows two relatively differentiated types of behaviour. At C4 the phytoplankton abundance has shown two blooms, taking place in spring and in autumn (Figure 8). At C3 one observes also a spring bloom and another in the autumn, although of lower magnitude than at C4, the autumn one somewhat earlier. At C2 and C1 the phytoplankton dynamic follows a different model. Here, during 1993 there is a small spring bloom but the maximum cell concentration occurs in the summer, values being higher in the deeper layers. At C2 cell concentration in the deeper layers increased greatly in January of 1994, coincident with a retention of water of higher salinity (Figure 3). From March of 1994 to the completion of the study the available samples are reduced at C2 and C1. During 1994, C1 showed the same annual cycle with a slight spring bloom and a peak in summer. At C2 and C1 very high cell concentrations were detected in November of 1994, these being higher at C2 than at C1 and higher at surface than at deeper layers.

A Principal Components Analysis (PCA) was carried out in order to obtain an integrated view of hydrological and biological traits and their relationships (Figure 9). Component I (39.8 % of the variance) is highly determined by the salinity
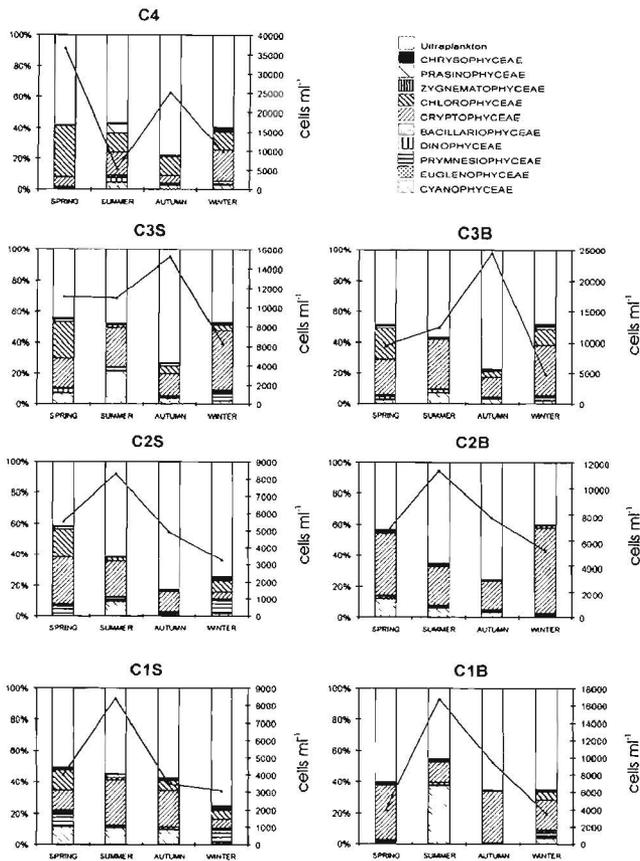
Figure 10. Mean phytoplankton abundance (cells ml⁻¹) for each season (based on samples taken from December 1992 to February 1994) and contribution of phytoplankton by groups. (S: surface; B: bottom)

and it seems to be related with the inland-marine waters interaction. Waters from the inner part of the Albufera are rich in nitrogen compounds caused by rural inputs in the upper areas. Component II (22.7 % of the variance) is highly determined by temperature and it seems to be related with production. It segregates phytoplankton (Chl a and cell abundance) from the macronutrients, showing the effect of phytoplankton growth on nutrient depletion in the canal. The position of the other parameters used in the PCA, such as alkalinity, pH or oxygen, agree with the above and show their relation with phytoplankton biomass.

Phytoplankton Composition and Annual Cycle

Phytoplankton cell concentration from December 1992 to February 1994 have been analysed for the different seasons. Samples from December to February, March to May, June to August and September to November represent winter, spring, summer and autumn samples respectively. Figure 10 shows mean cell abundances for each site and season, the contribution of the different phytoplankton groups to total cell abundance are also shown.

Phytoplankton in the Gran Canal may be classified into two large groups of forms, *i.e.* algae smaller than 5 μm (ul-

traplankton) and algae of 5 μm or larger. The high proportion of ultraplankton, which reached 40 to 83% of total cell counts, is notable as it was the dominant group throughout most of the study.

Among those forms larger than 5 μm, the most abundant were the filamentous Cyanophyceae, Chlorophyceae and Cryptophyceae. The most abundant species and genera observed over the entire studied area were *Oscillatoria, Monoraphidium minutum* (Nägeli) Komárková-Legnerová, *Cryptomonas* and *Rhodomonas lacustris* Skuja.

The Bacillariophyceae contained the highest number of taxa, although cell concentrations were low. Many forms were typical of a benthic community, such as *Achnantes minutissima* Kützing, *Licmophora* sp., *Cocconeis* sp., *Navicula* spp., *Pleurosigma normanii* Ralfs and *Rhoicosphenia curvata* (Kützing) Grunow. This is a common case in shallow Mediterranean coastal systems (COMÍN, 1984; DELGADO, 1987; MARTÍN, 1995). The most abundant Bacillariophyceae were *Cyclotella meneghiniana* Kützing, *A. minutissima, Navicula* spp., *Nitzschia acicularis* Smith, *Nitzschia closterium* (Ehrenberg) Smith and *Nitzschia* spp.

The Dinophyceae, although low in abundance, came second in number of forms identified, with genera such as *Gymnodinium, Gyrodinium, Peridinium* and *Prorocentrum*.

One finds in the Gran Canal typically marine forms such as *Ceratium furca* (Ehrenberg) Claparde and Lachmann, *Oxyrrhis marina* Dujardin, *Chaetoceros* and *P. normanii,* mixed with freshwater forms such as *Synedra ulna* (Nitzsch) Ehrenberg, *Scenedesmus, Chlamydomonas* and *Spyrogira*. This is also an usual trait in fresh-marine waters interaction areas (COMÍN, 1984; DELGADO, 1987; MARTÍN, 1995; among others).

We will now describe the main characteristics of the phytoplankton community in the Gran Canal at different sites and seasons (Figure 10). The November 1994 sample is presented separately.

Spring:

The spring phytoplankton showed a gradually reduced cell abundance from C4 to C1. At C4 the phytoplankton mainly contained ultraplankton and the Chlorophyceae *M. minutum*. At C3 the community was represented by ultraplankton, *M. minutum* and the Cryptophyceae *R. lacustris* var. *nannoplanctica* (Skuja) Javornicky. At the two sites closest to the sea, C2 and C1, there was a clear reduction of Chlorophyceae in general and of *M. minutum* in particular as we approached the sea. In the surface samples at C2 and C1 *Oscillatoria* sp., *Cryptomonas* sp., *R. lacustris* var. *nannoplanctica* and *Pleurochrysis pseudoroscoffensis* Gayral and Fresnel were abundant. The presence of Chlorophyceae was very low in the bottom samples, where the most abundant forms, second to the ultraplankton, were various *Oscillatoria, Cryptomonas* and *R. lacustris* var. *nannoplanctica*.

Summer:

A great reduction in cell concentration was detected at C4, resulting in the lowest mean for the year, and clearly reducing the proportion of Chlorophyceae with respect to the

spring. An increase in cell concentration is observed at C3, C2 and C1, and it is higher in the bottom samples and near the sea. The diminishing gradient observed towards the outlet into the Bay in the spring is thus cancelled. At these sites the ultraplankton, the Cyanophyceae (especially *Oscillatoria* sp.) and the Cryptophyceae (mainly *R. lacustris* var. *nannoplanctica*) were the most abundant forms; especially in the bottom samples at C1 where *Oscillatoria* sp. became dominant.

Autumn:

An increase in phytoplankton cell concentration is observed at C4 and C3. The abundance of Chlorophyceae, mainly *M. minutum* and *Chlamydomonas* spp. at C4, C3 and at the surface of C1 again increased, although at C4 they maintained their proportion on the whole community. At this time, the Cyanophyceae (especially *Oscillatoria* sp.) and the Cryptophyceae (mainly *Cryptomonas, Hemiselmis* sp. and *R. lacustris* var. *nannoplanctica*), were abundant groups throughout the canal.

Winter:

There is a clear reduction in cell concentration at all the sampling sites, attaining the lowest mean values for the year except for C4 which, as already pointed out, had its minimum in the summer. The community was chiefly made up of ultraplankton. The proportion of Cryptophyceae increased, with abundant *Cryptomonas* species at the inner sites, C4 and C3, and at the bottom samples of the outer sites, C2 and C1. At C4 and in the bottom samples at C3 there was a high proportion of Chlorophyceae, mainly *M. minutum*. At C3, C2 and C1 *P. pseudoroscoffensis* made up an important proportion of the phytoplankton. This species showed a very heterogeneous distribution throughout the yearly cycle and along the canal (PUIGSERVER *et al.*, 2000a). It was mainly detected in winter at the outer sites and with much higher concentrations at the surface than at the bottom samples.

November 1994:

The November 1994 sample represents an outstanding case in the Gran Canal, as the Albufera experienced a very large *plena* as a result of the heavy rainfall which occurred in the area in the previous month. This is reflected in the phytoplankton community, which showed very high cell concentrations at C2 throughout the column and at the surface of C1. It is worth recalling that for this sampling date we only have data for C2 and C1. The ultraplankton was clearly dominant (Figure 11), although at the surface of C2 the Chlorophyceae represented 37% of the total cell concentration, with *M. minutum, Scenedesmus ecornis* (Ehrenberg) Chodat and *Chlamydomonas* spp. as the most abundant forms. It represents a flow disturbance typical of Mediterranean climate and its effects on phytoplankton has been focused by PUIGSERVER *et al.* (2000b).

A second Principal Component Analysis (PCA) based on phytoplankton composition data has been used as a tool to understand the factors controlling changes in community
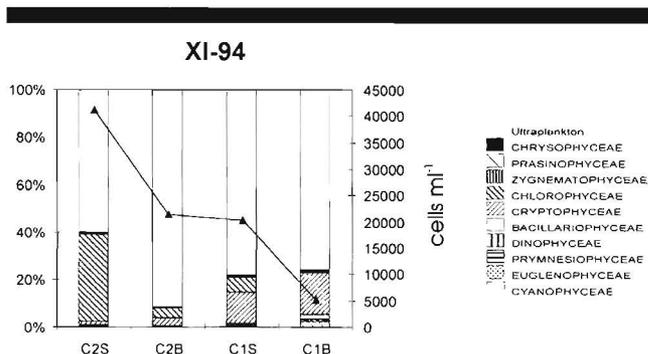
Figure 11. Phytoplankton abundance (cells ml⁻¹) and contribution of phytoplankton by groups in November 1994 at C2 and C1 sites. (S: surface; B: bottom)

both in time and space. The PCA was carried out using 53 taxa or group of taxa, the most common in the system. The first three components explain only 22.9 % of the variance, which means that there are a lot of factors affecting phytoplankton composition in this system. The results are summarised in Table 1. Component I seems to be related with salinity and it segregates species gradually. Component II seems to be related with nutrient requirements. It segregates three groups: one of eutrophic waters, one of oligotrophic waters, both composed by few species, and a third group (39 taxa) without a clear range of nutrient requirements. Component III has a temporal meaning. It shows different phytoplankton composition from winter to summer, which can be related mainly with temperature. As in the first case, Component III shows a gradation of species. Therefore in Table 1, both for salinity and yearly season species have been segregated only depending the correlation sign. We also notice that this PCA based on phytoplankton species is not accurately coincident with the PCA based on hydrological data explained before.

DISCUSSION

The Gran Canal features important physical and chemical gradients, both vertical and horizontal, because waters with lower salinity from the Albufera are found on the surface and those from the bay entering the canal remains in the bottom. Thus, it is a typical example of an interaction system by which the Gran Canal constitutes a transect across fresh water environments, represented by the Albufera, and marine ones, represented by the Alcudia Bay (MORRIS, 1985; IBAÑEZ *et al.*, 1997).

These physical and chemical gradients are responsible for the dual heterogeneity (vertical and horizontal) observed in the phytoplankton community. The sites more affected by fresh waters generally have a larger phytoplankton biomass (Chl *a* and cell abundance) as well as a greater resemblance with communities characteristic of fresh waters (MARGALEF, 1983; KILHAM and HECKY, 1988). This heterogeneity generally determines an horizontal gradient of diminishing phytoplankton biomass and specifically of groups characteristic of fresh waters such as Chlorophyceae, from the inland sites,

Table 1. *Summary of the most common 53 taxa or group of taxa based on their ordination in the space defined by Principal Component I, II and III.*

	Salinity		Eutrophy			Seasonal var.	
	Low	High	More	→	Less	Win.	Sum.
Oscillatoria tenuis	+			+		+	
Oscillatoria sp. 1		+		+			+
Pseudoanabaena sp. 1		+		+			+
Pseudoanabaena sp. 2		+		+		+	
Euglenaceae	+			+		+	
Eutreptiella sp.		+		+			+
Monoraphidium minutum	?			+		+	
Monoraphidium contortum	+		+				+
Scenedesmus ecornis	+		+				+
Chlamydomonas spp.	?		+				+
Spyrogira sp.	+			+		+	
Tetraselmis suecica		+		+			+
Tetraselmis sp. 1	+				+		+
Cyclotella meneghiniana	+			+		+	
Achnantes minutissima	+				+	+	
Amphora sp.		+		+			+
Licmophora spp.	+				+	+	
Synedra ulna	+			+		+	
Diploneis bombus		-		+			+
Navicula spp.	+				+		+
Pleurosigma normanii		+		+			+
Nitschia acicularis		+		+			+
Nitzschia closterium		+		+			+
Nitzschia spp.	+		?				+
Chroomonas sp.	+				?	+	
Cryptomonas acuta		+		+			+
Cryptomonas marssonii	+			+		+	

	Salinity		Eutrophy			Seasonal var.	
	Low	High	More	→	Less	Win.	Sum.
Cryptomonas sp. 1	?		+				+
Cryptomonas sp. 2	+			+		+	
Cryptomonas sp. 3		+		+		+	
Cryptomonas major	+				+	+	
Cryptomonas sp. 4		+		+		?	
Cryptomonas spp.	+			+		+	
Leucocryptos marina		+		+			+
Rhodomonas lacustris	+			--		+	
Rh. lac. nannoplanctica		+		+			+
Hemiselmis sp.	+			--			+
Ochromonas sp. 1	+		+				+
Ochromonas sp. 2	+			+			+
Ochromonas sp. 3		+		+			+
Pseudopedinella pyriformis	+			+		+	
Chrysophyceae	+			+		+	
Gymnodinium splendens		--		+			+
Gymnodinium sp. 1	+				+		+
Gymnodinium sp. 2		+		+			+
Gyrodinium sp.		+		+			+
Heterocapsa sp.		?		+			+
Peridinium sp.	+			+			+
Peridinials	+				+	+	
Prorocentrum minimum		+		+		+	
Oxyrrhis marain		+		+		+	
Pleur. pseudoroscoffensis		+		+		+	
Ultraplankton	+			+			+

C4 and C3, towards the outer ones, C2 and C1. At particular times, however, these gradients can disappear for various reasons. An example is founded in the autumn where the proportion of Chlorophyceae was higher at C1 than at C2, and this may be explained by the entry of waters of lower salt concentration between the two sampling sites along the adjacent canals (Figure 1 and 3).

With regard to vertical heterogeneity, this generally involves an increasing gradient of Chl *a* and cell abundance with depth, although sometimes this is inverted, as happened in November 94. This gradient must be related to nutrient dynamics, discussed below.

Following MARGALEF's (1983) classification of the degree of eutrophy of a system as a function of phytoplankton cell density, the waters of the Gran Canal should be defined as eutrophic or highly eutrophic. Phytoplankton cell abundances obtained here are similar of those observed in other eutrophic estuaries (SABATER and MUÑOZ, 1990). The high proportion of small-sized cells, mostly of ultraplankton, characterised by fast growth rates (MARGALEF, 1978), also reflects the eutrophic conditions of this system. Although small sized cells dominate in oligothrophic ocean waters; in coastal and estuarine environments ultraplankton dominance is often indicative of a stressed environment (SHAPIRO and GUILLARD, 1986). One really detects a gradation in the trophic state in the Gran Canal, with a reduction in the degree of eutrophy from the Albufera to the Alcudia Bay.

These results agree with the high nitrates concentrations measured. The distribution of nitrates and silicates suggest that N and Si circulation is associated with water derived from the Albufera (Figure 9), which circulates at the surface towards the sea. The DIN content is so high and the PO_4 concentrations are so low that PO_4 might be limiting for phytoplankton growth. In fact the N/P ratio is very high. The low P concentrations in the inner part of the canal should be related with the high alkalinity which favours the P precipitation. This is a process well known in freshwater systems (WETZEL, 1975). Also, benthic burial is the main phosphorus sink during transport from land to open sea and mainly in coastal areas with long residence times (BORUM, 1996). In contrast, P retention in marine sediments is relatively less efficient than in fresh-water sediments (JØRGENSEN, 1996). On the basis of phosphates concentrations, it would be reasonable to assume that there is a fast recycling of P along the canal, either directly from that in the water or through redissolution from the sediment, although one should not ignore its possible origin in urban sewage. All this confirms the results obtained by MARTÍNEZ-TABERNER *et al.* (1991 and 1995b). They show that the nutrients entering the Albufera are mainly derived from leaching from farmed soil, especially on the southern side of the upper Albufera. As well as from the urban sewage mainly from the north of the lower Albufera, where one finds a large tourist development. Either of which could be the source of the increase in eutrophy in the system.

Moreover, as a general trait in the Gran Canal, the opposite relation between phytoplankton production and mainly
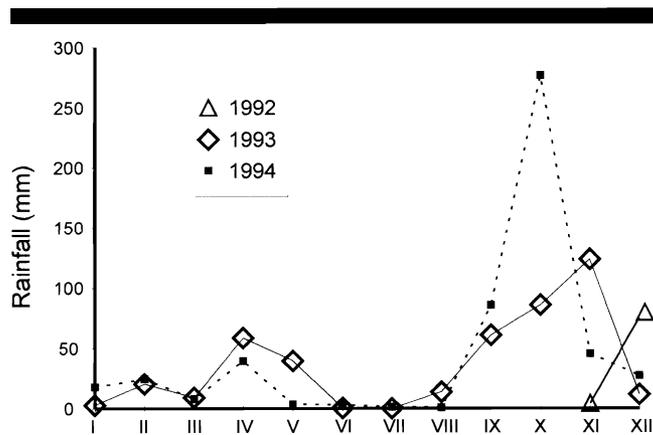
Figure 12. Rainfall pattern at the Albufera during the monitoring period.

phosphorus (Figure 9) makes evidence of the effect of phytoplankton growth on nutrient depletion.

The maximum values of nutrient concentrations, nitrates and phosphates, detected in winter and early spring seems to be the result that some other factor was controlling phytoplakton growth at this time. As it was expected by the geographic position of our study area in the Western Mediterranean, the light intensity measured in the present study leads to think that light is not limiting in surface layers nor at the whole water column the most part of the year. It could be only in bottom levels during winter or early spring at particular moments. During winter and early spring, when there are nutrients available, temperature seems to be the main limiting factor for phytoplankton growth. The high abundance of Cryptophyceae during the entire study (Figure 10) are evidence that this group is widely distributed in brackish and marine waters. The Cryptophyceae blooms detected during the colder months make evidence of the limiting effect of temperature. This is a group able of high growth rates at low temperatures (KLAVENESS, 1988) because of its low rates of cell respiration under those conditions (LEE, 1999). In fact, winter blooms of Cryptophyceae have been reported in diverse Mediterranean brackish systems (PRETUS, 1985; ANDREOLI et al., 1986; MARTÍN, 1995; among others).

In the inland part of the Gran Canal, at C4, the change in time of phytoplankton biomass are mainly related with rainfall when temperature is not a limiting factor. High rainfall took place mainly in spring and autumn (Figure 12). When days become warmer phytoplankton uses the nutrients accumulated during last autumn and winter, starting the spring bloom. But it is the use of nutrients coming from external inputs in waters from the Albufera that lead to the highest development of this bloom. These nutrients are mostly incorporated to the system in situ. In terms of cell concentration, the spring bloom coincided with the increase in temperatures. The autumn ride occurred when temperatures were still high and new inputs of nutrients were involved with autumn rainfalls. This agree with the dynamics expected in fresh waters (REYNOLDS, 1996) and in other temperate

estuaries (WARD and TWILLEY, 1986; COMÍN and VALIELA, 1993).

Whether grazing is important or not in this system cannot be judged as no data are available. In any case, top-down controls are difficult to find in the classic food web and most of the examples come from warm oligotrophic ocean waters, where primary production rates may be lower than in coastal areas and grazers are active most of the year (VALIELA, 1995).

Previous data on phytoplankton cell composition and abundance are not available for the study area. However, there are data on Chl a concentration (MARTÍNEZ-TABERNER et al., 1991 and 1995b). These show minimal concentrations in the middle and higher parts of the canal and highest in the lower parts, which are subject to sewage effluents. They generally increase in the spring and summer. The above studies are based on samples taken prior to the declaration of the Albufera as a Natural Park. Some of the management that has taken place since in order to rehabilitate the Albufera have been the repair of the sluices in canals joining the Gran Canal as well as the regulation of water levels by means of a sluice on the Gran Canal itself. Which is meant to allow for the release of inland water in a slower and gentler way (SECONA, 1990; MARTÍNEZ-TABERNER et al., 1995a). The differences observed between the results obtained by MARTÍNEZ-TABERNER et al. (1991 and 1995b) and by us in the annual cycle of Chl a concentrations, especially at C4, are probably caused by this anthropic regulation.

C3 represents an intermediate situation in the Gran Canal and is a function of the higher or lower influence by the interacting waters. It must be recalled that the influence of the Albufera on the outer canal is artificially regulated by the sluices. Thus, the effect of rainfall, and in general of waters collected in the Albufera, at the end portion of the Gran Canal and further on into the Bay will vary as a function of the anthropic water regulation. The Chlorophyceae have been an useful indicator of the fresh water influence in the system (Table 1). They can be associated with the input of waters with low salinity and high nitrogen concentration (ROUND, 1981; MARGALEF, 1983; ABOAL, 1989).

The summer phytoplankton bloom at C2 and C1 coincides with the period of maximal influence of marine waters. Also with an increase in phytoplankton density at the mouth of the Gran Canal (MOYÀ et al., 1995) and a general increase in primary production throughout the water column, both at C2 and C1 within the Gran Canal and at his mouth (SINTES, 1993). This summer proliferation may be related to a period of maximum stability of the system, involving an increase in nutrients which may be of diverse sources. On the one hand high temperatures accelerate processes of organic mineralization. On the other, macrophytes initiate nutrient liberation (OGWADA et al., 1984), which increases during their senescence towards the end of summer and autumn (MARTÍNEZ-TABERNER et al., 1990 and 1995b). In August we detected sudden drops in dissolved oxygen, especially in the bottom samples at C2 and C1, which may be related to an increase in temperature as well as in suspended organic matter (MOYÀ et al., 1995). Furthermore, during the summer the input of seawater into the canal homogenises the water column,

favouring redistribution processes of P from the sediments. In fact, we have detected slight increases in phosphate concentration in water in bottom samples at the beginning of summer, although they quickly dropped. We may thus conclude that P is rapidly consumed as it is being liberated. Alternatively, an increase in nutrient inputs from urban sources in the lower part of the canal, as a consequence of a rise in tourist activity during the summer, cannot be excluded.

All the above, in addition to the strong reduction in N concentration as waters flow through the Albufera and to denitrification processes from the sediments in the outer canal (LÓPEZ et al., 1995) may explain why the outer sites favour the growth of Cyanophyceae. The abundance of Cyanophyceae in the warmer months is typical of many eutrophic lakes, to the point of defining a phytoplankton association (HUTCHINSON, 1967). In shallow coastal systems this distribution has also been repeatedly observed (COMÍN, 1984; MARTÍN, 1995).

The lower part of the canal also presents a small phytoplankton spring bloom, which can be explained in the same way as that of the inner canal. The phytoplankton bloom observed in November 94 is a direct consequence of nutrient inputs in the inner Albufera caused by the very severe *plena*. This is shown by the characters of the bloom itself, i.e.: high concentrations of Chl *a*, of total cell abundance and specially of Chlorophyceae, along with a clear diminution gradient from the inner C2 towards the outer C1, and from the surface to the bottom levels (PUIGSERVER et al., 2000b). It was precisely at this stage when SINTES (1993) measured very high primary production at these locations as well as in the bay, but only at sites nearest to the Albufera and especially at surface layers.

In this way, in the outer Gran Canal phytoplankton change in time is much less related to rainfall regimes than in the inner parts and it is only clearly affected by these when they are very intense. In this area the phytoplankton may be much more associated with the mineralization of organic matter and, most important, with the recycling of P from the sediments.

Changes in phytoplankton species composition in the Gran Canal, both in time and space, are affected by a lot of factors and it becomes difficult to relate them with an individual one. In any case, in our system the most important factors involving changes in phytoplankton composition seems to be the fresh-salt water gradients, the trophic state and the seasonal variations.

CONCLUSIONS

The Gran Canal features important physical and chemical gradients, affected by fresh and marine waters fluxes, which are responsible of phytoplankton heterogeneity. The high phytoplankton biomass and the dominance of small-sized cells are evidence of its eutrophic conditions.

The studied system shows the two phytoplankton dynamic models described for temperate estuaries. The innermost part of the canal shows two blooms throughout the annual cycle, one in the spring and the other in the autumn, both associated with nutrient input through inland waters. This follows the model of DUGDALE and GOERING (1967) in which the

external source of nutrients supports "new production" in the estuary. In the outer part of the canal is detected a summer phytoplankton bloom that is tied up with mineralization processes of the organic matter, and mainly with phosphorus recycling from the sediment. This phytoplankton annual pattern follows the model described by KEMP and BOYNTON (1984) also for temperate estuaries.

As a consequence of the second model, there is an asynchrony between the nutrient inputs and phytoplankton growths in the outer part of the Gran Canal. This fact along with the reduction in the degree of euthophy in the direction Albufera-Alcudia Bay confirm the filter role of these coastal systems, which reduce the impact of inland systems to the marine ones. Only at particular moments, it is subject to heavy torrential rainfalls typical of Mediterranean climate which leads to floods and to significant changes in the system. At those moments the effect of the freshwaters are also observed at the end part of the canal and further on into the Bay.

The small sized systems like the Gran Canal, that reproduce in a small area the dynamics of other systems both with meso or macroscale, are important tools on the study of eutrophication in coastal areas. They can also be useful to evaluate the management of coastal wetland with a view to promote their preservation.

ACKNOWLEDGEMENTS

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□RESUMEN□

Se presentan y discuten los resultados correspondientes a la composición y distribución del fitoplanton en un canal mediterráneo de drenaje costero con régimen estuarino. El estudio se refiere al tramo final del Gran Canal de la Albufera de Mallorca durante el período entre Diciembre de 1992 y Noviembre de 1994. Se detectan gradientes físicos y químicos influidos por los flujos de aguas epicontinentales y marinas, y que son responsables de la heterogeneidad del fitoplanton. Se observa un gradiente de disminución de la abundancia fitoplantónica (clorofila *a* y células) desde las estaciones más internas (epicontinentales) a las más externas (marinas). El fitoplanton está dominado por formas de pequeñas dimensiones, mayormente inferiores a 5 μm; lo cual junto con las altas concentraciones celulares detectadas muestra el carácter eutrófico de este sistema. El sistema estudiado presenta al mismo tiempo los dos modelos descritos para la dinámica del fitoplanton en estuarios templados. La zona más interna del canal presenta dos proliferaciones a lo largo del ciclo anual, una en primavera y la otra en otoño, ambas asociadas a la entrada de nutrientes a través del agua que se recoge en la Albufera. En la zona más externa del canal, la dinámica del fitoplancton, caracterizada por una proliferación estival, está ligada a procesos de mineralización de materia orgánica y principalmente de reciclaje de fósforo desde el sedimento. Asimismo se confirma el papel de filtro que desempeñan este tipo de zonas húmedas litorales.