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# Seasonal and inter-annual plankton variability in the Gulf of Trieste (northern Adriatic)

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Seasonal and inter-annual variability of environmental characteristics and of plankton were analysed based on monthly surveys of the physical structure of the water column, nutrients, phytoplankton, and zooplankton biomass and abundance in the Gulf of Trieste (1989–1995). Seasonal plankton dynamics were related to Soča River run-off, the main freshwater source, and peaks of autotrophic biomass were associated with extended periods of high freshwater inflow. Our results indicate that the freshwater discharge during spring was more important for annual phytobiomass than total yearly input. In 1993, which was characterized by a relatively high total annual freshwater input but by a dry spring, the lowest average chlorophyll biomass (0.85 μg $l^{-1}$) and cumulative monthly mesozooplanktonic biomass (123 mg AFDW $m^{-3}$) were observed over the entire period. Annual peaks of phytoplankton biomass were mainly due to increases in diatom abundance, while small-sized cells (microflagellates, coccolithophores) dominated during periods of low Chl *a* concentrations. Consumer community patterns followed autotrophic biomass evolution with high abundance of herbivores and mixed feeders in spring, and fine-filter feeders and planktonic protists during summer. A large inter-annual variability emphasizes the importance of long-term monitoring in areas like the Gulf of Trieste for distinguishing anthropogenic trends from natural variations of plankton.

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Key words: Adriatic Sea, freshwater inputs, Gulf of Trieste, plankton, trophic structure.

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## Introduction

Plankton studies in the Gulf of Trieste were begun more than two centuries ago (e.g., Steur, 1902; see review by Fonda Umani and Specchi, 1979) and have continued with varying intensity and spatial coverage up to the present. Consistent observations of plankton variability and environmental conditions, such as water column structure and nutrient concentrations, have been performed since the early 1970s (Fonda Umani *et al.*, 1992). Analysis of selected data sets in the recent past has demonstrated a large spatial, seasonal, and inter-annual variability of the ecosystem (Cataletto *et al.*, 1995; Fonda Umani *et al.*, 1995; Malej *et al.*, 1995), but the forcing mechanisms controlling the variability are still far from properly understood. Water quality problems, such as recurrent red tides, presence of toxic phytoplankton, build-up of mucilaginous masses (Mozetič *et al.,* 1997; Sellner and Fonda Umani, 1998), and seasonal depletion of oxygen below the pycnocline (Orel *et al.*, 1993; Malej and Malačič, 1995), emphasize the need for assessing temporal trends and for identifying the causes of observed changes.

This paper describes the results of 7 years of monitoring of water-column properties and plankton variability in this semi-enclosed Mediterranean gulf with one main freshwater source, the Soča (Isonzo) river. The flow rates of this river exceed other rivers by at least one order of magnitude (Olivotti *et al.*, 1986; Malačič *et al.*, 1994). Results on phytoplankton community structure and mesozooplankton time series have been published previously (Cataletto *et al.*, 1995; Fonda Umani *et al.*, 1995), while some of the other data have only been presented in national reports (Celio *et al.*, 1990) or in a thesis (Mozetič, 1993, 1997). Our aim is to compare seasonal and inter-annual variability of environmental characteristics and alterations in the plankton in order to highlight possible relationships between hydrological characteristics and biological features. Our hypothesis is that freshwater discharge dominates nutrient inputs to

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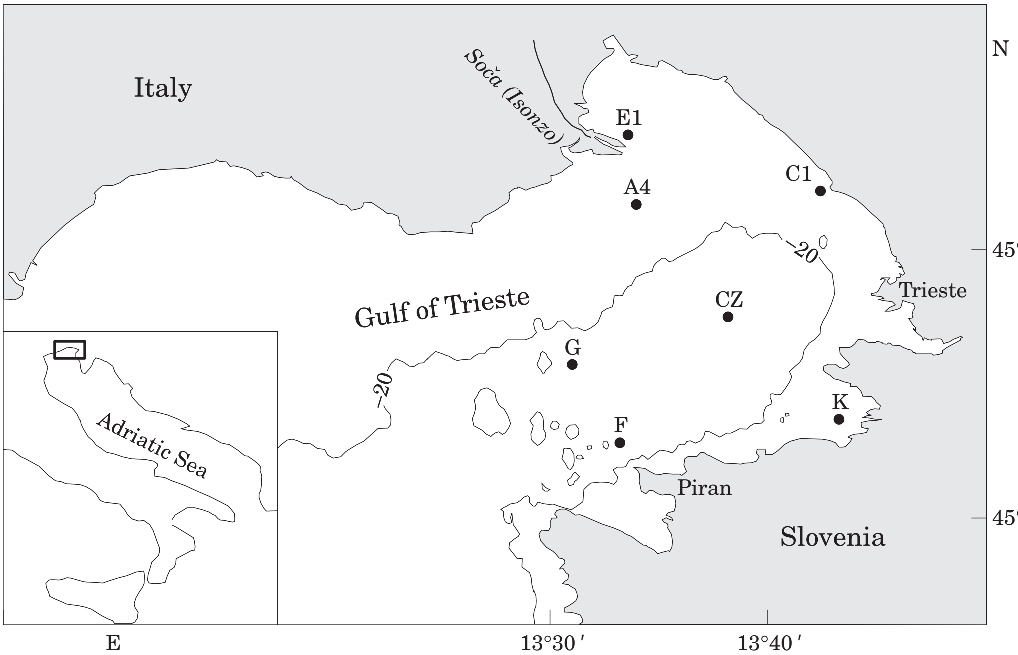


Figure 1. Map of the Gulf of Trieste with sampling stations indicated.

the Gulf and regulates the extent of primary production as well as plankton community structure (Harding, 1994; Malej *et al.*, 1995).

## Materials and methods

The Gulf of Trieste is located in the northernmost part of the Adriatic Sea, reaching a maximum depth of about 25 m in the central part (Fig. 1). Fresh water enters the gulf mainly along the shallow north-western coast (the Soča river being the most important source), with typical values in the range of 90–130 $m^3\ s^{-1}$ but sometimes exceeding 1500 $m^3\ s^{-1}$ (Malačič *et al.*, 1998). Freshwater inputs along the south-eastern coast are comparatively small (annual average inflow <10 $m^3\ s^{-1}$). In winter, the water column is characterized by considerable vertical homogeneity, while increased freshwater inflow during spring, in combination with heating of the surface layer, establishes a pycnocline which intensifies during summer (Malačič, 1991). The stratification is broken down by autumnal cooling and wind mixing. Because of its shallowness, the Gulf responds to local atmospheric forcing (i.e. dominant winds) and the circulation pattern cannot be generalized. The bora (NE wind) driven circulation is most efficient for water exchange (Stravisi, 1983). Tidal currents (amplitude ~10 $cm\ s^{-1}$) move the water mass only within a range of a few kilometres (Malačič and Viezzoli, 1998), and contribute little to water renewal. Density currents follow the peaks in Soča river discharges (Malačič *et al.*, 1998), but their role in overall water mass exchange has not yet been examined.

Regular surveys of the physical structure of the water column (temperature, salinity, density), nutrient concentrations, phytoplankton and zooplankton biomass and abundance have been carried out on a monthly basis from 1989 to 1995. Plankton biomass has been measured from 1984 onwards. Missing data have been interpolated. Daily run-off data of the Soča river were provided by the Hydrometeorological Survey of the Republic of Slovenia.

Water samples were collected at seven stations (Fig. 1), varying in depth between 3 and 24 m. Profiles of temperature and salinity were obtained by Hidronaut and CTD fine-scale probes, while Niskin bottles (5 l) were used for water sampling at standard depths (0.5, 5, 10 m and above bottom). To produce monthly or annual values, data from all depths at all stations were averaged. In the case of phytoplankton and microzooplankton abundance, data from discrete depths were integrated over the water column.

Temperature and salinity data were used to calculate an overall density gradient (c) for stations deeper than 15 m as follows:

$$c=(\sigma_{Tb}-\sigma_{Ts})/H$$

where $\sigma_{Tb}$ and $\sigma_{Ts}$ are bottom and surface water densities (kg $m^{-3}$), respectively, and $H$ is water column depth

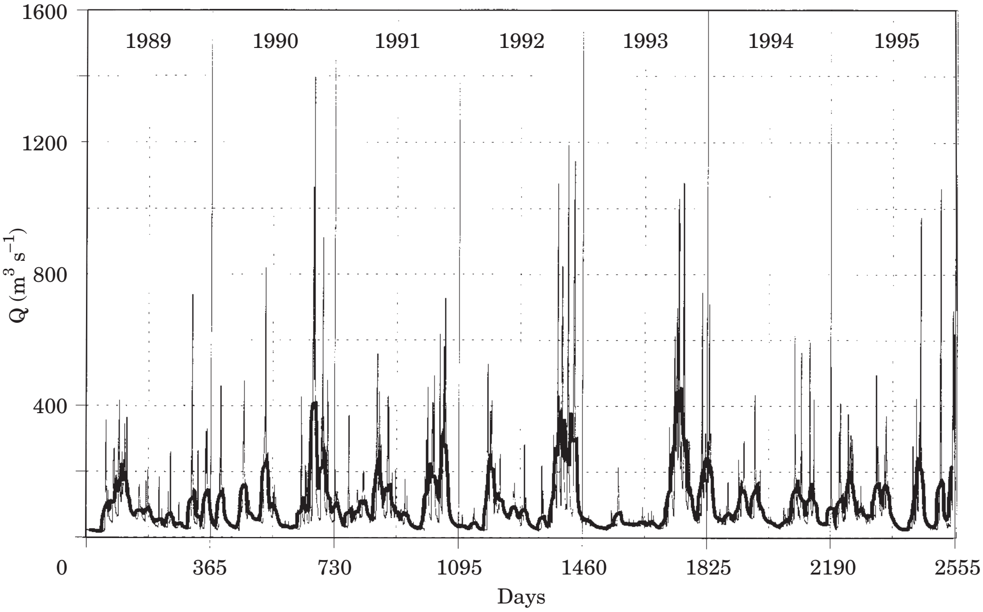


Figure 2. Seasonal and inter-annual variability of Soča river run-off: mean daily flow (thin line) and running average (thick line), 1989–1995.

(m). In addition, freshwater content (f) was calculated for the central part of the Gulf in accordance with Bowden (1983):

$$f=(S_0 - S)/S_0$$

where S denotes surface salinity, and $S_0$ the reference salinity of the water outside the region of mixing (37.4).

Concentrations of inorganic nutrients were measured on unfiltered water samples using standard colorimetric methods (Grasshoff, 1983). Chl *a* concentrations, corrected for phaeophytins, were determined fluorometrically (Holm-Hansen *et al.*, 1965) in 90% acetone extracts using a Turner 112 fluorimeter.

Samples for enumerating phytoplankton (800 ml) and microzooplankton (2–5 l) were preserved in buffered formalin (1.5 and 4% final concentration, respectively) and organisms were counted on an inverted microscope using the technique of Utermöhl (1958). Phytoplankton organisms were counted at 200 × (if necessary, 400 × ) magnification in 100 (or 50) fields of the bottom chamber after overnight sedimentation of a 50 ml subsample. Phytoplankton cell numbers were depth integrated over upper (0–10 m) and bottom layers. Zooplankton samples were collected by vertical hauls from near bottom to surface using a WP 2 net (200 μm mesh) and fixed in 4% buffered formalin. Dry weight and ash-free dry weight were determined following recommendations of Lovegrove (1966) and UNESCO (1976).

# Results

## Seasonal variability

The flow regime of the Soča river is generally characterized by low values in early winter and summer and high values in early spring and autumn (Fig. 2). Freshwater input, together with the seasonally developing thermal stratification, controls the overall density gradient of the water column (Fig. 3). The water column was generally well mixed from November through April, while a density stratification was present from May to October at all stations. Increased freshwater input in spring created a buoyant surface layer spreading from the north-west towards the south-east which, together with downward heat flux, increased water-column stability during summer. However, there were marked differences in water-column stability between years (Fig. 3).

As examples, two years (1993 and 1994) have been selected as representative of the seasonal variability in the main parameters. Persistent high river run-off at the end of 1992 during an extended period of nearly 3 months (Fig. 2) was reflected in fairly high nitrate concentrations (Fig. 4) during the winter–early spring period of 1993 (up to 5.6 μmol $l^{-1}$ in the upper layer). The first half of 1993 was very dry and the absence of a significant spring freshwater pulse (Fig. 2) coincided with low nitrate concentrations from May throughout the summer (<1.0 μmol $l^{-1}$). Concentrations increased

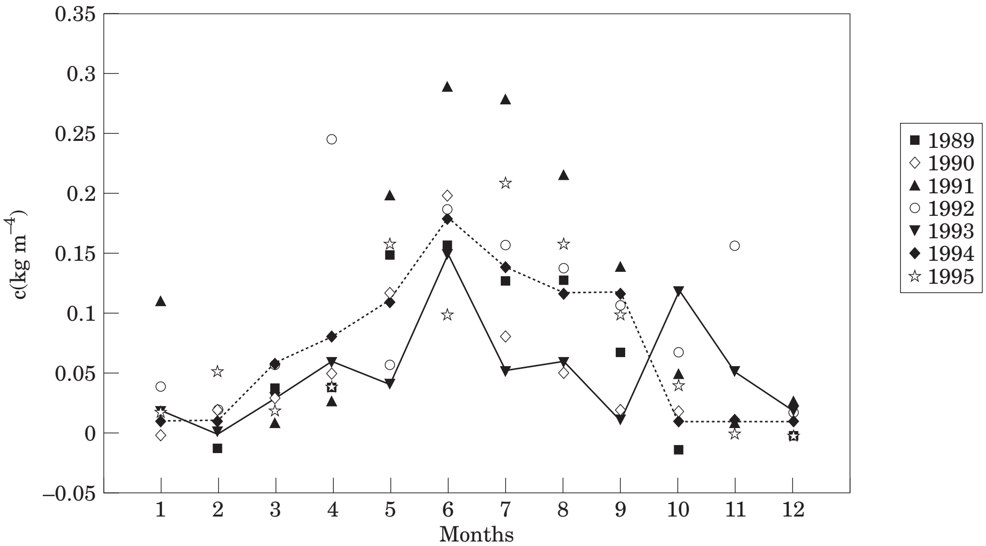


Figure 3. Monthly means of overall density gradient in the water column by year (1989–1995). 1993 (——), 1994 (- - -).

again in October and November (max. 4.7 µmol $l^{-1}$ in the surface layer), during the period of high river run-off.

Compared with 1993, the flow regime of the Soča river in 1994 was closer to the long-term average (Fig. 2), with periods of high inflow both in spring (March–May) and autumn (September–November). During these periods, nitrate concentrations increased in the central and south-eastern parts of the Gulf (Fig. 4). While higher concentrations were observed only at the surface during spring, they covered the entire water column during autumn (up to 7.9 µmol $l^{-1}$).

In both years, low concentrations of ammonium and silicate in the upper layers and maximum concentrations of these nutrients just above the bottom during late summer and autumn (maximum in 1994 of 5.6 and 11.9 µmol $l^{-1}$, respectively) were observed, indicating the importance of regeneration processes during this time of year (Fig. 4).

High nutrient concentrations during winter 1993 were reflected in increased phytoplankton biomass in the surface layer in January ($\approx$1.5 µg Chl *a* $l^{-1}$; Fig. 5). From February until September Chl *a* concentrations remained fairly low throughout the water column, with slightly higher values above the bottom. The highest concentrations were measured in October ($\approx$3 µg $l^{-1}$) coinciding with the autumn pulse of freshwater enriched with nitrate. Compared with 1993, Chl *a* showed a small peak during spring (0.9 µg $l^{-1}$) and an extended one during autumn (2.0–2.9 µg $l^{-1}$). Noteworthy are the higher values measured at the bottom during summer, which probably reflects both nutrient availability and higher light penetration. Conditions of a mixed and nutrient-rich water column during autumn induced phytoplankton growth at all depths.

During the biomass peak in January 1993, microflagellates were the predominant group (Fig. 6) of the phytoplankton community ($1.9 \times 10^5$ cells $l^{-1}$ in the upper 10 m layer). This group remained the most important one until July, when diatoms increased markedly in both the upper and bottom layer (maximum $4.8 \times 10^5$ cells $l^{-1}$). Diatoms also dominated the community during the peak in October (maximum $9.9 \times 10^5$ cells $l^{-1}$) representing over 81% of total cell abundance. The numerically less important group "other" phytoplankton was composed of dinoflagellates, coccolithophores, silicoflagellates, and unidentified algae. Within this group, dinoflagellates were the most abundant during summer months, while coccolithophores prevailed in January.

Higher chlorophyll concentrations during most of 1994 (Fig. 5) coincided with higher phytoplankton abundances than in 1993, with values regularly exceeding $10^6$ cells $l^{-1}$ (Fig. 7). In January, coccolithophores and microflagellates (5.6 and $5.5 \times 10^5$ cells $l^{-1}$, respectively) dominated the community, while during the spring and extended autumn peaks diatoms were the most abundant (up to $1.3 \times 10^6$ cells $l^{-1}$). The January and spring abundance maximum was restricted to the upper 10 m layer, whereas high cell numbers were also counted in the bottom layer during autumn. During months of low phytoplankton abundance, microflagellates dominated followed by dinoflagellates and coccolithophores.

Micro- and mesozooplankton also showed considerable seasonal variability and abundances were generally higher in 1994 (Fig. 7) compared to 1993 (Fig. 6). In

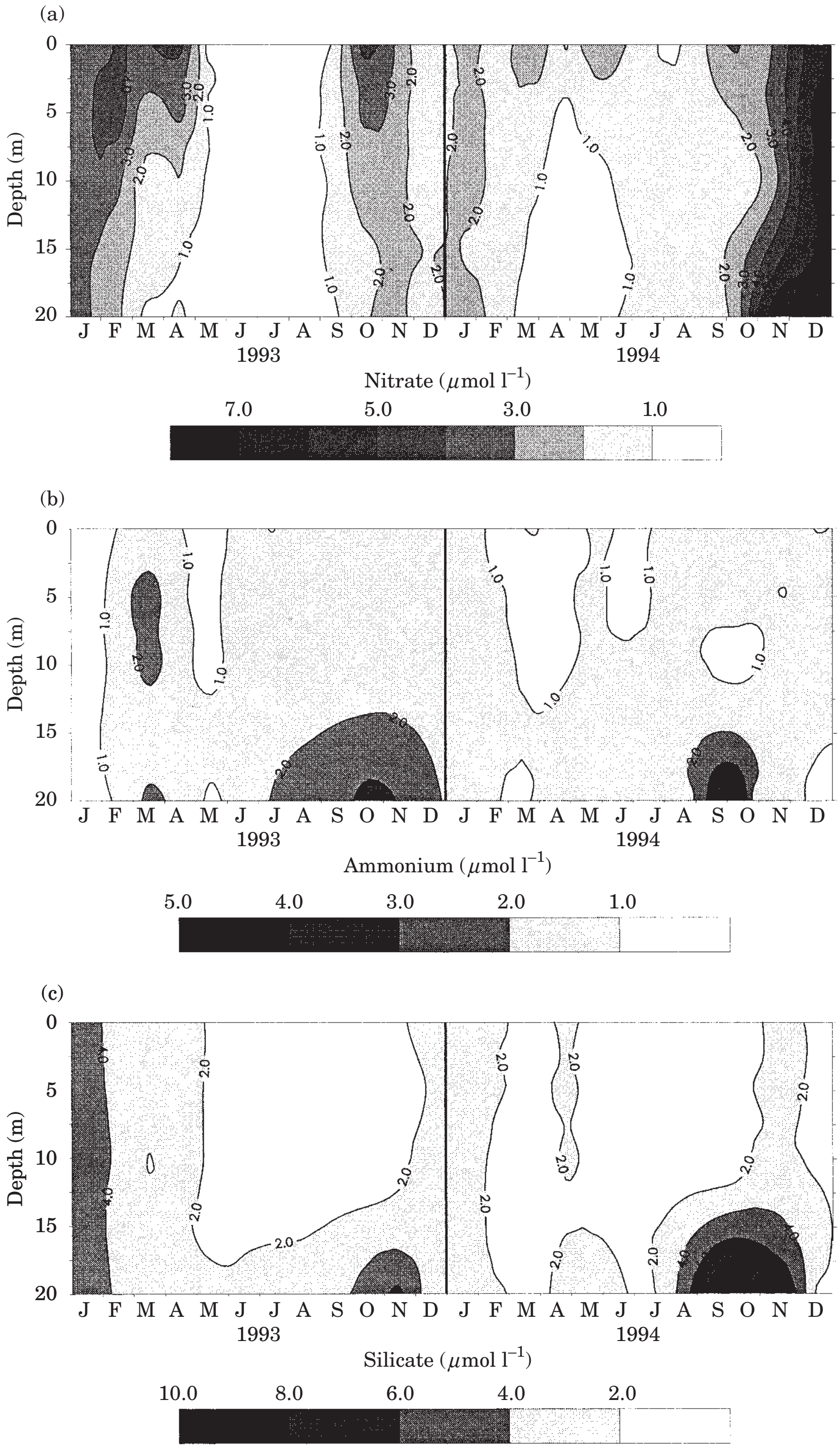


Figure 4. Time-depth isopleths of nitrate (a), ammonium (b), and silicate (c) concentrations in the central and south-eastern Gulf during 1993 and 1994.

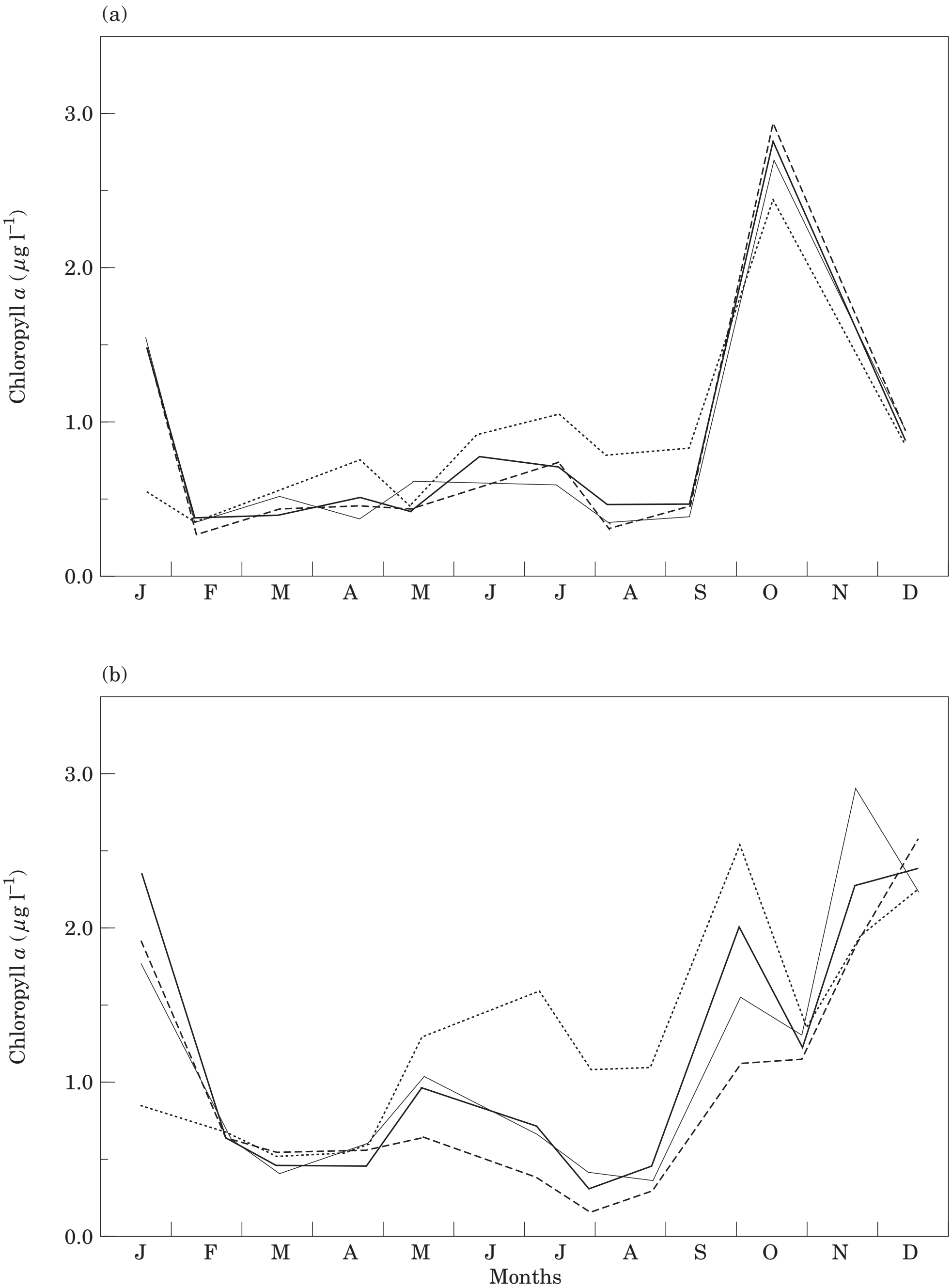


Figure 5. Seasonal variations of Chl *a* concentration at four depths at station F in 1993 (a) and 1994 (b). 0 m (**——**); 5 m (——); 10 m (– – –); bottom (· · · ·).

both years, the highest abundances of microzooplankton were recorded in winter–early spring and autumn (Figs 6c, 7c), when ciliates other than tintinnids prevailed (up to 2070 ind. dm$^{-3}$). Tintinnids only dominated the community in October 1993 and September 1994 (up to 900 ind. dm$^{-3}$ or approximately 60% of total abundance), while micrometazoans dominated in late summer of 1993. Late spring–early summer was the period of lowest microzooplankton abundance in both years.

The picture of mesozooplankton seasonality is incomplete because of missing data. Nevertheless, some

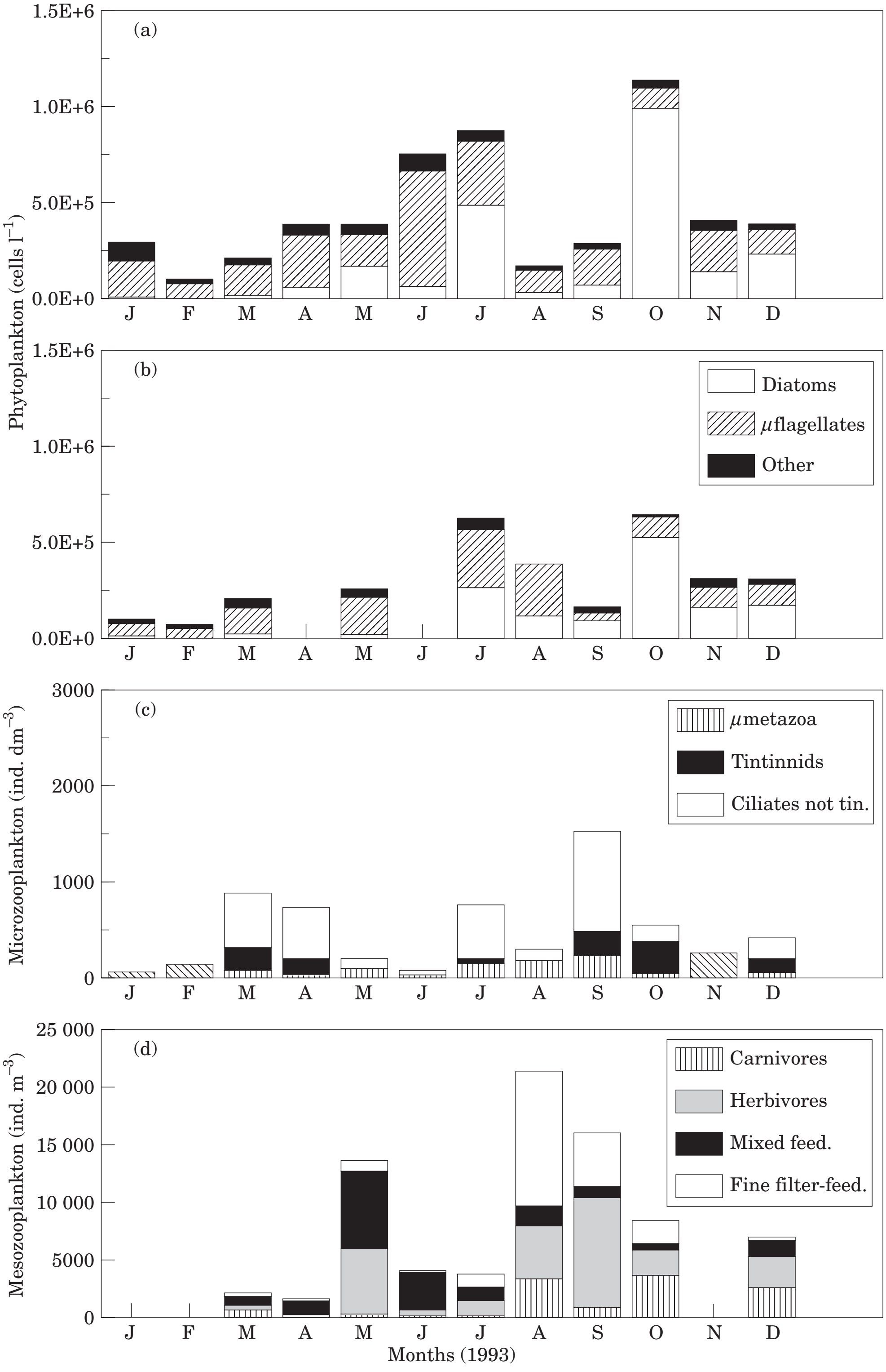


Figure 6. Seasonal variations in plankton abundance by dominant groups in 1993: (a) phytoplankton in the 0–10 m surface layer; (b) phytoplankton in the bottom layer; (c) microzooplankton (oblique striped bars in January, February, and November represent data from a different location); (d) mesozooplankton.

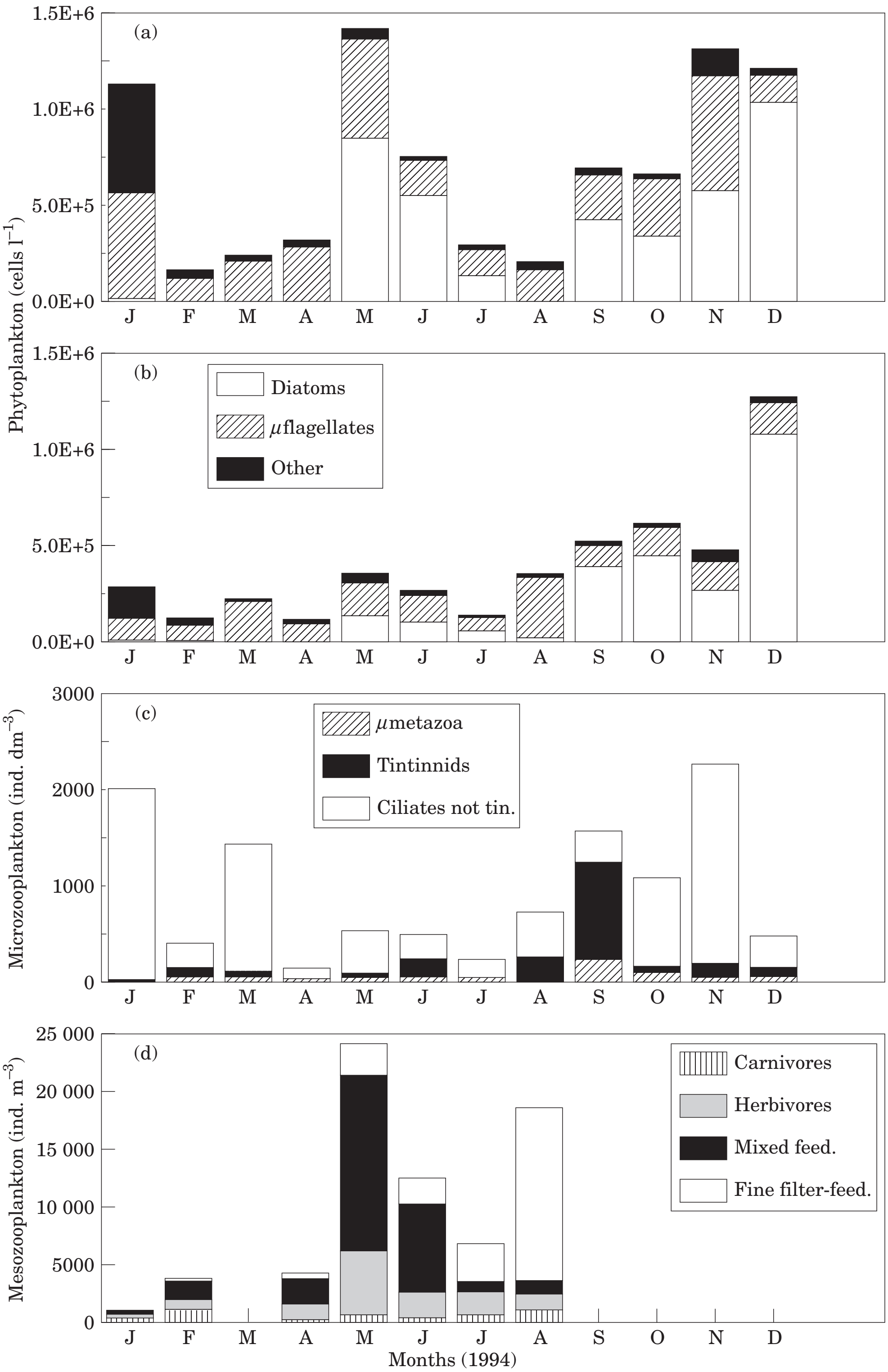


Figure 7. Seasonal variations in plankton abundance by dominant groups in 1994: (a) phytoplankton in the 0–10 m surface layer; (b) phytoplankton in the bottom layer; (c) microzooplankton; (d) mesozooplankton.

Table 1. Annual Soča river run-off (SRR total) based on daily measurements, percentage of the annual total discharged during February through May (SRR spring), and average annual freshwater content (f) in the central part of the Gulf.

| Year | SRR ($\times 10^9$ t) | SRR spring (%) | f (%) |
|---|---|---|---|
| 1989 | 2.48 | 44 | 2.95* |
| 1990 | 3.43 | 22 | 2.69 |
| 1991 | 3.40 | 35 | 5.47 |
| 1992 | 3.65 | 27 | 5.09 |
| 1993 | 3.17 | 14 | 3.70 |
| 1994 | 2.92 | 33 | 3.36 |
| 1995 | 3.34 | 34 | 2.79 |

*Period May–December only.

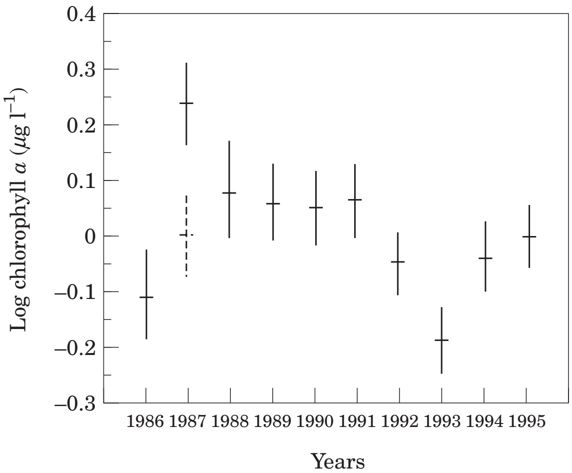


Figure 8. Annual means of Chl *a* concentration (logarithmic scale) in the central and south-eastern Gulf, 1986–1995. Dotted symbol in 1987 represents the average annual excluding December values (see text).

common characteristics were observed in the 2 years (Figs 6d, 7d). A first peak was observed in May (2.6 $10^4$ ind. $m^{-3}$ in 1994), followed by a decrease during early summer and a second peak in August (>2 $10^4$ ind. $m^{-3}$). In both years, the late spring maximum was due to the copepod *Acartia clausi* (constituting the largest part of mixed feeders) and the summer maximum to the massive development of the cladoceran *Penilia avirostris* (fine-filter feeder). In the autumn–winter period, herbivorous (*Clausocalanus* spp.) and carnivorous species (*Oncaea* spp.) were predominant.

## Inter-annual variability

On the basis of daily run-off data for the Soča river, the cumulative annual freshwater mass entering the Gulf and the percentage contribution of the months of February through May were calculated and compared with the estimated average freshwater content in the central part (Table 1). The year 1992 was characterized by the highest cumulative discharges, whereas 1989 was a relatively dry year. However, the difference is only by a factor of 1.5. The differences are much larger when only the winter/spring season is taken into account. For example, 1993 was characterized by a relatively high freshwater discharge over the entire year, but the spring period was extremely dry.

The calculated freshwater content only roughly paralleled yearly river water discharge, suggesting that factors other than river run-off affect salinity in the central Gulf. The highest fractions of freshwater in the surface layer were calculated for 1991 and 1992, years among the highest in respect of annual run-off. Moreover, they were also characterized by a strongly stratified water column during the winter–early spring period according to the estimated overall density gradient (Fig. 3). In contrast, 1990 and 1995 were characterized by the lowest fractions of fresh water in the Gulf, while the annual run-off in those years was above average. Since freshwater content calculated for the centre appears not to be directly related to concurrent run-off, these results suggest that a high proportion of the fresh water discharged by rivers may be exported from the Gulf of Trieste along the western coast.

Generally, high annual averages of Chl *a* concentrations (measured since 1986; Fig. 8) were observed during years characterized by extended periods of freshwater inputs during spring (e.g., 1989, 1991; cf. Fig. 2, Table 1), whereas the lowest average concentration was observed in 1993, characterized by a long dry period (January–October). This suggests the importance of enhanced spring run-off on the annual phytobiomass balance. However, there is a discrepancy between the dry spring period and high Chl *a* concentration in 1990. The exceptionally high average value for 1987 was due to a December bloom of the diatom *Hemiaulus hauckii* throughout the Gulf (highest concentrations >14 µg Chl *a* $l^{-1}$). However, if the December values are omitted, the annual average for 1987 seems to fit the other observations better.

Annual mesozooplankton biomass, expressed as the cumulative monthly average Ash-Free Dry Weight (measured since 1984; Fig. 9) clearly showed a period of high values (>300 mg $m^{-3}$) from 1986 to 1992. The lowest biomass was recorded in 1993, concomitant with the chlorophyll minimum. The high values during 1986–1992 were largely due to an increase in biomass during the spring months (February–May) and also in August, while autumn biomass was relatively constant throughout the investigated period.

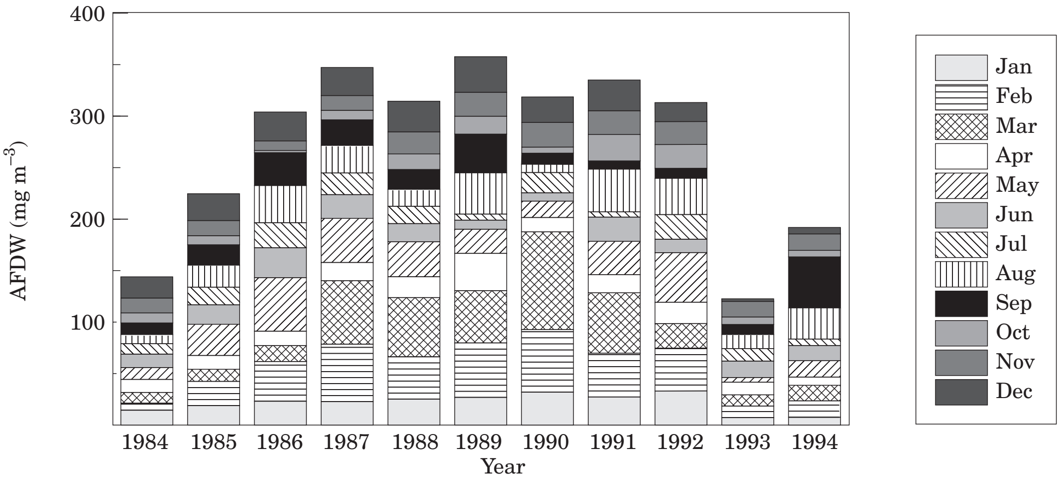


Figure 9. Cumulative monthly mesozooplankton biomass as ash-free dry weight (AFDW) by year (1984–1994).

## Discussion

The analysis of environmental variables and plankton indicates the absence of a regular and recurrent pattern and confirms the large inter-annual variability observed in previous studies in the Gulf and in the rest of the northern Adriatic Sea (Benović *et al.*, 1984; Degobbis *et al.*, 1995). The seasonal plankton dynamics appear to be strongly related to the flow regime of the main freshwater source, the Soča river, which supports earlier conclusions (Malej *et al.*, 1995). Other freshwater nutrient sources, such as minor rivers and local precipitation (Malej *et al.*, 1997), may contribute to increased phytoplankton biomass but only for a limited time (a few days) and in a limited space (the thin upper layer).

The two years (1993 and 1994) selected from the 1989–1995 time series as representative of the seasonal patterns in physico-chemical parameters and plankton community characteristics were chosen to reflect differences in patterns in river run-off. Development of nitrate concentration and plankton community evolution appears to be governed to a large extent by freshwater input. Peaks of autotrophic biomass were related to extended periods of high freshwater discharge. In contrast, spring phytoplankton bloom did not develop when river flow was low for a prolonged period during spring 1993. The results suggest that fresh water and nutrient input govern the timing and magnitude of the spring biomass maximum, but they may subsequently also affect the summer–early autumn biomass peak in bottom waters which appear to be under the influence of nutrient recycling (Malone *et al.*, 1988; Jordan *et al.*, 1991). Thus, events and developments during spring may greatly affect annual production, as reflected in the inter-annual variability of the system. Moreover, inter-annual zooplankton biomass variability was largely restricted to the winter–spring stocks, while biomass was less variable during summer/autumn (Fig. 9).

Annual peaks of phytoplankton biomass in the Gulf were mainly due to increases in diatom abundance, particularly evident during the spring and autumn months. The community in these months was dominated by opportunistic, fast-growing diatoms like *Skeletonema costatum*, *Pseudonitzschia pseudodelicatissima*, *Chaetoceros* sp., *Cyclotella* sp. and *Cylindrotheca closterium*. These organisms seem to respond quickly to new nutrients introduced by rivers or precipitation; this has also been observed in controlled enrichment experiments (Malej *et al.*, 1998). In January, an increase of coccolithophores is often observed which may approach bloom densities (e.g. in 1994), while during summer small-sized phytoplankton (microflagellates and autotrophic picoplankton) are predominant. Because of their small cell size and low chlorophyll content they do not contribute significantly to the total autotrophic biomass (Švagelj *et al.*, 1996). Phytoplankton composition is also affected by the advection of water from the southern Adriatic, which is enhanced in winter–spring (Franco and Michelato, 1992). Advected waters bring species into the Gulf which may prevail in the developing annual succession. Species composition and relative abundances have changed dramatically from year to year (Fonda Umani *et al.*, 1995), resulting in quite different community structures in which a dominant spring diatom species in one year may completely disappear in the next (Fonda Umani, 1992).

Consumer community patterns followed autotrophic biomass evolution with higher abundances of herbivores and mixed feeders in spring and fine-filter feeders during summer. Greater phytobiomass in spring is reflected in increased zooplankton biomass and grazing activity (Cataletto *et al.*, 1993; Mozetič and Lipej, 1998).

However, consumers proved not to be able to control development of nuisance mucilage accumulations in 1988, 1989, and 1991 (Sellner and Fonda Umani, 1998). During the summer period of stratification, mesozooplanktonic fine-filter feeders (*Penilia avirostris*) and planktonic protists grazed most of the available phytobiomass (Lipej *et al.*, 1997). In spite of the high chlorophyll concentrations in autumn, mesozooplanktonic consumers did not increase correspondingly, which may have been due to faster export of water masses along the western coast and shorter residence time in the Gulf (Olivotti *et al.,* 1986). Inter-annual variations in mesozooplankton (Fig. 9) roughly paralleled changes in chlorophyll biomass (Fig. 8). The cumulative annual biomass in 1986–1992 was roughly twice the value in 1984 and 1993 and also significantly higher than in 1972–1981 (Benović *et al.*, 1984).

Both seasonal differences of the main biotic parameters as well as results from the longer study period indicate considerable inter-annual variability in the plankton of the Gulf of Trieste. The large seasonal and inter-annual variations observed in many estuarine and coastal systems have been related to freshwater run-off (San Francisco Bay: Cloern *et al.*, 1983; Chesapeake Bay: Malone *et al.,* 1988 and Harding, 1994; northern Adriatic Sea: Gilmartin *et al.*, 1990; northern Gulf of Mexico: Turner and Rabalais, 1991; Kiel Bight: Maske, 1994). Hydrological characteristics of receiving waters and the nutrient and plankton dynamics in such systems are governed by riverine input, which depends on climate and characteristics of the watershed area. Consequently, high spatial and temporal variability may be expected rendering the establishment of definite cause–effect relationships a difficult task. In such systems, it will be extremely difficult to discriminate between long-term trends in natural parameters and anthropogenic inputs, but sustained monitoring is a first prerequisite.

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