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OVERVIEW OF EUTROPHICATION-RELATED EVENTS AND OTHER IRREGULAR EPISODES IN SLOVENIAN SEA (GULF OF TRIESTE, ADRIATIC SEA)

Valentina TURK, Patricija MOZETIČ & Alenka MALEJ
Marine Biology Station Piran, National Institute of Biology, SI-6310 Piran, Fornače 41, Slovenia
E-mail: turk@mbss.org

ABSTRACT

Eutrophication is one of the important drivers of marine ecosystems degradation and is a particularly evident problem near the centre of human population. Although advances have been made during the past 30 years, eutrophication remains one of the primary problems affecting coastal marine ecosystems and semi-enclosed seas. An overview of eutrophication and its consequences in the Slovenian sea is presented with a focus on the pelagic domain, communities of the coastal ecosystem in particular on bacterio- and phytoplankton abundance, production, frequency of blooms and dominant organisms, occurrence of harmful toxic algal species, swarming of gelatinous zooplankton, the mucilage phenomenon and on hypoxia/anoxia events in the bottom layers.

Key words: eutrophication, nutrients, plankton, blooms, anoxia, mucus aggregates, Gulf of Trieste

VALUTAZIONE SU EVENTI LEGATI ALL'EUTROFIZZAZIONE E ALTRI EPISODI SPORADICI IN MARE SLOVENO (GOLFO DI TRIESTE, MARE ADRIATICO)

SINTESI

L'eutrofizzazione è uno dei vettori più importanti della degradazione degli ecosistemi marini ed è un problema particolarmente evidente in prossimità dei centri abitati. Benchè negli ultimi trent'anni la ricerca abbia fatto progressi, l'eutrofizzazione rimane uno dei problemi primari che affliggono gli ecosistemi marini costieri e i mari semichiusi. L'articolo presenta una valutazione dell'eutrofizzazione e delle conseguenze in mare sloveno, incentrata soprattutto sul dominio pelagico. Vengono trattate le comunità degli ecosistemi costieri, in particolare l'abbondanza di batterio- e fitoplancton, la produzione primaria, la frequenza delle fioriture, la presenza di organismi dominanti, specie algali tossiche e zooplancton gelatinoso, i fenomeni mucillaginosi e l'ipossia/anossia degli strati di fondo.

Parole chiave: eutrofizzazione, nutrienti, plancton, fioriture, aggregati mucillaginosi, Golfo di Trieste

AREA DESCRIPTION

The semi enclosed Gulf of Trieste is the northernmost part of the Mediterranean Sea opened to the rest of the northern Adriatic along its western side (Fig. 1). The surface area of the Gulf is about 600 km^2, while its volume is estimated at 9.5 km^3. With few exceptions, the water depth does not exceed 25 m, and only 10% of the Gulf is shallower than 10 m (Malej & Malačič, 1995). Oceanographic properties of the Gulf were described recently by Malačič & Petelin (2001); they are strongly affected by water mass exchange from the southern Adriatic, river inflow and meteorological conditions. It is the river Soča (Isonzo) that exerts the greatest impact on the Gulf's dynamics. Except during the summer months, a plume of freshwater from the Soča (Isonzo) river is always present in the surface layer of the Gulf, and freshwater may spread on the surface as far down as to the middle of the Gulf (Malej *et al.,* 1995). Oligotrophic, southern Adriatic bottom water enters the Gulf at the southern side and flows out after mixing with the upper waters. Circulation of deeper water is cyclonic and can be opposite to that in the upper layer (Malačič & Petelin, 2001). Discharge by other rivers along the eastern and southern coastline is minor (about 10%; Olivotti *et al.,* 1986a; Malačič *et al.,* 2006), and might have an impact on the ecology of the inner shallow bays.

Mean monthly temperatures in the last ten years vary from 9.2 to 25.0 °C, with salinity fluctuating from 32.8 to 36.7, showing quick changes in the upper layers of the water column. Statistical analysis of the inter-annual variations of mean seasonal temperatures over the past ten years show an increase in temperature between 0.12 and 0.23 °C per year. In addition, an inter-annual trend for increasing salinity in the surface layer of the Gulf was observed (Malačič *et al.,* 2006). Strong variations of sea water temperature, stratification of the water column and total irradiance during the year determine the pronounced seasonal cycles in the Gulf of Trieste (Malačič & Petelin, 2001).

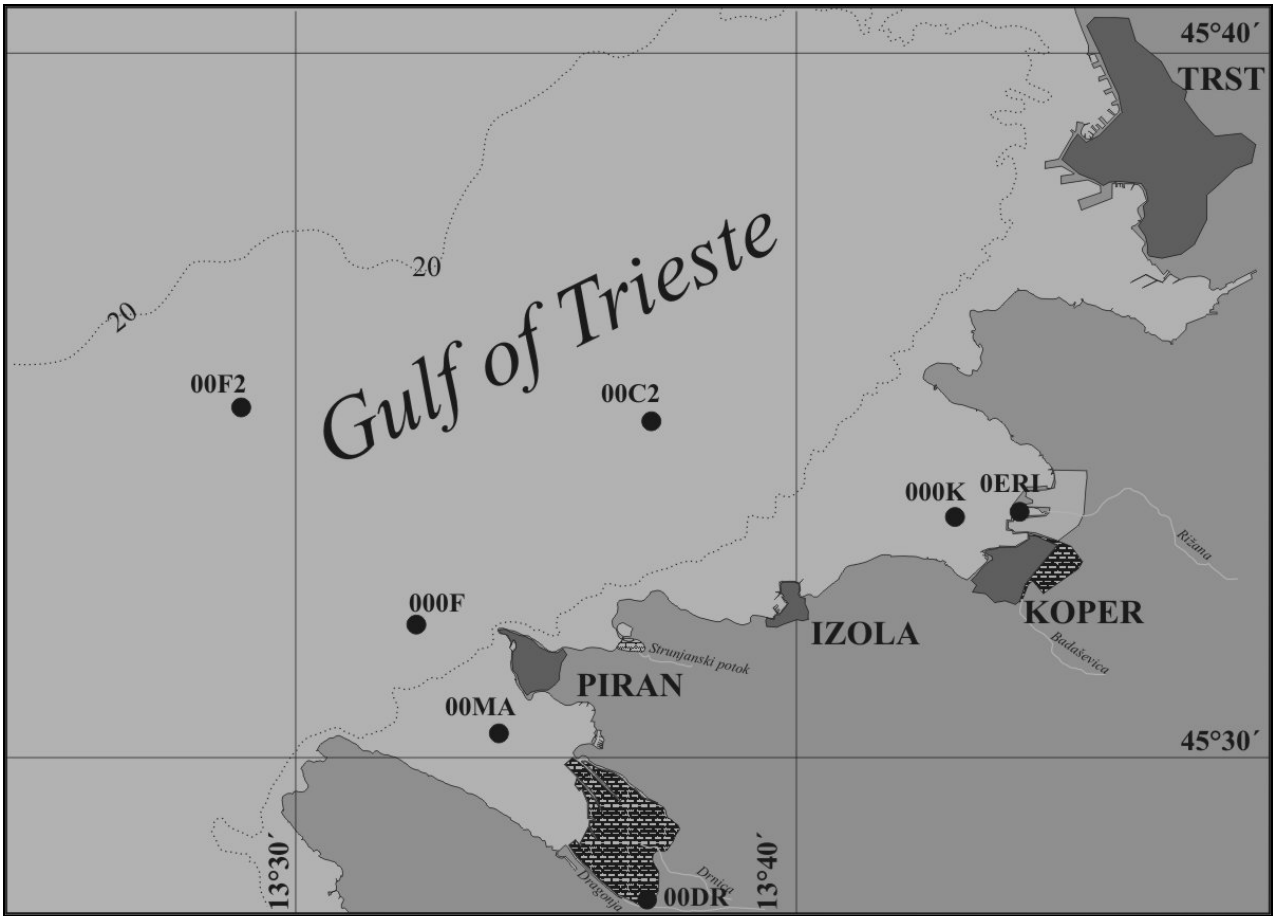

Fig. 1: Location of sampling stations for the purpose of eutrophication monitoring in the Slovenian sea (Gulf of Trieste).
Sl. 1: Prikaz merilnih mest evtrofikacijskega monitoringa v slovenskem morju (Tržaški zaliv).

LAND-BASED SOURCES OF POLLUTION AND TROPHIC STATUS OF MARINE ENVIRONMENT

Impact of anthropogenic nutrient inputs on the quality of the coastal waters has been studied in the Gulf of Trieste since the early seventies (Štirn, 1968, 1971a, 1971b; Štirn *et al.,* 1974; Olivotti *et al.,* 1986a, 1986b; Štirn, 1993). The main sources of potential pollutants, including those from fresh water inflows and sewage discharges into the Gulf of Trieste, were presented by Olivotti *et al.* (1986a, 1986b), whereas those directly affecting the Bay of Koper were studied by Turk & Potočnik (2001). According to the data and criteria of the severity of the effects on the marine environment, the estuaries of the Rižana and Badaševica rivers are the main pollution hot spots along the Slovenian coast (Turk & Potočnik, 2001). The rivers receive mainly untreated or primarily treated urban and industrial wastewater from the town of Koper and inland agglomerations along the river banks. The input of some pollutants into the coastal sea is estimated annually on the basis of the average flow rates and average concentrations of pollutants in the river estuaries and at the outlets of wastewater treatment plants (WWTP) in Koper and Piran (Tušnik *et al.*, 1989; Turk *et al.,* yearly reports 2000–2006). The gross fluxes for suspended solids, nitrogen and phosphorous attained the 2340 t, 935 t and 45 t per year, respectively (Tab. 1) for the 2000–2006 period. The evaluation inputs do not differ if compared with previous years (Tušnik *et al.*, 1989). Statistical evaluation of maximal values of nutrient concentrations from seasonal measurements in river estuaries along the Slovenian coast showed an increase in total nitrogen and decrease in total phosphorous for the 1988–2006 period (Fig. 2). The quantities of estimated inputs along the Slovenian coast are minimal in comparison with other areas of the Northern Adriatic (Tušnik *et al.*, 1989; Pagnotta *et al.*, 2000). However, high inputs of nitrogen and phosphorous influence the quality of the estuary in the inner part of the Bay of Koper.

The impact of organic and bacterial polluted wastewater discharged into the stratified estuary of the Rižana River and the inner part of the shallow Bay of Koper was studied only in the late 80's (Faganeli & Turk, 1989; Turk & Faganeli, 1990). The results of seasonal measurements of chemical and bacterial parameters showed that dissolved organic matter is mainly controlled by bacteria and related to the water temperature and river discharge. Dissolved organic nitrogen and dissolved organic phosphorous are mineralized and ammonia is nitrified, while dissolved organic carbon is controlled by mineralization and chemical precipitation. During the summer, when the estuary is characterized with low flow rate and high water temperature, oxygen and nitrate depletion prevail, showing dominance of denitrification processes. The application of such biogeochemical studies is important for prediction of anthropogenic impacts on small estuaries and inner part of the bays. The high concentrations of faecal coliforms, as the main pollution indicators, were found in the area close to the main sewage outfall. The concentration of faecal bacteria declined towards the middle of the Bay of Koper, and could be detected approximately 400–800 m from the pollution source (Lenarčič, 1980; Turk *et al.,* 1982; Turk, 1987).

In the seventies and eighties, several studies examined the impact of untreated sewage on ecosystems in experimental lagoons (Malej *et al.*, 1979; Vukovič, 1994), and the impact of the underwater sewage outfall on surroundings in the Bay of Piran (Avčin *et al.,* 1979; Malej *et al.,* 1979, 1980a). In sewage pollution experiments in the enclosed lagoon system, the phytoplankton biomass was significantly reduced and phytoplankton community changed (Fanuko, 1984). In contrast, a high

Tab. 1: Gross input of total phosphorous (Tot P), total nitrogen (Tot N) and total suspended solids (TSS) in the Slovenian coastal sea in the 1989–2006 period. Estimates are based on yearly average flow rates and on nutrient/TSS concentrations in the riverine inflows and in the effluents of wastewater treatment plants (WWTP).

Tab. 1: Celoten vnos celokupnega fosforja (Tot P), celokupnega dušika (Tot N) in suspendirane snovi (TSS) v slovensko obalno morje v obdobju 1989–2006. Ocena vnosa je narejena na osnovi povprečnih letnih pretokov in koncentracij hranil/TSS v rečnih pritokih in odplakah čistilnih naprav (WWTP).

Inflows / effluents	**Flow rate (10^6 m^3 yr^{-1})**	**Tot P (t yr^{-1})**	**Tot N (t yr^{-1})**	**TSS (t yr^{-1})**
Rižana	110	4	464	1136
Badaševica	8.5	1	63	45
Drnica	8.9	2	48	52
Dragonja	23	1	89	98
WWTP Koper	4.3	22	146	581
WWTP Piran	3.4	15	125	428
Total		**45**	**935**	**2340**

concentration of nutrients provoked a proliferation of the nitrophilic benthic macroalgae, mainly *Ulva rigida* (Vukovič, 1994). More recently, yearly studies examined the distribution of wastewater in the water column from diffusers of the Piran sewage outfall (Malačič & Vukovič, 1997; Malačič *et al.*, 2000). The initial spread of sewage from diffusers in the Bay of Piran was studied with numerical modelling (Malačič, 2001), whereas the impact of nutrients on selected biological parameters has been presented by Mozetič *et al.* (1999) and Flander Putrle & Malej (2003). The influence of anthropogenic emissions was also recorded by the measurements of atmospheric depositions during the 10 June – 10 September 1993 period (Malej *et al.*, 1997). Rainfall events delivered considerable amount of nutrients (127 t of nitrogen and 9.5 t of phosphorous), which enhanced primary production and phytoplankton biomass in mesocosm experiment as well as in field measurements, and were connected with a shift in community structure of phytoplankton (Malej *et al.*, 1997).

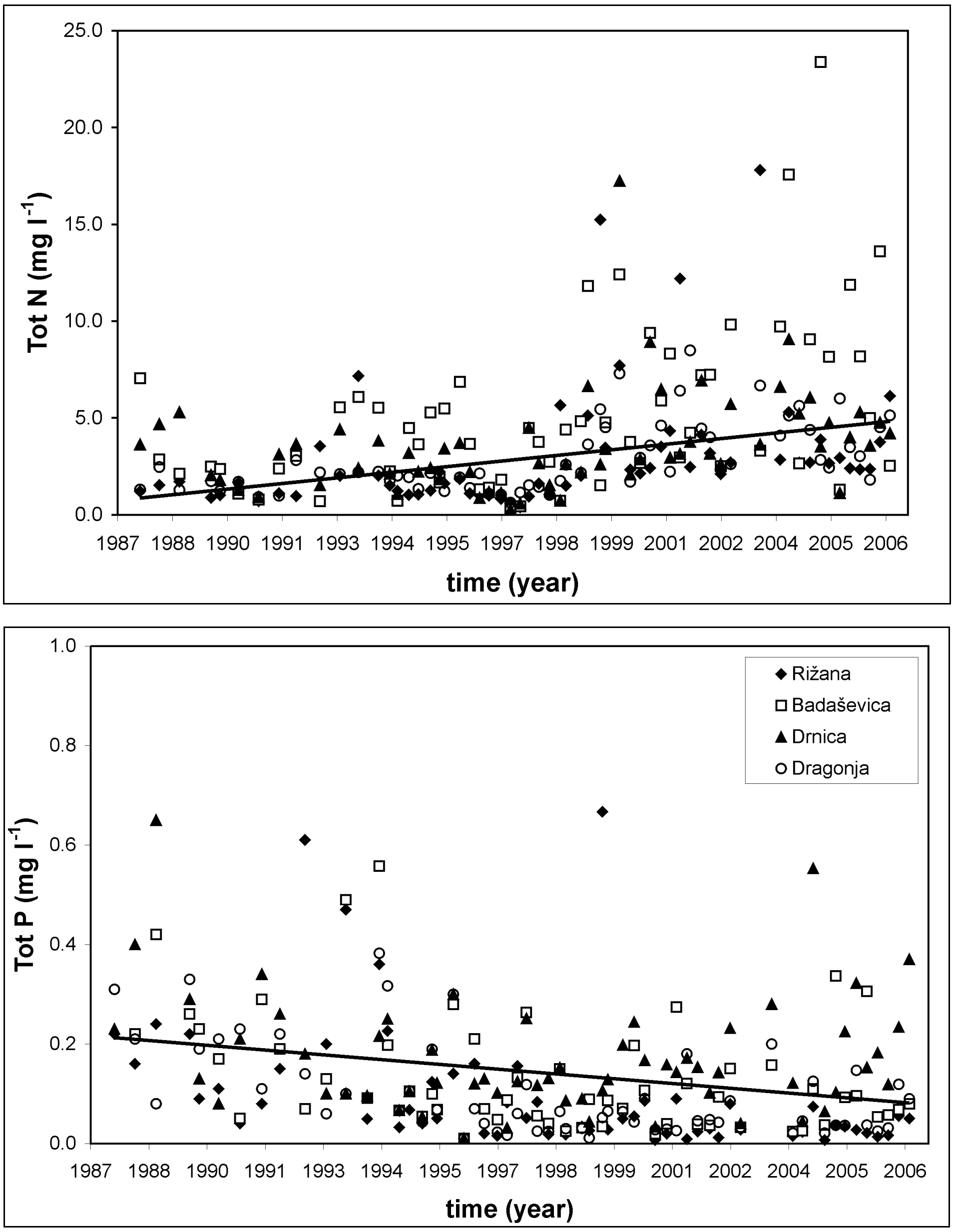

Fig. 2: Total nitrogen (top) concentrations and total phosphorus (bottom) concentrations in the river estuaries (Rižana, Badaševica, Drnica, Dragonja) along Slovenian coast in the 1988–2006 period.
Sl. 2: Koncentracije celokupnega dušika (zgoraj) in celokupnega fosforja (spodaj) v estuariju rek (Rižana, Badaševica, Drnica, Dragonja) vzdolž slovenske obale v obdobju 1988–2006.

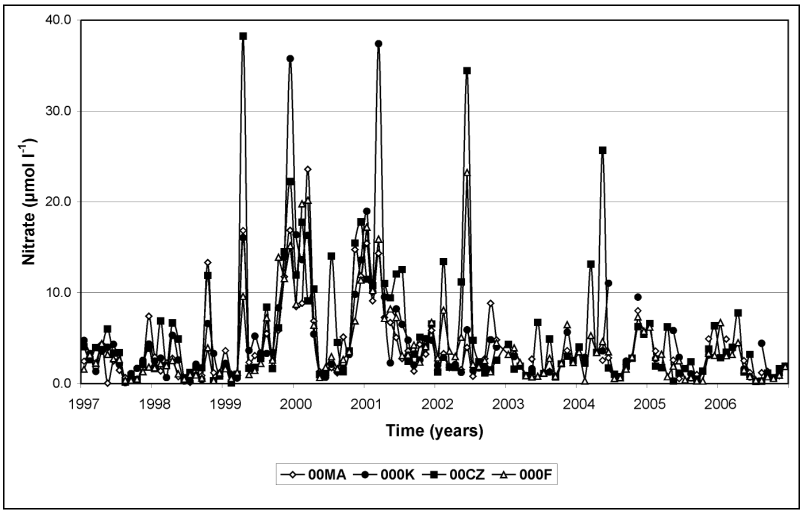

Fig. 3: Concentrations of nitrate in the surface layer in the Gulf of Trieste in the 1997–2006 period.
Sl. 3: Koncentracije nitrata v površinskem sloju v Tržaškem zalivu v obdobju 1997–2006.

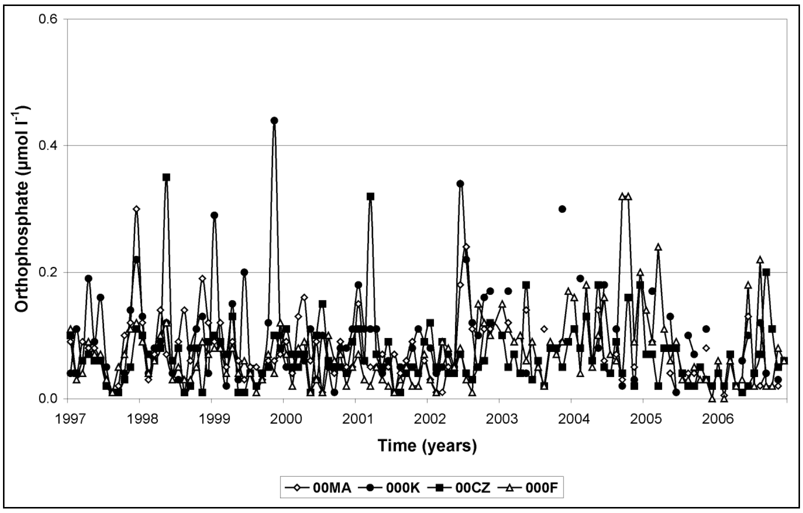

Fig. 4: Concentrations of orthophosphate in the surface layer in the Gulf of Trieste in the 1997–2006 period.
Sl. 4: Koncentracije ortofosfata v površinskem sloju v Tržaškem zalivu v obdobju 1997–2006.

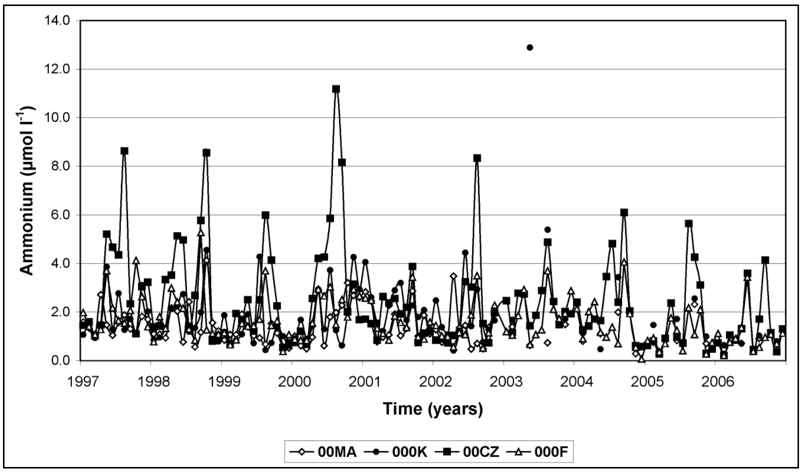

Fig. 5: Concentrations of ammonia in the bottom layer in the Gulf of Trieste in the 1997–2006 period.
Sl. 5: Koncentracije amonija v pridnenem sloju v Tržaškem zalivu v obdobju 1997–2006.

River inputs influence the dynamics of nutrients in the Gulf's sea water (Faganeli, 1983; Faganeli & Tušnik, 1983; Olivotti *et al.* 1986a, 1986b; Tušnik *et al.,* 1989; Mozetič *et al.*, 2005). High concentrations of inorganic nitrogen, especially nitrate, at the sea surface generally coincide with lower salinity. The concentration of nitrate in the surface is high in winter, low in summer and rises again in late autumn. Nitrate values generally range from 0.2 to 20.0 µmol l^{-1} with a peak around 40 µmol l^{-1} (Fig. 3). Concentrations of orthophosphate are generally low, the highest being below 0.5 µmol l^{-1} (Fig. 4). The values in the surface and in the bottom layer are fairly equal, with the dynamics varying from month to month and year to year. The ammonium concentrations are higher in layers above bottom (between 0.07 and 11.5 µmol l^{-1}) (Fig. 5), due to the intense regeneration processes during late summer and autumn. Higher ammonium concentrations coincide with increased concentrations of silicate and low concentration of oxygen (Turk *et al.,* 2000). Nutrient concentrations, N:P ratios in the ambient pool of inorganic nutrients, and bioassays indicate that both phytoplankton biomass and growth rates are P-rather than N-limited in the Northern Adriatic Sea (review in Malone *et al.*, 1999). Enrichment experiments proved that phosphorous has been the primary limiting element for the growth of phytoplankton as well as for bacterioplankton in the Gulf of Trieste (Mozetič *et al.,* 1998a; Cauwet *et al.*, 1999; Fajon *et al.*, 1999; Malej *et al.*, 2003).

Individual studies on the variability of organic nitrogen, organic phosphorus and dissolved organic matter along the Slovenian coast were performed only during the 1983–1990 period (Faganeli, 1983; Faganeli & Herndl, 1991). The influence of processes occurring in the marine sediment on organic carbon and nitrogen cycling in the sea water column is evident in the shallow Gulf of Trieste (Faganeli *et al.*, 1987; Herndl *et al.*, 1987; Bertuzzi *et al.*, 1996).

In recent years, the trophic status of the eastern part of the Gulf has been assessed by means of a numeric scale, *i.e.* the Trophic Index (TRIX) (Vollenwaider *et al.*, 1998). According to the TRIX classification criteria, the annual mean values of <4 correspond to elevated trophic state, scarce productive waters and good coastal quality condition. The mean annual value between 4 and 5 corresponds to good trophic state, moderately productive waters with occasional water turbidity, anomalous water colours and bottom water hypoxia episodes. The annual TRIX values between 5–6 and < 6 correspond to mediocre and bad trophic status, indicating very productive waters with high water turbidity, persistent anomaly in the water colour and regular anoxic episodes with high mortality rate of benthic organisms as well as other effects on the state of the ecosystem (*e.g.* decreased biodiversity). Apart from concentrations of dissolved inorganic nitrogen, total phosphorus and chlorophyll *a*, the proposed index also observes oxygen saturation. The TRIX calculated values at stations in coastal waters during the 2004–2006 period fell mostly between 3 and 4 (Fig. 6). Seasonal variability is characteristic, with lower values during the summer months and peak values in spring and autumn. Oscillations are more pronounced in the surface layer, with the TRIX values varying particularly at station in the middle of the Gulf. The TRIX values are higher in the inner part of the Bay of Koper, due to the effects of the Rižana River inflow, compared to the lower values along the transect from the middle of the Bay of Piran and at reference station (sampling station 000F) where the anthropogenic impact is negligible. Overall, according to the trophic TRIX and Fp indexes, calculated from the analyses of phytoplankton pigments biomarkers (Flander Putrle & Malej, 2003), the Gulf of Trieste could be classified as oligotrophic and in some parts as moderate eutrophic area, especially in the inner part of the Bay of Koper.

VARIABILITY OF PHYTOPLANKTON

A large spatial, seasonal and inter-annual variability of plankton has been documented for the Gulf of Trieste. Variability depends upon the combined effects of the river nutrient input, meteorological conditions, the degree of water column stratification and horizontal water advection from the middle Adriatic (Malej *et al.*, 1995; Mozetič *et al.*, 1998b; Malačič & Petelin, 2001). Studies on phytoplankton taxonomy have been performed since the mid-1800s and they covered mainly abundances of the most common species of microphytoplankton (review in Fanuko, 1980; Fonda Umani *et al.*, 1990; Harding *et al.,* 1999). Phytoplankton studies since the 1970s' have shown the importance of the autotrophic nanoplankton fraction (Fonda Umani *et al.*, 1990; Mozetič *et al.*, 1998b). Picoplankton fraction was evaluated only recently (Fanuko & Turk, 1990; Turk *et al.*, 2001a; Fuks *et al.*, 2005).

The variability of phytoplankton biomass and structure has been systematically followed along the Slovenian coast since 1976 (Fanuko, 1980, 1981; Mozetič *et al.*, 1998b, 2005). Seasonal, monthly, weekly and even daily sampling of phytoplankton demonstrated abrupt changes in abundance and community composition in phytoplankton assemblages (Fanuko, 1981, 1990). The relationship between nutrients and chlorophyll biomass has been studied in the Bay of Koper (Fanuko & Justić, 1986). More recently, a study performed over 14-year period evaluated trends of phytoplankton biomass in relation to physical and chemical parameters (Mozetič *et al.*, 2005). Although changes of nutrients through time were observed, there was no statistically significant trend in phytoplankton biomass that could be related to the eutrophication of the area (Mozetič *et al.*, 2005). The overall means of chlorophyll *a* concentrations over the past 14 years (1989–2002) at five sampling stations were between 1.0 and 1.3 μg l^{-1} (Fig. 7) with absolute values ranging from 0.2 to 8.8 μg l^{-1}. The highest values are characteristic of the Bay of Koper and for the centre of the Gulf, while the lowest values are found at reference station, which is affected by oligotrophic waters from the southern Adriatic. Seasonal distribution of mean chlorophyll *a* values indicated great differences between months (Fig. 8). High values are measured from February to April, but after reaching the spring peak values, they are relatively modest in May and June. During the summer months, chlorophyll *a* concentrations are the lowest, while in October and November concentrations reach the second seasonal peak. Inter-annual differences between mean values are also quite significant, although no trend was detected in the 1989–2002 period (Fig. 9). Although phytoplankton biomass increased gradually from 1993, it dropped below 1 μg l^{-1} again in 2000; in 2001 and 2002, it did not differ significantly from the 1989–1991 period.

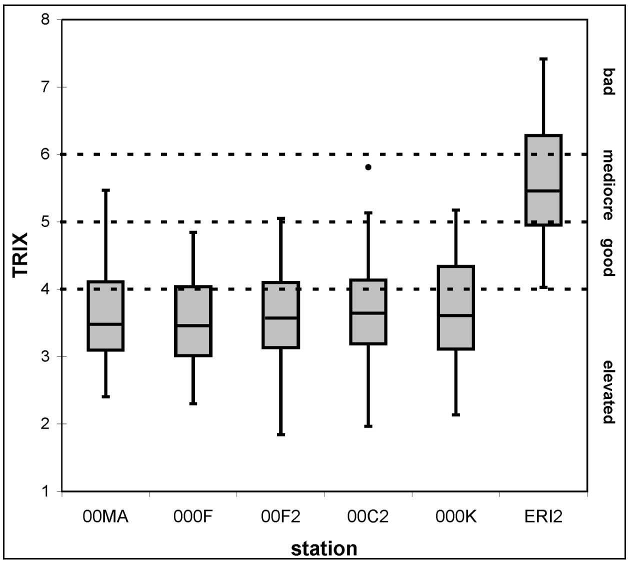

Fig. 6: Boxplots of TRIX index of the six sampling stations in the Gulf of Trieste (2004–2006 period).
Sl. 6: Boxplot graf za vrednosti TRIX indeksa na šestih merilnih mestih v Tržaškem zalivu (obdobje 2004–2006).

Eutrophication effects can also be displayed as a shift in algal species composition and an increase in the frequency and intensity of nuisance algal blooms. The most important groups of phytoplankton in the Gulf of Trieste are nanoflagellates that include various classes of autotrophic flagellates, and are followed by diatoms, dinoflagellates, coccolithophores and silicoflagellates. The results of monthly measurements of phytoplankton abundance in the 1989–2002 period showed a rather uniform annual distribution of total abundance with some inter-annual changes of particular phytoplankton groups (Mozetič & Francé, 2004). Diatoms and nanoflagellates maintain a very constant distribution and abundance throughout the years, but with different seasonal characteristics. Nanoflagellates are the dominant group in spring, while diatoms abrupt significantly in late autumn as well as in July. Dinoflagellates and coccolithophores are characterized by larger inter-annual changes, due to different occurrence/absence of seasonal blooms (Mozetič & Francé, 2004). This general picture of phytoplankton community structure and total abundance would suggest that physical-chemical and biological (*e.g.*, grazing) properties of the Gulf of Trieste remained relatively stable in the 1989–2002 period or they did not affect the structure at the group level.

As a complement to the classical optical methods of the group-specific phytoplankton biomass has been assessed using the reverse-phase high pressure liquid chromatography (HPLC) method. Results of the most prominent biomarker pigment indicated that the increase in chlorophyll is mainly due to diatoms, generally the most represented group during spring and autumn at the surface layer and below the pycnocline layer during the summer months (Flander Putrle *et al.*, 2000). This was also the main phytoplankton group found in mucilage aggregates (Baldi *et al.*, 1997; Flander Putrle *et al.*, 2000). In the spring period, the contribution of 19'-hexanoyloxyfucoxanthin containing phytoplankton (prymnesiophytes) has been significant preceding the accumulation of gelatinous material (Flander Putrle & Malej, 2003; Turk *et al.*, 2005b). Picoplankton is also a substantial component of the autotrophic biomass and production in the Gulf of Trieste (Fanuko & Turk, 1990; Turk *et al.*, 1992) as well as in the entire northern Adriatic (Fuks *et al.*, 2005). Unicellular cyanobacteria may represent 10–42% of the total autotrophic carbon, an estimate based on chlorophyll measurements. Some blooms of cyanobacteria start in spring, but during the summer cell densities increase rapidly and remain relatively high throughout the summer (Turk *et al.*, 2001a; Fuks *et al.*, 2005).

VARIABILITY OF OTHER MICROORGANISMS

The species composition of the bacterial community is largely unknown. The bacterioplankton assemblage has been treated, until now, as a single group, classified by dominant cell shape and determined by abundance and activity. Free living heterotrophic bacteria are not randomly distributed vertically and horizontally, according to concentration gradients in microenvironments in order to maximize dissolved organic matter uptake. The abundance of heterotrophic bacteria (0.7 to 2.0×10^{9} cells l^{-1}) is within the range reported for other coastal areas in the northern Adriatic Sea (Turk, 1992;

Turk & Hagström, 1997; Turk *et al.*, 2001a). The bacterial production measured with the tritiated tymidine incorporation method varied between 0.5 and 16 µg C l^{-1} d^{-1}, showing seasonal and diel variations. The ratio between production and biomass (P/B ratio) indicated turnover of between 0.28 and 1.1 times per day, with higher rates during the summer. Similar results were obtained by measuring the bacterial growth rates *in situ*, using dialysis bags (Herndl *et al.,* 1987). Bacterial nutrient incorporation and remineralization is controlled by the substrate's chemical composition and bacterial gross growth efficiency.

Bacterial abundance shows a remarkable stability in most aquatic systems. The seasonal dynamics of heterotrophic organisms at different trophic levels and function in pelagic communities was first studied during the 1986–90 period in sea waters of the eastern part of the Gulf (Northern Adriatic) (Turk, 1992). Monthly sampling of microorganisms and dissolved carbohydrates over the two-year period in the Gulf of Trieste suggested that accumulation of dissolved carbohydrates occurred when bacterial abundance was controlled by predators (Turk *et al.*, 2001a). During the summer months, when oligotrophic conditions prevailed, the processes of transformation of organic matter through a microbial loop type of food web are important in the water column. The seasonal fluctuation of bacterial standing stocks and bacterial growth are not correlated over time due to mortality and predation.

Most of the bacterial biomass is utilized by protozoa, as shown by measurements of protozoa grazing on bacteria and the recorded growth of nanoflagellates (Turk *et al.*, 1992; Turk & Hagström, 1997). Heterotrophic nanoflagellates are the major consumers of bacteria, since the flagellates can efficiently capture marine bacteria. The number of heterotrophic nanoflagellates varied between 0.4 and 3.5×10^{6} cells l^{-1} in the Gulf of Trieste. The variation in numbers and their relationships with bacteria have been shown in a two-stage chemostate experiment and in diel measurements of *in situ* measurements in the Gulf of Trieste (Turk *et al.*, 1992). In the bag experiment, ^{14}C-labeled bacteria were incorporated into nanoflagellate size fractions, and only a limited amount of label was transferred into larger size fractions, due to predation. The range of predation varied between 2 and 14×10^{7} cells l^{-1}, which represent an ingestion rate of between 44 and 85 bacterial cells per flagellate per hour.

While consuming bacteria, nanoflagellates release a substantial amount of dissolved organic matter, such as dissolved DNA. The degradation and transfer of phosphorous from ^{32}P-labeled plasmid DNA added to seawater samples from the station in the Gulf of Trieste indicated a rapid turnover of DNA (4.7 hours) mediated a release of inorganic phosphorous. Furthermore, a tight coupling between released inorganic phosphorous and uptake by nano- and picoplankton size fraction was demonstrated. In P-limited systems, the coupled uptake of released phosphate has been shown to be effective, and bacteria compete efficiently with algae (Turk *et al.,* 1992). Bacteriophages have been also suggested as an important factor for bacterial mortality in the Gulf of Trieste (Baldi *et al.,* 1997; Stopar *et al.*, 2004). The total viral abundance ranged between 2.5 and 29×10^{9} per litre. According to virus morphology determined by transmition electron microscopy, bacteriophages represent a significant (26%) fraction of the virus community. A relatively high occurrence of lysogenic bacteria in the Gulf of Trieste suggests that temperate phages may be important component of virioplankton (Stopar *et al.*, 2004). More recent results also showed that the bacterial lysate released as dissolved organic matter and their nutritional quality determine the growth rate and activity of other bacteria (Odić *et al.*, 2007).

Beside nanoflagellates, some studies suggest that ciliates and certain other protists are important consumers of bacteria and phytoplankton, which might influence the food web structure and function. An overview of seasonal patterns in organism abundance and biomass, species composition and the ecological roles of micro-consumers for the Northern Adriatic are presented by Coats & Revelante (1999). Little information is available on microzooplankton predation in the Gulf of Trieste (Lipej, 1992; Lipej *et al.*, 1997; Coast & Revelante, 1999). Ciliated protozoa constitute 89–99% of total microzooplankton abundance and 12–52% of the community biomass (Coats & Revelante, 1999). The study of inter-annual variations of plankton food webs confirmed high year-to-year variations in microzooplankton and mesozooplankton abundances and taxonomic composition during the 1999–2002 period (Fonda Umani *et al.*, 2005). Significant decrease in abundance of ciliate protozoa due to the total number of microzooplankton and dominance of *Oithona nana* has been recorded during the presence of mucous aggregates (Kršinić, 1995).

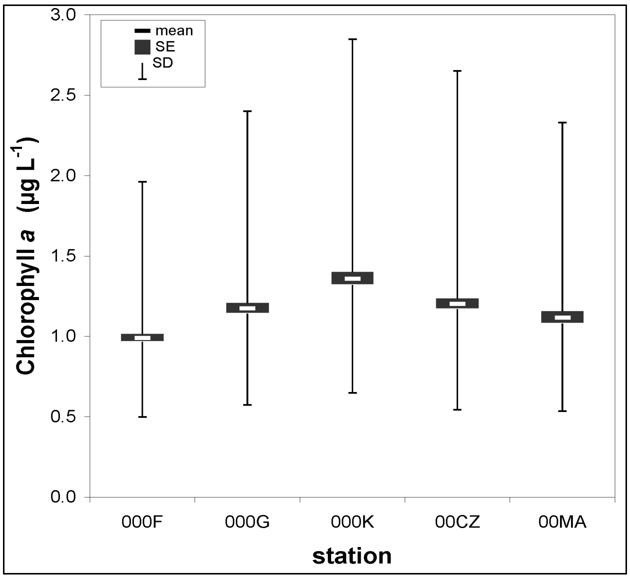

Fig. 7: Overall means of chlorophyll** a **concentrations (along the water column and in 14-year period) of five sampling stations in the Gulf of Trieste, 1989–2002 period.

Sl. 7: Celotne srednje vrednosti koncentracij klorofila** a **(vzdolž vodnega stolpa in v 14-letnem obdobju) na petih merilnih mestih v Tržaškem zalivu, obdobje 1989–2002.

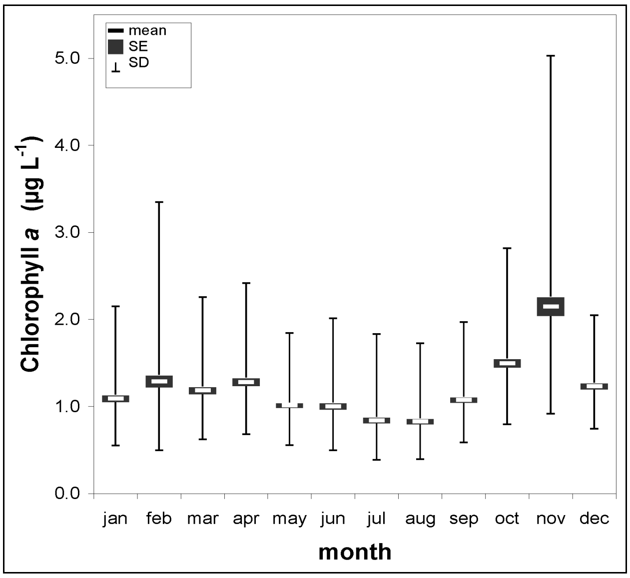

Fig. 8: Seasonal distribution of monthly means of chlorophyll** a**, consdering a 14-year period (1989–2002) and five sampling stations in the Gulf of Trieste (the same as in figure 7).

Sl. 8: Sezonska porazdelitev mesečnih srednjih vrednosti klorofila** a**, upoštevaje 14-letno obdobje (1989–2002) in pet merilnih mest v Tržaškem zalivu (iste kot na sliki 7).

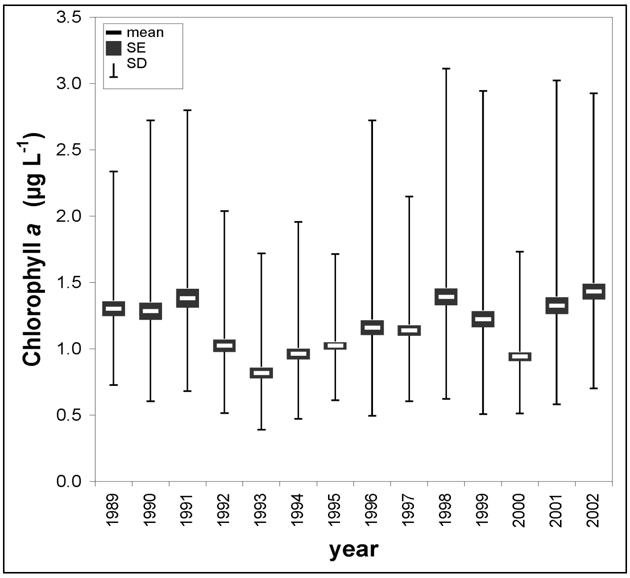

Fig. 9: Variations of annual means of chlorophyll** a**, consdering a 14-year period (1989–2002) and five sampling stations in the Gulf of Trieste (the same as in figure 7).

Sl. 9: Variacije letnih srednjih vrednosti klorofila** a**, upoštevaje 14-letno obdobje (1989–2002) in pet merilnih mest v Tržaškem zalivu (iste kot na sliki 7).

VARIABILITY IN PRIMARY PRODUCTION

Several studies of primary production have been performed on the Slovenian and Italian sides of the Gulf (Faganeli *et al.*, 1982; Fonda Umani & Ghirardelli, 1988; Malej *et al.*, 1995; Cabrini *et al.*, 2002; Cantoni *et al.*, 2003), with results indicating large variations.

First measurements of primary production in the southeastern part of the Gulf date back to the early 80's (July 1979 – June 1980; Faganeli *et al.*, 1982) and results vary from 0.8–14 mg C m^{-3} d^{-1}, giving an average annual estimate of 42 g C m^{-2} a^{-1}. Daily values of primary production measurements performed a decade later, i.e. in 1992 (Malej *et al.*, 1995), are higher than those reported by Faganeli *et al.* (1982), ranging from 2.3–57 mg C m^{-3} d^{-1}. However, an annual estimation was not made due to incomplete sampling across the seasonal cycle.

In the northwestern part of the Gulf, the latest primary production measurements encompass the period from October 1999 to February 2001, including the year 2000 with mucilage event (Cantoni *et al.*, 2003). The maximal daily rates (190 mg C m^{-3} d^{-1}) are much higher as compared to the southeastern part (see above), whereas the lowest rates (2.4 mg C m^{-3} d^{-1}) are very similar. However, the comparison of daily production rates, especially the highest one, between the southeastern and northwestern part of the Gulf is not strictly consistent. The latter measurements from 1992 in the southeastern part did not cover the entire annual cycle, thus the highest rate could be well underestimated.

Daily and annual primary production rates indicate relatively low pelagic production and are lower for the entire Gulf of Trieste compared to the estimates reported for the northern Adriatic. Residence time of freshwater and availability of the nutrients determine the rates of production in the Gulf of Trieste (Cantoni *et al.*, 2003). Comparisons of annual phytoplankton production with riverine nutrient inputs suggest that recycling nutrients support about 50% of phytoplankton production in the northern Adriatic (Harding *et al.,* 1999).

PLANKTON BLOOMS

In spite of the frequent plankton surveys carried out since the beginning of the 20th century, only few plankton records on blooms in the Adriatic Sea are at hand for the period prior to the 1970s (Fanuko, 1990; review in Sellner & Fonda Umani, 1999). In the Gulf of Trieste, algal blooms occurred more frequently in shallow areas, such as lagoons, bays and harbours (Tab. 2), but with lower intensity and frequency along the Slovenian coast compared to more eutrophic areas along the western coast, *i.e.* Emilia-Romagna region. Events resulting in visible water discolorations are linked mainly to highly stratified systems and the spring/summer period. For the Gulf of Trieste, there is a historical record from November 1902 on blooms of heterotrophic dinoflagellate *Noctiluca scintillans* (Sellner & Fonda Umani, 1999). A large-scale red tide of *N. scintillans* covering the entire Northern Adriatic was observed in June 1977 (Fonda Umani *et al.*, 2004). A red tide caused by the same organisms re-appeared in the summers of 1980, 1981 and 1983 (Malej, 1983; Honsell *et al.*, 1989; Fonda Umani *et al.*, 2004). After that, *N. scintillans* remained a constant plankton component until 1997, when summer bloom appeared yet again. During the 1970s, aggregations of *Peridinium ovum,* causing discoloration of the water, were recorded (Bussani, 1974). In June and September 1977, *Lingulodinium polyedrum* (syn. *Gonyaulax polyedra*) bloom was observed (Fonda Umani, 1985). Discoloration of sea water due to *Exuviella marina* was recorded in Trieste Harbour in June 1981. The sea was coloured brown due to *L. polyedrum* bloom also in 1978 and again in the entire Gulf of Trieste in September 1982. At the end of May 1983, *Scrippsiella faeroense* bloom was recorded in the inshore areas (Fonda Umani & Honsell, 1984), and there was a large bloom of *Gymnodinium* spp. in the whole northern Adriatic in the autumn 1984 (Artegiani *et al.*, 1985). During the 1986–89 period, several winter diatom blooms were recorded, such as *Hemiaulus hauckii* bloom in December 1987, which lasted until February 1988 with maximum chlorophyll *a* concentration of 12 $\mu g\ l^{-1}$ (Fanuko & Turk, 1990). Other blooms were also recorded, such as that of silicoflagellate species *Distephanus speculum* at a depth of 20 m (up to 0.6×10^{6}

Tab. 2: Records of plankton blooms and unusual events in the Gulf of Trieste during the 1970-2005 period.
Tab. 2: Zapisi planktonskih cvetenj in nenavadnih dogodkov v Tržaškem zalivu v obdobju 1970-2005.

Species / event	Year	Author
Peridinium ovum	1973	Bussani, 1974
Lingulodinium polyedrum (syn. *Gonyaulax polyedra*)	1977, 1978, 1982	Fonda Umani, 1985; Fanuko, 1990
Noctiluca scintillans	1977, 1980,1981, 1983, 1990, 2004	Cassinari *et al.*, 1979; Malej, 1983; Honsell *et al.*, 1989; Fonda Umani *et al.*, 2004
Exuviella marina	1981	Fonda Umani, 1985
Gonyaulax polyedra	1982	Fonda Umani, 1985
Scrippsiella faeroense	1983	Fonda & Honsell, 1984
Distephanus speculum	1983	Fanuko, 1989
Rhizosolenia alata f. *gracillima*	1983	Fanuko ,1984
Gymnodinum spp.	1984	Artegiani *et al.*, 1985
Prorocentrum micans	1984	Fanuko, 1990
Hemiaulus hauckii	1987/88	Fanuko & Turk, 1990
mucus aggregates	1988,1989,1991,1997, 2000, 2001, 2002, 2004	Fonda Umani *et al.*, 1989; Stachowitsch *et al.*, 1990; Sellner & Fonda Umani, 1999; Malej *et al.*, 2001; Precali *et al.*, 2005

cells l^{-1}), which may have contributed to anoxic conditions in August 1983 (Fanuko, 1989). Water discoloration by summer blooms of *Rhizosolenia alata* f. *gracillima* diatom were recorded along the Istrian coast in 1922, and appeared regularly in the 1977–1983 period (with abundance of $0.3–0.5\times10^6$ cells l^{-1}) (Fanuko, 1984a). A monospecific red tide of *Prorocentrum micans* dinoflagellate was recorded in the autumn of 1984 (Fanuko, 1990). The records of dominant phytoplankton bloom species in the Gulf of Trieste are summarized in Table 2 for the 1970–2005 period.

OCCURRENCE OF TOXIC PHYTOPLANKTON SPECIES

Increased abundance of some dinoflagellate and diatom species may sometimes have harmful consequences on the marine organisms as well as on humans. Among various types of intoxication, three are of major concern in the Gulf of Trieste, since the causative organisms are commonly found in the northern Adriatic. First is the diarrhetic shellfish poisoning (DSP), which is caused mainly by various dinoflagellate species of the genus *Dinophysis*. Other potentially toxic species that also produce DSP-related lipophilic toxins (yessotoxins) are *L. polyedrum* and *Protoceratium reticulatum*. Both are commonly found in the phytoplankton community of the Gulf of Trieste. Second, and more dangerous, is paralytic shellfish poisoning (PSP), which is caused by some dinoflagellate species of the genus *Alexandrium*. Recently (in 2006), analyses of ASP (amnesic shellfish poisoning) commenced due to regular occurrence of some diatom species of the genus *Pseudo-nitzschia*. At shellfish farms on the Slovenian coast, DSP toxins occur almost every year. Temporary bans of shellfish farms from 1989 onwards are quoted in Sedmak *et al.* (2003).

The first documented outbreak of DSP in Slovenian coastal waters dates from the autumn-winter 1989 period (Fanuko *et al.*, 1989; Sedmak & Fanuko-Kovačić, 1991); it was related to the occurrence and increased abundance of various *Dinophysis* species. Besides this event, several authors (Honsell *et al.*, 1992, 1996; Mozetič *et al.*, 1997) reported on the regular occurrence of toxic dinoflagellates over short time (mainly warm) periods in the Gulf of Trieste.

A longer series of data was evaluated for the 1995–2003 period (Francé & Mozetič, 2006a), showing the seasonal distribution and inter-annual variations of *Dynophysis* species. Comparison between 4 most recurrent *Dinophysis* species and environmental factors showed that only one and the most abundant species (*D. sacculus*) was significantly correlated to the specific environmental conditions (i.e. thermal and haline stratification), while none of the inorganic nutrients influenced the distribution and abundance of *Dinophysis* spp. *D. sacculus* appears to be influenced by freshwater inputs in other coastal Mediterranean areas as well (Caroppo, 2001; Villa *et al.*, 2001).

Contrary to the seasonal dynamics of the genus *Alexandrium*, which is found in relatively low numbers in colder months (early spring, autumn) but does not form toxic blooms, the abundance of *Dinophysis* spp. starts to increase with the warming of the sea in May and reaches its peak during the summer-early autumn months (Francé & Mozetič, 2006b).

JELLYFISH BLOOMS

Other massive plankton events in the northern Adriatic were outbreaks of large jellyfish, which may have a significant impact on fisheries, tourism and the food web trophic structures (Malej, 2001). Although eight scyphomedusae species have been determined over the last 150 years in the northern Adriatic (references in Purcell *et al.*, 1999), only a few of them have been observed in large numbers. Repeated massive occurrences of jellyfish in the northern Adriatic as well as in the Gulf of Trieste were recorded for *Aurelia aurita, Chrysaora hysoscella, Cotylorhiza tuberculata, Pelagia noctiluca* and *Rhizostoma pulmo* (Malej, 2001) (Tab. 3). *Aequorea forskalea* were mentioned several times since the 1970s. Most information is available for *P. noctiluca*, which was recorded in masses during two periods, during 1910–1914 and 1976–1986 (Malej, 1981, 2001; Malej & Vukovič, 1986; UNEP, 1991) and again during 2004–2006. Blooms of *P. noctiluca* have been shown to exert a significant influence on net zooplankton production, structure modification and releasing a considerable amount of nutrients (Malej, 1989).

Aurelia sp. has been abundant in the 1994–1997 period (Malej, 1995, 2001; Purcell *et al.*, 1999) and from 2004 on. Studies on *R. pulmo* started only recently (Malej *et al.*, 2006), but there has been no systematic study regarding the abundance and distribution of *C. tuberculata* and *C. hysoscella*.

Another plankton group, ctenophores, may be abundant in the Gulf of Trieste and the entire northern Adriatic in colder parts of the year (Malej, 2001). Enormous numbers of pteropod *Creseis acicula* were recorded in September 1974 and again in Jul/Aug 1990 near shore in the Bay of Piran (Malej, 2001). This species was again noted in 2007, but was not so abundant.

Tab. 3: Records of massive gelatinous zooplankton occurrence in four periods from 1971 to 2006 in the Gulf of Trieste.
Tab. 3: Zapisi masovnega pojavljanja želatinoznega zooplanktona v štitih zaporednih obdobjih v letih 1971–2006 v Tržaškem zalivu.

Organism	**1971–1980**	**1981–1988**	**1989–2000**	**2001–2006**
Hydromedusae				
Aequorea forskalea	+	+	++	++
Scyphomedusae				
Aurelia aurita	+	+	++	+
Chrysaora hysoscella		+	+	+
Cotylorhiza tuberculata	++	+		++
Pelagia noctiluca	++	++		+
Rhizostoma pulmo		+	+	+++
Ctenophora	+	+	++	++
Gastropoda				
Creseis acicula	++		+	+
Thaliacea	+	++	+	++

+ Event was observed once in the period
++ Event was observed several times in the period
+++ Event was observed every year during the period

OCCURRENCE OF MUCILAGE

Over the last 18 years, a shift from red tides to mucilage phenomena has been observed. Since 1988, almost every year a mucilage phenomena of different intensity appeared, manifested as dense macroflocs, cobweb, clouds, blankets, creamy/gelatinous layer (Stachowitsch *et al*., 1990; Precali *et al*., 2005) (Tab. 3).

In the Adriatic Sea, the occurrence of mucilage has been observed for at least two centuries: a record by Venetian authorities dated from 1729 exists, reporting mucilage masses covering coastal waters and making fishing impossible. This phenomenon was described for the first time in the Gulf of Trieste in 1872 (Syrski, 1872). The 18th and 19th century chronicles of the northern Adriatic towns and scientific journals reported similar events in 1873, 1880, 1881, 1892, 1893, 1903, 1905, 1906, 1920, 1928, 1930 and 1931 (Fonda Umani *et al*., 1989). Some describe this problem as local, while others mention mucilage masses spreading all over the northern Adriatic. More recently, large-scale mucilaginous aggregate formations occurred during the springs/summers of 1988, 1989, 1991, 1997, 2000, 2001, 2002 and 2004. The typology of aggregates was described by Stachowitsch *et al*. (1990) and more recently by Precali *et al*. (2005).

Large flocks reaching several cm are seasonally abundant in the northern Adriatic and have been generally related to decaying diatom blooms (Herndl & Peduzzi, 1988). Occasionally, masses of mucilage remain suspended in the water column of the northern Adriatic for up to several months during the summer stratified season (May to September), with the phenomenon dissipating by the time of autumnal vertical mixing (Degobbis *et al*., 1995; Malej *et al*., 1995; Sellner & Fonda Umani, 1999). The occurrence of mucilage is not limited to the Adriatic Sea. It is known all over the Mediterranean, especially in Greek waters, in the Tyrrhenian Sea and around the coasts of Sicily. In these areas, however, the mucilage masses usually stay in deeper layers of the sea and rarely emerge on the surface. Also, the duration is shorter than in the northern Adriatic. A similar phenomenon is known to occur in the Northern Sea, off the coasts of France, Belgium, The Netherlands and Germany, where foamy and mucilaginous masses accumulate in spring. Similar event to northern Adriatic mucilage is also reported from the coastal waters of New Zealand, where a dinoflagellate species *Gonyaulax hyalina* is repeatedly involved in the release of polysaccharide exudates and subsequent formation of gelatinous macroaggregates (MacKenzie *et al*., 2002). However, the intensity of this phenomenon seems to be unique to the northern Adriatic area, and when it occurs, mucilage accumulates in the water column and at the surface covering up to several hundreds of square kilometres, creating serious problems for tourism and fisheries (Rinaldi *et al*., 1995; Funari *et al*., 1999). For the summer 2000 mucilage event in the Gulf of Trieste, Malej *et al*. (2001) calculated that the total of integrated mucilage-associated particulate carbon was 82 g C m^{-2}.

In recent years, several hypotheses for explaining mucilage development in the northern Adriatic have been proposed. The role of phytoplankton has been tested in combination with specific environmental factors and changes in phytoplankton community structure (Degobbis *et al*., 1999), nutrient limitation (Fajon *et al*., 1999), phytoplankton cell lysis (Baldi *et al.,* 1997), and reduced grazing pressure (Malej & Harris, 1993). The extensive cell lysis was supported by analyses using scanning confocal laser microscopy in combination with different fluorescent molecular probes and lipid analyses (Baldi *et al.*, 1997). Phytoplankton response to the addition of different combinations of inorganic N, P and Si nutrients as well as rain and river water was studied in enclosure experiments (Mozetič *et al.*, 1998a; Malej *et al.*, 2003). The enrichment of nitrogen and phosphor accumulation and the release of polysaccharides by planktonic cells were studied in a controlled experiment (Fajon *et al.*, 1999; Malej *et al.*, 2003). These experiments showed that the microflagellate-dominated community released more dissolved organic carbon per unit biomass. At the transition to the stationary phase, the decay of autotrophic community was accompanied by a net accumulation of carbohydrate rich dissolved organic carbon. Azam *et al.* (1999) emphasized a sustained bacterial activity and the role of "slow-to-degrade" organic matter. Common to all proposed mechanisms are the steps of production and accumulation of dissolved organic matter (DOM) resistant to degradation. Understanding the processes that channel carbon flux in favour of DOM that is slow to degrade thus seems crucial for explaining the mucilage phenomenon in the northern Adriatic. Aluwihare & Repeta (1999) showed that a large fraction of high molecular weight DOM consisted of structurally related acylated polysaccharides. They demonstrated production of these compounds by phytoplankton and/or bacteria and accumulation of acylated polysaccharides after bacterial degradation in culture experiments. A similar macromolecular structure composed of carbohydrates was found for macroaggregates from the northern Adriatic (Kovač *et al.*, 2002, 2004). Nature of suspended particulate matter during density stratification in shallow coastal waters and characterization of macroaggregates has been studied by Kovač & Faganeli (1991) and Kovač *et al.* (1998, 2004, 2005).

Large mucus aggregates influence microzooplankton and mesozooplankton temporal and spatial variability directly by decreasing the naupliar copepod population (Kršinić, 1995) or changing feeding capability (Malej & Harris, 1993; Bochdansky & Herndl, 1995) and indirectly by altering food web structure and function (Cabrini *et al.*, 1992; Cataletto *et al.*, 1996; Fonda Umani *et al.*, 2005).

Mucus aggregates can severely affect some fish species that breed during the warm period of the year, for it is hard for the eggs to survive if trapped in mucilage mass. The fish that breed in the critical period are mostly sardines *(Clupea pilchardus)* and anchovies *(Engraulis encrasicholus),* but others suffer as well, for instance flounders *(Platichthys flesus),* sand smelt *(Atherina boyeri),* and whiting *(Gadus merlangus).* When the mucilage sinks to the bottom, it physically covers the organisms living on the bottom or in the sediment and thus makes normal physiological processes impossible. Filtering organisms (sponges and tunicates) are severely affected, as are some other organisms, such as coelenterates. Below the sedimented mucilage, total lack of oxygen occurs, which additionally affects the organisms living on the bottom, for they can not escape the mucilage area. In 2000, increased mortality of *Pitaria chione* was recorded in the Gulf of Trieste as well as mortality of various scallops *(Chlamys* spp., *Pecten jacobaeus*).

HYPOXIA AND ANOXIA

Periods of oxygen depletion below the thermocline have been observed almost every year in the Gulf of Trieste (Stachowitsch, 1984; Faganeli *et al.*, 1985; Malej *et al.*, 1989; Stachowitsch *et al.*, 1990; Malej & Malačič, 1995). In the last two decades, hypoxias have been occurring in the central part of the Gulf in late summer or in early autumn (August–October) (Malej & Malačič, 1995), while anoxia occurs occasionally and was recorded in 1974, 1980, 1983, 1987, 1989, and 1990. The most destructive anoxia was recorded in September 1983 (Stachowitsch, 1984; Faganeli *et al.*, 1985); it lasted for two weeks, covering one third of the Gulf. In the affected area, all the attached, partially attached and poorly mobile demersal animals died at that time. Almost the entire benthic associations of brittle star *Ophiotrix quinquemaculata*, sponges of the genus *Reniera* and ascidians of the genus *Microcosmos* (Stachowitsch, 1984) were destroyed, and have not recovered completely (Stachowitsch, 1991, 1992; Stachowitsch & Fuchs, 1995).

CONCLUSIONS

Increasing population in the coastal zone, land-use changes and land base sources of pollution influence the quality of coastal water and ecosystems. Eutrophication-related phenomena and the sanitary quality of the beaches appear to be the main coastal environment problems in the Adriatic, particularly in the Gulf of Trieste. Our study was concentrated on overview of literature and analyses of recent data for the Slovenian sea.

In semi-enclosed seas, such as the Gulf of Trieste, eutrophication problems are mainly subject to the combined effects of oceanographic, chemical and biological interactions. The highly variable conditions in the pelagic ecosystem influence the frequency of blooms, occurrence of harmful toxic algal species, swarming of gelatinous zooplankton, the mucilage phenomenon and hypoxia/anoxia events. Improper use of land and point-source discharges of untreated wastewater and sewage continue to pollute estuarine and inner parts of the bays. The trophic conditions of Slovenian coastal waters were assessed as TRIX index on the basis of chemical and biological parameters. The sea was characterized as oligotrophic to mesotrophic, indicating worse tropic status in the inner part of the Bay of Koper. Episodic high nutrient deposition may have a significant impact on microplankton as well as on the intensity and frequency of eutrophication phenomena. The wastewater discharges close to the coast may pose a health risk to anyone who comes into contact with the water or who consumes food collected from the sea water. An observation system should be designed in order to gather better scientific and technical information to useful early warning and to decide on suitable measures of intervention. A coastal area is the most valuable and dynamic region, so an integrated approach should be adopted to provide data for the optimization of control measures and clear indications for decision-makers.

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PREGLED POJAVOV EVTROFIKACIJE IN DRUGIH NENAVADNIH DOGODKOV V SLOVENSKEM MORJU (TRŽAŠKI ZALIV, JADRANSKO MORJE)

Valentina TURK, Patricija MOZETIČ & Alenka MALEJ
Morska biološka postaja, Nacionalni inštitut za biologijo, SI-6310 Piran, Fornače 41, Slovenija
E-mail: turk@mbss.org

POVZETEK

Evtrofikacija je pomemben dejavnik degradacije morskih ekosistemov in je v veliki meri posledica človekovega vpliva na okolje. Kljub številnim spoznanjem v zadnjih 30 letih ostaja evtrofikacija ključen problem, ki vpliva na kakovost obalnih območij, še posebno polzaprtih morij, kakršen je tudi Tržaški zaliv. Intenziteta in pogostost pojavov, povezanih z evtrofikacijo, sta odvisni predvsem od spleta razmer vnosa hranil s kopnega, meteoroloških razmer, stratifikacije vodnega stolpa in horizontalne advekcije vodnih mas.

Podan je pregled literaturnih podatkov pojavov in posledic evtrofikacije v Tržaškem zalivu s poudarkom na dominantnih pelaških združbah obalnega ekosistema, posebno na bakterijski in fitoplanktonski abundanci in produkciji, frekvenci planktonskih cvetenj, pojavljanja toksičnih vrst fitoplanktona in želatinoznega zooplanktona ter pojavljanja sluzenja morja in hipoksije/anoksije.

Ključne besede: evtrofikacija, hranila, planktonska cvetenja, anoksija, sluzasti agregati, Tržaški zaliv

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