original scientific paper

UDK 574.5(262.3 Tržaški zaliv)
546.21(262.3 Tržaški zaliv)

FACTORS AFFECTING BOTTOM LAYER OXYGEN DEPLETION IN THE GULF OF TRIESTE (ADRIATIC SEA)

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ABSTRACT

The Gulf of Trieste, a semi-enclosed shallow (depths <30 m) area situated in the north of the Adriatic Sea, is one of those coastal regions that show varying degrees of seasonal (late summer-autumn) oxygen impoverishment in its deeper waters (>20 m). Severely hypoxic/anoxic bottom waters of different spatial extent leading to localized benthic mortalities have been observed in 1974, 1983, 1987, 1989, 1990. Our contribution describes the characteristic seasonal changes of the water column stratification and bottom layer oxygen conditions. Benthic respiration rates, deep water oxygen consumption and oxygen production (estimated from primary production measurements) above the bottom were also determined. Our estimates of oxygen sources and sinks within the bottom water column layer and surface sediment in 1988 indicate that even during summers when critically low bottom oxygen levels have not been observed (1988), the oxygen demands were large enough to exceed the supply available from in situ production. We may conclude that during June-October the central part the Gulf of Trieste has exceeded its capacity to assimilate and deposit the present load of organic matter.

Key words: oxygen depletion, stratification, benthic respiration, Gulf of Trieste
Kjučne besede: pomanjkanje kisika, stratifikacija, bentoška respiracija, Tržaški zaliv

INTRODUCTION

The northern Adriatic Sea is one of a number of those marine coastal areas that show varying degrees of seasonal (late summer-autumn) oxygen impoverishment in their bottom waters (Justić, 1991). Anoxic bottom waters leading to benthic mortalities have been observed several times during the last three decades (Piccinetti & Manfrin 1969; Stefanon & Boldrin, 1981; Montanari *et al.*, 1984) and most recently in November 1989 (Degobbis *et al.*, 1993).

Severly hypoxic (< 2.0 ml l^{-1}) and anoxic (below detection limit of Winkler titration) zones have been documented in 1974, 1983, 1987, 1989, 1990 in the Gulf of Trieste, the northernmost and the shallowest part of the Adriatic Sea. The areal extent of oxygen-deficient bottom waters and benthic mortalities was the largest in September 1983 affecting nearly 1/3 of the Gulf's bottom waters (Stachowitsch, 1984; Faganeli *et al.*, 1985, Orel *et al.* 1986). The deep waters (>20 m) of the Gulf of Trieste were anoxic in the bottom layer of thickness ≤ 1 m for about two weeks. The 1974, 1987, 1990 anoxias were of shorter duration and impaired only restricted areas (Fedra *et al.*, 1976; Malej *et al.*, 1989, Malej *et al.*, 1991). Localized benthic mortalities were reported by fishermen and divers in other instances (Vukovič *et al.*, 1984, Aleffi *et al.*, 1992), but on most occassions the causes have not been determined.

Some lively discussions took place on whether the hipoxia/anoxia problem has been exacerbated by anthropogenic loading of nutrients and organic matter or whether there were other causes for such developments. This dilemma is especially important with regard to future Adriatic management strategies and the sea protection programs.

This paper presents an analysis of the distribution of dissolved oxygen (DO) and its seasonal decline in the bottom waters of the Gulf of Trieste. Physical profile data (temperature, salinity) were used to characterise the vertical water column structure and to analyse the relationship of stratification to DO conditions. Finaly, we explore physical and biological mechanisms which create and maintain seasonal hypoxia/anoxia in the Gulf of Trieste.

STUDY AREA

The Gulf of Trieste is approximately bounded by the line connecting Savudrija and Grado (Fig. 1). The Gulf's average depth is less than 20 m and ~ 20% of its area has a depth of less than 10 m. Its overall surface is ~ 600 km^2 and volume ~ 9.5 km^3. The freshwater inputs are larger along the northern (approx. annual rate of flow of 90 - 130 m^3/s) than the southern coast (approx. 5-10 m^3/s). The structure of the water column and water movements vary greatly with dominant seasonal influence. In winter, the waters of the Gulf are characterized by considerable homogeneity. In spring, heating of the surface layer and freshwater inflows begin to establish a pycnocline which intensifies during the summer. Seasonal dynamics of thermal stratification is governed by the seasonal cycle of solar irradiance (Malačič, 1991). Autumnal cooling and wind mixing reestablish vertical water column homogeneity; stormy winds may cause destratification also during summer.

Due to its shallowness, the Gulf is responsive to the local atmospheric forcing and it is difficult to make generalizations about its circulation. Measurements, mostly done on the Italian side (Mosetti, 1972; Michelato 1973), revealed that tidal currents (mean velocities of ~ 3 cm/s) and density gradient currents (mean velocity ~ 2 cm/s) contribute little to the renewal of the water mass in the Gulf of Trieste. Stravisi (1983) indicates that a bottom layer below about 10 m rotates counter-clockwise with a mean velocity of 2 - 5 cm/s. The surface layer is mainly driven by the local wind field and rotates clockwise with westerly winds. The bora (NE wind) driven circulation is counterclockwise from the surface to the bottom (Stravisi, 1977) and is most efficient for water mass exchange. On the basis of

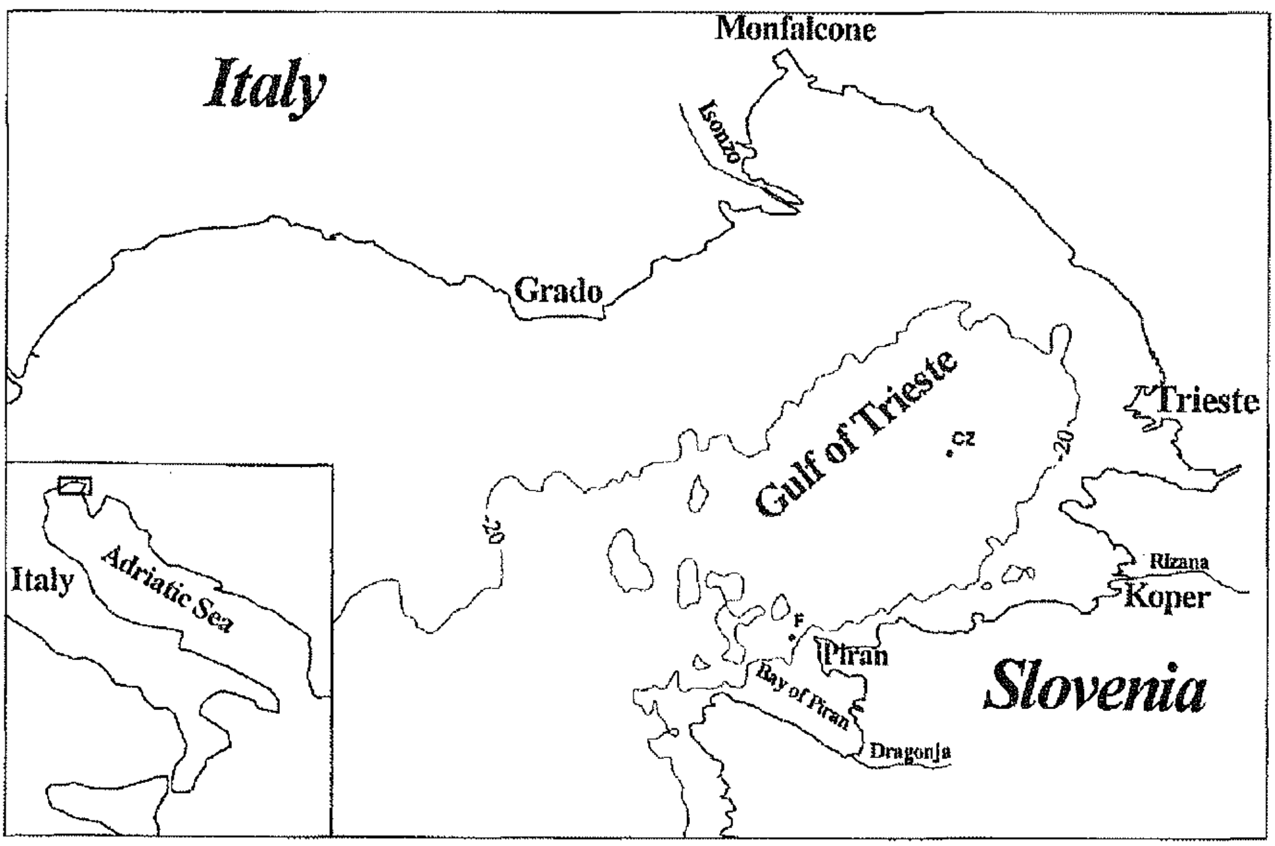

Fig. 1: The map of the study area with sampling points.
Slika 1: Območje raziskav z vzorčevanimi mesti.

salinity data and the average freshwater inflow to the Gulf, and more recently on the basis of current measurements, Mosetti (1973) has estimated that the rate of exchange of water in the Gulf of Trieste ranged from a few days (with strong NE winds) to a few weeks. Whether or not this renewal time has decreased recently, as observed by Degobbis (1989) for the northern Adriatic basin, it is not known.

Olivotti *et al.* (1986 a, b) summarized anthropogenic loading to the Gulf from the Italian and Slovenian sides. Types of inputs include mainly municipal (~2.2 m^3/s) and industrial (food and chemical industry) waste waters, atmospheric input, runoff; Table 1 gives an estimate of the yearly inorganic input from various sources.

Besides nutrient inputs, the organic matter loading is of primary concern with respect to oxygen depletion events. Faganeli *et al.* (1988) tried to evaluate the organic matter sources to the Gulf by using stable isotopic composition and C: N: P ratios as indicators of their origin. Their conclusion was that the particulate organic matter of the Gulf of Trieste was prevalently autochtonous marine in origin. On the other hand, Malej *et al.* (1995) have shown that the phytoplankton standing crop, community structure and primary production were profoundly influenced by freshwater inputs and water column stratification.

Source	ΣN_{in}	PO^{3-}_4	Si
Sewage	44 (24)	9.5 (86)	10
Rivers	114 (62)	1 (11)	3*
Precipitation	25 (14)	0.5 (3)	
Total	184	11	

Table 1: Approximate estimation (x 10^6 mol/year) of inorganic nutrient inputs into the Gulf of Trieste (the percentage of the total input is given in parentheses; *estimate only for Slovenian part); after Olivotti et al. 1986, Tušnik et al. 1989

Tabela 1: Ocena vnosov neorganskih hranil (x 10^6 mol/leto) v Tržaški zaliv (v oklepaju % celotnega vnosa); *ocena samo za slovensko stran; po Olivotti et al. 1986, Tušnik et al. 1989

No systematic study of the oxygen conditions has been carried out in the deeper waters (> 20 m) of the central part of the Gulf, neither on Italian nor Slovenian side until 1990, when common field programme within the framework of Alps-Adria activities (The Observatory of the northern Adriatic) have started. The majority of existing data therefore refers to the narow coastal belts where bottom layer hypoxia seems to have been an exception. Scarse earlier data from deeper part of the Gulf indicated typical seasonal variations with lower values during late summer-autumn but values < 3 ml/l (saturation ~ 70%) were recorded rarely. Nevertheless, reports of limited benthic mortalities indicate that seasonal hypoxia/anoxia problem did occur in the Gulf of Trieste at least since late 60's.

MATERIALS AND METHODS

This report brings together the results from extensive sampling carried out from April 1986 to August 1989 in the southeastern part of the Gulf of Trieste which included physical structure of the water column, sediment and oxygen consumption below the pycnocline and oxygen production in near the bottom as well. The largest set of data was collected at the station F located approx. 1.5 mile from the southeastern shore at a depth of 22 m. A series of diel measurements (12 daily) of oxygen conditions and hydrographic structure during the period of stratified water column (April - September of 1987 and 1988) was made at same station. From 1989 on samples were collected also at other sites (Fig. 1) at depths > 20 m. Simultaneous measurements of oxygen consumption and production rates were performed in summer 1988 at station F; consumption was determined also in 1986 and 1989 at the same location. We also include oxygen data collected during 1991 within the programme of the Observatory of the northern Adriatic and Marine Station data collected in the central part of the Gulf during 1990-94.

Temperature measurements were made with reversing thermometers attached to water bottles and with a KAHLSICO bathythermograph. From 1991 on, the vertical water column characteristics were obtained by CTD fine-scale probe (University of Western Australia) and a Sea-Tech Inc. fluorometer. Water samples were collected with 5 l plastic Niskin bottles. Analyses were carried out using standard methodology (Grasshoff, 1976).

Stratification data, developed from temperature and salinity measurements, were obtained by subtracting surface values of σ_t from σ_t values in the bottom layer, normalized with the density of pure water (10^3 kg m^{-3}) and expressed as $|\sigma_t|$ (m^{-1}).

Primary production was measured by addition of 10 μCi of carrier-free $Na^{14}CO_3$ to water samples which were incubated *in situ* at different depths (Steeman Nielsen, 1952) and oxygen estimated applying a photosynthetic quotient of 1.66 (Tijssen & Eygenraam, 1982).

Oxygen consumption of near bottom water was determined in 500-ml flasks in the darkness at ambient temperature. For determination of sediment oxygen consumption samples were collected by SCUBA-diving, samples were incubated at in situ temperature in darkness and continuos recording of oxygen content achieved by respiration set equipped with polarographic oxygen sensors (Tušnik, unpublished).

SEASONAL DEVELOPMENT OF WATER COLUMN STRATIFICATION AND OXYGEN CONDITIONS

The water column density structure was characterized by weak vertical gradients during late autumn - early spring ($|\sigma_t| < 0.05$ m^{-1}) which increased with surface warming and larger freshwater runoff in spring ($|\sigma_t| = 0.03$ - 0.15 m^{-1}), to become the strongest during late summer - early autumn with the average $|\sigma_t|$ of 0.17 m^{-1} (0.08 - 0.29 m^{-1}), see also Tab. 2.

Month	$\lvert\sigma_t\rvert$ (m^{-1})		Bottom DO (ml.l^{-1})		
	Mean	Max	Mean	Min	n
June 1983	0,12	0,14	5,42	4,76	6
June 1986	0,14	0,15	4,87	4,56	16
June 1987	0,26	0,28	4,49	4,27	14
June 1988	0,14	0,15	4,56	4,55	3
June 1989	0,14	0,15	4,96	4,95	5
July 1983	0,19	0,29	5,51	4,41	4
July 1986	0,21	0,23	4,95	4,90	14
July 1987	0,17	0,19	3,32	3,28	14
July 1988	0,21	0,29	4,25	4,21	4
July 1989	0,11	0,12	3,52	3,50	10
August 1983	0,20	0,21	4,23	3,17	6
August 1986	0,22	0,25	5,33	4,75	16
August 1987	0,16	0,17	2,79	2,27	16
August 1988	0,16	0,17	4,33	3,36	3
August 1989	0,13	0,14	2,96	2,86	6
September1983	0,03	0,09	3,04	0,00*	12
September1986	0,08	0,12	4,74	4,11	14
September1987	0,12	0,13	2,01	1,52	15
September1988			3,92	3,34	2
September1989	0,06	0,11	3,69	3,58	9

***Table 2:** Vertical gradient of normalized density $|\sigma_t|$ (monthly averages and monthly maxima) and bottom dissolved oxygen (monthly means and minima) for 1986-89 as compared to 1983 at the station F (*H_2S detected)*

***Tabela 2:** Vertikalni gradienti normalizirane gostote $|\sigma_t|$ (mesečna povprečja in viški) ter pridnene koncentracije kisika na postaji F (mesečna povprečja in najnižje vrednosti za obdobje 1986-89 v primerjavi z letom 1983.*

The annual cycle of dissolved oxygen (DO) level (ml l^{-1}) and saturation (%) in the surface and bottom layers for the station F are shown in Figs. 2 and 3. Clearly, the DO concentrations followed similar pattern throughout the water column. Warming of the surface layer during spring and summer decreased the solubility and concentrations declined, but the upper 10 - 15 m layer was over saturated during the warmer part of the year (Fig. 3 top). On the contrary, the bottom layer was generally

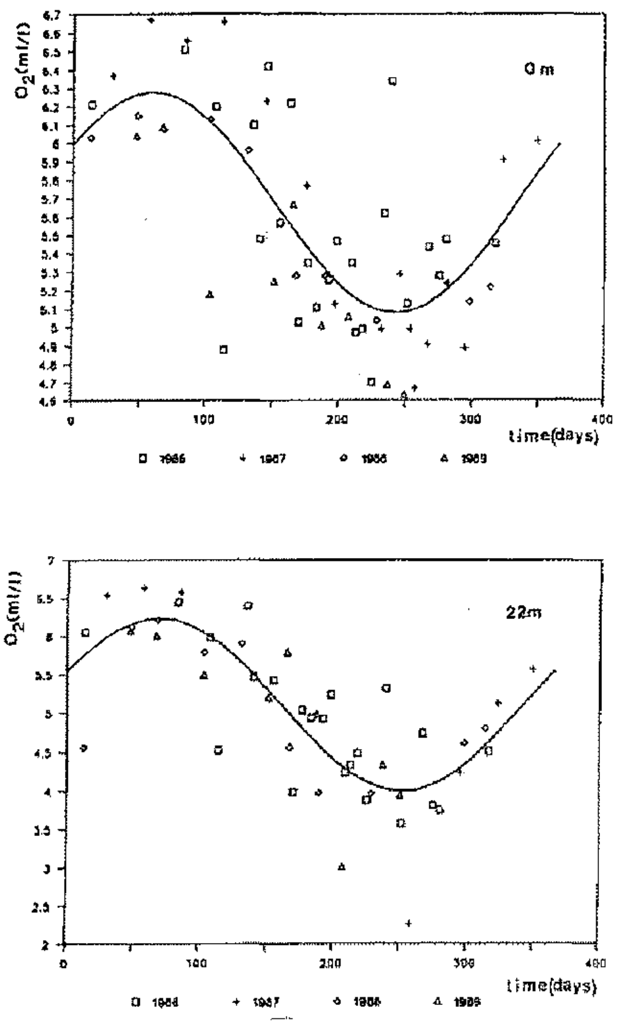

***Fig. 2:** The annual cycle of dissolved oxygen (ml/l) in surface and bottom layer (22 m) for the station F during 1986-89.*

***Slika 2:** Letni potek koncentracije kisika (ml/l) v površinskem in pridnenem sloju (22 m) na postaji F v obdobju 1986-89.*

under saturated from May through October (Fig. 3 bottom) with strong oxygen gradient in the 15 - 20 m layer. However, there were large year to year variations in the bottom layer oxygen conditions and Table 2 shows the vertical gradients of density and the bottom layer oxygen concentrations in different years for the station F. Although no clear relationship is evident between the degree of stratification and the bottom - layer oxygen, the lowest concentrations were associated with a thick pycnocline or stepwise stratification with layers of thickness ≥ 1 m.

The diel changes in oxygen levels measured at station F were significant in the whole water column but did not conform to the expected sinusoidal curve with maxima around noon and minima near midnight. In

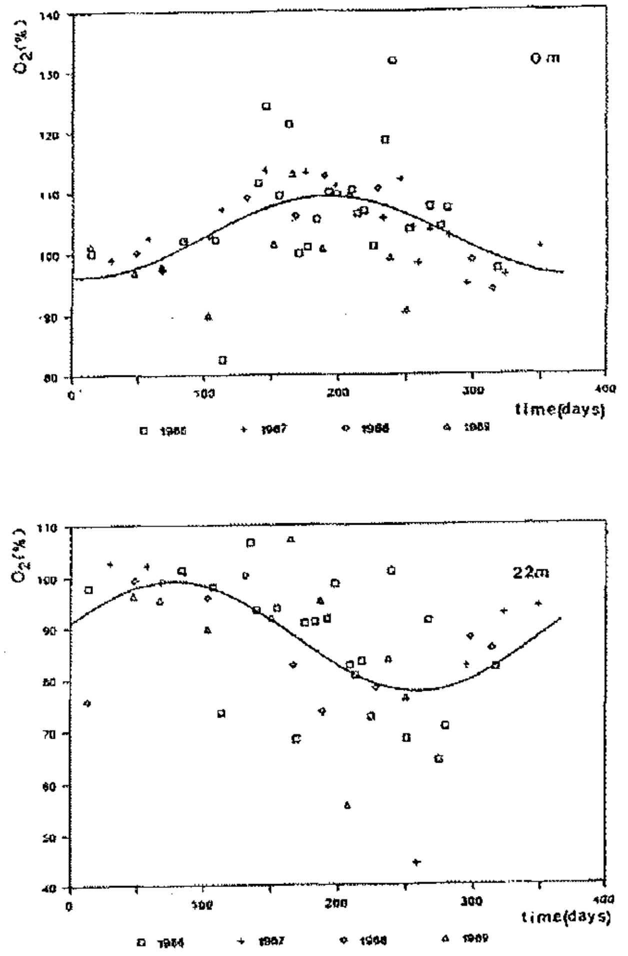

Fig. 3: The annual cycle of oxygen saturation (%) in surface and bottom layer (22 m) for the station F during 1986-89.

Slika 3: Letni potek nasičenosti s kisikom v površinskem in pridnenem sloju (22 m) na postaji F v obdobju 1986-89.

Year	a_2	a_1	a_0	SD
1987	2,63 .10^{-4}	-8,01.10^{-2}	8,74	0,77
1988	1,11.10^{-4}	-3,27.10^{-2}	6,53	0,42

Table 3: Parameter values for the equation ($c = a_2t^2 + a_1t + a_0$) describing the progression of oxygen depletion in the bottom layer at the station F during 1987, where t is time starting with March 31 (c and a_0 in ml/l; a_1 in ml/l/d; a_2 in ml/l/d²).

Tabela 3: Vrednosti parametrov za enačbo ($c = a_2t^2 + a_1t + a_0$), ki opisuje zmanjšanje kisika v pridnenem sloju postaje F v letu 1987 (začetni čas je 1. marec; c in a_0 v ml/l; a_1 v ml/l/d; a_2 v ml/l/d²).

general, we observed the lowest oxygen values between 7 and 10 PM, however, the night variability was usually significantly higher that the daily one. The oxygen in the upper part of water column varied around saturation values, while oxygen values in the bottom layer (22 m) decreased from April to September (Fig. 4, data for 1987).

For 1987 and 1988, the rates of changes in the bottom layer oxygen concentration (c) from early spring to late summer for the station F were described by the linear time dependence $dc/dt = 2a_2t + a_1$, where $t = 0$ was taken as March 31 (Table 3). Parameter a_1 represents dc/dt at that time and a_2 represents the linear deviation of dc/dt with time from the constant a_1. So the oxygen concentration development in the same period was described with $c = a_2t^2 + a_1t + a_0$, where the parameter a_0 represents c at $t = 0$. The average rate of oxygen depletion in the bottom layer from winter maximum to early autumn minimum (time interval Julian day 70 - 250) during 1986-1989 was $5.8 * 10^{-3}$ ml/l/d and maximal rate of oxygen decay (Julian day 120 - 180) during the same period was $2.4 * 10^{-2}$ ml/l/d.

More recently, oxygen concentrations have been monitored also in the central part of the Gulf of Trieste (station CZ) and significantly lower values than at station F have been found in the bottom layer during late summer/autumn (Fig. 5). Data collected within the framework of the Alps Adria programme concurrently for the whole Gulf of Trieste indicate that low oxygen area is typically situated in its central part (Fig. 6).

OXYGEN SOURCES AND SINKS IN THE BOTTOM LAYER

Simultaneous estimates of the production of oxygen on the basis of ^{14}C uptake measurements (Turk, 1992) and respiration in the sub-pycnocline water column have only been done at the station F during July, August and September 1988. Fig. 7 shows DO concentrations in the layer above the bottom together with benthic and sub-pycnocline respiration rates.

The measured deep water column respiration rate was on average -1.02, -0.19 and -0.41 g O_2 m^{-2} d^{-1} in July, August and September, respectively; these values are similar to those experimentally determined for phytoplankton detritus (Bauerfeind, 1985).

The contribution of the sediment to the total oxygen consumption (the below pycnocline water column plus bottom) was about 20% in July, while in August sediment oxygen demand was much higher (25.5 and 34.6 ml/m²/h) than sub-pycnocline respiration (5.5 ml/m²/h). In September, water column and bottom respiration were lower and ranged between 8.3 and 15.3 ml/m²/h. Benthic respiration rates determined in the summers of 1986 (July) and 1989 (August) at the same station were in the same range as for 1988.

The oxygen equivalent of the measured carbon fixation rate for the water layer below the pycnocline during the same period averaged + 0.12 g O_2 m^{-2} d^{-1} in

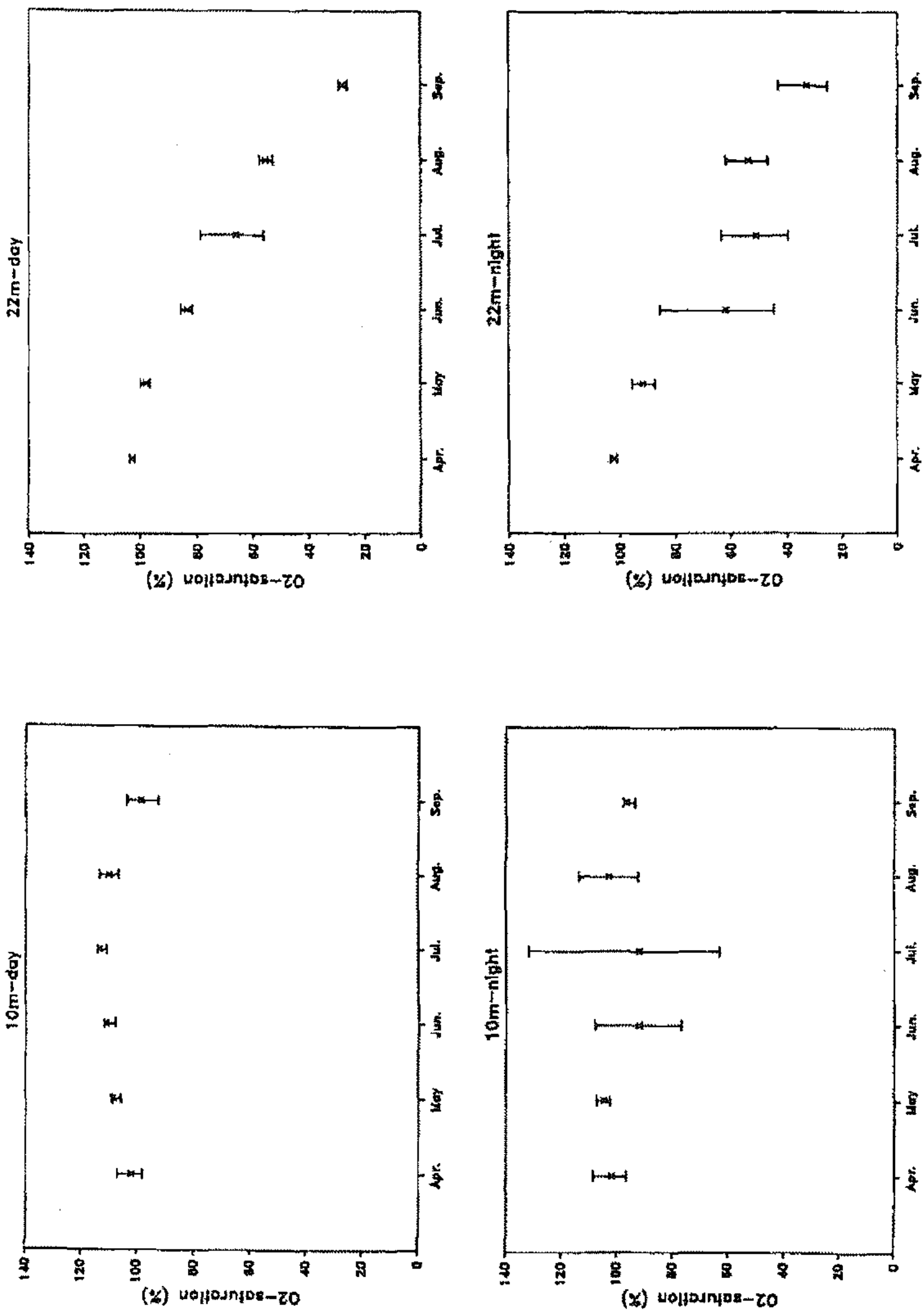

Fig. 4: Seasonal and diel changes in oxygen saturation from April to September 1987 at the station F: bottom layer (22 m) and 10 m layer. Means and 95% CL for day (n = 12) and night measurements (n = 12).
Slika 4: Sezonske in dnevne spremembe nasičenosti s kisikom od aprila do septembra 1987 na postaji F: pridneni sloj (22 m) in globina 10 m. Podane so srednje vrednosti in 95 % CL za dnevne (n=12) in nočne (n=12) meritve.

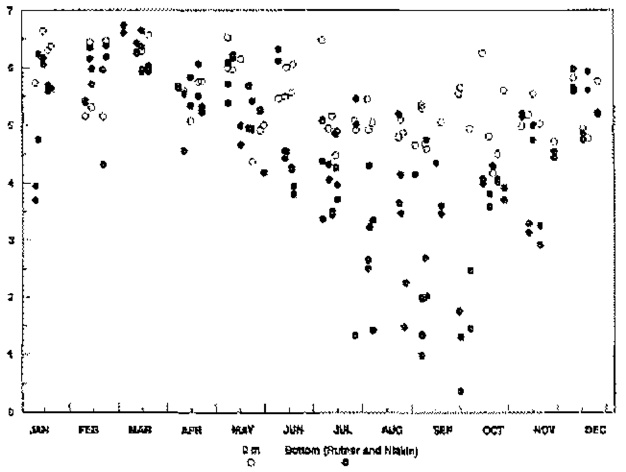

Fig. 5: The annual cycle of dissolved oxygen (ml/l) in surface and bottom layer (24 m) in the central part of the Gulf of Trieste (station CZ) during 1990-94.
Slika 5: Letni potek kisika (ml/l) v površinskem in pridnenem sloju (22 m) na postaji CZ v obdobju 1990-94.

July and + 0.52 g O_2 m^{-2} d^{-1} in September. These levels are comparable to summer values reported by Faganeli *et al.* (1981) for the same area.

Bottom water oxygen demand is usually considered to be strongly related to temperature, while our data indicate that benthic respiration may vary 6-fold for a very small temperature range (20.0 ± 1.0 °C). The elevated rates of benthic oxygen demand measured in August may have been caused by a large input of oxidizable organic carbon due to sedimentation of macro aggregates (previously observed within the water column, Malej & Faganeli, 1988; Fanuko & Turk, 1990) following a stormy event after a period of stable weather. This observation is consistent with an experimental microcosm study (Kelly & Nixon, 1984) where a sharp increase of benthic metabolism was observed after addition of organic matter ("large pulse").

The oxygen demand of deep water column and sediment could not be covered by *in situ* oxygen production during summer even if oxygen production by the benthic micro flora was similar to deep water column photosynthesis. The estimates of oxygen

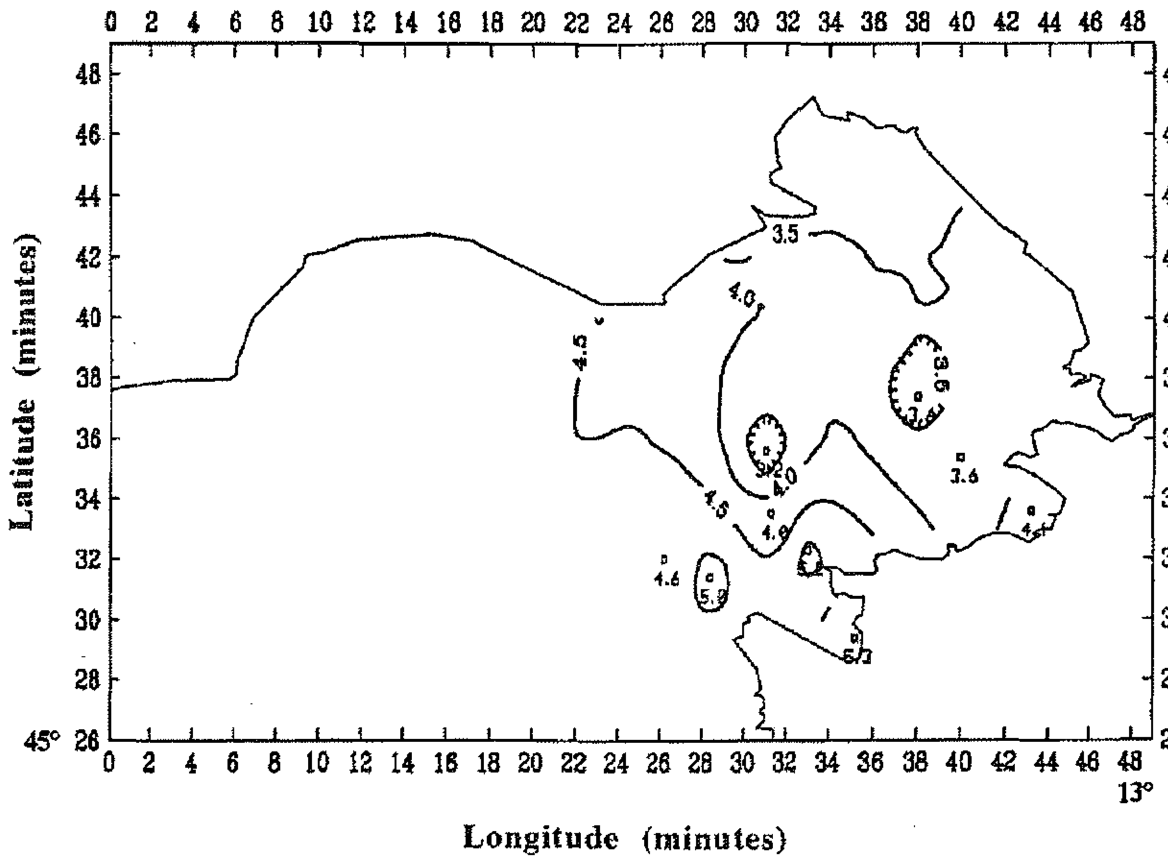

Fig. 6: Bottom layer dissolved oxygen (ml/l) in the Gulf of Trieste during August 1991.
Slika 6: Koncentracije kisika (ml/l) v pridnenem sloju Tržaškega zaliva v avgustu 1991.

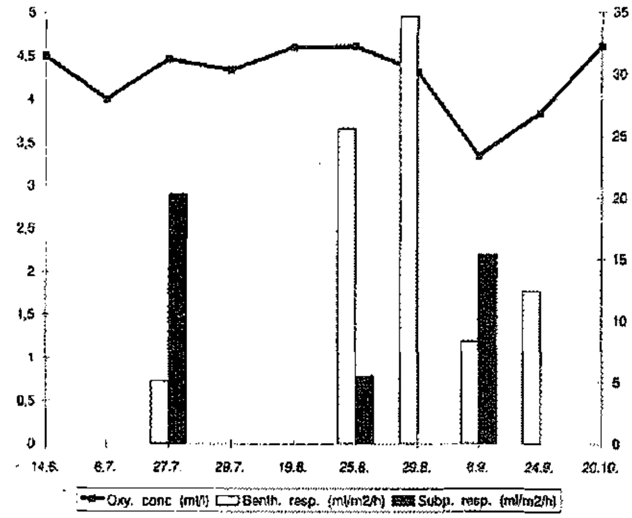

Fig. 7: Benthic and sub-pycnocline respiration rates (ml/m^2/h; right scale) and bottom layer dissolved oxygen (ml/l; left scale) at station F from July to October 1988.
Slika 7: Bentoška in pridnena poraba kisika (ml/m^2/h; desno merilo) ter pridnena koncentracija kisika (ml/l; levo merilo) na postaji F od julija do oktobra 1988.

production and demands within bottom layer water column and sediment would suggest considerably more rapid progression of oxygen depletion in the bottom layer (DO decline to critical levels in < 10 days) than actually observed. Therefore physical mechanism affecting oxygen resupply were contributing to slower deep water oxygen depletion. Wind driven vertical mixing (acting probably also through enhancement of water renewal) seemed to be an important mechanism for reoxygenation (linear regression between bottom DO and wind velocity, $r^2 = 0.54$, $p = 0.054$, DF = 26), while the effect of tidal mixing seems to be of lesser importance ($r^2 = 0.26$, $p > 0.05$, DF = 28).

Nevertheless, data from deep 40-m core serving as an indicator of paleoenvironmental changes showed that the past biogeochemical processes were not markedly different from those of the present day (Faganeli *et al., 1991)*; moreover, sedimentary organic C, total N and P profiles did not reveal an accelerated rate of organic matter deposition recently. These data indicate that anoxic events may not be of recent origin in the Gulf of Trieste. However, reduced vertical mixing, a possible detrimental modification of current patterns as indicated for the northern Adriatic (Degobbis, 1989) and human activities such as the discharge of additional oxygen-demanding substances, may aggravate the situation and further modify the ecology of the Gulf of Trieste.

CONCLUSIONS

Our estimates indicate that even during summers not characterized by critically low oxygen concentrations in the bottom layer (like 1986 and 1988) the oxygen demand of sub-pycnocline water column and sediment were large enough to exceed the supply available from *in situ* pelagic (below pycnocline water column layer) and bottom (benthic micro algae) photosynthesis. Therefore, severe hypoxia patches can be expected almost in any summer-autumn with unfavorable meteorological conditions and we may conclude that the Gulf of Trieste in its deeper parts (> 20 m) has exceeded its capacity to assimilate and deposit the present load of organic matter from June to October.

POVZETEK

V prispevku predstavljamo kisikove razmere v Tržaškem zalivu in dejavnike, ki vplivajo na sezonsko (pozno poleti-jeseni) pomanjkanje kisika v pridenem sloju, globljem od 18-20 m. Tržaški zaliv je polzaprt plitev zaliv, v katerem beležimo sezonsko zniżanje kisika (hipoksija) v pridnenem sloju; v najhujših primerih pride celo do popolnega pomanjkanja kisika (anoksija). Zelo hipoksične (koncentracije pod 2,0 ml/l) in anoksične razmere so bile v Tržaškem zalivu ugotovljene v letih 1974, 1983, 1987, 1990, vendar je bila razsežnost anoksičnega dna največja l. 1983, ko je zajela približno tretjino zaliva, huda hipoksija/anoksija pa je trajala dva tedna. Posledica pomanjkanja kisika je bil obsežen pogin bentoških organizmov. V ostalih primerih so bila prizadeta manjša območja v osrednjem delu zaliva.

V našem prispevku podajamo meritve koncentracij kisika v Tržaškem zalivu v obdobju 1986-89 na postaji v jugovzhodnem delu. Kasnejše meritve (1990-94), ki so redno vključevale tudi osrednji del zaliva so pokazale, da so kisikove razmere v jugovzhodnem delu praviloma boljše ter da se v centralnem delu zaliva skoraj vsakoletno kisik v obdobju avgust-oktober približa kritični meji (2,0 ml/l).

Meritve virov in ponorov kisika smo opravili le na postaji v jugovzhodnem delu zaliva in sicer v obdobju 1986-88. Celo na tem območju meritve kažejo, da so ponori kisika v poletnem času bistveno višji kot viri. Na osnovi teh meritev bi lahko predvidevali, da naj bi koncentracije kisika v pridnenem sloju hitreje padale kot pa dejanske meritve koncentracij kažejo. Predvidevamo, da so fizikalni mehanizmi (zmanjšanje stratifikacije oz. destratifikacija vodnega stolpa, dotok bolj oksigenirane vode) tisti, ki preprečujejo padec pod kritično mejo. To potrjujejo tudi primerjave koncentracij kisika v pridnenem sloju in hitrosti vetra ter plimskih nihanj. Vendar lahko zaključimo, da je Tržaški zaliv v svojem osrednjem delu presegel asimilacijske zmožnosti za sedanjo organsko obremenitev ter da lahko v primeru stabilnega, nevetrovnega vremena in zmanjšane advekcije pridnene vode pričakujemo hude hipoksije oz. anoksije vsako leto.

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