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Dystrophic event in Papas lagoon, Araxos Cape, western Greece in the summer 2012

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Abstract

A dystrophic crisis occurred in late June 2012 in the lagoon of Papas, Araxos region, western Greece (Ionian Sea), resulting in massive mortalities of aquatic organisms. The whole event was monitored through the basic aquatic physicochemical parameters (temperature, salinity, dissolved oxygen and pH) recorded before, during, and after its occurrence. Although the phenomenon was manifested locally, it resulted in complete anoxia in the largest part of the lagoon and lasted ten days. Water quality of the entire lagoon was greatly affected by this dystrophic event and first signs of recovery were observed four months later.

Keywords: Araxos, coastal lagoon, anoxia, dystrophic crisis, fish mortalities.

Introduction

Dystrophic crises in coastal lagoons occur during the summer months and first appear with the characteristic odour of hydrogen sulphide released into the water, the water changing colour, and mass mortalities of aquatic organisms (Valiela, 1984). They arise as a result of high eutrophication and the resulting anoxia of water masses in conjunction with the specific climatic conditions prevalent in the area. For them to occur there should be high water temperatures, high solar irradiation, calm wind conditions and other factors that do not favour hydrological circulation of the lagoon (Tournier *et al.*, 1979; Souchu *et al.*, 1998a; Chapelle *et al.,* 2001; Vignes *et al.,* 2009). Eutrophication of the ecosystem is especially favoured by late seasonal rains (Harzallah & Chapelle, 2002).

In coastal lagoons, natural eutrophication is further aggravated by anthropogenic activities such as agriculture; often periods of prolonged severe hypoxia do not necessarily leading to dystrophic crises. The lagoons are often used for extensive culture of fish species able to withstand periods of low oxygen concentrations. Dystrophic crises, however, have detrimental effects on their populations. As anoxia and dystrophic crises in lagoons occur seasonally, their relationship is with the prevailing conditions of temperature and salinity, as well as with basic water quality parameters; dissolved oxygen concentration (DO) and pH are of particular interest. These parameters are largely influenced by the photosynthetic and respiratory activity of the lagoon organisms, as well as by the oxidation of dissolved organic compounds, insofar as the exchange of water with the open sea is generally limited. Although there is a large amount of data on fluctuations of these parameters in the lagoons of the Mediterranean (Wilke & Boutiere, 2000; Christia & Papastergiadou, 2006; Roselli *et al.,* 2009. Lucena-Moya *et al.*, 2012; Avramidis *et al.,* 2013 etc), there is no common pattern of seasonal trends. This is quite reasonable, since, apart from the differences in regional weather (annual temperature profile, precipitation and wind patterns) the lagoons also differ in geomorphology (dimensions, bathymetry, sediment type), orientation, the location of points of communication with the sea, the amount of freshwater input, and the possible chemical pollution from agricultural or industrial activity.

The lagoon of Papas is a relatively extended ecosystem of economic importance due to its production of fish and shellfish. Information on the seasonal fluctuations of the main physical and chemical parameters of the water is available in the works of Chrissanthakopoulou (2008), Krasakopoulou & Pagou (2011) and Nestoridou (2011). Despite the fact that the ecosystem has often displayed dystrophic crises, nine of which they have been reported in the last thirty-five years (1979, 1984, 1987, 1996, 1997 (NCMR, 2000), 2004, 2010 and 2012), no data are available for the actual period of a crisis. Such information is provided by the present study which took place during the period from March 2012 to April 2013, during when the last dystrophic crisis occurred.

Materials and Methods

The site

Papas is a coastal lagoon fishery with very unique characteristics due to its position, morphology, and the absence of anthropogenic influences on the waterfront as a whole, due to the existence of the nearby naval base. It is located at Cape Araxos, opposite the delta of the two major rivers of western Greece, Evinos and Acheloos, approximately 7 and 15 miles from their mouths respectively. It is elongated on a SE-NW axis with maximum diameter of nearly 5 km and an average width of approximately 1 km, while its total area is approximately 6.2 km^2 (Papatheodorou *et al.*, 2012) . The average depth is 1.8 m, with a maximum of 5 m in the central part. According to these depths, the Papas lagoon is characterised as one of the deepest Greek coastal lagoons. It communicates with the sea by three openings, two in the east side (O1 and O2) and one in north (O3) (Fig.1). The O2 opening was created in 1992 to facilitate the exchange of waters of the lagoon with the sea. In these openings, fish barriers and traps are installed for trapping and catching fish from July to February according to the model of exploitation of Mediterranean lagoons (Kapetsky 1984; Ardizzone *et al.*, 1988) and local production patterns (Katselis *et al.*, 2003). For the remainder of the year fish barriers are removed.

The lagoon is characterized by a wide variety of physicochemical and biological characteristics (NCMR, 2000). The south-eastern part of the lagoon receives runoff from neighbouring farms that contribute to the dense growth of the macroalga *Ulva rigida.* According to Krasakopoulou & Pagou (2011), the deposition of large amounts of nutrients, in combination with the decomposition of *U. rigida*, contribute greatly to the increasing eutrophication of Papas lagoon ecosystem.

Monitoring

Water temperature, salinity, and dissolved oxygen (DO) were recorded at three stations (S1, S2, and S3) positioned along the longitudinal axis of the lagoon (Fig.1). S1 was situated near the marshy area of the south-east region, S2 in the central and deeper region, while S3 was located in the north-western part of the lagoon. Measurements were taken at the 0.5 m depth at all stations and at 3.5 m only at S2. YSI EcoSense® portable instruments were used: EC300 Conductivity Meter was utilised for measuring salinity, DO200 Dissolved Oxygen Meter was used for oxygen concentration and water temperature measurements, and pH100 pH Meter for pH. Measurements were taken once a day at midday on a monthly basis, but during the dystrophic crisis period, additional measurements were carried out on 30 Jun, and 3, 10 and 30 July.

Oxygen concentrations at saturation C_{sat} (normoxia) in mgO_2L^{-1} as a function of water temperature T and salinity S was calculated according to the relation (APHA, 1989):

$$C_{sat} = 14.6244 - 0.367134T + 0.0044972T^2 - 0.0966S + 0.00205TS + 0.0002739S^2.$$

Data analysis

Environmental parameters were tested for normality (Kolmogorov-Smirnov test) and subsequently, depending on their distribution, spatial and seasonal differences observed were evaluated with ANOVA or Kruskal-Wallis Test. Statistically significant differences were further examined through Least Significant Differences (LSD) multiple range test. The aforementioned statistical analysis was performed with the statistical software package STATGRAPHICS Centurion XV.

Principal component analysis (PCA), a multivariate statistical technique, was applied on the environmental data. Data were normalized prior to analysis and PCA was performed to describe the relationships among the environmental descriptors and to identify the general spatio-temporal patterns of water-mass conditions.

Results

Water temperature at the period of investigation ranged from 11.6 ° C in January to 32 ° C in July and the salinity from 21.0 in March to 41.6 in September. This dystrophic crisis erupted at dawn of 30 June with the appearance of a large milky turquoise coloured spot in the eastern part of the lagoon, close to the central channel of communication with the sea (O2 on Fig. 1). During that day, the average temperature of the water at the three stations was 29.6 ± 0.2 ° C (Fig. 2A), the salinity 39.4 ± 0.4 (Fig. 2B), and the wind was NE 1-4 Beaufort. At the onset of the crisis large numbers of live fish concentrated near the openings to the sea. Exit from the water and beaching on the coast of soles *Solea solea*, eels *Anguilla anguilla*, and crabs *Carcinus aestuarii* were also observed. Soon after, dead bodies of lagoon fish species were floating in the central and southern part, while an intense decomposition scent prevailed in the region. Dead crabs *C. aestuarii*, cockles *Cerastoderma glaucum*, and clams *Ruditapes decussatus* were also noticed. In the subsequent days the colour of the lagoon water became a brown tint.

The dystrophic event and the hypoxic crisis are reflected in the recordings of DO in surface waters (Fig. 2C). Three different phases can be distinguished: a) the period before the outbreak of the dystrophic crisis, from March to June 2012, when the oxygen in the lagoon ranged at relatively high levels from 10.3 to 14.6 mgO_2L^{-1}; b) the period following the dystrophic event, from July to October, when the values were mostly hypoxic ranging from 0 to 8,6 mgO_2L^{-1}; c) the period following the crisis, from October to April 2013, which was characterized by DO levels near water saturation values 7.8 up to 11,6 mgO_2L^{-1}. During the first and third phases lowest DO values were recorded at station S3 ranging from 10.3 up to 11.63 mgO_2L^{-1}, and 6.6 to 8.5 mgO_2L^{-1} respectively. By contrast, during the dystrophic event lowest values

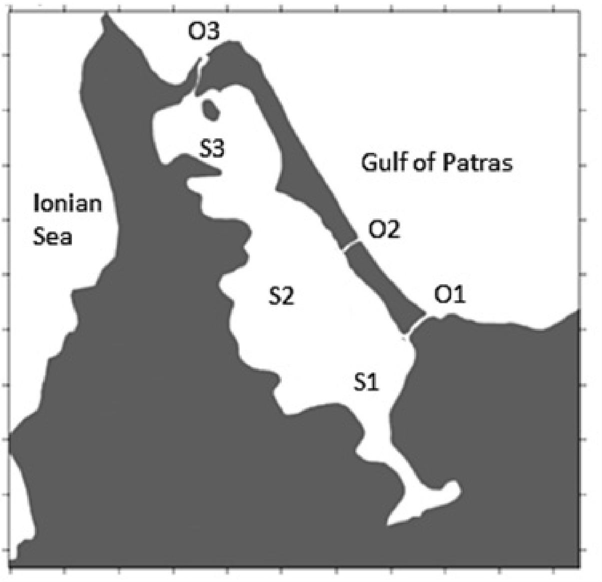

Fig. 1: Papas lagoon, in Araxos Cape, outlets communicating with the sea (O1, O2, O3) and sampling stations (S1, S2, S3).

were recorded at stations S1 and S2 reaching zero on 30 June. At the same time, DO values recorded in S3 were reduced, reaching minimum values ten days later. Thus, a severe hypoxia of 1.4 ppm was recorded in S3 station at 6:34 am on 10 July, the DO rising up to 4.6 ppm at noon. *Mugilida* of all sizes were seen jumping high above the water in the early morning of that day.

DO at depth (3.5 m) was measured at station S2. In Figure 4 the values are compared with those taken at the surface and with the normoxic values corresponding to temperature and salinity measured . Overall, DO values were higher at the surface than in the bottom layer. These differences were found statistically significant (t-test, $P < 0.05$) although in some cases bottom DO values were higher than the surface ones (on 9/6/13, 13/11/13 and 23/11/13). During July, the surface water layer was hypoxic while in August DO concentrations increased. The values of DO in the lagoon remained low, often below 50% saturation for the next three months.

The pH, which ranged at relatively high levels throughout the study, decreased during the dystrophic event showing the minimum statistically significant values ($P < 0.5$) (Fig. 2D).

The PCA (Fig. 3) revealed a positive correlation between temperature and salinity, and DO and pH, while a covariance of the two parameter pairs was identified. From June to October when the values of temperature and salinity covaried in a relatively narrow range, a large variation in DO and pH values was recorded in the same period. Although spatial variability of environmental variables was less pronounced than temporal, it was de-

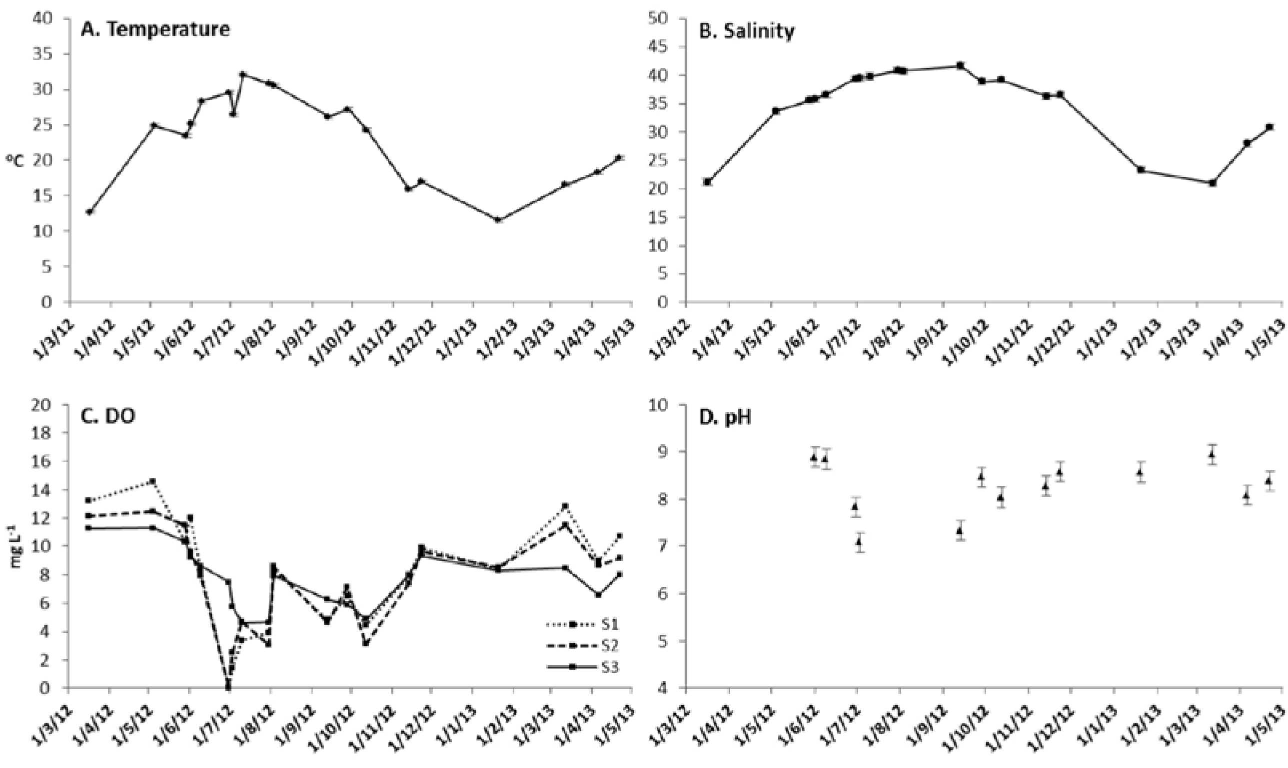

Fig. 2: Temporal fluctuations of temperature (A), salinity (B), dissolved oxygen (C), and pH (D) in Papas lagoon at midday during the study period. Temperature, salinity, and pH are expressed as average values of surface water measurements at the three stations.

tected in June and July when station S3 was not grouped with S1 and S2, due to the higher DO values as mentioned earlier (Fig. 3).

Discussion

Water temperature range (11.6 °C to 32 °C) in Papas lagoon during the present study is in agreement with the seasonal pattern observed in other lagoons in western Greece, exhibiting minimum values of 9 to 12 °C in January and maximum values of 28 to 35 °C in July and August (Hotos & Avramidou, 1997; Christia & Papastergiadou, 2006; Avramidis *et al*., 2013). Water temperature fluctuations in 2012-13 were found identical to those recorded by previous studies conducted in the area (Chrissanthakopoulou, 2008; Krasakopoulou & Pagou, 2011). However, maximum salinity values recorded in 2012 were lower than the corresponding maximum values measured in 1998 (43) (Krasakopoulou & Pagou, 2011), in 2000 (41) and 2001 (44). The salinity fluctuated at similar levels in 2002 (Chrissanthakopoulou, 2008) and were lower than the values recorded in September 2009 (45) (Nestoridou, 2011). Although the aforementioned summer salinity values in early July, ranging from 40 to 41.4, were higher than those recorded during the current study, no dystrophic events were observed. Therefore, the dystrophic event in Papas lagoon could not be attributed to increased salinity values, in contrast to Lesina lagoon where, according to Vignes *et al*. (2009), the dystrophic crisis in the summer 2008 was correlated to an increase in salinity.

The high concentrations of DO and alkaline pH values recorded during the period prior to the dystrophic crisis are typical of eutrophic aquatic ecosystems (Viaroli & Christian, 2003; Giordani *et al*., 2009). Overall, DO values at the water surface were higher than at the bottom layer except on three occasions (on 9/6/13, 13/11/13 and 23/11/13). These differences were probably due to a photo-inhibition phenomenon in the surface layers, since it was accompanied by the same sign differences between the respective pH values, indicating enhanced photosynthetic activity in the deeper layers (Platy *et al*., 1980; Vincent *et al*., 1984; Moeller, 1994). During the same period recorded values of DO at station S3 were lower than at the others stations and this was repeated during next spring 2013. According to Kartsakli *et al.,* (2014), water renewal through tidal currents seems to be more pronounced at the northern part of the lagoon, thus probably affecting the photosynthetic activity of this region compared to the other more confined water masses of the lagoon. The separation of the northern basins' water mass is also demonstrated by the limited influence of the dystrophic event on DO values at station S3. The dramatic decline of dissolved oxygen observed ten days after the dystrophic crisis is attributed to the mixing of the waters of the lagoon occurring after a sudden change in the water circulation, rather than the extension or recurrence of the anoxic episode.

The local, although extensive, manifestation of the dystrophic phenomenon agrees with the observations of Souchu *et al.* (1998b) and Vignes *et al*. (2009), that white tides are indicative of temporal and localized development of anoxia in lagoons subsequent to benthic decomposition of organic matter. The distribution of organic matter and the depth of the lagoon are crucial factors for the development of dystrophic episodes (Souchu *et al.,* 1998b). In Thau lagoon at the south of France, dystrophic crisis, locally called "eaux blanches" or "malaigue" (Tournier *et al.,* 1979; Minghelli-Roman *et al.,* 2011), affected only the deeper areas of the lagoon and the initial

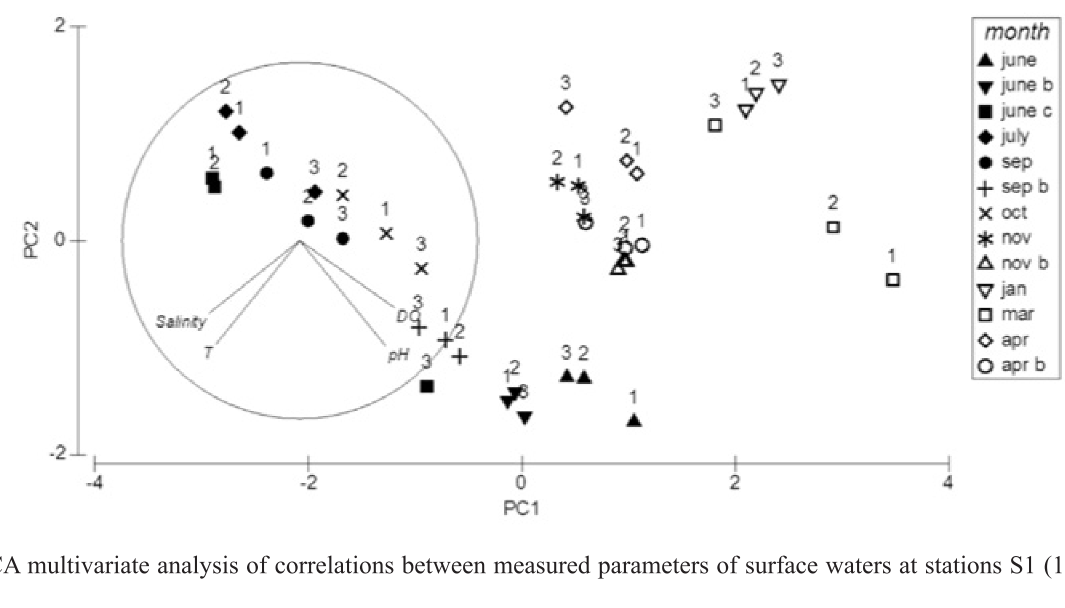

Fig. 3: PCA multivariate analysis of correlations between measured parameters of surface waters at stations S1 (1), S2 (2), and S3 (3).

flare-up was recorded at areas with high concentrations of organic matter (Souchu *et al.*, 1998a; Chapelle *et al.*, 2001) while in Lesina lagoon in Italy, dystrophic crisis affected a hydrologically isolated part of the lagoon (Vignes *et al.,* 2009). Surprisingly, in Papas lagoon, the dystrophic crisis originated from an area near the communication opening with the open sea, and not in a confined part of the lagoon.

It is well known that the values of pH in wetlands are mediated through the dynamics of photosynthetic consumption and respiratory/decomposition production of carbon dioxide. In anoxic conditions high concentrations of inorganic carbon compounds (e.g. bicarbonate, carbonic acid) are observed due to the limited photosynthetic activity and the subsequent oxygen depletion. This mainly explains decreasing pH values due to the dissociation of the bicarbonate produced and the subsequent precipitation of carbonates in the form of $CaCO_3$. This procedure leads to the milky colouration of the water (Dupraz *et al.*, 2009). As stated in the above mentioned study, the evolution of the dystrophic event is attributed to a microbiologically induced mineralization. Oxygen depletion is an ideal condition for de-nitrification by facultative heterotrophic bacteria because after dissolved oxygen, they turn to the second best electron acceptor, which in coastal lagoon water is nitrate. Subsequently, once nitrate is consumed and under very high reduced conditions, sulphate is reduced by bacteria to hydrogen sulphide (Stumm & Morgan, 1996). Hydrogen sulphide release in the water column leads to further acidification of the lagoon water. On the other hand, Souchu *et al.* (1998b) attributes the milky water colouration to the proliferation of photosynthetic bacteria of the family Chlorobiaceae, which re-oxidize the hydrogen sulphide, while according to Minghelli-Roman *et al.* (2011) this colour is due to a temporary accumulation of sulphur particles within the bacterial cells.

In August DO concentrations increased and the water colour became green, indicative of important phytoplankton growth. The values of dissolved oxygen in the lagoon remained low, often below 50 % saturation for more than 90 days. The slow recovery of DO in the water mass of the lagoon indicates that the water renewal through tidal action is very limited, despite the existence of the three communication openings with the sea. Interestingly, the O2 opening (Fig. 1) was created in 1992 in order to facilitate the water exchange of the lagoon with the open sea. Frequent dystrophic crises in the last twenty years have not vindicated such effort. On the contrary, many communication openings with the open sea seem to facilitate the exit of the lighter brackish water from the surface layers, thus contributing to increased salinity values in the lagoons during summer. The literature on the time required for the restoration of dissolved oxygen in the Mediterranean lagoons after dystrophic phenomena is limited. It is also difficult to evaluate and compare such information, since the re-oxygenation of the water depends on local conditions such as wind direction and intensity, tides and sunshine. However, it seems to be a very slow process in all cases. Souchu *et al*., (1998b) describing the evolution of an anoxic crisis in the summer of 1997 in the affected area of the Tau lagoon, France, and reported a rise in DO up to 50 % and 80 % of the saturation value 20 days and 50 days after the crisis, respectively. In this case the corresponding periods were 20 and 34 days for the surface layer while the bottom layer recovered in 20 and 135 days, respectively (Fig. 4). Based on satellite images of Lesina lagoon along the Adriatic coast of Italy in the summer 2008, Vignes *et al*.,

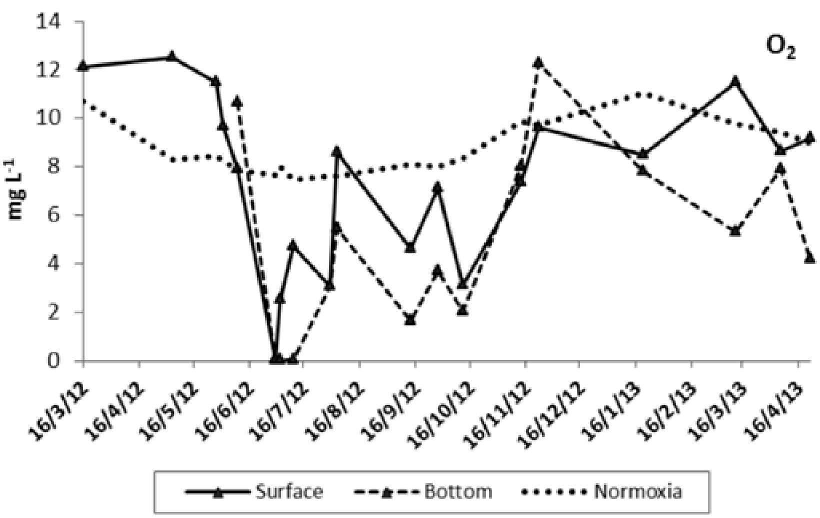

Fig. 4: Temporal fluctuations of dissolved oxygen concentrations at the central part of the lagoon (station S2) during midday, at 0,5 m depth (solid line, replotted) and 3,5 m depth (dashes). Normoxia values fluctuation is drawn as dotted line.

(2009) stated that the recovery of the lagoon by dystrophic crisis took one month.

Fish in Papas lagoon showed different reactions to anoxia depending on their adaptive strategies. Generally, species that colonize coastal lagoons have special mechanisms and adopt appropriate strategies to overcome the anoxic conditions. These include escape behaviours to avoid areas of oxygen-poor waters (Wannamaker & Rice, 2000), as exhibited in the present case by the fish accumulating at the openings of the lagoon at the beginning of the crisis; aquatic surface respiration ASR (Kramer, 1983), achieved by swallowing air or jumping to enrich the water in the gills with atmospheric oxygen, e.g. in Mugilidae species (Dickson Hoese, 1985; LeFrançois *et al.*,2009) was also observed in the present case; the use of cutaneous respiration i.e. in eels (Berg & Steen, 1965; Nonnotte & Kirsch, 1978) and sole (Couturier *et al.,* 2008) can explain the observed beaching on the coast behaviour, etc. In the case of dystrophic crises, however, the combined effect of prolonged anoxia and the toxic hydrogen sulphide excludes chances of survival (Gray *et al.,* 2002), especially if the phenomenon is generalized and there exists no possibility of escape, i.e. in case of species with limited escape options like sole (Lagardere *et al.,* 1988) and gobies, or in cases of entrapment of fish in the context of fishery management of lagoons.

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