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AN ECOSYSTEMIC APPROACH FOR AN ECOLOGICAL CRISIS IN BERRE LAGOON

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LAGOON ECOLOGY
ECOLOGICAL CRISIS
ZOSTERA MEADOW
ECOSYSTEM RESILIENCE

ABSTRACT. – Berre lagoon is a Mediterranean lagoon deeply impacted by industry and urban activities. Since 1966, a hydroelectric powerplant has discharged large quantities of freshwater and nutrients into the lagoon, inducing major ecosystemic changes. The lagoon ecosystem has declined to a eutrophic state with the loss of *Zostera* meadows and marine macrofauna. In 1994, an extensive monitoring network for Berre lagoon was set up. Different compartments of the ecosystem were measured: water quality, sediment quality, macrophytes (including Magnoliophyta), benthic macrofauna, fisheries, and ichthyofauna. Results show a pattern of change in the ecosystem linked to the different phases of eutrophication reduction. However, in 2018, a major ecological crisis occurred, inducing anoxia over more than 90 % of the lagoon surface area. Analysis of data from the monitoring network during and after this crisis, taking into account environmental and climatic factors, provides a basis for understanding the degradation of the different compartments of the ecosystem. The origin of this crisis is a 'cocktail effect' of high spring nutrient inputs, high water temperature, strong water stratification, lack of wind, lack of Zostera meadows and high benthic biomass. This crisis highlights the extreme fragility of the Berre lagoon ecosystem and shows the importance of an ecosystemic approach for the monitoring network.

INTRODUCTION

Coastal lagoons and estuaries have, since the early or middle 20th century, become among the coastal ecosystems the most impacted by disturbances worldwide (Valiela *et al*. 1997, Cardoso *et al*. 2004). Berre lagoon is one of the largest Mediterranean deep lagoons (155 km^2, maximum depth 9.5 m; mean depth: 6 m). It communicates with the Mediterranean Sea through the Caronte Channel and receives freshwater from several natural rivers (Deslous-Paoli 1996). At the beginning of the 20th century, Berre lagoon was a biodiversity hot spot, with an abundance of marine species and large *Zostera* meadows from the surface to 6 m depth (Rioual 1972, Gourret 1907, Roux *et al*. 1985, 1993). During the industrial revolution, Berre lagoon was impacted by severe chemical pollution resulting from industry, agriculture and urbanization (Arfi 1989, GIPREB 2012). Despite this industrial impact, the ecology of the lagoon remained in good condition with high biodiversity and extensive *Zostera* meadows (Bernard 2007).

Since 1966, the installation of a hydroelectric power plant induced high freshwater and nutrients inputs into the lagoon (Roux *et al*. 1985). Initially, this disturbance caused major changes in the Berre ecosystem: the heavy inputs of freshwater (up to seven times the volume of the lagoon per year) induced a decline of the surface water salinity from 24-36 to 1-22) and a water column stratification with low salinity water down to 5 m and more salty water at depth (under calm conditions) (Kim 1985). The associated nutrient inputs caused the decline of the ecosystem to a eutrophic state with high chlorophyll *a* concentration, anoxic episodes at depth, benthic macrofauna biodiversity loss (Stora and Arnoux 1983, Stora 1995, Zaghmouri *et al*. 2013) and a dramatic loss of the *Zostera* meadows from 6,000 ha in 1960 to 1.5 ha in 1998 (Bernard *et al*. 2007) France. A first limitation of freshwater inputs was initiated in 1994 (2.5 Gm^3 per year), and a second in 2005 after European litigation (Truilhé-Marengo 2013). Since this litigation, the freshwater inputs have been limited to 1.2 Gm^3 per year, and in addition the salinity must be controlled to avoid high variations (75 % of the time above 20, 95 % of the time above 15). In parallel, since the 1990s, a major effort has been deployed throughout the watershed to reduce nutrient inputs resulting from urban and industrial activities (Gouze *et al*. 2008a, b).

Overall, these input reductions have led to a major change in the ecosystem as a whole. The Berre lagoon-monitoring network, which has been in existence since 1994, has shown improvement in most of the ecosytem components. After a phase of instability, the lagoon eutrophication level has declined: the chlorophyll *a* has decreased, the macrophyte community has become more diversified, the *Zostera marina* Linnaeus meadows have become more extensive (17.93 ha in 2017), the shore benthic macrofauna biodiversity has increased (GIPREB 2019). In particular, a large manila clam *Ruditapes philip-*

pinarum (A. Adams & Reeve, 1850) population is present along the shore (up to 4-5 m), with very high density at some points (Mahé *et al.* 2020).

But the restoration trajectory of a lagoon is complex (Bettinetti *et al.* 1996, Derolez *et al.* 2019, Leruste *et al.* 2019a). Anoxic crisis episodes could occur and impact the ecosystem in various ways and could be recurrent as in some other French Mediterranean lagoons such as Thau lagoon (Souchu *et al.* 1998, Harzallah & Chapelle 2002) located in southern France, suffers episodically in summer from anoxic crises known as 'malaïgues'. Such crises mostly occur under warm conditions and low winds. In this paper we investigated effects of local weather conditions (air temperature, wind speed and precipitation over southern France. The origin of these crises could be diverse such as climatic conditions, pollution, high nutrient inputs, and may be difficult to explain (Harzallah & Chapelle 2002).

During the summer-autumn 2018, a major ecological crisis occurred in Berre lagoon and affected the whole ecosystem. This crisis impacted all the ecosystem compartments at different levels. On the basis of the monitoring network results and the environmental data, might it be possible to understand the mechanisms of this crisis?

MATERIALS AND METHODS

Water quality: physical and chemical parameters: Ten stations were sampled monthly in Berre lagoon since 1994. At each point, a TSO (temperature, salinity, % of O_2 saturation) profile is established using a multi-parameter probe (hydrolab DS5). Depth and surface water were sampled using a Niskin bottle and then analyzed to measure nutrient concentrations (NO_3, NO_2, NH_4, total nitrogen, PO_4, total phosphorus) and chlorophyll *a* (Gouze *et al.* 2008b).

Biological parameters: Phytoplankton analysis is based on monthly samples at two stations. Macro- and nano-phytoplankton are identified and counted under the microscope.

The benthic macrophytes are monitored across 31 stations close to the shore every year. At each station, a survey is carried out by SCUBA diving transects perpendicular to the shore over a distance of 100 m. The abundance of each macrophyte group is noted using a semi-quantitative method from 0 (species absent to 500 for 100 % cover at the station; Astruch & Schohn 2019). For each macrophyte or group of macrophytes, an abundance index is calculated based upon the presence frequencies and the abundance along the transect (Astruch & Schohn 2019). The macrophyte survey was performed in June 2018, before the crisis, and was compared to the survey performed in June 2019 after the crisis.

A more specific survey was carried out on the *Zostera noltei* Hornemann meadows. In order to calculate their covered surface, aerial or satellite photography was used in 1998, 2009, 2014, 2017 and 2019. The photographs used were taken in June at the period of maximum growth of the *Zostera* meadows with a 30-cm resolution. A photo-interpretation was performed and the meadow was mapped using a GIS (QGIS v3.4). Verification by diving was undertaken to validate the interpretation and to estimate visually the meadow vitality (intermattes, coverage, epiphytes).

Shore benthic macrofauna has been monitored across 10 stations twice a year (summer and winter) since 2005. The stations are at around 4-5 meter depth. At each station, three replicates of sediments were sampled with an orange-peel bucket and were sieved at 1 mm. The surface area sampled at each replicate is 208 cm^2. At the laboratory, the living organisms were identified and counted. The species richness and abundance per species (number of individuals per m^2) were calculated.

To estimate the surface impacted by the crisis, different transects were undertaken around the lagoon to determine the minimum depth where living macro-organism were observed. *In situ* observations were performed in September, after the first period of anoxia.

Meteorological data: Meteorological data (pluviometry, wind, air temperature) are based on data collected by Infoclimat (infoclimat.fr) every 3 hours at the Marseille-Marignane weather-station located to the south of Berre lagoon.

RESULTS

Water quality: physical and chemical parameters

The water temperature was particularly high during summer 2018. Temperatures over 30 °C were recorded in August. The average temperature in August was 28.1 °C for all the stations and all depths. A high water column stratification was observed with very wide differences in salinity between the surface and the bottom layer. The difference of salinity between these layers was more than 10 PSU during the whole summer (June to August). In June, the surface salinity was around 20 and increased

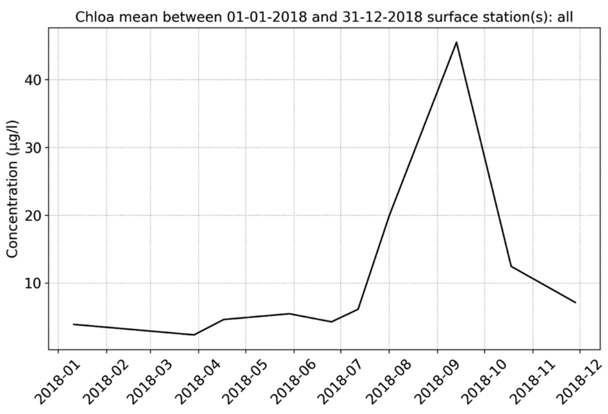

Fig. 1. – Mean concentration of Chlorophyll *a* (µg/l) at the surface in 10 stations in Berre lagoon in 2018.

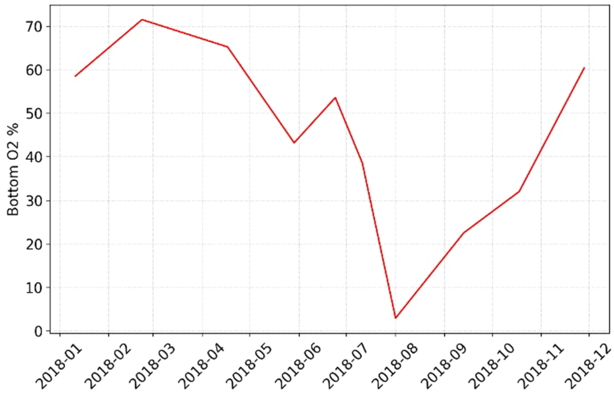

Fig. 2. – Mean percentage of bottom (last meter) dissolved oxygen (% of O_2 saturation) in 10 stations in Berre lagoon in 2018.

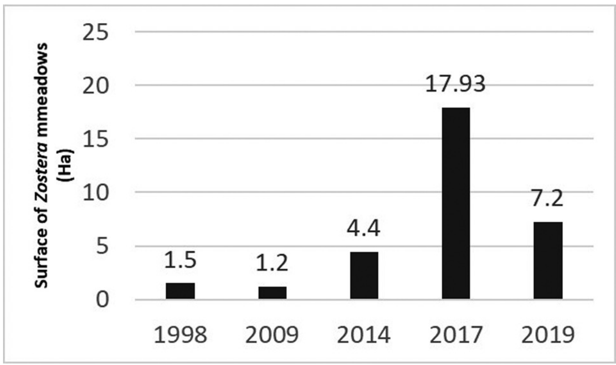

Fig. 3. – *Zostera* meadows surface (ha) in Berre lagoon between 1998 and 2019.

slowly to 25 in August. The bottom salinity (below 8 m) was quite constant, around 35, close to the marine salinity.

The results of the monitoring during the year show a high state of water eutrophication during summer 2018 with a very high concentration of chlorophyll *a* (Fig. 1). The spatial average surface concentration in September reached 45.54 $\mu g \cdot h^{-1}$ (standard deviation = 24.81 $\mu g \cdot h^{-1}$). Such a high value has not been recorded by the GIPREB monitoring network since 1998. Similar observations were made for suspended matter, total nitrogen and PO_4 concentrations with high concentrations during the late summer (September-October). Continuous recording of dissolved oxygen (S. Rigaud, unpubl data) show up to 25 consecutive days of anoxia (0% of O_2 saturation) at 9 m depth, 10 days at 5 m depth and 5 days at 3.5 m. From September to December, hypoxic and anoxic conditions were recorded in the bottom layer (last meter; Fig. 2).

Biological parameters

Phytoplankton community analysis showed in August an efflorescence of nanoflagelates (< 10 µm). In September, a bloom of dinoflagellate *Gymnodinium impudicum* (S. Fraga & I. Bravo) Gert Hansen & Moestrup (more than 2.5 million cells per liter) was observed. According to G. Gregori (MIO, pers comm), during the same period, high concentrations of picoplankton were observed in the samples analyzed by cytometry.

The macrophyte populations after the crisis (in June 2019) compared to before (in June 2018) showed lower abundance of *Enteromorpha* species and regression of some marine species such as *Codium fragile* (Suringar) Hariot or *Bryopsis hypnoides* J. V. Lamouroux. *Ulva* sp. stayed abundant and showed no variation. *Cladophora* sp. showed a decrease after this episode. But the most important variation occurred in *Zostera noltei* with an abundance index reduced by 5. In terms of surface area, the estimated surface area of the *Zostera* meadows declined from 17.93 ha in June 2017 to 7.2 ha in June 2019 (Fig. 3).

The shore benthic macrofauna showed a strong decline in September 2018. The mean species richness dropped from 11.4 to 0.9 (Fig. 4). At the 10 stations monitored, only 2 still had living organisms. These 2 stations were located near the seawater entrance (Caronte Channel). The abundance of benthic organisms also decreased from 4,100 $ind \cdot m^{-2}$ to 162 $ind \cdot m^{-2}$.

The *in situ* observations carried out by diving at different depths and locations around the shore enabled us to estimate that anoxic condition impacted more than 90 % of the lagoon's surface area (Fig. 5). Depending on the zone, anoxia impacted shallow areas down to 1 m depth. For a few zones such as south of Vaïne lagoon or Saint-Chamas Bay (at the north), anoxia impacted the whole

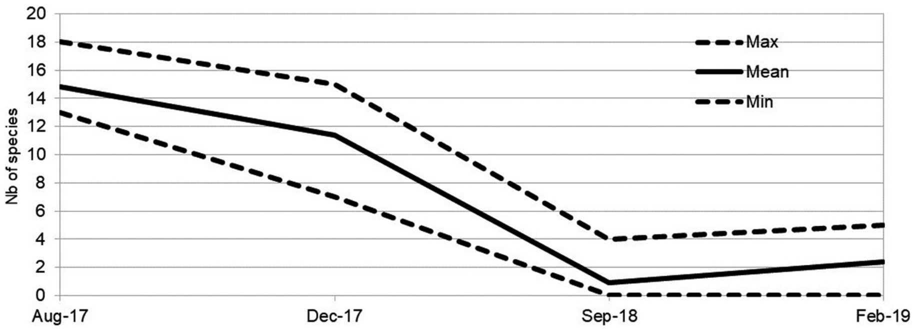

Fig. 4. – Maximum, mean and minimum shore (4-5 m depth) benthic macrofauna species richness (number of species) in 10 stations in Berre Lagoon.

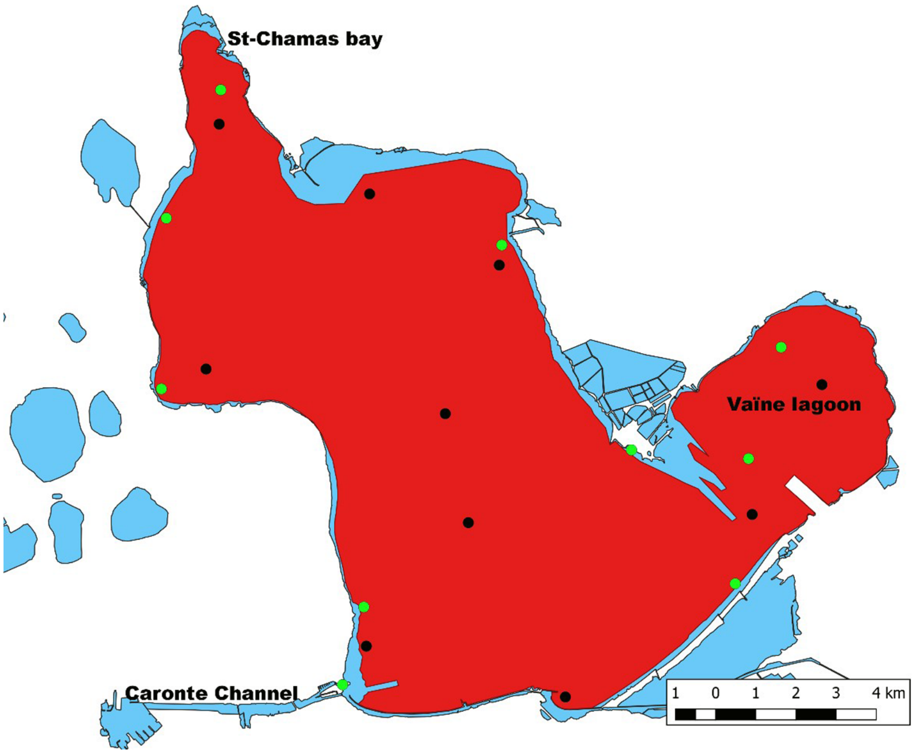

Fig. 5. – Estimated surface impacted by anoxia during the 2018 crisis in Berre lagoon (in red). The surface impacted is estimated at 14,400 ha representing 93 % of the total surface area.

of the water column (phenomenon called *malaïgue* in Provence).

Meteorological and environmental data

During summer 2018, the air temperature was quite high with an average of 25.87 °C (based on mean daily temperature, June to September). The temperature anomaly was +2.2 °C (compared to the 1981-2010 period). According to Meteofrance, summer 2018 was the second warmest summer in France since the beginning of the 20th century. The sunshine duration was 1,061.3 hours during the three summer months (July, August and September). During summer 2018, the wind velocity was quite low and an episode of 19 days without wind (above 23.4 km·h^{-1}) was recorded. Twenty-two high wind episodes (*i.e.*, > 23.4 km·h^{-1}) occurred during the summer period from June to September. The pluviometry during the first six months of 2018 was higher than normal (331 mm, + 35 % of the 1981-2010 climatology). Some rain episode also occurred during the summer (July: +121 % and August +103 %). High pluviometry was also recorded in autumn (October-November and December) (446.6 mm, +265 %).

The freshwater inputs during the six first months of 2018 represented 864 billion m^3, with 85.5 % coming from the hydroelectrical powerplant (the rest was accounted for by the three main rivers, direct watershed and pluviometry). These freshwater inputs also represent input into the lagoon of 36 tons of total phosphorus and 952 tons of total nitrogen (Gouze *et al*. 2014).

DISCUSSION

The Berre lagoon-monitoring network made it possible to record the impact of the 2018 crisis on several ecological compartments. The results show a high level of eutrophication of the water with high concentrations of nutrients and chlorophyll *a*. Anoxic conditions were observed in most of the lagoon (more than 90 %) and at very low depths (1.5 m). In some cases, anoxia impacted the whole of the water column and white water was observed, caused by the presence of green sulfur bacteria (*Chlorobiaceae,* Souchu *et al*. 1998).

As a consequence of these anoxic conditions, massive benthic mortalities were observed through macrofauna monitoring. In September 2018, only 2 of the 10 shore stations (4-5 m depth) presented living organisms. A stock survey of the manila clam (*Ruditapes philippinarum*) estimated a loss of more than 75 % of the population abundance during this crisis (Mahé *et al*. 2020). During the spring of 2019, a survey of the macrophytes showed a community change: less of *Enteromorpha* and a strong decline of abundance of Magnoliophyta such as *Zostera noltei*. The effects of this crisis were more severe with regard to the surface area of the *Zostera noltei* meadow. The 2019 survey showed a surface area loss estimated at 60 % of the 2017 surface. This Zostera meadow degradation could have been caused by the low transparency of the lagoon water (high concentrations of chlorophyll *a* and suspended matter) that reduced photosynthesis (Santos *et al.* 2010). In addition, the *Zostera noltei* meadows and in particular the rhizomes could have been stressed by the anoxic conditions and burned by the released sulfurdihydrogen (H_2S) (Pulido & Borum 2010). The meadows located where white waters occurred completely disappeared, confirming this link between H_2S and the decline of the meadows.

On the basis of the environmental parameters, how could the occurrence of such a crisis be explained?

At the beginning of the summer, the surface salinity was relatively low (22) due to the high freshwater inputs during the winter and spring. The water column was stratified, and the delta of salinity between the surface and the bottom was high (> 10 points of salinity for the deeper stations). The freshwater input was due to the direct and indirect (through the natural rivers) watershed and from the hydroelectric powerplant. As a consequence, the lagoon surface salinity stayed relatively low (20-22) in June 2018 compared to previous years. These freshwater inputs also represent an input of nutrients (nitrogen and phosphorus) into the lagoon ecosystem. These nutrient inputs increased the growth of phytoplankton during the summer. However, such high inputs have already been recorded without causing an ecological crisis later. Similar observations could be made for the air and water temperature. If the temperature recorded during that summer was particularly high, similar temperatures have already been recorded without causing any crisis. For example, in 2019, high air temperatures were also recorded.

The climatic parameter that could have been quite exceptional during summer 2018 is the low wind activity resulting in reduced water column mixing. The freshwater input installed a pattern of stratification. The lack of wind, coupled with high temperatures, high phytoplanktonic production and benthic consumption generated oxygen depletion at depth. In the bottom water layer, dissolved oxygen is consumed by benthic organism respiration and organic matter degradation. Part of the organic matter results from the sedimentation of dead phytoplankton cells. Such stratification linked with in depth anoxia is unfortunately recurrent phenomenon in Berre lagoon (GIPREB 2017). But in 2018, during this crisis, the absence of strong wind prevented the mixing of water, and the anoxic layer increased and impacted an increasingly extensive surface area. However, winds of 6.5 $m.s^{-1}$ (*i.e.*, 23.4 $km{\cdot}h^{-1}$) are enough to mix the water column (Nerini *et al.* 2001) and such wind speeds were recorded during the summer (22 times). Moreover, the high primary production at the surface represented an important source of organic matter at the bottom and increased the biological oxygen demand. With high water temperatures, the dissolved oxygen concentration was lower. This oxygen consumption was higher at the shore, where there was a very high biomass of manila clams. As the anoxic layer increased, benthic mortality occurred and these dead organisms became a new source of organic matter, which also needed oxygen for its degradation. During the anoxic conditions, the sediment constituted a source of phosphorus (PO_4) for the water column and thus a new source of nutrient to sustain the eutrophic conditions (Rigaud *et al.* 2013, 2017). The system was thus locked in a self-reinforcing feedback loop.

Another factor, which may explain the severity of this crisis, compared to other lagoons with higher ecological status, is the absence, or at least the low abundance, of seagrass meadows, natural oxygen producers for the ecosystem. In fact, even if the *Zostera noltei* meadow cover was the most extensive observed over the last decades, it only represented 0.9 % of the 0-3 m depth surface area. This low abundance is insufficient to produce enough oxygen and to mitigate the anoxic crisis.

Thus, taken separately no single explanation parameter could explain the crisis. The 2018 crisis cause was a cocktail-effect of different environmental parameters that acted in synergy, with these dramatic results: high spring inputs, strong water stratification, high water temperature, lack of strong wind, absence of *Zostera* meadows, and relatively high shore faunal benthic biomass.

After the beginning of the crisis in late July, new freshwater inputs from the hydroelectric powerplant (in mid-August and September) represented a new source of nutrients and have led to the extension of the duration of the crisis. The bloom of dinoflagellates observed in autumn could be linked to these enrichments (Leruste *et al.* 2019b). Due to these freshwater inputs, even after a wind episode that mixed the water column, stratification was quickly restored. The high organic matter stock, due to the dead organisms, represents a sink of dissolved oxygen. For this reason, high concentrations of chlorophyll *a* in October and hypoxic or anoxic conditions up to November were still observed.

The occurrence of this ecological crisis in Berre lagoon illustrates the fact that the restoration policy (freshwater inputs reduction) is perhaps insufficient to avoid such a major crisis. This crisis illustrates that the Berre lagoon ecosystem remains unstable. Adverse climatic conditions, such as during summer 2018, can make the ecosystem vulnerable to a major ecological crisis that will affect all its compartments. Such a severe crisis is a step backwards after the improvements observed over recent years and the restoration of some major compartments such as the *Zostera* meadows is uncertain. To limit the risk of a new crisis, or to limit its impact on the ecosystem, a solution could be to limit the stratification and the nutrient inputs.

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