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Man-induced hydrological changes, metazooplankton communities and invasive species in the Berre Lagoon (Mediterranean Sea, France)

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ABSTRACT

The Berre Lagoon has been under strong anthropogenic pressure since the early 1950s. The opening of the hydroelectric EDF power plant in 1966 led to large salinity drops. The zooplankton community was mainly composed of two common brackish species: *Acartia tonsa* and *Brachionus plicatilis*. Since 2006, European litigation has strongly constrained the input of freshwater, maintaining the salinity above 15. A study was performed between 2008 and 2010 to evaluate how these modifications have impacted the zooplankton community. Our results show that the community is more diverse and contains several coastal marine species (i.e., *Centropages typicus*, *Paracalanus parvus* and *Acartia clausi*). *A. tonsa* is still present but is less abundant, whereas *B. plicatilis* has completely disappeared. Strong predatory marine species, such as chaetognaths, the large conspicuous autochtonous jellyfish *Aurelia aurita* and the invasive ctenophore *Mnemiopsis leidyi*, are now very common as either seasonal or permanent features of the lagoon.

1. Introduction

Lagoons are shallow basins of natural or anthropogenic origin (Guelorget and Perthuisot, 1983), subject to significant temperature and salinity variations linked to seawater and/or freshwater inputs. Their biological production is usually very high due to large nutrient inputs from their catchment basin, which often leads to eutrophication (Caddy, 2000). Over the years, lagoons have become economic engines and strategic sites for industrial development. The functioning of these ecosystems is, therefore, strongly influenced by anthropogenic activities (Marcus, 2004). Coastal lagoons under the influence of large freshwater discharges from hydraulic-driven power plants are strongly impacted by mechanical, thermal and/or biocide effects (Capuzzo, 1980), which in turn, deeply modify benthic and pelagic ecosystems (Stora, 1983; Bernard et al., 2007; Rissik et al., 2009; Peirera et al., 2010). Colonization by eurythermal and/or euryhaline species, which can survive in these highly variable conditions, are also observed (Von Vaupel-Klein and Weber, 1975; Gaudy and Viñas, 1985), weakening the specific diversity and, consequently, trophic interactions.

Metazooplankton are often considered as a good bio-indicator of aquatic environmental quality, especially in brackish water ecosystems (Wilson, 1994; Murrel and Lores, 2004; Webber et al., 2005; Landa et al., 2007; Etilé et al., 2009; Ferdous and Muktadir, 2009). Some of these organisms, depending on their tolerance, can be very sensitive to pollution and changes in environmental factors, resulting in being either present or absent from an ecosystem. For example, rotifers represent a typical bio-indicator of environments subjected to high nutrient inputs (Ferdous and Muktadir, 2009). In lagoon ecosystems, copepods of the genus *Acartia* are often associated with inshore polluted waters, while *Oithona* species are generally related to cleaner environments of oceanic origins (Siokou-Frangou et al., 1998).

Among several lagoons located along the Mediterranean shore of France, the Berre Lagoon (northwest of Marseilles; Fig. 1) is the largest and has been under intense anthropogenic pressure for several decades. The deepening of the Caronte Canal (1868–1925) increased the influx of marine water into the southwestern portion of the lagoon. The development of large chemical and petrochemical industries (1920–1970) and the massive urbanization of surrounding cities (1973–1990) led to increased inputs of organic and inorganic pollutants. However, the largest influence on the functioning of the lagoon was the completion of the hydroelectric power plant at Saint-Chamas (northern part of the lagoon) in 1966, conveying water from the derivation canal of the Durance River into the lagoon. At the time, these inputs represented $3.3 \times 10^9\ m^3\ y^{-1}$ of freshwater (3.7 times the lagoon volume) and $520{,}000\ t\ y^{-1}$ of silt. Due to no or very few controls for a long time, the release of freshwater and silt in the lagoon led to modifications of the morphology (i.e., topography of the bottom, quality and size of sediments), the hydrodynamic and the ecological functioning of

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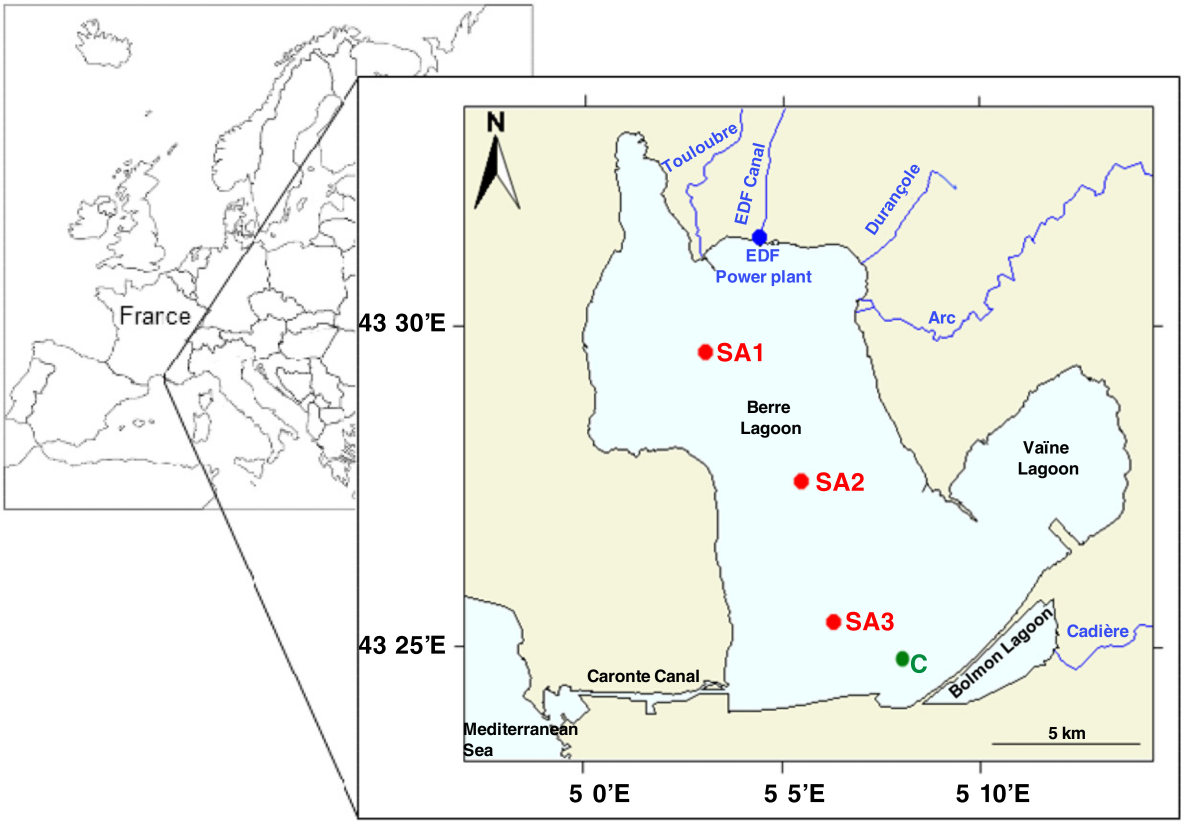

Fig. 1. Map of the study area; location of the three sampled stations SA1, SA2 and SA3 and of the station C corresponding to the study of Cervetto (1995).

the entire lagoon, causing intense eutrophication (Minas, 1974, 1976b; Arfi, 1989, 1991; Caddy, 2000; Gouze et al., 2008), leading to significant anoxia events (Minas, 1974, 1976a; Nerini et al., 2000).

Since the 1990s, various steps have been taken toward the rehabilitation of the lagoon. In 1994, the Barnier Plan (Article 16 of Law No. 92-3, 3 January 1992) led to a 60% reduction in freshwater inflow ($1.2 \times 10^9\ m^3\ y^{-1}$) and a fivefold decrease in silt ($100,000\ t\ y^{-1}$). These restrictions were not enough; salinity continued to indicate large and rapid fluctuations, and eutrophication persisted. In 2006, the European Union Court ruling, stemming from litigation, imposed more stringent limitations, reducing silt inputs to less than $60,000\ t\ y^{-1}$, with a mandatory smoothing over a weekly basis of both freshwater and silt releases. These restrictions aimed to maintain the salinity of the lagoon above 15. Monitoring of temperature, salinity, nutrients, benthos substrate, phytoplankton, macrophytes, mussels and ichtyofauna have been since conducted to track the biological and ecological responses of the lagoon to these changes.

The pelagic ecosystem of the lagoon has only been sporadically studied, and all the studies were conducted after the opening of the power station but before any rehabilitation efforts (Kerambrun, 1970; Minas, 1974, 1975, 1976b; Kim, 1982, 1983, 1985; Kim and Travers, 1983; Arfi, 1991; Gaudy et al., 1995; Cervetto et al., 1999; Robert et al., 2006). Only one study (Cervetto, 1995) addressed the metazooplankton community, showing that it was typical of brackish environments subjected to significant salinity variations, with two dominant species: the rotifer *Brachionus plicatilis* and the invasive copepod *Acartia tonsa*. Most of the published works were devoted to understanding the success of this invasive species (Gaudy and Viñas, 1985; Gaudy, 1992; Cervetto, 1995; Cervetto et al., 1995, 1999; Gaudy et al., 1996, 2000).

Here, we present results from the first study conducted on the zooplankton of the Berre Lagoon since the ruling from the European litigation in 2006. The main goals of this ongoing study are the following: (1) to analyze temporal and spatial variations of the metazooplankton communities and their relationships with environmental factors (temperature, salinity and chlorophyll-*a* concentration) and (2) to evaluate how modifications in the hydrology have impacted the zooplankton biodiversity of the lagoon.

2. Materials and methods

2.1. Study area and sampling strategy

The Berre Lagoon is a large ($155\ km^2$) and shallow (7 m average depth) brackish water basin located northwest of Marseilles, in southeast France. It is composed of two parts: the main lagoon and the Vaïne Lagoon in the east (Fig. 1).

Freshwater inputs comprise three small rivers, the Touloubre, Durançole and Arc, located on the northern side. The main contributor of freshwater is the man-made Durance River derivation canal, which supplies the EDF power plant at Saint-Chamas. This lagoon is also connected to the Mediterranean Sea in the southwestern part through the Caronte Canal.

Three mooring stations were visited once a month: SA1 in the north, SA2 in the middle and SA3 in the southern part of the lagoon (Fig. 1, Table 1). Seventeen samplings were conducted between May 2008 and 2010: May 5, June 2, July 28, September 24, November 12