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AN ECOSYSTEM-BASED APPROACH TO STUDY THE BIGUGLIA LAGOON SOCIO-ECOSYSTEM (MEDITERRANEAN SEA)

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MEDITERRANEAN LAGOON
ECOSYSTEM-BASED APPROACH
ECOSYSTEM FUNCTIONING
GROUNDWATER
RESTORATION

ABSTRACT. – The Biguglia lagoon, located in the northwestern Mediterranean Sea (Corsica), is a natural reserve, which has been affected by a tremendous territorial change since last decades. An ecosystem-based approach should enable to understand the functioning of an ecosystem, which can be considered, as a socio-ecosystem in order to provide decision support for its conservation and restoration. The objective of this work is to present the research approach carried out on the Biguglia lagoon. The decreasing of the water quality is reflected by a shift from a dominance of aquatic magnoliophytes in the 1970s to varying dominance of phytoplankton and opportunistic macroalgae in the early 2000s. At the same time, it has been observed an ongoing deterioration of the quality of groundwater partly providing the lagoon with fresh water, which can be attributed to the uncontrolled urbanization development all over the alluvial plain surrounding the lagoon. Efforts undertaken to improve the hydraulic management and the reduction of nutrient inputs in the watershed allowed to observe signs of ecological restoration. Nevertheless, the socio-ecosystem functioning study requires a multidisciplinary approach where the natural and social scientists must work together as it is conducted within the framework of the Human-Environment Observatory of the Mediterranean coast (OHM-LM).

INTRODUCTION

Coastal lagoons are among the richest reservoirs of ecological diversity and biological productivity and provide different ecosystem services associated to high economic potential (*e.g.*, Costanza *et al.* 1997, Barbier *et al.* 2011). Owing to their transitional location between continental and marine domains, these ecosystems are naturally subject to environmental variations that induce deep spatio-temporal changes in their physical, chemical and biological properties (Telesh & Khlebovich 2010). Many of these ecosystems have suffered ecological degradation because of human activities, including for example eutrophication, contamination and habitat destruction. This combination of disturbances can dramatically compromise the ecological integrity of these ecosystems, as regularly documented for Mediterranean coastal lagoons (Alvarez-Cobelas *et al.* 2005, Flo *et al.* 2011). To face the huge degradation of lagoons and more generally aquatic ecosystems, European Union (EU) public authorities have designed a new legal managerial framework to reverse adverse anthropic impacts and achieve their good ecological status (Newton *et al.* 2014). In particular, the EU water framework directive in 2000 (WFD, 2000/60/EC) recommends the implementation of management measures to improve the ecological and physico-chemical states of water bodies, in parallel with the monitoring of their ecological and physico-chemical characteristics to evaluate their recovery trajectories.

While the species-centered approach has been adopted for long to meet these expectations, it is now necessary to consider an ecosystem-based approach (Boudouresque *et al.* 2020). An ecosystem-based approach happens to be more adapted to understand the functioning of an ecosystem. This ecosystem displays an organization that includes all the organisms and their interactions, along with the different components of the abiotic environment. The ecosystem functioning can be partly studied through primary producers (phytoplankton, macroalgae and aquatic angiosperms), which react quickly to changes in the environment. Eutrophication can lead to vegetation shifts, described as a transition between alternative states, from pristine slow-growing benthic plants (aquatic angiosperms) to rapidly growing ephemeral plants (macroalgal or phytoplankton communities; Schramm 1999, Pasqualini *et al.* 2017, Le Fur *et al.* 2019). These variations then have major consequences on the overall ecosystem functioning. Another problem that can cause ecosystem disruption is invasive species. In fact, invasive species rarely have an impact on given species, but on entire communities; therefore, understanding their role and impact can only be achieved by considering the whole ecosystem (Boudouresque *et al.* 2011).

The ecosystem-based approach also highlights the importance in tackling the coupling between adjacent

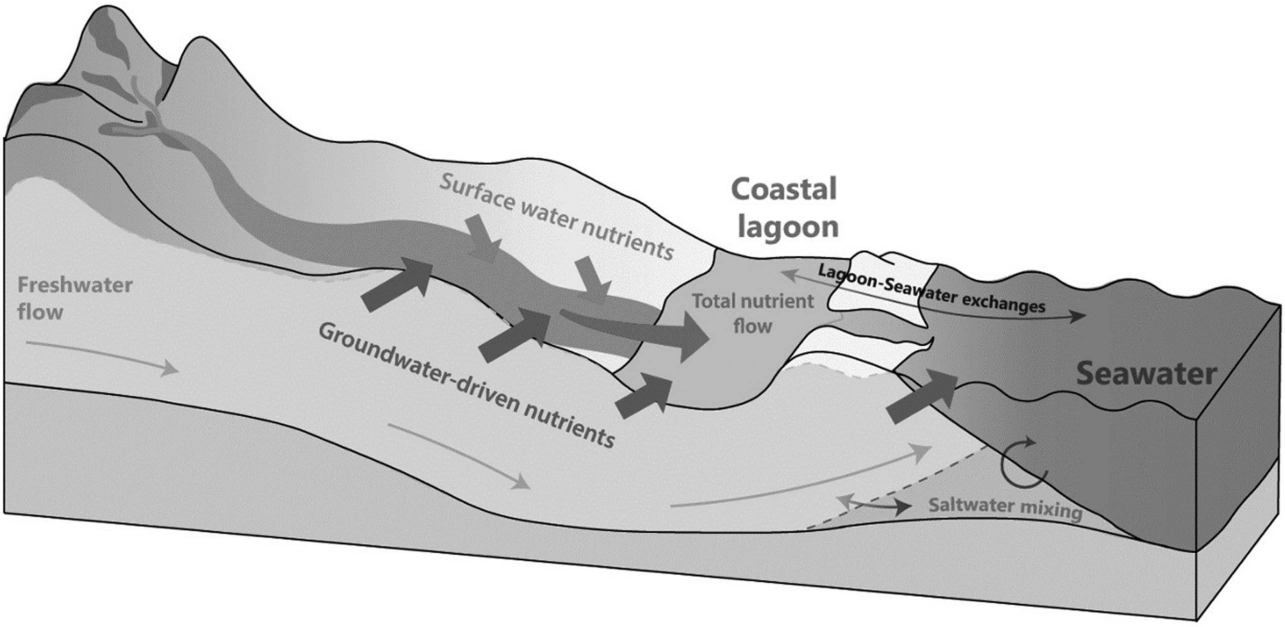

Fig. 1. – Conceptual diagram of the hydrogeological behavior of coastal hydrosystems including a coastal Groundwater Dependent Ecosystem (adapted from Erostate *et al.* 2020).

ecosystems, including groundwater and watershed. In most cases, coastal lagoons are maintained by direct or indirect groundwater supplies, and constitute therefore Groundwater Dependent Ecosystems (GDEs; Krogulec 2016, Menció *et al.* 2017). Since the last decades, several studies have highlighted the importance of groundwater supplies for coastal lagoons (Fig. 1; Malta *et al.* 2017, Erostate *et al.* 2018, Rodellas *et al.* 2018, Correa *et al.* 2019, David *et al.* 2019, Erostate *et al.* 2019). These studies highlight the contribution of groundwater discharge to coastal streams in water and nutrient budgets of coastal zone ecosystems (Fig. 1). During the infiltration, nutrients are leached from the soil and they percolate until the groundwater and migrate directly (groundwater-driven nutrient discharge) or indirectly (via the river) to coastal GDEs (Fig. 1; Rapaglia 2005, Jimenez-Martinez *et al.* 2016, David *et al.* 2019). Human activities in the watershed have an impact on the whole coastal lagoons and within its functional compartments. Depending on the hydraulic behavior of the aquifer, groundwater can thus represent a direct short and/or long-term vector of nutrients/pollutions for coastal GDEs. The efforts undertaken to improve the hydraulic management and the reduction of nutrient inputs in the watershed reduce impacts and can induce ecosystem restoration. However, the ecosystems responses do not result exactly in reversing the processes that occurred during the eutrophication for example (Leruste *et al.* 2019). Moreover, the ecosystem-based approach allows the integration of humans in the ecosystem functioning, thus passing from the notion of ecosystem to that of social-ecological system. In this perspective, an integrated approach for sustainable development in coastal lagoons with a strong partnership among researchers, managers and stakeholders has been proposed (Newton 2012, Newton *et al.* 2014). In this way,

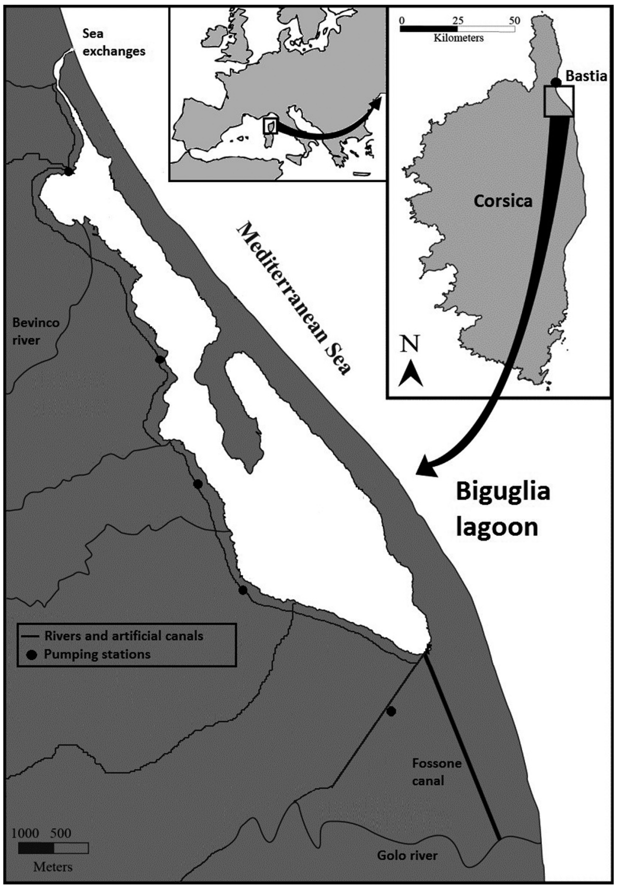

Fig. 2. – The location of Biguglia lagoon (Western Mediterranean Sea) with rivers, artificial canals and pumping stations.

coastal lagoons including their watershed and their coastal zone can be considered as social-ecological systems in which human activity is an integrated part of their own ecology. To better understand the functioning of coastal lagoons as social-ecological systems, organizing multidisciplinary studies and connections between scientists is a prerequisite but also a critical issue (Ostrom 2009).

The objective of this work is to present the ecosystem-based approach carried out on the Biguglia lagoon, located in the northwestern Mediterranean (Corsica; Fig. 2) and affected by a tremendous territorial change these last decades. A diachronic analysis of the ecosystem functioning is carried out on the basis of the primary producers (phytoplankton, macroalgae and aquatic angiosperms) and the ecosystem disturbance observed, coupled with the analysis of groundwater providing the lagoon with freshwater. Studying the hydrogeological component, the dynamics of the aquifer and its capacity to remediate or store pollutants, is indeed essential to assess potential future threats to coastal lagoons. This work is undertaken with regard to the evolution of human activities in the watershed and management actions of the natural reserve. Finally, a multidisciplinary approach on the Biguglia lagoon with the natural and social scientists is conducted within the framework of the Human-Environment Observatory of the Mediterranean coast (OHM-LM) will be presented.

MATERIAL ET METHODS

Biguglia lagoon is a choked, shallow, brackish coastal lagoon located on the Northeast coast of Corsica close to Bastia city (Fig. 2). With a surface of 1,460 hectares, this lagoon is linked to the Mediterranean Sea through a long natural channel to the North (Pasqualini *et al*. 2017). Marine water inputs are limited because the sea channel tends to close (due to the accumulation of sand). Biguglia lagoon receives freshwater from the rivers draining its watershed (180 km^2), mostly in the Northwest part (Bevinco River) and from an old artificial channel and pumping stations draining the agricultural plain, sewage plants and rainfall in the West and South parts (Fig. 2). Freshwater inputs dominate the water budget and lagoon renewal is rapid (several weeks or months; Garrido *et al*. 2016). Biguglia lagoon was recognized as a very important site for waterfowl and was included in the RAMSAR list of wetlands of international importance in 1991. Moreover, it was classified as a natural reserve in 1994 and it belongs to the Natura 2000 network since 2006 (Special Protected Areas of the Bird Directive – EU). The property of the whole lagoon is in the hand of the Collectivity of Corsica (local public authority), with its dedicated service that executes the management. The whole lagoon surface and a small part of the fringing wetlands are no-entry zones with the exception of a small number of professional fishermen allowed for this traditional use.

In order to realize the diachronic analysis of the ecosystem functioning, the information is obtained on the basis of the primary producers such as phytoplankton, macroalgae and aquatic angiosperms. For the phytoplankton, the data come from the Lagoon Monitoring Network since 1999 (Souchu *et al*. 2010) and from bibliographic data (Cecchi *et al*. 2016, Garrido *et al*. 2016, Leruste *et al*. 2019). For the macroalgae and aquatic angiosperms, the data are obtained from the Lagoon Monitoring Network since 1999 and from bibliographical data (De Casabianca *et al*. 1973, Frisoni & Dutrieux 1992, Pasqualini *et al*. 2006, 2017). The ecosystem disturbance observed come from by personal observations and from the monitoring carried out by the natural reserve since 2007. The database developed by the Lagoon Monitoring Network can also be used to assess the eutrophication status of lagoons (Souchu *et al*. 2010, Pasqualini *et al*. 2017). For the Lagoon Monitoring Network, sampling was carried once monthly during the summer period from 1999 to 2014. Mean summer lagoon salinity data were obtained from records published since 1978 (Burelli *et al*. 1979, Frisoni & Dutrieux 1992, Lagoon Monitoring Network and monitoring carried out by the natural reserve).

After demonstrating the dependence of the Biguglia lagoon on groundwater (Erostate *et al*. 2019), the assessment of the groundwater quality was carried out in order to understand the potential influence of groundwater in the quality status of the lagoon. To this end, nitrate (NO_3^-) and emergent organic compounds (EOCs) concentrations were measured in groundwater, river water and lagoon water. Data acquisition was carried out through two sampling campaigns in May 2016 and May 2017. The concentration of dissolved major ions was determined at the Hydrogeology Department (CNRS UMR 6134 SPE), University of Corsica, France, using a Dionex ICS 1100 chromatograph. Regarding EOCs, 51 organic compounds were analyzed, including pharmaceuticals and other substances, such as artificial sweeteners, caffeine and so forth were done using positive (ESI+) and negative (ESI-) modes of the electrospray at the "Povodi Vltavy" laboratory, Pilsen, Czech Republic. Finally, tritium (^3H) contents of groundwater were also measured in order to distinguish the contemporary or historical origin of the pollution and thus to assess the aquifer' remediation capacity. Analyses were carried out by liquid scintillation counting (Thatcher *et al*. 1977) after electrolytic enrichment (Kaufman & Libby 1954) at the Hydrogeology Department of the University of Avignon, France.

RESULTS

The diachronic analysis of the ecosystem functioning shows a shift from a dominance of aquatic magnoliophytes in the 1970's to varying dominance of phytoplankton and opportunistic macroalgae in the early 2000's (Fig. 3A). In the early 1970s, four aquatic angiosperms were well developed in Biguglia lagoon: *Zostera noltei* Hornemann close to the sea channel in the north, *Ruppia cirrhosa* (Petagna) Grande and *Stuckenia pectinata* (Lin-

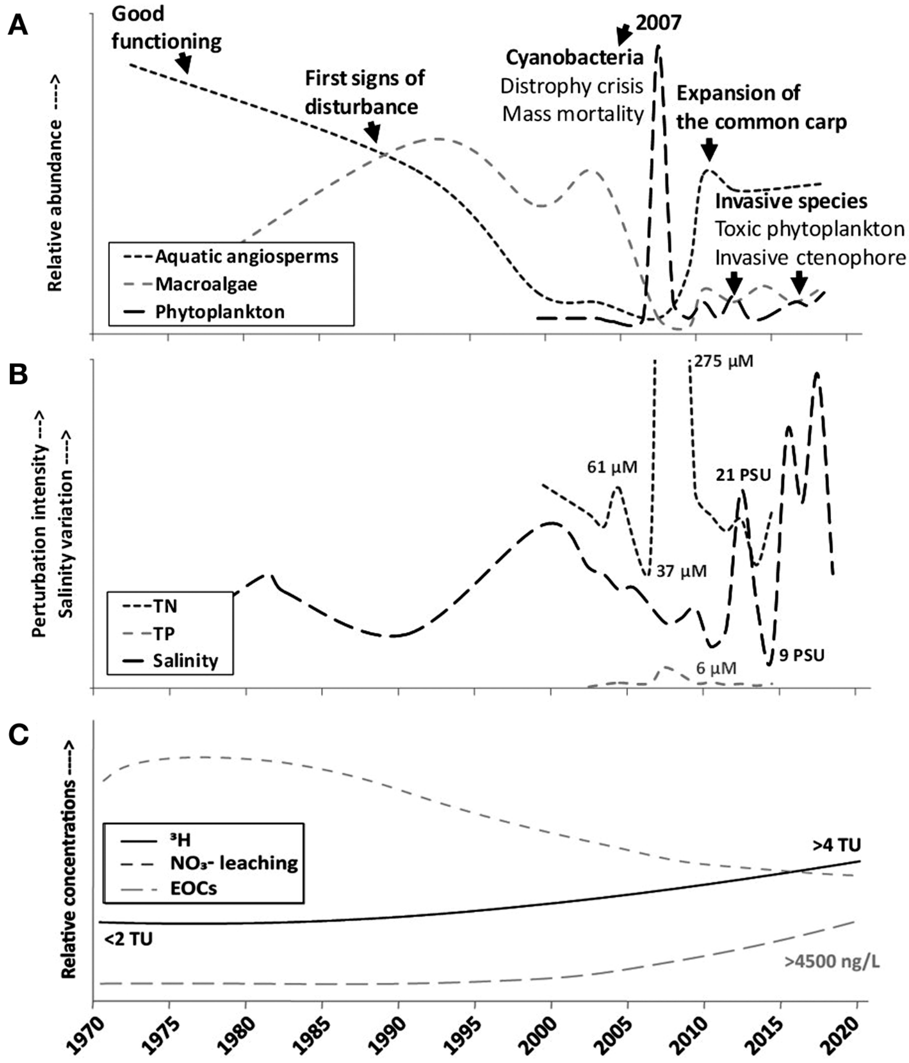

Fig. 3. – Conceptual representation, (**A**) of the relative abundance of aquatic vegetation, phytoplankton communities and ecosystem disturbance observed in Biguglia lagoon (adapted from Pasqualini *et al.* 2017); (**B**) of the eutrophication status and salinity variations in Biguglia lagoon (adapted from Pasqualini *et al.* 2017), (**C**) of the nitrate leaching evolution and EOCs concentrations as a function of water residence time. TN: total nitrogen, TP: total phosphorus.

naeus) Börner throughout the lagoon and *Najas marina* Linnaeus in the southern basin, which testifies to a good functioning of the lagoon. In the early 2000's, *Ulva* sp., *Ulvaria obscura* (Kützing) P. Gayral ex C. Bliding (green algae) and *Gracilaria dura* (C. Agardh) J. Agardh (red algae) occupied a large part of the lagoon. At this period, the concentrations of total nitrogen reached about 60 µM (Fig. 3B). In the summer of 2007, Biguglia lagoon suffered a dystrophic crisis associated with a toxic cyanobacterium bloom, *Anabaenopsis circularis* Woloszynska. The concentrations of total nitrogen reached 275 µM and there was a massive mortality of all organisms in the ecosystem (Fig. 3A, B). After this episode, Biguglia lagoon presented a predominance of aquatic angiosperms, mostly in the southern basin for *Najas marina*, throughout the lagoon for *Ruppia cirrhosa* and/or *Stuckenia pectinata*, and a decrease in macroalgae. The progressive desalination observed in the lagoon at this time has hugely impacted the ecosystem, particularly with the marked development of freshwater magnoliophytes (*Najas marina*), a disappearance of *Zostera noltei* and the expansion of the common carp (*Cyprinus carpio* Linnaeus, 1758), never reported before in the Biguglia lagoon (Fig. 3A, B). The phytoplankton community was strongly influenced by freshwater and nutrients inputs that have led to different physiological and behavioral responses. There ecosystem modifications have dramatically facilitated the successful installation of opportunistic invasive organisms, as a potentially toxic phytoplankton (Fig. 3A; *e.g.*, *Prorocentrum cordatum* (Ostenfeld) J. D. Dodge; dinoflagellate with mixotrophic strategies; Cecchi *et al.* 2016) or an invasive ctenophore (*Mnemiopsis leidyi* A. Agassiz, 1865).

These ecosystem modifications and the variations in total nitrogen concentrations observed in the lagoon (in particular NO_3^-) have raised questions about the NO_3^- origin. The NO_3^- concentrations measured in river water are often very low and cannot explain the NO_3^- concentrations in the lagoon. The good correlation of the dynamics between groundwater flow and NO_3^- concentrations in the lagoon suggests that groundwater has a predominant impact on the NO_3^- supply to the lagoon (Erostate

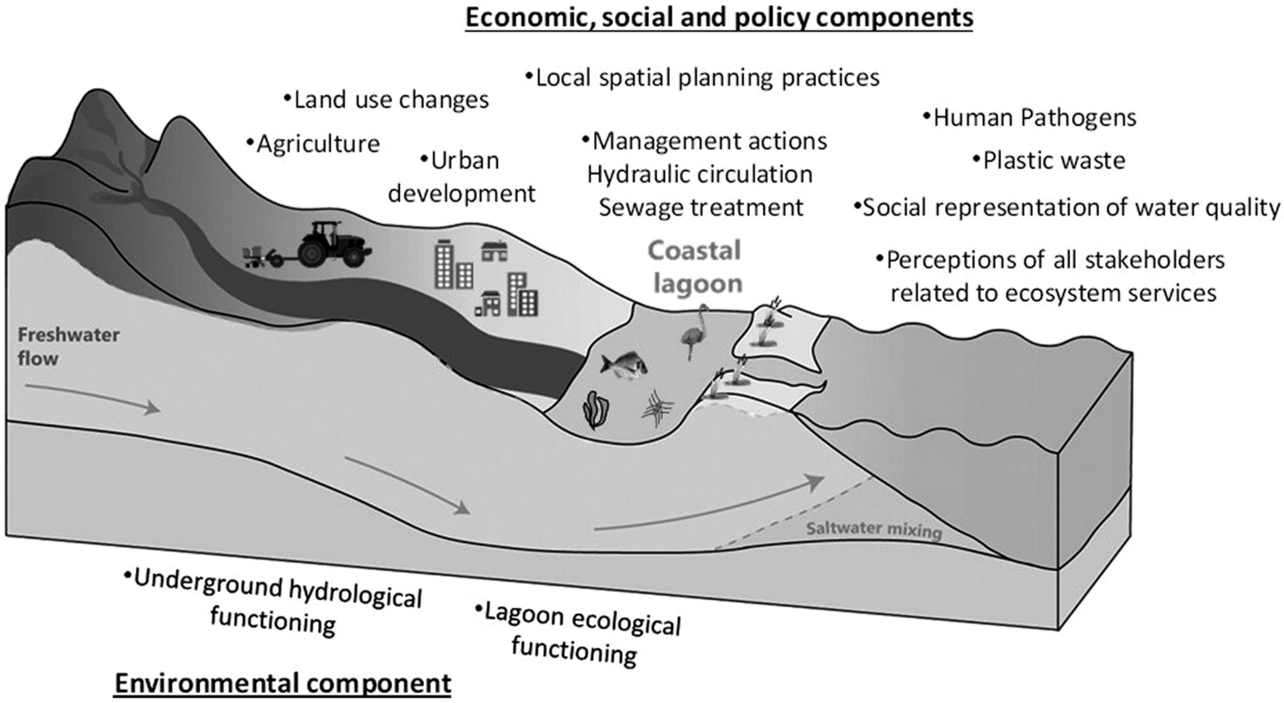

Fig. 4. – Schematic representation of the Biguglia socio-ecological system including hydrological and ecological functioning and the aspects covered by the scientific projects supported by the Human-Environment Observatory of Mediterranean Coasts (OHM-LM).

et al. 2018). The correlation between NO_3^- concentrations and ^3H contents made it possible to assess the temporal dynamic of NO_3^- in groundwater (Fig. 3C). The groundwater with the longest residence times ($^3H < 2$ TU; TU = Tritium Unit) has the highest NO_3^- concentrations (between 40 to 70 mg/L or 650 to 1,100 µM; Fig. 3C). As decrease the residence time (2 TU $< {}^3H <$ 4 TU), NO_3^- concentrations also decrease (> 15 mg/L on average; Fig. 3C). High NO_3^- concentrations in the aquifer are therefore the result of accumulated historical pollution inherited from the 1960s-1970s. Groundwater, by flowing towards the lagoon, contributes to a NO_3^- enrichment. However, this phenomenon is tending to decrease due to the observed decrease in NO_3^- concentrations in groundwater (Fig. 3C).

This recently observed improvement in groundwater quality with respect to NO_3^- concentrations is consistent with current observations in the lagoon. At present, the salinity is higher and the concentration of total nitrogen seems to decrease in the lagoon, which has led to a reduction in carp, a reappearance of *Zostera noltei*, and which demonstrates the beginning of the Biguglia lagoon restoration. However, a persistence of dinoflagellate blooms is observed, which can reflect the vulnerability of the whole ecosystem. In addition, the vulnerability of the hydrosystem is also underlined by the detection of EOCs in groundwater and lagoon water, EOCs was not detected in the river (Fig. 3C). These pollutants, entirely human-made, illustrate a strong anthropic pressure on the watershed.

DISCUSSION

An ecosystem-based approach must enable to consider the global functioning of an ecosystem, in particular the interactions between organisms, along with the different components of the abiotic environment. The originality of our study lies in a) considering the lagoon ecosystems with groundwater since these are ecosystems dependent on groundwater, and b) indicators of human activities in the watershed, which have an impact on the whole coastal lagoons and within its functional compartments (Fig. 4). Biguglia lagoon has been affected by a tremendous territorial change these last decades, as is the case with a large number of Mediterranean lagoons due to their location in the coastal zone (La Jeunesse *et al.* 2002, Alvarez-Cobelas *et al.* 2005, Serrano *et al.* 2006, Shili *et al.* 2007, Flo *et al.* 2011). In the Biguglia watershed, agricultural practices have experienced strong modifications while the whole area has been facing the increasing development of urban settlements related to the extension of Bastia city (Fig. 4; Département de la Haute-Corse 2013). Over the last century, the urbanized areas of the catchment area have grown five-fold in size, mainly on the alluvial plain (Fox *et al.* 2012). The strong urban pressure (Robert *et al.* 2015), the lack of urban planning (Prévost & Robert 2016), and the construction of isolated residential areas have amplified the risk of localized pollution and leakage from the extensive sanitation network (*i.e.*, leakage from water pipelines and septic tanks). Agricultural land-use has decreased by almost 40 %. Over the last decades, orchard and vineyard farming was progressively replaced by cattle breeding and vegetables production. Consequently, ecosystem functioning of Biguglia lagoon has been profoundly altered, with changes in the aquatic vegetation, from a predominance of aquatic angiosperms to macroalgae and phytoplankton during a dystrophic crisis in 2007. Massive soil remodeling due to urban developments and culture type changes has led to a significant soil N mobilization in the 1970/1980's, resulting in high nitrate inputs to the aquifer (as indicated by the relatively high nitrate concentrations in the oldest groundwater samples; Daum 1997).

To face the huge degradation of lagoons, the Water Framework Directive in 2000 (WFD, 2000/60/EC) recommends the implementation of management measures to improve the ecological and physico-chemical states of water bodies. In this context, the managers of the Biguglia natural reserve led various remedial measures, such as cleaning the Fossone Canal between 2009 and 2012 to decrease the confinement of the southern basin. This action, as a consequence, causes significant freshwater inputs from the Golo River and desalination of the lagoon (Fig. 4; Département de la Haute-Corse 2013, Garrido *et al.* 2016). Other interventions were also carried out, such as periodically opening up the channel connecting the lagoon with the sea by mechanical means, which led to significant salt-water input and an increase in the salinity of the lagoon afterwards. Nevertheless, ecological restoration efforts realized to improve hydraulic management must be accompanied by the reduction of nutrient inputs in the watershed with an awareness of regional authorities that goes beyond the boundaries of the nature reserve. Substantial efforts have been made recently to improve sewage treatment in the watershed under the *Schéma d'Aménagement et de Gestion des Eaux* (SAGE; Fig. 4).

Within the studied hydrosystem, the resilience capacity of water bodies seems to be strongly contrasted. For the lagoon, such management measures improved the quality of the water column, favoring the resettlement of aquatic magnoliophytes and the decrease of macroalgae and phytoplankton over a relatively short period of time (4-5 years; Pasqualini *et al.* 2017). The observed shift in communities suggests that Biguglia lagoon is resilient and that the transition may be reversible, even if the whole ecosystem remains vulnerable. The alterations in the ecosystem have drastically facilitated the successful installation of invasive and tolerant organisms, which weakens the whole ecosystem. Such modifications can weaken the entire ecosystem and have significant impacts on fish resources, but certainly also on bird populations, which have a key role in the conservation of the Biguglia lagoon. Such responses of lagoon ecosystems to a disturbance have already been observed in other Mediterranean lagoons, but ecosystem restoration depends on the intensity and persistence of the disturbance (Souchu *et al.* 2010, Leruste *et al.* 2016, Kermagoret *et al.* 2019, Le Fur *et al.* 2019). For groundwater, management measures are struggling to restore the qualitative degradation. While the relatively low nitrate contamination in modern groundwater (groundwater with short residence time) underlines that ongoing management practices to reduce surface nitrate pollution produce their effect, progressive nitrate contamination in groundwater with long residence time indicate the poor self-remediating capacity of the aquifer. The time lag of several decades between pollution and groundwater contamination indicates that even a complete halt of anthropogenic nitrate inputs to the groundwater would not result in an immediate improvement of the groundwater quality. In addition, the occurrence of EOCs in groundwater is an indicator of an ongoing groundwater degradation related to wastewater infiltration (Erostate *et al.* 2019, Vystavna *et al.* 2019). Once infiltrated, the pollutants follow the groundwater flow and can migrate to the lagoon (Knee & Paytan 2011, Jimenez-Martinez *et al.* 2016, David *et al.* 2019). Thus, legacy and current pollution in groundwater threaten the resilience and long-term protection of the lagoon, which directly rely on groundwater supply.

The ecosystem-based approach allows the integration of humans in the ecosystem functioning, with the notion of social-ecological system. Social-ecological systems are linking people and nature, emphasizing that humans are a part of, and not apart from, nature (Berkes *et al.* 1998). An integrated approach for sustainable development in coastal lagoons with a strong partnership among researchers, managers and stakeholders has been proposed (Hopkins *et al.* 2012, Newton 2012, Newton *et al.* 2014). Lagoon conservation requires an integrated and multidisciplinary approach where the natural and social sciences collaborate together. Since 2012, the Biguglia lagoon is the subject of particular attention in this direction through the Human-Environment Observatory of the Mediterranean Coasts (OHM-LM, under the CNRS and LabEx DRIIHM). This research initiative has contributed to a better understanding of Biguglia lagoon within its watershed, through multidisciplinary research projects (Fig. 4; *e.g.*, land use changes, local spatial planning practices, coastal aquifers, social representation of water quality, perceptions of all stakeholders related to ecosystem services; Robert *et al.* 2015, Prévost & Robert 2016, Sy *et al.* 2018, Audouit *et al.* 2019, Jaunat *et al.* 2019, Leruste *et al.* 2019, Robert *et al.* 2019; see details in http://www.ohm-littoral-mediterraneen.fr/spip.php?rubrique8). Data acquisition is still continuing notably in the natural sciences (ecological integrity) and must intensify in the social sciences. The OHM promotes communication between the scientific community and coastal zone stakeholders. The originality of its approach lies in integration of social and natural sciences and in the analysis of the interactions between Humans and the Environment, which are necessary for the study of a socio-ecosystem. In the frame of ecosystem-based approach, this integrated multidisciplinary approach is essential to optimize the conservation of coastal lagoons subject to anthropogenic pressures and climate change.

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