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The challenge of assessing the proper functioning conditions of coastal lagoons to improve their future management

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1 **Abstract**

2 The sustainable management of coastal lagoon hydrosystems is a key issue for the socio-economic and
3 environmental development of many coastal areas worldwide. Often maintained by direct or indirect
4 groundwater supplies, they provide a large range of ecosystem services, from which human societies
5 take advantage. Twenty years after its implementation, a large majority of the Mediterranean lagoons
6 have still not reached the “good status” required by the WFD. Several questions then arise as to the
7 representativeness of the WFD indicators or the relevance of the restoration objectives considering the
8 complexity, evolutionary and unpredictable nature of lagoon hydrosystems. This study proposes an
9 innovative, multidisciplinary, long-term approach to define the proper functioning conditions of a
10 coastal lagoon hydrosystems, *i.e.* all the factors that contribute to the functioning of coastal lagoon
11 hydrosystems and the connectivity with other biodiversity reservoirs, be they ecological, hydrological,
12 social or political. By considering the lagoons and all its hydrological, ecological and societal proper
13 functioning conditions over almost 200 years, this approach makes it possible to assess the influence
14 of past natural and anthropogenic disturbances and support the implementation of future relevant
15 hydrosystem-based management plans which have to be coordinated and politically driven. Defining
16 proper restoration and management objectives should ensure that ecological functions are maintained
17 based on current and future ecosystem benefits and uses. Considering the highly unpredictable nature
18 of coastal hydrosystems, the state of an ecosystem should not only be evaluated on ecological or
19 chemical criteria but also take into account socio-economic and political indicators. The
20 implementation of the 3rd river basin management plan of the WFD as soon as 2022 could be the
21 appropriate occasion to reassess the restoration objectives towards more realistic goals and to give
22 more significance to the definition of the “resilience capacity” of water bodies in place of
23 inappropriate restricted restoration objectives.

24 **Key words:** Integrated water resources management; Multidisciplinary approach; Long-term
25 trajectories of socio-hydrosystems; Coastal socio-hydrosystems; Groundwater dependent ecosystems;
26 Corsica

1. Introduction

Coastal lagoons provide a large range of ecological, cultural and economic benefits, also known as ecosystem services, from which human societies take advantage (Newton et al., 2018). As a transitional environment, these complex coastline components are full part of large social-ecological hydrosystems (Pérez-Ruzafa et al., 2019), characterized by a highly dynamic biophysical environment continuously undergoing changes and considering human activities as an integrated part of their own ecology (Clewell and Aronson, 2013). Human activities influence the lagoons behavior and their watersheds since decennia and contribute to build present-day lagoons morphology and quality, leading to a rich, singular, eco-cultural heritage (Corbau et al., 2019; El Mahrad et al., 2020).

Coastal lagoons have yet suffered severe environmental degradation because of human activities developed in coastal areas such as eutrophication, pollution or habitat destruction (Newton et al., 2014; Jones et al., 2018; Erostate et al., 2020). Since the growing awareness of the importance of coastal lagoon ecosystems in the 1950s (Kjerfve, 1994; Nixon, 1995; Basset et al. 2013; Newton et al., 2014; Menció et al., 2017; Wit et al., 2017; Newton et al., 2018), the protection, preservation and even restoration of these environments has become a major issue. However, management strategies are often focused on directly connected surface water and excludes other main fresh water contributors like the essential groundwater component although, in most cases, coastal lagoons are maintained by direct or indirect groundwater supplies and constitute therefore groundwater dependent ecosystems (GDEs; Krogulec, 2016). The importance of groundwater is further exacerbated in coastal Mediterranean regions where the lack of surface water is combined with a high anthropogenic pressure (Malek et al., 2018; Erostate et al., 2020). As for all Member States of the European Union (EU), the Mediterranean EU Member States have implemented measures for the protection of coastal lagoons under the Water Framework Directive (WFD, 2000/60/EC). These measures may involve human interventions (active restauration) to optimize and accelerate the restoration of coastal lagoon hydrosystems (Wit et al., 2017). However, a large majority of Mediterranean lagoons have still not achieved the ecological and chemical "good status" required by the WFD. Several questions thus arise:

- i) What was the evolution of the coastal lagoons in the past and how these systems can be restored?,
- ii)

54 Did previous management measures always had the expected effect on the system? and finally, iii)
55 How to pertinently evaluate the system's response to human actions and what will be required in the
56 future?

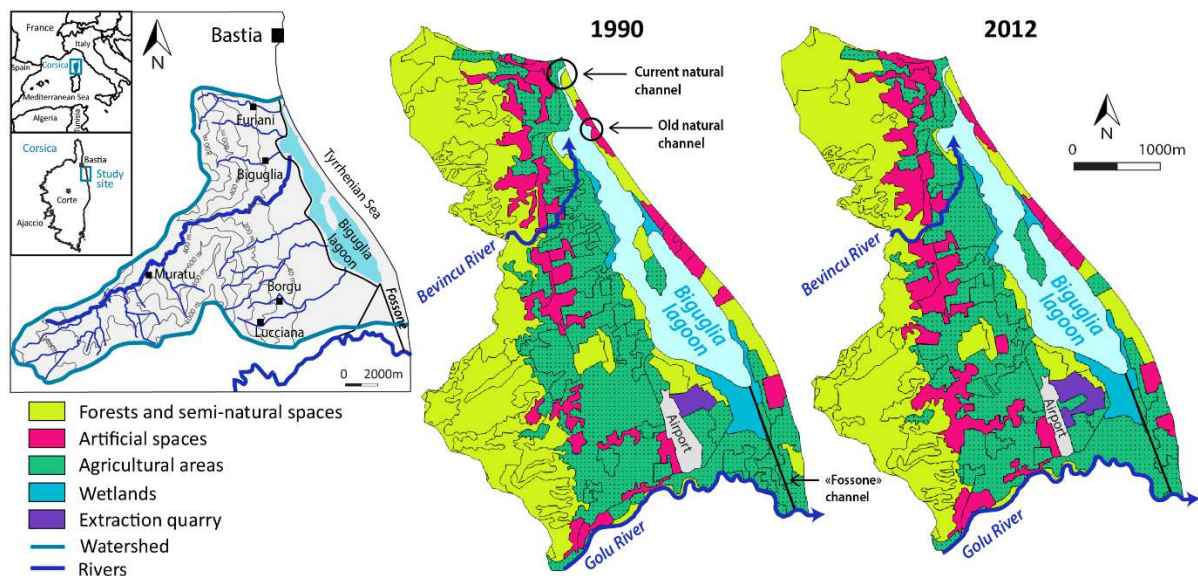
57 To answer these questions, this study proposes an innovative, multidisciplinary, long-term approach
58 that takes into account the evolution of lagoon ecosystems and their entire watershed (surface and
59 ground water). The reconstitution of ecological, hydrological and socio-economic evolutions, also
60 called "trajectories", allows to assess the influence of natural and anthropogenic events that have
61 affected the hydrosystem. Proper functioning conditions of the hydrosystems, *i.e.* all the factors that
62 contribute to the functioning of coastal lagoon hydrosystems and the connectivity with other
63 biodiversity reservoirs, be they ecological, hydrological, social or political can thus be determined
64 through this integrated approach. This approach has been applied to the hydrosystem of the Biguglia
65 lagoon (Corsica, France) as a particularly relevant example of EU Mediterranean hydrosystems. First
66 of all, it is representative of the management policies, as well as the regulatory and legislative tools
67 implemented in the EU Member States under the WFD. The hydrosystem of the Biguglia lagoon also
68 combines both the socio-economic development and the climatic and hydrological conditions
69 characteristic of the Mediterranean coastal regions (Erostate et al., 2020). Finally, this hydrosystem is
70 extremely well documented, with archives over the last 200 years. This wide range of historical data
71 provides an ideal opportunity to understand the patterns of change in the hydrological and ecological
72 functioning of this hydrosystem and the history of its management and governance. This learning from
73 the past supports the implementation of hydrosystem-based management to ensure the future integrity
74 of coastal lagoon hydrosystems (Burt et al., 2017; Gross and Hagy, 2017; Pasqualini et al., 2017;
75 Derolez et al., 2020) as well as the development of a more relevant evaluation system for restoration
76 measures.

77 **2. Materials and methods**

78 **2.1. Study site**

79 The Biguglia lagoon is a confined, shallow, brackish coastal lagoon (maximum depth of 1.8 m)
80 located in the northern part of Corsica island (France), just south of Bastia city (Figure 1). Corsica

81 island is characterized by a typical Mediterranean climate with marked inter-annual fluctuations in
 82 atmospheric temperature and precipitation amount (Tagliapietra and Ghirardini, 2006). The mean
 83 annual temperature and precipitation measured at the Bastia Météo France Station are 15.8°C and 768
 84 mm, respectively (average calculated from 1950 to 2016) (Erostate et al., 2019). The lagoon is part of
 85 the largest wetland of Corsica covering 14.5 km². It is separated from the Mediterranean Sea by a long
 86 sand bar and seawater exchanges are controlled by only one narrow, shallow, natural channel to the
 87 North. Marine water inputs are limited because the sea channel tends to close naturally by sand
 88 accumulation and human intervention is regularly required to open it again. The lagoon receives fresh
 89 surface and ground water from a 182 km² watershed. One major river, the Bevincu River, at the North,
 90 flows continuously towards the lagoons, supplemented by several smaller ephemeral creeks (Figure 1).
 91 Fresh water is also supplied by an artificial drainage network constructed in the 19th century. The
 92 lagoon is directly connected at the south to the Golu River through an artificial channel, the “Fossone
 93 Canal” (Figure 1). Drainage channels on the west shore of the lagoon drain run-off and shallow
 94 groundwater from the Marana alluvial plain, which constitutes the largest aquifer system in the region.
 95 Groundwater is then discharged towards the lagoons through five pumping stations, making the
 96 Biguglia lagoon a coastal GDE (Erostate et al., 2019). Groundwater from this alluvial aquifer is also
 97 used for the drinking water supply of the Bastia’s urban area (almost 72 000 inhabitants).



99 Figure 1: Localization map of the watershed of the Biguglia lagoon and land use on the alluvial plain
100 (Source: Corine Land Cover). (2-column fitting image, no color in printing)

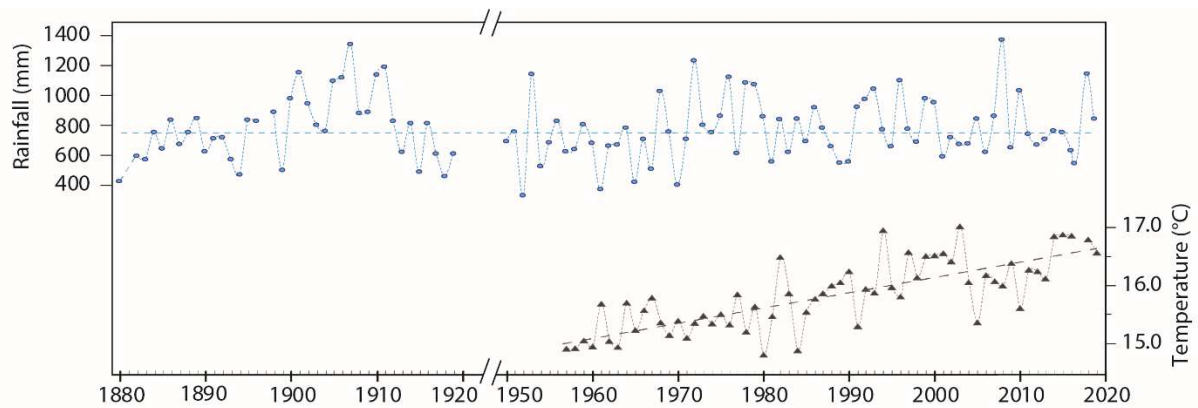
101 The Biguglia lagoon watershed is subject to an important development since the end of the 20th
102 century (Département de la Haute-Corse, 2012). The Marana alluvial plain is currently largely
103 anthropized since it constitutes the southern extension of the economic capital of Corsica. Urban
104 sprawl and agricultural activities are currently the two main anthropogenic activities developed on the
105 alluvial plain. This area is covered by an important transportation network associated with a dynamic
106 economic context, including an airport, housing and several business parks. Four towns are extending
107 in the immediate vicinity of the lagoon (Furiani, Biguglia, Borgo and Lucciana) with an increase in
108 artificial areas about 3% per year between 2002 and 2011 (Robert et al., 2015). This urban sprawl has
109 led to an important growth in the population living around the lagoon. In addition, tourism has become
110 an important component of the local economy, especially during the summer period. The sand bar is
111 particularly attractive and experiments a strong population growth in summer months.

112 The anthropogenic pressures have increasingly disturbed the lagoon's ecosystems through
113 eutrophication over the past decades (Département de la Haute-Corse, 2012; Garrido et al., 2016;
114 Pasqualini et al., 2017). Nutrient in this lagoon are higher than in most other Mediterranean lagoons
115 (Orsoni et al., 2001; Souchu et al., 2010) due to the limited exchanges with seawater. Concerned about
116 the vulnerability of the main wetland in Corsica, the Collectivity of Corsica voted the acquisition of
117 the Biguglia lagoon in 1988 which belonged to a private owner. Since then, the Collectivity of Corsica
118 has been managing the Nature Reserve to ensure its protection as well as its ecological and heritage
119 enhancement. The Biguglia lagoon is classified as Ramsar site since 1991 and nature reserve in 1994
120 but also as sensitive natural area (ENS), natural zone of ecological interest for fauna and flora
121 (ZNIEFF), Important Bird and Biodiversity Area (ZICO), Special Protection Area (ZPS), Area of
122 Community Interest for Birds (SIC), Special Area of Conservation (ZSC). Access to the public is
123 restricted to the hiking, educational paths along the lagoon and is prohibited on the water body. The
124 professional fishing is the only authorized activity, in line with the historical exploitation of the
125 lagoon.

2.2. Research of historical data

We used historical documents and maps to analyze the dynamics of the Biguglia lagoon hydrosystem and to identify the major anthropogenic pressures acting on the watershed on the long term. An extensive, multi historical-sourced data analysis gathering from 1800 to 2020 has been carried out through the consultation of regional and national archives as well as local stakeholders. These documents are extremely diverse, both in terms of nature (scientific reports, pictures, newspapers, administrative acts...) and subject matter (natural and human sciences, management, planning, law, etc.). Each information relating to the study area was collected in a database including: fauna, flora, quantity and nature of fisheries, salinity, any waters quality parameters, climate, water extraction, land use planning, human intervention on the lagoon... The main sources for the numerical and cartographic data are listed below. The number of inhabitants per town (4 towns in the watershed and the Bastia city) were available (i) from 1800 to 1999, at intervals of about five years (http://cassini.ehess.fr/cassini/fr/html/6_index.htm) and (ii) from 1999 to 2011 at intervals of seven to nine years (French National Statistics and Economic Studies Agency (INSEE)). Historical land cover in the watershed was analyzed using two sources. The first modern and scientific cartography of Corsica based on new triangulation method "*Plan Terrier*", ordered in 1770 by Louis XV of France, provides an inventory of the natural resources of the island after its integration into the Kingdom of France (Caratini, 1995). This map is precise, at a scale of 1:10,000 (Source: Archives départementales de Corse du Sud). It was processed with ArcGis version 10.0 (ESRI®). The CORINE land-cover program established a precise land-cover map of the study site for 1990, 2006, 2012 (<https://www.data.gouv.fr/fr/datasets/corine-land-cover-occupation-des-sols-en-france/>). We considered three generic land-cover types, as defined by the CORINE land cover program: forests and shrublands, farmland, and urban areas. The surface areas corresponding to these three generic land-cover types were calculated for the two maps. Detailed information on local meteorological and hydrological behavior started to be available from the 20th century onwards. Since 1948, Météo-France® has been recording cumulative rainfall in Bastia, at a station near to the lagoon. Historical records in local press and local monitoring network make it possible to reconstitute i) long time precipitation series at Bastia since 1880 (Figure 2) and ii) fishing volumes. Data on the mean summer

154 salinity of the lagoon for the northern and southern basins were obtained from records published since
155 1930 (Frisoni et al. and Durieux, 1992; Orsoni et al., 2001; Pasqualini et al., 2017). Information on the
156 extraction (drinking water supply, pumping stations) and quality of water resources (groundwater
157 nitrate) has been collected from local operators and managers (Regional Health Agency (State health
158 service), “Cullettività di Corsica” (regional assembly), “Acqua Publica” (water operator).



159
160 **Figure 2:** Mean annual rainfall reconstructed from archive data, from 1880 to 1919 and rainfall and
161 temperature measured at the Bastia Météo France Station from 1949 to 2019. (2-column fitting image,
162 no color in printing)

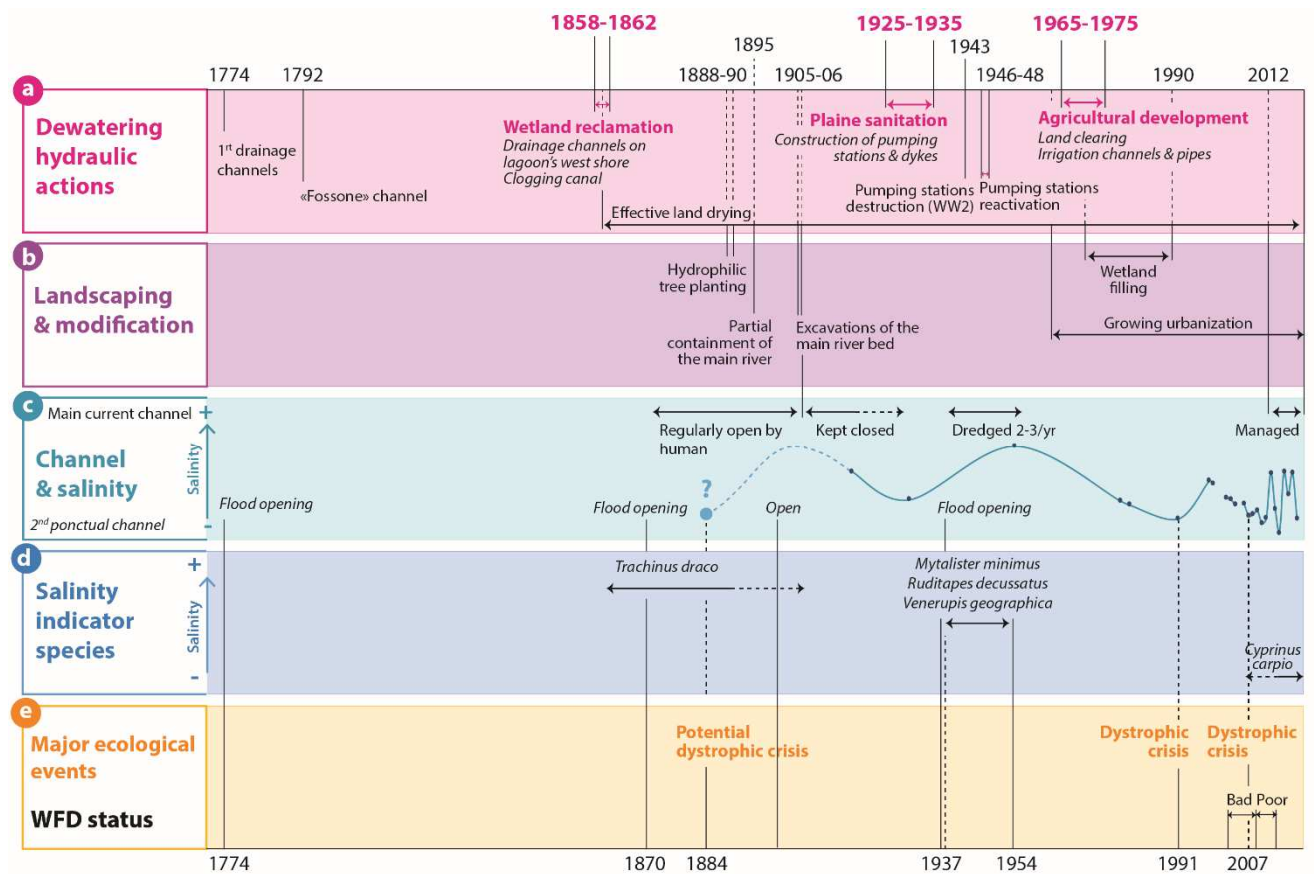
163 3. Results and discussion

164 3.1. Evolution of the territory

165 3.1.1. *Wetland remediation*

166 Tracing back the dynamics of land use planning is a necessary first step to understand the historical
167 hydrosystem behavior and how it has been influenced by human activities and land cover changes
168 (Erostate et al., 2018; Corbau et al., 2019; Tănăsescu and Constantinescu, 2020). When Corsica was
169 incorporated to France in 1768, the government was committed to the problem of land remediation in
170 Corsica (Jaujou, 1954). The objectives were therefore to combat malaria and to increase the amount of
171 arable land, including the Biguglia watershed (Letteron, 1923; Jaujou, 1954). To this end, several
172 remediation programs based on surface water flows were carried out. However, like many other
173 wetlands, the Biguglia lagoon results from shallow groundwater and surface water contributions
174 (Sánchez-Martos et al., 2014; David et al., 2019; Erostate et al., 2020). At the time, the groundwater

175 component was still unknown and remediation programs followed one after another without
176 meaningful good results. The first draining measures were implemented in 1774 with the digging of
177 channels to favor cultivation and periodical openings of the lagoon to the sea, to ensure efficient
178 emptying of the lagoon (Figure 3.a; Jaujou, 1954; Département de la Haute-Corse, 2012). A few years
179 later, the “Fossone” channel at the South of the lagoon was created between the Golu River and the
180 lagoon (Figure 1), with no significant improvement in water drainage. A new remediation program
181 began in 1855 with the establishment of new drainage channels surrounding the lagoon to eliminate
182 the adjacent marsh (Figure 3.a). This new drainage system was accompanied by complementary
183 measures, such as the planting of hydrophilic tree species or the diking of the river (Figure 3.b). It was
184 quickly found that drainage channels were not sufficient to dry out the plain. Indeed, in addition to
185 collecting some surface water, the drainage channels mostly drain shallow groundwater and represent
186 a specified head boundary condition which exacerbates the natural hydraulic flow of the alluvial
187 aquifer. The total water collected by the channels was therefore well in excess of their capacity and
188 these channels could not ensure the drying up of the plain. Without really understanding the origin of
189 the water saturating the drainage network, five pumping stations were set up between 1925 and 1935
190 to complete the dewatering (Figure 3.a). This system was functional before the World War 2 (WW2)
191 and first effects were quickly visible. Located on the west coast of the lagoon, these stations pump the
192 water in the channels when the levels are too high (0.8m below the ground) and reject it towards the
193 lagoon. As a result, the natural discharge of groundwater toward the lagoon has become marginal.
194 Currently, after more than 70 years of pumping, the huge water volumes withdrawn are ranged
195 between 23 Mm³/y and 39 Mm³/y. Given the past water saturation of the plain, the volumes of water
196 withdrawn were probably much higher in the past. Destroyed during the WW2, pumping stations were
197 repaired between 1946 and 1948 (Figure 3.a).



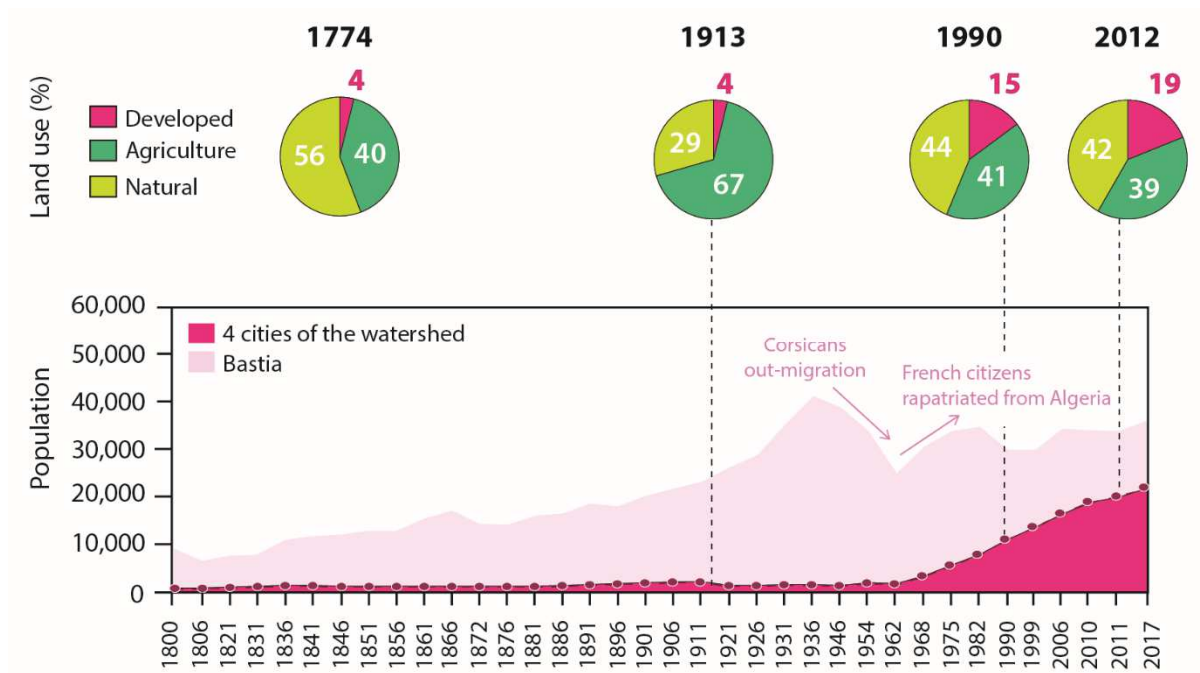
198

199 **Figure 3:** Multi-parameter timelines for a cross-comprehension of the hydraulic behavior of the
 200 system and the long-term reconstruction of salinity variations in lagoon water. (2-column fitting
 201 image, no color in printing)

202 Despite the land reclamation program, the surface and the configuration of the lagoon basin remained
 203 almost identical since the 18th century. A main natural channel connects the lagoon to the sea at the
 204 north (Figure 1). Yet, the creation of Fossone Canal in 1774 (Figure 1) has modified the
 205 freshwater/salt water balance. This channel also constitutes a source of contention with the fishermen
 206 of the lagoon, who regularly block this communication with the Golu River to prevent the escape of
 207 fish. Finally, the punctual opening of a second natural channel (Figure 1) due to extreme flood events,
 208 has also been identified in 1774, 1870, 1901 and 1937 (Figure 3.c). Unlike its neighbor, this channel
 209 has never been subject to human intervention to keep it open and is definitively closed since the
 210 urbanization of the sand bar in the 1960s. This channel is still visible as it is the thinnest part of the
 211 sandbar (Figure 1).

212 3.1.2. *Human settlement*

213 Considered as an inhospitable, disease-causing area mainly because of malarial issues, the alluvial
214 plain remained underdeveloped since the 18th century. Only the mountainous inland regions of the
215 watershed supported a subsistence pastoral economy and community-based social structures. Drinking
216 water supply works started in 1916 but above all the remediation completed at the end of the 1940s
217 boosted the development of the plain. The watershed of the Biguglia Lagoon gradually became
218 conducive to human settlement, reflecting a new human/space relationship (Figure 4). With the
219 changes in land use in the Mediterranean mountains and the development of urban coastal hubs (San
220 Roman Sanz et al., 2013), populations left the mountainous, inland areas of the watershed in favor of
221 the suburban area of the Bastia city. These migration movements were complemented by the
222 installation of the population repatriated from Algeria in 1962 (Figure 4) after the independence of this
223 country. If the population of Bastia seems relatively constant from the 1970s onwards, the population
224 of the 4 cities of the plain has increased considerably (Figure 4). The plain turned into a residential
225 area. The sand bar that separates the lagoon from the sea, mainly developed by vineyard, was rapidly
226 urbanized right after the construction of the first sturdy bridge to cross the lagoon to the North in 1969.
227 An important agricultural development program started in 1965 in order to develop mainly viticulture
228 and citrus growing on the plain. From 1980 to 2020, the land use is mainly characterized by a
229 conversion of the agricultural areas into urbanized areas (Figure 4) and natural areas were relatively
230 constant over the past 40 years. Shrinking of the agricultural area was accompanied by a modification
231 of agricultural practices. Over the last decades, orchards and vineyards were progressively replaced by
232 cattle breeding and vegetables production. Massive soil remodeling due to culture type changes and
233 urban construction have led to significant soil nitrogen mobilization resulting in high nitrate inputs
234 accumulated into the aquifer (Erostate et al., 2018).



235

236 Figure 4: Evolution of developed, agricultural and natural areas on the alluvial plain and demography
 237 of the watershed's municipalities and the nearby Bastia city. (2-column fitting image, no color in
 238 printing)

239 3.2. Tracing back the hydrosystem dynamics

240 *3.2.1. Long-term ecological and hydrological dynamics*

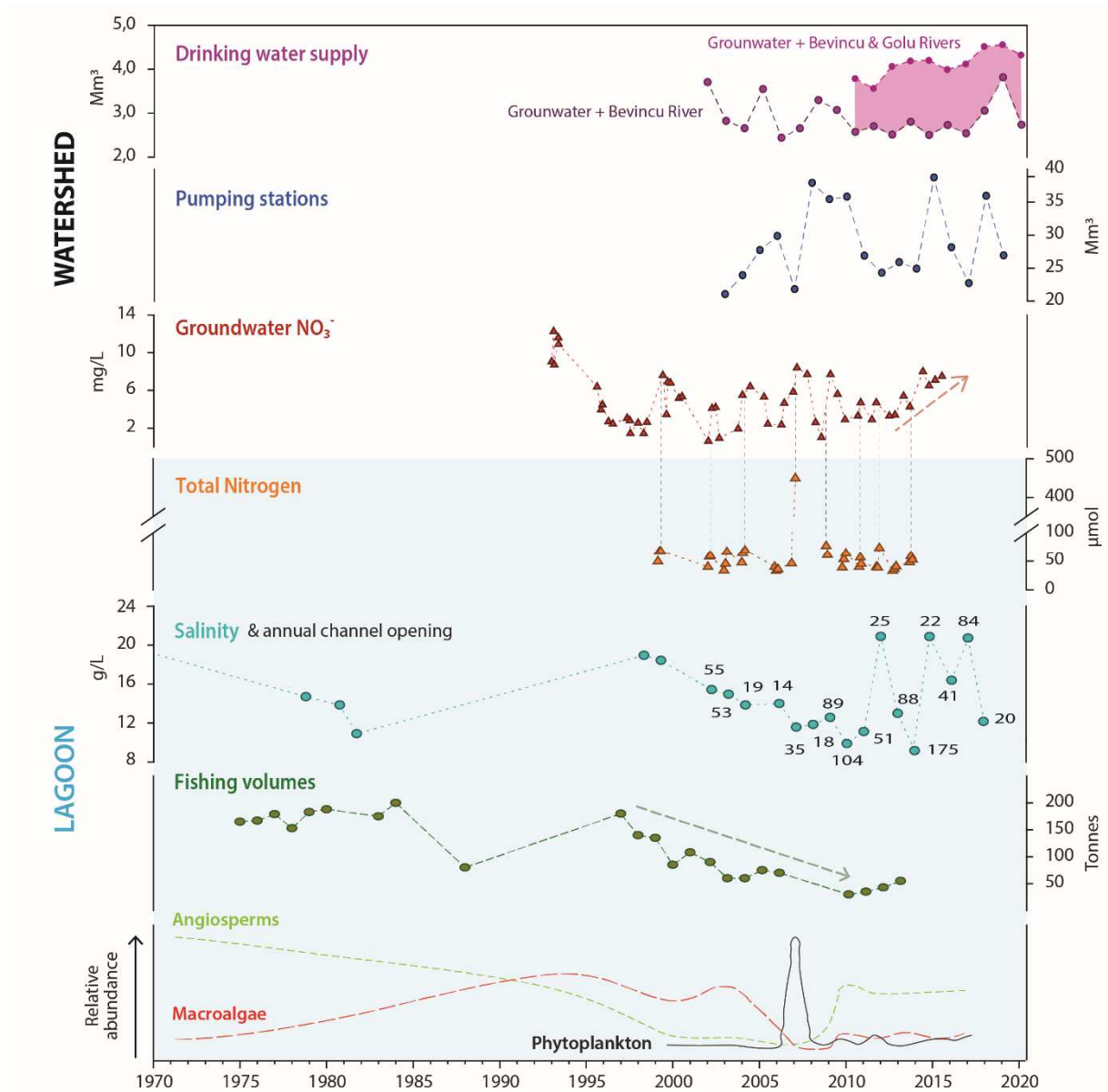
241 Salinity is, along with nutrients, a key factor influencing lagoon ecosystems. However, salinity is also
 242 an excellent indicator of the hydrosystem's hydrology. Highly dependent on both watershed hydrology
 243 and lagoon management, salinity can be considered as a relevant indicator of the behavior and
 244 condition of the whole hydrosystem. Salinity records provide a better understanding of the ecological
 245 modifications as well as the hydrological disturbances affecting it. This parameter, at the confluence of
 246 hydrological and ecological sciences, provides a link between hydrologists and ecologists to support
 247 integrated water resource management at the hydrosystem level. Because of the low number of
 248 available, measured values in the past, reconstructing salinity dynamics is not easy yet. Additional
 249 elements to support salinity dynamics can be found by studying animal and plant species evolution as
 250 well as their living conditions (Figure 3.c). For example, marine fish indicate both a good connection
 251 with the sea and consequently a relatively high salinity. Conversely, river fish indicate a significant

252 freshwater supply and thus a significant decrease in salinity. Necessary precautions must be taken to
253 confirm the presence or disappearance of species by crossing a large number of sources. These
254 indicators provide elements for assessing past salinity trends but also show the long-term ecosystem
255 modifications. Correlated with climatic conditions and hydrological developments, the correlation of
256 indicators makes it possible to retrace the ecological and hydrological trajectories of the system. For
257 this study, the long-term reconstitution of rainfall (Figure 2) shows the marked inter-annual
258 fluctuations, typical of the Mediterranean climate. However, the rainfall remains very stable over the
259 whole period. No significant long-term trend can explain the marked drop in salinity in the lagoon
260 since 1950.

261 During the 18th and the 19th centuries, the Biguglia lagoon was characterized by a high biological
262 productivity. Large quantities of mules and eels were exported to supply Corsica, French East coast
263 (cities of Nice and Marseille) and Italy (Letteron, 1923). The manual opening of the main natural
264 channel (Figure 1) as early as the 1870s, the opening of a secondary punctual channel due to flood
265 events and the occurrence of *Trachinus draco* (sea weeverfish) at the North of the lagoon indicate a
266 good communication between the lagoon and the sea and suggest a relatively high salinity. The first
267 salinity measurement (30g/L and 12g/L in the northern and the southern basin respectively) was
268 recorded in 1917 (Figure 2). In barely 15 years, salinity decreased significantly (20g/L and 10g/L in
269 the northern and the southern basins respectively) (Figure 3.c) due to the important inflow of fresh
270 surface and groundwater drained and rejected towards the lagoon. This period also coincides with
271 changes in the management of the main natural channel which is voluntarily kept closed since the
272 beginning of the 20th century in order to prevent fish escapes from the lagoon. In 1954, salinity reaches
273 its highest value (32g/L and 21g/L in the northern and the southern basins respectively). This is
274 consistent with 3 major events: i) the destruction of the pumping stations, ii) the regular re-opening of
275 the main natural channel and iii) the exceptional floods of 1938 (Figure 3). The destruction of the
276 pumping stations considerably reduced the freshwater inflow towards the lagoon and the regular
277 dredging of the channel allows exchanges with the sea. Finally, the exceptional rains of 1938 allowed
278 the reopening of the second natural channel and contribute to increase interactions with the sea. These

279 high salinity values are supported by the occurrence of mollusks species particularly adapted to the
280 saline environment (*Mytilaster minimus*, *Ruditapes decussatus* and *Venerupis geographica*) (Figure 3).
281 Then, the pumping network was re-established in 1948 and the second natural channel never opened
282 again. Salinity started to steadily fall, as confirmed by the progressive disappearance of *Mytilaster*
283 *minimus*, *Ruditapes decussatus* and *Venerupis geographica*. This disappearance testifies of an
284 evolution of the ecosystem that has become unfavorable to their subsistence but the fishing volumes
285 are still relatively high (Figure 5). In the early 1970s, four aquatic angiosperms were well developed in
286 Biguglia lagoon: *Zostera noltei*, *Ruppia cirrhosa*, *Stuckenia pectinata* and *Najas marina*. These
287 aquatic angiosperms are indicators of water quality. Their presence then suggests the good qualitative
288 status of the lagoon water (Pasqualini et al., 2017) (Figure 5). So far, the lagoon ecosystem has
289 therefore been able to adapt to the physico-chemical variations of the waters. However, in the 1990s,
290 the ecosystem reached a tipping point. The predominance of angiosperms gave way to a variable
291 dominance of phytoplankton and opportunistic macroalgae (Figure 5) (Pasqualini et al., 2017). The
292 volumes of fish caught were constantly decreasing (Figure 5). Nitrate concentrations increased
293 significantly into the aquifer (Figure 5) and urbanization was developing rapidly. A first dystrophic
294 crisis has affected the lagoon in 1991 when the salinity was particularly low (12g/L and 9g/L in the
295 northern and the southern basins respectively). After a slight increase, the salinity continued to
296 decrease from 1999 (18g/L and 13g/L in the northern and the southern basins respectively) to 2012
297 (15g/L and 5g/L). A second major crisis has affected the lagoon in the summer of 2007 (salinity about
298 14g/L and 9g/L) (Figure 3.c) with the proliferation of a toxic cyanobacterium, *Anabaenopsis*
299 *circularis*. The concentrations of total nitrogen reached 470 μM (Figure 5). These ecosystem
300 modifications and the dynamics of total nitrogen concentrations observed in the lagoon raise questions
301 about the nitrogen origin (especially NO_3^-). The groundwater flow toward the lagoon, the low NO_3^-
302 concentrations in river water and the good correlation between NO_3^- concentrations in groundwater
303 and in the lagoon suggests that groundwater has a predominant impact on the NO_3^- supply to the
304 lagoon (Figure 5) (Erostate et al., 2018). Since 2010, barely three years after the dystrophic crisis,
305 macroalgae and phytoplankton are decreasing in favor of the development of aquatic angiosperms.
306 The resettlement by aquatic angiosperms suggests then a significant improvement in water quality

307 within a few years. This relatively short period of time highlights the reactivity of the lagoon
308 ecosystem. The major disruptions caused by the dystrophic crisis of 2007 do not appear to have
309 exceeded the threshold beyond which the lagoon could no longer recover its ecological potential
310 (Pasqualini et al, 2017). However, the progressive desalination hugely impacts the ecosystem with the
311 marked development of freshwater angiosperms (*Najas marina*) and the expansion of the common
312 carp (*Cyprinus carpio*), never reported before in the Biguglia lagoon. As a GDE, the ecological state
313 of the lagoon need to be related to the status of the groundwater. Nitrate concentrations in groundwater
314 appear to be increasing over the last 10 years (Figure 5). Since 2012, focusing efforts to keep the
315 channel open leads to sudden marine inflow resulting in marked salinity variations into the lagoon
316 (Figure 5).



317

318 **Figure 5:** Compilation of reconstructed key parameter data in order to trace back the social (drinking
 319 water supply), hydrological (pumping stations, groundwater NO₃⁻) and ecological (lagoon water total
 320 nitrogen, salinity, fishing volumes, angiosperms, macroalgae, phytoplankton) evolution of the system
 321 since the implementation of the first local development program. (2-column fitting image, no color in
 322 printing)

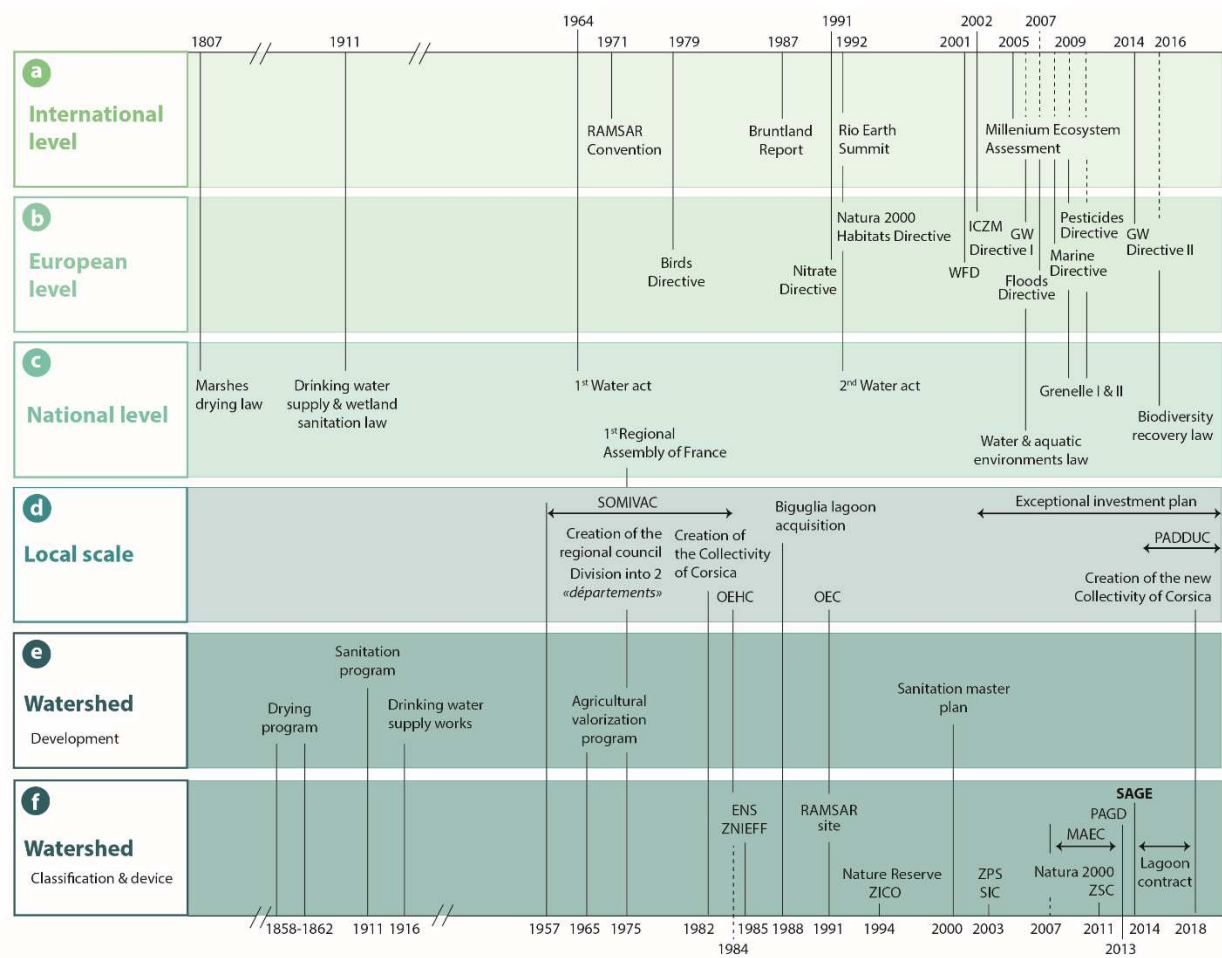
323 Tracing back land development and ecological and hydrological conditions make it possible to define
 324 past socio-ecological conditions of the hydrosystems. However, these conditions do not constitute a
 325 natural, pristine or preferable state of the hydrosystem that should be achieved as a matter of urgency.
 326 Rather, it is a historical link between the ecological conditions of the lagoon and human activities

327 (fishing especially), before a recent change due to the land development (drainage network,
328 urbanization, agriculture). Above all, this long-term approach allows us to understand the evolution of
329 the system and thus to take a critical look at the established management strategies in order to better
330 define future relevant ones.

331 3.2.2. *Management deadlock*

332 Complementary information from historical and modern data provides relevant information to assess
333 the efficiency of the Biguglia lagoon protection. In addition to the classification of the lagoon as
334 nature reserve, the lagoon and its wetlands currently benefit from 8 classifications implemented
335 between 1985 and 2011 (ENS, ZNIEFF, ZICO, ZPS, SIC, ZSC) (Figure 6.f). However, over the same
336 period, two major dystrophic crises affected the ecosystem highlighting the ineffectiveness of
337 protective statutes. The classification as a nature reserve was sometimes perceived by local
338 populations as an expropriation by politicians. The stakeholders as well as population then found it
339 very difficult to find their place and to get involved in the implementation of integrated management.
340 The major dystrophic crisis of the summer 2007 constituted yet a trigger. Active management
341 measures in order to improve the situation were implemented through several strategic planning
342 programs and management tools (PAGD, SAGE, lagoon contract, MAEC) (Figure 6.f). Substantial
343 efforts have been made to improve sewage treatment, to develop sustainable agricultural practices over
344 the watershed and to reduce the confinement of the lagoon. Artificial opening of the current channel
345 and/or cleaning of drainage channels have been regularly carried out. These active restoration
346 measures seem to be beneficial to the lagoon ecosystem on the medium-term and to highlight the
347 resilience capacity of the lagoon. Conversely, the progressive nitrate accumulation into the
348 groundwater indicates the poor self-remediating capacity of aquifers (Erostate et al., 2018). Historic
349 nitrate legacies therefore continue to degrade current groundwater quality (Jaunat et al., 2019). In
350 addition, the occurrence of human-made organic pollutants in groundwater is an indicator of an
351 ongoing groundwater degradation related to wastewater infiltration (Erostate et al., 2019). At present,
352 all the improvements made in the hydrosystem's management have still not allowed the lagoon to
353 reach the "good qualitative status" required by the WFD. On-going degradation quality of

354 groundwater due to legacy and current pollution threaten the resilience and long-term protection of the
 355 whole hydrosystem.



356
 357 **Figure 6:** Timeline of key dates relating to the development and management of the lagoon from 1807
 358 to 2020. Among the abbreviations used are : b) WFD Water Framework Directive; ICZM integrated
 359 coastal zone management; GW groundwater; d) SOMIVAC Local agency for the Development of
 360 Corsica; OEHC Local agency for hydraulic equipment; OEC Environmental agency of Corsica;
 361 PADDUC development and sustainable development plan for Corsica and f) ENS sensitive natural
 362 area; ZNIEFF natural zone of ecological interest, fauna and flora; ZICO important bird and
 363 biodiversity brea, ZPS special protection area; SIC area of community interest for birds; ZSC special
 364 area of conservation; MAEC agri-environmental and climate measures; PAGD sustainable
 365 development and management plan; SAGE water development and management plan (2-column
 366 fitting image, no color in printing).

3.3. Towards a really sustainable management of coastal lagoon hydrosystems

3.3.1. *A sectorial management approach*

The recognition of wetlands as specific natural areas came about as a result of the Ramsar Convention, the Birds Directive and, above all, the Rio process in 1992 (Figure 6.a, 6.b). From this date, the standard-setting or regulatory activities has intensified (Figure 6.b, 6.c). At the same time, the attractiveness of coastal areas is increasing, particularly in the Mediterranean context (Erostate et al., 2020). With the greening process, priorities changed and were given to the protection of natural coastal areas considered remarkable and vulnerable. Since the WFD was established, restoration measures are most often implemented in order to achieve the "good status". Restoration should allow the ecosystem to return to a previous, more "natural" state, called the "reference state". According to the WFD, achieving this ideal state should then allow to preserve and improve, if necessary, the ecological status of aquatic systems in order to promote their sustainable use and ensure water supply.

In the case of coastal lagoon hydrosystems, this concept of past, undisturbed state is irrelevant. Human modifications of lagoons environment have been significant for several millennia. As many others lagoons, the Biguglia lagoon is used and managed since centuries, especially for fisheries. Human activities - especially artificial opening - both influence the natural evolution of the system, *i.e.* the closure and filling up, and the biological communities as well as the dynamics of the ecosystems (Conde et al., 2015). Natural and social characteristics of coastal hydrosystems are inseparable and human-nature interactions play a central role in the construction of lagoon landscapes and dynamics. Human activity is not an external factor that does not fit well into natural processes, but rather a full part of those processes. Present-day system is resulting from both natural and human influences since decades or centuries. The presence of man cannot therefore be reduced to an external degradation. Moreover, events currently considered to be ecosystem dysfunctions, such as dystrophic crises, are not necessarily the result of human actions. Most coastal lagoons have always been very nutrient-rich environments, potentially affected by anoxic episodes long before human eutrophication (Kjerfve, 1994; Nixon, 1995; Newton et al., 2014). In the case of the Biguglia lagoon, the archives describe frequent events of anoxia: "when the rainy season has passed, when the temperature rises, when the

394 water in the marshes recedes and leaves enormous quantity of rotting plants and animals” (Newspaper
395 “*Le Petit Bastais*” of July 14, 1882). Local newspapers even mention a major crisis during the summer
396 of 1884 that led to the putrefaction of huge quantities of plants and eels on the shores (Figure 3.e). In
397 addition to the near-impossibility of defining a relevant period for the reference state, it may not
398 correspond to "good ecological conditions" according to the current WFD indicators. All these
399 specificities make coastal lagoons very complex to apprehend and to manage efficiently and
400 sustainably.

401 3.3.2. *Ensure resilience capacity of coastal lagoon hydrosystems*

402 One of the principles behind restoration operations is that the restoration of past conditions and
403 associated disturbance patterns lead to a recovery of previously predominant ecological conditions.
404 The aim is to achieve sustainable use by returning to a previous “better” state, whereas the coastal
405 hydrosystem is, by definition, in perpetual evolution. This approach does not fit with the complexity,
406 evolving and unpredictable nature of coastal lagoon hydrosystems. Defining precise restoration
407 objectives is then almost impossible when they are supposed to return to a previous state that is poorly
408 known and/or irrelevant with the uses and the complexity of coastal lagoon hydrosystems. As a result,
409 restoration effects are often unpredictable, as is the response time of the hydrosystems (Facca et al.,
410 2014; Wit et al., 2017). Rather than returning to a reference state, restoration should aim at achieving a
411 new state of ecological and hydrological equilibrium, which would allow the maintenance of
412 ecosystem functions and the sustainable development of their use. It is therefore necessary to set up a
413 participative reflection between all stakeholders (scientists, managers, operators, local population...) in
414 order to predetermine the uses and ecosystem functions that are considered as priorities and then to
415 define restoration objectives in line with the territory's development objectives (Eriksson et al., 2016;
416 Sy et al., 2018). Evaluation of the success of restoration measures must be linked to what a restoration
417 project is designed to do, by whom and when (Baker and Eckerberg, 2016). The involvement of
418 stakeholders and the perception of populations for example are also essential parameters that reflect
419 the effectiveness of sustainable management. Moreover, the indicators used by the WFD are often
420 based on defined and non-dynamic reference states. The current indicators support a normative and

421 simplified approach of coastal lagoon hydrosystems, which are in fact as unique as they are complex.
422 Their mandatory use then became a means of assessing managers and the effectiveness of
423 management policies even if they do not make it possible to achieve sustainable restoration. Finally,
424 restoration strategies must take into account the entire proper functioning conditions of the coastal
425 lagoon hydrosystems. Perceptions of hydrologic interactions are often restricted to lateral and
426 longitudinal flows and connectivity with groundwater is still under-documented. Widely used,
427 manipulation of natural dynamics represents an inadequate short-term solution to address a long-term
428 complex socio-economic problem (Conde et al., 2015). This approach leads to strong and rapid
429 changes in physico-chemical conditions which can strongly affect communities and processes. In
430 order to reduce sudden disturbances due to artificial openings and to make progress toward sustainable
431 physico-chemical conditions improvement, upstream management of freshwater and nutrient flows
432 appears as essential. The often neglected role of groundwater in water and nutrient inputs needs to be
433 better understood. Defining and managing groundwater flows is the only way to achieve sustainable
434 management of coastal lagoon hydrosystems and stabilization of physico-chemical conditions in
435 lagoon waters.

436 3.3.3. *Integrating global change into management strategies*

437 Conservation management plans are often the result of short or medium-term planning. They assume
438 regular species distributions in the absence of human-induced disturbance. Sustainable management
439 plans must incorporate future changes in species distribution due to climate change. Although difficult
440 to quantify, future changes in precipitation, temperature and evaporation patterns foreshadowed by the
441 climatic data of the last century (visible at local level on Figure 2) could significantly affect future
442 populations (IPCC, 2018). Changes in species distribution, population size, timing of reproduction or
443 migratory events are already observable. The current species loss and the establishment of invasive
444 species could be significantly facilitated. Invasive species cause changes, often irreversible or difficult
445 to control, in biodiversity and the ecosystem services it provides. It is therefore essential that policy
446 makers and management strategies take into account the need for adaptation. This involves
447 understanding how invasive species adapt to new environments and how other species adapt to

448 invasions, but more importantly how humans adapt to invasive species, and how this adaptation could
449 affect ecosystems and human well-being (Howard, 2019).

450 Many coastlines are projected to be impacted by rising sea levels. While the risk of marine flooding is
451 often mentioned first – and need to be assessed, the risk of groundwater flooding would probably be
452 the first to impact coastal areas (Rotzoll and Fletcher, 2013). For aquifers with a groundwater level
453 very close to the surface, the rise in sea level will lead to a simultaneous rise of the groundwater level,
454 which may exceed the topographic elevation surface (Rotzoll and Fletcher, 2013). This process could
455 then lead to significant and costly problems related to water management and infrastructure
456 (salinization, flood...). It could increase the mobilization of salts and soil pollutants currently trapped
457 in the unsaturated zone and threaten groundwater quality and hydraulically connected ecosystems.
458 Long-term storage and restitution capacity of soil pollutants thus need to be assessed. Finally, the
459 increasing coastlines development induces a strong pressure on water resources, both for human and
460 environmental needs. With water withdrawals expected to increase in a drier climate, the outflow
461 toward the coastal GDEs could be strongly reduced by the end of the century which could accelerate
462 their drying up (Erostate et al., 2020). In response to these treats, an appropriate management of
463 groundwater appears as essential to ensure the preservation and sustainability of coastal GDEs.

464 **4. Conclusion**

465 Given the coastline development and climate change effects, the sustainable management and
466 governance of coastal lagoon hydrosystems is a key issue for the socio-economic and environmental
467 development of many coastal areas worldwide. The innovative multidisciplinary long-term approach
468 developed in this study allows to better assess the influence of past management actions and supports
469 the implementation of future relevant hydrosystem-based management plans which have to be
470 coordinated and politically driven. It supports the establishment of integrated water resources
471 management by considering the lagoons and all its hydrological, ecological and societal proper
472 functioning conditions. Taking into account the dynamic nature of the coastal lagoon hydrosystems is
473 essential to defined relevant restoration and management objectives. The stable conditions of the WFD
474 reference values isolate the system in a past, static state, disconnected from the land development and

475 climate change impacts, considering human as the major disturbing element. Restoration objectives
476 should ensure that ecological functions are maintained based on current and future ecosystem benefits
477 and uses. The state of an ecosystem should not only be evaluated on ecological criteria but also take
478 into account socio-economic and political indicators. In any case, considering the highly unpredictable
479 nature of coastal lagoon hydrosystems, restoration measures may lead to unexpected results that do not
480 constitute a failure of management measures. The implementation of the 3rd river basin management
481 plan of the WFD as soon as 2022 could be the appropriate occasion to reassess the restoration
482 objectives towards more realistic goals and to give more significance to the definition of the
483 “resilience capacity” of water bodies in place of inappropriate restricted restoration objectives.

484

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491

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Supplementary materials

Table 1 : Main archive sources consulted using a keyword search referring to the study site, including "Corse", "Marana", "Biguglia", "Chiurlinu", "étang", "lagune", "Bastia".

Documents type	Publisher	Name	Source	Date	Consulted documents
Administrative acts	Deliberating assembly	General Council deliberations	Regional state archives	1859-1912	106
Administrative acts	Deliberating assembly	Water services cases	National Archives of France	1881	1
Newspaper	Historical daily regional press	Le Petit Bastiais	Regional state archives	1881-1930	19413
Scientific newsletters	Regional public association of researchers in the Natural Sciences	Bulletin de la Société des sciences historiques et naturelles de la Corse	BnF - French National Library	1881-1937	103
Scientific newsletters	Regional public association of researchers in the Natural Sciences	Flore de France	BnF - French National Library	1893-1913	14
Scientific newsletters	Regional state archives	Corse historique : études et documents	BnF - French National Library	1953	3
Scientific newsletters	Regional public association of researchers in the Social Sciences and Humanities	Etudes corses : revue trimestrielle	BnF - French National Library	1954-1960	24
Aerial photographs	National institute of geographic and forest information (IGN)	-	National on-line database	1960 & 2016	-
Scientific newsletters	Regional state archives	Revue d'études corses : revue d'études historiques littéraires et scientifiques corses	BnF - French National Library	1961	4
Scientific newsletters	Regional state archives	Corse historique, archéologique, littéraire, scientifique	BnF - French National Library	1962-1969	22
Newspaper articles	Private society - Current daily regional press	Corse Matin	On-line website	2008-2020	-
Management documents	Local authority	Management plan of the Biguglia Lagoon Nature Reserve	Biguglia Lagoon Nature Reserve	1997-2017	23

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