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# Groundwater dependent ecosystems in coastal Mediterranean regions: Characterization, challenges and management for their protection

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1                   **Groundwater dependent ecosystems in coastal**  
2                   **Mediterranean regions: Characterization, challenges and**  
3                   **management for their protection**

4  
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25

26 **Abstract**

27 Coastal lagoons deliver a wide range of valuable ecosystem goods  
28 and services. These ecosystems, that are often maintained by direct or  
29 indirect groundwater supplies, are collectively known as groundwater  
30 dependent ecosystems (GDEs). The importance of groundwater  
31 supplies is greatly exacerbated in coastal Mediterranean regions  
32 where the lack of surface water and the over-development of  
33 anthropogenic activities critically threaten the sustainability of  
34 coastal GDEs and associated ecosystem services.

35 Yet, coastal GDEs do not benefit from a legal or managerial  
36 recognition to take into account their specificity. Particular attention  
37 should be paid to the characterization of environmental and  
38 ecological water requirements. The hydrogeological knowledge  
39 about the management and behavior of coastal aquifers and GDEs  
40 must be strengthened. These investigations must be supplemented by  
41 a stronger assessment of potential contaminations to develop local  
42 land-uses and human activities according to the groundwater  
43 vulnerability. The quantitative management of water resources must  
44 also be better supervised and/or more constrained in order to ensure  
45 the water needs necessary to maintain coastal GDEs.

46 The transdisciplinary approach between hydrogeology, hydrology,  
47 social sciences and law is essential to fully understand the socio-  
48 economic and environmental complexity of coastal GDEs. Priority  
49 must now be given to the development of an appropriate definition of  
50 coastal GDEs, based on a consensus between scientists and lawyers.  
51 It is a necessary first step to develop and implement specific

52 protective legislation and to define an appropriate management scale.  
53 The investment and collaboration of local water users, stakeholders  
54 and decision-makers need to be strengthened through actions to favor  
55 exchanges and discussions. All water resources in the coastal areas  
56 should be managed collectively and strategically, in order to  
57 maximize use efficiency, reduce water use conflicts and avoid over-  
58 exploitation. It is important to continue to raise public awareness of  
59 coastal aquifers at the regional level and to integrate their  
60 specificities into coastal zone management strategies and plans. In  
61 the global context of unprecedented anthropogenic pressures, hydro-  
62 food crises and climate change, environmental protection and  
63 preservation of coastal GDEs represents a major challenge for the  
64 sustainable socio-economic and environmental development of  
65 Mediterranean coastal zones.

66

67 Key words: coastal aquifer, coastal hydrosystems, Mediterranean  
68 climate, groundwater management, anthropogenic impact

69

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## Introduction

107 Coastal lagoons cover about 13% of the coastlines from arid to  
108 humid environments (Kjerfve, 1994). Being transitional areas from  
109 land to sea, the water balance of coastal lagoons is resulting from  
110 both terrestrial (fresh groundwater and surface water) and marine  
111 water influences. This dual influence allows the development of  
112 specific ecosystems that provide a wide range of ecosystem goods  
113 and services (Newton et al., 2014; 2018). Over the past few decades,  
114 several studies have highlighted the importance of groundwater in  
115 maintaining the physico-chemical conditions of these sensitive  
116 ecosystems. Coastal lagoons and surrounding wetlands may then  
117 constitute "groundwater-dependent ecosystems" (GDEs) (Krogulec,  
118 2016; Menció et al., 2017) and are referred in the document as  
119 "coastal GDEs".

120 The importance of groundwater is further exacerbated in regions  
121 suffering from water stress, when surface water is chronically  
122 unavailable. Groundwater inputs support or compensate for surface  
123 water inputs and play a vital role in maintaining coastal GDEs. This  
124 problem is encountered in a majority of coastal regions with an arid  
125 or semi-arid Mediterranean climate (Fig. 1) (Köppen, 1936) such as  
126 the Mediterranean basin (European Union –EU- and non-EU  
127 countries) but also on the southwestern coasts of Australia, Chile and  
128 the State of California (United States) and on the southern coast of  
129 South Africa. In these regions, referred to throughout this document  
130 as "Mediterranean regions", the lack of surface water is combined  
131 with a high anthropogenic pressure (UNEP/MAP, 2012). Population  
132 growth proceed together with the development and expansion of

133 human activities, such as urbanization, agriculture, tourism and  
134 industrial activities (Lotze et al., 2006). Increasing human water  
135 needs often lead to overexploitation of aquifers and/or degradation of  
136 groundwater quality, which present a risk both to the well-being of  
137 human activities and to the freshwater needs of coastal GDEs.

138 These degradations are expected to be worsen under the effects of  
139 climate change. Climatic disturbance in terms of increasing  
140 temperatures (Bille et al., 2009; Hallegatte et al., 2009), global  
141 hydrological cycle (IPCC, 2014) and sea level rise (FitzGerald et al.,  
142 2008; Carrasco et al., 2016; Benjamin et al., 2017) should greatly  
143 affect the groundwater and coastal GDEs. This is true not only for the  
144 Mediterranean basin, considered as a Hot Spot of climate change, but  
145 also for all the Mediterranean regions.

146 Since the 1990s and the Rio de Janeiro Earth Summit, the  
147 conservation, the maintenance of potentialities and the improvement  
148 of the ecological status of the coastal water bodies constitute a major  
149 concern. Nowadays, a first statement can be made on the progress  
150 and limitations of groundwater management strategies and  
151 consideration given to coastal GDEs in coastal Mediterranean  
152 regions. To this aim, this review proposes to:

153 - Expose the specificities of coastal GDEs and the key role of  
154 groundwater in their sustainable development

155 - Highlight the vulnerability of coastal GDEs to the socio-economic  
156 development and climate conditions of Mediterranean regions



157 - Revise the consideration given to GDEs and particularly to coastal  
158 GDEs in the management policies of Mediterranean regions and  
159 discuss their implication for the sustainability of coastal GDEs.

## 160 **1. Specificities and importance of coastal GDEs**

### 161 **1.1. The wide diversity and essential functions of** 162 **coastal GDEs**

163 GDEs are defined as “*ecosystems that require access to*  
164 *groundwater on a permanent or intermittent basis to meet all or*  
165 *some of their water requirement so as to maintain their communities*  
166 *of plants and animals, ecological processes and ecosystem services*”  
167 (Richardson et al., 2011). This definition clearly expresses the crucial  
168 role of groundwater in the functioning of GDEs. However, the  
169 multitude of processes and services grouped under the terms  
170 “ecological processes” and “ecosystem services” does not necessarily  
171 make it possible to understand all the specificities and complexity  
172 inherent to certain types of GDEs, such as coastal GDEs. The Table 1  
173 summarizes the morphologic and hydrological characteristics, the  
174 hydrological knowledge and the protection and conservation status of  
175 14 of the most studied lagoons present in Mediterranean regions  
176 subject to Mediterranean climate (Fig. 1) (Newton et al., 2018; Pérez-  
177 Ruzafa and Marcos, 2008).

178 The coastal GDEs are distinguished by their diversity, making  
179 each of them a special case. This diversity is expressed on several  
180 levels. From a morphological point of view, water bodies of coastal  
181 GDEs are separated from the sea/ocean by a barrier, connected at

182 least intermittently to the ocean by one or more restricted inlets  
183 (Kjerfve, 1994). According to the most widely used classification,  
184 these coastal lagoons can be classified into three categories including  
185 (i) choked, (ii) restricted and (iii) leaky lagoons Kjerfve (1994).  
186 These categories reflect the importance of interactions between  
187 coastal lagoons and seawater. Choked lagoon are connected to the  
188 sea by a single or few narrow and shallow entrances, resulting in  
189 delayed and dampened tidal oscillation or low water exchange with  
190 the open sea. Leaky lagoons are connected by many entrances to the  
191 adjacent sea and are therefore characterized by almost unimpaired  
192 water exchange. The stretch of coastal lagoon can greatly vary, from  
193  $<0.01 \text{ km}^2$  to more than  $10\,000 \text{ km}^2$ , as is the size of the hydrological  
194 watersheds, without an obvious proportionality relationship between  
195 the two (Table 1). If the mean depth can also vary, coastal lagoons  
196 still remain shallow water environments, generally characterized by  
197 shallow mean depth ( $< 2\text{m}$ ) (Table 1).

198         Although rainfall, pounding of surface flows or flooding are an  
199 important source of water for most of coastal GDEs, groundwater  
200 plays also a role in many coastal wetlands (Le Maitre et al., 1999).  
201 Coastal GDEs can be completely dependent on groundwater  
202 discharge, whilst others may have limited dependence, such as only  
203 under dry conditions (Howe et al. 2007). Thus, depending on the  
204 hydrologic balance, water bodies of coastal GDEs could vary from  
205 coastal fresh-water lake to a hypersaline lagoon.

206         The fauna and flora that make up coastal GDEs are also very  
207 diverse. The type of vegetation and wildlife is mainly defined by the  
208 salinity of the water and the moisture level of the environment

209 (permanent, semi-permanent or ephemeral wetlands) but also the  
210 location and climate. Several thousand plant species grow in coastal  
211 wetlands such as reeds, grasses and shrubs (Frieswyk and Zedler,  
212 2007; Lemein et al., 2017; Ramírez G. and Álvarez F., 2017).  
213 Hundreds of animal species can also be listed, including fish, reptiles,  
214 mammals, frogs and birds. The degree of dependence of wildlife on  
215 coastal GDEs ranges from those who need wetlands for part of their  
216 life cycle to those who are totally dependent on them.

217 The environmental importance of coastal GDEs is greatly recognized  
218 for most of them, as evidenced by the establishment of various  
219 protection or conservation status (Table1). Because of their relatively  
220 low flushing rates, the important availability of nutrients allows high  
221 rates of primary production (phytoplankton and aquatic plants)  
222 thereby supporting high rate of secondary production (fisheries  
223 nurseries) compared to other aquatic ecosystems (Nixon 1995).  
224 Coastal GDEs contribute to the overall productivity of coastal waters  
225 by supporting a variety of habitats, including salt marshes, seagrasses  
226 or mangroves. These habitats host specific and sensitive ecosystems  
227 and provide a rich support for biodiversity, including vital habitats  
228 for many fish, shellfish and bivalves (Basset et al., 2013). They  
229 constitute also refuge from predation, nursery and feeding habitats  
230 for estuarine, marines and terrestrial species (Heck and Thoman,  
231 1984; Harris et al., 2004). Many coastal GDEs support a variety of  
232 migratory water bird and shore bird species. Some birds depend on  
233 coastal GDEs almost totally for breeding, nesting, feeding, or shelter  
234 during their annual cycles. The main migratory birds utilizing the  
235 coastal GDEs are ducks, shorebirds, gulls, terns and flamingos.

236

## 237 **1.2. Ecosystem services and coastal GDEs**

238 Coastal GDEs harbor a large part of the human population that  
239 depends directly on these ecosystems (Willaert, 2014) and provide  
240 not only livelihoods but also numerous benefits to human health and  
241 welfare (Newton et al., 2014, 2018). Coastal GDEs have therefore a  
242 socio-economic interest which makes them complex social-  
243 ecological systems (Newton et al., 2014; Wit et al., 2017). Since the  
244 1970s, and more particularly in the 2000s, the concept of “ecosystem  
245 services” has attempted to express the complex relationship between  
246 human communities, their environment and the non-human living  
247 beings to which they are linked (Sartre et al., 2014). The “ecosystem  
248 services” can be defined as the full range of benefits that humans  
249 derive from the functioning of ecosystems. Ecosystem services  
250 include 4 major types of services (Blanchart et al., 2017):

- 251 - Provisioning services: correspond to direct products provided  
252 or produced by ecosystems such as water, food, construction  
253 materials,
- 254 - Regulating services: include benefits from regulation of  
255 ecosystem processes such as carbon storage, climate  
256 regulation, flood and erosion protection,
- 257 - Cultural services: include nonmaterial benefits from  
258 ecosystems such as recreation, aesthetic or educational  
259 benefits,

260 - Supporting services: are related to necessary factors for  
261 producing ecosystem services (photosynthesis, nutrient  
262 cycle, refuge areas...).

263 Ecosystem services are linked to the ecological structure and  
264 functions of the environment. In coastal GDEs, many ecosystem  
265 services are derived or supported by the presence of groundwater  
266 inflow because of its role in regulating the hydrology of wetlands and  
267 lagoons (UNEP-MAP, UNESCO-IHP, 2015). One of the main  
268 ecosystem services provided by coastal GDEs is related to  
269 provisioning services (livestock, fishing, aquaculture) (UNEP-MAP,  
270 UNESCO-IHP, 2015). Coastal GDEs are highly productive and food  
271 provisioning can often be key for regional economy (Newton et al.,  
272 2014). For example, the Ria Formosa in Portugal provided up to 90%  
273 of the national production of clams (Newton et al., 2003). Coastal  
274 GDEs also have a very important place in the hydrological cycle.  
275 They contribute to water flow regulation and control and therefore  
276 help to flood protection. They also participate to water retention,  
277 quality (salinity regulation) and purification. Finally, cultural  
278 services, *e.g.* cultural heritage, tourism or aesthetics are also very  
279 profitable for several coastal GDEs. In some specific case, such as  
280 the Venice lagoon (Italy), cultural services can exceed  $5.10^8$   
281 euros/year (Newton et al., 2018).

282 The various protection and/or conservation status applied to  
283 coastal GDEs (Table 1) does not necessarily involve a high level of  
284 knowledge of the hydrosystems' behavior. For a large majority, the  
285 role and the dependence on groundwater is largely under studied,  
286 even if it is suspected (Table 1). Very few coastal lagoons have a

287 sufficient level of knowledge to understand their level of dependence  
288 to groundwater (Table 1) and then developed sustainable  
289 methods/policies to ensure their conservation. Moreover, even in the  
290 case of good knowledge of hydrological functioning and  
291 establishment of a conservation/protection status, it does not seem to  
292 guarantee the good state of these environments (Leruste et al., 2019;  
293 Leterme et al., 2015). The lack of hydrological knowledge then  
294 appears to be as much a problem as the lack of specific protection  
295 status adapted to the particular cases of the GDES.

### 296 **1.3. Understanding the dependence on groundwater** 297 **supplies**

298 Under natural conditions, without pumping, fresh groundwater flows  
299 from recharge to discharge areas (Fig. 2). Local groundwater flow is  
300 mostly near the surface and over short distances, i.e. from a higher  
301 elevation recharge area to an adjacent discharge area. In this case, the  
302 discharge of the aquifer (Fig. 2) occurs as diffuse outflow, as for  
303 coastal GDEs. Coastal GDEs are thus relying on the surface  
304 expression of groundwater (Richardson et al., 2011). On a larger  
305 scale, over long distances, groundwater flow is preferentially at  
306 greater depths and fresh groundwater meets salt marine water at  
307 depth in the transition zone. The discharge of groundwater is  
308 composed by two processes: i) the discharge of fresh groundwater  
309 (fresh submarine groundwater discharge, FSGD) toward the sea and  
310 the discharge of saline groundwater (recirculated submarine  
311 groundwater discharge, RSGD) (Fig. 2). Groundwater supplies to  
312 coastal GDEs can originate from one or several aquifer formations of

313 variable nature and extension (Table 1). This dependence on  
314 groundwater can be variable, ranging from partial and infrequent  
315 dependence (seasonal or episodic) to total, continual dependence  
316 (Hatton and Evans, 1998).

317 Groundwater and surface water are the most often characterized by  
318 strong interactions (Fig. 2). These interactions result in groundwater  
319 discharge to the river (groundwater discharge, Fig. 2) or, conversely,  
320 in aquifer recharge through river and lake water infiltration (Fig. 2).  
321 Rivers and streams that flow all year (perennially flowing) are often  
322 groundwater dependent because a significant proportion of their daily  
323 flow is supported by the groundwater flow discharging into the river  
324 course (Acuña et al., 2005; Bonada and Resh, 2013; Datry et al.,  
325 2014). Groundwater is particularly important in arid and semi-arid  
326 regions and in case of extended dry periods, during which  
327 evaporation markedly exceeds precipitation and surface water is  
328 scarce or even disappeared (Eamus et al., 2006). Both groundwater  
329 and surface water flow toward the lagoon, which constitute the last  
330 collector of the watershed (Fig. 2). The discharge of groundwater  
331 toward coastal GDEs can be either directly into the wetland or  
332 indirectly via the river (Fig. 2).

333 For a long time, groundwater studies in coastal areas focused mainly  
334 on seawater intrusion impacting coastal aquifers. The groundwater  
335 has only recently been recognized as important contributors to  
336 hydrological and biogeochemical budgets of coastal environments  
337 such as coastal GDEs (Table 1) (Johannes, 1980; Burnett et al., 2001,  
338 2006; Slomp and Van Cappellen, 2004; Moore, 2006, 2010; Rodellas  
339 et al., 2015; Luo and Jiao, 2016; Malta et al., 2017; Correa et al.,

2019; David et al., 2019). The presence of groundwater drives the evolution, persistence and resilience of coastal GDEs and their ecosystems on at least two aspects including i) physical characteristics, such as the quantity, location, timing, frequency and duration of groundwater supply (Jolly et al., 2008; Rodríguez-Rodríguez et al., 2008; Bertrand et al., 2012, 2014) and ii) chemical characteristics (Burnett et al., 2006; Moore, 2010), such as water quality (Ganguli et al., 2012), salinity (Menció et al., 2017), nutrient concentrations (Szymczycha et al., 2012; Ji et al., 2013; Rodellas et al., 2015; Hugman et al., 2017) and temperature (Brown et al., 2007; Richardson et al., 2011). Although recognized as essential, the characterization of coastal hydrosystems' behavior still remains under studied in many cases (Table 1) due to the important monitoring and financial resources required to improve their understanding.

#### 1.4. Groundwater dependence monitoring

The “Groundwater dependence” clearly expresses that the prolonged absence of groundwater as well as its quality degradation have a negative impact on the growth, health, composition, structure and function of the ecosystem. Potential threats to groundwater inflow toward the coastal GDEs can be assessed through the study of the groundwater flow paths, the spatial and temporal variability of groundwater discharge and surface/ground water interactions (Kløve et al., 2011). Yet, the groundwater dependence of coastal GDEs remains still difficult to characterize. This difficulty is exacerbated by the thinness of the unsaturated zone, *i.e.* the thickness of the soil between the soil surface and the top of the saturated zone, which



367 allows important mixing between surface and ground waters.  
368 Differentiating and quantifying the contribution of these end-  
369 members is highly complex. A wide range of methodologies have  
370 been developed to improve the understanding of coastal GDEs  
371 (Sophocleous, 2002; Kalbus et al., 2006; Howe et al., 2007). First of  
372 all, the monitoring of groundwater levels and the establishment of  
373 piezometric map are often the first steps to highlight the groundwater  
374 dependence of coastal GDEs (Sena and Teresa Condesso de Melo,  
375 2012). Then, in the particular case of coastal GDEs, the two main  
376 approaches commonly used to assess surface/ground water  
377 interaction are i) temperature, geochemical and isotopic tracers  
378 (Dimova et al., 2017; Duque et al., 2016; Mudge et al., 2008; Sadat-  
379 Noori et al., 2016; Sánchez-Martos et al., 2014; Santos et al., 2008;  
380 Schubert et al., 2011) and ii) numerical modeling (De Pascalis et al.,  
381 2009; Martínez-Alvarez et al., 2011; Sena and Condesso de Melo,  
382 2012; Read et al., 2014; Menció et al., 2017). Less common  
383 approaches, such as geophysical method can also be carried out to  
384 obtain information on the spatial scales and dynamics of the fresh  
385 water–seawater interface, the rates of coastal groundwater exchange  
386 and the total fresh water discharge (Dimova et al., 2012).

## 387 **2. Dominant human and climatic stressors on** 388 **groundwater and consequences for coastal** 389 **GDEs in Mediterranean regions**

390 Although essential, coastal GDEs are one of the most threatened  
391 ecosystems in the world. Human activities are exerting increasing  
392 pressure on these sensitive systems or on the resources on which they

393 depend, such as groundwater. Water withdrawal, drying, pollution,  
394 habitat destruction or overexploitation constitute the main causes of  
395 their degradation (Millennium Ecosystem Assessment, 2005). More  
396 than 50% of wetlands have disappeared during the 20<sup>th</sup> century in  
397 some regions of Australia and Europe (Millennium Ecosystem  
398 Assessment, 2005). Only in the Mediterranean basin, national or sub-  
399 national datasets suggest a probable loss of 50% of its wetlands  
400 (Perennou et al., 2012). In the specific case of coastal wetlands,  
401 global losses are estimated at between 64 % to 71% during the 20<sup>th</sup>  
402 century (Gardner et al., 2015).

403 The characteristic overdevelopment of coastal Mediterranean regions  
404 has already led, for several decades, to a significant pressure on  
405 groundwater resources. The growing drinking, industrial or  
406 agricultural water requirements tend to the overexploitation of the  
407 coastal aquifers. Coastal aquifers are threatened by both horizontal  
408 exchanges with seawater and vertical infiltrations of pollutants. The  
409 development of human activities often constitutes an important  
410 source of pollutants and groundwater can constitute an important  
411 vector of pollution towards the coastal GDEs (Moore, 2006).

## 412 **2.1. The harmful human overdevelopment of coastal** 413 **Mediterranean regions**

414 The strong and increasing urbanization as well as fast growing  
415 demography represent the two main pressures. For example, in  
416 Australia, more than 85% of the population is living within 50km of  
417 the sea. The population density of Australian's coastal areas  
418 increased by 14% between 2001 and 2009, from 3.75 hab/km<sup>2</sup> to 4.27

419 hab/km<sup>2</sup> (Fig. 3a). A very important difference is observed for the  
420 urban, coastal population. The population density measured in  
421 coastal capital cities is 94 times higher than the average population  
422 density of coastal areas (Fig. 3a).

423 In the Mediterranean basin, the coastal population grew from 95  
424 million in 1979 to 143 million in 2000 and could reach 174 million  
425 by 2025 (UNEP/MAP, 2012) (Table 1). In the Mediterranean basin'  
426 population, France is the 3<sup>rd</sup> most populated country (after Turkey  
427 and Egypt) (UNEP/MAP, 2012) and allows for a good observation of  
428 the attractiveness of the Mediterranean coastline (Insee/SOeS, 2009).  
429 Indeed, among the 3 French coasts (Mediterranean, Atlantic and  
430 Channel coasts), the Mediterranean coast is clearly distinguished by a  
431 rapid population growth (Fig. 4) (Insee/SOeS, 2009). Between 1960  
432 and 2010, the French Mediterranean coast recorded the highest  
433 population increase with 56%, although it is the least extensive  
434 coastline (Fig. 4). The highest growth of population rate is recorded  
435 in the Mediterranean island of Corsica, with an annual increase of  
436 1.3% between 2006 and 2010. The coastal municipalities accounting  
437 for 80% of the Corsican population and 30% of the urbanization is  
438 concentrated within 1 km of the shoreline (SDAGE, 2015).

439 In USA, California tops the coastal populations chart. Currently, of  
440 the total population of 39.6 million in California, 69% is living in  
441 coastal areas (U.S. Census Bureau, 2019) and 95% is living in urban  
442 areas. Coastal population density is 3 times higher than the state'  
443 population density (Fig. 3b). In less than 60 years, coastal population  
444 density went up by a factor of 2.5, from 135.6 hab/km<sup>2</sup> in 1960 to  
445 278.4 hab/km<sup>2</sup> in 2017 (U.S. Census Bureau, 2019) (Fig. 3b). In the

446 major coastal cities, such as San Francisco and Los Angeles,  
447 population density exceeds several thousand inhabitants per km<sup>2</sup>. In  
448 2018, population density was 7003 hab/km<sup>2</sup> and 3230 hab/km<sup>2</sup>  
449 respectively.

450 This demographic growth is accompanied by a very fast development  
451 of urban infrastructure. In the Mediterranean basin, the urbanization  
452 increased from 54% in 1970 to 66% in 2010 (Table 1) and the urban  
453 coastal population could increase by 33 million between 2000 and  
454 2025 (UNEP/MAP, 2012). The South and the East Mediterranean  
455 countries (Non-EU countries) are urbanizing more rapidly than the  
456 rest of the world. These that were essentially rural countries, with  
457 average urbanization of 41% in 1970, will become urban countries,  
458 with 66% urbanization by 2025 (UNEP/MAP, 2012). This tendency  
459 is also observed in Australia. Peri-urban and rural cadastral parcels  
460 are progressively replaced by urban areas leading to an increased  
461 artificialization of coastal areas (Clark and Johnston, 2017).

## 462 **2.2. Perturbations induced by groundwater** 463 **degradation**

### 464 **2.2.1. Reduction of groundwater inputs and coastal** 465 **GDEs dewatering**

466 The modification of fresh groundwater flowing to the lagoons  
467 disrupts the fragile balance of the coastal GDEs' ecosystems. As  
468 surface water is limited and increasingly affected by pollution and  
469 eutrophication, the exploitation of groundwater from coastal aquifers  
470 as a source of freshwater has become more intense (Bocanegra et al.,  
471 2013; Liu et al., 2017). The number of groundwater abstraction

472 infrastructures have drastically increased. This process is the one  
473 most frequently exacerbated by unsuitable water resource  
474 management plans and/or poor control of water extraction facilities.  
475 Unregulated but also illegal pumping draws a high and unreasoned  
476 amount of water which is uncountable in the water management  
477 policies and leads to groundwater depletion and reduce river, spring  
478 and wetland flows. The progressive lowering of the groundwater  
479 level reduces or removes the connections between the aquifer and the  
480 coastal GDEs. As a result, aquatic vegetation in these transitional  
481 wetlands is gradually being replaced by terrestrial vegetation. This  
482 process leads to the drying, reduction and disappearance of coastal  
483 GDEs. In the worst case, changes in the structure and the functioning  
484 of the ecosystem (Balasuriya, 2018; Pérez-Ruzafa et al., 2019) results  
485 in a partial or total loss of ecosystem services provided by coastal  
486 GDEs.

487 Anthropogenic activities require a growing demand for space for  
488 agricultural production, housing or industrial land use. The land gain  
489 can be achieved by the conversion of natural lands or by partially or  
490 totally draining wetlands (El-Asmar et al., 2013). The construction of  
491 artificial drainage network in order to control the humidity is an old  
492 and relatively common practice (Gerakis and Kalburtji, 1998;  
493 Avramidis et al., 2014). These practices are highly constraining for  
494 the hydrosystems. They drastically alter the natural flow of surface  
495 groundwater and greatly affect the coastal GDEs, which are relying  
496 on the surface expression of groundwater.

497 Changes in land use can have a significant impact on aquifer  
498 recharge processes and thus on fresh groundwater supplies to coastal

499 GDEs. . Infiltration is increasing with the proportion of bare soil and  
500 evapotranspiration's patterns are conditioned by the type and the  
501 stages of crops development. Soil compaction by urbanization or  
502 intensive agriculture may reduce the infiltration and enhance the  
503 surface runoff (van den Akker and Soane, 2005; Gregory et al., 2006;  
504 Nawaz et al., 2013). In addition, the urban pavement of the shore (El-  
505 Asmar et al., 2013) makes the soil impermeable and drastically  
506 reduces infiltration and recharge into the aquifer. 40% of the 46,000  
507 km of Mediterranean coast were already artificialized in 2000 and it  
508 is expected to exceed 50% by 2025 (AViTeM, 2018).

509 If groundwater extraction is clearly the main threat in coastal  
510 Mediterranean regions, it is important to underline that increasing  
511 groundwater flow is also problematic. Some activities, such as  
512 irrigation, terracing, land-clearing or managed artificial recharge of  
513 aquifers, can appreciably increase the permeability of upper soils and  
514 then lead to the increase of the aquifer recharge (Baudron et al.,  
515 2014). In urban areas, tap water leaks can also constitute a significant  
516 source of groundwater recharge (Minnig et al., 2018; Vystavna et al.,  
517 2019). The flow of fresh water to the coastal GDEs can therefore be  
518 significantly increased. The physical and chemical disturbances can  
519 disturb and modify bio-community structure of the coastal GDEs.

### 520 **2.2.2. The role of groundwater as a vector of pollution**

521 Coastal GDEs often represent the last collector of water and their  
522 quality degradation results, and reflects human activities over the  
523 watershed. Anthropogenic activities such as the demographic,  
524 economic, industrial and commercial development often introduce

525 new potential contamination sources (Appelo and Postma, 2005)  
526 which infiltrate towards the aquifer.

527 In the coastal Mediterranean regions, the main problem is related to  
528 the sewage inputs. The fast growing of urbanization is not always  
529 accompanied by the development of sewage infrastructures that  
530 results in less efficient treatment of urban wastewater and sewer leaks  
531 (Michael et al., 2013). In the Mediterranean basin, almost 40% of  
532 coastal settlements with more than 2000 inhabitants do not have any  
533 wastewater treatment plant (UNEP/MAP, 2012). This problem is  
534 especially exacerbated on the southern Mediterranean basin due to  
535 the rapid growth of many coastal cities and towns. In addition,  
536 coastal Mediterranean regions are privileged tourism destinations  
537 (UNEP/MAP, 2012). The touristic flow picks lead to higher rates of  
538 sewage inputs in urban sewerage networks that are often aged and  
539 failing. Wastewater and associated pollutants from domestic and  
540 industrial sources consequently infiltrate towards the aquifer or  
541 through the interaction between groundwater and river water  
542 (McCance et al., 2018; Erostate et al., 2019; Koelmans et al., 2019;  
543 Vystavna et al., 2019). Nitrogen pollutants, phosphorus, but also  
544 organic compounds and heavy metals are the most frequent  
545 contaminant affecting the groundwater resources (Wakida and  
546 Lerner, 2005; Petrie et al., 2015; Xu et al., 2019). The second main  
547 source of groundwater quality degradation is the agricultural activity.  
548 The excess of nutrients from fertilizers (nitrogen and phosphorus),  
549 pesticides, emerging compounds and, less frequently, pathogenic  
550 microorganisms related to agricultural activities contribute to the

551 degradation of both ground and surface water quality (Symonds et  
552 al., 2018; Xin et al., 2019).

553 Once infiltrated, the pollutants follow the groundwater flow and can  
554 migrate to coastal GDEs (Rapaglia, 2005; Knee and Paytan, 2011;  
555 Jimenez- Martinez et al., 2016; David et al., 2019). According to the  
556 temporal dynamic of the aquifer, groundwater can represent a direct  
557 short and/or long term vector of pollution for coastal GDEs.  
558 Groundwater with short residence times (a few years) into the aquifer  
559 will rapidly flow towards the lagoons, carrying pollutants along its  
560 way. In case of groundwater with long residence time (several  
561 decades) and if no remediation process occurs, pollutants can be  
562 accumulated into the aquifer for several decades. The currently  
563 observed groundwater contamination can therefore be the result of  
564 the legacy of pollution related to human activities previously  
565 developed over the watershed (Erostate et al., 2018). This  
566 groundwater archiving capacity allows the storage of pollutants that  
567 will reach the coastal GDEs in the future.

568 Once the pollutants are in the coastal GDEs, prolonged groundwater  
569 residence times favor the accumulation of pollutants in water but also  
570 in aquatic organisms. The progressive accumulation of pollutants,  
571 especially heavy metals, along the food chain can pose serious  
572 human health issues and greatly impact economical profit by  
573 deteriorating ecosystems services such as aquaculture and fisheries.  
574 The most frequent impact of exceed in nutrients, sediments and  
575 organic matters is the eutrophication which can lead to important  
576 degradation or loss of seagrass beds, community structure and  
577 biodiversity (National Research Council, 2000; Pasqualini et al.,



578 2017). More than 400 coastal areas have been identified worldwide  
579 as experiencing some form of eutrophication (Selman et al., 2008).

580 **2.2.3. Impacts of climate change on aquifer recharge**  
581 **and implications for coastal GDEs**

582 Important changes regarding the aquifer recharge in terms of timing,  
583 duration and magnitude (McCallum et al., 2010; Hiscock et al., 2012;  
584 Taylor et al., 2013) as well as the storage and the quality of  
585 groundwater are expected in a context of climate variability. These  
586 modifications will be more pronounced in arid regions and especially  
587 in the Mediterranean basin, considered as a Hot Spot of climate  
588 change (IPCC, 2014). By the middle to the end of the century, the  
589 southern European regions as well as Australia are expected to suffer  
590 from increasing arid conditions with longer and more frequent  
591 droughts (Stigter et al., 2014) due to the increase in the temperature  
592 (Ducci and Tranfaglia, 2008; McCallum et al., 2010), in  
593 evapotranspiration (Hiscock et al., 2012), modification of seasonal  
594 patterns of precipitation (Polemio and Casarano, 2008; Stigter et al.,  
595 2009; Barron et al., 2011) and of average effective infiltration (Ducci  
596 and Tranfaglia, 2008). An amplification in the frequency and  
597 intensity of drought is also expected in the southern Mediterranean  
598 basin, such as in Morocco (Stigter et al., 2014).

599 The results of predictive models to assess the impact of the climate  
600 change on aquifer recharge are often highly variable. The main  
601 tendency highlights a decrease in the groundwater recharge in  
602 Mediterranean regions, leading to a significant loss of groundwater  
603 resources (IPCC, 2007; Barron et al., 2011). In the Mediterranean  
604 basin, the decrease of the recharge can reach 30% to up to 80%

605 (Ducci and Tranfaglia, 2008; Döll, 2009; Moseki, 2017).  
606 Modification in coastal aquifer recharge as well as the expected sea  
607 level rise (Hertig and Jacobeit, 2008; Somot et al., 2008; Mastrandrea  
608 and Luers, 2012) can lead to the inland migration of the mixing zone  
609 between fresh and saline water .

610 Climate change will exacerbate existing pressures rather than bring a  
611 new set of threats. With the water requirements that are projected to  
612 increase under a drier climate, severe water shortages can occur. The  
613 outflow into the coastal GDEs can be strongly reduced by the end of  
614 the century which could accelerate their drying up. Groundwater  
615 degradation by salinization could also greatly affect the physico-  
616 chemical conditions and thus the ecosystem balance of the GDEs  
617 lagoons. In response to these treats, a decrease in groundwater  
618 abstraction and an appropriate management appear as the principal  
619 way to ensure the preservation and sustainability of coastal GDEs  
620 (Candela et al., 2009; Stigter et al., 2014).

621 There may be exceptions to this general trend at the local level. In  
622 some cases, the modification of rainfall patterns and/or land uses  
623 modification can favor the recharge of the aquifer and improve the  
624 groundwater quality (Cartwright and Simmonds, 2008; Crosbie et al.,  
625 2010; Santoni et al., 2018). For example, in the Murray-Darling  
626 Basin in Australia, the clearing of the native vegetation is likely to  
627 favor the infiltration and increase the recharge of 5% for future  
628 climate around 2030 (Crosbie et al., 2010). If land-clearing could  
629 favor the recharge, the strong alteration of the hydrological cycle by  
630 vegetation cutting also has strong negative aspects which should be  
631 underlined. Among others things, land-clearing can increase runoff

632 and streamflow, favor soil erosion, massive drainage of natural  
633 nutrients and salinization of soils and waters (Koivusalo et al., 2006;  
634 Cowie et al., 2007; Peña-Arancibia et al., 2012; Kaushal et al., 2018;  
635 Cheng and Yu, 2019). The consequences of these practices are often  
636 irreversible. Yet, for watersheds severely degraded by salinization,  
637 this increase in recharge could help the dilution and potentially  
638 improve quality of groundwater (Cartwright and Simmonds, 2008).

639 The existence of local specificities shows the importance of  
640 establishing adaptive case-by-case water management strategies.  
641 Water resource management requires the definition of appropriate  
642 management scale which makes it possible to manage the  
643 hydrosystem as a whole, taking into account the complexity of  
644 interactions between water bodies but also between humans and their  
645 environment.

### 646 **3. Management strategies and current** 647 **considerations for coastal GDEs**

#### 648 **3.1. From international environmental** 649 **awareness to Integrated Water Resource** 650 **Management**

651 The definition and establishment of water resources management  
652 strategies and policies result from an awareness of environmental  
653 issues initiated in the 1970s, with in particular the Stockholm Earth  
654 Summit in 1972 (Fig. 5a). This ecological awakening then continued  
655 in the 1980s with a collective awareness of the existence of pollution  
656 and harmful disruption on a global scale. It is in this context that the

657 Bruntland Report define for the first time in 1987 the concept of  
658 “sustainable development”: “*The sustainable development is*  
659 *development that meets the needs of the present without*  
660 *compromising the ability of future generations to meet their own*  
661 *needs*”. This report requires the management of water resources as a  
662 common heritage and lays the foundations for integrated natural  
663 resource management. Only 5 years later, the Rio Earth Summit  
664 marked a turning point in the sustainable management of water  
665 resources with the “rediscovery” of the concept of Integrated Water  
666 Resource Management (IWRM) (Petit, 2006) and Integrated Coastal  
667 Zone Management (ICZM) (Deboudt, 2005).

668 These two concepts, which appeared in the 1970s (Deboudt, 2005;  
669 Petit, 2006), were then highlighted in the 1990s through the media  
670 coverage of the Rio Earth Summit and became a key concept in the  
671 2000s thanks to the launch of the concept of sustainable development  
672 on the international political scene. In 2000, the Global Water  
673 Partnership, an international network created to advance governance  
674 and management of water resources, published its first’s report on  
675 IWRM and clearly define the concept as a “process which promotes  
676 the coordinated development and management of water, land and  
677 related resources, in order to maximize the resultant economic and  
678 social welfare in an equitable manner without compromising the  
679 sustainability of vital ecosystems” (GWP, 2000). The IWRM was  
680 and remains widely promoted by many international organizations or  
681 donor agencies (Rahaman and Varis, 2005; Biswas, 2008), as a  
682 strategic approach to water management (Meublat and Le Lourd,  
683 2001). The Johannesburg Earth Summit in 2002 even recommended

684 its implementation in all countries by 2005. This summit also insists  
685 on the establishment of ICZM. Sharing the same precepts as IWRM,  
686 ICZM is nevertheless committed to taking into account the specific  
687 risks associated with water on the coast (Morel et al., 2004). ICZM is  
688 developing rapidly, particularly in Europe, thanks to its  
689 institutionalization and recommendation of the Council and the  
690 European Parliament in 2002 (Ghézali, 2009). Although coastal  
691 GDEs are in theory elements in their own right in integrated  
692 management strategies, they are still too often forgotten and do not  
693 benefit from legal or managerial recognition to take their specificity  
694 into account (Cizel, 2017).

### 695 **3.2. Integrated groundwater management** 696 **without specific regards for coastal GDEs**

697 Since the 2000s, we have seen an acceleration of sustainable resource  
698 management measures at the global, regional and national levels  
699 (Fig. 5a). GDEs have been partially propagated in water management  
700 policies developed over the past two decades, that recognize a link  
701 between groundwater and surface water. Some countries or group of  
702 countries particularly vulnerable to shortage of water and repeated  
703 severe droughts *e.g.* Australia, countries of the EU, the United-States  
704 (California) and South Africa, have yet incorporated specific  
705 reference to general GDEs into the legislation. Even if the protection  
706 of GDEs is included under water management policies, the  
707 implementation of an appropriate management policy is often lacking  
708 (Rohde et al., 2017).

709 Countries of the EU and Australia are the first to have included  
710 GDEs in their legislative framework (Rohde et al., 2017). The French  
711 model of water management by Water Agencies (created by the law  
712 of 1964) and the Australian model, derived from the experience of  
713 the Murray Darling Basin (Murray Darling Basin Authority created  
714 in 1987) are often considered as a reference model in terms of river  
715 basin management (GWP/RIOB, 2009; Brun and Lasserre, 2018).  
716 Legislative framework and groundwater managerial strategies set up  
717 by the EU and Australia however have shortcomings that undermine  
718 their effectiveness in protecting the resource (Fig. 6).

719 Australia provides the most comprehensive groundwater governance  
720 (Ross, 2016). As early as 1994, the agreement of the Council of  
721 Australian Governments (COAG) (Fig.5c) required the development  
722 of a comprehensive system of water allocations and rights to ensure  
723 better, more sustainable water management. The water reform  
724 program initiated by the COAG agreements was then updated in  
725 2004 by developing a new National Water Initiative (NWI) (Fig. 5c).  
726 The NWI - currently signed by all states and territories - has been  
727 recognized as the national blueprint for water sector reform to  
728 improve the state of industry and provide long-term environmental  
729 benefits (Willett, 2009). The annually adjustable water entitlements  
730 and related water market provide a great flexibility and a better  
731 adaptability to the state of the resource (Ross, 2016). However,  
732 monitoring of groundwater quality is limited (except for drinking  
733 water) and is often carried out on a short-term basis without  
734 consistent national program (Geoscience Australia, 2010). In Europe,  
735 on the other hand, both the quantitative and qualitative aspects

736 benefit theoretically from an equivalent level of attention. The  
737 legislative framework implemented by the Water Framework  
738 Directive of 2000 (WFD) (Fig. 5b) provides thus the most  
739 comprehensive groundwater protection (European Commission,  
740 2008; Ross, 2016). Member states are required to preserved the  
741 groundwater quantity and quality based on threshold values  
742 established to prevent any significant diminution of the ecological or  
743 chemical quality of surface water nor in any significant damage to  
744 terrestrial ecosystems which depend directly on the groundwater  
745 body (European Directive 2000/60/CE). The degree of freedom given  
746 to the member states to define groundwater and GDEs management  
747 plans and the wide disparity between them can yet reduce the  
748 enforcement of EU recommendations (Lieverink et al., 2011). While  
749 some countries are considered as models for their efficiency in water  
750 management, such as France, Spain or Germany (Rahaman and  
751 Varis, 2005) (Fig. 5b, c), others are experiencing significant delays in  
752 the transposition of the EU recommendations (Ghiotti, 2011). In EU  
753 frameworks, an important point of divergence is the concept of  
754 “water bodies” that supports the WFD. This concept requires precise  
755 identification, delimitation and definition. However, the scientific  
756 knowledge is often incomplete or inaccurate and fails to provide the  
757 appropriate level of precision (Bartout, 2015). The lack of knowledge  
758 represents a significant bias for the definition of priority actions and  
759 the implementation of effective public policies to achieve the good  
760 qualitative and quantitative status set by the European  
761 recommendations (Maillet, 2015).

762 These two management models, one based on strong qualitative  
763 regulation of the resource (Australia) and the other on the monitoring  
764 of threshold values (EU), lead to significant disparities in GDEs  
765 management. In Australia, management decisions are based on an  
766 ongoing monitoring and research which help to establish an adaptive  
767 GDEs management (Richardson et al., 2011; Rohde et al., 2017). The  
768 great adaptability of annual water allocation allows a better  
769 consideration to the vulnerability of GDEs, particularly in a case of  
770 severe drought. However, the poor water quality monitoring exposes  
771 lagoons to high risks of undetected contamination. Efforts made for  
772 the qualitative management of the water resource clearly need to be  
773 completed and reinforced by an improvement of groundwater quality  
774 management to ensure the preservation of GDEs (Ross, 2016). In  
775 EU, monitoring threshold values allows a better understanding and  
776 thus, a better prevention of qualitative and quantitative degradation  
777 risks for GDEs. The groundwater allocation is often included in river  
778 basin plans of member states but the adaptability of water  
779 withdrawals, particularly in the event of drought, can lack reactivity  
780 and damage the GDEs (Sommer et al., 2013; Stein et al., 2016). To  
781 really benefit from the European directives, particular attention must  
782 be paid to their concrete application in all member countries. In  
783 addition, the concept of “water bodies” must be better defined in  
784 order to enable the implementation of truly effective public policies.

785 In the particular case of coastal lagoons, considered by the WFD as  
786 “transitional water bodies”, the lack of knowledge and data in the  
787 early 2000s has triggered the development of monitoring networks  
788 implementation. Indeed, the monitoring programs developed for



789 freshwater ecosystems are not relevant for coastal GDEs. These  
790 transition environments are subject to many influences that induce a  
791 large variation in physical parameters, including salinity. The  
792 consideration of biological indicators and the evaluation of shifts in  
793 the species presence on coastal ecosystems has emerged as a valid  
794 strategy to characterize ecological status (Delpech et al., 2010; Pérez-  
795 Domínguez et al., 2012). This approach, followed in the same way by  
796 several EU countries, has led to the creation of indicators validated  
797 by the EU to improve the assessment of the status of transitional  
798 water bodies in the North-East Atlantic (Le Pape et al., 2015). For the  
799 Mediterranean region, this work has yet to be completed. Currently,  
800 only Greece, Italy and France have developed classification tools, but  
801 further developments are still needed to properly assess the  
802 ecological status of coastal lagoons (Le Pape et al., 2015).

803 Even if the groundwater resource management plans help to manage  
804 GDEs, specifics on GDEs management are often lacking (Rohde et  
805 al., 2017). Coastal GDEs form part of a continuum between  
806 continental and marine ecosystems and share common  
807 characteristics, species and ecological functions (Pérez-Ruzafa et al.,  
808 2010). Inland and coastal waters must be managed as a whole and  
809 coordination at river basin and coastal sea levels is required (Pérez-  
810 Ruzafa and Marcos, 2008). The IWRM is generally focused on the  
811 inland watersheds but likely neglects coastal specificity. Conversely,  
812 ICZM focuses exceptionally on coastal areas. However, the coastal  
813 area rarely extends to the entire watershed, which influences the  
814 quality and quantity of water resources that reach the coast. The link  
815 between IWRM and ICZM appears essential to respect the physical,

816 ecological and social continuum of watersheds and their coastal  
817 zones.

### 818 **3.3. Limitations of the project-based approach**

819 The IWRM does not automatically lead to the sustainability of  
820 resource uses, although it is a prerequisite (Aubin, 2007). The  
821 project-based approach, often applied in environmental protection,  
822 makes it difficult to develop a coherent policy. Encouraged by  
823 cooperation projects, several countries have tried to initiate the  
824 IWRM (Garnaud and Rochette, 2012). This is particularly the case in  
825 non-EU countries, such as Morocco and Algeria (Vecchio and  
826 Barone, 2018). The coastal GDEs of Nador (Morocco) (Fig. 5b)  
827 constitutes a representative example (Garnaud and Rochette, 2012).

828 Since the 1970s, coastal development has been announced as a  
829 priority by the Moroccan government, but there is no national public  
830 policy for coastal areas. The growing development exerts a strong  
831 pressure on the coastal GDEs, classified as RAMSAR site (Nakhli,  
832 2010). The Nador lagoon is thus the subject of a succession of  
833 projects (Fig. 5b) whose objective is to establish a sustainable  
834 management of this area (Garnaud and Rochette, 2012). To be  
835 "sustainable", resource management must yet be both based on  
836 previous actions and forward-looking. Most often, projects follow  
837 one another, without taking into account previous results. The  
838 standardized procedures proposed by donors do not sufficiently take  
839 into account the specificities of the territories. The multiplicity of  
840 projects is often counterproductive and compromises the  
841 effectiveness of this environmental development assistance. The

842 succession of projects without convincing results ends up reducing  
843 the mobilization of local actors and users. This generally too short-  
844 term approach limits the involvement and appropriation of target  
845 actors. This problem of appropriation is in addition to the problem of  
846 the limited funding period, which threatens the sustainability of the  
847 actions undertaken (Garnaud and Rochette, 2012). By the end,  
848 Morocco's commitment to Integrated Coastal Zone Management  
849 (advocated by the - too short - Cap Nador project, from 2006 to  
850 2008) finally found little support in these international collaborations  
851 (Garnaud and Rochette, 2012).

#### 852 **4. Better global understanding for a better** 853 **management of GDEs**

854 Due to their complexity, the development of management  
855 strategies adapted to coastal GDEs is particularly complex  
856 because it requires a strong transdisciplinary approach. Scientists  
857 in the technical sciences (at least hydrology, ecology,  
858 hydrogeology, oceanography) need to develop collaborative  
859 approach between them but also with social and legal scientists.  
860 Although difficult and slow to implement, this transdisciplinary  
861 approach has two major advantages. Firstly, it allows scientists to  
862 question their own discipline, in particular by putting into  
863 perspective the relevance of their own concepts and methods.  
864 Then, the development and construction of common methods and  
865 concepts results from a shared reflection. These new concepts are  
866 thus more relevant because they come from a collaboration work

867 and not from the interweaving of specificities borrowed from  
868 each discipline.

#### 869 **4.1. Improving the understanding of GDEs**

870 The improvement of GDEs' management inevitably involves an  
871 increasing knowledge of their hydrogeological and ecological  
872 condition and processes (IAH, 2016). This information is the most  
873 often unavailable and gaps at the intersection of groundwater  
874 hydrology and ecology do not facilitate the study of GDEs  
875 (Tomlinson, 2011). These gaps are even more important in the case  
876 of coastal GDEs which require collaboration between terrestrial  
877 hydrology and marine sciences - two epistemic communities that are  
878 not necessarily, or very rarely, used to working together. In addition,  
879 the implementation of the necessary monitoring systems to improve  
880 the understanding of GDEs is often financially and technically  
881 expensive and/or difficult to implement (Bowmer, 2003; Roll and  
882 Halden, 2016). Improving the management of coastal GDEs  
883 inevitably requires the management and understanding of hydraulic  
884 processes throughout the water cycle (fresh and salt water).

885 To overcome the lack of knowledge about GDEs, EU countries and  
886 Australian Government and the scientific community have been  
887 working together to establish practical guides. These "GDE practical  
888 guides" can in theory assist state agencies in the identification and  
889 management of GDEs for water management plans (Clifton et al.,  
890 2007; Richardson et al., 2011; Hinsby et al., 2015). They offer a  
891 range of methods for determining ecosystem reliance to groundwater  
892 and help water managers conducting the necessary technical

893 investigations and monitoring protocols to define ecological water  
894 requirements for GDEs. In practice, these often complex guides seek  
895 data keys to understand all types of systems but each GDE is an  
896 individual case, having specific characteristics and behavior that  
897 prohibit any generalization of diagnoses and solutions. The  
898 identification of appropriate study tools requires significant scientific  
899 support and the evaluation and monitoring of the relevance of the  
900 tools used is yet another debate.

901 Generally, the improving of knowledge depends on the strategic and  
902 economic interest of GDEs, assessed by the costs and benefits related  
903 to their protection (Millennium Ecosystem Assessment, 2005). The  
904 "ecosystem services approach" of the United Nations Millennium  
905 Ecosystem Assessment Project thus recommend to complete the  
906 technical approach of GDEs by a relevant assessment of the GDEs'  
907 valuation and relationship between ecosystems and human well-  
908 being. While the evaluation of ecosystem services tends to highlight  
909 man's dependence on his environment, this economist approach to  
910 nature raises two concerns. Firstly, this new way of thinking about  
911 nature conservation places nature at the service of mankind (Dufour  
912 et al., 2016). GDEs are then considered as providers of valuable  
913 goods and services. The diversity and complexity of the relationship  
914 between humans and nature cannot be summarized as a monetary  
915 evaluation exercise (Sartre et al., 2014). Moreover, human societies  
916 had already understood the importance of coastal GDEs and how to  
917 benefit from them well before the concept of "ecosystem services"  
918 was adopted. Secondly, the economic assessment of GDEs requires a  
919 clear definition of the benefits of these ecosystem services including

920 direct (fish and plant production, water storage and purification...)  
921 and indirect values (cultural, aesthetic, social reasons...) to the  
922 human population (IAH, 2016). Estimating the economic values of  
923 ecosystem services is far from easy. Recreation and tourism are the  
924 most easily quantifiable services, firstly because the direct revenue  
925 they generate are easily quantifiable but also because they receive  
926 special attention due to the attractiveness of coastal GDEs (Rolfe and  
927 Dyack, 2011; Clara et al., 2018). On the other hand, essential services  
928 such as protection against erosion, climate regulation or pollution  
929 control are neglected, largely underestimated and/or under-studied  
930 due to the lack of available data (Barbier et al., 2011)

#### 931 **4.2. Determining the appropriate management** 932 **scale**

933 The watershed is considered as the most environmentally and  
934 politically relevant management unit. This watershed-based approach  
935 can contribute to reinforce the lack of consideration given to  
936 “hidden” groundwater resources, while they are essential to establish  
937 an integrated management of GDEs. An appropriate management  
938 scale is a necessary first-step for the sustainable management of  
939 supporting aquifers and of the coastal GDEs (Bertrand et al., 2014;  
940 Vieillard-Coffre, 2001).

941 Firstly, surface and ground water are not constrained by the same  
942 geological boundaries. The hydrogeological and hydrological  
943 watershed do not necessarily (or rarely) overlap (Affeltranger and  
944 Lasserre, 2003). The extension of an aquifer and the drained  
945 groundwater can extend well out of the boundaries defined by the

946 hydrological basin. Human activities developed outside the  
947 hydrological basin can impact qualitatively and/or quantitatively the  
948 groundwater resources flowing within the basin and/or hydraulically  
949 connected. A significant water supply-demand gap can therefore be  
950 induced. A broader consideration of a "water-supply area" would  
951 allow a better assessment of the water resources actually available.  
952 This approach would ensure a better allocation of water between  
953 human and ecosystem needs.

954 Surface and groundwater have very different flow dynamics.  
955 Groundwater flow takes on average several years, even centuries,  
956 compared to a few days or a few weeks for river water (Fetter, 2018).  
957 The capacity of recharge and renew is much longer. Their inertial  
958 behavior supports their capacity to accumulate the pollutants and to  
959 record the degradation caused by human activities over several  
960 decades (section 3.2.2.). The positive or negative effects of the land  
961 use planning made over the hydrological basin can take several  
962 decades or even centuries before being noticeable on groundwater  
963 quality and quantity (Boulton, 2005). The notion of sustainability  
964 preached by IWRM can then be strongly questioned if the  
965 groundwater dynamics are not enough understood and/or not  
966 considered by management strategies.

967 The existing hydraulic exchanges between the different water bodies  
968 and the vertical linkages are not always fully appreciated (Boulton,  
969 2000). Part of the problem relates to the difficulties of assessing  
970 groundwater volumes, recharge rates and sources but also to the low  
971 recognition of the linkages between groundwater and many surface  
972 water ecosystems (Boulton, 2005). The qualitative and quantitative

973 status of a water body has an impact - positive or negative - on all the  
974 water bodies connected. It is then important to understand the  
975 existing relationships between the aquifer and all the other water  
976 bodies, which means neighboring aquifers, fresh surface water and  
977 brackish surface water.

978 More and more water resources managers are becoming familiar with  
979 the necessity of considering large spatial areas to establish a relevant  
980 water management (Boulton, 2005). Even if their perceptions of  
981 hydrologic interactions are often restricted to lateral and longitudinal  
982 flows (Pringle, 2003), the importance of vertical connectivity is  
983 slowly being appreciated (Boulton, 2000). A greater consideration of  
984 the ecological processes that support the proper functioning of the  
985 GDEs is being given. The study of the “proper functioning areas” of  
986 GDEs would define the extension of the surrounding area that  
987 supports the ecological processes that ensure the sustainability and  
988 resilience of the wetland (Chambaud and Simonnot, 2018). It would  
989 take into account all the factors that contribute to the functioning of  
990 the GDE, *i.e.* water qualitative and quantitative supply, but also  
991 animal species for which all or part of the life cycle occurs near the  
992 GDE and the connectivity of the GDE with other biodiversity  
993 reservoirs, animal and plant populations.

### 994 **4.3. Partnership, appropriation and relevant** 995 **definition of coastal GDEs**

996 The efforts required to establish effective multi-scale governance are  
997 not often sufficient to ensure the sustainable management of  
998 groundwater and GDEs (Molle et al., 2007) (Fig. 7). Several



999 shortcomings already mentioned above, partially explain these  
1000 difficulties (Fig. 7). The development of regional guidelines based on  
1001 too approximate or minimalist knowledge of GDEs, inevitably leads  
1002 to inconsistencies in management strategies at the local level. Coastal  
1003 GDEs often suffer from incomplete, inappropriate or even  
1004 contradictory definitions. Scientific definitions are sometimes in  
1005 conflict with legal definitions and make the recognition and  
1006 conservation of these environments more complex (Cizel and Groupe  
1007 d'histoire des zones humides 2010; Cizel, 2017). Coastal GDEs are  
1008 often recognized and grouped into the large family of wetlands. A  
1009 simplification that does not take into account their specificity,  
1010 consisting of a wetland, a water body and an aquifer, all hydraulically  
1011 connected, which must be recognized and managed as an inseparable  
1012 whole. Improving the definition of coastal GDEs is essential both to  
1013 better understand and to delimit them, but also to develop and to  
1014 apply specific and appropriate protective legislative acts.

1015 While the advancement of scientific knowledge and its better  
1016 consideration at the regional level could be a way to improve the  
1017 management of GDEs, a large part of the solution also seems to come  
1018 from the local level. At the local scale, collaboration between water  
1019 stakeholders for integrated resource management can be complicated  
1020 (Chanya et al., 2014; Mostert, 2003). The initial appropriation by  
1021 state entities (Water Agencies or Basin Organizations) of the  
1022 recommendations formulated by regional and national institutions  
1023 often appears insufficient for the local implementation of adapted and  
1024 sustainable management strategies (Fig. 7). A real appropriation of  
1025 existing regulations on coastal GDEs by all local stakeholders,

1026 decision-makers and actors in the territory appears essential for the  
1027 preparation of relevant planning or development documents and the  
1028 implementation of appropriate action programs. The elements  
1029 required to define the challenges and perspectives related to GDEs  
1030 must not be a local adaptation of regional recommendations but  
1031 rather a collective elaboration by all the actors concerned. Efforts  
1032 must be made to develop a framework for effective public  
1033 participation at six levels: information, education, consultation,  
1034 involvement, collaboration and capacity building (Das et al., 2019).

1035 Coastal aquifers are particularly vulnerable to water users conflicts  
1036 (Zepeda Quintana et al., 2018). All water users want to be able to  
1037 benefit from the quality and quantity of water resources they need.  
1038 No user can be abandoned in favor of another, nor can the need for  
1039 environmental waters. Environmental water needs cannot be  
1040 forgotten and must be taken into account in management strategies.  
1041 Sustainable water management thus requires water demand  
1042 management, which must be achieved through agreements and  
1043 collaboration at an appropriate scale. The establishment of a strong  
1044 collaborative processes appears as the only way to guarantee the  
1045 essential groundwater supply to coastal GDEs and their sustainability  
1046 (Boulton, 2005). The management of coastal GDEs must take into  
1047 account its hydrological basin as well as its territorial water  
1048 management unit and all territorial units important for its  
1049 management, *i.e.* tourist unit, geographical unit, air of influence of  
1050 neighboring cities or migratory bird management (Mermet and  
1051 Treyer, 2001)...

## 1052 **Conclusion**

1053 Nowadays, coastal Mediterranean regions suffer from an over-  
1054 development of anthropogenic activities which strongly impact the  
1055 groundwater resources and depending coastal GDEs. Although some  
1056 Mediterranean regions have included the protection of GDEs in their  
1057 water management policies, the implementation of an appropriate  
1058 intergraded and collaborative management is often lacking and  
1059 coastal GDEs do not benefit from a particular status due to their  
1060 complexity.

1061 The preservation of coastal GDEs is subject to the stability over time  
1062 of fresh water supplies (ground and surface water) in sufficient  
1063 quantity and quality. However, the determination of the qualitative  
1064 and quantitative needs of coastal GDEs is difficult to evaluate and  
1065 each coastal GDE is a unique case. Particular attention should  
1066 therefore be paid to the characterization of environmental and  
1067 ecological water requirements. The hydrogeological knowledge  
1068 about the management and behavior of coastal aquifers and GDEs  
1069 must be strengthened. Hydrogeology must be considered as an  
1070 integral component of the coastal GDEs and not a sub-discipline of  
1071 hydrology, as is too often the case at present. The inventory and  
1072 characterization of coastal GDEs must be improved through in-depth  
1073 systemic approaches. To this end, the coupling of hydrogeochemical  
1074 and geophysical techniques, which are inexpensive, seem to  
1075 constitute a relevant strategy. These investigations must be  
1076 supplemented by the identification and evolution of the sources of  
1077 contamination present in the catchment areas. In order to better  
1078 understand the role of groundwater as a vector of pollution, particular

1079 attention should be paid to the identification of the main groundwater  
1080 discharge areas and the assessment of contaminant flows and loads.  
1081 The systematic mapping of groundwater vulnerability in the coastal  
1082 areas must be promoted, using methods accounting for both the  
1083 intrinsic and specific vulnerability of groundwater. This kind of data  
1084 must help to develop land-uses and human activities according to the  
1085 groundwater vulnerability. Finally, in the case of effective  
1086 degradation processes, restoration plans should be considered. A  
1087 reflection must be carried out for the definition of relevant indicators  
1088 of the ecological coastal GDEs status. For these environments subject  
1089 to high variabilities, particularly in terms of salinity, there is a  
1090 necessity of developing sensitive indicators for monitoring ecological  
1091 status. Biological indicators seem to be helpful but needs to be  
1092 further and widely developed.

1093 From a qualitative point of view, the estimation of groundwater  
1094 withdrawals is often very approximate because of the poor  
1095 knowledge of the extraction points. It seems essential to carry out an  
1096 exhaustive inventory of wells and boreholes in the coastal GDE  
1097 watershed. The implementation of retroactive measures for reporting  
1098 private wells would also allow a better knowledge of the existing  
1099 structures, which are currently not recorded. Regularly monitored  
1100 water quotas for private individuals could also be helpful for the  
1101 qualitative management of the resource.

1102 At present, the lack of an appropriate definition for coastal GDEs is a  
1103 huge problem. Lack of discussion and consensus between lawyers  
1104 and scientists does not facilitate the establishment of management  
1105 strategies. To be efficient, this definition needs to be the result of a

1106 joint reflection between several disciplines. As showed in this  
1107 synthesis, the transdisciplinary approach between hydrogeology,  
1108 hydrology, social sciences and law is essential to fully understand the  
1109 socio-economic and environmental complexity of coastal GDEs. The  
1110 inventory of coastal GDEs characteristics could help to establish a  
1111 complete and relevant definition of coastal GDEs. In addition to  
1112 involve several discipline, thoughts about coastal GDEs definition  
1113 need to be based on the mobilization of scientist, lawyers but also  
1114 water users and stakeholders. Information, appropriation and  
1115 collaboration are clearly strategic, interdependent points to be  
1116 developed. Local water users and managers must feel concerned by  
1117 the problems related to coastal GDEs to build appropriate and  
1118 sustainable management plans. Without this process, all possible  
1119 efforts can be taken, but their chances of achieving successful results  
1120 will remain low. The creation of permanent mechanisms such as  
1121 water user groups or groundwater forums could be useful. These  
1122 moments of exchange and discussion would also allow managers and  
1123 decision-makers to better understand the role and benefits of coastal  
1124 GDEs. Indeed, evaluation of the ecosystem services is essential for  
1125 valuing the coastal GDEs and decision makers at many levels are  
1126 unaware of the connection between wetland condition and the  
1127 provision of wetland services and consequent benefits for people.

1128 All water resources in the coastal areas should be managed  
1129 collectively and strategically, in order to maximize use efficiency,  
1130 reduce water use conflicts and avoid over-exploitation. In other  
1131 words, the management strategy must consider the lagoon water  
1132 body, the surrounding wetland and groundwater as an inseparable set

1133 of communicating vessels whose nature of exchanges is subject to  
1134 temporal and spatial variations. In the global context of  
1135 unprecedented anthropogenic pressures, hydro-food crises and  
1136 climate change, the consideration given to coastal GDEs represents a  
1137 key issue for the socio-economic and environmental sustainable  
1138 development of many coastal Mediterranean areas. Integrated water  
1139 management strategies that consider environmental needs on an equal  
1140 footing with socio-economic constraints within the coastal  
1141 hydrosystem need to be improved. The ICZM is the management  
1142 strategy that most considers water resources in the coastal zone and  
1143 refers to coastal aquifers as such and specifies a monitoring  
1144 requirement. However, despite the growing consideration for coastal  
1145 aquifers, there are still gaps. It is important to continue to raise public  
1146 awareness of coastal aquifers at the regional level and to integrate  
1147 their specificities into coastal zone management strategies and plans.  
1148 Collaboration between states or countries, sharing of knowledge and  
1149 technology facilitated by the creation of exchange material could also  
1150 contribute to improving the integration of coastal aquifers into local  
1151 guidelines and policies.

1152 These practical suggestions could help for improving the  
1153 management of coastal aquifers and coastal GDEs. In this way,  
1154 groundwater and coastal water GDEs could really benefit from the  
1155 optimal environmental conditions required to ensure their  
1156 sustainability.

1157

1158

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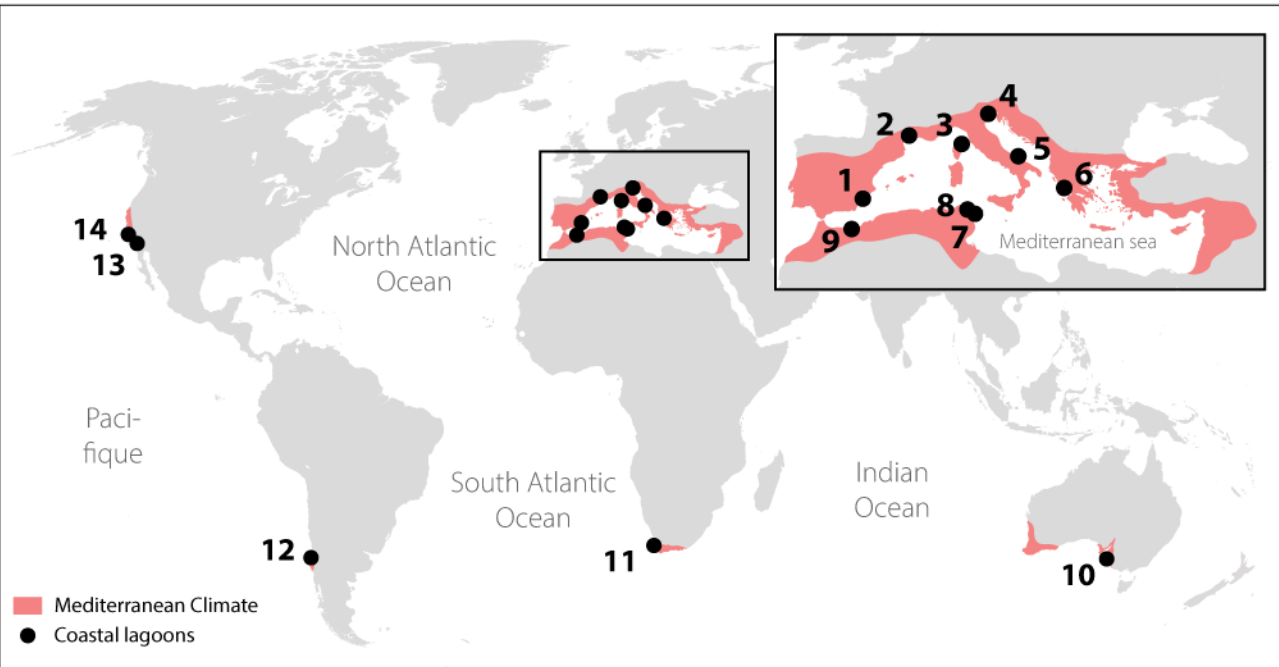
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2314 **List of tables**

2315 Table 1: Morphological and hydrological characteristics, protection  
2316 and conservation status and level of knowledge on hydrosystems'  
2317 behavior and groundwater dependence for 14 of the most studied  
2318 coastal lagoons under Mediterranean climate according to data  
2319 available in scientific literature. Lack of available information is  
2320 symbolized by a “?”.

2321 Table 2: Demographic trends and rate of urbanization in the  
2322 Mediterranean basin.





- |              |             |                |            |             |               |               |
|--------------|-------------|----------------|------------|-------------|---------------|---------------|
| 1. Mar Menor | 3. Biguglia | 5. Varano      | 7. Korba   | 9. Nador    | 11. Langebann | 13. San Diego |
| 2. Thau      | 4. Venecia  | 6. Messolonghi | 8. Bizerte | 10. Coorong | 12. El Yali   | 14. Malibu    |

Fig. 1: Coastal regions under Mediterranean climate and location of the 14 coastal lagoons exposed in Table 1.

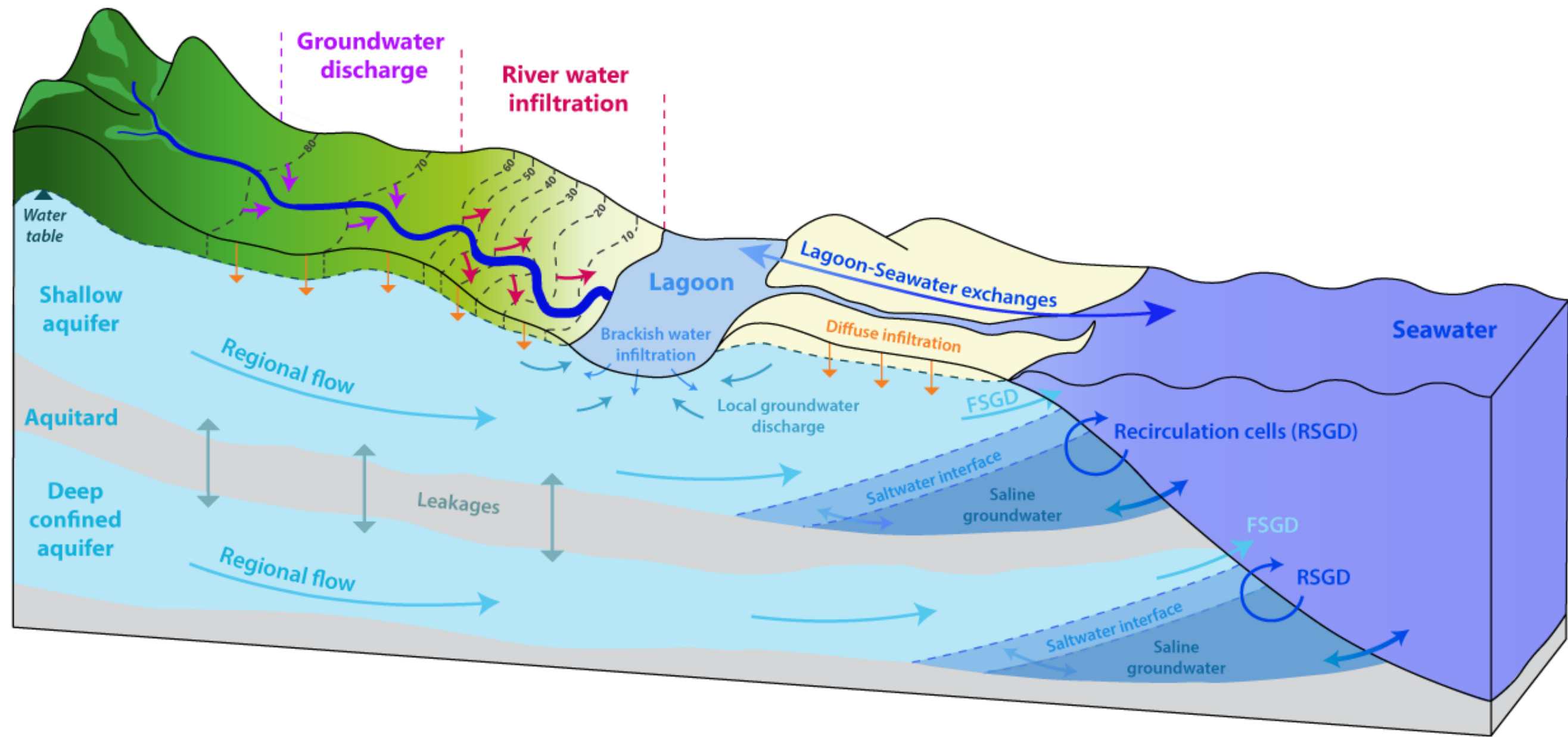
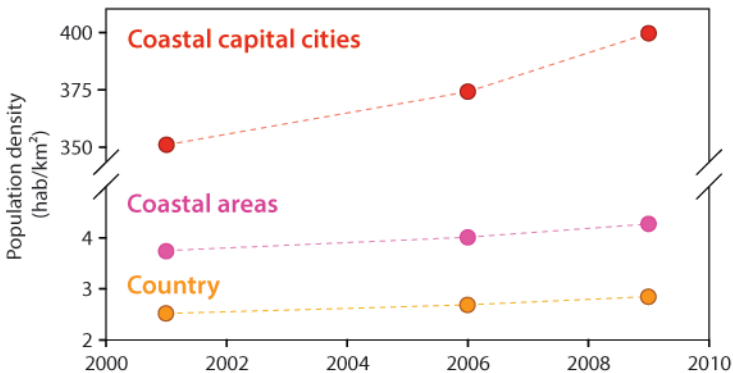


Fig. 2: Conceptual diagram of the hydrogeological behavior of coastal hydrosystems including a coastal GDE. On a large scale, the discharge of groundwater is composed by two processes: i) the discharge of fresh groundwater toward the sea (fresh submarine groundwater discharge, FSGD) and ii) the discharge of saline groundwater, i. e. the discharge of a mixture of fresh water and seawater after recirculation through the transition zone (recirculated submarine groundwater discharge, RSGD).

## a. Australia



## b. California

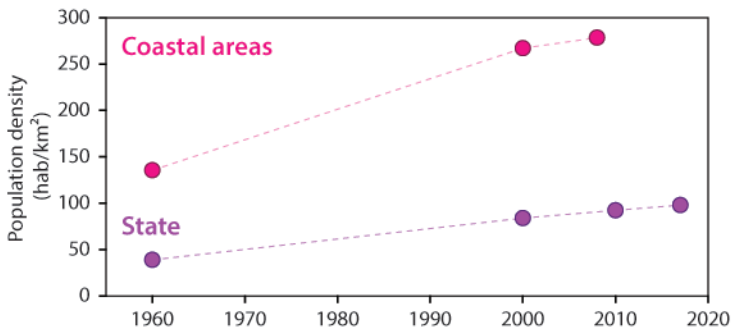


Fig. 3: Population density trends in Australia (a) and California (b).

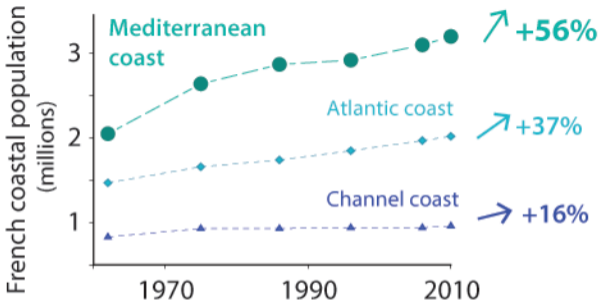


Fig. 4: Demographic trends on the three French coasts.

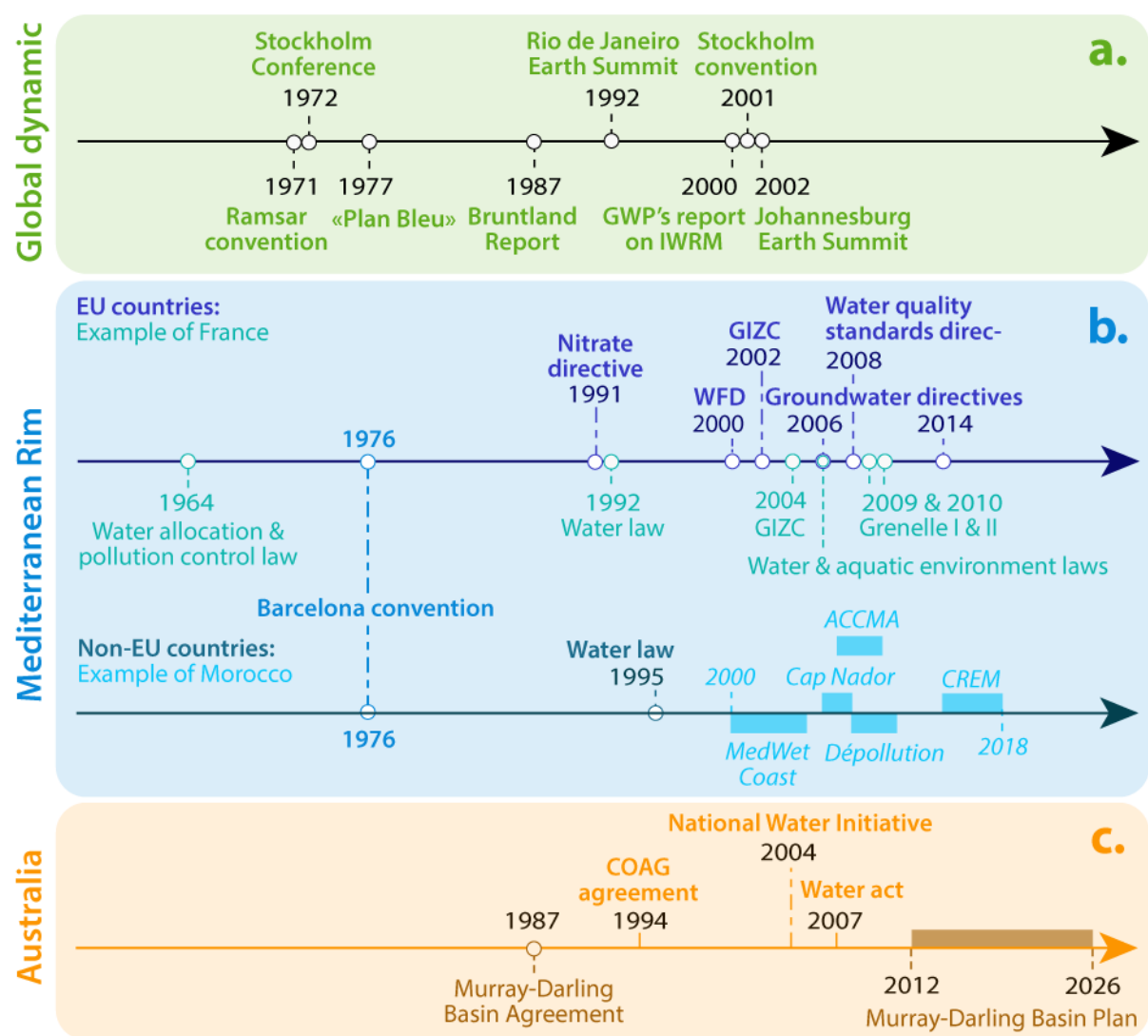


Fig. 5: Main world events that have guided the establishment of sustainable water resources management (a) and their translation into local laws and measures in the case of France (EU country), Morocco (Non-EU country) (b) and Australia (c).

## Australia

### Most comprehensive governance of groundwater



Water allocation  
Water rights  
Water market



**Great flexibility and adaptability**



**Better consideration to the vulnerability of GDEs**



**Good quantitative management need to be reinforced by groundwater quality monitoring**



Poor quality monitoring



**Weak groundwater quality regulation**  
*(except drinking water)*



**High risks of GDEs contamination**



## EU countries

### Most comprehensive protection of groundwater



Management based on thresholds  
(quality & quantity)



**Faster detection of degradations**



**Better prevention of damages to GDEs**



**Need to improve the definition of water bodies to ensure the application of EU standards in each country**



Local implementation of EU standards  
Poor definition of «water bodies»



**Wide disparity between member states**  
**Difficulty in implementing appropriate public policies**



**Lack of specific management for GDEs**



Fig. 6: Comparison of the strengths and weaknesses of management strategies in Australia and Europe.

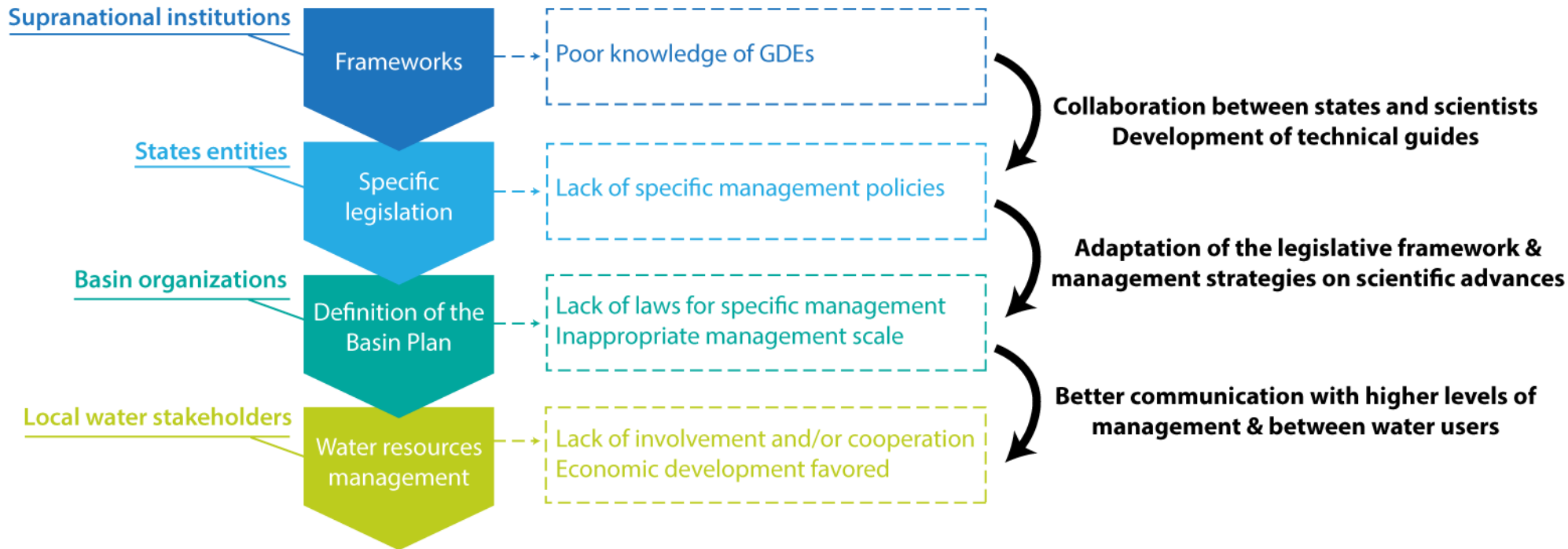


Fig. 7: Conceptual diagram showing the institutions and their roles in water resources management, highlighting major gaps and the points to be improved between two hierarchical levels.

Lagoons	Countries	Characteristics				Conservation and protection status	Hydrosystem behavior and groundwater dependence		References
		Surface (km <sup>2</sup> )	Mean depth (m)	Main aquifer formation(s)	Hydrological watershed (km <sup>2</sup> )		Strongly suspected	Demonstrated	
1	<b>Mar menor</b>	Spain, South-East	135	4.5	5 aquifers: Detrital deposits Sandston Limestone Sandy limestone and conglomerate Marble	1200	Ramsar site Special bird habitat Regional park Site of Community importance Specially protected area of Mediterranean importance	Studied and relatively well known	De Pascalis et al., 2012; Baudron et al., 2014; Velasco et al., 2018; Alcolea et al., 2019
2	<b>Thau</b>	France, South-Est	75	4	Karstified limestone	280	Special bird habitats Natura 2000 Water Framework Directive site	Studied but lack of data to understand the global behavior	Tournoud et al., 2006; Fleury et al., 2007; Stieglitz et al., 2013; Loiseau et al., 2014; La Jeunesse et al., 2016
3	<b>Biguglia</b>	France, Corsica island	14	1.2	Detrital deposits	182	Ramsar site Nature Reserve Special bird habitats Natura 2000 Water Framework Directive site	Studied and relatively well known	Lafabrie et al., 2013; Erostate et al., 2018; Jaunat et al., 2018; Erostate et al., 2019; Leruste et al., 2019
4	<b>Venice</b>	Italy, North-East	550	1.5	Detrital deposits	1800	Ramsar site Natura 2000 Special bird habitat	Largely studied and relatively well known	Ravera, 2000; Ferrarin et al., 2008; Rapaglia et al., 2010; Da Lio et al., 2013; Mayer et al., 2014
5	<b>Varano</b>	Italy, South-East	65	3.5	2 main aquifers: Detrital deposits	300		Under-documented	Ferrarin et al., 2010; Roselli et al., 2013; Fabbrocini et al., 2017
6	<b>Messolonghi central lagoon</b>	Greece, North-West	80	0.8	2 main aquifers: Limestone and breccia Detrital deposits	1979	Ramsar site National Park Important Bird Area Natura 2000	Under-documented	Alexakis, 2011; Karageorgis et al., 2012; Stamatis et al., 2013
7	<b>Korba</b>	Tunisia, plain of Cap Bon	3.1	1	Detrital deposits	27	Ramsar site Important Bird Area	Under-documented	Kouzana et al., 2010; Zghibi et al., 2013; Slama and Bouhlila, 2017



8	<b>Bizerta</b>	Tunisia	128	8	Detrital deposits	380	Ramsar site UNESCO-MAB Reserve	Under-documented		Bouzourra et al., 2015; PNUE-PAM, UNESCO-PHI, 2017
9	<b>Nador</b>	Marocco, Nord-Est	115	5	2 mains aquifers: Detrital deposits	?	Ramsar site Nature Reserve Site of biological and ecological interest	Groundwater contribution known but under-studied		Maanan et al., 2015; Mohamed et al., 2017; Aknaf et al., 2018
10	<b>Coorong</b>	Australia, South-East	140	1.8	Limestone Sands	6	Ramsar site National Park		Studied and well known	Haese et al., 2008; Richardson et al., 2011; Leterme et al., 2015
11	<b>Langebaan</b>	South Africa	40	3	Detrital deposits and calcrete	?	Ramsar site National Parks	Under-documented		Flemming, 1977
12	<b>El Yali</b>	Chile	115	0.5	Detrital deposits	?	Ramsar site National reserve	Groundwater contribution known but under-documented		Dussailant et al., 2009; Vidal-Abarca et al., 2011
13	<b>San Diego</b>	California (U.S.A)	42	5	Detrital deposits	146	National Wildlife Refuge	Under-documented		Delgadillo-Hinojosa et al., 2008
14	<b>Malibu</b>	California (U.S.A)	0.05	?	Detrital deposits	280		Groundwater contribution known but under-documented		Dimova et al., 2017; Hoover et al., 2017

<b>Mediterranean basin</b>	<b>1970</b>	<b>2000</b>	<b>2010</b>	<b>2025</b>
Whole population (millions)	276	412	466	529
Coastal population (millions)	95	143	-	174
Urbanisation rate (%)	54	-	66	-

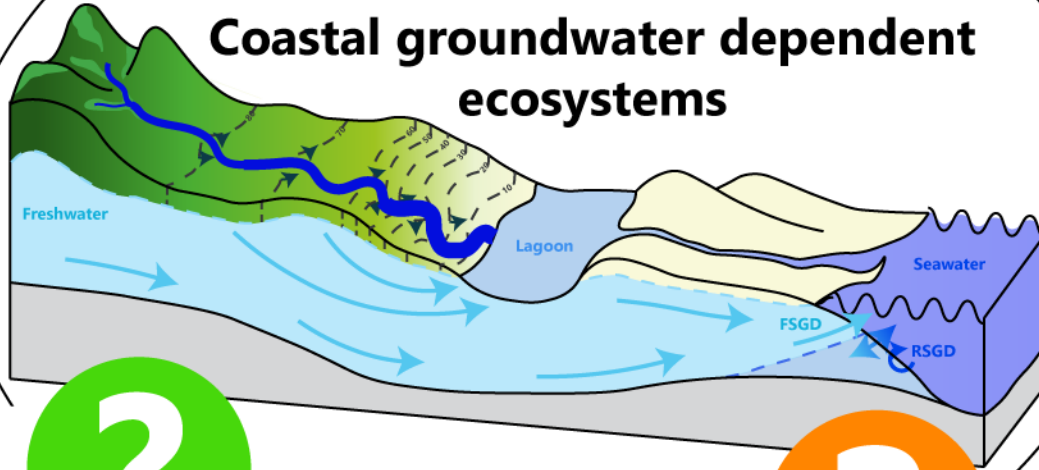
**Current  
consideration**



**Knowledge  
Definition**



**Coastal groundwater dependent  
ecosystems**



**Management  
policies**



**Legislative  
frameworks**

