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Predicting the vulnerability of seasonally-flooded wetlands to climate change across the Mediterranean Basin

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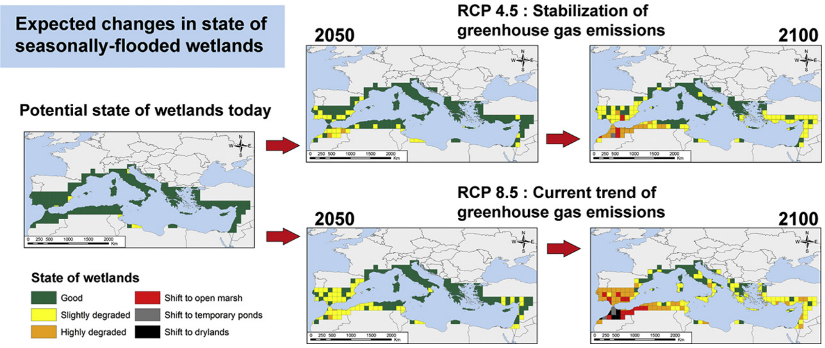
HIGHLIGHTS

- Seasonal wetlands with emergent plants provide multiple services to humankind.
- Water deficit will increase heterogeneously across the Mediterranean Basin.
- Wetland degradation is expected at 73% of localities under RCP8.5 in 2100.
- Amount of water needed to maintain wetland functions and values is provided.
- Practitioners can use mar-o-sel.net to anticipate local impacts of climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

Wetlands have been declining worldwide over the last century with climate change becoming an additional pressure, especially in regions already characterized by water deficit. This paper investigates how climate change will affect the values and functions of Mediterranean seasonally-flooded wetlands with emergent vegetation.

We simulated the future evolution of water balance, wetland condition and water volumes necessary to maintain these ecosystems at mid- and late- 21st century, in 229 localities around the Mediterranean basin. We considered future projections of the relevant climatic variables under two Representative Concentration Pathway scenarios assuming a stabilization (RCP4.5) or increase (RCP 8.5) of greenhouse gases emissions.

We found similar increases of water deficits at most localities around 2050 under both RCP scenarios. By 2100, however, water deficits under RCP 8.5 are expected to be more severe and will impact all localities. Simulations performed under current conditions show that 97% of localities could have wetland habitats in good state. By 2050, however, this proportion would decrease to 81% and 68% under the RCP 4.5 and RCP 8.5 scenarios, respectively, decreasing further to 52% and 27% by 2100. Our results suggest that wetlands can persist with up to a 400 mm decrease in annual precipitation. Such resilience to climate change is attributed to the semi-permanent character of wetlands (lower evaporation on dry ground) and their capacity to act as reservoir (higher precipitation expected in some countries during winter). Countries at highest risk of wetland degradation and loss are Algeria, Morocco, Portugal and Spain. Degradation of wetlands with emergent vegetation will negatively affect their biodiversity and the services they provide by eliminating animal refuges and primary

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resources for industry and tourism. A sound strategy to preserve these wetlands would consist of proactive management to reduce non-climate stressors.

1. Introduction

Although wetlands cover only 6% of the Earth's surface, they play a key role in hydrological and biogeochemical processes, while holding a significant part of the world's biodiversity and providing multiple services to humankind (Junk et al., 2013). Yet, wetland loss has been estimated at 64–71% since 1900 CE, with climate change scenarios adding pressure to non-climate stressors such as land reclamation, resource exploitation, hydrological modifications, and pollution (Davidson, 2014). Global and regional analyses have identified the Mediterranean region as an area that is particularly sensitive to climatic change and vulnerable to its impacts (Giorgi and Lionello, 2008; Cramer et al., 2018). Indeed, a Regional Climate Change Index (RCCI) developed by Giorgi (2006), identified the Mediterranean as the second most-prominent climate change hotspot. It was found that a large decrease in mean precipitation and precipitation variability during the dry season has the greatest contribution to the Mediterranean's RCCI. Most global circulation models also agree that there will be an increase in temperature in all seasons and for all parts of the Mediterranean area by the end of the twenty-first century (Dubrovský et al., 2014). A pronounced warming, reduction in precipitation and increased inter-annual precipitation variability are all expected to be highest in the summer season (Zachariadis, 2016). These changes are likely to have profound effects on both terrestrial and aquatic habitats (Cramer et al., 2018). Among the latter, productivity of seasonally-flooded wetlands is particularly at risk (Johnson et al., 2005). Short et al. (2016) found that emergent plant communities respond most directly to climate change related hydrological alterations. The response of plant growth to a reduction in rainfall will depend on existing factors such as salinity and soil saturation, whereby, rainfall reduction could improve or decline productivity (Short et al., 2016). Rising temperatures are expected to lead to a reduction in salt marsh species richness and changes in marsh species composition (Gedan and Bertness, 2009; McKee et al., 2012). Higher temperatures would also lead to lower water levels and a greater abundance of drought-tolerant species in freshwater marshes and are likely to shift the location of seasonally-flooded wetlands to currently wetter regions (Johnson et al., 2005).

Impact of climate change on wetlands will be tightly related to changes in water deficits, which are currently heterogeneous across the Mediterranean region. For instance, Trieste in Italy has an average annual precipitation of 1203 mm and evapotranspiration of 1602 mm, whereas Ksar El Boukhari in Algeria has 381 mm average annual precipitation and 2030 mm evapotranspiration (Muñoz and Grieser, 2006; Schneider et al., 2016). Evapotranspiration on dry soil is much lower than on flooded soil (Muñoz and Grieser, 2006; Verstraeten et al., 2008). Accordingly, periods of increased water deficit will have less impact on wetland hydrological balance if occurring when the ground is dry than when it is flooded. It is therefore difficult to predict the extent of hydrological changes related to climate projections and how they will affect any particular wetland within the Mediterranean region. Yet, this information is crucial for setting new water management and water allocation strategies (Turner, 1991; Euliss et al., 2008).

This study is original because it combines hydrological and climate models for an entire biogeographical region to predict the impact of climate change on hydrology of seasonally-flooded wetlands at high spatial resolution (0.125°). This was done by integrating the greenhouse gas projection scenarios for 229 localities around the Mediterranean in the free online interactive software Mar-o-sel.net developed to promote rational management of Mediterranean marshes (Lefebvre et al., 2015). We used the Representative Concentration Pathway scenarios, RCP 4.5 and RCP 8.5, for the mid- (2050) and late (2100) century. Based on a priori defined eco-hydrological thresholds, we quantified the impact of climate changes on a standardized virtual seasonally-flooded wetland through six possible habitat outcomes ranging from a productive marsh with tall helophytic vegetation to a dryland. The water volumes needed to maintain these wetlands in good condition were also modelled for the 229 Mediterranean localities. Our aim is to provide spatially explicit projections on the future conditions of wetlands and of their hydrologic needs in light of a changing climate, in order to encourage managers and practitioners to orient adaptive management and territorial planning for saving as many wetlands as possible for future generations.

2. Methods

2.1. Study area

The current Mediterranean climate is characterized by dry, hot summers and mild, wet winters with accentuated inter-annual variability (Lionello et al., 2006; Peel et al., 2007). Annual water balance (amount of annual precipitation minus water loss by evapotranspiration) is negative (Shaltout and Omstedt, 2012, 2015), resulting in the formation of seasonally-flooded marshes, which dry-up in summer and refill with water in winter. These wetlands are characterized by the presence of helophytes (i.e., emergent plants whose buds overwinter under water) whose productivity is far greater compared to terrestrial ecosystems in the region (Mesléard and Perennou, 1996). As a result, these ecologically important areas are utilised for a host of economic activities (Poulin et al., 2010; Rhazi et al., 2012). Wetland services and biodiversity are tied to hydrological conditions (Postel and Carpenter, 1997; Finlayson et al., 2005; TEEB, 2010). These wetlands provide food and habitat for animal species which are endemic, endangered and of heritage interest: maturation grounds of the European eel (*Anguilla anguilla*), spawning grounds for fish and amphibians and feeding and breeding grounds for birds such as the marbled duck (*Marmaronetta angustirostris*), white-headed duck (*Oxyura leucocephala*), Greater flamingo (*Phoenicopterus roseus*) and Eurasian spoonbill (*Platalea leucorodia*). The marshes regulate water quality (Song et al., 2006; Guittonny-Philippe et al., 2014), erosion and flooding as well as filtering groundwater (Finlayson et al., 2005). They provide resources for reed harvesting (Monti et al., 2015), fishing (Berkes, 1986) and hunting (wildfowl and boar) (Caro et al., 2015) industries. Agricultural practices benefit from a water supply and pollination services (Costanza et al., 1997). Tourism, educational and recreational activities such as bird watching have developed around the landscape and wildlife of these areas (Rhazi et al., 2012).

The wetlands modelled naturally flood and dry each year; their functions and values are directly associated with the duration of flooded and dry periods. Where flooding is deepest, the marshes are typically vegetated by tall emergent plants such as club-rushes and bulrushes (e.g., *Schoenoplectus lacustris, Schoenoplectus litoralis* and *Typha* spp.) (Mesléard and Perennou, 1996). In the zone in-between these species and the edges of marshes, sea club-rush (*Scirpus maritimus*) and common reed (*Phragmites australis*) predominate. Temporary drawdown is good for emergent plant species because it increases soil oxygenation, nutrient uptake, plant growth (particularly underground), and the overall stability of the plant formation (Morris and Dacey, 1984; van Wijck and De Groot, 1993). However, if the dry period is too long, vegetation growth and invertebrate abundance is reduced, resulting in a loss of productivity and biodiversity (Poulin et al., 2002, 2005), with repercussions on ecosystem services (e.g., provisioning of building materials and food, water purification and recreation). If flooding periods are too short, tall helophytes are replaced by smaller helophytes, such as sedges (Cyperaceae), sea club-rush and species with annual growth (e.g., *Salicornia* spp.). Over several years of prolonged dry seasons, the habitat is replaced by temporary ponds with a procession of completely different plant and animal species, such as pteridophytes (*Isoetes*, *Marsilea*, *Pilularia*), water-starwort (*Callitriche*) and *Lythrum* (Grillas et al., 2004). Lastly, if the flooding periods of temporary ponds are too limited, the growth of typical wetland vegetation ceases and more terrestrial species develop.

2.2. Mar-O-Sel

The simulation tool Mar-O-Sel (mar-o-sel.net, Lefebvre et al., 2015) was used to investigate how much water level change could be expected under climate change projections, and whether these new hydrological patterns would translate into ecosystem transitions.

Drawing upon an empirical dataset combining hydrological and climate data (see flow chart of model variables in Lefebvre et al., 2015), Mar-O-Sel software integrates marsh physical parameters, hydrological characteristics and management strategies to predict monthly water levels and water volumes needed to achieve a variety of management goals. These goals can correspond to increasing the carrying capacity of marshes to *Acrocephalus* warblers that rely on an abundant supply of insect during the breeding season; or to improve yields of reed harvested mechanically by favouring the dominance and growth of common reed while preserving the bearing capacity of the ground; or to improve the density and diversity of submerged macrophytes for attracting waterfowls while limiting invasive plant species such as *Ludwigia* spp. Users can select a locality, specify the desired water level at different months of the year and set the marsh parameters. The parameters used in this study are: 1. Overflow level: the water level beyond which the marsh loses water by overflow (e.g., dike height); 2. Catchment area coefficient: the ratio between the amount of precipitation and the increase of water level in a marsh. For example, this coefficient will have a value of 2 if 5 mm of rain results in a 10 mm increase in the water level of the marshes; 3. Minimum water table: the level of ground water below which the marsh cannot descend due to a supply of water by the water table or to the presence of a layer of waterproof substrate. The user can alternate up to three water management strategies comprised of the minimum or maximum (cm) monthly water levels desired. For each year, the user can choose which strategy to use. Simulation outcomes take into consideration precipitation and evapotranspiration for a marsh with helophytes (Lefebvre et al., 2015). The user can select historical data for precipitation (Schneider et al., 2016) and evapotranspiration (Muñoz and Grieser, 2006) from any year back to 1993, as well as future projections representative of 2050 and 2100 for 242 localities (1° in size) in 21 Mediterranean countries. The results, which can be exported as spreadsheets, are visualized graphically and show the predicted monthly water levels, both with and without application of management strategy, and monthly water volumes that must be added or extracted to achieve the management goal, if any.

2.3. Climate model simulations

Precipitation and evapotranspiration projected by one state-of-the-art Regional Climate Model (RCM) under different emission scenarios were taken from the Rossby Centre RCA4 RCM (SMHI-RCA4; Jones et al., 2004, Samuelsson et al., 2011), made available within the frame of the Coordinated Regional Downscaling Experiment European branch (EURO-CORDEX, Jacob et al., 2014, Giorgi et al., 2009). An assessment of the performances of the RCA4 model against observational datasets can be found in the technical report by Strandberg et al. (2014) and in several inter-comparison studies (e.g., Kotlarski et al., 2014; Casanueva et al., 2016; Vautard et al., 2013) showing that RCA4, driven by ERA-Interim reanalyses, is able to simulate the seasonal cycle of temperature and precipitation in relatively close agreement with the reference data.

At the time of downloading model data (May 2016), RCA4 was the only model available proving climate outputs at the highest spatial (0.11° or 12 km) and temporal (3 h) resolution, in the Euro-CORDEX archive. Five members of RCA4, driven by the following Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models (GCMs) were available: EC-Earth, CNRM-CM5, IPSL-CM5A-MR, MOHC-HadGEM2-ES and MPI-ESM-LR. We analysed all five members in three different timeframes, including recent climate (1981–2000) and two future periods in mid- (2031–2050) and late (2081–2100) 21st century. Future projections were analysed under two different RCP scenarios: RCP 4.5, corresponding to a stabilization of the radiative forcing at ~4.5 W/m^2 after 2100, and RCP 8.5, characterized by increasing greenhouse gas emissions beyond 8.5 W/m^2 after 2100, also known as the “business as usual” scenario (Moss et al., 2010). We used the simulated total precipitation and potential evapotranspiration for all model members, time periods and scenarios at 3 h and daily temporal resolution.

To quantify RCA4 biases over the Mediterranean region, the mean daily precipitation of each RCA4 member was compared to that of the observational gridded dataset E-OBS (Haylock et al., 2008), available over land areas in the European domain at ~25 km spatial resolution. The biases varied according to the driving GCM, with some model members showing a local tendency to overestimate (e.g., MOHC) or underestimate (e.g., IPSL) total precipitation compared to E-OBS. In order to account for these biases, the GCM-driven RCA4 data were adjusted by applying a constant, multiplicative factor to the daily data in such a way that the model's long-term climatology was the same as in the E-OBS reference data (Hempel et al., 2013; Casanueva et al., 2016; Durman et al., 2001). Owing to the unavailability of E-OBS data over sea, bias adjustment was not possible for those coastal areas falling into an E-OBS “water gridpoint” (this occurred for 22 out of 264 pixels) and these locations were thus excluded from further analysis.

2.4. Selection of regional climate models (RCMs)

For all RCA4 members, the potential evapotranspiration values were transformed into evapotranspiration for a marsh with helophytes (Lefebvre et al., 2015). For each location, paired *t*-tests at a significance level of 0.05 were used to compare the cumulated monthly values of precipitation and evapotranspiration between the observed and predicted data for the 1993–2013 period to choose the best RCM for each variable. Timings of the wet and dry periods are essential to these wetlands and it was important that climate projections reproduce the seasonal variations in precipitation and evapotranspiration as accurately as possible. We therefore multiplied the modelled data by a coefficient to match the observed mean values of July (critical period of the year when precipitation is lowest and evapotranspiration is highest), while respecting the annual total averages at each locality.

The model members that best predicted the temporal variations of precipitation and evapotranspiration for the period 1993–2013 were integrated into Mar-O-Sel. Since RCA4 members diverged mainly on precipitation estimate, we selected the best performing model based on its accuracy after bias correction on precipitation only. We used the MOHC GCM, with an overall correction factor of *1.41 for precipitation and *0.9096 for evapotranspiration. Using these correction factors, the simulated cumulative values of precipitation were not significantly different from the historical data for all months except January (respectively: $t = 3.88$, $p < 0.001$; $t = 5.31$, $p < 0.001$), February ($t = 3.48$, $p < 0.001$; $t = 5.19$, $p < 0.001$) and March ($t = 3.11$, $p < 0.001$; $t = 2.53$, $p < 0.05$) (Fig. 1). These significant differences at the beginning of the year are due to very low confidence intervals because of the large number of samples and little variability (Fig. 1). They represent a difference of 3 to 7 mm per month. Twenty occurrences of such projected

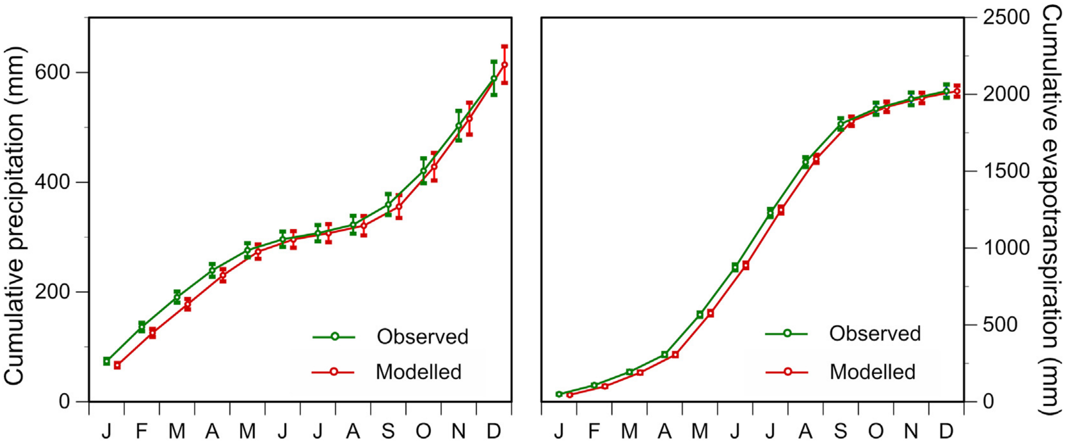

Fig. 1. Comparison between the observed and predicted values of cumulative precipitation (left) and evapotranspiration (right) averaged over the 1993–2013 period from bias-adjusted Met Office Hadley Centre (MOHC) HadGEM2-ES regional climate model.

climate conditions were incorporated into Mar-O-Sel for each period (2050 and 2100) and greenhouse gas scenarios (RCP4.5 and RCP 8.5).

2.5. Extraction of data in Mar-O-Sel

To calculate the minimal conditions necessary for a seasonally-flooded wetland to be maintained, catchment area size, overflow level and water table depth were estimated through an iterative approach for each locality. Catchment area coefficient was kept between 1 and 4, overflow level between 30 cm and 200 cm and water table depth between −30 cm and −200 cm (see Appendix). Using these pre-defined constants, 200 simulations (2 runs of 100 years using monthly values) using observed and simulated climate data over a historical period were performed for each locality (242) and checked to ensure that the simulated data were in agreement with the observed data. Thirteen localities for which we did not find a satisfactory agreement were removed. It turned out that these localities were under semiarid, arid, or humid subtropical climatic influence, lying outside the Mediterranean climate zone. For the remaining 229 localities (19 countries), 300 simulations were run in Mar-O-Sel using future climate projections with RCP 4.5 and RCP 8.5 scenarios extracted for 2050 and 2100. The simulations were performed in three sets of 100; the first set simulated a permanent watering of 10 cm to estimate the evolution of water deficit; the second set had no human intervention, in order to estimate the maintenance and evolution of seasonally-flooded marshes; the third set maintained a minimum of 10 cm of water from November through April and a maximum of −5 cm in July and August to estimate the water volumes managers would need to input during each month to preserve wetland functions. Habitat change was estimated based on eco-hydrological thresholds (Table 1) set by empirical data and a wetland expert (Patrick Grillas, Tour du Valat). To be considered in good condition, a marsh with tall helophytes must be flooded for at least six months and dry for a minimum of two months, for at least 70% of the simulations. Outside of these parameters, productivity of the marshes decreases, with reduced growth of emergent plants and lower abundance of aquatic invertebrates and passerine birds. This state of slight degradation corresponds in terms of hydrology to having water for at least five months, for 60% of the simulations with an average annual drying exceeding 5 months. If these conditions are not met, but flooding occurs at least four months per year in 50% of the simulations, without drying out periods exceeding five consecutive years, the marsh become highly degraded with a switch from tall to short emergent plants. If these periods of flooding become too rare or too short, emergent vegetation is expected to be replaced by annual marsh species. If, on average, wetlands still contain standing water for at least two months per year, they are considered as seasonal open marsh. If the average annual flooding is less than two months, they will be considered as temporary ponds (vernal pools). Lastly, if the habitat remains dry for more than ten years in a row, we consider that the wetland has collapsed and become a terrestrial dry habitat. Hydric changes, habitat changes and the volumes of water needed to preserve the functions and values of seasonally-flooded marshes under each scenario were calculated for each of the 229 Mediterranean localities in Mar-O-Sel software. The results were mapped using ArcGIS version 10 (ESRI) at the spatial resolution of the climate models (0.125°).

3. Results

3.1. Evolution of water stress

The contemporary mean water balance, such as calculated under constant flood conditions of wetlands, is indicated for each locality in Fig. 2. Water balance is systematically negative with no clear geographical pattern, aside from higher deficits at the eastern edge of the basin. However, when climate projections for 2050 and 2100 are used, a geographical pattern emerges with little changes in water deficits in the

Table 1
Hydrological thresholds corresponding to change in states of seasonally-flooded wetlands.

State of seasonally-flooded marsh	Flooded conditions		Dry conditions			
	Minimum (per simulated year)				Maximum (in a row)	
	Months	% simulations	Months	% simulations	Months	Years
Good	6	70	2	70		
Slightly degraded	5	60	2	70	5	
Highly degraded	4	50	2	70	>5	5
Shift to open marsh	2	On average	2	70	>5	
Shift to temporary pond	<2	On average	2	70	>5	10
Shift to dryland	<2	On average	2	70	>5	>10

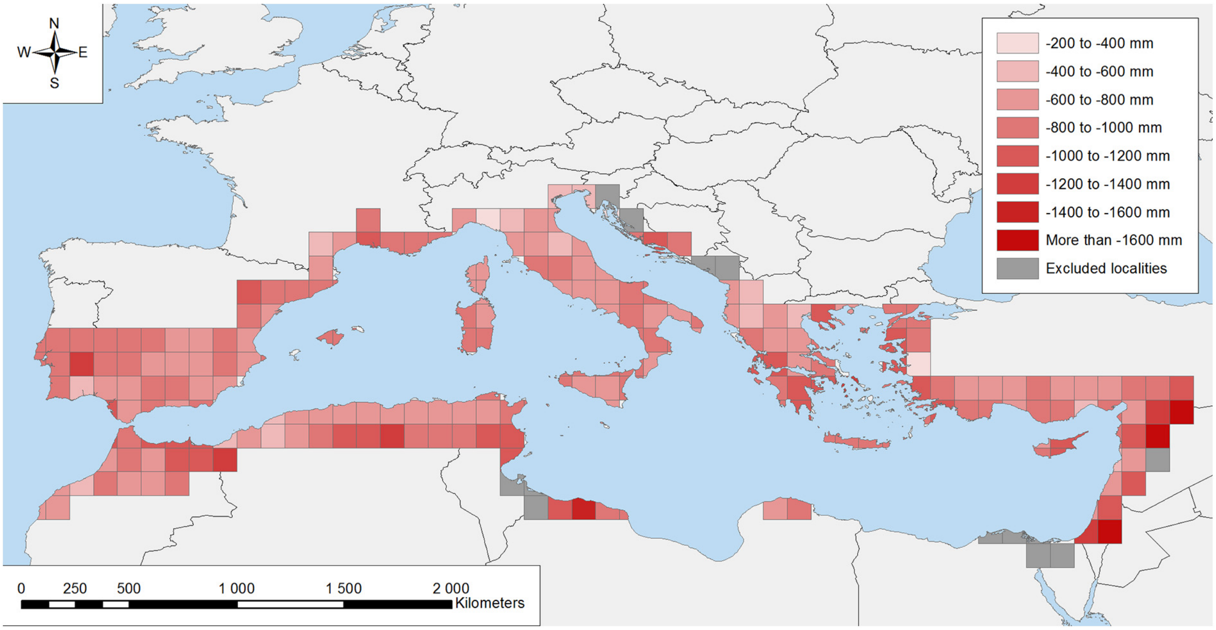

Fig. 2. Contemporary (1981–2013) annual water balance (precipitation minus evapotranspiration) for each of the 229 Mediterranean localities under constant flood conditions. The thirteen localities for which seasonal flooding patterns could not be simulated under the current climate conditions are shown in grey.

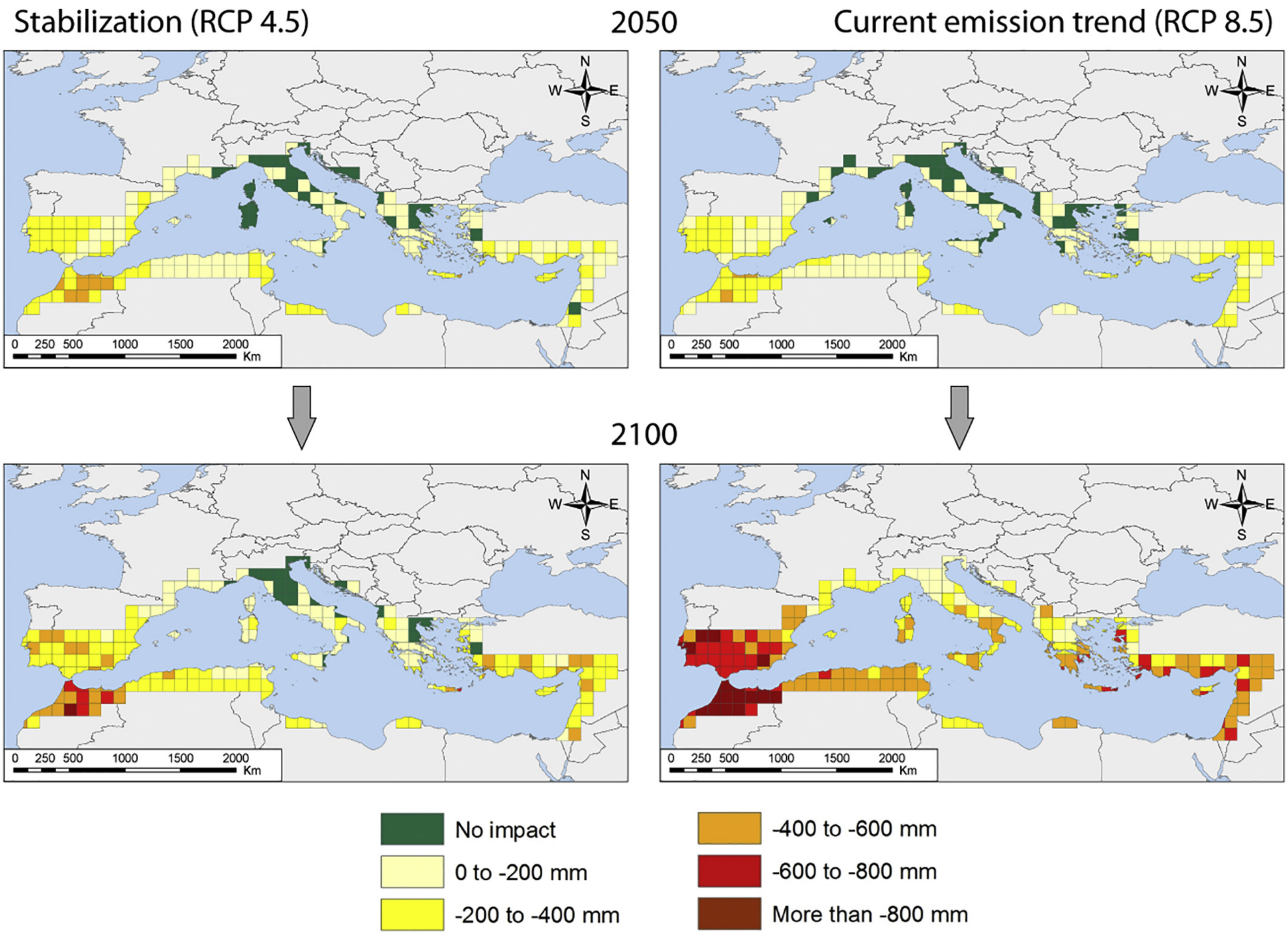

Fig. 3. Expected change in annual water balance under constant flooding conditions for each of the 229 localities under the RCP 4.5 and RCP 8.5 scenarios of greenhouse gas emissions at the 2050 and 2100 horizons.

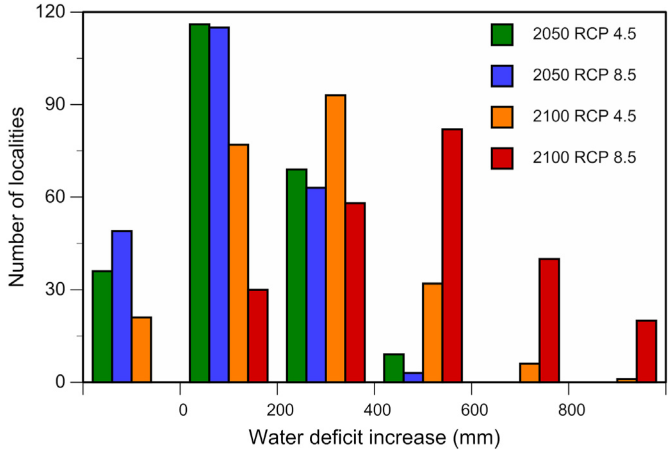

Fig. 4. Distribution of the 229 localities according to the mean annual increase in water deficits for each scenario and time period.

centre of the Mediterranean region and higher deficits in Northern Africa, Spain and at the eastern edge of the basin (Fig. 3, Fig. 4). When values are averaged by countries, contemporary water deficits range between −571 and −1227 mm (Table 2). Impact of climate changes on water stress can differ among countries having similar contemporary deficits. For example, water stress in France (−820 mm), Spain (−817 mm) and Morocco (−883 mm) is expected to increase by 22, 192 and 368 mm in 2050, and by 95, 299 and 554 mm in 2100 under the RCP4.5 scenario. Under the RCP 8.5 scenario, the differences are generally greater, with respective water deficit increases of 3, 180 and 299 mm in 2050 and 265, 573, and 902 mm in 2100. Syria has the highest contemporary water deficit (−1227 mm) but its water stress will evolve similarly to countries such as Spain (−817 mm) and Algeria (−802 mm) which have a much lower contemporary deficit (Table 2).

3.2. Evolution of seasonally-flooded wetlands

Assuming a constant catchment area and water table depth, our virtual seasonally-flooded wetlands, of which 96.5% currently meet our eco-hydrological criteria, will suffer habitat degradation under RCP 4.5 and RCP 8.5 scenarios (Figs. 5-6). By 2050, the changes in both scenarios are relatively similar: wetlands become slightly degraded at 17.4% (RCP 4.5) and 30.4% (RCP 8.5) of localities and highly degraded at 1.3% of localities, for both RCPs, according to a similar geographical pattern, with most degradations occurring in Spain and Northern Africa (Fig. 5). By 2100, there is a stronger distinction between the scenarios' outcomes: the RCP 8.5 scenario shows a more dramatic degradation of habitat, both in degree of degradation and number of localities affected (Fig. 6). With the RCP 4.5 scenario, wetlands become slightly degraded at 35.5% of localities, highly degraded at 9.6%, shifting to open marsh at 2.6% and to temporary ponds at 0.4%. With the RCP 8.5 scenario, wetlands become slightly degraded at 37.8% of localities, highly degraded at 24.4%, shifting to open marsh at 6.5% and to temporary ponds 1.3%, with a collapse to dry lands at 2.6% of localities. The eastern and western parts of the basin are the most affected, while northern Italy, France and Greece experience less habitat change (Fig. 5).

3.3. Water management to compensate increased water stress

Based on the simulation performed in Mar-O-Sel, the amount of water that would be needed annually to preserve the functions and values of wetlands are on average 1055 m^3/ha for slightly degraded wetlands, 1722 m^3/ha for highly degraded wetlands, 2263 m^3/ha for habitat shifting to open marsh, 2857 m^3/ha for habitat shifting to temporary ponds and 3537 m^3/ha for wetlands collapsing into dry land. Amount of water that would be required to maintain seasonally-flooded wetlands according to our eco-hydrological thresholds is provided for each locality in Appendix A.

4. Discussion

Although the impact of climate change on wetlands has received a lot of attention (Johnson et al., 2005; Erwin, 2009; Short et al., 2016; Dwire et al., 2018), quantitative assessments on how climate will affect wetland integrity remain scant (but see Johnson et al., 2005). We believe our projections are conservative because they measure the impact of water deficit on wetland hydrology without taking into consideration the consequences of increased competition for the water resource that will further reduce water allocation to wetlands (Cramer et al., 2018). Although seasonally flooded wetlands are mainly under freshwater influence, sites located in coastal areas could further be affected by sea

Table 2
Simulated conditions of catchment area coefficient and water table depth needed for contemporary wetlands by country with mean change in water balance expected under the RCP 4.5 and RCP 8.5 scenarios for 2050 and 2100.

Country	Mean catchment area coefficient	Mean minimum water table (cm)	Contemporary water stress (mm)		Change in water stress (mm)			
					RCP4.5		RCP8.5	
			mean	SE	2050	2100	2050	2100
Albania	1.1	-200	−731	48	−11	−72	−6	−219
Algeria	2.6	−163	−802	51	−144	−299	−167	−544
Bosnia and Herzegovina	1	−200	−800		40	−129	−54	−317
Croatia	1.2	−200	−796	211	64	−23	38	−220
Cyprus	2.7	−95	−965	68	−312	−355	−330	−504
France	1.3	−200	−820	46	−22	−95	3	−265
Greece	2.1	−194	−936	28	−126	−197	−59	−433
Israel	3.5	−50	−1169	508	−292	−406	−331	−705
Italy	1.5	−197	−753	21	−17	−65	13	−266
Lebanon	2.7	−150	−835	150	−179	−240	−224	−537
Libya	3.7	−76	−1015	99	−195	−226	−177	−373
Macedonia	1	−200	−571		−58	−157	−66	−431
Morocco	2.9	−127	−883	39	−368	−554	−299	−902
Palestinian territory	4	−80	−1203		−45	−159	−252	−430
Portugal	2	−200	−912	61	−230	−333	−248	−743
Spain	2.3	−192	−817	18	−192	−299	−180	−573
Syria	3.2	−117	−1227	141	−159	−332	−162	−537
Tunisia	2.8	−163	−906	53	−195	−240	−169	−439
Turkey	2.1	−189	−772	33	−153	−282	−160	−450
All localities	2.2	−175	−849	13	−142	−239	−124	−472

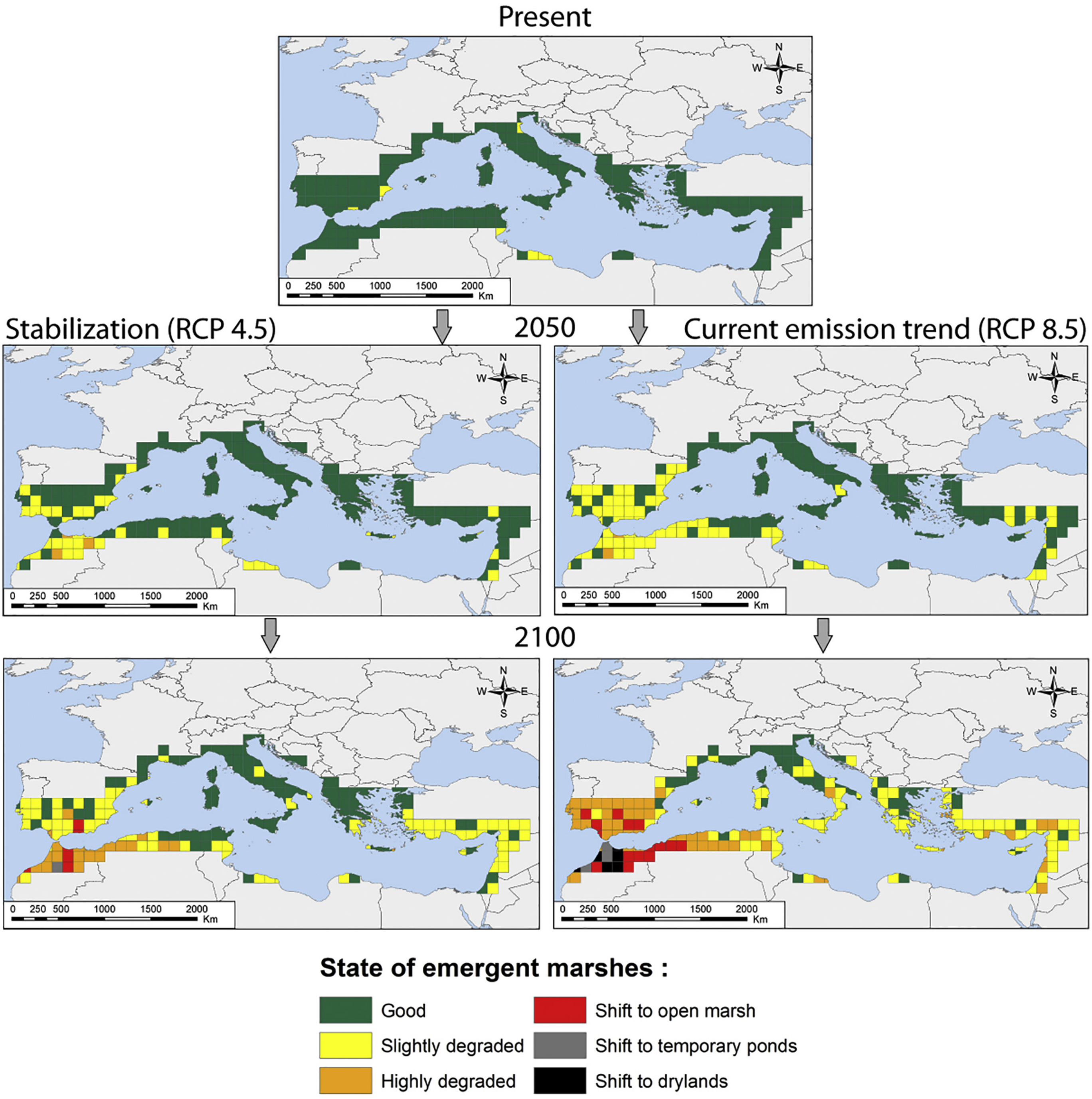

Fig. 5. Expected habitat change of seasonally-flooded marshes under the greenhouse emission scenarios RCP 4.5 and RCP 8.5 in 2050 and 2100.

level rise and increase in salinization. Sea level rise estimations for the Mediterranean Sea vary and depend on the future climatic conditions simulated. Mean estimates for thermosteric sea-level rise fall between 2 and 61 cm during the 21st century (Marcos and Tsimplis, 2008; Carillo et al., 2012; Adloff et al., 2015). Salinization is also expected to occur due to a decrease in river runoff, an increase in evapotranspiration, salt fingering processes and deep water formation events (Mariotti et al., 2008; Vargas-Yáñez et al., 2010; Borghini et al., 2014). Sea level rise was not integrated into our projections because it would have required working at the wetland unit level and we wanted to provide generic trends on water deficit for the whole Mediterranean region. However, when salinization risks are present, Mar-O-Sel can be used for modelling fluctuations of ground and surface water salinity, in addition to water levels (Lefebvre et al., 2015).

4.1. Water stress and climate change

The projected increase in annual water stress varies spatially throughout the Mediterranean Basin. In general, water deficits are highest in the western edge and lowest in the centre and north of the basin. Both RCP scenarios provide similar outcomes in 2050, the largest differences being observed between 2050 and 2100 with the RCP 8.5 scenario. Countries prone to higher water deficits are Portugal, Spain, Morocco, Algeria, Turkey, Syria and Israel. On the contrary, France, Italy, Croatia, Albania and Greece, and particularly the northern localities of Italy and Greece are expected to be less impacted. This spatial pattern is echoed in a study by Jacob et al. (2014) whereby precipitation decreases and temperature increases are less severe in the centre and north of the basin for the period 2071–2100 and more severe in RCP

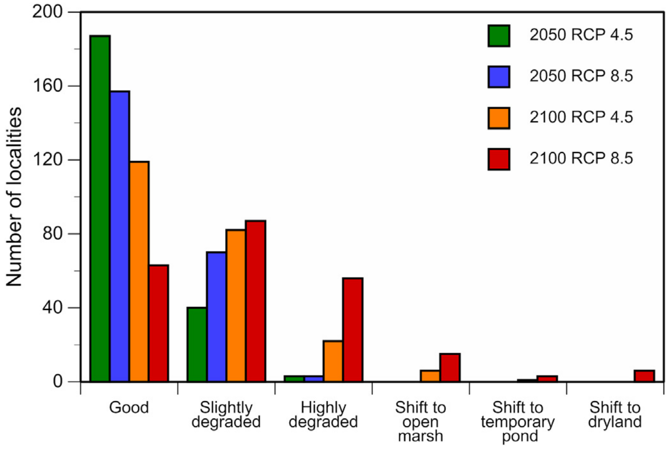

Fig. 6. Distribution of the 229 localities according to change in wetland state for each scenario and time period.

8.5 than RCP 4.5 scenario. Jacob's study also modelled the mean length of dry spells for 2021–2050 and 2071–2100, compared to 1971–2000, and the spatial patterns are similar to those found for the water balance, with largest differences between RCP 4.5 and RCP 8.5 at the end of the century. Other studies also predict the intensification of water deficits with stronger alterations to the water budget towards the end of the 21st century (Sanchez-Gomez et al., 2009).

4.2. Wetland response to climate change

Spatial trends in habitat shift are similar to spatial changes in water stress, but are less severe. It appears that our virtual wetlands will persist with a certain decrease in water (up to −400 mm), without suffering impact on their functions and values. All localities in Portugal, Spain, Morocco, Algeria, Tunisia and Libya are expected to undergo water deficit increases by 2050, yet 61% (RCP 4.5) and 38% (RCP 8.5) of these localities have wetlands potentially remaining in good condition. One locality in Libya offers good conditions for wetlands through all scenarios despite sometimes having increased water deficits between 400 and 600 mm. For RCP 8.5 in 2100, many localities in southern Italy, Greece and Cyprus are expected to face water deficits increased by 400 to 800 mm, but the simulated wetlands only become slightly degraded. Resilience of wetlands to climate change is largely related to their semi-permanent character. The highest decrease in precipitation occurs in summer when many wetlands dry out. Because actual evapotranspiration on dry ground is far less than on wet ground, the impact of water stress on wetlands is reduced. The higher precipitation predicted in most northern Mediterranean countries during winter (Gao et al., 2006; Dubrovský et al., 2014; this study), combined with the water storage capacity of wetlands, would further reduce the impact of summer dry spells in these countries. Hence, wetland evolution in response to climate change is not only related to the annual increase in water deficit but also to whether the period of increased evapotranspiration is occurring when the ground is dry or flooded.

4.3. Consequences on biodiversity and ecosystem services

Without changes in water allocation and management, the physical parameters currently providing good conditions for seasonal wetlands to persist would lead to a loss of functionality (slightly and highly degraded wetland states based on our eco-hydrological thresholds) at 61% of the localities, and habitat shifts with loss of helophytes at another 29% of localities spread across Spain, Portugal, Morocco and Algeria by 2100 should greenhouse gas emissions follow their current rate of increase (RCP 8.5). Degradation of helophytes in wetlands will have various consequences on biodiversity and ecosystem services. These stands of vegetation growing in water provide sheltered and nutrient-rich refuges for various animal species of conservation and economic interest: invertebrates having aquatic and terrestrial developmental stages (e.g., Odonates); spawning fish; nesting waterfowl and waders, etc. They provide nurseries to various amphibian and fish species (e.g., eels), and several insect and bird species depend strictly upon these ecosystems during the breeding season (Barbraud et al., 2002; Poulin et al., 2002; Poulin et al., 2009; Tscharntke and Greiler, 1995). In winter, helophytes such as common reed (*Phragmites australis*), cattail (*Typha* sp.) and rush (*Juncus* sp.) provide fibre used for roof thatching, windbreaks, brush, fence, parasol and interior objects that generate income and improve the living standards of local people (Rhazi et al., 2012). Extensive grazing is another common practice in these Mediterranean wetlands, with reed being one of the most appetent plants to cattle owing to its high protein content (Mesléard and Perennou, 1996). Beds of helophytes typically increase the mercantile or aesthetic value of large open-water areas used for bird watching, waterfowl hunting, commercial or sport fishing, and landscape sightseeing. Owing to the bacterial activity around the rhizomes, helophytes also have excellent phyto-purification properties (Chu et al., 2006; Stamati et al., 2010), contributing to increased water quality. All these services will be affected to some extent depending upon the degree of ecosystem degradation (Fig. 5) and the management actions that will be taken to counteract the effects of climate change locally (water inputs, reduced pumping of the water table, restoration of the catchment area, etc.)

4.4. Conservation actions and mitigation measures

Given the discrepancies between the outcomes of RCP 4.5 and RCP 8.5 scenarios, limiting greenhouse gas emissions would obviously help to reduce water deficit and preserve functions of Mediterranean wetlands for the next generations. However, if preventing global warming requires a worldwide cooperation, local interventions to enhance ecosystem resilience to climate change does not (Scheffer et al., 2015). As a start, non-climate stressors on wetland ecosystems could be significantly reduced by refraining land reclamation for urban and agricultural development, as well as massive human alterations affecting wetlands integrity through modification of river flow and water runoff such as construction of dams, roads, dikes, levees and drainage ditches or canals.

At the regional and national levels, we must develop a strategy to ensure the preservation of as many wetlands as possible (Finlayson et al., 2019; Moomaw et al., 2018). A first conservative criterion would be to select wetlands that are the least vulnerable to climate change owing to their geographic location (Fig. 4) and hydrological conditions (Table 2, Appendix A). This would correspond, for instance, to wetlands located in France, Italy and northern Greece (North), Tunisia and Libya (South) and some localities in Turkey, Cyprus and Israel (East), and those which have a larger catchment area and/or shallower aquifer than the threshold values used to run our simulations. Knowing that 64–71% of wetlands have disappeared over the last century worldwide (Davidson, 2014), it should not be considered that wetlands less affected by climate change will automatically persist and maintain their functions and values overtime. A second criterion could be to select wetlands of international importance because they provide a number of critical ecological functions and support a significant percentage of the world's biodiversity, even if active management and restoration actions are required to maintain their integrity. The 230 sites designed by the Ramsar Convention within our study area would correspond to this criterion. By conserving these wetlands we would also ensure the preservation of the spatial coherence and complementarity of stopover sites used by migratory birds.

There is abundant literature predicting the effects of climate change on ecosystems functions and species' ranges (Erwin, 2009; Junk et al., 2013; Moomaw et al., 2018). However, climate change models are rarely incorporated into restoration and conservation plans because they are not developed at the spatial and temporal scales used by territorial planners and environmental managers (Gitay et al., 2011). The software used in this study (mar-o-sel.net) is a user-friendly online tool that can be used freely to simulate how a specific wetland will be affected by climate change and for testing different management scenarios depending upon the amount of water locally available at different times of year. With the integration of future climate data, Mar-O-Sel has become a valuable exploratory tool to understand how wetland hydrology will be impacted by climate change and to what extent these changes can be counteracted by water inputs or restoration of the watershed. We strongly encourage its use by wetland managers and territorial planners who wish to integrate climate change projections into decision making processes to better preserve the biodiversity and ecosystem services provided by Mediterranean seasonally-flooded wetlands over the next decades (Marazzi et al., 2018). At the local scale, wetlands can play a vital role in buffering the effects of climate change on human populations. Adapting management and territorial planning to the wetland resilience thresholds identified in this study should be a priority on the agenda, not only to fulfil environmental goals, but also to sustain Mediterranean rural populations.

5. Conclusion

The seasonal character of many wetlands in the Mediterranean Basin is a consequence of the negative water balance that characterizes the area. Climate projections suggest that water deficit will further increase, affecting the availability of water resources for wetlands and other socio-ecosystems, including agricultural lands. Based on our simulations, only 27% of the 229 Mediterranean localities would still offer the hydrological conditions needed for these wetlands to persist in good conditions by 2100 under current greenhouse gas emissions. In parallel to worldwide cooperation for reducing global warming, we must develop and implement strategies at the regional, national and local levels to mitigate climate impacts on biodiversity and human wellbeing. Climate-related degradation of wetlands will vary according to localities with a clear geographical pattern around the Mediterranean Sea. Practitioners can refer to the interactive web tool used in this study (www.mar-o-sel.net/) to better appraise the water sustainability challenge at local level.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.07.263.

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