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Large-scale mapping of existing and lost wetlands: Earth Observation data and tools to support restoration in the Sebou and Medjerda river basins

A. Guelmami¹

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Abstract

Mediterranean wetlands are the richest and most productive ecosystems in the region, and are essential for climate change adaptation and mitigation. However, despite their importance, they have suffered significant destruction over time. We estimate that half of the natural wetlands have been lost since the 1970s, and the regional trend shows no signs of slowing down. It is therefore urgent to implement concrete solutions that can preserve the remaining wetlands and restore those that have been lost. The increasing availability of free and open Earth Observation (EO) data and tools has provided a basis for mapping these ecosystems and monitoring their status and trends. In this paper, we show how EO-based data and tools can support the pre-identification of candidate sites for wetlands restoration at large scale through the mapping and delineation of existing and lost wetland habitats, their current land use status, and the estimation of the efforts needed to recreate the lost and transformed ones. We used this approach in the Sebou river basin in Morocco and the transboundary Medjerda watershed between Algeria and Tunisia. The resulting products, i.e., Potential Wetland Areas and Potentially Restorable Wetlands maps, enabled the identification of more than 7000 km² and 1700 km² of lost wetland habitats that could be regained in the Sebou and Medjerda basins, respectively. These results hold immense value for water resources management and land planning as they can enhance and assist prioritization efforts for wetland restoration at local, national, and regional scales. They can serve as baseline data to identify candidate sites to implement wetland restoration actions as Nature-based Solutions, regenerate their habitats, and restore the ecosystem services they provide to society.

Keywords Wetland habitats · Earth Observation · Large scale · Restoration · Nature-based Solutions · Sebou · Medjerda

Introduction

The Mediterranean Basin is one of the richest biodiversity hotspots worldwide (Cuttelod et al. 2009; Mittermeier et al. 2011) and wetlands are of paramount importance, although they cover only 2–3% of the Basin area (Perennou et al. 2012). Unfortunately, too long perceived as insalubrious, sources of nuisance for human populations particularly with vector-borne diseases such as malaria and areas to be “developed”, natural Mediterranean wetlands were massively destroyed in the past and it is estimated that nearly

50% of them have disappeared since the 1970s (Mediterranean Wetland Observatory 2018; Perennou et al. 2020). In the Mediterranean Maghreb countries (Algeria, Libya, Morocco, and Tunisia), large floodplain wetlands were drained during the nineteenth and twentieth centuries, e.g., in the Mitidja plains in Algeria (Sergent and Sergent 1947) and the Gharb province in Morocco (Taky 2020). Still, in Morocco, Green et al. (2002) estimate that the area of 24 major wetlands decreased by 25% between 1978 and 1999, while in Tunisia, 46% of the inland wetlands have been lost since 1700 (Fluet-Chouinard et al. 2023) and in Libya the area of the main coastal wetlands dropped by 15% between 1975 and 2005 (Beltrame et al. 2015). However, in good ecological conditions where main functions are maintained, these ecosystems provide multiple services to society, especially in a context of climate change, where they offer a wide range of Nature-based Solutions (Bridgewater 2008; De Groot et al. 2012; Mediterranean Wetland Observatory

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2018; Geijzendorffer et al. 2018). They play, for instance, an irreplaceable role in climate buffering (McInnes 2013; Cohen-Shacham et al. 2016) and protecting goods and people from flood hazards and marine submersions, particularly in coastal areas facing rising sea levels (Schuerch et al. 2018). Investments in the conservation, restoration, and sustainable use of wetlands therefore directly contribute to the countries' objectives in meeting the Paris agreement to combat climate change, adapt to its effects (United Nations 2015), and make progress on the Sustainable Development Goals (Leberger et al. 2020).

The change of perception of these ecosystems as solutions to the challenges of humanity and no longer as problems is already old among conservation scientists (Costanza et al. 1997, 2014; Mitsch and Gosselink 2000) and is also taking place among the general population and political leaders (Maltby and Acreman 2011). Therefore, more tangible actions and results will need to be achieved on the ground, with increased protection of the still existing natural wetlands (Geijzendorffer et al. 2019; Popoff et al. 2021; Verniest et al. 2022) and significant efforts to restore those that have been degraded or lost (Mediterranean Wetland Observatory 2018). However, identifying “ready to restore” wetlands is often the first obstacle encountered by the different actors when it comes to allocating funds for concrete actions on the ground (O'Neill et al. 1997; Klemas 2013). Several conditions must be met before implementing ecological restoration activities (Silva et al. 2023), such as recoverability of lost habitats (e.g., not yet urbanized), ecological and conservation relevance (biodiversity value, ecological corridor role, potential gains in ecosystem services, etc.), favorable land tenure status (public or private), good local governance, political support, availability of scientific and technical expertise, etc. It is thus very often that funding opportunities available for wetlands restoration are not allocated due to the lack of sufficiently well-identified candidate sites (Klemas 2013).

Earth Observation (EO)-based data and tools can play a crucial role in developing relevant approaches to match on-the-ground needs with available funding opportunities. By using EO-based data and tools, biophysical criteria can be built to prioritize wetland sites for restoration, enabling cost-effective selection as well as monitoring the changes before, during, and after the implementation of restoration actions (Klemas 2013). The objective of this work is to show how EO-based data and tools can support the pre-identification of candidate sites for wetlands restoration on a large scale through the mapping and the delineation of existing and lost wetland areas, their current land use status, and the estimation of the needed efforts to regenerate lost and transformed habitats. The study is conducted in the framework of the Mediterranean Wetlands Observatory (MWO). Therefore, a focus will be made on two river basins in North

Africa belonging to the Mediterranean Biodiversity Hotspot (Marchese 2015): the Sebou (in Morocco) and the Medjerda (transboundary between Algeria and Tunisia). These basins were selected as they both hold major stakes for wetlands conservation in the Maghreb in relation to water and land management policies.

Study areas

Two main geographical scales were defined in this work (Fig. 1): the watershed scale with the Sebou and the Medjerda river basins and the national scale with the three countries to which they belong (Algeria, Morocco, and Tunisia). The two selected river basins are vital for the supply of freshwater to key socioeconomic sectors, particularly in Morocco and Tunisia, while hosting wetlands of critical importance for biodiversity in the whole region, including 11 sites of international importance, as well as the only 2 Ramsar cities designated in North Africa to date (Ghar el Melh in Tunisia and Ifrane in Morocco). The first one, Sebou, is in north-west Morocco with an area of about 40,000 km² (6% of the national territory). It is the second most populated basin in the country, and its water resources, with an average supply of 5560 Mm³ per year, are essential to the livelihood and sector-based activities of more than 7.5 million people. It holds 33% of the national water resources (the highest rate) and encompasses 39 important wetlands, including 7 Ramsar sites, 2 national parks, and 17 national sites of biological and ecological interest. The socioeconomic activities within the basin are mainly related to agriculture (Qadem 2015). The Medjerda is a transboundary basin, of which one-third belongs to Algeria (the upper part, where the Medjerda River springs) and the other two-thirds to Tunisia. It occupies an area of 23,250 km² with a total length of 350 km. The availability of freshwater allows for the development of intensive agriculture along its main floodplains. In the Tunisian part, it is even the main socioeconomic sector by far. Besides that, some industries, primarily textile and mining (e.g., marble and iron) are also implemented along the river basin in both the Algerian and Tunisian sides (Hadour et al. 2020). The Medjerda river basin provides drinking water to more than 40% of the Tunisian population (Rajosoa et al. 2021).

In recent decades, socioeconomic activities, particularly agriculture, along with rapid population growth, have significantly impacted the landscapes of both basins, mainly through the drainage and conversion of many natural wetlands and the development of water abstraction infrastructures (Mediterranean Wetland Observatory 2018). As a consequence, more than half of these habitats were destroyed in both basins (Kotti et al. 2018; Guejjoud 2019; Fluet-Chouinard et al. 2023). Climate change exacerbates these pressures, further threatening the biodiversity and ecosystem

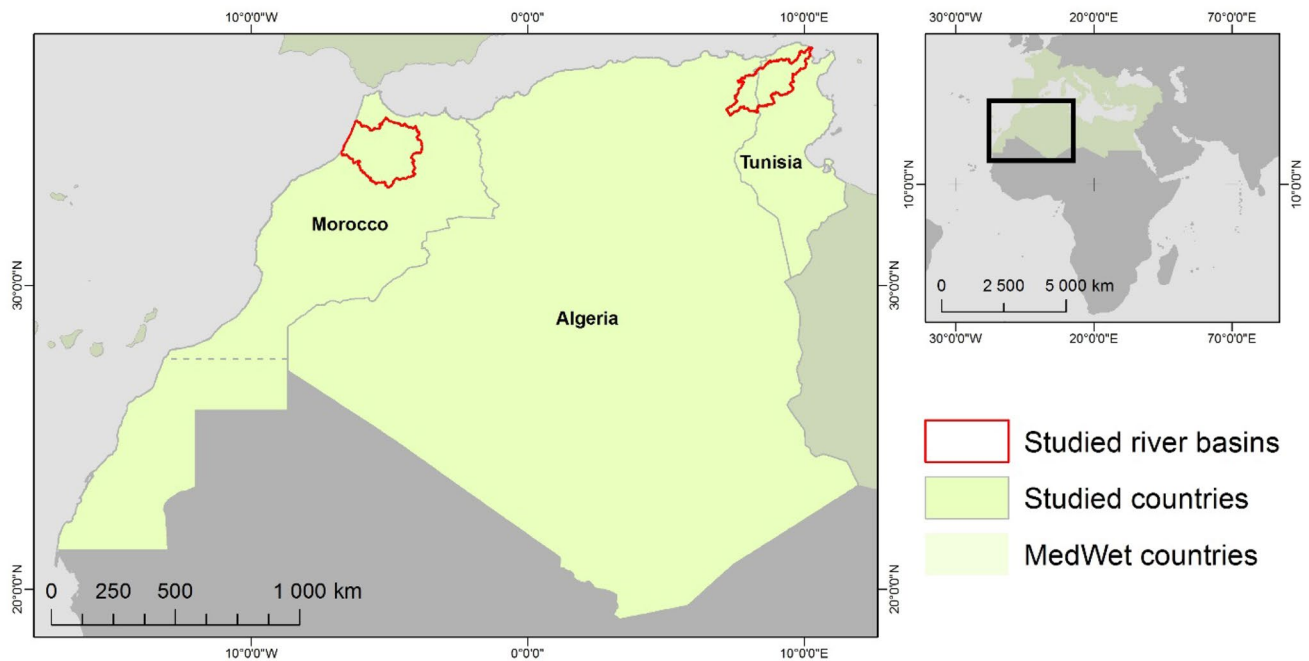


Fig. 1 Location of the study areas: the Sebou (Morocco) and the Medjerda (Algeria/Tunisia) river basins and the three Mediterranean countries to which they belong

services provided by the natural wetlands of the Sebou and Medjerda basins (Dakki et al. 2015; Ouni et al. 2021). However, a lack of comprehensive and reliable data on these ecosystems has hindered conservation efforts. To address this critical situation, the MWO, in collaboration with local and national stakeholders, is seeking innovative and urgent solutions to improve the knowledge needed to recover lost wetlands, while preserving those that remain. In this context, cost-effective EO-based data and tools can play a central role in tracking and delineating lost wetland habitats on large scales and facilitating more effective prioritization of restoration actions at local scales.

Material and methods

The overall approach (Fig. 2) is based on identifying wetlands, as well as areas where restoration of lost habitats is possible, using EO-derived products and following three steps: (i) mapping Potential Wetland Areas (PWA); (ii) characterizing current Land Use/Land Cover (LULC) status; and (iii) mapping Potentially Restorable Wetlands (PRW).

Mapping Potential Wetland Areas

This first mapping step allows the delineation of areas where wetland ecosystems could occur with a high level of probability, using mainly environmental criteria (Weise et al. 2020; Rapinel et al. 2023). The delineation of PWA often

relies on topographic indices or their combination with EO-based data (Beven and Kirkby 1979; Bwangoy et al. 2010; Ågren et al. 2014; Hiestermann and Rivers-Moore 2014; Ludwig et al. 2019; Rapinel et al. 2019). The present assessment is based on the methodology developed by the MWO (Weise et al. 2020). It consists, first, on combining hydrological and topographic variables derived from the open source and globally available Copernicus Digital Elevation Model COP90 DEM (European Space Agency 2021). They include the slope (calculated in degrees), the Topographic Wetness Index (TWI) using the algorithm proposed and tested by Merot et al. (2003) and Sørensen et al. (2006), and a new improved hydro-geomorphological index for identifying Flood Plain areas (FP), which is largely inspired by the Path Distance developed by the European Joint Research Centre (JRC) for the delineation of riparian zones (Clerici et al. 2013). All the DEM-derived metrics were rescaled and represented with similar value distributions ranging from 0 to 99, with the highest value being the most likely to indicate the presence of wetlands (Abou Diwan and Doumit 2012; Weise et al. 2020). Each hydrological and topographic variable was then adjusted using the potential evapotranspiration metric (EVT) derived from the WorldClim 2.1 database (Fick and Hijmans 2017). This step aims to weight them according to the local climatic context depending on whether it is favorable or not to the occurrence of wetlands (e.g., avoid high values of topographic depressions in arid zones). Once the aforementioned hydrological and topographic variables processed, a raster calculator tool was

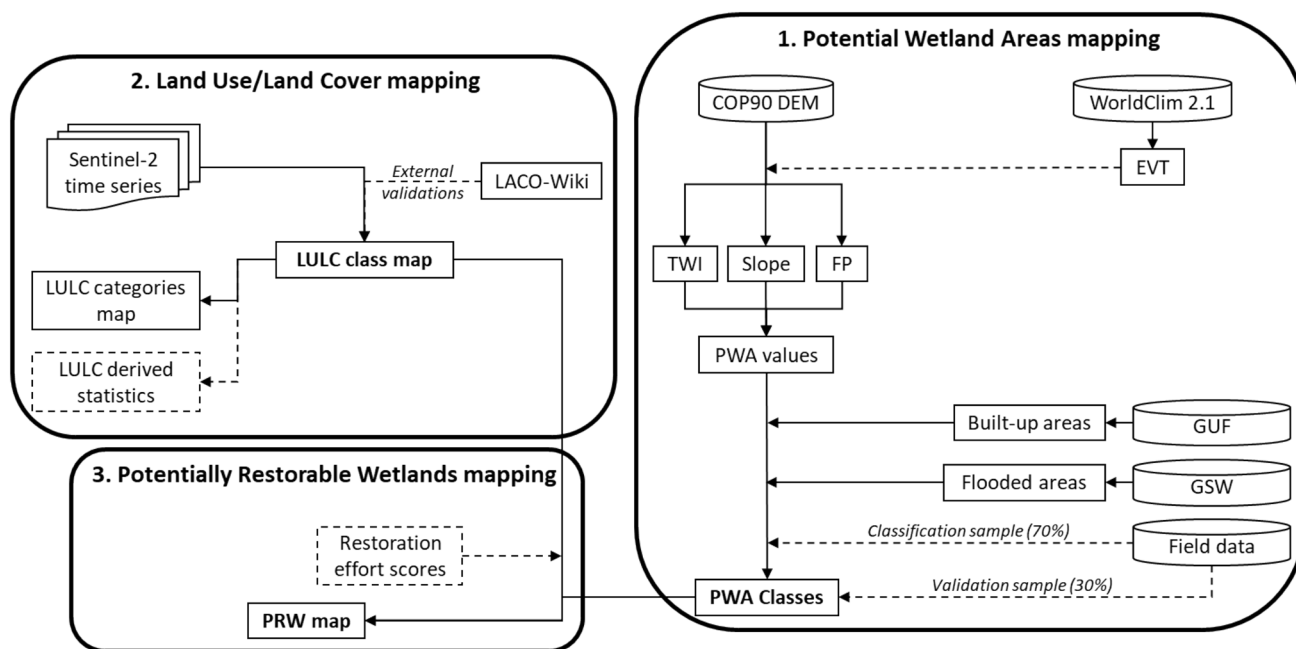


Fig. 2 Flowchart of the overall mapping approach developed in this study

used to combine them by averaging the values. The PWA thus produced would be a large-scale raster data layer with a spatial resolution of 90 m, representing wetland occurrence probability with values ranging from 0 to 99, with the higher ones corresponding to suitable surfaces for their presence within the study areas. However, as the PWA map is based only on hydrological and topographic conditions, it thus encompasses all types of habitat (not just wetlands). Therefore, the higher values should not be considered as a delineation of existing/remaining wetland habitats, but rather as a map of their probability of occurrence, and could be used, for instance, as support for wetland field inventories (Weise et al. 2020; Rapinel et al. 2023). In the case of the current study, the PWA has been used to define and delineate areas where wetland habitats could occur on a large scale and to detect ancient wetlands that have been lost due to their conversion into other land use classes (Abou Diwan and Doumit 2012).

Even if the PWA map was produced by the MWO at the scale of all MedWet countries (27 countries from Morocco to Portugal), only the area covering Algeria, Morocco, and Tunisia was post-processed here. Using a set of field data (approximately 15,000 points), derived from the national wetlands inventory in Tunisia and local datasets in Algeria (El Kala province, Chott Chergui and Chott El Hodna wetlands) and Morocco (two Ramsar sites in the Sebou watershed), the PWA values (probability of occurrence) have been classified and the maps validated. First, 70% of the field data were randomly sampled and used to classify the PWA probability values into four classes—1. Low; 2. Medium; 3.

High; and 4. Very high—according to the following rules: if it includes, respectively, 99%, 95%, 80%, and 65% of the sampled points. Three more classes were added at the end to mask built-up areas (class “0”) using the Global Urban Footprint (GUF) dataset (Esch et al. 2013), and temporarily and permanently flooded areas (i.e., classes “5” and “6”) using surface water maps derived from the Global Surface Water Explorer (GSW) developed by Pekel et al. (2016). The remaining 30% of the field data were used for the validation of the produced map, through spatial cross-referencing with the PWA classes (wetland versus non-wetland) and the calculation of the overall accuracy, as well as errors of commission and omission (Congalton and Green 2009).

Mapping Land Use/Land Cover

Based on Sentinel-2 High Resolution (HR) time series covering the annual hydro-period 2020, detailed LULC maps have been produced for the Sebou and Medjerda river basins. The mapping approach was built upon the Satellite-based Wetlands Observation Service (SWOS) image processing methodology and was performed using the GEOclassifier software (Weise et al. 2020; Guelmami et al. 2023). It includes object- and rule-based classification algorithms and integrates a hybrid LULC nomenclature combining CORINE Land Cover (CLC) classes with the Ramsar wetland habitat definitions (Mediterranean Wetlands Observatory 2014; Guelmami et al. 2023). To facilitate the discussion of the obtained results, all the defined LULC classes were grouped into seven main categories (Perennou et al.

2018): 1. Built-up areas (includes also commercial and transport infrastructures, mines, construction sites, and urban green areas); 2. Agricultural areas (including rice fields and excluding wet pastures); 3. Natural drylands (e.g., forests, shrubland, natural grasslands, etc.); 4. Natural wetlands (based on Ramsar definitions); 5. Semi-natural wetlands (mainly wet pastures); 6. Artificial wetlands (based on Ramsar definitions but excluding rice fields); and 7. Sea (see the Section “LULC status in the Sebou and Medjerda river basins”). Hence, each LULC map captures the status of natural ecosystems, including wetlands, regarding their habitat composition, their spatial extent, and the main agriculture- and urbanization-related pressures they face in the two studied river basins (Beltrame et al. 2015; Guelmami et al. 2023). Finally, an external validation and accuracy assessment of the produced LULC maps was conducted using a standard protocol based on the LACO-Wiki platform (<https://laco-wiki.net/>). It is an established, open, and free online validation package of EO-derived LULC maps that compares the results obtained with very high-resolution images (i.e., Google and Bing), on the basis of a randomly sampled 2500 points covering all the LULC classes identified in both river basins.

Mapping Potentially Restorable Wetlands

Lastly, PRW were mapped at the scale of the two studied river basins. On the basis of expert knowledge, the first step in PRW mapping was to assign scores to each of the identified LULC classes with respect to the effort required for wetland habitats restoration: 1. Unconverted natural wetlands; 2. Low effort; 3. Moderate effort; 4. High effort; and 5. Very high effort. This assignment was made based on the degree of transformation of the hypothetical lost wetland habitat, as well as its reversibility (Horvath et al. 2017). For instance, if the former wetland habitat has been filled or built, the score in terms of the effort required to recover it will be very high. On the contrary, a conversion into an agricultural land would be more easily reversible. However, even in this last case, scores will vary depending on whether key hydrological functions have been preserved (McLaughlin and Cohen 2013). Some cases of wetlands artificialization, i.e., transformation from natural to human-made wetlands (such as the creation of excavations and artificial ponds at the expense of riparian forests or alluvial marshes), will have very low scores, as their re-conversion into wetland habitats, with more or less a natural functioning, would be less costly in terms of efforts and investments.

The second step was to spatially represent this assessment at the scale of the two catchments: (i) crossing LULC with PWA maps would allow for the detection and delineation of potentially lost natural wetlands. If we assume that the four highest PWA probability classes (High probability and

above) contain still existing natural wetlands, but also those that most likely existed in the past, it then suggests that their current LULC classes, excluding natural wetlands, probably result from the conversion of the latter (Horvath et al. 2017). This therefore provides initial spatially explicit information on the potential for wetland habitat recovery in each basin (Gleason et al. 2005, 2007). (ii) Based on the LULC class into which the assumed former natural wetlands have been transformed, PRW maps have been produced using the expert scoring previously described. An additional class was also included in the PRW map (0. Unsuitable), for all areas not prone to the occurrence of wetlands (where the identified PWA class is Medium probability or lower).

Results

Large-scale maps of PWA

The first analysis enabled the production of PWA maps covering the three studied countries; Algeria, Morocco, and Tunisia (Fig. 3). It shows the occurrence probability of wetland habitats, with values ranging from 0 to 99. To facilitate discussion and interpretation of this result, PWA values were grouped into seven classes ranging from 0 to 6 in ascending order of wetland occurrence probability, and defined using the first set of field data derived from national and local wetland inventories: 0. Built-up; 1. Low probability; 2. Medium probability; 3. High probability; 4. Very high probability; 5. Temporarily flooded; and 6. Permanently flooded. All the derived statistics are also represented in Fig. 3.

The second set of field data was used for the validation process (Table 1). It reveals that more than 86% of the wetlands inventoried in the field are well detected by the PWA map (belonging to the class 3. High probability and above), with a large majority of them fitting in the class 4. Very high probability. Only 8% of the inventoried wetlands fall into the class 2. Medium probability and 5.2% seem not to be identified as such in the PWA layer (belong to classes 0. Built-up and 1. Low probability in the PWA maps). According to the results presented in Table 1, we could therefore assume that the approach developed and tested here can identify and delineate potential wetlands at a very broad scale with a quite good confidence level (only 1% of omission error). However, the high rate of commission error (67%) suggests that the PWA map (classes 3. High probability and above) overestimate the total extent of the effective (or remaining) wetland habitats.

According to the resulting PWA map (Fig. 3), more than 10% of the mapped area in the three countries gather hydrological, topographic, and climatic conditions favorable to the occurrence of wetland habitats (all areas falling into classes 3 to 6). This includes both temporarily and

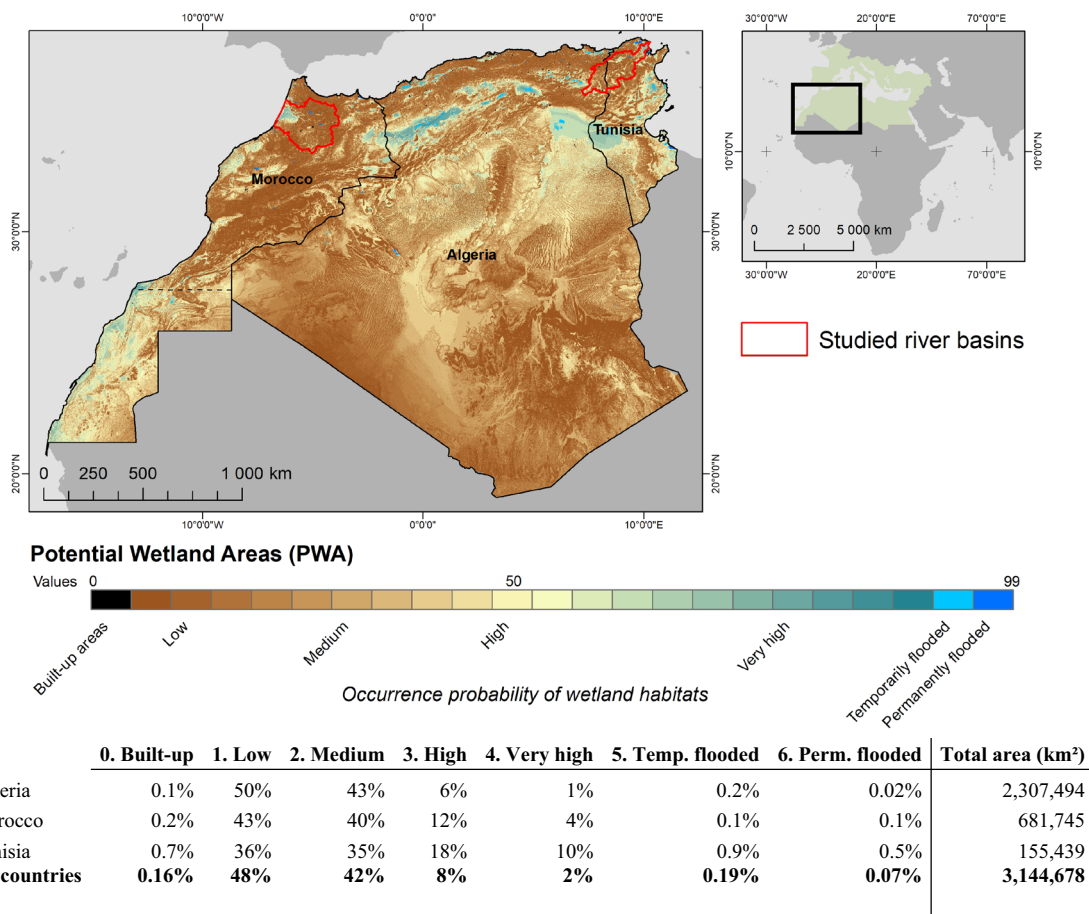


Fig. 3 PWA maps covering Algeria, Morocco, and Tunisia (above) and the main derived statistics (below)

Table 1 Matching existing wetlands (~5000 points randomly sampled from local and national inventories) with PWA probability classes and estimation of the overall accuracy, as well as errors of commission and omission)

	% of points
Class 0, built-up	0.2
Class 1, low probability	5
Class 2, medium probability	8
Class 3, high probability	5
Class 4, very high probability	56
Class 5, temporarily flooded	20
Class 6, permanently flooded	5

PWA map validation statistics: overall accuracy = 84%, omission error = 1%, commission error = 67%

permanently flooded areas that are considered, de facto, as most likely wetland habitats (Perennou et al. 2018). Not surprisingly, many of the well-detected wetland habitats by the PWA map are found in the topographic depression areas where hydrological flows accumulate the most

(Fig. 4). It is the case of most inland lakes, such as the large intermittent/seasonal brackish/salt chotts and sebkhas, where the calculated mean PWA value is 66. Similarly, most of the floodplain and alluvial wetland habitats, such as riparian forests, inland marshes, riverbanks, watercourses, and excavations, are also well defined in the PWA map (mean PWA values 63, 61, 59, 51, and 50, respectively), as well as natural coastal wetlands (mean PWA values 76 for coastal lagoons and estuaries and 73 for coastal marshes). Wet meadows, however, seem to be less well delineated by the PWA map, with a calculated mean value of 45 (medium probability class). Finally, human-made wetlands show contrasting values: very high for saltpans and rice fields (mean PWA values 76 and 72, respectively), but lower for large artificial reservoirs (mean value 48), and even less for small agricultural ponds (mean value 35, which is the lowest of all habitats analyzed here). This could be explained by the spatial resolution of the data used (90 m for the COP90 DEM), which would not allow for good detection of these features.

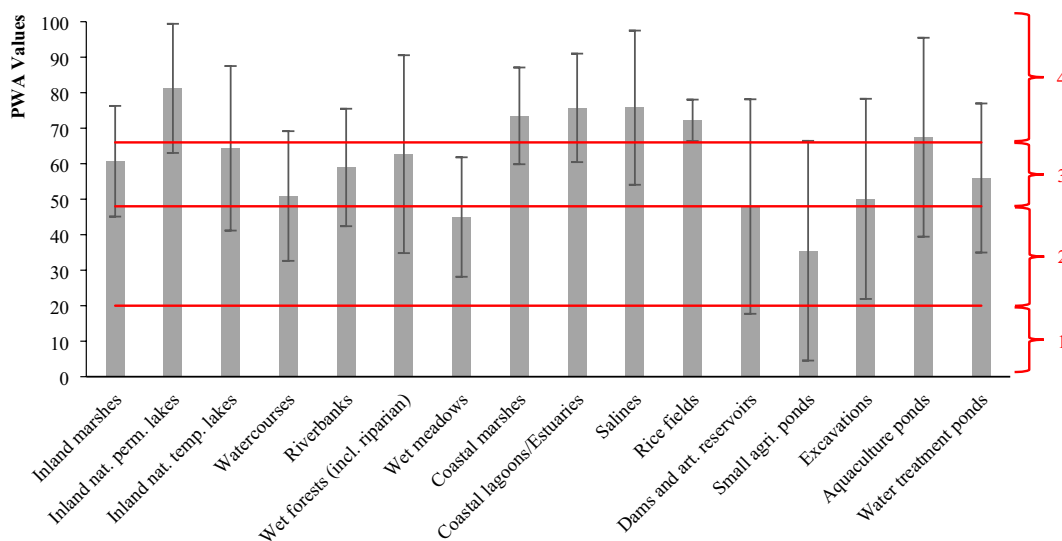


Fig. 4 PWA mean values for the main wetland habitats found in the studied countries (Algeria, Morocco, and Tunisia), with the four PWA probability classes represented in red (1. Low; 2. Medium; 3. High; and 4. Very high)

LULC status in the Sebou and Medjerda river basins

The two resulting LULC category maps are shown in Fig. 5. The validation assessment for both maps, based on a sample of 2500 points, shows overall accuracies of 86.2% (Kappa = 0.85) for the Sebou and 84.5% (Kappa = 0.83) for the Medjerda, which represent very low error rates for results derived from HR satellite images (Congalton and Green 2009).

According to the statistics derived from the LULC maps (Table 2), the landscape in both basins is largely dominated

by agriculture, with more than 60% of the mapped area in the Sebou and 70% in the Medjerda. Most of these agricultural lands are rain-fed crops and extensive pastures, including a small proportion of wet meadows (0.3% of the agricultural lands in the Sebou and 0.6% in the Medjerda). The rest is covered by irrigated crops, with 7% out of the total cultivated areas in the Sebou (including 90 km² of rice paddies) and 5% in the Medjerda. Permanent crops (such as olive groves, vineyards, and fruit trees) figure prominently in both basins, with 9% of the total cultivated lands in the Sebou and 4% in the Medjerda. Natural dryland habitats

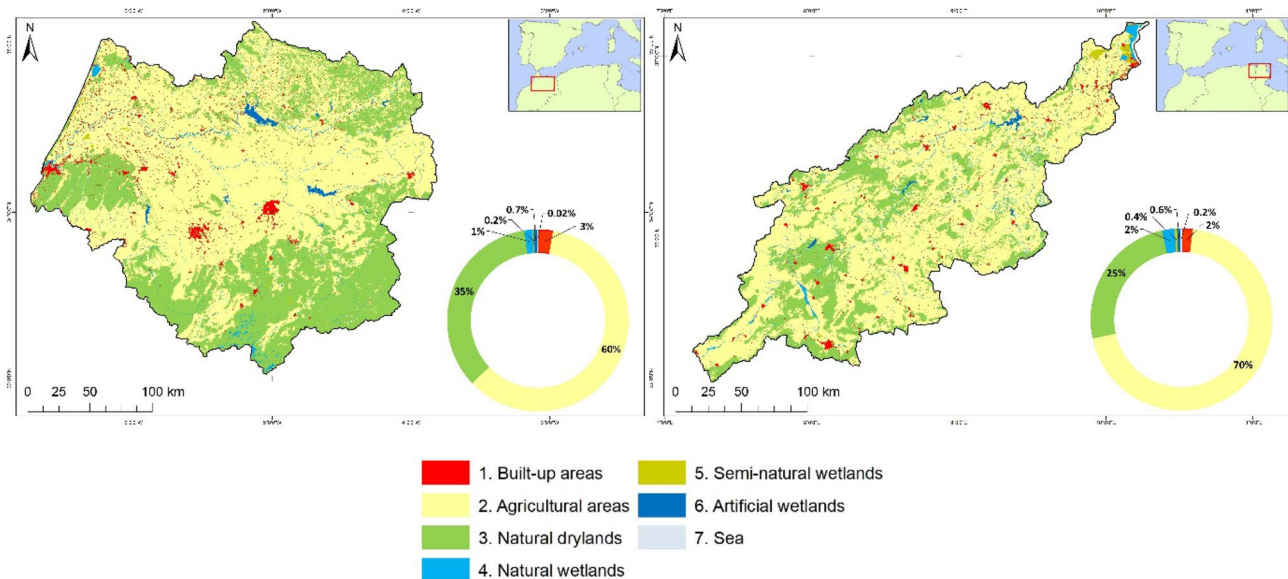


Fig. 5 LULC category maps and statistics derived from Sentinel-2 2020 annual time series for the Sebou (left) and Medjerda (right) river basins

Table 2 Main derived statistics from LULC classification maps 2020 of the Sebou and Medjerda river basins

LULC categories	LULC classes	Sebou (km ²)	Sebou (%)	Medjerda (km ²)	Medjerda (%)
1	Urban fabrics and industrial and commercial units	908	2.3	323	1.4
1	Transport and communication infrastructures	95	0.2	103	0.4
1	Mine, dump, and construction sites	85	0.2	65	0.3
2	Non-irrigated arable lands	19,987	50.6	14,858	63.3
2	Permanently irrigated lands	3709	9.4	1493	6.4
3	Forests	4949	12.5	2903	12.4
3	Shrub and/or herbaceous vegetation association	4694	11.9	2734	11.6
3	Open spaces with little or no vegetation	3985	10.1	195	0.8
3	Beaches, sand, and dunes	41	0.1	3	0.01
4	Inland marshes	132	0.3	59	0.3
4	Inland natural lakes	9	0.02	5	0.02
4	Watercourses	372	0.9	363	1.5
4	Floodplain wetlands (including riparian forests and riverbanks)	82	0.2	27	0.1
5	Wet meadows	72	0.2	103	0.4
4	Coastal marshes	17	0.04	35	0.1
4	Coastal lagoons/estuaries	11	0.03	42	0.2
6	Salines	1	0.003	0.05	0.0002
2	Rice fields	90	0.2	0	0.0
6	Dams and artificial reservoirs	220	0.6	102	0.4
6	Small agricultural ponds	19	0.05	15	0.1
6	Excavations	4	0.01	0.5	0.002
6	Aquaculture ponds	0	0.0	0.2	0.001
6	Water treatment ponds	0.6	0.002	0.05	0.0002
7	Sea/ocean	7	0.02	40	0.2

also occupy a large portion of these territories with, respectively, 35% and 25% of the total mapped areas in the Sebou and Medjerda. They are mainly represented by Mediterranean forests (13% in the Sebou and 12% in the Medjerda), shrubs and herbaceous vegetation (12% in both basins), as well as bare soils and sparsely vegetated lands mostly in the Middle Atlas Mountains of the Upper Sebou (10% of the basin surface). Lastly, the LULC category 1. Built-up areas (including industrial and commercial units, transportation infrastructures and networks, mines, dumps, and construction sites) represent 3% of the mapped area within the Sebou river basin limits (essentially the three main cities of Fez, Meknes, and Kenitra). A little less in the Medjerda, with 2% of the basin's area mainly in the cities of Tebessa and Souk Ahras (Algeria) and El Kef, Beja, and Jendouba (Tunisia). Note the presence of the largest iron-mining complex in Algeria in this basin, near the city of Ouenza (close to the Tunisian border).

The produced LULC maps also show that wetland habitats cover 2% of the Sebou river basin and 3% of the Medjerda (939 km² and 752 km², respectively), which is slightly above the Mediterranean average (~ 1.8% according to

Perennou et al. 2012). Among them, natural wetlands have the highest areas in both watersheds, with 661 km² in the Sebou and 623 km² in the Medjerda (Fig. 6). It thus appears that the proportion of human-made wetlands is higher in the Sebou, which is also the case if we look at the raw surfaces (369 km² versus 129 km² in the Medjerda). This is mainly due to a larger surface area of big artificial lakes in the Sebou (220 km² versus 102 km²), but also to a much higher number of small water storage and agricultural ponds, compared with the Medjerda (more than 1780 in the Sebou, whereas only 292 in the Medjerda).

PRW maps

The PRW mapping approach was tested for both watersheds and is based on the crossing of the PWA layer (clipped at the scale of the two basins) with the LULC maps. According to the obtained results (Fig. 7), we estimate that the Medjerda basin has lost more than 77% of its historical wetlands and this percentage even reaches 93% in the Sebou (baseline areas 2259 km² and 7859 km², respectively). Most of the observed conversions are to agricultural lands, followed

Fig. 6 Wetlands area in both Sebou and Medjerda river basins (in %)

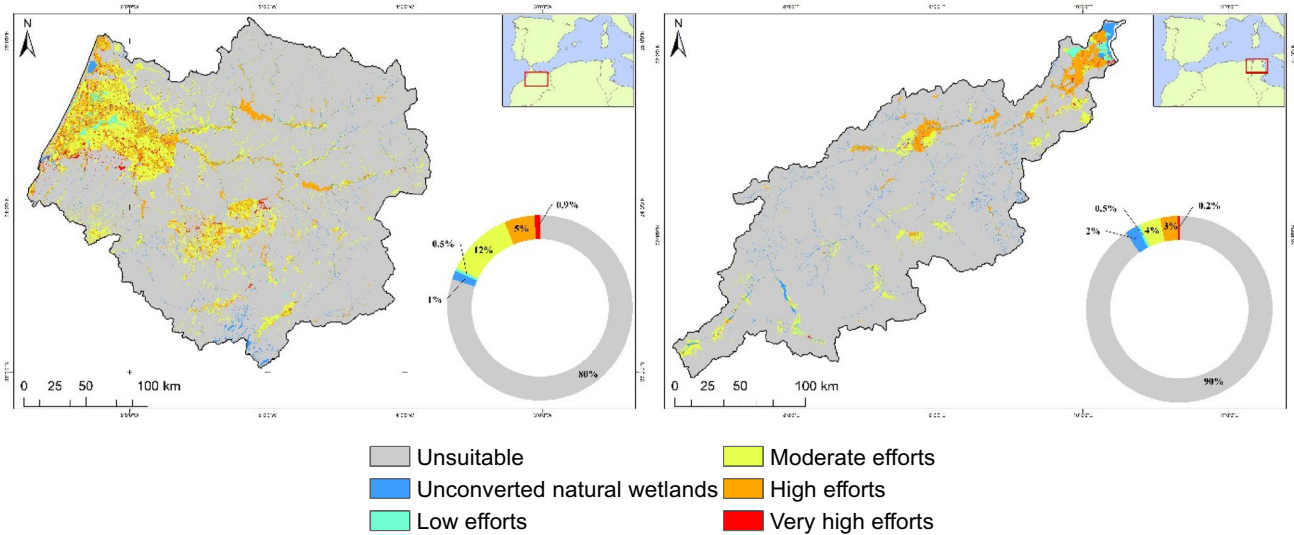
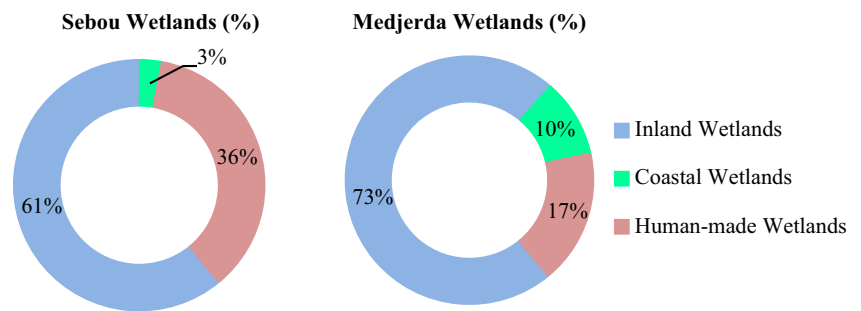


Fig. 7 Potentially Restorable Wetlands (PRW) in the Sebou (left) and Medjerda (right) river basins, with an estimation of the needed regain efforts

Table 3 Conversion rates of lost wetlands in the Sebou and Medjerda river basins (in %)

	Sebou	Medjerda
Into Built-up areas	5%	3%
Into Agricultural lands	89%	85%
Into Semi-natural wetlands	1%	6%
Into Artificial wetlands	5%	5%
Baseline area (km²)	7272	1739

The reference area, estimated using the PWA maps, corresponding to the historical extent of converted natural wetlands (in bold)

by constructed and impervious surfaces, then transformations into artificial wetlands (Table 3). The PRW mapping approach also enables the definition of wetland habitats recovery classes, i.e., areas where lost wetland habitats could be regained, based on the degree of reversibility and an estimation of the required efforts. The derived PRW maps for both basins suggest that the regaining potential of wetland habitats is very important, with 1739 km² in the Medjerda

and 7272 km² in the Sebou, where 56% and 66% of these areas could be restored with low to moderate efforts.

Discussion

EO-based mapping products to track and restore lost wetlands

The unavailability of reliable and comprehensive wetland maps has often been one of the main obstacles to implementing policies for their conservation and sustainable use (Davidson and Finlayson 2018; Ling et al. 2018; Rapinel et al. 2023). Through a combination of topographic, hydrological, and climatic variables, the developed PWA maps have enabled us to better delineate areas that are most likely to host wetland habitats at national scales in Algeria, Morocco, and Tunisia. This new database could considerably improve the knowledge baseline of these ecosystems in the entire Mediterranean Basin, particularly through their use as a supporting georeferenced layer to implement and/

or update local and national wetland inventories (Weise et al. 2020). Furthermore, these data could also be very useful in helping with reporting obligations under international agreements like the Ramsar Convention, the Convention on Biological Diversity, and the Sustainable Development Goals (United Nations 2015; Ramsar 2018; Xu et al. 2021). Lastly, the PWA maps revealed several interesting features, such as areas where probability values are high but do not seem to host wetland habitats. This could also explain why the calculated commission error was very high (67%). Some of these areas are already known, e.g., the Mitidja former swamp in Algeria, north to the city of Boufarik (36°35'37.0"N, 2°54'32.1"E). It appears with the highest probability of being a wetland, although it is now a large agricultural area, mainly dedicated to the production of citrus. It was indeed a large swamp before being drained during the French colonial period between the nineteenth and twentieth centuries (Sergent and Sergent 1947). Likewise, the former marshes of the Loukkos floodplain (35°08'59.8"N, 6°04'02.6"W) were one of the largest wetlands complexes in northern Morocco and were highly impacted by major investments in the 1970s and 1980s, enabling the drainage of wetlands and the development of irrigated agriculture in this region (Vercueil 1982). In addition to these "famous" cases, many other relevant examples of lesser-known lost wetlands could also be found in these countries through a fine and meticulous analysis of the PWA map. This could, for instance, provide a better basis for efforts to rehabilitate some of the lost and converted wetlands (Horvath et al. 2017).

The combination of PWA and LULC layers and the derived PRW maps have allowed for a better definition of the types of transformation that lost wetlands have faced in the Sebou and Medjerda river basins. Most of these conversions were caused by agricultural development, particularly on floodplains, which were drained and then massively turned into irrigated crops (Debbarh et al. 1991, 1998; Cherif 1995, 1998). In the Sebou, for instance, many of the transformations of ancient wetlands have occurred within the Gharb floodplain, in the downstream part of the basin (34°29'32.7"N, 6°06'23.3"W). They were intensively dried out in the beginning of the twentieth century, mainly for the development of irrigated crops (e.g., sugar beet and rice fields), as these vast alluvial swamps offered the perfect topographic, climatic, hydrological, and pedological conditions for this type of agriculture (Debbarh et al. 1991; Office Régional de Mise en Valeur du Gharb 1997; Taky 2008). Consequently, less than 250 km² of natural and semi-natural wetland habitats remain in the Gharb floodplain (out of more than 3500 km² estimated historically), mainly rivers, wet pastures, a few thin strips of untouched riparian forests, and some remnant freshwater marshes and swamps, such as the Merja of Fouwarate near the city of Kenitra (designated as Ramsar site since 2018). Similarly, the Medjerda

has also faced a huge decline of its alluvial wetlands over time. Particularly in the region of the Utique floodplain (37°05'03.9"N, 10°05'30.0"E), where the reclamation of marshy areas for flood and disease control purposes, but above all for the development of intensive agriculture early in the last century, has deeply modified the landscape of this coastal floodplain (Cherif 1998; Samaali 2011). This has also led to a eutrophication of downstream water bodies (e.g., the coastal lagoon of Ghar El Melh) due to the excessive use of fertilizers (Moussa et al. 2005).

In addition, many of the observed losses have most likely led to a significant reduction of the ecosystem services provided by these habitats, including sediment and nutrient retention, water purification, flood abatement, carbon storage, and wildlife habitat (Horvath et al. 2017). Therefore, to help revive these services and address societal challenges related to the effects of climate change (Geijzendorffer et al. 2018), the PRW maps highlight large areas in both basins where low to moderate efforts could be made to recreate some of the lost wetlands as Nature-based Solutions (Thorslund et al. 2017). For example, our results showed that most of the alluvial wetlands along the Medjerda river have been completely destroyed. Nevertheless, it is known that flood risk prevention, especially in the middle and lower parts of the basin, is a major concern for water resource management authorities (Abidi et al. 2019). Thus, combined with socioeconomic criteria, the use of the PRW map could significantly help them prioritize areas where actions, such as replanting riparian forests as a main natural barrier against flooding, could be undertaken. The mapping products developed here can also help improve ecological corridors for biodiversity. In the Sebou catchment, for instance, among the many lost wetland habitats detected are some former temporary ponds. This typical Mediterranean wetland ecosystem represents a major conservation issue in Morocco, especially due to the richness of the plant communities it hosts (El Madihi et al. 2017). However, it is also highly threatened by the overexploitation of water resources for agricultural uses (Barchiesi et al. 2022), as well as the impacts of climate change (Grillas et al. 2021). Through the identification of disappeared temporary ponds, the PRW map could therefore better inform on potential sites for the restoration of this habitat.

Limitations and recommendations

The first identified technical limitation of the produced PWA layer, and thus the derived PRW maps, is the spatial resolution of some of the used input data (namely the COP90 DEM and WorldClim 2.1 database). The choice was to integrate these datasets at moderate spatial resolutions (90 m for the final product) to facilitate the analysis at a very large scale (pan-Mediterranean), also considering the limited

computing capacities available at the MWO. However, with the future improvement of these capacities, including through the integration of Artificial Intelligence (AI)-based algorithms, an enhanced version of this PWA layer will be developed by the MWO, integrating finer and more accurate data. This is already the case for similar mapping initiatives at smaller geographical scales, such as the work done for the national wetlands mapping in France (Rapinel et al. 2023). The other possible area of improvement for the PWA layer would be to include, during the processing phase, data on soil characteristics. This could help to overcome some of the limitations in identifying potential wetlands (i.e., commission errors with an overestimation of wetland areas) by adding new variables on the water-holding capacities of soils (McCauley and Jenkins 2005; Rapinel et al. 2023). Finally, the development of PRW layers needs to have recent, accurate, and reliable LULC data available. Through the local wetland monitoring programs set up by the MWO, this has been possible for the two important coastal basins. However, this kind of data, with high levels of thematic and spatial accuracy, is unfortunately not yet comprehensively available at the pan-Mediterranean scale. While waiting for the development of this type of product, other sources of global or regional LULC data could be used to produce large-scale PRW maps, such as CORINE Land Cover layers (Trombetti et al. 2022). Nevertheless, this would introduce a bias in the resulting PRW products, as these LULC maps do not allow for the identification and delineation of the remaining wetland habitats with a high level of confidence (Perennou et al. 2012, 2018).

These EO-based mapping approaches provide relevant and valuable information on existing and past wetlands on a very large scale, particularly for the development of regional or national restoration strategies. However, these tools are far from sufficient when it comes to “taking action”, i.e., to bring funding to sites where restoration activities could be implemented. Further steps are therefore necessary to complement these mapping tools, such as incorporating supplementary data layers to refine spatial priorities, considering factors like biodiversity importance (e.g., Key Biodiversity Areas), ecological connections (e.g., Protected Areas), climate change mitigation, and land ownership (public or private). Furthermore, these spatial priorities should also reflect the guidelines and roadmaps provided in national strategies related to wetlands, biodiversity, and climate change adaptation and mitigation, as well as the benefits for society in terms of potential future ecosystem services provided by the regained wetlands. Finally, to ensure a better efficiency in the prioritizing of wetlands to be restored, it would also be relevant to complement the information provided by the PWA and PRW maps on lost wetlands with data on the conservation status of existing ones to identify those that are severely degraded but not yet destroyed (Verniest et al. 2022).

Conclusion

This study demonstrates the feasibility of combining various EO-based data and tools to produce large-scale, cost-effective, and reliable spatial data for prioritizing wetlands restoration areas. Our findings indicate that: (i) the PWA map can identify and delineate most existing and lost Mediterranean wetlands, with an estimation of their probability of occurrence based on hydrological, topographic, and climatic factors; (ii) using recent Sentinel-2 HR time series, detailed LULC maps have been produced enabling the characterization of the remaining wetland habitats; (iii) the combination of information on existing and lost wetland habitats has allowed us to produce the PRW map, which comprehensively identifies areas suitable for wetlands re-creation. Implementing this approach to the Sebou river basin in Morocco and the transboundary Medjerda catchment between Algeria and Tunisia reveals considerable potential for wetland restoration in both basins. The resulting maps identified more than 7272 km² and 1739 km² of lost habitats that could be restored in the Sebou and Medjerda catchments, respectively. Moreover, about 66% (Sebou) and 56% (Medjerda) of these areas could be regained with low to moderate efforts. However, the developed PWA and PRW maps have two main limitations: (i) technical, due to the moderate spatial resolution of some input datasets and lack of soil characteristics data, and (ii) the prioritization of wetlands to be restored, based only on the identification of the lost wetland habitats that could be re-created, might be improved by adding other relevant information such as data on the conservation status of the remaining wetlands. Moreover, integrating information on the relevance of wetlands restoration to biodiversity conservation, climate change mitigation, ecological continuity, and socioeconomic co-benefits can also significantly enhance the overall approach. Meanwhile, the results of this work are already being used in ongoing wetland conservation and protection initiatives. In the Sebou, for instance, the produced PWA and PRW maps are fully included in the freshwater ecosystem monitoring program implemented as part of the Sebou Water Fund and provide valuable information for deriving spatially explicit indicators to help prioritize areas where wetlands could be restored.

Maps and boundaries

All boundaries, names, and designations used on the maps in this article are those recognized by the United Nations and do not imply official endorsement or acceptance by the author or the affiliated organization.

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Declarations

Conflict of interest The author declares no conflict of interests.

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