Exploring the heterogeneity and conservation status of mires and other wetlands in North Macedonia (SE Europe): Insights from mapping efforts

Marija Chobanova[1], Daniela Jovanovska[1],
Franziska Tanneberger[2], Alexandra Barthelmes[2], Slavcho Hristovski[1]

[1] Institute of Biology, Ss. Cyril and Methodius University, North Macedonia
[2] Institute of Botany and Landscape Ecology, Greifswald University, partner in the Greifswald Mire Centre, Germany

SUMMARY

Inconsistent definitions and different approaches towards wetland typology indicating absence or under-representation of wetland area from available data, underscore the need for improved mapping efforts in areas with significant knowledge gaps. In response, this study adopts a broader ecological definition which provides a comprehensive map of the wetland area in North Macedonia, with additional estimates of the mire area. The results show that naturally occurring wetlands occupy 1.5 % of North Macedonia (380.55 km²), including riparian forests (184.03 km²) and other wetland areas (196.52 km²). Only 22 % (84 km²) of the total wetland area is under official protection or proposed for protection. High-altitude mires have been mapped for the first time. There remains a need to explore alternative methodologies for delineating peatlands in the lowlands, particularly those that have been historically converted to agricultural use. Integrating hydrogeological insights with recent surface wetness data has alleviated mapping limitations and revealed four key regions with potential to host wetlands and peatlands, primarily in lowlands. These results can guide future research focused on gathering ground truth data to improve estimates of the extent of lowland peatlands to support future restoration targets. The enhanced delineation and resolution of the area of mires and other wetlands addresses the spatial discrepancies that are particularly evident in larger European datasets. Such improvements provide updated information for diverse research and management purposes. The geospatial data provide a basis for in-depth exploration of remote sensing approaches and classifications that could enable the improvement of mire or wetland maps extending beyond national borders in Southeast Europe.

KEY WORDS: Balkan Peninsula, fens, map, mountains, peatlands

INTRODUCTION

In efforts to map wetland areas, special attention should be paid to their definition and categorisation because this can significantly influence the extent recorded. Numerous definitions of wetlands exist, with ecological viewpoints often framing wetlands as transitional between the wettest and driest ecosystem types. We adopt the definition provided by Joosten *et al.* (2017), which describes wetlands as "areas inundated or saturated by water to the extent that their vegetation is dominated by plants adapted to life in anoxic soil conditions." Mires are wetlands characterised by peat-forming vegetation and all mires are inherently peatlands; however, not all wetlands qualify as mires, as many do not support suitable conditions for peat accumulation. Peatlands are defined by a naturally accumulated layer of peat, regardless of the presence or absence of vegetation. Peatlands may be wetlands but are not necessarily so, i.e., they may include former mires where peat formation has ceased due to drainage, land conversion or other factors (Joosten & Clarke 2002, Joosten *et al.* 2017, Tanneberger *et al.* 2017, Tanneberger *et al.* 2021).

Mires and other wetlands deliver a large array of important ecosystem services including carbon sequestration, water retention and purification, formation of Histosols (peat soils) and habitat for specialised flora and fauna, genetic and ecosystem diversity, etc. (Okruszko *et al.* 2011, Lamers *et al.* 2015). In addition, their role with regard to climate mitigation is increasingly appreciated (Erwin 2009, Were *et al.* 2019, UNEP 2022). Yet wetlands are amongst the most vulnerable ecosystems globally (IPBES 2019). Although their high conservation importance is globally recognised, their surface area continues to decrease (Fluet-Chouinard *et al.* 2023). Some 85 % of the wetland area has been lost in the last 300 years, and 54 % of the original area since 1990 (IPBES 2019). On the other hand, the importance of peatlands, especially in terms of carbon storage, is outstanding in relation to their global extent (UNEP 2022).

The total peatland area in Europe is estimated to be almost 5.4 % of the total land area (Tanneberger *et al.* 2017), and this is the continent with the largest proportional loss of mires (Tanneberger *et al.* 2021). However, knowledge about the extent of wetlands and peatlands is unevenly distributed, with particularly pronounced knowledge gaps in Southeast Europe where such ecosystems are relatively scarce. In the southern European marsh region (Region IX; 2 % of Europe's wetlands), most wetlands are found in river deltas, floodplains, coastal lagoons and freshwater lakes around the Mediterranean and the Black Sea, while the central and southern European mountain compound region (Region X; < 1% of Europe's wetlands) is characterised by the vertical distribution of mire types including flat fens, percolation fens, sloping fens and bogs (Joosten *et al.* 2017, Tanneberger *et al.* 2021).

Positioned amidst the predominant (dry) forests and pastures, wetlands in North Macedonia hold a distinctive status owing to their valuable provisioning of diverse ecosystem services as wet 'oases' in generally drier landscapes. Even so, they have received insufficient attention from researchers and decision makers. Only three North Macedonian wetlands are designated as Ramsar sites, namely: Prespa Lake, Ohrid Lake and Dojran Lake (WWT Consulting 2017, MoEPP 2018). While the recent increase in protected areas in North Macedonia has improved the conservation status of the country's nature, wetlands and peatlands remain on the margins of the agenda for conservation, management and monitoring. The lack of a national wetland inventory not only hinders conservation efforts but also has implications for cross-border ecological connectivity and climate resilience. According to the National Strategy and Action Plan for Biodiversity (MoEPP 2018), wetlands in North Macedonia are regarded as threatened habitats. However, lack of knowledge results in low awareness of wetlands among policy makers, decision makers and practitioners. As an example, to date there have been no measurements of greenhouse gas (GHG; CO_2, CH_4, N_2O) emissions from wetlands or peatlands, while only Cukaliev *et al.* (2008) have reported analyses of GHG emissions from rice fields and agricultural land on Histosols. Moreover, there are no national GHG emission factors for CO_2, CH_4 and N_2O and the national inventory uses Intergovernmental Panel on Climate Change (IPCC) default values, as do most countries in this region (Lokupitiya & Paustian 2006). Although smaller in size than farther north in Europe, peatlands in southern Europe can play a significant role in regional inventories (Danevčič *et al.* 2010). Datasets such as the databases of the European Environmental Agency (https://www.eea.europa.eu/en/datahub/) and the Mediterranean Wetlands Observatory (https://medwet.org/observatory/), the Global Peatland Database (https://maps.work/gpd/), etc., provide wetland and peatland related spatial data for North Macedonia in which we perceive notable gaps. There have been additional national-scale efforts to map the main lowland wetlands in the country (Markoski 2019, Markoski *et al.* 2022), but there is a significant knowledge gap for the highlands. Most recently, the spatial information on wetlands in North Macedonia was improved as part an ecosystem mapping effort to underpin an assessment of ecosystem service supply capacity (Chobanova *et al.* 2024), then again later as part of the national habitat map initiative (MES 2022, Maneko Solutions 2023). Nevertheless, clarity is lacking regarding heterogeneity, threats or conservation status; and their precise spatial extent remains inadequately assessed, leading to their oversight by both practitioners and policymakers.

The aim of this study is to provide a comprehensive and detailed assessment of the spatial extent, distribution and characteristics of mire and other wetland areas in North Macedonia. A key objective was to estimate the area of mires within the country, while another significant focus was on identifying regions with high wetland and peatland potential. Finally, the study sought to evaluate the conservation status of mire and other wetland areas, as a foundation for future conservation and restoration initiatives.

METHODS

Study area

North Macedonia is a landlocked mountainous country situated in the central part of the Balkan Peninsula, with an approximate surface area of 25,436 km^2. The complex geology and intricate configuration (Milevski 2015), comprising numerous geological formations, has led to development of a wide array of soil types (Petrušev *et al.* 2021). According to the world reference base for soil resources classification, the country has 64 soil types which are divided into four main groups according to the relief (Filipovski 2016). Geographically, the country's terrain predominantly lies between 500 and 1000 m above sea level (a.s.l.). The western part is dominated by the Shar-Pindus Mountain Range, which has a total of 141 peaks exceeding 2000 m a.s.l. The central lowland region mainly comprises the Vardar River Valley (elevation range 80–300 m a.s.l.), the Pelagonia Plain (650 m a.s.l.) and the Ovche Pole Plain (350 m a.s.l.). The eastern mountains feature only three peaks whose altitudes exceed 2000 m a.s.l. (Melovski *et al.* 2013). North Macedonia has an average annual air temperature of 11.1 °C, with July typically the warmest month at 20.3 °C and January the coldest at 0.3 °C (Stojmilov 2003). The average annual precipitation is 742 mm (Lazarevski 1993) but precipitation patterns vary across the country (Figure 1). The surface waters are predominantly dendritic stream networks draining into the Aegean, Adriatic and Black Sea basins (Radevski *et al.* 2020). A total of 41 distinct landscape types have been recognised and organised into eight hierarchical landscape groups based on topography, climatic conditions, geological composition, soil characteristics and vegetation along an elevation gradient (Melovski *et al.* 2019). Despite encompassing only ~0.25 % of the European territory, North Macedonia boasts remarkably high biodiversity owing to the intricate interplay of geology, climate and relief (Melovski *et al.* 2013). Based on regional climates, soil distribution and vegetation patterns, the country presents a mosaic of eight distinct climate-vegetation-soil zones, as delineated by Filipovski *et al.* (1996).

Mapping methods

Accurate remote sensing of mires and other wetlands in the Balkans is particularly challenging owing to the combination of small patch size, scattered distribution, complex vegetation, cloud-cover and terrain effects, as well as insufficient localised training data. To address this challenge, the mapping approach applied here involves on-screen visual interpretation and digitisation combined with field-based validation to build robust region-specific models (Figure 2). The resulting wetland map is a composite created through synthesis of selected habitat types extracted from the national habitat map (Maneko Solutions 2023) and improved in terms of delineation, with the addition of new polygons.

The polygons in the composite wetland map are restricted to naturally occurring wetlands relating to habitat types included within groups C and D of the European Nature Information System (EUNIS; https://eunis.eea.europa.eu/) habitat classification. This provides alignment with the spatial information presented in the national habitat map. Vector data for habitat types belonging to group F (Heathland, scrub and tundra; F9.1, F9.3) and group G (Woodland, forest and other wooded land; G1.1, G1.2, G1.3) were directly extracted from the national habitat map

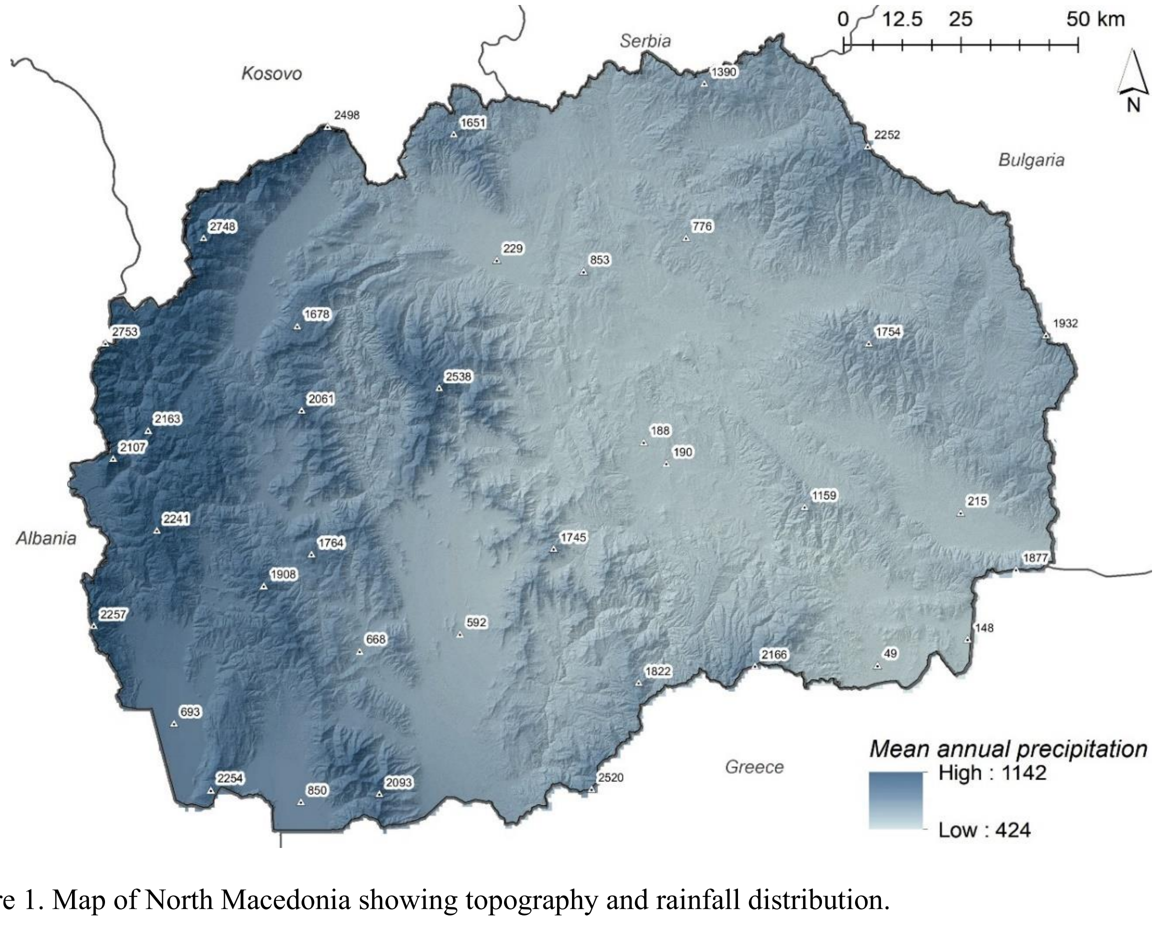

Figure 1. Map of North Macedonia showing topography and rainfall distribution.

and integrated into the composite map. Open water was omitted, but spatial information on habitat types within group C was included to encompass spring mires and vegetation associated with ponds and pools. Specifically, the composite wetland map includes the group C (Inland surface waters) habitat types C1.3 (partly), C1.4, C1.6, C2.1, C3.1, C3.2 (C3.21, C3.23) and C3.32; and the group D (Mires, bogs and fens) types D2.2, D2.3, D4.1, D5.1 (D5.11, D5.12, D5.13), D5.2, D5.3, D6.1, D6.2.

Improvement of existing polygons and additional mapping were conducted by visual interpretation and manual digitisation of topographic maps (Agency for Real Estate Cadastre 2002, Military Geographic Institute of the Yugoslav National Army 1970), ortho-photo imagery with 0.3 × 0.3 m resolution (Agency for Real Estate Cadastre 2017), combined with Google Earth Pro satellite imagery (2016 to 2022 sensing date, eye altitude 2.0–3.0 m, standard satellite imagery resolution ~ 50 cm to 1 m per pixel).

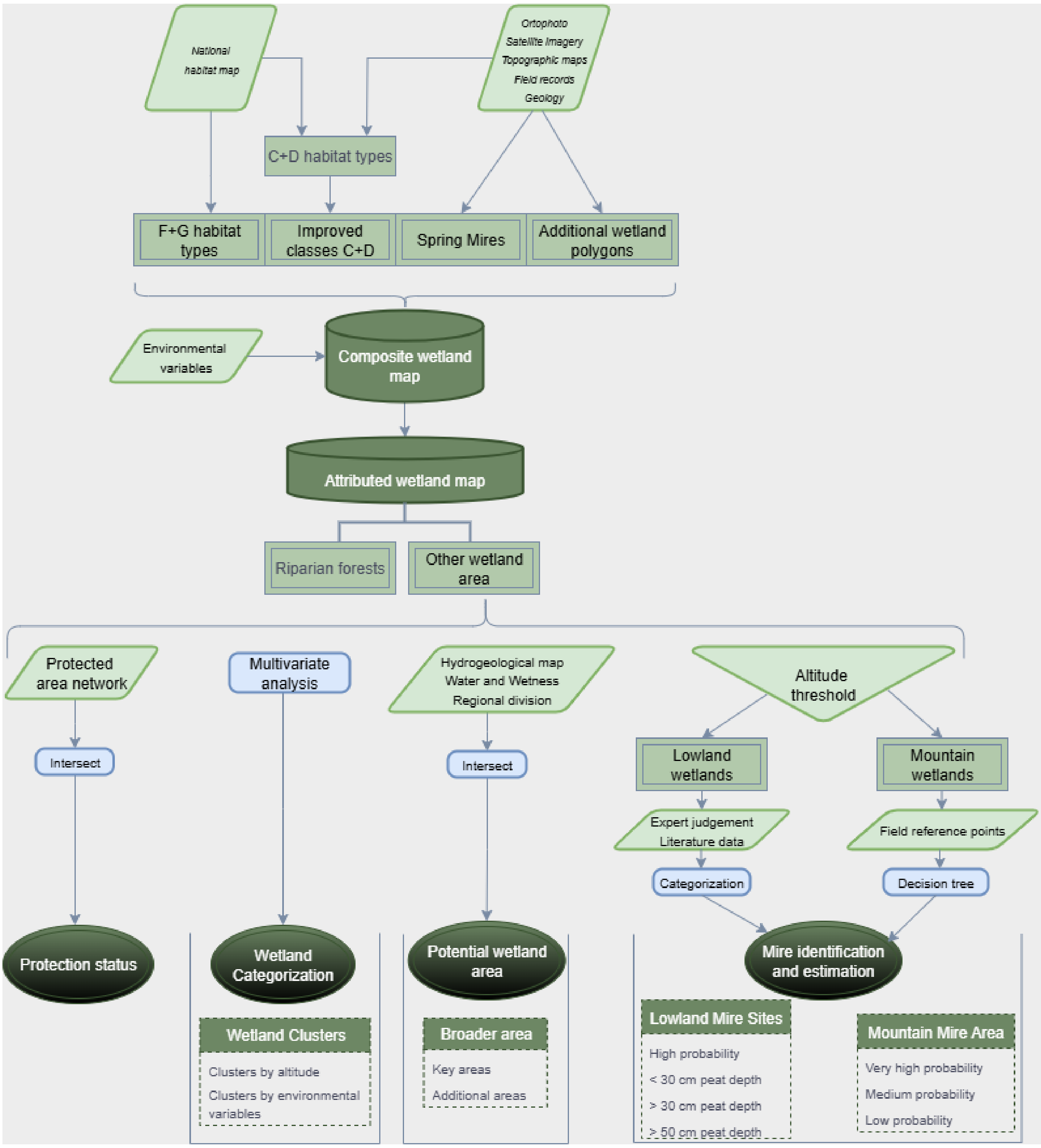

Figure 2. Methodological flowchart.

Habitat identification was carried out without specifically dedicated fieldwork, relying instead on the evaluation of both published sources (mainly project reports) and unpublished data. Habitat type assignments were made by extrapolating information from nearby polygons and applying expert judgment.

The composite map was further enhanced with spatial information for previously omitted wetlands. For some wetlands, especially peatlands not detectable on satellite imagery e.g. because they are located in forests, but also high-altitude wetlands, point presence data based on personal field records were used (~ 200 records). This body of field data provided site-specific confirmation of wetland features including the presence of springs, spring mires, peat layers, habitat types and other relevant ecological indicators. These verified field points were integrated into the mapping workflow and used to support aspects of the digitisation process in several ways including: navigating and interpreting during manual digitisation; validating or refining the classification of wetland types; and guiding delineation decisions. In this way, the field observations served not only as ground-truthing reference points but also contributed to improving the ecological accuracy and spatial precision of the resulting composite map. Further assessment in the wetland map was done for the springs (C2.1 Springs, spring brooks and geysers) which were mapped as point data from a 1:25000 topographic map (Agency for Real Estate Cadastre 2002). With regard to spring mire ecology (e.g. Spitale *et al*. 2012, Peterka *et al.* 2023), springs above 1600 m were intersected with three predefined categories (carbonates, silicate or mixed) of the geology map (Melovski *et al.* 2019) to provide spatial references to potential spring mire habitat types in the wetland map.

The final map is presented as a vector file in the Macedonian national geographic projection, which utilises Gauss-Kruger coordinates, zone 7 (MGI 1901 / Balkans zone 7) without the application of threshold-based filtering or generalisation. All mapped features are included in their original forms without additional post-processing, ensuring that the dataset reflects the raw spatial information as delineated during mapping. The full dataset will be referred to here by the general name ‘wetland map’, while polygons assigned to groups C and D will be termed ‘Other wetland area’ and those assigned to groups F and G will be termed ‘Riparian forests’.

Analysis methods

The characteristics of the mapped wetlands were assessed according to a set of criteria relating to the most important aspects of wetlands. Nine criteria were selected for which raw data were collected and processed (Table 1). These variables were used for a multivariate analysis. The raw data originated mainly from national datasets which were intersected with the wetland polygons. Zonal statistics (Zonal Statistics Tool in ArcGIS 10.6) were calculated and attribute values were assigned based on the calculation of *majority* value. We treated riparian forests as a distinct homogenous wetland category which was not subsequently subdivided. A non-hierarchical multivariate clustering method (K-means) was employed to systematically categorise the Other wetland area. This was done with a predefined number of clusters by calculating optimised pseudo F-statistics. Character data were transformed into numerical values for the clustering process, which also included grouping of variables based on their similarity. The latter was done for vegetation types, soils and geology (Tables A1–A3 in the Appendix).

Considering all nine criteria, the multivariate analysis highlighted altitude as the most statistically significant variable and provided an initial classification of Other wetland area into lowland and mountain wetland areas. The threshold altitude of 1200 m a.s.l. was used to distinguish between lowland and mountain wetlands. This figure was calculated on the basis of the multivariate analysis and consideration of ground truth data. The generated wetland map which included these two categories was then used to conduct mire identification. This was done using two different approaches. Lowland mires were identified on the basis of previous field observations and the published data of Filipovski (1999). Four different categories of peat depth were presented as point data. High altitude mires were identified by considering the slope, hydrology and vegetation type values for all polygons belonging to the mountain wetland area, by analysing these variables with the *Tree* function in R (R Core Team 2021) (Figure 3). The conditions for the variables were constructed based on previous field observations/expert judgement. The model was tested by analysis of the same variables for 23 polygons representing high-altitude mires with peat layer confirmed by ground truth data. Other variables were not considered due to their low resolution in relation to the polygon sizes. In this way, the high-altitude mire area was classified into three different categories which represented the confidence levels.

The wetland area was also analysed in terms of its conservation status by intersecting the wetland map with nationally designated protected areas or areas with initiatives for protection or former protection but without current legal status. Additionally, the internationally important Ramsar sites were considered.

Table 1. Selected criteria for assessment of wetland characteristics in North Macedonia, their variables and source data. The wetland polygons were further attributed with information regarding relief (Melovski *et al.* 2013), landscape type (Melovski *et al.* 2019) and conservation status (Melovski *et al.* 2011).

Criterion	Variables	Source	Scale/resolution
Vegetation type	1–17	National habitat map EUNIS Level 3 (Maneko Solutions 2023)	50 m × 50 m
Altitude	Range 42–2572 m	Digital Elevation Model (DEM)	30 m × 30 m
Slope	1. Near level (0–3 degrees) 2. Gentle slope (3–5 degrees) 3. Moderate slope (5-8.5 degrees) 4. Moderately steep (8.5–24 degrees) 5. Steep (25–45 degrees) 6. Very steep (45–78 degrees)	Classification by Balabathina (2019); GIS	DEM (30 m × 30 m)
Precipitation	Range 444–1100 mm	Milevski *et al.* 2015	100 m × 100 m
Temperature	Range 1–14 °C	Milevski *et al.* 2015	100 m × 100 m
Geology	1–19	National geology map modified by Melovski *et al.* (2019)	1:100,000
Soils	1–23	MASIS 2015	1:50,000
Hydrology	0. No intersect 1. Intersects Intermittent stream 2. Intersects River 3. Intersects Spring 4. Intersect Springs and Streams	National hydrological network (National Agency for Real Estate Cadastre 2002)	1:25,000
Wetness status	1. Permanent water 2. Temporary water 3. Permanently wet 4. Temporarily wet	Water and Wetness raster 2018 (EEA 2020)	10 m × 10 m

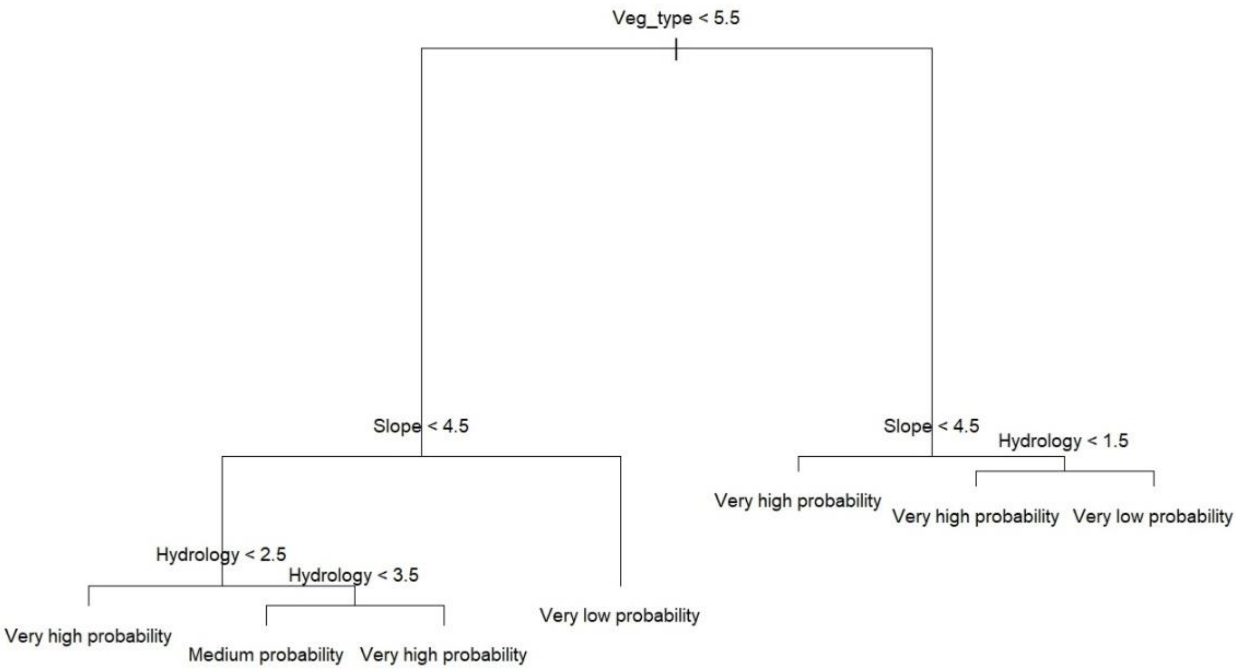

Figure 3. Decision tree for mire estimation at altitudes above 1200 m using the conditioning approach.

We identified additional areas with high wetland and peatland potential by using two datasets, namely: the 1977 National hydrogeological potential map (Gjuzelkovski & Kotevski 1977), focusing on "Very high yield capacity (>10 L/s)" and "High yield capacity (1–10 L/s)" categories; and the Water and Wetness 2018 raster dataset (EEA 2020), excluding "Dry" and "Permanent Water" categories. These datasets enabled identification of broader areas with high potential for wetland and peatland occurrence, particularly in combination with the network of drainage channels (Hristovski *et al.* 2020). Land cover and land-use patterns within areas with high potential for wetlands and peatlands were derived from the national habitat map (Maneko Solutions 2023). To provide a spatial framework, the boundaries of these areas with high potential for wetland and peatland occurrence were intersected with the regions presented in Melovski *et al.* (2013). The identified regions were then classified into the two categories *Key* and *Additional* regions, based on area coverage and restoration importance.

Mapping and processing were performed using ArcGIS 10.6 and ArcGIS Pro 3.3.

RESULTS

Spatial distribution, extent and characteristics of the mire and other wetland area

Data integration, digitisation and data processing resulted in creation of the first comprehensive wetland map for North Macedonia (Figure 4). The wetland area is distributed across the whole country and, according to our results, has a current total extent of 380.55 km^2 or 1.5 % of the country's area.

We identify riparian forests as a distinct wetland category prevalent across the country with an extent of 184.03 km^2 and high heterogeneity of environmental variables. The density of the riparian belts is lowest in the Pelagonia valley (SW part of the country) where they are almost absent, as well as in the central Ovche Pole region which is the driest part of the country. The rest (196.52 km^2) of the wetland area is attributed to all of the other categories, and has a more fragmented distribution across the country. Small areas are scattered over almost all of the high mountains (Shar Planina, Korab, Bistra, Jakupica, Stogovo, Jablanica, Pelister, Nidze, Kozhuf,

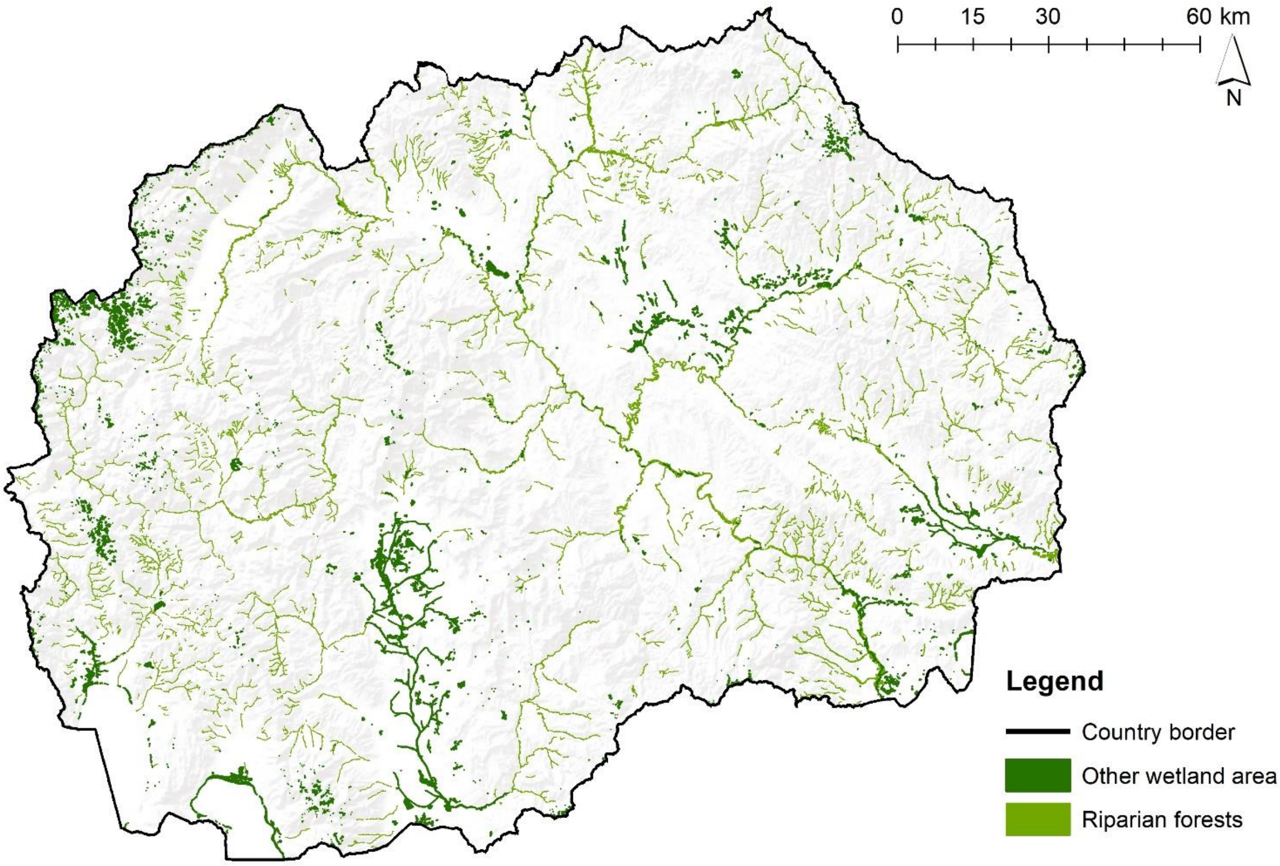

Figure 4. Map of wetlands in North Macedonia.

Meleshevski Planini, Osogovski Planini, etc.). Higher abundance is apparent in the large valleys of the lowlands (Pelagonija, Ohridsko Pole, Strushko Pole, Gevgelisko Pole, Valandovsko Pole, Strumichko Pole, Kochansko Pole, Skopsko Pole).

Based on the variables of the main criteria (Table 1), the optimised pseudo-F statistics of the non-riparian wetland area highlighted two clusters, with altitude being statistically the most important variable. Considering this, we divide the wetland area into lowland and mountain, where the larger area is attributed to the lowland category (Figure 5A). Besides the initial clustering, the spatial distribution with a predefined number of clusters presents the similarity/differences of the wetland polygons with regard to the environmental variables (Figure 5B). The first clustering is again mainly influenced by altitude. Clusters 2 and 3 include polygons at average altitude 1870 m, while the majority of other clusters are in an average altitude range of 333–565 m. The mountain wetland area is divided into two clusters (cluster 2 and cluster 3, Figure 5B) which differ mainly in terms of hydrology (areas with and without surface water supply). The lowland wetland area is divided into four clusters that differ mainly in terms of soil type, geology and wetness status. Cluster 1 includes the majority of mapped polygons, which exclude ten soil types that are present in the other clusters such as the complexes with Cambisols, Leptosols and Gleysols. Clusters 4 and 6 differ from the other clusters mainly on the basis of geology. Due to this, cluster 4 is mainly distributed around the tectonic lakes and Pelagonia valley, with higher representation of lake sediments, while cluster 6 has more scattered distribution related to river sediments. Cluster 5 has higher values for water and wetness status and is distributed mainly around the three tectonic lakes (Prespa, Dojran, Ohrid) as well as along Vardar River. This cluster includes habitat types mainly from groups D5 and D6.

Identification of mire area

In most cases the lowland wetland area is positioned close to agricultural land and is often quite fragmented. According to our personal observations, the peat layer is heterogeneously distributed in many polygons, which creates uncertainties in location. Due to this, the location of the mire area in the lowlands is represented as point data, and quantification is not feasible without future collection of ground truth data. The point data presented in Figure 6 reflect the distribution of assessed mire area in the lowlands. The assessment resulted in four different categories, namely: high probability of peat layer; peat depth < 30 cm; peat depth > 30 cm; and peat depth > 50 cm.

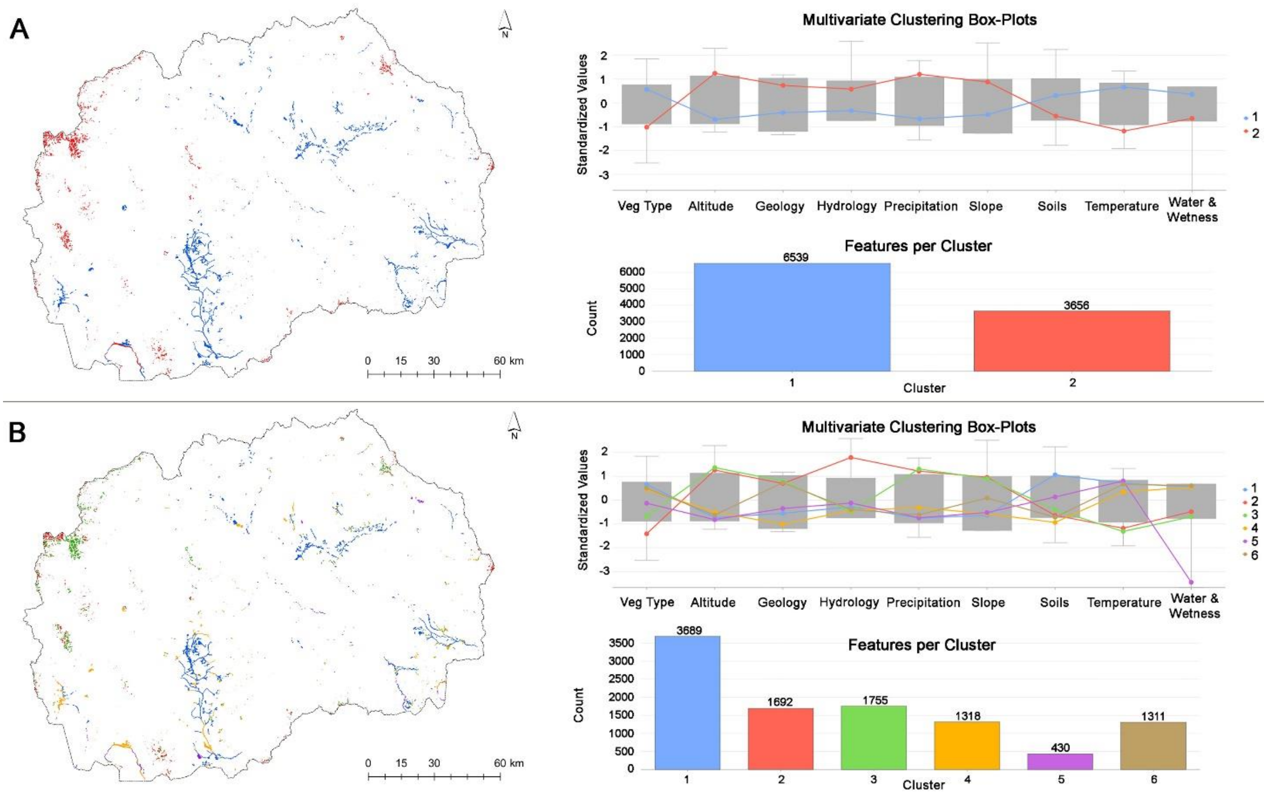

Figure 5. Clustering of Other wetland area. A: clustering by altitude; B: clustering by environmental variables.

Considering land use on the mountains, there is high confidence that our estimate is close to the current mire area above 1200 m. According to our results, the extent of high-altitude mires is 22.5 km^2, including 16.9 km^2 of estimated mires and 5.3 km^2 of potential mire area. The estimation approach enabled us to distinguish between varying degrees of certainty regarding mire presence. The analysis yielded three confidence-level categories reflecting the likelihood of actual mire occurrence, namely: very high probability, medium probability, and very low probability (of peat layer) (Figure 6).

Conservation status of mire and other wetland area

Only 22 % (84 km^2) of the total wetland area in North Macedonia is under official protection or initiative for protection (Figure 7). The latter category mostly concerns the mountain mire area within the National Parks Mavrovo, Shar Planina and Pelister. The mire area under protection was recently increased by the designation of two large protected areas (Osogovski Planini and Maleshevski Planini protected landscapes) in the eastern part of the country. On the other hand, there are insignificant areas of any category of lowland wetland under protection. Indeed, the two lowland wetlands Monospitovsko Blato and Katlanovsko Blato have outdated protection status, meaning a new designation process is required. The only lowland wetland area under protection is Ezerani Nature Park (alongside Prespa Lake), for which most of the wetland area is also covered by the Lake Prespa Ramsar Site protection.

Identification of regions with high peatland and wetland potential and land cover data analysis

The representation of habitat types selected for our map led to restrictions in relation to anthropogenic wetlands and areas without current peatland vegetation; and in particular to the omission of potential peatland areas. To address this, we synthesised available spatial data with the produced wetland map, which resulted in the identification of (key and additional) broader regions that have high potential for wetlands and peatlands (Figure 8). Thus, we identified Pelagonia region, and Bitolsko Pole in particular, as the most extensive area with high wetland and peatland potential. On the other hand, it can be observed that this area has one of the densest drainage systems in the country, and this is actively draining the valley. In addition to Bitolsko Pole, the

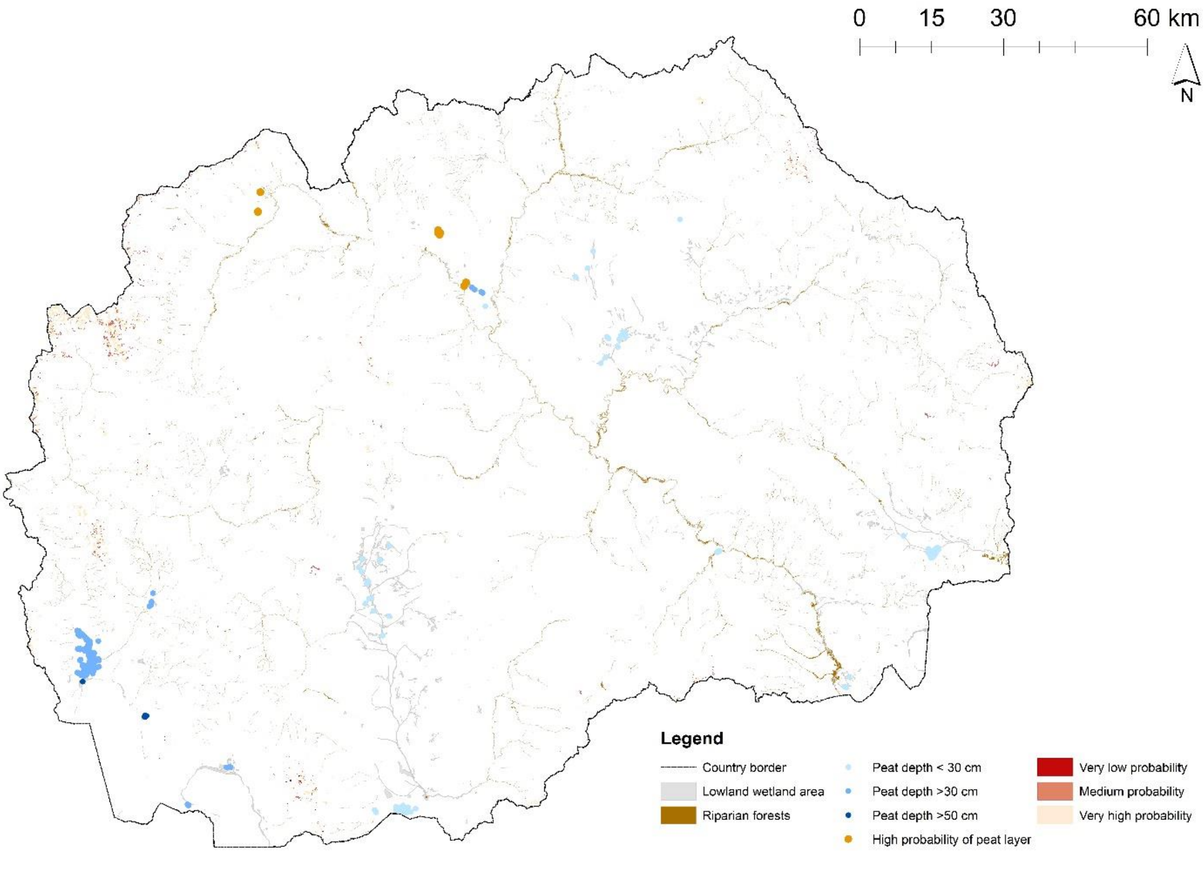

Figure 6. Map showing lowland sites with four categories for peat layer, and the high-altitude mire area estimated with three levels of confidence.

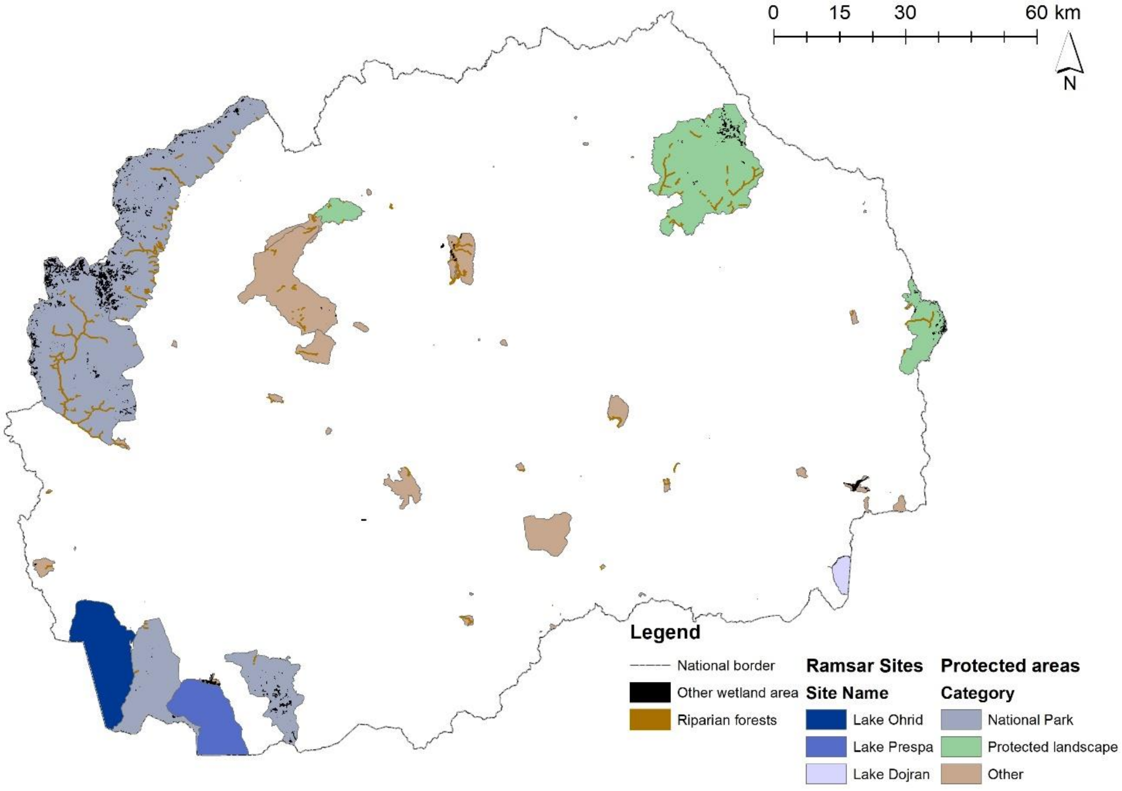

Figure 7. Map of wetland areas within nationally protected areas, Ramsar Sites and initiatives for protection.

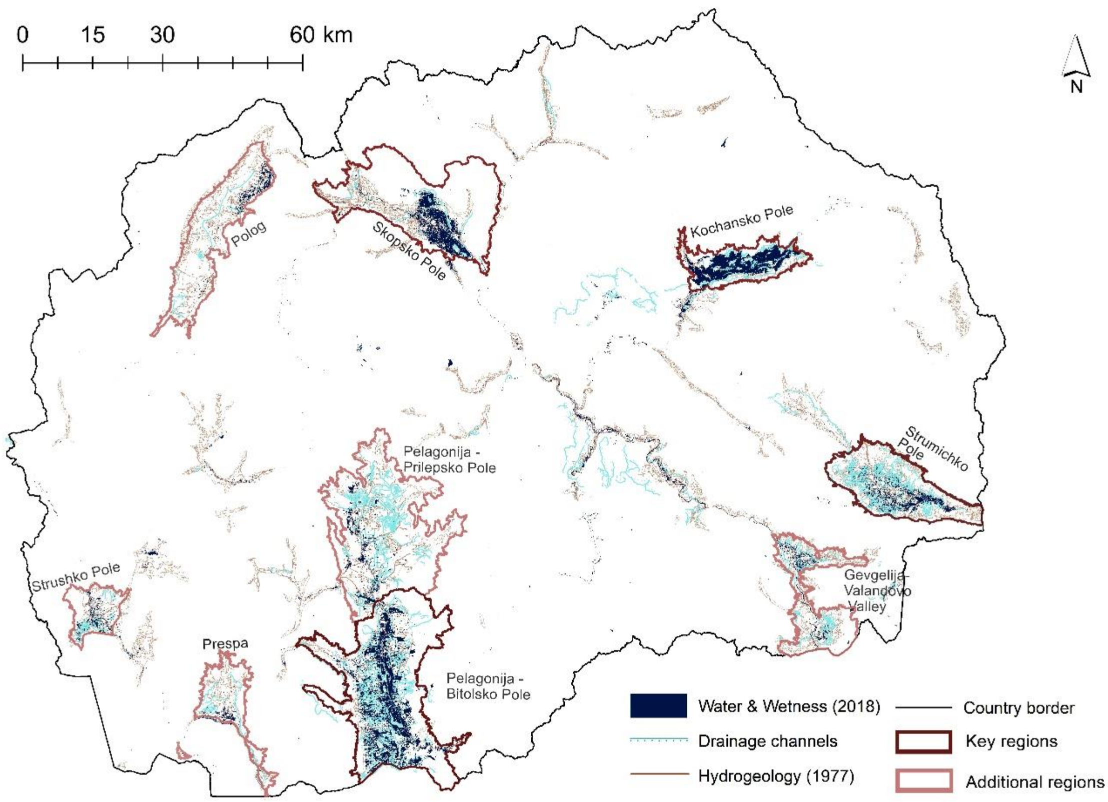

Figure 8. Map of the broader area of high wetland and peatland potential in North Macedonia, showing key and additional regions with high potential.

following three regions were also identified as key regions with high wetland and peatland potential: Skopsko Pole, Strumichko Pole and Kochansko Pole. Skopsko Pole is the most urbanised region in the country and has the most intensely developed infrastructure. Because of this, it is likely that most of the potential wetland or peatland areas have been lost and further research is needed to locate any small areas that may remain. Strumichko Pole, on the other hand, is mostly under agriculture with a dense network of drainage channels. Despite this, remnants of large wetland and peatland areas such as Monospitovsko Blato witness the high potential of this region. Kochansko Pole is the fourth key region which still retains wetlands, although as cultivated rice plantations. These wetlands are not included in our map owing to their anthropogenic origin, but if they were included the total wetland area would increase (significantly) by 160 km^2, or from 1.5 % to 2.1 % of the total area of the country. For other regions, namely Polog, Strushko Pole, Prespa, Prilepsko Pole and Gevgelija-Valandovo Valley, we consider that the data presented in the wetland map represent only remnants of wetland and peatland areas that should be a secondary priority for future studies. Lastly, all other regions of the country (Melovski *et al.* 2013) are not considered to be relevant as potential wetland and peatland areas even though small exceptions are possible.

Table 2 presents results from the land cover analysis in terms of intersect areas of the EUNIS Level 1 categories with (a) the water and wetness categories and (b) the map of hydrogeological potential categories. Because the hydrogeological potential map has lower resolution than the others, the values for all habitat types in this analysis are exaggerated. The total area covered by (a) and (b) with land cover other than wetlands or mires is 252,108 ha. The potential area for the key regions with high wetland and peatland potential was estimated to be 87,932 ha with the highest contribution (35,604 ha) from Bitolsko Pole (Table A4). The mapped water and wetness dataset provides generally lower values than the map of hydrogeological potential due to its higher resolution. The total area covered by the three water and wetness categories with land cover other than wetlands or mires is 37,109 ha. The potential area for the key regions was estimated at 28,684 ha, again with the highest contribution (13,266 ha) from Bitolsko Pole (Table A4). For both (a) and (b), agriculture is the dominant land cover category (Table 2). These results are supported by the distribution of the drainage system network in the lowlands (Figure 8).

Table 2. Intersect areas (in hectares) from the map of broader area of high wetland and peatland potential and the land cover categories.

EUNIS Level 1 categories	(a) Water and wetness categories			(b) Map of hydrogeological potential categories	
	Temporary water	Permanent wet	Temporary wet	High yield capacity (1–10 L/s)	Very high yield capacity (>10 L/s)
E: Grasslands and lands dominated by forbs, mosses or lichens	3	72	912	3,499	4,739
F: Heathland, scrub and tundra	3	22	477	1,559	12,686
G: Woodland, forest and other wooded land	17	13	548	15,424	13,199
H: Inland unvegetated or sparsely vegetated habitats	3	9	23	4	48
I: Regularly or recently cultivated agricultural, horticultural and domestic habitats	25	4,766	29,435	95,556	88,114
J: Constructed, industrial and other artificial habitats	36	17	645	11,120	15,231
X: Habitat complexes	1	1	82	330	601
Total	88	4,900	32,121	127,490	134,618

DISCUSSION

Importance of wetland classification in mapping efforts

Wetlands can be classified either as part of an ecological gradient or as distinct community types (Brinson 2011). Various classification systems aim to typify wetland types at different levels, although it is recognised that the absence of a unified classification concept hinders mapping efforts (Hu *et al.* 2017), condition assessments and efficient conservation (Zedler & Kercher 2005). In North Macedonia, the ecosystem map categorises wetlands primarily on the basis of altitude (Chobanova *et al.* 2024). However, the mapping approach within the European Union MAES (Mapping and Assessment of Ecosystems and their Services) classification encompasses a mixture of Corine (Coordination of Information on the Environment) Land Cover data and EUNIS habitat classification (Maes *et al*. 2013), resulting in the inclusion of wetland types such as riparian forests and wet meadows within other ecosystem types. A similar situation is observed in the North Macedonian national habitat map (Maneko Solutions 2023), where wetlands are nested within group D, thereby excluding other wetland types. While available methods give potentially high resolution for larger sites (Bhatnagar *et al.* 2020), delineating habitat types at level 3 within the EUNIS typology poses additional challenges, as many small wetlands in our study present as mosaics of different habitat types. The Ramsar classification, although widely accepted, has been criticised for its broadness (Mitra *et al.* 2003). The Mediterranean typology (a modified Ramsar typology appropriate to North Macedonia) has only five categories (UKLO_FTU 2020), primarily comprising open water bodies. Lakes and wetlands are closely interlinked (Björk 2010), but databases often approach them individually (Lehner & Döll 2004, Hu *et al.* 2017, Wu 2018). Similarly, our data exclude the habitat types Permanent oligotrophic lakes, ponds and pools (C1.1), Permanent mesotrophic lakes, ponds and pools (C1.2), and most Permanent eutrophic lakes, ponds and pools (C1.3) which, according to the national habitat map, extend across 55,771 ha (558 km^2) of the country. This means that their inclusion would significantly influence the total wetland area. Lakes (especially deep lakes such as Ohrid Lake) can have completely different nutrient and energy cycling (Håkanson 2005) in comparison to wetlands (Nyman 2011). However, wetlands in the proximity of open water bodies can expand and contract vastly, which creates significant difficulties for correct classification if based solely on remotely received signals (Lehner & Döll 2004). To mitigate this, we have set a surface area threshold and have included the Permanent eutrophic lakes, ponds and pools (C1.3) smaller than 1130 m^2. Similarly, we have included the Permanent dystrophic lakes, ponds and pools (C1.4) and Temporary lakes, ponds and pools (C1.6) in our map due to their generally small spatial extent and thus close ecological ties to wetland systems rather than to lakes.

Initially, the mapping efforts in our study focused on habitats to facilitate the development of a national habitat map. However, categorising wetland habitats in isolation may restrict the potential utility of the data. Moreover, employing the EUNIS structured classification system obscured information relating to our definition of wetlands, as provided by Joosten *et al*. (2017). Delineation and spatial distribution of wetlands can be pivotal factors influencing decision-making in wetland conservation. Therefore, the accuracy of wetland mapping is paramount for providing a realistic portrayal of their extent and distribution (Wu 2018, Cha *et al.* 2024). However, the creation of such maps encompasses a diverse array of methodologies, each carrying the risk of either overestimating or underestimating the wetland area. Perrenou *et al*. (2012) presented estimates of wetland area in North Macedonia ranging from 60,000 to 80,000 ha. These estimates, primarily derived from Micevski (2002), are predominantly based on open water bodies, meaning that numerous inland areas with wetland vegetation are excluded. Conversely, Markoski (2019) estimated the wetland area to be only 2900 ha. This could be attributable to the exclusion of open water bodies, such as artificial, glacial or natural lakes, as well as surface running water bodies. Additionally, this reduction may stem from a focus only on larger lowland wetland sites, such as Katlanovsko Blato, Ezerani, Badar, Monospitovsko Blato etc. The most recent wetland area estimation reports 162 wetland sites in North Macedonia (Fitoka *et al.* 2020), covering total area of 56,296 ha (UKLO_FTU 2020). Among these, the largest areal contribution (75 %) is from lakes, ponds and reservoirs. These data have been cited for their high mapping accuracy and were utilised in the recent assessment of wetland ecosystems in the Mediterranean region (Trombetti *et al.* 2022). Despite our study indicating a lower extent compared to some of the abovementioned sources, we contend that the currently available data reflect an underestimation and underrepresentation of wetland areas in North Macedonia. Our database comprises over 18,000 mapped polygons (8375 riparian and

10,195 other wetland areas), contrasting sharply with the 31 sites reported by Markoski (2019) or the 162 sites reported by Fitoka *et al.* (2020). This indicates a much higher spatial and general heterogeneity, as well as a higher resolution in delineation. In addition, high-altitude mires are largely absent from any available data for North Macedonia and are likely to be underrepresented throughout the Balkans. Remote areas present unfavourable conditions for mapping high-altitude mires (Wakulińska & Marcinkowska-Ochtyra 2020, Karlson & Bastviken 2023), while their small surface areas (an average of 0.64 ha in our study) pose challenges for accurate mapping. Despite their small size, the cumulative area of high-altitude mires in North Macedonia contributes significantly to the total wetland area, and particularly to the estimated mire area. Our mapping experience underscores the efficacy of manual digitisation and visual interpretation supported by ground truth data and expert knowledge in achieving reliable results, especially when smaller-scope mapping is being undertaken.

Towards a national-scale wetland inventory

Ultimately, different classifications can serve distinct purposes such as restoration, monitoring, conservation, utilisation, management, etc. Therefore, for a national-scale inventory, a more comprehensive approach that encompasses all aspects of wetland ecosystems including water, soils and vegetation is crucial for understanding their structure, function and utility. Our study adopts a set of variables that are highly specific to the country context, thereby enhancing accuracy and relevance. Nevertheless, it is important to note that some of our data remains coarse, particularly considering the national scale of the study. This is especially evident with soils data, limiting the soil map's utility for peatland mapping and omitting wetland and peatland areas. Various estimations have been reported for wetland soils in the country. For instance, it is considered that before the major meliorations of the 1960s, the extent of wetland soil was ~ 86,000 ha (Filipovski 2016). Also, Filipovski (2016) argues that at least 65,000 ha of wetland has been drained even though these estimations are not objectively quantified. Ultimately, the official national soil database (MaSIS 2015) reports a total wetland soil area of 16,777 ha, predominantly in the lowlands. Filipovski (1999) identifies 1303 ha of peat soils deeper than 30 cm, while in terms of Histosols in particular he reports 700 ha with ~ 8 million m^3 of peat (Filipovski 2016). More recently, Tanneberger *et al*. (2017) report peatland estimates of 281 km^2 of which 13 km^2 is mire area. Conversely, our results for high-altitude mires already exceed these estimates, indicating an area of 22.5 km^2. This discrepancy is expected because the small site sizes can result in underestimations when defined through expert judgement, while our study provides the first spatial information on high-altitude mires.

Agricultural intensification in North Macedonia after World War II, along with efforts to eradicate malaria, led to a vast development of drainage systems particularly affecting lowland wetlands. There remains a notable gap in our understanding of wetland and, more significantly, peatland extent for examples that have been altered or impacted by anthropogenic land use. Intensive agriculture is mostly dominant in the lowlands, where the country had made efforts in mapping wetland areas for the purposes of the national GHG inventory report (Grncharovska Obradovik 2021). A range of 53,393.7–53,625.9 ha of wetland area is reported for the time period 1990–2019, yet the exact inclusions in terms of wetland types or their distribution remains unclear. The land cover of this wetland area is also not clearly reported, even though larger lowland wetlands (Monospitovsko Blato, Katlanovsko Blato and Ezerani) located predominantly around agricultural landscapes are mentioned. The methodological ambiguities in this report are additionally confirmed by the inability to obtain results for GHG emissions or removals from the mapped area. These high uncertainties and data unavailability pose restrictions for comparison, utilisation of these data or its potential integration into our wetland map. Mapping efforts using historical topographic sources were mostly hindered by the data availability constraints pre-1950s. However, the national hydrogeological potential map from the 1970s offers valuable insights, aligning well with recent data from the Water and Wetness (2018) dataset. Although broad, our analysis of the regions with high potential in the lowlands actually provides insights about the regions where the highest losses of wetlands and peatlands have occurred. This is an overlooked and ongoing threat that requires more attention, particularly for peatlands, in light of our country's commitment to the Paris Agreement.

Our study provides a robust foundational dataset that provides an opportunity for formal integration into an official national wetland inventory. Such an inventory should be regularly updated and maintained according to predetermined criteria, protocols and guidelines. Augmenting the dataset to incorporate threats and pressures is paramount. This augmentation not only facilitates objective assessments of condition and degradation status, but will also unveil restoration priorities.

General conservation notes and the way forward

Even though wetlands are recognised as important ecosystems, their targeted protection and conservation in North Macedonia is still poor (Melovski & Matevski 2017). With the exception of Ezerani Nature Park, the wetland area is mainly protected by inclusion in larger protected areas such as national parks, which are primarily designated for other natural values. Consequently, wetlands and peatlands are largely underrepresented in the management plans. Moreover, our results show that the conservation status of lowland and mountain wetland areas is very disproportional (Figure 7). The imperative need to prioritise wetland conservation and management emerges starkly from the marginalised status of wetlands, compounded by persistent threats and underestimations. Efforts to improve wetland mapping accuracy and coverage are essential to address the significant threats facing wetland ecosystems in North Macedonia. Our study advocates for a comprehensive approach that considers all aspects of wetland ecosystems to enhance multi-layered application and utilisation of the data. The clustering outcomes delineate the spatial arrangement of similar and dissimilar wetland areas in terms of the analysed variables, offering valuable insights for conservation or restoration planning actions. Improved accuracy of the wetland attributes can be achieved by collecting additional data, particularly pertaining to soil characteristics. This would significantly improve peatland identification or peat extent estimates in the future. In this regard, future research should focus on confirmation of the peatland area that is currently under agricultural land use, especially in Kochansko Pole, Bitolsko Pole and Strumichko Pole, since such areas pose major mapping challenges without ground truth data. The broader perspective of key and additional regions with high wetland and peatland potential is essential for informed land-use planning, restoration efforts and the development of sustainable management strategies that integrate both natural and human-modified ecosystems. Considering its small extent, the wetland area provides disproportionately important ecosystem services which should be better recognised and prioritised on the national and regional agendas. Moving forward, it is imperative to widely communicate our findings, to both policymakers and practitioners. In this regard, our data serve as an indispensable contribution towards the development of a long-awaited national wetland strategy.

ACKNOWLEDGEMENTS

Several contributions have been instrumental in achieving the objectives of this study and advancing our understanding of wetlands, mires and peatlands in North Macedonia. We express our sincere appreciation to Deutsche Bundesstiftung Umwelt for funding the first author's fellowship at the Greifswald Mire Centre (GMC) in Germany. Additionally, we thank all colleagues at GMC for their invaluable support and knowledge transfer, which significantly improved this study. Many of the results were generated through the national habitat map project, for which we acknowledge the European Bank for Reconstruction and Development (EBRD) for funding. Last but not least, we sincerely thank the Macedonian Ecological Society for their support, openness and provision of valuable data and advice.

AUTHOR CONTRIBUTIONS

MC: conceptualisation and writing original draft; MC and DJ: methodology development and spatial analysis; SH: lowland mire extent estimates; AB, FT and SH: validation. All authors: writing, revision and editing of this manuscript.

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Submitted 03 Jan 2025, final revision 22 Jul 2025
Editor: Colin McCarter

Author for correspondence:
Marija Chobanova, Institute of Biology, Faculty of Natural Sciences and Mathematics, Arhimedova 3, 1000 Skopje, Republic of North Macedonia. Tel: +38978344408; E-mail: mtrenceva@gmail.com

Appendix

Table A1. Coding and grouping of vegetation types. L3/L4 Codes = EUNIS Level 3 and Level 4 codes.

Code and grouping	L3/L4 codes	EUNIS names
1	C1.3	Permanent eutrophic lakes, ponds and pools
2	C1.4	Permanent dystrophic lakes, ponds and pools
3	C1.6	Temporary lakes, ponds and pools
4	C2.1 D4.1	Springs, spring brooks and geysers Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks
	C2.1	Springs, spring brooks and geysers
5	C3.1	Species-rich helophyte beds
6	C3.2	Water-fringing reedbeds and tall helophytes other than canes
	C3.21 C3.23	*Phragmites australis* beds *Typha* beds
7	D2.2 D2.3	Poor fens and soft-water spring mires Transition mires and quaking bogs
	D2.2 D2.3 D5.2	Poor fens and soft-water spring mires Transition mires and quaking bogs Beds of large sedges normally without free-standing water
	D2.2	Poor fens and soft-water spring mires
8	D2.2 D2.3 D4.1	Poor fens and soft-water spring mires Transition mires and quaking bogs Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks
	D2.2 D2.3 D4.1 D5.2	Poor fens and soft-water spring mires Transition mires and quaking bogs Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks Beds of large sedges normally without free-standing water
9	D2.3	Transition mires and quaking bogs
10	D2.3 D4.1	Transition mires and quaking bogs Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks
	D2.3 D5.3	Transition mires and quaking bogs Swamps and marshes dominated by *Juncus effusus* or other large *Juncus* spp.
11	D4.1 D5.2	Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks Beds of large sedges normally without free-standing water
	D4.1	Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks

Code and grouping	L3/L4 codes	EUNIS names
12	D5.11 D5.13	*Phragmites australis* beds normally without free-standing water *Typha* beds normally without free-standing water
	D5.12	*Scirpus lacustris* beds normally without free-standing water
	D5.1	Reedbeds normally without free-standing water
13	D5.1 D5.2 D5.3	Reedbeds normally without free-standing water Beds of large sedges normally without free-standing water Swamps and marshes dominated by *Juncus effusus* or other large *Juncus* spp.
14	D5.21	Beds of large *Carex* spp.
	D5.2	Beds of large sedges normally without free-standing water
15	D5.2 D5.3	Beds of large sedges normally without free-standing water Swamps and marshes dominated by *Juncus effusus* or other large *Juncus* spp.
	D5.3	Swamps and marshes dominated by *Juncus effusus* or other large *Juncus* spp.
16	D6.1	Inland saline and brackish marshes and reedbeds
	D6.1 D6.2	Inland saltmarshes Inland saline or brackish species-poor helophyte beds normally without free-standing water
	D6.2	Inland saline or brackish species-poor helophyte beds normally without free-standing water
17	C3.32	*Arundo donax* beds

Table A2. Coding and grouping of substrate types.

Code	Substrate	Code	Substrate
1	Alluvium	10	Carbonate
2	Alluvium and deluvium	11	Carbonate and silicate
3	Marsh and lake sediments	12	Lake
4	Gravels, sands and clays	13	Moraine
5	Deluvium	14	Sandstones
6	Eluvium	15	Proluvium
7	Lake terrace	16	River terrace
8	Glacial sediments and deposits	17	River sediments
9	Clays	18	Silicate
		19	Peat

Table A3. Coding and grouping of soil types.

Code and grouping	Soil type
1	Rendzic Leptosols Complex of Rendzic Leptosol and Chromic Luvisol on hard limestones Complex of Rendzic Leptosol and Leptosol
2	Complex od Cambisol and Leptosol Complex of Cambisol and Regosol Complex of Cambisol, Leptosol and Regosol Chromic Luvisol on hard limestones Complex of Cambisol, Mollic and Umbric Leptosol and Leptosol Cambisol Complex of Cambisol, Mollic and Umbric Leptosol and Regosol Complex of Cambisol and Mollic and Umbric Leptosol
3	Fluvisol - deluvial
4	Leptosol (Leptosol on limestones and dolomites) Leptosol
5	Complex of Albic Luvisol and Regosol Albic Luvisol
6	Gleysol Complex of Gleysol and Histosol Complex of Fluvisol and Gleysol
7	Urbic Anthrosol Populated Site
8	Planosol
9	Complex of Mollic and Umbric Leptosol Complex of Mollic and Umbric Leptosol and Leptosol Complex of Mollic and Umbric Leptosol and Albic Luvisol Complex of Mollic and Umbric Leptosol and Regosol Complex of Mollic and Umbric Leptosol, Regosol and Leptosol
10	Regosol Complex of Regosol and Fluvisol Complex of Regosol and Leptosol Complex of Regosol and Vertisol

Code and grouping	Soil type
11	Rendzina
	Complex of Humic Calcaric Regosol and Leptosol
	Complex of Humic Calcaric Regosol and Regosol
	Complex of Humic Calcaric Regosol, Regosol and Leptosol
	Complex of Humic Calcaric Regosol, Regosol and Vertisol
12	Aric Anthrosol Aric Anthrosol (Regosol colluvial terraced)
13	Vertisol Complex of Vertisol and Humic Calcaric Regosol Complex of Vertisol, Regosol and Leptosol Complex of Vertisol, Humic Calcaric Regosol and Regosol Complex of Vertisol, Chromic Luvisol on saprolite and Regosol
14	Complex of Solonchak and Solonetz
15	Histosol
16	Fluvisol - aluvial
18	Complex of Fluvisol and Mollic Fluvisol Complex of Mollic Fluvisol and Mollic Vertic Gleysol Mollic Fluvisol
19	Mollic Vertic Gleysol
20	Hortic Anthrosol
21	Chromic Luvisol on saprolite Complex of Chromic Luvisol on saprolite and Fluvisol Complex of Chromic Luvisol on saprolite and Albic Luvisol Complex of Chromic Luvisol on saprolite and Regosol Complex of Chromic Luvisol on saprolite and Vertisol Complex of Chromic Luvisol on saprolite, Albic Luvisol and Regosol Complex of Chromic Luvisol on saprolite, Regosol, Humic Calcaric Regosol and Vertisol Complex of Chromic Luvisol on saprolite, Humic Calcaric Regosol and Regosol Complex of Chromic Luvisol on saprolite, Humic Calcaric Regosol and Vertisol
22	Ferric Luvisol on hard limestones Complex of Ferric Luvisol and Chromic Luvisol on hard limestones
23	Complex of Chernozem, Humic Calcaric Regosol and Vertisol Complex of Chernozem and Humic Calcaric Regosol

Table A4. Intersection of area (in hectares) of key (red) and additional (yellow) regions with land cover types within different categories of the Water and Wetness (WAW) dataset and the Map of hydrogeological potential.

Data	Land cover within different categories	Bitolsko Pole	Gevgelisko Pole	Kochansko Pole	Polog	Prespa	Prilepsko Pole	Skopsko Pole	Strumichko Pole	Strushko Pole	Valandovsko Pole	Total
Water and Wetness (2018)	**Permanent wet**	0.91	0.03	4716.87	2.78		5.24	35.32	12.91	0.16	0.02	4774
	E: Grasslands and lands dominated by forbs, mosses or lichens			1.76				0.63	0.14			2.53
	F: Heathland, scrub and tundra		0.01	0.03				0.02	0.62		0.00	0.69
	G: Woodland, forest and other wooded land			2.93	0.87			1.99	0.01			5.79
	I: Regularly or recently cultivated agricultural, horticultural and domestic habitats	0.74	0.02	4708.49	1.64		5.24	30.17	9.57	0.00	0.02	4755
	J: Constructed, industrial and other artificial habitats	0.17		3.67	0.27			2.42	2.57	0.07		9.17
	X: Habitat complexes							0.08		0.09		0.17
	Temporary water	11.58	0.91		0.15		0.19	7.98		0.00	2.21	23.02
	E: Grasslands and lands dominated by forbs, mosses or lichens						0.01	0.36				0.37
	F: Heathland, scrub and tundra		0.17					0.02			0.04	0.23
	G: Woodland, forest and other wooded land		0.02		0.15		0.16	0.01			0.19	0.54
	I: Regularly or recently cultivated agricultural, horticultural and domestic habitats	0.27	0.73				0.01	3.60		0.00	1.98	6.59
	J: Constructed, industrial and other artificial habitats	11.31						3.73				15.04
	X: Habitat complexes							0.25				0.25
	Temporary wet	13253.67	269.80	2215.65	1308.09	375.78	2138.73	5419.77	3008.92	639.19	554.35	29183
	E: Grasslands and lands dominated by forbs, mosses or lichens	99.03	64.69	11.50	0.52	169.80	116.07	44.70	79.62	4.67	0.48	591
	F: Heathland, scrub and tundra	82.43	9.77	2.36			79.52	11.00	40.95		48.99	275
	G: Woodland, forest and other wooded land	43.91	0.74	7.54	7.73	1.75	8.38	48.57	17.45	1.63	0.80	138

Data	Land cover within different categories	Bitolsko Pole	Gevgelisko Pole	Kochansko Pole	Polog	Prespa	Prilepsko Pole	Skopsko Pole	Strumichko Pole	Strushko Pole	Valandovsko Pole	Total
WAW (2018)	I: Regularly or recently cultivated agricultural, horticultural and domestic habitats	12931.26	193.88	2148.21	1287.00	164.29	1926.53	5137.31	2660.09	602.06	503.76	27554
	J: Constructed, industrial and other artificial habitats	96.70	0.73	46.04	12.84	0.46	8.23	170.87	210.65	13.78	0.31	560
	X: Habitat complexes	0.34				39.48		7.33	0.16	17.05		64.36
	Total	13266	271	6933	1311	376	2144	5463	3022	639	557	33981
Map of hydrogeological potential (1977)	**High yield capacity (1-10 L/s)**	34056			7287	7806	37500	6292		7634	1967	102542
	E: Grasslands and lands dominated by forbs, mosses or lichens	503			112	302	820	71		34	11	1852
	F: Heathland, scrub and tundra	175			10		137	95			610	1026
	G: Woodland, forest and other wooded land	280			366	2989	678	145		864	267	5590
	I: Regularly or recently cultivated agricultural, horticultural and domestic habitats	31077			4386	3943	34391	4366		5759	945	84867
	J: Constructed, industrial and other artificial habitats	1984			2400	478	1432	1611		890	116	8911
	X: Habitat complexes	37			13	94	41	5		87	19	296
	Very high yield capacity (>10 L/s)	1548	7556	8415	18936		55	13217	24404		4356	78488
	E: Grasslands and lands dominated by forbs, mosses or lichens	65	244	165	52		1	302	364		46	1240
	F: Heathland, scrub and tundra	56	1430	37	12			86	1542		959	4121
	G: Woodland, forest and other wooded land	160	842	146	1040		0	478	930		177	3772
	H: Inland unvegetated or sparsely vegetated habitats							9				9
	I: Regularly or recently cultivated agricultural, horticultural and domestic habitats	1238	4225	7488	16367		33	6682	18455		2985	57474
	J: Constructed, industrial and other artificial habitats	29	811	578	1457		20	5424	3101		190	11610
	X: Habitat complexes		4	2	9			235	12			262
	Total	35604	7556	8415	26224	7806	37555	19509	24404	7634	6323	181030