



Transdisciplinary approach to the characterisation and current status of Spanish karstic lakes on gypsum

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Abstract

Karstic lakes on gypsum are a very peculiar type of ecosystem declared as a Habitat Type of Community Interest (Type 3190) by the European Habitats Directive. They are usually small lakes but often displaying a high relative depth, located in active gypsum karst areas, with a high saturation of Ca_2^+ and SO_4^{2-} in its waters. These lakes can usually stratify from spring to early autumn when the depth is high enough, then a sulphide-rich anoxic hypolimnion can develop in deep layers. So far, neither a comprehensive scientific definition of their ecological characteristics nor an exhaustive catalogue of their occurrence in a particular territory are available. This paper delves on their biotic and abiotic features needed for their identification as an ecosystem type. A proper methodology was also designed and applied for the evaluation of their conservation status, with the definition of reference values and assessment methods following the criteria of the Habitats Directive. The Spanish karstic lakes on gypsum (THCI 3190) were here identified, statistically representative sites were selected, and spatial GIS methods and multimetric indices were applied to assess the range, area, structure and function, and future prospects of this Habitat Type, as requested for the reporting according to Article 17 of the Habitats Directive. Results showed a favourable conservation status of this habitat type in the Alpine and Atlantic regions of Spain, but unfavourable-inadequate status in the Mediterranean, due to the pressures and impacts acting on some specific sites. A critical analysis of the methodologies and the values obtained for its conservation status was carried out.

Keywords EU habitats directive · Habitat types of community interest · Karstic lakes on gypsum · Conservation status · Assessment

Introduction

Lentic ecosystems (standing waters) are affected worldwide by anthropogenic pressures, and they are one of the most threatened ecosystem types (Verhoeven 2014). Further, they are highly vulnerable to environmental shifts caused by climate change (Reid et al. 2019). These impacts may result

in a degradation of the ecological structure and an alteration of their functioning (Dodson et al. 2005; Camacho et al. 2012, 2016). Proper management and conservation are essential aspects to ensure their ecological integrity, biodiversity, and functioning, for instance, promoting biogeochemical mechanisms that provide ecosystem services such as carbon sequestration (Morant et al. 2020). To this end, a proper assessment of their condition is essential, to better define mechanisms to maintain or improve their ecological condition and integrity. But for that purpose, it is also necessary a proper characterisation of the ecosystem type, with the knowledge of their main ecological features both abiotic and biotic.

In Europe, the assessment of the status of lentic waterbodies is currently regulated by two European Directives that establish the framework for the management and conservation of aquatic ecosystems and water resources. The Water Framework Directive (WFD; 2000/60/EC) (European Commission 2000) is the legal basis for water policy

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in the European Union (EU), which aims to achieve the good ecological status of aquatic ecosystems. The Habitats Directive (HD; 92/43/EEC) (European Commission 1992) is the framework for the EU's biodiversity policy, aiming to protect, maintain or restore, at a favourable conservation status, the Habitat Types of Community Interest (HTCI) and their characteristic species, as well as, particularly, specific species. Among these HTCI, there are some types that are directly, (Group 31 of Annex 1, standing waters) or indirectly associated with aquatic ecosystems.

The “ecological status” (assessed according to the WFD) is an expression of the quality of the structure and functioning of the aquatic ecosystems associated with surface waters. Meanwhile, the “conservation status” (HD) is the set of influences on a natural habitat type and on their typical species that can affect its natural distribution, its structure and function in the long term, as well as the survival of its typical species. There is a partial convergence of the objectives set by both Directives with the achievement of the good status for waterbodies and the conservation of HTCI and species included in Annexes II and IV of the HD as the final goals (Stefanidis et al. 2021), by considering management and protection measures to improve water-dependent habitats, species and water quality (European Commission 2011).

The definition and classification of ecosystems and their associated habitats is essential, first to identify them, then to allow a proper assessment and management. HTCI in general, and habitats associated to aquatic ecosystems in particular, are usually described based on the structuring role of plants in the ecosystems (DG Environment 2013). As in other HTCI, in lentic habitats, plant communities can also play a determining role, but other defining elements of the habitat type are also needed for a proper habitat characterisation. Therefore, and especially in the case of HTCI in group 31 (standing waters), attention must be also paid to the global ecological characteristics of the habitat type, knowing that the occurrence of a HTCI is not solely described by the presence or absence of certain taxa, but rather by a sort of biotic and abiotic features. Consequently, the assessment of the conservation status must be based on the consideration of all those abiotic and biotic properties as defining the habitat /ecosystem type.

Within the group of lentic ecosystems, which can be associated with the habitat types of standing waters (group 31 of Annex I of the HD), there are some characteristic lake and pond types, very rare worldwide, featured by their karstic character on areas rich in gypsum, providing specific ecological properties being key in their definition as a specific type of ecosystem and HTCI (Camacho et al. 2009). In this work we focus on this HTCI 3190, “Karstic lakes on gypsum”, one of the less known HTCI of Annex I of the HD

from an ecological point of view. Officially, there are only 19 sites within the N2000 network classified as HTCI 3190 throughout the EU, 9 in Germany, 5 in Spain, 3 in Latvia, and 2 in Lithuania (European Environmental Agency 2022).

The objectives of this paper were (1) to improve the information and knowledge of this restrictive HTCI (3190), with a detailed ecological description, (2) to identify the habitat and assess its global conservation status in Spain from the four parameters by the established protocols, following a scientific approach (Range of distribution, Area of occupancy, Structure and function, and Future prospects), and (3) to make a critical analysis of the methodologies established for the evaluation and the global value of the conservation status.

Materials and methods

Ecological definition

Following the Interpretation manual of European Union habitats EUR28 (DG Environment 2013), a deeper ecological characterisation of the Spanish karstic lakes on gypsum from the ecological features described in the scientific literature, accompanied with several field campaigns, was carried out. The main ecological features, including abiotic and biotic parameters, as well as the presence of the typical species, were used for the classification of the lentic habitat sites featured as HTCI 3190.

Validation of sites classified as HTIC 3190: karstic lakes on gypsum

A validation of lakes with potential features linked to the HTCI 3190 previously selected from a database was carried out by overlaying the localities to the Geological Map of Spain 1:50,000 (GEODE) to ensure they were located on karstic areas with gypsum content. A deeper study of the rest of abiotic and biotic parameters, from bibliographic references and field data, was done to ensure they fit to the ecological description of the karstic lakes on gypsum. Some small ponds or other localities not included in the database up to the moment of the study could not be included in this assessment, though ongoing updates of the database would slightly increase the number of lakes identified as HTCI 3190 in Spain.

Selection of a minimum number of sites and data images sources

In order to select a representative number of Iberian sites for the assessment of the conservation status among all the

sites identified as HTCI 3190, specific criteria were used to avoid biases in the assessment and extrapolation of the conservation status. The minimum number of statistically representative sites (n) was obtained from the total population (total number of lakes on gypsum karst officially catalogued in Spain until the moment of the work) using the following formula (Camacho et al. 2019a):

$$n = \frac{Z_{\alpha}^2 N p q}{e^2 (N - 1) + Z_{\alpha}^2 p q}$$

where:

N =population size (total number of lakes on gypsum karst in Spain).

Z_{α} = confidence level, expressed in values relative to the desired confidence percentage. The most used values are: 1.28 for a confidence level of 80%, 1.44 for 85%, 1.65 for 90%, 1.69 for 91%, 1.75 for 92%, 1.81 for 93%, 1.88 for 94%, 1.96 for 95% and 2.58 for 99% (Camacho et al. 2019a).

p =probability of success. As any study characteristics for success are defined in this case, by default it is usually assumed that $p = q = 0.5$.

q =proportion of localities that do not have the probability of success, $q = 1 - p$.

e =desired sampling error (in percentage).

Once the minimum number of sites to be assessed was determined, specific criteria to select the sites were defined (Camacho et al. 2019a) as follows:

- Extent, covering the largest area possible per site within the type, avoiding evaluating a greater number of different sites.
- Representativeness in the Natura 2000 Network and other protection figures at the international (Ramsar), national or regional level, also considering sites not officially classified as such.
- Threat status (or danger of disappearance), with a selection of sites in, a priori, both good and poor condition, indistinctively.
- Environmental-ecological diversity subtypes, e.g., shallow and deeper lakes, small ponds and bigger lakes).
- Existing information.
- Environmental and geographic variability.
- Accessibility and representativeness of the localities.

Each of these criteria were valued and weighted to obtain the final sites to be included in the assessment as representative of the habitat type.

Once all the sites classified as HTCI 3190 were designed, and the sites for their assessment were selected, the assessment of the four parameters of the conservation status

established for the reporting of the Article 17 of the HD was carried out. The assessment was obtained by determining, for the four parameters ('Range of distribution', 'Area of occupancy', 'Structure and function', and 'Future prospects') an evaluation as favourable, unfavourable-inadequate or unfavourable-bad status, by comparing the period 2013–2018 (following the Article 17 of the HD) with Google Earth images collected along this period for the determination of the 'Range of distribution' and 'Area of occupancy' parameters. Further than the assessment of changes along the period 2013–2018 used for the reporting according to the Article 17 of the HD, a historical recreation based on images collected in several flight missions was build-up. These missions were: American Flight 1956–1957; *Inter-ministerial* Flight 1973–1986; National Flight 1981–1986; Five-Year Flight 1998–2003, and current (since 2012) high-resolution images series from the Spanish National Aerial Orthophotography Plan (PNOA), available at the Spanish Centre for Geographic Information (<https://centrodedescargas.cnig.es/CentroDescargas/index.jsp>).

Range of distribution

The 'Range of distribution' of a habitat type is defined as the outer limits of the general area in which the habitat is found. The range of the HTCI 3190 in Spain was obtained from all the localities designed as 3190, using the Range Tool (EIONET 2022) in a GIS environment, following the guidelines of the toolbox (Camacho et al. 2019b). A gap (or maximum distance between grids of distribution) of 40 km was used, as being karstic lakes on gypsum a non-zonal habitat type, following the unified criteria of the European Commission (DG Environment 2017).

The status assessment of the parameter 'Range of distribution' was defined by comparing the range obtained in 2018 with the range obtained in 2013. The favourable reference range (FRR) was considered as the range when the Directive came into force, in 1994.

Area of occupancy

The parameter 'Area of occupancy' of a habitat type accounts for the real area it occupies. Each of the sites included as HTCI 3190 were delineated by using the Google Earth Pro® delineation tools as described by Camacho et al. (2019b), differentiating the total area of the wetland, then breaking it down further into its different components: maximum flooded area, current flooded area, marginal vegetation coverage, other land uses or coverages. As said, not only the current flooded area, but also other areas of the wetland that have the characteristics of the habitat type are considered when assessing the area coverage at each site.

For the assessment of the parameter ‘Area of occupancy’, only the total surface parameter was used, being quantified with images of 2018 (or the closest), and 2013, to assess the differences among the 6-year period established between the assessment reports. As for the ‘Range of distribution’ FRR, the favourable reference area (FRA) was considered as the area when the Directive came into force in 1994. The latter was obtained by viewing and delineating each of the localities with historical images in a GIS (Camacho et al. 2019b). Alternatively, the reference area was also estimated based on the minimum area that can support all species associated with the habitat type. In this method the cumulative surface area of each site added was correlated with the cumulative species present in the set of sites evaluated. The sorting of these sites when adding the surface areas and species to the curve was done randomly using 999 random iterations. An average curve was drawn showing the response of the coverage of the whole set of species with an increase in the total area of the habitat type when adding sites into the curve build-up.

Structure and function

The parameter ‘Structure and function’ refers to the assessment of the status of the intrinsic ecological characteristics of the habitat types or ecosystems. Structure is understood as the configuration of the different biotic and abiotic elements, while the function refers to the processes linked to those elements. According to the procedures for the monitoring of habitat types, the ECLECTIC multimetric index was used to assess the ‘Structure and function’ (Camacho et al. 2009, 2019c). This index considers typical biological, physical-chemical, and hydromorphological variables of the habitat/ecosystem type, whose values are compared with reference values for each variable specific for the habitat type, from which a quantification was obtained. Some of these variables are compulsory, meanwhile others are optional for the final assessment (Camacho et al. 2009). The final value of the ECLECTIC index was obtained after the weighting of each of the variables (Camacho et al. 2009), being the HTCI at each site assessed as being in a favourable status when $ECLECTIC \geq 70$, an unfavourable-inadequate status when $50 \leq ECLECTIC < 70$, and unfavourable-bad status when $ECLECTIC < 50$.

Future prospects

The evaluation of the parameter ‘Future prospects’ for the conservation of lentic habitat types or ecosystems was associated with the estimation of the pressures and threats.

The methodology used was described by Camacho et al. (2009). A group of pressures and impacts was evaluated in a weighted way, considering hydrological and geomorphological pressures and impacts, water quality, pressures and impacts on the structure of the communities, land uses, or presence of invasive species, accordingly to the potential impact each can have on the conservation status of the HTCI 3190. As calibrated, overall scores between 0–20 points, mean a low level of pressures and threats, thus a favourable conservation status. Scores between 21–50, indicated moderate pressures and threats, meaning an unfavourable-inadequate status, whereas scores higher than 51 points show high or very high level pressures and threats, thus an unfavourable-bad status.

Conservation status

For the assessment of the conservation status at the level of the biogeographical region, the assessments carried out in each of the selected sites for the parameters ‘Structure and function’ and ‘Future prospects’ were weighted by its occupied surface area:

Global parameters assessment

$$= \sum_{i=1}^n index\ value\ site * \% \ surface\ site\ [up\ to\ 18.7\%]$$

Considering the great difference between the surface areas in the different sites due to the nature of THIC 3190, in which there are small ponds of a few square metres, to large lakes with extensions of dozens of hectares, a factor was applied limiting the surface area over which the results could be extrapolated. This factor was three times the percentage of a site in relation to the total, if they all had the same surface area ($1/16$ selected sites)*3 (%). The results of the assessment of the parameters ‘Range of distribution’ and ‘Area of occupancy’ were obtained by the sum of the values for all sites assessed.

Once the four parameters included in the general conservation status assessment matrix were evaluated, the results were provided as: favourable, unfavourable-inadequate, unfavourable-bad and unknown, following the guidelines of DG Environment (2017). The global value of the conservation status of the HTCI 3190 for each of the three biogeographic regions in Spain (Mediterranean, Atlantic and Alpine, given that this HTCI is not present in the Canary Islands – Macaronesia) was obtained according to the evaluation matrix, using the combination procedure given in Table 1.

Table 1 Procedure for the combination of the results of the conservation status using the four parameters of the evaluation matrix, for the assessment of the conservation status for a HTCI at the biogeographical region scale. *Source* DG Environment (2017)

Status of the parameters	All favourable and one unknown	One or more inadequate, but no bad	One or more bad	Two or more unknown combined with favourable, or all unknown
Overall assessment conservation status	Favourable	Unfavourable-inadequate	Unfavourable-bad	Unknown

Results

Ecological characterisation

Karstic lakes on gypsum, mostly feed by groundwater, are formed by the collapse of karstic structures that evolved from the dissolution of materials on a basin lying on gypsum (CaSO_4), a highly soluble material that provides the water with a high concentration of sulphates that normally exceed bicarbonates, whose concentration is also high as in other types of karstic lakes. The morphometry of the basin is usually of the sinkhole type, generally with steep slopes walls and a high relative depth, although some basins (ponds) can just display small depressions formed by dissolution when collapse has not yet occurred. The size of the lake is usually small, unless the lake spans throughout several deep sinkholes or even a polje. Their waters are generally subsaline (*sensu* Hammer 1986), although the conductivity range (generally $1.5\text{--}5\text{ mS cm}^{-1}$) can occasionally overlap with the oligosaline or the low hyposaline range (Camacho et al. 2009). In lakes with a high relative depth, the formation of a sulphide-rich hypolimnion allows for its colonisation by green and purple sulphur bacteria. Table 2 indicates the

main abiotic features of the HTCI “karstic lakes on gypsum”, used for the determination of sites assigned to the HTCI 3190. Communities of Charetea, Lemnetea and Potamogetonion are the dominant elements of the submerged vegetation (DG Environment 2013).

The definition of “karstic lakes on gypsum” by the EU Interpretation Manual does not fit to all lakes that lie on gypsum. From the geological and hydrogeological point of view, this name could include a high number of lakes in Spain because gypsum outcrops broadly extend in the Spanish Alpine Orogenes and in some Neogene basins. However, many of these lakes present hypersaline waters; therefore, the Habitats Directive classified them differently as the definition of the HTCI 3190 includes only subsaline lakes.

Deeping on the short definition given by the interpretation manual for Habitats of Community Interest (DG Environment 2013), Spanish karstic lakes on gypsum, are characterised by a high concentration of sulphate, allowing that, in anaerobic respiration processes in the sediments or in the anoxic hypolimnion (for deep enough lakes), sulphate can be used as an electron acceptor (Atlas and Bartha 2002), causing the accumulation of hydrogen sulphide in the deep layers while stratification is maintained, which greatly determines the biological communities in these depths. If altered by increased inputs of nutrients, phytoplankton massive growth in surface waters derived from a hypothetical eutrophication process would considerably reduce light penetration and hinder or prevent the formation of dense deep populations of photosynthetic microorganisms that normally include cryptophyceans, cyanobacteria and/or photosynthetic sulphur bacteria, around the oxic-anoxic interface (Camacho 2006), which characteristic of this habitat.

Under natural (non-altered) conditions, and linked to the arrangement of the populations in the vertical profile mediated by the physical-chemical structuring of the water column, surface waters are usually relatively poor in nutrients, especially in phosphorus. Therefore, phytoplankton growth is controlled by the availability of these nutrients mediated

Table 2 Main abiotic properties characterising THIC 3190, and other characteristic data. *Source* (Camacho et al. 2009)

Variable	Feature
Trophic status	Oligo-mesotrophic
Mineralisation	Relatively high (freshwaters –oligosaline to subsaline). Conductivity: $1.5\text{--}5\text{ mS/cm}$
Content in bases	High
Water colour	Colourless
pH	> 7.5
Transparency	High
Hydroperiod	Generally permanent, sometimes temporary
Lithology	Gypsum and limestones
Substrate	Marls
Depth	Generally deep ($> 2\text{ m}$)
Distribution in the Iberian Peninsula	Gypsum-rich areas

by recirculation. Surface chlorophyll concentrations are naturally in the oligo-mesotrophic range (usually below 10 mg m^{-3}). However, very high concentrations of chlorophyll and/or bacteriochlorophyll of even several hundred mg m^{-3} can be found at depths around the oxic-anoxic interface (Camacho 1997; Chicote 2004). This summer chlorophyll maximum can thus be considered as characteristic of this type of ecosystems in conditions of good functional conservation. In the Iberian stratified karstic sinkholes (both on gypsum and limestone) the formation of these chlorophyll-*a* metalimnetic maxima is common (Camacho 2006; Camacho et al. 2009), generally formed by one or a few species of cryptophyceans (Pedrós-Alió et al. 1987; Gasol et al. 1992; García-Gil et al. 1993; Camacho et al. 2001a; Chicote 2004) and/or cyanobacteria (Camacho et al. 1996, 2000a), which form dense populations at the oxic-anoxic interface coinciding with the bottom of the thermocline. In this type of lakes, the appearance, in anoxic zones, of populations of photosynthetic sulphur bacteria that use hydrogen sulphide as an electronic donor for photosynthesis, is also a common feature (Van Gernerden and Mas 1995; Camacho et al. 2000b).

In karstic lakes on gypsum with metalimnetic chlorophyll maxima, the highest photosynthetic rates, in absolute terms, can be found in the narrow range of depths occupied by these deep populations of algae, cyanobacteria, and/or photosynthetic bacteria (Planas 1973, 1990; Camacho and Vicente 1998), although their productivity (production per biomass unit) is normally lower than that of more superficial layers (Camacho 2006). This, together with the narrow range of depths they cover, means that only a part of the primary planktonic production is located in the deep metalimnion, although in certain systems the metalimnetic contribution may account for most of the planktonic primary production of the lake (Camacho et al. 2001b).

Due to the high slope of the shores, the relative extent of the littoral zone is generally small compared to the pelagic zone (open waters), although the saturated zone colonised by helophytes can be quite extensive, especially in non-collapsed shallow ponds. When the subsidence is small and the depth of the basin formed is low, the flooding is maintained only temporarily or occurs in the central area, originating a shallow lake essentially with littoral characteristics, and a higher relative importance of macrophyte communities. The submerged macrophytic vegetation can include both charophytes and higher plants, as well as several species of emergent helophytes in the littoral zone (Cirujano 1990, 1995; Cirujano and Medina 2002).

The contribution of organic matter from the marginal and riverside vegetation, mainly the remains of leaves from deciduous trees, can generate an important contribution of allochthonous organic materials that, given the often small size of the lakes, can induce an increase in the trophic level

and, indirectly, a greater production of hydrogen sulphide. Even, a few of these lakes can remain completely anoxic during a part of the annual cycle, with high concentrations of hydrogen sulphide and populations of purple sulphur bacteria that can reach up to the surface, giving a characteristic red colour to the waters.

In the Iberian Peninsula, karstic lakes on gypsum show zooplankton populations with a heterogeneous vertical distribution, with species of crustaceans and rotifers with a epilimnetic distribution, whereas others display a metalimnetic distribution (Alfonso et al. 1987; Esteve et al. 1988; Miracle and Alfonso 1993; Gasol et al. 1995; Miracle and Armengol 1995), or also migratory capacity, and even populations of anaerobic ciliates (thanks to mutualistic symbiosis with bacteria; Finlay et al. 1991; Esteban et al. 1993). The latter can colonise the anoxic hypolimnion rich in hydrogen sulphide in a markedly reducing environment. In the systems exclusively fed by groundwater (small sinkholes) without connections to surface watercourses, fish, when they exist, are generally introduced, while in systems with surface water connections, which serve as dispersal, the fish community may be more diverse and more structured by ecological interactions (Granado 2000).

Sites identified as karstic lakes on gypsum in Spain and selection of sites for the assessment of the structure and function, and future prospects

Considering the ecological characterisation, and after the validation process following the procedures indicated in the Methods section, up to 79 lakes from the available data set on which we started (UVEG 2022), some of them grouped in lake complexes, were finally considered in Spain as belonging to THIC 3190 (Supplementary Table 1). Sites are mostly distributed throughout the East half of the Iberian Peninsula, in three of the four biogeographic regions of Spain. Though they are mostly located in the Mediterranean biogeographic region, they also appear in the Atlantic and Alpine regions, but do not appearing in the Macaronesian Canary Islands. Part of the typified sites were located in lakes complexes, associated with geological areas characterised by the presence of gypsum, and the genesis by karst dissolution. Figure 1 shows the sites of this THIC throughout the Spanish territory and their location within the three biogeographic regions of the Spanish part of the Iberian Peninsula and the Balearic Islands (through this HTCI was not identified so far in the Balearic Islands).

Following the number of sites needed for a proper assessment of the for the assessment of the structure and function, and future prospects (with the population size of 79 sites, and a defined error of 15%), and considering the amount of information necessary to carry out the relevant evaluation,



Fig. 1 Location of the lakes or lake complexes assigned as THIC 3190 in Spain, with the delimitation of the biogeographic regions

the selection of a sample size was estimated with a total of 18 lakes representative of the type of habitat/ecosystem, based on the criteria defined in the [material and methods](#) section. Table 3 shows the sites finally selected as representative of the heterogeneity and intrinsic characteristics, protection and availability of information on the type of habitat/ecosystem.

Range and area of distribution of HTCI 3190 in Spain

The sites classified as HTCI 3190, karstic lakes on gypsum, showed an uneven distribution throughout the Iberian Peninsula (Fig. 2), being located mainly concentrated in specific areas.

The Mediterranean region showed sites spread in several areas of its eastern part, with a range of distribution of 3,000 km². The Alpine region showed only one site (Estany de Montcortés, in Lleida), with a range, equivalent to the distribution, of 100 km². Finally, two sites were in the Atlantic region (Laguna de Olandina, in Álava, and Laguna de Arbieta, in Vizcaya), with a range of distribution of 200 km².

The area of the HTCI 3190 (considering the 79 sites classified) distributed in the three biogeographic regions in Spain shows a clear predominance of the Mediterranean region, with more than 94% of the total surface of this HTCI in Spain, and with very specific areas located in the Alpine and Atlantic regions (Table 4). All the karstic lakes on gypsum occupied an area of 308 ha in Spain. The maximum water flooded area was around 250 ha, meanwhile the emerged vegetation (helophytes) coverage was of 83 ha (Table 4).

The assessment of the changes separated by biogeographic regions showed stable values in the Alpine and Atlantic regions, and changes of around 1% in the total surface in the Mediterranean region (Table 5) for the six-years evaluation period. The variations in the current flooding surface showed negative trends in contrast with the increases in the marginal vegetation coverage in this evaluation period, especially in lower latitudes of the Mediterranean region, being the “current flooding area” more linked with hydro-climatic features.

Both range and area covered by the HTCI 3190 did not significantly decrease when compared to the values when the Habitats Directive came into force (1994), as assessed

Table 3 Final selection of sites evaluated as representative from the HTC1 3190 Karstic lakes on gypsum in Spain according to the defined criteria. (ALP: Alpine; ATL: Atlantic; MED: Mediterranean biogeographical region). Codes of the different protection figures (Ramsar, Water Framework Directive, WFD, and Spanish Inventory of Wetlands) are also included in each lake included in each case

Site	Region	Hydroperiod	Province	Lake complex	Natura 2000 network	Ramsar site code	Waterbody code (WFD)	Code Spanish Inventory of Wetlands
Lago de Arreo	MED	Permanent	Álava		ES2110007	1258	ES091MSPF1019	IH211002
Laguna de Arbieto	ATL	Permanent	Vizcaya					
Estanque Grande de Abajo de Estaña	MED	Permanent	Huesca	Estaña	ES2410072		ES091MSPF1014	
Laguna de Tortajada	MED	Permanent	Teruel		ES2420131			
Laguna de Barcena,	MED	Permanent	Burgos	Gayanes				
Laguna de Alboraj	MED	Permanent	Albacete		ES4210011			IH421059
Laguna de La Atalaya	MED	Permanent	Cuenca	Fuentes - Río Moscas			ES080MSPFL11_a	
Laguna de los Capellanes	MED	Temporary	Cuenca					IH423033
Estany de Banyoles	MED	Permanent	Girona	Banyoles	ES5120008	1257	ES100MSPF0450401	
Estanyol de Vilà	MED	.	Girona	Banyoles	ES5120008	1257	ES100MSPF0450401	
Estanyol de La Coromina	MED	.	Girona				ES100MSPFH1040040	
Estany de Montcortés	ALP	Permanent	Lleida		ES5130019		ES091MSPF1029	
Laguna de Zóñar	MED	Permanent	Córdoba	Sur de Córdoba	ES0000034	446	ES050MSPFES0512000007	IH613017
Laguna Grande de Archidona	MED	Permanent	Málaga	Archidona		1911	ES060MSPF0614520	IH617023
Ballesteros-5	MED	Permanent	Cuenca	Arcas	ES4230008		ES080MSPFL13	IH423003 (refers to the complex)
Arcas-2	MED	Permanent	Cuenca	Arcas	ES4230008		ES080MSPFL13	
Arcas-4	MED	Temporary	Cuenca	Arcas	ES4230008		ES080MSPFL13	
Lagunillo de las Tortugas	MED	Permanent	Cuenca	Cañada del Hoyo	ES4230014		ES080MSPFL12	IH423006 (refers to the complex)

by historic aerial images (Supplementary Fig. 1 to 26), therefore, they were assessed as favourable for the three biogeographic regions. Using the alternative procedure of the species-area curve, a ‘favourable reference area’ (FRA) for this THIC at national level could be determined of being around 300 ha, where increases in the total area of the THIC did not associate to large increases in the accumulation of species associated with the habitat type (Fig. 3). Thus, the ‘Area of occupancy’ of this HTC1 in Spain is still above the FRA, and this assessment procedure for the ‘favourable reference area’ also gives a favourable conservation status when all country is considered for this parameter.

Structure and function, future prospects, and overall conservation status

When assessing the ‘Structure and function’ parameter using the ECLECTIC index, the results obtained for each of

the 18 sites selected as representative of the type, compiled in Table 6, showed that none of the assessed sites had an unfavourable-bad status (U2). However, notable differences appear between some of the studied sites, with 50% of them in an unfavourable-inadequate status (U1), and another 50% with a favourable status.

Regarding the ‘Future prospects’ parameter, the results obtained for each of the 18 sites, compiled in Table 7, showed the values obtained from the pressure and threat evaluation method, and their equivalence to the conservation status class, with up to 10 sites with low levels of pressure, which was assimilated to favourable status for this parameter. In the same way, 7 sites, with moderate pressures, showed an unfavourable-inadequate status, and only one showed high pressure levels and threats, and thus, a bad status.

Supplementary Table 4 collects the references to assess the ‘Structure and function’ and ‘Future prospects’ in each selected site for the assessed indices.

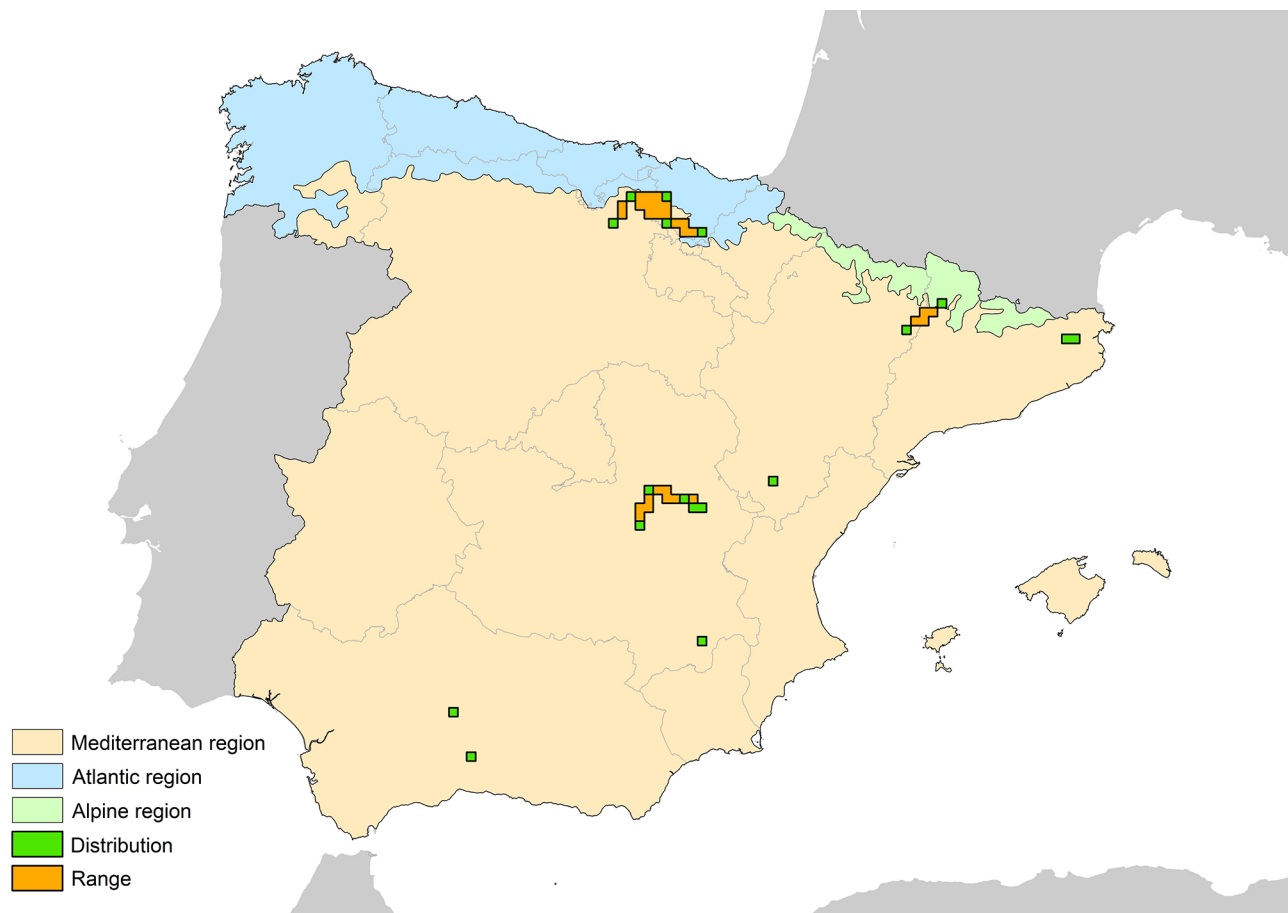


Fig. 2 Map of distribution and range of HTCI 3190 Karstic lakes on gypsum in Spain, generated from the Range tool in a GIS environment

Table 4 Area covered by the HTCI 3190 and its different components at the end of the period 2013–2018 using Google Earth Pro® by biogeographic regions. (ALP: Alpine; ATL: Atlantic; MED: Mediterranean region). Since these are average values, an overlap can occur

Surface (ha)	Total	Maximum flooded area	Flooded area in the assessment	Emerged vegetation	Others
ALP	15.2	12.3	12.3	2.8	0.0
ATL	2.1	1.2	1.1	1.2	0.0
MED	290.9	236.1	203.1	79.0	7.1
Total	308.1	249.6	216.5	83.1	7.2

Comparing the status of the ‘Structure and function’ parameter, from the ECLECTIC index, with the ‘Future prospects’ parameter, from pressures and threats, almost all the sites showed similar status assessment (Table 7).

When considering the set of the statistically representative sites, per biogeographic region, and following the weighting and extrapolation method explained above, both the ‘Structure and function’ and ‘Future prospects’ were classified as unfavourable-inadequate in the Mediterranean region, as the weighted final value of the ECLECTIC index was 62.2, slightly below the limit established by the favourable status (70), and the total value for pressures and threats extrapolated from the weighting by area meant a value of

Table 5 Values of change (in ha) in occupied surface area of HTCI 3190 during the period 2013–2018 using Google Earth Pro® by biogeographic regions in Spain. (ALP: Alpine; ATL: Atlantic; MED: Mediterranean region). Positive values represent an increase in coverage, whereas negative values show a decrease

Assessment period (ha) 2013–2018	Total	Maximum	Current	Vegetation	Others
ALP	0.2	-0.1	-0.1	0.2	0.0
ATL	0.0	0.1	0.0	0.2	0.0
MED	3.2	1.0	-7.7	8.7	0.8
Total	3.4	1.0	-7.8	9.1	0.8

Fig. 3 Example of the results of one of the iterations for the species-area curve for THIC 3190, obtained by a random sorting iteration method

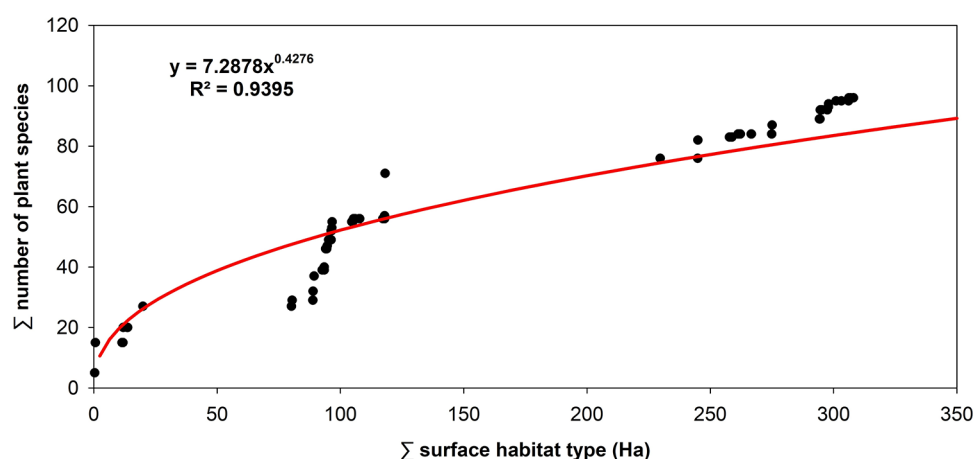


Table 6 Final value of the application of the ECLECTIC index, both with the evaluation only of the compulsory variables, and with the evaluation of all variables (compulsory and optative), based on the available information, for the 18 sites selected as representative. The complete and disaggregated evaluations are compiled in Supplementary Table 2 (FV: favourable status; U1: unfavourable-inadequate status; ALP: Alpine; ATL: Atlantic; MED: Mediterranean region)

Site	Region	ECLECTIC compulsory index value	Status	ECLECTIC all index value	Status
Lago de Arreo	MED	73.9	FV	78.9	FV
Laguna de Arbieto	ATL	85.4	FV	79.2	FV
Estanque Grande de Abajo de Estaña	MED	92.7	FV	86.5	FV
Laguna de Tortajada	MED	60.4	U1	59.8	U1
Laguna de Barcena	MED	87.5	FV	88.1	FV
Laguna de Alboraj	MED	63.5	U1	63.5	U1
Laguna de La Atalaya	MED	57.3	U1	59.8	U1
Laguna de los Capellanes	MED	67.7	U1	66.5	U1
Estany de Banyoles	MED	65.8	U1	61.6	U1
Estanyol de Vilà	MED	63.5	U1	63.5	U1
Estanyol de La Coromina	MED	59.4	U1	59.4	U1
Estany de Montcortés	ALP	87.5	FV	83.3	FV
Laguna de Zóñar	MED	56.3	U1	56.3	U1
Laguna Grande de Archidona	MED	80.2	FV	84.4	FV
Ballesteros-5	MED	95.8	FV	95.8	FV
Arcas-2	MED	100	FV	91.7	FV
Arcas-4	MED	95.8	FV	95.8	FV
Lagunillo de las Tortugas	MED	50	U1	52.8	U1

45, meaning moderate pressure levels, and thus, unfavourable inadequate status. Both parameters were classified as favourable in the representative lakes for the Atlantic (Laguna de Arbieto) and the Alpine (Estany de Montcortés) biogeographical regions (Table 8), as the values of the ECLECTIC and pressures and threats indices indicated the good condition and lower pressures level in the two sites assessed for these regions.

Combining these two parameters with the previous assessment of the ‘Range of distribution’ and ‘Area of occupancy’ in the General Matrix, the final conservation status for the Mediterranean region of Spain of the HTCI 3190, karstic lakes on gypsum, for the period 2013–2018 was assessed as unfavourable-inadequate, whereas for both the

Atlantic and Alpine biogeographical regions, the conservation status was favourable (Table 8).

Discussion

Karstic lakes on gypsum are a very peculiar type of lentic ecosystem, with very restrictive characteristics, included by the Habitats Directive (HD) as a habitat type (3190). These ecosystems are strongly linked with the geological and hydrogeological context associated with gypsum areas (Almécija 1997; Rodríguez-Rodríguez et al. 2006; Andreo et al. 2016), although their ecological definition is also related to their morphology, physical-chemical water features, and biotic processes and components, particularly

Table 7 Final value of the application of the pressure and threat index, based on the available information, and structure and function for comparison, for the 18 sites selected as representative for the assessment. The complete and disaggregated evaluations are compiled in Supplementary Table 3. FV: favourable status; U1: unfavourable-inadequate status; U2: unfavourable-bad status; ALP: Alpine; ATL: Atlantic; MED: Mediterranean biogeographic region; P&A: Pressures and threats; S&F: Structure and function)

Site	Region	P&T index value	P&A Status	S&F Status
Lago de Arreo	MED	10	FV	FV
Laguna de Arbieto	ATL	12	FV	FV
Estanque Grande de Abajo de Estaña	MED	12	FV	FV
Laguna de Tortajada	MED	16	FV	U1
Laguna de Barcena	MED	13	FV	FV
Laguna de Alboraj	MED	43	U1	U1
Laguna de La Atalaya	MED	30	U1	U1
Laguna de los Capellanes	MED	33	U1	U1
Estany de Banyoles	MED	106	U2	U1
Estanyol de Vilà	MED	31	U1	U1
Estanyol de La Coromina	MED	28	U1	U1
Estany de Montcortés	ALP	8	FV	FV
Laguna de Zóñar	MED	26	U1	U1
Laguna Grande de Archidona	MED	8	FV	FV
Ballesteros-5	MED	17	FV	FV
Arcas-2	MED	17	FV	FV
Arcas-4	MED	19	FV	FV
Lagunillo de las Tortugas	MED	31	U1	U1

Table 8 Evaluation of the conservation status of each of the four parameters included in the General Matrix, and global evaluation of the THIC 3190 for the period 2013–2018. FV: favourable status; U1: unfavourable-inadequate status; U2: unfavourable-bad status; ALP: Alpine; ATL: Atlantic; MED: Mediterranean biogeographical region

	Range of distribution	Area of occupancy	Structure and function	Future prospects	Overall conservation status
MED	FV	FV	U1	U1	U1
ATL	FV	FV	FV	FV	FV
ALP	FV	FV	FV	FV	FV

their microbial communities (Van Gernerden and Mas 1995; Camacho et al. 2000b). However, the definition included in the interpretation manual for HTCI (DG Environment 2013), does not reflect exactly the ecological features observed in Spanish karstic lakes on gypsum. Under natural conditions, the large level fluctuations indicated in the Habitat Interpretation Manual (DG Environment 2013) are not so large in the Spanish lakes, being even infrequent in many cases, and highly dependent on the relations with the aquifer. In some cases, these lakes are the origin of more or less important streams or watercourses depending on the upwelling flow and the capacity of the aquifer that feeds them (Camacho et al. 2009). In Spain as well, there are lakes with a maximum depth higher than 7 m. Otherwise, the importance of some abiotic features, characteristic of this HTCI, indicated in Table 2, are good indicators for the identification of sites as 3190, even more than macrophyte communities that, at least for some species, can also be found in other habitat types of group 31 of the annex 1 of the HD (Camacho et al. 2009).

The particularities of this type of habitat, which is located in specific conditions where the karstification process takes place on materials with a high content in gypsum, means that its distribution is not attributable to bioclimatic factors,

rather to specific geological factors. The distribution and range showed how the sites were located in specific areas where the geological characteristics allowed the formation of these systems. Their assessment was determined by comparison with the range when the Directive came into force, defining a reference range. However, the number of 79 lakes identified as HTCI 3190 are still far from the current 5 sites officially classified and protected within the N2000 network for this habitat type in Spain, and just 19 in all the EU (European Environmental Agency 2022), which shows that further declaration of Special Conservation Areas within the Natura 2000 Network is needed to enlarge the protection of this habitat type of community interest. Not only at the European level, but other protected figures in Spain do not include a large number of these ecosystems either. Of the 18 lakes identified as HTCI 3190 studied here with detail as representative, only 7 are included in the Spanish Inventory of Wetlands (Table 3). Up to now, this inventory did not include some of the most important sites of the type, such as the Estaña or Banyoles complexes, neither the Estany de Montcortés. These and other sites, such as the Arbieto, Atalaya or Bárcena lakes, meet the requirements defined for their inclusion in this inventory, as well as having the

peculiarity of being a HTCI 3190. However, since the Spanish Inventory of Wetlands is a legal figure that requires the regional governments to submit to the central government the localities to be included, until each regional government sends this information, a lake/wetland cannot be included in the Inventory, thus is not officially recognized.

The specific area occupied by the sites classified as HTCI 3190 was also calculated by aerial images, following a widespread method in ecology and conservation biology (Camacho et al. 2019b). This method allows the area to be assessed by manual delineation, which can be quite accurate, especially with high quality images. However, it is costly when the number of sites to be surveyed is very large, so other methods that automate the identification and delineation of these surfaces may be more suitable, although the accuracy may be reduced (Doña et al. 2021). The status assessment related to the habitat distribution and coverage was also carried out on the basis of the differences to the moment when the Directive came into force. Looking at the historic aerial images, it seems evident an encompassed balance between disappeared sites (due to clogging processes and changes in land use), and those newly appearing by genesis due to karstic collapse during the last decades (Supplementary Figs. 4 and 26), or restored after having disappeared, like Laguna de Santiago (Supplementary Fig. 15). This encompassing of newly appearance and disappearance is one of the most outstanding dynamic features of this HTCI, as the time scale of genesis is assimilable to the time scale of natural and anthropogenic processes causing its disappearance (see, e.g., Supplementary Figs. 4 and 26), showing how several sites were formed by karstification processes during the last decades). This is one of the reasons why, despite being a geographically restricted habitat found under specific geologic conditions, its conservation status referring to the range and area was assessed as favourable. Particularly for the Atlantic region, in the area occupied by the Laguna de Arbieto, a karstic lake on gypsum disappeared in the 1980s, as observed in aerial images. However, and following the criteria to determine the status, as this site had disappeared before the moment when the Habitats Directive came into force, there were no implications for the assessment of these two parameters. Therefore, methods other than the comparison to the 1994 range and surface to define favourable reference values should be considered, such as, for example, the species-area curve we proposed, a method that is also used for other ecological applications (Tjørve 2003; Ibáñez et al. 2006) which here helped to determine a minimum area capable of harbouring the maximum number of plant species characteristic of the habitat type.

With respect to the assessment of the area of occupancy for the evaluation period 2013–2018, differences among

the surfaces (total, maximum flooded, current flooded, vegetation coverage, others) were also identified, though only the total area was used for the overall conservation status assessment. Results showed how most of the total surface corresponded to the flooded areas (70.6%), followed by 27% of the surface occupied by marginal emerged vegetation, and 2.4% the surface occupied by other uses. Looking at the differences along the period, a trend was found for the increase in the helophyte coverage and a reduction of open waters, especially in lower latitudes of the Spanish Mediterranean biogeographical region. This trend could be attributed to environmental changes, some of them related to climate change, such as the decrease in water supply thus reducing the water depth and favouring the helophyte colonisation, especially that of *Phragmites australis*, a highly invasive, though autochthonous, species in littoral shallow areas of lakes (Cirujano et al. 2010), as well as to a possible acceleration the lakes siltation in the long term due to increased sediment transport in the agricultural areas surrounding many of these sites. However, the large inter- and intra-annual variability associated with hydro-climatic characteristics in the Mediterranean area, as well as other management actions that may influence the hydrological dynamics of wetlands, should be taken into account. Trends should be framed only in the period when they were assessed, as these short-term trends may vary. Therefore, the assessment of the area parameter is only based on the total surface of the wetland, and not on the relative coverages of its components. It would be necessary to continue this evaluation in future periods to see if these trends continue, which would indicate a change in the structure of the habitat type, at least in shallow systems.

The ‘Structure and function’ parameter was assessed by the multimetric ECLECTIC index, obtained from a quantification and weighting of different parameters. Apart from the importance of the chlorophyll-*a* concentration (Poikane et al. 2010; Carvalho et al. 2013), other parameters, such as the biological community composition and coverage of submerged and emerged macrophytes, are relevant in the biological part of this index, given the role of plants in the structure and functioning of the habitats (Camacho et al. 2016). Hydro-geomorphological factors and physical-chemical parameters are also included in the index, given the importance of these components in the lentic ecosystems condition (Verhoeven et al. 2006; Poikane et al. 2020). The evaluation of the parameter ‘Structure and function’ by the ECLECTIC index is carried out based on a sum of weighted values of different metrics, whose final value defines the parameter “structure and function” of the conservation status based on the global score obtained.

Looking at the results of the ECLECTIC index, and their assimilations to status classes, lakes with impacts that

directly or indirectly affect their ecological integrity showed lower index value, and unfavourable status. Estany de Banyoles, with human pressures on its banks and catchment, Laguna de los Capellanes located within a cattle farm with a progressive modification of its hydroperiod and morphology, and Laguna de Alboraj as well as Laguna de Zóñar, with intensive agriculture activity in the surroundings, were assessed as unfavourable-inadequate for the 'Structure and function' parameter. These sites showed, in general, relatively high concentrations of total phosphorus in water and high values of chlorophyll-*a*. In Laguna de Zóñar, the loss of typical species, both plants (submerged macrophytes and helophytes) as well as zooplankton and benthic invertebrates, contributed to the reduction of the value of the conservation status (Junta de Andalucía 2005). Contrarily, sites such as Laguna de Arbieto, in the Atlantic region, or Estany de Montcortés, in the Alpine region, showed a favourable status for the structure and function parameter. In both cases, the evaluated variables identified the ecosystem as displaying a good ecological integrity, due to their biological diversity, the maintenance of their natural hydromorphological functioning, and the values of their physical-chemical parameters within the appropriate range for the HTCI.

The multimetric ECLECTIC index combines the evaluation and application of different metrics referring to the specific elements of lentic ecosystems and their functioning. Some of the main assessing variables included in the index, such as the chlorophyll-*a* concentration, and the nutrients concentrations, might make vary the final value (from favourable to unfavourable) due to their importance in the weighting, especially when not all the variables, both compulsory and optional, are assessed. Some of these variables are also used as the metrics for the assessment of the ecological status according to the WFD (Poikane et al. 2010, 2020; Carvalho et al. 2013). Both approaches, the ECLECTIC method, and the different metrics according to the WFD, coincide in the determination of some common biological, physical-chemical and hydromorphological features, whose separate values integrated in the multimetric ECLECTIC index, allow the global evaluation of the status of ecological health of these lentic ecosystems. However, the ECLECTIC index differs from those used by the WFD, in which the lowest value of those obtained in the evaluations of biological quality elements, physical-chemical and hydromorphological factors, is the one that gives the overall status value (one out, all out). Therefore, the proposed method could overestimate the final status value compared to other multimetric methods (European Commission 2000). The two legal frameworks for the protection of water (WFD) and nature (HD) converge when evaluating and achieving similar objectives (European Commission 2011). However,

WFD and HD are currently implemented separately, which can make more difficult to achieve their respective goals (Stefanidis et al. 2021).

The 'Future prospects' parameter was obtained from the assessment of pressures and threats that were previously demonstrated to affect the ecosystem condition, such as hydrology and geomorphology (Jusik and Macioł 2014; Evtimova and Donohue 2016; Poikane et al. 2020), water quality (Verhoeven et al. 2006), land uses and pollution (Nielsen et al. 2012; Morant et al. 2021) and exotic species (Reid et al. 2019). There was a notable difference in the level of pressure exerted in each of the sites selected as representative of the THIC 3190. Up to 10 from 18 assessed sites showed low levels of pressure, which assimilates to favourable future prospects (e.g., in Laguna de Arbieto, Estanque Grande de Estaña, and Estany de Montcortés). The levels of pressure exerted, both directly on hydrology and on their communities, as well as indirect pressures, were low and did not significantly affect the structure and ecological function of these ecosystems, as the same favourable status was generally obtained for the 'Structure and function' parameter. In the same way, those sites with moderate pressures, and a unfavourable-inadequate status in the 'Future prospects' parameter, showed a unfavourable-inadequate status in the 'Structure and function' parameter, since the pressures exerted on the components of aquatic systems resulted on damages on their structure and functioning (Camacho et al. 2009). This was the case of Laguna de la Atalaya, Laguna de los Capellanes, Laguna de Zóñar, and Lagunillo de las Tortugas, where management actions are needed to reduce or eliminate these sources of pressure affecting their structure and ecological functioning, thus, their conservation status. This multimetric method, like the ECLECTIC index, could overestimate the calculated status, due to the integration of a set of variables. Additionally to the method used here, alternative methodologies have been proposed for the assessment of pressures and threats that can be spatially explicit, thus advising for the identification of the areas for actuation. An example is for instance, assessing the land uses in the catchment area as a proxy to estimate the pressure level over lentic ecosystems by the LUPLES method (Morant et al. 2021), which demonstrated to be correlated with ecological indicators of impacts.

Overall, the conservation status assessed within the four parameters. for the HTCI 3190 in Spain showed its unfavourable-inadequate status in the Mediterranean region, reflected by the moderate pressures and impacts and their response in the structure and functioning of some of the sites included in the assessment. In this region, the area of occupancy was maintained over the decades, because of an equilibrium between new formed sites that counterbalanced the disappeared lakes. Meanwhile, the status

was favourable in the Atlantic and Alpine regions, though this was determined with a low sample size, with only two and one karstic lakes on gypsum assessed, respectively. As indicated above, this HTCI is highly specific and quite particular, thus, the low number of sites classified as HTCI 3190, and the low area occupied was not equivalent to a poor status, as the sites remain over the decades. Thus, by applying the different methods defined in this article, and following the criteria for the definition of the conservation status, it seems that the results mostly reflect the real condition of the HTCI in Spain, considering the particularities of the ecosystem type.

Conclusions

For the ecological characterisation of the lakes, the main parameters identifying karstic lakes on gypsum were physical-chemical features associated to the active gypsum karst areas where they are located, conferring particular hydro-morphometric characteristics, as well as the presence of certain types of submerged macrophytes species, though a revision should incorporate additional ecological features as those indicated in this study. Located in certain areas with specific characteristics, these lakes cover an area of about 300 ha in Spain, being the main catalogued contribution to this habitat type (HTCI 3190) by Western European countries. Their global conservation status was favourable in the Spanish Alpine and Atlantic regions, and unfavourable-inadequate in the Spanish Mediterranean region. This assessment was based on range and area of distribution of the HTCI, plus the assessment and extrapolation of the 'Structure and function' and 'Future prospects' parameters with multimetric indices, which followed the criteria established by the HD.

From the assessment approach defined and applied, management actions of the HTCI should ensure the integrity and protection of the structure and functioning of the ecosystems in current and future scenarios, by minimising threats and maintaining their range and area throughout the biogeographic regions where they are located. However, additional efforts and detailed studies of these systems are needed to identify possible new locations that could be classified as HTCI 3190, especially small temporary ponds associated with geological environments rich in gypsum. A more detailed evaluation of their characteristics and condition is necessary for a more detailed overall assessment of their conservation status. Further, the methods here developed, as well as the specific results of the assessment, would help for the purposes of the Strategic Plan for Wetlands 2030, published

by the Government of Spain in 2023 (MITECO 2023). This plan aims to improve the conservation status and establish restoration targets for Spanish wetlands, which would be especially important for the conservation of this very scarce habitat type both at the Iberian and European level, as Spain plays a prominent role for the preservation of most of its sites in Western Europe.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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