LHYMO: a new WFD-compliant multimetric index to assess lake hydromorphology and its application to French lakes

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Abstract

1. Hydromorphology provides a physical framework for aquatic biocenoses. Its condition directly affects the quality of habitats available for fauna and flora and its assessment is therefore required by the EU Water Framework Directive (WFD) to assess the ecological status of lake water bodies.

2. In this study, we developed an index of Lake HYdroMOrphology (LHYMO) to provide a quantitative assessment of the hydromorphological status of natural and non-natural lakes that can be used for the implementation of the WFD and is consistent with CEN standards.

3. This new index addresses the shortage of methods describing adequately hydromorphological alterations on lakes on both hydrology and morphology. LHYMO includes nine metrics related to morphological WFD quality elements (QE) and six metrics related to hydrological WFD QE, all of which considered to support biological elements. The reference conditions were defined for each metric using an original approach: the degree of alteration is measured in relation to the natural characteristics of each lake, relative to a state that 'would be expected in the absence of disturbances'.

4. Besides its use for regulatory purposes, this index is also an interesting tool to monitor the efficacy of hydromorphological restoration projects or to help target effective conservation measures on lakes.

5. Application of this index to 72 French lakes provides the first quantitative and homogeneous assessment of the hydromorphological quality of lakes over a whole territory and gives the first overview of the hydromorphological status of lakes in France, with classification into five classes ranging from 'high' to 'bad'.

6. LHYMO is already operational for large French lakes as it relies mostly on reference datasets available at a national scale, and may also be used in a wider scope through gathering or completing data from other sources.

Keywords

assessment, conservation, hydromorphology, index, lakes, multimetric, reference conditions, WFD

1. Introduction

Lakes provide many ecological services and give habitats to numerous plants and animal species. They also support a wide range of services for human needs (*e.g.* water dumping, hydropower, irrigation, recreational activities) that involve modifications of their inherited morphology and hydrological dynamics (Ostendorp et al., 2004). Hydromorphological alterations impact the functioning of lakes in many ways by modifying structural complexity and heterogeneity of littoral habitats, altering the natural water level fluctuations thus affecting the physical structure of food-gathering areas and macrophyte cover in the littoral zone, changing water circulation and thermal stratification patterns, and impacting internal nutrient cycling (Poikane, Zohary, et al., 2020). Consequently, alteration of lake hydromorphology strongly affects the quality of aquatic biocenoses living environment, eventually impacting the composition and structure of biological communities (Logez et al., 2016; Radomski & Goeman, 2001; Twardochleb & Olden, 2016).

Since 2000, the European Water Framework Directive (DIRECTIVE 2000/60/EC, 2000) establishes a regulatory framework to assess the ecological status of continental water bodies in Europe. Along with biological and physico-chemical elements, hydromorphology is one of the key compartments to assess this ecological status. Hydromorphology of lakes is considered through quality elements related to both morphological conditions (structure of the lake shore, quantity, structure and substrate of the lake bed and lake depth variation) and to the hydrological regime (quantity and dynamics of water flow, residence time and connection to the groundwater body). A lake can achieve high ecological status only if the aforementioned quality elements coincide with reference conditions or deviate from them very slightly. The WFD requires each Member State to assess status of its water bodies and set up management plans to achieve at least good chemical and ecological status (or good potential) of these water bodies by 2027.

In Europe, hydromorphological pressures on surface waters are increasing since the last decades (Poikane, Zohary, et al., 2020) and represent one of the most common type of pressure on aquatic ecosystems along with eutrophication, which may itself at least partly result from hydromorphological alterations. According to the report of the European Environment Agency (2018) on the state of Europe's water, hydromorphological pressures affect around 40% of surface water bodies. In addition, the WFD inventory conducted in 2019 for France shows that nearly 50% of lakes at risk of not achieving good ecological status due to hydromorphological issues (Office Français de la Biodiversité, 2019). In this context, there is an urgent need to integrate hydromorphology into the monitoring and assessment of all European water bodies (Belletti et al., 2015).

Since the seminal work of Håkanson (2005) on lake morphometry, and despite the adoption of the WFD in Europe, methods for characterizing lake hydromorphology and its alterations remain few in number (Ciampittiello et al., 2017). In addition, a recent overview of these methods used in Europe show that few of them describe the hydromorphology of lakes in a comprehensive way and that they are often not easily accessible because published in grey literature (Argillier, Carriere, Wynne, et al., 2022) .

Among the most well-known methods, we can mention the Lake Habitat Survey (LHS) (Rowan et al., 2006) and the Lake Shorezone Functionality Index (SFI) (Siligardi et al., 2010), based on field observation data, the HydroMorphology of Lakes (HML) protocol (Ostendorp & Ostendorp, 2015) based on geomatics derived data, as well as methods listed in the detailed study of Bragg et al. (2003). Some indices were furthermore developed to assess the hydromorphological quality of lake ecosystems. We can listed for example the Lake Habitat Quality index (LHQ) and Lake Habitat Modification Score (LHMS) resulting from the application of the LHS, the Morphological Impact Assessment System (Lake-MImAS) (Rowan et al., 2012), the Lakeshore Modification Index (LMI) (Peterlin & Urbanič, 2013) or the Morphological Stressor Index (Miler et al., 2013). These indices are based on a combination of several metrics, *i.e.* measurable characteristics whose values varies according to a disturbance gradient (Karr & Chu, 1999), nonetheless mostly refer to morphological features. Hydrological alterations and their quantification have received more attention on Northern European lakes where these alterations are predominant, but the methods, mainly described in technical reports or regulatory documents (e.g. HVMFS (2019), in Swedish) still remain relatively confidential. In addition to these different methods, two European standards have been published (Boon et al., 2019; CEN, 2011, 2017) to ensure a consistent assessment of the ecological status of water bodies across Europe.

However, it was shown that most of the methods do not currently meet WFD requirements and two major limitations to the development of classification systems based on hydromorphological characteristics of the lakes were identified. Firstly, measuring the degree of alteration of an ecosystem, whatever its nature, requires measuring a deviation from a reference status (Boon et al., 2019). It appears that, in aforementioned methods, the definition and use of reference conditions are usually not clearly stated. Actually, defining reference conditions remains one of the main difficulties reported by European experts and a challenge for hydromorphological assessment methods in Europe (Argillier, Carriere, Wynne, et al., 2022), especially for non-natural lakes designed to meet human needs and for which it is essential to take this mandatory constraint into account. Secondly, the hydromorphological state is considered in the regulatory framework of the WFD as supporting biological elements. This notion of supporting biology needs to be explained. However, only a few studies describe precisely the responses of biological communities to certain hydromorphological parameters and some are poorly studied (e.g. the impacts of changes in water residence time). Measurements of biological responses to the various parameters must then be aggregated into a single one, a step that is a significant difficulty given the multiple interactions existing between both the different hydromorphological elements and the biological communities (McParland & Barrett, 2009) with either cumulative or antagonist effects, as well as potential confounding factors.

To our knowledge, many countries still do not use a standardized method to assess the hydromorphological conditions of their lakes (Argillier, Carriere, Poikane, et al., 2022). Therefore, in spite of progress already made, there is always an urgent need to develop new methods that provide a quantitative assessment of hydromorphological conditions of lakes with a measure of the degree of alteration (Lyche-Solheim et al., 2013; Poikane, Zohary, et al., 2020; Reyjol et al., 2014). Although this is a regulatory requirement, quantifying these hydromorphological alterations could contribute to a better understanding of their impacts on biological communities and would also benefit the development of more accurate bioindicators, most of them being currently mainly sensitive to lake nutrient enrichment (Poikane, Herrero, et al., 2020). Looking at lakes hydromorphology may also be relevant for other specific purposes, for example to study the risk of alterations of ecosystem functioning, to monitor mitigation operations or simply to assess the quality of habitats in the perspective of biodiversity conservation.

In this paper we introduce the new multimetric LHYMO (Lake HYdroMOrphology) index, that has been developed to address the shortage of methods that adequately assess both hydrological and morphological alterations on lakes and meet regulatory requirements. We designed several metrics to represent and measure the extent of different types of hydromorphological degradation, at various functioning scales, and likely to have a significant impact on biological communities. Although designed for a potentially wider use, a particular effort was made to adapt and make operational this index for the assessment of the hydromorphological status of French lakes. The results of its application over the French metropolitan territory is presented in the last section.

2. LHYMO: the methodological framework

Five main steps were followed to develop this index (Figure 1), from the identification of morphological and hydrological alterations to the computation of the final score. Three nesting levels were considered in this approach: the alteration level (steps 1 to 3), the WFD hydromorphological QE level (step 4) and finally the lake level (step 5). Steps 1 to 3 are related to the identification of alterations, definition of reference conditions and quantitative measurement of these alterations through the calculation of metrics. These three steps were conducted for each alteration identified. Aggregation of the metrics in a single LHYMO score for each lake was done according to directions given in steps 4 and 5. Each of the five steps are described in the following sections 3 to 6.

Our approach and the decision process occurring all along the development of the index were driven by 3 factors: the WFD requirements and normative constraints (Boon et al., 2019), the existence of very heterogeneous hydromorphological and environmental characteristics and the availability and accessibility of the data required for metrics calculation.

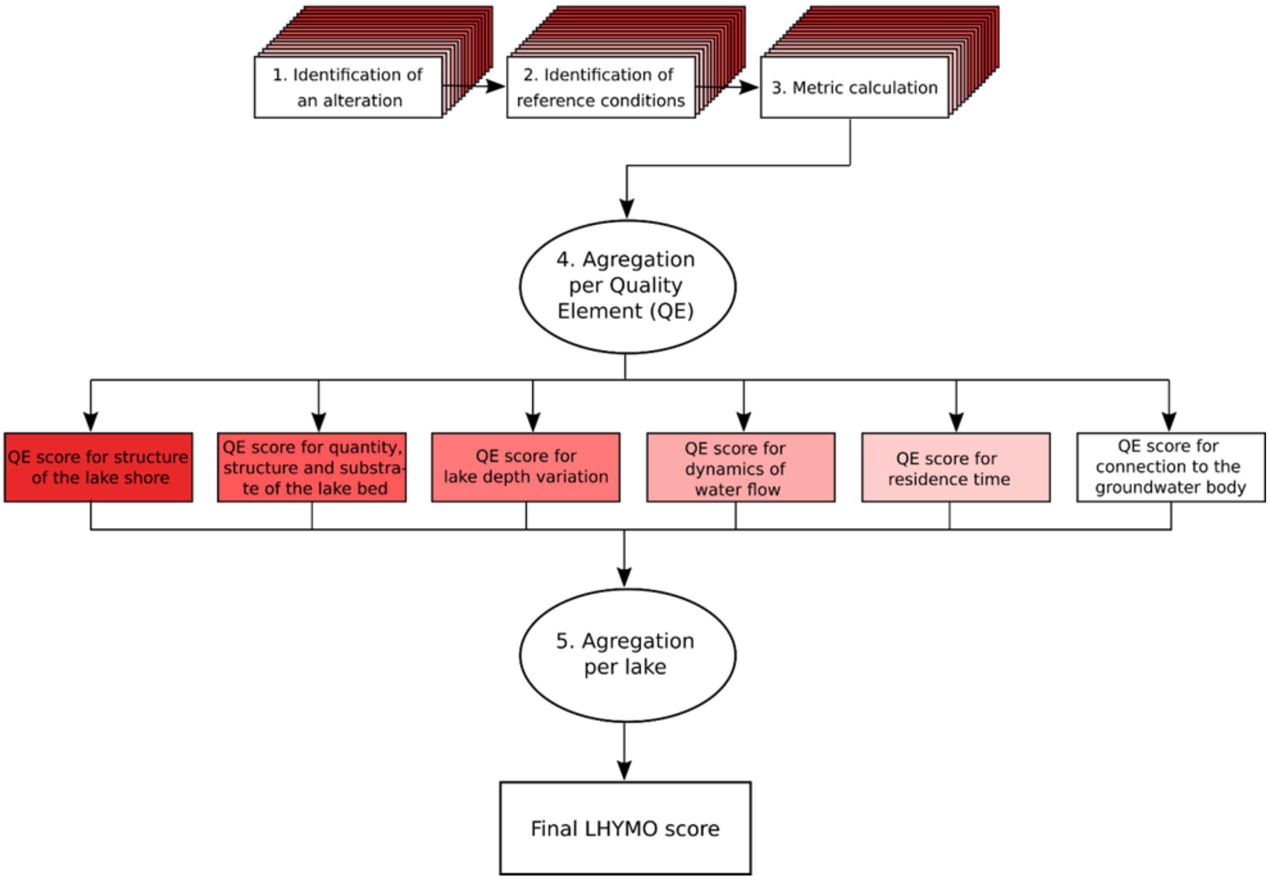

Figure 1. Flowchart of LHYMO calculation method.

3. Identification of hydromorphological alterations and candidate metrics

In a first step, we listed significant hydromorphological alterations likely to affect lake water bodies, ecosystem functioning and more specifically the biological communities (Table 1). This inventory was carried out on the basis of a literature review, particularly scientific studies on the impact of anthropogenic pressures on lake hydromorphology (Bragg et al., 2003; Denys et al., 2014; Nicolas et al., 2015; Ostendorp, 2004; Ostendorp et al., 2004; Peterlin & Urbanič, 2013; Rowan et al., 2006), supplemented by existing expert knowledge.

Table 1. Alterations identified and their correspondence within the six WFD quality elements for the assessment of hydromorphological quality of lake water bodies.

Hydromorphological alterations	Structure of the lake shore	Quantity, structure and substrate of the lake bed	Lake depth variation	Quantity and dynamics of water flow	Residence time	Connection to the groundwater
Material dumping		X	X			
Material extraction		X	X			
Bank erosion	X					
Bank compaction	X					
Change in riparian vegetation	X					
Change in aquatic vegetation	X					
Bank artificialization and fragmentation	X	X				X
Lake bed artificialization		X				X
Fine particles supply		X	X			X
Change in water quantity				X	X	
Modification of tributaries				X		
Flow obstacles				X	X	
Water level fluctuations				X		

Following this inventory, a first set of metrics was defined to account for the impact of each of the hydromorphological alterations identified on the six hydromorphological QE to be considered in order to meet the requirements of the WFD (Table 2). As some alterations may have an impact on several QE, as they influence differently several aspects of the ecosystem (Bragg et al., 2003), several metrics were considered in order to assess the impact of these alterations on the various components of lake hydromorphology, when relevant, while avoiding redundancy. For example, fine materials supplies were considered independently according to their impact on the substrate of the lake bed (siltation), on the lake depth (infilling) or on the connection to groundwater (clogging).

Table 2. Candidate metrics designed to assess identified alterations for the different QE and their final status in the index.

Components	QE	Metrics	Final status
Morphological conditions	Structure of the lake shore	Proportion of artificialized banks	Included
		Proportion of compacted banks	Included
		Proportion of eroded banks	Included
		Condition of the riparian vegetation	Included
		Aquatic vegetation composition	Included
	Quantity, structure and substrate of the lake bed	Proportion of sand dumping	Included
		Proportion of gravel dumping	Included
		Proportion of material extraction	Included
		Proportion of silted lakeshore	Included
	Lake depth variation	Volumes of material supply	Not included
		Volumes of extracted materials	Not included
		Filling rate increase	Not included
Hydrological regime	Quantity and dynamics of water flow	Proportion of modified tributaries	Included
		Flow obstacles in the watershed	Included
		Change in daily to monthly water level fluctuations	Not included
		Change in seasonal water level fluctuations	Included
	Residence time	Volumes of water abstraction	Included
		Volumes of water supplemented	Not included
		Volumes of upstream water impoundment	Included
	Connection to the groundwater	Proportion of concreted banks	Included
		Proportion of concreted basin surfaces	Not included
		Proportion of surface clogged by fine particles	Not included

4. Definition of reference conditions

Normative definitions of the WFD describe hydromorphological reference conditions as ‘totally or almost totally undisturbed conditions’, with ‘no or only very little anthropogenic alteration’ and with a ‘minor ecological impact’ (European Communities, 2003b). In the WFD context, reference conditions are usually considered relative to a pool of water bodies defined as ‘references’. In France, only very few lakes (less than 6% of lakes included in WFD monitoring) were identified as ‘references’ following regulatory criteria (Circulaire DE/MAGE/BEMA 04/N 18 n° 2004-08 DCE, 2004) and it turns out that they do not encompass the typological diversity of French lakes that cover a wide range of morphological, geological, climatic, hydrological and catchment characteristics (Holley et al., 2006). According to the WFD, reference conditions are also expected to be established on a type-specific basis for each surface water body. With regard to French lakes, Nicolas et al. (2015) have shown the difficulty of establishing a typology based on hydromorphological criteria, that is both representative of the great diversity of lakes and at the same time clusters enough lakes in each type to allow comparisons or conduct relevant analysis.

To overcome these difficulties, reference conditions for LHYMO were defined for each hydromorphological alteration and each lake, as a theoretical expected status, based on criteria highlighted by expert knowledge and supported by the literature. Using this method, each metric reflects a difference between the status observed for a lake and the status of that same lake in an ideal unaltered situation. In some cases, different reference conditions may also be set for specific categories of lakes. For some metrics, intrinsic characteristics of the lake environment are also considered as a mitigating or worsening criterion to assess the degree of alteration. Non-natural lakes are also an exception given their origin and purpose, which are strongly linked to human use. For non-natural Heavily Modified Water Bodies (HMWB) and Artificial Water Bodies (AWB) (European Communities, 2003a), the reference conditions shall correspond to the maximum ecological potential taking into account the Mandatory Technical Constraints (MTC) related to the use (European Communities, 2005). Thus, some metrics had to be adapted for lakes in these categories. For example, in the case of a reservoir, the presence of the dam is essential to maintain the use and existence of the lake, so its direct physical impacts on the morphology of the lake cannot be considered as an alteration. Reference conditions for each metric are described in section 5; values given in brackets are adapted for French lakes.

5. Selection and calculation of metrics

5.1 General principle

From the list of candidate metrics (Table 2), a selection was made based on data availability criteria. The use of already available data and geolocated databases is one of the recommendations of the EN16039 standard in a context of the development of a regulatory tool (CEN, 2011). Thus, as developed in the first instance for French lakes, input data used to develop this index are primarily and mostly derived from national reference datasets covering the entire French territory. Some rely on data resulting from the application of standardized protocols, referenced in the WFD regulatory monitoring program and designed to describe riparian habitats and their alterations (AFNOR, 2016b, 2016a). Some data relating to hydrology, which are difficult to measure or for which there is no homogeneous national dataset, had to be obtained by modelling or collected from local management organizations or agencies.

Correlations between values within each QE were checked using Pearson correlation coefficient calculation. Each test gives a correlation coefficient value lower than the absolute value of 0.25, indicating low correlation and avoiding redundancy within a QE (see **Appendix 1**).

5.2 Metrics relating to morphological quality elements

5.2.1 Structure of the lake shore

Lakeshore areas are particularly productive and of primary importance for many ecological processes (Wetzel, 2001). The physical structure of lakeshore habitats, determined by the composition and distribution of substrate and vegetation, is one of the key elements influencing biological assemblages (fish, invertebrates, macrophytes) in the lake (Rennie & Jackson, 2005; Schmieder, 2004; Winfield, 2004). Given their localization at the interface between terrestrial and pelagic environments, lakeshore areas are subject to several types of human pressures (Ostendorp et al., 2004), more exposed to the risks of alteration and therefore particularly sensitive (Strayer & Findlay, 2010). Five metrics targeting different structural elements of the shoreline and riparian zone of lakes were calculated to assess the alteration of lakeshore structure and condition.

Metric 1.1 - Bank artificialization

The presence of artificial structures to reinforce the bank against erosion or the risk of collapse, and/or to support economic or recreational human activities, alters the shape and structure of the littoral zone. These structures may limit the availability and attractiveness of habitats and the functions they provide for aquatic biocenoses (Brauns et al., 2007). They also contribute to the fragmentation of the bank, thus hindering the circulation of fish and macroinvertebrates between habitats of potential interest. For natural lakes, the reference condition corresponds to the absence of artificial structures of any kind. However, in the case of artificial or heavily modified lake created by damming, hydraulic structures (dykes or dams) shall be considered a 'Mandatory Technical Constraint' necessary for the maintenance of the lake ecosystem and thus cannot be considered an alteration. Thus, two different calculation formula are used depending on the natural (Equation 2a) or heavily modified/artificial (Equation 2b) origin of the lake. Both formulations take into account both the percentage of the shoreline affected by artificial structures and the spatial distribution of those structures that influences the fragmentation level of the bank and habitats. Bank fragmentation calculation is adapted from the degree of landscape division as defined by (Jaeger, 2000) which reflects the probability that two random locations in a landscape are located in two dissociated areas (Equation 1).

$$D = 1 - \sum_{i=1}^{n} \left(\frac{A_i}{A_t}\right)^2 \qquad (1)$$

With A_i the surface area of each patch and A_t the total surface area of the landscape. This index, initially designed for surface features, can easily be transposed to linear features.

$$M1.1 = \frac{L_{artif} * 100}{P} * \left(1 - \sum_{i=1}^{n} \left(\frac{L_{unartif\_i}}{P}\right)^2\right) \qquad (2a)$$

$$M1.1 = \left(\frac{L_{artif} * 100}{P} - \frac{L_{dam} * 100}{P}\right) * \left(1 - \sum_{i=1}^{n} \left(\frac{L_{unartif\_i}}{P}\right)^2\right) \qquad (2b)$$

With L_{artif} the cumulative length of artificialized banks, L_{dam} the length of the dam, $L_{unartif\_i}$ the length of each unartificialized section of the bank *i* and *P* the total length of the shoreline, expressed in the same unit.

The value of the metric ranges from 0 to 100 and increases as the degree of alteration worsens.

Metric 1.2 - Bank compaction

Compaction of the banks may result from repeated trampling caused by animals or humans (O’Toole et al., 2009), livestock grazing (Trimble & Mendel, 1995) and/or heavy mechanical equipment. Compaction tends to densify the substrate, limits the root development of aquatic or riparian vegetation and therefore floristic growth on the banks.

The reference condition for all lakes corresponds to the absence of bank compaction related to anthropogenic activities. The metric is calculated as the percentage of artificially compacted shoreline (Equation 3).

$$M1.2 = \frac{L_{compacted} * 100}{P} \qquad (3)$$

With $L_{compacted}$ the length of the shoreline compacted due to anthropogenic activities and *P* the total length of the shoreline, expressed in the same unit. The value of the metric ranges from 0 to 100 and increases as the degree of alteration worsens.

Metric 1.3 - Bank erosion

Severe unnatural erosion of the banks may be related to various anthropogenic activities, such as water regulation or power boating (Bilkovic et al., 2019). Extensive water movement and waves weaken the structure of the banks, making them unstable, prone to collapse and likely to be subject to a massive input of sediment into the lake and siltation on areas of high ecological importance. Bank erosion also alters the shape of the shoreline and the littoral zones and exposes the root system of aquatic and riparian vegetation possibly leading to uprooting.

The reference condition for all lakes corresponds to the absence of strong bank erosion, except for those resulting from natural phenomena (wind action, etc.) not being considered. The metric is calculated as the percentage of severely eroded shoreline (Equation 4).

$$M1.3 = \frac{L_{eroded} * 100}{P} \qquad (4)$$

With L_{eroded} the length of eroded banks and P the total length of the shoreline, expressed in the same unit. The value of the metric ranges from 0 to 100 and increases as the degree of alteration worsens.

Metric 1.4 – Absence of riparian vegetation

Riparian forests are widely recognized to support bank stability through mechanical and hydrological beneficial effects of their root system (Simon & Collison, 2002) and greatly contribute to the filtration of sediments and pollutants coming from adjacent land areas, with positive impacts on water quality (Lowrance, 1998). Alteration of the riparian forest also reduce shading and therefore increase the temperature on the bank areas, eventually causing physiological stress for many organisms (Naiman & Decamps, 1997).

In temperate climates, the reference condition corresponds in most of the case to the presence of a continuous forested strip on the bank of the lake, except for high-altitude lakes and lakes fully or partially surrounded by wetland. Several abiotic factors related to altitude inhibit tree growth in mountain areas; hence, lakes located over the altitudinal limit of tree growth are naturally lacking riparian woodland. Wetlands as marshes, bogs or fens are often dominated by herbaceous plants or mosses (Keddy, 2010) and do not consistently develop wooded areas. Thus, when connected to a lake, wetlands should be considered as a continuation of the riparian vegetation. It should be noted that dikes and dams built on lakeshores also prevent the establishment of riparian vegetation; however, as the impact of these infrastructures on the structure of the banks is already assessed with metric 1.1, the relevant sections shall not be considered here. The metric calculation (Equation 5) takes into account both the percentage of the shoreline without riparian cover and the longitudinal continuity of the riparian forest, that is one of the main characteristics of intact aquatic environments corridors, given its ecological significance (González del Tánago & García de Jalón, 2006). As for metric 1.1, continuity is assessed through fragmentation and calculated according to Jaeger's (2000) degree of landscape division.

$$M1.4 = \left(\frac{\left(L_{wo\_ripi} - L_{dam}\right) * 100}{P}\right) * \left(1 - \sum_{i=1}^{n}\left(\frac{L_{ripi\_i}}{P - L_{dam}}\right)^2\right) \qquad (5)$$

With L_{wo_ripi} the cumulative length of bank sections without a riparian forest in a 20 m width corridor, L_{dam} the cumulative length of dikes and/or dams, L_{ripi_i} the length of each continuous riparian section on the bank and P the total length of the shoreline, expressed in the same unit. The value of the metric ranges from 0 to 100 and increases as the degree of alteration worsens.

Metric 1.5 - Change in aquatic vegetation

Aquatic vegetation has a major role in many physical and chemical processes, such as water purification by regulating nutrient cycles (nitrogen and phosphorus) or sediments trapping. It is an essential key component of lakeshore habitats, as its distribution, richness and complexity strongly influence fauna assemblages (Weaver et al., 1997). Anthropogenic management of aquatic vegetation, through mowing or herbicide application, by locally destroying habitats and reducing the diversity and continuity of vegetated areas, can thus cause a significant imbalance for the lake and the fauna it supports.

Under reference condition, aquatic vegetation is expected throughout the littoral zone, if slope and substrate conditions are suitable. The presence of artificial infrastructures can also represent a limiting factor for the development of vegetation, however in order to avoid redundancy with metric 1.1, only the non-artificialized portions of the shoreline of the lakes are evaluated. The metric calculation (Equation 6) takes into account both the aquatic vegetation cover of the littoral zone and vegetation diversity according to Simpson's index (Simpson, 1949), as well as the proportion of colonizable sections of the lakeshore.

$$M1.5 = \left(\frac{P_{colonizable}}{P}\right) * \left(1 - \frac{L_{aqua\_veg}}{P}\right) * \left(\sum_{i=1}^{n} \left(\frac{L_{aqua\_veg\_i}}{L_{cumu\_aqua\_veg}}\right)^2 + 1\right) \qquad (6)$$

With L_{aqua_veg} the length of the lakeshore with aquatic vegetation cover, P the total length of the shoreline, $L_{aqua\_veg\_i}$, the length of the lakeshore covered by each floristic group i, $L_{cumu\_aqua\_veg}$ the cumulative length of the lakeshore covered by each of the floristic groups and $P_{colonizable}$, the length of the lakeshore with gentle slopes (<10%) and low granularity substrate (<250 mm), expressed in the same unit. The value of the metric ranges from 0 to 1 and increases as the degree of alteration worsens.

5.2.2 Quantity, structure and substrate of the lake bed

Lake bottom substrate is a physical support for many ecological functions occurring during the life cycle of aquatic organisms (feeding, spawning, resting, hiding...) and also partly determines the presence of macrophytes. Altering the distribution, quantity and/or granulometry of this substrate, especially in the littoral zone, can lead to the loss of essential habitats for biological communities, with significant effects on the composition of fish (Jennings et al., 1999; Logez et al., 2016) and macroinvertebrate (McGoff & Sandin, 2012) assemblages as well as on the productivity of the lake. Quantity, structure and substrate of the lake bed is assessed using four metrics taking into account different practices, phenomena and substrate categories.

Metric 2.1 - Sand dumping

Sand dumping along the shoreline of lakes is a common practice to create or maintain beaches (Bird & Lewis, 2015). However, adding a large amount of exogenous sand, especially if not the original substrate of the lake bottom, strongly alters the size and characteristics of the substrate in the target area, with an impact on habitats available for the fauna and flora (Dean, 2002; de Schipper et al., 2021).

The reference condition for all lakes corresponds to the absence of sand dumping areas. Nevertheless, the metric calculation (Equation 7) takes into account both the proportion of sand dumping areas and the proportion of sand on the whole lakeshore zone as a weighting element.

$$M2.1 = \frac{L_{sand\_dump}}{P} * \left(1 - \frac{L_{sand} - L_{sand\_dump}}{P}\right) \qquad (7)$$

With L_{sand_dump} the length of the shoreline showing anthropogenic sand deposits, L_{sand} the length of shoreline with sand substrate and P the total length of the shoreline, expressed in the same unit. The value of the metric ranges from 0 to 1 and increases as the degree of alteration worsens.

Metric 2.2 - Gravel dumping

Gravel dumping can result from lakeshore development, lake use as in the case of gravel pits and sometimes even from malicious acts such as illegal dumping of building rubble. As with sand, dumping gravel alters the nature and size of the substrate, depending on the original substrate.

The reference condition for all lakes corresponds to the absence of a gravel dumping zone. The metric calculation (Equation 8) is similar to the previous one (metric 2.1).

$$M2.2 = \frac{L_{gravel\_dump}}{P} * \left(1 - \frac{L_{gravel} - L_{gravel\_dump}}{P}\right) \qquad (8)$$

Whith L_{gravel_dump} the length of the shoreline showing anthropogenic gravel deposits, L_{gravel} the length of the shoreline with gravel substrate and P the total length of the shoreline, expressed in the same unit. The value of the metric ranges from 0 to 1 and increases as the degree of alteration worsens.

Metric 2.3 - Material extraction

Extraction of materials (sand, sediment, gravel or rocks) on the lakeshore zone alters the shape of the lake, both horizontally (shoreline development index) and vertically (slope index) and may indirectly modify wave action on the bank, eventually increasing erosion and disturbing sediment balance (de Leeuw et al., 2010; Peduzzi, 2014). Depending how deep materials are extracted and sediment deposition, the nature of the substrate may also change. This activity is therefore likely to alter the diversity and distribution of habitats available for fauna and flora, and even lead to the destruction of key habitats.

The reference condition for all lakes corresponds to the absence of material extraction area of any kind on the lakeshore. The metric is calculated as (Equation 9) the percentage of the lakeshore affected by material extraction.

$$M2.3 = \frac{L_{extracted} * 100}{P} \qquad (9)$$

Whith $L_{extracted}$ the length of the lakeshore affected by material extraction and P the total length of the shoreline, expressed in the same unit. The value of the metric ranges from 0 to 100 and increases as the degree of alteration worsens.

Metric 2.4 - Siltation

As receptacles for liquid and solid flows from their watersheds, water bodies are largely influenced by land use and land cover changes, with potential impact on all biological communities (Bierschenk et al., 2019; Cheruvelil & Soranno, 2008; Johnson et al., 2018; Sperlea et al., 2021). Phenomena such as deforestation, agricultural intensification and/or urban development in the catchment area are likely to increase sediment influx and thus induce silting of lakes (Bragg et al., 2003). Siltation decreases habitat attractiveness to aquatic fauna because of substrate clogging. Resuspension of fines accumulated on the lakeshore can also decrease water transparency and reduces light available for the development of flora.

Under reference conditions, only lakeshore areas located very close to tributary inflows or lying on a predominantly clay and/or silt soil should be covered with silt. The metric (Equation 10) is calculated as the proportion of the lakeshore covered with silt apart from the areas described in the reference conditions.

$$M2.4 = \frac{L_{silt} * 100}{P} \qquad (10)$$

Whith L_{silt} the length of the lakeshore covered with silt, outside the area of influence of tributary inflows (>200m) and distant (>1000 m) from a clay, clay-silt or silt soil and *P* the total length of the shoreline, expressed in the same unit. The value of the metric ranges from 0 to 100 and increases as the degree of alteration worsens.

5.3 Metrics relating to hydrological quality elements

5.3.1 Quantity and dynamics of water flow

Alteration of flow dynamics, and in particular of water level fluctuation regimes, is complex to apprehend because we need to take into account its natural variability linked to climatic conditions and to lake-aquifer hydraulic interactions. This dynamic is also the result of processes operating at different temporal (daily, monthly and annual, or even multi-annual) and spatial scales (from the watershed to the circulation of water within the lake basin) (Grill et al., 2015; Hofmann et al., 2008). Consequently, quantity and dynamics of water flow is assessed through three metrics integrating different scales of functioning.

Metric 3.1 - Change in tributaries

Alteration of stream morphology and longitudinal profile by channelisation has become very common since the intensification of agriculture in the 1970s. These operations can cause serious hydrosedimentary dysfunctions that may persist for decades (Landemaine et al., 2015) and lead to significant change in the dynamics of liquid and solid flows entering the lakes.

The reference condition for all lakes corresponds to the absence of modified tributaries. The metric is calculated as the proportion of modified tributaries weighted by their stream order according to the Strahler method (Strahler, 1957) (Equation 11).

$$M3.1 = \frac{\sum_{i=1}^{n}(Stnm_i)}{\sum_{j=1}^{n}(Stn_j)} \qquad (11)$$

With *Stnm* the Strahler order of each modified tributary *i* and *Stn* the Strahler order of each tributary *j* flowing into the lake. The value of the metric ranges from 0 to 1 and increases as the degree of alteration worsens.

Metric 3.2 - Flow obstacles

Artificial obstacles, such as dams or weirs, are one of the most significant stressor of aquatic ecosystems that impedes hydrological, sedimentary and biological continuity of rivers and lake drainage networks (Søndergaard & Jeppesen, 2007). The impacts of these barriers, particularly large and high-head dams, can occur on a very large spatial scale, sometimes several hundred kilometers downstream, and have cumulative effects that are difficult to assess (Rosenberg et al., 1997).

The reference condition for all lakes corresponds to the absence of anthropogenic flow barriers. The metric calculation (Equation 12) takes into account both the number of barriers in the lake drainage network and the proportion of the lake drainage network located upstream of at least one barrier. Considering that weirs and dams do not necessarily have equally severe impacts (Garcia de Leaniz, 2008; Poff & Hart, 2002), due in particular to the difference in height of the structures, a weighting relative to the type of obstacle is applied, according to a ratio of 1/10. Note that for reservoirs, the dam downstream should not be included.

$$M3.2 = \left(1 - \frac{1}{n_d + 0.1 * n_{sw} + 1}\right) * \frac{L_{idn}}{L_{dn}} \quad (12)$$

With n_d the number of dams, n_w the number of weirs, L_{idn} the cumulative length of the lake drainage network upstream of at least one barrier and L_{dn} the total cumulative length of the lake drainage network. The value of the metric ranges from 0 to 1 and increases as the degree of alteration worsens.

Metric 3.3 - Seasonal shift of water level fluctuations

Water level fluctuations (WLF) are natural patterns in many lakes which are necessary for the survival of many species, however untimely floods and droughts have deleterious effects for biota (Wantzen et al., 2008). Human lake-use for recreational activities, irrigation or hydropower production commonly induce artificial management of water levels that may alter the natural seasonal hydrological regime of lakes. WLF can thus be shifted in time with an impact on thermal stratification, lake productivity and habitat availability for organisms at critical periods of their life cycle (reproduction, winter dormancy, etc.).

Under reference conditions, seasonal WLF of all lakes depend mostly on the hydrological regime of their catchment: in temperate climate of the Northern Hemisphere, a rainfall regime should lead to higher water levels in winter than in summer whereas a nival regime should lead to water levels higher in spring/summer than in winter. The metric calculation (Equation 13) assesses the seasonal shift between the water level fluctuations regime of lakes and the hydrological regime of their catchment by comparing, over each year, the difference between the highest and lowest mean monthly water levels of the lake to the difference between the mean monthly water levels of the lake on the months with the highest and lowest inflows respectively.

Considering that a seasonal shift in lakes with low WLF has a lesser impact on biological communities, lakes with annual WLF range not exceeding 3m should be excluded. This threshold was highlighted by a study by (Sutela et al., 2013) that analyzed the impact of annual tidal range on littoral macrophyte and macroinvertebrate communities and fish assemblages in 30 regulated and unregulated Finnish lakes.

$$M3.3 = \left(\frac{\sum_{i=1}^{n} \frac{H_{q\_\max\_i} - H_{q\_\min\_i}}{H_{\max\_i} - H_{\min\_i}}}{n} \right) \qquad (13)$$

With $H_{q\_max\_i}$ the mean water level on the month for each year *i* for which the inflow is the highest, $H_{q\_min\_i}$ the mean water level on the month for each year *i* for which the inflow is the lowest, H_{max_i} the highest monthly mean water level for each year *i*, H_{min_i} the lowest monthly mean water level for each year *i* and *n* the number of years. Note that we consider hydrological years, i.e. from September to August in temperate climate. The value of the metric ranges from -1 to 1 and decreases as the degree of alteration worsens.

5.3.2 Residence time

Residence time of water in a lake is one of the main characteristics that controls the concentrations and accumulative capacity of all the substances entering the lake basin (Ambrosetti et al., 2003). Change in residence time, especially when increasing, can have significant consequences on water quality and the aging of lake ecosystems (Jørgensen, 2003; Zhao et al., 2022). Metrics used to assess residence time are expressed as a ratio of observed residence time to theoretical unaltered residence time and take into account phenomena occurring both in the lake basin and in its watershed.

Metric 4.1 - Water abstraction

Abstraction of large water volumes from lakes, as for irrigation, drinking water supply or hydropower generation, causes a shortening of the residence time by reducing the volume of water in the lake basin. Although increasing water renewal frequency can show some benefits (such as a better oxygenation of the water), changes induce to the hydrological balance limit thermal stratification, with major consequences on biological communities due to deep waters warming, even potentially leading to cyanobacterial blooms (Zohary & Ostrovsky, 2011).
The reference condition for all lakes corresponds to the absence of water abstraction for human needs. We also consider that water in lakes is renewed according to their theoretical residence time.

The metric (Equation 14) is calculated as the ratio of water volume available in the lake basin with and without water abstraction, taking into account the theoretical residence time of the lake:

$$M4.1 = \frac{V_{lake} + \left(n * \frac{V_{lake}}{\tau_{res}}\right) - \sum_{i=1}^{n} V_{extracted\_i}}{V_{lake} + \left(n * \frac{V_{lake}}{\tau_{res}}\right)} \qquad (14)$$

With V_{lake} the theoretical volume of the lake, τ_{res} the theoretical residence time of the lake, $V_{extracted\_i}$ the volume of water abstracted from the lake on year *i* and *n* the number of years. The value of the metric ranges from 0 to 1 and decreases as the degree of alteration worsens.

Metric 4.2 - Upstream water impoundment

Water impoundment due to artificial reservoirs alters the hydrologic regime of watersheds (Magilligan & Nislow, 2005). The residence time of water in lakes catchment areas may then artificially increase.

The reference condition for all lakes corresponds to the absence of artificial water impoundment in their catchment area. The metric calculation (Equation 15) is derived from the equations developed by Vörösmarty et al. (2003), to predict basin-scale sediment trapping efficiency for large reservoirs and corresponds to the ratio of theoretical residence time to regulated residence time from upstream reservoirs.

$$M4.2 = \frac{\tau_{lake}}{\tau_{reg}} = \frac{V_{lake}}{V_{lake} + (\sum_{i=1}^{n} V_i)} \qquad (15)$$

With τ_{lake} the theoretical residence time of the lake, τ_{reg} the regulated residence time of the lake catchment, V_{lake} the theoretical volume of the lake and V_i, the volume of each upstream reservoir *i*. The value of the metric ranges from 0 to 1 and decreases as the degree of alteration worsens.

5.3.3 Connection to the groundwater

Lake water budget is driven by several elements including surface runoff, precipitation, evapotranspiration and groundwater exchanges in varying proportions (see Shaw et al., 2004). Groundwater is the major water source to seepage lakes and groundwater drainage lakes, therefore altering groundwater flows can destabilize their water budget, with major consequences for the hydrological and ecological functioning of the lake and the amount of water available in the lake basin. The connection to groundwater also may play an essential role in the chemistry of lakes and water quality (Fränzle & Kluge, 1997). Assessing alterations of lake-groundwater exchanges of water first requires identifying lake-groundwater connections. Consequently, connection to the groundwater is assessed only for lakes located on an unconfined aquifer where water exchanges are likely to occur.

Metric 5.1 - Bank concreting

Bank reinforcement with concrete, usually undertaken to support human activities and/or infrastructures around the lakeshore, reduces the permeability of the banks and restrict lateral connections between the lake basin and the most superficial groundwater.

The reference condition corresponds to the absence of concrete structures on the banks. The metric is calculated (Equation 16) as the proportion of the shoreline covered with concrete.

$$M5.1 = \frac{L_{concrete} * 100}{P} \qquad (16)$$

With $L_{concrete}$ the cumulative length of the banks covered with impervious concrete structures and *P* the total length of the shoreline, expressed in the same unit. The value of the metric ranges from 0 to 100 and increases as the degree of alteration worsens.

5.4 Standardization of metrics

The values of the 15 selected metrics are standardized by calculating Ecological Quality Ratios (EQR) according to the method proposed by Hering et al. (2006), in order to bring them to a common and comparable scale. EQR are calculated according to Equation (17a) for metrics whose value decreases with increasing degradation or according to Equation (17b) for metrics whose value increases with increasing degradation. Values greater than 1 are reduced to 1 and values less than 0 are reduced to 0. This ratio yields a numerical value between 0 and 1, with a value of 0 corresponding to the most degraded status and a value of 1 to the least degraded status.

$$EQR1 = \frac{Metric - Lower\ Anchor}{Upper\ Anchor - Lower\ Anchor} \qquad (17a)$$

$$EQR2 = 1 - \frac{Metric - Lower\ Anchor}{Upper\ Anchor - Lower\ Anchor} \qquad (17b)$$

In the absence of preconception on the natural variability of the values of the different metrics and of well-established level of impact with regard to biocenoses, the values of the lower and upper bounds used for the calculation of EQRs correspond to the mathematical extremum of each metrics. That means, the lowest and highest theoretical possible values according to the equation for the lower and upper anchor points respectively.

6. Aggregation of metrics and final score computation

For each lake, a single final LHYMO score is obtained by combining the values of the 15 metrics using the 'one-out, all-out' (OOAO) principle. That principle stipulates that when several metric values are calculated in a multimetric index, the lowest of the values, representing the greatest impact, is used to reflect the global status of the water body (European Communities, 2005). This rather severe but very conservative approach (Borja & Rodríguez, 2010; Zacharias et al., 2020) is in line with the precautionary principle, providing protection for each lake to the most dominants pressures (Hering et al., 2010). It was approved and validated by experts, following a national consultation, as the most representative of the hydromorphological status of French lakes. As an intermediate step, the OOAO principle has also been applied at the level of QE by combining independently the metrics of each QE. This step allows to highlights the QE with the lowest scores, which are the most degraded. The final LHYMO score ranges from 0 for very degraded lakes to 1 for lakes with almost totally undisturbed conditions.

A final step required by the WFD is to assign one status class to each water body according to the calculated index values. Although class boundaries are supposed to be established on the basis of observed significant changes in biological communities (DIRECTIVE 2000/60/EC, 2000), characterizing and especially quantifying impacts on biology is difficult and requires a lengthy process of pressure/impact analyses. In the first instance, five standard status classes, ranging from 'high' (no, or only very minor, anthropogenic alterations compared to reference conditions) to 'bad' (severe anthropogenic alterations compared to reference conditions), were therefore defined, with boundaries set with basic ranges of equal magnitude: bad (0-0.2), poor (>0.2-0.4), moderate (>0.4-0.6), good (>0.6-0.8) and high (>0.8).

7. Application of the LHYMO index to French lakes

The final LHYMO score and corresponding status classification was calculated for 72 French lakes for which the data required for the calculation of the 15 metrics were available (Figure 2). The data used to calculate the metrics comes mainly from WFD field monitoring and national GIS datasets, supplemented when necessary by modelling or local datasets. The data sources are given in Supplementary material 2.

Among these 72 lakes included in this study, 24 are natural lakes and 48 are non-natural (46 reservoirs and two artificial man-made lakes). They represent about 15% of all French lakes covered by the WFD monitoring program. These lakes have various characteristics and are located all over the French metropolitan territory in very different environmental contexts, with altitudes ranging from 1 to 2061m, surfaces from 0.1 to 58km², and mean depths from 0.9 to 82m (see Supplementary material 1).

LHYMO scores calculated on the 72 lakes dataset ranges from 0 to 0.98 (Table 3) with a relatively homogeneous distribution in the three lowest status (21%, 17% and 25% classified respectively in bad, poor and moderate hydromorphological status), a significantly higher proportion in good hydromorphological status (32%) while a lesser proportion in high hydromorphological status (5%). An almost similar pattern is observed for both natural and non-natural lakes, except for an inverse proportion of natural lakes in good and moderate hydromorphological status. This result suggests that Mandatory Technical Constraints are well accounted for, as no systematic downgrading bias occurs for non-natural lake.

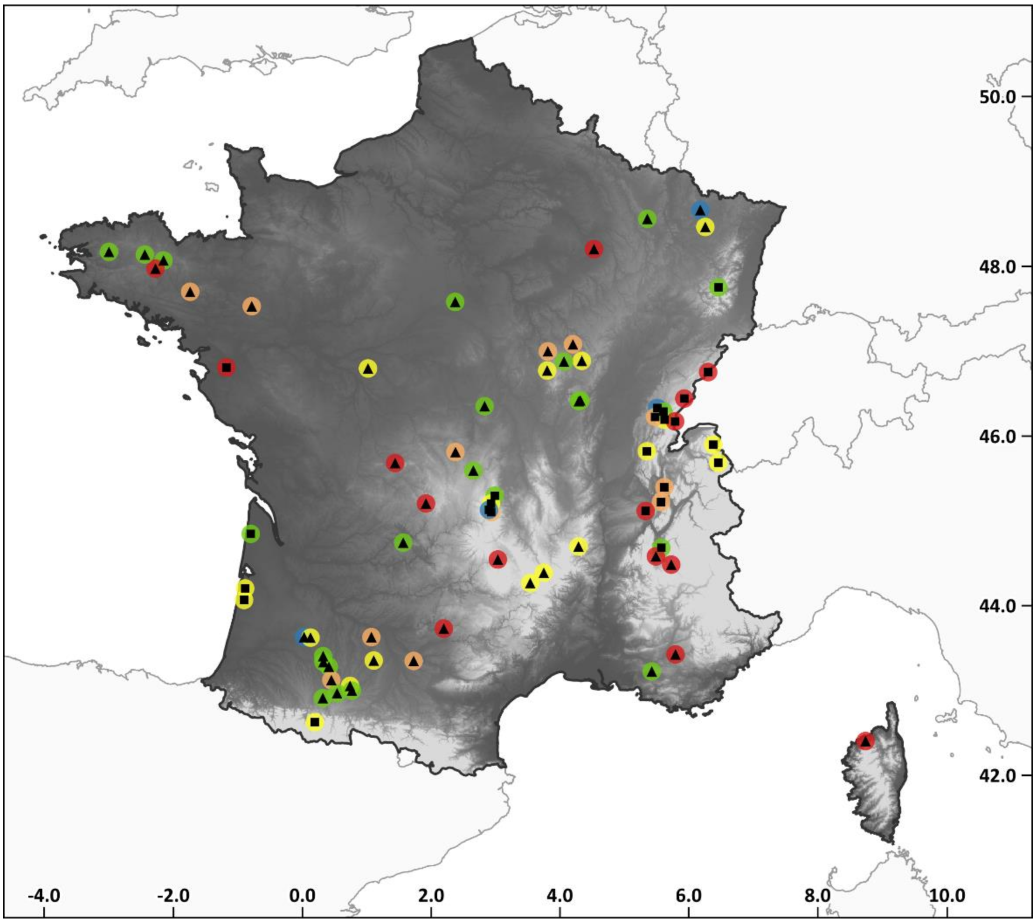

Figure 2. LHYMO hydromorphological status (blue: high, green: good, yellow: moderate, orange: poor, red: bad) of French lake water bodies (squares: natural lakes; triangles: non-natural lakes)

Nine out of the 15 metrics and four out of the five QE shows a wide range of values (Table 3). Overall, the hydrological metrics show a greater range of variation than the morphological metrics. The smallest ranges are observed for Bank erosion, Bank compaction, Sand and Gravel dumping, Materials extraction and the metric related to connection to the groundwater, assuming that those types of alteration are of less concern over the French metropolitan territory. The connection to the groundwater could only be assessed through one metric, which may explain a poorer representation of this QE and its lower weight in the final index results.

The medians are mostly very high, with a value >0.8 for all metrics and QE and a value of 1 (i.e. the maximum value) for 11 metrics and four QE. These results can be explained in part by the systematic assignment of the maximum value for some metrics to lakes meeting certain typological criteria (e.g. high-altitude lakes for Absence of riparian vegetation). They also suggest that, depending on the sample studied, there is a greater proportion of unaltered than altered lakes for each type of impairment assessed. The median of the final score is however 0.5, which shows that most of the French lakes still suffer at least one major alteration.

Assuming that the sample of this study is representative of the national situation and that restauration measures should be required for lakes in less than good status, more than 60% of the French lakes could be affected.

Table 3. Range of values and proportion of occurrence in first and second position for each metric (normal), QE (bold) and LHYMO scores on the 72 lakes included in the study.

	Minimum value	Maximum value	Median	Number of values below high/good threshold	Number of values below good/moderate threshold
Structure of the lake shore	**0.05**	**1**	**0.97**	**49**	**21**
Bank artificialization	0.43	1	0.95	13	5
Bank compaction	0.71	1	1	2	0
Bank erosion	0.77	1	1	2	0
Absence of riparian vegetation	0.05	1	0.85	32	12
Change in aquatic vegetation	0.30	1	0.88	26	6
Quantity, structure and substrate of the lake bed	**0.13**	**1**	**1**	**13**	**7**
Sand dumping	0.89	1	1	0	0
Gravel dumping	0.74	1	1	1	0
Material extraction	0.95	1	1	0	0
Siltation	0.13	1	1	12	7
Quantity and dynamics of water flow	**0**	**1**	**1**	**43**	**27**
Change in tributaries	0	1	1	7	3
Flow obstacles	0.07	1	0.83	33	23
Seasonal shift of WLF	0.38	1	1	18	10
Residence time	**0**	**1**	**1**	**9**	**7**
Water abstraction	0	1	1	2	2
Upstream water impoundment	0.06	1	1	8	5
Connection to the groundwater	**0.70**	**1**	**1**	**2**	**0**
LHYMO Score	**0**	**0.98**	**0.5**	68	45

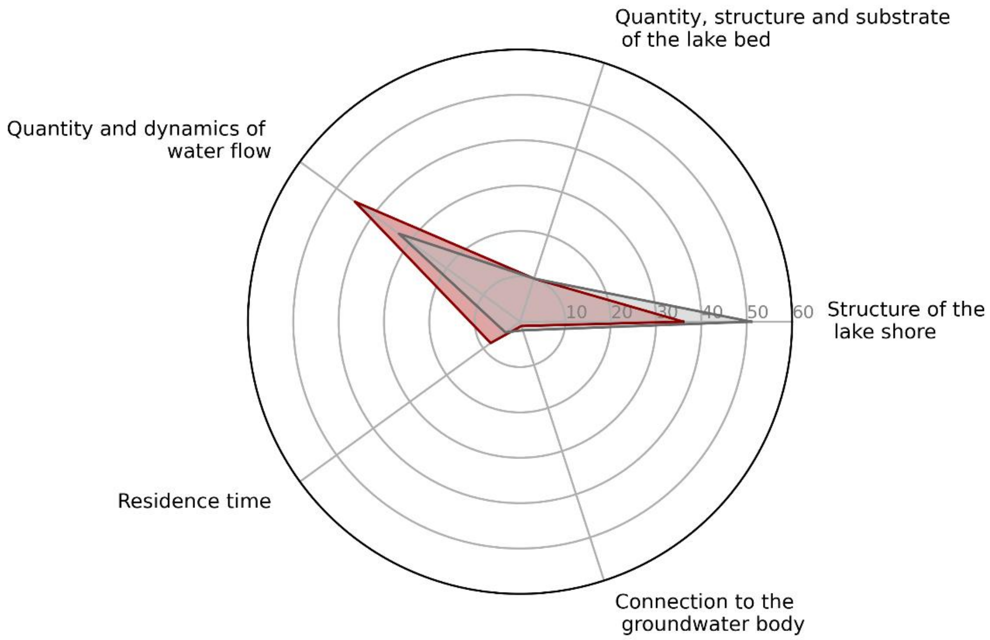

Figure 3. Frequency with which respectively the five WFD QE downgrade the LHYMO score on French lakes (red: first downgrading QE, light grey: QE with the second lowest value).

All five QE are responsible for the degradation of at least one lake, but in very different proportions (Figure 2). Quantity and dynamics of water flow is the main source of downgrading for 45% of French lakes, when only 2% due to Connection to the groundwater. Furthermore, all metrics appear to be a source of degradation, except for Sand dumping and Material extraction, which indicates that French lakes are subject to a great variety of hydromorphological issues. Of these, Flow obstacles and Absence of riparian vegetation are the most frequent types of alteration. Indeed, it is widely admitted that the presence of obstacles on river networks is one of the major issue affecting French hydrosystems by disrupting hydrological, sedimentary and ecological continuity (Van Looy et al., 2014). Alteration of riparian vegetation has also been a long-standing concern in France, although its occurrence has mostly been described on rivers (Décamps et al., 1988; Stella & Bendix, 2019). It is also worth noting that, despite the difference in the number of metrics and alterations assessed, LHYMO scores for French lakes are almost equally driven by morphology (46%) and hydrology (54%).

8. Discussion

The method described in this paper lead to the development of a new index that allows to provide the very first homogeneous quantitative assessment of hydromorphological conditions and status of lakes all over the French territory. This index was developed to overcome the great environmental heterogeneity of French lakes (Nicolas et al., 2015), as well as taking into account regulatory requirements (DIRECTIVE 2000/60/EC, 2000), normative constraints (Boon et al., 2019) and environmental data availability, data accessible to perform the computation on a large and representative pool of lakes.

8.1 Metrics

The LHYMO index addresses the morphological and hydrological status of lakes through 15 metrics representative of five of the six WFD hydromorphological QE and covering almost all the categories of the standard EN 16039 (CEN, 2011). With this method, we further consider hydromorphological alterations at different spatial and temporal scales of lakes hydromorphological functioning including watersheds and riparian corridors. Each metric is designed to be as simple but comprehensive as possible with regard to the alteration and mitigation factors, considering our knowledge of the impact of each impairment on lake ecosystems. Depending on which degradation is addressed, the equation is therefore more or less complex and requires more or less data, which might be a hindrance for the calculation of some metrics.

Due to the lack of data of the French territory, the lake depth variation QE is ultimately not assessed by LHYMO. This QE is usually rather addressed through the prism of hydrology, in particular in relation to water level fluctuations because these parameters are highly related and often interdependent (Hellsten & Dudley, 2006). Nevertheless, in accordance with the WFD, these variations shall be directly related to morphological alterations (Boon et al., 2019; CEN, 2011). Three potential metrics considering the volumes of material dumped into or extracted from the lake basin for anthropogenic purposes and the rate of infilling were considered to assess this QE from a strictly morphological point of view, but the lack of data available and easily accessible made it impossible to integrate those metrics into the final LHYMO index. A very first effort could be to identify, at the national level, natural lakes whose depth has been artificially increased through the construction of artificial structures to raise the water level. Accurate assessment of hydrological regimes and especially connection to the groundwater is also limited by the unavailability of suitable data. Lakes-groundwater interactions are assessed indirectly by using bank impermeabilization as a proxy to characterize the alteration of lateral connections between lake basins and the most superficial groundwater. Ideally, water exchanges from the lake bottom with deeper groundwater should also be considered and these exchanges should be quantified in volumes, but direct measurement of groundwater discharge to lakes is difficult (Wilson & Rocha, 2016).

Consequently, the total number of metrics for each QE in LHYMO varies from one to five. However, despite this discrepancy, almost all of them and all five QE assessed actually play a part in the results obtained over French lakes.

The variability in the accuracy and precision of multi-source data can also represent a significant source of error (Borja & Rodríguez, 2010). Future improvements of the method should include sensitivity analyses and uncertainty calculation in order to associate a level of confidence with each LHYMO score. Nevertheless, some recommendations can already be made to reduce uncertainty for each metric, such as: (1) integrating data over several years (>5) for hydrological metrics, in order to smooth out the effects of possible extreme events; (2) using the most recent and/or reliable data and if possible time-consistent when multi-sourced.

It is obvious that the availability of data is one of the key issues to improve lake hydromorphology assessment. Therefore, continued efforts to collect confident data with reliable methods, with a particular focus on the less documented elements (such as groundwater flows or water level fluctuations in the case of France), are still necessary. In this context, the gathering, organization and opening of scientific data from all fields and sources is of the highest importance. A thorough application of regulatory monitoring programs and protocols is also crucial to produce high-quality data and allow the monitoring of possible changes over time. Innovative acquisition methods, such as remote sensing for example (Tormos et al., 2021; Wilson & Rocha, 2016), which allow information to be acquired uniformly and at lower cost over the whole territory, should be encouraged and developed in the future as recommended by EN 16039 standard.

8.2 References

Defining reference conditions is one of the biggest challenge for ecological status assessment (Nõges et al., 2009) and is currently considered by European experts a major hurdle for the implementation of hydromorphology assessment methods by the EU Member States (Argillier, Carriere, Wynne, et al., 2022). The method used in LHYMO is an innovative hybrid type/site-specific approach where reference conditions are set independently for each lake and each hydromorphological alteration assessed. Reference conditions then reflect, in regards to each alteration, the expected status of the lake in unaltered conditions, apart from disturbance potentially due to MTC in relation to the main anthropogenic use. In this way, artificial and heavily modified lake water bodies can also be assessed through the same method on the basis of the best achievable status given their initial purpose. Although we had to rely on expertise first to establish the criteria relating to reference conditions, no additional expert input is required to apply the LHYMO method. To our knowledge, this is a major step forward in improving the assessment of the hydromorphological alteration of lakes. Nevertheless, some points still deserve to be investigated. Indeed, the reference conditions for natural lakes refer to a theoretical ideal status without any alteration whatever insignificant although a very slight deviation from this ideal status may sometimes be tolerated, as provided for by the WFD, especially in the absence of significant impact on the biological communities. A better understanding of the effects of hydromorphological pressures on biocenoses is therefore necessary. Finally, for some metrics, reference conditions are related to historical situations (e.g. riparian vegetation) but the question of the choice of the time period as the reference period remains open.

Nevertheless, this approach enabled us to face the difficulty of establishing a typology of French lakes to define a reference for each type (type-specific approach; (Roset et al., 2007)), which are naturally very diverse in their environmental and intrinsic characteristics. It also makes it possible to override the problem of defining reference conditions by determining them specific to each water body (site-specific approach; (Roset et al., 2007)).

8.3 Aggregation and definition of thresholds

As a first approach to highlight lake water bodies the most affected by hydromorphological alterations, all the metrics are aggregated without considering the possible difference in their degree of impact on biodiversity or on the functioning of lakes, due to the lack of evidence to define the possible weighting factors. Knowledge concerning the link between biology and anthropogenic disturbances on lakes is mostly focused on eutrophication issues (e.g. (Harper, 1992; Pieczyñska, 1993; Sutcliffe et al., 1992; Tamminen & Kuosa, 1998). The importance of lakes hydromorphology on biocenoses is now widely accepted in the scientific literature, although the links between the two still requires further investigation to be well understood and quantified, in particular in a context of multi pressures and climate change (Lyche-Solheim et al., 2013; Poikane, Herrero, et al., 2020). In addition, several publications also show that these relationships may be influenced by many other factors (location, community structures, etc.) (e.g. Edwards & Whiters, 2007; Larsen et al., 1994; Paulsen et al., 1997; Rowan et al., 2012; Whittier et al., 2002).

Consequently, improving our understanding and quantifying the impacts of the hydromorphological alterations and related metrics on biological communities (macrophytes, macro-invertebrates, phytoplankton and fish in particular) still needs to be done, at least at the French national scale. It should be pointed out that these analyses should also allow improving the ecological relevance of the thresholds that discriminate the five WFD hydromorphological status. More research is needed to identify what deviation from the natural status can exist without affecting biodiversity and ecosystem services (Elosegi et al., 2010) for hydromorphological features, in order to adjust hydromorphological status class boundaries in the assessment.

In addition, we can assume that the application of different methods of aggregation of metrics can lead to more or less discriminating and more or less severe evaluations of the water bodies. We chose to focus on the OOAO method, applied both on metrics and on quality elements, which favors the discrimination of hydromorphological status (results not shown). By doing so, we preserve the representativeness of the different morphological and hydrological aspects in the final score. In addition, although this method can be criticized as being particularly severe (Borja & Rodríguez, 2010; Prato et al., 2014), it is the most conservative method for environments in a strictly ecological approach. It remains also relevant for an initial assessment in the absence of *a priori* knowledge of the status of the systems studied. Unlike the computation of averages and medians, which tend to smooth out the values, the OOAO method has the advantage of always considering the lowest values, indicative of dysfunctions, in the final score. Moreover, the results obtained through this approach were validated by experts as the most coherent and representative of the known hydromorphological status of French lakes.

Even if not required by the implementation of the WFD that only imposes to distinguish high hydromorphological status from a less good status, we provide an assessment on a five classes scale, given the importance of hydromorphology on lake ecosystems functioning (Kutyla et al., 2021) and a possible wider non-regulatory use of the index.

8.4 Operational implementation

The LHYMO method has been successfully used to provide the first quantitative assessment of the hydromorphological status of 72 French lakes. This application allows us to identify which lakes are already not achieving good ecological status and helps to identify which types of alterations cause a degradation of the hydromorphology quality of lake water bodies within the French metropolitan territory. However, considering that 482 lakes are historically part of the French WFD monitoring program and that there are more than 550000 lakes over 0.01 hectare on the French territory (Bartout & Touchart, 2013), this study only gives a very partial picture of the hydromorphological status of the French lakes. The method can nevertheless be applied to small lakes outside the WFD scope in order to complete this initial incomplete inventory.

Although designed to meet the regulatory requirements for the assessment of the ecological status of lake water bodies in application of the WFD, LHYMO could also be a useful management tool to assist environmental conservation policies in broader contexts, although improvements can still be made to improve the reliability and sensitivity of the method and its representativeness of biological responses. Regarding French context specifically, LHYMO is fully operational for stakeholders as most of required input data are freely accessible at a national scale and easily reusable, although it may also be refined or completed if necessary according to local data resources. The multi-level design of the index allows to switch view at different aggregation levels and also helps highlighting dysfunctional processes and prioritize management or conservation actions for each lake or on an entire territory (which lakes should be restored first). LHYMO may also be used to assess the effectiveness of previous hydromorphological restoration measures on lakes and provide guidance for future management strategies by testing and designing management, restoration or mitigation scenarios using simulated data on some selected metrics related and then analyzing the evolution of the final LHYMO score. Values calculated through the LHYMO index could finally be used as a quantification of physical habitat alterations that is necessary to design reliable predictive models of habitat suitability for various biological communities in order to achieve conservation goals on a global scale (Fernández et al., 2011).

Consequently, this index and the method described for its development can be a source of inspiration for countries wishing to develop a tool for assessing hydromorphology of lacustrine environment, as there is little scientific literature in this field.

9. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

10. Acknowledgments

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Appendix 1

Table 4. Pearson correlation tests between metrics EQR values for each quality element.

	Bank artificialization	Bank compaction	Bank erosion	Riparian vegetation	Aquatic vegetation
Bank artificialization	1.00	0.15	-0.07	-0.001	-0.01
Bank compaction	0.15	1.00	-0.05	0.12	**0.23**
Bank erosion	-0.07	-0.05	1.00	0.20	-0.02
Riparian vegetation	-0.001	0.12	0.20	1.00	-0.20
Aquatic vegetation	-0.01	**0.23**	-0.02	-0.20	1.00

	Sand dumping	Gravel dumping	Material extraction	Siltation
Sand dumping	1.00	0.18	-0.12	0.17
Gravel dumping	0.18	100.	-0.07	0.05
Material extraction	-0.12	-0.07	1.00	-0.04
Siltation	0.17	0.05	-0.04	1.00

	Change in tributaries	Flow obstacles	Seasonal WLF
Change in tributaries	1.00	0.03	0.18
Flow obstacles	0.03	1.00	0.11
Seasonal WLF	0.18	0.11	1.00

	Water abstraction	Water impoundment
Water abstraction	1.00	0.11
Water impoundment	0.11	1.00

Supplementary material 1. Physical characteristics of the 72 French lakes included in the study.

lake	type	altitude (m)	surface area (km²)	volume (Mm³)	mean depth (m)	max depth (m)	basin district
Abbaye	N	879	0.814678	6	7.1	19.5	Rhône
Aiguebelette	N	374.4	5.157127	166	32.2	74	Rhône
Anterne	N	2061	0.109905	1	6.1	13	Rhône
Arrêt Darré	R	269	1.176041	11	9.2	23.2	Adour-Garonne
Astarac	R	247	1.615932	10	6.2	13.7	Adour-Garonne
Aydat	N	837	0.5547745	4	7.5	15	Loire
Baradée	R	163.2	0.554412	2	4.1	9.6	Adour-Garonne
Bimont	R	330	1.186615	14	11.8	55	Rhône
Bischwald	A	251	1.971578	3	1.6		Rhin
Bleu	N	1947	0.5230945	12	22.4	124	Adour-Garonne
Bosmeleac	R	167	0.6030695	4	6	15	Loire
Bourdouze	N	1168	0.2203915	1	3	5	Loire
Bourget	N	231.5	43.71685	3600	82.3	145	Rhône
Candau	R	171.8	0.5779805	2	3	7.2	Adour-Garonne
Carcans-Hourtin	N	13	57.5735	210	3.6	9.4	Adour-Garonne
Causse	R	124	0.7335435	3	3.4	7	Adour-Garonne
Cazaux	N	21	48.29416	499	10.3	22.8	Adour-Garonne
Cercey	R	372	0.5331035	3	5.9	12.3	Seine
Chaillexon	N	750	0.7445385	6	8.6	31.5	Rhône
Chalain	N	488	2.198481	49	22.1	45	Rhône
Chambon	N	875	0.474194	1	3	4	Loire
Chamboux	R	496	0.705249	6	7.8	18	Loire
Chancelade	R	662	0.971003	4	4.3	5	Loire
Charpal	R	1325.3	1.827389	8	4.4	15.3	Adour-Garonne
Clairvaux	N	525	0.416132	5	12	20	Rhône
Codole	R	113	0.5066835	7	13.8	25	Corse
Crescent	R	274	1.20761	13	11.1	23.5	Seine
Der-Chantecoq	R	135	41.61427	324	7.8	16	Seine
Devesset	R	1074	0.477041	2	4.8	16	Rhône
Duc	R	33	2.119755	5	2.4	7	Loire
Esparron	R	359	2.552312	79	30.8	54	Rhône
Forge	R	62	0.6247925	1	0.9	<3	Loire
Gensac-Lavit	R	129.4	0.4301225	2	4.7	9.25	Adour-Garonne
Goule	R	213	0.971752	3	2.6	7	Loire
Grand-lieu	N	1	54.19213	98	1.8	2.7	Loire
Guerlédan	R	120	2.848564	50	17.5	45	Loire
Ilay	N	774	0.7085345	8	10.9	32	Rhône
Kerne Uhel	R	215	0.6137195	2	3.9	10	Loire
Laffrey	N	916	1.143142	28	24.7	39.3	Rhône
Lanau	R	669	1.579291	18	11.4	24.7	Adour-Garonne
Landes	R	378	1.166974	1	1	2	Loire
Laragou	R	173	0.3439735	2	5.4	9.8	Adour-Garonne
Lindre	A	211	5.797206	12	2.1	5	Rhin

Longemer	N	733	0.7535075	10	13.3	29.5	Rhin
Louroux	R	98	0.6070285	1	1	4	Loire
Lunax	R	268.5	2.226439	25	11.2	27	Adour-Garonne
Madine	R	227	10.46238	35	3.3	14	Rhin
Miélan	R	217	0.6640365	4	5.6	13	Adour-Garonne
Monteynard - Avignonet	R	490	5.062763	270	53.3	135	Rhône
Montriond	N	1060	0.256742	3	12.1	19.7	Rhône
Nantua	N	475	1.323431	40	30.3	42.8	Rhône
Naussac	R	935	10.43173	189	18.1	40	Loire
Paladru	N	500	3.546134	97	27.4	35.9	Rhône
Pannecière	R	320	4.521657	69	15.3	40	Seine
Parentis	N	21	31.90897	241	7.6	20.7	Adour-Garonne
Pavin	N	1196	0.4522175	23	50.8	96	Loire
Pont	R	301	0.6769115	6	9	16.8	Seine
Puydarrieux	R	269	1.688321	15	8.6	21	Adour-Garonne
Remoray	N	850.7	0.9718615	10	9.9	27.6	Rhône
Roucarie	R	259	0.6373665	6	9	28	Adour-Garonne
Rousses	N	1059	0.898324	7	7.7	18.2	Rhône
Saint Michel	R	226	4.448976	13	3	8	Loire
Saint Pardoux	R	361	3.242692	23	7	16.7	Loire
Saint-Jean	R	173.4	0.6093405	3	4.1	8.85	Adour-Garonne
Sautet	R	765	3.162575	108	34.1	115	Rhône
Tailluret	R	96.8	0.418697	2	3.6	6	Adour-Garonne
Thoux-Saint-Cricq	R	166	0.599643	4	5.8	13.1	Adour-Garonne
Torcy Neuf	R	316	1.504892	9	6.2	17	Loire
Torcy Vieux	R	316	0.59859	2	4	11	Loire
Treignac / Bariousses	R	513	0.8566775	7	8.7	22.5	Adour-Garonne
Uby	R	108	0.6540405	3	3.8	9	Adour-Garonne
Vallée	R	125	0.535388	1	2	5.1	Loire

Supplementary material 2. Sources of the data used for French lakes.

data source	provider	access link
Alber database	OFB - INRAE	https://geocatalogue.ecla.inrae.fr/geonetwork/srv/fre/catalog.search#/metadata/6e3888b0-6c4e-48a9-bb23-abaf2687a5f2
Charli database	OFB - INRAE	https://geocatalogue.ecla.inrae.fr/geonetwork/srv/fre/catalog.search#/metadata/f03f1673-93af-4c96-a6c0-292352a14430
BD_PLANDO database	OFB - INRAE	http://geo.ecla.inrae.fr
BD LISA database	BRGM	https://www.sandre.eaufrance.fr/atlas/srv/fre/catalog.search#/metadata/769f36e0-eb23-4014-ad63-fb468fcd7488
LITHO_1M	BRGM	http://geoservices.brgm.fr/geologie (WFS service)
LOIEAU model	INRAE	https://loieau.recover.inrae.fr/
WLF dataset	various	none
BD ALTI®	IGN	https://geoservices.ign.fr/bdalti
BD CARTHAGE	IGN - French Water Agencies	https://www.sandre.eaufrance.fr/atlas/srv/fre/catalog.search#/metadata/3409c9c3-9836-43be-bac3-b110c82b3a25
ROE	OFB	https://www.sandre.eaufrance.fr/atlas/srv/fre/catalog.search#/metadata/5a2cdc66-36be-4bc7-be00-e04736bc7ba6
BNPE	BRGM	https://bnpe.eaufrance.fr/acces-donnees
HER2	INRAE	https://www.sandre.eaufrance.fr/atlas/srv/fre/catalog.search#/metadata/40b17d2a-5d4a-48ed-acdd-0728c080598c
BD TOPO® Vegetation	IGN	https://geoservices.ign.fr/bdtopo
SYRAH	INRAE	https://www.data.gouv.fr/fr/datasets/syrah-ce-systeme-relationnel-daudit-de-lhydromorphologie-des-cours-deau/
SIOUH	BETCGB	siouh.din.developpement-durable.gouv.fr