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Assessing the ecological effects of hydromorphological pressures on European lakes

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ABSTRACT

In European countries, hydromorphological (HyMo) pressures are the second most commonly occurring types of pressures on aquatic ecosystems (after eutrophication). HyMo pressures (i.e., man-made alterations to the hydrology and morphometry of aquatic ecosystems) impact the functioning of lakes and rivers in multiple ways. Initially, they have profound effects on littoral communities, such as macrophytes, benthic invertebrates, and fish. Ultimately, they result in pervasive alteration of whole-lake ecosystems. Extensive efforts have been devoted to the development of ecological assessment methods and management measures focusing mainly on eutrophication, whereas HyMo alterations are less understood and not properly addressed. We attempted to clarify the conceptual background, to highlight achievements in method development, including pressure–response relationships and metrics used in assessment, and to underscore issues requiring urgent attention. We concluded that the currently used biological methods do not reliably address HyMo alterations. The need to develop specifically responding biological and HyMo assessment methods and to measure the necessary variables in routine monitoring programs is urgent. This review paper also serves as an introductory article to a small special series of papers on the ecological impacts of water level fluctuations. Papers in this series include an updated literature review on the ecological effects of water level fluctuations on lake macroinvertebrates, a review article specifically devoted to water level fluctuations indicators in the littoral of natural and artificial lakes, and a paper addressing the relationships between water level fluctuation alteration and spatial and temporal patterns of cladoceran communities in a dammed lake.

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Introduction

Hydromorphological (HyMo) pressures on European surface waters are increasing (ETC/ICM 2012, EEA 2018). These man-made pressures affecting the hydrological and morphological features of inland waters include water flow regulation by dams, weirs, sluices, and locks; water diversions and abstractions; morphological alterations to landscapes such as straightening of waterways and channelisation; and the disconnection of flood plains from active river channels. In European countries, HyMo alterations are the second most commonly occurring pressures after nutrient enrichment leading to eutrophication, affecting 38% of all lakes by lake area (22% by number of waterbodies; ETC/ICM 2012). In several countries, the proportion of lake surface area affected by HyMo pressures is higher (e.g., 94% in the Netherlands vs. 69% in Sweden; EEA 2018).

HyMo pressures impact the functioning of lakes and rivers in multiple ways: by reducing structural complexity and heterogeneity of littoral habitats; by changing the natural water-level regimes and hence impacting the physical structure, macrophyte cover, and food webs of littoral zones; by modifying water circulation and stratification patterns; by impacting internal nutrient cycling; and by altering conditions to advantage of invasive species (Brauns et al. 2007, Zohary and Ostrovsky 2011, Urbanič et al. 2012, Porst et al. 2019, Wang et al. 2020). These pressures not only have profound effects on lake littoral communities—such as macrophytes (Radomski and Goeman 2001, Hellsten 2002, Elias and Meyer 2003, Helmers et al. 2016), benthic invertebrates (Aroviita and Hämäläinen 2008, Rosenberger et al. 2008, Twardochleb and Olden 2016), and fish (Sutela et al. 2011, Dustin and Vondracek 2017)—but may also result in a pervasive alteration of whole-lake

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ecosystems (Zohary and Ostrovsky 2011, Jeppesen et al. 2015). For example, a decrease in water level caused a shift to cyanobacteria dominance and a marked increase in phytoplankton biomass in subtropical reservoirs of southeast China (Yang et al. 2016). Similarly, significant impact of water level fluctuations on phytoplankton communities was found both in Mediterranean reservoirs (Naselli-Flores and Barone 2005) and in large shallow temperate lakes (Nõges et al. 2003). All these effects can significantly impede ecosystem services such as providing drinking water, recreation, and fisheries (Strayer and Findlay 2010). Therefore, the need to plan effective policies and restoration measures to reduce the impact of these anthropogenic pressures on lake ecosystems is urgent (Lorenz et al. 2017).

In Europe, the Water Framework Directive (WFD) was adopted to tackle different pressures and ensure sustainable management of all river basins (EC 2000). A core concept of the WFD is that the structure and functioning of aquatic ecosystems is used to assess the ecological status of surface waters. Assessment of quality is based on the extent of deviation from reference conditions, defined as the biological, chemical, and morphological conditions associated with no or minor human pressure. The WFD classification scheme for water ecological quality includes 5 status categories: high, good, moderate, poor, and bad. The general objective of the WFD is to achieve good status for all surface waters of the European Member States by 2015, or at the latest by 2027. Good status means "slight" deviation from reference conditions, providing sustainable ecosystems and acceptable conditions for human use. Member States should develop and harmonize biological status assessment methods for all principal surface water categories (lakes, rivers, coastal waters, and estuaries) and all biological quality elements (phytoplankton, macrophytes, periphyton, benthic invertebrates, and fish). Furthermore, the WFD requires an "intercalibration exercise" to ensure comparability of the ecological classification scales and to obtain a common understanding of the good ecological status of surface waters.

Extensive efforts have been devoted to the development and implementation of biological assessment methods (Birk et al. 2012, 2013, Poikane et al. 2014b, 2015). River basin management plans and restoration measures have been developed and implemented (Hering et al. 2010, 2015). In most cases, however, the desired outcome of improved ecological status has not been reached; little or no improvement in ecological status of European lakes and rivers occurred between 2009 and 2015 (EEA 2018). In many cases, rapid improvement cannot be expected because of internal nutrient loading (Søndergaard et al. 2007) or biological factors stabilizing lake alternative states (Scheffer and van Nes 2007). Another possible explanation is that most management measures address the "traditional" pressures of eutrophication and acidification, whereas HyMo alterations are less understood and, as a consequence, not properly addressed (Lyche-Solheim et al. 2013, Reyjol et al. 2014).

The use of biological communities as indicators in lake assessment has mainly focused on eutrophication and acidification. Methods for assessing eutrophication effects are well developed for phytoplankton (Carvalho et al. 2013, Phillips et al. 2013), macrophytes (Penning et al. 2008, Poikane et al. 2018), littoral diatoms (Kelly et al. 2014, Poikane et al. 2016b), fish (Rask et al. 2010), and benthic invertebrates (Jyväsjärvi et al. 2014, Poikane et al. 2016a). European reference conditions have been determined for the most important eutrophication metrics such as total phosphorus (Cardoso et al. 2007) and chlorophyll *a* (Poikāne et al. 2010), and a conceptual model of status evaluation has been developed (Poikane et al. 2014a) and applied for setting good status boundaries.

By contrast, metrics and methods to assess the effects of HyMo pressures are still missing or under development. Only in recent years has considerable progress been made in understanding the effects of HyMo pressures on lake ecology (e.g., Brauns et al. 2007, 2008, Mastrantuono et al. 2015) and in developing methods to assess these effects (Miler et al. 2013a, 2013b, Mjelde et al. 2013, Urbanič 2014). Despite this progress, practical application has been scarce and uneven (Lyche-Solheim et al. 2013, Reyjol et al. 2014).

Here we review biological assessment methods currently applied in Europe to address HyMo pressures. First, we attempt to clarify the conceptual background and provide a brief literature review; second, we highlight achievements in method development, including pressure–response relationships and metrics used in assessment; and third, we identify the issues that must be addressed in the future.

We included only intercalibrated methods used in the Member States WFD monitoring and assessment programs: those in the European Commission Decision on intercalibration (EC 2018) and those intercalibrated by November 2018. The method descriptions are available in the WFD intercalibration technical reports (e.g., Böhmer et al. 2014, Solimini et al. 2014) and Member State reports (all reports are available at "WFD CIRCABC" library, an information exchange platform to share documents under the WFD Common Implementation Strategy (https://circabc.europa.eu/).

This review paper also serves as an introductory article to a special series of papers on the ecological impacts of water level fluctuations (WLFs). Subsequent articles in this series include: a study of the responses of cladocerans to an altered water level regime due to dam construction (in Haixi Lake, southwest China), in particular the displaced littoral habitats with consequent loss of benthic taxa and increase in planktonic *Bosmina* species (Wang et al. 2020); a study of the resilience of zooplankton communities in temperate reservoirs with extreme WLFs (Murphy et al. 2019); and a physical study examining WLFs at short time scales of hours to days (Iwaki et al. forthcoming 2020). Most of these papers were presented at a special session on the same topic in the frame of the XXXIV Congress of the International Society of Limnology (SIL) in Nanjing (China), 19–24 August 2018.

Conceptual background

Ecological assessment needs to be rooted in knowledge of the relationships between drivers, pressures, and their effects on hydromorphological conditions and biological communities (Fig. 1). A considerable body of knowledge exists on the effects of HyMo pressures on biological communities that could be used as a base for method development (Table 1–3). For lakes, 3 main study directions can be described: ecological effects of (1) lakeshore alterations, (2) WLFs, and (3) a combination of all HyMo alterations.

A number of studies have addressed the effects of lakeshore alterations (Table 1, only European countries included), usually focused on littoral benthic invertebrates as bioindicators of change, with only a few addressing fish, periphyton, and macrophytes. Shore alterations are linked to reduction in habitat diversity, complexity, and the loss of specific habitats such as boulders and rocks, coarse woody debris, submerged tree roots, and macrophyte stands. The metrics are similar to those used in river assessment (e.g., Böhmer et al. 2004) and describe the decrease of taxon richness and diversity (Brauns et al. 2007, Urbanič et al. 2012), increase of non-native taxa (Pilotto et al. 2015, Pätzig et al. 2018, Porst et al. 2019), increase of r-strategists (Urbanič et al. 2012, Miler et al. 2013a), and a change from more specialized and sensitive taxa toward generalists and tolerant taxa (Brauns et al. 2007, Urbanič et al. 2012, Miler et al. 2013a, Urbanič 2014, Mastrantuono et al. 2015). Few studies address the effects of man-made alterations to lake shorelines on macrophyte (Jusik and Macioł 2014) and fish communities (Gafny et al. 1992, Mehner et al. 2005, Lewin et al. 2014, Cummings et al. 2017).

The second most-explored line of research revolves around the effects of WLFs (Table 2), mainly focused on macrophytes and benthic invertebrates (Leira and Cantonati 2008, Mjelde et al. 2013), with fewer studies addressing effects on fish (Sutela et al. 2011) and phytobenthos (Cantonati et al. 2014a, 2014b, Leira et al. 2015, Spitale et al. 2015, Evtimova and Donohue 2016). The results have been somewhat contradictory, with some studies revealing effects on benthic invertebrate species richness (Aroviita and Hämäläinen 2008) or biomass and abundance (Tikkanen et al. 1989, Palomäki 1994)

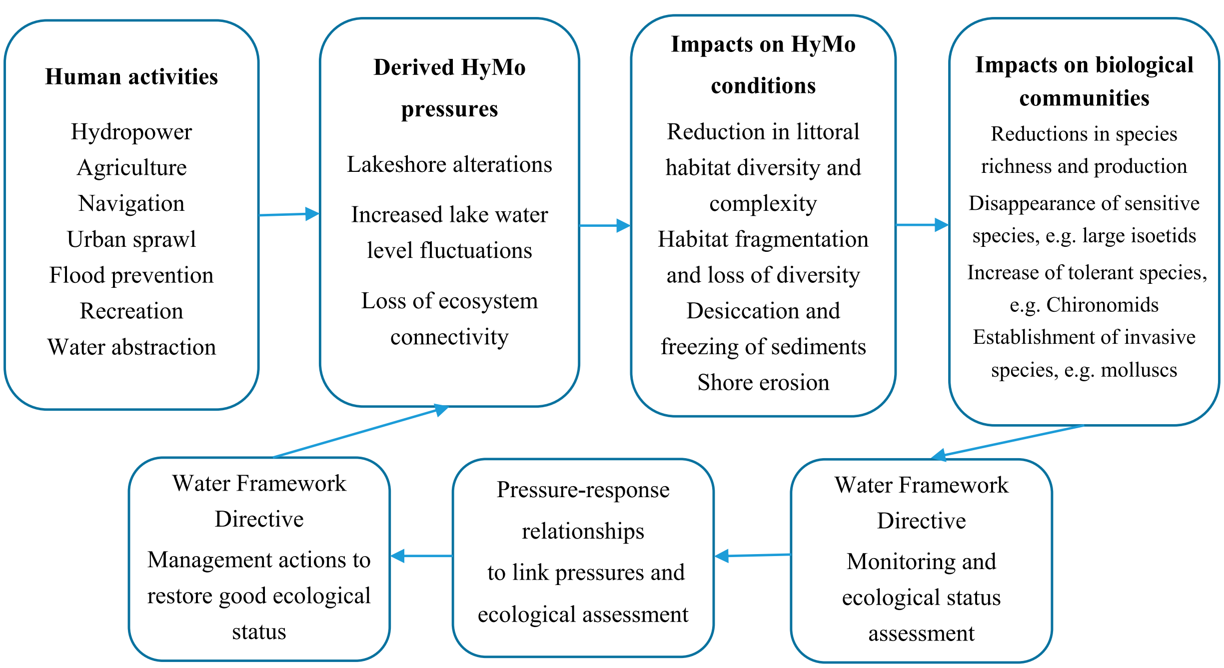

Figure 1. Conceptual overview of the relationships between drivers, hydromorphological (HyMo) pressures, their effects, and WFD assessment and management (modified from ETC/ICM 2012 and Solimini et al. 2009).

Table 1. Response of biological communities to lake shore alterations in European countries.

HyMo pressure proxy	Country	Biological response	Reference
Biological quality element: benthic invertebrates			
Natural shorelines vs. artificial interfaces	Switzerland	Taxonomic richness and diversity↓ Macroinvertebrate density↓	Bänziger (1995)
Human shoreline development (natural shorelines vs. modified)	Germany	Eulittoral: Species richness ↓ Coleoptera↓ Crustacea↓ Gastropoda↓ Hirudinea ↓Trichoptera ↓ Shredders↓ Xylophagous species ↓ Infralittoral: Species richness ↓ Crustacea↓ Ephemeroptera↓ Trichoptera↓ Shredders↓ *No effect: collectors/gatherers*	Brauns et al. (2007)
Shannon-Wiener index of habitat diversity	Germany	Diversity of food resources and consumers ↓ Number of trophic links in food webs↓ *No effect: Macroinvertebrate consumer biomass*	Brauns et al. (2011)
% altered shoreline	Spain	*Plant-associated invertebrates: no effect*	García-Criado et al. (2005)
Shoreline types (natural, soft altered, hard altered)	Italy	Species richness and diversity ↓ Ephemeroptera↓ large Crustacea↓ Mollusca↓ Odonata↓ Trichoptera↓ Oligochaeta ↑ Chironomidae ↑	Mastrantuono et al. (2015)
Near shore land-use and within-lake habitat alteration	Denmark, Germany, Ireland, Italy, Sweden, UK	Beta diversity (compositional heterogeneity of biotic assemblages among sites) ↓	McGoff et al. (2013b)
LHQA (Lake Habitat Quality Assessment)	Denmark, Germany, Finland, Ireland, Italy, Sweden, UK	Coleoptera↓ Diptera ↓ EPT (Ephmeroptera + Plecoptera + Trichoptera) taxa ↓ Oligochaeta ↑ (different between regions)	McGoff et al. (2013a)
Shore zone intensive use		Number of taxa↓ Coleoptera ↓ (Northern region) or ↑ (Southern region) Diptera↑	McGoff et al. (2013a)
HabQA (Habitat Quality Assessment) score	Ireland	Taxon richness ↓ Aranea↓ Ephemeroptera↑ Hemiptera↓ *No effect: overall abundance*	McGoff and Irvine (2009)
Morphological stressor index	Denmark, Germany, Finland, Ireland, Italy, Sweden, UK	Family richness↓ Margalef diversity index↓ Crustacea ↓ ETO (Ephmeroptera+Trichoptera+Odonata) taxa↓ Odonata ↓ Chironomidae ↑ Diptera ↑ Shredders ↓ Gatherers/collectors↑ r/K ratio↑	Miler et al. (2013a)
LHQA (lake habitat quality assessment) and LHMS (lake habitat modification score)	Italy	Limoniidae ↓ Chironomidae↑ *Dreissena polymorpha*↑ Oligochaeta↑ Invasive species ↑	Pilotto et al. (2015)
Shoreline types	Denmark, Germany, Finland, Ireland, Italy, Sweden, UK	Taxa richness↓ Bivalvia↓ Crustacea↓ Ephemeroptera↓ Gastropoda↓ Trichoptera↓ Diptera↑ Oligochaeta↑ Invasive taxa ↑	Porst et al. (2019)
Shoreline types (natural, marinas, beaches)	Germany	Macroinvertebrate diversity↓ Change in species composition	Pätzig et al. (2015)
Shoreline types (natural, marinas, beaches)	Germany	Benthic macroinvertebrate production in the upper littoral ↓ Productivity of nonnative species in upper littoral habitats ↑	Pätzig et al. (2018)
MI (Morpho-index)	Lithuania	Diversity metrics ↓ Coleoptera↓ Ephemeroptera↓ Odonata↓ Plecoptera ↓	Šidagytė et al. (2013)
M (lake shore modification) classes	Slovenia	Taxa richness↓ Family richness↓ Margalef diversity index↓ EPTCBO taxa (Ephemeroptera+Plecoptera+Trichoptera +Coleoptera+Bivalvia+Odonata)↓ Gastropoda↓ Odonata↓ Hypocrenal taxa↓ Predators↓ r/K ratio↑	Urbanič et al. (2012)
LMI (lake shore modification index)	Slovenia	Taxa richness ↓ Shannon-Wiener diversity index ↓ Astacidae and other sensitive families ↓ Chironomidae and other tolerant families ↑	Urbanič (2014)
Biological quality element: Fish fauna			
Shoreline types	Germany	Abundance of most fish species ↓	Lewin et al. (2014)
Shore alterations	Germany	*No effect: fish populations*	Mehner et al. (2005)
Biological quality element: Macrophytes			
Intensity of morphological transformation of the littoral zone	Poland	Number of taxa↑ (! Not mistake) Total cover of macrophytes ↓ Helophytes↓ Nymphaeids↓ Elodeids ↑ Filamentous algae↑ Alien species ↑	Jusik and Maciol (2014)
Shoreline types (natural, marinas, beaches)	Germany	Macrophyte biomass in the upper littoral (0–1.5 m water depth) ↓ *No effect: macrophyte biomass in the lower littoral*	Pätzig et al. 2015

↓ metrics decrease along ecological status gradient; ↑ metrics increase along ecological status gradient.
Italics indicate lack of effect.

Table 2. Response of biological communities to water level fluctuations (WLFs; only European countries included).

HyMo variables examined	Country	Biological response	Reference
Biological quality element: Benthic algae			
High WLF lakes vs. low WLF lakes	Ireland	Motile diatoms ↑ *No effect: Periphyton biomass or any measure of diatom diversity*	Evtimova and Donohue (2016)
Biological quality element: Benthic invertebrates			
Habitat type (loss of root habitats)	Germany	Coleoptera↓ Odonata↓ Trichoptera ↓ Functional groups piercers↓ predators↓ shredders↓ xylophagous↓ *No affect: species richness*	Brauns et al. (2008)
Water level fluctuations	Spain	*No effect: plant-associated invertebrates*	García-Criado et al. (2005)
Amplitude of water level fluctuation measured as the mean wintertime fall (winter drawdown)	Finland	Species richness ↓ Coleoptera↓ Ephemeroptera↓ Megaloptera↓ Trichoptera↓ *No effect: abundance of littoral invertebrates*	Aroviita and Hämäläinen (2008)
Water level fluctuation in the previous year	Finland	Benthic invertebrate biomass in the littoral area ↓	Palomäki (1994)
Regulated vs. unregulated lake	Finland	Benthic invertebrate biomass and abundance↓	Tikkanen et al. (1989)
High WLF lakes vs. low WLF lakes	Ireland	Crustaceans↓ Chironomids ↑ Oligochaetes↑ Invasive amphipods ↑ Filter feeders ↑ Gatherers/collectors↑ Omnivorous (at shallow depth)↑ Predators ↑ Shredders ↓ *No effect: species richness, total density, diversity of benthic invertebrates, ASPT and EPT scores*	Evtimova and Donohue (2016)
Decrease of water level	Italy	Mobile and/or feeding opportunistic taxa ↑ Sessile and/or herbivorous taxa ↓	Mastrantuono et al. (2008)
Winter drawdown	Finland	EPT (Ephmeroptera+Plecoptera+Trichoptera) taxa/non-EPT taxa ratio ↓	Sutela et al. (2013)
Biological quality element: Fish fauna			
Winter drawdown	Finland	Littoral and zoobenthivore fish species ↓ *Not affected: species richness and fish abundance*	Sutela and Vehanen (2008)
Winter drawdown	Finland	Total fish abundance ↓ Proportion of disturbance-sensitive species↓ Occurrence of young individuals within disturbance-sensitive species↓	Sutela et al. (2011), Sutela et al. (2013)
Biological quality element: Macrophyte vegetation			
High WLF lakes vs. low WLF lakes	Ireland	Macrophyte cover ↓	Evtimova and Donohue (2016)
Regulated vs. unregulated lake	Finland	Species richness ↓ Large isoetids ↓ Frequency of helophytes and nymphaeids ↑	Hellsten (2001)
Regulated vs. unregulated lake	Finland	Species richness ↓ Large isoetids ↓	Hellsten (2002)
Winter drawdown	Finland, Norway	Number of sensitive large isoetids ↓ Tolerant species ↑ Sensitive species ↓ *No sign of effect: total species richness*	Hellsten and Mjelde (2009)
Winter drawdown	Finland, Norway, Sweden	Species richness in storage lakes ↓ in natural lakes ↑ Tolerant species ↑ Sensitive species ↓	Mjelde et al. (2013)
Regulated lakes ("hydrolakes") vs. unregulated lake	Norway	Species richness ↓ Submerged macrophytes ↓ Species possessing plant strategies of the ruderal type ↑	Rørslett (1989)
Winter drawdown	Finland	Abundance of all species ↓ Abundance of regulation-sensitive species ↓	Sutela et al. (2013)

↓ metrics decrease along ecological status gradient; ↑ metrics increase along ecological status gradient.
Italics indicate lack of effect.

but other studies finding no such effects (García-Criado et al. 2005, Evtimova and Donohue 2016). However, all studies (except García-Criado et al. 2005) have reported a shift in taxonomic and trophic structure of benthic invertebrates (Mastrantuono et al. 2008) with potential importance for the structure and functioning of littoral zones (Evtimova and Donohue 2016). Aquatic vegetation is another well-studied community, with numerous studies showing an overall response to WLFs of decreasing macrophyte cover and abundance as well as a shift from regulation-sensitive species such as large isoetids to regulation-tolerant species, mainly amphiphytic or polymorphic taxa such as *Juncus bulbosus* L. and *Hippuris vulgaris* L. (Mjelde et al. 2013) or *Tamarix jordanis* (Zohary and Gasith 2014).

Lastly, several studies have explored the effect of combined HyMo pressures on lake communities (Table 3). A Lake Habitat Modification Score (LHMS) was developed by Rowan et al. (2006) to assess the magnitude of all hydromorphological

Table 3. Response of biological communities to combined metrics of HyMo alterations (only European countries included).

HyMo variables examined	Country	Biological response	Reference
Biological quality element: Benthic invertebrates			
LHMS (Lake Habitat Modification Score)	Denmark, Germany, Finland, Ireland, Italy, Sweden, UK	*No effect: macroinvertebrate community composition*	McGoff et al. (2013a)
Biological quality element: Fish fauna			
LHMS (Lake Habitat Modification Score)	France	Invertivorous species ↑ Planktivorous species ↑ Strictly lithophilic species ↑ *No effect: species richness, diversity, alien species*	Launois et al. (2011)
LHMS (Lake Habitat Modification Score)	Greece	Introduced species (translocated and aliens) ↑	Petriki et al. (2017)
HMI (Hydromorphological index)	Lithuania	Benthivorous fish (silver bream, bream, and ruff) ↑ Perch and stenothermic species ↓ Number of type-specific species ↓ *No effect: introduced species*	Virbickas and Stakėnas (2016)

↓ metrics decrease along ecological status gradient; ↑ metrics increase along ecological status gradient.
Italics indicate lack of effect.

impacts on lakes, including shore alterations, WLFs, and other stressors. Therefore, in theory, this index could be the most relevant proxy to assess the impact of HyMo pressures on biological communities, but in practice it has been used in few studies and with contradictory results. For instance, McGoff et al. (2013a) found no relationship between LHMS and lake benthic invertebrate community composition, based on a database of 7 European countries. Some significant relationships between LHMS and fish metrics were reported for lakes in France (Launois et al. 2011) and Greece (Petriki et al. 2017). Virbickas and Stakėnas (2016) applied in Lithuania a similar holistic approach including both shore alterations and WLFs to assess effects on fish communities, although with contradictory results (Table 3).

Biological assessment methods addressing HyMo pressures

To date, 109 biological lake assessment methods have been intercalibrated and included in the Member States monitoring toolkits, including phytoplankton (26), macrophyte (23), phytobenthos (13), benthic invertebrate (23), and fish-based (24) assessment methods (Fig. 2). According to the WFD, the biological assessment methods should integrate the effects of all relevant pressures, meaning that at least one method in each country should address HyMo pressures. However, most European lake assessment methods (97 of 109) focus on eutrophication. Most countries use 3–4 (or even 5) methods to assess eutrophication, which might result in collection of redundant information (Kelly et al. 2016).

As many as 37 methods are reported to address HyMo pressures (at least one biological quality element in 16 countries); however, in most cases HyMo pressures are mentioned as a secondary pressure in addition to eutrophication, and pressure–response relationships are not

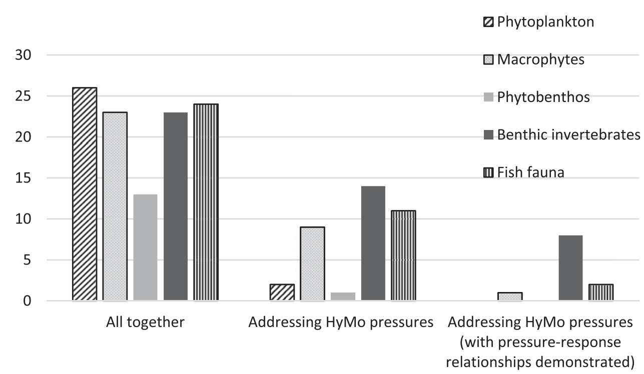

Figure 2. Lake assessment methods addressing all pressures, HyMo pressures, and with evidence of HyMo pressures (only intercalibrated; status quo Nov 2018).

demonstrated (Table 4). The methods addressing HyMo pressures are mostly based on the communities of benthic invertebrates (14 methods), fish (11), or macrophytes (9).

To illustrate key aspects of biological assessment systems, descriptions of 2 methods are provided in Appendix I, following the scheme proposed by Birk et al. (2013): (1) data acquisition; (2) numerical evaluation; and (3) classification.

Many studies have aimed to develop EU-wide (Moss et al. 2003) or regional assessments methods (Lyche-Solheim et al. 2013, Phillips et al. 2013). For HyMo pressures, common indices have been developed for lake benthic invertebrates (Miler et al. 2013b, Poikane et al. 2016a) and lake macrophytes (Mjelde et al. 2013; Table 5). The use of common indices has been strongly advocated (Carvalho et al. 2013), especially in cases where the assessment methods have not been developed or have performed poorly. However, in most cases the application of common indices has been limited (e.g., countries chose to develop country-specific indices). The reasons are manifold, but the most important are the following: (1) Biogeographical differences: typically, a

Table 4. Overview of Member States biological assessment methods addressing HyMo pressures (with relationships demonstrated with HyMo metrics).

Member State/region	Pressures addressed (in order of importance)	Biological quality element assessed	HyMo pressure proxy	Regression coefficient R^2	Reference
Austria	HyMo	Benthic invertebrates, littoral zone	Austrian pressure index	0.41	Wolfram et al. (2017)
Denmark	*Eutro; HyMo*	*Benthic invertebrates, littoral zone*	*Pressure index*	*0.03*	Wiberg-Larsen and Rasmussen (2017)
Finland	Eutro, HyMo	Macrophytes, transect method	Winter drawdown	0.58	Vuori et al. (2009)
Germany (alpine lakes)	HyMo	Benthic invertebrates, littoral zone	Stressor index	0.23–0.45*	Miler et al. (2013b)
Germany (lowland lakes)	*HyMo; Eutro*	*Benthic invertebrates, littoral zone*	*Morpho-index*	*0.1–0.25*	Miler et al. (2013a)
Greece	Eutro; HyMo	Fish fauna (benthic and pelagic gillnets)	LHMS	0.74	Petriki et al. (2017)
Lithuania	*Eutro; HyMo*	*Benthic invertebrates, littoral zone*	*Morpho-index*	*0.11*	Šidagytė et al. (2013)
Lithuania	*Eutro; HyMo*	*Fish fauna (benthic gillnets)*	*HMI*	*0.19*	Virbickas and Stakėnas (2016)
The Netherlands	HyMo; Eutro	Benthic invertebrates, littoral zone	Shore alterations	0.45	Altenburg et al. (2007), Böhmer et al. (2014)
Poland	*Eutro; HyMo*	*Benthic invertebrates, littoral zone*	*Land-use*	*0.06*	Bielczyńska et al. (2018)
Slovenia	HyMo	Benthic invertebrates, littoral zone	LMI	0.80	Solimini et al. (2014), Urbanič (2014)

Methods with weak predictive capacity ($R^2 < 0.25$) are marked in italics.
Eutro: eutrophication pressure; HyMo: hydromorphological pressures; HMI: Hydromorphological Index; LHMS: Lake Habitat Modification Score; LMI: Lakeshore Modification Index HyMo pressure proxies described in Table 6.
*for different types of lakes.

country-specific index performs better in the country of origin than outside its original range, where it may yield less accurate results because conditions (e.g., associations of species) differ from those of the sites for which it was developed (Birk et al. 2013). (2) However, tradition and pragmatic reasons also play an important part in choice of biological indices (Kelly et al. 2015). In addition, development of a common assessment system has proved

Table 5. Overview of common biological assessment methods addressing HyMo pressures (with relationships demonstrated with HyMo indices).

BQE; pressure and proxy	Member States	Metrics included in the pressure index	Regression coefficient R^2	Reference
Benthic invertebrates – shore morphological alterations; Pressure proxy—hydromorphological stressor index	Denmark/ Germany	LIMCO: Margalef diversity; Gatherers and collectors%; Chironomidae%; No. EPTCBO taxa	0.48	Miler et al. (2013b)
		LIMHA (stones): Margalef diversity; gatherers and collectors%; Coleoptera%; No. EPTCBO taxa	0.53	
	Finland and Sweden	LIMCO: No. families; shredders%; Crustacea%; No. Odonata taxa	0.15	
		LIMHA (macrophytes): evenness, Predators%; Coleoptera%; EPTCBO taxa%;	0.19	
	Ireland and UK	LIMCO: Margalef diversity; gatherers and collectors%; Diptera%; No. ETO taxa	0.22	
		LIMHA (sand): Shannon diversity; swimming/diving%; Diptera%; EPTCBO taxa%	0.50	
	Central and Northern Italy	LIMCO: Margalef diversity; r/k ratio; Odonata %; No. ETO taxa	0.24	
		LIMHA (silt): Shannon diversity; Psammal%; Oligochaeta%; EPT taxa%	0.16	
Benthic invertebrates – shore morphological alterations; Pressure proxy—morphological index	Germany and Slovenia	ALP-ICM: Fauna index; No. taxa; Gatherers and collectors%; r/k ratio	0.32	Poikane, et al. (2016a)
	Belgium, Germany, Estonia, Lithuania, the Netherlands and UK	CB-ICM: ASPT index; No. EPTCBO taxa; Lithal%; ETO taxa%	0.18	
Macrophytes—water level fluctuations; proxy—winter drawdown	Finland and Norway	Water level drawdown index (WIc): ratio between sensitive and tolerant macrophyte species	0.09 (lakes) 0.77 (storage reservoirs)	Mjelde et al. (2013)

EPTCBO: Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Bivalvia, and Odonata taxa; ETO: Ephemeroptera, Trichoptera, Odonata taxa; LIMCO: Littoral Invertebrate Multimetric based on composite samples; LIMHA: Littoral Invertebrate Multimetric based on habitat samples; ALP-ICM: Alpine region intercalibration common metric used; CB-ICM: Central Baltic region intercalibration common metric.

Table 6. Metrics included in lake assessment methods addressing HyMo pressures.

Biological quality element	Metrics and direction of change across pressure gradient	Member State in which metric was applied
Benthic invertebrates	**Composition/abundance metrics**	
	Coleoptera, Odonata and Plecoptera (COP) (%) ↓	Denmark, Lithuania
	Odonata (% abundance) ↓	Germany (Alpine and lowland lakes)
	Oligochaeta (abundance) ↑	Austria
	Neozoa (% abundance) ↑	Austria
	Diptera (% abundance) ↑	Poland
	Sensitivity/tolerance metrics	
	Average score per taxon ASPT ↓	Denmark, Lithuania, Poland
	Fauna index (Miler, et al. 2013b)	Germany (Alpine and lowland lakes)
	Littoral fauna index (Urbanič 2014) ↓	Slovenia
	Positive and negative dominant taxa (% abundance) ↓↑	The Netherlands
	Type-specific indicator taxa (% abundance and % taxa number) ↓	The Netherlands
	Richness diversity metrics	
	Hill's number ↓	Denmark, Lithuania
	Margalef diversity index ↓	Slovenia
	Shannon-Wiener Diversity index ↓	Germany (Alpine lakes), Poland
	Number of taxa ↓	Austria, Slovenia
	Number of Coleoptera, Ephemeroptera, Plecoptera taxa (CEP) ↓	Lithuania
	Number of Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Bivalvia, and Odonata taxa (EPTCBO) ↓	Denmark, Poland
	Number of Epheremoptera, Trichoptera, Odonata taxa (ETO) ↓	Germany (lowland lakes)
	Relative richness of indicator (for water type) species in a sample ↓	The Netherlands
	Functional metrics	
	r/K = taxa ratio of r and K strategists ↑	Austria, Germany (Alpine lakes)
	Feeding type collectors (% abundance) ↑	Austria, Germany (Alpine lakes)
	Habitat type lithals (%) ↓	Germany (lowland lakes)
Fish	**Composition/abundance metrics**	
	Nonnative+translocated species (% biomass) ↑	Greece, Lithuania
	Functional metrics	
	Benthivorous species (% biomass) ↑	Lithuania
	Omnivorous species (% biomass) ↑	Greece
	Stenothermic species and *Perca fluviatilis* (% biomass) ↓	Lithuania
	Sensitivity/tolerance metrics	
	Number of type-specific sensitive species ↓	Lithuania
	Age structure	
	Mean weight of *Rutilus rutilus* ↓	Lithuania
Macrophytes	**Sensitivity/tolerance metrics**	
	Reference Index ↓	Finland
	General metrics of community change	
	Proportion of type-specific taxa ↓	Finland
	Percent Model Affinity ↓	Finland

Metrics were grouped into categories according to Hering et al. (2006) and Kanninen et al. (2013).
↓ metrics decrease along ecological status gradient; ↑ metrics increase along ecological status gradient.

difficult because of strong spatial differences in macroinvertebrate community composition between geographical regions and countries (Miler et al. 2013b).

Pressure–response relationships in biological assessment methods addressing HyMo pressures

For management, linkages between pressure and ecology are of utmost importance (Karr 2006, Birk et al. 2012), yet only 11 biological assessment methods (applied in 9 countries) provide evidence of addressing HyMo pressures (i.e., a pressure–response relationship between HyMo pressures and biological metrics; Fig. 2, Table 6). Of those methods, 8 are based on benthic invertebrates, 2 on fish, and 1 on macrophytes. Pressure–response relationships were developed with various HyMo indices, with explained variance ranging from 3% to 80%. Only 2 methods exclusively address HyMo pressures (German and Slovenian benthic invertebrate assessment methods), whereas other methods address both eutrophication and HyMo pressures.

Some of these methods have low explanatory power (with $R < 0.5$; Cohen 1988) and limited value for lake management (O'Toole et al. 2008, Søndergaard et al. 2011). Only 6 methods demonstrate pressure–response relationships with sufficient predictive capacity ($R > 0.5$ or $R^2 > 0.25$). Benthic invertebrates are the most widely used group to detect effects of HyMo alterations with sufficiently strong evidence (Table 6). All benthic invertebrate methods that address the effects of lakeshore alterations focus on the littoral benthic invertebrate community and follow a multi-habitat sampling strategy.

Table 7. Variables included in HyMo indices used for developing pressure–response relationships.

Member State	Biological quality element	HyMo pressure index	Metrics included in the pressure index
Austria	Benthic fauna—littoral	Austrian pressure index (Wolfram 2017)	% forest (land use); % urban (land use); number of pressures within the lake habitat survey; presence/absence of hard alterations of the shore
Denmark	*Benthic fauna—littoral*	*Pressure index* (Miler et al. 2012)	*Number of low-intensity anthropogenic impacts within/next to the habitat sampling area; number of high-intensity anthropogenic impacts within/next to the habitat sampling area*
Germany	Benthic fauna—littoral for alpine lakes	Stressor index (Böhmer et al. 2014)	Landuse from the % of land uses in the 15 m and 100 m belt around the whole lake; naturalness classification by expert judgement, based on morphology and land use of the shoreline and adjacent areas at the sampling sites; % shore alteration (total, hard, soft)
Germany	*Benthic fauna—littoral for lowland lakes*	*Morphoindex* (Pilotto et al. 2011)	*% shore alteration; land use from the % of land uses in the 15 m belt around the whole lake; land-use index from the % of land uses in the 100 m belt around the whole lake*
Finland	Macrophytes	Winter drawdown (Mjelde et al. 2013)	Winter drawdown—the average difference between the highest water level during the Oct–Dec period and the lowest level during the following Apr–May period
Greece	Fish fauna	LHMS—Lake Habitat Modification Score (Rowan et al. 2006)	Shore zone modification (% hard engineering, shore reinforcement); shore zone intensive use (% shore zone non-natural land-cover); number of in-lake pressures (angling, boating, etc.); hydrology (hydrological structures, upstream impoundment); sediment regime (shore erosion, deposition)
Lithuania	*Benthic fauna*	*Morpho index* (Šidagytė et al. 2013)	*Land-use index from the % of land uses in the 15 m and 300 m belts around the whole lake;*
Lithuania	*Fish fauna*	*Hydromorphological index* (Virbickas and Stakėnas 2016)	*Water-level alterations; shore structure (natural riparian vegetation, shore alterations, shore erosion); substrate in the littoral zone*
Netherlands	Benthic fauna	Shore alteration (Böhmer et al. 2014)	% altered shore length of total shore length
Poland	*Benthic fauna*	*Land use*	*% agricultural land use in the catchment*
Slovenia	Benthic fauna	LMI—Lakeshore Modification Index (Peterlin and Urbanič 2012)	Water-level changes in the littoral zone; presence of wooden structures in the littoral zone; substratum alteration, extent of area covered by buildings and infrastructure; zone-use intensity; land use in lakeshore region up to 100 m offshore

Methods with weak predictive capacity ($R^2 < 0.25$) are marked in italics.

Which metrics are used in biological assessment methods addressing HyMo?

Numerous studies have assessed the effect of lakeshore alterations on benthic invertebrate richness and diversity (Table 1). The decrease of taxon richness is mainly linked to the lower habitat diversity and complexity at developed shorelines (Brauns et al. 2007) and might have far-reaching consequences for the whole-lake ecosystem (Brauns et al. 2011, McGoff et al. 2013b). Many studies have reported shifts in the taxonomic composition of benthic invertebrates in response to shore alterations (Urbanič et al. 2012, Miler et al. 2013a, Urbanič 2014). Most of the metrics used in these assessments were based on changes in species composition and richness/diversity (Table 5 and 6).

Far fewer studies have investigated the effect of lakeshore alterations on functional groups of macroinvertebrates (but see García-Criado et al. 2005, Brauns et al. 2007). An increase in the relative abundance of feeding type collectors/gatherers along the pressure gradient has been reported for lakes of Denmark, Germany, Ireland, and UK (Miler et al. 2013a) and an increase in the ratio of r to K strategists for lakes of Italy, Germany, and Slovenia (Urbanič et al. 2012, Miler et al. 2013a, 2013b). These functional metrics are included in the Austrian and German assessment methods.

The effect of WLFs on biological communities has been studied widely, especially on benthic invertebrates (Aroviita and Hämäläinen 2008, Evtimova and Donohue 2016) and macrophytes (Hellsten 2002, Mjelde et al. 2013). However, only one assessment method addresses WLFs (Table 4): the Finnish macrophyte assessment method, developed primarily for eutrophication assessment, shows a strong relationship with winter drawdown. This method includes 1 eutrophication-related index and 2 general measures of community change. However, Kanninen et al. (2013) showed that general measures (Bray–Curtis distance index and percent model affinity index) yield robust ecological quality estimates across both water level fluctuation and eutrophication gradients, whereas the water-level drawdown index

(Mjelde et al. 2013) reacted only in the most heavily impacted lakes.

Response of fish to HyMo pressure has been studied comparatively less and with contradictory results. For instance, Mehner et al. (2005) found no effect of shore alterations on the fish community, Sutela et al. (2013) reported a decrease of fish abundance due to WLFs, and Lewin et al. (2014) showed an increase of fish abundance of all species (except roach) in response to shoreline degradation. Cummings et al. (2017) reported that with declining water levels, native fish lose their spawning habitats; this loss was considered to be a major contributor to a subsequent fishery collapse. Only one country has a fish-based method showing a significant strong relationship (Greece; $R^2 = 0.74$) to HyMo pressures, including the relative biomass of nonnative species and omnivorous species. However, no effect of HyMo pressures on introduced species has been found in lakes of France (Launois et al. 2011) and Lithuania (Virbickas and Stakėnas 2016).

How is the HyMo gradient assessed using HyMo metrics?

When developing methods and pressure–response relationships, the pressure gradient must be described with appropriate pressure metrics (Hering et al. 2006). Eutrophication pressure metrics (nutrient, mainly total phosphorus, concentrations; Lyche-Solheim et al. 2013) and acidification (pH or acid neutralizing capacity) have surprising consensus (McFarland et al. 2010), but metrics describing HyMo pressures are surprisingly variable. The 11 different HyMo metrics used to describe HyMo alterations (Table 7) include 2 simple indices ("winter drawdown," calculated as the difference between the highest and lowest water levels, and "shore alterations," calculated as percentage of altered shore length of total shore length) and other more complex indices synthesizing a wide array of different pressure proxies, such as land use, number of in-lake pressures, description of shore structure, shore erosion, and water fluctuation regime.

HyMo pressures affect lake ecology through a multitude of different factors: WLFs, shore alteration, and connectivity of the inflowing streams. The HyMo stressor gradient should comprise all these factors, but in the WFD assessment methods, HyMo alterations are described mainly by nonspecific pressure metrics such as percent land use and number of in-lake pressures. These metrics describe general degradation (Böhmer et al. 2004) and do not adequately characterize HyMo pressures. In some cases (Šidagytė et al. 2013, Bielczyńska et al. 2018), land use is the only proxy of HyMo pressures. Additionally, each country used its own approach describing HyMo gradients, which makes method comparison problematic.

Challenges encountered and proposed solutions

Lack of assessment methods addressing HyMo pressures and pressure–response relationships documenting HyMo effects on lake biota

Despite the importance of HyMo pressures (EEA 2018), only 16 countries (of 29) have at least one biological assessment method addressing HyMo. Most of the biological assessment methods addressing HyMo pressures lack pressure–response relationships; only 11 methods in 9 countries provide these relationships, and only 6 of those assessment methods demonstrate pressure–response relationships with sufficient strength ($R > 0.5$).

Lack of HyMo-specific biological assessment methods

Most HyMo-addressing biological methods target several pressures with main focus on eutrophication (e.g., Šidagytė et al. 2013). These methods show a strong response along the nutrient enrichment gradient but only a weak response to HyMo indices. Most do not separate the impacts of different stressors; instead, they aim to assess the general degradation caused by multiple stressors. While multiple-stressor assessment methods can be useful (Kanninen et al. 2013, Poikane et al. 2017), stressor-specific tools are needed to advise environmental managers on the cause of degradation and management measures needed to improve the status.

Lack of assessment methods addressing different types of biological communities and of HyMo pressures, including water level fluctuations

HyMo pressures have significant effects on all biological communities (Zohary and Ostrovsky 2011, Jeppesen et al. 2015). However, most assessment tools focus on littoral benthic invertebrates, with only one method addressing macrophytes (Finland) and only one method addressing fish (Greece).

Similarly, it is well understood that HyMo pressures include several types of impacts (e.g., shore alterations, WLF). However, most HyMo methods focus on shore alterations, and only one method (Finland, macrophytes) demonstrates pressure–response with WLFs.

Lack of common understanding of describing the HyMo gradient

Last, but not least, how to describe the HyMo alteration gradient must be addressed. Currently, countries use many different approaches to characterize the HyMo gradient, including nonspecific metrics characterizing general degradation, such as land use. In theory, LHMS was developed to indicate the degree of hydromorphological pressures around the lake, but it has rarely been used for pressure–response method development and with unsatisfactory results (McGoff et al. 2013).

Conclusions

We conclude that the biological methods currently in use do not reliably address the effects of hydromorphological alterations. To ensure that hydromorphological pressures and their effects do not remain undetected, it is urgent to (1) develop biological assessment methods responding specifically to hydromorphological pressures; (2) develop HyMo assessment methods and use them alongside the biological methods; and (3) include the measurement of the variables needed for the biological assessments in routine monitoring programs of lakes.

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Appendix I. Examples of biological assessment systems targeting HyMo pressures

Country	Denmark	Slovenia
	Danish lake macroinvertebrate index (DLMI)	Littoral benthic invertebrate index (LBI)
Data acquisition: field sampling and sample processing		
Sampling frequency and month(s)	Once per sampling season (Sep–Oct)	Once per sampling season (Jul–Aug)
Sampling device	Hand net with mesh-size of 500 µm	Hand net with mesh size of 500 µm, Surber or Hess sampler
Sampling protocol	Kick sampling (composite sample) during a fixed period (2 min) on solid substrates (sand, gravel, stones). Thus, one sample is collected on a specific site. Number of sites is not fixed yet but probably at least 4 in each lake	Multi-habitat sampling in proportion to their presence. Sum of 10 spatial replicates (one per stream microhabitat >10%). Sediments must be disturbed to a depth of 15–20 cm (where possible) depending on substrate compactness.
Level of taxonomical identification	Groups like Ephemeroptera, Plecoptera, Odonata, Coleoptera, Trichoptera, and Bivalvia are identified to species; most other groups (especially Oligochaeta and Diptera) to family or subfamily or less (e.g., Hydrachnidia)	Most taxa determined to the species and genus level, Chironomidae to subfamily, Tubificidae and some Brachycera to family.
Numerical evaluation: biological metrics derived from the data and their combination		
Biological metrics	(1) ASPT index (average score per taxon);(2) Hill's number (exp Shannon-Wiener index);(3) %COP (relative abundance of Coleoptera, Odonata, Plecoptera taxa);(4) No. EPTCBO (number of taxa of Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Bivalvia, and Odonata)	(1) Number of taxa using a Slovenian operational taxa list;(2) Margalef diversity index;(3) Littoral fauna index (LFI; Urbanič 2014)
Combination rule for multi-metric	Average metric scores	Weighted average metric scores (LFI is equally weighted as both richness/diversity metrics together)
Classification: reference conditions and boundaries between status classes		
How reference conditions were derived	Because unimpacted lakes no longer exist in Denmark, "best achievable condition" using pressure criteria (<10% agriculture and <10% artificial land) and physical and chemical characteristics were defined.	Reference conditions were derived using existing near-natural reference sites. A type-specific reference values was calculated as a mean of reference sites.
How class boundaries were derived	Boundary values obtained by dividing the DLMI axis into 5 equal intervals representing each of the 5 ecological status classes.	Boundary values between ecological status classes were defined based on the changes in ration between the number of sensitive and tolerant taxa.
Detected pressures	Eutrophication, anthropogenic impacts in the littoral zone	Hydromorphological degradation
Validated pressure-response relationship	Linear regression between DLMI and the estimated proxy for eutrophication, PCA1 (including total phosphorus, total nitrogen, chlorophyll *a*, pH, and Secchi depth) $R^2 = 0.3$; $p < 0.001$ Linear regression between DLMI and the proxy for littoral pressures: pressure index (PI) $R^2 = 0.03$; $p < 0.001$	Linear regression between LBI-EQR and Lakeshore Modification Index (LMI; Peterlin and Urbanič 2012), $R^2 = 0.8$; $p < 0.001$
Reference	Wiberg-Larsen and Rasmussen (2017)	Solimini et al. (2014), Urbanič (2014)