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PRIMARY RESEARCH PAPER

Assessment of the ecological status of regulated lakes: stressor-specific metrics from littoral fish assemblages

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Abstract Following the European Water Framework Directive (WFD), the ecological status of lakes should be classified based mainly on biota, including fish fauna. In Finnish regulated lakes, littoral fish assemblages may be especially vulnerable to winter drawdown in water level. In this study, we sampled littoral fish assemblages by electrofishing in 14 regulated and 9 reference lakes, and developed three stressor-specific metrics based on total fish density, proportion of disturbance-sensitive species, and occurrence of juveniles. Ecological status was classified from bad to high in regulated lakes, whereas standard WFD assessment based on NORDIC gillnet sampling indicated high status and no response to water level regulation. We suggest that stressor-specific metrics should be integrated into the assessment of the ecological status of regulated lakes in the WFD.

Keywords Regulated lake · Littoral zone · Electrofishing · Ecological status · WFD

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Introduction

In Finland, over 300 lakes, representing about 1/3 of the total inland water area, are regulated mainly for hydropower production and flood control. The water level is drawn down usually 1–3 m in winter, when the demand for electricity is highest. In the typically shallow, gently sloping Finnish lakes a considerable proportion of the lakebed is desiccated and partly frozen. Ice of about 0.5–1 m in thickness descends on the littoral zone and presses the bottom, thus widening the impact of winter drawdown still deeper. In spring and early summer meltwater from snow refills the lakes supported by the minimized water abstraction. Natural spring flooding does not occur and the water level is usually kept quite constant over the summer until late autumn (Alasaarela et al., 1989; Marttunen et al., 2006).

Water level regulation by winter drawdown has been documented to affect littoral geomorphology (Rørslett, 1988; Hellsten, 1997), vegetation (Hellsten & Riihimäki, 1996), macroinvertebrates (Palomäki &

Koskenniemi, 1993; Aroviita & Hämäläinen, 2008), and fish fauna (Gaboury & Patalas, 1984; Paller, 1997). Breeding of fish species that spawn in shallow parts of the littoral zone may be disturbed by water level fluctuation (Gafny et al., 1992), and available food resources for fish may lessen following a reduction in macroinvertebrates (Palomäki & Koskenniemi, 1993). Benthic littoral fish species, like bullhead, *Cottus gobio* L., and stone loach, *Barbatula barbatula* (L.), favor stony habitat where they can hide within stone interstitials (Hyslop, 1982; Fischer & Eckmann, 1997). During winter drawdown, littoral fish are forced to shift from their nearshore stony habitat to a deeper zone often with soft bottom and thus no shelter against predation (Sutela & Vehanen, 2008). Besides predation effects, lack of sheltering stony habitat may affect metabolism and somatic growth rates in benthic fish (Fischer, 2000). Altogether, littoral benthic fish species may be especially vulnerable to winter drawdown.

The European Water Framework Directive (WFD), which was adopted in 2000, has set the goal of attaining good chemical and ecological status in all surface waters by 2027 (European Union, 2000). The ecological status of lakes should be assessed largely basing on four biological quality elements, namely phytoplankton, other aquatic flora, benthic invertebrate fauna, and fish fauna. The NORDIC multimesh survey net is a standard monitoring tool (CEN 14757:2005) in sampling pelagic and profundal lake fish communities for the WFD in Finland, Sweden, and Norway, and it is increasingly used also in other countries (Malmquist et al., 2001; Olin et al., 2004). However, this method is poorly applicable in sampling shallow littoral areas in comparison to electrofishing (Sutela et al., 2008). The metrics developed for the NORDIC gillnet in the assessment of the ecological status (EQR4 index, Rask et al., 2010) predominantly respond to eutrophication. As water level regulation is a powerful stressor especially in the littoral zone, there is an urgent need to develop new specific assessment tools for regulated lakes.

In this study, we sampled regulated and non-regulated reference lakes by littoral electrofishing, developed stressor-specific metrics for water level regulation, and classified the ecological status of the lakes following the principles in WFD. Finally, classification results were compared to those achieved by the standard monitoring by NORDIC gillnets.

Materials and methods

Lakes studied

We studied 14 lakes with regulated water level fluctuation and 9 reference lakes with natural water level fluctuation in Northern Finland (Table 1). Intensity of regulation was quantified as a long span average of winter drawdown, which was calculated as the difference between the highest and lowest water level in winter (1 Nov–30 Apr). The lake area in the sampled lowland lakes (altitude <200 m) ranged from 12 to 887 km^2, whereas the mean depth varied between 5.0 and 9.7 m. The lakes were classified as oligotrophic or mesotrophic based on their total phosphorus content. Discharge from forestry and agriculture slightly deteriorate the water quality in all of the lakes. The lakes belong to three WFD compliant Finnish national lake types, and the eight most regulated lakes have been designated as heavily modified water bodies (Table 1). For those water bodies the objective in WFD is the achievement of good ecological potential, i.e., ecological quality expected under the conditions of the implementation of all possible mitigation measures (see Lammens et al., 2008).

Fish sampling and data acquisition

In August 2003–2007 a total of 430 electrofishing events were conducted in 23 lakes (Table 2). The number of electrofishing events per lake averaged 19, and increased with lake area. In the randomized site selection only non-wadable rocky shores were excluded. Average depth on the sampled 100 m^2 areas was 30 cm. Fish were captured with Hans Grassl Gmbh ELT 6011 GI Honda GXV50 electrofishing gear using pulsed (50 Hz) DC current with 800–1000 V voltage. Each area was fished once by two waders, one using the anode and an assistant collecting the stunned fish with a dip-net. Escape nets were used only in some exceptional pure sand bottoms having no stones or vegetation, which could offer a hiding place for the fish.

Total length (TL) of every fish was measured to the nearest 1 mm and pooled individuals of each fish species were weighed to the nearest 0.1 g. Presented fish densities represent the catch of one electrofishing

Table 1 Characteristics of the lakes studied. Abbreviations for the Finnish WFD compliant lake types: LH = Large humic lakes, MH = Moderate size humic lake, PH = polyhumic lake

Lake	Reference/ Regulated lake	Winter draw-down (m)	Lake area (km^2)	Mean depth (m)	Total *P* (µg/l)	Lake type	Heavily modified lake
Tyräjärvi	Ref.	0.09	25	3.7	18	MH	
Simojärvi	Ref.	0.22	55	5.0	9	LH	
Kivesjärvi	Ref.	0.27	26	4.1	14	MH	
Pesiöjärvi	Ref.	0.27	13	4.2	12	MH	
Miekojärvi	Ref.	0.27	53	5.2	15	LH	
Änättijärvi	Ref.	0.32	24	9.7	9	MH	
Lentua	Ref.	0.40	78	7.4	9	LH	
Kellojärvi	Ref.	0.43	22	5.0	16	MH	
Pielinen	Ref.	0.48	984	10.4	10	LH	
Iijärvi	Reg.	1.19	22	5.2	16	MH	
Hyrynjärvi	Reg.	1.30	18	5.8	12	MH	
Nuasjärvi	Reg.	1.52	96	8.5	14	LH	
Oulujärvi	Reg.	1.54	887	8.4	14	LH	
Raanujärvi	Reg.	1.75	25	6.0	19	MH	
Koitere	Reg.	1.76	164	8.2	11	LH	
Iso-Vietonen	Reg.	2.62	36	5.5	18	MH	x
Kiantajärvi	Reg.	3.12	188	7.6	11	LH	x
Irnijärvi	Reg.	3.24	32	5.6	12	MH	x
Iso-Pyhäntä	Reg.	3.50	12	6.9	16	PH	x
Ontojärvi	Reg.	3.51	105	5.8	15	LH	x
Kostonjärvi	Reg.	4.02	44	5.1	11	LH	x
Vuokkijärvi	Reg.	4.71	51	5.0	18	LH	x
Kemijärvi	Reg.	6.75	206	5.5	16	LH	x
Average	Ref.	0.31	142	6.1	12.4		
Average	Reg.	2.90	135	6.4	14.5		

run. Environmental conditions including water temperature, mean and maximum depth of the area, bottom quality and coverage of vegetation (%) were recorded. Stony bottoms predominated in the electrofished areas (Table 2).

Results

Intensity of regulation

The range of the average winter drawdown in the regulated lakes was 1.18–6.75 m. Natural winter drawdown in the non-regulated reference lakes was 0.09–0.48 m (Table 1). This winter drawdown approximates the amplitude in annual water level fluctuation in the lakes studied.

Selection and definition of metrics

WFD specifies that the ecological status of lakes should be assessed based on composition, abundance and age structure of the fish fauna. To quantify these biological elements we needed to find some measurable factors (metrics) which should change in value along a gradient of human influence (Karr & Chu, 1997). No fish species popped out as a clear indicator species for water level regulation in the inspection of the occurrence data. Nine-spined stickleback, *Pungitius pungitius* (L.) and dace, *Leuciscus leuciscus* (L.) were recorded only in some regulated lakes (Table 3), but the evidence for being an indicator species was interpreted to be insufficient.

Next, the responses of the fish assemblages to regulation were sought from absolute and relative fish

Table 2 Number of electrofished areas and some of their characteristics

Lake	Reference/ Regulated	Number of electrofished areas	Mean depth (cm)	Percentage of stony bottom (%)	Coverage of macrophytes (%)
Tyräjärvi	Ref.	16	20	67	4.3
Simojärvi	Ref.	21	29	84	3.1
Pesiöjärvi	Ref.	12	24	50	3.1
Kivesjärvi	Ref.	17	24	64	5.2
Miekojärvi	Ref.	19	19	66	7.7
Änättijärvi	Ref.	20	31	71	2.2
Lentua	Ref.	23	35	60	6.8
Kellojärvi	Ref.	16	27	51	10.6
Pielinen	Ref.	21	28	90	0.9
Iijärvi	Reg.	17	26	60	4.5
Hyrynjärvi	Reg.	16	28	72	3.1
Nuasjärvi	Reg.	18	33	87	2.1
Oulujärvi	Reg.	22	31	75	8.7
Raanujärvi	Reg.	16	24	60	6.1
Koitere	Reg.	20	27	55	2.3
Iso-Vietonen	Reg.	18	25	58	3.2
Kiantajärvi	Reg.	18	30	57	0.6
Irnijärvi	Reg.	16	22	58	4.0
Iso-Pyhäntä	Reg.	18	40	15	15.8
Ontojärvi	Reg.	20	29	66	2.5
Kostonjärvi	Reg.	20	27	79	4.6
Vuokkijärvi	Reg.	20	27	60	3.6
Kemijärvi	Reg.	26	29	65	3.4
Average in reference lakes		18	26	67	4.9
Average in regulated lakes		19	28	62	4.6

densities (Table 3). At first, we tested the metrics used with NORDIC gillnet sampling (Tammi et al., 2006; Alahuhta et al., 2009), but found them inappropriate or nonresponsive. For example, the proportion of piscivorous perch, *Perca fluviatilis* L. (>15 cm), used as a metric with NORDIC gillnet sampling, was judged inappropriate for littoral electrofishing catches which are dominated by young perch individuals. More candidate metrics were searched in an iterative process guided by ecological relevance, responsiveness, and avoidance of redundancy among metrics (CIS, 2003; Roset et al., 2007). As an outcome, following candidate metrics were chosen: (1) Species richness, (2) Total density, (3) Proportion of disturbance-sensitive species on stony shores (in biomass), and (4) Occurrence of young individuals within disturbance-sensitive species.

In the candidate metrics 3 and 4, following littoral fish species were considered to be disturbance-sensitive: minnow, *Phoxinus phoxinus* (L.), bullhead, alpine bullhead, *Cottus poecilopus* (Heckel), and stone loach. Of the other fish species which inhabit littoral areas mainly in juvenile stage, burbot, *Lota lota* (L.) and ruffe, *Gymnocephalus cernua* (L.) were also considered to be disturbance-sensitive. In an ecological perspective, we hypothesized that these dominantly insectivorous fish suffer from the negative impact of winter drawdown on littoral macroinvertebrates (Palomäki & Koskenniemi, 1993; Aroviita & Hämäläinen, 2008). Besides, these mainly lithophilous or demersal fish species were speculated suffer from loosing their stony nearshore habitat during winter (Sutela & Vehanen, 2008). This separation was supported by the observed fish

Table 3 Average fish densities (ind./100 m^2) in the littoral electrofishing catch of 9 reference lakes and 14 regulated lakes

	Reference or regulated lake	Nine-spined stickleback	Min-now	Bullhead	Alpine bullhead	Stone-loach	Perch	Roach	Pike	Burbot	Ruffe	Dace	0+ cyprinid	Sum
Tyräjärvi	Ref.			1.0			3.3	0.4	0.3	0.9	0.3		0.9	7.1
Simojärvi	Ref.			3.9			1.0		0.5	1.2	17.2			23.8
Pesiöjärvi	Ref.		31.9				0.1		0.3	1.3				33.6
Kivesjärvi	Ref.			7.1		0.2	4.4	0.4	0.5	0.6	11.4			24.5
Miekojärvi	Ref.			20.3			2.8			0.5	1.4		0.2	25.2
Änättijärvi	Ref.		4.7	5.2	3.0		0.2		0.1	1.1	6.9			21.0
Lentua	Ref.		23.1	1.7			0.6	0.1		0.7	5.3		0.1	31.6
Kellojärvi	Ref.			4.8			0.9		0.2	1.4	1.4			8.6
Pielinen	Ref.		6.4	1.5		4.0	1.7	0.0	0.1	0.4	4.0			18.2
Iijärvi	Reg.	0.1		6.3			4.2	0.2	0.1	0.5	6.1	0.4		17.8
Hyrynjärvi	Reg.			14.2			5.4	0.4	0.1	0.5	2.0		0.1	22.7
Nuasjärvi	Reg.	0.2		3.7			14.2	1.7	0.3	0.4	10.8		0.1	31.4
Oulujärvi	Reg.	0.3		1.3		2.7	6.8	2.6	0.3	0.8	2.1	0.5	18.2	35.5
Raanujärvi	Reg.			4.9			0.6	0.3	0.1	0.4	12.9		1.0	20.1
Koitere	Reg.		4.1		1.1		14.1	0.1	0.2	1.2	2.2	0.1	0.1	22.9
Iso-Vietonen	Reg.			2.8			3.1		0.1		1.6		0.2	7.7
Kiantajärvi	Reg.	1.1	0.5		0.6		8.2		0.3	1.6	2.6			14.7
Irnijärvi	Reg.		4.7		0.8		0.9		0.6	1.4	3.4			11.6
Iso-Pyhäntä	Reg.						5.1		0.3	0.1	0.1			5.5
Ontojärvi	Reg.		4.7	4.4			18.2	0.2	0.2	1.2	2.5		0.6	31.9
Kostonjärvi	Reg.		21.5	0.4			4.0			0.2	3.1		0.2	29.3
Vuokkijärvi	Reg.						0.6	0.2	0.5	0.7	0.9	0.1		2.9
Kemijärvi	Reg.	0.0		0.7			0.8	0.0	0.3	0.6	1.5	0.0		4.0

densities, and it matched quite well the divisions to tolerant and intolerant species made in the literature (Malmquist et al., 2001; FAME CONSORTIUM, 2004). All 0+ individuals of the disturbance-sensitive littoral fish species and all burbot individuals (mainly 0+ or 1+) were classified as young individuals in candidate metric 4. These 0+ and 1+ age groups were identified based on the length distribution. Occurrence of young individuals in metric 4 was expressed as an average number of fish species represented by young individuals in the electrofished areas.

Of the four candidate metrics, species richness was rejected because it was found to correlate strongly with lake area (Sutela & Vehanen, 2008). The surface area of the studied lakes varied quite a lot (Table 1). Also the varying number of electrofishing samples per lake apparently caused some extra variation in species richness. Each of the three accepted metrics indicated statistically significant relationship with winter drawdown, although the high variation in total density led to a rather weak response (linear regression analysis, $r^2 = 0.18$, $P = 0.046$).

Classification of the ecological status

According to the WFD, ecological status of a water body should be defined relative to its deviation from reference conditions, i.e., the expected ecological quality in the absence of anthropogenic influence. Ecological quality ratios (EQR) were calculated following the principles presented in a guidance document (CIS, 2003). At first, EQR_{raw} values within each metric were calculated as follows:

$$EQR_{raw} = \text{measured value/arithmetic average value in the nine reference lakes}$$

Next, we performed linear rescaling so that the boundary between high and good equals the 10th percentile of the reference lakes:

$$EQR_{final} = \left(0.8/EQR_{hg}\right) * EQR_{raw},$$

where EQR_{hg} = 10th percentile of the reference values.

After combining the EQR values of the three metrics by using the median method, linear rescaling was performed again. Classes and EQR boundaries settle linearly as follows: High $\geq 0.8 >$ Good $\geq 0.6 >$ Moderate $\geq 0.4 >$ Poor $\geq 0.2 >$ Bad. Studied lakes represented three Finnish WFD compliant lake types, large humic lakes (area >40 km^2, brown color 30–90 mg Pt l^{-1}), medium-sized humic lakes (area 5–40 km^2, brown color 30–90 mg Pt l^{-1}), and polyhumic lakes (brown color >90 mg Pt l^{-1}) (Table 1), which may cause some extra variation in the results. Still, large and medium-sized humic lakes were anticipated to be ecologically close to each other especially considering the littoral zone and the fish assemblages within it. The only polyhumic lake, Iso-Pyhäntä, is based on its water quality (brown color) in the boundary between a humic and polyhumic lake. Altogether, a large number of lakes was prioritized in this pilot study even at the cost of some extra variation in results due different lake types.

High variation in total densities among reference lakes (Table 3) induced exceptionally high values in the corresponding ecological quality ratios (EQR) (Fig. 1a). Total density of fish and the corresponding EQR values were lowest in the two most heavily regulated lakes (Table 3; Fig. 1a). EQR values derived from the proportion of disturbance-sensitive species on stony shores (in biomass) showed high average values with low variation among reference lakes (Fig. 1b). The pattern among regulated lakes was clearly different, characterized by a large variation and declining tendency along winter drawdown. Occurrence of juveniles in disturbance-sensitive species showed a declining EQR trend across winter drawdown, but also a quite high variation among reference and regulated lakes (Fig. 1c).

When the EQR values were converted into WFD classes, eight reference lakes indicated high ecological status across all metrics and their combination (Table 4). As the only exception within these lakes, Tyräjärvi coherently indicated good ecological status. In the national WFD monitoring, five of our reference lakes had been sampled with a NORDIC gillnet and were classified by the EQR4 index as high status (National database Hertta managed by the Finnish Environment Institute). Among regulated lakes more variation was seen across metrics, and the whole range from bad to high class emerged. Four of the regulated lakes were also sampled with NORDIC gillnets and classified by the EQR4 index, which suggested high status for all of the four lakes, indicating discrepancies in comparison to our results from the littoral zone (Table 4).

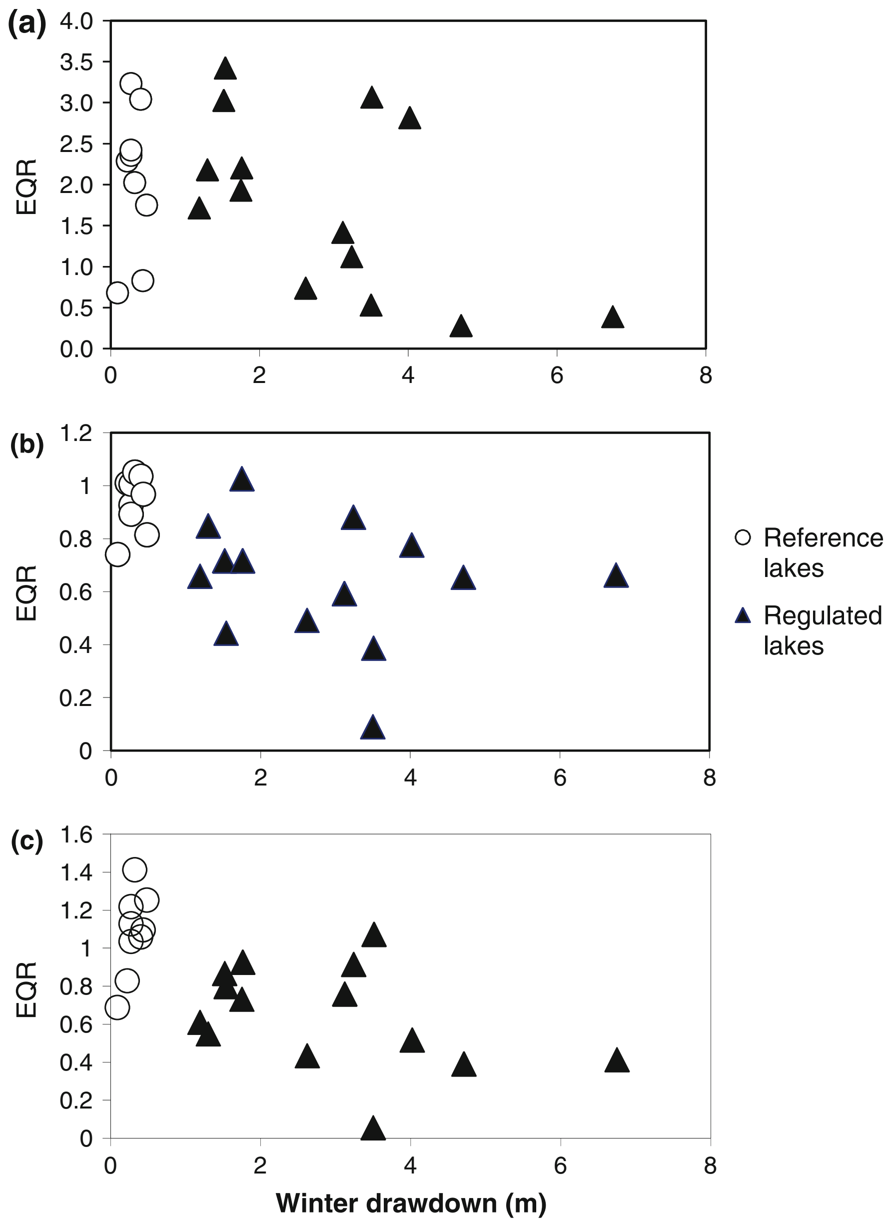

Fig. 1 Ecological quality ratio (EQR) in relation to winter drawdown in water level in the three metrics. EQR values were scaled so that the score 0.8 represents the boundary between high and good, and further at 0.2 score intervals to moderate, poor, and bad. **a** Total density. **b** Proportion of disturbance-sensitive species (in biomass). **c** Occurence of juveniles in disturbance-sensitive species

Discussion

The Water Framework Directive (WFD) requires assessment of the ecological status of lakes based on biota, including fish. In this study, stressor-specific metrics from littoral fish assemblages were developed to respond to abnormal water level fluctuation in regulated lakes. Calculation of these metrics led to an assessment from bad to high ecological status in regulated lakes, whereas a standard assessment based on NORDIC survey gillnets fishing indicated high status with no response to regulation.

Biological metrics should sensitively reflect only the anthropogenic deviations from reference conditions (Nõges et al., 2009). Finding good metrics may be difficult because biological processes and responses to stressors are often complex, non-linear, and unspecific. Abundance metrics often have high variances (Karr & Chu, 1997; Barbour et al., 1999), and the appearance of our first metric, total fish

Table 4 Ecological status in the lakes studied based on the three littoral metrics: (1) Total density, (2) Proportion of disturbance-sensitive species, (3) Occurrence of juveniles in disturbance-sensitive species, and their combination derived by taking their EQR median and linear rescaling

	Reference or regulated lake	Winter draw-down (m)	Metric 1	Metric 2	Metric 3	Ecological status based on littoral electrofishing	Ecological status based on NORDIC gillnet monitoring
Tyräjärvi	Ref.	0.09	Good	Good	Good	Good	
Simojärvi	Ref.	0.22	High	High	High	High	High
Pesiöjärvi	Ref.	0.27	High	High	High	High	
Kivesjärvi	Ref.	0.27	High	High	High	High	
Miekojärvi	Ref.	0.27	High	High	High	High	High
Änättijärvi	Ref.	0.32	High	High	High	High	High
Lentua	Ref.	0.40	High	High	High	High	High
Kellojärvi	Ref.	0.43	High	High	High	High	
Pielinen	Ref.	0.48	High	High	High	High	High
Iijärvi	Reg.	1.18	High	Good	Good	Moderate	
Hyrynjärvi	Reg.	1.30	High	High	Moderate	Good	
Nuasjärvi	Reg.	1.52	High	Good	High	Good	
Oulujärvi	Reg.	1.54	High	Moderate	Good	Good	High
Raanujärvi	Reg.	1.75	High	High	Good	High	
Koitere	Reg.	1.76	High	Good	High	High	High
Iso-Vietonen	Reg.	2.62	Good	Moderate	Moderate	Moderate	
Kiantajärvi	Reg.	3.12	High	Moderate	Good	Good	High
Irnijärvi	Reg.	3.24	High	High	High	High	
Iso-Pyhäntä	Reg.	3.50	Moderate	Bad	Bad	Bad	
Ontojärvi	Reg.	3.51	High	Poor	High	High	
Kostonjärvi	Reg.	4.20	High	Good	Moderate	Good	
Vuokkijärvi	Reg.	4.71	Poor	Good	Poor	Poor	
Kemijärvi	Reg.	6.75	Poor	Good	Moderate	Poor	High

Standard monitoring results of nine lakes based on NORDIC gillnet fishing are also presented

density, supported this preconception. However, abundance measures are explicitly demanded in the WFD (Ofenböck et al., 2004), and thereby total density was accepted as a metric despite its high variance. Low redundancy among the metrics is an objective in multimetric indices (Roset et al., 2007). To enhance variation across metrics, we used density, biomass, and occurrence as the units of measure in our three metrics. Dissimilar plots for each metric in Fig. 1 support the conception that our metrics did not measure factors that were too closely related.

Nordic lake ecosystems are subject to a variety of stressors having multifaceted effects. Responses to the stressors in fish species level may be reverse. For example, eutrophication may favor the roach, *Rutilus rutilus* L., but acidification may depress it (Tammi et al., 2003). The implementation of WFD has mainly focused on the most common stressors, like eutrophication and acidification, and to a lesser degree on hydromorphological stressors (Solheim et al., 2008; Hering et al., 2010). The results of this study suggest that standard WFD monitoring with the NORDIC gillnet and associate metrics respond weakly or not at all to water level regulation. The relatively weak response in fish assemblages outside the littoral zone on water level fluctuation, and the gap in specific metrics development, is probable reasons for this non-response. Besides, obligatory stocking of fish species that suffer from lake regulation, for example whitefish, *Coregonus lavaretus* L., probably masks the effects of regulation on the fish assemblages in the lakes studied. WFD monitoring with NORDIC gillnets is based on stratified random sampling in different depth zones with benthic, metalimnetic, and pelagial nets (Olin et al., 2002; Rask et al., 2010).

Development of indices for full implementation of WFD will require either generalization to multiple stressor types, or development of stressor-specific indices (Ofenböck et al., 2004; Hering et al., 2006). Diagnostic, stressor-specific metrics are currently available for common types of stressors. In this study, we put forward new regulation-specific metrics developed for littoral fish assemblages. From a wider point of view, we suggest that stressor-specific metrics should be developed further to approach a comprehensive assessment of the ecological status and to prioritize measures to improve the ecological status of lakes and rivers in water management.

Diekmann et al. (2005) fished with NORDIC gillnets in the benthic and pelagic habitats of German lowland lakes, and also electrofished the littoral habitats of these lakes. The authors strongly recommend littoral electrofishing as a supplementary method to pelagic and benthic NORDIC gillnetting. They concluded that only simultaneous consideration of all these three habitats would fulfill the requirements of the WFD for evaluating the ecological status of lakes. We support this view especially in lakes, where regulation in addition to some other stressor, like eutrophication, has simultaneous influences. Regulation-specific metrics from littoral zone electrofishing can be coupled with eutrophication-specific metrics from profundal and pelagic gillnetting. As a result, all habitats and stressors will be covered in the assessment of the ecological status.

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