Ecological Indicators 61 (2016) 248–257

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Ecological classification of lakes: Uncertainty and the influence of year-to-year variability

Martin Søndergaard[a,b,*], Søren E. Larsen[a], Liselotte S. Johansson[a], Torben L. Lauridsen[a,b], Erik Jeppesen[a,b]

[a] Aarhus University, Department of Bioscience, Vejlsøvej 25, 8600 Silkeborg, Denmark
[b] Sino-Danish Centre for Education and Research, Beijing, China

ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form
15 September 2015
Accepted 15 September 2015
Available online 6 November 2015

Keywords:
Lake monitoring
Water Framework Directive
Ecological quality
Phosphorus
Chlorophyll a
Uncertainty

ABSTRACT

Regular monitoring of lakes is important to determine their ecological state and development and of key significance when deciding whether action should be taken to improve their quality, for instance by reducing the external loading of nutrients. Imprecise or inadequate knowledge of the ecological state increases the risk of misclassification and of wrong management decisions. Based on Danish lake data, we aimed to determine temporal variations, in particular natural year-to-year differences, and to describe the uncertainty in assessing the ecological state of lakes. We analysed environmental data from ca. 350 Danish lakes (1100 lake years), including three case studies, with long-term data series (up to 24 years), with no significant changes in external nutrient loading. We used summer means of selected water chemical variables, phytoplankton and submerged macrophytes as indicators of ecological state and found considerable variations in all indicators, which could not be ascribed alone to meteorological variation. In shallow lakes, chlorophyll a concentrations exhibited large year-to-year variations, especially at TP ranging between 0.05 and 0.15 mg L^{-1} where the lakes may shift between a macrophyte- and a phytoplankton-dominated state. For example, chlorophyll a varied by a factor 5–10 between years and was particularly low when submerged macrophyte coverage exceeded 20% compared with lakes without macrophytes. Use of a multimetric index including four phytoplankton indicators reduced the coefficient of variation. Generally, the 95% confidence interval of ecological classification was approximately 50% lower when the assessment of ecological state was based on 4–5 years' measurements than if based on only one year's measurements. Knowledge and awareness of the uncertainty of indicators used in ecological classification are highly relevant for lake managers and policy makers when defining efficient monitoring and restoration strategies.

1. Introduction

Careful monitoring and accurate measurements of indicators or indices describing the state and development of an ecosystem are essential in guiding management decisions. Often the primary role of ecological indicators is to detect the ecosystem response to anthropogenic impacts (Niemi and McDonald, 2004). In lake management, measurement of nutrients or chlorophyll a concentrations has long been central for water quality assessments and used for making decisions on whether action should be taken to improve lake water quality (Jeppesen et al., 2005; Pearl et al., 2011; Vollenweider, 1976). In Europe, the European Water Framework Directive (WFD) defines how ecological quality should be measured based on a number of biological quality elements (European Union, 2000). The decision on whether measures to improve the ecological quality should be implemented, for example, reduction of the external nutrient loading, is based on such measurements and is influenced by how precisely they express eutrophication (Lyche-Solheim et al., 2013; Søndergaard et al., 2005). Correspondingly, in whole-lake restoration experiments comparing before and after conditions, it is usually not possible to carry out a proper statistical setup with replicates. Here, evaluation of effects and decisions on how to proceed depend on how reliable before and after conditions can be monitored and determined.

Monitoring is often costly and resource demanding and assessment of the overall ecological quality is, therefore, usually based on relatively few and simple monitoring variables that describe only a fraction of the whole ecosystem. Furthermore, monitoring variables are often based on summer mean data determined from relatively few seasonal samplings and on data from only one or

* Corresponding author.
E-mail address: ms@bios.au.dk (M. Søndergaard).

http://dx.doi.org/10.1016/j.ecolind.2015.09.024
1470-160X/

a few years. The latter increases the risk of imprecise determination, potentially leading to wrong conclusions regarding ecological quality and to uncertain or even wrong management decisions, with the peril of doing either too little or too much to achieve good ecological quality. From a management point of view, it might be more cost-effective to introduce an adequate monitoring programme than to act on uncertain data. Moreover, it is important to include the variables providing the highest certainty in ecological quality assessment. For example, zooplankton have a strong indicator value but are nevertheless not used as a biological indicator in the WFD ecological classification of lakes, and this despite that they would provide more cost-effective information than, for example, fish and phytoplankton (Jeppesen et al., 2011). The European Communities (2009) have stated that "*Uncertainty in classification, particularly for water bodies close to the good–moderate boundary, is an important issue for river basin management planning. Information on confidence and precision of classifications is important for informing decisions about the appropriate follow up action*". Similarly, Carpenter and Lathrop (2014) concluded that assessment of variability and knowledge of the variability in ecological classification allow researchers to convey more realistic expectations to managers and the public and to design monitoring programmes with adequate statistical power to detect changes. Hering et al. (2010) suggested that ecological status classification results should always be given in terms of probabilities.

Variability in chemical and biological indicators used to assess the ecological quality of lakes is well known and is particularly dependent on changes in the external or internal nutrient loading (Jeppesen et al., 2000; Rolland et al., 2013). However, not all changes in lakes can be clearly related to nutrient availability. For example, shallow lakes with intermediate nutrient concentrations may alternate between a clear water state dominated by submerged macrophytes or benthic primary producers and a turbid state dominated by phytoplankton primary producers (Blindow et al., 1993; Sanchez et al., 2015; Vadeboncoeur et al., 2003). Such shifts are causing fundamental changes in trophic structure and in many of the biological indicators used to characterise ecological quality as well as in the cycling of nutrients (Gray et al., 2012; Søndergaard et al., 2002). In these intermediate systems, larger interannual variations are expected to occur than in less eutrophic and perhaps also in more eutrophic lakes. Increasing variability of an indicator, for instance lake water phosphorus concentrations, has been suggested to be used as an early warning signal of a regime shift to eutrophic conditions (Carpenter and Brock, 2006).

Another component introducing variability in lakes is fish that in many studies have been emphasised as an important structuring factor for the overall lake water quality through their top-down effects in the food web (Jeppesen et al., 1997; Søndergaard et al., 2007; Vanderploeg et al., 2012). However, large year-to-year fluctuations have often been observed in the recruitment of fish (Irwin et al., 2009; Juza et al., 2014), and this may introduce large year-to-year variability in many other quality indicators (Hanson et al., 2005). The variability is the result of complex interactions among abiotic and biotic variables influencing the growth and mortality of the cohort (Neuman et al., 1996), and Juza et al. (2014) concluded that it is extremely difficult to identify the factors impacting fish recruitment and that a scarcely identifiable complex of biological and environmental characteristics may influence fish density at the end of the first growing season. Similarly, not easily explainable fluctuations in the fecundity and reproduction success from year to year have been recorded for crayfish (Skurdal et al., 2011) and submerged macrophytes (Søndergaard et al., 2010), which may lead to high variability in annual recruitment and plant development, respectively, adding to the variability in other food web components. Large interannual variations have been observed in both chemical and biological variables due to the introduction and fast colonisation of invasive species such as Zebra mussel (*Dreissena polymorpha*), decoupling chlorophyll a and nutrient relationships (Greene et al., 2015). Meteorological conditions have a fundamental role in triggering system shifts, modifying the spawning success of mussels, fishes and nutrient loading rates (Jeppesen et al., 2009; Probst et al., 2009; Wilhelm and Adrian, 2007).

Logically, variables with high natural variability will have less statistical power in determining changes than a variable with low natural variability and they thus require a more intensive sampling effort in order to obtain the same statistical power. Many different statistical approaches have been used to describe the uncertainty of environmental monitoring with the overall aim to improve monitoring efficiency (Levine et al., 2014), including eutrophication indicators such as phytoplankton (Thackeray et al., 2013), macrophytes (Dudley et al., 2013) and fish (Comte et al., 2013) using different groups to test their robustness for ecological status assessment and to what extent the variability can be explained by, for example, meteorological conditions. Carstensen (2007) described the statistical principles for ecological classification according to the WFD and emphasised the need for sufficient monitoring data to permit classification. Clarke (2013) provided a practical approach to assess the confidence of ecological classification in relation to the WFD based on prior sampling uncertainty estimates and pointed out that any measure of aquatic ecological quality is of little value without some knowledge and quantitative estimates of the uncertainty.

In this study we use a large dataset from Danish lakes, including also long-term monitoring data on central biological and chemical variables to describe their variability and how this influences the uncertainty in ecological classification. We particularly aim to illustrate the natural year-to-year variability and unravel some of the reasons behind it. We provide suggestions as to how variability can be handled in the management of lakes and be used by policy makers.

2. Material and methods

2.1. Type of data and analyses

We used three types of data and analyses: (1) time series with yearly data for up to 24 years from three case study lakes to illustrate year-to-year variability, (2) correlation analyses of seven-eight lakes covering 6–19 sampling years to identify common year-to-year patterns and (3) analyses of a large dataset comprising data on ca. 350 lakes (up to 1100 lake-years) to illustrate some of the mechanisms responsible for the variability and to use knowledge of variability when predicting the uncertainty of ecological classification using phytoplankton as an indicator. A general description of the lakes and datasets used in our study is given in Table 1. Overall, the lakes were relatively small, shallow and eutrophic.

2.2. Lakes and indicators

In the analyses of the time series, we used only lakes where no significant changes in external nutrient loading had occurred during the study period. In the correlation analyses, we only used data from 1995 and onwards to avoid any major impacts from a decreased internal loading of phosphorus. To most Danish lakes phosphorus loading was reduced before 1990, and often also before 1985, and internal phosphorus loading is therefore expectedly less important for lake water phosphorus concentrations after 1995 (Jeppesen et al., 2005; Søndergaard et al., 2013a).

Three case study lakes were chosen out of a small number of Danish lakes on which long-term data exist for the purpose of illustrating interannual variability: a lake with low (Lake