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Integrated assessment of ecological status and misclassification of lakes: The role of uncertainty and index combination rules

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ABSTRACT

The European Water Framework Directive (WFD) requires that the ecological status of waterbodies is assessed using multiple biological quality elements (BQEs) that are combined into a single status class. The recommended combination rule (the “one-out, all-out” rule; OOAO) has been criticised for being unreasonably conservative and for being sensitive to uncertainty. In this study, the objective was to compare the sensitivity to uncertainty of four different combination rules: (1) OOAO, (2) OOAO with exclusion of one element, (3) average and (4) weighted average. Index values for 5 BQEs (phytoplankton, phytobenthos, macrophytes, macroinvertebrates and fish) sampled from 10 lakes in the Wel River catchment in Poland were used to classify the lakes according to the OOAO and the three alternative combination rules. Based on the mean and (where possible) standard deviation of these index values, we modelled the risk of misclassification by simulating 10,000 resamples for each BQEs in each lake, classifying each resample and calculating the proportion of misclassified resamples under each combination rule. For individual BQEs, the risk of misclassification increased both with higher uncertainty (standard deviation) and with the proximity of the index value to a class boundary. Under the OOAO rule, the risk of misclassification was more biased towards worse status (“underclassification”) than towards better status. Furthermore, risk of underclassification was more affected by uncertainty under the OOAO rule compared with the alternative combination rules. This analysis has demonstrated the weaknesses associated with the OOAO rule for integration of BQEs for lake classification. However, the alternative combination rules are associated with other shortcomings, such as the need for subjective judgement, and involve a higher risk of not protecting the most sensitive BQE and thus the whole ecosystem. We recommend that future versions of instructions for WFD implementation consider alternatives to the OOAO combination rule, and provide guidelines for weighting of individual BQEs.

1. Introduction

The Water Framework Directive (WFD; European Commission, 2000) of the European Union requires that member states must assess the ecological status of their surface waterbodies, including lakes. Across Europe, WFD-compliant national classification systems have been developed and adapted for assigning waterbodies to one of five classes of ecological status (high, good, moderate, poor and bad) (Hering et al., 2010). The WFD further requires that all waterbodies obtain good ecological status by 2015, and consequently all waterbodies found to be in moderate

Abbreviations: BQE, biological quality element; EQR, ecological quality ratio; nEQR, normalised ecological quality ratio; OOAO, one-out, all-out (combination rule); WFD, Water Framework Directive.

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or worse status must be restored. Moreover, the WFD states that estimates of confidence and precision attained by the monitoring system should be provided in river basin management plans (Annex V, Section 1.3.4). Since restoration measures can be expensive, the uncertainty associated with waterbody classification should be of high interest for water resource management (Højberg et al., 2007; Irvine, 2004). If a lake in good or better status is wrongly classified as having less-than-good status ("underclassified"), money may be wasted on restoration measures that were not strictly needed (Prato et al., 2014). On the other hand, if a lake in less-than-good status is wrongly classified as good or better ("overclassified"), the ecosystem quality and services may be compromised.

Classification of ecological status of lakes should be based on a set of biological quality elements (BQEs) representing main ecosystem components, i.e. (1) phytoplankton, (2) macrophytes and phytobenthos, (3) benthic invertebrate fauna (here called "macroinvertebrates") and (4) fish (WFD, Annex V, Section 1.2.2). The WFD states that the policy should be based on the precautionary principle (§ 11); the idea of this principle is that if at least one component of ecosystem is impaired, this indicates that something is wrong in the ecosystem (waterbody) as a whole. Moreover, the WFD requires that the ecological status class for a waterbody "shall be represented by the lower of the values for the biological and physico-chemical monitoring results for the relevant quality elements" (Annex V, Section 1.4.2 (i)). This implies that the status is determined by either the combined biological monitoring result or by the physical-chemical monitoring result (the lower of the two). However, the directive does not specify how to combine the values of multiple BQEs into one biological monitoring result. The guidance on classification provided by the Common Implementation Strategy for the WFD (European Commission, 2005) has recommended the method known as "One-out, all-out" (OOAO): the waterbody status is determined by the BQE with the worst status. However, based on comparison with alternative rules for integrating BQEs, such as (weighted) average, median or other weight-of-evidence approaches, several authors have stated that the OOAO tend to result in a stricter classification than what seems reasonable (Alahuhta et al., 2009; Borja and Rodriguez, 2010; Caroni et al., 2013; Gottardo et al., 2011; Hering et al., 2010; Moss et al., 2003; Nõges et al., 2009; Nõges and Nõges, 2006; Prato et al., 2014; Rask et al., 2010; Sutela et al., 2013; Søndergaard et al., 2005). Another concern with the OOAO method is that higher uncertainty in index values tend to result in even stricter classification (Caroni et al., 2013; European Commission, 2005; Nõges et al., 2009; Sandin, 2005).

Uncertainty in biological index values results from many sources, including natural temporal and spatial variation and sampling variation (see Clarke, 2013). The quantification of sources of uncertainty in index values and their significance for status classification have been addressed in many studies (Carvalho et al., 2013; Clarke and Hering, 2006; Kelly et al., 2009b; Thackeray et al., 2013). Nevertheless, few studies have investigated the role of joint uncertainty of indices when several BQEs are integrated (but see Caroni et al., 2013). There is therefore a need for more research on how the OOAO and other BQE combination rules perform in waterbody classification based on real data under different levels of sampling uncertainty.

In our study, we have analysed the effects of joint uncertainty for five BQEs (phytoplankton, phytobenthos, macrophytes, macroinvertebrates and fish) sampled from 10 lakes in Poland. The analysis was based on simulations of index values for all BQEs with three levels of uncertainty (Section 3.1), and application of four different combination rules (Section 2.3) for the resulting BQE status classes. The objective of this paper was to address the following question: How does increasing levels of uncertainty affect the risk of misclassification of lakes under different BQE combination rules? To answer this question, we also investigated how uncertainty in index values affect the risk of misclassification at the BQE level, and how this risk was transferred to the whole-lake level under the different combination rules.

2. Materials and methods

2.1. Data

The study area is the catchment of the lowland river Wel in central Poland, with a surface area of 822 km^2. Surface waters in the Wel catchment are affected mainly by eutrophication due to agricultural runoff (approx. 60% of areas of extensive agriculture in the catchment) and also by a few point sources of organic pollution. Ten lakes with surface area above 0.5 km^2 are located in this catchment (Fig. 1, Table 1). The biological data used in this study were collected from all of the ten lakes in 2009 during the Polish-Norwegian project deWELopment (Soszka, 2011).

2.2. Biological index values and classification system

In this study, each biological quality element (BQE) was represented by one index, as follows:

- *Phytoplankton*: Phytoplankton Metric for Polish Lakes (Hutorowicz et al., 2011).
- *Phytobenthos*: Diatom Index for lakes (phytobenthos) (Picińska-Fałtynowicz, 2011).
- *Macrophytes*: Ecological State Macrophyte Index (Kolada et al., 2011).
- *Macroinvertebrates*: Benthic Quality Index based on Chironomid Pupal Exuviae Technique (macroinvertebrates; based on Ruse, 2010; Gołub et al., 2011).
- *Fish*: Lake Fish Index N2 (Białokoz and Chybowski, 2011).

For each index, the sampling method, calculation, the responses to eutrophication pressure gradients as well as classification scheme are described in the given references. For phytoplankton and macrophytes, respectively, a full description of the national assessment methods are given in the Technical Reports from the Intercalibration phase 2 (Phillips et al., 2014; Portielje et al., 2014). Although the WFD defines phytobenthos and macrophytes as one BQE, the two organism groups are treated as two separate BQEs in this paper. The reason is that Poland, like most countries in the Central-Baltic region, has chosen to develop separate assessment methods for macrophytes and phytobenthos (Kelly et al., 2009a), and no integration rules exist at the moment (Table 4.4 in Portielje et al., 2014). Moreover, changing environmental conditions may affect macrophytes and phytobenthos indices differently due to the differences in generation time and dispersal rate; therefore these organism groups may provide different information about ecosystem stability (Schneider et al., 2012).

The ecological classification system used in this study (Soszka, 2011) comprises, for each biological index, a *reference condition* representing the index value assumed for lakes undisturbed by anthropogenic impact, and *class boundaries* defining the index values on the borders between the five ecological status classes (high, good, moderate, poor and bad). More information on the methods used for setting reference conditions and class boundaries for the Polish classification system is available in the WISER database on national assessment methods (http://www.wiser.eu/results/method-database; Birk et al., 2012), for all BQEs except macroinvertebrates. The full ecological classification system includes also physico-chemical variables, which