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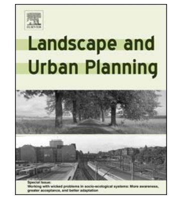

Research Paper

How much ecological integrity does a lake need? Managing the shores of a peri-urban lake

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A B S T R A C T

Physical modifications leading to a homogenization of previously diverse littoral habitats increasingly affect the ecological integrity of lake shores in urban landscapes. The European Water Framework Directive (EU WFD) requires integrative assessment of the ecological status of lake ecosystems including lake shore assessment aimed at reaching good ecological status (GES). The ecological consequences of lake shore modifications can be assessed site-specifically by ecological assessment tools based on benthic invertebrates in compliance with the EU WFD. However, it still remains unclear which percentage of the lake shore may be morphologically altered until whole-lake ecological status is affected. We studied a peri-urban lake with ~50% of the shoreline altered by urban developments and recreational facilities and the other 50% still remaining in a near-natural, undeveloped state. We assessed the ecological status of each shore type using the Littoral Invertebrate Multimetric Index based on Composite Sampling (LIMCO). Additionally, we used data of a physical habitat survey conducted for each 100-m section within the 12-km long shoreline. We extrapolated site-specific biological assessments to the whole shore length based on pressure-response regressions using physical survey data. Our results showed an overall 'moderate' whole-lake ecological status and consequently the present share of near-natural shoreline is not sufficient to reach GES as required by the EU WFD. GES may be obtained by either further improving existing near-natural shorelines, or by revitalizing developed shorelines. Thus, our approach allows for the quantification of the amount of restoration necessary to derive EU WFD-compliant management objectives for lake shores subjected to human use.

1. Introduction

Mankind has fundamentally altered lake shore morphology in addition to the frequent alteration of adjacent aquatic and terrestrial landscapes (Brauns et al., 2011; Strayer & Findlay, 2010). Lakes situated in urban landscapes or in regions with high population density are most affected, as technical structures (steel pilings, retaining walls, wooden palisades) often replace shores and decrease the ecological connectivity of terrestrial and aquatic habitats across the land-water interface. Technical bank stabilization also prevents the formation of typical riparian and littoral habitat structures (reed belts, coarse woody debris), and alters sediment features (e.g., Elias & Meyer, 2003; Jennings, Emmons, Hatzenbeler, Edwards, & Bozek, 2003; Marburg, Turner, & Kratz, 2006).

Natural littoral zones provide a variety of ecological functions such as energy dissipation, habitat provision, and processing of nutrients and organic matter (Jeppesen et al., 1998; Strayer & Findlay, 2010; Traut & Hostetler, 2004). However, human alterations of the littoral zone regularly impact macrophyte, macroinvertebrate, and fish assemblages (Brauns et al., 2011; Elias & Meyer, 2003; Jennings, Bozek, Hatzenbeler, Emmons, & Staggs, 1999). Habitat removal simplifies the structural heterogeneity of the littoral zone and, thus, causes a loss of more specialized species that are linked to typical substrates, three-dimensional structures, and food resources (Armitage, Pardo, & Brown, 1995; Kovalenko, Thomaz, & Warfe, 2012; Taniguchi, Nakano, & Tokeshi, 2003). Complex structured littoral habitats effectively shelter benthic invertebrates from wind wave and ship wave action, which subsequently often enhances the risk of being preyed on by fish, and contribute to the dissipation of the kinetic energy of waves (Gabel et al., 2008; Gabel, Garcia, Schnauder, & Pusch, 2012; Lorenz, Pusch, & Blaschke, 2015; Strayer & Findlay, 2010). Therefore, habitat loss increases the hydraulic disturbance in the remaining habitats (Bonham, 1983; Gabel et al., 2012; Lorenz, Pusch, & Blaschke, 2015), and thus starts a downward spiral of habitat degradation and species loss.

In recent years, the awareness of the ecological functions of intact

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littoral zones has grown both in landscape ecology and practical lake management (Porst, Gabel, Lorenz, & Miler, 2015). Additionally, science increasingly recognizes hydromorphological alterations as major human pressures on lake ecosystems (Sandin & Solimini, 2012). The European Union Water Framework Directive (EU WFD) requires the hydromorphological assessment of lake shores based on benthic invertebrate communities (European Commission, 2000). Water bodies failing to reach 'good ecological status' (GES) demand appropriate restoration measures in order to fulfill the requirements of the EU WFD (European Commission, 2000; Hering et al., 2010). Morphological alterations of the littoral zone directly affect the structure of littoral benthic invertebrate communities (Brauns, Garcia, Walz, & Pusch, 2007; Brauns et al., 2011; Porst, Bader, Münch, & Pusch, 2012), which take a central position in food webs and nutrient cycling processes, and hence provide essential ecosystem functions and services (Covich, Palmer, & Crowl, 1999). Benthic invertebrates constitute the most widely used organism group for assessing morphological alterations in lakes and rivers (Birk et al., 2012; Poikane et al., 2016) because of their central importance for freshwater ecosystems, especially for the littoral zone, and their suitability as biomonitoring tools (Bonada, Prat, Resh, & Statzner, 2006).

Presently, more than 300 different assessment tools exist to assess Europe's surface waters of which 27% focus on hydromorphological pressures, mostly in river systems (Birk et al., 2012). For lakes, only a few assessment tools assess hydromorphological degradation impacts based on benthic invertebrates (Böhmer et al., 2014; Miler et al., 2013; Poikane et al., 2016; Sidagyte, Visinskiene, & Arbaciauskas, 2013; Solimini et al., 2014; Timm, Kairo, Möls, & Virro, 2011; Timm & Möls, 2012; Urbanič, 2014). However, so far no tool exists that estimates the minimum percentage of unaltered shorelines that is necessary to support full ecosystem functioning. Until now, hydromorphological assessments are mainly conducted at the site scale (Miler et al., 2013) but approaches to interpolate site-specific to whole lake assessments are recently developed (Miler, Ostendorp, Brauns, Porst, & Pusch, 2015). Whole-lake assessment may be accomplished by weighted averaging of the site-specific assessment scores according to their shoreline proportion (e.g., for the German lake assessment method AESHNA (Miler, Brauns, Böhmer, & Pusch, 2013)), as the EU WFD requires the assessment at water body level.

However, the weighted averaging step may be performed in a more precise way by the use of information from physical lake habitat surveys (Fig. 1) that may already exist (Lyche-Solheim et al., 2013; Miler, Ostendorp, Brauns, Porst, & Pusch, 2015). Whole-lake physical habitat surveys lead in such cases to site-specific physical habitat survey scores. These scores can be related to specific stressor index scores that are calibrated against site-specific biological scores. Hence, the correlation of physical habitat survey scores with biological assessment scores allows for interpolation of the assessment scores from the biological

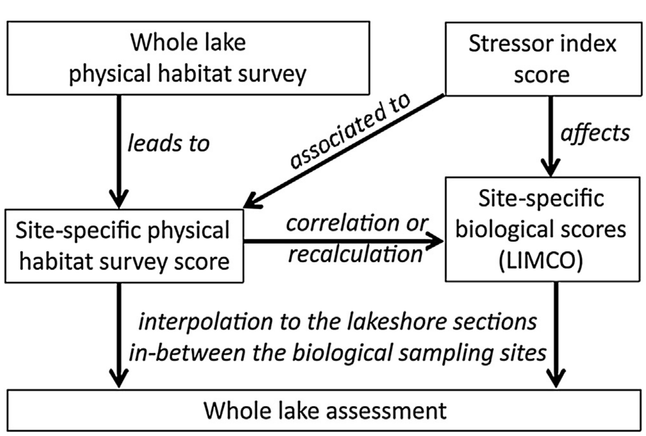

Fig. 1. Conceptual scheme of the applied whole-lake assessment approach.

sampling site to the whole-lake level. Using information about physical habitat structures may help minimize potential under- or overestimations of lake ecological status arising from possible small-scale variation in shoreline structures and benthic invertebrate assemblages (Harrison & Hildrew, 1998; Miler et al., 2013; Solimini & Sandin, 2012).

Whole lake ecological status assessment comprising physical habitat surveys allows for the first time to estimate the minimum percentage of unaltered shorelines necessary to systematically reach GES according to the EU WFD. Continuing interest to develop larger shares of the shoreline or to construct marinas necessitates the estimation of such a minimum percentage of unaltered shorelines for landscape managers. Thus, we applied this method to a *peri*-urban lake subjected to multiple and partially conflicting uses, such as residential development, beach recreation, navigation, and nature conservation. We also determined the potential restoration effort needed to significantly improve ecological whole-lake assessment scores. We hypothesize that GES can be systematically reached by following specific targeted restoration strategies.

2. Methods

2.1. Study site

We conducted the study at Lake Müggelsee, a polymictic, eutrophic peri-urban lake (Berlin, Germany) with an area of 7.3 km^2 and a maximum depth of 7.7 m (Driescher, Behrendt, Schellenberger, & Stellmacher, 1993). The main wind direction is South-East, exposing northern shorelines to high wind wave levels. The shallow water zone with a water depth < 1.5 m covers 12.1% of the total lake area and in certain locations extends more than 100 m lakewards. At the beginning of the 20th century, one third of the lake was covered by macrophyte stands that extended to a maximum water depth of 4 m (Körner, 2001). From 1970 onwards, the number of macrophytes declined dramatically due to eutrophication, but recovered partially due to strongly decreased catchment nutrient emissions since 1990 (Hilt & van de Weyer, 2011). Historically, benthic invertebrate communities differed markedly in their taxonomic composition between the wind-exposed shallow Northeastern shore and the steeper Southwestern shore (Pauly, 1917). These differences in community structure related mainly to differences in habitat structure caused by wind exposure, and not by human impacts (Pauly, 1917). Compared to the conditions ~100 years ago, the current number of taxa at the Southwestern shore is considerably lower, and taxonomic densities at the Northeastern shore are significantly lower than at the Southwestern shore.

In the past decades, Lake Müggelsee has been used in multiple ways for professional and recreational fishing, boating, cargo and passenger navigation, beach recreation, drinking water supply through bank filtration technique, and nature conservation. The Northeastern shore ('peri-urban shore') faced high residential development, especially private housing properties, which exhibit artificial bank stabilization and lack reed belts, while the Southwestern shore ('forested shore') remains largely in a near-natural status. The lake is designated as part of a Natura 2000 protected area, representing 'naturally eutrophic lake' habitat type 3150, including in its Eastern bay a breeding colony of endangered Black Tern (*Chlidonias niger*) nesting on floating material at the water surface. Moreover, the EU WFD requires management and development of the lake in a way to reach GES based on assessments of phytoplankton, fish, benthic algae, macrophytes, and benthic invertebrates.

2.2. Benthic invertebrate sampling

We sampled benthic invertebrates at nine sites on Lake Müggelsee following a standardized one-minute sampling protocol covering all available mesohabitats in April 2010 (Miler et al., 2013). Briefly,