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Hydroacoustic quantification and assessment of spawning grounds of a lake salmonid in a eutrophicated water body

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ABSTRACT

Accurate information on the location and condition of spawning grounds of environmentally-demanding lithophilic fish species, which may use only a very small area of their habitat for spawning, is critical to their conservation and fisheries management but is frequently lacking. Here, the new hydroacoustic system BioBase, which enables the rapid characterisation of features including lake bottom hardness (with soft, medium hard and hard bottoms represented by values of 0 to 0.25, 0.25 to 0.40, and 0.40 to 0.50, respectively), was applied to known spawning grounds of Arctic charr (*Salvelinus alpinus*) in the north basin of the eutrophicated lake of Windermere, U.K. The output of BioBase was successfully ground-truthed using an independent video-based system ($r^2 = 0.48$, $F = 17.705$, $p < 0.001$) and depth and bottom hardness descriptive statistics were produced for six spawning grounds. Average depth ranged from 9.4 m (North Thompson Holme) to 38.5 m (Balla Wray), while average bottom hardness ranged from 0.254 (Low Wray Bay) to 0.303 (North Thompson Holme). Detailed visual outputs were also produced for contrasting shallow (North Thompson Holme) and deep (Holbeck Point) spawning grounds, both of which showed high within-site spatial variation in bottom hardness and thus in suitability for spawning. Findings were consistent with earlier, less quantitative, interpretations of the possible effects of eutrophication and associated increased deposition of fine sediments on local Arctic charr reproduction.

1. Introduction

Fish are highly mobile and highly selective in their use of habitat, especially in their use of spawning grounds in lakes (Winfield, 2004). Lithophilic species such as members of the widespread genera *Coregonus*, *Salmo* and *Salvelinus* require gravel or other hard substrates for spawning and as a result may use only a fraction of the total habitat for such purposes, even within the littoral zone where erosive processes often dominate (Low et al., 2011). Furthermore, the quality of such limited spawning areas is particularly sensitive to the local deposition of fine sediments and as a result the widespread environmental problem of eutrophication has frequently led to declines in recruitment and even to the local extinction of a number of lithophilic species (e.g. Maitland et al., 2007; Winfield et al., 2012, 2013).

Accurate information on the location and condition of spawning grounds of such environmentally-demanding fish species is critical to their conservation and fisheries management. In lakes where significant commercial or sport fisheries occur, valuable background information may be derived from the fishing community. However, such information rarely extends to a knowledge of the condition of the spawning grounds and is usually entirely absent in the absence of such fisheries. In such cases, appropriate knowledge usually depends on the use of laborious direct underwater observations by divers or remotely-deployed cameras (e.g. Coyle and Adams, 2011), subjective or qualitative measures that are difficult to verify or repeat (e.g. Ray and Burgamn, 2006), or the use of indirect indicators such as using the spraints of opportunistic piscivores such as otters (*Lutra lutra*) to reveal the locations of inshore spawning aggregations (Hewitt and Winfield, 2013).

The technique of hydroacoustics is commonly used in lake studies of the abundance and distribution of fish (e.g. Jones et al., 2008; Winfield et al., 2007a), but it also has further value for investigations of lake habitats (Godlewska et al., 2004). Its ability to produce rapid and highly accurate lake bathymetries and distribution maps of macrophytes has been exploited for some time (e.g. Abukawa et al., 2013; Spears et al., 2009; Valley et al., 2005; Winfield et al., 2007b), but more recent advances in hardware and particularly in software mean that hydroacoustic systems can now also generate information on the nature of the bottom substrate. For instance, Miller et al. (2015) recently used hydroacoustics in a multi-technique revisit to the spawning grounds of the salmonid Arctic charr (*Salvelinus alpinus*) in the lake of Windermere in north-west England, U.K. These spawning grounds were first described in qualitative detail on the basis of netting, limited observations by divers and local knowledge by Frost (1965) and are remarkable because they

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include both shallow inshore sites in the littoral zone and much deeper areas in offshore locations. The quantitative ability of the hydroacoustic and other systems deployed by Miller et al. (2015) facilitated the documentation of the impacts of several decades of eutrophication on the condition of the spawning grounds. However, although the elaborate SIMRAD Kongsberg EM3002D dual head hydroacoustic system used by Miller et al. (2015) was able to give 100% coverage of lake areas deeper than 5 m, it could not be deployed in the extreme inshore areas of the known inshore spawning grounds. This limitation was due to technical reasons, including the system's requirement for deployment from a relatively large vessel with associated substantial draft. In the context of studies of fish spawning grounds there is clearly a need for hydroacoustic systems which can be deployed from small vessels operating in the vitally important but shallow and logistically challenging littoral zone, ideally with a minimum of operating complexity in the field and at low cost.

Benefitting from a remarkable recent advance in consumer hydroacoustic systems developed primarily for the recreational fishing market as 'echo sounders' and from the ubiquitous advance in internet and mobile technologies, new tools have recently been developed that automate the processing and creation of aquatic habitat maps using 'off-the-shelf' echo-sounder systems with internal GPS and cloud-based software. In particular, the BioBase system (Navico Inc., 2014) has an ability to produce bathymetries and assessments of macrophytes and lake bottom characteristics from hydroacoustic data files recorded by consumer echo sounders. This has opened up new opportunities for the crowd-sourcing of spatially-referenced environmental data at an unprecedented scale (Valley et al., 2015). The ease of the field operation of the system's portable, low-cost hardware component coupled with its extremely shallow draft allows it to be used effectively wherever a shallow-draft vessel can be deployed.

In this study, we deploy the BioBase system on the known spawning grounds of Arctic charr in the north basin of Windermere in order to allow us to extend the observations of Miller et al. (2015) to make more effective use of hydroacoustic data to assess bottom conditions and to encompass the entire spawning grounds up to the approximately 1 m depth contour. In addition, we use an independent visual assessment of spawning ground condition to ground-truth these hydroacoustic observations and so for the first time produce comprehensive assessments of the current conditions of the spawning grounds with respect to eutrophication-associated impacts from sedimentation.

2. Methods

2.1. Study site

Windermere is situated (54°22′N, 2°56′W; altitude 39 m) in the English Lake District, U.K. It comprises a mesotrophic north basin (surface area 8.1 km^2, maximum depth 64 m) and a eutrophic south basin (surface area 6.7 km^2, maximum depth 44 m). The lake level is partially controlled by a weir at the southern end which over-rides natural drainage patterns, although these effects are limited. The first detailed observations of Arctic charr spawning in the lake were made by Frost (1965) who concluded that shallow spawning grounds ranged from 1 to 3 m depth, while deeper spawning grounds ranged from 15 to 20 m depth. The spawning substrate for shallow-water sites was described as always hard with a range of particle sizes from sand through to large stones or small boulders up to 0.25 m in diameter, with some areas also having some silt or a few macrophytes in the form of *Littorella* sp. Deep-water sites were characterised as having a stony bottom. The lake has subsequently experienced significant cultural eutrophication and while increased nutrient levels have been most pronounced in its south basin, some effects are also evident in the north basin (Winfield et al., 2008). Nevertheless, a recent review of historic and contemporary evidence from netting spawning surveys collated by Miller et al. (2015) recorded Arctic charr at the four locations of Holbeck Point, Low Wray Bay, North Thompson Holme and Red Nab of the original six demonstrated or putative spawning grounds described in the north basin by Frost (1965). No evidence was found for contemporary use of the remaining two locations of Balla Wray and Meregarth, although spawning individuals were recorded from a site just west of the latter location.

2.2. The BioBase system

2.2.1. Overview

BioBase (www.cibiobase.com) is a cloud-based GIS software system that analyses hydroacoustic and GPS signals from Lowrance™ High Definition System (HDS®) consumer echo sounders (www.lowrance.com) to produce data on depth, macrophyte presence/absence, macrophyte height and bottom hardness.

The specific echo sounder used in this study was a Lowrance Gen 2 HDS-5, operating at a sound frequency of 200 kHz with a beam angle of 20°. Pulse rates are user-defined and typically vary between 10 and 20 pulses s^{-1}, with 15 pulses s^{-1} used in the present study. Pulse width is not user-controlled but is dynamic and varies depending on depth. BioBase algorithms are optimised at user settings of 3200 bytes s^{-1} and a range window set to 'Auto' which maximises the resolution of the acoustic envelope at the full range of depths sampled. GPS signals were European Geostationary Navigation Overlay Service (EGNOS)-corrected. In the field, hydroacoustic and GPS signals were logged to data storage cards (.sl2 format) and subsequently uploaded post-survey to centralised servers of the BioBase system for analysis using the January 2014 release of BioBase.

GPS position is typically recorded every 1 s and bottom features from pulses that elapse between positional reports are averaged for each coordinate/data point. Therefore, the attribute value (i.e. depth, macrophyte presence/absence, macrophyte height and bottom hardness) of each data point along a travelled path comprises a summary of 5 to 30 pulses. Each pulse is subjected to a quality test to determine whether features can be extracted and, if so, it is sent on to feature detection algorithms. Those failing quality assurance tests are removed from the set used for subsequent analysis and the production of summary statistics.

2.2.2. Bottom hardness

Bottom hardness is determined by the amplitude of the second bottom echo. Relative bottom hardness values vary continuously with harder bottoms (rock, sand, gravel or hard clay) generating higher second echo amplitudes than soft bottoms (mud, silt) from which a second echo may in fact not be generated due to rapid signal attenuation. BioBase bottom hardness values are on a relative scale ranging with values of 0 to 0.25 representing soft bottoms, 0.25 to 0.40 medium hardness bottoms, and 0.40 to 0.50 representing hard bottoms. Minimum depth for bottom hardness detection was 0.73 m below the transducer face.

2.2.3. Map creation

Processed values for depth, macrophyte presence/absence, macrophyte height and bottom hardness were automatically sent to an ordinary point kriging algorithm in BioBase that predicted values in unsampled locations based on the geostatistical relationship of the input points. The kriging algorithm was an 'exact' interpolator in locations where sample points were close in proximity (approximately 1 to 5 m) and did not vary widely. Kriging smoothed bottom feature values where the variability of neighbourhood points was high.

2.3. Assessment of system performance

The ability of the bottom hardness algorithm of BioBase in terms of its ability to identify areas of lake bottom offering suitable spawning habitat for Arctic charr was ground-truthed by comparing its hydroacoustically derived hardness values with visually derived suitability values. The latter were generated by a technique developed by Coyle and Adams (2011) for the assessment of underwater video recordings in the context of vendace