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Assessment in two shallow lakes of a hydroacoustic system for surveying aquatic macrophytes

I.J. Winfield, C. Onoufriou, M.J. O’Connell, M. Godlewska, R.M. Ward, A.F. Brown, M. L. Yallop

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I. J. Winfield, Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK e-mail: ijw@ceh.ac.uk

C. Onoufriou and M. L. Yallop, School of Biological Sciences, University of Bristol, Woodland Road, Bristol BS8 1UG, UK

M. J. O’Connell R. M. Ward, Wildfowl & Wetlands Trust, Slimbridge, Gloucestershire GL2 7BT, UK

M. Godlewska, International Centre for Ecology, ul. Tylna 3, Lodz 90 364, Poland

A. F. Brown, English Nature, Northminster House, Peterborough PE1 1UA, UK

Abstract

A technique for the rapid surveying of submersed aquatic vegetation by post-processing of data collected using a high frequency (420 kHz) digital echo sounder (BioSonics DT4000) has recently been developed and successfully tested in an estuarine environment by Sabol et al. [Sabol, B. M., R. E. Melton, R. Chamberlain, P. Doering & K. Haunert, 2002. Evaluation of a digital echo sounder system for detection of submersed aquatic vegetation where it was used to map the cover and height of freshwater tape grass (Vallisneria americana) and seagrasses (Thalassia testudinum, Haladule wrightii and Syringodium filiforme). This technique, which is also spatially referenced by input from a global positioning system, has many potential applications in macrophyte studies in shallow lakes, although it has not yet been extensively tested in such habitats using systems of lower sound frequency. This paper reports such a test in two shallow (maxi- mum depth c. 5.9 m) lakes of the Cotswold Water Park, U.K., using a 200 kHz digital echo sounder (BioSonics DT6000 and DT-X upgrade) and post- processing analysis using the now commercially available software EcoSAV, which incorporates the algorithms of Sabol et al. (2002). Hydroacou- stic assessment of the coverage by macrophytes, mainly Nuttall’s pondweed (Elodea nuttallii) and charophytes (Chara spp.), showed high agreement with those recorded during a simultaneous visual survey by underwater video recording ($r^2 = 0.8478$, $n = 74$, $P < 0.001$). Assessment of macrophyte height was also apparently consistent between the two systems, although the video system could not produce quantitative data and so statistical assessment of the agreement was not possible. Repeated hydroacoustic surveys over the course of the winter of 2003–2004 were conducted in one lake and illustrate the application of this new macrophyte survey technique. Such applications include the rapid measurement of mean Percentage Volume Inhabited (PVI), which fell from 12.15% (95% confidence limits, ±0.55%) to 7.10% (±0.40%) over the course of the winter.

Introduction

Established manual techniques for characterising and monitoring aquatic vegetation are labour- intensive and generate observations of very limited spatial extent. Alternative optical techniques, such as aerial photography, provide large synoptic assessments of spatial patterns but are highly dependent on uncontrollable environmental factors such as water clarity, water surface roughness and cloud cover (see review by Madsen (1993)). In contrast, hydroacoustic techniques are largely free of these limitations and are now widely used in the assessment and study of other components of lake ecosystems, providing rapid, extensive and spatially-referenced data on fish, zooplankton and bottom sediments (e.g. Godlewska et al., 2002; Hoffman et al., 2002; Godlewska et al., 2004). The use of this approach for the assessment of macrophyte populations in lakes and rivers is now receiving increasing attention.

Hydroacoustic methods developed for macrophyte surveys include the use of horizontally-aimed side scanning sonar systems for delineating macrophyte beds (Bozzano et al., 1998; Moreno et al., 1998) and vertically-aimed echo sounders for quantifying vegetation height and density (Sabol & Burczyń ski, 1998). Although a number of researchers have reported success in detecting and qualitatively characterising macrophytes using hydroacoustics for over two decades (Mace- ina & Shireman, 1980; Duarte, 1987; Thomas et al., 1990; Fortin et al., 1993; Tegowski et al., 2003), fully quantitative assessment has been hampered by hardware and software limitations. Following technological advances including the advent of highly portable Global Positioning Systems (GPS), the development of fully quantitative macrophyte assessment has recently made major advances as described by Sabol et al. (2002) in an estuarine environment, where one such system was used to map the cover and height of freshwater tape grass (Vallisneria americana) and seagrasses (Thalassia testudinum, Haladule wrightii and Syringodium filiforme). The software component of this system is now commercially available as EcoSAV (BioSonics Inc, Seattle, U.S.A., www.biosonicsinc.com) and is further described by Hoffman et al. (2002). However, this recent development and its subsequent application have almost exclusively used only relatively high sound frequencies of 420 kHz (Hoffman et al., 2002; Sabol et al., 2002) or 430 kHz (Valley et al., 2005). In contrast, most hydroacoustic systems currently used in fresh waters, which are deployed primarily in fish studies, operate at considerably lower frequencies of c. 70 to 200 kHz (e.g. Jurvelius, 1991; Elliott et al., 1996; George & Winfield, 2000; Wanzenböck et al., 2003; Schmidt et al., 2005). Only two EcoSAV studies have used such frequencies. Firstly, Schneider et al. (2001) employed a sound frequency of 208 kHz in an apparently successful survey of the seagrasses Zostera marina and Z. noltii in the estuary of the River Ason, Spain, although no rigorous assessment was made of the efficacy of the system at this sound frequency. Secondly, Hoffman et al. (2002) used a frequency of 70 kHz, together with one of 420 kHz, in an EcoSAV study of unspecified milfoil species and elodeids in Lake Washington, U.S.A. When results were compared from the two sound frequencies, Hoffman et al. (op. cit.) concluded that the higher frequency system performed significantly better than that of 70 kHz, with the latter resulting in a horizontal difference in the placement of macrophyte boundaries of over 100 m. Given the prevalence in lake studies of hydroacoustic systems operating at c. 200 kHz or less, further assessment of the performance of EcoSAV at such relatively lower frequencies is highly desirable. Changes in sound frequency are potentially technically significant for EcoSAV for a number of reasons, including influences on reflectivity, vertical resolution and penetration into bottom sediments. The objectives of the present study were to test the efficacy of EcoSAV when used with a 200 kHz hydroacoustic system in two shallow lakes of the Cotswold Water Park, U.K., by comparing hydroacoustic and underwater video assessments, and to use it to survey the distribution and abundance of macrophytes in a shallow lake over the course of a winter as an illustration of the application of this technique.

Materials and methods

Study site

The Cotswold Water Park in south-west England, U.K., covers over 100 km^2 and includes over 130 shallow lakes of varying age and size created by gravel extraction. Many of the lakes support extensive growths of macrophytes, two of which were selected for study in the present investiga- tion: Lake 31 (surface area 10.3 ha, maximum depth c. 4.5 m, latitude 51°, 39.870¢ N, longitude 1°, 57.640¢ W) and Lake 32 (surface area 20.0 ha, maximum depth c. 5.9 m, latitude 51°, 39.520¢ N, longitude 1°, 57.587¢ W).

Hydroacoustic system

The hydroacoustic system was based on a Bio- Sonics DT6000 (upgraded to a DT-X in Novem- ber 2004) echo sounder with a 200 kHz split-beam vertical transducer of circular beam angle 6.5° operating under the controlling software Visual Acquisition Version 4.0.2 (upgraded to Version 5.0.4 in November 2004) (BioSonics Inc, Seattle, U.S.A., www.biosonicsinc.com). Throughout the comparisons and surveys, data threshold was set at –130 dB, pulse rate at 5 pings s^{-1}, pulse duration at 0.1 ms, and data were recorded from a range of 0 m from the transducer. Positional data were inputted from a Magellan SporTrak Color (EU basemap) GPS (www.magellangps.com) with accuracy to less than 7 m, which was upgraded in November 2004 to a JRC Model DGPS212 GPS (www.jrc.co.jp) with accuracy to less than 5 m and a fix update interval of 1 s. In addition to the real- time production of an echogram through a colour display on a laptop computer, data were also recorded to hard disc. The system was deployed from a rigid punt powered by an outboard engine and moving at a speed of c. 4 km h^{-1}. The transducer was positioned approximately 0.5 m below the surface of the water. Prior to the comparisons and surveys, the hydroacoustic sys- tem had been calibrated using a tungsten carbide sphere of target strength (TS) –39.5 dB at a sound velocity of 1470 m s^{-1}. Data were subsequently processed using Eco- SAV Version 1.0 (BioSonics Inc, Seattle, U.S.A., www.biosonicsinc.com), using default values for all parameters with the exception of Bottom Thickness Limit (see BioSonics (2004)) which was increased from 12 to 30 on the basis of a pilot study carried out at Derwent Water, Cumbria, U.K. (Godlewska et al., 2004). The EcoSAV algorithm outputs lake bottom depth, macrophyte cover (expressed as a percentage), macrophyte height and location (latitude and longitude) summarised by 10-ping segments within each data file. Macrophyte cover values were subsequently aver- aged over arbitrary 1 min intervals (correspond- ing to c. 67 m segments along transects) to facilitate their comparison with video data. For surveys, lake bottom depth (LBD) (corrected for transducer depth), macrophyte cover (MC) (expressed as a percentage) and macrophyte height (MH) were subsequently used to calculate Percentage Volume Inhabited (PVI) for each 10-ping sequence according to the equation

PVI = ((MH*(MC/100))/LBD)*100

which simplifies to

PVI = (MH/LBD)*MC

Comparison of hydroacoustic and underwater video assessments

When water clarity made such work viable, an underwater video camera system (Simrad OE 1372 Miniature High Definition Colour Underwa- ter Camera recording to a Sony Video Walkman GV-S50E) orientated vertically downwards was attached to the transducer of the hydroacoustic system and simultaneous recordings made during transects as described below. In the laboratory, the video recordings were digitised using the hardware and software system WinTV-USB (Hauppauge Computer, Inc., www.hauppauge.com) before being reviewed and scored for macrophyte presence or absence within the part of the image insonified by the hydroacoustic system. Such scores were made at 2 s intervals for the duration of each transect, before being summed into 1 min segments (corresponding to c. 67 m segments along transects) and macrophyte cover calculated as a percentage for each segment. This procedure produced totals of 50 such segments from a total of 16 transects from Lake 31 between c. 10.15 and 12.00 h on 1 October 2004 (8 transects) and 12 January 2005 (8 transects), and 24 such segments from 10 transects from Lake 32 between c. 14.45 and 15.30 h on 12 January 2005. Grapnel and Ekman Grab samples were also taken at each lake to allow identification of the dominant macrophyte species. Statistical assessments of the degree of agreement between the measure of macrophyte cover produced by the hydroacoustic and underwater video systems in the two lakes were made by linear regression. The video system could not produce quantitative data for macrophyte height and so statistical assessment of agreement was not possible for this parameter, although a qualitative comparison was made by comparing appropriate EcoSAV output, echograms and video recordings from different areas of the two lakes.

Surveys

Although full surveys were carried out for both lakes, only those of Lake 31 are considered here. Prior to undertaking surveys, transects were planned such that they followed a discrete sys- tematic parallel design as far as field conditions allowed. Fourteen transects were followed, run- ning west-east across the lake (Fig. 1). Navigation was facilitated by a Magellan SporTrak Pro (EU basemap) GPS (www.magellangps.com) with accuracy to less than 7 m, preloaded with appro- priate way points. Immediately before each sur- vey, inshore surface water temperature was taken to an accuracy of 0.1°C and entered into the hydroacoustic system. Total transect length for each survey was 3,313 m, giving a ratio of cover- age (length of surveys: square root of research area) of 10.3:1.

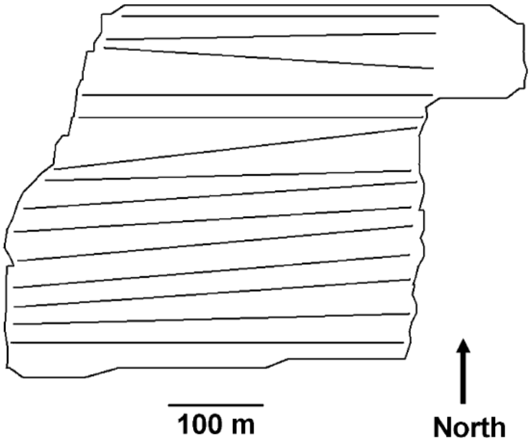

Fig. 1 Outline map of Lake 31 of the Cotswold Water Park, U.K., showing the locations of 14 hydroacoustic transects (straight lines) undertaken during surveys on 29 October 2003, 20 January 2004 and 30 April 2004. At the time of the surveys, access to the small north-east extension to the lake was denied by a boom

Such surveys, each of which took c. 50 min to complete, were performed between 09.00 and 14.00 h on 29 October 2003, 20 January 2004 and 30 April 2004. Spatial patterns in selected EcoSAV output variables were examined using the software package Surfer (Version 8.05, Golden Software, Inc., Colorado, U.S.A., www.goldensoft- ware.com) to perform point kriging with a linear variogram model (slope = 1, anisotropy ratio = 1 and angle = 0).

Results

Comparison of hydroacoustic and underwater video assessments

Fig. 2 shows that macrophyte coverages in both lakes as assessed by underwater video recording and by EcoSAV were similar and fell around the line of equality. Specific regressions for Lake 31 (EcoSAV = 0.9417(Video) + 4.8248; $r^2 = 0.8749$, n = 50, $P < 0.001$) and Lake 32 (EcoSAV = 1.2099(Video)–19.8152; $r^2 = 0.7932$, n = 24, $P < 0.001$) were analysed by a variance ratio test following Mead & Curnow (1983). This revealed that these relationships were not significantly different (F = 2.613, df = 22.48, $0.05 > P > 0.10$).

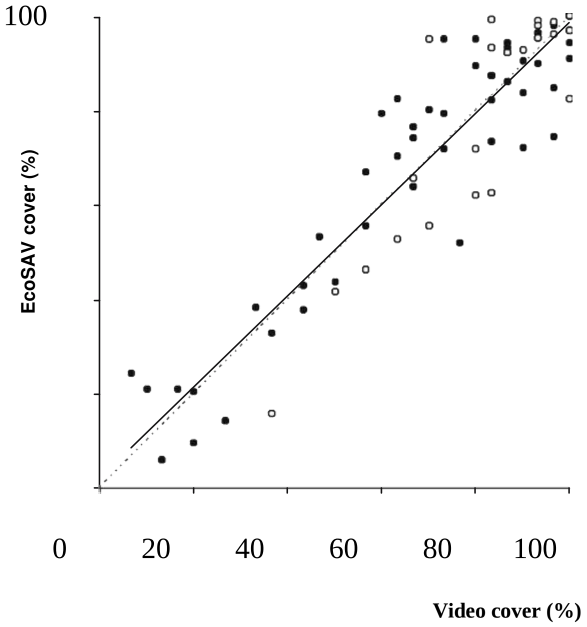

Fig. 2 The relationship between macrophyte cover assessed by underwater video recording and by EcoSAV in Lake 31 (derived from 50 1-minute segments of 16 transects surveyed on 1 October 2004 and 12 January 2005, closed symbols) and Lake 32 (derived from 24 1- minute segments of 10 transects surveyed on 12 January 2005, open symbols). The line of equality is indicated by a broken line.

Statistics for the overall regression (continuous line) are $r^2 = 0.8478$, $n = 74$, $P < 0.001$. Other regression statistics are given in the text and so the relationship is most appropriately described by an overall regression (Eco- SAV = 0.9695(Video) + 1.9577; $r^2 = 0.8478$, $n = 74$, $P < 0.001$). For this overall regression, the intercept was not significantly different from 0 (t-test; $t = 0.5242$, $P > 0.10$) and the slope was not significantly different from 1 (lower and upper 95% confidence limits of 0.8730 and 1.0660, respectively). Qualitative assessment of the efficacy of Eco- SAV at estimating macrophyte height also indicated a good agreement, as far as this parameter could be assessed by examination of simultaneous echograms and video recordings. In some areas of the lakes, echograms showed occasional tall strands of macrophytes protruding from lower- growing masses, while corresponding macrophyte heights produced by EcoSAV increased notably. In the same areas, video recording showed tall strands of macrophytes, primarily Elodea nuttallii or Lagarosiphon major, emerging from lower beds. Even though height measurements could not be made, the relatively greater height of these protruding individual strands was evident as the video camera passed over them. Macrophyte species recorded by grapnel and Ekman Grab samples in Lake 31 during the comparison of techniques included Chara curta, C. virgata, C. globularis, Nitella flexilis, Tolypella intricata, Elodea nuttallii, Myriophyllum spica- tum, Ranunculus circinatus, Potamogeton tricho- ides and P. pusillus. In Lake 32 they included Chara curta, C. contraria, C. globularis, Elodea nuttallii, Lagarosiphon major, Myriophyllum spic- atum and Ranunculus circinatus.

Surveys

Figure 3 illustrates trends in macrophyte cover, macrophyte height and PVI over the winter of 2003–2004 in Lake 31. Macrophyte cover fell from a mean of 60.26% (95% confidence lim- its, ± 2.16%) in October at the beginning of the winter to a low of 45.64% (±2.40%) in January, before increasing slightly to 49.18% (±2.18%) at the end of the winter in April. Mean macrophyte height fell successively from 0.54 m (±0.01 m), through 0.48 m (±0.01 m), to 0.46 m (±0.01 m) over the same time period. Mean PVI, which is influenced by changes in both of the above parameters, fell markedly between October and January from 12.15% (±0.55%) to 7.36% (±0.49%), with a further slight decrease to 7.10% (±0.40%) in April. Finally, Fig. 4 shows examples of further anal- yses that can be performed rapidly with

EcoSAV output in the form of contour maps of lake bottom depth and macrophyte cover for Lake 31 on 29 October 2003. Macrophyte species recorded by grapnel and Ekman Grab samples during the surveys of Lake 31 included Chara curta, C. virgata, C. globularis, Nitella flexilis, Tolypella intricata, Elodea nuttallii, Myriophyllum spicatum, Ranunculus circinatus, Potamogeton trichoides and P. pusillus.

Discussion

The present assessment in two shallow lakes of a hydroacoustic system using a sound frequency of 200 kHz against simultaneously collected visual study lakes, suggesting that the described relationship may be generically applicable to any lake with a predominantly hard bottom and macrophyte species with growth forms similar to those observed here. Future studies should seek to examine additional hard-bottomed lakes, as well as expanding to lakes with softer substrates. However, the latter conditions can be expected to present not only a considerable challenge because of the greater hydroacoustic similarity between a soft bottom and macrophytes, but they are also likely to make visual assessment more difficult because of a reduced visual contrast between macrophytes and organic sediments. Soft-bottomed lakes or areas of lakes are also frequently associated with higher levels of suspended sediments in the water column itself, the levels of which although relatively low in the present study lakes were still sufficient to compromise video recordings on some transects and thus preclude their data from the present analysis. The present assessment was incapable of a quantitative examination of the efficacy of Eco- SAV and a sound frequency of 200 kHz at estimating macrophyte height due to the technical limitations of the visual recording system. How- ever, in their estuarine study Sabol et al. (2002) found a good agreement between EcoSAV estimates of this parameter using 420 kHz sound and direct measurements made by a diving team. data revealed a high degree of agreement in terms of macrophyte cover. Furthermore, the degree of agreement observed was comparable with that recorded by Sabol et al. (2002) in a sandy estuary using a 420 kHz system and a more sophisticated underwater video system. In fact, the agreement found here was considerably better than that found by Sabol et al. (op. cit.), although this was probably because the present analysis averaged data into 1 min segments rather than used single data points as did the former study. It is also encouraging that the present agreement between hydroacoustic and visual surveys was statistically indistinguishable between the two. Given that detecting the top of a macrophyte is technically much easier than determining the true bottom depth below a fully developed macrophyte canopy (see Sabol et al. (2002)), it is likely that the present system is also capable of accurate measurement of macrophyte height although this should be established in future assessments. Certainly, the present transects showed qualitative agreement between macrophyte heights estimated by EcoSAV and those apparent from the video recordings. The technical limitations of the video recording system, particularly its resolution, also prevented a quantitative assessment of the ability of the hydroacoustic system to distinguish between macrophyte species. However, it was clear that macrophytes of substantially different growth forms such as low-growing Chara species and tall-growing Elodea, Myriophyllum and Lagarosiphon species could be readily distinguished. This study demonstrates that EcoSAV works effectively with hydroacoustic data collected using a sound frequency of 200 kHz in shallow lakes for a range of previously untested freshwater macrophytes including Chara, Nitella, Tolypella, Elodea and Lagarosiphon spp. Furthermore, this success was achieved with very little alteration to the default analysis parameters, i.e. just an increase from 12 to 30 in the Bottom Thickness Limit (see BioSonics (2004)). A requirement for the latter is to be expected from the underlying physics of sound in water, specifically its differential penetration into bottom sediments as a function of frequency. Nevertheless, with a lowering of sound frequency there is an inherent consequent loss of resolution and Hoffman et al. (2002) found that an EcoSAV system using 70 kHz performed significantly poorer than one using 420 kHz, although it should be noted that pulse duration also differed and was longer for the former system. Given this observation and the present results, it can be concluded that sound frequencies suitable for use in both macrophyte and fish studies lie in the upper range of those used for the latter alonein fresh waters, i.e. greater than c. 70 kHz but less than c. 200 kHz. Given the relatively high capital cost of hydroacoustic systems, such dual use has great practical benefit.

The successful ground-truthing of EcoSAV with a sound frequency of 200 kHz enables this system to be used with confidence in full macrophyte surveys. The demonstration data presented from Lake 31 illustrate some of the direct (macrophyte cover, macrophyte height) and indirect (Percentage Volume Inhabited) types of data that can be generated by such surveys. The latter are both relatively fast, e.g. a c. 10 ha lake can be surveyed in c. 50 min, and independent of environmental conditions such as water clarity. A particularly powerful feature of the hydroacoustic approach is that surveys can be repeated with high fidelity and are not compromised by seasonal changes in environmental parameters. Thus seasonal progressions in macrophyte developments within and between lakes can be easily and objectively detected and measured, with the incorporation of GPS data within the system also allowing detailed spatial analyses. The spatial error variance of the latter depends primarily on the transect spacing employed during the surveys, although the interpolation technique, transect point density and interpolation search area are also of critical importance (Guan et al., 1999; Valley et al., 2005). Generated 'surfaces' of macrophyte percentage cover, height, depth below surface and bathymetry interpolated from hydroacoustic data have a variety of ecological and site management applications. For example, data from the work described in this paper are being used as part of an integrated study to model waterbird disturbance risk as a function of a variety of environmental variables, in particular the availability of food resources in the form of aquatic macrophytes (O'Connell et al., in press).

As concluded by Schneider et al. (2001), Hoff- man et al. (2002), Sabol et al. (2002) and Valley et al. (2005) working in other aquatic systems, recent technological developments in the field of hydroacoustics now make this a viable technique for the survey of aquatic macrophytes in shallow lakes. This does not mean that biological sampling is redundant, anymore than the more mature application of hydroacoustic techniques to fish studies has removed the need for sampling by netting in order to secure biological specimens for species identification and other examination. However, hydroacoustic techniques facilitate more quantitative and spatially-referenced studies of macrophyte abundance, paralleling recent studies of lake fish populations such as those by Elliott et al. (1996), George & Winfield (2000) and Schmidt et al. (2005). As such, hydroacoustic techniques have many potential applications in studies of macrophytes within shallow lake systems.

Conclusion

The analysis software EcoSAV works effectively with hydroacoustic data collected using a sound frequency of 200 kHz in shallow lakes for a range of freshwater macrophytes including Chara, Ni- tella, Tolypella, Elodea and Lagarosiphon spp. As such, it facilitates rapid, extensive, quantitative and spatially-referenced surveys of macrophyte distribution and abundance, with many potential applications in studies of shallow lake systems.

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