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Monitoring aquatic plants: An evaluation of hydroacoustic, on-site digitising and airborne remote sensing techniques

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Abstract – Aquatic macrophytes are often monitored to detect change in ecosystem function and state, as well as assessing the effectiveness of invasive aquatic plant management. This study compares seven methodologies to monitor the distribution and abundances of aquatic macrophytes. Four line transect methodologies and three spatial mapping techniques were employed in parallel over a broad turbidity gradient in two lentic habitats of south-eastern Australia. The methodologies examined included hydroacoustic surveys, on-site digitising, and digitisation of airborne remote sensing imagery. Variation in estimates of macrophyte coverage were observed between methodologies. Consistency in the collection and interpretation of data was greatest for the line transect methodologies and the digitisation of satellite imagery. Duel-frequency identification sonar proved to be an effective novel hydroacoustic technique to monitor macrophyte abundances over broad spatial scales. Single beam sonar transects was also an objective, repeatable and scalable methodology. Videography and on-site handheld PDA mapping were of limited utility due to restrictions imposed by turbidity. The utility of sidescan sonar could be improved when used in conjunction with on-site handheld PDA mapping. This study outlines important considerations when selecting a methodology to monitor macrophyte distribution and abundance. Results indicate that no one specific method can be employed across all macrophyte monitoring studies. The method or combination of methods employed during macrophyte monitoring studies is dependent upon the study objectives, budget and environmental conditions of the study site.

Keywords: aquatic macrophyte / aquatic plant / hydroacoustic mapping / aquatic habitat mapping / macrophyte monitoring / DIDSON / sidescan sonar

Résumé – Suivi des plantes aquatiques : une évaluation des techniques hydroacoustiques, de numérisation sur site et de télédétection aérienne. Les macrophytes aquatiques font souvent l'objet d'un suivi pour déceler les changements dans le fonctionnement et l'état de l'écosystème, et pour évaluer l'efficacité de la gestion des plantes aquatiques envahissantes. Cette étude compare sept méthodologies pour surveiller la distribution et l'abondance des macrophytes aquatiques. Quatre méthodes de transects linéaires et trois techniques de cartographie spatiale ont été employées en parallèle sur un large gradient de turbidité dans deux habitats lentiques du sud-est de l'Australie. Les méthodologies examinées comprenaient les levés hydroacoustiques, la numérisation sur place et la numérisation de l'imagerie de télédétection aéroportée. Des variations dans les estimations de la couverture des macrophytes ont été observées entre les méthodologies. L'uniformité dans la collecte et l'interprétation des données était la plus grande pour les méthodes de transects linéaires et la numérisation de l'imagerie par satellite. Le sonar d'identification à double fréquence s'est avéré être une technique hydroacoustique novatrice efficace pour surveiller l'abondance des macrophytes sur de vastes échelles spatiales. Les transects sonar à faisceau unique étaient également une méthode objective, répétable et évolutive. La vidéographie et la cartographie à l'aide d'un assistant numérique personnel sur place étaient d'une utilité limitée en raison des restrictions imposées par la

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turbidité. L'utilité du sonar à balayage latéral pourrait être améliorée s'il était utilisé en conjonction avec la cartographie PDA portable sur site. Cette étude souligne des considérations importantes dans le choix d'une méthodologie de surveillance de la distribution et de l'abondance des macrophytes. Les résultats indiquent qu'aucune méthode spécifique ne peut être utilisée pour toutes les études de surveillance des macrophytes. La méthode ou la combinaison de méthodes employées pendant les études de surveillance des macrophytes dépend des objectifs de l'étude, du budget et des conditions environnementales du site à l'étude.

Mots clés : macrophyte / plante aquatique / cartographie hydroacoustique / DIDSON / sonar à balayage latéral

1 Introduction

Aquatic macrophyte communities play an important role in freshwater aquatic ecosystems by: influencing nutrient cycling and trophodynamics; forming an important structural habitat component; influence fish productivity; altering the geophysical characteristics of a systems, and; influencing water quality variables such as turbidity and dissolved oxygen (Caraco and Cole, 2002; Genkai-Kato and Carpenter, 2005; Choi et al., 2014). However, in high abundances invasive aquatic plants can be detrimental to ecosystem function and the public utility value of water resources (Kelly and Hawes, 2005; Zhang and Boyle, 2010). The spatial and temporal extent of aquatic macrophyte communities are often dynamic, responding to change in variables such as hydrology, water temperature, nutrient levels, turbidity, grazing and implementation of control measures (Lacoul and Freedman, 2006; Szoszkiewicz et al., 2014; Yu et al., 2016). Consequently, aquatic macrophytes are monitored to detect change in ecosystem function and state, as well as assessing the effectiveness of invasive aquatic plant management (Netherland and Jones, 2015).

Various techniques are available to measure and analyse quantitative and qualitative attributes of aquatic macrophytes, such attributes include: species composition, spatial distribution, depth distribution, density, biomass and plant height (Johnson and Newman, 2011). Sabol et al. (2002) categorised methods into three broad groups:

– physical;
– on-water remote;
– off-water remote.

Physical methodologies generally involving quadrat or point transect application of rake tosses, diver quadrats and bathyscopes (Madsen, 1999; Havens et al., 2002; Skogerboe et al., 2008; Johnson and Newman, 2011). These can provide both quantitative and qualitative data, but are labour intensive and more appropriate for small spatial extents.

On-water remote methodologies generally involve the collection of data from a vessel using hydroacoustic sensing equipment or towed video cameras. Hydroacoustic sensing equipment may include single beam, multi beam and sidescan sonar systems (Bickers, 2003; Kruss et al., 2009; Kaeser and Litts, 2010; Christia et al., 2014; Netherland and Jones, 2015; Radomski and Holbrook, 2015; Valley et al., 2015). Single beam sonar uses acoustic signals that travel through submerged vegetation canopies on the way to bottom sediments. The substratum typically registers a sharper echo-return than the aquatic vegetation, allowing the presence/absence of aquatic macrophytes to be determined. Georeferenced single beam hydroacoustic data can be interpreted manually or automated processing is offered through multiple cloud-based software platforms (Radomski and Holbrook, 2015; Valley et al., 2015). Sidescan sonar is an acoustic imaging process that provides wide-area, high-resolution acoustic images. Georeferenced acoustic data can then be digitised in a GIS to provide spatial information on macrophyte communities. The increasing availability of reliable, low cost recording sonar units has made single beam and sidescan sonar data collection possible under most monitoring program budgets.

Towed optical video systems can often provide easily interpretable images for qualitative and quantitative assessment; however, the field of view is highly dependent upon turbidity and data processing can be labour intensive. Duel-frequency Identification Sonar (DIDSON, Sound Metrics, Bellevue, WA, USA) is an acoustic camera providing video imagery in turbid or dark water where optical systems are ineffective (SoundMetrics, 2008). The application of DIDSON to fisheries research includes observations of fish behaviour, estimate of fish abundances and fish size (Moursund et al., 2003; Holmes et al., 2006; Boswell et al., 2008; Boys et al., 2013; Langkau, 2018). The use of DIDSON to monitor the distribution and abundance of macrophyte communities is a novel hydroacoustic technique that has been rarely assessed (Mizuno et al., 2018). Mizuno et al. (2018) validated the use of DIDSON to estimate macrophyte biomass in small 3-dimensional quadrats, however, the application of DIDSON transects to monitor macrophyte coverage over larger spatial scales is a novel technique.

Off-water remote methodologies involve the collection and interpretation of airborne or satellite derived remote sensing imagery (Everitt et al., 1999; Creese et al., 2009). Such techniques have significantly improved survey speeds and allow monitoring over large spatial scales; however, are limited by resolution, water penetration and cloud obstruction. Processing of imagery generally involves digitising macrophyte beds and can be done manually or automated through software platforms (CMAP, 2018). These software platforms use algorithms that classify imagery based on the unique reflectance properties of aquatic vegetation.

The macrophyte monitoring method employed will be dependent upon the data requirements of the study. In some studies, quantitative measures of abundance and density may be of importance, whereas in other instances further information on qualitative attributes such as species composition may be required. The scale and spatial extent of monitoring will also influence the methodology employed (Johnson and Newman, 2011). However, when selecting a methodology, considerations common to all studies include accuracy, precision, sensitivity to tubidity and cost-effectiveness of an objective repeatable procedure.

The primary objective of this study was to assess and compare a selection of current methods available to monitor the percentage area cover (PAC) of macrophytes in aquatic habitats with varying turbidities. More specifically, this study aimed to:

– assess conformity between methodologies;
– assess variation in data collection and interpretation between operators;
– assess time and cost of equipment, data collection and processing;
– assess pros/cons and limitations of each method.

This was achieved by comparing seven methodologies employed in parallel over a broad turbidity gradient in two lentic habitats. The methodologies examined included four line transect methodologies: 200 kHz sonar, 800 kHz downscan sonar, DIDSON & optical videography; and three spatial mapping techniques: 800 kHz sidescan sonar, handheld PDA Trimble mapping and satellite imagery.

2 Materials and methods

2.1 Study location

Macrophyte community assessments were conducted in two lentic habitats of South-Eastern Australia during the autumn of 2017. The study sites included a small urban lake (Landsdowne Lake), and Green Bay within Prospect Reservoir; each having an area of approximately 3 hectares. Study sites were chosen to incorporate a range of water depths and turbidities. Landsdowne Lake had the highest turbidity of 0.58 m secchi depth, with a maximum depth of 4 m. Green Bay within Prospect Reservoir had the lowest turbidity of 1.64 m secchi depth and a maximum depth of 6 m.

2.2 200 kHz sonar & 800 kHz downscan sonar

Hydroacoustic georeferenced line transect data of aquatic macrophyte presence/absence was collected with a Lowrance HDS7 Gen3 GPS integrated echo-sounder with a total-scan transducer. At each site, sonar recordings were collected from three 500-m transects spaced at 5 m intervals from the bank. A track was recorded during each transect and displayed on the Lowrance head-unit in 'split screen mode' to assist with transect spacing. Mapping was conducting from a flat bottom punt with a transom-mounted transducer. Sonar logs were recorded at a consistent speed of 1 knot using an outboard petrol engine. The sonar recordings were logged at a rate of 15 to 20 data signals.s^{-1} at 200 kHz with a 208-beam angle; 800 kHz downscan imagery was simultaneously recorded. The sounder display was continually monitored to ensure the unit was detecting bottom and producing a clear reading. Transects where the sounder 'lost' bottom identification or the soundings were not clear were repeated.

Manual processing of the georeferenced 200 kHz sonar and 800 kHz downscan sonar was performed in 'ReefMaster Sonar Viewer' version 1.0.36.0 software package (https://reefmaster.com.au/). Lowrance sonar .sl3 files containing both the 200 kHz sonar and 800 kHz downscan sonar recordings were analysed independently to prevent bias. Start and end times for macrophyte beds and bare substratum were recorded along the
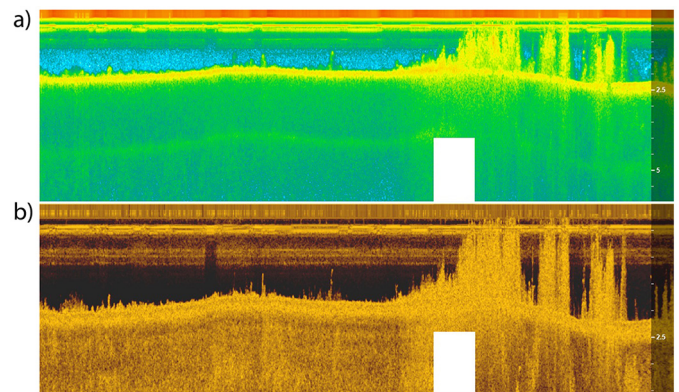

Fig. 1. a) 200 kHz sonar, and; b) 800 kHz downscan imagery collected using a Lowrance HDS Gen3 echosounder displayed in 'ReefMaster Sonar Viewer' illustrating macrophyte presence along a lake transect.

transect. Macrophyte beds were easily distinguishable from bare substratum (Fig. 1).

2.3 800 kHz sidescan sonar

During each transect, sidescan imagery was simultaneously recorded using the same Lowrance HDS7 Gen3 GPS integrated echosounder with total-scan transducer. Sidescan sonar imagery was collected at 800 kHz with a range of 2–3 times the water depth. The outermost transect was conducted in a direction to ensure the transom mounted sidescan transducer had a clear view towards the bank, without the outboard motor leg blocking the sonar signal.

SonarTRX Pro (http://www.sonartrx.com/) was used to convert Lowrance .sl3 sidescan sonar files to georeferenced .png image tiles compatible for GIS ArcMap processing. Macrophyte beds distinguishable from the sidescan imagery were digitised into polygons and the total macrophyte surface area calculated (Fig. 2); the identification of species was not possible from sidescan imagery alone. The water column was eliminated from the sidescan imagery to ensure true spatial scale when digitising the macrophyte beds.

2.4 DIDSON & optical videography

During each transect a gunnel mounted forward facing DIDSON and GoPro video camera collected imagery of the aquatic bathymetry. The DIDSON and GoPro were submerged 20 cm below the water surface and aimed downwards at an angle of between 20–40° from horizontal depending upon water depth (a larger angle was used during deeper transects). GoPro and DIDSON recordings were synchronised with the sonar recordings allowing for standardization when comparing each of the methods. The GoPro footage was recorded in wide-angle mode at 920 × 1080 pixels and 60 FPS. The DIDSON data was collected at 1.8 MHz (high-frequency mode) with a window start of 2.5 m, maximum range of 12 m and frame rate of 7 FPS. The DIDSON and GoPro imagery was analysed using a line transect methodology. The time point along the transect at the boundary between bare bottom, macrophyte
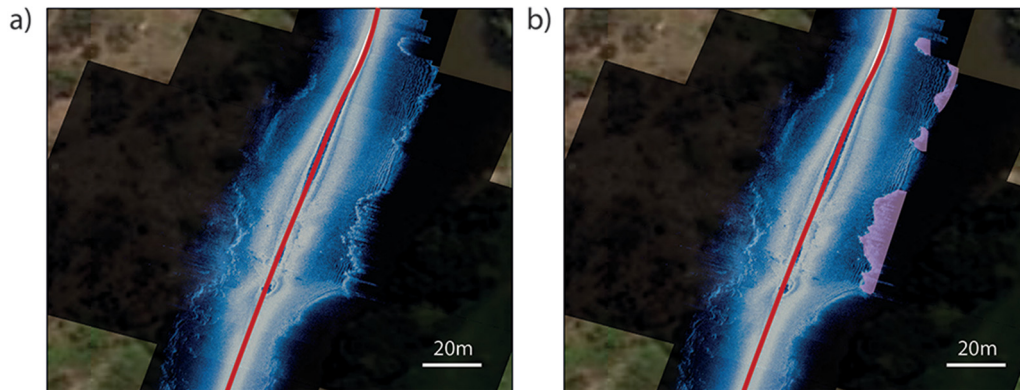
Fig. 2. a) 800 kHz sidescan imagery collected from a single pass transect (red line) of a narrow lake section using a Lowrance HDS Gen3 echosounder, and; b) digitised 800 kHz sidescan imagery illustrating a macrophyte beds (pink polygons) on the right shore of the lake separated by rippled sandy substrate.
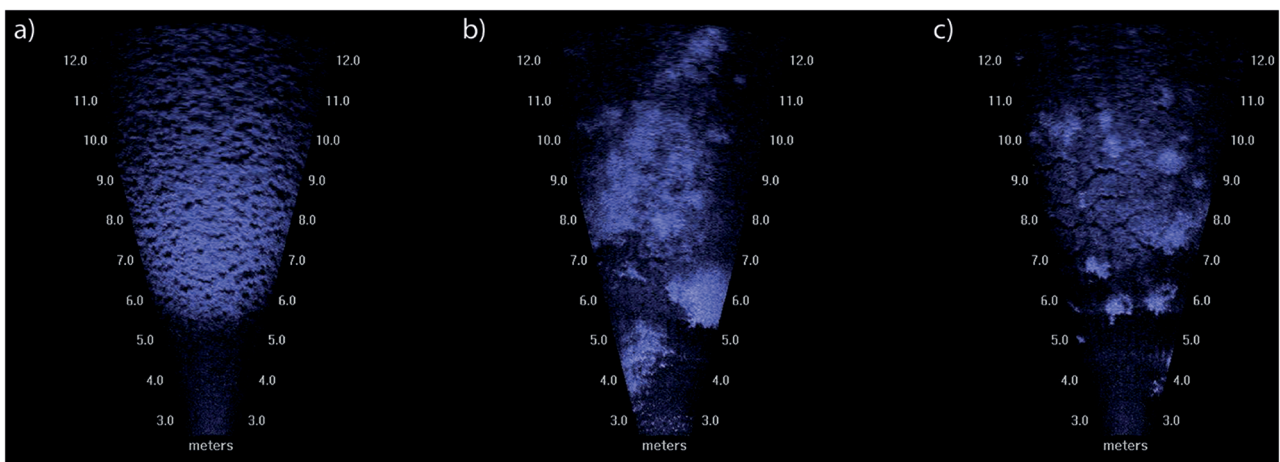

Fig. 3. Freeze-frame of Duel-Frequency Identification Sonar (DIDSON) recordings in 2 m depth illustrating: a) bare sediment substrate; b) dense macrophyte coverage, and; c) sparse macrophyte coverage over cracked clay substrate.

presence and 'unknown substrate' was recorded. From the DIDSON footage the presence/absence of macrophytes was categorised at the 7 m focal point (Fig. 3) and between 0.58–1.64 m for the GoPro footage, depending upon turbidity. The presence of macrophytes from both the DIDSON and GoPro footage was further categorized as either sparse ($< 50\%$ macrophyte coverage in the horizontal field of view) or dense ($> 50\%$ macrophyte coverage in the horizontal field of view). A category of 'Unknown' was assigned when the presence/absence of macrophyte could not be determined from the recorded footage. It was not possible to identify the species of macrophyte from DIDSON footage, however, the macrophyte species was recorded from GoPro footage where possible.

2.5 Handheld PDA Trimble mapping

Spatial distribution of aquatic macrophytes was mapped by two independent field teams from a boat using a handheld differential GPS PDA Trimble unit (Trimble Nomad, Sunnyvale, CA) with TerraSync data acquisition software.

Prior to field mapping, the PDA Trimble was loaded with a base map of the study site. Macrophyte mapping was conducted from the shore to the outermost transect. The spatial distribution of macrophytes was mapped by creating polygons around macrophyte beds. Spatial data was recorded in either of two formats, position-dependent or position-independent, depending on the ability to maneuver the boat around the macrophyte bed. Macrophytes were recorded to genus level using Sainty and Jacobs (2003). All data was uploaded into a GIS (ArcGIS 10.3.1, ESRI Inc.) for processing and the total area of the macrophyte polygons calculated.

2.6 Satellite imagery

Nearmap satellite imagery collected within 2 weeks of field sampling was attained for each study site at a 0.2-m pixel resolution. Macrophyte beds were digitised and macrophyte surface area calculated from the cloud-free georeferenced satellite imagery within ESRI ArcGIS. Classification of macrophyte species was not possible from the satellite

Table 1. Comparison of macrophyte percentage area coverage derived from the 3 spatial monitoring techniques assessed over the same spatial extent within Prospect Reservoir and Landsdowne Lake. Handheld PDA Trimble mapping data was collected by two trained independent field teams; sidescan and satellite imagery was digitised by two trained independent technicians.

	Prospect Reservoir		Landsdowne Lake	
	Team/ technician I (%)	Team/ technician II (%)	Team/technician I (%)	Team/technician II (%)
Digitised sidescan imagery	24.21	37.14	15.31	12.16
PDA Trimble mapping	18.62	21.98	8.02	13.80
Digitised satellite imagery	53.31	45.99	18.12	17.48

imagery alone, all macrophyte species were therefore digitised with no distinction made between species and the total area of the macrophyte polygons were summed.

2.7 Analytical methodology

To compare estimates of macrophyte abundance between each simultaneously recorded line transect methodology (200 kHz sonar, 800 kHz downscan sonar, DIDSON and GoPro), the proportion of time that macrophytes occupied each transect was calculated as a percentage of the total transect time. To allow comparisons between methods, periods throughout a transect that were categorized as 'unknown' for any of the methods were removed from the time series of all methods. The percentage of each transect classified as 'unknown' was also calculated individually for each of the 4 transect methodologies. This procedure was repeated for data sets processed by each of the two data interpreters individually.

A nested Analysis of Variance (ANOVA) was used to compare macrophyte percentage cover estimates between the four line transect methodologies. All data were arcsin transformed prior to analysis. ANOVA was also used to compare the mean percentage of transects classified as 'unknown' macrophyte presence/absence between the four line transect methodologies.

Macrophyte PAC was calculated from each of the three spatial mapping methodologies (sidescan, Handheld PDA Trimble mapping & satellite imagery). Handheld DPA Trimble mapping data was collected by two trained independent field teams; sidescan and satellite imagery was digitised by two trained independent technicians.

3 Results

The nested ANOVA comparing estimates of macrophyte coverage between each line transect methodology indicated a significant difference between methods ($F_{3,39} = 4.04$; $P < 0.05$). Estimates of macrophyte coverage collected using DIDSON were significantly ($P < 0.05$) lower than that of all other methods (DIDSON = 74.59% ± 4.77 S.E, optical videography = 80.45% ± 5.16 S.E, 800 kHz downscan = 82.45% ± 4.78 S.E, 200 kHz sonar = 81.53% ± 4.89 S.E). There was no significant difference in the macrophyte coverage estimates between observers for each of the line transect methodologies ($F_{3,52} = 0.38$; $P > 0.05$). However, substantial differences in macrophyte PAC were identified between observers for two of the three spatial mapping techniques, sidescan & PDA Trimble mapping; there was minimal variation in PAC estimates between observers digitising satellite imagery (Tab. 1).

For the sonar and downscan methods, no proportion of the transects were classified as 'unknown' macrophyte presence/absence. The average percentage of transects that were categorised as 'unknown' was significantly greater for videography when compared against DIDSON ($F_{1,55} = 34.66$; $P < 0.001$). For videography transects a significantly greater proportion of transects were classified as 'unknown' in the more turbid Lansdown Lake (Prospect = 37.67% 'unknown' ± 5.18 S.E; Landsdowne = 73.30% 'unknown' ± 2.79 S.E; $F_{1,55} = 34.66$; $P < 0.001$). Of the line transect methods, DIDSON had the second greatest proportion of transects categorized as 'unknown', making up 6.96% ± 2.13 S.E and 11.69% ± 2.93 S.E for Prospect and Landsdowne Lake respectively. There was no significant difference in the proportion of a DIDSON transect classified as 'unknown' between observers ($F_{1,52} = 0.02$; $P > 0.05$).

The PAC measure for macrophytes varied considerably between spatial mapping techniques (Tab. 1). Within both reservoirs, digitised satellite imagery resulted in the highest estimates of PAC, whereas PDA Trimble mapping had the lowest (Tab. 1). The mean percentage difference of macrophyte PAC estimates between digitised satellite imagery and PDA Trimble mapping was 48.52% ± 9.55 S.E. Large variation in PAC was observed between field teams collecting handheld PDA Trimble mapping data (mean % difference = 28.57% ± 13.29 S.E.) and between technicians digitising sidescan imagery (mean % difference = 27.71% ± 7.13 S.E.). The least variation in PAC was observed between technicians digitising satellite imagery data (mean % difference = 8.66% ± 5.08 S.E.).

4 Discussion

Variation in estimates of macrophyte coverage were observed between methodologies. Consistency in the collection and interpretation of data was greatest for the line transect methodologies and the digitisation of satellite imagery. Duel-Frequency Identification Sonar proved to be an effective novel hydroacoustic technique to monitor macrophyte abundances over broad spatial scales, independent of water turbidity. Single beam sonar transects was also an objective, repeatable and scalable methodology under a range of turbidities; whereas videography and on-site handheld PDA mapping were of limited utility due to restrictions imposed by turbidity.

There was no significant difference in the macrophyte coverage estimates between observer interpretations for each of the line transect methodologies. However, substantial differences in macrophyte surface area coverage were

identified between observers for two of the three spatial mapping techniques, sidescan and PDA Trimble mapping; there was minimal variation in PAC estimates between observers digitising satellite imagery. Consistency in data interpretation and collection is important for monitoring studies in order to maximize power to detect change. While strict standardized protocols can reduce measurement error, some methods have more inherent potential for variation, as illustrated by the handheld PDA Trimble mapping and sidescan techniques.

Hydroacoustic macrophyte monitoring techniques can be applied and analysed independent of turbidity, proving to be advantageous over optical techniques. When using the 200 kHz sonar and 800 kHz downscan methods, no proportion of transects were classified as 'unknown' macrophyte presence/absence within each of the study lakes. Similarly, only a small proportion of DIDSON footage was classified as 'unknown'; this was due to either debris obscuring of the lens or failure to adjust the DIDSON recording angle to account for changes in water depth. In contrast a high proportion of optical video footage was classified as 'unknown' from both lakes, significantly reducing the utility of optical videography as a means to effectively monitor macrophyte coverage.

Field data collected using sidescan sonar is comparatively quicker than all other hydroacoustic techniques assessed, as large areas (40+ m range: dependent upon water depth, sonar transmission frequency and required image quality) can be mapped from a single pass transect. However, in some instances identifying and digitising macrophyte beds from the sidescan imagery can be subjective and difficult without ground truthing data as illustrated by the large variation between technician interpretations when digitising sidescan imagery. The importance of ground truthing has been highlighted by others using sidescan sonar for aquatic habitat mapping (Bickers, 2003; Kaeser et al., 2013). Sidescan imagery can also be restricted when the water column is fully occupied by dense macrophyte beds (Kaeser and Litts, 2013). In some instances within this study, the sidescan sonar did not penetrate dense macrophytes canopies, and thus only provided information on the boundary of the near-side edge rather than the full spatial extent of the macrophyte bed (Fig. 2). However, when used in conjunction with handheld PDA Trimble mapping the two methods are complementary. Sidescan provides accurate turbidity independent spatial data on the deeper boundary edge of macrophyte beds and the turbidity sensitive handheld PDA Trimble mapping technique provides information on species composition and on the shallow boundary extent of macrophyte beds.

Both 800 kHz downscan and 200 kHz sonar provide an objective, repeatable and scalable methodology to monitor macrophyte communities. Both are effective quantitative methods unbiased by turbidity; however, neither provides qualitative data such as species composition when used in isolation. Where species composition is of interest, qualitative investigations by divers or alternative biological sampling methods are required. The 800 kHz Downscan sonar provided more structural detail to aid in the distinction between fallen timber and macrophyte beds, whereas the 200-kHz sonar showed better distinction of the boundary between hard substrates and the softer echo-return of macrophytes (Fig. 2). Given that most sonar units can record both 800 kHz downscan

and 200 kHz sonar simultaneously, viewing both frequencies in unison can aid in data interpretation. Both standard sonar and downscan sonar provide information on the depth distribution and proportion of the water column occupied by macrophytes (Kruss et al., 2009; Valley et al., 2015). However, as with all transect methodologies collected from a propeller driven vessel, fouling of the propeller when motoring through dense macrophytes can be problematic. Furthermore, in dense surface-to-substrate macrophyte beds, the sounder unit can lose 'bottom detection' resulting in data gaps throughout a transect.

Manual processing of 200 kHz sonar and 800 kHz downscan sonar recordings within the 'ReefMaster Sonar Viewer' software package was substantially less labour intensive than applying line/point transect analyses to DIDSON and optical videography; with little variation in interpretation between observers for the former. Software platforms are available that automate 200 kHz sonar and GPS signal processing and create GIS data layers of macrophyte depth distribution, PAC and plant height; completely eliminating any biases introduced by observer interpretation (Valley et al., 2015). Although not examined in this study, other scientific echosounders and automated data processing software are available for aquatic habitat mapping that can simultaneously provide information on fish distribution and biomass (BioSonics, 2019).

For both DIDSON and videography, data processing can be labour intensive, as the footage from each transect has to be viewed and a point/line transect analysis applied to obtain quantitative data. This will likely not be cost effective over large spatial scales. Qualitative data such as species composition can be obtained from video footage, however can be difficult to determine from DIDSON footage without ground truthing data. However, studies have used a modified DIDSON apparatus and image processing technology to generate 3D imaging for aquatic plant species identification (Mizuno et al., 2013; Xu et al., 2013; Mizuno and Asada, 2014). Optical videography proved to be of limited utility in the two-study lakes due to the limitations imposed by turbidity. In this study, the camera was mounted from the boat gunnel at a consistent depth of 20 cm below the surface. A towed optical camera with an adjustable depth or remote underwater vehicle mounted camera would reduce the proportion of the transect classified as 'unknown' in deeper waters where macrophytes were not visible. The DIDSON did however provide clear footage of the substratum, allowing easy distinction of macrophyte beds independent of turbidity at transect depths between 0.3 to 5 m (Fig. 3). Monitoring in depths of > 15 m would be achievable, however the area of insonified substrate is reduced in greater water depths as the mounting angle is increased to maintain sonar contact with the substrate. However, the price of purchasing a DIDSON, with a current market value of > \$90,000 AUD, would reduce the practicality of employing this method under most monitoring budgets, eliminating this technique as a 'cost-effective' methodology.

As a standalone technique, handheld PDA Trimble mapping did not prove to be an objective, repeatable methodology. Considerable divergence in onsite data collection was observed between field teams. The method does provide both qualitative and quantitative data, however it is significantly limited by turbidity and surface chop that reduce visibility. The method does however provide georeferenced

Table 2. Summary table identifying consideration when employing each macrophyte monitoring methodology.

Consideration	Method Trimble mapping – On site digitizing	Hydroacoustic 200 khz sonar	Hydroacoustic 800 khz downscan	Hydroacoustic 800 kHz side scan	Duel-frequency identification sonar (DIDSON)	Aireborn remote sensing (satelite imagery)	Optical videography
Turbidity	Turbidity dependent	Turbidity independent	Turbidity independent	Turbidity independent	Turbidity independent	Turbidity dependent	Turbidity dependent
Identifies species	Can identify species	Cannot distinguish between species	Cannot distinguish between species	Cannot distinguish between species	Cannot distinguish between species	Cannot distinguish between species; grond truthing data required	Can identify species
Macrophytes mapped	Submerged, emergent, floating	Submerged	Submerged	Submerged	Submerged	Submerged, emergent, floating	Submerged
Provides spatial distribution maps	Yes	Provides georeferenced transect data	Provides georeferenced transect data	Yes	Provides georeferenced transect data	Yes	Provides georeferenced transect data
Consistency of data collection between field operators	High variation	Minimal variation	Minimal variation	Minimal variation	Minimal variation	N/A	Minimal variation
Consistency of data processing between interpretors	N/A	Minimal variation	Minimal variation	High variation	Minimal variation	Minimal variation	Minimal variation
Data collection time	Highly dependent upon macrophyte abundance	Independent of macrophyte abundance	Independent of macrophyte abundance	Independent of macrophyte abundance	Independent of macrophyte abundance required	No field data collection required	Independent of macrophyte abundance
Post-data collection processing	Minimal	Moderate	Moderate	High	High	Moderate	High
Equipment expenses	High	Moderate	Moderate	Modeate	Very high	Nill	Low
Identifies depth of macrophyte growth	No	Yes	Yes	No	No	No	No
Identifies percentage of water column occupied by macrophytes	No	Yes	Yes	No	No	No	No
Other	Visibility of macrophytes during on site digitising is highly dependent upon turbidity and surface conditions at the time of sampling	Sonar may not penetrate through dense macrophytes resulting in lost Can be difficult to run boat transects through dense macrophyte due to fouling of boat propellor False macrophyte detections can result from submerged tree branches and other debris	Sonar may not penetrate through dense macrophytes resulting in lost Can be difficult to run boat transects through dense macrophyte due to fouling of boat propellor	Identifying macrophyte beds from sidescan imagery can be difficult without ground truting data Sidescan sonar in some instances may not penetrate through dense surface-to-substrate macrophyte beds, therefore only indicating near edge macrophytes boundaries, not full spatial extents	Can be difficult to run boat transects through dense macrophyte due to fouling of boat propellor	Temporal availability of cloud free satelite imagery may be restrictive	Can be difficult to run boat transects through dense macrophyte due to fouling of boat propellor

ground truthing data and allows for species identification, complementing the more spatially accurate and highly repeatable hydroacoustic 200 kHz sonar and 800 kHz downscan techniques.

Digitising macrophytes from airborne remotely sensed imagery provides the most cost-effective means to monitor macrophyte distribution over large spatial scales. No field data collection is required and high-resolution satellite imagery is available through a number of commercial sources. Airborne remotely sensed imagery provides a means to monitoring not only submerged macrophytes but also floating and emergent macrophytes. However, the monitoring of submerged macrophytes is turbidity dependent and ground truthing is required for discrimination between species.

This study outlines important considerations when selecting a methodology to be implemented in macrophyte monitoring studies (Tab. 2). Results indicate that no one specific method can be employed across all macrophyte-monitoring studies. The method or combination of methods employed during macrophyte monitoring studies will be dependent upon the study objectives, budget and environmental conditions of the study site. Significant limitations were identified for all monitoring techniques assessed. However, these limitations may be of little concern depending upon the study objectives or can be overcome by implementing complementary methodologies. When species identity is important, such as when monitoring invasive aquatic vegetation, a combination of air-borne remote sensing and PDA Trimble mapping for species identification would provide an effective technique. However, when macrophyte PAC is the primary metric of interest, line transect hydroacoustic techniques including 200 kHz sonar and 800 kHz downscan sonar or DIDSON are the most applicable across a range of turbidities.

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