UNIVERSITÉ DU QUÉBEC À TROIS-RIVIÈRES

ÉVALUATION D'UN SYSTÈME DE TÉLÉMÉTRIE ACOUSTIQUE POUR LE SUIVI DES POISSONS SOUS DIFFÉRENTES CONDITIONS ENVIRONNEMENTALES

MÉMOIRE PRÉSENTÉ
COMME EXIGENCE PARTIELLE
DE LA MAÎTRISE EN SCIENCES DE L'ENVIRONNEMENT

PAR
VICKIE LAPOINTE

DÉCEMBRE 2021

REMERCIEMENTS

Je voudrais dans un premier temps, remercier mon directeur de maîtrise M. Pierre Magnan pour m'avoir donné l'opportunité de vivre une expérience de recherche riche en savoir. Je le remercie de m'avoir encadré. Ses conseils et son mentorat m'ont permis de développer plusieurs de mes compétences personnelles. Je tiens à remercier également mon codirecteur, M. Denis Leroux, pour sa disponibilité et pour ses judicieux conseils, qui ont contribué à alimenter mes réflexions tout au long du projet. Je remercie M. Marc Pépino pour son aide tant au niveau de la réalisation des travaux sur le terrain que lors des analyses statistiques. Sa rigueur et son professionnalisme auront contribué à bonifier mon projet. Je remercie M. Andrea Bertolo pour son aide précieuse dans l'élaboration des cartes de végétation du lac Ledoux. Je remercie également M. Pierre-André Bordeleau pour l'aide précieuse apportée au sein du projet tant au niveau des relevées sur le terrain qu'au niveau du pré-traitement des données de base. Merci aux membres de mon laboratoire Vincent Rainville, Matteo Giacomazzo, Riwan Leroux, Alexandre East, Antoine Fillion, Benjamin Gosselin et Olivier Chouinard pour leur aide précieuse durant les travaux terrain ainsi qu'au laboratoire. Merci à mes parents Paul Lapointe et Linda Charrette ainsi qu'à mes deux frères Patrick Proteau et Steve Lapointe pour leurs encouragements et leur soutien moral tout au long de ce cheminement. J'ai bénéficié du support financier de la Chaire de recherche du Canada en écologie des eaux douces (P. Magnan) ainsi que du programme FONCER-CRSNG Écolac pour la réalisation de ce projet.

AVANT-PROPOS

Mon projet de recherche a été supervisé par le professeur Pierre Magnan et cosupervisé par le professeur Denis Leroux, dans le cadre du programme de maîtrise en sciences de l'environnement de l'Université du Québec à Trois-Rivières. L'objectif du projet a été d'évaluer la performance d'un système hydroacoustique pour le suivi de poissons sous différentes conditions environnementales. Pour ce faire, nous avons utilisé un système de télémétrie acoustique composé d'émetteurs témoins et de receveurs installés dans un lac du Bouclier canadien afin de valider la performance de celui-ci en fonction de la profondeur et de la végétation aquatique. Ce mémoire est constitué de trois chapitres : le premier chapitre (Introduction) présente la problématique, les bases théoriques de la télémétrie acoustique, le projet ainsi que ses objectifs spécifiques. Le chapitre II, rédigé sous forme d'article scientifique, décrit le travail de recherche effectué. Il est rédigé en anglais et sera soumis à la revue *Animal Biotelemetry*. Enfin, le troisième chapitre (Conclusion) présente les principaux résultats du projet ainsi que les perspectives futures.

RÉSUMÉ

Notre capacité à suivre les organismes aquatiques dans leur environnement, notamment l'échelle, la précision et la fréquence à laquelle leur localisation peut être enregistrée, a grandement favorisé les développements récents de la télémétrie acoustique. Cependant, une meilleure connaissance de l'impact des facteurs environnementaux comme la bathymétrie et la végétation aquatique est essentielle pour comprendre les différences de performance de ces technologies au sein des systèmes d'étude. Le but de cette étude était d'évaluer la performance du système de positionnement VEMCO à haute résidence (angl. : High Residence Receiver 2- Vemco Positioning System : HR2-VPS) dans un petit lac du Bouclier canadien afin d'estimer la variabilité spatiale et temporelle des erreurs de positionnement et du pourcentage de détection des signaux dans des conditions variables de bathymétrie et de végétation aquatique. Nous avons effectué une série d'essais stationnaires et mobiles avec des émetteurs HR2 et avons comparé leur position calculée par le VPS avec celle d'un dGPS à haute résolution (erreur 60 cm). Pour les essais stationnaires, la moyenne de l'erreur de positionnement était de 4,67 ± 11,20 m en août 2017 comparativement à 1,22 ± 0,80 m en juin 2018, tandis que celle des essais en mouvement, était de 5,62 ± 2,42 m en août 2017 comparativement à 1,36 ± 0,51 m en juin 2018. Pour les essais stationnaires, le pourcentage moyen de détection des signaux était de 89,05 ± 24,9 % en août 2017 comparativement à 77,94 ± 28,8 % en juin 2018, tandis que celui des essais en mouvement était de 73,51 ± 22,92 % en août 2017 comparativement à 71,08 ± 22,42 % en juin 2018. Les résultats ont également mis en évidence que la profondeur affecte principalement l'erreur de positionnement tandis que la végétation aquatique affecte principalement la détection des signaux. Le HR2-VPS a fourni de bonnes estimations des positions des émetteurs avec des erreurs de positionnement moyennes entre 1,22 et 4,67 m en 2018 et 2017 respectivement, et des pourcentages de détection de signaux généralement supérieurs à 90 % les deux années. L'impact démontré de la végétation et de la profondeur sur les erreurs de positionnement et le pourcentage de détection indique que les variations spatiales et temporelles de la qualité du positionnement des poissons doivent être prises en compte dans les études utilisant des systèmes de télémétrie acoustique comparables à celui utilisé dans notre étude.

Mots-clés : Système de télémétrie acoustique, récepteurs, émetteurs, pourcentage de détection, erreur de positionnement, bathymétrie, végétation aquatique

TABLE DES MATIÈRES

CHAPITRE I

INTRODUCTION

De nombreuses études s'intéressent au suivi des déplacements des animaux pour comprendre leur comportement (Cooke et al. 2004; Cooke et al. 2013; Hawley et al. 2016). Ces études vont porter entre autres sur les mouvements et les migrations (Heupel et al. 2015), l'alimentation des espèces (Semmens et al. 2013), la densité d'une population (Murphy et al. 2019) ainsi que la relation entre les habitats et la répartition des individus (Farmer et al. 2018). Les résultats découlant de ces études permettent souvent de mettre en place des actions de conservation efficaces pour les espèces étudiées (McGowan et al. 2017). Différentes techniques peuvent être employées pour effectuer la localisation et le suivi des animaux. La radiotélémétrie est une technologie qui a permis d'accroître notre compréhension des mouvements des animaux, tant terrestres qu'aquatiques (McGowan et al. 2017). Cette approche requière l'installation d'émetteurs sur des animaux (ou dans leur cavité abdominale) et de localiser leurs positions à l'aide d'un receveur muni d'antennes directionnelles qui sont d'une portée limitée (Winter, 1983) Il est donc nécessaire de faire un suivi des animaux pour être à portée de détection (ex. : en hélicoptère ou en bateau), ce qui nécessite une intervention humaine. Les signaux d'émetteurs radiotélémétriques plus évolués peuvent aujourd'hui être captés par des satellites et retransmis directement au laboratoire (Perras et Nebel, 2012), mais cette technologie n'est pas opérationnelle en milieu aquatique parce que la densité de l'eau ne permet pas au signal de se rendre dans l'atmosphère. La télémétrie acoustique quant à elle, se réalise spécifiquement en milieu aquatique. Cette technologie permet d'obtenir la position d'un animal et certaines informations de son environnement (ex. température ambiante) sans intervention humaine active. La télémétrie acoustique se réalise à l'aide d'un système composé d'émetteurs et de récepteurs. Les émetteurs sont implantés à l'animal et émettent une onde acoustique dans un intervalle de temps donné. Les récepteurs quant à eux captent les signaux des émetteurs et les enregistrent sans manipulation humaine (Karp 2014; Huveneers et al. 2016). Lorsque plusieurs récepteurs captent le signal de l'émetteur, il devient alors possible d'obtenir la position de celui-ci par multilatération. Cette technique est utilisée pour positionner la source d'un signal en fonction des différences de temps d'arrivée de celui-ci aux récepteurs, qui eux sont en positions connues (Smith et al. 2000). Étant donné que la vitesse de propagation de l'onde acoustique est connue, il devient alors possible de comparer les temps d'arrivées d'un même signal enregistrés sur plusieurs récepteurs afin de calculer une position. Les chercheurs peuvent donc implanter des émetteurs dans plusieurs animaux et déployer de nombreux récepteurs sur de grandes étendues pour faire le suivi des déplacements des individus. La télémétrie acoustique est devenue aujourd'hui un outil standard dans les applications aquatiques (Huveneers et al. 2016). Cependant, la performance d'un système de télémétrie acoustique n'est pas universelle et une validation doit être réalisée au début de chaque étude (Roy et al. 2014). Pour déterminer la performance d'un système de télémétrie acoustique, plusieurs paramètres doivent faire l'objet d'une évaluation.

Premièrement, la variabilité spatio-temporelle de la détection du signal doit être évaluée, c'est-à-dire le pourcentage de signaux émis qui sont reçus. Cette dernière doit être calculée en fonction de chaque récepteur pour comprendre l'ampleur de la détection des signaux dans l'espace. Le pourcentage de détection sera moindre pour un récepteur lorsque l'onde acoustique n'est pas captée par celui-ci. La variabilité spatio-temporelle des erreurs de positionnement est également une composante importante à déterminer lors de l'évaluation de la performance d'un système de télémétrie acoustique. L'erreur de positionnement représente l'amplitude de l'erreur sur les positions calculées par le système de télémétrie acoustique. Cette erreur est déterminée en fonction de la précision du positionnement. Elle représente l'écart entre la position calculée et la position réelle. Cette dernière, qui peut être estimée à l'aide d'un GPS de grande précision (ex. dGPS), permettra d'établir l'erreur de positionnement.

L'impact de la structure de l'habitat sur la performance du système de télémétrie acoustique a été très peu documenté à ce jour (Kessel et al. 2014; Baktoft et al. 2015). La détection du signal ainsi que les erreurs de positionnement peuvent différer selon plusieurs facteurs comme la configuration du système de télémétrie acoustique (c.-à-d. position des receveurs dans l'espace), la bathymétrie, la végétation aquatique, les conditions thermiques de l'eau et les conditions météorologiques (Roy et al. 2014; Gjelland et Hedger 2013; Huveneers et al. 2016).

Selon plusieurs études, la configuration des récepteurs peut avoir un impact sur la performance du système de télémétrie acoustique. Plusieurs récepteurs doivent couvrir une même zone pour une meilleure précision au niveau du positionnement (VEMCO, 2018). Si une zone est couverte par moins de trois récepteurs les positions seront moins précises puisque l'écart entre la position réelle et la position calculée sera plus grand étant donné le faible nombre de récepteurs ayant reçu le signal. La bathymétrie joue un rôle crucial dans la performance d'un système de télémétrie acoustique. En effet, les formes géomorphologiques d'un lac peuvent agir comme des barrières physiques à la propagation de l'onde entre l'émetteur et les récepteurs (Roy et al. 2014). Les différentes structures de l'habitat comme les hauts fonds ainsi que les zones littorales peuvent agir comme des barrières ou réflecteurs de l'onde émise par l'émetteur. Ainsi, un signal émis en zone plus profonde et centrale permet une propagation adéquate des ondes acoustiques vers les récepteurs. À l'inverse, la zone littorale, peu profonde comporte souvent plusieurs obstacles (ex. : arbres morts, rochers) à une bonne propagation de l'onde acoustique jusqu'aux récepteurs. Si les ondes acoustiques ne se rendent pas aux récepteurs, le pourcentage de détection diminuera et les erreurs de positionnement augmenteront dû aux faibles nombres de récepteurs recevant l'onde acoustique. Très peu d'études ont à ce jour évalué l'effet de la végétation aquatique sur la performance d'un système de télémétrie acoustique (Baktoft et al. 2015; Espinoza et al. 2021; Weinz et al. 2011). Les plantes aquatiques sont présentes dans de nombreux lacs lors de la période estivale. Elles peuvent influencer la détection du signal en agissant comme une barrière physique à la propagation de l'onde, empêchant ainsi une transmission adéquate du signal de l'émetteur vers le récepteur (Gjelland et Hedger 2013). La végétation aquatique peut également influencer la précision du positionnement en empêchant des récepteurs de recevoir adéquatement le signal, réduisant le nombre de récepteurs détectant le même signal et résultant en une augmentation de l'erreur de positionnement. Enfin, les conditions thermiques de l'eau peuvent aussi avoir un impact sur la performance d'un système de télémétrie acoustique (Gjelland et Hedger 2013). La vitesse de propagation de l'onde acoustique dépend de la densité de l'eau. Une eau plus froide aura tendance à être plus dense et l'onde acoustique sera plus lentement dirigée vers le récepteur. À l'inverse, une eau chaude favorisera la propagation de l'onde acoustique. En période de stratification, un lac affiche un gradient thermique. La propagation de l'onde sera donc influencée par la strate thermique dans laquelle elle se trouve. Si l'émission se fait dans une strate thermique froide du lac, cela influencera le temps d'arrivée de l'onde jusqu'au récepteur et donc la précision du positionnement. De plus, si l'onde ne se rend pas au récepteur dû à une trop grande densité de l'eau, certains récepteurs ne recevront pas le signal émis par l'émetteur, ce qui influencera le pourcentage de détection. Enfin, la force et la direction des vents ainsi que les précipitations peuvent causer du mouvement des eaux de surface. Les récepteurs situés dans ces zones seront donc plus affectés par les mouvements des eaux de surface causés par les mauvaises conditions météorologiques (Huveneers et al. 2016; Gjelland et Hedger 2013). Les récepteurs peuvent ainsi se déplacer dus aux intempéries et ne pas recevoir l'onde acoustique émise par les émetteurs ou la recevoir dans des délais plus longs.

1.1 Problématique

Les systèmes de télémétrie acoustique sont de plus en plus utilisés pour les études comportementales chez les poissons. Cependant, dans ces études, la performance des systèmes de positionnement est cruciale puisque l'amplitude des erreurs de positionnement peut être du même ordre de grandeur que les phénomènes biologiques étudiés (ex. mouvements et comportements de deux écotypes de poissons). Étant donné que le système de télémétrie acoustique utilisé dans ce projet vise à étudier des patrons de déplacement de poissons à fines échelles spatio-temporelles, les erreurs de positionnement doivent donc être connues. Dans le présent projet, la bathymétrie et la végétation aquatique sont les deux plus grands facteurs qui risquent d'affecter la performance du système de télémétrie acoustique dans le site à l'étude. Les effets de ces deux facteurs sur la détection du signal et l'erreur de positionnement feront donc l'objet d'une investigation dans ce mémoire.

1.2 Objectif du projet

Ce programme de recherche a pour but d'évaluer la performance du système de télémétrie acoustique HR2 de la compagnie VEMCO Ltd. (Bedford, Nouvelle-Écosse, Canada; angl. : High Residence Receiver 2- Vemco Positioning System : HR2-VPS) afin de vérifier la validité des données recueillies à l'aide de cette technologie. L'erreur de positionnement (précision et biais) ainsi que la variabilité de la détection du signal seront quantifiées en fonction de la bathymétrie et de la végétation aquatique dans un lac du Bouclier canadien.

CHAPITRE II

PERFORMANCE OF THE HR2 VEMCO POSITIONING SYSTEM UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

Vickie Lapointe, Marc Pépino, Andrea Bertolo, Denis Leroux and Pierre Magnan

Research Centre for Watershed - Aquatic Ecosystem Interactions Université du Québec à Trois-Rivières, C. P. 500, Trois-Rivières, Québec, G9A 5H7 Canada

Corresponding author: Pierre.Magnan@uqtr.ca

ABSTRACT

Background: Our ability to track aquatic organisms in their environment, including the scale, the accuracy and the frequency at which their location can be recorded, was greatly enhanced due to recent developments in acoustic telemetry. However, a better knowledge of the impact of environmental factors like bathymetry and aquatic vegetation is essential to better understand the differences in performance between and within the systems studied. The aim of this study is to evaluate the performance of the high residence 2 VEMCO positioning system (HR2-VPS) in a small Canadian Shield Lake, in order to estimate the spatial and temporal variability of positioning errors and signal detection under variable conditions of bathymetry and aquatic vegetation. We conducted a series of stationary and moving trials with HR2-tags and compared their position calculated by the HR2-VPS with that of a high-resolution differential GPS (dGPS).

Results: For the stationary trials, the average of positioning error was 4.67 ± 11.20 m (± standard deviation) in August 2017 compared to 1.22 ± 0.80 m in June 2018, while for the moving trials, the average positioning error was 5.62 ± 2.42 m in August 2017 compared to 1.36 ± 0.51 m in June 2018. For the stationary trials, the average of percent of signal detection was 89.05 ± 24.9% in August 2017 compared to 77.94 ± 28.8% in June 2018, while for the moving trials, the average percent of signal detection was 73.51 ± 22.92% in August 2017 compared to 71.08 ± 22.42% in June 2018. The results also highlighted that depth mainly affect the positioning error while the aquatic vegetation mainly affect the signal detection.

Conclusion: The HR2-VPS provided good estimates of the tag positions with average positioning errors between 1.22 and 4.67 m in 2018 and 2017 respectively, and percent of signal detection generally higher than 90% in both years. However, our study highlights that depth and presence of aquatic vegetation can impair both the positioning errors and percent of signal detection. This indicates that spatial and temporal variations in the quality of fish positioning should be considered in studies using comparable acoustic telemetry systems.

BACKGROUND

Recent developments in acoustic telemetry have greatly improved our ability to track aquatic organisms in their environment, including the scale, the accuracy and the frequency at which their location can be recorded (1, 2, 41). These systems are composed of transmitters and receivers. The transmitters (commonly referred to "tags") are implanted into the animal and emit an acoustic wave in a given time interval while the receivers are anchored at regular intervals in an ecosystem, in a way that their detection range overlaps (9, 10, 41). When several receivers detect the signal from a transmitter, it becomes possible to compare the arrival times of the same signal recorded on these receivers and to calculate the position of the source by multilateration (20, 23, 41). Another advantage of this technique over radio telemetry systems is that it does not require a real time human intervention because the data are recorded by the receivers and can be downloaded periodically.

VEMCO has developed an acoustic telemetry positioning system (VPS) based on a pulse-position modulation (PPM) coding (at 69 and 180 kHz; VEMCO Ltd., Bedford, Nova Scotia, Canada; 20, 23). In the first generation of the VPS system, the PPM tags required few seconds to transmit with a receiver having to detect all the transmission pulses, without interference from other tags, to decode the tag identification (32, 41). It is then possible that the transmissions of two or more tags collide and not be detected by a receiver. In this context, the transmission delay must be set to keep the collision rates as low as possible, which is for these PPM a period that exceed 1 min or more, thus limiting the temporal resolution of positioning and/or the number of organisms that can be tracked (41).

VEMCO recently upgraded its VPS system with high residence (HR) tags and receivers capable of monitoring organisms at a temporal resolution < 1 s and thus allowing more tags to be used at the same time with higher temporal resolution compared to PPM tags. Guzzo et al. (2018) found that HR-VPS can provide more representative estimates of movement metrics than the PPM-VPS system but that a better knowledge of the impact of environmental factors like bathymetry and aquatic vegetation is essential to understand the differences in the performance of these system among and within study systems.

The bathymetry can have a great influence on wave propagation in acting as a physical obstacle to the propagation of the wave between the transmitter and receivers (13). Thedeep and central zones of a lake allow for adequate propagation of the acoustic waves to the receivers due to the absence of obstacles. Conversely, the littoral zones are composed of several obstacles (e.g. rocks, submersed trees, landscape architecture) that can hinder the propagation of the acoustic wave to the receivers. If the acoustic waves do not reach the receivers, the efficiency of signal detection will decrease and the positioning errors will increase due to the small number of receivers detecting the acoustic wave. Submerged aquatic vegetation are present in many lakes during the summer period and can also act as barriers to the propagation of the acoustic wave (6). To date, very few evaluated the effect of bathymetry and aquatic vegetation on the performance of an acoustic telemetry system (1, 40, 41, 42).

The purpose of this study is to evaluate the performance of the HR2-VPS acoustic telemetry positioning system in a small Canadian Shield Lake in order to evaluate the spatial and temporal variability of the signal detection and positioning errors under variable conditions of bathymetry and submersed aquatic vegetation. We conducted a series of stationary and moving trials where we compared the position of the HR-tags calculated by the VPS with that of a high-resolution dGPS system.

METHODS

Study lake and acoustic telemetry system

The study was done in Lake Ledoux, Mastigouche Wildlife Reserve, Québec, Canada (46º48 '08"N, 73º16 '38"W). Lake Ledoux is a typical small oligotrophic temperate zone lake with respect to surface area (11.9 ha), mean depth (5.5 m), maximum depth (17.0 m), and general physicochemical characteristics (14). Brook charr is the only fish species in the lake and sport fishing is rigorously controlled by the Québec Government. The lake was closed to fishing for the duration of the study.

The acoustic telemetry positioning system (HR2 180kHz) used in the present study was from VEMCO Ltd. (Bedford, Nova Scotia, Canada Canada). The number of receivers (23) as well as their distribution in the lake were determined by VEMCO to ensure maximum coverage of the different areas of the lake for high positioning accuracy (Figure 1). The average distance between the receivers was 113.15 m (range: 52 m to 206 m) and their average depth was 2.14 m (range: 0.8 m to 4.2 m). According to VEMCO the depth of a receiver should be as much as possible in the middle of the water column. The control transmitters (V9TP-180 kHz) used for this study had a transmission frequency of 1 second on average (random transmission: between 0.9-1.1sec). The raw data recorded by the receivers were processed by VEMCO into 2D positions using hyperbolic positioning algorithms based on time difference of arrival for each acoustic transmission detected by three or more receivers in the array (20).

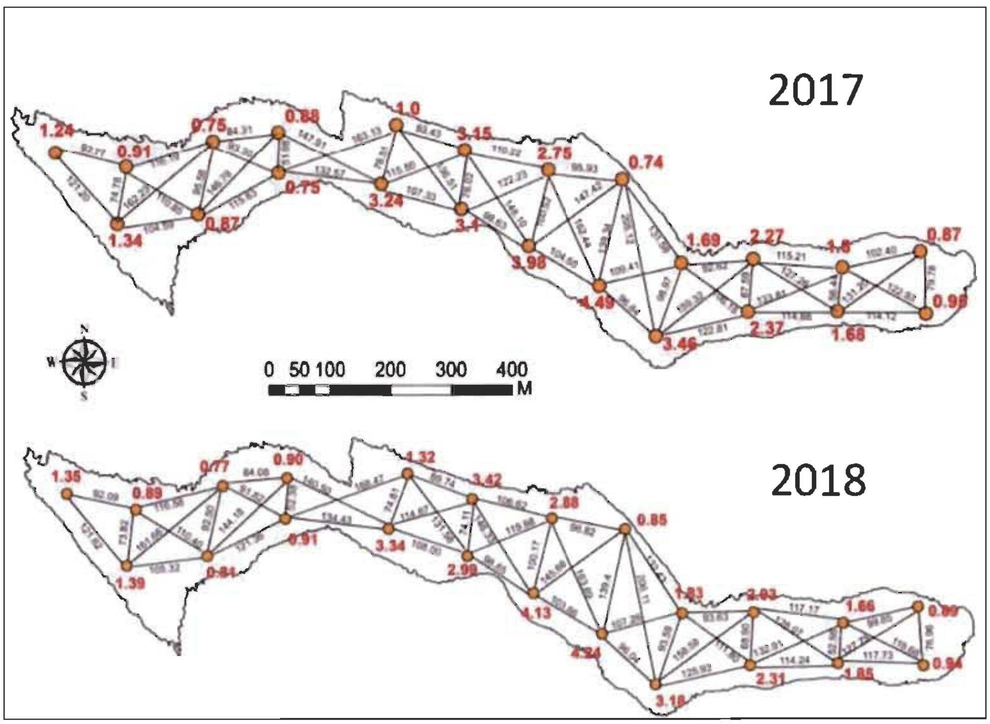


Figure 1 : Distribution of the receivers in Lake Ledoux in 2017 and 2018. Orange dots: receivers; Red numbers: receiver depths (m); black lines: distance between the receivers (m).

Stationary and moving trials

Stationary and moving trials were performed on 5 July, 16 and 17 August 2017 and 5, 6 and 7 June 2018 to estimate the position errors and the percent of signal detection. The actual (georeferenced) position of the transmitters was measured every second by a dGPS (GENEQ inc., model Sx-Blue) using the tracklog function. The DGPS used in this study has an average error of 60cm. For the stationary trials, the transmitters were located under a floating raft anchored to the bottom, with the dGPS on top of the of the raft, aligned vertically with the transmitter. A total of 17 geo-referenced fixed stations were positioned to cover the different areas of the lake (Additional file 1). Data were collected for 10 minutes at each station. For the moving trials, the floating raft was pulled at a constant speed by a rowboat along different patterns. There was a weight at the end of the rope to make sure the transmitter was aligned with the DGPS. First, three transects were done at the deepest area of the lake with transmitters located at 1 m, 3 m, 5 m and 7 m depth (Additional file 1). Second, the littoral zone was covered with transmitters at 0.5 m and 1 m-depth (Additional file 1). Third, the whole lake was covered by making a continuous zigzag transect with transmitters at 0.5 m and 1m-depth, to simulate the fish movement (Additional file 1), a standard procedure to evaluate the performance of acoustic telemetry systems (16, 41).

Positioning errors

We define the position error as the difference between the position of HR2-tags estimated by the VPS with that of the high-resolution dGPS. For the stationary trials, we compared the average center of the distribution of points estimated from the VPS to that of the georeferenced dGPS point of the corresponding station. For the moving trials, we compared the VPS and the dGPS tracks by computing the difference in meters of each corresponding point by time stamps. First, the VPS and the dGPS database were synchronised in the same time zone using the temporal functions in ArcGIS Pro. A temporal association was then made between the two tracks using the dGPS and VEMCO time stamps. This allowed to link each of the VEMCO points to its corresponding dGPS point in time. Then using Cartesian coordinates and the Pythagorean formula, a distance in meters between the position of HR2-tags and that of the dGPS could be calculated for each paired point. An interpolation model was applied to the distance data (m) to create a map of error magnitude for the entire lake. The interpolation model (simple kriging; cell size = 10 m; neighborhood = min: 20 max:25) was run using ArcGIS Desktop 10.0. Kriging was selected since it provides an accurate prediction surface. In addition, it allows to predict the uncertainty of the model. It was important to obtain an accurate prediction when performing the interpolation since one of the objectives of the study was to produce an error map of the entire lake. To ensure the reliability of the data, the cross-validation of the model was performed; by combining the result of RMS and means included in the cross-validation, the accuracy as well as the bias of the model is known. The standardized RMS was 0.88 m in 2017 and 0.85 m in 2018. The standardized means was -0,009 m in 2017 and -0,003 m in 2018.

Percent of signal detection

For the stationary trials, the percent of detection was calculated according to the residence time versus the number of points emitted by the VPS. For the moving trials, the entire lake has been subdivided into a 10x10 m pixel matrix. As the raft was moving along a transect, a variable number of points were detected from the VPS within a given 10 m x10 m pixel. With the help of the dGPS track, it was possible to determine the time of entry of a signal into the pixel and the time of its exit. Then, knowing the exact residence time of the signal into a pixel and the transmission frequency of the control transmitter, a percent of signal detection could be calculated for each pixel. An interpolation model (simple kriging; cell size = 10 m; neighborhood = min: 20 max: 25) was applied to the detection data in order to extend the results over the entire lake in the same way than for the positioning errors. A similar cross-validation of the model was also performed to ensure the reliability of the interpolation. The standardized RMS was 0.96% in 2017 and 0.98% in 2018. The standardized means was 0.02% in 2017 and 0.01% in 2018.

Bathymetry and aquatic vegetation

The bathymetry and submersed aquatic vegetation profiles were determined with a Biosonics DT-X echo sounder. The bathymetry was done by creating a digital elevation model (DEM) on ArcGIS 10.0 with 10 x 10 m pixels. Surveys were conducted on 23 August and 6 October 2017, and 2 June 2018 to determine the change in vegetation abundance during the summer season. For each survey, several transects were conducted to cover the entire lake (Additional file 2). The vegetation data were analyzed with software Visual habitat v2.0.3.9824, a data processing software provided by Biosonics. Visual habitat determines a background line (bottom of the lake) and a vegetation line. These lines are plotted according to an amplitude scale (dB) where a color is associated with each decibel. The assignment of an average value of this parameter allows the software to create an isoline. Once the isolines are determined, the software computes the difference between them to determine the density of aquatic vegetation found in the water column being detected. The software can interpret other structures (e.g. submerged trees, rocks) as vegetation. Therefore, a visual validation was performed to ensure the reliability of the data. The visual validation was based on the areas known by the experimenters. Some areas are more likely to have vegetation than other areas in the lake. The visual validation was based on the comparison of certain locations across the three sampling dates. Some structures were identical in the same transect and at the same location at the three sampling dates, so we concluded that these signals were not aquatic vegetation. The file was exported to ArcGIS 10.0 and an interpolation model (simple kriging; cell size = 10 m; neighborhood = min: 20 max: 25) was applied to the detection vegetation data in order to extend the results over the entire lake, in the same way than for the positioning errors and percent of signal detection. A cross-validation of the model was performed to ensure the reliability of the data. For the vegetation interpolation the standardized RMS was 0.94% in 2017 and 0.90% in 2018. The standardized means was -0,00% in 2017 and -0,00% in 2018.

Relationships among variables

To determine the effects of bathymetry and aquatic vegetation on the positioning error and signal detection we first computed Spearman correlations coefficient among these variables. With the help of the function join by location a geoprocessing function of ArcGIS Desktop 10.0 it was possible to link by location each 10 m x 10 m pixel of the interpolation models of each variable (bathymetry, aquatic vegetation, positioning error and percent of signal detection), and group them in the same database. We used the R statistical software to calculate the Spearman correlation coefficient between each variable (R Core Team 2018). Second, we compared visually the interpolation models to assess the effect bathymetry and aquatic vegetation on the positioning error and percent of signal detection, more specifically to each zone of the lake. In these analyses, we used the aquatic vegetation profiles of August 2017 and June 2018 to make the link with the positioning errors and percent of signal detection estimated in the same periods. A condition for Spearman's correlation is the independence of observations, what we do not meet when using interpolated data, which have strong spatial autocorrelation. In this context, the p-values are not valid and we used the Spearman's correlation coefficients on an indicative basis only.

RESULTS

Positioning errors

For the stationary trials, the average of positioning error was 4.67 m ± 11.20 in August 2017 compared to 1.22 m ± 0.80 in June 2018 (Figure 2). The distribution of positioning errors was lower in 2018 (range 0.22-2.81 m) than in 2017 (0.37-49.37 m) (Figure 2). The highest positioning error (49.37 m) was observed in the lake constriction (west bay) in 2017 (Figure 2).

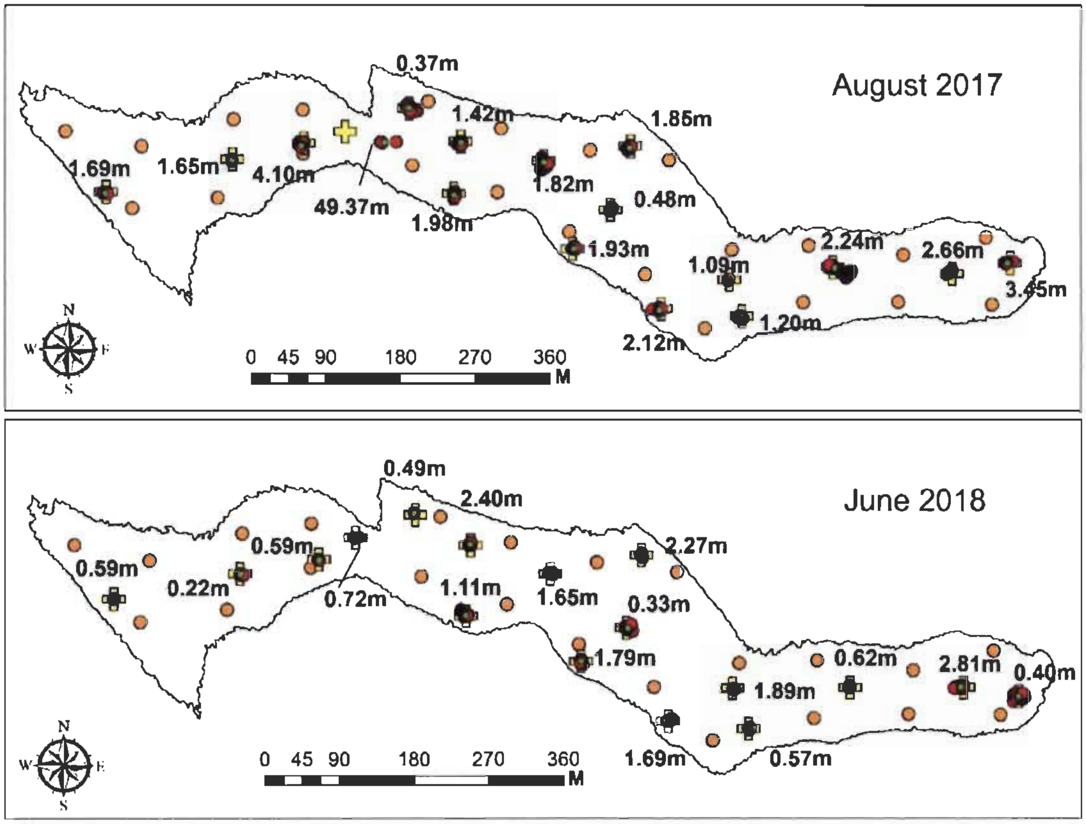


Figure 2. Positioning error for the stationary trials. Orange dot: receiver; red dot: control transmitters; green dot: mean center of VEMCO position; yellow cross: dGPS position.

For the moving trials, the average positioning error was 5.62 ± 2.42 in August 2017 compared to 1.36 ± 0.51 in June 2018 (Figure 3). The distribution of positioning errors estimated from the interpolation model was lower in 2018 (0.03-6.91 m) than in 2017 (0.20-18.90 m) (Figure 3). The positioning error was consistently higher in the constriction located in the west part of the lake with values between 16.01 m and 18.90 m in 2017 and between 6.19 m and 6.91 m in 2018 (Figure 3). The area with the lowest positioning errors was the west bay with values between 0.20 m and 6.00 m in 2017 and between 0.03 m and 4.64 m in 2018.

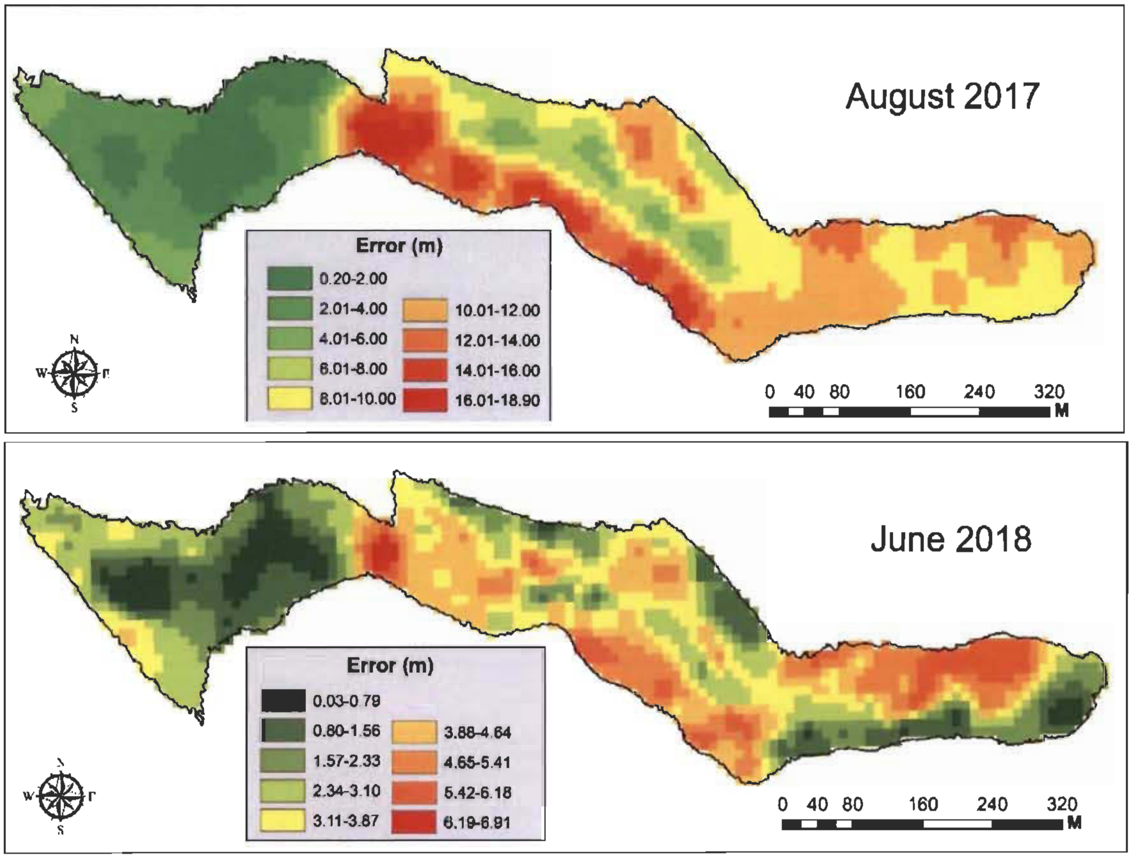


Figure 3: Interpolation model applied on the positioning errors of the VEMCO system, lake Ledoux. Representation on a 10 m x 10 m pixel. All test results from August 2017 and June 2018 were used for these results.

The positioning error, estimated for the moving tests, tended to be lower at 5 m and 7 m compared to 3 m, for 2017 and in 2018, the positioning error tended to be lower at 3m compared to 5m and 7m. (Table 1).

Table 1. Positioning error and percent of signal detection relative to depth in lake Ledoux, August 2017 and June 2018. Data are mean ± SD with sample size in parentheses.

Depth (m)	Positioning error (m)	Percent of signal (%)
	August 2017	
3	4.36 ± 1.12 (70)	94.13 ± 1.91 (74)
5	4.10 ± 1.31 (60)	94.42 ± 1.72 (66)
7	4.27 ± 1.14 (61)	94.38 ± 1.80 (69)
	June 2018	
3	1.26 ± 0.18 (41)	91.92 ± 5.48 (43)
5	1.40 ± 0.24 (45)	93.95 ± 3.84 (44)
7	1.38 ± 0.18 (46)	93.28 ± 5.35 (45)

Percent of signal detection

For the stationary trials, the average of percent of signal detection was 89.05 ± 24.9% in August 2017 compard to 77.94 ± 28.8% in June 2018 (Figure 4). The distribution of percent signal was lower in 2018 (0.33-100.8%) than in 2017 (3.0-101.34%) (Figure 4). The percent of signal detection was low for both years in the constriction located in the west part of the lake (Figure 4).

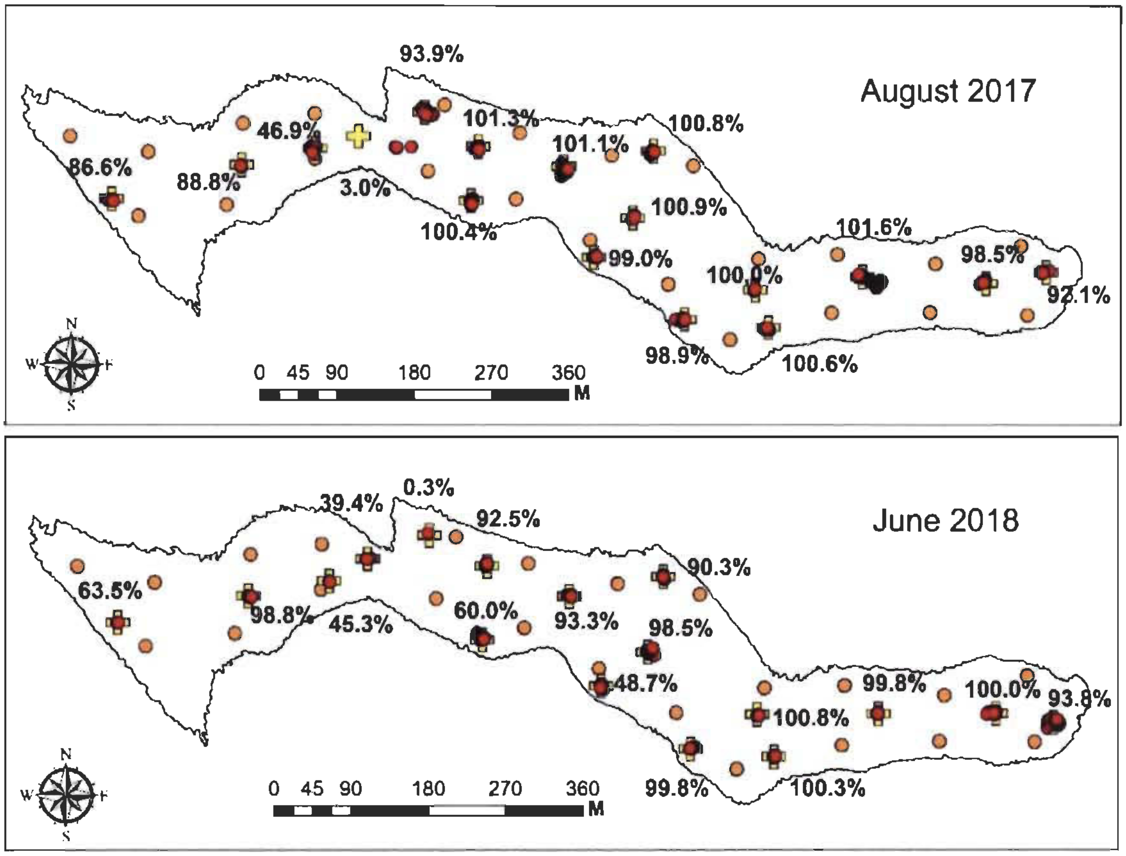


Figure 4. Percent of signal detection for the stationary trials. Orange dot: receiver; red dot:control transmitter; yellow cross: dGPS position. Note: The percent higher than 100% are due to a transmitter emission faster than 1 s.

For the moving trials, the average percent of signal detection was 73.51 ± 22.92 in August 2017 compared to 71.08 ± 22.42 in June 2018 (Figure 5). The percent of signal detection, estimated from the interpolation model is the lowest in the west bay and to some extent in the east bay of the lake, and highest in the central part of the lake (Figure 5).

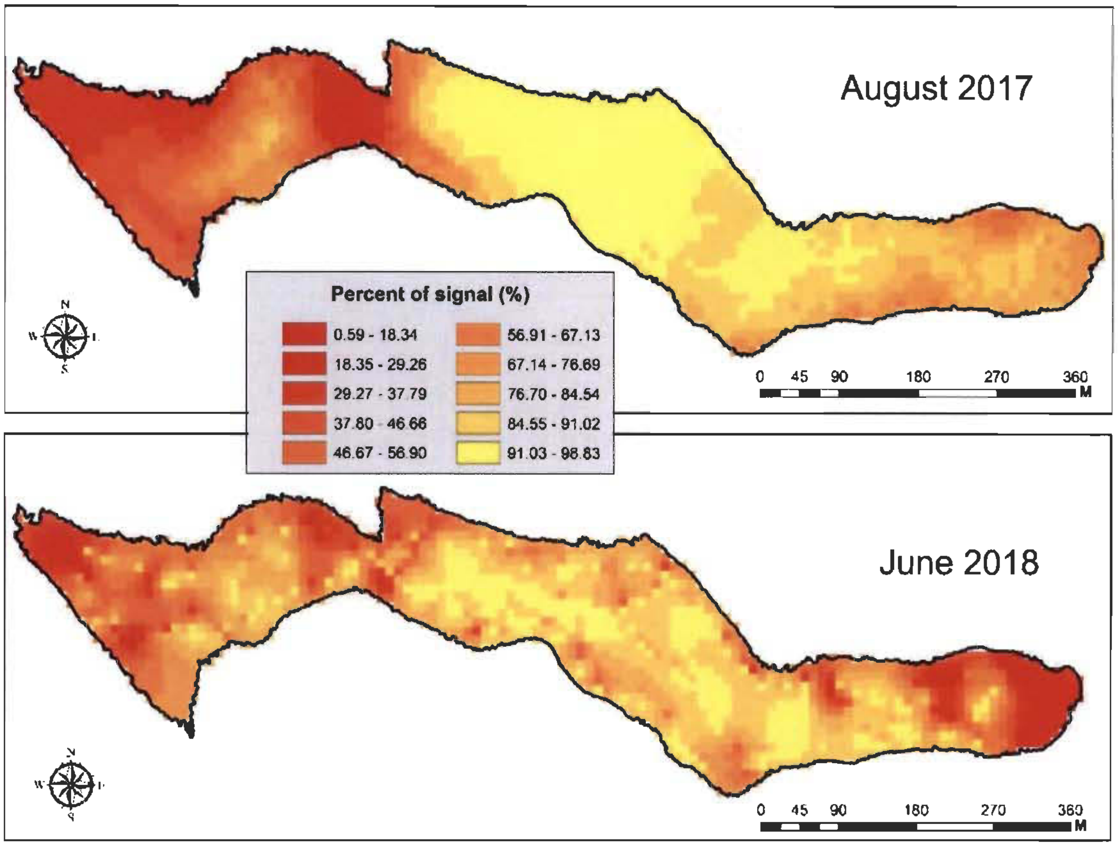


Figure 5. Interpolation model applied to the percent of signal detection from the VEMCO positioning system. Representation on a 10 m x 10 m pixel.

Effect of bathymetry and aquatic vegetation on the signal detection

High density of aquatic vegetation was correlated to both low positioning error and low percent of signal detection in 2017 and 2018 (Table 2). However, the density of aquatic vegetation was better correlated with percent signal detection (by twice) than with the positioning error (Table 2). In the same way, high depth was positively correlated to both positioning error and percent of signal detection (Table 2). The depth also tended to be better correlated with percent signal detection than with the positioning error in 2017 but not in 2018 (Table 2).

Table 2. Spearman correlation coefficients between the different variables in 2017 and 2018. Data are correlation coefficients with p value. The numbers in parentheses are the sample size.

	Positioning error		Signal detection	
Variables	**2017** (1614)	**2018** (1662)	**2017** (1614)	**2018** (1662)
Vegetation	-0.22 $p < 0.0001$	-0.22 $p < 0.0001$	-0.49 $p < 0.0001$	-0.45 $p < 0.0001$
Depth	0.33 $p < 0.0001$	0.34 $p < 0.0001$	0.51 $p < 0.0001$	0.44 $p < 0.0001$

Comparing the interpolation model applied on the density of aquatic vegetation (Figure 6) to those of positioning error (Figure 3) and percent of signal detection (Figure 5) highlight that depth mainly affect the positioning error and aquatic vegetation mainly affect the signal detection. These interpretations are based on the fact that the higher positioning errors were observed along the deepest escarpment, located on the southern shore in the central part of the lake, and in the constriction located in the west part of the lake, two areas where aquatic vegetation was absent (except in the constriction located in the west part of the lake in 2017; Figure 3 *vs.* Figure 6), and on the fact that the percent of signal detection better matches the density of aquatic vegetation (Figure 5 *vs.* Figure 6).

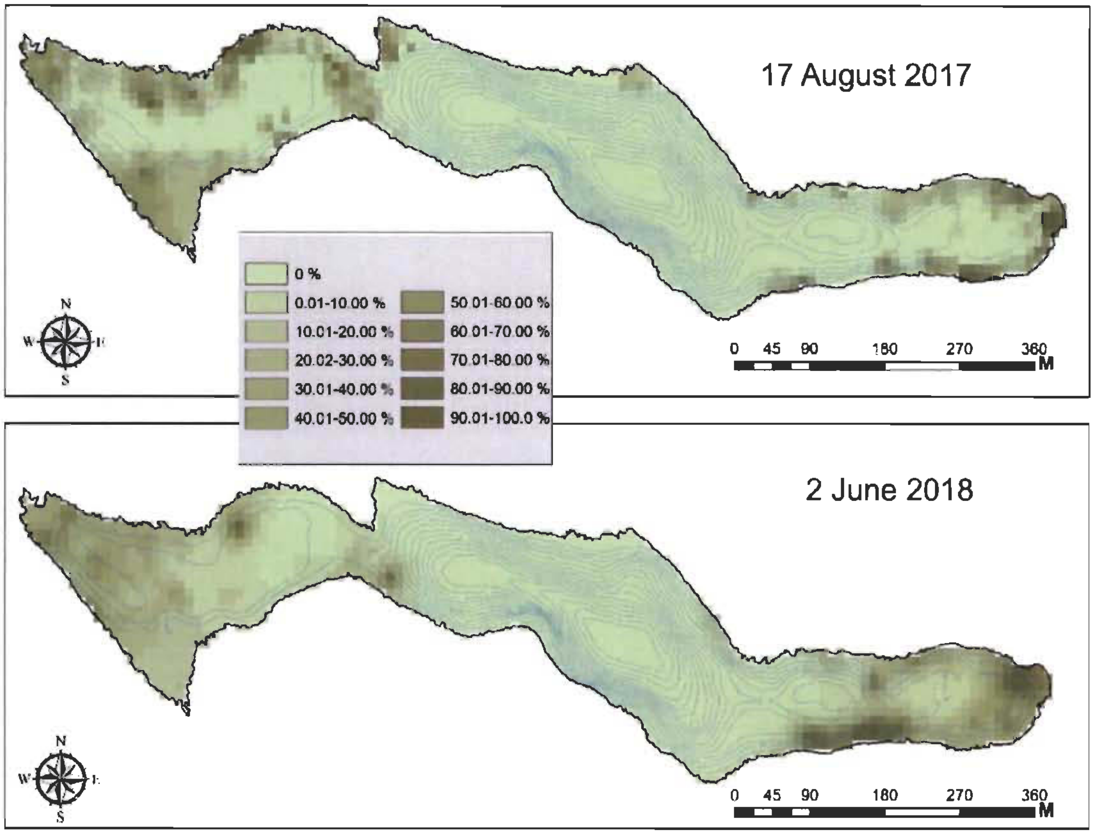


Figure 6. Interpolation model applied on the density of aquatic vegetation. Blue line: isobaths 1-m spaced.

DISCUSSION

The results of this study show that the HR2-VPS provided globally low positioning errors and high signal detections for both the stationary and moving trials, when comparing the tag positions estimated by the VEMCO system with those of dGPS. Furthermore, our results highlighted that depth mainly affect the positioning error while the aquatic vegetation mainly affect the signal detection.

Positioning error

The average positioning error varied between 1.22 ± 0.80 m and 4.67 ± 11.20 m for the stationary trials and between in 1.36 ± 0.51 m and 5.62 ± 2.42 m for the moving trials in the two years of the study. Guzzo et al. (2018), who evaluated a similar system (HR-VPS) in a 10 ha, shallow (mean depth 5 m) lake of Scotland, UK, found accuracy and precision estimates (median 5th-95th percentile) of 5.6 m (4.2-10.8 m) and 0.1 m (0.02-0.07 m), respectively, for stationary trials, and an average of ≈9 m for the moving trials. In their study the accuracy was estimated for stationary trials by calculating the distance in meters between the estimated position of the VEMCO system and those recorded by a GPS, by using the Pythagorean theorem. For the moving trials, the accuracy was evaluated as the distance between each estimated position and the median position of all estimated VEMCO system. On the other hand, they estimated the precision for the stationary trials by calculating the median position of all estimated VPS positions and calculating the distance of each position from this median position. For moving trials, a time-matched by the GPS and each position of VPS positions was compared to obtain the distance between both. Despite the slight differences in the way of computing the performance variables of the VPS, our estimate of positioning errors are in the same order of magnitude than those of Guzzo et al. (2018) for the stationary trials (positioning errors between 1.22-4.65 m in our study *vs.* an accuracy of 5.6 m in Guzzo et al. 2015) and lower for the moving trials (positioning errors between 1.36-5.62 m in our study *vs.* an accuracy of ≈9 m in Guzzo et al. 2015).

The positioning error were consistently higher in the constriction located in the west part of the lake, in the two years of the study. In this area, the receivers were farthest apart. Moreover, the number of receivers used to calculate the positions in this zone three was on average compared to four in the rest of the lake. Furthermore, this area is shallow (≤ 2 m) and low depth were associated to higher positioning errors. Finally, this area exhibited higher vegetation density, that was associated to lower signal detection, which in turn affect the positioning errors (see section on the effects of bathymetry and aquatic vegetation, below). The positioning errors were also higher on the southern shore in the central part of the lake. These results cannot be explained by the presence of aquatic vegetation and the shallow depths, because this area correspond to a deep, rocky area with a steep slope, without aquatic vegetation. Furthermore, this area is located along a high cliff. The dGPS signal could have been of lower quality due to the cliff, impairing the tags positioning in this area. The positioning errors were very small in the west bay, in the two years of the study. This result is unexpected because this area is shallow (≤ 2 m) and contained high vegetation densities. However, the receivers were positioned at a similar depth, the average distance among them was lower and they covered uniformly the area, compared to other areas of the lake. In addition, the transmitters and the receivers are always in the same vertical plane in the western bay, which is not the case in the other areas of the lake. There could also be a combined effect of the thermocline which can play a role on the propagation of the signal in the water (7). Guzzo et al. (2018) explained that the accuracy and the precision of the VEMCO system positions may differ depending on the location of the tags and the receivers. These authors suggested that it would be useful to test the system under different environmental conditions (bathymetry, macrophyte abundance, ice conditions...) since certain environmental conditions could impact the effectiveness of the VEMCO positioning system (40).

Signal detection

The average percent of signal detection varied between 77 and 89% for the stationary trials, which were done at ≲ 2 m depth, and between in 94.42 and 91.67% for the moving trials, which were done at 3, 5 and 7 m depth, in the two years of the study. This first suggest that shallow areas could provide lower rates of signal detection. Globally, the percent of signal detection was rarely higher than 70% in areas ≲ 4m. The percent of signal detection was low in the constriction located in the west part of the lake for both years. Furthermore, the percent of signal detection, was lowest in the west bay, in the two years of the study, and in the east bay of the lake in 2018, compared to the central part of the lake. These two later results suggest an effect of vegetation (but see a more detailed discussion on the effects of bathymetry and aquatic vegetation in the next section below). We do not know any other study that investigated the percent of signal detection of such a system so that it is not possible to do comparisons with other systems.

Effects of bathymetry and aquatic vegetation

Depth and aquatic vegetation were two confounding factors in our system, and this may have biased our correlation analyses. However, the fact that aquatic vegetation profiles changed between August 2017 and June 2018, especially in the east bay of the lake, allowed us to disentangle their effects on the error positioning and percent of signal detection. The comparison of interpolation models of aquatic vegetation to those of positioning error and percent of signal detection shown that depth mainly affect positioning error and aquatic vegetation mainly affect the signal detection. These results suggest that once the signal is detected by at least three receivers in vegetated area, the positioning error is reliable.

Baktoft et al. (2015) highlighted that the performance of these systems has rarely been tested on whole ecosystems and that the effect of habitat structure is only very poorly documented. Baktoft et al. (2015), estimated the performance of an acoustic telemetry system (Lotek Wireless) in two lakes: a lake with a structurally complex vegetated system (lake 1) and an open-water lake (lake 2). They estimated an accuracy of 3.1 m and a precision of 1.1 m in lake 1 and an accuracy of 1.0 m) and a precision of 0.2 m in lake 2 indicating that the performance of the system was affected by the complexity of the aquatic vegetation. This type of system seems better suited for structurally simple ecosystems or the study focuses on pelagic species (Baktoft et al. 2015). Weinz et al. (2021) investigated the detection efficiency and range of the V9–2H 180 kHz Innovasea Systems Inc. by performing range tests and hydroacoustic surveys to evaluate the seasonal influence of submerged aquatic vegetation (SAV) biovolume on transmitter detection in near shore (1.5 m) habitats of a temperate freshwater riverine ecosystem. In general, the biovolume of SAV significantly reduced the effectiveness of transmitter detection. Range varied from 6.85 ± 1.98 m when SAV coverage was high (mean biovolume of 0.98) to 196.08 ± 51.89 m when SAV coverage was low (mean biovolume of 0.01). This study highlighted the need for range testing in study design and analysis to improve the quality of data interpretation in vegetated habitats.

In our study, the percent of signal detection was not calculated as in other studies. However, the results support the effect of vegetation on the performance of the system. At depth of 4 m and less, the vegetation is more present and the percent of signal detection is lower. In 2017 and 2018 the correlation shows that as the abundance of vegetation increases, the percent of signal detection decreased.

Finally, we observed that the percent of signal detection was higher in the deepest zone (7 m) than in the 3 and 5 m zones for 2017 and 2018. The effect of depth on system performance is only poorly documented in the literature. For example, the thermal stratification of the water with different densities may cause an attenuation of the signal and thus disturb the detection of the signal (7).

CONCLUSION

The HR2-VPS provided good estimates of the tag positions with average positioning errors between 1.22 and 5.62 m and percent of signal detection generally higher than 90% in both years of the study. However, our study highlights that the depth and the presence of aquatic vegetation can impair both the positioning errors and percent of signal detection. This indicates that spatial and temporal variations of the quality of fish positioning must be considered in studies using comparable acoustic telemetry systems. Future studies evaluating these systems should consider the effect of habitat structure for a better interpretation of the results. Several studies have investigated the performance of these systems and most have limited their interpretation to accuracy and precision, without quantifying explicitly the effect of environmental conditions in their system. Furter studies should focus on the effects of bathymetry, aquatic vegetation and thermal conditions of the water to improve our understanding of the effectiveness of acoustic telemetry systems.

REFERENCES

1. Baktoft H, Zajicek P, Klefoth T, Svendsen J, Jacobsen L, Pedersen MW, Morla DM, Skov C, Nakayama S and Arlinghaus R. Performance assessment of two whole-lake acoustic positional telemetry systems is reality mining of free ranging aquatic animals technologically possible? PLoS ONE 10(5): e0126534. 2015. https://doi.org/10.1371/journal.pone.0126534

2. Binder R, Holbrook CM, Hayden TA and Krueger CC. Spatial and temporal variation in positioning probability of acoustic telemetry arrays: Fine-scale and variability and complex interactions. Animal biotelemetry. 4, 4. 2016. https://doi.org/10.1186/s40317-016-0097-4

3. Bertolo A, Pépino M, Adams J and Magnan P. Behavioural thermoregulatory tactics in lacustrine brook charr, *Salvelinus fontinalis*. PLoS ONE 6(4): e18603. 2011. https://doi.org/10.1371/journal.pone.0018603

4. Billal H, Shivam S, Kuppusamy S, Priya RS, and Vinod BM. Three decades of wildlife radio telemetry in india: a review. Animal Biotelemetry. 2, 4. 2014. https://doi.org/10.1186/2050-3385-2-4

5. Ceballos G, Ehrlich PR, Barnosky AD, García A, Pringle RM and Palmer TM. Accelerated modern human-induced species losses: entering the sixth mass extinction. *Science Advances*, Vol. 1, no. 5, e1400253 doi: 10.1126/sciadv.1400253. 2015

6. Donaldson M, Hinch S, Suski C, Fisk A, Heupel M and Cook S. Making connections in aquatic ecosystems with acoustic telemetry monitoring. Frontier Ecology Environmental, 12 (10): 565-573. 2014. https://doi.org/10.1890/130283

7. Gjelland K and Hedger RD. Environmental influence on transmitter detection probability in biotelemetry: developing a general model of acoustic transmission. Methods in Ecology and Evolution. 2013. https://doi.org/10.1111/2041-210X.12057

8. Goyer K, Bertolo A, Pépino M and Magnan P. Effects on lake Warming on behavioural thermoregulatory tactics in a cold-water stenothermic fish. PLOS one 9(3): e92514. 2014. https://doi.org/10.1371/journal.pone.0092514

9. Heupel MR, Simpfendorfer CA, Espinoza M, Smoothey AF, Tobin A and Peddemors V. Conservation challenges of sharks with continental scale migrations. Frontiers in Marine Science, 2, 12. 2015. https://doi.org/10.3389/fmars.2015.00012

10. Huveneers C, Simpfendorfer CA, Kim S, Semmens JM, Hobday AJ, Pederson H, Stieglitz T, Vallee R, Webber D, Heupel MR, Peddemors V and Harcourt RG. The influence of environmental parameters on the performance and detection range of acoustic receivers. Methods in Ecology and Evolution, 7: 825-835. 2016. https://doi.org/10.1111/2041-210X.12520

11. Karp Cathy. Research project: Summary of Freshwater Fisheries Telemetry Methods. Reclamation Managing Water in the West. Research and Development Office Science and Technology Program Final Report 2014-01-1219. 2014.

12. Kessel ST, Hussey NE, Webber DM, Gruber SH, Young JM, Smale MJ and Fisk AJ. Close proximity detection interference with acoustic telemetry: the importance of considering tag power output in low ambient noise environments. Animal Biotelemetry 3,5. 2015. https://doi.org/10.1186/s40317-015-0023-1

13. Kessel ST, Cooke SJ, Heupel MR, Hussey NE, Simpfendorfer CA, Vagle S and Fisk AT. A review of detection range testing in aquatic passive acoustic telemetry studies. Reviews in Fish Biology and Fisheries 24:199-218. 2014.

14. Magnan P. Interactions between brook charr, Salvelinus fontinalis, and nonsalmonid species: ecological shift, morphological shift, and their impact on zooplankton communities. Can. J. Fish. Aquat. Sci. 45: 999–1009. 1988.

15. Pépino M, Magnan P and Proulx R. Field evidence for a rapid adaptive plastic response in morphology and growth of littoral and pelagic brook charr: A reciprocal transplant experiment. Func. Ecol. 32:161–170. 2017. https://doi.org/10.1111/1365-2435.12929

16. Roy R, Beguin J, Argillier C, Tissot L, Smith F, Smedbolet S and De-Oliveira E. Testing the VEMCO Positioning System: spatial distribution of the probability of location and the positioning error in a reservoir. Animal Biotelemetry, 2:1. 2014. https://doi.org/10.1186/2050-3385-2-1

17. Semmens J, Payne N, Huveneers C, Sims DW and Bruce B. Feeding requirements of white sharks may be higher than originally thought. Scientific Reports, 3, 1471. 2013. https://doi.org/10.1038/srep01471

18. Withey J, Bloxton T and Marzluff J. Chap 3; Effects of tagging and location error in wildlife radiotelemetry studies. Radio tracking and Animal populations. 2001. https://doi.org/10.1016/B978-012497781-5/50004-9

19. Smith Frank. Understanding HPE in the VEMCO Positioning System (VPS). VEMCO organization. 2013. https://www.vemco.com/wpcontent/uploads/2013/09/understanding-hpe-vps.pdf

20. VEMCO. 2018. VR2W User Manual. DOC-4400-22. 2014. https://www.vemco.com/wp-content/uploads/2014/06/vr2w-manual.pdf

21. VEMCO.Fathom HR2 Receiver and software user guide. Version 2.3.0. DOC- 5726-06. 2018. https://www.vemco.com/wp-content/uploads/2016/06/hr2-receiver-fathom-sw-manual.pdf

22. Biesinger Z, Bolker BM, Marcinek D, Grothues TM, Dobarro JA and Lindberg WJ. Testing an autonomous acoustic telemetry positioning system for fine-scale space use in marine animals. Journal of Experimental Marine Biology and Ecology 448:46-56. 2013. https://doi.org/10.1016/j.jembe.2013.06.007

23. Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG and Butler PJ. Biotelemetry: a mechanistic approach to ecology. Trends in Ecology and Evolution 19:334-343. 2004. https://doi.org/10.1016/j.tree.2004.04.003

24. Cooke SJ, Midwood JD, Thiem JD, Klimley P, Lucas MC, Thorstad EB, Eiler J, Holbrook C and Ebner BC. Tracking animals in freshwater with electronic tags: Past, present and future. Animal Biotelemetry 1. 2013. https://doi.org/10.1186/2050-3385-1-5

25. Farmer NA and Ault JS. Accounting for detection gaps when evaluating reef fish habitat use in an acoustic array. Canadian Journal of Fisheries and Aquatic Sciences 75:375-388. 2018. https://doi.org/10.1139/cjfas-2016-0494

26. Farmer NA, Ault JS, Smith SG and Franklin EC. Methods for assessment of short-term coral reef fish movements within an acoustic array. Movement Ecology 1. 2013. https://doi.org/10.1186/2051-3933-1-7

27. Gjelland KØ and Hedger RD. On the parameterization of acoustic detection probability models. Methods in Ecology and Evolution 8:1302-1304. 2017. https://doi.org/10.1111/2041-210X.12732

28. Hayden TA, Holbrook CM, Binder TR, Dettmers JM, Cooke SJ, Vandergoot CS and Krueger CC. Probability of acoustic transmitter detections by receiver lines in Lake Huron: Results of multi-year field tests and simulations. Animal Biotelemetry 4. 2016. https://doi.org/10.1186/s40317-016-0112-9

29. Hawley KL, Rosten CM, Christensen G and Lucas MC. Fine-scale behavioural differences distinguish resource use by ecomorphs in a closed ecosystem. Scientific Reports 6. 2016. https://doi.org/10.1038/srep24369

30. McGowan J, Beger M, Lewison RL, Harcourt R, Campbell H, Priest M, Dwyer RG, Lin HY, Lentini P, Dudgeon C, McMahon C, Watts M and Possingham HP. Integrating research using animal-borne telemetry with the needs of conservation management. Journal of Animal Ecology, 54: 423-429. 2017. https://doi.org/10.1111/1365-2664.12755

31. Meckley T D, Holbrook CM, Wagner CM and Binder TR. An approach for filtering hyperbolically positioned underwater acoustic telemetry data with position precision estimates. Animal Biotelemetry 2,7. 2014. https://doi.org/10.1186/2050-3385-2-7

32. Murphy SM, Wilckens DT, Augustine BC et al. Improving estimation of puma (Puma concolor) population density: clustered camera-trapping, telemetry data, and generalized spatial mark-resight models. Sci Rep 9, 4590. 2019. https://doi.org/10.1038/s41598-019-40926-7

33. Smith EA, Mclean D, Woodbridge DL. Multilateration auto-calibration and position error correction. United states Patent. US006094169A. 2000.

34. Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD, Fisk AT et al. Aquatic animal telemetry: a panoramic window into the underwater worlds. *Science*, **348**, Vol. 348, Issue 6240, 1255642. doi: 10.1126/science.1255642. 2015.

35. Kays R, Crofoot MC, Jetz W and Wikelski M. Terrestrial animal tracking as an eye on life and planet. *Science*, **348**, aaa2478. 2015. Vol. 348, Issue 6240, aaa2478. doi: 10.1126/science.aaa2478. 2015.

36. Campbell HA, Beyer HL, Dennis TE, Dwyer RG, Forester JD, Fukuda Y et al. Finding our way: on the sharing and reuse of animal telemetry data in Australasia. *Science of the Total Environment*, **534**, 79-84. 2015. doi:10.1016/j.scitotenv.2015.01.089

37. Jeffers VF and Godley BJ. Satellite tracking in sea turtles: how do we find our way to the conservation dividends? *Biological Conservation*, **199**, 172-184. 2016.

38. Maxwell SM, Hazen EL, Lewison RL, Dunn DC, Bailey H, Bograd SJ et al. Dynamic Ocean management: defining and conceptualizing real-time management of the ocean. *Marine policy*, **58**, 42-50. 2015. https://doi.org/10.1016/j.marpol.2015.03.014

39. Metcalfe JD, Le Quesne WJ, Cheung WW and Righton DA. Conservation physiology for applied management of marine fish: an overview with perspectives on the role and value of telemetry. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **367**, 1746-1756. 2012. doi: 10.1098/rstb.2012.0017

40. Guzzo MM, Van Leeuwen TE, Hollins J, Koeck B, Newton M, Webber DM, Smith FI, Bailey DM and Killen SS. Field testing a novel high residence positioning system for monitoring the fine-scale movements of aquatic organisms. Methods in Ecology and Evolution 9:1478-1488. 2018.

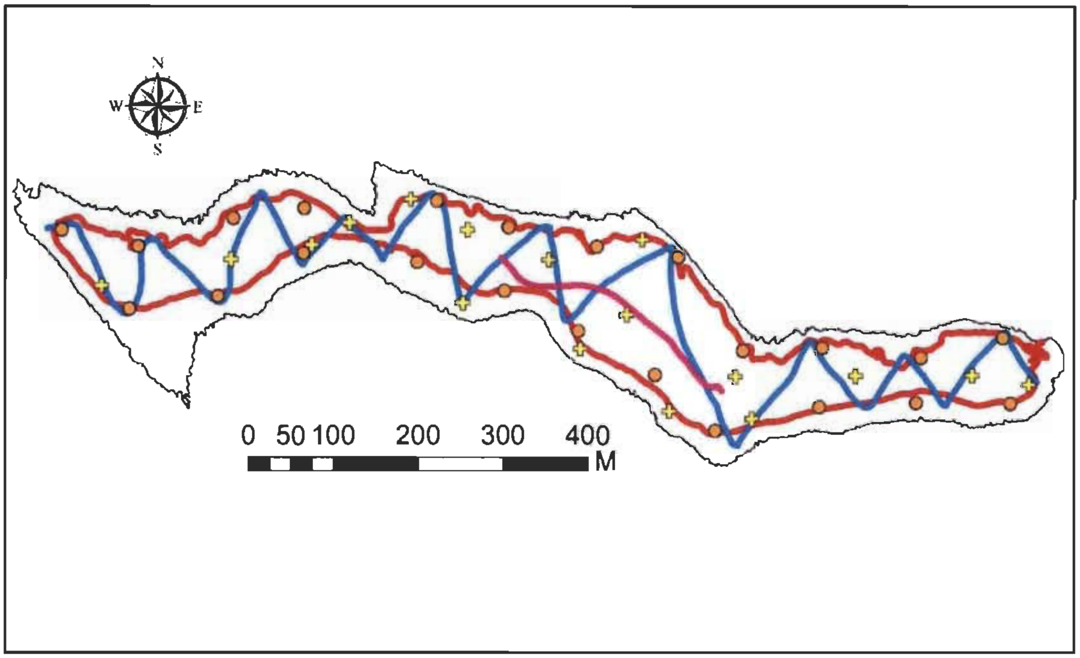
41. Weinz AA, Matley JK, Klinard NV, Fisk AT and Colborne SF. Performance of acoustic telemetry in relation to submerged aquatic vegetation in a nearshore freshwater habitat. Marine and freshwater Research. 72. 1033-1044. 2021. https://doi.org/10.1071/MF20245

42. Espinoza MT, Farrugia J, Webber DM, Smith F and Lowe CG. Testing a new acoustic telemetry technique to quantify long-term, fine-scale movements of aquatic animals. Fisheries Research 108:364-371.2011.

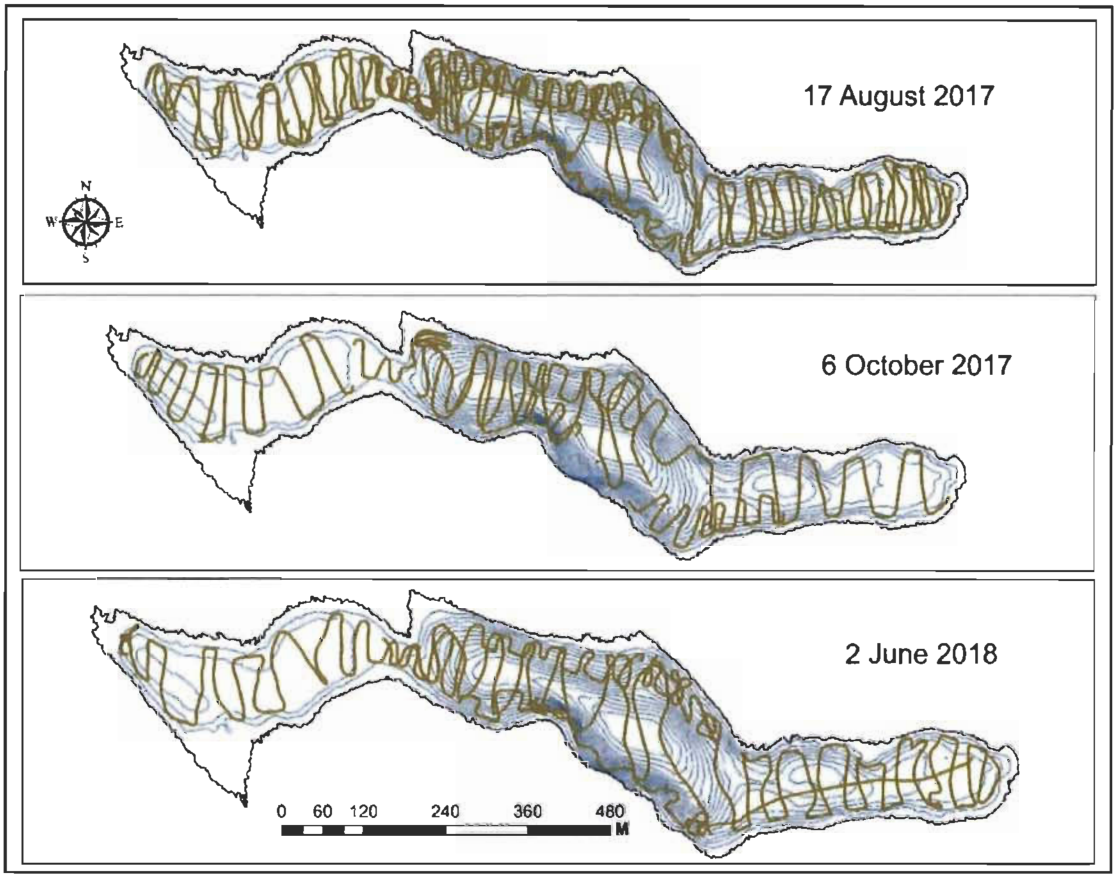
43. R Core Team (2018). R: A language and environment for statistical computing. R foundation for statistical computing, Vienna. R archive. http://www.R-project.org/

ADDITIONAL FILES

Additional file 1. Representation of the stationary and moving trials done in 2017 and 2018. Orange circle: receiver position; yellow cross: fixed station; pink line: transect at the deepest area of the lake; red line: transect covering the littoral zone; blue line: zigzag transect covering the whole lake.



Additional file 2. Representation of the path done with the Biosonics DT-X echo sounder to estimate the density of submersed aquatic vegetation on 17 August and 6 October 2017 and 2 June 2018.



CHAPITRE III

CONCLUSION

3.1 Contextualisation

Les systèmes de télémétrie acoustique sont de plus en plus utilisés dans les études comportementales des poissons. Les études qui portent sur des patrons de déplacements à fines échelles spatio-temporelles doivent faire l'objet d'une évaluation du système utilisé avant l'interprétation des résultats puisque les phénomènes biologiques étudiés (ex. mouvements et comportements de deux écotypes de poissons) dans l'étude peuvent être dans le même ordre de grandeur que les erreurs de positionnement du système. De plus, les prochaines études utilisant ces systèmes devraient également prendre en compte l'effet de la structure de l'habitat pour une meilleure interprétation des résultats. Plusieurs études ont examiné la performance de ces systèmes et la plupart ont soulevé des limites possibles à l'interprétation de leurs résultats en raison de l'effet des conditions environnementales comme la bathymétrie, la végétation aquatique, les conditions thermiques de l'eau et le bruit ambiant (Espinoza et al. 2011, Guzzo et al. 2018, Baktotf et al. 2015, Weinz et al. 2021). Cependant, très peu d'études ont évalué systématiquement l'effet de ces conditions environnementales sur la performance des systèmes de télémétrie acoustique. De telles études pourraient grandement améliorer notre compréhension de l'efficacité de ce type de systèmes.

3.2 Principaux résultats du mémoire

Lors des tests en position fixe, l'erreur de positionnement moyen a été de 4,67 m en 2017 et de 1,22 m en 2018. La distribution des erreurs de positionnement a également été plus faible en 2018 (0,22-2,81 m) qu'en 2017 (0,37-49,37 m). L'erreur de positionnement moyen a été plus faible lors des tests en position fixe que lors des tests en mouvements. L'erreur de positionnement moyen lors des tests en mouvements a été de 5,62 m en août 2017 et de 1,36 m en 2018. La distribution des erreurs de positionnement a aussi été moins élevée en 2018 (0,03-6,91 m) qu'en 2017 (0,20-18,90 m). De grandes erreurs de positionnement sont observables pour les deux années dans le resserrement du lac où la profondeur est moindre et la végétation aquatique plus présente. Ce phénomène a été observé lors des tests en position fixe et en mouvement.

Le pourcentage de détection moyen pour les tests en position fixe a été de 89,05 % en août 2017 et de 77,94 % en juin 2018. La distribution du pourcentage de détection a également été plus faible en 2018 (0,33-100,8 %) qu'en 2017 (3,0-101,34 %). Le pourcentage de détection a été plus faible lors des tests en mouvement. Le pourcentage de détection moyen a été 73,51 % en 2017 alors qu'il a été de 71,08 % en 2018. Des valeurs faibles de détection ont été enregistrées dans le resserrement du lac, où la profondeur est faible et le niveau de végétation élevée.

Le système HR2 de VEMCO que nous avons évalué a fourni de bonnes estimations de la position des émetteurs en position fixe et en mouvement, avec un pourcentage de détection du signal généralement supérieur à 90 %. Cependant, notre étude a mis en évidence que la profondeur et la présence de la végétation aquatique peuvent altérer les erreurs de positionnement et le pourcentage de détection des signaux. Cela signifie que les variations spatiales et temporelles de ces facteurs environnementaux doivent être prises en compte dans l'évaluation de la qualité du positionnement des poissons, dans les études utilisant des systèmes de télémétrie acoustique comparables. Plusieurs études ont examiné les performances de ces systèmes et la plupart ont limité leur interprétation à l'exactitude et à la précision, sans quantifier explicitement l'effet des conditions environnementales dans leur système. Des études plus approfondies devraient se concentrer sur les effets de la bathymétrie, de la végétation aquatique et des conditions thermiques de l'eau pour améliorer notre compréhension de l'efficacité des systèmes de télémétrie acoustique.

RÉFÉRENCES BIBLIOGRAPHIQUES

Baktoft H, Zajicek P, Klefoth T, Svendsen J, Jacobsen L, Pedersen MW, Morla DM, Skov C, Nakayama S and Arlinghaus R. Performance assessment of two whole-lake acoustic positional telemetry systems is reality mining of free ranging aquatic animals technologically possible? PLoS ONE 10(5): e0126534. 2015. https://doi.org/10.1371/journal.pone.0126534

Bertolo A, Pépino M, Adams J and Magnan P. Behavioural thermoregulatory tactics in lacustrine brook charr, *Salvelinus fontinalis*. PLoS ONE 6(4): e18603. 2011. https:// doi.org/10.1371/journal.pone.0018603

Biesinger Z, Bolker BM, Marcinek D, Grothues TM, Dobarro JA and Lindberg WJ. Testing an autonomous acoustic telemetry positioning system for fine-scale space use in marine animals. Journal of Experimental Marine Biology and Ecology 448:46-56. 2013. https://doi.org/10.1016/j.jembe.2013.06.007

Billal H, Shivam S, Kuppusamy S, Priya RS, and Vinod BM. Three decades of wildlife radio telemetry in india: a review. Animal Biotelemetry. 2, 4. 2014. https://doi.org/10.1186/2050-3385-2-4

Binder R, Holbrook CM, Hayden TA and Krueger CC. Spatial and temporal variation in positioning probability of acoustic telemetry arrays: Fine-scale and variability and complex interactions. Animal biotelemetry. 4,4. 2016. https://doi.org/10.1186/s40317-016-0097-4

Campbell HA, Beyer HL, Dennis TE, Dwyer RG, Forester JD, Fukuda Y et al. Finding our way: on the sharing and reuse of animal telemetry data in Australasia. *Science of the Total Environment*, **534**, 79-84. 2015. doi:10.1016/j.scitotenv.2015.01.089

Ceballos G, Ehrlich PR, Barnosky AD, García A, Pringle RM and Palmer TM. Accelerated modern human-induced species losses: entering the sixth mass extinction. *Science Advances*, Vol. 1, no. 5, e1400253 doi: 10.1126/sciadv.1400253. 2015.

Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG and Butler PJ. Biotelemetry: a mechanistic approach to ecology. Trends in Ecology and Evolution 19:334-343. 2004. https://doi.org/10.1016/j.tree.2004.04.003

Cooke SJ, Midwood JD, Thiem JD, Klimley P, Lucas MC, Thorstad EB, Eiler J, Holbrook C and Ebner BC. Tracking animals in freshwater with electronic tags: Past, present and future. Animal Biotelemetry 1. 2013. https://doi.org/10.1186/2050-3385-1-5

Donaldson M, Hinch S, Suski C, Fisk A, Heupel M and Cook S. Making connections in aquatic ecosystems with acoustic telemetry monitoring. Frontier Ecology Environmental, 12 (10): 565-573. 2014. https://doi.org/10.1890/130283

Espinoza MT, Farrugia J, Webber DM, Smith F and Lowe CG. Testing a new acoustic telemetry technique to quantify long-term, fine-scale movements of aquatic animals. Fisheries Research 108:364-371.2011.

Farmer NA and Ault JS. Accounting for detection gaps when evaluating reef fish habitat use in an acoustic array. Canadian Journal of Fisheries and Aquatic Sciences 75:375-388. 2018. https://doi.org/10.1139/cjfas-2016-0494

Farmer NA, Ault JS, Smith SG and Franklin EC. Methods for assessment of short-term coral reef fish movements within an acoustic array. Movement Ecology 1. 2013. https://doi.org/10.1186/2051-3933-1-7

Gjelland K and Hedger RD. Environmental influence on transmitter detection probability in biotelemetry: developing a general model of acoustic transmission. Methods in Ecology and Evolution. 2013. https://doi.org/10.1111/2041-210X.12057

Gjelland KØ and Hedger RD. On the parameterization of acoustic detection probability models. Methods in Ecology and Evolution 8:1302-1304. 2017. https://doi.org/10.1111/2041-210X.12732

Goyer K, Bertolo A, Pépino M and Magnan P. Effects on lake Warming on behavioural thermoregulatory tactics in a cold-water stenothermic fish. PLOS one 9(3): e92514. 2014. https://doi.org/10.1371/journal.pone.0092514

Guzzo MM, Van Leeuwen TE, Hollins J, Koeck B, Newton M, Webber DM, Smith FI, Bailey DM and Killen SS. Field testing a novel high residence positioning system for monitoring the fine-scale movements of aquatic organisms. Methods in Ecology and Evolution 9:1478-1488. 2018.

Hawley KL, Rosten CM, Christensen G and Lucas MC. Fine-scale behavioural differences distinguish resource use by ecomorphs in a closed ecosystem. Scientific Reports 6. 2016. https://doi.org/10.1038/srep24369

Hayden TA, Holbrook CM, Binder TR, Dettmers JM, Cooke SJ, Vandergoot CS and Krueger CC. Probability of acoustic transmitter detections by receiver lines in Lake Huron: Results of multi-year field tests and simulations. Animal Biotelemetry 4. 2016. https://doi.org/10.1186/s40317-016-0112-9

Heupel MR, Simpfendorfer CA, Espinoza M, Smoothey AF, Tobin A and Peddemors V. Conservation challenges of sharks with continental scale migrations. Frontiers in Marine Science, 2, 12. 2015. https://doi.org/10.3389/fmars.2015.00012

Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD, Fisk AT et al. Aquatic animal telemetry: a panoramic window into the underwater worlds. *Science*, **348**, Vol. 348, Issue 6240, 1255642. doi: 10.1126/science.1255642. 2015.

Huveneers C, Simpfendorfer CA, Kim S, Semmens JM, Hobday AJ, Pederson H, Stieglitz T, Vallee R, Webber D, Heupel MR, Peddemors V and Harcourt RG. The influence of environmental parameters on the performance and detection range of acoustic receivers. Methods in Ecology and Evolution, 7: 825-835. 2016. https://doi.org/10.1111/2041-210X.12520

Jeffers VF and Godley BJ. Satellite tracking in sea turtles: how do we find our way to the conservation dividends? *Biological Conservation*, **199**, 172-184. 2016.

Karp Cathy. Research project: Summary of Freshwater Fisheries Telemetry Methods. Reclamation Managing Water in the West. Research and Development Office Science and Technology Program Final Report 2014-01-1219. 2014.

Kays R, Crofoot MC, Jetz W and Wikelski M. Terrestrial animal tracking as an eye on life and planet. *Science*, **348**, aaa2478. 2015. Vol. 348, Issue 6240, aaa2478. doi: 10.1126/science.aaa2478. 2015.

Kessel ST, Cooke SJ, Heupel MR, Hussey NE, Simpfendorfer CA, Vagle S and Fisk AT. A review of detection range testing in aquatic passive acoustic telemetry studies. Reviews in Fish Biology and Fisheries 24:199-218. 2014.

Kessel ST, Hussey NE, Webber DM, Gruber SH, Young JM, Smale MJ and Fisk AJ. Close proximity detection interference with acoustic telemetry: the importance of considering tag power output in low ambient noise environments. Animal Biotelemetry 3,5. 2015. https://doi.org/10.1186/s40317-015-0023-1

Magnan P. Interactions between brook charr, Salvelinus fontinalis, and nonsalmonid species: ecological shift, morphological shift, and their impact on zooplankton communities. Can. J. Fish. Aquat. Sci. 45: 999–1009. 1988.

Maxwell SM, Hazen EL, Lewison RL, Dunn DC, Bailey H, Bograd SJ et al. Dynamic ocean management: defining and conceptualizing real-time management of the ocean. *Marine policy*, **58**, 42-50. 2015. https://doi.org/10.1016/j.marpol.2015.03.014

McGowan J, Beger M, Lewison RL, Harcourt R, Campbell H, Priest M, Dwyer RG, Lin HY, Lentini P, Dudgeon C, McMahon C, Watts M and Possingham HP. Integrating research using animal-borne telemetry with the needs of conservation management. Journal of Animal Ecology, 54: 423-429. 2017. https://doi.org/10.1111/1365-2664.12755

Meckley T D, Holbrook CM, Wagner CM and Binder TR. An approach for filtering hyperbolically positioned underwater acoustic telemetry data with position precision estimates. Animal Biotelemetry 2,7. 2014. https://doi.org/10.1186/2050-3385-2-7

Metcalfe JD, Le Quesne WJ, Cheung WW and Righton DA. Conservation physiology for applied management of marine fish: an overview with perspectives on the role and value of telemetry. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **367**, 1746-1756. 2012. doi: 10.1098/rstb.2012.0017

Murphy SM, Wilckens DT, Augustine BC et al. Improving estimation of puma (Puma concolor) population density: clustered camera-trapping, telemetry data, and generalized spatial mark-resight models. Sci Rep 9, 4590. 2019. https://doi.org/10.1038/s41598-019-40926-7

Pépino M, Magnan P and Proulx R. Field evidence for a rapid adaptive plastic response in morphology and growth of littoral and pelagic brook charr: A reciprocal transplant experiment. Func. Ecol. 32:161–170. 2017. https://doi.org/10.1111/1365-2435.12929

Perras, M. & Nebel, S. (2012) Satellite Telemetry and its Impact on the Study of Animal Migration. Nature Education Knowledge 3(12):4

R Core Team (2018). R: A language and environment for statistical computing. R foundation for statistical computing, Vienna. R archive. http://www.R-project.org/

Roy R, Beguin J, Argillier C, Tissot L, Smith F, Smedbolet S and De-Oliveira E. Testing the VEMCO Positioning System: spatial distribution of the probability of location and the positioning error in a reservoir. Animal Biotelemetry, 2:1. 2014. https://doi.org/10.1186/2050-3385-2-1

Semmens J, Payne N, Huveneers C, Sims DW and Bruce B. Feeding requirements of white sharks may be higher than originally thought. Scientific Reports, 3, 1471. 2013. https://doi.org/10.1038/srep01471

Smith EA, Mclean D, Woodbridge DL. Multilateration auto-calibration and position error correction. United states Patent. US006094169A. 2000.

Smith Frank. Understanding HPE in the VEMCO Positioning System (VPS). VEMCO organization. 2013. https://www.vemco.com/wp-content/uploads/2013/09/understanding-hpe-vps.pdf

VEMCO. 2018. VR2W User Manual. DOC-4400-22. 2014. https://www.vemco.com/wp-content/uploads/2014/06/vr2w-manual.pdf

VEMCO. Fathom HR2 Receiver and software user guide. Version 2.3.0. DOC- 5726-06. 2018. https://www.vemco.com/wp-content/uploads/2016/06/hr2-receiver-fathom-sw-manual.pdf

Weinz AA, Matley JK, Klinard NV,Fisk AT and Colborne SF. Performance of acoustic telemetry in relation to submerged aquatic vegetation in a nearshore freshwater habitat. Marine and freshwater Research. 72. 1033-1044. 2021. https://doi.org/10.1071/MF20245

Withey J, Bloxton T and Marzluff J. Chap 3; Effects of tagging and location error in wildlife radiotelemetry studies. Radio tracking and Animal populations. 2001. https://doi.org/10.1016/B978-012497781-5/50004-9