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Hydroacoustic differentiation of adult Atlantic salmon and aquatic macrophytes in the River Wye, Wales

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Abstract − Split-beam hydroacoustic techniques have been used to enumerate adult Atlantic salmon (*Salmo salar*) passage on the River Wye since 1994. Aggregations of aquatic macrophytes, principally *Ranunculus fluitans,* are seasonally present at the monitoring site. At high densities, these macrophytes return target strength (TS) values similar to those of adult salmon. Target direction-of-movement information readily resolves upstream-migrant salmon from static- or downstream-traveling macrophytes. However, Atlantic salmon are iteroparous, and downstream-migrant kelts must be factored into the acoustic estimates. Net upstream target movement and/or TS were not reliable indicators of salmon passage at the River Wye site when aquatic macrophyte aggregations were present. In 1995, a subset of data (*n* = 71) was selected from the ongoing monitoring program to determine the feasibility of resolving salmon from macrophytes using acoustic parameters other than target direction-of-movement or mean TS. Individual targets were visually identified as either salmon or macrophytes based on concurrent video records. Distributions of available acoustic parameters were statistically compared between the two target-types using a two-tailed t-test assuming equal variance (*P* = 0.05). Available acoustic parameters included echo position, pulse width (at –6, –12, and –18 dB power points), amplitude, beam pattern factor and target strength. Pulse width standard deviation (PWSD) measurements were determined to be the most effective individual parameters for discriminating macrophytes from salmon. Based on PWSD at the –6 dB echo power points, 77% of all macrophyte targets were removed from the mixed data set. Multiple selection criteria increased total target discrimination. Applying a combination of –6 and –12 dB PWSD, and Y–axis target slope criteria rejected 94% of all macrophytes, retaining all salmon targets. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

acoustic assessment / acoustic target identification / macrophytes / Atlantic salmon

Résumé − Différenciations hydroacoustiques entre les saumons de l'Atlantique adultes et les macrophytes aquatiques du fleuve Wye, au Pays de Galles. Des techniques hydroacoustiques à faisceaux partagés sont utilisées pour énumérer les passages de saumons adultes (*Salmo salar*) sur le fleuve Wye depuis 1994. Des agrégations de macrophytes aquatiques, principalement *Ranunculus fluitans,* sont présentes de façon saisonnière sur le site opérationnel. A grande densité, ces macrophytes présentent des indices de réflexion (TS) similaires à ceux de saumons adultes. Les informations concernant la direction des déplacements permettent de distinguer les saumons en migration, remontant le fleuve, des plantes macrophytes statiques ou entraînées vers l'aval. Cependant, le saumon de l'Atlantique peut se reproduire plusieurs fois au cours de sa vie et les saumons, après avoir frayé, retournant vers l'aval doivent être pris en compte dans les estimations acoustiques. Ainsi, les déplacements des cibles vers l'amont, et/ou TS, ne sont pas des indicateurs fiables des passages de saumons sur ce site, en présence d'agrégations des macrophytes. En 1995, une série de données, issue d'un programme en cours, a été choisie pour être analysée, afin de déterminer la possibilité de distinguer les saumons des macrophytes, en utilisant des paramètres acoustiques autres que la direction des déplacements et l'indice TS moyen. Des cibles individuelles ont été visuellement identifiées soit en tant que saumon soit comme macrophyte au moyen d'enregistrements simultanés en vidéo (*n* = 71). Les répartitions des paramètres acoustiques ont été statistiquement comparées entre les 2 types de cibles au moyen d'un test *t* bilatéral, supposant l'égalité des variances (*P* = 0,05). Les paramètres acoustiques disponibles incluent la position des échos, la durée de l'impulsion (à –6 dB, –12 dB et –18 dB), l'amplitude, le facteur de directivité (distance par rapport à l'axe acoustique) et l'indice de réflexion. Les mesures des écarts-types de la durée de l'impulsion (PWSD) ont été déterminées comme étant les paramètres les plus efficaces pour distinguer individuellement les macrophytes des saumons. Basés sur PWSD à –6 dB, 77% des cibles de macrophytes ont été éliminés de l'ensemble des données. Des critères de sélection multiple augmentent la discrimination des cibles. En appliquant une combinaison de PWSD mesurés à –6 et à –12 dB et un critère sur la position des cibles par rapport à l'axe acoustique vertical, on peut ainsi rejeter 94% des macrophytes en conservant toutes les cibles de saumons. © 2000 Ifremer/CNRS/INRA/IRD/Cemagref/Éditions scientifiques et médicales Elsevier SAS

estimation acoustique / identification acoustique de cibles / macrophytes / saumon de l'Atlantique

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1. INTRODUCTION

Split-beam hydroacoustic techniques have been used to enumerate Atlantic salmon (*Salmo salar*) populations at the Redbrook gauging station on the River Wye, Wales since 1994 (Gregory et al., 1996). Unlike many hydroacoustic evaluations of Pacific salmon species in North America, net upstream movement is not an absolute indicator of target type at the River Wye site. Atlantic salmon are iteroparous, potentially spawning multiple times, and downstream-migrant kelts must be factored into the River Wye acoustic counts.

Aggregations of an aquatic macrophyte (*Ranunculus fluitans*) are seasonally present at the River Wye monitoring site, and coincide with the presence of Atlantic salmon. This weed grows in long strands. These strands periodically break off, typically following an increase in river flow and form large rafts with associated air bubbles. The target strength (TS) values from these macrophyte aggregations are frequently comparable to those of adult salmon.

In general, split-beam acoustic observations of macrophytes indicated either a static position or downstream movement with river flow. However, the amorphous structure of the *Ranunculus* aggregations were observed to frequently return scattered three-dimensional echo positions, resulting in some proportion of the macrophytes being erroneously tracked as upstream-moving targets.

The observed conditions at the River Wye monitoring site precluded using solely TS or upstream–downstream movement as target classifiers. However, the split-beam acoustic data set included a suite of additional descriptive parameters, which had not previously been investigated with respect to target-type correlation. Previous research indicated that some of the additional parameters, in particular echo pulse width, demonstrated promise with respect to differentiating fish species (Ehrenberg and Johnston, 1996; Burwen and Fleischman, 1998; Rose and Leggett, 1988).

The primary objective of the River Wye target discrimination study was to determine if significant differences existed between the distributions of available acoustic parameters to allow separation of adult salmon and aquatic macrophytes in a mixed data set. If differences were found to be present, a secondary objective was to identify criteria bound values for each significant parameter that maximized resolution of the two target groups.

To determine if adult Atlantic salmon could be resolved from macrophytes based on acoustic parameters other than upstream-downstream movement and mean TS, a subset of representative data were selected from the ongoing River Wye hydroacoustic monitoring program. Individual targets were visually identified as either salmon or macrophytes based on concurrent video records. Data files were created which summarized all of the available descriptive acoustic parameters for each observed target and the visually identified target type. These files were used for all subsequent analyses.

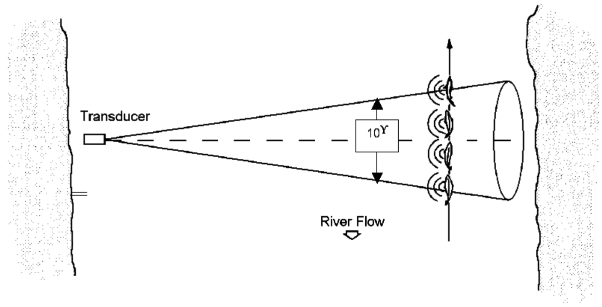

Figure 1. General orientation of the 4° × 10° split-beam transducer used during River Wye monitoring.

2. METHODS

2.1. Data collection

The *HTI Model 243 Split-Beam Hydroacoustic System* used at the site was capable of tracking individual targets based on a range of user-defined parameters, including velocity, number of echo returns, movement in the X, Y and Z– axes, acoustic target size, and others. The system recorded a series of attributes for each accepted echo return, and summary statistics for each tracked target. Descriptions of the specific echo attributes and summary tracked target statistics recorded by the system are presented in *tables I* and *II*, respectively. The echo and tracked target data were written to hourly computer files, designated as *.ECH* and *.FSH* files.

Data were collected using an elliptical 4 × 10 split-beam transducer operating at a center frequency of 200 kHz. The transducer was aimed horizontally across the River Wye, perpendicular to flow, such that the 10 axis of the elliptical transducer was oriented upstream–downstream. General transducer placement is shown in *figure 1*.

A frequency-modulated (FM) slide or 'chirped' signal was used to maximize the signal-to-noise ratio,

Table I. Hydroacoustic system data collection parameters.

Transducer beamwidth	Operating frequency	Source level	Receiving sensitivity	Detection threshold	Broadcast pulse width	Pulse repetition rate
4° × 10°	200 kHz	218.71 dBµPa@1m	–170.63 dBµPa@1m	–38 dB	0.18 ms	20 pings·s^{-1}

Table II. Acoustic descriptors available for each accepted echo return in the *.ECH* file.

Echo File Parameter	Description
Target number	tracked target associated with that echo in the tracked fish *(.FSH)* file
Ping number	sequential transmitted echo identifier
Echo position in the X–axis	horizontal (left–right) position of the echo relative to the acoustic axis (m)
Echo position in the Y–axis	vertical (up–down) position of the echo relative to the acoustic axis (m)
Echo position in the Z–axis	range from the transducer (m)
–6 dB echo pulse width	measured echo pulse length at the 1/2 amplitude point
–12 dB echo pulse width	measured echo pulse length at the 1/4 amplitude point
–18 dB echo pulse width	measured echo pulse length at the 1/8 amplitude point
Sum channel voltage return	measured peak echo amplitude
Beam pattern factor (BPF)	a measure of target position off-axis to calculate signal intensity loss
Target strength (TS)	acoustic echo size (dB)

Table III. Acoustic descriptors available for each tracked target in the *.FSH* file.

Target File Parameter	Description
Target number	sequential tracked target identifier
Start ping number	first echo number associated with the tracked target (from the *.ECH* file)
End ping number	last echo number associated with the tracked target (from the *.ECH* file)
Initial target position in the X–axis	horizontal (left–right) position of the target relative to the acoustic axis (m)
Initial target position in the Y–axis	vertical (up–down) position of the target relative to the acoustic axis (m)
Initial target position in the Z–axis	range to the target (m)
Distance traveled in the X–axis	net target movement (m) in the horizontal (left–right) plane
Distance traveled in the Y–axis	net target movement (m) in the vertical (up–down) plane
Distance traveled in the Z–axis	net target movement in range (m) relative to the transducer
Mean target velocity	Mean transit velocity of the target through the ensonified area
Mean target strength (TS)	Mean acoustic size of the tracked target (dB)
TS standard deviation (TSSD)	standard deviation surrounding the mean TS estimate (dB)

sweeping a broadcast frequency between 198.75 and 201.25 kHz (Burdic, 1984; Skolnik, 1990; Ehrenberg and Torkelson, 2000). A broadcast pulse width of 0.18 ms was used, corresponding to approximately 9 digital samples per echo return at the 48 kHz digitizing rate employed by the *Model 243 Echo Sounder*. Additional data collection parameters are shown in *table I*. Detailed site description and study methods are presented in Nealson et al. (1997).

2.2. Data analyses

Two analysis approaches were applied. The first was designed to remove macrophytes from the combined data set based on unique parameter characteristics, with no exclusion of designated salmon records. It was applied where the parameter distribution for macrophytes was larger than (or exclusive from) that observed for salmon. This approach used the observed parameter distribution of the salmon-only data set to determine criteria bounds, with the goal of 100% salmon retention and maximum macrophyte exclusion. For cases where the parameter distribution for salmon was larger than that of macrophytes, a second approach was used, applying exclusionary bounds based on the more tightly-distributed macrophyte data set. In this latter case, all macrophytes were excluded, as well as some percentage of the salmon targets. Distributions of available acoustic parameters were statistically compared between the two target-types using a two-tailed t-test assuming equal variance ($P = 0.05$).

For each of the pertinent parameters, separate distributions were generated for the aquatic macrophyte and salmon data files. These were compared to determine selective bounds that maximized separation of the two groups. Individual parameters that exhibited the highest percentage resolution were then combined into multiple parameter arguments, and tested to determine combinations with the greatest overall selection efficiency.

The data records used for discrimination were the echo *(.ECH)* and fish (*.FSH*) file outputs of the *Model 243 Hydroacoustic System*. These two files were collected concurrently and describe echo and summary statistics for each tracked target. The acoustic parameters available in the *.ECH* output data files describe each individual accepted echo within each tracked target (*table II*).

Based on the accepted single-target echoes summarized in the *.ECH* file, the *HTI Model 243 Split-Beam Hydroacoustic System* tracked individual targets within the ensonified area based on user-defined inputs. These *.FSH* files describe summary statistics on a tracked target basis (*table III*).

Frequency distributions for each of the acoustic parameters were generated for both the macrophyte and salmon data files and statistically compared using a two-tailed t-test assuming equal variances ($P = 0.05$). Parameters which differed significantly between the two groups were evaluated to determine the specific bound values which either excluded the largest percentage of macrophytes, or included the highest percentage of adult salmon. After the selection/exclusion values were optimized for individual parameters, these individual parameter arguments were grouped into multiple arguments to maximize resolution between the two target groups. Individual parameters were combined to form multiple arguments, providing greater resolution between the two target groups. All multiple parameter selections were based on the boolean and/or argument, such that at least one of the parameter arguments had to be true for a given target to be accepted or excluded.

From the acoustic parameters directly available in the *.ECH* and *.FSH* output data files, additional descriptors were calculated (*table IV*).

These calculated metrics included mean target pulse width at the 1/2, 1/4 and 1/8 echo amplitude power points. These values were the average of all echo measurements at a given power point within a given target. Pulse width standard deviation (PWSD) was also estimated at each of the echo amplitude power points. For each observed target, mean positions in the X– (vertical), Y– (horizontal), and Z–axes (range from the transducer) were calculated, corresponding to the average target position from the acoustic axis in meters following the Cartesian coordinate system. The variability surrounding the mean position estimates in each of the three planes was also estimated by calculating the standard deviation and the R^2 value (coefficient of determination) for each observed target, based on the individual echo positions. Target slope in the X, Y and Z planes were calculated by regressing echo position in the given plane against elapsed ping number (time). Y–axis slope, the ping-to-ping regression of Y–axis (up–down) echo position in the acoustic beam provided a measure of vertical movement of targets in the water column.

For each observed salmon or macrophyte, a mean ping-to-ping target velocity (PPV) was calculated by averaging the estimated velocity between each successive echo returns within the tracked target. The chord length (distance) between each pair of three-dimensional echo positions was divided by the elapsed time between the echoes, then all ping-to-ping velocity estimates were averaged within a target. The calculated mean PPV per target values differ from the mean target velocities available in the in the tracked fish (.FSH) files, in that the latter is calculated as total three-dimensional distance between all successive pings within a target divided by total elapsed time from the first to last ping. Both of these velocity estimators will tend to overestimate true target velocity if echo positions are scattered, either due to acoustic noise, or target morphology, but remain comparable between target groups for a given parameter ping-to-ping target velocity standard deviation (PPV SD) was estimated as the standard deviation of all PPV estimates for each target, and provides a measure of variability within velocity estimates.

Mean target position relative to the transducer axis was evaluated by analysis of the mean beam pattern

Table IV. Calculated acoustic descriptors for each tracked target based on data from the *.ECH* and *.FSH* files.

Target file parameter	Description
Mean –6 dB echo pulse width	mean echo pulse width at the 1/2 amplitude point
Mean –12 dB echo pulse width	mean echo pulse width at the 1/4 amplitude point
Mean –18 dB echo pulse width	mean echo pulse width at the 1/8 amplitude point
–6 dB echo pulse width standard deviation (PW SD)	pulse width standard deviation at the 1/2 amplitude point
–12 dB echo PW SD	pulse width standard deviation at the 1/4 amplitude point
–18 dB echo PW SD	pulse width standard deviation at the 1/8 amplitude point
X–axis mean target position	mean horizontal (left–right) target position relative to the axis
Y–axis mean target position	mean vertical (up–down) target position relative to the axis
Z–axis mean target position	mean range to the target
X–axis target position standard deviation	standard deviation of the echo positions in the X–axis
Y–axis target position standard deviation	standard deviation of the echo positions in the Y–axis
Z–axis target position standard deviation	standard deviation of the echo positions in the Z–axis
X–axis slope	regression of X–axis position on ping number
Y–axis slope	regression of Y–axis position on ping number
Z–axis slope	regression of Z–axis (range) position on ping number
X–axis echo position R^2	coefficient of determination for the X–axis echo positions
Y–axis echo position R^2	coefficient of determination for the Y–axis echo positions
Z–axis echo position R^2	coefficient of determination for the Y–axis echo positions
Absolute change in X–axis + Y–axis target position	total up–down and left–right target movement
Absolute change in TS + absolute Z–axis position	total change in echo TS and target range
Ping-to-ping target velocity (PPV)	distance between all echo locations/elapsed time
Ping-to-ping target velocity standard deviation (PPV SD)	standard deviation of all PPV estimates for a target.

Table V. Non-significant individual acoustic parameters for Atlantic salmon and aquatic macrophyte targets, River Wye, Wales, October 1995.

Non-significant Acoustic Parameters
Mean sum channel echo voltage return
Standard deviation sum channel echo voltage return
Mean target position in the Y–axis (vertical)
Standard deviation of mean target position in the Y–axis
Mean TS standard deviation
X–axis R^2 (horizontal)
Y–axis R^2 (vertical)
Z–axis R^2 (range in m)

factor (BPF), which describes target position relative to the transducer axis in both X and Y planes. The BPF is zero for an on-axis target, and increasingly negative as the target moves off-axis.

3. RESULTS

3.1. Study background

Data files containing visually identified adult salmon targets were collected at the River Wye site on October 1 and 3, 1995. Comparative data including only verified aquatic macrophyte targets were obtained on October 23, 1995. Total sample size for the feasibility experiment was 23 salmon and 48 macrophytes ($n = 71$).

Results of the acoustic parameter comparisons between the two target groups are presented in *tables V-VII*. Significant differences were not observed between the distributions of several parameters (*table V*), such that group separation was marginal or non-existent. These included mean sum channel echo voltage return, SD of mean sum channel echo voltage return, mean target position in the Y–axis, SD of mean target position in the Y–axis, R^2 coefficients in all three axes, and target strength SD.

Table VI. Discriminant efficiency of significant individual acoustic parameters for Atlantic salmon and aquatic macrophyte targets. Values in *italics* represent parameters biased by the segregated upstream–downstream nature of the feasibility data set.

Acoustic parameter description	Significant single parameter comparison			
	Exclusionary			
	lower bound	upper bound	retained salmon (%)	excluded macrophytes (%)
Distance traveled in the X–axis (horizontal)	*< 0*	–	*100.0*	*100.0*
X–axis slope (regression of X–position on ping number)	*< 0.005*	–	*100.0*	*100.0*
Mean target swimming speed (velocity)	–	*> 2.25*	*100.0*	*85.4*
–6 dB pulse width standard deviation per target	–	> 1.4	100.0	77.1
–12 dB pulse width standard deviation per target	–	> 2.5	100.0	66.7
–18 dB pulse width standard deviation per target	–	> 3.0	100.0	56.3
Ping-to-ping target velocity (PPV) #1	–	*> 3.5*	*100.0*	*54.2*
Y–axis slope (regression of Y position on ping number)	> 0.0015	< 0.055	100.0	41.7
Mean target position in the Z–axis (range)	< 11	–	100.0	37.5
Mean –12 dB pulse width per target	–	> 12.0	100.0	37.5
Ping-to-ping target velocity standard deviation (PPV SD) #1	–	*> 3.3*	*100.0*	*37.5*
Mean –18 dB pulse width per target	–	> 13.0	100.0	33.3
Mean –6 dB pulse width per target	< 8.5	> 9.5	100.0	31.3
Z–axis slope (regression of Z position on ping number)	< –0.002	–	100.0	18.8
Standard deviation of mean target position in the X–axis	–	> 0.7	100.0	12.5
Beam pattern factor standard deviation	< 1.2	–	100.0	2.1
Ping-to-ping target velocity (PPV) #2	–	*> 2.8*	*95.7*	*83.0*
Ping-to-ping target velocity standard deviation (PPV SD) #2	–	*> 2.25*	*95.7*	*68.1*
Mean target position in the X–axis (horizontal)	> –0.5	< 0.5	65.2	100.0
Beam pattern factor	> –12	< –4	47.8	100.0
Distance traveled in the Z–axis (range from the transducer)	> –0.5	< 0.4	43.5	100.0
Standard deviation of mean target position in the Z–axis	–	< 0.2	39.1	100.0
Absolute change in Y–axis + Z–axis target position	< 0.7	–	34.8	100.0
Absolute TS × absolute change in Z–axis range	< 10	–	30.4	100.0
Mean target strength (TS)	–	> –20	17.4	100.0
Mean Y–axis + Z–axis distance traveled	< 0.5	–	13.0	100.0
Distance traveled in the Y–axis (vertical)	> –0.4	< 0.3	8.7	100.0

Table VII. Discriminant efficiency of multiple acoustic parameter arguments for Atlantic salmon and aquatic macrophyte targets.

Parameter argument	Significant multiple parameter comparison			
	Exclusionary			
	lower bound	upper bound	retained salmon (%)	excluded macrophytes (%)
–6 dB pulse width standard deviation per target and/or,	–	> 1.4	100.0	87.5
–12 dB pulse width standard deviation per target	–	> 2.5		
–6 dB pulse width standard deviation per target and/or,	–	> 1.4	100.0	93.8
–12 dB pulse width standard deviation per target and/or,	–	> 2.5		
Y–axis slope	–	> 0.0015		
–6 dB pulse width standard deviation per target and/or,	–	> 1.4	100.0	95.8
–12 dB pulse width standard deviation per target and/or,	–	> 2.5		
Y–axis slope and/or	–	> 0.0015		
Mean target position in the Z–axis (range)	< 11	–		
–6 dB pulse width standard deviation per target and/or,	–	> 1.4	100.0	91.7
–12 dB pulse width standard deviation per target and/or,	–	> 2.5		
Ping-to-ping target velocity (PPV).	–	> 3.5		
–6 dB pulse width standard deviation per target and/or	–	> 1.4	100.0	89.6
–12 dB pulse width standard deviation per target and/or,	–	> 2.5		
Ping-to-ping target velocity standard deviation (PPV SD).	–	> 3.3		
Mean target position in the X–axis (horizontal) and/or,	> –0.5	< 0.5	73.9	100.0
Absolute change in X–axis + Y–axis target position	< 0.7	–		
Mean target position in the X–axis (horizontal) and/or,	> –0.5	< 0.5	78.3	100.0
Absolute change in X–axis + Y–axis target position and/or,	< 0.7	–		
Standard deviation of mean target position in the Z–axis	–	< 0.2		

Where significant differences in the distributions of individual acoustic parameters were observed, the percent retention/exclusion efficiency for each target type was estimated (*table VI*). These included distance traveled in the X–axis (horizontal), X–axis slope (regression of X–position on ping number), mean target velocity, target pulse width and pulse width standard deviation at the –6, –12, and –18 dB echo amplitude power points, mean target position and slope in the X–, Y– and Z–axes, ping-to-ping target velocity and standard deviation, beam pattern factor and standard deviation, and distance traveled in each axis.

The most discriminant individual acoustic parameters were combined in multiple parameter arguments to optimize separation between the two target types (*table VII*).

Several acoustic descriptors were considered to be biased in the small feasibility data set and were not considered in subsequent analyses. All visually-identified salmon exhibited net upstream movement and all macrophytes were moving downstream. Longer-term observations indicated that this was not representative of conditions in a larger sample at the River Wye site. Significant downstream-movement of salmon does occur, depending on season and flow conditions. Descriptors effected by the apparent upstream-downstream bias in the evaluated data set included distance traveled in the transducer X–axis (upstream–downstream movement), mean number of echo returns per target and mean target velocity (downstream-moving targets exhibited higher velocities). Although these parameters demonstrated levels of target separation between 85–100%, they were not representative of long-term conditions. The biased descriptors were not considered in the final analyses, but are presented in *italics* in *table VI*.

In addition, target strength distributions of the two groups overlapped. Observed mean adult salmon TS values in this data set varied between –17 and –26 dB. Mean TS values for the macrophyte data set varied between –20 and –28 dB, generally overlapping the salmon-only data set. Excluding targets smaller than –20 dB removed 100% of the observed macrophytes, but also 83% of all salmon targets.

Based on these site observations, target strength and upstream–downstream movement were not considered as discriminators for the mixed salmon and macrophyte data set evaluated during the feasibility study.

3.2. Pulse width

Mean echo pulse width distributions generally overlapped at the measured –6, –12, and –18 dB echo amplitude points for the salmon and macrophyte target groups. Pulse elongation consistent with multiple-scattering was observed to a greater degree for macrophytes, but the majority of identified plant targets returned single-target echo returns similar to those of observed salmon. At the –6 dB pulse width, 31% of all macrophytes were excluded from the data set by removing all targets with a mean pulse width < 8.5 and/or > 9.5 samples. Removing all targets with a –12 dB mean pulse width ≥ 12 samples resulted in

38% macrophyte exclusion. Exclusion of all targets with a mean –18 dB pulse width of > 13 samples, removed 33% of the macrophytes by excluding targets with PW SD ≥ 3.0 samples. All of the exclusionary macrophyte values assume 100% retention of salmon targets in the mixed data set.

3.3. Pulse width standard deviation

From the evaluated data set, pulse width standard deviation (PWSD) at the –6, –12, and –18 dB power points were the most effective single parameters for differentiating macrophytes from adult salmon. Using the –6 dB PWSD (1/2 power point) measurement as the sole separation criterion, 77% of the macrophyte targets were excluded from the data set by removing all targets with PWSD ≥ 12 samples. Removing all targets with a –12 dB PWSD (1/4 power point) ≥ 2.5 samples resulted in 67% macrophyte exclusion. The –18 dB PWSD (1/8 power point) was less discriminant, removing 56% of the macrophytes by excluding targets with PWSD ≥ 3.0 samples.

3.4. Mean target velocity

Mean target velocity distributions, as calculated in the *.FSH* output files, were also found to differ between the macrophyte and fish groups. Macrophytes typically returned higher estimated velocities, up to 6.5 $m \cdot s^{-1}$, relative to a maximum observed fish velocity of 2.2 $m \cdot s^{-1}$. These velocity values are calculated based on estimated echo-to-echo positions over the total ensonified period, and may be biased high, but are comparable between groups. Removing targets with mean velocities ≥ 2.0 $m \cdot s^{-1}$ eliminated 85% of the macrophytes (41 of 48 targets), with no exclusion of salmon targets.

3.5. Ping-to-ping target velocity

Ping-to-ping target velocities (PPV) and standard deviation (PPV SD) were investigated to determine if the relatively diffuse structure of the macrophytes, with multiple associated air bubbles, returned more widely scattered echo positions relative to salmon. If consecutive echoes were more widely distributed in three-dimensional space, estimated target velocity between pings would be artificially elevated.

The observed range of PPV values for macrophytes was between 0.9 and 8.1 $m \cdot s^{-1}$, with a mean target PPV of 3.1 $m \cdot s^{-1}$. The range of PPV for salmon targets was between 0.9 and 3.3 $m \cdot s^{-1}$, with a mean target PPV of 1.9 $m \cdot s^{-1}$. Excluding targets with mean PPV ≥ 3.5 $m \cdot s^{-1}$ eliminated 54% of the macrophytes, with no exclusion of salmon targets (26 of 48 targets). However, as discussed above, this difference may have been due to either the potentially higher velocity of downstream-moving macrophyte targets, or increased variability in successive echo position from macrophyte targets, relative to upstream-migrant salmon.

3.6. Ping-to-ping target velocity standard deviation

The standard deviation for each target was then calculated based on the PPV values. For macrophyte targets, the range of PPV SD was 0.5 to 5.9 $m \cdot s^{-1}$, with a mean PPV SD of 4.1 $m \cdot s^{-1}$. For salmon targets, the range of PPV SD was 0.9 to 3.3 $m \cdot s^{-1}$, with a mean PPV SD of 1.6 $m \cdot s^{-1}$. Excluding targets with mean PPV SD ≥ 3.3 $m \cdot s^{-1}$ eliminated 38 % of the macrophytes, with no exclusion of salmon targets (18 of 48 targets). One of the salmon targets appeared to be an outlier, with significantly higher PPV and PPV SD values (3.3 $m \cdot s^{-1}$ for both values) relative to the remainder of the salmon data set. For the remainder of the salmon data set, maximum PPV was 2.8 $m \cdot s^{-1}$ and PPV SD was 2.25 $m \cdot s^{-1}$. If the single salmon outlier is excluded from the combined data set), 83% of all macrophytes could be removed by excluding all targets with a mean PPV > 2.8 $m \cdot s^{-1}$ (39 of 47 targets), and 68% of all macrophytes could be removed by applying a PPV SD > 2.25 $m \cdot s^{-1}$ (32 of 47 targets).

3.7. Y-axis slope

Mean target Y–axis slope reflects net up–down target movement in the water column. Applying exclusionary bounds of mean Y–axis slope > 0.0015 and < 0.055 removed 42% of all aquatic macrophytes, retaining all salmon. Macrophytes appeared to exhibit greater measured vertical movement over time relative to salmon.

3.8. Multiple parameter arguments

Combinations of multiple PW SD criteria increased target resolution in the combined data set (*table VII*). Rejecting all targets with a –6 dB PWSD ≥ 1.4 samples and/or a –12 dB PWSD ≥ 2.5 samples resulted in an 88% macrophyte rejection rate (42 of 48 targets). Incorporating the –18 dB PWSD parameter in a combined PWSD argument (–6, –12 and –18 dB power points) did not increase total macrophyte exclusion.

Adding Y–axis slope exclusionary criteria of ≥ 0.0015 and ≤ 0.055 to the above –6 and –12 dB PWSD argument resulted in 94% macrophyte removal.

If mean Z–axis range ≤ 11.0 m argument is added to the above argument (in addition to the above three criteria), 96% of all macrophytes were removed from the data set, without excluding any identified salmon.

This final argument, which provided the highest percentage of macrophyte exclusion in the feasibility data set can be expressed as exclusion of all targets with: –6 dB PWSD ≥ 1.4 dB, and/or –12 dB PWSD ≥ 2.5, and/or Y–axis slope between 0.0015 and 0.055, and/or mean target Z–axis range < 11.0 m.

Although velocity was suspect as a representative parameter for the feasibility data set (due to biases in upstream-downstream directionality of the selected data), multiple-criteria combinations were tested to assess potential overall macrophyte exclusion efficiency for future study. A combination of removing all targets with –6 dB PWSD ≥ 1.4 and/or –12 PWSD ≥ 2.5 and/or PPV ≥ 3.5 $m \cdot s^{-1}$ resulted in a 92% rejection rate for macrophytes (44 of 48 macrophytes). If PPV SD > 3.3 $m \cdot s^{-1}$ (*figure 1*) is substituted in place of PPV ≥ 3.5 $m \cdot s^{-1}$ in the above argument, 90% of all macrophytes are rejected (43 of 48 macrophytes), with no impact on total salmon counts.

For cases where the salmon target parameter distribution overlapped (was greater than) that of the macrophyte targets (i.e. criteria bounds of that parameter which excluded all macrophytes also removed some fish), a second analysis was conducted with the objective of retaining the maximum number of salmon while excluding all macrophytes. The descriptors tested with these distributions were mean target position in the X–axis, Z–axis SD (change in range from the transducer), mean beam pattern factor (BPF), absolute distance traveled in the Y–axis, absolute distance traveled in the Z–axis, absolute change in the Y–axis + Z–axis target position, absolute TS × absolute distance traveled in the Z–axis, mean distance traveled in the Y–axis + Z–axis, and mean TS. These parameters were evaluated individually (*table VI*) and combined in multiple parameter arguments (*table VII*).

Excluding all targets with a mean horizontal (X–axis) position of < –0.5 m left and/or ≤ 0.5 m right of the transducer beam axis, and/or an absolute net distance traveled in the Y + Z axes of ≤ 0.7 m resulted in 74% retention selection of all identified salmon (17 of 23), and removal of all macrophytes. Adding a Z–axis (range) standard deviation exclusionary argument of ≤ 0.2 m to the above selection argument retained 78% of all salmon (18 of 23), while excluding 100% of macrophytes.

4. DISCUSSION

Pulse width standard deviation (PWSD) at the –6 and –12 dB echo amplitude points was determined to be the best univariate descriptor of target type, providing the greatest degree of resolution between the macrophyte and Atlantic salmon groups. This is consistent with Burwen and Fleischman (1998), who determined –12 dB PWSD to be the most effective single parameter for resolving two species of tethered Pacific salmon on the Kenai River.

Macrophytes exhibited greater PWSD relative to Atlantic salmon. The differences observed in PWSD distributions between the two groups may indicate that aquatic macrophytes were less ideal point-source reflectors than adult salmon. The diffuse morphology of the *Ranunculus* aggregations, with associated scattered air bubbles may act as multiple-point reflectors. Macrophytes demonstrated greater pulse elongation relative to salmon, which are generally expected to act as point-source targets.

Incorporating the –18 dB PWSD criterion in a multiple PWSD argument did not improve overall macrophyte exclusion in the tested data set. This may have been due to noise impacts. Riverine acoustic monitoring sites typically have low signal-to-noise ratios due to both reverberant and non-reverberant sources. Although FM slide techniques were implemented at the River Wye study to minimize non-reverberant noise, the –12 dB pulse width value could not be resolved for 30% of the returning echoes, and the –18 dB value could not be resolved for 67% of the samples. The use of a narrower transducer beamwidth in future studies may minimize reverberant noise and allow improved resolution of echo pulse widths at the –12 and –18 dB echo amplitude points.

Combined measurements of target echo PWSD at the –6 and –12 dB power points were determined to be the most effective discriminators between the macrophyte and adult salmon populations. These parameters should be used as the starting point for future investigations on a larger data set. If signal-to-noise ratios can be achieved which allow consistent measurement of the –18 dB echo pulse width, a multiple PWSD argument incorporating observations at all three available power points (–6, –12, and –18 dB) should be investigated. Echo pulse width selection criteria should not be applied in future studies, allowing all pulse width returns to be written to data file for comparison.

Echo pulse width at the three measured echo amplitude points (–6, –12, and –18 dB) provided only moderate resolution between Atlantic salmon and macrophytes, excluding between 31–38% of macrophytes with 100% salmon retention. Burwen and Fleischman (1998) reported mean proportions of correct target classification of 80% and 85% based on –6 and –12 dB pulse widths during comparison of chinook *(Oncorhynchus tshawyscha)* and sockeye *(O. nerka)* salmon.

Mean target velocity distributions were also found to differ between the macrophyte and fish groups. Macrophytes typically returned higher estimated velocities than salmon. This was true for both methods of target velocity estimation, as calculated as mean velocity through the ensonified area and on a mean ping-to-ping basis. Discrimination based on mean target velocity removed 85% of all macrophytes from the data set retaining all salmon. Based on mean ping-to-ping velocities, 54% of macrophytes were removed.

Two possibilities were considered as the cause of this observed difference in mean velocity between groups. As the HTI tracking software calculates velocity based on echo-to-echo distance over time for each grouped target, the macrophytes may have returned high overall velocity estimates due to their acoustic reflective characteristics, i.e. the scattered positions of their echo returns. However, it was also possible that the higher macrophyte velocity was an artifact of the direction of travel of the macrophyte and salmon groups in the feasibility data set. The visually identified aquatic macrophyte targets all exhibited downstream movement with current flow, while all of the salmon targets were moving upstream. The lower velocities for the salmon data set may have been due to slower movement upstream against the current, while the macrophyte targets had faster net downstream movement consistent with the direction of water flow.

Target velocity standard deviation was investigated to determine if echo position was more variable for the tracked macrophyte data, i.e. if these targets returned more widely scattered echo positions relative to salmon. For the entire data set, velocity standard deviation was able to remove only 38% of all macrophytes. As velocity standard deviation offered only moderate levels of macrophyte discrimination relative to mean target velocity, it is possible that the observed difference in mean velocity between the two target types was due to both an actual difference in the rate of change of movement (upstream–downstream) and increased variability in successive echo position from macrophyte targets, relative to salmon. The segregated nature of upstream–downstream movement in the feasibility data may have impacted the ability to objectively evaluate velocity standard deviation as a descriptor between the two groups. Future evaluations on a larger data set should include both upstream- and downstream migrant salmon.

Measurements of absolute target position in the transducer beam (X, Y and Z–axes) and target BPF were tested during the feasibility evaluation, but may not be suitable as discriminators for future separation of salmon and macrophytes. These parameters provided relatively low levels of target separation and were likely specific to the small tested data set. Future monitoring at any site should evaluate a large data set over time to determine if consistent differences in spatial distribution exist between target groups.

The hydroacoustic feasibility evaluation of Atlantic salmon and macrophyte discrimination on the River Wye determined that the side-aspect hydroacoustic data contained substantial information, which could be extracted to estimate target type. Although target strength and upstream–downstream direction-of-movement distributions overlap between the two target groups, pulse width standard deviation demonstrated promise for resolving the two groups. Pulse width variability was generally greater for macrophytes, presumably due to their diffuse morphology relative to salmon.

Future investigations at the River Wye site should evaluate a larger data set and include representative salmon behavior (both upstream and downstream migrants). Equipment deployment should be optimized to minimize ambient acoustic noise and utilize a narrower-beam (2×10) elliptical transducer to minimize reverberant noise. Single-target pulse width selection filters should not be applied during data collection to maximize pulse width resolution in the data set.

Data collection and/or analysis software should be revised to output a data file format including all variables of interest. Relational databases provide a powerful tool for quickly evaluating differences between all possible combinations of parameters in large data sets and should be employed for future analyses.

Periodic target verification using video techniques should be conducted during future studies to ensure that changes in target population, distribution, behavior, or hydraulic conditions do not effect the discrimination of the selection parameter arguments.

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