Fisheries Research 220 (2019) 105347

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Using acoustic telemetry to expand sonar escapement indices of Chinook salmon to in-river abundance estimates

Suzanne L. Maxwell[a,*], Greg B. Buck[b], April V. Faulkner[a]

[a] Alaska Department of Fish and Game, 43961 K-Beach Road, Suite B, Soldotna, Alaska, 99669, USA
[b] Alaska Department of Fish and Game, 333 Raspberry Road, Anchorage, Alaska, 99518, USA

ARTICLE INFO

Handled by George A. Rose

Keywords:
Acoustic telemetry
Chinook salmon
Dual-frequency identification sonar (DIDSON)
Drift gillnetting
Migration behavior

ABSTRACT

Acoustic telemetry was combined with a project that uses sonar and drift gillnetting methods to estimate Chinook salmon *Oncorhynchus tshawytscha* escapement in the Nushagak River, Alaska. The sonar project uses dual-frequency identification sonars (DIDSONs) to count passing fish and drift gillnetting to apportion sonar estimates to species. These estimates are indices because the river's width (~300 m) and uneven bottom topography allow for only a third of the river to be sampled. This range is enough to fully enumerate sockeye salmon *O. nerka*, the dominate species, but not Chinook salmon, which are known to migrate beyond the sampling range. Acoustic telemetry was used to determine what proportion of Chinook salmon traveled within the sampling range of the sonar project. We inserted acoustic tags into Chinook salmon ~13 km downriver and deployed an array of acoustic receivers at the sonar site to track tagged fish. From 2011 to 2014, 799 Chinook salmon were tagged. The tagged fish used the entire river width while migrating through the acoustic array exhibiting a wide variety of behaviors that included moving straight through the array, making multiple up and down trips, holding, and crossing over from one side of the river to the other. On average, 57% of tagged fish traveled through regions sampled by the sonar with annual percentages of 65% (2011), 54% (2012), 64% (2013), and of 47% (2014). These proportions were used to expand the sonar-derived indices to in-river abundance estimates.

1. Introduction

Acoustic telemetry has been widely used to track movements of juvenile and adult fish in a variety of environments including lakes (Hayden et al., 2014), estuaries (Childs et al., 2008), oceans (Chittenden et al., 2009; Starr et al., 2005), and rivers (Heublein et al., 2009; Mathes et al., 2010; McMichael et al., 2010). Dual-frequency identification sonar (DIDSON; Belcher et al., 2002) and ARIS (Adaptive Resolution Imaging Sonar; i.e., the DIDSON replacement) have been successfully evaluated for assessing passage rates of migrating adult sockeye salmon *Oncorhynchus nerka* (Holmes et al., 2006; Maxwell and Gove, 2007) and other fish species (Egg et al., 2018). DIDSON or ARIS imaging sonars are widely used to assess fish escapement (Buck, 2013; El Mejjati et al., 2010; English et al., 2017; Maxwell et al., 2011; Miller et al., 2013; Pipal et al., 2012), as well as fish composition and species-specific movement patterns (Crossman et al., 2011; Grote et al., 2014). If multiple species co-migrate and are similar in size, then estimating salmon abundance using DIDSON requires a method to apportion the sonar counts to species. The Alaska Department of Fish and Game (ADF&G) operates a sonar project ~50 km upriver from the mouth of the Nushagak River to estimate escapement into the watershed of sockeye, chum *O. keta*, and Chinook salmon *O. tshawytscha*. The project combines sonar (DIDSON) to estimate fish passage and drift gillnetting methods (test fishing) to apportion the sonar estimates to species (Buck et al., 2012; Buck, 2013). These methods are satisfactory for estimating chum and sockeye salmon. However, Chinook salmon escapement estimates are considered indices and not abundance estimates because this species is known to migrate beyond the sampled regions (Miller, 2000). The stability of the indices had not been assessed. This is a concern because commercial and sport fishery management plans based on this Chinook salmon index have been in place since 1992 (Nushagak-Mulchatna King Salmon Management Plan 5 AAC 06.361).

Mark-recapture studies have been used to ground-truth salmon estimates from sonar projects (Mora et al., 2015; Rakowitz et al., 2009; Rawding and Liermann, 2011; Reimer and Fleischman, 2016). Although mark-recapture studies provide an abundance estimate for comparison, it does not provide specific information on where salmon are traveling in the river and what changes might be made to the sonar

* Corresponding author.
E-mail addresses: suzanne.maxwell@alaska.gov (S.L. Maxwell), gregory.buck@alaska.gov (G.B. Buck), april.faulkner@alaska.gov (A.V. Faulkner).

https://doi.org/10.1016/j.fishres.2019.105347
Received 14 November 2018; Received in revised form 31 July 2019; Accepted 18 August 2019
0165-7836/ Published by Elsevier B.V.

project to improve it. Acoustic telemetry had the potential to provide this additional information. However, large, shallow rivers are a difficult environment for acoustics (Faulkner and Maxwell, 2015). Surface and boundary layers interfere with signal propagation and cause multipathing of the signal, and uneven bottom topography produces acoustic shadow zones. We first tested an acoustic telemetry system in the Kenai River, Alaska, a smaller river on the road system that is easier to access, to determine how well the system would work in a riverine environment. A single hydrophone was deployed on one bank and then moved to the opposite bank. Acoustic tags were placed at stationary positions for a period of time and then pulled alongside a boat through the test region. The acoustic tags were detectable across the river and up and downriver as far as 200 m in each direction. These results convinced us to proceed with the study at the Nushagak River.

For this study, acoustic tags were inserted into Chinook salmon in the lower Nushagak River ~13 km below the sonar site. An array of receivers was deployed at the sonar site to detect tagged fish. Our objectives were to: 1) Examine the spatial distribution of migrating Chinook salmon to determine the proportion that passed within the sonar and test-fishing sampling range; 2) Examine Chinook salmon behavior to determine the effects on sonar estimates; and 3) Examine differences in fish lengths between fishing zones and between the upriver and downriver sites.

2. Methods

2.1. Sonar and gillnetting operations

At the sonar site, a DIDSON was deployed several meters from each shoreline in water deep enough to ensure the sonar remained underwater throughout a tidal stage that is typically ~0.4 m at the project site. A weir was constructed immediately downstream of each sonar extending ~1 m beyond the face of the sonar to prevent fish passage behind the sonar. Drift gillnets were deployed just below the ensonified regions for species apportionment (Buck, 2013). The DIDSONs were deployed with the beams pointed offshore perpendicular to current flow. The sampling range along each bank was divided into 2 strata, a 1–10 m nearshore stratum off both banks, a 10–30 m offshore stratum on the left side of the river (facing downstream) and a 10–50 m offshore stratum on the right bank. For each stratum, fish were counted from DIDSON files for 10 min. h, a sampling design that has been tested for sockeye salmon (Seibel, 1967) and a variance has been estimated (Reynolds et al., 2007). Three gillnet mesh sizes (20.6 cm (8.125 in., 29 meshes deep; 15.2 cm (6.0 in., 45 meshes deep; and 13.0 cm (5.125 in., 45 meshes deep) each 18.3 m long (10 fathoms) were drifted through regions directly below each sonar strata. Buoys marked the end range of each stratum. Daily estimates of Chinook salmon were obtained by counting all fish images in DIDSON 10-min/h files, expanding the counts to an estimate of daily passage by counting strata, and apportioning the strata estimates using proportional catch per unit effort (CPUE) of each species in each stratum. A DIDSON Chinook salmon count as it is used in this paper is a simplification that refers to a count obtained from the expanded and then apportioned sonar estimates.

2.2. Tag insertion

Acoustic tags were inserted into Chinook salmon at a site that was presumed to be far enough upriver from the mouth (37 km) to avoid tagging fish whose ultimate destination might not be the Nushagak River and far enough downriver of the sonar site (13 km) to allow fish to normalize their swimming behavior before reaching the detection zone. At the insertion site (Fig. 1), the river flows through one unobstructed main channel (Tag Insertion Site 1) with a small side channel (Tag Insertion Site 2). The sites experienced tidal fluctuations of ~2 m.

A bathymetry map of the 2 channels was produced in 2011 to determine the depths across the river and whether the site was adequate for drifting gillnets. A Simrad EK60 echo sounder with a 4° 200 kHz single-beam transducer (ping rate 5 pings/s, pulse duration 0.128 ms, power 250 W) was used to obtain depth data. The unit was pole-mounted to a boat with the transducer placed ~0.25 m below the water surface. A Trimble DSM212H Global Positioning System (GPS) unit provided positioning information at a rate of 10 Hz with differential corrections received from the U.S. Coast Guard Differential GPS station in Kodiak. Hypack version 2011 was used to follow survey lines, bottom-track the acoustic data, and correct depth information for the vertical mounting offset and changes in water surface elevation that occurred over the course of the survey. Water surface elevation was read from a staff gauge at half-hour intervals during the surveys. Depth values were referenced to the water surface elevation at the beginning of each survey. Bathymetry data were processed using ESRI ArcGIS version 10.2 with the Spatial Analyst extension for raster-based spatial analyses and the Geostatistical Analyst extension for the interpolation of the bathymetric data using kriging without anisotropy. Map data were projected in WGS 1984 UTM Zone 4 N coordinates. The resulting geostatistical surface was converted to a raster. The final map was generated from a triangulated irregular network built from 0.05 m contour lines extracted from the raster.

The main channel was a long, straight stretch ~275 m wide. The bathymetry showed the river bottom dropping off smoothly from both shores with no significant debris obstructions or sand bars (Fig. 2). The shallow side channel was deepest at the downriver end, had a low flow rate, and was inaccessible by boat during low tide. Although the side channel did not appear to be a significant migratory route, it was included as a drift station so that all Chinook salmon migrating the Nushagak River would be available for capture.

A tagging schedule was implemented to tag fish in proportion to their abundance across a 6-week period based on historical run timing. Fish were captured using drift gillnets with effort concentrated around the high tides. Three fishing zones were established at Site 1 (zone1: right-bank, zone 2: mid-channel, and zone 3: left-bank). Zone 4 was established at Site 2 close to where it rejoined the main channel upriver. Two gillnet mesh sizes were used (20.6 cm (8.125 in., 29 meshes deep and 15.2 cm (6.0 in., 45 meshes deep), both 18.3 m long (10 fathoms). These nets were identical to the two nets that account for the overwhelming majority of Chinook captured for apportionment at the sonar site. The nets were mono twist filament webbing dyed a translucent green, identical to the nets used at the sonar site for apportionment (Buck, 2013). The primary difference between the netting at the upper and lower river sites was that the upper river test fishing included a smaller mesh size (13.0 cm) geared for sockeye salmon that was omitted from the acoustic tag study.

To minimize stress on fish, nets were pulled in as soon as a fish was detected, limiting each haul to 1 or 2 fish. The short drift time reduced the amount of time a fish had to become tangled and reduced the stress of capture. A live tank held the captured salmon prior to tagging. The tank was emptied and refilled multiple times daily to freshen the water. Once the net was pulled in, the 1 or 2 fish were processed in approximately 1.5–2 min and released. Captured Chinook salmon in poor shape were released without a tag. The biggest factor in determining 'poor shape' was fish energy. Lethargic fish or those with damaging hook or net marks were deemed poor. Few fish, an estimated 2%, were rated as poor.

Lotek, Inc. model MM-TP 16–25 MAP acoustic tags were inserted into the gullet of Chinook salmon using a long plastic tube (Fig. 3). Fish length from mid-eye to tail fork (MEF) was measured, a scale sample was collected, and the tag identification number (ID) was recorded. The acoustic tags were 16 mm (diameter) x58 mm (length), weighed 27 g in air, and transmitted a 76 kHz pulse every 2 s continuously. We discussed the possibility of producing tags that would emit a sound pulse at one of the DIDSON frequencies. However, a pulse emitted from a tagged fish would not be synchronized with the DIDSON's listening

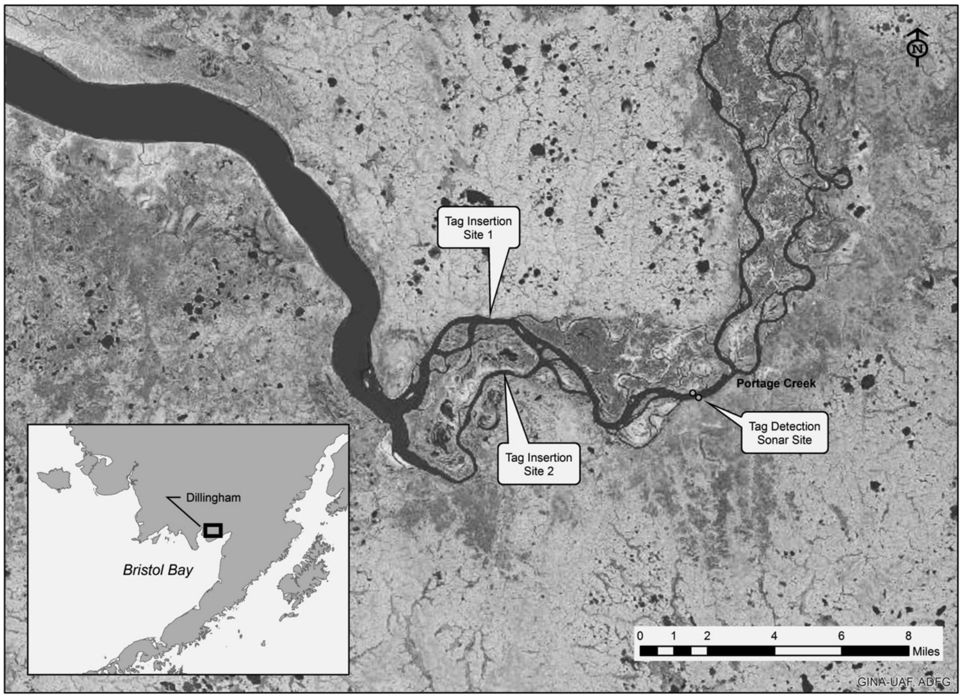

Fig. 1. Acoustic tag insertion and detection sites in the lower Nushagak River.

range. The DIDSON determines the range of a returned signal, i.e., an echo, based on the time it takes the sound pulse to travel to the end of the range setting and return to the DIDSON receiver. A transmitted pulse from a tagged fish, if detected, would not represent the actual range of the fish relative to DIDSON. In addition, active pings are easier to detect than echoes and may be detected whether the tagged fish physically passed through the DIDSON beam or not.

2.3. Tag detection

An array of receivers was installed at the sonar site to detect the acoustic tags. The sonar project and acoustic tag array were operated concurrently. The site is 50 km upriver from the mouth of the Nushagak

Fig. 3. The tube used to insert acoustic tags into salmon (left), and a tag recovered by the test-fish crew at the sonar site (right).

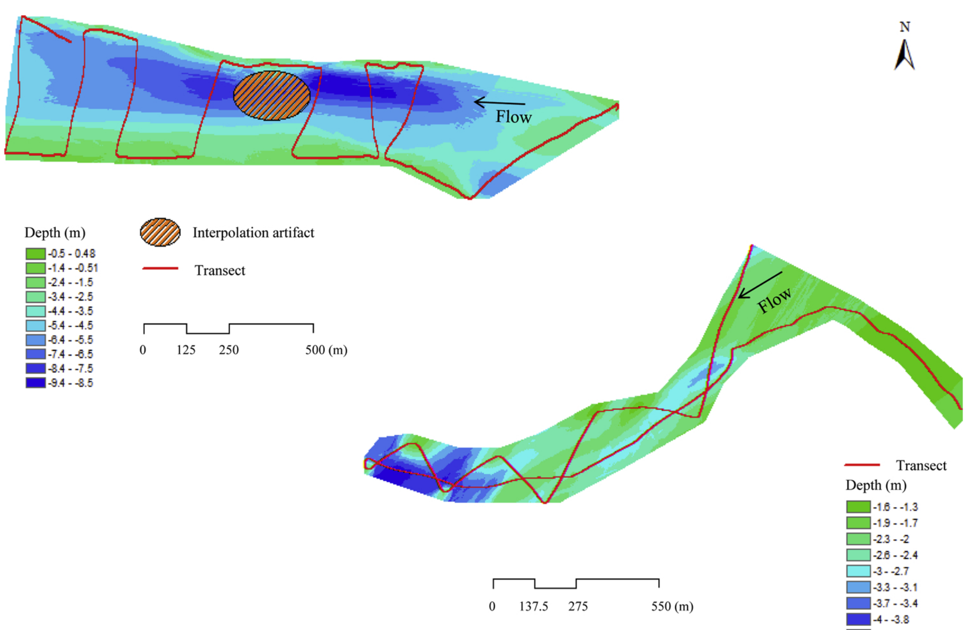

Fig. 2. Bathymetry of the acoustic tag insertion site within the Nushagak River's main channel (top-left) and side channel (bottom-right), 6/8/2011.

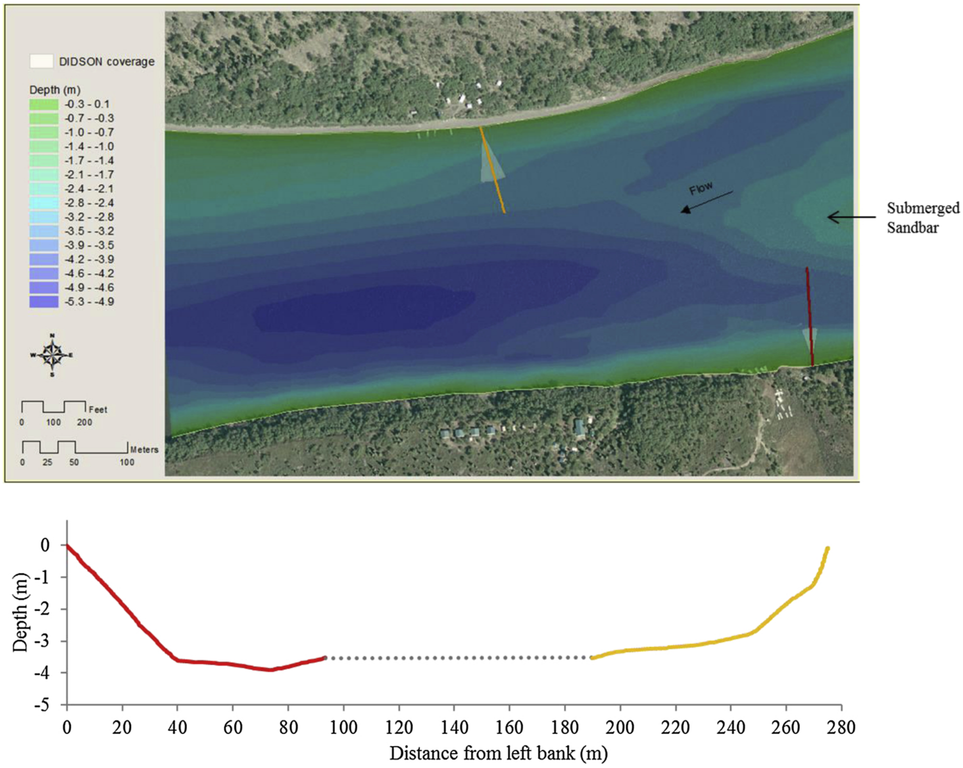

Fig. 4. Bathymetry map of the Nushagak River at the sonar site (top) and a river bottom profile (bottom) extracted from the bathymetry data to show the DIDSON deployment sites along either side of the river, 6/7/2011.

River and 4 km downriver from the village of Portage Creek. Here, the river is 300 m wide and flows within a single channel. While the river height fluctuates by ~0.4 m due to tides, no flow reversal occurs. Water level typically drops across the summer as snow melt declines, although temporary surges follow periods of excessive rain.

Bathymetry maps were produced in 2011 and 2012 at the sonar site to provide information on the best placement for the acoustic array and determine whether changes in the bottom topography occurred between years. In 2011, the bathymetry equipment described for the lower river tag insertion sites was used. In 2012, we used the vertical beam of a Sontek River Surveyor M9 Acoustic Doppler Current Profiler (ADCP; dual 4-beam 3.0 MHz/1.0 MHz) to collect depth data and an Ashtech Mobile Mapper 100 GPS with GLONASS (Global Navigation Satellite System) to georeference the data. Survey lines were spaced 15 m apart. The relative difference in depth between the 2011 and 2012surveys was calculated with ArcGIS Spatial Analyst Extension (map algebra with cell size 10 m × 10 m). The mode of the depth differences between the two surveys was used to empirically reference the 2012 data to the reference elevation determined for 2011.

At the array site, the river channel is characterized by a gradual slope along the right bank, steeper slope along the left bank, relatively flat center, and submerged mid-river sandbar (Fig. 4). Profiles extracted from the 2011 bathymetry data show smooth sloping shores along both sides of the river where the sonars are deployed. The 2012 bathymetry map (Fig. 5) was similar to the 2011 map with differences caused by a buildup of substrate along the right shore and erosion along the left shore (Fig. 6).

Prior to the first year of the study, a series of feasibility tests were done at the Nushagak River sonar site to determine whether the acoustic tags would be detectable across the river. The tests included static tests where a tag was moored at a surveyed location within the array footprint, tow tests where a series of 3 tags at different depths were suspended from a boat or buoy and drifted downriver through the array, accuracy tests where position estimates of the towed tag were compared with GPS tracks, and cross-channel detection tests where two boats were located on opposite shores and receivers were mounted closer to shore and farther from shore to determine the best locations. For tests 1–3, 4 Lotek WHS 3050 wireless acoustic data-logging receivers (DLs) were deployed, two along each side of the river 200 m apart. Beacon tags (MM-16-50, high power, 76 kHz) were attached to three of the DLs. Beacons were similar to fish tags except they had a larger battery, slower burst rate (30 s intervals), and no pressure or temperature sensors. The beacon tags were used to synchronize the array and determine whether each DL could detect the other beacons. Detection ranges up to 600 m were observed, with 300 m more typical. Detection ranges varied with weather conditions and other factors including the orientation of the tag and DL. Lotek, Inc. produced a report with descriptions and results of each test, which is included in its entirety in Maxwell et al. (2019b). Following deployment each year of the study, the array was retested for blind spots by drifting test tags through the array at various depths. The DL's were moved as needed to improve detection.

Based on the feasibility tests, Lotek, Inc. recommended deploying 6 DLs. In 2011, 6 DLs were deployed, 7 in 2012 and 2013, and 8 in 2014. A beacon tag was attached to each DL, with an additional beacon attached to a buoy placed at the end range of the right-bank sonar. It was thought that this offshore beacon might be in a better position to be detected by the DLs and improve the synchronization of the array. In 2011–2013 arrays consisted of two lines of tripods close to each shore with no mid-river deployment due to heavy boat traffic in this region. In 2014, an additional DL was deployed on the mid-river sandbar. We felt this posed minimal risk to boat traffic while potentially improving tag detection. The DLs were attached to tripods with the transducers pointed down to place them at deeper depths. The tripods were carried out from the bank at low tide and set in water ~1.5 m deep (i.e., maximum chest wader depth). The latitude and longitude of each tripod was recorded with the Ashtech Mobile Mapper. We ran a cable to shore from one DL on each bank to download data without having to move the tripods. These were periodically checked to assess tagging mortality in-season and to determine when the DLs could be pulled at the seasons'

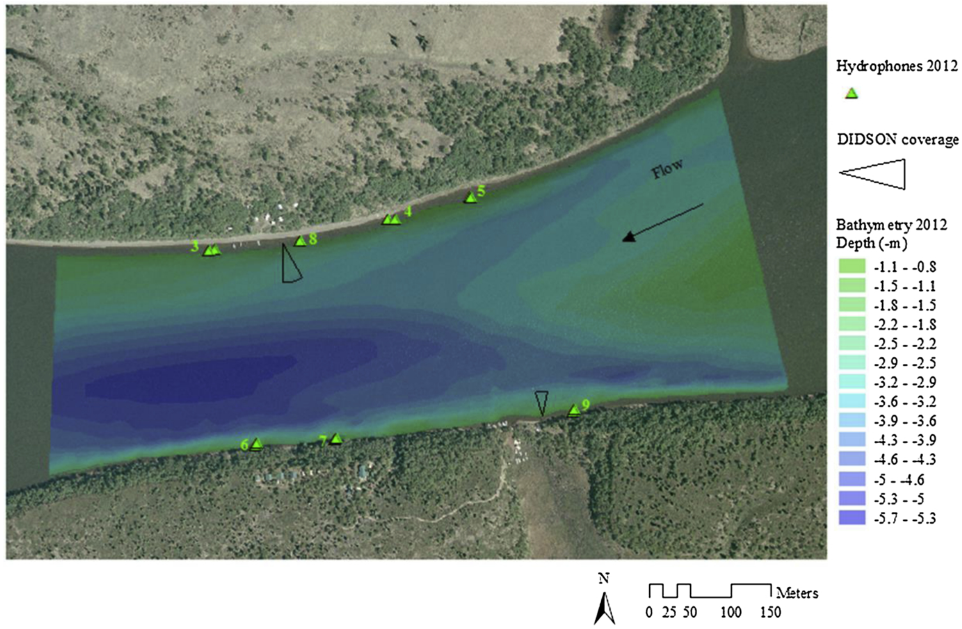

Fig. 5. Bathymetry map of the region encompassing the acoustic array, 7/2/2012.

end without missing tags. In 2011, all DLs were pulled from the river multiple times during the field season to check batteries and ensure the hard drives did not overfill. After the first year, we learned that the battery life and hard drive space of the DLs were sufficient for the entire field season, so downloads were reduced to the cabled DLs. Not moving the DLs in-season improved our ability to process the tag data. Eventually, we cabled all DLs to avoid moving them in and out of the water in season.

2.4. Tag processing

Tag data were processed using software packages from Lotek, Inc. To determine which tagged fish had been detected, WHS Reader version 2.1 was used to convert the tag data to text files. The text files were condensed by tag ID and DL to produce the date and time of the first and last detection and number of rows of data (i.e., the number of detections). Two positioning software programs were used to produce position estimates for the tagged fish, Asynchronous Logger Positioning Software (ALPS) and U-Map. Data processing from 2011 to 2013 used different versions of ALPS software updated each year by Lotek, Inc. to

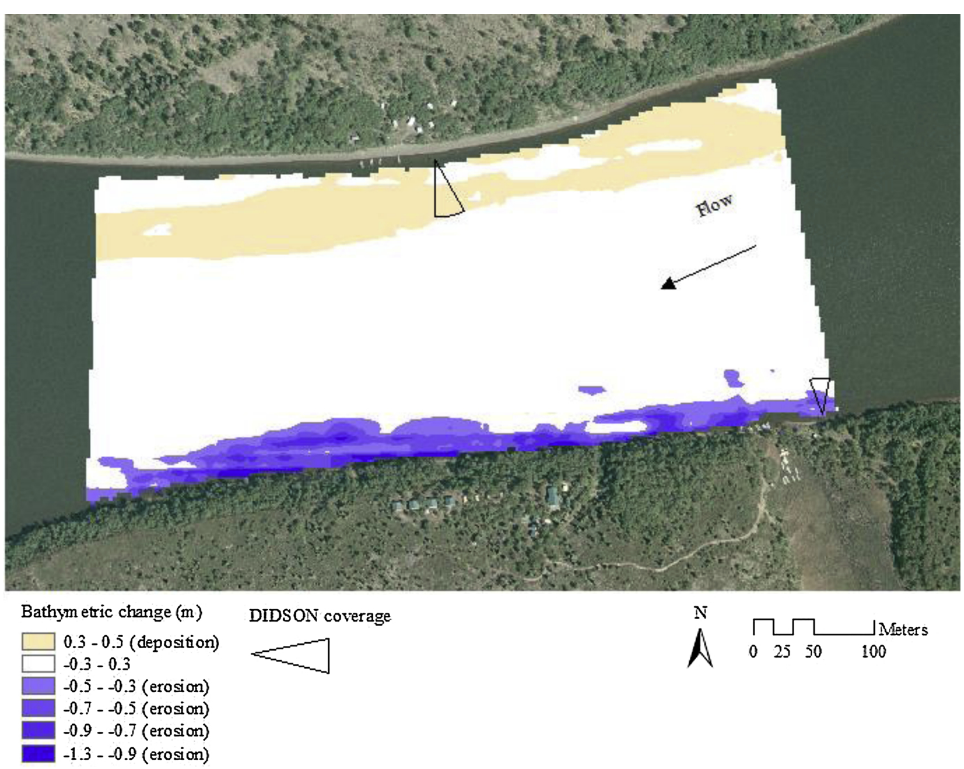

Fig. 6. Change in the river bottom from 2011 to 2012 showing the deposition and erosion that occurred.

fix bugs that were encountered. The ALPS vers. 2.2, 2.3, and 2.4 required inputting Universal Transverse Mercator (UTM) coordinates for the DLs, sound speed in water, and filtering parameters. To reduce the possibility of losing fish at this early stage to filtering, we set the dilution of precision (DOP) filtering parameter to 20 (twice the default) and the conditioning number (CN) and H–R (a reliability number which attempts to quantify the reliability of a position estimate) to default values. These filtering parameters were not input by the user in U-Map. Sound speed was calculated from the river temperature based on Simmonds and MacLennan (2005).

In the first year of the study, a synchronization problem in the ALPS algorithm caused the program to stop processing following a break in the array, which caused many detected fish to be eliminated from the output. According to Lotek, Inc., the DLs needed time to synchronize, so running longer periods of data through the ALPS program should have been a better approach. Lotek, Inc.'s programmers were unable to tell us how long a time period was needed for the synchronization of the beacons to occur. This was problematic in 2011 when we pulled the DLs from the water multiple times during the field season to ensure the DL's storage was not filling up, but unfortunately this caused numerous breaks in the dataflow. We reprocessed the data through ALPS selecting a variety of time periods ranging from multiple weeks to a few days and determined that a period of one week or less resulted in the output of many previously omitted tags. To determine whether fish were omitted from the data processing or not detected, we compared the number of unique tag IDs output from ALPS with the output from the WHS Reader program and reprocessed data for periods when numerous detections of specific tags occurred in the WHS Reader output, but no position estimates were produced in ALPS. This resulted in fewer missed tags. Since we were able to obtain the missed tags using this method, this data was not reprocessed in later years when new software became available.

Although beacons were attached to every DL, only a single beacon was needed to synchronize the array. For each tag ID, we processed data using one beacon at a time and selected the output from the beacon that produced the most complete and coherent track. The offshore beacon attached to the buoy was never selected as the 'best' beacon to synchronize the array. This was likely due to the beacon's movement, which swirled around due to current flow. Beacons attached to the DLs were more stable. In 2014, Lotek, Inc.'s new program, U-Map vers. 1.2.2. was used to process the tag data. U-Map fixed the synchronization problem and automatically selected the best beacon for each tag, so it was not necessary to reprocess data using each beacon. U-Map required inputting the DL's UTM coordinates, river temperature, and salinity. Sound speed was automatically calculated. U-Map did not include user-configurable filtering parameters. The files containing the position estimates were concatenated using script files written in TIBCO Spotfire SPLUS (version 8.1).

Each fish track (unique tag ID) was plotted and viewed sequentially during the filtering process. Preliminary filtering was done using SPLUS. We first eliminated obvious errors such as position estimates that were well beyond the boundaries of the array or incorrectly placed on land. For tracks with excessive scattering or multipathing, we removed points with low DOP, CN, or H–R values. Multipathing, which occurs when a ping emitted from an acoustic tag follows an indirect path to the DL, was sometimes observed as double or even triple pathways with the track appearing to jump back and forth between parallel locations. For some tracks, further restricting the filtering parameters reduced the number of extraneous positions making the direct path more obvious. Secondary filtering was done using ESRI ArcMap version 10.2. A more precise point-to-point filter was applied to remove points outside of the dominant track. To help identify and delete obvious outliers, points were converted to lines with each line connecting consecutive detections from an individual fish. Fish that generated no coherent track or a track < 100 m long were removed from the dataset. In the final step, fish tracks were smoothed. Edited points with 5 consecutive records spanning < 2.5 min were smoothed with a 7-point running average of x and y. The smoothed coordinates were plotted, reviewed, and edited to remove any additional missed outliers.

2.5. Accuracy of position estimates

Many environmental factors affect whether a ping is detected and the detection quality or accuracy of a position estimate. Acoustic signals may bounce off structure in the river such as weirs, sonar mounts, boats, and other fish, which can cause multipathing or even loss of detection. Uneven bottom topography and surface and boundary layers may also interfere with signal propagation. Anything that alters the direct path from the signal to the detector will cause error in a position estimate. To examine this error, we processed position estimates from known, stationary targets—the beacons. Using U-Map, processing the beacon data was like processing fish tags except that it was necessary to remove the DL paired with the beacon being analyzed from the list of DLs in the array. Beacon position estimates were plotted, and a simple spatial filter was applied to remove position estimates outside the of array and obvious outliers. A bootstrap procedure was used that randomly selected 400 points without replacement from a single beacon's dataset. The percentage of points within 5 and 10 m from the GPS-measured beacon location was determined, and the process was repeated 1,000 times. A standard deviation was calculated from the bootstrapped data. This process was repeated for each beacon. Heat plots were made by randomly selecting 2,000 position estimates from one beacon's dataset without replacement, rounding the northing and easting coordinates to the nearest 1 m, and plotting a frequency matrix. For a combined plot of data from all beacons, we randomly selected 20,000 position estimates from the database and plotted the frequency matrix with an overlay of the shoreline, sonar beams, and beacon coordinates.

2.6. Fish depth

Fish depths (FD) were superimposed as a point layer onto bathymetry maps using the 2011 map for the 2011 fish depths and the 2012 map for all remaining years' data. Since we expect that most Chinook salmon travel along the river bottom when moving upriver to reduce energy loss due to current flow (Hinch and Rand, 2000), aligning fish depth with the bathymetry provided another means of assessing the accuracy of fish positions. The depth of each fish position was obtained using pressure output from the acoustic tags (pT) according to an equation supplied by Lotek, Inc.,

$$FD = \frac{0.3 \times pT}{1.43} \tag{1}$$

The pressure range of the acoustic tags was 15 psi divided into 50 steps for a conversion of $15/50 = 0.3$ psi/step. The 1.43 conversion is based on water density (ρ) at 5 °Celsius, the gravitational constant (g), and the conversion factor (C) of pressure in psi to Pascals; i.e., $\rho g/C$.

2.7. Tag fish proportions

To generate a potential DIDSON count (p), a tagged fish had to pass through the footprint of a DIDSON beam regardless if it passed while the DIDSON was recording. An algorithm written in SPLUS and/or a visual assessment was used to determine whether a given track passed inside or outside of a DIDSON beam footprint. The layout of the sonar beams and acoustic receivers is shown in Fig. 7A. Uncertainty in the position estimates and detection issues made classification more difficult. To handle the uncertainty, we drew three probability regions around each beam footprint (Fig. 7B). In the cross-river dimension, the first probability region extended from shore to 5 m short of the DIDSON end range. Tagged fish that traveled through this region were assigned a p of 1 or -1 depending on their direction of movement and a bank

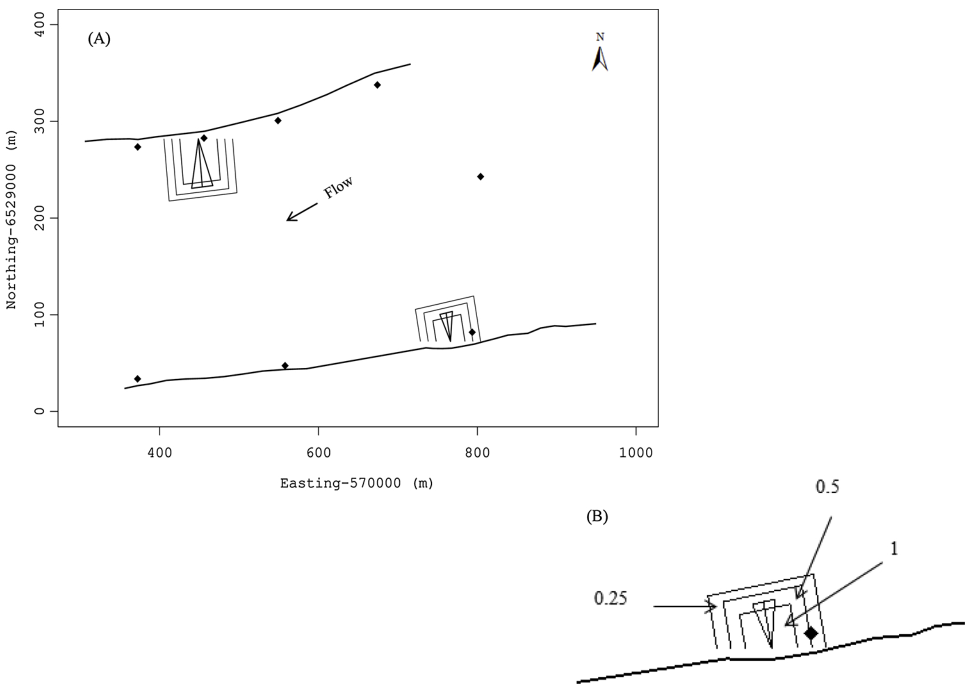

Fig. 7. A) The acoustic array showing the position of the DIDSON beams (large triangles), shorelines, data loggers (solid, black diamonds), and rectangular regions of uncertainty around each beam. B) The probability regions used to classify tagged fish as either inside or outside of the DIDSON beam, with a probability of 1.0 assigned to fish passing through the inner rectangle and probabilities of 0.5 and 0.25 assigned to fish passing through the middle and outer rectangles, respectively.

assignment; i.e., left bank (*LB*) or right bank (*RB*), for fish passing through one of the DIDSON beam footprints or *Os* if it passed outside of either footprint. For example, a tagged fish traveling upriver through this first region along the right bank was assigned [*0 LB, 1 RB, 0 Os*] for a potential DIDSON count of 1. The second region extended from the end of the first region to 5 m offshore of the DIDSON end range for a *p* assignment of 0.5. The assignment for a fish traveling along the left bank through this region would be [*0.5 LB, 0 RB, 0.5 Os*], an equal chance of passing inside or outside of the beam footprint. The third region (p = 0.25) extended from the end of the second region to 5 m farther offshore. Fish passing through the second or third regions were classified as edge fish.

Some fish traveled through both DIDSON beams during a single upriver trip. For a given fish that traveled through the first region of the LB beam footprint, crossed the river, and then traveled through the first region of the RB beam footprint, a *p* value of 2 would be assigned because the DIDSON would have counted 2 fish. If a fish traveled through the first region along LB and then went through the third region along RB, the assignment [1 LB, 0.25 RB, 0 OS] would result in a *p* value of 1.25.

Truncated fish tracks (short tracks) occurred when a track moving along the shoreline ended prior to reaching a beam footprint. Short tracks were likely the result of environmental conditions interfering with detection. For these tracks there were multiple possibilities: the fish may have continued through the sonar beam, moved offshore, reversed direction and headed downriver, or was captured by a fisherman. To handle short tracks, the probability regions were extended 10-m in the upriver-downriver dimension (Fig. 7). A fish was assigned a zero probability of going through a sonar beam unless the fish entered a probability region before detection was lost. A fish traveling along the left bank that entered the outermost probability region before detection was lost was given an assignment of [*0.25 LB, 0 RB, 0.75 Os*].

Many tagged fish made a single, upriver trip through the array (ST fish), but several made multiple up and downriver trips. Fish tracks with ≥1 h between 2 successive observations were divided into multiple tracks and classified as multiple-trip (MT) fish. For these fish, each trip was assessed in the same manner as the ST fish except that downriver trips yielded negative potential counts and assignments for multiple trips were summed. For example, a fish observed traveling upriver through the LB beam footprint and then downriver through the RB beam footprint would be assigned a *p* value of 0 [1 LB, -1 RB, 0 OS]. If a fish traveled upriver through the LB beam footprint, downriver through the RB beam footprint, and then back upriver in the middle of the river, the *p* value would be 1 [1 LB, -1 RB, 1 OS]. A special case was presented by implied trips. Tagged fish first detected moving downriver through the array were assumed to have traveled upriver unobserved or the track was rejected by filters. Also, a fish that made two consecutive upriver trips had to have made an unobserved (implied) downriver trip. We assumed these fish had an equal probability of traveling through the *RB*, *LB*, or *Os* so implied upriver trips were assigned [*0.33 LB, 0.33 RB, 0.33 Os*] and implied downriver trips were assigned [*-0.33 LB, -0.33 RB, -0.33 Os*]. Fish trips were classified as upriver, downriver, both if the fish moved upriver and downriver within a single trip, or undetermined. Whether implied or observed, multiple assignments for a given fish were summed to produce a single *p* value per fish. Probability assignments for each fish were put into Assignment Tables by year (Maxwell et al., 2019b).

To obtain an overall proportion of fish that traveled through a DIDSON beam footprint, we first tallied the right $\hat{R}_i$ and left $\hat{L}_i$ bank potential counts for each tagged fish i by year y from the assignment tables,

$$\hat{R}_y = \sum_{i=1}^{n_y} (\hat{R}_i) \tag{2}$$

and

$$\hat{L}_y = \sum_{i=1}^{n_y} (\hat{L}_i) \tag{3}$$

Where, n is the number of tagged, filtered fish. Next, we calculated yearly proportions $\hat{P}_y$ from summed right and left bank potential DIDSON counts, yearly variances $Var\ (\hat{P}_y)$, and a total (all years) variance $Var\ (\hat{P})$:

$$\hat{P}_y = \frac{(\hat{R}_y + \hat{L}_y)}{n_y} \tag{4}$$

$$Var(a_y) = \frac{a_y \bullet (1 - a_y)}{(n_y - 1)} \tag{5}$$

and

$$Var(a) = \frac{1}{16}\sum_{y-1}^{4} Var(a_y) \tag{6}$$

where $a = \hat{P}$. Yearly proportions were averaged to obtain a mean proportion ($\hat{P}_m$).

2.8. In-river abundance estimates

In-river abundance estimates $\hat{A}_y$ were obtained by expanding apportioned Chinook salmon escapement indices from the sonar project $\hat{S}_y$ for each year using $\hat{P}_y$,

$$\hat{A}_y = \frac{\hat{S}_y}{\hat{P}_y} \tag{7}$$

with variances $Var(\hat{A}_y)$,

$$Var(I_y) \approx b_y^2 Var(\frac{1}{a_y}) + \left(\frac{1}{a_y}\right)^2 Var(b_y) - Var(\frac{1}{a^y})Var(b_y) \tag{8}$$

where $I = \hat{A}$, $a = \hat{P}$, and $b = \hat{S}$. The $Var(\frac{1}{a_y})$ was approximated using the Delta method (Seber, 1982),

$$Var(\frac{1}{a_y}) \approx a_y^{-4} Var(a_y) \tag{9}$$

The $Var(\hat{S}_y)$ obtained from the sonar project incorporates variance in the sonar estimates and test-fishing catch per unit effort (CPUE). The total sonar variance $Var(\hat{S})$ was calculated using Eq. (5) with $a = \hat{S}$. For the total variance *Var* ($\hat{A}$), the total sonar variance $Var(\hat{S})$ and mean values of a and b were used in Eqs. (8) and (9).

Yearly and total standard errors (*SE*) and coefficients of variation (*CV*) were calculated from the variances:

$$SE_y = \sqrt{Var(\hat{I}_y)} \tag{10}$$

and

$$CV_y = \frac{SE_y}{\hat{I}_y} \tag{11}$$

2.9. Fish length analyses

We analyzed length data to determine whether a bias occurred in fish lengths. A length bias was possible between tagged fish detected nearshore versus mid-river; i.e., we might expect that larger fish would travel mid-river while smaller fish would travel closer to shore. A second potential bias examined was between tagged Chinook salmon captured in the nearshore zones versus Chinook salmon captured at the upriver site. A potential bias between the two projects would stem from either site differences or differences between netting operations. At the tagging site, the small mesh net (13.0 cm) was omitted because it typically tangles rather than gills Chinook salmon. Tangled salmon often fall out of the net as it is pulled in. Another difference between netting operations was the length of the drift. Nets were pulled at the tagging site as soon as a fish was detected, while at the sonar site, nets were pulled after timed 2.5 min drifts were completed. Since both projects recorded MEF fish lengths, a length comparison was possible.

Length frequency distributions from the sonar test-fishing and tagging projects were plotted as density plots and compared using Kolmogorov-Smirnov Goodness-of-Fit Tests (K–S tests). Two hypotheses were tested: 1) length frequencies from tagged fish that passed within the sonar footprint (inside fish) were similar to length frequencies from tagged fish that passed outside the sonar footprint (outside fish); and 2) length frequencies from the inside tagged fish were similar to length frequencies from fish captured at the upriver test-fishing site (sonar fish). For this second hypothesis, we used the inside tagged fish rather than all tagged fish because we wanted to compare the length frequencies within the same region of coverage. The sonar's nearshore and offshore drifts are both within the 'inside' region of the tagged fish. There are four potential outcomes from these hypotheses: 1) both are true, 2) 1 is true and 2 is false, 3) 1 is false and 2 is true, and 4) both are false. If the K–S tests showed no significant differences in the first analysis in a given year; i.e., hypothesis 1 was true, we assumed that Chinook salmon were randomly mixing by size as they passed the sonar and any length differences would not affect the odds of a fish passing inside or outside a sonar footprint. If the K–S tests showed no significant differences in the second analysis in a given year; i.e., hypothesis 2 was true, we assumed that the sonar and tagging projects were capturing fish with similar lengths; therefore, if a length bias existed, it was similar for both projects. Of the four potential outcomes, only the last one, where both potential outcomes are false would necessitate stratifying the datasets by length.

2.10. Length-stratified in-river abundance estimates

To obtain in-river abundance estimates stratified by length, we divided Chinook salmon into two length categories typically used by research biologists in the Bristol Bay area (small fish < 66 cm and large fish ≥66 cm) (Chuck Brazil, ADF&G, Anchorage, personal communication) and followed the procedures below.

For the acoustic tag data, we:

1 Merged tagged fish from the assignment tables with their corresponding fish lengths.
2 Separated tagged fish into small and large fish datasets.
3 Tallied potential right $\hat{R}_i$ and left $\hat{L}_i$ bank counts for each fish i by year y from the small fish dataset s using Eqs. (2 and 3) where $\hat{R} = \hat{R}_s$, $\hat{L} = \hat{L}_s$, and $n = n_s$.
4 Summed the right and left bank potential DIDSON counts by year and calculated the small fish proportion using Eq. (4) where $\hat{P} = \hat{P}_s$, $\hat{R} = \hat{R}_s$, $\hat{L} = \hat{L}_s$, and $n = n_s$. Yearly variances *Var* ($\hat{P}_{sy}$) and a total variance *Var* ($\hat{P}_s$) were calculated using Eqs. (5) and (6) where $a = \hat{P}_s$ and $n = n_s$.
5 Repeated steps 3 and 4 using the large fish dataset l to obtain a large fish proportion $\hat{P}_{ly}$ where $\hat{P} = \hat{P}_l$, $\hat{R} = \hat{R}_l$, $\hat{L} = \hat{L}_l$, and $n = n_l$. Calculated yearly variances *Var* ($\hat{P}_{ly}$) and a total variance *Var* ($\hat{P}_l$) using Eqs. (5) and (6) where $a = \hat{P}_l$ and $n = n_l$.

For the sonar data, we:

6 Extracted Chinook salmon lengths from the sonar's mixed-species Age-Sex-Length (ASL) database.
7 Calculated the proportions of small $S\hat{P}_{sy}$ and large $S\hat{P}_{ly}$ Chinook salmon by year,

$$S\hat{P}_{sy} = \frac{Sn_{sy}}{Sn_y} \tag{12}$$

and

$$S\hat{P}_{ly} = \frac{Sn_{ly}}{Sn_y} \tag{13}$$

where Sn_{sy} is the number of small Chinook salmon in the ASL database, Sn_{ly} is the number of large Chinook salmon, and Sn_y is the total number. Yearly variances *Var* ($S\hat{P}_{sy}$) and *Var* ($S\hat{P}_{ly}$) and total variances *Var* ($S\hat{P}_s$) and *Var* ($S\hat{P}_l$) were calculated using Eqs. (5) and (6) where $a = S\hat{P}_s$ and $n = Sn_s$ for small fish and $a = S\hat{P}_l$ and $n = Sn_l$ for large fish.

8 Apportioned yearly sonar estimates $\hat{S}_y$ into small $\hat{S}_{sy}$ and large $\hat{S}_{ly}$ Chinook salmon,

$$\hat{S}_{sy} = (S\hat{P}_{sy})(\hat{S}_y) \tag{14}$$

Table 1
Tag summaries by year for Chinook salmon fitted with acoustic tags.

	2011		2012		2013		2014		All years	
	No.	%	No.	%	No.	%	No.	%	No.	%
Tags inserted	193	100.0	193	100.0	189	100.0	224	100.0	799	100.0
Tags detected[a]	180	93.3	181	93.8	181	95.8	214	95.5	756	94.6
Tags that produced position estimates[b]	132	68.4	158	81.9	158	83.6	206	92.0	654	81.9
Tags remaining after filtering	124	64.2	150	77.7	137	72.5	202	90.2	613	76.7
Mortalities during capture	0		0		2	1.1	0	0.0	2	0.3
Tagged fish recaptured at sonar site	0		0		1	0.5	0	0.0	1	0.1
Tagged fish recaptured by sport fishermen	none reported		none reported		1	0.5	3	1.3	4	0.5

[a] Detected by one or more data loggers.
[b] Position estimates output by ALPS or U-Map (Lotek, Inc.'s Asynchronous Logging Positioning Software).

and

$$\hat{S}_{ly} = (S\hat{P}_{ly})(\hat{S}_y) \tag{15}$$

with variances $Var\,(\hat{S}_y\ \hat{S}_{sy})$ and $Var\,(\hat{S}_y\ \hat{S}_{ly})$,

$$Var(b_y c_y) \approx c_y^2 Var(b_y) + b_y^2 Var(c_y) - Var(b_y) Var(c_y) \tag{16}$$

where $b = \hat{S}$, and $c = \hat{S}_s$ for small fish and $\hat{S}_l$ for large fish. For the total variances $Var\,(\hat{S}\ \hat{S}_s)$ and $Var\,(\hat{S}\ \hat{S}_l)$, b is the mean $\hat{S}$, and c is the mean $\hat{S}_s$ for small fish and mean $\hat{S}_l$ for large fish in Eq. (16).

Combining the tag and sonar data, we:

9 Estimated the in-river abundance for small $L\hat{A}_{sy}$ and large $L\hat{A}_{ly}$ Chinook salmon each year by,

$$L\hat{A}_{sy} = \frac{\hat{S}_{sy}}{\hat{P}_{sy}} \tag{17}$$

and

$$L\hat{A}_{ly} = \frac{\hat{S}_{ly}}{\hat{P}_{ly}} \tag{18}$$

Variances $Var(L\hat{A}_{sy})$ and $Var(L\hat{A}_{ly})$ were calculated using Eqs. (8) and (9) where $I = L\hat{A}_s$, $a = \hat{P}_s$, and $b = \hat{S}_s$ for small fish, and $I = L\hat{A}_l$, $a = \hat{P}_l$ and $b = \hat{S}_l$ for large fish. For total variances $Var\,(L\hat{A}_s)$ and $Var\,(L\hat{A}_l)$, $Var(\hat{S})$ and mean values of a and b were used in Eqs. (8) and (9).

10 Summed $L\hat{A}_{sy}$ and $L\hat{A}_{ly}$ to obtain $L\hat{A}_y$, the length-stratified estimates. Summed the variances from the small $Var\,(L\hat{A}_{sy})$ and large $Var\,(L\hat{A}_{ly})$ fish estimates to obtain the yearly $Var\,(L\hat{A}_y)$ and total $Var\,(L\hat{A})$ variances for all sizes of fish.

11 Determined the length-stratified proportion $L\hat{P}_y$ for the combined small and large fish by,

$$L\hat{P}_y = \frac{\hat{S}_y}{L\hat{A}_y} \tag{19}$$

and calculated yearly $Var\,(L\hat{P}_y)$ and total variances $(L\hat{P})$ using Eqs. (5) and (6) where $a = L\hat{P}$ and $n = n$.

Ideally, the sonar estimates would be reapportioned daily; however, apportioning daily estimates by length and species was not possible because zone information (i.e., right-bank nearshore, right-bank offshore, left-bank nearshore, and left-bank offshore) is not part of the ASL database. Instead, annual sonar estimates $\hat{S}_y$ apportioned into length categories $\hat{S}_{sy}$ and $\hat{S}_{ly}$ served as a reasonable proxy for the reapportioned daily estimates.

2.11. Bank ratios

We examined the bank orientation of Chinook salmon for both acoustic tagged fish and fish captured at the sonar site. To compare these two datasets, we removed tagged fish that swam outside of the beam footprints, comparing the remaining right $Ratio_y$ and left $Lratio_y$ bank ratios from the tagged fish,

$$Rratio_y = \frac{\hat{R}_y}{(\hat{R}_y + \hat{L}_y)} \tag{20}$$

and

$$Lratio_y = \frac{\hat{L}_y}{(\hat{R}_y + \hat{L}_y)} \tag{21}$$

with bank ratios from the sonar project.

2.12. Climate and water data

Climate and water data were collected across all study years. In 2011, climate data included daily precipitation and twice daily (0800 and 2000 h) measurements of wind speed, direction, and air temperature from Meteorological Terminal Aviation Routine Weather Report (METAR data) stations located at airports in Dillingham (46 km northwest of the sonar site) and New Stuyahok (60 km north of the sonar site). From 2012 to 2014, these same data were obtained using a Davis Vantage Vue wireless weather station at the sonar site. Water temperature was recorded using a HOBO Model UA-001-08 data logger attached to the right-bank DIDSON mount with settings of 1-h (2011), 2-h (2013), and 5-min (2012 and 2014) increments. Light penetration of the water column was measured using a HOBO Model UA-002-08 attached to the left-bank DIDSON mount in 2011, 2013, and 2014. In 2012, the unit wasn’t functioning so water clarity was recorded based on a visual assessment of the water’s color.

3. Results

3.1. Tags inserted

A total of 799 acoustic tags, 189–224 per year (Table 1), were inserted into Chinook salmon during the months of June and July 2011–2014, of which 93–96% were detected at the upriver array site each year, a potential mortality and/or failed tags of < 7%. After filtering the tracks, 613 fish remained for analyses, 124–202 per year. Of the tagged fish that produced position estimates, 6% were discarded during filtering in 2011, 5% in 2012, 13% in 2013, and 2% in 2014. The low percentage of fish tracks discarded in 2014 was likely due to either the additional mid-river DL deployment, improvements made to the U-Map software, or both.

3.2. Travel time and bank orientation

Travel time and bank orientation were determined using the 2014 dataset. On average, tagged fish traveled from the insertion site to the detection site in 2.54 d ± 2.38 (SD), traveling at a speed of 5.1 km/d ± 5.5 (SD), with a minimum travel time of 0.05 d and maximum

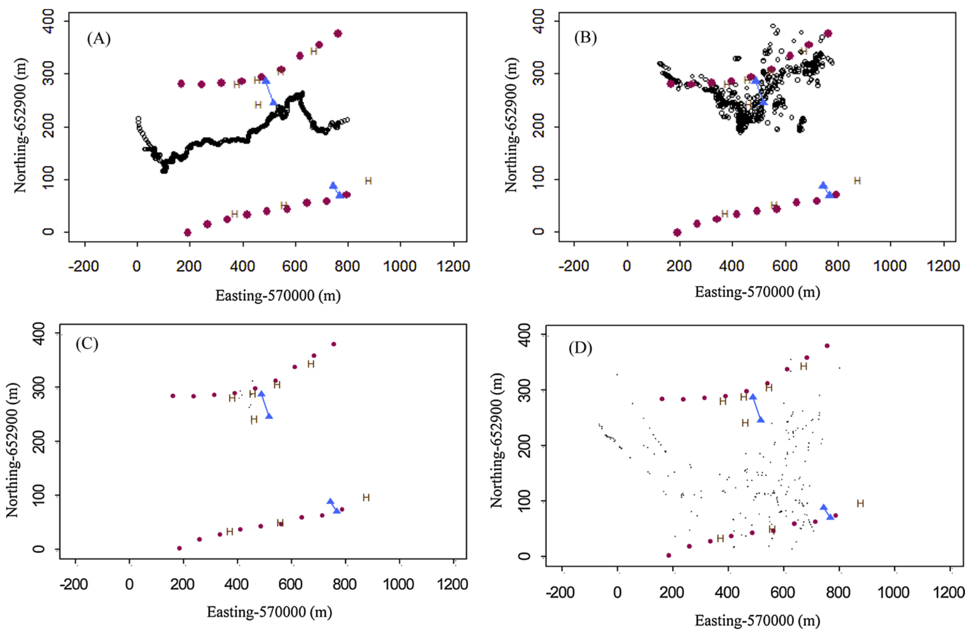

Fig. 8. The quality of the fish tracks varied widely from high-quality tracks that required minimal filtering (A), to tracks that were discarded because the actual route of the fish could not be determined (B), too few points were obtained (C), or the points were randomly scattered with no coherent track (D). Open black circles represent tagged fish position estimates, closed circles represent the shoreline, H's represent beacons, and triangles the sonar positions.

travel time of 10.37 d. The zone a fish was captured in did not determine the zone the fish was first detected in. Of the 202 Chinook salmon tagged in 2014, only 68 (33.7%) were first observed at the array in the same zone that they were tagged in, a percentage similar to what would occur by chance. Of these fish, 24 (35.3%) were captured and first detected within Zone 1, 30 (44.1%) within Zone 2, and 14 within Zone 3 (20.6%).

3.3. Quality of fish tracks and position uncertainty

The quality of fish tracks varied widely. Many tracks formed a single smooth line through the array (Fig. 8A), some tracks included numerous detections, but it was unclear where the actual track was headed (8B), others produced too few detections to make a track (Fig. 8C), and some resembled a random collection of points (Fig. 8D).

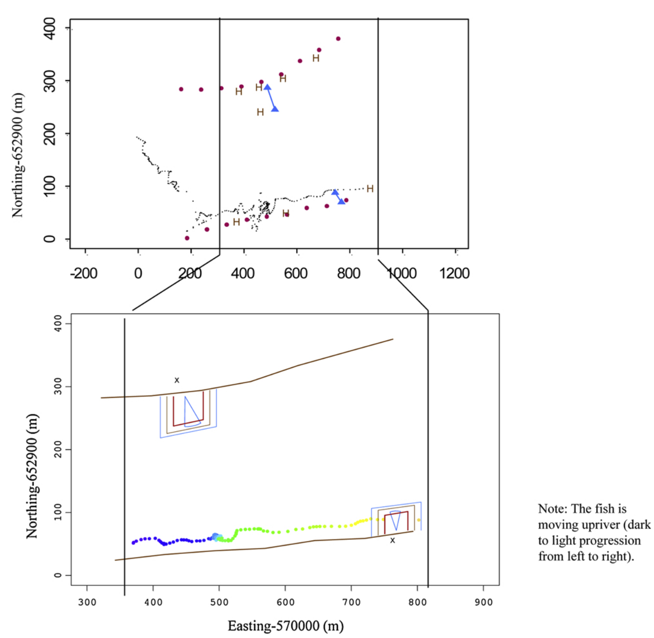

Fig. 9. Example of a fish track showing the first level of filtering (top) and secondary level (bottom). The left side of the track was discarded during the second stage because the segment was outside the array boundaries.

Table 2
Deviations of beacon position estimates from their actual locations.

	Minimally filtered		No filtering		Difference
Beacon no.	%	SD[a]	%	SD	%
Within 5 m from the actual beacon location:					
LB beacons					
29	53.2	2.5	51.2	2.5	1.9
31	89.1	1.5	87.2	1.6	1.9
36	60.6	2.4	50.9	2.6	9.7
Mean LB	67.6	2.2	63.1	2.3	4.5
RB beacons					
32	88.3	1.6	83.9	1.8	4.3
33	81.8	1.9	67.9	2.4	13.9
34	95.2	1.1	92.8	1.3	2.4
35	59.8	2.4	53.4	2.4	6.4
Mean RB	81.3	1.8	74.5	2.0	6.8
Center beacon					
30	37.1	2.3	32.6	2.4	4.5
Mean all beacons:	70.6	2.0	65.0	2.2	5.6
Within 10 m from the actual beacon location:					
LB beacons					
29	86.6	1.7	83.5	1.8	3.0
31	98.5	0.6	97.5	0.8	1.0
36	84.7	1.8	73.4	2.2	11.3
Mean LB	89.9	1.5	84.8	1.7	5.1
RB beacons					
32	98.7	0.6	94.4	1.1	4.3
33	98.2	0.7	83.7	1.9	14.6
34	99.9	0.2	97.6	0.8	2.3
35	88.7	1.5	79.6	1.9	9.1
Mean RB	96.4	0.9	88.8	1.5	7.6
Center beacon					
30	71.1	2.3	63.1	2.5	8.0
Mean all beacons:	90.8	1.4	84.1	1.7	6.7

[a] Standard deviation from bootstrapped data using a random sample of 400 without replacement, 1,000 iterations.

Of the tracks shown in Fig. 8, all were discarded except for 8A. Many tracks required a second level of filtering to produce a smooth track (Fig. 9).

We evaluated position uncertainty using data from the 2014

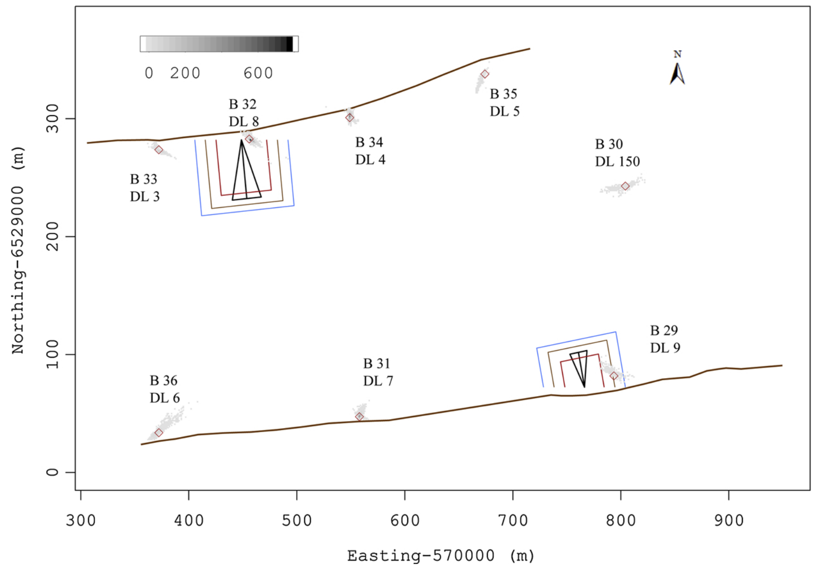

Fig. 10. Layout of the beacons (B) and data loggers (DL) along with a 20,000-point random sample of minimally filtered position estimates from the stationary beacons used to synchronize the data loggers, 2014.

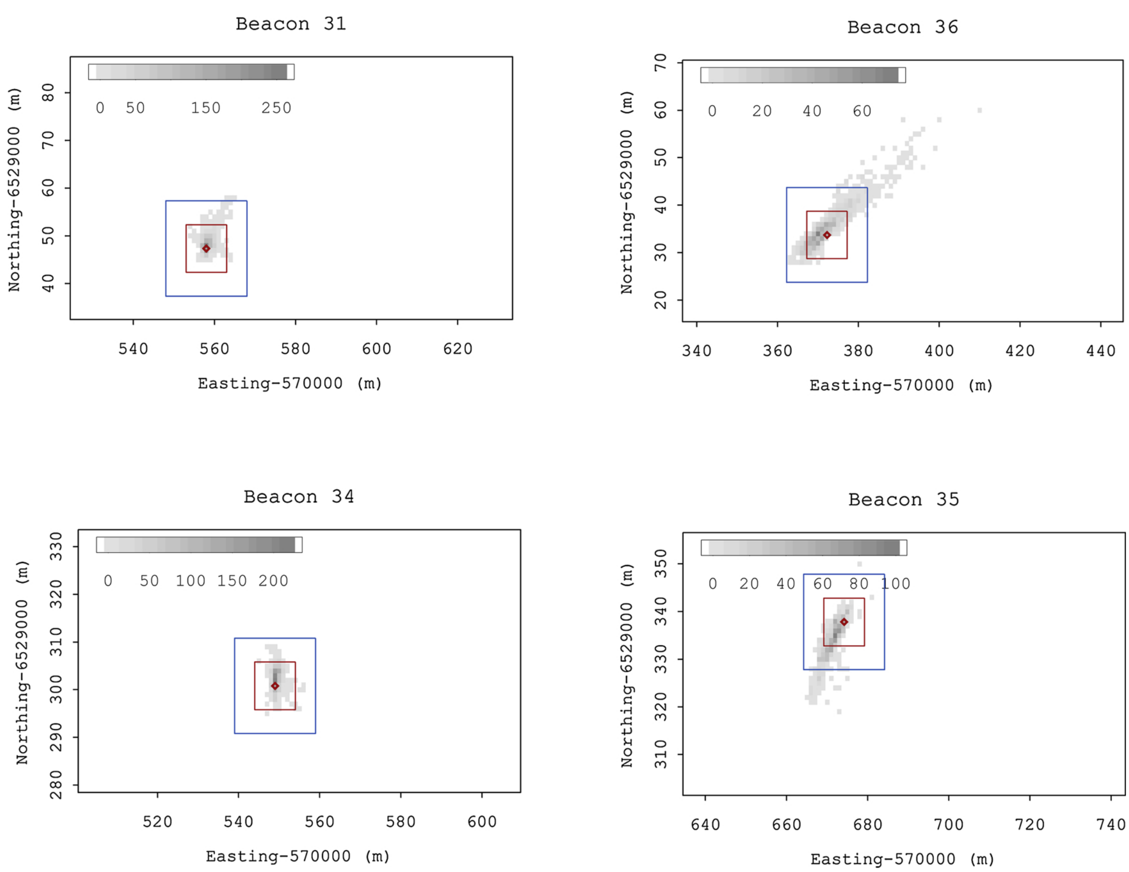

Fig. 11. A 2,000-point random sample of position estimates showing the beacons from LB and RB with the tightest spread of points (beacons 31 and 34) and with the widest spread (beacons 36 and 35), with 5 and 10 m distances marked around the GPS-measured beacon locations (rectangles), 2014.

stationary beacons. Of the minimally filtered position, estimates a mean of 70.6% of all beacons were within 5 m of their GPS locations and 90.8% within 10 m; for the nonfiltered position estimates, 65.0% were within 5 m and 84.1% within 10 m (Table 2). Beacon position estimates were centered on or near their GPS locations, noted by small triangles in Fig. 10. Position uncertainty was higher for the LB beacons, with a mean of 67.9 ± 2.2% of position estimates within 5 m from the actual beacon locations compared to RB beacons, with a mean of 81.3 ± 1.8%. For position estimates within 10 m from the actual beacon location, the LB mean was 89.9 ± 1.5%, the RB 96.4 ± 0.9%. The most tightly clustered position estimates for LB were around beacon 31, the middle beacon, with the widest spread around beacon 36, the most downriver one (Fig. 11). For the RB, the beacon with the lowest uncertainty was beacon 34; the highest was beacon 35.

Table 3
Fish tracks categorized by their movement through the acoustic array (%).

	2011	2012	2013	2014	All years
Single-trip fish	84.7	85.3	82.5	81.7	83.4
Multiple-trip fish	15.3	14.7	17.5	18.3	16.6
Fish whose last trip was downriver	8.9	5.3	3.6	7.9	6.5
2-bank fish	12.1	10.0	8.8	5.9	8.8
Edge tracks	14.5	6.0	14.6	25.2	16.0
Short tracks-both banks	5.6	12.7	5.8	1.5	6.0
Left bank	3.2	10.7	5.8	0.5	4.7
Right bank	2.4	2.0	0.0	1.0	1.3
Implied upriver trips[a]	6.5	2.7	2.9	0.5	2.8
Implied downriver trips	0.0	0.0	0.7	0.0	0.2

[a] An implied trip is from a tagged fish that traveled through the array but wasn't detected.

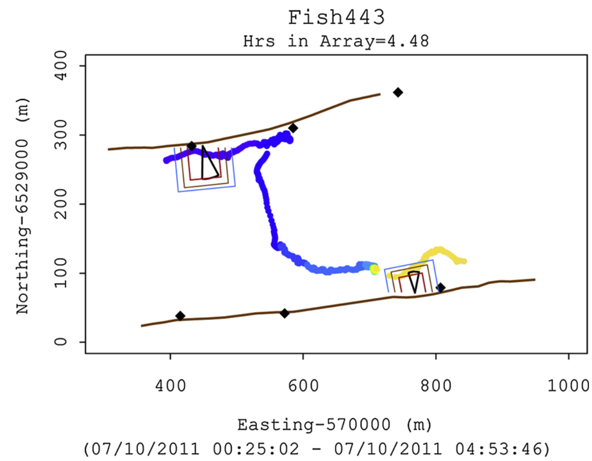

Fig. 13. Example of a tagged fish that moved through both DIDSON beam footprints.

3.4. Classification of fish tracks

Most tagged fish went straight though the array one time (83.4%), and this percentage was relatively constant between years (Table 3). These fish were classified as single-trip fish. Fish that traveled through the array more than once were classified as multi-trip fish. We also classified tagged fish based on whether they moved through the right or left bank beam footprint (Fig. 12A), through the middle of the river (Fig. 12B), or produced short (Fig. 12C), edge (Fig. 12D), 2-bank (Fig. 13) or implied tracks. Short tracks averaged 6.0% across study years with more observed along the left bank (4.7%) than the right bank (1.3%). Edge tracks averaged 16.0%. Fish that traveled through both beam footprints made up 5.9–12.1% of the total. The edge fish, fish that travel through both beams, and multi-trip fish are problematic for DIDSON counting by creating more uncertainty in the counts. Plots of all fish tracks are included in Maxwell et al. (2019b).

The most common scenario for MT fish was either three trips/fish (upriver, downriver, and upriver) or two trips/fish (upriver, downriver), but a few fish made as many as 5, 6, or 7 trips through the array. The percentage of implied upriver trips was highest in 2011, likely due to the frequent downloading of the DLs that interrupted the ALPS synchronization process and caused more missed or incomplete tracks. The fewest implied upriver trips occurred in 2014, the year the mid-river DL was deployed. Only 1 implied downriver trip was observed and that occurred in 2013.

Multi-trip fish often presented unexpected behavioral patterns as

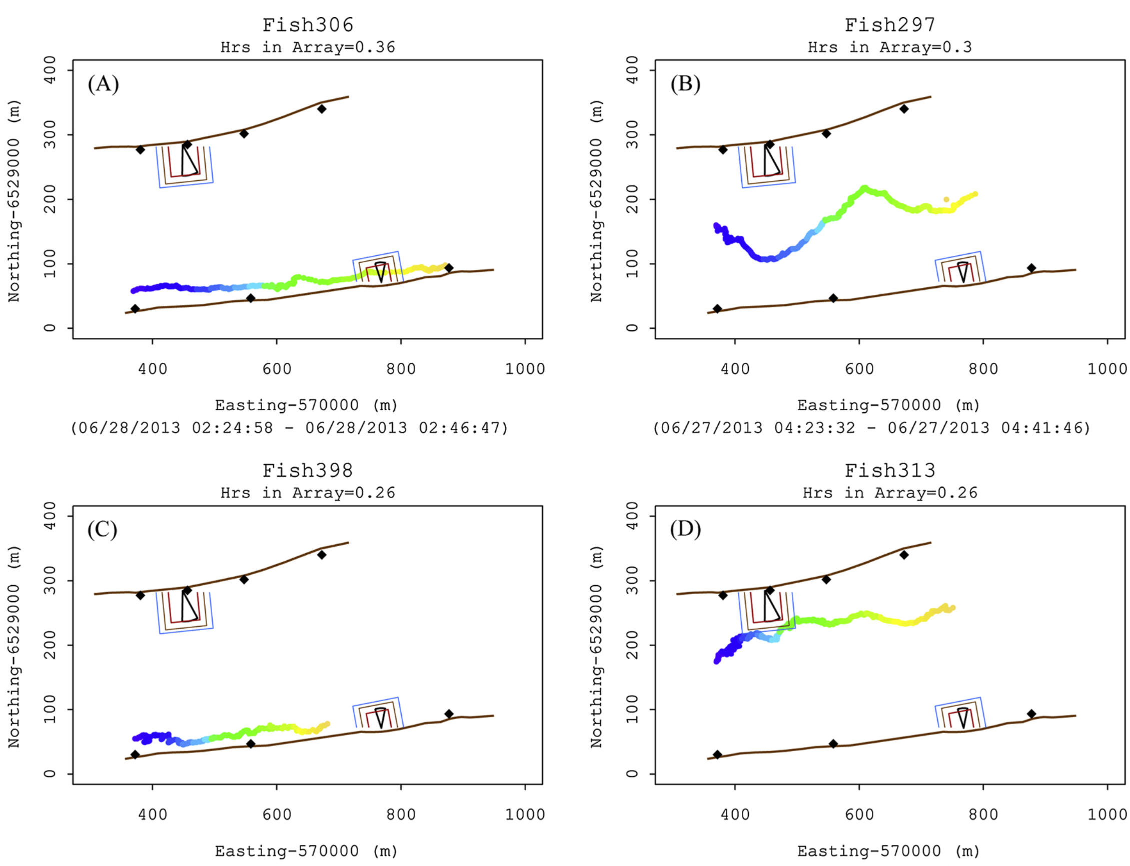

Fig. 12. Examples of tagged fish clearly traveling through a DIDSON beam footprint (A), traveling outside of the footprint (B), creating a short track that ended before reaching the footprint (C), and traveling through the edge of the footprint (D).

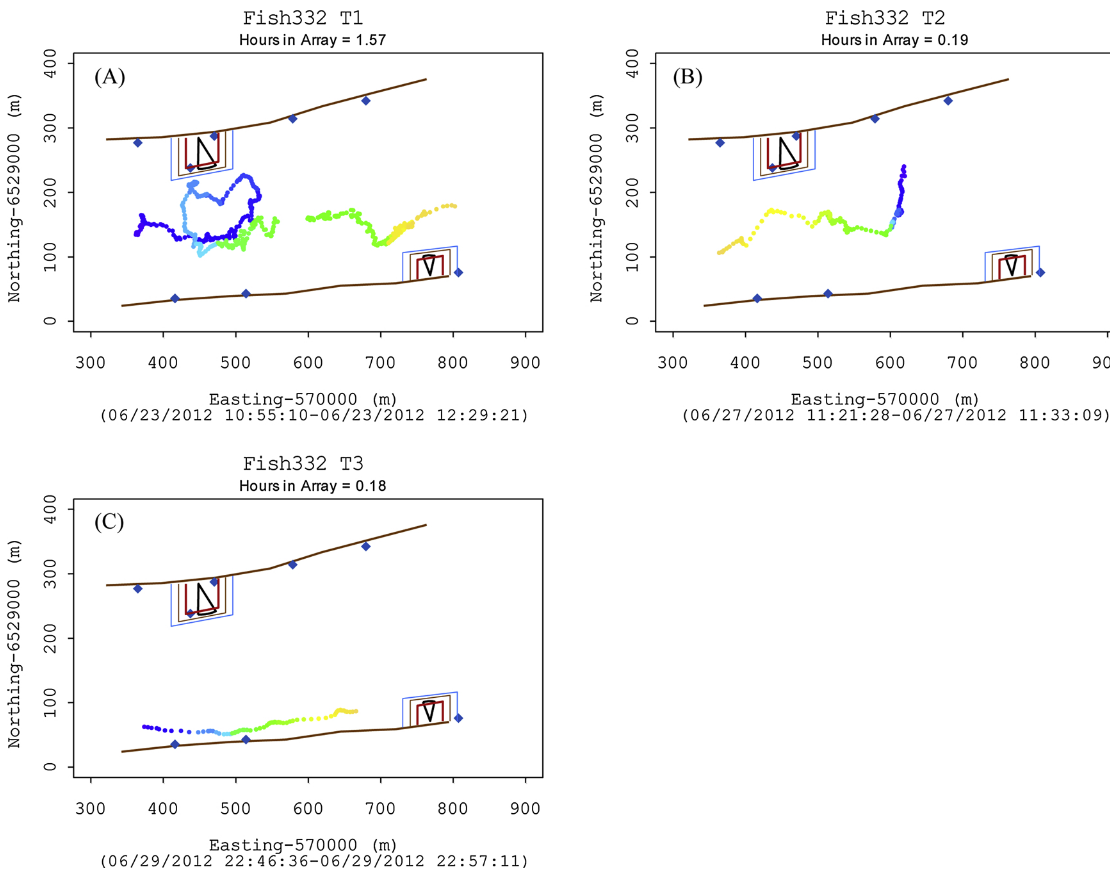

Fig. 14. Fish 332, a 3-trip fish that created a large looping track in its first trip (A), returned 4 d later heading downriver (B), and then 2 d later traveled upriver along left bank where detection was lost prior to reaching the DIDSON beam footprint (C).

they traveled back and forth through the array. Fish 332 (Fig. 14), a 3-trip fish, made a large loop in trip 1 that spanned most of the river, moved toward left bank, and exited the array upriver. The fish returned 4 d later traveling down the middle of the river (trip 2), and again 2 d later moving upriver along the left bank. The track stopped short of the left-bank probability region (trip 3). Assignments for the 3 trips were summed for a final assignment of [*0 LB, 0 RB, 1 Os*].

Fish 416 (Fig. 15), a 2-trip fish, traveled upriver along the left bank (trip 1), then returned 7 d later traveling beyond the left-bank beam footprint where it held for a period of time before crossing the river and looping between right bank (an edge fish) and the river's center, spending close to 6 h in the array (trip 2). The final assignment for this fish was [*1 LB, 0.5 RB, 0.5 Os*]. This fish showed a typical example of holding behavior, first spending a considerable amount of time offshore of the right bank and then offshore of the left bank before moving on (Fig. 15B).

3.5. Fish depth

Tagged fish swimming upriver migrated near the river bottom most of the time, as shown by the close alignment of fish depth with the bathymetry map (Fig. 16). Fish depths were nearly identical between years with only occasional tracks observed out of alignment with the river bottom. In 2012, the example shown, one upriver track ran mid-river at a near-surface depth. Downriver-moving fish, which were relatively rare, tended to swim near the surface except when traveling

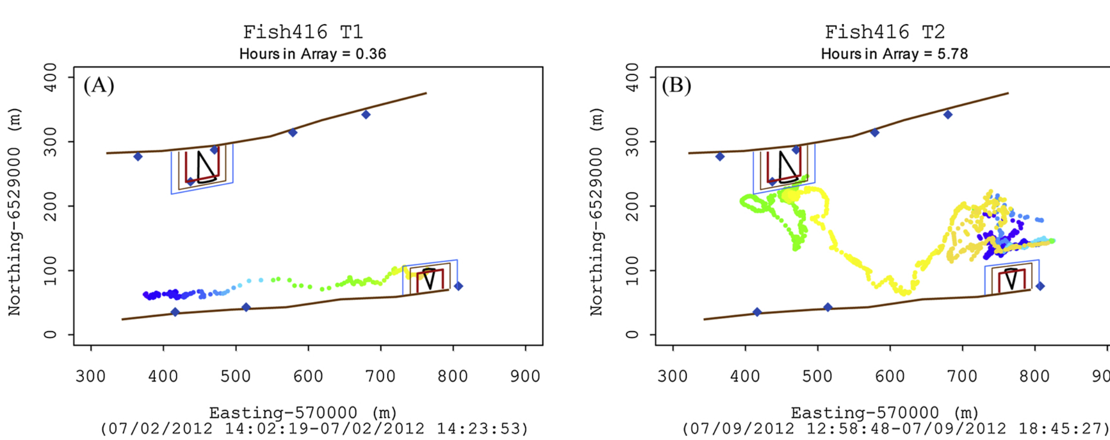

Fig. 15. Fish 416, a 2-trip fish that traveled upriver along the left bank, returned 7 d later along left bank where it held for a period of time before crossing the river and looping between right bank and the river's center. No additional upriver trip was observed, so it was assumed the fish moved downriver and did not return.

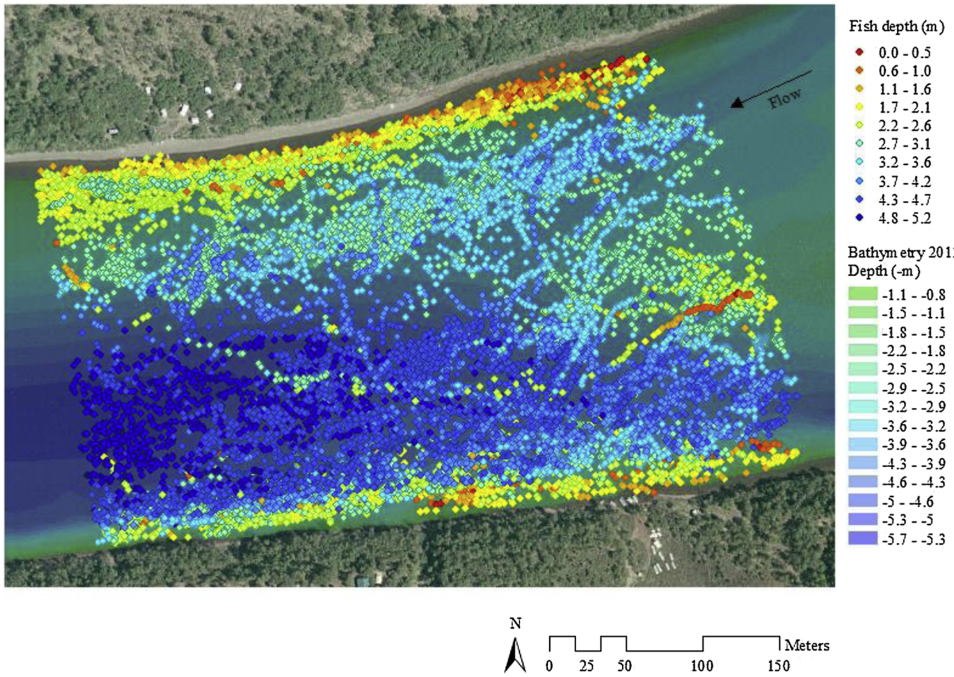

Fig. 16. Depth of tagged Chinook salmon moving upriver through the study area, 2012.

through the deepest portion of the river where they traveled closer to the bottom, likely due to the propensity of fish to hold in the deeper portions of the river (Fig. 17). Note, tracks from these downriver fish showed active movement with the fish often moving upriver, cross-river, or downriver, but the net result of the movement was downriver, indicating these fish were alive.

3.6. Fish length distributions

Mean lengths for the Sonar ASL fish were 44.2, 57.8, and 80.1 cm for length categories 1 (< 50 cm), 2 (≥50 cm & < 66 cm), and 3 (≥66 cm), respectively (Table 4). Length category 1 contained 52 Sonar ASL fish, and only 1 Tag inside and 1 Tag outside fish. The mean lengths in categories 2 and 3 were similar between the Sonar ASL and tagged fish. For length category 2, the mean Tag inside, Tag outside, and all Tagged fish lengths were 58.7, 59.4, and 58.8 cm, respectively, for category 3, mean lengths were 78.3, 79.7, and 79.2 cm, respectively.

Length frequency curves from acoustic tagged fish and sonar fish were mostly bimodal with peaks at 60 and 80 cm that represent the peak efficiency of the two gillnets (Figs. 18 and 19). Comparing sonar fish with tagged fish that traveled inside the sonar footprint (Fig. 18), the 60-cm peaks from the tagged inside fish were smaller every year except 2012, with 60-cm and 80-cm peaks from the sonar fish more similar to each other in 2011, 2013, and 2014. For tagged fish that

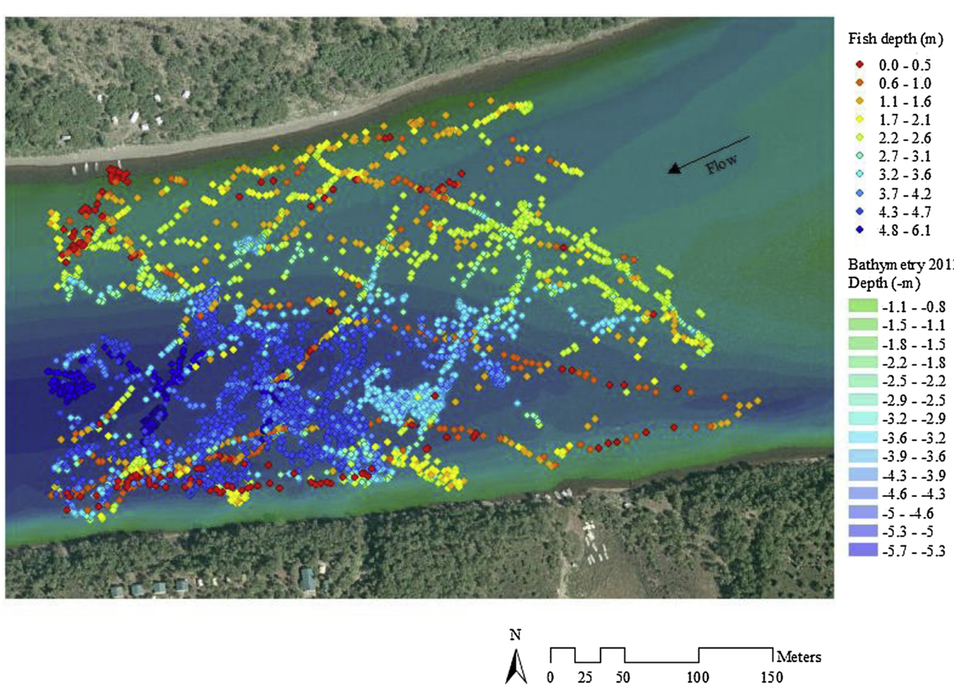

Fig. 17. Depth of tagged Chinook salmon moving downriver through the study area, 2013.

Table 4
Mean lengths (mid eye to tail fork) of Chinook salmon from the sonar project's Age-Sex-Length database (Sonar ASL) and from acoustic tagged fish (Tag) by length category.

	Length Category (cm)[c]	*n*	% of *n*	Mean	SD	Min	Max
Sonar ASL	< 50	52	2.3	44.2	3.9	36.5	49.8
	≥50 & < 66	736	32.9	57.8	3.9	50.0	65.9
	≥66	1,452	64.8	80.1	7.3	66.0	105.0
Tag (inside fish[a])	< 50	1	0.3	46.6	NA	46.6	46.6
	≥50 & < 66	82	22.5	58.7	4.1	50.6	65.5
	≥66	282	77.3	78.3	6.9	66.0	104.0
Tag (outside fish[b])	< 50	1	0.4	49.5	NA	49.5	49.5
	≥50 & < 66	41	16.9	59.4	3.5	52.0	65.8
	≥66	200	82.6	79.7	6.7	66.5	96.0
Tag (all captured fish)	< 50	2	0.3	48.0	2.1	46.6	49.5
	≥50 & < 66	155	19.5	58.8	3.8	50.6	65.8
	≥66	636	80.2	79.2	6.8	66.0	104.0

[a] Inside fish are tagged Chinook salmon that passed through a sonar beam footprint.
[b] Outside fish passed offshore of the beam footprints.
[c] The 66 cm cutoff is used to separate small and large Chinook salmon at the Nushagak River (Chuck Brazil, ADF&G, Anchorage, personal communication).

traveled outside the sonar footprint, the second peak was slightly larger each year (Fig. 19). The most notable difference between the sonar fish and tagged fish was the lack of the 60 cm peak in 2014. The K–S tests showed that length frequency distributions for the inside versus outside tagged fish were significantly different in 2014 but not in the other years, while the sonar versus inside fish lengths were significantly different in all years except 2013 (Table 5). The only year where length frequency distributions were significantly different for both tests was 2014, suggesting that length-stratified in-river abundance estimates would better represent the true population for that year.

3.7. Tag proportions and in-river abundance estimates

On average, 32% of tagged Chinook salmon passed through the RB DIDSON beam footprint, 24% through the LB footprint, and 44% outside of either footprint during the four study years (Table 6). Due to the length bias observed in 2014 and because we wanted consistency in the data processing between years, we calculated length-stratified data for all years to compare with non-stratified data (Table 6). Length-stratified abundance estimates ($L\hat{A}_y$) were lower than non-stratified estimates in 2011, 2013, and 2014, and higher in 2012. The across years' average length-stratified abundance estimate of Chinook salmon (204,512) was lower than the non-stratified abundance estimate (209,264) by 4,752 fish, a percent difference of 0.57. The largest difference between the two methods occurred in 2014 when the percent difference between them was 2.47. Annual proportions from the length-stratified method (i.e., dividing the apportioned sonar estimate by the length-stratified estimate) ranged from 0.47 to 0.65, averaging 0.57, an across years' average that is similar to the non-stratified proportion of 0.56 (Table 6).

Bank ratios of the percentage of tagged fish that traveled through the DIDSON beam (inside fish) were mostly the reverse of sonar bank ratios (Table 7). On average, more than half (57%) of the inside tagged fish passed through the RB footprint while the sonar RB ratio averaged 35%. The tagged fish RB ratios of 54–59% were more consistent between years, while the sonar ratios were more dynamic (24–41%).

3.8. Climate and water data

Mean morning air temperatures ranged from 8.30 to 10.27 °C, mean afternoon temperatures ranged from 10.65 to 14.88 °C, and mean

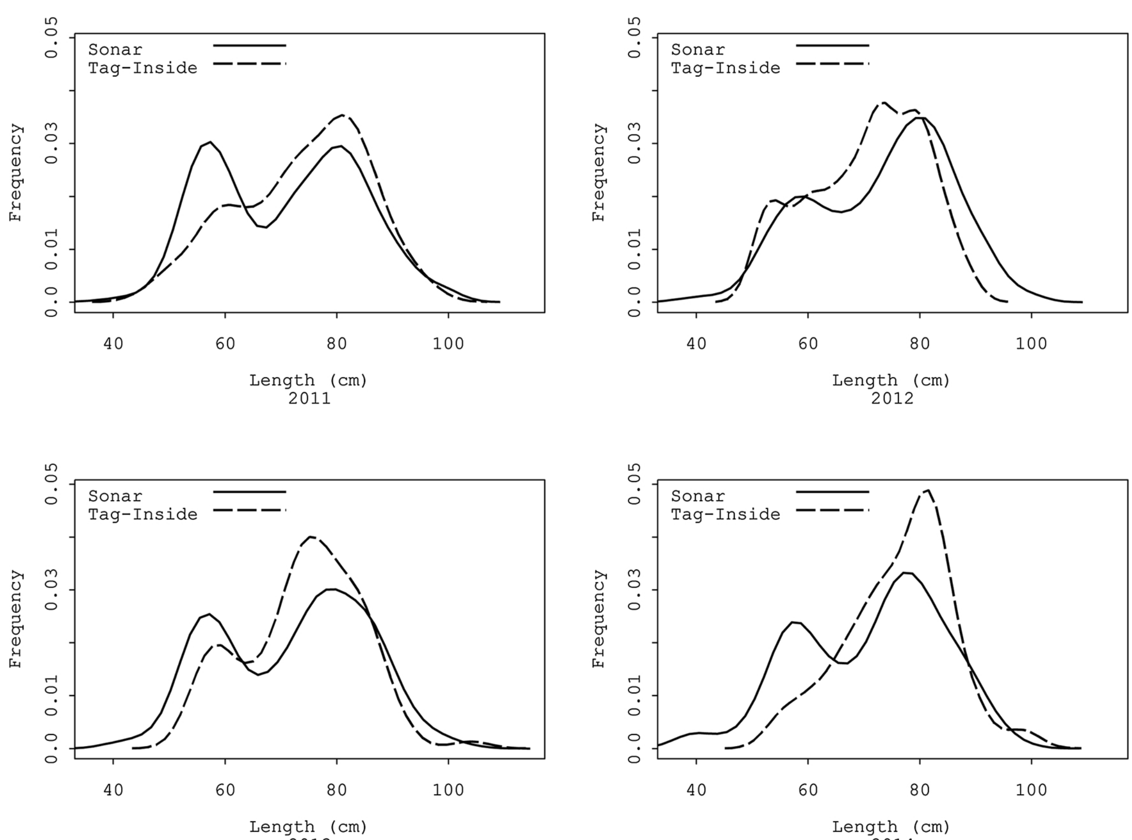

Fig. 18. A comparison of Chinook salmon length distributions from fish captured at the sonar site for apportioning the sonar estimates to species (Sonar) and acoustic-tagged fish that migrated through a sonar beam footprint (Tag-inside).

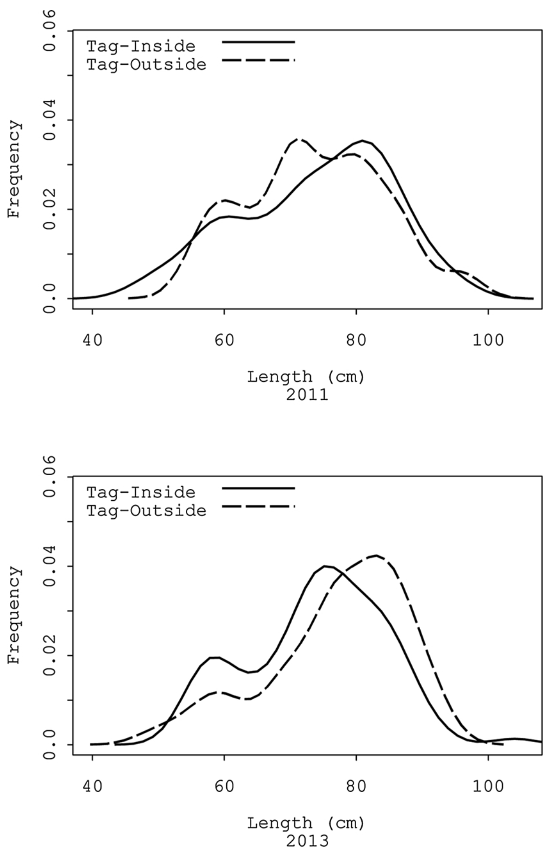

Fig. 19. A comparison of Chinook salmon length distributions from acoustic-tagged fish that migrated through a sonar beam footprint (Tag-Inside) and fish that migrated offshore of the sonar beam footprint (Tag-Outside).

Table 5
Kolmogorov-Smirnov Goodness-of-Fit results (KS) comparing length distributions of Chinook salmon.

	2011	2012	2013	2014
Inside vs outside tagged fish[a]				
KS	0.112	0.141	0.221	0.196
p	0.794	0.400	0.072	0.033
Significant at *p*(0.05)	no	no	no	yes
Sonar[b] vs inside tagged fish				
KS	0.163	0.176	0.137	0.243
p	0.040	0.012	0.096	0.000
Significant at *p*(0.05)	yes	yes	no	yes

[a] Inside fish are acoustically tagged Chinook salmon that passed through a sonar beam footprint. Outside fish passed offshore of sonar beam footprints.
[b] Sonar fish refers to Chinook salmon lengths from gillnet captures used to apportion sonar estimates.

precipitation from 0.11 to 0.28 cm (Table 8). The warmest year, 2013, was also the driest. Mean wind speed was dramatically higher in 2011, 17.61 km/h, compared to 2012 (6.27 km/h) and 2013 (6.26 km/h), and lowest in 2014 (3.40 km/h) (Table 8).

4. Discussion

4.1. Stability in the Chinook salmon distribution

Going into this study, it was known that Chinook salmon migrate beyond the sonar and test-fish sampling range. Sport fishermen frequently catch them beyond this range, and a cross-river drift gillnet study conducted at the sonar site on this river (Miller, 2000) found that Chinook salmon utilized the entire river channel for their migration. The Nushagak River is one of many large rivers in Alaska where salmon are assessed using sonars that do not ensonify the entire river (Maxwell et al., 2013; McDougall and Lozori, 2018; Schumann and McIntosh, 2017). If the assessed species are shore-oriented, this coverage is adequate. At the Nushagak River, the coverage is adequate for sockeye but not Chinook salmon. The relatively flat middle region coupled with uneven bottom topography make it difficult to fully ensonify the river (Fig. 4). The sonar range is limited, and the uneven river bottom creates acoustic shadow zones where fish can be missed. Ideally, a site would have been selected that was better suited for full sonar coverage. Unfortunately, there isn't a better site where the river flows within a single channel. Much of the river is divided into multiple channels. Apart from a small, shallow slough that runs behind the sonar site, the site is considered a single channel relative to salmon passage. Chinook salmon assessment was an add-on to an existing sockeye salmon project and subsequently, Chinook salmon estimates became part of fishery management plans. Although the site is not ideal, the Chinook salmon passage estimates obtained were better than no information.

Miller (2000) estimated that only 18% of Chinook salmon traveled within the sampling range of the sonar used at the time, a Bendix echo-counting sonar (Gaudet, 1990). Although the DIDSON covers more of the river's width, two-thirds of the ~300 m width is not sampled. In a comparison study of the two sonars, Maxwell et al. (2011) found that fish counts in the nearshore strata were similar between the Bendix counter and DIDSON, but offshore counts, where most Chinook salmon are captured, were highly variable, suggesting Chinook salmon shift their migration toward and away from shore—moving in and out of what was the sampling range of the Bendix counter. The acoustic telemetry showed that, on average, 57% of tagged salmon migrated through regions sampled by DIDSON during the study years, a much higher percentage than Miller's 18%. This suggests that much of the shifting movement occurred within and not beyond the larger sampling

Table 6
Proportions and in-river abundance estimates for Chinook salmon.

	2011	2012	2013	2014	Average[a]
No. tagged fish[b] (n)	124	150	138	202	154
Bank ratio:					
(R/n)	0.37	0.32	0.34	0.23	0.32
(L/n)	0.26	0.23	0.28	0.19	0.24
Proportions (non-stratified; P_y)	0.63	0.55	0.63	0.42	0.56
SE	0.044	0.041	0.041	0.035	0.020
Sonar estimates (S_y[c])	108,278	174,085	113,709	70,482	116,639
SE	4,687	8,604	6,423	6,778	3,384
CV	0.043	0.049	0.056	0.096	0.029
Abundance estimates (A_y, non-stratified)	171,950	317,481	181,934	167,007	209,264
SE	11,878	23,577	12,021	13,724	8,008
CV	0.069	0.074	0.066	0.082	0.038
A_y - S_y	63,672	143,396	68,225	96,525	92,625
Tag proportions (length-stratified)					
Small fish (< 66 cm) - n_s	30	45	27	23	31
Prop through DIDSON footprint	0.70	0.63	0.69	0.72	0.68
SE	0.085	0.073	0.090	0.096	0.043
Large fish (≥ 66 cm) - n_l	88	105	111	178	120.50
Prop through DIDSON footprint	0.61	0.51	0.61	0.39	0.53
SE	0.052	0.049	0.047	0.037	0.023
$n_s + n_l$ [d]	118	150	138	201	152
Sonar estimates (length-stratified)					
No. ASL small fish	258	188	226	116	197
Prop ASL small fish	0.402	0.294	0.353	0.363	0.352
No. ASL large fish	383	451	414	204	182
Prop ASL large fish	0.598	0.706	0.647	0.638	0.647
No.sonar small fish	43,581	51,218	40,154	25,550	40,126
No. sonar large fish	64,696	122,868	73,556	44,932	76,513
Abundance estimate (LA_y, length-stratified)	167,528	320,494	178,765	151,259	204,512
SE	14,364	29,976	15,653	18,204	9,528
CV	0.086	0.094	0.088	0.120	0.047
Differences between abundance estimates	4,422	−3,013	3,170	15,748	5,082
Percent difference	0.65	−0.24	0.44	2.47	0.57
LA_y - S_y	59,251	146,409	65,056	80,777	87,873
Proportions (length stratified, LP_y)	0.65	0.54	0.64	0.47	0.57

[a] SE values in this column are not averages, they are the SE for all years.
[b] The number of tagged fish includes the filtered fish tracks; incoherent tracks were removed from the dataset. (Note: this is the number of fish, not fish trips.).
[c] Greg Buck, ADF&G, Anchorage, Alaska personal communication.
[d] These totals do not match n above because 2 fish from 2011 did not get length measurements, and 4 tags from 2011 and 1 from 2011 of detected fish did not match any tag insertion numbers.

Table 7
Bank ratios of Chinook salmon from DIDSON and tagged fish estimates.

	DIDSON % by bank[a]		Tagged fish % by bank[b]	
	Right	Left	Right	Left
2011	40	60	59	41
2012	24	76	58	42
2013	36	64	54	46
2014	41	59	55	45
Average	35	65	57	43

[a] Greg Buck, ADF&G, Anchorage, Alaska, personal communication.
[b] Tagged fish percentages only include tagged fish that traveled through a DIDSON footprint.

Table 8
Climatological and water data, Nushagak River sonar site, 2011–2014.

	Air temperature (°C) 0800 h[a]				Air temperature (°C) 2000 h			
	Mean	Max	Min	SD	Mean	Max	Min	SD
2011	8.39	11.39	4.56	1.62	10.65	13.15	7.50	1.75
2012	8.30	19.00	4.00	2.90	12.25	22.00	6.00	3.98
2013	10.27	19.00	6.00	2.62	14.88	24.00	8.00	5.11
2014	9.81	17.00	1.00	2.78	14.17	20.00	7.00	3.62
Precipitation (cm)[a]								
	Mean	Max	Min	SD				
2011	0.28	4.04	0.00	0.71				
2012	0.25	2.26	0.00	0.51				
2013	0.11	1.19	0.00	0.27				
2014	0.12	1.55	0.00	0.31				
Wind speed (km/h) 0800 h[a]					Wind speed (km/h) 2000 h			
	Mean	Max	Min	SD	Mean	Max	Min	SD
2011	17.61	33.03	0.00	7.87	16.84	30.69	0.00	6.41
2012	6.27	24.08	0.00	5.13	9.60	22.22	0.00	5.83
2013	6.26	20.37	0.00	6.04	8.77	27.78	0.00	6.04
2014	3.40	14.82	0.00	3.70	6.92	22.22	0.00	4.46
Water temperature (°C)[b]								
	Mean	Max	Min	SD				
2011	10.81	13.24	8.06	1.49				
2012	11.03	14.88	8.53	1.44				
2013	12.53	16.25	9.47	1.96				
2014	13.52	16.85	10.48	1.89				

[a] In 2011, daily precipitation, and twice daily wind speed and air temp were averaged from METAR. (Meterological Terminal Aviation Routine Weather Report) stations at Dillingham and New Stuyahok. From 2012–2014, measurements were from the sonar site using a Davis Vantage Vie wireless weather station.
[b] Water temperature was recorded with a UA-001-08 HOBO data logger attached to the right-bank DIDSON mount in 1-h (2011), 2-h (2013) and 5-min (2012 and 2014) increments.

range of the DIDSON. From 2011 to 2014, the acoustic telemetry study found that percentages of fish moving through ensonified regions were 65, 54, 64, and 47, respectively. These percentages show that a relatively stable proportion of Chinook salmon passage is ensonified and apportioned each year, making the indices of abundance used by fishery managers reasonable, unlike the indices produced by the Bendix counter prior to the transition to DIDSON.

4.2. Effects of Chinook salmon behavior on sonar estimates

This study provided a wealth of information on Chinook salmon behavior within the acoustic array that highlighted some of the limitations of the sonar/test fishing system. The most obvious shortfall of the sonar is the inability to ensonify the entire river. Like the Miller (2000) gillnet study, the acoustic telemetry showed that tagged Chinook salmon used the entire river width as they traveled through the array, whereas sonar and test fishing covered approximately a third of the river. Expanding the indices of abundance to full-river estimates required knowing the proportion of Chinook salmon that traveled through each sonar beam. This knowledge was confounded by uncertainty in the position estimates for the 16% of fish tracks classified as 'edge' fish (Table 3). Although we attempted to identify tagged fish in DIDSON images based on time, the average combined return of largely overlapping Chinook, chum, coho, and sockeye runs to this river total 1.3 million fish within a few months. This results in multiple fish passing through the beam at one time, which made it impossible to determine if a given DIDSON image was from a tagged fish. Measuring fish image lengths might appear to be a good method to narrow the search since the actual lengths of the tagged fish were known. Burwen et al. (2010) measured DIDSON image lengths of tethered Chinook and sockeye salmon and showed that they were similar to live fish measurements. Based on this research, they were able to enumerate and separate large Chinook from sockeye salmon using DIDSON fish lengths (Burwen et al., 2011). Measuring image lengths was not an option for us due to equipment limitations. For the offshore strata, the DIDSON's low frequency setting is needed to achieve the desired sampling range. At low frequency, the DIDSON transmits half the number of beams (48). The number of pixels from these beams does not provide enough data to obtain a reasonable and repeatable length measure unless a high-resolution (HR) lens is used. This lens reduces the composite beam to one-half the field of view compressing the size of the 48 beams to more closely match the individual beam widths of the 96 beams. At close range, where many sockeye salmon migrate, this narrowed beam is smaller than the length of a sockeye salmon which makes measurement impossible and makes it more difficult to count fish in large schools. Burwen et al. (2011) were able to use the HR lens because they weren't interested in estimating sockeye salmon. At the Nushagak River, sockeye salmon are the primary species of interest for managing the commercial fishery so adding the HR lens would only be an option if we had been able to deploy side-by-side DIDSONs along each bank, one with an HR lens for the offshore strata and one with a standard lens for the nearshore strata. Instead, to account for the uncertainty in 'edge' fish, we set up probability regions around the beam edge (Fig. 7) and assigned a probability of detection by DIDSON to each fish (Maxwell et al. (2019b)).

One assumption of salmon migration behavior is that fish conserve energy by traveling where the flow is less, staying within shallower regions and remaining close to the river bottom (Hinch and Rand, 2000). Chinook salmon do not fit this assumption. Many tracks did not make sense energetically as fish traveled upriver through the deepest, higher flow regions. Most fish did, however, take advantage of the resistance between flow and the river bottom. Comparing fish depth with bathymetry (Fig. 16) showed that most upriver-moving fish swam near the river bottom. Chinook salmon are the largest salmon species that migrate the Nushagak River. Their size and musculature allow them to swim against stronger current. Hughes (2004) explored a hypothesis that larger salmon may experience wave drag from the river's surface when traveling in shallower water and may benefit energetically from traveling farther offshore. Wave drag may explain why Chinook salmon don't migrate close to shore, but it doesn't explain why they move so far offshore. A potential reason for moving farther offshore into higher flow regions may be congestion. As smaller salmon species (sockeye and chum) arrive in large numbers, the high density of fish may push Chinook salmon farther offshore. This topic needs further exploration and could be resolved from existing sonar and acoustic tag datasets.

When it was decided to use the sonar estimates of Chinook salmon to manage fisheries, little was known about their behavior at this site other than the limited range coverage. Additional problems for the sonar and test fish sampling include cross-over behaviors, multiple trips through the array, and milling. Fish traveling back and forth across the river have the potential of being double counted by the sonar and captured in test nets on both sides of the river. Tagged fish were not bank oriented as they traveled from the tag insertion site to the detection array 13 km upriver. The probability of a fish captured in Zone 1 and then entering the array in same zone purely by chance would be 33.3%. Our results showed a percentage only slightly higher than chance (33.7%), which indicates migrating Chinook salmon cross the river at least once or potentially multiple times as they travel between the two sites. The 68 fish that stayed true to a zone may have traveled within the same zone or may have made multiple crossings to end up in the same zone. We frequently observed tagged fish crossing the river within the array, some traveling through both sonar beams. For example, Fish 433 traveled through the right-bank beam footprint, crossed the river and then traveled through the edge region of the left-bank beam footprint (Fig. 13). Although Fish 332 trip 1 (Fig. 14A) and Fish 416 trip 2 (Fig. 15B) also traveled cross-river, both passed through only 1 beam footprint. Fish that traveled through both beam footprints were assigned a probability of capture greater than one to account for potential double counting. The percentage of fish that passed through both beam footprints while within the array (5.9–12.1%) suggest that cross-over behavior is common in this species and may involve multiple cross-over points, behaviors that are not possible to assess with DIDSON.

Although sonar operators count upriver fish and subtract downriver fish, if some of the trips occur outside the ensonified area, this biases the sonar estimate. On average, 16.6% of tagged fish were classified as multi-trip fish (Table 3). The proportions from this study account for these multiple trips and the expansion to a full-river estimate reduces this bias. For some of the multi-trip fish, their last observed trip was downriver. This occurred in an average of 6.5% of fish (Table 3). Anecdotal evidence suggests that a small portion of Chinook salmon may spawn downriver of the sonar site. The test-fish crew at the sonar site has reported catching blushed and spawned out Chinook salmon in early August during years the project was extended to assess coho salmon, but this occurred after the time frame covered in this study. Another possibility is that spawned-out salmon may have drifted downriver. We know of no reports of sport fishermen catching spawning Chinook salmon below the sonar site during June and July. These fish may have gone back downriver to spawn, returned upriver to spawn after the project ended, not been detected on their final upriver trip, or died without spawning. We have no evidence to suggest which possibility is the most probable.

We observed several instances of milling fish similar to Fish 416 trip 2 (Fig. 15B) (Maxwell et al., 2019b). Whether fish are crossing back and forth, milling, or making multiple trips through the array, the more time they spend within the sonar sampling region, the more likely they are to be counted more than once. This information is not available from sonar images, nor would it be available from a simple mark-recapture project which would only tell us if the sonar estimates were biased high or low, not why. An acoustic tag study similar to this one is beneficial when setting up a new site or adding a new species with potentially different behaviors to an existing project. The acoustic tag information provided a means to better understand the bias in our estimates due to these behaviors and correct for it.

4.3. Bias in bank ratios

A bias was found in the bank ratios between the sonar and acoustic tag projects. The sonar project estimated more Chinook salmon along LB, 59–76%, with more variability between years, while the acoustic tag study estimated fewer Chinook salmon along LB, 41–46%, with less variability (Table 7). We explored three potential explanations for this reversal in the bank ratios between the projects. First, netting zones that are not well matched to the sonars' nearshore and offshore sampling regions would bias the species apportionment. Large numbers of sockeye and chum salmon migrate close to shore resulting in nearshore fish counts that comprise 87–96% of the RB count and 77–92% of the LB count (Maxwell et al., 2011). Because of the higher number of nearshore fish counted, a Chinook salmon inappropriately classified as a nearshore fish would substantially increase the estimate of that species for that day. Buoys mark the dividing line between strata and the end point of the counting range on both banks. They are placed at the start points of the drifts but do not define the entire drift corridor. Although it is possible that current could push the boat and nets closer to one bank than the other, we have no reason to believe that this is more likely on one bank than the other.

Differences in bank ratios would also occur if the RB sonar was missing fish. A study performed at three large Alaska rivers turned the DIDSON vertically to record fish depth (Maxwell et al., 2013). The study showed that very few fish traveled under or over a modeled horizontal DIDSON beam. The 14° vertical beam provides good coverage and the sonar is aimed just above the river bottom, where fish tend to travel. The river bottom along the RB has a flatter slope that allows better coverage of the water column by DIDSON. The current flow is less along RB, which extends the offshore range of fish. To compensate for this, a sampling range of 50 m is used on RB, compared

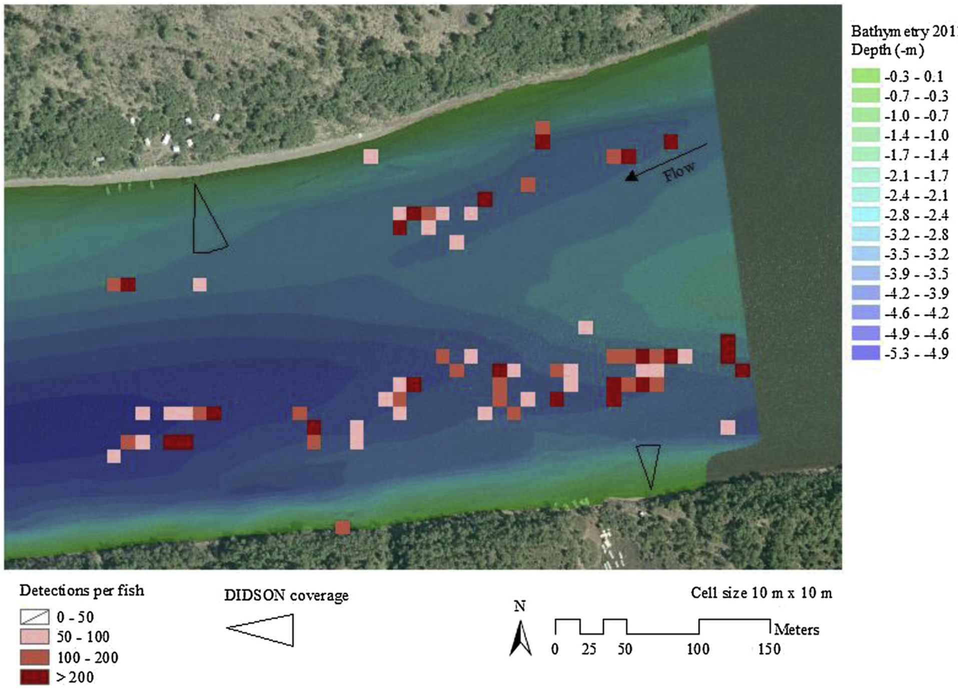

Fig. 20. A comparison of Chinook salmon length distributions from fish captured for the acoustic tag and mark-recapture (MR) studies (Maxwell et al., 2019a).

to 30 m on LB. These differences make it unlikely that the RB sonar would miss more fish than LB.

The most likely explanation for the bank ratio differences is the larger number of Chinook salmon that we observed holding and milling along LB (Fig. 20; from Maxwell et al., 2019a). This contrasts with Miller (2000) where nearly half (47.6% of the adjusted CPUE in 1998 and 43.3% in 1999) of Chinook salmon were captured in an offshore station closer to RB, where we observed fewer holding fish. The thalweg is partially within the LB offshore drift region (Fig. 4) where Chinook salmon tend to hold, and the sonar's test-fish crew capture more Chinook salmon in these offshore drifts. We observed more holding and milling of Chinook salmon along LB during every year of the acoustic tag study (Maxwell et al., 2019a), which would make them more vulnerable to capture and bias the sonar project's bank ratios.

4.4. Bias in fish lengths

Comparing Chinook salmon lengths from the sonar test fishing program (sonar fish) and tagged fish that traveled through a sonar beam footprint (inside fish) showed that sonar fish lengths contained a larger proportion of small Chinook salmon, suggesting that netting at the tagging site was biased toward larger fish (Fig. 18). This bias is not important if the distribution of fish across the river at the sonar site is not segregated by size (Fig. 19). We found that hypothesis to be true in every year except 2014 (Table 5). Because of the bias in the 2014 data, we stratified estimates for each year by length. If larger fish are more likely to migrate outside of the sonar beam footprints and if the ratio of tagged small fish is less than the true proportion, the mid-river population would be over-represented. Correcting for the length bias resulted in small differences between the original proportion (0.42) and length-stratified proportion (0.47) for 2014 (Table 6). As expected from the K–S tests, differences between original and length-stratified proportions for 2011–2013, the years that there was no significant bias, were even smaller (−0.01 to 0.02).

We have no evidence to explain why the 2014 tagged fish lengths were more biased against small fish, but in that year, changes were made to the tag-insertion portion of the project. A mark-recapture study utilizing pit tags was initiated and the same fishing crew inserted both acoustic tags and a much larger number of pit tags. We originally thought the crew might have inadvertently saved the expensive acoustic tags for the more fit fish; i.e., larger fish, but length frequency curves for all fish captured at the lower site showed a lack of small fish with curves very similar to the acoustic tag fish curves (Fig. 21; from Maxwell et al., 2019a). Environmental conditions were different in 2014. The river's mean temperature rose steadily from 2011 to 2014 (Table 8). Water level appeared to be unusually low in 2014 based on comments from fishermen and barge operators on the river. Low water may affect the catchability of fish in drift nets, but whether these changes affected our ability to catch smaller Chinook salmon at the lower site is unknown.

4.5. Accuracy of position estimates

Ehrenberg and Steig (2003) demonstrated that an acoustic array with receivers placed 15 m apart in X, Y, and Z directions produced more accurate position estimates for a stationary tag than an array with

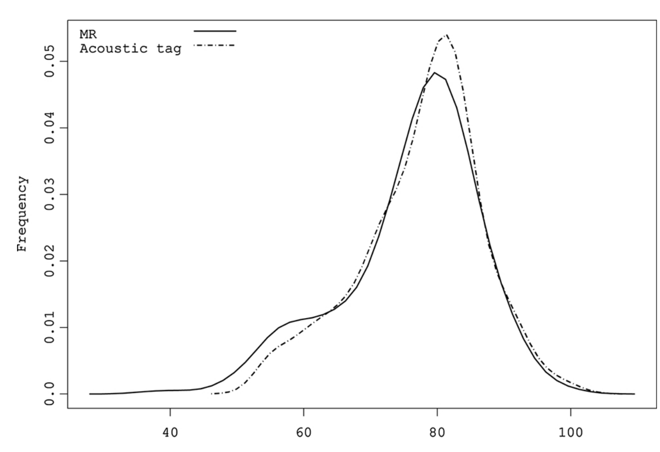

Fig. 21. Fish holding regions within the acoustic array based on the number of detections per tagged fish where areas with more than 50 detections per fish per 100 m^2 indicate holding fish, 2011 (Maxwell et al., 2019a).

X and Y spaced 15 m with the Z direction only 3–4 m apart. Error estimates from both placements were small, 0.2–1.8 m. In our study, the acoustic tags had pressure sensors to measure depth, leaving estimation error in the X and Y dimensions. Our DLs were spaced approximately 50 m apart in the upriver-downriver dimension and close to 300 m apart in the cross-river dimension, which should have yielded more accurate position estimates, yet uncertainty in the stationary tag position estimates (Fig. 10) and the poor quality of some of the fish tracks (Fig. 8C and D) raised questions regarding accuracy. Our study was performed over a much longer time period allowing for interference from many factors not observed in the 19-min sample from Ehrenberg and Steig (2003). Interference and multi-pathing from passing boats, stationary objects like weirs, sonar mounts, and parked boats likely contributed to position error in the fish tracks and stationary tags. From the stationary beacon analyses, we found that 70.6% of the minimally filtered position estimates from all beacons were within a 5-m radius of the beacons' actual locations and 90.8% were within 10 m (Table 2, Fig. 10). Watching the data plot point by point made it apparent which position estimates were the result of multipathing. The plotting resembled a bull's eye pattern as points plotted around a central point with very narrow scatter but occasionally 'jumped' to a distant region. Distal points accumulated as the number of detections grew creating the smear of points observed around the beacons' GPS location. Position estimates for the fish tracks were similar with some containing jumped points, but their time in the array was short compared to the stationary beacons, so there were far fewer distal points. Distal points were readily apparent in the fish tracks and were removed during the filtering process.

Additional evidence for the accuracy of the position estimates came from the depth of tagged fish heading upriver (Fig. 16). The depths of most tagged fish traveling upriver through the array aligned well with the river bottom bathymetry, indicating fish were traveling near the river bottom and their positions estimates were aligned correctly with their depths. The alignment of these very different methods provided additional evidence for the reliability and accuracy of the fish tracks.

Environmental interference caused errors in position estimates that resulted in occasional random patterns in fish tracks, outliers, missing segments (shorts) or entire trips through the array (implied trips). Kessel et al. (2014) describes the influence of numerous environmental parameters on detection rates including physical and chemical properties, surface conditions such as wind and wave action, water depth and tides, bathymetry and obstructions. Humston et al. (2005) selected deployment sites protected from wind to improve their detection range, which varied from 230 m to 750 m. These detection ranges were similar to detection ranges in our initial testing (300 m to 600 m; Maxwell et al., 2019b). Gjelland and Hedger (2013) found that detection rate was strongly dependent on wind speed, dropping off dramatically as wind speed increased. Wind mixes air bubbles into the water, which dissipates transmitted sound and may prevent detection. Gjelland and Hedger (2013) found that wind can drive air bubbles deeper into the water than rain, noting that during an hour of wind, sound reflections from entrained air reached 4–5 m deep. Their models confirmed that rain had less effect on detection rate than wind. At the Nushagak site, rain was less of a factor than wind, with mean rainfalls of less than 0.3 cm, while wind speeds reached maximum speeds great than 30 km/h; i.e., 8.3 m/s, (Table 8). These wind speeds are higher than Gjelland and Hedger's maximum observed speed of 6 m/s which reduced their detection rate to 0. The strong winds at the Nushagak River undoubtedly had a large effect on detection rates.

Transmitted signals propagating into shallow water bounce off river bottom or surface and have the potential to misdirect signals and cause multipathing. Obstructions in the river, such as the weirs used to route migrating fish offshore of the sonars or parked boats, may also misdirect transmitted signals from the tagged fish and reduce detection rates. Claisse et al. (2011) found that detection range was greater in deeper, less structurally complex habitats. Their shallow receivers (water depths 5 to 10 m) had a maximum detection distance of 30 m compared to deeper receivers (15 to 20 m) whose maximum detection was 50 m. Ideally, receivers are deployed in deeper water than our deployments. The DLs in our acoustic array were deployed at similar depths in approximately chest-deep water. Low tides reduced the depth even further. To ensure that fish were detected in the nearshore regions, it was necessary to position the DLs as close to shore as possible because triangulating positions outside of the array is less effective. Gjelland and Hedger (2013) found that depth range of transmitters (defined as the difference between the deepest and shallowest transmitters) was second to wind in importance as a predictor for detection rate, with rain being third. Most of our tagged fish traveled near the river bottom, so the depth range of our transmitters was similar to the river bottom depth, approximately 1 to 5 m (Fig. 16). River bottom topography also plays a role in detection range. We observed more short tracks along LB (Table 3) and hypothesize the missed pings may have been due to either river bottom topography or the placement of the weirs and boats along this side of the river.

Wind, river bottom topography, obstructions, and shallow water depths likely played the largest roles in detection rates at the Nushagak River creating the problematic tracks. Despite these potential issues, overall detection was high (94.6%) and the number of usable tracks, i.e., those that produced enough of a track to determine whether a fish went through one or more sonar beams, was 76.7% (Table 1).

5. Conclusions

- The acoustic tag proportions allowed us to expand Chinook salmon indices of abundance to full-river estimates. These expansion proportions were relatively stable between years, which indicates the indices of abundance from the sonar project were adequate for fisheries management.
- For assessing behaviorally diverse species like Chinook salmon, full-river coverage is desirable with careful observations of downstream movements which can bias counts. Additional problems for the sonar project included cross-over behavior, multiple trips through the array, and milling and holding fish. These factors were accounted for in the acoustic tag proportions.
- The variability in the sonar's abundance indices could be reduced by weighting the differences in catchability between banks using an averaged bank ratio from the acoustic tag study.
- Future topics to explore from the information in the acoustic tag, sonar, test fish, and environmental datasets from this study include the effects on track quality of changes in DL depth due to tidal fluctuations and wind speed; effects of tides and storms on fish movement; effects of nearshore fish congestion on Chinook salmon migratory pathways; and effects of fishing pressure from the test fishing on Chinook salmon behavior.

Funding

This work was supported by the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, administered by the Alaska Department of Fish and Game [grant no. NA09NMF4380373], and in 2014 was partially funded by the State of Alaska, U.S.A., Chinook Salmon Research Initiative [appropriation number 43106-18; Project 11329046, Nushagak Adult In-river Abundance].

Acknowledgements

Mitch Sisak and Hao Guan of Lotek, Inc. assisted with setting up and testing the acoustic array, training staff on use of the equipment and assisting with data questions. Henry Tam of Lotek, Inc. provided information and assistance with Lotek Inc.'s software. Anna-Maria Mueller of Aquacoustics, Inc. provided the second level of filtering and smoothing of fish tracks, processed the ArcGIS data, and provided editorial support. Xinxian Zhang provided biometric support. Don Degan of Aquacoustics, Inc. directed the collection of the bathymetry data. Jack Erickson provided editorial support. Special thanks to the drift gillnet crews that inserted tags at the lower site and the sonar crew that assisted with field operations and shared their field camp.

References

Belcher, E.O., Hanot, W., Burch, J., 2002. Dual-frequency identification sonar. Proceedings of the 2002 International Symposium on Underwater Technology, April 16–19 187–192.

Buck, G.B., 2013. Sonar Enumeration of Pacific Salmon Escapement into the Nushagak River, 2009. Alaska Department of Fish and Game, Fishery Data Series No, Anchorage, pp. 13–34.

Buck, G.B., Brazil, C.B., West, F., Fair, L., Zhang, X., Maxwell, S.L., 2012. Stock Assessment of Chinook, Sockeye, and Chum Salmon in the Nushagak River. Alaska Department of Fish and Game, Anchorage Fishery Manuscript Series No. 12–05.

Burwen, D.L., Fleischman, S.J., Miller, J.D., 2011. Estimating Chinook salmon passage in the Kenai River using dual frequency identification sonar. J. Acoust. Soc. Am. 129 (4), 2695. https://doi.org/10.1121/1.3589042.

Burwen, D.L., Fleishchman, S.J., Miller, J.D., 2010. Accuracy and precision of salmon length estimates taken from DIDSON sonar images. Trans. Am. Fish. Soc. 139, 1306–1314. https://doi.org/10.1577/T09-173.1.

Childs, A.R., Cowley, P.D., Naesje, T.F., Booth, A.J., Potts, W.M., Thorstad, E.B., Økland, F., 2008. Estuarine use by spotted grunter *Pomadasys commersonnii* in a South African estuary, as determined by acoustic telemetry. Afr. J. Mar. Sci. 30 (1), 123–132. https://doi.org/10.2989/AJMS.2008.30.1.12.462.

Chittenden, C.M., Beamish, R.J., Neville, C.M., Sweeting, R.M., McKinley, R.S., 2009. The Use of Acoustic Tags to Determine the Timing and Location of the Juvenile Coho Salmon Migration out of the Strait of Georgia, Canada. Trans. Am. Fish. Soc. 138 (6), 1220–1225. https://doi.org/10.1577/T09-037.1.

Claisse, J.T., Clark, T.B., Schumacher, B.D., McTee, S.A., Bushnell, M.E., Callan, C.K., Laidley, C.W., Parrish, J.D., 2011. Conventional tagging and acoustic telemetry of a small surgeonfish, *Zebrasoma flavescens*, in a structurally complex coral reef environment. Environ. Biol. Fish 91, 185–201.

Crossman, J.A., Martel, G., Johnson, P.N., Bray, K., 2011. The use of Dual-frequency IDentification SONar (DIDSON) to document white sturgeon activity in the Columbia River, Canada. J. Appl. Ichthyol. 27 (2), 53–57. https://doi.org/10.1111/j.1439-0426.2011.01832.x.

Egg, L., Pander, J., Mueller, M., Geist, J., 2018. Comparison of sonar-, camera- and net-based methods in detecting riverine fish-movement patterns. Mar. Freshw. Res. 69 (12), 1905–1912. https://doi.org/10.1071/MF18068.

Ehrenberg, J.E., Steig, T.W., 2003. Improved techniques for studying the temporal and spatial behavior of fish in a fixed location. ICES J. Mar. Sci. 60, 700–706. https://doi.org/10.1016/S1054-3139(03)00087-0.

El Mejjati, S., Bell, J., Botz, J., Faulkner, A., Maxwell, S., 2010. Using Hydroacoustic Methods to Enumerate Migrating Salmon in the Copper River, Miles Lake Sonar Project, 2007. Alaska Department of Fish and Game, Anchorage Fishery Data Series No. 10–98.

English, K.K., English, B.L., Roias, S.M., 2017. Waanukv River Multi-Species Escapement Monitoring System Using Dual-Frequency Identification Sonar (DIDSON), ARIS Sonar, and Test Fishing. Rivers Inlet Salmon Initiative Steering Committee. LGL Limited, 9768 Second St., Sidney, BC V8L 3Y8.

Faulkner, A.V., Maxwell, S.L., 2015. The Feasibility of Using Sonar to Estimate Adult Sockeye Salmon Passage in the Lower Kvichak River. Alaska Department of Fish and Game, Anchorage Fishery Manuscript Series No. 15–05.

Gaudet, D.M., 1990. Enumeration of migrating salmon populations using fixed-location sonar counters. Rapports et Proces-Verbaux des Reunions, Conseil International pour l'Exploration de la Mer 189, 197–209.

Gjelland, K., Hedger, R.D., 2013. Environmental influence on transmitter detection probability in biotelemetry: developing a general model of acoustic transmission. Methods Ecol. Evol. 4, 665–674. https://doi.org/10.1111/2041-210X.12057.

Grote, A.B., Baily, M.M., Zydlewski, J.D., Hightower, J.E., 2014. Multibeam sonar (DIDSON) assessment of American shad (Alosa sapidissima) approaching a hydroelectric dam. Can. J. Fish. Aquat. Sci. 71, 545–558. https://doi.org/10.1139/cjfas-2013-0308.

Hayden, T.A., Holbrook, C.M., Fielder, D.G., Vandergoot, C.S., Bergstedt, R.A., Dettmers, J.M., 2014. Acoustic telemetry reveals large scale migration patterns of walleye in Lake Huron. PLoS One 9 (12), e114833. https://doi.org/10.1371/journal.pone.0114833.

Heublein, J.C., Kelly, J.T., Crocker, C.E., Klimley, A.P., Lindley, S.T., 2009. Migration of green sturgeon, *Acipenser medirostris*, in the Sacramento River. Environ Biol Fish 84, 245–258. https://doi.org/10.1007/s10641-008-9432-9.

Holmes, J.A., Cronkite, G.M.W., Enzenhofer, H.J., Mulligan, T.J., 2006. Accuracy and precision of fish-count data from a "dual-frequency identification sonar" (DIDSON) imaging system. ICES J. Mar. Sci. 63, 543–555. https://doi.org/10.1016/j.icesjms.2005.08.015.

Hinch, S.G., Rand, P.S., 2000. Optimal swimming speeds and forward-assisted propulsion: energy-conserving behaviours of upriver-migrating adult salmon. Can. J. Fish. Aquat. Sci. 57, 2470–2478. https://doi.org/10.1139/f00-238.

Hughes, N.F., 2004. The wave-drag hypothesis: an explanation for size-based lateral segregation during the upstream migration of salmonids. Can. J. Fish. Aquat. Sci. 61, 103–109. https://doi.org/10.1139/f03-144.

Humston, R., Ault, J.S., Larkin, M.F., Luo, J., 2005. Movements and site fidelity of the bonefish Albula vulpes in the northern Florida Keys determined by acoustic telemetry. Mar. Ecol. Prog. Ser. 291, 237–248. https://doi.org/10.3354/meps291237.

Kessel, S.T., Cooke, S.J., Heupel, M.R., Hussey, N.E., Simpfendorfer, C.A., Vagle, S., Fisk, A.T., 2014. A review of detection range testing in aquatic passive acoustic telemetry studies. Rev. Fish Biol. Fish. 24, 199–218. https://doi.org/10.1007/s11160-013-9328-4.

Mathes, M.T., Hinch, S.G., Cooke, S.J., Crossing, G.T., Patterson, D.A., Lotto, A.G., Farrell, A.P., 2010. Effect of water temperature, timing, physiological condition, and lake thermal refugia on migrating adult Weaver Creek sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 67, 70–84. https://doi.org/10.1139/F09-158.

Maxwell, S.L., Gove, N.E., 2007. Assessing a dual-frequency identification sonar's fish counting accuracy, precision, and turbid river range capability. J. Acoust. Soc. Am. 122 (6), 3364–3377. https://doi.org/10.1121/1.2799500.

Maxwell, S.L., Faulkner, A.V., Fair, L., Zhang, X., 2011. A Comparison of Estimates From 2 Hydroacoustic Systems Used to Assess Sockeye Salmon Escapement in 5 Alaska Rivers. Alaska Department of Fish and Game Fishery Manuscript Series No. 11–02, Anchorage.

Maxwell, S.L., Faulkner, A.V., Hacklin, T.D., 2013. Evaluating Error in Sockeye Salmon Abundance Estimates from Salmon Traveling Outside the Sonar Beam at the Yentna, Copper, and Kenai Rivers. Alaska Department of Fish and Game, Anchorage Fishery Manuscript Series No. 13-07.

Maxwell, S.L., Buck, G.B., Faulkner, A.V., 2019a. Using acoustic telemetry to expand sonar escapement indices of chinook salmon to in-river abundance estimates. Mendeley Data V1. https://doi.org/10.17632/c8jr8x9r4y.1.

Maxwell, S.L., Buck, G.B., Faulkner, A.V., 2019b. Expanding Nushagak River Chinook Salmon Escapement Indices to Inriver Abundance Estimates Using Acoustic Tags. In press. Alaska Department of Fish and Game, Fishery Manuscript Series No. __, Anchorage.

McDougall, M.J., Lozori, J.D., 2018. Sonar Estimation of Chinook and Fall Chum Salmon Passage in the Yukon River near Eagle, Alaska, 2017. Alaska Department of Fish and Game, Anchorage Fishery Data Series No. 18–20.

McMichael, G.A., Eppard, M.B., Carlson, T.J., Carter, J.A., Ebberts, B.D., Brown, R.S., Weiland, M., Ploskey, G.R., Harnish, R.A., Deng, Z.D., 2010. The juvenile salmon acoustic telemetry system: A new tool. Fisheries 35 (1), 9–22. https://doi.org/10.1577/1548-8446-35.1.9.

Miller, J.D., 2000. Sonar Enumeration of Pacific Salmon Escapement Into Nushagak River, 1999. Alaska Department of Fish and Game Regional Information Report No. 2A00–19, Anchorage.

Miller, J.D., Burwen, D.L., Fleischman, S.J., 2013. Estimates of Chinook Salmon Passage in the Kenai River Using Split-beam and Dual-frequency Identification Sonars, 2010. Alaska Department of Fish and Game, Anchorage Fishery Data Series No. 13–58.

Mora, E.A., Lindley, S.T., Erickson, D.L., Klimley, A.P., 2015. Estimating the riverine abundance of green sturgeon using a dual-frequency identification sonar. N. Am. J. Fish. Manage. 35 (3), 557–566. https://doi.org/10.1080/02755947.2015.1017119.

Pipal, K.A., Notch, J.J., Hayes, S.A., Adams, P.B., 2012. Estimating escapement for a low-abundance steelhead population using Dual-Frequency Identification Sonar (DIDSON). N. Am. J. Fish. Manage. 32 (5), 880–893. https://doi.org/10.1080/02755947.2012.697096.

Rakowitz, G., Kubečka, J., Fesl, C., Keckeis, H., 2009. Intercalibration of hydroacoustic and mark–recapture methods for assessing the spawning population size of a threatened fish species. Rev. Fish Biol. Fish. 75 (6), 1356–1370. https://doi.org/10.1111/j.1095-8649.2009.02368.x.

Rawding, D., Liermann, M., 2011. Comparison of DIDSON sonar based estimates of Chinook salmon escapement with other methods in the Coweeman River, Washington. J. Acoust. Soc. Am. 129 (4), 2692. https://doi.org/10.1121/1.3589030.

Reimer, A.M., Fleischman, S.J., 2016. Stock-specific Abundance and Run Timing of Chinook Salmon in the Kenai River, 2007–2014. Alaska Department of Fish and Game, Anchorage Fishery Manuscript Series No. 16–06.

Reynolds, J.H., Woody, C.A., Gove, N.E., Fair, L.F., 2007. Efficiently estimating salmon escapement uncertainty using systematically sampled data. American Fisheries Society Symposium 54, 121–129.

Schumann, K.J., McIntosh, B.C., 2017. Sonar Estimation of Salmon Passage in the Yukon River near Pilot Station, 2014. Alaska Department of Fish and Game, Anchorage Fishery Data Series No. 17–31.

Seber, G.A.F., 1982. On the Estimation of Animal Abundance and Related Parameters, 2nd-. Charles Griffin and Sons, Ltd., London, pp. 7–9 64–69, 654.

Seibel, M.C., 1967. The Use of Expanded Ten-minute Counts As Estimates of Hourly Salmon Migration Past Counting Towers on Alaskan Rivers. Informational Leaflet 101, Alaska Department of Fish and Game, Juneau Division of Commercial Fisheries.

Simmonds, E.J., MacLennan, D.N., 2005. Fisheries Acoustics: Theory and Practice. Blackwell Science Ltd., Oxford, UK, pp. 39–69.

Starr, R.M., O'Connell, V., Ralston, S., Breaker, L., 2005. Use of acoustic tags to estimate natural mortality, spillover, and movements of lingcod (*Ophiodon elongatus*) in a marine reserve. Mar. Technol. Soc. J. 39 (1). https://doi.org/10.4031/002533205787521677. Spring, 19–30(12).