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Anadromous Arctic char – Mapping of migration and area use in Isfjord, Svalbard

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Master Nature management

Acknowledgments

This master thesis marks the end of five years of study at the faculty of Environmental science and Natural recourse Management (MINA), Norwegian University of Life Science (NMBU). The thesis is the beginning of the project “Mapping of anadromous Arctic charrs migration and area use in Isfjorden,”, which is also in close cooperation with the project “genetic tracking of anadromous Arctic charr in Isfjorden” (Johnsen et al., 2021), all funded by Svalbard’s Environmental fund and led by Akvaplan-niva (Christensen, unpublished data). The main goal of this project is to get an overview of the anadromous Arctic charr migration pattern and population ecology so that the Governor of Svalbard can make a long-term sustainable plan for the populations on Svalbard (Johnsen et al., 2021).

A special thanks to the employees at Akvaplan-niva, R&D manager Guttorm Christensen and scientist Jenny Jensen for implementing the project and for an excellent fieldwork period on Svalbard. Thanks to Tomas Strand, Oddmund Isaksen and Ellie Ward for practical help and making fieldwork feasible. A great thanks to my supervisor, professor Thrond Haugen (NMBU), for guiding me through the writing period and data analysis. I will thank again Jenny Jensen and Ellie Ward for proofreading my thesis.

Unless otherwise stated: maps, catchment areas, Figures, and photographs are generated or taken by the author.

Norwegian University of Life Sciences

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Abstract

The movements of 90 anadromous Arctic charr *Salvelinus alpinus* (mean ± s.d. fork length = 45.63 ± 5.6 cm) in fresh-, brackish-, and marine waters were studied from mid-July to mid-September 2021 use of acoustic telemetry in Isfjorden, Svalbard (WGS: 84 - 78.84˚ N, 13.30˚ – 17.37˚ E). Anadromous Arctic charr was tagged with acoustic transmitters at 5 different locations in Isfjorden, and their movements were recorded on 27 receivers placed in strategic places in the fjord and around river mouths. During the migration phase, most tagged individuals (> 80 %) was detected close to the river mouth, with a depth utilization almost exclusively in the upper aquatic zone (0 - 3 m depth). While migrating outside the river mouth zone, a capacity of migration > 70 km was recorded, with individuals swimming offshore and crossing the straight across over Isfjorden, taking advantage of both lakes (Bretjørna and Lovénvannet) covered in this study. Area utilization calculations showed differences between groups tagged in the southern and northern part of Isfjorden, but there was also overlap in area utilization. The marine phase of the migration ended for most individuals (59 %) by the end of July, followed by a week-long residency in the brackish environment close to the river mouths. The time of freshwater return could mainly be explained by the day in the season and length of the individual (AIC-weight = 67 %), including 2 days differences between lake Lovénvannet and Bretjørna. Modeling showed a significant earlier return to the freshwater environment by the increased length of the individuals. Larger individuals were also found utilized greater depths in the lakes (up to 32 m depth). Finally, this study submitted a stock mixing between watercourses based on individuals' detection in the same lake (Lovénvannet) from almost all (4 of 5) groups. Still, a genetic examination must be done to investigate the genetic flow in more detail.

Sammendrag

Migrering av 90 anadrome røyer *Salvelinus alpinus* (gjennomsnitt ± s.d. gaffel lengde = 45.63 ± 5.6 cm) gjennom ferskvann, brakkvann og marint miljø ble undersøkt fra midten av Juli til midten av September 2021 med akustisk sporing i Isfjorden, Svalbard (WGS: 84 - 78.84˚ N, 13.30˚ – 17.37˚ E). Det ble samlet inn og merket anadrom røye fra 5 forskjellige områder, basert på forskningsgruppens kunnskap og erfaring om populasjonsøkologien i Isfjorden. I den marine migreringsfasen brukte de fleste av individene (> 80 %) området nært elvemunningen, med dybdebruk nærmest utelukkende i øvre vannlag (0 - 3 m). Det ble også registrert sjørøye som vandret > 70 km i marint miljø, over åpent hav, langt fra kystlinjen (> 6 km). Kalkulert områdebruk viste seg å differensiere mellom gruppene merket i søndre og nordre del av Isfjorden, men også en overlapp i områdebruk så ut til å forekomme. Slutten på den marine fasen viste at røya oppholdt seg nær elvemunningen en ukes tid før de vandret opp til innsjøen. Innen slutten av juli hadde de fleste (59 %) individene vandret opp i innsjøene. Tiden for tilbakevandring var i hovedsak forklart med dato og lengde på fisken (AIC-vekt = 67 %). Det var to dager forskjell i oppvandring mellom innsjøene Lovénvannet og Bretjørna. Modellering antyder en signifikant tidligere tilbakevandring til innsjøene med økende lengde på individene. Økende lengde ble også koblet til økende dybdebruk i innsjøene (opptil 32 m dybde). Til slutt, denne studien antyder en miksing i populasjoner basert på deteksjonene i samme innsjø (Lovénvannet) for nesten alle merket gruppene (4 av 5) og vandring mellom innsjøer. Uansett, det må gjøres genetiske undersøkelser for å kunne fastslå genetisk blanding mellom populasjonene.

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1. Introduction

The Arctic charr (*Salvelinus alpinus)* is the northernmost freshwater fish on earth and has a circumpolar distribution in the Holarctic (Hammer, 1989, Power et al., 2008). Arctic charr is also a more frequent species with higher latitude and dominates most of the Arctic freshwater fish community (Svenning and Gullestad, 2002, Klemetsen et al., 2003). Over millions of years, the species has evolved into an aquatic environment that is cold, little productive, and often catastrophically unsTable (Power, 2002). Adaptions to this are, for example, plasticity to use different habitats and niches, traits to spawn in still water, physiological adaptations to low temperature, migration behavior, and seasonal storage of energy to survive the long winter season (Jørgensen and Johnsen, 2014, Gulseth and Nilssen, 2001). These adaptions have made the Arctic charr, probably, the only fish species that can live and reproduce in the watercourses on Svalbard today (Brittain et al., 2020, Klemetsen et al., 2003).

The Arctic charr appears in two “main forms”: anadromous and stationary (resident). The stationary variant are found in over 100 watercourses on Svalbard, while the anadromous variant is found in less than 20 lake systems (Brittain et al., 2020). While the stationary variant stays in fresh water throughout life, the anadromous variant migrates to the sea to feed on rich marine resources when conditions allow (Gulseth and Nilssen, 2001). Because of the availability to feed in the marine environment, anadromous individuals have the potential to grow very fast and reach a body weight of several kilos, in contrast to stationary individuals who often stagnate below 130 g on Svalbard (Gulseth and Nilssen, 2001).

Unfortunately, an overview from the mainland shows a declining trend for anadromous Arctic charr population in northern Norway (Svenning, 2010), which raises concern about the anadromous Arctic charr population on Svalbard. We also know that Arctic ecosystems are under increasing pressure from different sources, such as invasion by non-native species (Thomassen et al., 2017), commercial fishing (Brittain et al., 2020, Johnsen et al., 2021), and changes in both marine and freshwater habitats as a result of climate change (Forsgren et al., 2015, Finstad and Hein, 2012). Still, more studies are needed to understand how all these threats affect the ecosystem and populations.

Until 1996, no scheme was established to record anadromous Arctic charr catches and fishing efforts on Svalbard (Hansen and Overrein, 2000). Since then, catches from recreational fishing have been reported, but these results are far from sufficient to give us some knowledge about the population size and dynamics. The few surveys that have been done on the anadromous Arctic charr population on Svalbard are from the watercourse Vårfluesjøen and Linnévassdraget (north and northwest on Svalbard) (Svenning et al., 2006, Skogstad and Skogstad, 2006). Here, a sharp increase in the anadromous Arctic charr population occurred after a protection against net fishing was implemented in 1993, which indicates that the harvesting was too heavy (Skogstad and Skogstad, 2006, Cottier et al., 2007). At the same time as its taxation of the anadromous Arctic charr population in the lakes, there is ongoing net fishing in the marine system, and it is unknown which fish stock there is harvesting (Johnsen et al., 2021).

Overall, there is little knowledge about the anadromous Arctic charr’s marine phase on Svalbard. Significant uncertainties exist about sea survival, habitat use, and migration patterns, such as how long they reside at sea and how long distances they migrate. Currently, its assumed that the anadromous Arctic charr utilize the fjords and shallow areas close to the shoreline (Christensen, unpublished data). Studies from the mainland show the anadromous Arctic charr can migrate over 30 km from their native river (Berg and Berg, 2011, Spares et al., 2015). Surveys done in watercourse Linnévannet, show migration back to the watercourses mainly takes place in July and August (Ebne, 2009, Brittain et al., 2020), while recent investigations by Akvaplan-niva have detected anadromous Arctic charr in the marine environment throughout October (Christensen, unpublished data).

Lack of knowledge creates considerable uncertainty about whether the ongoing fishing on anadromous Arctic charr at sea on Svalbard is sustainable. Therefore, the governor, responsible for managing anadromous Arctic charr populations on Svalbard, is currently preparing a new management plan (Johnsen et al., 2021). According to the latest regulations, requirements have been set for the management of anadromous Arctic charr to be knowledge-based and stock-oriented (Brittain et al., 2020, Johnsen et al., 2021). This requires obtaining new and updated knowledge.

This exploratory study aims to describe the migratory behavior of anadromous Arctic charr in Isfjorden, Svalbard. Here, I use acoustic telemetry data to investigate (1) habitat utilization based on environment (marine-, brackish- and freshwater) and spatial (area and depth) distribution, (2) timing of freshwater return, (3) abiotic and biotic impact on depth utilization and freshwater return, and (4) minimum distance traveled through the study period. Hopefully, this project with acoustic telemetry and another study, “genetic tracking of anadromous Arctic charr in Isfjorden”, will also (5) indicate which stocks are harvested on in the different marine areas and if the stocks are genetically mixing.

2. Materials and Methods

2.1 Study area

Svalbard consist of six big islands (Spitsbergen, Nordaustlandet, Barentsøya, Edgeøya, Bjørnøya and Hopen), all between 74˚ – 81˚ N, 10˚ - 35˚ E (WGS84). The main study area, Isfjorden (Figure 1), is located west on Spitsbergen (WGS84: 77.96˚ - 78.83˚ N, 13.30˚ – 17.37˚ E). Isfjorden is the second-largest fjord on Svalbard with over 2100 km^2 in area and stretches over 100 km from the Greenland Sea in the west to Dickson Land in the east (Barr, 2020).

There are four lakes with known anadromous Arctic charr populations in Isfjorden, those are Linnévannet, Lovénvannet, Straumsjøen and Bretjørna (Figure 1) (Brittain et al., 2020). In addition, due to glacial melt-of, a new lake (Trebrevatnet) has occurred which have potential to be populated by anadromous Arctic charr. In this study, the following locations were considered critical marine areas for anadromous Arctic charr and selected as sampling areas: Grønfjorden, Trygghamna, Borebukta, Gipsvika, and Ekmanfjorden (appendix A). Those areas were selected based on the team's earlier experience and information from the local fishers (Figure 1).

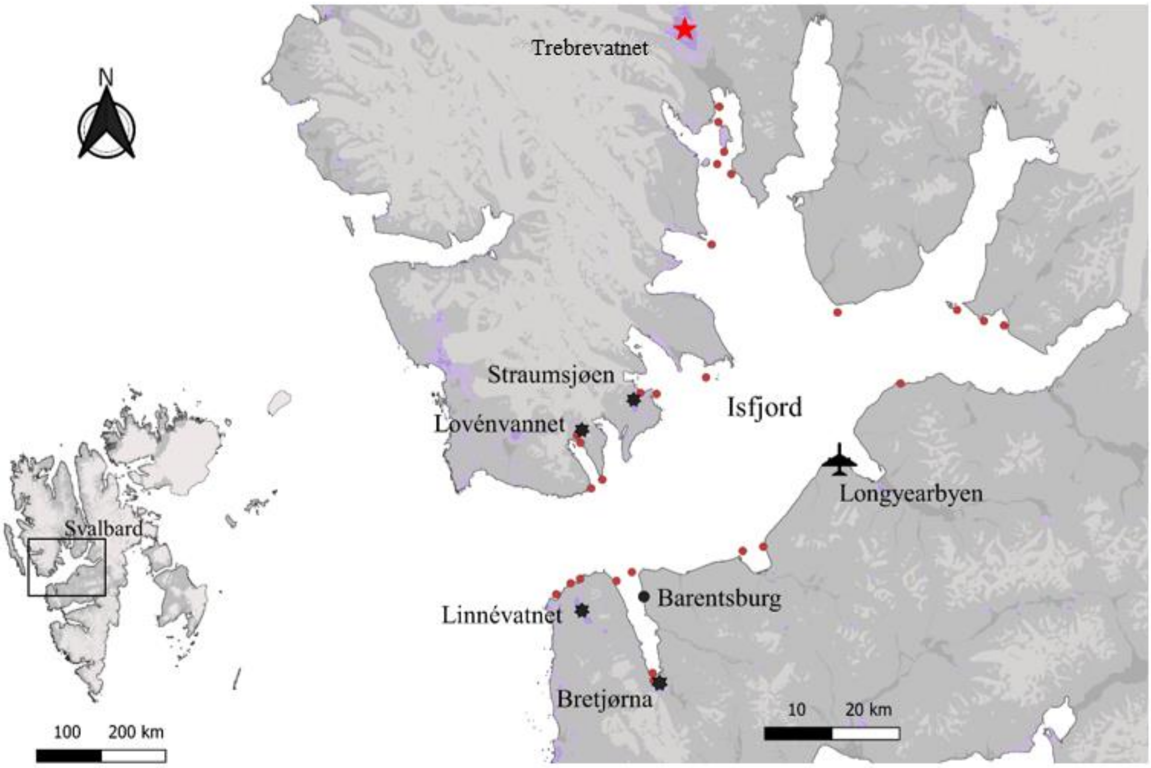

Figure 1. *Map of Svalbard to the left with a zoom in on Isfjorden to the right. Black stars are watercourses with known stocks of anadromous Arctic charr. The red star is a watercourse with potential stocks of anadromous Arctic charr. Red dots indicate locations of acoustic receivers.*

2.2 Study species

Based on the flexibility of Arctic charr to use different trophic niches and habitats, it seems like the anadromous Arctic charr are a plasticity variant of the species with another life-history trait (Makhrova et al., 2018, Gulseth and Nilssen, 2001, Eloranta et al., 2011, Hooker et al., 2020, K.Kristjánsson et al., 2017). The differences in life-history traits can be seen in different morphology, for example, body shape and growth (Kusznierz et al., 2008). On Svalbard, three main morphotypes are observed: slow-growing resident individuals (dwarf), cannibalistic individuals, and anadromous individuals (Gulseth and Nilssen, 2001, Kusznierz et al., 2008).

Like the individuals with other life history and morphology, anadromous Arctic charr hatch in freshwater and live their first years here (Hansen and Overrein, 2000). On Svalbard, the first year's diet is dominated by zooplankton and chironomids (Chironomidae spp.) (Skogstad and Skogstad, 2006, Hegseth, 2007, Svenning et al., 2006), and they grow no more than 2-3 cm yearly (Svenning, 2010). A significant increase in growth does not occur before the anadromous Arctic charr migrates to sea (Svenning, 2010). In the marine habitat, they increase their weight by more than 70 % during the first marine migration (Mathisen and Berg, 1993), eating mainly krill (*Euphausiacea*), amphipods *Gammaridea,* and fry from various sculpin species (*Scorpaeniformes)* (Svenning, 2010). Analyses of otolith readings based on Sr/Ca isotope ratio from the Dieset watercourse and lake Vårfluesjøen (north-west and north on Svalbard) have shown that anadromous Arctic charr shifts to a marine habitat at 5 - 7 of years (Radtka et al., 1996, Gulseth and Nilssen, 2001).

Before reaching saltwater, the anadromous Arctic charr goes through a parr-to-smolt transformation (smolting process) (Arnesen et al., 1992). From cryptically colored, bottom-dwelling juveniles (parr), they prepare for a pelagic life and get a more silvery color and streamlined morphology (Døving and Reimers, 1992). Physical alterations to tolerate high salt levels include functional changes in osmoregulatory organs such as the gills, kidney, gut, and urinary bladder (Døving and Reimers, 1992, McCormick and Saunders, 1987).

After the smolting, the anadromous Arctic charr often starts their seaward migration in May/Jun, at least on mainland Norway (Berg and Berg, 2011). How long the anadromous Arctic charr migrates and how long they stay in the sea varies greatly. There is some evidence for long-distance migratory capacity. In a study from northern Norway, individuals were caught more than 100 km from the river mouth (Berg and Berg, 2011). On the other hand, records of longer distances in the open sea are lacking; it is mainly observed that anadromous Arctic charr migrates along the coast in the littoral zone (Nordli, 2021, Kirkemoen, 2015). Long-term investigation shows individuals moving upstream and downstream the river throughout the summer (Berg and Berg, 2011), indicating no specific time for downstream and upstream runs, at least in their study system. Registrations from Lake Vårfluesjøen showed anadromous Arctic charr swimming up to the lake from the middle of July, reaching a peak in individuals in the middle of August (Skogstad and Skogstad, 2006).

The most common spawning time for Arctic charr is throughout September/October, and since the rivers dry up during winter the spawning takes place in lakes on Svalbard (Hansen and Overrein, 2000, Brittain et al., 2020). Spawning depth is mainly unknown for Svalbard Arctic charr. In other areas, the Arctic charr show great local adaptation, and spawning has been registered from 1 meter to 100 meter depth (Hoglund, 1961, Frost, 1965).

Examinations on anadromous Arctic charr from Vårfluesjøen and Linnévannet found that the earliest individuals mature at age 7 - 8, while the mean was around 10 years (Ebne, 2009, Bergane, 2018). The mean length at maturity in Linnévannet was calculated to be 43 cm for males and 48 cm for females, with a stagnating in growth at 9-10 years. The oldest registered individuals were 15 years old, but very few individuals reached ages beyond 11 years (Bergane, 2018).

***Figure 2**. Anadromous Arctic charr caught in the side-fjord Trygghamna, Isfjorden. The fish was internally tagged with an acoustic transmitter and externally tagged with a Floy-tag, recovered from anesthesia, and was ready for release. Like this individual, caught anadromous Arctic charr had a silvery color opposed to a red body with a clear white edge on the pectoral fin, as they usually have in the spawning session (Balon, 1980).*

2.3 Capture of anadromous Arctic charr individuals

For transportation around Isfjorden, a 50 - feet long sailboat (M/S Meridian) was used for accommodation and storage of equipment. A 15 feet long rubber boat (Zodiac) were used for getting to land and gillnetting. A total of 6 - 8 gillnets with 35 - 50 mm mesh size (1.5 m high x 25 m length) were connected in pairs (50 m) and set perpendicular from the shoreline, with a red buoy on the end. A maximum of two hours after the gillnet was functionally operative, they were checked for fish by lifting them over the surface. If fish were trapped in the gillnets after the first round, the gillnets were checked for fish more frequently to minimize the risks of fish mortality. Living anadromous Arctic charr was carefully retrieved from the gillnets, placed in 60 l tanks with seawater from the location, and transported to the sailboat for tagging.

2.4 Acoustic telemetry

Acoustic telemetry is a well-known method for tracking animals from a distance in the aquatic environment, giving individual information about distribution in space and time (Hussey et al., 2015, Lennox et al., 2017). Studies incorporating acoustic telemetry on anadromous salmonids have given information about for example abiotic and biotic factors on marine migrations (Spares et al., 2012), depth use (W Welch et al., 2014), the timing of shifting between marine and freshwater environments (Hammer et al., 2021), and overall spatial distribution and habitat utilization (Spares et al., 2015, Nordli, 2021).

The method of acoustic telemetry consists of transmitters (tags) and receivers (or hydrophones) (Stasko and Pincock, 1977a). The transmitters can be attached externally or surgically implanted into the fish´s abdomen (Crossin et al., 2017). Active or passive hydrophones and receivers receive sonic pulses from the acoustic transmitters (Stasko and Pincock, 1977a). As the tagged anadromous Arctic charr individuals in this study resided within the receiver’s detection rang, the receivers registered individual’s date, ID and depth. The received data was stored in the receivers internal memory, together with date, time and the receivers’ temperature and noise data (Thelmabiotel, 2021b).

Figure 3. *The method of acoustic telemetry requires a transmitter to send sonic pulses and a receiver to receive and store the detection. 1: A receiver being attached to a rope. 2: Multiple transmitters. Both the receiver and transmitter are produced by Thelma Biotel AS, Norway.*

2.4.1 Tracking

This study used acoustic receivers (*n* = 28, TBR700, diameter: 75 mm, length: 230 mm, weight in the air: 1140 g, battery lifetime: 9 months, kHz: 63 – 77, (Thelmabiotel, 2021b)) from Thelma Biotel AS, Norway. The receivers were strategically placed in and around Isfjorden through the field period (Figure 1) and grouped into three main sections (habitats / sections); lake (*n* = 2), river mouth (*n* = 5), and fjord (*n* = 20). All receivers were placed less than 1 km from the shoreline, attached to a 10 mm wide braided polyester rope 5 m beneath a red floating buoy, with an anchor at the bottom (Figure 3, left).

Anadromous Arctic charr individuals were either tagged with only identification transmitters (*n* = 54, diameter: 13 mm, length: 33.3 mm, weight in air/water: 11.5/7.1 g, kHz: 69, power output: 153 dB, battery life: 29 months, (Thelmabiotel, 2021a)) or identification transmitters including depth registration (*n* = 36, diameter: 13 mm, length: 36.4 mm, weight in air/water: 12/7.2 g, kHz: 69, the power output: 153 dB, battery life: 29 months, (Thelmabiotel, 2021a)).

Signals from the transmitters can be received at up to 800 m, depending on different environmental conditions (Reubens et al., 2019, Klinard et al., 2019). No range test was performed in this study. The detection range was set to 500 m for all receivers for further analysis, based of earlier studies on acoustic telemetry which have shown a significantly lower detection rate than specified by the manufacturer (Babin et al., 2019, Kessel et al., 2013).

In total, 90 individuals of anadromous Arctic charr were captured and tagged at 5 different locations: Gipsvika 20th July (*n* = 20), Ekmanfjord 21st July (*n* = 30), Borebukta 21st to 22nd July (*n* = 18), Trygghamna 23rd to 24th July (*n* = 12), and Grønfjord 25th July (*n* = 10). Mean fork length was 46.3 cm (± 5.6 cm *SD*) ranging between 35.5 - 62 cm. See the appendix C for a complete list of tagged individuals.

2.5 Tagging process

A 60 l black tank with seawater was used as a holding tank for the fish storage (Figure 4, picture 1), with frequent changing of fresh saltwater. The team carefully observed the anadromous Arctic charr, looking for any signs of oxygen deficiency. These could be individuals who lacked movement or were rolling over on their side. Only individuals who were assumed to be in good health were selected for tagging.

Immediately after individuals had recovered after the transport, one fish at a time was carefully moved from the holding tank to a tank with anesthesia (0.3 - 0.4 ml benzocaine/ l seawater). This minimizes the stressful intervention by affecting the central nervous system and sensory processing, while it also makes the Arctic charr immobile and easier to handle during the surgery (Machnik et al., 2018).

The anesthetized anadromous Arctic charr was placed in a tagging tube filled with seawater, with the abdomen facing up and the head and gills submerged. Fork length (L_F) was registered, whereafter the acoustic transmitters were surgically implanted through a 15 mm ventral incision (between the pelvic and pectoral fins), made with a scalpel, into the abdominal cavity (Figure 4, picture 2). The implantation was completed by closing the incision with two independent stitches using a 3 - 0 Ethicon braided suture.

Tissue samples for genetics were secured by clipping a piece of the adipose fin and placed in 96 % ethanol. Finally, the anadromous Arctic charr was tagged with Floy-tag, an external tag shot into the back muscle under the dorsal fin base using a pistol needle applicant (Figure 4 picture 3).

Tagged fish were placed in a holding tank for observation. As soon as the anadromous Arctic charr had recovered from the anesthesia and surgery, they were placed in a submerged cage (Figure 4, 4) for observation and further recovery. Eventually, all the anadromous Arctic charr caught on the same day were released together, subject to seemingly normal behavior.

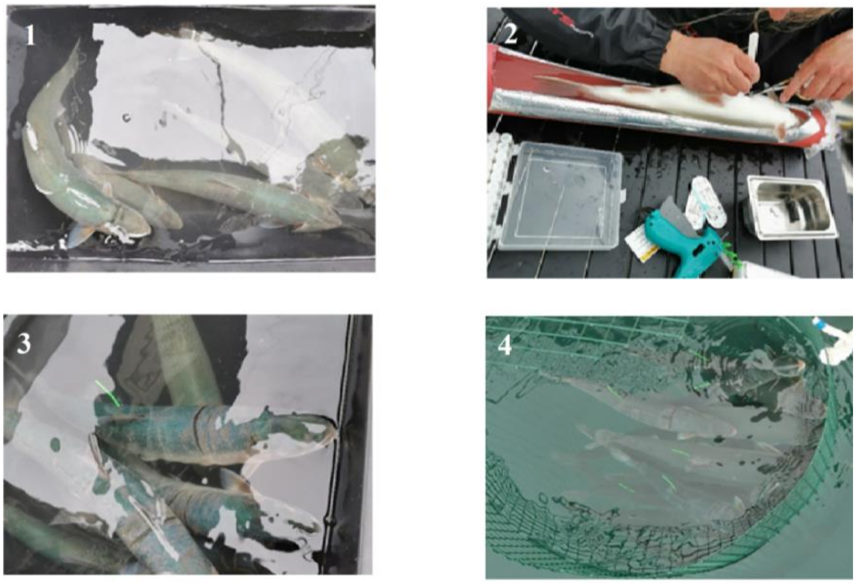

Figure 4. *Pictures of the tagging process. 1: Bucket with freshwater for storage of 5 anadromous Arctic charr. 2: An anesthetized individual getting an internally implanted transmitter. 3: Tagged individuals in temporary storage for observation. 4: Recovered individuals in a submerged cage ready for release.*

2.6 Quantitative analyses

Maps were made in QGIS 3.22 (QGIS Development Team, 2020). Microsoft Excel office 365 was used for data sorting. For data visualization, *ggplot2* (Wickham, 2016), *actel* (Hugo Flávio, 2020), and *RSP* (Niella, 2020) packages were used in RStudio version 3.3.0 (RStudio Team, 2020).

All significance tests were conducted in Rstudio using function *kruskal.test()* and *pairwise.wilcox.test()* in *stats* package (RStudio Team, 2021), with a chosen significance level of p = 0.05.

2.6.1 Filtering and preparing the data

Uploading data from the receivers and initial detection filtering were performed in Thelma Biotel´s software, ComPort (Thelmabiotel, 2022). All false transmitter-ID not included in this study's ID list were removed in Comport. False detections can also occur as a transmitter ID included in the study's ID list. To avoid this in the analysis, single detections were excluded, setting minimum detection to 2 within the functions explore and residency, in *actel* packaged.

Actel and RSP

Actel is a package designed for standardizing the method of acoustic telemetry and helping researchers analyze telemetry data from animals' movements (Hugo Flávio, 2020). The toolkit RSP refines the shortest paths for animal movements between receivers, exclusively in water (Niella, 2020).

The packages require organized inputs in a specific fashion with 4 files named: "Spatial.csv", "Biometrics.csv", "deployments.csv", and "detections.csv" (Hugo Flávio, 2020). It also requires spatial parameter "section" and "array" and have biometrical option parameter, as in this study "group". The "sections" were distributed in different habitats: "Fjord" as the marine habitat, "River mouth" as the brackish habitat, and "Lake" as the freshwater habitat. This environmental separation is based on assumptions, as no salinity tests were done in this study. The "Array" is in this study consisting of single receivers and was given name after the receiver location name (see appendix D for complete list). The parameter "group" was allocated as the location in which the Arctic charr was captured: "Gipsvika", "Ekmanfjord", "Borebukta", "Trygghamna", and "Grønfjord". For analysis with *actel* in Rstudio, a transition-layer and a map over the study area in the shapefile are required. The *explorer()* and *residency()* functions combined all CSV files to an output data list with quantitative data for further analysis.

2.6.2 Habitat use

To examinate habitat utilization by anadromous Arctic charr, was it calculated spatial distribution and time spent in area. Sections used for the different environments (fresh-, brackish, and marine) and depth use for an indication of the utilization of vertical aquatic zone. After running the function *residency()* was a data list named *global.ratios* calculated, giving containing number of individuals detected in each section each day. This data was further used for visualizing section used through the study period with packages *ggplot2*. Time spent between receivers, called “tracks” in RSP, was used to calculate area use with the *dynBBM()* and *getAreas()* function. The dynamic Brownian Bridge Movement models (dbbmm) allow calculating the area (m^2) utilized by the anadromous Arctic charr through the study period. After running *getAreas()* and *plotAreas()* functions were area calculated and plotted with 25 %, 50 %, and 95 % space use contours.

Of the 90 transmitters, 36 transmitters sent a total of 215410 pings with positive depth values (the water surface = 0) to the receivers during the study period. Depth values were registered in fraction values of the maximum depth of the receivers. Those values were converted to negative meters for analyzing and visualizing in *ggplot2*.

2.6.3 Freshwater return

The detections from receivers in lake Bretjørna and Lovénvannet were used to predict freshwater returns by individuals. In the watercourse (Straumsjøen, Linnévannet, and Trebrevatnet) with no deployed receiver in the lake, the receiver was deployed in the river mouth used, assuming anadromous Arctic charr would swim nearby this receiver before entering the lake. The first day an individual was detected in the lake or river mouth, was called arrival day. Output data from running *residency()* function gave first-time detection for each individual in each section.

2.6.4 Variables impacts on depth use and freshwater return

To investigate which variables affecting the depth utilization and migration from the marine environment to the lakes, Akaike’s information criterion (AICc) was used. Models were selected in the package *AICcmodavg* in Rstudio (Mazerolle, 2020). Both fixed and random effects were included in this study, and a linear mixed effect model (LME) was therefore applied. The *lme4* package was used for testing variables’ effect on depth utilization (Bates et al., 2015). A general linear mixed model (GLM) was used for modeling when the anadromous Arctic charr returned to the lakes. GLM is a flexible generalization of ordinary regression, which allows using data that are not normally distributed (Müller, 2004). Here, binominal data was used with binary levels: “in lake” or “not in the lake”. It was assumed that the anadromous Arctic charr that were not detected in the lake were in one of the other environments, river mouth or fjord.

2.6.5 Distance traveled

The function *distanceMatrix()* in the RSP package was used for calculating the distance traveled. The distance matrix uses a rasterized shapefile of land and water masses projected in a set metric projection (UTM 33, EPSG:32633). This allows a more realistic overview of the distance between receivers, while it does not allow space over landmasses but refines the shortest distance in the water (Niella, 2020). The distance between receivers is in a straight line and will be the minimum distance traveled. This refining minimum traveled distance was further visualized with plots in *ggplot2* and distributed between groups. Only distances > 0 m registered were included for analysis.

3. Results

3.1 Length distribution

The fork length of tagged individuals ranged from 31.5 to 62 cm, with a mean length of 45.63 cm (Figure 5, left). Mean length in group Gipsvika was: 48.27 cm, Ekmanfjord: 46.6 cm, Borebukta: 44.8 cm, Trygghamna: 44.7 cm, and Grønfjord: 40.8 cm (Figure 5, right). The length of tagged individuals in Gipsvika shown to be significantly higher (*p-value < 0.05*) than the length of tagged individuals in the group from Grønfjorden (Figure 5, right).

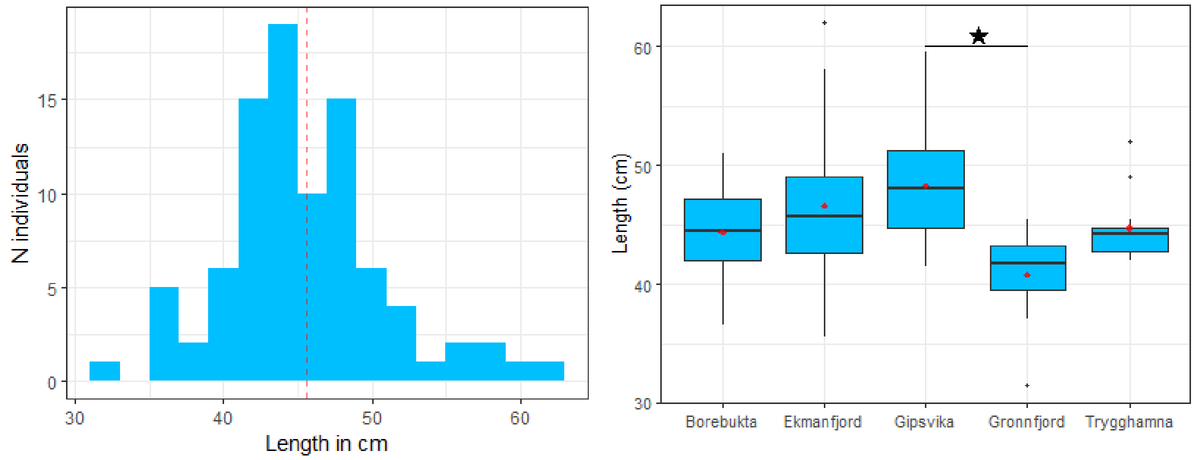

Figure 5. *Left: Histogram over length distribution of total tagged anadromous Arctic charr, variation from 31.5 cm to 62 cm, red dashed line shows the mean. Right: Boxplot over length distribution oversampled and tagged anadromous Arctic charr between the groups. The mean length showed to be different between all groups (red dots). Length of tagged individuals in Gispvika showed to be significantly (p-value < 0.05) higher than length of tagged individuals in Grønfjord (black star).*

3.2 Detections

Between 25th July and 15th September had 13 of the 27 operative receivers (Figure 6) recorded a total of 224 000 valid acoustic detections. The number of anadromous Arctic charr individuals was significantly higher in the section "lake" and "river mouth" than in the "fjord". Exclude fjord Ekmanfjord and Borebukta were there no other locations where a receiver had > than 1 individual detected (Figure 6). Of the 90 tagged individuals were 64 (71 %) individuals detected after the release. Of the individuals tagged in Ekmanfjorden was 27 individuals detected (90 %), Borebukta had 17 individuals of the tagged individuals detected (94 %), Trygghamna had 9 individuals of the tagged individuals detected (75 %), Grønfjorden had 10 individuals of the tagged individuals detected (100 %), and only 1 individual was detected in Gipsvika after the release (5 %). Remining individuals were never recorded. See the appendix B for more information on last registrations.

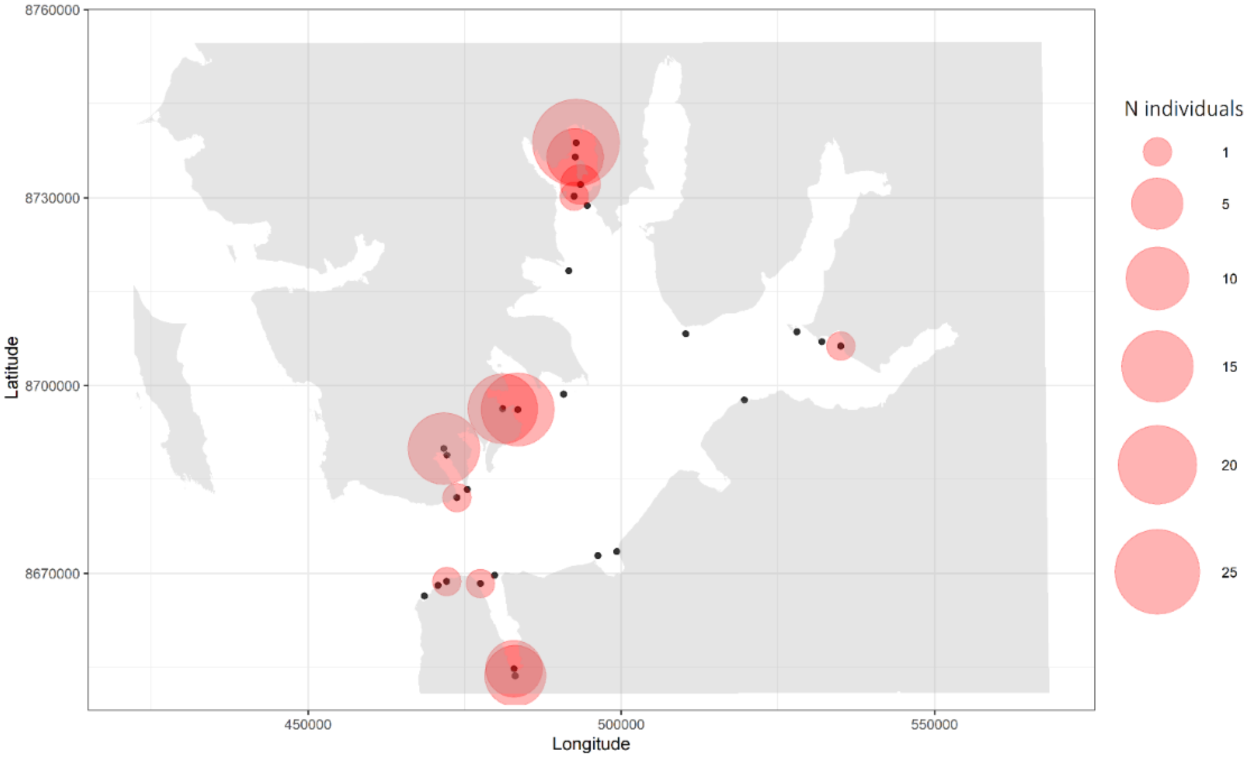

Figure 6. *Map of the study area with the number of individuals detected on each receiver through the study period. Black dots show the location of receivers. Red circles indicate the number of individuals detected, the rings increasing in size with number of individuals detected.*

3.3 Habitat utilization

Anadromous Arctic charr were detected in all sections of the study area during the study period. The section lake had the greatest number of single detections (> 96 % of total). The highest number of individuals were detected in the section river mouth, with 50 individuals detected, while the section lake had 22 individuals and fjord had 25 individuals. After 4th August, no single individual was detected in either section fjord or river mouth. The river mouth was utilized 7 days longer than the fjord (Figure 7).

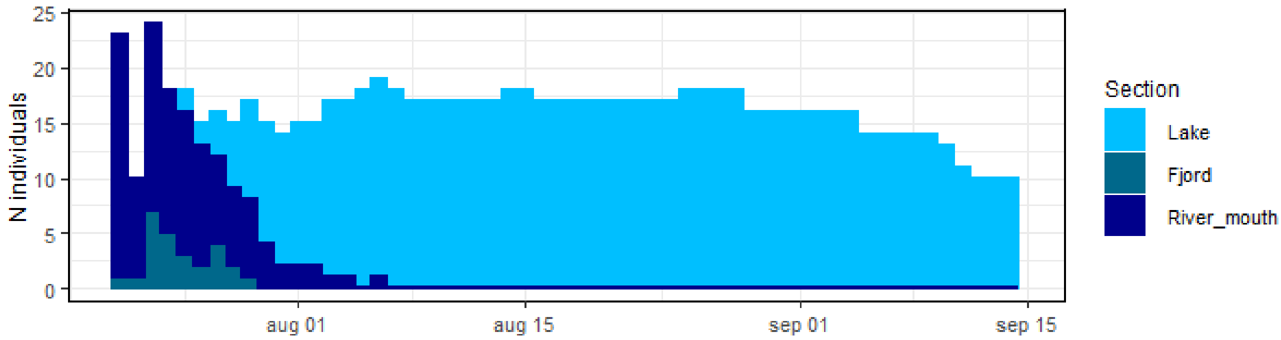

Figure 7. *Environmental distribution of anadromous Arctic charr throughout the study period, 24th July to 15th September. Colored by sections and stacked on individuals. Section "Lake" as the freshwater environment, "Fjord" as the marine environment and "River mouth" as the brackish environment.*

During the study period, the area utilized by group "Grønfjord", "Trygghamna", "Borebukta" and "Ekmanfjord" was limited to the western and northern side of Isfjorden (Figure 8). Anadromous Arctic charr caught and tagged in Ekmanfjord and Borebukta used the site from their release location all the way to Lovénvannet. In contrast, tagged individuals released in Trygghamna were limited from Lake Lovénvannet to outer Trygghamna (Alkepynten). Tagged individuals released in Grønfjord expanded the area out of Grønfjord over the fjord to Lovénvannet (Figure 8).

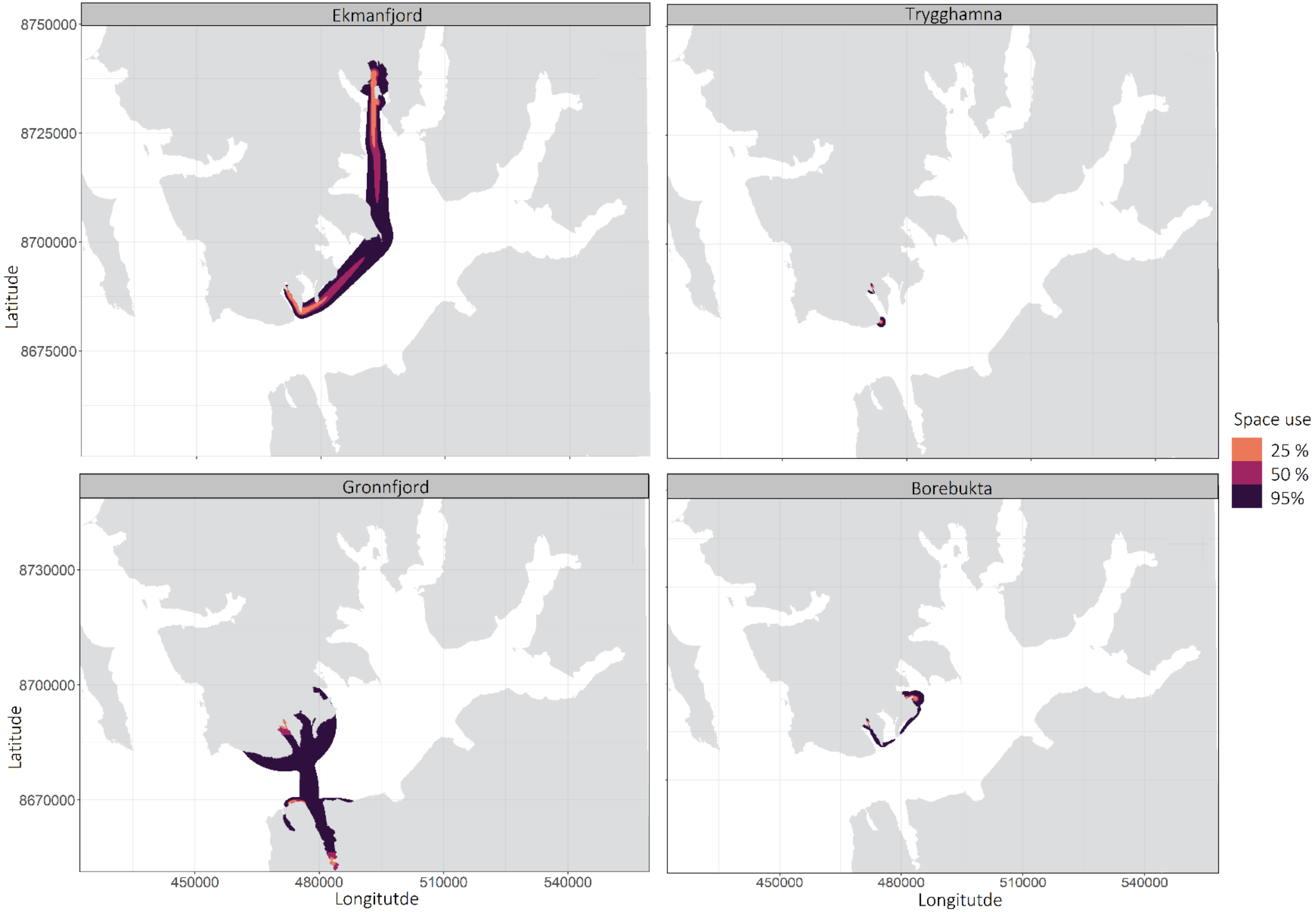

***Figure 8**. The area used throughout the study period, distributed by tagging area. The red area indicates the area used 25 % of the time. Red and the gray area together indicate the area used 50 % of the time. All colored areas together indicate the area used 95 % of the time.*

3.4 Freshwater return

Freshwater return (arrival to the river mouth) of anadromous Arctic charr ranged from 21st July to 4th August, with only one individual registered in this habitat after 28th July. On the same day as the release of tagged fish (21st July) from Ekmanfjord, 26 individuals (87%) were registered as arriving on the receiver closest to the river mouth of Trebrévatnet (Figure 9). From the group tagged in Borebukta, 15 individuals (83 %) arrived at the river mouth of Straumsjøen between 21st and 22nd July, while 5 individuals (50 %) from group Grønfjord arrived river mouth of Bretjørna on 26th July, and 0 individuals were detected in the river mouth of Lovénvannet (Figure 9). Even though 0 individuals detected in the river mouth of Lovénvannet, 14 individuals were detected in Lake Lovénvannet. Those individuals were from different tagging groups: Trygghamna (*n* = 8), Borebukta (*n* = 2), Ekmanfjord (*n* = 2) and Grønfjorden (*n* = 2) (Table 1). The first detections in Lovénvannet were on 25th July, and the last individual was detected as arriving 27th August (Figure 9 and 10). The first arrival to Lake Bretjørna was on 27th July, and the last arrival was on 5th August (Figure 9 and 10). Only the individuals caught in Grønfjorden were detected in lake Bretjørna. By the end of the study period, only 20 individuals (22 %) of the total 90 individuals were detected in Lake Bretjørna or Lovénvannet (Table 3).

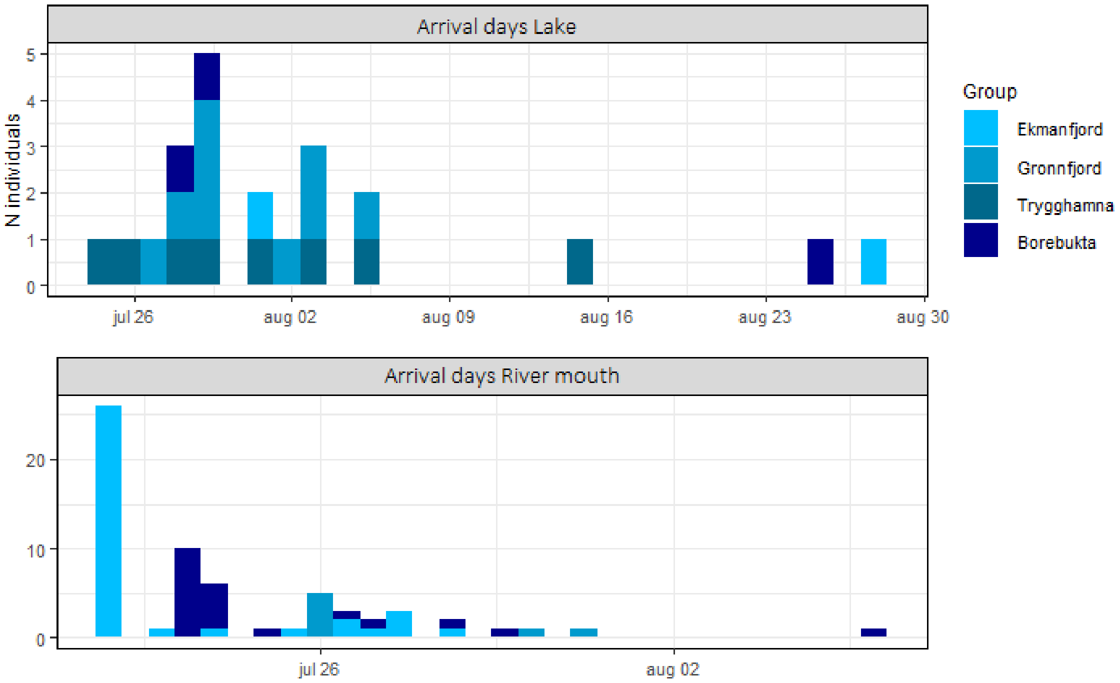

Figure 9. *Arrival days for anadromous Arctic charr in section "Lake" on the top and "River mouth" on the bottom, with number of individuals staked and colored by the group. Note differences in scale in time and number of individuals between the two plots.*

Table 1. *Anadromous Arctic charr last seen in percent of each group. River mouth (R.M.) is used to compensate for missing data in Lakes. In the bottom of the Table is the sum of number of individuals detected in each location.*

Group	**Lovénvannet (Trygghamna)**	**Bretjørna (Grønfjord)**	**R.M. Straumsjøen (Borebukta)**	**R.M. Linnévannet**	**R.M. Trebrévatnet (Ekmanfjorden)**
Gipsvika (n = 20)	0 %	0 %	0 %	0 %	0 %
Ekmanfjord (n = 30)	6.6 %	0 %	0 %	0 %	76 %
Borebukta (n = 18)	16.6 %	0 %	72.2 %	0 %	0 %
Trygghamna (n = 12)	66.6 %	0 %	0 %	0 %	0 %
Gronnfjord (n = 10)	10 %	80 %	0 %	0 %	0 %
Total (N)	13	8	13	0	23

The model including “date” addition “fork length” and “lake” was the model that explained most (AICc-weight = 67 %) of the variation in returning to the lakes (Table 2). The model including tagging location, ocean temperature or last recording found very low AICc values (Table 2). The largest anadromous Arctic charr returned to the lakes before the smaller individuals, and anadromous Arctic charr entering Lake Bretjørna returned earlier than anadromous Arctic charr returning to Lake Lovénvannet (Figure 10).

Table 2. *Ranking of the 12 tested linear mixed models (LMM) based on AICc values for the effect of abiotic and biotic variables (Fork length, Date, Lake, Location, Temperature) on the returning time to the freshwater environment (exclusively lake Lovénvannet and Bretjørna).*

LMM-Model	**K**	**AICc**	**ΔAICc**	**AICc weight**	**Cum.Wt**	**LL**
~ L_F + Date + Lake	5	94.43	0	0.67	0.67	- 42.19
~ L_F + Date	4	96.95	2.52	0.19	0.85	- 44.46
~ Date	3	98.14	3.71	0.10	0.96	- 46.06
~ Date + Lake	4	100.15	5.72	0.04	1	- 46.06
~ Date * Lake	5	105.26	10.83	0	1	- 47.61
~ L_F * Date	5	109.33	14.90	0	1	- 48.63
~ Location + Date	6	120.61	26.18	0	1	- 55.28
~ Location * Date	9	137.78	43.35	0	1	- 59.82
~ L_F + Temp	4	1067.72	971.89	0	1	- 529.14
~ L_F * Temp	5	1067.72	973.29	0	1	- 528.84
~ L_F	3	1293.21	1198.78	0	1	- 643.70
~ Lake	3	1293.42	1198.99	0	1	- 643.70

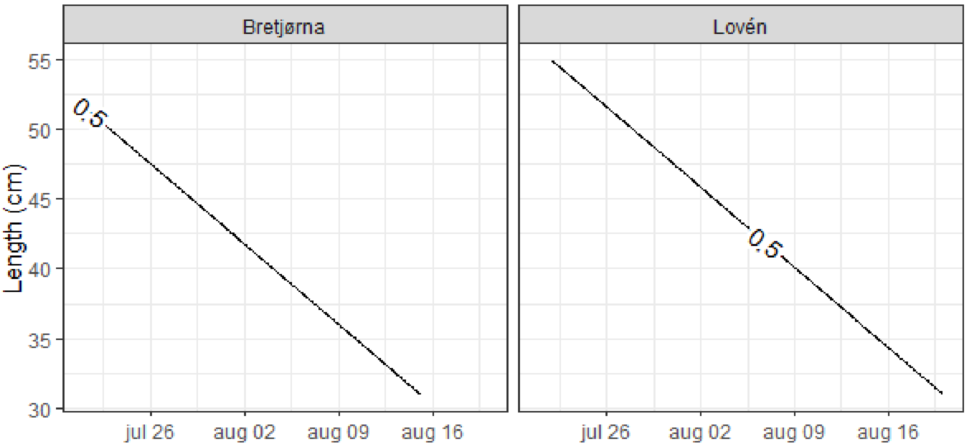

Figure 10. *Prediction plot of the LME - model with most AICs – support. Predicted returning date to freshwater explained by length (L_F) of the individuals The two lakes differ by 2 days both in when they start returning and the last to return.*

3.5 Depth utilization

The mean depth detected and registered through all sections and the study period was 4.4 m (Figure 11). Mean depth in the fjord were 0.839 m, in the river mouth 1 m, and 4.6 m in the lakes (Figure 12). The maximum depth detected in the lakes was 32.4 m, while the maximum detected depth in the river mouth and fjord were 4.2 m and 3.6 m, respectively (Figure 12). The depth utilization in section "lake" showed to be significantly (p-value > 0.05) deeper than the other sections. (Figure 12 and 13). The model "fork length (L_F) multiple sections" explained all (AICc-weight = 100 %) of the differences in depth utilization (Table 3). There was a significant difference in depth use related to fish length in the lakes, but not in the other areas (Figure 13).

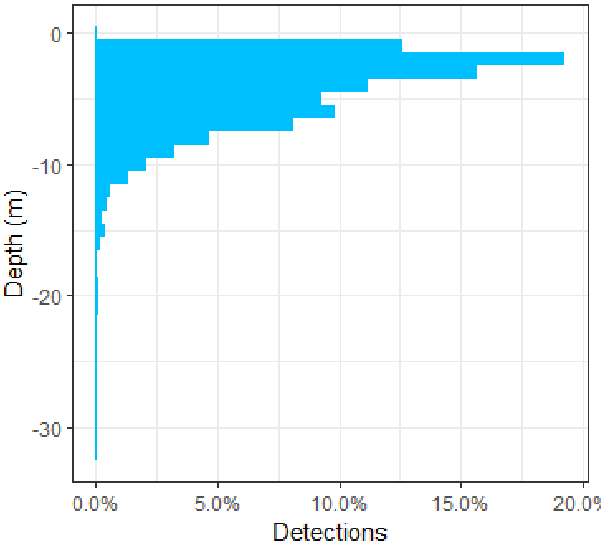

Figure 11. *Plot over depth distribution of all detection throughout the study period (24th July to 15th September), independent of section and converted to percentage of total registrations.*

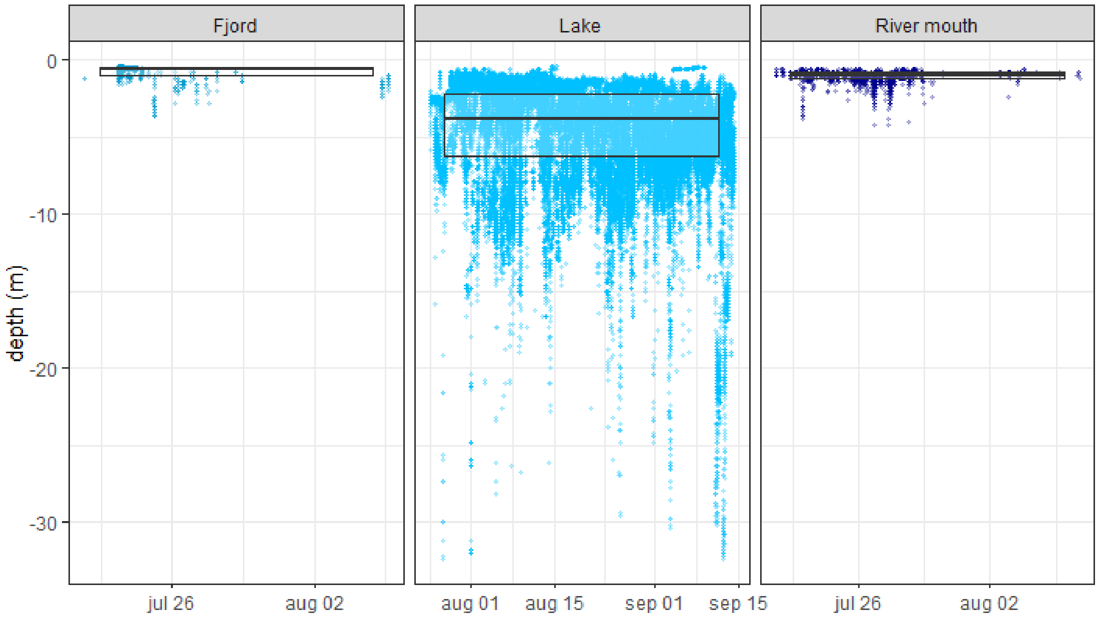

Figure 12. *All depth detections (dots) throughout the study period, 24th July to 15th September. Multipaneled by the sections "Fjord", "Lake", and "River mouth". The boxplot indicates the 25 %- (upper line), 50 %- (middle line) and 75 % tile (bottom line).*

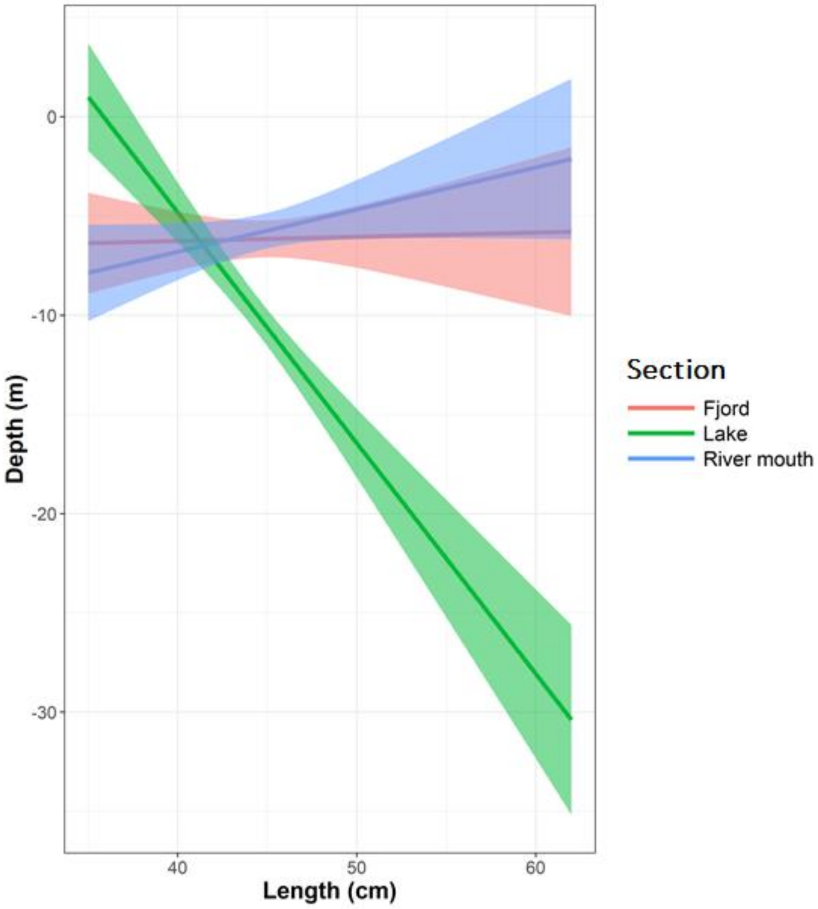

Figure 13*. Prediction plot of GL - model with most AICc - support (Table 3). Predicted depth use by the fork length (L_F) of the anadromous Arctic charr, distributed and colored by section. Transparent color either side of the lines are the 95 % confidence intervals.*

Table 3. *Ranking of the 5 tested general linear mixed models (GLM) based on AICc values for the effect of abiotic and biotic variables (fork length, section, location) on the depth utilization, using individuals as a random factor.*

GL-Model	K	AICc	ΔAICc	AICcwt	Cum.Wt	LL
L_F * Section	8	-212232.8	0	1	1	106124.4
Section	5	-212001.8	230.93	0	1	106005.9
L_F + Section	6	-211990.7	242.05	0	1	106001.4
Location	7	-211470.3	762.48	0	1	105742.1
L_F	4	-211442.7	790.06	0	1	105725.4

3.6 Distance traveled

The distance traveled by anadromous Arctic charr varied between 1 – 80 km (excluding distances = 0). Only group Borebukta (mean = 7 km), Ekmanfjord (mean = 18 km), and Grønfjord (mean = 16 km) had valid tracks from individuals who traveled > 0. Distances > 30 km were covered by 6 individuals (Figure 14).

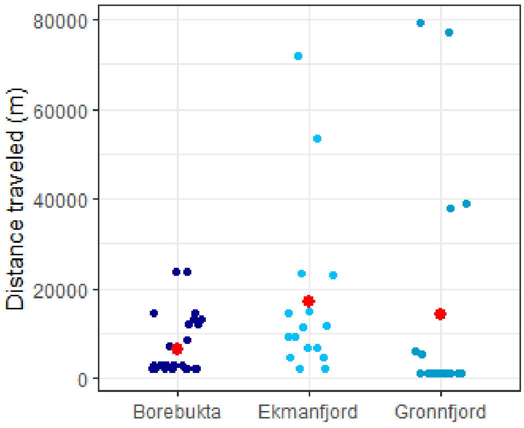

Figure 14. *Overall total distance traveled (meter) through the study period for tagged individuals (dots), separated by groups "Borebukta", "Ekmanfjord" and "Grønfjord". Red dots show the mean value in the groups. Only distances > 0 are included. Even though distances are calculated in water with RSP, its minimum distance, as the calculating is in a straight line.*

4. Discussion

This exploratory study has started the work on filling the knowledge gap in the migratory pattern, habitat use, and population ecology of anadromous Arctic charr in Isfjorden, Svalbard. The marine phase of the migration ended for most individuals by the end of July, followed by a week longer residency in the brackish environment close to the river mouth. The timing of freshwater return could mainly be explained by date and length of the individual, and in addition two days differences between lakes Lovénvannet and Bretjørna. Increased length of individuals was negatively related to time of freshwater return, and positively related to increased depth utilization in the lakes (up to 32 m depth). In the migration phase, most tagged individuals utilized the environment close to the river mouth, with a depth utilization almost exclusively in the upper aquatic zone (0 - 3 m depth). While migrating outside the river mouth zone, a capacity of migration > 70 km was recorded, with individuals swimming offshore and crossing the straight across over Isfjorden, taking advantage of both lakes covered in this study. Calculated area utilization showed differences between groups in the southern and northern part of Isfjorden, but there was also overlap in area utilization. Finally, this study recorded a stock mix between watercourses based on individuals' detection in the same lake (Lovénvannet) from almost all (4 of 5) tagging groups.

4.1 Marine migratory behavior and habitat utilization

The patterns of detections, both in the number of detections and the number of individuals on each receiver, suggest that anadromous Arctic charr in Isfjorden prefer the brackish environment close to the river mouth over the marine environment in the open ocean (> 1 km from the shore). This result is consistent with previous studies on the species' habitat utilization from other locations, such as mainland Norway and north Canada (Balon, 1980, Moore et al., 2016, Kirkemoen, 2015, Spares et al., 2015). A capacity of long migration distances outside the brackish zone has been recorded in previous mainland studies (Berg and Berg, 2011) and the anadromous Arctic charr on Svalbard can obviously migrate similar distances (> 70 km) while for example crossing the fjord. However, these long-distance migrations were only performed by few individuals, and calculated time spent in different areas the study period builds upon the hypothesis that the anadromous Arctic charr prefers the near-shore habitat close to the river mouth.

Anadromous behavior requires major physiological changes so that the fish can survive the salinity variations and reach optimal growth (McCormick et al., 1985, Folmar and Dickhoff, 1980). A.D. Spares (2015) examined the migration of anadromous Arctic charr in Frobisher, Canada, and found a significantly higher brackish residency during the final 15 days of migration and suggested that a transition phase may occur before the return to freshwater for salinity acclimatization. Laboratory testing of anadromous Arctic charr indicates that salinities and temperature are critical for survival. Exposing small individuals (fork length < 12 cm) to salinities at 30 % and temperatures below 0 ℃ suggested that the small individuals depended on periodic access to fresh or brackish water (Dempson, 1993). Jobling (1994) experimented with salinity levels' impact on anadromous Arctic charr growth by exposing groups to different salinity levels and concluded that seawater reduced growth rates compared to fresh- and brackish water. A brackish environment, specifically estuarine, is also known for the rich nutrition concentration coming from the freshwater and marine environment, which forms the basis of high secondary production (Pepper et al., 2015). Favorable salinity levels and food availability could probably explain the utilization of the environment close to the river mouth.

In addition to preferring an environment close to the river mouth, anadromous Arctic charr were recorded essentially in depth between 0 – 3 m (> 95 % of the detections, excluding lakes). These results support the hypothesis that anadromous Arctic charr utilizes the uppermost part of the fjord system's water column and agree with previous studies on the mainland (Nordli, 2021, Kirkemoen, 2015). Like the behavior of staying close to the river mouth, the utilization of the uppermost part of the water column can may be explained by favorable salinity, temperature, and food availability. Theoretically, the water with the lowest salinity and highest temperature (with some exceptions) would lay in the surface of the water column (Webb, 2019), which could be beneficial for anadromous Arctic charr growth (McCormick et al., 1985). In addition, shallow water exposed to solar radiation is potentially warmer at the beginning of the summer (Boyd, 2020). Yearly measurements in the summer period (July - September) from 1987 to 2017 in Isfjorden have shown warmer temperature and less salinity in the surface layer (R. Skogseth, 2020). Higher temperatures can be a significant factor for rapid anadromous Arctic charr growth, and higher temperatures can also be necessary to increase primary and secondary production building up the food web for anadromous Arctic charr (Gibert, 2019, Davison, 1991). In an optimal foraging theory, the anadromous Arctic charr should find the environment that gives the highest net energy, which probably balances salinity, temperature, prey availability and predation risk (Choe, 2010).

4.2 Freshwater return

Most of the individuals detected in the lakes had an arrival before the start of August, with a range from 25th July to 27th August. This is nearly a month earlier than reported from the fjord system Balsfjord in Troms, mainland Norway (Nordli, 2021). In contrast to observations in the Vardnes river in Troms, Norway, very few individuals were detected in the river mouth or marine environment after returning to freshwater (Berg and Berg, 2011). The early freshwater return and low frequency migrations between the lakes and the marine habitat suggest an evolutionary adaption to the unique environment. Water flow in the rivers on Svalbard mainly consists of run-off from melting glaciers, and therefore, the river will dry out in the fall or winter (Brittain et al., 2020). This will be highly problematic for the anadromous Arctic charr, as they risk that there is no water in the river if they start the return to freshwater too late.

The LME - models indicated that the fork length was a critical variable to freshwater return, with an increased probability of earlier return for increased fork length. This supports observations from mainland Norway done on three salmonid species; anadromous Arctic charr, anadromous brown trout (*Salmo trutta L.*) and Atlantic salmon (*Salmo salar L.*) (Friis, 2021). The individuals of all three species with the larger body length migrate first up the rivers (Friis, 2021). This was explained with the “asset-protection principle”, which states that the larger the reproductive asset, the more critical it becomes to protect it (Clark, 1994). This assumes that the marine environment has a lower survival rate than the freshwater environment and earlier return to freshwater increases the survival rate. Another study on Atlantic salmon suggests that returning at different times may be because of varying marine feeding areas (Ulvan et al., 2018). However, anadromous Arctic charr does not usually migrate near the distance of Atlantic salmon (Ulvan et al., 2018). The utilization of different habitats has probably a more negligible effect on the anadromous Arctic charr. Also, there is no support in different returning time in the models with variable as the location the individuals was released. Then, the “asset-protection principle” hypothesis could be a more faithful driver for earlier freshwater return. I hypothesize that small individual has more to gain to stay longer for feeding than large individuals. For example, in other species, it is demonstrated that gaining weight and size can have an advantage in reproductive success, but with an optimum point before it will cost more than it will be beneficial (Jones and Hutchings, 2002, Uusi-Heikkilä et al., 2012). Provided that a longer migration time in the sea reflects an increased gain in weight, it could be beneficial for the small individuals to stay long and for further increased growth.

4.3 Depth use in lakes

In contrast to utilizing shallow water exclusively in the brackish and marine environment, the anadromous Arctic charr used the whole water column in the lakes, down to 32 m. Similar observations were made during a behavior study on anadromous Arctic charr in Lake Botnvatnet, mainland Norway. Here Arctic charr were also found to utilize the whole water column and to perform several deep dives (> 30 m) (Monsen, 2019). Interspecific competition and temperature have been used for explaining differences in depth use for salmonids (Lunde, 2014, Monsen, 2019). In the freshwater ecosystems on Svalbard, where no other population of fish species is observed, interspecific competition can naturally be excluded. Intraspecific competition, competition between individuals in the same species, is on the other hand, potentially possible. The generalized linear model found the most support for differences in depth use by length (L_F), where depth utilization increased with length (L_F). This can indicate intraspecific competition, but it is unclear; habitat separation can also occur due to factors, such as predation, life history characteristics or environmental conditions (Persson et al., 2013). I suggest that the low freshwater production on Svalbard minimize habitat separation by niche differentiation (Brittain et al., 2020). However, some feeding in the freshwater environment seems to occur by anadromous Arctic charr on Svalbard (Brittain et al., 2020), and a study from north Canada recorded anadromous Arctic charr eating in cold, shallow water and using deeper water with higher temperature for increasing degradation of stomach contents (Spares et al., 2012). Hypothetically, this behavior is possible in freshwater as well. If deep dives are not for increased degradation of stomach contents, searching for a more optimal environment may provide other benefits such as increased growth rate and reproduction (Radtka et al., 1996, Islam et al., 2019, Gilbert et al., 2020).

4.4 Population ecology in Isfjorden

Calculated area utilization indicates that the fish tagged in Ekmanfjord, Trygghamna and Borebukta were limited to the northern side of Isfjorden, while fish tagged in Grønfjorden utilized both the southern and northern parts. However, there was overlap in the marine area use from Borebukta to Trygghamna by almost all tagging groups (4 of 5).

In addition to mixing and overlap in distribution in the marine environment, almost all groups (4 of 5) had individuals detected in Lovénvannet. Also, two individuals were detected in both lakes covered in this study. This indicates a stock mixing and possible genetic exchange. However, no genetic examination has been done on the populations in Isfjorden yet and it’s not clear whether individuals detected in Lake Lovénvannet spawned here. A study from

Canada examined anadromous Arctic charr stock mixing in six rivers using acoustic telemetry and genomic data, suggesting that dispersal does not necessarily lead to gene flow (Moore et al., 2017). Instead, salmonids have been shown to use different locations for spawning and overwintering (Moore et al., 2017), as may be the case for some individuals in Isfjorden. Probably, the project "genetic tracking in Isfjorden" will provide further answers to questions about genetic flow and mixing between stocks.

The last recordings of fish suggest that there is anadromous Arctic charr in the new lake Trebrevatnet, which has occurred in recent years due to melting of the glaciers. No receivers were deployed in in the lake, and to the authors best knowledge, is hasn't been examined whether there are Arctic charr in this watercourse at all. If inhabited by straying fish, a new stock of anadromous Arctic charr can occur if the location suitable spawning areas. There may also be unregistered watercourses inhabited by anadromous Arctic charr, as the 20 individuals captured and tagged in Gipsvika were not registered anywhere else in the fjord.

4.5 Evaluation of methods and future research

4.5.1 Evaluation of capture method

Since the anadromous Arctic charr typically start their seaward migration just after the ice break in June (Gulseth and Nilssen, 2000), it was expected that they would be in the sea during the field-work period. Based on previous experience in the research team, gillnets were known to be effective for catching anadromous Arctic charr while at sea this time of the year. Gillnets are a rough method for capture of live fish but provided frequent inspections of the gillnet and the cold-water conditions, it was assumed to have a high survival rate. The low temperatures in the fjords system were assumed to minimize the risk of oxygen deficiency while being entrapped in the gillnet. Although measures were made to reduce the risk of injury, the tagging team expected that some of the anadromous Arctic charr would not survive. Fish that did not survive were used for diet analysis and in the other mentioned study, "Genetic tracking in Isfjord".

Gillnet fishing is a very selective method, both in the way it selects the size and behavior of the fish (Lucena et al., 2001, Millar and Fryer, 1999). Earlier studies have shown low gillnet catchability for smaller individuals and it will therefore be reasonable to believe that the sampling does not provide a good representation of the first years migratory individuals (Svenning, 2010). Also, the gillnet was exclusively set near the shore, and fish potentially residing in the pelagic zone were not captured. This could represent a skewed picture of the migration pattern, with underrepresentation of individuals using the pelagic zone. However, gillnetting in the pelagic marine zone can be practical difficult.

4.5.2 Evaluation of acoustic telemetry

While acoustic telemetry has potential for increasing the knowledge of an animal’s ecology and behavior, the method also has certain limitations and challenges: (1) size of the study area makes it difficult and expensive to cover it all with receivers, which leads to (2) study design and receiver placement being highly depend on precursory knowledge or educated prediction of the species movements or habitat utilization (Heupel et al., 2006), (3) challenges with deploying receivers in some habitats, for example, deep water or shallow water within the tidal zone (James, 2005), (4) the only certain information is when an individual has been detected on an acoustic receiver (Kessel et al., 2013), and (5) detection range and efficiency are highly affected by environmental differences (Reubens et al., 2019, Huveneers et al., 2015).

For this study area, 28 receivers do not provide adequate cover and therefore misses some habitats utilizes by anadromous Arctic charr in Isfjorden. Receiver deployment was based on the team’s knowledge and experience, which minimized the number of receivers needed. Deploying receivers where it’s assumed the species migrate can give confirmation of this. On the other hand, it may limit new knowledge, as receivers aren’t deployed to cover all habitats. For example, deploying receivers near the shore and zero receivers in the open ocean can only give information about migration behavior near the shore. Deployment of receivers in deep or extremely shallow waters can be practically difficult, as the deep water require loner rope and the extremely shallow water can be dried out in low tide.

Various environmental conditions can disrupt effective transmission (Medwin and Clay, 1997, Klinard et al., 2019). This study area includes major differences in environmental conditions, such as temperature and salinity, as the study includes freshwater -, brackish -, and marine environments. As the results suggest, environmental differences hugely impacted the results and analysis. For example, many individuals were detected in Lake Lovénvannet, but no single detections were on the receiver close to the river mouth (< 100 m). As this is the only known way up to the lake for anadromous Arctic charr, tagged anadromous Arctic charr must have come near this receiver in the river mouth.

Another tracking gap is in the bay Gipsvika, where 20 individuals were tagged, and one receiver was deployed on each side of the bay < 500 m from the shore. There were only two detections from one individual throughout the study period. Based on registered data such as temperature and noise from these receivers, it’s suggested that the receiver was operative.

Previous studies with acoustic telemetry have shown significantly reduced detection range and efficiency in shallow waters (Stott et al., 2021, Stasko and Pincock, 1977b). Shallow water often has no direct path between transmitter and receiver because of bottom contours. Therefore is the only way for the signal to reach a receiver is after several reflections in the bottom or water surface which reduced the distance a soundwave can travel (Stasko and Pincock, 1977b). This may also explain the low detection rates in Gipsvika and the river mouth of Lovénvannet, as a big area of the bay and river mouth are < 1 m during high tide. This may be some of the biggest challenges for tracking the species, as anadromous Arctic charr seems to use much of the marine residency time in extremely shallow water as seen during gillnetting.

4.5.3. Future research

As gillnetting can be a rough method, with potential for harming the fish, capture by fyke nets in the river would be beneficial for further research for reasons; 1) This will likely increase the survival rate and decrease injuries, as well as stress for the fish, and 2) it will give a more representable picture of migration for the whole population of anadromous Arctic charr, including the first year’s migrants. Setting the fyke net in the river as early as possible will also 3) allow catchment of the anadromous Arctic charr who migrate early in the season. This will provide information about when migration starts and enable for calculations of marine residency times. However, even though fyke net can be a less rough method and have some benefit, it can be difficult with operative fyke nets in the river early in the season because of the damage from ice that come with the melt off.

To improve the setup and the design of the receiver can range testing be a useful tool. Together with deployment of several receivers in arrays or grids, it may also increase the detection efficiency of the tagged fish. Deploying receivers in areas that do not expect the fish to migrate can also reveal surprising movement patterns or critical habitat or eventually help confirm prior expectations about an area not being a critical habitat (Reubens et al., 2019). However, conducting acoustic telemetry study in such big area have economic constraints. Before eventually changes in study design it must have the probability to benefit the costs. For example, it may be beneficial to deploy some few extra receivers in the areas there it was no detection in this study year, but it’s still suspected that the anadromous Arctic charr utilize.

Also range testing can be done in those areas it’s a high confidence that anadromous Arctic charr utilize, it’s not necessarily cost-beneficial to rang-test all locations or receivers.

Further research should follow up on the potential population in Trebrevatnet and the population utilization of the marine area Gipsvika. Deploying a receiver in Trebrevatnet would elucidate whether anadromous Arctic charr utilize this watercourse. The results also suggest there may be another watercourse with an unknown population of anadromous Arctic charr, as none of the individuals tagged in Gipsvika were detected. One possibility is the new lake in Ragnardalen, which have a river mouth of Billefjord. The fish may also have migrated further than expected and come from outside the study area.

4.6. Management implantation

First, I want to highlight the vulnerability of the anadromous Arctic charr to gillnet catches. Theoretically, the probability of catching a fish with a gillnet that migrates large distances is higher than catching a stationary fish moving at low distances in a limited area. Utilizing almost exclusively the upper water column and the littoral zone make this species extremely exposed to gillnet fishing along the shore. Also, low visibility in the water increases the probability that the fish cannot see the gill net and increases the likelihood of catching them. Therefore, I hypothesize that the anadromous Arctic charr in this study system is highly vulnerable to gillnet catches. Gillnetting on good locations can probably remove a considerable amount of the stock without large fishing efforts.

I highly support the general regulations on protection zones 200 m from the river mouth out in the ocean. The river mouth is a vulnerable area for migrating salmonids as this is a gate between freshwater and the sea. This study also supports that anadromous Arctic charr spend most of the marine residency time close to the river mouth, making this zone an even more vulnerable area for the species. I hope this would follow up with an equivalent protection zone for the river mouth from the river of Trebrevatnet out in the fjord Ekmanfjord. This study indicates that there is a stock connected to this new watercourse.

For sustainable management, it would be necessary to get an overview of the population status for each lake with anadromous Arctic charr, as each lake has its own individual potential of production. To target the abundance of the species in a lake, the method catch per unit effort (CPUE) can be used (Maunder et al., 2006). The taxation of the fish population should be based on the surplus of the population production. Calculation of the population's production can provide a basis for setting total catch quotas for a total catch in the sea and the lakes. Some mixing of stocks in the marine habitat can lead to management problems, but as this study shows: most of the individuals stay close to the river mouth, or at least in the inner fjord, which provides a basis for giving each fjord individual quotas based on fish population production in the lakes.

I also suggest a protection zone for Gipsvika, at least temporarily, until there is more knowledge about the stock using this area. No knowledge about those individuals' natal homing, or how extensive the stock is, creates significant uncertainty about the sustainability of fishing in this area. I suggest that this is an area that can easily be harvested too heavy, for reason 1) it was given relatively low gill net effort to catch 20 individuals during the fieldwork period, 2) the shallow water in this bay may do it easy to fill the water column all the way from the bottom to the surface with gillnets, and 3) the behavior of anadromous Arctic charr from the other location around Isfjorden, that indicate anadromous Arctic charr use almost exclusively the shallow water close to the shore.

5. Conclusion

The results from this study show that anadromous Arctic charr prefers the habitat close to the river mouth in the upper water column (0 – 3 m depth). The species also have a capacity for migrating over more considerable distances in marine waters across the fjord system (> 70 km). In 2021, the freshwater returns of anadromous Arctic charr occurred mainly in the transition of July/August. The variable explaining most of the returning time was length of the individuals, where the largest individuals returned first. Length of individuals was also the most explainable factor for depth utilization in the lake, with larger individuals residing at greater depths.

The results also provide support for stock mixing in marine and freshwater habitats. Genetic exchange has not yet been documented, and it's a possibility that individuals are just overwintering and not spawning. A combination of acoustic telemetry and genetic data will give a more accurate overview of the genetic flow. Stock mixing in stock can provide a challenge in the management of the stock, but the knowledge that most of the individuals stay close to the river mouth or inner fjord provides a basis for setting individual quotas for different marine areas.

There is also reason to believe that there is a stock attached to the new Lake Trebrevatnet, which would provide further research and management challenges. Future research will also be necessary to further investigate the behavioral strategies of individuals caught in the bay Gipsvika, as these were not detected in any of the known watercourses with anadromous Arctic charr in Isfjorden.

6 References:

ARNESEN, A. M., HALVORSEN, M. & NILSSEN, K. J. 1992. Development of hypoosmoregulatory capacity in Arctic char (*Salvelinus alpinus*) reared under either continuous light or natural photoperiod. *Canadian Journal of Fisheries and Aquatic Sciences,* 49**,** p.229-237.

BABIN, A., FITZPATRICK, L., LINNANSAARI, T. & CURRY, R. A. 2019. Detection Range of Acoustic Receivers in a Large Hydropower Reservoir. *Fishes,* 4.

BALON, E. K. 1980. *CHARRS - samlonid Fishes of the Genus Salvelinus,* The Hague, The Netherlands, Dr. W. junk bv Publishers.

BARR, S. 2020. *Isfjorden* [Online]. Store norske leksikon: Store norske leksikon. Available: https://snl.no/Isfjorden_-_fjord_p%C3%A5_Svalbard [Accessed 15.08.2021].

BATES, D., MÄCHLER, M., BOLKER, B. & WALKER, S. 2015. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software,* 67.

BERG, O. K. & BERG, M. 2011. Sea Growth and Time of Migration of Anadromous Arctic Char (*Salvelinus alpinus*) from the Vardnes River, in Northern Norway. *Canadian Journal of Fisheries and Aquatic Sciences,* 46**,** p.955-960.

BERGANE, V. Å. 2018. *Anadromous Arctic charr (Salvelinus alpinus) in the Linné watercourse, Svalbard – life history traits and population structure ten years after the introduction of quota-based harvest* [Online]. Ås: Norges miljø- og biovitenskapelige universitet. Available: https://nmbu.brage.unit.no/nmbu-xmlui/bitstream/handle/11250/2565399/bergane2018.pdf?sequence=1&isAllowed=y [Accessed 23.10 2021].

BOYD, C. E. 2020. *Solar Radiation and Water Temperature,* link.springer.com, Cham Springer.

BRITTAIN, J. E., SCHARTAU, A. K. & SVENNING, M. A. 2020. *Biologisk mangfold i ferskvann på Svalbard: kunnskapsgrunnlag, påvirkninger og forslag til framtidig overvåking* [Online]. Norges vassdrag- og energidirektorat, Norsk institutt for naturforskning. Available: https://publikasjoner.nve.no/rapport/2020/rapport2020_13.pdf [Accessed 13.09 2021].

CHOE, J. C. 2010. *Encyclopedia of Animal Behavior,* Amsterdam, Elsevier Academic Press.

CLARK, C. W. 1994. Antipredator behavior and the asset-protection principle. *Behavioral Ecology,* 5**,** p.159-170.

COTTIER, F. R., NILSEN, F., INALL, M. E., GERLAND, S., TVERBERG, V. & SVENDSEN, H. 2007. Wintertime warming of an Arctic shelf in response to large-scale atmospheric circulation. *Citation Reports (Clarivate Analytics),* 34**,** p.5.

CROSSIN, G. T., HEUPEL, M. R., HOLBROOK, C. M., HUSSEY, N. E., LOWERRE-BARBIERI, S. K., NGUYEN, V. M., RABY, G. D. & S.J., C. 2017. Acoustic telemetry and fisheries management. *Ecological Aplications,* 27**,** p.1031-1049.

DAVISON, I. R. 1991. Environmental effects on algal photosynthesis: Temperature. *Journal of Phycology,* 27**,** p.2-8.

DEMPSON, J. B. 1993. Salinity tolerance of freshwater acclimated, small-sized Arctic charr, *Salvelinus alpinus* from northern Labrador. *Journal of Fish biology,* 43**,** p.451-462.

DØVING, K. & REIMERS, E. 1992. *Fiskens fysiologi,* Bergen, John Grieg.

EBNE, I. 2009. *Anadromous Arctic charr (Salvelinus alpinus) in the Linné Watercourse, Svalbard. Diet, ascendance, population composition and catchability* [Online]. Ås: Norges miljø- og biovitenskapelige universitet. Available: https://static02.nmbu.no/mina/studier/moppgaver/2009-Ebne.pdf [Accessed 08.09 2021].

ELORANTA, A. P., SIWERSSON, A., KNUDSEN, R. & AMUNDSEN, P.-A. 2011. Dietary plasticity of Arctic charr (Salvelinus alpinus) facilitates coexistence with competitively superior European whitefish (Coregonus lavaretus). *Ecology of freshwater fish,* 20**,** p.558-568.

FINSTAD, A. G. & HEIN, C. 2012. Migrate or stay: terrestrial primary productivity and climate drive anadromy in Arctic char. *Global Change Biology,* 18**,** p.2487-2497.

FOLMAR, L. C. & DICKHOFF, W. W. 1980. The parr-smol transformation (Smoltification) and seawater adaption in Salmonids. *Aquaculture,* 21**,** p.1-37.

FORSGREN, E., AARRESTAD, P. A., GUNDERSEN, H., CHRISTINE, H., FRIBERG, N., JONSON, B., KASTE, Ø., LINDHOLM, M., NILSEN, E. B., SYSTAD, G., VEIBERG, V. & ØDEGAARD, F. 2015. Klimaendringenes påvirkning på naturmangfoldet i Norge. *NINA Rapport 1210.* Norsk institutt for naturforskning (NINA).

FRIIS, M. E. L. 2021. *Timing of homing migration of anadromous brown trout, Arctic char and Atlantic salmon in two rivers in Northern Norway.* Master, Norwegian University of Science and Technology.

FROST, W. E. 1965. Breeding habits of Windermere charr, *Salvelinus willughbii* (Giinther), and their bearing on speciation of these fish. *The Royal Society publishing,* 163**,** p. 232-284.

GIBERT, J. P. 2019. Temperature directly and indirectly influences food web structure. *Scientific reports,* 9**,** 5312.

GILBERT, M. J. H., HARRIS, L. N., MALLEY, B. K., SCHIMNOWSKI, A., MOORE, J.-S. & FARRELL, A. P. 2020. The thermal limits of cardiorespiratory performance in anadromous Arctic char (*Salvelinus alpinus*): a field-based investigation using a remote mobile laboratory. *Conservation Physiology,* 8.

GULSETH, O. A. & NILSSEN, K. 2001. Life–History Traits of Charr, Salvelinus alpinus, from a High Arctic Watercourse on Svalbard. *JSTOR* 54 No. 1**,** p. 1-11.

GULSETH, O. A. & NILSSEN, K. J. 2000. The Brief Period of Spring Migration, Short Marine Residence, and High Return Rate of a Northern Svalbard Population of Arctic Char. *Transactions of the American Fisheries Society,* 129**,** p.782-796.

HAMMER, J. 1989. Freshwater Ecosystems of Polar Regions: Vulnerable Resources. *AMBIO,* 18**,** P.6-22.

HAMMER, L. J., HUSSEY, N. E., MARCOUX, M., PETTITT-WADE, H., HEDGES, K., TALLMAN, R. & FUREY, N. B. 2021. Arctic char enter the marine environment before annual ice breakup in the high Arctic. *Environmental Biology of Fishes***,** p.9.

HANSEN, J. R. & OVERREIN, Ø. 2000. Røye på Svalbard og Jan Mayen. *Norsk polarinstitutt rapportserie Nr. 114.* Norsk polarinstitutt.

HEGSETH, H. 2007. *Length, Growth and diet of Arctic charr parr in lentic and lotic habitats in three watercourses on Svalbard.* 2021 Master thesis, Norwegian universitet of life sciense.

HEUPEL, M., SEMMENS, J. & HOBDAY, A. 2006. Automated acoustic tracking of aquatic animals: Scales, design and development of listening station arrays. *Marine and Freshwater Research,* 57**,** p.1-13.

HOGLUND, L. B. 1961. The reactions of fish in concentration gradients. *In:* NILSON, N. (ed.) *The effect of water-level fluctuations on the feeding habits of trout and char in the Lakes Blasjon and Jormsjon, North Sweden.* Gothenburg University library.

HOOKER, O. E., ADAMS, C. E. & CHAVARIE, L. 2020. Arctic charr phenotypic responses to abrupt temperature change: an insight into how cold water fish could respond to extreme climatic events. *biorxiv - Evolutionary Biology,* 2**,** p.31.

HUGO FLÁVIO, H. B. 2020. actel: Standardised analysis of acoustic telemetry data from animals moving through receiver arrays. *Mehods in Ecology and Evolution,* 1**,** 196-203.

HUSSEY, N. E., KESSEL, S. T., AARESTRUP, K., COOKE, S. J., COWLEY, P. D., FISK, A. T., HARCOURT, R. G., HOLLAND, K. N., IVERSON, S. J., KOCIK, J. F., FLEMMING, J. E. & WHORISKEY, F. G. 2015. Aquatic animal telemetry: A panoramic window into the underwater world. 348**,** p.12.

HUVENEERS, C., SIMPFENDORFER, C. A., KIM, S., SEMMENS, J. M., HOBDAY, A. J., PEDERSON, H., STIEGLITZ, T., VALLEE, R., WEBBER, D., HEUPEL, M. R., PEDDEMORS, V. & HARCOURT, R. G. 2015. The influence of environmental parameters on the performance and detection range of acoustic receivers. *Methods in Ecology and Evolution,* 7**,** p.825-835.

ISLAM, A., UDDIN, H., UDDIN, J. & SHAHJAHAN 2019. Temperature changes influenced the growth performance and physiological functions of Thai pangas (*Pangasianodon hypophthalmus*). *Aquaculture Reports,* 13.

JAMES, L. 2005. Acoustic Tracking of Marine Fishes: Implications for the Design of Marine Protected Areas. *Marine Technology Society Journal - MAR TECHNOL SOC J,* 39**,** p.7-9.

JOHNSEN, H., IVERSEN, H. R. & SIGURDSEN, T. 2021. Svalbardrøye (*Salvelinus alpinus*) - sammenstilling av forvaltningsrelevant kunnskap. npola.no: Norsk Polarinstitutt.

JONES, M. W. & HUTCHINGS, J. A. 2002. Individual variation in Atlantic Salmon fertilization success: Implications for effetive population size. *Ecological Society of America,* 12**,** p.184-193.

JØRGENSEN, E. H. & JOHNSEN, H. K. 2014. Rhythmic life of the Arctic charr: adaptations to life at the edge. *Marine Genomics,* 14**,** p.71-81.

K.KRISTJÁNSSON, B., LEBLANC, C.-A.-L., SKÚLASJON, S., SNORRASON, S. S. & NOAKES, D. L. G. 2017. Phenotypic plasticity in the morphology of small benthic Icelandic Arctic charr (S*alvelinus alpinus*). *Wiley Online Libary,* 27**,** p.636-645.

KESSEL, S. T., COOKE, S. J., HEUPEL, M. R., HUSSEY, N. E., SIMPFENDORFER, C. A., VAGLE, S. & FISK, A. T. 2013. A review of detection range testing in aquatic passive acoustic telemetry studies. *Reviews in Fish Biology and Fisheries,* 24**,** p.199-218.

KIRKEMOEN, O. L. 2015. *Area use of Arctic charr (Salvelinus alpinus) and brown trout (Salmo trutta) in an Arctic fjord system, a two-year acoustic telemetry study* Master, Norwegian university of life sciense.

KLEMETSEN, A., AMUNDSEN, P.-A., DEMPSON, J. B., JONSSON, B., JONSSON, N., O'CONNELL, M. F. & MORTENSEN, E. 2003. Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*) and Arctic charr (*Salvelinus alpinus*): a review of aspects of their life histories. *Ecology of freshwater fish,* 12**,** p.1-59.

KLINARD, N. V., HALFYARD, E. A., MATLEY, J. K., FISK, A. T. & JOHNSON , T. B. 2019. The influence of dynamic environmental interactions on detection efficiency of acoustic transmitters in a large, deep, freshwater lake. *Animal Biotelemetry,* 17**,** p.17.

KUSZNIERZ, J., KOTUSZ, J., KAZAK, M., POPILEK, M. & WITKOWSKI, A. 2008. Remarks on the morphological variability of the Arctic charr (*Salvelinus alpinus*) from Spitsbergen. *Polish Polar Research,* 29**,** p.227-236.

LENNOX, R. J., AARESTRRUP, K., COOKE, S. J., COWLEY, P. D., DENG, Z. D., FISK, A. T., HARCOURT, R. G., HEUPEL, M. R., HINCH, S. G., HOLLAND, K. N., HUSSEY, N. E., IVERSON, S. J., KESSEL, S. T., KOCIK, J. F., LUCAS, M. C., FLEMMING, J., NGUYEN, V. M., STOKESBURY, J. W., VAGLE, S., VANDERZWAAG, D. L., WHORISKEY, F. G. & YOUNG, N. 2017. Envisioning the Future of Aquatic Animal Tracking: Technology, Science, and Application. *BioScience,* Vol. 67**,** p.13.

LUCENA, F. M., O'BRIEN, C. M. & REIS, E. G. 2001. The effect of fish morphology and behaviour on the efficiency of gill nets, their selectivity and by-catch: two examples from southern Brazil. *Environmental Science,* 11**,** p.1-16.

LUNDE, R. 2014. *Lake-habitat use of post-juvenile sea trout over time and space - An acoustic telemetry study in a regulated river.* Master, Norwegian Unversity of Life Sciences.

MACHNIK, P., SCHIRMER, E., GLÜCK, L. & SCHUSTER, S. 2018. Recordings in an integrating central neuron provide a quick way for identifying appropriate anaesthetic use in fsh. *Scientific Reports* 8**,** 11.

MAKHROVA, A. A., BOLOTOVB, I. N., SPITSYN, V. M., GOFAROV, M. Y. & ARTAMONOVA, V. S. 2018. Resident and Anadromous Forms of Arctic Charr (*Salvelinus alpinus*) from North-East Europe: An Example of High Ecological Variability without Speciation. *Biochemistry, Biophysics, and molecular biology* Vol. 485**,** p.199-122.

MATHISEN, O. A. & BERG, M. 1993. Growth Rates of the Char *Salvelinus alpinus* (L.) in the Vardnes River, Troms, Northern Norway Aquaculture: Elsevier Science Publishers B.V., Amsterdam.

MAUNDER, M., SIBERT, J., FONTENEAU, A., HAMPTON, J., KLEIBER, P. & HARLEY, S. 2006. Interpreting catch per unit effort to assess the status of individual stocks and communities. *Ices Journal of Marine Science - ICES J MAR SCI,* 63**,** p.1373-1385.

MAZEROLLE, M. J. 2020. Model selection and multimodel inference using the AICcmodavg package. Department of Wood and Forest Sciences, Universit´e Laval.

MCCORMICK, S. D., NAIMAN, R. J. & MONTGOMERY, E. T. 1985. Physiological Smolt Characteristics of Anadromous and Non-anadromous Brook Trout (*Salvelinus fontinalis*) and Atlantic Salmon (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Sciences,* 42**,** p.529-538.

MCCORMICK, S. D. & SAUNDERS, R. L. 1987. Preparatory Physiological Adaptations for Marine Life of Salmonids: Osmoregulation, Growth, and Metabolism. *American fisheries society* p.211-229.

MEDWIN, H. & CLAY, C. S. 1997. *Fundamentals of acoustical oceanography,* Elsevier Science.

MILLAR, R. B. & FRYER, R. J. 1999. Estimating the size-selection curves of towed gears, traps, nets and hooks. *Reviews in Fish Biology and Fisheries,* 9**,** p.89-116.

MONSEN, G. J. 2019. *Behavioral Study of Coexisting Populations of Anadromous Brown Trout and Arctic Char that Overwinter in a Subarctic Lake.* Master, Norwegian University of Life Seciences.

MOORE, J. S., HARRIS, L. N., KESSEL, S. T., BERNATCHEZ, L., TALLMAN, R. F. & FISK, A. T. 2016. Preference for nearshore and estuarine habitats in anadromous Arctic char (*Salvelinus alpinus*) from the Canadian high Arctic (Victoria Island, Nunavut) revealed by acoustic telemetry. *Canadian Journal of Fisheries and Aquatic Sciences,* 73**,** p.1434 - 1445.

MOORE, J. S., HARRIS, L. N., LUYER J.L., SUTHERLAND, B. J. G., ROUGEMONT, Q., TALLMAN, R. F., FISK, A. & BERNATCHEZ, L. 2017. Genomics and telemetry suggest a role for migration harshness in determining overwintering habitat choice, but not gene flow, in anadromous Arctic Char. *Molecular Ecology,* 26**,** p.39.

MÜLLER, M. 2004. Generalized Linear Models. Handbook of Computional Statistics. Institute for Industrial Mathematics (ITWM), Germany, 1, p.24

NIELLA, Y. 2020. *Refining the Shortest Paths (RSP) of animals tracked with acoustic transmitters in estuarine regions* [Online]. github.com. Available: https://github.com/YuriNiella/RSP [Accessed 01.01.22 2022].

NORDLI, E. 2021. *The behaviour of anadromous Arctic charr during their first marine migration.* Master, The Arctic University of Norway.

PEPPER, I., GERBA, C. & GENTRY, T. 2015. *Environmental Microbiology (Third edition),* Academic press.

PERSSON, L., AMUNDSEN, P. A., M., D. R. A., KNUDSEN, R., PRIMICERIO, R., KLEMETSEN, A. & MAGNAN, P. 2013. Density-dependent interactions in an Arctic char – brown trout system: competition, predation, or both? *Canadian Journal of Fisheries and Aquatic Sciences,* 70**,** p.610-616.

POWER, G. 2002. Charrs, glaciations and seasonal ice. *Environmental Biology of Fishes,* 64**,** p.17-35.

POWER, M., REIST, J. D. & DEMPSON, J. B. 2008. *Polar Lakes and Rivers: Limnology of Arctic and Antarctic Aquatic Ecosystems,* reaserchgate.net, Oxford Scholarship Online.

QGIS DEVELOPMENT TEAM. 2020. *QGIS Geographic Information System.* [Online]. qgis.org. Available: http://qgis.osgeo.org [Accessed 08.10 2022].

R. SKOGSETH, L. L. A. O., F. NILSENE. FALCK, N. FRASER, V. TVERBERG, A.B. LEDANG, A. VADER, M.O. JONASSEN, J. SØREIDEF. COTTIER, J. BERGEB.V. IVANOV, S. FALK-PETERSEN 2020. Variability and decadal trends in the Isfjorden (Svalbard) ocean climate and circulation – An indicator for climate change in the European Arctic. *Progress in Oceanography,* 187.

RADTKA, R., SVENNING, M., MALONE, D., KLEMENTSEN, A., RUZICKA, J. & FEY, D. 1996. Migrations in an extreme northern population of Arctic charr Salvelinus alpinus: insights from otolith microchemistry *Marine ecology progress series (MEPS),* 136**,** p.13-23.

REUBENS, J., P. VERHELST, P., VAN DER KNAAP, I., DENEUDT, K., MOENS, K. T. & HERNAND, F. 2019. Environmental factors influence the detection probability in acoustic telemetry in a marine environment: results from a new setup. *Hydrobiologia,* 845**,** p.81-94.

RSTUDIO TEAM. 2020. *RStudio: Integrated Development Environment for R.* [Online]. PBC, Boston, MA Available: https://www.rstudio.com/ [Accessed 03.02 2022].

RSTUDIO TEAM. 2021. *The R Stats Package* [Online]. Available: https://stat.ethz.ch/R-manual/R-devel/library/stats/html/00Index.html [Accessed 04.01 2022].

SKOGSTAD, O. C. & SKOGSTAD, Ø. 2006. *Dynamics and resource utilization in anadromous and resident Arctic charr (Salvelinus alpinus) in Lake Vårfluesjøen on the Svalbard Archipelago after several years of protection* [Online]. Ås: Norwegian university of life sciense. Available: https://static02.nmbu.no/mina/studier/moppgaver/2006-Skogstad&Skogstad.pdf [Accessed 23.10 2021].

SPARES, A. D., SKOESBURY, M. J., DADSEWLL, M. J., O'DOR, R. K. & DICK, T. A. 2015. Residency and movement patterns of Arctic charr (*Salvelinus alpinus*) relative to major estuaries. *Journal of Fish biology,* 86**,** p.1754-1780.

SPARES, A. D., STOKESBURY, J. W., O'DOR, R. K. & DICK, T. A. 2012. Temperature, salinity and prey availability shape the marine migration of Arctic char, *Salvelinus alpinus*, in a macrotidal estuary. *Marine Biology,* 159**,** p.1633-1649.

STASKO, A. B. & PINCOCK, D. G. 1977a. Review of Underwater Biotelemetry, with Emphasis on Ultrasonic Techniques. *Journal of the Fisheries Research Board of Canada,* 34**,** p.126l-1285.

STASKO, A. B. & PINCOCK, D. G. 1977b. Review of Underwater Biotelemetry, with Emphasis on Ultrasonic Techniques. *Wsq: Women's Studies Quarterly,* 34**,** p.1261-1285.

STOTT, N. D., FAUST, M. D., VANDERGOOT, C. S. & MINER, J. G. 2021. Acoustic telemetry detection probability and location accuracy in a freshwater wetland embayment. *Animal Biotelemetry,* 9**,** p.19.

SVENNING, M.-A., KLEMETSEN, A. & OLSEN, T. 2006. Habitat and food choice of Arctic charr in Linnévatn on Spitsbergen, Svalbard: the first year-round investigation in a High Arctic lake. *Wiley Online Libary,* 16**,** p. 70-77.

SVENNING, M. & GULLESTAD, N. 2002. Adaptations to Stochastic Environmental Variations: The Effects of Seasonal Temperatures on the Migratory Window of Svalbard Arctic Charr. *Environmental Biology of Fishes,* 64**,** P.165-174.

SVENNING, M. A. 2010. Metodikk for prøvefiske etter røye på Svalbard *NINA Rapport 645.* NINA.

THELMABIOTEL. 2021a. *Tag builder* [Online]. thelmabiotal.com. Available: https://www.thelmabiotel.com/tag-builder/ [Accessed 03.03.2022].

THELMABIOTEL. 2021b. *TBR 700* [Online]. thelmabiotel.com: thelmabiotel. Available: https://www.thelmabiotel.com/receivers/tbr-700/ [Accessed 11.11 2021].

THELMABIOTEL. 2022. *Software* [Online]. thelmabiotel.com: Thelmabiotel. Available: https://www.thelmabiotel.com/software/ [Accessed 01.01.22 2022].

THOMASSEN, J., DAHLE, S., HAGEN, D., HENDRICHSEN, D., HUSA, V., MILLER, A., MOE, B., RAVOLAINEN, V., RENAUD, P. E. & WESTERGAARD, K. B. 2017. *Fremmede arter i Arktis - med fokus på Svalbard og Jan Mayen* [Online]. Available: file:///C:/Users/thor_/Downloads/1413%20(1).pdf [Accessed 15.09 2021].

ULVAN, A. F., JENSEN, A. J., FINSTAD, B., THORSTAD, E. B., RIKARDSEN, A. H. & NÆSJE, T. F. 2018. Return migration of adult Atlantic salmon (*Salmo salar L.*) to northern Norway. *Journal of Marine Science,* 75**,** 653-661.

UUSI-HEIKKILÄ, S., KUPARINEN, A., WOLTER, C., MEINELT, T. & ARLINGHAUS, R. 2012. Paternal body size affects reproductive success in laboratory-held zebrafish (*Danio rerio*). *Environmental Biology of Fishes,* 93**,** p.461-474.

W WELCH, D., PORTER, A. D. & WINCHELL, P. 2014. Migration behavior of maturing sockeye (*Oncorhynchus nerka*) and Chinook salmon (*O. tshawytscha*) in Cook Inlet, Alaska, and implications for management. *Animal Biotelemetry,* 2**,** p.17.

WEBB, P. 2019. *Introduction to Oceanography,* Roger Williams University, Rebus Community.

WICKHAM, H. 2016. *ggplot2: Elegant Graphics for Data Analysis* [Online]. Springer-Verlag New York. Available: https://ggplot2.tidyverse.org [Accessed].

Appendix A: Detailed maps of the study area

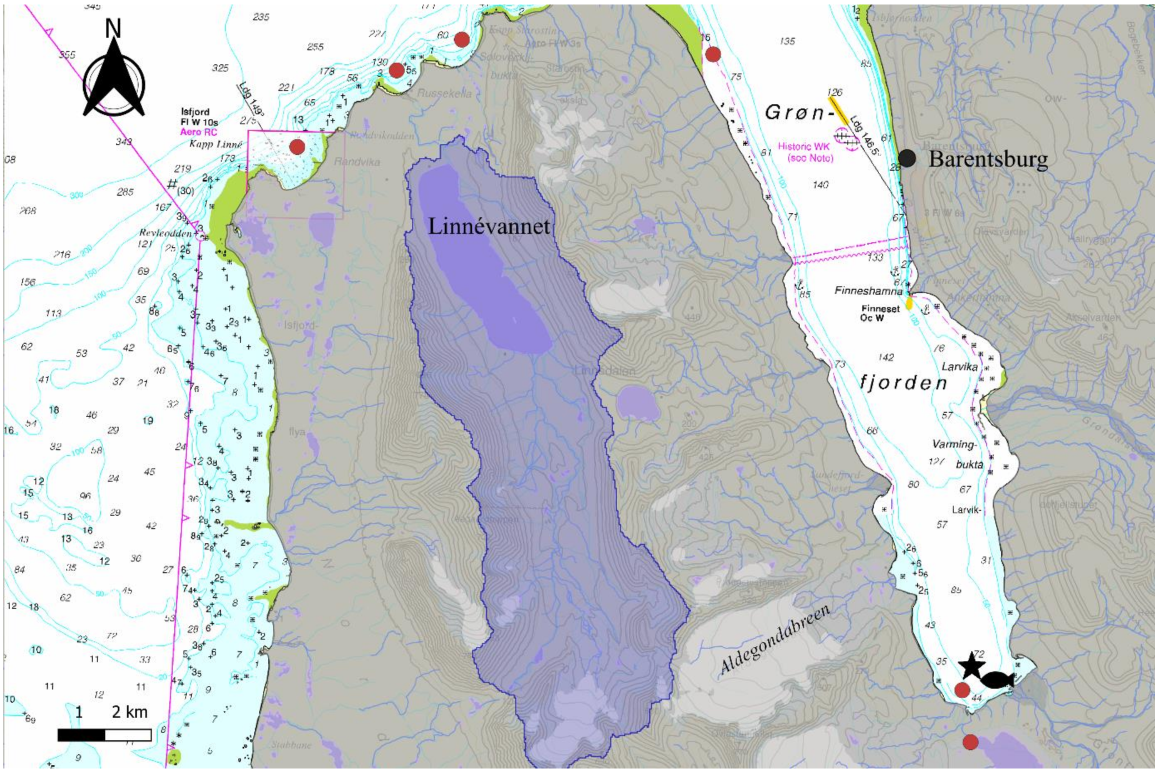

Figure 15. Map of Linnévannet (catchment on 4.4 km^2) and Grønfjord. Red dots are the location of receivers. Black fish mark is the area where fishing and tagging was done. Black star shows where the fish were released (UTM: 8654702 N, 483650 E).

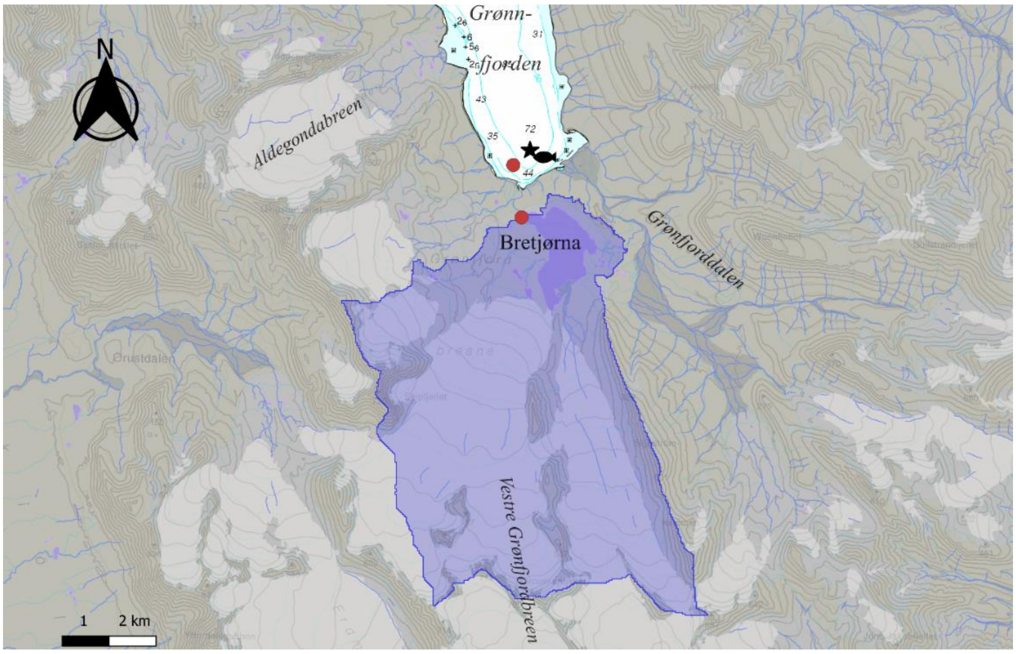

Figure 16. Map over Bretjørna (catchment on 4 km^2) and Grønfjorden. Red dots are location for receiver. Black fish mark shows the area where fishing and tagging was done. Black star show where the fish was released (UTM: 8654702 N, 483650 E).

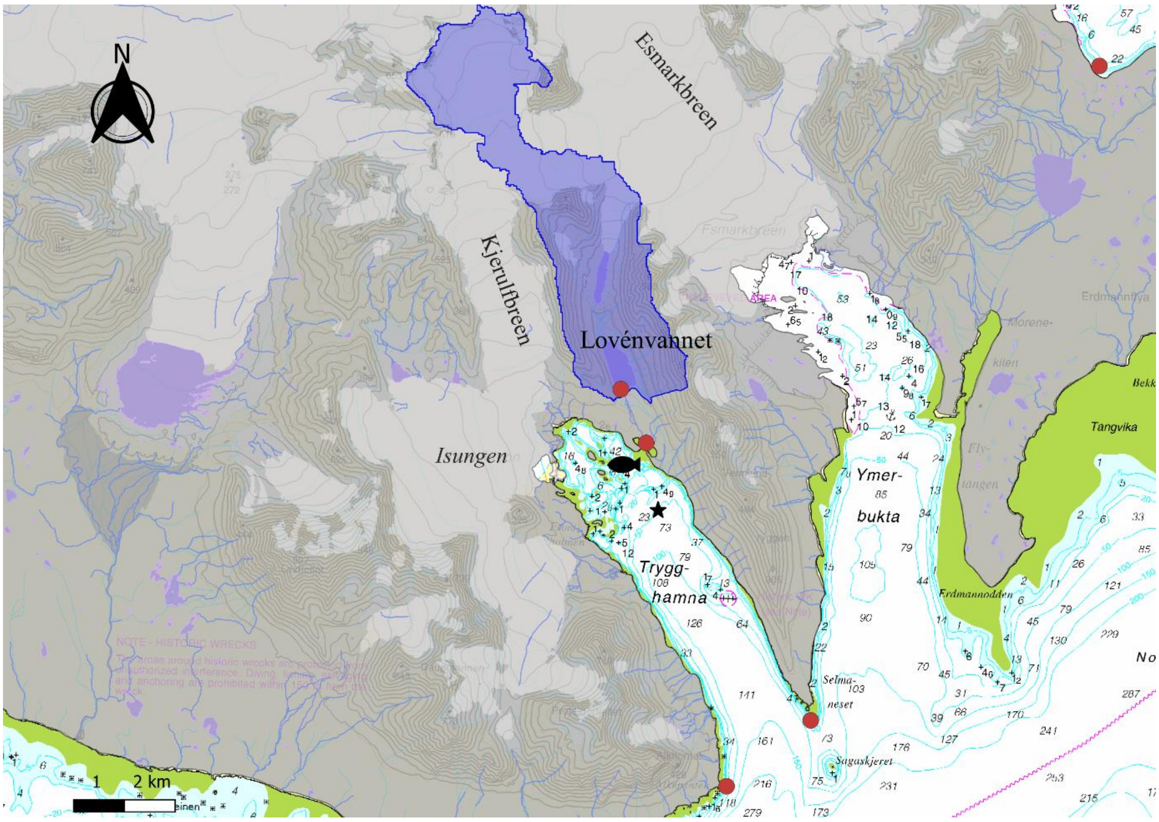

Figure 17*. Map of Lovénvannet (catchment on 1.45 km^2) and Trygghamna. Red dots are the locations for the receiver. Black fish mark is the area where fishing and tagging was done. Black star show where the fish were released (UTM: 8687992 N, 472082 E).*

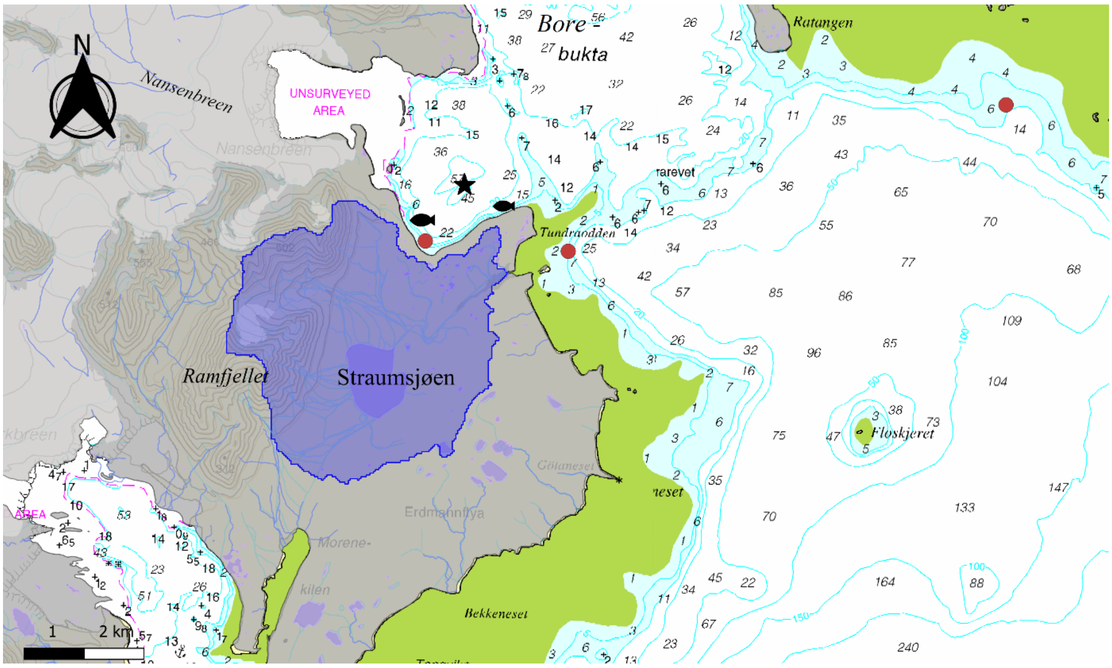

Figure 18*. Map of Straumsjøen (catchment on 1.49 km^2) and Borebukta. Red dots are the location of the receiver. Black fish mark shows the area where fishing and tagging was done. The black star shows where the fish were released (UTM: 8697147 N, 481644 E).*

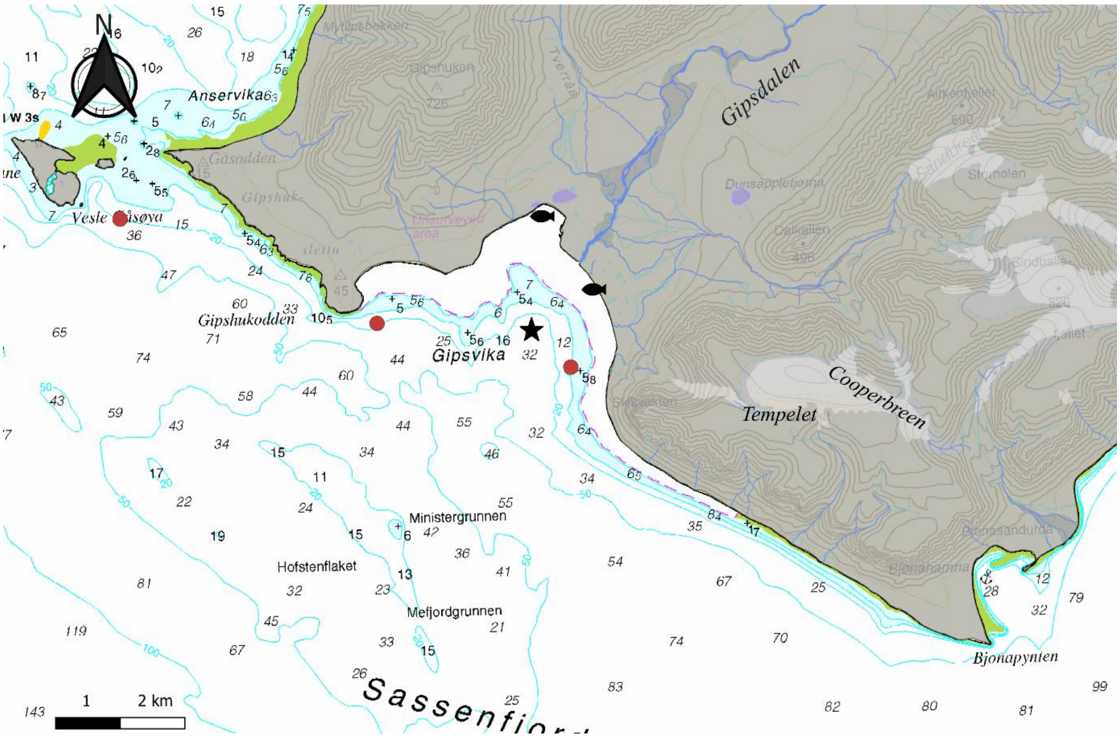

Figure 19. Map of Gipsvika, bay in Sassenfjorden. Red dots are the location for the receiver. Black fish mark shows the area where fishing was done. The black stars shows where the fish were released (UTM: 8707250 N, 534452 E).

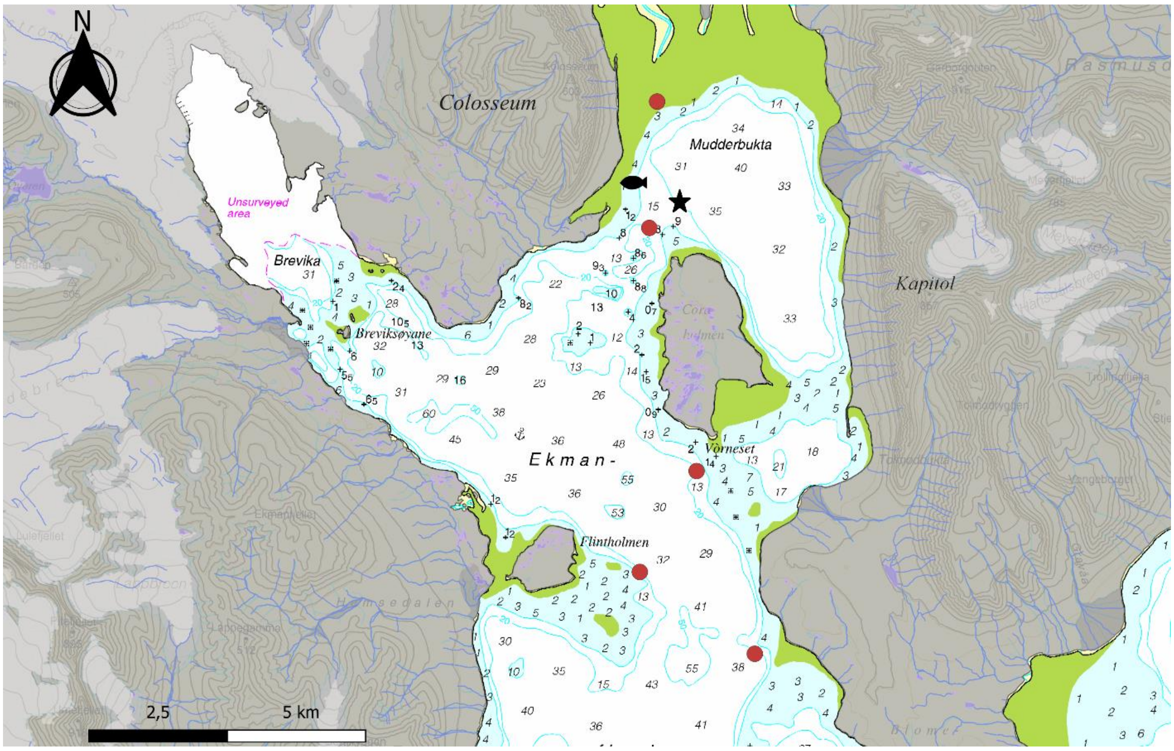

Figure 20. Map of northern part of Ekmanfjorden. Red dots are the location for the receiver. Black fish mark shows the area where fishing was done. The black star shows where the fish were released (UTM: 8736858 N, 493158 E).

Appendix B: Individuals last seen

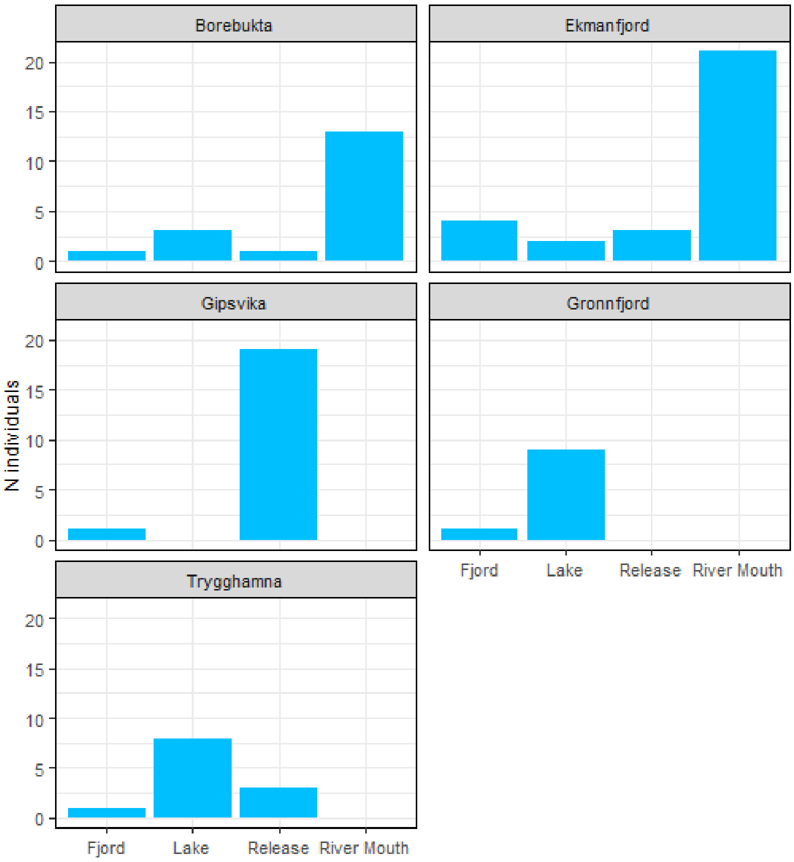

Figure 21. *The last section (Fjord, Lake, release place and River mouth) in which individuals were detected, given as the frequency of individuals and multi-paneled by groups.*

Appendix C: Tag list

Table 4. *Full list of tagged individuals throughout the study period.*

Date	Location	Ak. ID	Floy	LF	Depth	Serial nr.
7/25/2021	Grønfjord	84	3098	44,5	YES	1811
7/25/2021	Grønfjord	85	3099	42	YES	1811
7/25/2021	Grønfjord	86	3100	43,5	YES	1811
7/25/2021	Grønfjord	1282	3105	41	NO	1666
7/25/2021	Grønfjord	1283	3106	31,5	NO	1666
7/25/2021	Grønfjord	1483	3101	39	NO	1620
7/25/2021	Grønfjord	1484	3102	42,5	NO	1620
7/25/2021	Grønfjord	1485	3103	37	NO	1620
7/25/2021	Grønfjord	1486	3104	45,5	NO	1620
7/25/2021	Grønfjord	3127	3097	41,5	YES	2051
7/23/2021	Borebukta	1920	3076	41,5	YES	2011
7/23/2021	Borebukta	1921	3077	40	YES	2011
7/23/2021	Borebukta	1922	3078	44	YES	2011
7/23/2021	Borebukta	1923	3079	36,5	YES	2011
7/23/2021	Borebukta	1924	3080	46	YES	2011
7/23/2021	Borebukta	1925	3081	49	YES	2011
7/23/2021	Borebukta	1926	3082	45	YES	2011
7/23/2021	Borebukta	1927	3083	43,5	YES	2011
7/22/2021	Borebukta	4635	3063	51	YES	2125
7/22/2021	Borebukta	4636	3065	44	YES	2125
7/22/2021	Borebukta	4637	3066	48,5	YES	2125
7/22/2021	Borebukta	4638	3067	44	YES	2125
7/22/2021	Borebukta	4639	3068	37	YES	2125
7/22/2021	Borebukta	4640	3069	47,5	YES	2125
7/22/2021	Borebukta	4641	3070	40,5	YES	2125
7/22/2021	Borebukta	4642	3072	46	YES	2125
7/22/2021	Borebukta	4643	3073	45	YES	2125
7/22/2021	Borebukta	4644	3075	50	YES	2125
7/21/2021	Ekmanfjord	2547	3032	49	NO	2125
7/21/2021	Ekmanfjord	2548	3033	45,5	NO	2125
7/21/2021	Ekmanfjord	2549	3034	45	NO	2125
7/21/2021	Ekmanfjord	2550	3035	40,5	NO	2125
7/21/2021	Ekmanfjord	2551	3057	58	NO	2125
7/21/2021	Ekmanfjord	2552	3037	57	NO	2125
7/21/2021	Ekmanfjord	2553	3038	46	NO	2125
7/21/2021	Ekmanfjord	2554	3039	45,5	NO	2125
7/21/2021	Ekmanfjord	2555	3040	42,5	NO	2125
7/21/2021	Ekmanfjord	2556	3041	40,5	NO	2125
7/21/2021	Ekmanfjord	2557	3042	39	NO	2125
7/21/2021	Ekmanfjord	2558	3043	58	NO	2125
7/21/2021	Ekmanfjord	2559	3044	45	NO	2125
7/21/2021	Ekmanfjord	2560	3045	47,5	NO	2125

7/21/2021	Ekmanfjord	2561	3048	40	NO	2125
7/21/2021	Ekmanfjord	2562	3049	36	NO	2125
7/21/2021	Ekmanfjord	2563	3050	47,5	NO	2125
7/21/2021	Ekmanfjord	2564	3051	62	NO	2125
7/21/2021	Ekmanfjord	2565	3052	48,5	NO	2125
7/21/2021	Ekmanfjord	2566	3053	49	NO	2125
7/21/2021	Ekmanfjord	2567	3054	43,5	NO	2125
7/21/2021	Ekmanfjord	2568	3058	49,5	NO	2125
7/21/2021	Ekmanfjord	2569	3059	35,5	NO	2125
7/21/2021	Ekmanfjord	2570	3060	48	NO	2125
7/21/2021	Ekmanfjord	2571	3062	44,5	NO	2125
7/21/2021	Ekmanfjord	4630	3055	43	NO	2125
7/21/2021	Ekmanfjord	4631	3026	41,5	YES	2125
7/21/2021	Ekmanfjord	4632	3027	50	YES	2125
7/21/2021	Ekmanfjord	4633	3028	52	YES	2125
7/21/2021	Ekmanfjord	4634	3029	48,5	YES	2125
7/20/2021	Gipsvika	2532	3007	51	NO	2125
7/20/2021	Gipsvika	2533	3009	57	NO	2125
7/20/2021	Gipsvika	2534	3010	52,5	NO	2125
7/20/2021	Gipsvika	2535	3011	59,5	NO	2125
7/20/2021	Gipsvika	2536	3013	48	NO	2125
7/20/2021	Gipsvika	2537	3014	44	NO	2125
7/20/2021	Gipsvika	2538	3015	49,5	NO	2125
7/20/2021	Gipsvika	2539	3016	47	NO	2125
7/20/2021	Gipsvika	2540	3017	42,5	NO	2125
7/20/2021	Gipsvika	2541	3018	46	NO	2125
7/20/2021	Gipsvika	2542	3019	43	NO	2125
7/20/2021	Gipsvika	2543	3020	41,5	NO	2125
7/20/2021	Gipsvika	2544	3022	48,5	NO	2125
7/20/2021	Gipsvika	2545	3023	48	NO	2125
7/20/2021	Gipsvika	2546	3024	46	NO	2125
7/20/2021	Gipsvika	4625	3001	42	YES	2125
7/20/2021	Gipsvika	4626	3002	45	YES	2125
7/20/2021	Gipsvika	4627	3003	49	YES	2125
7/20/2021	Gipsvika	4628	3004	52	YES	2125
7/20/2021	Gipsvika	4629	3005	53,5	YES	2125
7/23/2021	Trygghamna	1293	3090	42	NO	1616
7/24/2021	Trygghamna	1295	3091	43,5	NO	1616
7/24/2021	Trygghamna	1296	3092	44	NO	1616
7/24/2021	Trygghamna	1297	3093	42	NO	1616
7/24/2021	Trygghamna	1298	3094	44,5	NO	1616
7/24/2021	Trygghamna	1479	3095	49	NO	1620
7/24/2021	Trygghamna	1480	3096	44,5	NO	1620
7/23/2021	Trygghamna	3128	3089	52	YES	2015
7/23/2021	Trygghamna	3129	3088	44,5	YES	2051
7/23/2021	Trygghamna	3130	3087	42	YES	2051

7/23/2021	Trygghamna	3131	3086	45,5	YES	2051
7/23/2021	Trygghamna	3132	3084	43	Y	2015

Appendix D: Receiver list

Table 5. Full list over receiver deployments**.**

Receiver nr.	Latitude (WGS84)	Longitude (WGS 84)	Location name	Deployment depth (m)
96	78.06873	13.63928	Randvika Kapp Linne	15
161	78.0839	13.73022	River mouth Linne elva	14
463	78.09008	13.79039	Soloveckibukta, øst Linne	16
461	78.08814	14.02489	Festningen, Grønfjord	17
113	77.96648	14.26451	Grønfjord indre sør	40
1694	77.95649	14.27268	Bretjørna	5
183	78.10015	14.122848	Isbjørnodden, Barentsburg	15
124	78.1296	14.8371	Kapp Laila	11
716	78.13531	14.96961	Rusanovoodeen, Kapp Laila	7
99	78.35104	15.87292	Konsusdalen, Diabas	16
712	78.42522	16.5646	Gipsvika, øst	11
120	78.43197	16.4316	Gipsvika, vest	16
706	78.44726	16.25568	Gåsøyane	13
384	78.44632	15.46221	Kapp Thordsen	12
442	78.6995	14.66397	Coraholmen, Nord	19
473	78.71999	14.6698	Mudderfjorden	1
436	78.66013	14.70404	Coraholmen, Sør	16
707	78.64372	14.65778	Flintholmen	8
533	78.63055	14.75255	Blomesletta	20
234	78.53674	14.62358	Sveaneset	20
202	78.33739	14.26826	River mouth Straumsjøen	5
220	78.36	14.5921	Boehem	7
168	78.33865	14.1622	Borebukta	10
212	78.22234	13.92109	Selmaneset, ytre Trygghamna	1,5
1696	78.28011	13.75111	Lovenvannet	20
139	78.27072	13.77406	River mouth Lovenvannet	4
249	78.21043	13.84953	Alkepynten	8

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