Weir Enumerations and Capture-Mark-Recapture Estimates of Population Size for Arctic Char (*Salvelinus alpinus)* from the Halokvik River, Nunavut

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WEIR ENUMERATIONS AND CAPTURE-MARK-RECAPTURE ESTIMATES OF POPULATION SIZE FOR ARCTIC CHAR (*SALVELINUS ALPINUS*) FROM THE HALOKVIK RIVER, NUNAVUT

by

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ABSTRACT

Harris, L.N., Malley, B.K., McDermid, C.G., Gallagher, C.P., Tallman, R.F., and Moore, J-S. 2020. Weir enumerations and capture-mark-recapture estimates of population size for Arctic Char (*Salvelinus alpinus*) from the Halokvik River, Nunavut. Can. Manuscr. Rep. Fish. Aquat. Sci. 3199: vi + 24 p.

Across the Canadian North, Arctic Char, *Salvelinus alpinus*, are culturally important and critical for maintaining subsistence lifestyles and ensuring food security for Inuit. Arctic Char also support economic development initiatives in many Arctic communities through the establishment of coastal and inland commercial char fisheries. The Halokvik River, located near the community of Cambridge Bay, Nunavut, has supported a commercial fishery for anadromous Arctic Char since the late 1960s. The sustainable management of this fishery, however, remains challenging given the lack of biological data on Arctic Char from this system and the limited information on abundance and biomass needed for resolving sustainable rates of exploitation. In 2013 and 2014, we enumerated the upstream run of Arctic Char in this system using a weir normally used for commercial harvesting. Additionally, we measured fish length and used T-bar anchor tags to mark a subset of the run. Subsequently, we estimated population size using capture-mark-recapture (CMR) methods. The estimated number of Arctic Char differed substantially between years. In 2013, 1,967 Arctic Char were enumerated whereas in 2014, 14,502 Arctic Char were enumerated. We attribute this marked difference primarily to differences in weir design between years. There was also no significant relationship between daily mean water temperature and number of Arctic Char counted per day in either year of the enumeration. The CMR population estimates of Arctic Char (those ≥450mm in length) for 2013 and 2014 were 35,546 (95% C.I 30,513-49,254) and 48,377 (95% C.I. 37,398-74,601) respectively. The 95% CI overlapped between years, suggesting that inter-annual differences may not be as extreme as what is suggested by the enumeration. The population estimates reported here are also the first estimates of population size for an Arctic Char stock in the Cambridge Bay region using CMR methodology. Overall, the results of this study will be valuable for understanding how population size may fluctuate over time in the region and for potentially providing advice on the sustainable rates of harvest for Halokvik River Arctic Char. Additionally, the results generated here may prove valuable for validating current stock assessment models that are being explored for estimating biomass and abundance for commercial stocks of Arctic Char in the region.

RÉSUMÉ

Harris, L.N., Malley, B.K., McDermid, C.G., Gallagher, C.P., Tallman, R.F., and Moore, J-S. 2020. Weir enumerations and capture-mark-recapture estimates of population size for Arctic Char (*Salvelinus alpinus*) from the Halokvik River, Nunavut. Can. Manuscr. Rep. Fish. Aquat. Sci. 3199: vi + 24 p.

Dans tout le Nord du Canada, l'omble chevalier (*Salvelinus alpinus*) revêt une importance culturelle et joue un rôle essentiel dans le maintien des modes de vie de subsistance et de la sécurité alimentaire des Inuits. L'omble chevalier donne également lieu à des initiatives de développement économique dans de nombreuses collectivités de l'Arctique par la mise en place de pêcheries commerciales dans les eaux côtières et intérieures. La rivière Halokvik, près de la collectivité de Cambridge Bay (Nunavut), soutient une pêche commerciale de l'omble chevalier anadrome depuis la fin des années 1960. La gestion durable de cette pêche reste toutefois difficile, étant donné le manque de données biologiques sur l'omble chevalier provenant de ce réseau hydrographique et l'information limitée sur l'abondance et la biomasse nécessaires pour assurer l'exploitation à des taux viables. En 2013 et 2014, nous avons recensé la montaison de l'omble chevalier dans ce réseau en utilisant une fascine normalement utilisée pour la pêche commerciale. De plus, nous avons mesuré la longueur des poissons et utilisé des étiquettes à ancrage en T pour marquer un sous-ensemble de la montaison. Par la suite, nous avons estimé la taille de la population en utilisant la méthode capture-marquage-recapture. Le nombre estimé d'ombles chevaliers varie considérablement d'une année à l'autre. En 2013, 1 967 ombles chevaliers ont été dénombrés, tandis qu'en 2014, le nombre était de 14 502. Nous attribuons cette différence marquée principalement aux différences de conception des fascines d'une année à l'autre. Il n'y avait pas de relation significative entre la température moyenne quotidienne de l'eau et le nombre d'ombles chevaliers comptés par jour, quelle que soit l'année du dénombrement. Les estimations de la population d'omble chevalier (≥450 mm) effectuées au moyen de la méthode capture-marquage-recapture pour 2013 et 2014 étaient respectivement de 35 546 (intervalle de confiance 95 % : 30 513-49 254) et de 48 377 (intervalle de confiance de 95 % : 37 398-74 601). Compte tenu de l'intervalle de confiance de 95 %, les estimations des deux années se chevauchent, ce qui laisse supposer que les différences d'une année à l'autre ne sont peut-être pas aussi extrêmes que ce que suggère le dénombrement. Les estimations de population présentées ici sont également les premières estimations de la taille de la population d'un stock d'omble chevalier de la région de Cambridge Bay obtenues à l'aide de la méthode capture-marquage-recapture. Dans l'ensemble, les résultats de cette étude seront précieux pour comprendre comment la taille de la population peut fluctuer dans le temps dans la région et pour éventuellement fournir des conseils sur les taux durables de récolte de l'omble chevalier de la rivière Halokvik. En outre, les résultats générés ici pourront s'avérer précieux pour valider les modèles d'évaluation des stocks actuels que l'on envisage d'adopter pour estimer la biomasse et l'abondance des stocks commerciaux d'omble chevalier dans la région.

INTRODUCTION

Arctic Char, *Salvelinus alpinus* (L.) is a salmonid fish with a Holarctic distribution common to lakes and near-shore marine environments where they occur (Scott and Crossman 1998; Reist et al. 2013). They are highly variable throughout their range exhibiting three distinct life history variants including landlocked (freshwater forms with no access to marine environments), resident (those that reside in fresh water throughout their lives despite having access to marine environments) and anadromous (sea run) forms (Reist et al. 2013; Taylor 2015). The anadromous form has been vital to the survival and culture of the Inuit who have relied on this species as a key subsistence resource for millennia (Friesen 2002; 2004; Norman and Friesen 2013). In Nunavut, Arctic Char provide a healthy and reliable food source for Nunavummiut, contributing substantially to food security while playing an important role in fostering and maintaining traditional Inuit lifestyles (Evans et al. 2015 Watts et al. 2017). Still one of the most harvested resources in Nunavut (Priest and Usher 2004; Tai et al. 2019), Arctic Char is widely considered one of the most important subsistence species in Nunavut, with a food replacement value estimated to be $7.2 million (Government of Nunavut 2016). In recent decades, the commercial potential for Arctic Char has also been realized and over 200 commercial and exploratory fisheries have emerged throughout Nunavut (Government of Nunavut 2016; Roux et al. 2011). The impact of these commercial fisheries is far-reaching, providing economic opportunities and seasonal and permanent jobs in several communities across the territory.

Cambridge Bay, on southern Victoria Island (Figure 1), has one of the longest histories of commercial fishing for Arctic Char in Nunavut. Since commercial fishing for Arctic Char commenced there in the early 1960s (Barlishen and Webber 1973; Harris et al. 2020), six stocks in the vicinity of Cambridge Bay have primarily been targeted: Ekalluk (Ekalluktok), Ellice, Halokvik (30 Mile), Lauchlan (Byron Bay or Palik), Jayko and Surrey (Paliryuak) rivers. Since the inception of the first commercial fishery over 2,300,000 kgs of this species have been commercially harvested (Harris et al. 2020). It is the largest active commercial fishery for Arctic Char in Nunavut with an annual quota approaching 60,000 kg and an estimated market value of $1,479,000 (DFO 2014). Additionally, the fishery employs dozens of Nunavummiut on an annual basis and therefore sustainable use and effective fishery management to ensure the short- and long-term conservation of fish stocks in the region is paramount (DFO 2014).

The management of Arctic Char from these fisheries, including assessments on the health and/or status of harvested stocks, has relied primarily on the analysis of trends in biological characteristics focusing on age, weight, fork-length and condition factor (Day and DeMarch 2004; Day and Harris 2013). These assessments are based on fishery-dependent data collected as part of the commercial plant sampling program operated annually at the local fish processing plant (Kitikmeot Foods Ltd.) since the early 1970s (Day and Harris 2013). Quantitative stock assessment modelling aimed at estimating safe harvest levels has been limited, primarily the result of insufficient data for robust stock assessments. Quantitative stock assessment modelling approaches have been explored (Zhu et al. 2014 a;b), but the results of these analyses were not river-specific therefore could not inform managers on river-by-river quotas.

Having information on abundance and/or biomass, or being able to resolve relative indices of these parameters, is crucial for effective fisheries management including providing recommendations for sustainable harvest levels. Tracking how these parameters may change through time is also important for understanding how population dynamics may be changing as a result of commercial harvest. Unfortunately, enumerating the number of fish within a commercially harvested stock is costly. These costs are exacerbated in Arctic locations where the logistics of conducting research are often prohibitively expensive. Hence, counts of absolute numbers of fish are rarely completed and assessment biologists and managers often rely on estimates of these parameters or indices that can be used as a proxy for abundance. In the Cambridge Bay region four of the commercial stocks were enumerated using a weir in the late 1970s and early 1980s (McGowan 1990). However, no other enumerations have been completed since then and thus these point-estimates do not provide information on how population sizes may change over time and/or as a result of commercial harvest.

In 2013 and 2014 we used a commercial fish weir for scientific purposes to enumerate the upstream run (return ocean migration) of Arctic Char at the Halokvik River. Through the use of the weir, we were also able to capture and physically mark (using T-bar anchor tags, Floy Tag & Mfg., Inc, Seattle, Washington) a subset of Arctic Char in each year to allow us to subsequently investigate Arctic Char movements in the region and estimate the population size of the Halokvik River char stock using capture-mark-recapture (CMR) methodology. This report summarizes enumeration, biological, and CMR data from this study and makes comparisons to the enumeration completed at this system in 1981 and the biological data collected at that time.

METHODS

STUDY AREA

The Halokvik River (69º 17'01"N, 107º 11' 58"W) is located on the west side of Wellington Bay, approximately 80 kilometers west of the community of Cambridge Bay (Figure 1). Harris et al. (2019) provide a detailed description of this system including the history of commercial harvest at the Halokvik River and here, we reiterate much of their description below. The Halokvik River (locally known as "30 Mile River") drains a large series of lakes (~2,450 km^2) before entering the west side of Wellington Bay (Kristofferson 2002). Commercial fishing at the Halokvik River began as a summer gill-net fishery in 1968 targeting Arctic Char in estuarine habitats near the mouth of the river. It has been fished under several different quotas since that time and is currently fished at a 5,000 kg quota that has been in place since 1994 (with the exception of 2003-2005 when it was fished at a quota of 6,800 kgs). The fishery transitioned to the use of a conduit-pipe weir in 1994 with fishing now occurring in mid- to late-August targeting the upstream migration of Arctic Char. Average harvest from 2010-2015 was 3,883 kg per year (Harris et al. 2020). The only enumeration previous to this study occurred in 1981 when 21,214 Arctic Char were counted during the upstream migration.

WEIR PLACEMENT AND CONSTRUCTION

The placement of the weir had to be consistent with the placement typically used during the commercial harvest (Figure 2 A,B; Figure 3 A,B). The weir was constructed and operated by DFO staff and local field assistants hired by the Ekaluktutiak Hunters and Trappers Organization (EHTO). During the commercial fishery, DFO staff did not operate the weir, however all Arctic Char harvested during this time were included in the enumeration. The weir itself was located in the main channel of the river just upstream of where the channel splits around two islands before entering the ocean approximately 400 meters upstream of the field camp (Figure 2 A,B; Figure 3 A, B). At this location the river is 57 meters wide and has a max depth of 1.2 meters. Stream flow was approximately 0.3 m/s allowing for reasonable setup and processing conditions.

Weir construction throughout the study generally followed the methodology outlined in Kristofferson et al. (1986) and McGowan (1990). Construction of the weir began with the erection of the holding pen (also referred to as the box) through which all Arctic Char would have to pass (Figure 3B; Figure 4). The pen was positioned roughly in the center of the channel and measured 3.05 meters wide x 12.2 meters in length. The holding pen was constructed using a combination of wooden tri-pod A-frame supports (constructed of 2.4 m length of 2'x4' lumber connected to an aluminum pipe all fastened together with a carriage bolt, Figure 5), aluminum rails with holes for conduit pipes that connected each A-frame with angle iron and a U-bolt, conduit pipe and rock bags as ballast on each of the A-frames (Figure 5, see Kristofferson et al. (1986) for a detailed description of all weir materials described above). Following that, the “wings” were constructed which extended from the downstream corners of the holding pen to the shoreline on their respective sides. The wings were constructed using the same materials as described above. Rock retaining walls were added where wings reached the shoreline to decrease the likelihood of Arctic Char being able to pass by during high water events. Upon completion of the weir, a counting/tagging chute was constructed using remaining materials (Figure 4; Figure 6). The addition of the chute assisted with fish capture for T-bar tagging, enumeration and biological sampling. Modifications were made to the 2013 design to improve enumeration accuracy. In 2013, only materials provided by the commercial fishers were used. In 2014, the modifications included the addition of 11 additional A-frames, 22 more aluminum rails and an additional 1,700 conduit pipes. These additional materials allowed for the construction of longer wings, which in turn produced an angle that better facilitated upstream movement. This allowed for the placement of conduit pipes into every hole on the aluminum rails, unlike in 2013, where conduit pipes were placed in every second hole following the advice of the commercial fishers and due to limited supplies at that time.

ENVIRONMENTAL DATA

Temperature data loggers (HOBO Pendant, Onset Computer Corporation, Bourne, Massachusetts) were used to record water temperature readings at five-minute intervals throughout the entire duration of weir operation for both study years.

ENUMERATION

In each year of the study, char were enumerated twice daily by removing a small number of conduit pipes from the upstream side of the holding pen. Counting was done visually by two technicians using tally counters as they continued their upstream migration. The 2013 and 2014 enumeration totals included char counted and released twice daily upstream through the holding box, tagged char (see below), commercially harvested char, and recreationally angled char. Two-sample Kolmogorov-Smirnov tests were used to test if the distributions of daily counts of Arctic Char differed among years. Additionally, linear models were fit to test the relationship between daily mean temperature and daily counts of Arctic Char.

TAGGING AND BIOLOGICAL DATA COLLECTION

Each day approximately 100-200 char were randomly released into the “tagging chute” to be tagged with T-bar anchor tags and measured for fork length (± 1 mm). Our tagging procedure followed protocols that have previously been used for Arctic Char in the Cambridge Bay region (e.g., McGowan, 1990). Fish were caught in the weir and directed to the ‘tagging chute’ which facilitated rapid capture and safe handling of Arctic Char for tagging. Fish were removed from the tagging chute using large dip nets and transferred to a V-shaped tagging cradle lined with wet towels to minimize the risk of injuries. Floy-tagging was completed while the fish remained in the cradle, with their eyes covered to reduce stress. The Floy tag was inserted in the left posterior side of the fish approximately one cm back from the dorsal fin at a 45º angle. Each tag was checked to ensure it was anchored between the pterygiophores, and to confirm the serial number. Fish were then released upstream of the weir. All tags contained a unique serial number and contact information. If caught commercially, recreationally or in subsistence nets, tags can be returned along with information on where and when it was caught to the Ekaluktutiak HTO or to a DFO representative in exchange for a cash reward. In 2014, 156 fish were double tagged so that recaptures would further our understanding of tag retention in this species.

In this report we only describe length data collected during all three enumerations. One-way analysis of variance (ANOVA) was used to compare means in fork length among years and a post-hoc Tukey Honest Significant Difference (HSD) test was performed to test the significance of yearly differences in mean fork length. Fishery independent data (including length, weight, age, sex and maturity) were collected in 2013 and 2014 have been fully described by Harris et al. (2019).

POPULATION ESTIMATES USING MARK-RECAPTURE

Population abundance was estimated by capturing and tagging a sample of Arctic Char using the weir in the fall (2013 and 2014) during the upstream migrations and sampling again one and two years later (2014 and 2015) in order to determine the number of marked and unmarked fish. Population size is determined for 2013 and 2014 using the single-year Peterson model (Seber 1982). In 2014, not all fish were physically checked for 2013 tagged Arctic Char during the enumeration as a large component of the population was visually enumerated and not handled. As such, only Arctic Char that were physically handled and checked for tags were included in the calculation. For the 2014 population size estimate, all data used in the calculation come solely from the 2015 commercial harvest which operated from August 23rd to September 1st.

The Peterson model assumes a closed (Seber 1982) including population; therefore six additional assumptions should be met including (1) no immigration or emigration (2) all fish are susceptible to the sampling gear and have the same probability of being captured in the first sample, (3) the tag does not affect catchability in the future, (4) the recapture sampling event is random, (5) there is no tag loss, and (6) all recaptures are reported. Due to possible biases produced by the Peterson model (Seber 1982), the Chapman modification of the Petersen equation was used to estimate population size (N):

$$N = \frac{(M+1)(C+1)}{(R+1)} - 1$$

where M = number of individuals marked, C = total number of individuals captured while trying to collect marked fish in the following year, and R = number of individuals marked that were recaptured. The uncertainty of N is determined by calculating the variance (Var):

$$Var = \frac{(M+1)(C+1)(M-R)(C-R)}{(R+1)2(R+2)} - 1$$

Seber (1982) recommends as a guide that the Poisson distribution should be used to calculate 95% confidence intervals (C.I.) if $R/C < 0.1$ and $R/M < 0.1$, which applies in this study. To calculate the intervals, coefficients were determined based on the frequency of R, according to Seber (1982) and applied to the product of $M*C$ to determine the lower and upper limits. To control for the issue of recruitment of unmarked individuals into the component of the population being evaluated (i.e., due to growth between sample 1 and sample 2), the lower end of the size range was adjusted upwards using the established growth relationship observed from tag recaptures to exclude those fish in the recapture event that would have been too small for tagging in sample 1. Consequently, the population size was estimated for Arctic Char ≥450 mm (i.e., minimum size of tagged fish). An annual tag loss rate of 8% was incorporated into the calculations, a loss rate established by Sandstrom et al. (2009) during a similar study in the closely related Northern Dolly Varden (*S. malma malma*) (Table 1).

RESULTS AND DISCUSSION

ENUMERATION AND TEMPERATURE DATA

Enumeration of Arctic Char was completed August 10th through September 5th in 2013. A total of 1,967 Arctic Char were enumerated (Figure 7), 957 of which were measured for fork length and Floy tagged. Daily counts of Arctic Char ranged from 0 (several days) to 563 (August 28th). Our field camp was impacted by a snow and wind storm on August 23rd and August 24th with persistent snow and wind gusts of up to ~100 km/hr which made it impossible to enumerate Arctic Char on those days. Daily mean river temperatures in 2013 ranged from 20.01°C (August 11th) to 1.15°C (September 3rd). There was a clear and steady decline in river temperature from the beginning of the study until August 24th (the second day of the storm described above, Figure 7). There was no significant relationship between daily mean water temperature and number of Arctic Char counted per day in 2013 ($P = 0.19$).

In 2014, the weir was operational from August 15th to September 5th. Daily counts of Arctic Char ranged from 21 (September 5th) to 2,414 (August 23rd) with a total of 14,502 char enumerated during the upstream run (Figure 8), of which1,548 were Floy-tagged. The weir was assembled later in 2014 than in 2013 due to higher than normal water levels. River temperatures were lower in 2014 with daily mean river temperatures ranging from 10.88°C (August 12th) to 3.58°C (September 3rd, Figure 8). River temperature declined throughout the enumeration but not as dramatic as the trend observed in 2013. There was also no significant relationship between daily mean water temperature and number of Arctic Char counted per day in 2014 ($P = 0.43$).

Significantly more Arctic Char were counted in 2014 than 2013, likely due to differences in how the weir was designed between years. As previously mentioned, conduit pipe was placed in every second hole of the rails secured to each A-frame to create the wings of the weir in 2013, based on recommendations from commercial fishers and materials available at that time. It was evident during enumeration that the wings of the weir were passable by all size classes of fishes resulting in an inaccurate and lower than expected count. In 2014, conduit pipes were placed in every hole of the rails connecting the A-frames (each hole was 3.2 cm apart to center). Additionally, the use of more A-frames in 2014 created a reduced angle of the wings towards the box of the weir, which facilitated the upstream migration and likely improved capture efficiency, probably producing a more accurate count. It is possible that in 2014 we missed a portion of the upstream run because of the delay in erecting the weir due to high water conditions. Indeed, during the construction and dismantling of the weir in 2014, Arctic Char were seen migrating up-river indicating that a portion of the early and late tails of the upstream migration was not counted. Given the different weir designs between years and the differences in duration of the enumeration in each year, comparing the 2013 and 2014 totals should be done with caution. It is likely that annual variations in enumerated char are a product of biological (e.g., overlapping generations, iteroparity, etc.) and life history complexities (e.g., the result of pervasive straying and dispersal and overwintering in non-natal systems, Moore et al. 2017; Harris et al. 2020) in the region. For example, the number of fish counted during the enumeration of the upstream migration of Arctic Char conducted at Freshwater Creek near the community of Cambridge Bay in 1982, 1988, and 1991 differed each year. Consecutive annual assessments at one or more fishing sites via weir or dual-frequency identification sonar (DIDSON) enumeration should be considered for future assessments of Arctic Char abundance in the Cambridge Bay region and for furthering our understanding of temporal differences in this parameter.

Although the 2014 enumeration was presumably more representative of the true count of the upstream migration of Halokvik River Arctic Char, the total number of fish counted also differed considerably from 1981 (Figure 9). In 1981, 21,214 Arctic Char were enumerated (from August 13th to September 8th) compared to 14,502 in 2014. There are several possible differences that might explain the variance between years. First, 26.8% (n = 710) of the Arctic Char randomly sampled/tagged in 1981 were <500mm, whereas less than 0.01% (n = 60) of Arctic Char biologically sampled and tagged in 2014 were ≤500mm. This suggests a sampling bias in weir design, which allowed these smaller fish to pass. It is also possible that smaller fish migrated upstream first in 2014 (i.e., during the first two weeks in August) before the weir was erected, however given the daily mean lengths observed in 1981 (see Figure 2), this hypothesis seems unlikely. Second, as mentioned above, during construction and takedown of the weir fish were seen migrating up-river, indicating we missed part of the upstream run in our enumeration. Last, it is also plausible that the Halokvik River population in 2014 is lower than it was several decades ago. Indeed, recent stock assessment modelling has suggested that Arctic Char biomass in this system has been decreasing since the late 1970s (Zhu et al. 2020). It should be noted however, that in any given year, not all adult Arctic Char migrate to marine habitats for feeding (Harris et al. 2020). Current-year spawning individuals typically stay in freshwater so they can access spawning lakes that become inaccessible as water levels drop throughout the summer (e.g., Johnson 1980; Gyselman and Broughton 1991). As such, it would appear that all enumerations are not representative of the entire population as those adults that remained in freshwater would not be counted.

Although the total number of fish enumerated differed markedly between years, proportional trends of number of fish enumerated by Julian day were similar for 1981 and 2013 and these were dissimilar when compared to 2014 (Figure 10). The distribution of daily counts of Arctic Char clearly shows that for both 1981 and 2013 the peak run began on approximately August 23rd with the peak daily counts occurring around August 28th. In 2014, the peak run began on August 19th, and peaked on August 23rd. These results, however, should be interpreted cautiously given it is evident that a large portion of the upstream run in 2013 was not enumerated. If the return migration for overwintering purposes in anadromous Arctic Char is influenced by river temperature, then the differences in the timing in the peak of the upstream migration between years may not be that surprising given the marked differences in temperature that we recorded between 2013 and 2014. Furthermore, unlike most anadromous salmonids, to avoid freezing over winter in sub-lethal seawater temperatures, Arctic Char must return to freshwater each fall (or late summer) (Gyselman 1994; Johnson 1989; Klemetsen et al. 2003). Therefore it is plausible that cooler sea surface temperatures (SST) in 2014 may have cued for an earlier upstream migration. Recording SST was beyond the scope of this study but should be investigated in the future for understanding how it might influence run-timing. Finally, it is also plausible that run-timing may be associated with the tidal cycle (i.e., more fish migrating during flood and high tides, Moore et al. 2016) but historical tide data spanning our enumerations were not available to make comparisons among years.

BIOLOGICAL DATA

Only length data are available for all three enumerations. Weight was not taken and Arctic Char were not sacrificed for otoliths in 2013 and 2014. Across all years, mean fork length ranged from 570 mm (± 125 mm, SD) in 1981 to 718 mm (± 177 mm, SD) in 2014 (Figure 11).

The smallest char were clearly sampled in 1981 (Figure 11). In 1981, a much larger range of lengths were sampled compared to those sampled in 2013 and 2014. Mean fork length was significantly different among all pair-wise comparisons of sampling years ($P < 0.01$). Differences in the sizes of Arctic Char sampled and mean lengths among years is most likely the result of differences in weir design for each year as previously mentioned.

There was no apparent pattern when visualizing the mean sizes of Arctic Char per day during the upstream migration for 2013 and 2014 (Figure 12). In 1981 however, it appears that larger individuals (~ 650 mm) started the upstream run during the first week of the migration (August 14th-20th). The following week (August 20th-26th), the mean size of Arctic Char migrating each day steadily decreased. The smallest individuals (~ 400 mm) appeared to migrate from August 26th-29th, after which there was a steady daily increase in the size of Arctic Char, which continued until the end of the enumeration.

Upstream migrations structured by size are common for anadromous salmonids including Arctic Char. For example, Dempson and Green (1985) found for an anadromous run of Arctic Char in Labrador that larger char entered the river first with a progressive decrease in daily mean length throughout the run. Similar patterns have also been observed for anadromous Arctic Char in Nauyuk Lake on the Kent Peninsula (Gyselman and Broughton 1991). It is plausible that larger, mature fish migrate first so they can access spawning lakes (which smaller and immature individuals would not require) that might not be accessible as summer progresses and water levels drop (e.g., Gyselman 1994) or to compete for specific spawning locations within the most optimal habitats (e.g., ideal cobble/gravel sizes, Sigurjónsdóttir and Gunnarsson 1989). Specific spawning locations for Halokvik River Arctic Char are not known. It is also possible that larger fish migrate first to avoid potential stranding later in the summer if water levels become too low (Gilbert et al. 2016). Although not discussed in previous studies, the increase in fish size at the tail of the run might be due to non-spawning individuals returning to fresh water that required more time feeding in the ocean to reach some sort of condition threshold required to survive the winter in freshwater. This latter hypothesis has not been formally tested but work to understand overwintering condition and potential atrophy in Arctic Char has been initiated.

POPULATION ESTIMATES USING MARK-RECAPTURE

The population estimates of Arctic Char ≥450mm in length were 35,546 (95% C.I. 30,513-49,254) in 2013 and 48,377 (95% C.I. 37,398-74,601) in 2014. Abundance estimates between years are considerably different, although the upper 95% C.I. from 2013 and the lower 95% C.I. from 2014 overlap, which suggests that inter-annual differences may not be as extreme as what is suggested by the direct weir counts. The estimates derived from the tagging study were extremely different from the direct counts from the weir, although the results from both methods were consistent by suggesting that a considerably higher number of anadromous Arctic Char migrated back into the Halokvik River in 2014 than in 2013. It is difficult to clearly determine the reasons why the abundance estimates from the mark-recapture study differ so much from the weir count. Issues with adhering to the assumptions of the Petersen model may have introduced error. For example, one assumption would be that the entire anadromous population inhabiting the watershed would have been susceptible to tagging or recapture in the following year. However, it is assumed that an unknown proportion of the population remain in the Halokvik River watershed all summer (well upstream of the weir) to spawn in lakes only to perform an ocean migration in the following year and would not be susceptible to capture in the weir and for tagging. Error may be introduced if the ratio of tagged to untagged fish from year 1 differs considerably in year 2 due to changes in the proportion of fish that migrate to the ocean in year 2 (i.e., recapture event). An additional potential source of variability is that in 2015, the weir was deployed for a shorter timespan (8 days) compared to 2013 (27 days) and 2014 (22 days) and may not have been a representative sample of the population that was going to return from an ocean migration. Further research in migratory tactics and dispersal of tagged Arctic Char is required to better inform the assumptions of the Petersen model on the CMR data obtained in consecutive years from a weir. Exploring the use of other appropriate CMR models (e.g., Bayesian approaches) may provide alternative and more accurate abundance estimates. A similar difference between CMR data and counts of migrating anadromous Dolly Varden using a DIDSON sonar was attributed to an incomplete enumeration of fish with the sonar and the methodological issues using either technique (Gallagher et al. 2013, 2018).

CONCLUSIONS

Effective management ensuring the long-term sustainability of Arctic Char in the Cambridge Bay region is part of DFO's mandate and a significant step towards this is the establishment of the first Integrated Fisheries Management Plan (IFMP) for Arctic Char in Canada (DFO 2014). Within this plan, there are long-term objectives identified to guide the management of the fishery categorized under stock conservation, ecosystem, shared stewardship, and social, cultural and economic objectives. Within stock conservation, updating stock assessment information and advice on sustainable harvest levels for each commercial waterbody and improving knowledge of Arctic Char biology are primary objectives. Information on biomass or abundance is required before sustainable exploitation rates can be recommended. Thus, the data collected as part of this study should be valuable for informing management of the Halokvik River stock. Indeed, enumeration data on char stocks in the Cambridge Bay region has previously been used to modify existing management strategies (e.g., Lauchlan River, Bodalay et al. 1992). Recent assessments have suggested the Halokvik River stock is commercially harvested at an exploitation rate of ~5% (Harris et al. 2020) which should be sustainable for an anadromous Arctic Char stock (Tallman et al. 2015). Biomass at this fishery however, appears to be steadily decreasing (Zhu et al. 2020). We suggest future enumerations be completed or stock-size be estimated via quantitative modelling to monitor how abundance may continue to change over time as a result of commercial harvest. Finally, it should be noted that thousands of char were tagged as part of this study, hundreds of which have been recaptured. These data will be valuable in furthering our understanding of the marine ecology, straying/dispersal, and stock mixing in Cambridge Bay Arctic Char.

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TABLES

Table 1. Capture-mark-recapture data used in the Petersen model to estimate abundance of Arctic Char from the Halokvik River in 2013 and 2014. The C,M, and R parameters used in the model are identified. Note, a fishing weir deployed during the fall upstream migration was used to capture fish between 2013 and 2015.

Model informationa and parameters	Capture year	
	2013	2014
Minimum size tagged (mm) in capture year	450	472
Number of fish tagged in capture year	942	1,438
Theoretical number of tags available in following year assuming 8% tag loss rate (M)	867	1,323
Number of fish examined during recapture year (C)	2,703	1,351
Number of tags enumerated in the recapture year (R)	65	36
Population estimate	35,546	48,377

FIGURES

Figure 1. Map of the current Arctic Char commercial fishing locations including the Halokvik River (red circles) in the Cambridge Bay region of Nunavut. The community of Cambridge bay is shown with a black star.

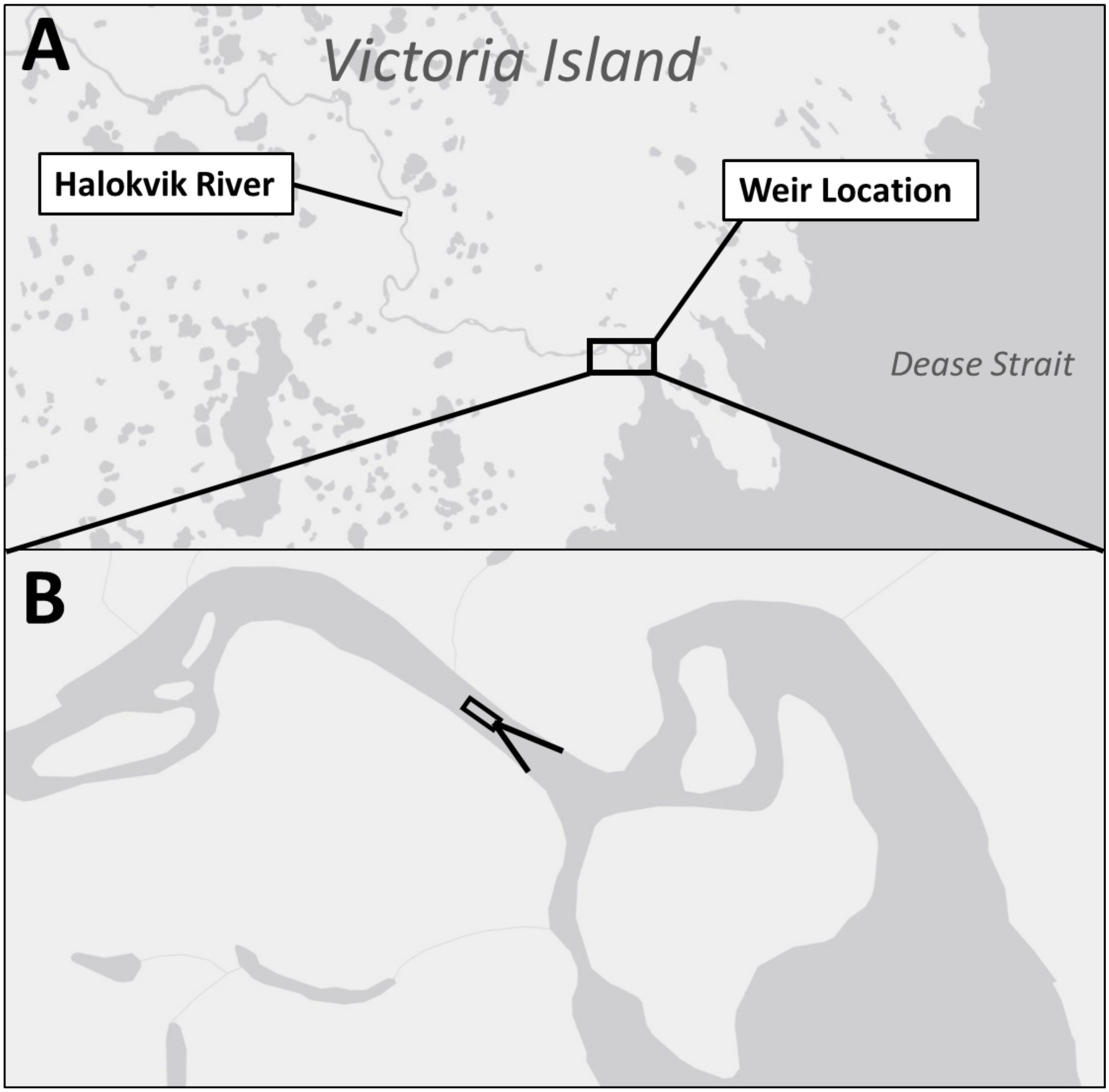

Figure 2. Maps of the study area showing where the Halokvik River drains to Dease Strait (A) and the a close up of the immediate study area highlighting the weir location within the Halokvik River (B).

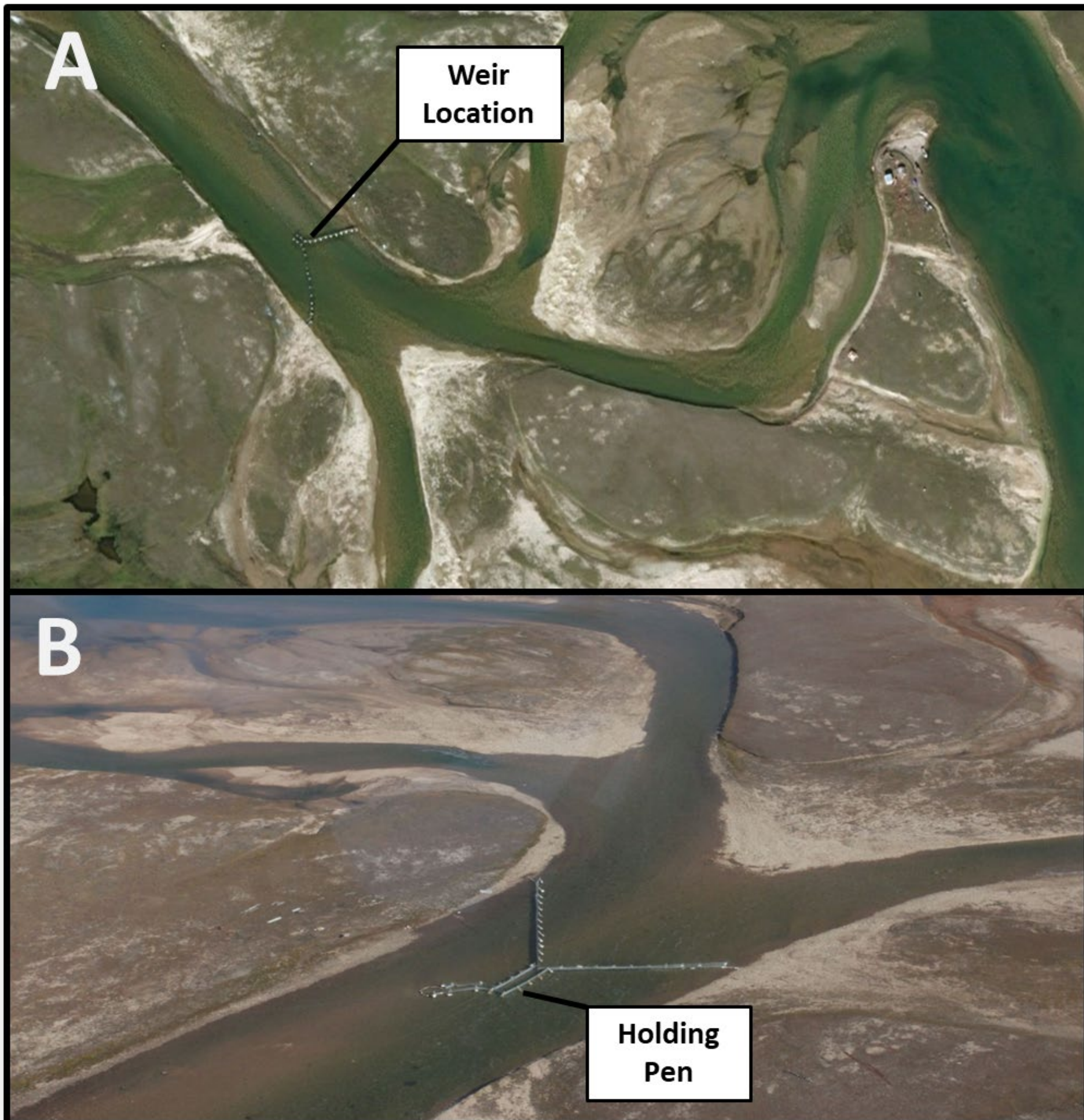

Figure 3. Satellite (A) and aerial (B) views of the weir used in the enumeration and tagging of Halokvik River Arctic Char.

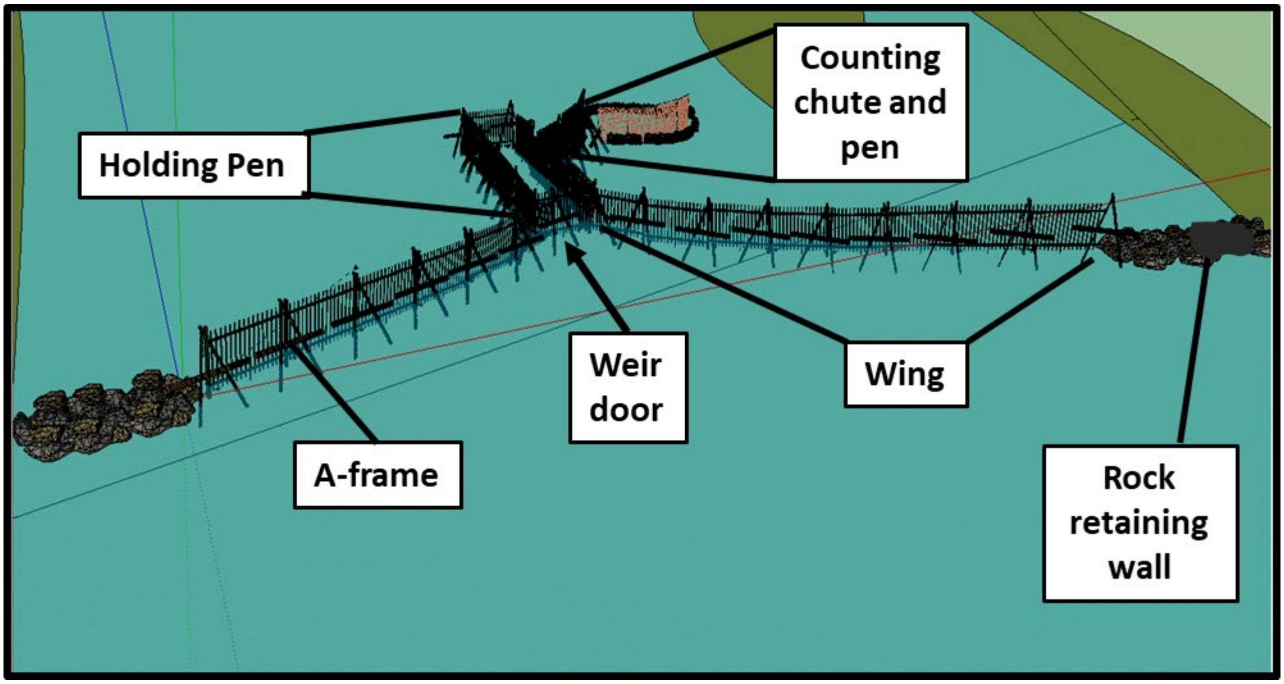

Figure 4. A schematic of the weir constructed on the Halokvik River, Nunavut in 2013 and 2014.

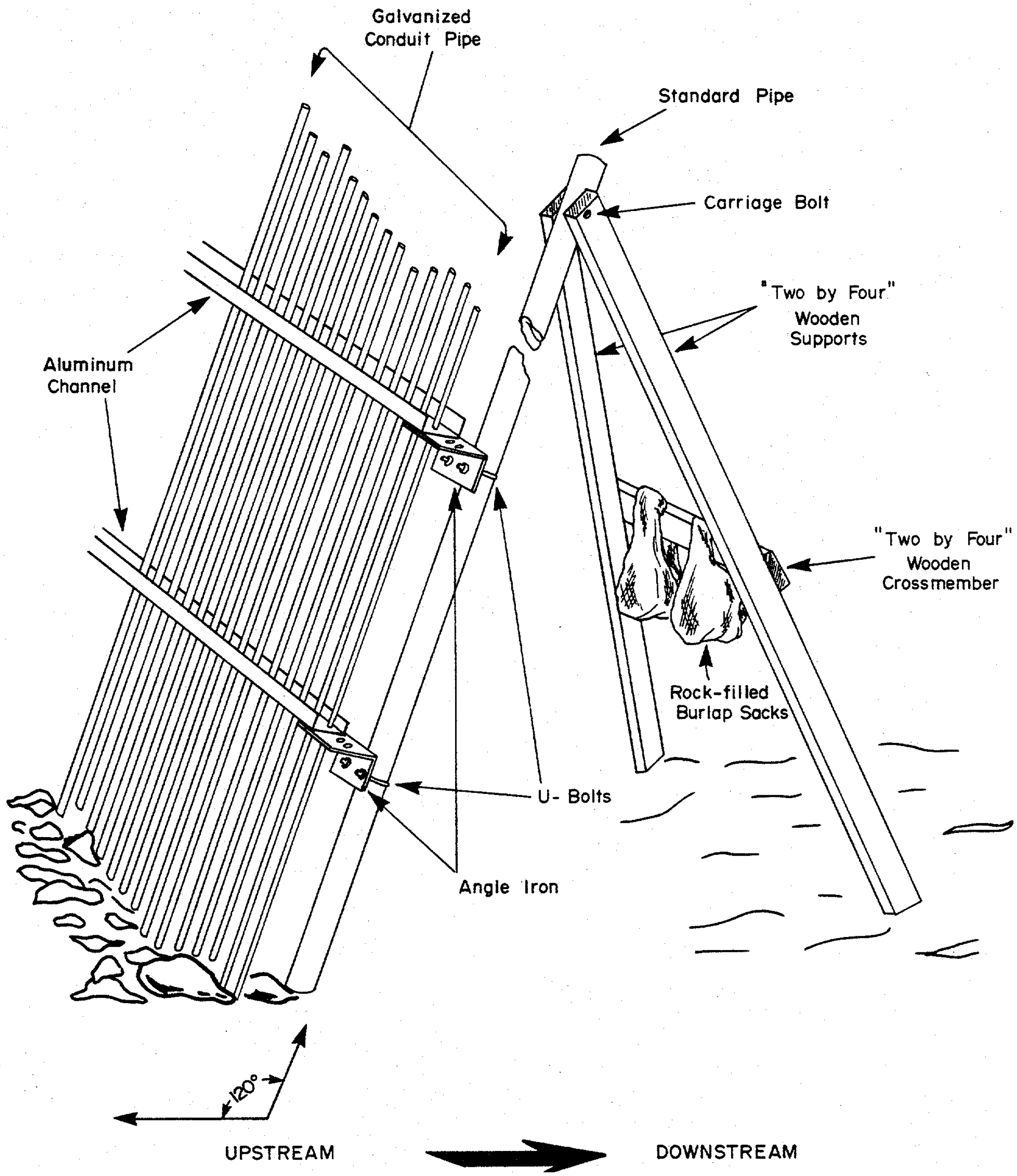

Figure 5. A schematic of the A-frames used for construction of the weir (specifically the wings of the weir and the box of the weir). Taken from Kristofferson et al. (1986).

Figure 6. A view from the rock holding pen looking down the counting chute. Photo: JS Moore.

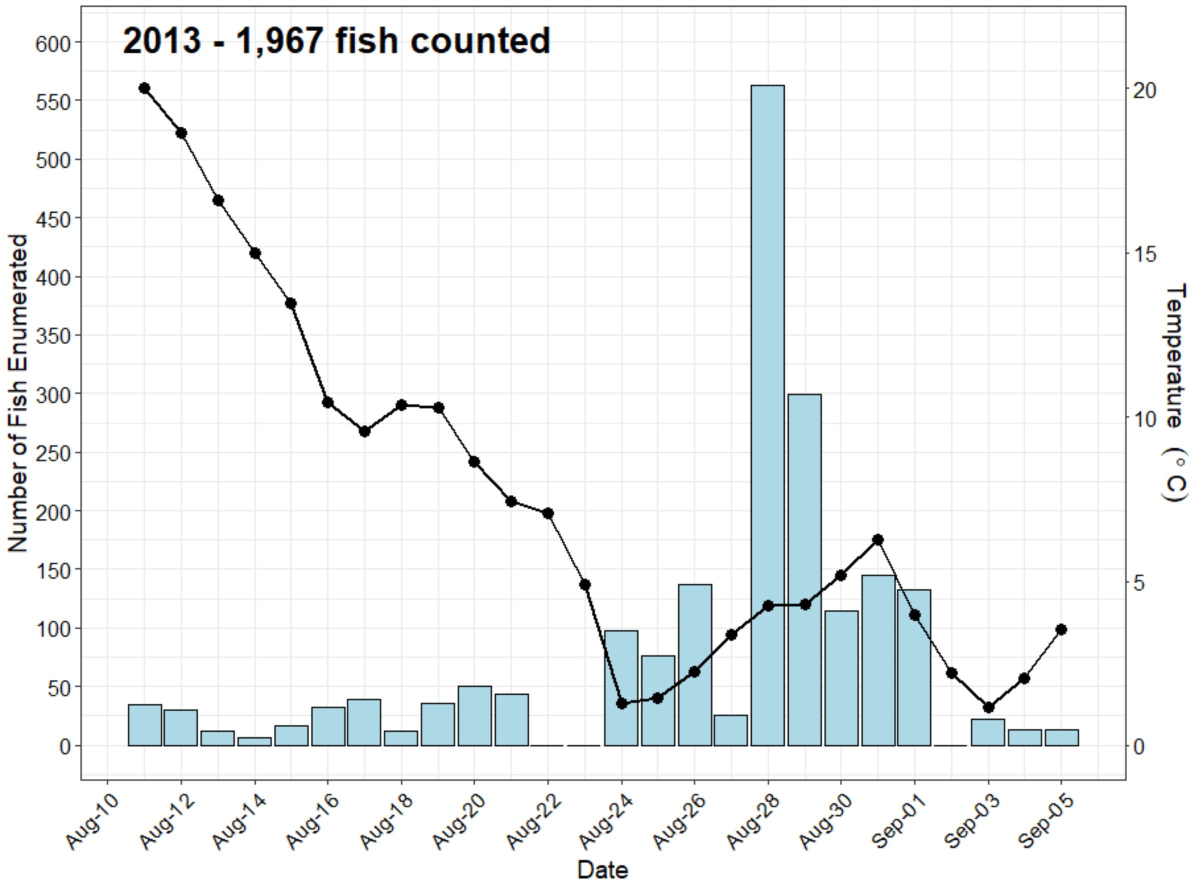

Figure 7. The 2013 daily counts (blue bars) of Arctic Char enumerated from the Halokvik River. Also shown is the daily mean river temperature during each day of the enumeration.

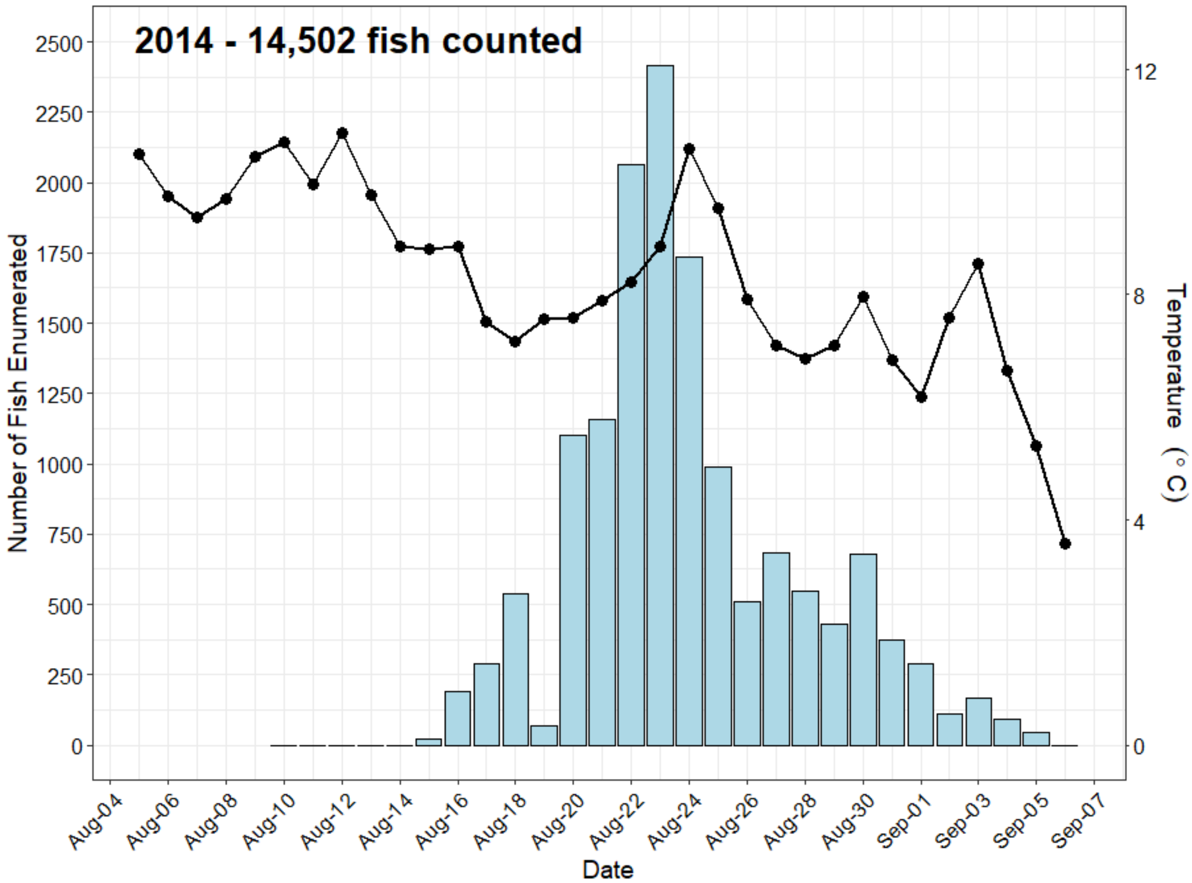

Figure 8. The 2014 daily counts (blue bars) of Arctic Char enumerated from the Halokvik River. Also shown is the daily mean river temperature during each day of the enumeration.

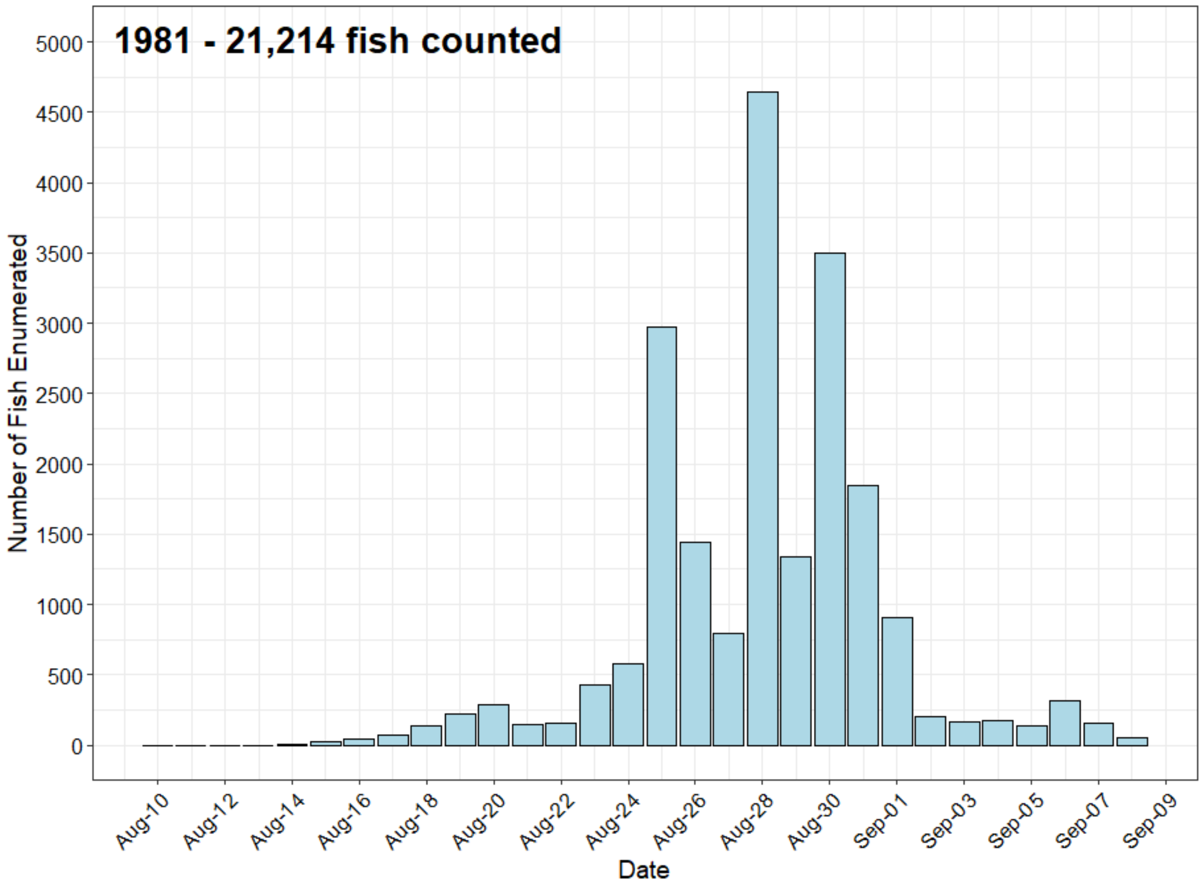

Figure 9. The 1981 daily counts (blue bars) of Arctic Char enumerated from the Halokvik River.

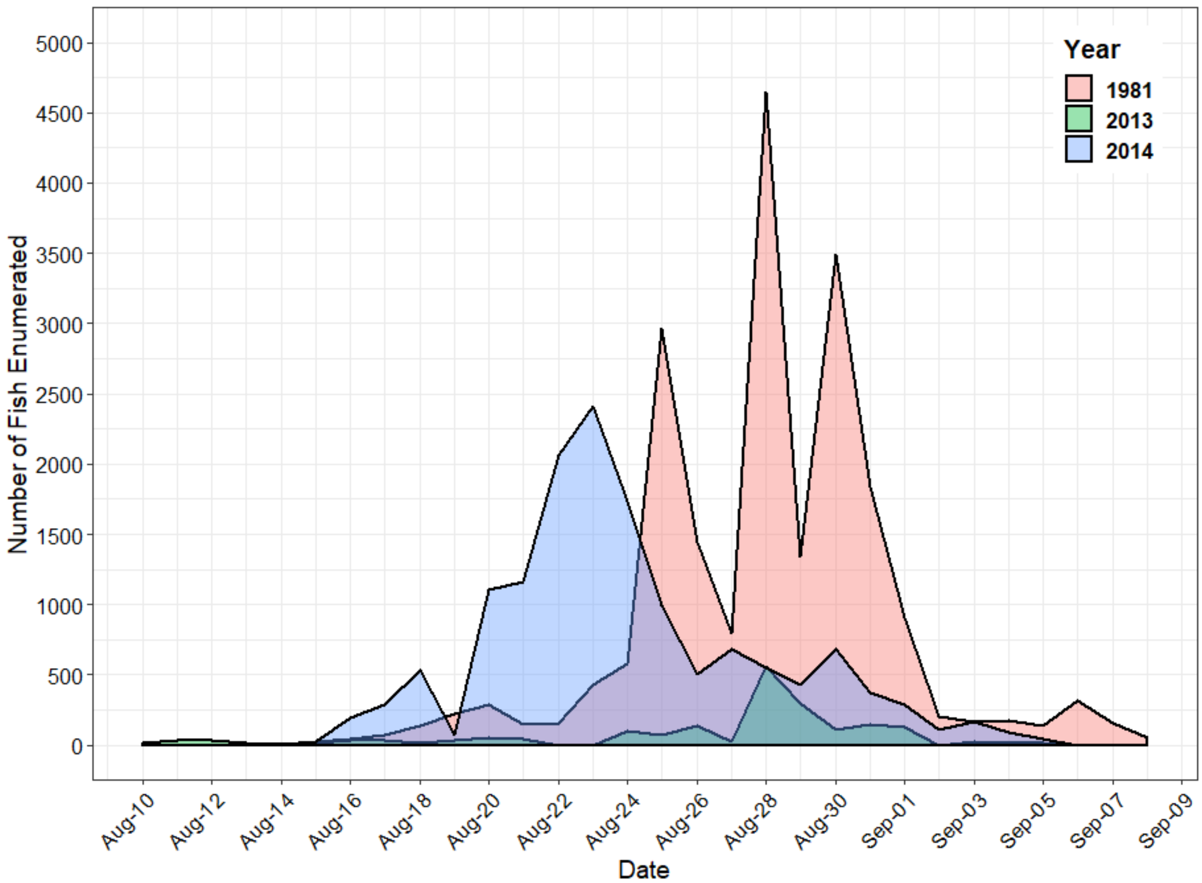

Figure 10. Density plots of daily counts for each year in which there was an enumeration of upstream-migrating Arctic Char in the Halokvik River, Nunavut.

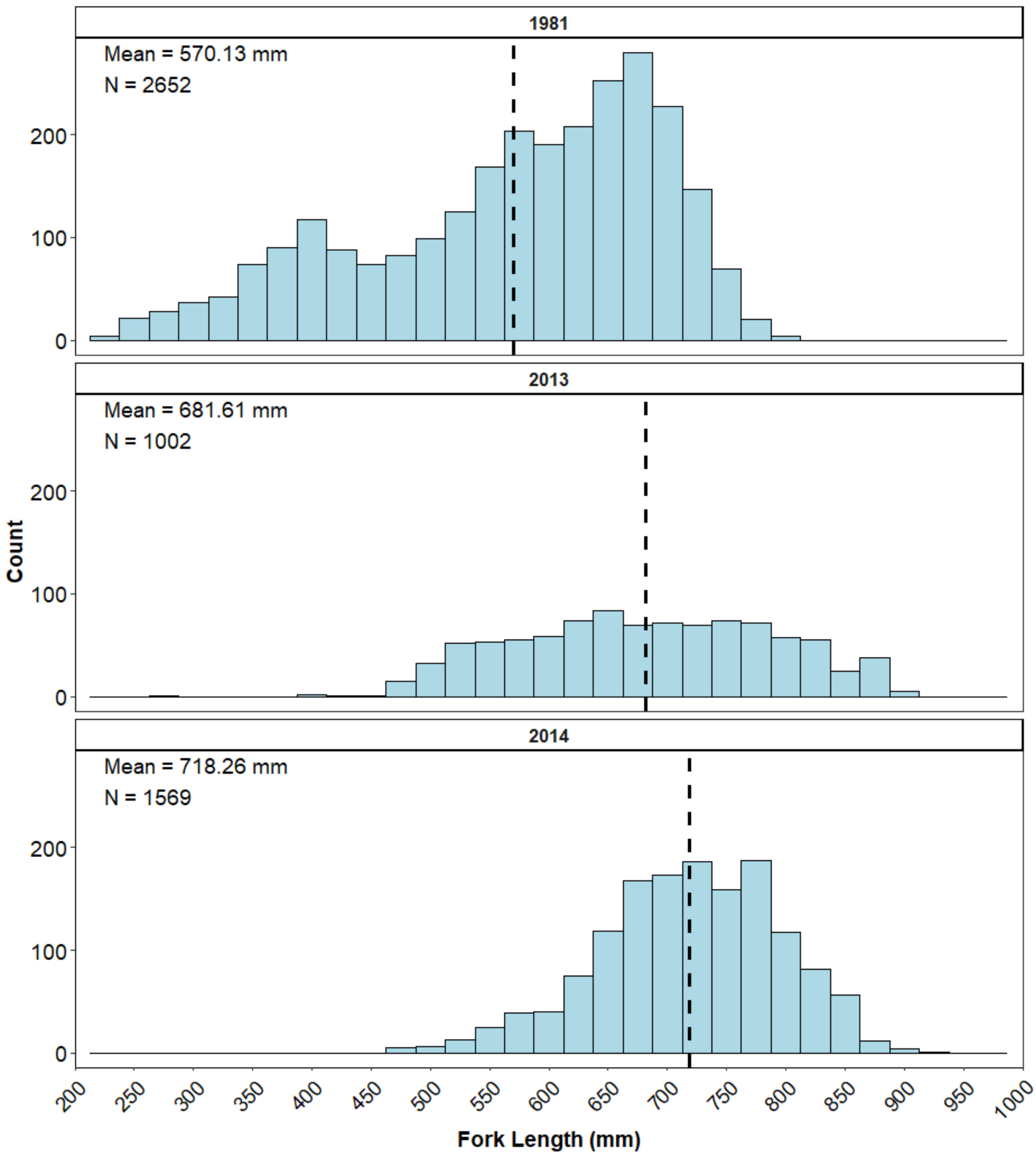

Figure 11. Frequency distributions of fork length for each year in which there was an enumeration of upstream-migrating Arctic Char in the Halokvik River, Nunavut. The mean for each year is shown with the dashed line.

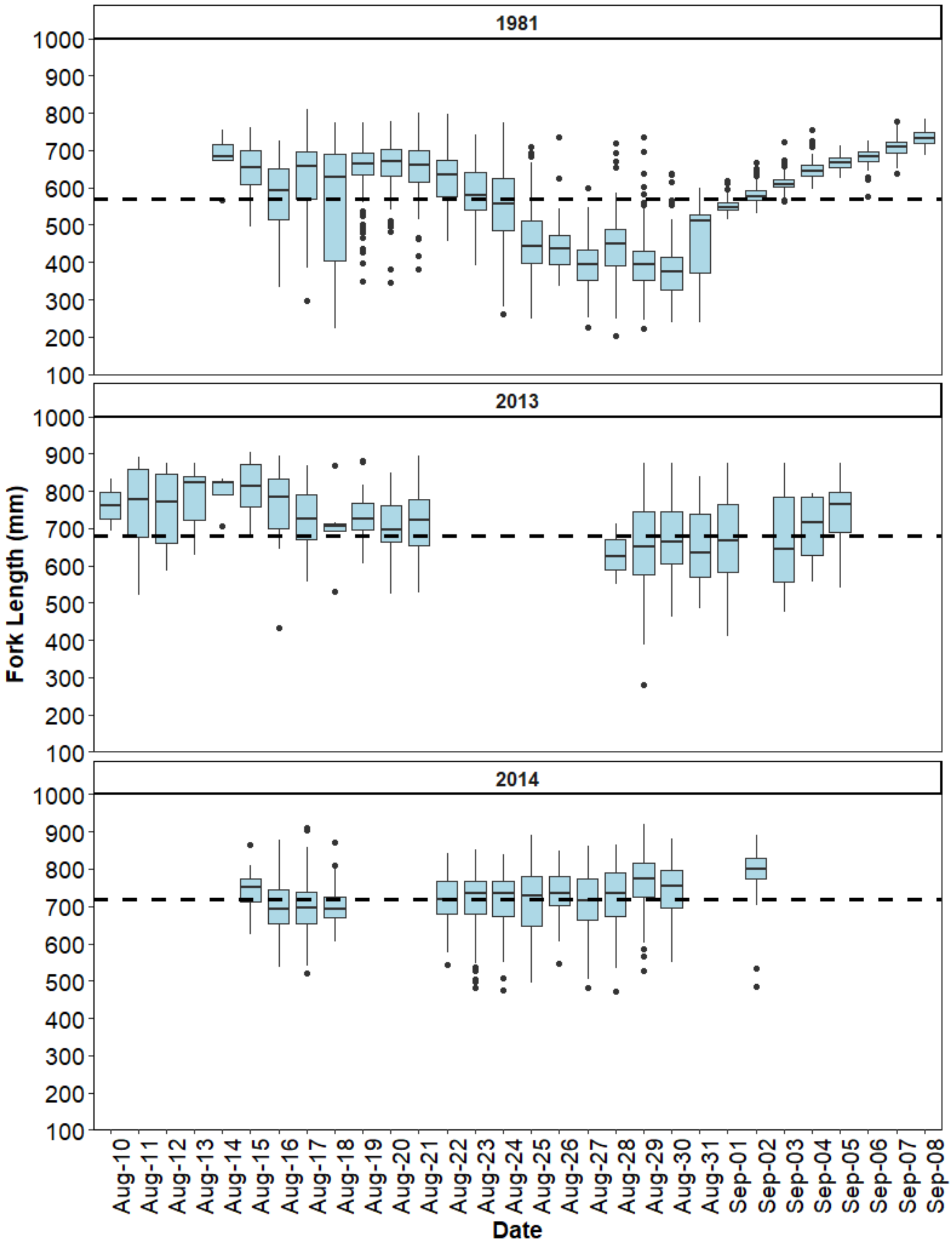

Figure 12. Mean fork length for each day of the upstream migration for Halokvik River Arctic Char for each year in which there was an enumeration.