Université du Québec

INRS
Institut national de la recherche scientifique
Centre Eau, Terre, Environnement

CARACTÉRISATION ET MODÉLISATION DE L'HABITAT DE L'OMBLE CHEVALIER ANADROME (*SALVELINUS ALPINUS*) EN EAU DOUCE, À PARTIR DES SAVOIRS TRADITIONNELS INUITS ET DES MÉTHODES SCIENTIFIQUES

Par
Véronique Dubos

Thèse présentée pour l'obtention du grade de
Philosophiae Doctor (Ph.D.)
en sciences de l'eau

Jury d'évaluation

Président du jury et examinateur interne	Eva Enders, Professeure agrégée INRS
Examinateur externe	Heidi Swanson, Associate Professor Department of Biology Wilfrid Laurier University
Examinateur externe	Karen Dunmall, Adjunct Professor, Department of Biology Carleton University
Directeur de recherche	André St-Hilaire, Professeur INRS
Codirecteur de recherche	Normand Bergeron, Professeur INRS

REMERCIEMENTS

Quelle expérience extraordinaire que ce doctorat ! Jamais je n'étais sortie de ma zone de confort à ce point, mais jamais je n'avais non plus appris autant. J'ai pris plusieurs années avant de me décider, mais arrêter de travailler pour retourner aux études faire de la recherche est définitivement une des meilleures décisions de ma vie. Quelques mois avant de faire le saut, j'ai croisé les chemins d'Yves Secretan, mon ancien directeur de maîtrise, et de Taha Ouarda, qui m'ont donné la poussée dans le dos et les encouragements dont j'avais besoin, je les en remercie.

L'expérience du nord a été bouleversante de beauté et d'intensité. Je me sens très privilégiée d'avoir pu la vivre. Pour m'avoir donné la chance de faire ce projet que j'ai tant aimé, je suis infiniment reconnaissante envers André, mon directeur, ou coach (!) de recherche. Merci André pour ta confiance, ton positivisme constant, ta grande disponibilité et tes conseils toujours pertinents. Merci de m'avoir donné tant de liberté. Mon enthousiasme a été était supporté par ta bienveillance sans faille. Si un jour je supervise des étudiants, tu seras définitivement mon modèle et j'espère faire aussi bien.

Merci à Normand, mon co-directeur, pour tes conseils pertinents. Tu m'as appris un peu à la dure comment écrire un article scientifique avec rigueur ! Je t'en suis reconnaissante et je sais maintenant que le temps rend les textes meilleurs. Je remercie Isabelle Laurion pour la collaboration, le coup de main pour l'instrumentation sur le terrain et le financement. Merci à mes camarades du labo d'André, qui ont rendu mes visites ponctuelles à l'INRS très agréables et enrichissantes, j'espère que nos routes vont continuer de se croiser.

Le Nord, je l'aimais avant de débuter ce projet. Maintenant, j'en suis devenue dépendante. En débutant ce doctorat en habitat du poisson, je ne m'attendais pas à ce qu'il y ait un aspect humain. Et ça a été pour moi l'aspect le plus transformateur, le plus déroutant et le plus beau. J'ai eu l'opportunité de rencontrer des personnes qui m'ont fait vivre des expériences incroyables. Thanks to my Inuit friends and collaborators who taught me so much, about their land, their culture and about Life. I have received these teachings with humility. I met strong people who loved their land. Many thanks to those who made this work an awesome learning adventure: Elijah Snowball, Noah Eetook, Tommy Kudluk, Zebedee Annahatak, Henri Ittulak, Johnny Nassak, Saomie Thomassie, Eva Morgan and many more people that crossed my way. I am grateful to the LNUKs of Kangiqsualujjuaq, Tasiujaq and Kangirsuk for their support in this work. Je tiens à remercier les organismes partenaires, Makivik (Mathilde Lapointe St-Pierre, Peter May et Laurie Beaupré) et la direction régionale du MFFP à Chibougamau (Véronique Nadeau). Ce travail n'aurait pas été possible sans les rencontres faites dans le Nord et dans le sud autour du Nord. La recherche en milieu Arctique est vibrante et remplie de personnes passionnées et dédiées qui ont été d'innombrables sources d'inspirations.

Cette aventure a été partagée, pas toujours volontairement et parfois à distance, avec Robert et Capucine. Robert, merci de m'avoir laissé prendre la décision de faire un doctorat sans trop sourciller ! Merci pour ta présence et ton soutien pendant mes absences. Merci pour ton écoute, même quand tu n'avais pas envie d'entendre encore une présentation PowerPoint. Toi aussi, tu es presque devenu un expert en omble chevalier ... et c'est pas fini ! Pour ma petite Capucine qui a grandi une bonne partie de sa vie pendant ce projet, merci de ta patience, de ta gentillesse et de ta curiosité nourricière. Pardon d'avoir dit trop souvent « Non, désolée, faut que je travaille ». T'avoir à mes côtés est, et sera toujours une source de joie et d'apaisement. Je vous suis immensément reconnaissante à tous les deux de m'avoir donnée cette liberté ❤.

RÉSUMÉ

L'omble chevalier anadrome est un poisson d'eau froide qui a une distribution circumpolaire. Il est culturellement et économiquement important pour les Inuits du Nunavik qui le pêchent toute l'année depuis des temps immémoriaux. Plusieurs communautés du Nunavik s'inquiètent cependant pour la pérennité de cette pêche de subsistance sous les conditions de changements climatiques alors qu'elles observent déjà des changements environnementaux et, pour certaines, des diminutions de stock. Les ombles anadromes passent la plus grande partie de leur cycle de vie en eau douce, en rivière et en lacs, pour la reproduction, l'hivernage et le stade juvénile. Comme les habitats qu'ils utilisent sont peu décrits dans la littérature, les savoirs Inuits ont été pris en compte par des méthodes qualitatives et quantitatives pour les associer aux méthodologies scientifiques utilisées pour la description et l'analyse de l'habitat du poisson. L'objectif principal de la thèse était de caractériser et modéliser les habitats utilisés lors des différents stades de vie en eau douce.

Des entrevues d'experts inuits de l'omble chevalier ont été réalisées dans les trois communautés de Kangiqsualujjuaq, Tasiujaq et Kangirsuk. Les savoirs partagés ont été mis en relation avec la littérature scientifique pour fournir un portrait holistique de l'omble chevalier anadrome. Des comportements non documentés et des avenues de recherche ont été identifiés. Toujours à partir des entrevues, la description détaillée des habitats de fraie en rivière a permis de déterminer les préférences d'habitat et de bâtir un premier modèle d'habitat prédictif pour l'omble chevalier, basé uniquement sur les savoirs Inuits. Le modèle utilise la logique floue et permet de prédire la qualité d'habitat pour la fraie d'un site en fonction des caractéristiques locales de la rivière (profondeur, vitesse et substrat).

La caractérisation de l'habitat d'hiver a été faite en collaboration avec des pêcheurs Inuits. Par leur pratique régulière de la pêche et leur savoir intergénérationnel, ceux-ci connaissaient bien les sites utilisés par les poissons, correspondant aux sites de pêche, et quelques sites de fraie dans les lacs d'hivernage. Ils ont également mesuré les caractéristiques abiotiques des sites lors de leur pratique de pêche. L'analyse a mis en évidence l'utilisation du littoral par les ombles adultes. Les sites de fraie en lac, également situés en zone littorale ont montré des profondeurs plus faibles et une température au fond relativement plus chaude. Il s'agit d'une première caractérisation hivernale de sites d'incubation des œufs. L'approche combinant le savoir des pêcheurs avec la prise de mesures simples et adaptée à leur pratique de pêche s'est avérée prometteuse pour caractériser l'habitat de l'omble chevalier et obtenir plus d'informations sur l'écologie hivernale de l'espèce.

L'habitat des juvéniles a été caractérisé à partir de relevés de pêche électrique jumelés à des analyses statistiques. Les alevins ont montré des préférences d'habitats à différentes échelles alors que les tacons se sont montrés plastiques dans l'utilisation des habitats et n'ont pas montré de préférences. La vitesse du courant s'est cependant avérée être un facteur limitant pour l'utilisation de l'habitat par les tacons

L'utilisation des savoirs Inuits en respect avec la culture inuite a impliqué de ma part un engagement pour bâtir des relations de réciprocité. En parallèle au travail scientifique, j'ai eu une pratique de communication et de dissémination des résultats proactive. Mon engagement avec la communauté de Kangirsuk a conduit au financement et au démarrage d'un nouveau projet de recherche sur les populations locales d'ombles chevaliers, mené par la communauté et intégré dans un principe de décolonisation de la recherche.

Le travail réalisé dans cette thèse apporte une meilleure compréhension de l'habitat et du cycle de vie de l'omble chevalier anadrome au Nunavik. En mettant les savoirs inuits à l'avant-plan, j'ai voulu souligner à quel point ils étaient significatifs pour la connaissance de l'écologie de cette espèce.

Mots-clés

Omble chevalier anadrome; Frayère; Habitat d'hiver; Coproduction de savoirs ; Inuit Qaujimajatuqangit; Savoirs Inuits; Modèle d'habitat du poisson ; Migration de l'omble chevalier.

ABSTRACT

Anadromous Arctic char is a cold-water fish with a circumpolar distribution. This fish is culturally and economically important for Inuit in Nunavik who fish them year-round since time immemorial. However, several Nunavik communities are concerned about the sustainability of this subsistence fishery under climate change conditions. Indeed, they already observed environmental changes and, for some communities, stock depletions. Anadromous char spend most of their life cycle in freshwater rivers and lakes, for reproduction, overwintering, and the juvenile stage. As the habitats they use are poorly described in the literature, Inuit knowledge has been braided with the scientific methodologies used in fish habitat by qualitative and quantitative methods. The overall objective of the thesis was to characterize and model the habitats used during the different life stages in fresh water.

Interviews with Inuit knowledge holders were conducted in three Nunavik communities (Kangiqsualujjuaq, Tasiujaq and Kangirsuk). The knowledge shared by interviewees and the scientific literature have been linked to provide a holistic portrait of anadromous Arctic char. Undocumented fish life histories and research avenues have been identified. Also based on interviews, the detailed description of spawning habitats in rivers allowed to determine habitat preferences and to build a first predictive habitat model for Arctic char, based solely on Inuit knowledge. The model uses fuzzy logic and makes it possible to predict the spawning habitat suitability of a site based on the local characteristics of the river (depth, velocity and substrate).

Winter habitat characterization was done in collaboration with Inuit hunters. Through their fishing practice and their intergenerational knowledge, they knew the sites used by the fish, corresponding to the fishing sites, and some spawning areas in the overwintering lakes. The specific objective was to detect if the characteristics of sites used by the fish were different than unused sites. The analysis highlighted the use of the littoral zone by adult char. In the lakes, spawning sites were also located in the littoral zone, showed shallower depths and a relatively warmer bottom temperature than non-spawning areas. This is a first winter characterization of incubation sites. The approach combining the knowledge of hunters with simple measurements adapted to their fishing practice has proven to be promising for characterizing the habitat of Arctic char and obtaining more information on the winter ecology of the species.

Juvenile habitat was characterized using electrofishing surveys combined with statistical analyses. Fry showed habitat preferences at different scales while parr were plastic in their habitat use and showed no preferences, although velocity was a limiting factor.

The use of Inuit knowledge with respect with Inuit culture implied a commitment to build reciprocal relationships. In parallel to the scientific work, I had proactive communication and research outreach practice. My engagement with the community of Kangirsuk led to the funding and start-up of a new research project to assess local populations of Arctic char. The project is community-led and embedded in a principle of research decolonization.

The work carried out in this thesis provides a better understanding of the habitats and life cycle of anadromous Arctic char in Nunavik. By putting Inuit knowledge at the forefront, I wanted to emphasize how significant it was for understanding the ecology of anadromous Arctic char.

Key words

Anadromous Arctic char; Spawning habitat; Winter habitat; Knowledge co-production; Inuit Qaujimajatuqangit; Inuit knowledge; Arctic fish; Overwintering; Fish habitat model, Arctic char migration

ABSTRACT IN INUKTITUT

ᑕᐃᑦᓱᒪᓂᓂᑐᖃᖅ ᐃᖃᓗᑉᐲᑦ ᐱᒻᒪᕆᐅᕗᑦ ᐃᓄᓐᓄᑦ ᐅᑭᐅᖅᑕᑐᒥᐅᓄᑦ, ᐃᖃᓪᓕᐊᓲᓄᑦ ᐊᖅᑰᑎᓕᒫᖅ. ᑭᓯᐊᓂ ᒫᓐᓇᐅᓕᖅᑐᖅ ᓄᓇᕕᒻᒥᐅᑦ ᐃᓱᒫᓗᒍᑎᖃᓲᖑᓕᖅᑐᑦ ᐃᖃᓗᑉᐱᓂᒃ, ᓯᓚᐅᑉ ᐊᓯᑦᔨᐸᓪᓕᐊᓂᖓᓄᑦ ᐊᑦᑐᑕᐅᒪᓂᐊᖖᒎᓯᑦᓱᑎᒃ. ᓱᓕᔪᖅ, ᐃᐸᐱᕆᔭᖃᓲᖑᕗᑦ ᓯᓚᑎᒥᑕ ᐊᓯᑦᔨᐸᓪᓕᐊᓂᖓᓂᒃ, ᐃᓚᖏᓪᓗ ᓄᓇᓖᑦ ᐃᖃᓗᓕᑦᑖᖏᓐᓂᓴᐅᓕᖅᓱᑎᒃ. ᐃᖃᓗᑉᐲᑦ ᐃᓅᓯᓕᒫᖅᒥᓂᒃ ᐃᒪᑦᓯᐊᒦᓐᓂᓴᐅᓲᖑᕗᑦ. ᓱᕙᐃᔭᓕᖅᒥᒃ, ᐅᑭᐅᖅᔨᐅᓕᖅᒥ, ᐃᓅᓯᑮᑕᓇᓕᖅᒥᓪᓗ ᑰᓐᓂᓗ ᑕᓯᖂᕙᓪᓗᓲᖑᕗᑦ. ᐃᓪᓕᓇᓲᖏᑦ ᐃᖃᓗᑉᐲᑦ ᖃᓄᐃᓕᖖᓚᑦᓯᐊᒪᖖᒑᑕ ᐅᖄᔭᐅᓪᓗᐊᖏᒃᑲᓗᐊᖅᓱᑎᒃ ᓱᑯᐃᔨᔫᓄᑦ, ᑭᓯᐊᓂ ᐃᓄᐃᑦ ᖃᐅᔨᒪᓂᖏᓐᓄᑦ ᑐᑭᓯᑎᑕᐅᕆᐊᓪᓚᓯᒪᔪᑦ, ᐃᖃᓗᐃᑦ ᐅᐸᑲᑦᑕᓂᓇᓱᖕᒌᑦ.

ᐊᐱᖅᓲᔭᖅᓂᖅ ᐃᓄᐃᑦ ᖃᐅᔨᒪᓂᖏᓐᓄᓕᖕᒐᔪᒥᒃ, ᐃᓄᒻᒪᕆᓐᓂᕙᓪᓗᒃ ᐱᓯᒪᕗᖅ. ᐱᖓᓱᓂᒃ ᓄᓇᓕᓐᓂᒃ ᓄᓇᕕᒻᒥ (ᑲᖏᖅᓱᐊᓗᑦᔪᐊᖅ, ᑕᓯᐅᔭᖅ, ᑲᖏᖅᓱᒥᓪᓗ) ᐊᓪᓚᓯᒪᓐᓂᖅᑎᑦᑐᐃᑦ ᐃᖃᓗᐃᑦ ᐱᐅᓯᖅᑎᑦ ᖃᐅᔨᓴᐅᒍᓐᓇᓯᑦᓯᑎᒃ, ᖃᐅᔨᓴᓇᐊᓪᓚᑕᐅᒍᓐᓇᓛᖖᒋᓯᑎᒃ ᐅᑭᐅᓂ ᖃᐃᔭᓂᒃ. ᑖᑯᐊ ᐊᐱᖅᓲᔭᖅᓃᑦ ᑐᑭᓯᑎᑦᓯᒋᓪᓛᓚᐅᖅᑯᑦ ᓇᓂ ᓱᕙᐃᔭᓕᖕᒍᓂᖏᓂᒃ, ᐊᒻᒪᓗ ᓇᓂᑯᑦᓯᐊᓃᖕᒍᓂᖏᓂᒃ ᑰᓐᓂ, ᐃᓄᐃᑦ ᖃᐅᔨᒪᓂᖏᓐᓄᑦ ᑐᑭᓯᓇᓇᐊᓪᓛᑎᑕᐅᓯᒪᔪᑦ. ᓱᕙᐃᔭᖅᕙᒋᓕᒃᒋᖅ ᓇᓂᑯᑦᓯᐊᓃᖓᓂᒃᓯᒪᔪᑦ ᐃᓯᒪᒥᔭᐅᓚᖅᓯᑎᒃ ᑯᒻᒥᓂᖅᓱᐅᓂᐊᖖᒎᓇᔭᐅᑦᓯᑎᒃ.

ᐅᑭᐅᒥ ᓇᔪᖅᑕᐅᓲᖑᓂᖏᑦ ᐃᖃᓗᑉᐱᓄᑦ ᖃᐅᔨᒋᐊᓪᓚᕈᑎᐅᓯᒪᕗᑦ ᐃᓄᐃᑦ ᐊᖑᓇᓱᑦᑎᖏᓐᓄᑦ. ᑕᑯᐊ ᐊᖑᓇᓱᑦᑏᑦ ᐃᖃᓗᓐᓂᐊᓕᖅᒪᑕ, ᐃᖃᓗᐃᑦ ᓇᓃᓲᖑᓂᖏᓂᒃ ᖃᐅᔨᓴᖅᑎᓱᒋᑦ. ᐊᖑᓇᓱᑦᑏ ᖃᐅᔨᒪᕗᑦ ᓇᓂ ᐃᖃᓗᖃᖅᑯᒪᖖᒑᑦ. ᑖᑯᐊ ᐃᖃᓗᐃᑦ ᓱᖅᑳᑎᖅᑕᐅᓂᖃᖅᓯᑎᒃ ᖃᐅᔨᓴᐅᓇᖅᓯᓕᕿᖅᓯᑎᒃ ᖃᓄᐃᓕᖓᓕᖅᒪᖖᖑᓂᖏᑦ ᐱᐅᓯᓇᓕᖅᒪᑕ. ᑐᑭᓯᒋᐊᓪᓚᑎᑦᓯᓯᑎᒃ ᖃᓄᖅ ᓱᕙᐃᔭᖅᐸᓪᓕᖅᒪᖖᖑᓕᖅᑯᓐ ᓯᓈᓄᑦ. ᑕᓯᖅᒥᓕ ᓱᕙᐃᔭᖅᓂᐅᓃᑦ ᐃᑎᓂᖅᓴᒥᖖᖑᕙᓗᑦᑐᑦ ᓂᕈᒥᓐᓂᖅᓴᒥᖖᒐᓚᓱᐊᖅᓯᑎᒃ. ᑖᓐᓇ ᖃᐅᔨᓴᐅᖃᒥᐅᑉ ᐅᑭᐅᔨᐅᓂᖏᓐᓂ ᐃᖃᓗᐃᑦ ᓱᕙᐃᔭᖅᓂᓇᓕᖏᓐᓂᓗ.

ᐃᓅᓯᓐᓂᓴᐃᓪᓕ ᐃᖃᓗᑉᐲᑦ ᖃᐅᔨᓴᖅᑕᐅᓂᖓ ᖃᐅᔨᓴᐅᓯᒪᓕᖅᑐᖅ ᓇᓂᒪᓚᑐᐃᓐᓈᓂᖅᓯᐅᔨᔪᓗᓂᖅ ᐃᑎᓂᖅᒥᑦ ᒪᓕᑦᓯᒋᑦ.

ᐃᓄᐃᑦ ᖃᐅᔨᒪᓂᖏᓐᓂ ᐊᑐᖅᓯᑎᒃ ᐃᓗᖅᑯᓯᖏᓂᒃ ᐃᑲᔪᖃᑎᒌᓐᓂᒧᑦ ᖃᐅᔨᓴᖅᓂᑯᑦ ᐃᖃᓗᑉᐲᑦ ᒥᑦᓵᓄᑦ. ᓱᑯᐃᔭᐃᓂᓐᒧᑐ ᐃᖃᑎᖃᑦᓯᐊᓂᓐᒧᑐ ᐱᓇᓱᐊᕈᓇᓯᓯᒪᔭᖅᑲ ᑖᑯᐊ, ᖃᐅᔨᒪᖃᑎᖃᑦᓯᐊᓱᖓᓗ ᐱᕈᖅᐸᓕᐊᖃᑎᖃᓱᓐᓚ ᑐᑭᓯᓴᖅᓂᒥᒃ ᐃᖃᓗᑉᐲᑦ ᒥᑦᓵᓄᑦ.

ᑲᖏᕐᓱᒥᐅᓂᒃ ᖃᐅᔨᒪᖃᑎᖃᕐᓂᕆᓲᕋ ᓄᐃᑦᓯᓚᕿᐅᑎᐅᓚᐅᔪᕗᖅ ᑮᓇᐅᔾᔭᕐᓂᒃ ᑐᑦᓯᕋᕐᓂᑯᑦ, ᑐᑭᓯᓴᕆᐊᓪᓲᕈᓐᓇᓯᓚᕿᑦᓱᖕᒐ, ᓄᓇᓕᖕᓂᑦᑕ ᐃᖃᓗᑉᐱᖕᓂᑦ ᖃᓄᐃᑦᑐᑰᓕᕐᒪᖔᑕ. ᑖᓐᓇ ᐱᓇᓱᒐᖅ ᓄᓇᓕᒻᒥ ᐱᓇᓱᖅᑲᑎᖃᕐᕐᑯᖅ ᐃᑲᔪᖅᑎᒌᑦᓱᑕ, ᐃᖃᓗᑉᐱᑦ ᓄᖑᑐᐃᓐᓇᓕᕐᒪᖔᑕ ᖃᐅᔨᓴᕐᓂᖅ.

ᐱᓇᓱᐊᕐᓂᕗᑦ ᑖᑦᓱᒪᐅᑉ ᒥᑦᓵᓄ ᑐᑭᓯᓇᕐᓯᑎᑦᓯᑎᐊᓪᓲᓚᓚᖕᒐᕗᖅ ᐃᖃᓗᑉᐲᑦ ᓄᓇᕗᒻᒥ ᖃᓄᐃᓕᖓᓕᕐᒪᖔᑕ, ᐃᓄᐃᑦ ᖃᐅᔨᒪᓂᖏᓐᓂᒃ ᓯᕗᓪᓕᐅᔾᔨᑦ, ᐅᖃᓕᐊᓪᓲᕈᒪᑦᓱᖕᒐᓗ ᑐᑭᓯᐊᓪᓲᓇᐊᒥᒃ ᐊᓕᐊᓇᓚᐅᕐᒪᑦ ᐃᖃᓗᑉᐲᑦ ᖃᓄᐃᓕᖓᓕᕐᓂᖏᓂᒃ.

TABLE DES MATIÈRES

LISTE DES FIGURES

LISTE DES TABLEAUX

1 INTRODUCTION

1.1 Mise en contexte du projet

L'omble chevalier anadrome, *Salvelinus alpinus*, est un poisson culturellement et nutritionnellement important pour les Inuits du Nunavik, puisqu'il constitue la deuxième source de nourriture traditionnelle, après le caribou (Dewailly et al., 2002; Tremblay et al., 2020). Bien qu'anadrome, il passe la plus grande partie de son cycle de vie en eau douce où il utilise différents habitats pour la reproduction, la croissance des juvéniles et l'hivernage. Ces différents cycles et stades de vie sont synchronisés avec la thermie et/ou les débits des cours d'eau, qui sont eux-mêmes déjà impactés par les changements climatiques observables dans les régions arctiques (Reist et al., 2006; Galappaththi et al., 2019).

Lors d'une consultation réalisée par la société Makivik en 2018 auprès des associations de chasseurs de plusieurs communautés du Nunavik (Neelin 2021), des inquiétudes ont été soulevées quant à la pérennité des populations d'omble chevalier anadrome. Certaines communautés ont remarqué un déclin des stocks. Les participants aux consultations ont alors exprimé leur volonté que des recherches soient faites pour mieux comprendre l'impact potentiel des changements climatiques sur les habitats utilisés, particulièrement en eau douce où les problématiques ont surtout été observées. Or, les facteurs déterminant la sélection des habitats utilisés par les ombles anadromes en eau douce sont méconnus, en particulier au Nunavik.

Le présent projet a été conduit en partenariat avec les communautés de Kangiqsualujjuaq, Tasiujaq et Kangirsuk, pour lesquelles des diminutions de stock d'omble chevalier ont été notées. De façon plus spécifique, des chasseurs locaux ont mentionné avoir constaté que l'espèce subit des stress ou des modifications de son environnement à plusieurs occasions lors de son cycle de vie. Par exemple, ils ont remarqué que les ombles adultes reproducteurs rencontraient des difficultés à remonter les cours d'eau à l'automne, à cause du niveau d'eau trop bas dans les rivières. Certains ont observé ponctuellement des mortalités de juvéniles dans des petits cours d'eau par des chaudes journées d'été (A. Gordon, 2020, Kuujjuaq, pers.

communication) et d'autres, un changement dans les sites de pêches printaniers (E. Snowball, 2020, Kangiqsualujjuaq, pers. communication), associé à un niveau des lacs moins élevé.

Les trois communautés à l'étude couvrent une gamme d'habitats différents. Les ombles ont accès à plusieurs lacs dans la région de Tasiujaq, à des habitats principalement fluviaux dans la région de Kangirsuk et à des habitats fluviaux et lacustres autour de Kangiqsualujjuaq. Cette diversité d'environnement permet de faire une analyse représentative des habitats rencontrés dans le secteur de la Baie d'Ungava et possiblement une généralisation de l'écologie de l'omble chevalier anadrome.

1.2 Revue de la littérature sur l'omble chevalier

La présente section constitue une revue de la littérature scientifique et n'intègre pas les connaissances et observations partagés par les experts inuits lors des entrevues formelles ou de discussions informelles. Une analyse plus complète de l'écologie et des habitats, mettant les savoirs inuits à l'avant-plan est présentée au chapitre 2.

1.2.1 Cycle de vie

L'omble chevalier (*Salvelinus alpinus*) est une espèce de poisson d'eau froide qui démontre une écologie diversifiée (Klemetsen et al., 2003) et une grande flexibilité dans son cycle de vie et dans les habitats qu'il occupe (Hammar 2014). Il existe une forme résidente, qui reste dans le même lac toute sa vie et une forme anadrome, qui migre en eau salée durant l'été pour s'alimenter (Johnson 1980b). Une forme fluviale, qui passerait toute sa vie en rivière, a également été documentée (Reist et al., 2017). Le présent projet se limite à l'étude des habitats d'eau douce de la forme anadrome de l'omble chevalier, qui constitue la principale forme consommée au Nunavik.

La majorité de son cycle de vie se fait en eau douce, en particulier la reproduction, l'hivernage et le stade juvénile (Klemetsen et al. 2003a) (Figure 1.1). Les juvéniles restent en eau douce, jusqu'à ce qu'ils aient la capacité de s'adapter à l'eau salée (smoltification). La première migration en mer se fait principalement autour de l'âge de 3 ans, mais peut varier entre 2 ans et 9 ans selon la localisation mais aussi les variations individuelles (Dempson et Green, 1985). Les adultes matures et les immatures s'alimentent de un à deux mois durant l'été dans l'eau salée ou saumâtre (Moore et al. 2016). Ils utilisent principalement les milieux estuariens et côtiers. La migration amont débute à la fin de l'été. Les reproducteurs se dirigent vers les cours d'eau en amont pour rejoindre leurs sites de fraie. Les immatures et les non-reproducteurs se dirigent directement vers leurs sites d'hivernage. La période de migration peut être unimodale ou bimodale en fonction de la taille des individus, mais l'ordre de montaison en fonction de la taille semble varier en fonction des populations Dempson et Green, 1985; Boivin, 1994). La période d'hivernage débute immédiatement après la fraie, au moment où la température de l'eau décroit rapidement, et se poursuit jusqu'à la débâcle printanière (Cunjak et Power, 1986).

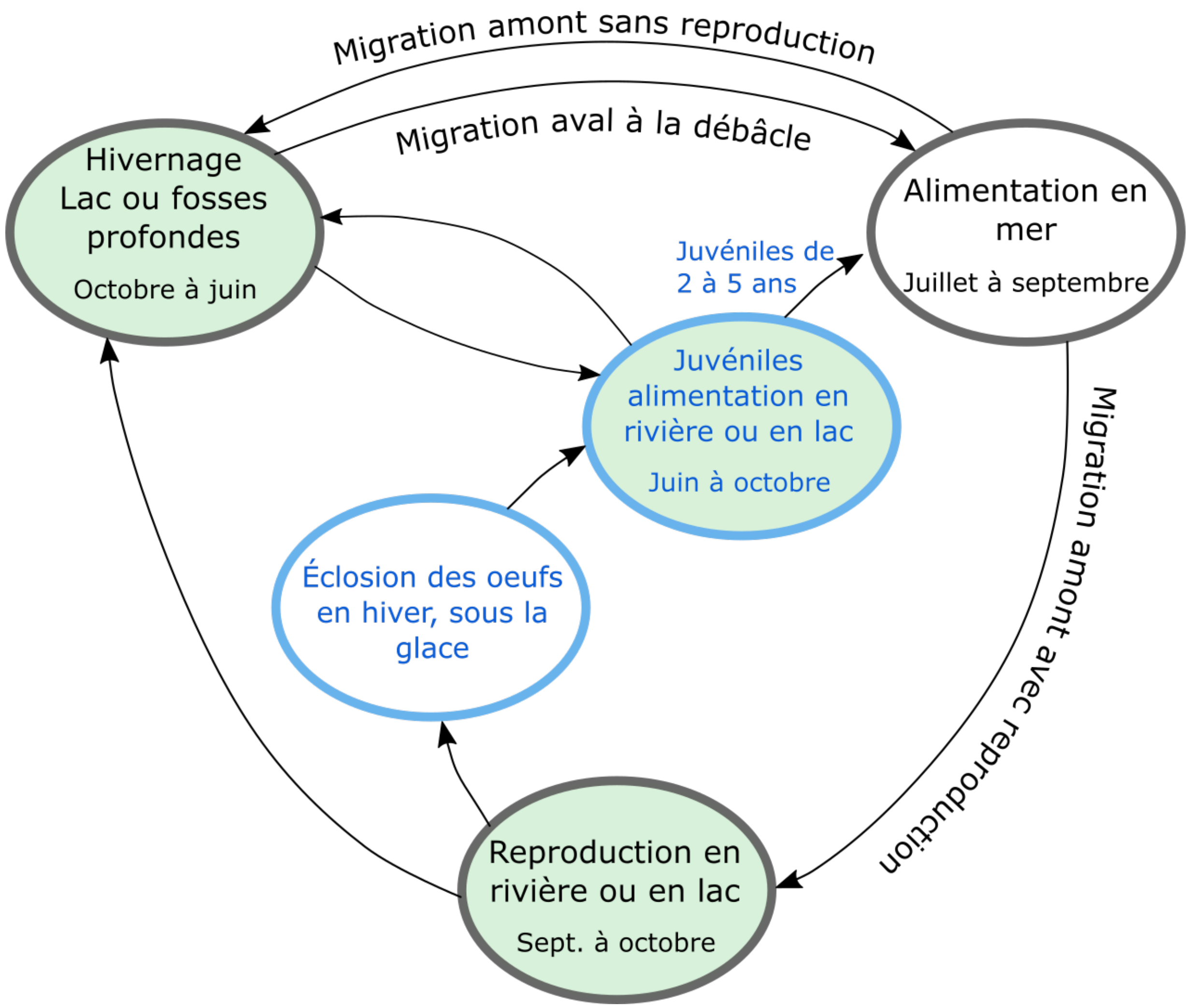


Figure 1.1 **Cycle de vie général de l'omble chevalier anadrome. Les stades de vie au contour gris concernent les adultes matures ou immatures, i.e., après smoltification (processus d'adaptation à l'eau salée). Les stades au contour bleu concernent les juvéniles avant smoltification. La présente étude des habitats traite des stades au fond vert.**

1.2.2 Habitats de reproduction

L'utilisation d'un habitat peut être évaluée par la présence (ou l'abondance ou la densité) de poisson dans cet habitat, sans égard à la disponibilité du type d'habitat dans l'environnement. Il y a une sélectivité ou une préférence d'habitat lorsque la proportion de poissons utilisant un type d'habitat est supérieure à la proportion de sa disponibilité (Johnson 1980a). Il faut donc connaitre la disponibilité de l'habitat pour estimer une préférence d'habitat.

Les sites de fraie des ombles anadromes sont situés principalement en rivière, mais les lacs peuvent aussi être utilisés (Johnson, 1980b; Reist et al., 2017). Les pêcheurs inuits interrogés dans les trois communautés (Kangiqsualujjuaq, Kangirsuk, Tasiujaq) ont également indiqué que la fraie des ombles anadromes se déroule essentiellement en rivière. Les reproducteurs sont fidèles à leurs sites de fraie (Kristofferson 2003) mais peuvent en utiliser plusieurs lors d'une même saison de reproduction (Johnson 1980b).

1.2.2.1 Caractérisation à l'échelle du microhabitat

Quelques sites de reproduction utilisés par l'omble chevalier anadrome ont été décrits dans la littérature mais ces descriptions n'ont cependant pas été faites dans une perspective spécifique à la caractérisation locale de l'habitat. Cependant, certaines variables typiques du microhabitat (habitat à l'échelle locale) ont pu être extraites et sont synthétisées au Tableau 1.1. Bien que les sites couvrent des régions géographiques diverses, en combinant les informations décrites, on peut obtenir des précisions sur les caractéristiques locales des habitats utilisés pour la fraie. Les ombles utilisent des substrats hétérogènes (Johnson 1980b; Cunjak et al., 1986; Beddow et al., 1998). La gamme de substrat utilisée va du sable grossier, en passant par le gravier et les blocs. Le diamètre supérieur du substrat ne semble pas être un facteur limitant, mais les substrats trop fins (sables fins et limons) ne sont pas utilisés. Le sable n'est utilisé qu'occasionnellement. Ils ne creusent des nids que lorsque le substrat est suffisamment fin (graviers et sables grossiers). Sinon, ils dispersent les œufs à travers les interstices du substrat (Dempson et Green, 1985). Les sites de fraie décrits sont situés à des profondeurs comprises entre 0,2 m et 2 m (Johnson 1980b; Dempson et Green, 1985; Cunjak et al., 1986; Beddow et al., 1998). Les vitesses sont également variables, mais un écoulement semble toujours présent. Il est à noter que les sites décrits par Beddow et al. (1998) sont des sites où la fraie est suspectée, mais n'a pas été directement observée.

Le Dolly Varden (*S. malma malma*), qui occupe les rivières situées à l'ouest de la vallée de la rivière Mackenzie (Stewart et al. 2010), est une espèce congénère proche de l'omble chevalier anadrome, tant pour ses caractères méristiques que pour son écologie (Johnson 1980c). Les variables caractéristiques des habitats du Dolly Varden (substrat, vitesse et profondeur) ont été décrites par Mochnacz et al. (2010) et semblent assez similaires à celles de l'omble chevalier.

Ils utilisent en effet un substrat constitué de gravier et comportant des blocs. Leurs sites de fraie sont situés à des profondeurs comprises entre 0,2 m et 1,5 m, et présentent des vitesses entre 0,2 et 0,9 m/s. Les frayères de Dolly Varden décrites étaient cependant clairement associées à des apports d’eau souterraine ce qui explique que les sites puissent se trouver dans ces cours d’eau de faible profondeur tout en étant à l’abris du gel près du lit.

Tableau 1.1 Description des caractéristiques physiques des sites de fraie d'omble chevalier décrits dans la littérature.

Substrat	Vitesse	Profondeur	Faciès géomorphologique	Localisation	Reference
Occasionnellement dans le sable.			Occasionnellement dans les rapides.	Salangen River, Norway	(Johnson 1980b)
Hétérogène mélange de sable grossier, gravier et quelques blocs.	0,2 m/s à 0,7 m/s			Rivers of Cumberland Sound, Baffin Island	(Johnson 1980b)
Gravier.	0,2 m/s à 0,8 m/s	0,2 m à 1 m		Yama et Yana River, east USSR	(Johnson 1980b)
Nids : sable fin à grossier jusqu'à des graviers de 4-5 cm. Dispersion des œufs sans nids : Blocs de 10-20 cm.		0,5 m à 1,5 m (rivière) 1,5 m à 2 m (lac)	Réseau de chenaux tressés secondaires Tête d'un petit lac, à l'arrivée d'un tributaire	Fraser River, Labrador	(Dempson et Green, 1985)
Hétérogène, de 1-15 cm de diamètre avec des blocs.	0,2 m/s à 0,5 m/s	0,6 m à 1,2 m	À l'amont d'un affleurement rocheux. Embouchure d'un tributaire.	Rivière Koroc, Nunavik	(Cunjak et al. 1986)
Hétérogène, 10% sable et gravier, 50% cailloux, 40% blocs.		1 m à 2 m approx.	Dans des fosses à l'aval de seuils ou à l'extrados d'un méandre.	Ikadlivik Brook, Labrador	(Beddow et al. 1998)

1.2.2.2 Caractérisation à l'échelle du mésohabitat

La caractérisation des cours d'eau à l'échelle du mésohabitat (10-100 m^2) peut se faire à partir des faciès géomorphologiques, soit des zones relativement homogènes d'une rivière, formées en fonction des conditions hydrodynamiques et géomorphologiques locales et dont les caractéristiques peuvent être définies (Tableau 1.2).

Tableau 1.2 Description des caractéristiques des faciès géomorphologiques ou mésohabitat (inspiré de Malavoi et Souchon (2002) et Gosselin et al. (2012))

Faciès	Profondeur	Vitesse
Seuil	Très peu profond, peut présenter des poches d'eau plus profondes.	Modérée avec des vitesses localement plus rapides. Écoulement turbulent.
Rapide	Peu profond	Rapide. Écoulement turbulent.
Courant	Modérée. Écoulement uniforme.	Modérée. Écoulement turbulent.
Écoulement en nappe	Modérée	Modérée. Écoulement non-turbulent.
Lentique	Modérée. Écoulement uniforme.	Lente
Fosse	Profond	Lente
Zone de refoulement	Modérée	Lente ou modérée. Peut-être être une zone de recirculation (gire).

Pour plusieurs salmonidés, la localisation des sites de fraie à l'échelle du mésohabitat est liée à certains faciès géomorphologiques spécifiques. Par exemple, l'utilisation préférentielle de la zone de transition entre les fosses et les seuils, correspondant à la partie aval des fosses et à l'amont du cassé de pente généré par les seuils, a été observée pour plusieurs salmonidés, dont pour la fraie du saumon Chinook (*Oncorhynchus tshawytscha*) (Moir et Pasternack, 2008) et du Dolly Varden (Mochnacz et al. 2020). Pour l'omble chevalier, aucun faciès géomorphologique spécifique ne semble ressortir de manière préférentielle des sites décrits dans la littérature (Tableau 1.1).

1.2.2.3 Écoulement hyporhéique

L'écoulement hyporhéique se définit comme l'écoulement interstitiel qui a lieu à travers le substrat du lit et des berges du cours d'eau. Cet écoulement est initié dans des zones où l'eau provenant de la rivière ou de source d'eau souterraine entre dans le substrat pour émerger dans des zones plus en aval, définis par la bathymétrie du lit du cours d'eau (Tonina et Buffington, 2009). Certaines configurations géomorphologiques du lit des cours d'eau favorisent l'écoulement hyporhéique (Baxter et Hauer, 2000; Tonina et Buffington, 2009) (Figure 1.2).

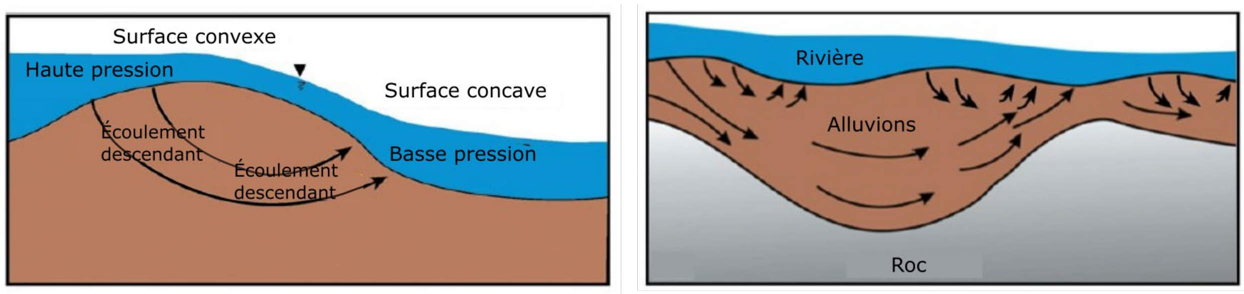


Figure 1.2 Schématisation de l'écoulement hyporhéique. (a) Échelle locale autour d'un seuil ; (b) Échelle du tronçon ou de la plaine alluviale. Tiré de Tonina et Buffington (2009).

Plusieurs espèces de salmonidés privilégient les zones montrant un plus fort écoulement hyporhéique comme sites de fraie. Par exemple, des ombles de fontaine peuvent utiliser la face amont ou aval des seuils alors qu'un écoulement hyporhéique ascendant ou descendant y est mesurable, avec ou sans la présence d'eau souterraine (Franssen et al., 2013). Les auteurs ont suggéré que les sites pourraient possiblement être sélectionnés pour la présence d'un écoulement significatif à travers le substrat, plutôt que la présence spécifique d'une source d'eau souterraine. Cette hypothèse n'a cependant pas été vérifiée.

Une observation assez similaire a été faite pour les nids d'ombles à tête plate, associés à la présence d'importants écoulements hyporhéiques descendants (Baxter et Hauer, 2000). En revanche, à l'analyse d'une échelle plus large comme la vallée, les auteurs ont noté que les sites de fraie étaient situés dans des zones où un écoulement interstitiel généralement ascendant était présent. En se basant sur le fait que l'écoulement était ascendant, ils ont décrit cet écoulement comme étant de l'eau souterraine.

Dans le cas de l'omble chevalier, des sites de fraie ont été associés à un cours d'eau dont la présence importante d'eau souterraine a été mesurée (Harwood et Babaluk, 2014). Plus localement, un écoulement hyporhéique ascendant a été mesuré dans des sites de fraie de la rivière Koroc, près de Kangiqsualujjuaq (Cunjak et al. 1986). Comme dans le cas des ombles de fontaine et à tête plate, il est possible que la localisation des sites de fraie soit sélectionnée en fonction de la présence d'un écoulement hyporhéique, qu'il soit ascendant ou descendant.

1.2.2.4 Importance de la température et rôle potentiel de l'eau souterraine

La température de l'eau joue un rôle important entre autres pour l'incubation des œufs, tant pour la durée de l'incubation que pour les limites inférieure et supérieure que peuvent tolérer les œufs (Figure 1.3). La fraie a lieu à l'automne lorsque la température de l'eau baisse rapidement et qu'elle se situe entre 0,5°C et 7°C (Johnson 1980b) en fonction de la localisation géographique des sites. Une température de 6°C durant les premières semaines d'incubation favorise le taux de survie des embryons, même lorsque la température diminue par la suite (Jeuthe et al. 2016). Par contre, la température minimale supportée par les embryons au début de l'incubation est de 2,8°C, qui a été qualifiée de relativement élevée pour une espèce d'eau froide (Jeuthe et al. 2016). En élevage, le taux d'éclosion diminue si l'incubation est faite à une température supérieure à 6°C (Sæther et al. 2016). La production d'ovocytes par les femelles reproductrices est retardée lorsque la température de l'eau atteint ou dépasse 8°C et elle est annulée si la femelle est placée à 11°C (Gillet 1991).

Ainsi, puisque les œufs d'omble chevalier peuvent être vulnérables à un réchauffement de l'eau ou au gel durant la période hivernale avant l'éclosion, la stabilité hivernale de la température et la présence d'un écoulement d'eau minimum sont des facteurs importants pour leur survie. Les sources d'eau souterraines créent localement des conditions hivernales stables en maintenant des températures constantes et en empêchant la prise de la glace de fond (Brown et al. 2011).

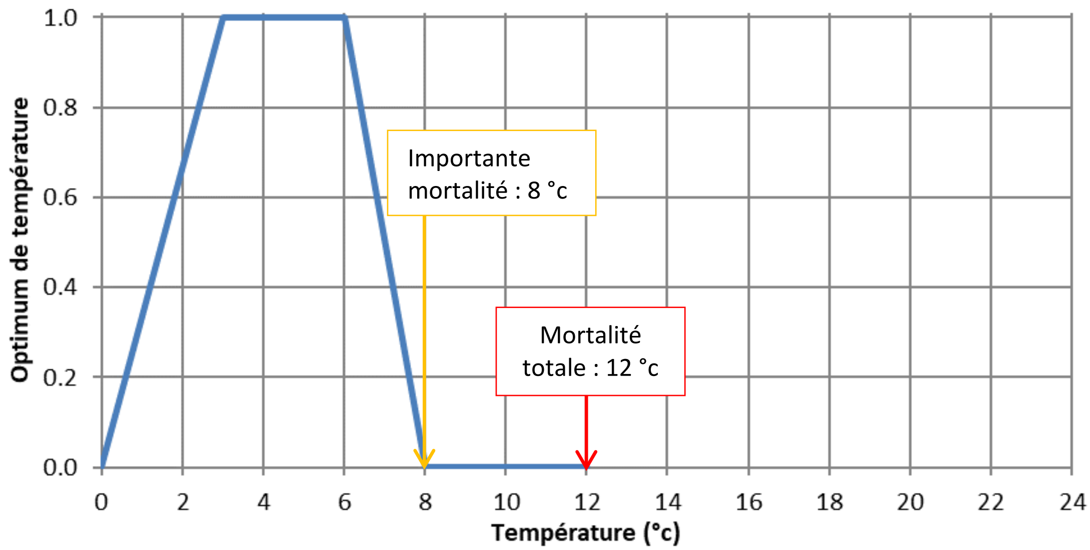


Figure 1.3 Optimum de température pour l'incubation des œufs d'omble chevalier (Jeuthe et al., 2016; Sæther et al., 2016; Gillet, 1991).

Certains salmonidés, comme l'omble de fontaine (*Salvelinus fontinalis*) (Curry et Noakes, 2011) ou l'omble à tête plate (*Salvelinus confluentus*) (Baxter et Hauer, 2000), sont connus pour frayer préférentiellement dans les secteurs avec de forts apports d'eau souterraine. L'eau souterraine est aussi favorable au développement des œufs de saumon Atlantique (*Salmo salar*) (Saltveit et Brabrand, 2013). Le Dolly Varden utilise des systèmes hydrographiques pour lesquels il n'y a généralement pas de lacs accessibles et dont le débit de base est fortement alimenté par des apports d'eau souterraine, que ce soit pour la fraie ou l'hivernage (Mochnacz et al., 2010; Stewart et al., 2010).

Pour l'omble chevalier anadrome, une observation similaire a été faite dans la rivière Hornaday (Territoires du Nord-Ouest, Canada) (Harwood et Babaluk, 2014). Leurs sites de reproduction seraient vraisemblablement similaires à ceux d'hivernage et seraient situés dans des fosses profondes. Bien que la fraie n'y ait pas directement été observée, des adultes matures prêts pour la reproduction étaient présents dans les fosses. Des apports d'eau souterraine ont été identifiés à l'amont des fosses utilisées et les auteurs soupçonnent que les fosses elles-mêmes pourraient aussi être directement alimentées en eau souterraine. Au Nunavik, dans une zone de fraie de la rivière Koroc, Cunjak et al. (1986) ont mesuré un gradient hydraulique positif (écoulement ascendant) dans le substrat de tous les nids mesurés et en ont conclu à un apport d'eau souterraine. Il est cependant possible que cet écoulement soit simplement un écoulement hyporhéique ascendant.

Bien que la présence ponctuelle de sources d'eau plus chaude que l'eau des rivières soit connue des chasseurs inuits sur le territoire de Kangiqsualujjuaq, la présence et l'influence de l'eau souterraine dans les cours d'eau ne fait pas partie du savoir traditionnel des participants interrogés dans les trois communautés. Ils ont cependant mentionné que les poissons savaient où l'eau ne gelait pas jusqu'au fond pour y déposer leurs œufs (Kangirsuk, Tasiujaq, Kangiqsualujjuaq, 2019). Si l'importance de l'eau souterraine est bien établie pour la survie générale des salmonidés (Power et al. 1999), il manque de données spécifiques à son importance pour la fraie (Heggenes et al. 2010). Il est cependant vraisemblable que l'omble chevalier en fasse un facteur de sélection pour ses sites de fraie.

1.2.3 Stades juvéniles

1.2.3.1 Habitats utilisés par les alevins

La littérature portant spécifiquement sur l'habitat utilisé par les alevins (jeunes de l'année) est plutôt générale et essentiellement basée sur des ombles chevaliers non anadromes résidant dans les lacs. Sandlund et al. (1988) ont constaté qu'ils occupent un environnement proche du rivage lorsque des prédateurs sont présents et qu'aucun affluent n'est disponible, car dans les lacs nordiques, le rivage offre un substrat hétérogène qui fournit des abris et constitue une source non limitative d'invertébrés benthiques (Byström et al. 2004). Les alevins peuvent également utiliser l'habitat pélagique en l'absence de prédateurs (Langeland et L'Abée-Lund, 1998). Lorsque des tributaires sont accessibles aux alevins résidents de lac, ils montrent une préférence relative pour l'embouchure de ces tributaires, qui présentent des zones à faible vitesse, bien que certains alevins utilisent également les rives du lac (Sinnatamby et al., 2012). Malgré ces observations, aucune caractéristique physique de l'environnement n'a été associée aux préférences d'habitat des alevins d'omble chevalier. L'habitat des alevins de Dolly Varden, qui pourrait avoir des similarités avec celui des alevins d'omble chevalier, est également peu décrit dans la littérature. Les alevins de Dolly Varden restent près du lit, dans des zones peu profondes au voisinage de leur site d'émergence. Ils semblent préférer le substrat de gravier qui leur permet de s'y enfouir. Les habitats utilisés par les alevins d'omble chevalier dans les cours d'eau restent à caractériser.

1.2.3.2 Habitats utilisés par les tacons

Les juvéniles d'ombles chevaliers anadromes âgés de plus d'un an (tacons) montrent plus de mobilité que les alevins et semblent occuper différents types d'habitats (Gulseth et Nilssen, 1999; Witkowski et al., 2008). Peu d'études ont analysé leurs préférences d'habitat spécifiques. Ils utilisent des habitats lacustres similaires aux juvéniles d'omble résidents (Reist et al., 2017) mais utilisent également les rivières. Lors d'une expérimentation avec des tacons placés dans un aquarium relié à leur rivière Koroc natale (Nunavik), Adams et al. (1988) ont observé que les juvéniles préféraient des substrats spécifiques en fonction de leur niveau d'activité. Ils utilisaient du gravier et des galets (10 cm-18 cm) lorsqu'ils étaient actifs pendant la journée, mais aussi un substrat sableux lorsqu'ils étaient actifs la nuit. Ils se cachaient entre les cailloux lorsqu'ils étaient inactifs. Le plus gros substrat est ainsi choisi comme abri contre les prédateurs visuels lorsqu'ils sont inactifs ou actifs à la lumière du jour. Les auteurs ont montré que leur niveau d'activité quotidien a augmenté progressivement tout au long de l'été. Ils étaient principalement nocturnes en juillet alors qu'à la fin du mois d'août, ils étaient majoritairement actifs toute la journée. Un changement de l'activité quotidienne a également été observé dans deux rivières du nord de la Norvège (Heggenes et Saltveit, 2007). Néanmoins, contrairement à ce qui a été observé pour les tacons de la rivière Koroc, un substrat légèrement plus fin a été utilisé la nuit alors qu'ils ne se nourrissaient pas. Les auteurs ont également observé que la plupart des ombles chevaliers se trouvaient regroupés dans des fosses profondes, en eau calme ou à faible vitesse, mais qu'ils utilisaient également des seuils dans l'une des deux rivières. Seule l'utilisation de l'habitat a été analysée et aucune préférence n'a pu être déduite car la disponibilité de l'habitat n'a pas été mesurée. De plus, les ombles chevaliers observés étaient en sympatrie avec le saumon Atlantique et la truite brune (*Salmo truta*) et leur utilisation de l'habitat était probablement adaptée pour éviter ces espèces dominantes (Heggenes et Saltveit, 2007). Cette utilisation d'habitat pourrait ne pas être représentative des ombles chevaliers anadromes d'Amérique du Nord, puisque la truite brune est absente de leur zone de répartition et le saumon Atlantique y est rare.

1.2.3.3 Préférences de température

La température de l'eau pourrait également avoir un effet sur la sélection de l'habitat. Pour la grande majorité des populations d'omble chevalier juvéniles et adultes, la croissance en laboratoire peut se faire à partir de 1°C à 3°C, avec un taux maximum atteint entre 14°C et 16°C (pouvant rester élevé jusqu'à 18°C) et un arrêt de l'alimentation autour de 21°C (Swift, 1965; Jobling, 1983; Larsson et Berglund 1998; Thyrel et al. 1999) (Figure 1.4). La limite supérieure létale est d'environ 24°C (Lyytikäinen et al., 1997).

Toujours, en laboratoire, les juvéniles montrent des préférences de température entre 9°C et 11,8°C (Larsson et Berglund, 1998; Larsson, 2005; Siikavuopio et al., 2014). Cette plage de température est inférieure à la température correspondant à la croissance maximale et correspondrait plutôt à la température d'efficacité énergétique pour la croissance (9°C) (Larsson et Berglund, 1998; Larsson, 2005; Siikavuopio et al. 2014). Cette préférence, différente de la plage de la croissance maximale, s'expliquerait par le fait que l'omble chevalier occupe un milieu peu productif où la nourriture est un facteur limitant pour la croissance (Larsson 2005). L'efficacité énergétique serait donc plutôt priorisée.

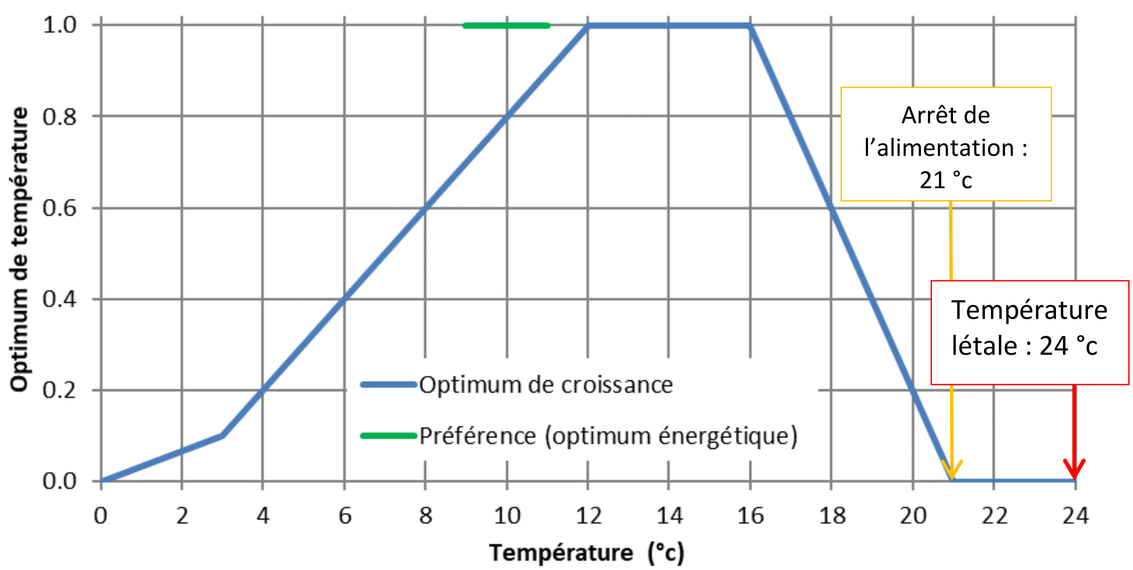


Figure 1.4 Optimum de température pour la croissance des ombles chevaliers juvéniles (Swift, 1965; Jobling, 1983; Larsson et Berglund 1998; Thyrel et al. 1999; Lyytikäinen et al., 1997; Larsson, 2005).

Dans les quelques études menées en milieu naturel, les juvéniles n'ont cependant pas montré de préférence claire pour une température spécifique (Sinnatamby et al., 2012; Godiksen et al., 2012; Sinnatamby et al., 2013). Ils évitent les températures supérieures à 16°C lorsqu'ils ont accès à des refuges plus froids, car il s'agit de la limite inférieure de la plage de températures maximales critiques (Gilbert et al., 2020).

1.2.4 Hivernage

1.2.4.1 Lieu d'hivernage et changement de lac d'une année à l'autre

Les ombles chevaliers anadromes utilisent généralement des lacs pour passer l'hiver ou certaines sections de grandes rivières comme la rivière George et Koroc près de Kangiqsualujjuaq ou Payne près de Kangirsuk. Ces habitats leur offrent un important volume d'eau libre de glace, des vitesses de courant nulles ou très faibles et des conditions thermiques stables, permettant de diminuer leurs dépenses énergétiques. Ils peuvent également utiliser des fosses en rivière lorsqu'il n'y a pas de lacs accessibles et qu'il y a présence avérée de sources d'eau souterraine (Harwood et Babaluk, 2014) ou lorsque les lacs accessibles sont à une grande distance (Smith 2020).

Bien que les ombles chevaliers restent vraisemblablement dans le même lac pour toute la saison hivernale puisque la faible hydrologie hivernale et la présence de la glace bloquent les passages migratoires, ils ne sont pas fidèles à leurs sites d'hivernage et peuvent utiliser des lacs différents d'un hiver à l'autre (Kristofferson, 2003, Moore et al., 2013). C'est particulièrement le cas des individus qui ne se reproduisent pas l'automne précédent l'hivernage. En effet, les années où ils ne se reproduisent pas, les ombles chevaliers anadromes ne retournent pas forcément dans leur système natal, mais utilisent plutôt des sites d'hivernage plus accessibles ou plus favorables (Gilbert et al. 2016), en particulier pour limiter la distance à parcourir par rapport aux sites d'alimentation estivale (Moore et al. 2017).

1.2.4.2 Alimentation hivernale

Contrairement aux ombles chevaliers résidant en lac à l'année, qui continuent de s'alimenter minimalement durant l'hiver à un taux qui correspond à leur métabolisme de base (Klemetsen et al., 2003), les ombles chevaliers anadromes ne s'alimenteraient pas ou très occasionnellement durant l'hiver (Moore et Moore, 1974; Rikardsen et al., 2003). Lors d'échantillonnage réalisé au Nunavik, les 273 ombles anadromes pêchés entre décembre et avril au nord de Kangiqsualujjuaq, avaient tous l'estomac vide depuis au moins plusieurs jours (Boivin et Power, 1990). Ainsi, la sélection de l'habitat n'est pas liée à la disponibilité de nourriture.

1.2.4.3 Niveau d'activité, habitat et mouvements saisonniers

Le niveau d'activité hivernale des ombles chevaliers semble corrélé avec l'intensité saisonnière de la lumière, que ce soit pour les ombles résidents ou anadromes et en milieu subarctique, où il n'y a pas de nuit polaire (Mulder et al., 2018b), ou dans le haut arctique, où il y a une nuit polaire (Svenning et al. 2007). Dans tous les cas, l'activité hivernale des ombles a diminué du mois d'octobre à janvier, pour augmenter graduellement jusqu'à la fonte du couvert de glace. Leur activité est minimale pendant la période de nuit polaire. Même si elle est ralentie au milieu de l'hiver, les ombles maintiennent une certaine activité quotidienne dont le niveau varie fortement en fonction des individus (Hawley et al., 2017; Mulder et al., 2018a; Monsen, 2019). Les déplacements ont lieu plutôt durant le jour (Hawley et al., 2017; Mulder et al., 2019). De quelques semaines à quelques jours avant la débâcle (identifiée par le retournement des eaux du lacs et un profil de température constant), les ombles augmentent significativement leurs déplacements et opèrent des mouvements arythmiques (Hawley et al., 2017). Mulder et al. (2018b et 2019) ont également observé que l'activité générale des ombles anadromes augmente significativement trois semaines avant leur départ des lacs avec une nette augmentation une dizaine de jours avant la dévalaison. En termes de distance parcourue, dans deux lacs du Labrador, les déplacements moyens des poissons sont passés respectivement de 30 m/jour et 80 m/jour pendant la période hivernale, à 531 m/jour et 917 m/jour une semaine avant de quitter le lac. La hausse d'activité se traduit par une augmentation des déplacements journaliers et un déplacement de certains individus à proximité de l'exutoire du lac. Les pêcheurs inuits remarquent aussi cette hausse du niveau d'activité, en particulier dans les zones déjà libres de glace. Ces mouvements indiqueraient que les ombles se préparent à quitter le lac (Kangirsuk, Kangiqsualujjuaq, 2020, pers. communication).

Durant la majeure partie de l'hiver, les ombles occupent une profondeur stable mais font des incursions ponctuelles, quotidiennement pour certains individus, à différentes profondeurs (Monsen, 2019; Mulder et al., 2018b). Les déplacements verticaux peuvent aller jusqu'à plusieurs mètres au-dessus ou au-dessous de leur zone habituelle d'occupation. Les individus utilisent une température moyenne relativement constante en hiver mais il peut y avoir une différence significative dans la température moyenne utilisée par différents individus (Monsen, 2019; Mulder et al., 2018b). Ces observations sur la température corroborent l'utilisation d'une profondeur constante. Cependant, la notion de sélectivité thermique n'est pas évidente à montrer puisque la plage moyenne des températures utilisées par les ombles se rapproche de l'intervalle des profils de températures mesurés dans les lacs qui ont une très faible stratification thermique et amplitude.

En termes de sélection d'habitat, les ombles chevaliers, essentiellement résidents, pêchés par Svenning et al. (2007) dans un lac du Svalbard (Norvège) étaient plus nombreux dans la zone littorale à 4 m de profondeur (température ≤ 0,7°C) mais également à 12 m de profondeur entre avril et juin La température maximale était de 1,3°C à 20 m de profondeur. En zone subarctique, Klemetsen et al., (2003) ont montré par l'effort de pêche (*catch per unit effort*, CPUE), que les ombles chevaliers résidents en lacs utilisaient principalement la zone littorale (0-15 m) bien que la température de l'eau y était plus froide, entre 0,2°C et 0,7°C. Cette zone est la plus riche en benthos, leur principale source de nourriture hivernale lorsqu'ils ne sont pas cannibales. Cette conclusion ne semble cependant pas s'appliquer aux ombles anadromes puisqu'ils passent l'hiver sans se nourrir.

1.2.4.4 Agrégation hivernale

L'hiver, les ombles montrent un comportement grégaire, toutes classes d'âge confondues, sans toutefois former véritablement de bancs. Lors de la pêche sur la glace à l'hameçon, en eau généralement peu profonde, à des endroits différents de ceux utilisés pour la pêche au filet qui sont plus profonds, les Inuits observent des ombles de toutes les tailles (Kangiqsualujjuaq, Kangirsuk, Tasiujaq, 2019). Il est également vraisemblable que les zones de pêche au filet soient aussi utilisées par les ombles de toutes les tailles mais que la largeur standard des mailles (8.75 cm (3,5 po) à 10 cm (4 po)) opère un tri en faveur des plus gros individus. Des regroupements ont également été observés au début de la saison d'hivernage dans la rivière Fraser au Labrador (Dempson et Green, 1985). La territorialité ou l'agressivité ne sont pas fréquemment reportés pour cette espèce (David, 1980). Au contraire, les expériences faites sur des élevages d'ombles anadromes montrent une baisse d'agressivité et une meilleure croissance lorsque la densité augmente, contrairement à plusieurs espèces (Sæther et al. 2016).

1.3 La modélisation de l'habitat

1.3.1 Les différents types de modèles

La modélisation de l'habitat d'une espèce permet de faire des liens entre ses préférences d'habitats, présence, son abondance, ou d'autres facteurs biologiques (taille, sexe, …) avec des variables de l'environnement. Bien que la sélection d'habitat soit multifactorielle, la modélisation peut aider à prévoir l'impact d'une modification de l'environnement sur la disponibilité de l'habitat, lui-même impactant la présence, la croissance ou la survie d'une population (e.g., Dunbar et al. 2012). Dans ce cas, le modèle peut servir d'outil de gestion. Dans le cas des préférences d'habitat des poissons à l'échelle du microhabitat (0-1 m^2) ou à l'échelle locale (0-10 m^2), l'habitat est souvent modélisé à partir de courbes de préférences basées sur un nombre limité de variables hydrauliques, à savoir la profondeur, la vitesse et le substrat (Bovee 1986). Pour les salmonidés, les caractéristiques hydrauliques peuvent être complétées par la présence d'abris (Armstrong et al. 2003) ou, de plus en plus, par la température de l'eau (Boudreault et al. 2021). À l'échelle du mésohabitat (10-100 m^2), les habitats peuvent être définis en utilisant les faciès géomorphologiques (Tableau 1.2) (Parasiewicz 2001). Les habitats peuvent aussi être modélisés par des combinaisons d'échelles (Habersack et al. 2014).

La modélisation permet également de déterminer les variables qui sont les plus déterminantes dans la sélection d'habitat (e.g., Long et al. 2009). Dans ce cas, ce sont les modèles statistiques qui permettent de déterminer les variables explicatives de présence ou d'abondance parmi de multiples variables potentielles. Les modèles peuvent alors être utilisés à des échelles plus vastes comme la rivière ou le bassin versant (Danandeh Mehr et al. 2022 ; Steel et al. 2012). Une synthèse des modèles d'habitats de poisson les plus utilisés est présentée par Conallin et al. (2010).

1.3.2 La modélisation par la logique floue

Lorsqu'il y a peu de données sur l'habitat ou lorsque les courbes de préférences ne sont pas disponibles, la logique floue permet de bâtir des modèles prédictifs de la qualité de l'habitat en utilisant l'opinion d'experts. La logique floue a été développée pour permettre de faire des opérations logiques sur des classes d'objets mathématiques qui n'étaient pas clairement définis ou qui pouvaient appartenir à plusieurs classes simultanément (Zadeh, 1965). Elle permet donc de formaliser un raisonnement basé sur des données imprécises. La logique en elle-même n'est pas floue, mais les données sont codifiées en ensembles flous. Elle est adaptée à la modélisation du comportement d'espèces vivantes puisqu'elle permet de considérer le continuum qui existe entre les variables descriptives et entre les conséquences obtenues (Mackinson et Nøttestad, 1998). Ainsi, les variables du microhabitat usuelles pour les poissons, comme la vitesse du courant, la profondeur d'eau ou le type de substrat peuvent être assimilées à des variables floues. Des règles simples, appelées règles logiques, sont appliquées à ces variables. La résultante de ces règles forme une solution qui représente un degré de vérité (0 : complètement faux, 1 complètement vrai) et qui est convertie (par défuzzification) en un indice de qualité de l'habitat (IQH).

Comme la logique floue permet d'approximer le raisonnement linguistique (Zadeh 1975), elle s'applique bien à la modélisation d'habitats à partir d'avis d'experts. Des experts peuvent définir les règles floues, c'est-à-dire les combinaisons de variables liées par des opérateurs logiques, qui déterminent déterminer la qualité de l'habitat. Cette méthode a été appliquée avec succès pour la modélisation de plusieurs espèces à partir d'avis d'experts scientifiques (Schneider et Jorde, 2003; Ahmadi-Nedushan et al., 2008; Mocq et al., 2013). Elle a également été appliquée à l'échelle du mésohabitat où les variables correspondent au type de faciès géomorphologique du cours d'eau (Mouton et al. 2006), toujours à partir d'avis d'experts scientifiques. La modélisation par logique floue se décompose en quatre étapes :

1. La fuzzification i.e., la transformation des variables d'entrée (c'est-à-dire les variables de l'habitat physique comme la profondeur, la vitesse et le substrat) en ensembles flous. Ainsi, chaque variable est séparée en catégories de valeurs (faible, moyen, élevé) décrite par une plage de valeurs de cette variable, à laquelle est associée une fonction d'appartenance (0 = pas

d'appartenance, 1 = 100% d'appartenance à la catégorie spécifiée) (Figure 4.3). Pour incorporer l'incertitude sur les limites de chaque catégorie (ce que l'on appelle le flou) et pour caractériser le continuum, chaque valeur de la variable spécifiée peut appartenir simultanément à une ou plusieurs catégories. Les experts déterminent les limites des catégories.

2. L'établissement des règles floues. Les règles floues sont des combinaisons des variables et leur implication sur l'IQH, par exemple : "SI le substrat est dans la catégorie "grossier (élevé)" ET la vitesse est dans la catégorie "moyenne" ET la profondeur de l'eau appartient à la catégorie « moyenne », ALORS l'IQH est dans la catégorie « élevée ».
3. L'application des règles à des données de terrain. Il faut que les variables de l'habitat (profondeur, vitesse et substrat) soient mesurées à chaque site de validation. Une valeur d'appartenance et une catégorie sont alors associées à chacune de ces mesures. Une variable peut appartenir à plus d'une catégorie simultanément (par exemple, une valeur de vitesse de 0,25 m/s peut appartenir à la catégorie "faible" avec une appartenance de 0,5 et à la catégorie "moyenne" avec la même valeur d'appartenance, représentant ainsi l'incertitude ou l'aspect flou). Par conséquent, plusieurs règles peuvent s'appliquer simultanément. Leur association est appelée agrégation et elle détermine comment sont combinés les résultats pour avoir une valeur d'appartenance de l'IQH, qui est lui-même une variable floue.
4. Défuzzification de l'IQH flou agrégé pour obtenir une valeur numérique précise de l'IQH, comprise entre 0 et 1 (0 = inadéquation de l'habitat et 1 = adéquation maximale de l'habitat). Plusieurs méthodes peuvent être appliquées (Ouellet et al. 2021).

Les savoirs traditionnels sont de plus en plus utilisés pour la modélisation de l'utilisation ou des préférences d'habitats pour plusieurs espèces, par exemple pour le caribou (Polfus et al. 2014) ou l'orignal (Tendeng et al. 2016). Dans ces deux études, qui n'utilisent pas la logique floue, la comparaison avec les données scientifiques met en lumière les informations complémentaires et spécifiques apportées par les savoirs traditionnels. Comme il a été montré que la provenance géographique des experts pouvait teinter les résultats d'un modèle de logique floue (Mocq et al., 2015), on peut alors s'attendre à ce que l'utilisation de savoirs locaux ou traditionnels ancrés dans des régions spécifiques puisse donner des résultats localement plus pertinents.

1.4 Nécessité de prendre en compte les savoirs inuits

1.4.1 Contextualisation des termes utilisés pour parler des savoirs

Science : Dans le contexte de cette thèse, le terme « science » ou « scientifique » est utilisé dans le sens de science occidentale de type cartésienne (comprendre dans le sens de l'anglais *Western science*), en contraste avec les savoirs inuits. Je reconnais cependant que les savoirs traditionnels expérienciels, comme les savoirs inuits, sont aussi des formes de science, qui permettent également la connaissance et la compréhension du monde.

Savoir écologiques traditionnels : Les savoirs écologiques traditionnels (souvent décrits dans la littérature par *TEK*, pour l'acronyme anglais de *Traditional Ecological knowledge*) sont des connaissances qualitatives et une manière de connaitre l'environnement dérivées de l'expérience et des traditions d'un groupe particulier de personnes (Usher 2000). Ils ont été définis comme :

> « *a cumulative body of knowledge, practice and belief, evolving by adaptative processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment.* »
>
> [« un ensemble cumulatif de connaissances, de pratiques et de croyances, évoluant par des processus adaptatifs et transmis de génération en génération par transmission culturelle, sur la relation des êtres vivants (y compris les humains) entre eux et avec leur environnement…»] (Traduction libre, Berkes, 2017).

Bien que l'expression comprenne le terme « traditionnel », ce ne sont pas des savoirs figés dans le passé, mais bien adaptatifs et actualisés, y compris pour les savoirs inuits (Berkes, 2017; Usher 2000). Pour éviter la connotation d'un savoir passé et dépassé, les expressions « savoirs autochtones » (ou *IK* en anglais pour *Indigenous knowledge*) ou « savoirs locaux » sont aussi utilisées selon le contexte.

Savoirs inuits : Les Inuits utilisent l'expression '*Inuit Qaujimajatugangit*' (*IQ*), qui a été traduite par *savoirs inuits*, mais qui englobe tous les aspects de la culture traditionnelle inuite, dont entre autres les valeurs, le langage, l'organisation sociales, les connaissances et les savoir-faire

(Nunavut Department of Education 2007). C'est une façon d'être, guidée par des valeurs définies, qui permettent de maintenir une société unie et en harmonie.

1.4.2 Considérations éthiques de la recherche en territoire inuit (*Inuit Nunangat*)

Le passé colonial envers les Peuples autochtones a eu et a encore un impact sur la façon de travailler des scientifiques (McGregor 2018). De façon non exhaustives, Nickels et al. (2006) ont relevé les critiques suivantes, faites à de nombreux chercheurs et qui restent toujours valides :

- Réaliser des recherches qui ne répondent pas aux préoccupations des populations locales ;
- Ne pas impliquer les populations locales dans la recherche et ne pas tenir compte de leur expertise ;
- Ne pas assurer la reconnaissance ou ne pas fournir de compensations aux participants ;
- Utiliser les savoirs traditionnels de façon inappropriée et décontextualisée en modifiant les significations ;
- Utiliser des méthodes de recherche inappropriées dans le contexte local, ou dommageables pour l'environnement ;
- S'approprier les savoirs traditionnels comme sa propre expertise ;
- Ne pas faire de suivi ou de retour des résultats vers la communauté de la part des chercheurs, ou présentation inappropriée des résultats.

Le manque d'éthique dans certaines recherches réalisées ont conduit à de la méfiance de la part des actrices/acteurs autochtones envers les chercheurs. Pour remédier à cette perte de confiance, les lignes directrices de la Politique des Trois Conseils encouragent fortement le dialogue et la collaboration entre les chercheurs et les communautés autochtones (EPTC 2014). Par exemple et concernant la recherche présentée dans cette thèse, la collaboration des communautés est obligatoire puisque la recherche se fait sur des terres inuites et que le projet nécessite la contribution de participants concernant des connaissances traditionnelles. Depuis 2018, une stratégie nationale a été implémentée par les communautés inuites du Canada pour déconstruire les anciennes façons de faire colonialistes et guider la recherche en territoire inuit (Inuit Tapiriit Kanatami 2018). Selon la stratégie proposée, les résultats doivent apporter de nouvelles connaissances qui répondent à un besoin prioritaire des communautés. Pour se faire, la recherche doit être faite en collaboration avec les communautés inuites tout au long du processus. Au moment de publier cette thèse, une nouvelle entité de gouvernance en matière de recherche, Atanniuvik, est en train d'être développée pour encadrer la recherche au Nunavik (Durkalec and Breton-Honeyman 2022).

Dans un contexte de décolonisation de la science, faisant suite à la Commission de Vérité et Réconciliation ("Truth and Reconciliation Commission of Canada." 2015), dix appels à l'action ont été énoncés spécifiquement pour les sciences environnementales par Wong et al. (2020). Puisque l'amélioration des connaissances sur l'environnement du nord est un objectif généralement partagé par les scientifiques du sud et les autochtones, bâtir des relations significatives, collaborer et partager les savoirs sont parmi les actions recommandées.

1.4.3 Complémentarité des savoirs inuits et de la méthode scientifique

Les savoirs scientifiques et Inuit bien que basés sur l'observation, fonctionnent sur des systèmes de pensée différents. Le savoir scientifique est basé sur la notion que la connaissance d'un tout peut être appréhendée en analysant des parties plus simples, prédictibles et contrôlables, à l'aide d'un raisonnement analytique. Les savoirs inuits appréhendent le tout dans son ensemble, comme quelque chose qui n'a pas de parties discernables. Tout est lié de sorte que rien ne peut être s'il n'est pas en relation avec le reste (Tester et Irniq, 2008).

La compréhension de l'environnement et des écosystèmes, en particulier les écosystèmes Arctique, changeant rapidement, requiert d'utiliser différentes sources de savoirs pour les comprendre (Johnson et al. 2020; Brooke, 1993). Plutôt que d'intégrer les savoirs autochtones à la science, reconnaitre leur différences et leur validité mutuelles, sans les comparer pour savoir lequel est le meilleur, permet de bâtir des ponts entre ces systèmes de connaissances et contribue à la décolonisation de la science (Snively et Williams, 2016). Pour ce faire, les différentes formes de savoirs peuvent être considérées ensemble en parallèle, comme présenté dans le concept de « *Two-eyed seeing* » (Bartlett et al., 2012; Reid et al. 2021). Le « *Two-eyed seeing* » consiste en un co-apprentissage et un bénéfice mutuel en conservant l'intégrité des savoirs dans le respect des différents systèmes de savoirs. Pour que la recherche se fasse en partenariat réel, elle doit se faire idéalement pour et par la communauté (Abu et al., 2020). Et c'est aussi dans ces circonstances que le chercheur peut bénéficier des connaissances traditionnelles.

Pour faire bénéficier les chercheurs des savoirs inuits, tout en respectant leur intégrité et avec l'objectif de donner du pouvoir aux communautés dans la recherche effectuée sur leur territoire, un groupe créé par des jeunes Inuit, Ikaarvik, a développé le concept de « *ScIQ* » (Pedersen et al. 2020). Ils proposent une liste de recommandations pour relier respectueusement science et *IQ*. L'aspect relationnel au niveau humain est un des points majeurs. En effet, en plus des connaissances sur l'environnement souvent recherchées par les scientifiques, l'*IQ* comprend implicitement une façon de se comporter et d'interagir avec les autres dans le respect et la réciprocité. Par conséquent, incorporer l'*IQ* dans la recherche signifie suivre les principes et les valeurs de l'*IQ* et aussi adopter, comme chercheur, un comportement qui répond aux valeurs et principes d'harmonie que l'*IQ* sous-tend.

Au cours du travail réalisé pour cette thèse, un élément important a été de respecter les savoirs inuits, par leur prise en compte dans toutes les étapes lorsque c'était possible, en respectant les principes et les recommandations du *ScIQ*. Le concept du « *Two-eyed seeing* » a également servi partiellement de guide pour respecter l'intégrité de ces savoirs. Le savoir inuit (*IQ*) est une façon d'être et englobe le fait d'entrer dans une relation réciproque (Nunavut Department of Education 2007). C'est par ce principe que j'ai cherché à bâtir un engagement à divers niveaux. Les relations de réciprocité faisant partie du respect du savoir inuit, le travail d'engagement réalisé fait partie intégrante de cette thèse.

1.5 Objectifs et organisation de la thèse

1.5.1 Objectif n°1 : Caractérisation des habitats

Comme les habitats occupés par l'omble chevalier anadrome en eau douce sont peu décrits dans la littérature scientifique, le premier objectif de la thèse est de caractériser et éventuellement modéliser les habitats physiques utilisés par les ombles au Nunavik pour la reproduction, l'hivernage et le stade juvénile en période estivale. Différentes échelles spatiales seront analysées selon le contexte.

La modélisation de l'habitat permet de faire le lien entre les sites utilisés préférentiellement par les ombles et les caractéristiques physiques des cours d'eau (vitesse, profondeur, substrat, température de l'eau, morphologie du cours d'eau). Elle permet, entre autres, d'évaluer le type de sites les plus favorables ou les plus critiques et éventuellement d'anticiper l'impact d'une modification de son habitat. À ce jour, aucun modèle d'habitat n'existe pour les stades de vie de l'omble chevalier précités.

1.5.2 Objectif n°2 : Travail avec les savoirs inuits

Comme l'omble chevalier anadrome est une ressource importante pour les Inuit, ceux-ci ont une bonne connaissance de son cycle de vie et des habitats qu'il utilise. Le second objectif est de travailler en partenariat avec plusieurs communautés pour :

1. Bénéficier de l'apport des savoirs inuits. L'apport de ces savoirs pourra être utilisé comme hypothèse de travail, comme intrant des modèles d'habitat, pour l'interprétation ou comme élément de discussion des résultats.
2. Développer des relations de réciprocité, de façon à produire une recherche utile aux communautés et non uniquement à l'avancement des connaissances scientifiques sur l'omble chevalier anadrome. Ceux-ci pourraient prendre la forme de modèles d'habitats opérationnels en fonction des caractéristiques de la rivière ou différentes formes d'engagement que ce soit envers organisations inuites collaboratrices, ou auprès des jeunes.

1.5.3 Organisation de la thèse

Dans le cadre de cette thèse par articles, j'ai combiné les savoirs inuits et scientifiques pour caractériser et/ou modéliser les habitats utilisés par l'omble chevalier anadrome durant les phases de son cycle de vie en eau douce. Certaines répétitions entre les chapitres, particulièrement concernant des définitions et la méthodologie des entrevues réalisées, ont été nécessaires pour les fins de publication de chaque chapitre comme un article indépendant.

Le chapitre 2 fait la synthèse en français des résultats des articles présentés dans les chapitres 3 à 5 qui ont été publiés ou soumis en anglais.

Le chapitre 3 (article publié) constitue une analyse détaillée des entrevues réalisées auprès d'experts inuits dans trois communautés du Nunavik. Le savoir inuit a été mis à l'avant-plan. Il est utilisé pour contextualiser et faire des liens avec la littérature scientifique existante et permet d'apporter un nouvel éclairage sur certains aspects de l'écologie de l'omble chevalier au Nunavik.

Les chapitres 4, 5, et 6 présentent la caractérisation des habitats utilisés par les ombles en eau douce. Savoirs inuits et méthodes scientifiques ont été combinés de différentes manières, selon les différents contextes. Le chapitre 4 (article publié) présente la caractérisation et la modélisation des sites de fraie par la logique floue. Le modèle bâti, basé uniquement sur les savoirs inuits, permet de quantifier l'adéquation d'un site en rivière par un indice de la qualité de l'habitat (IQH), à partir des caractéristiques physiques du cours d'eau (profondeur, vitesse du courant, substrat). Le chapitre 5 (article soumis) présente la caractérisation de l'habitat d'hiver utilisé par les adultes matures et immatures ainsi que la caractérisation de zones de fraies identifiées dans les lacs d'hivernage. La caractérisation a été faite en collaboration avec des pêcheurs inuits pour déterminer l'occupation des sites et pour réaliser les mesures. Le chapitre 6 (article publié) analyse la sélectivité des habitats en rivière par les ombles juvéniles (alevins et tacons), durant la saison estivale. Cette analyse a été réalisée à partir de relevés de pêche électrique.

Le chapitre 7 (Réciprocité et engagement) décrit le cheminement suivi pour que la prise en compte des savoirs inuits dans mon travail soit faite dans une perspective de décolonisation de la science. Il décrit le travail d'engagement et de mobilisation des connaissances réalisé auprès des communautés avec lesquelles j'ai travaillé.

Une discussion sur les résultats et ma contribution à l'avancement des connaissances sont présentées au chapitre 8.

2 SYNTHÈSE DES RÉSULTATS

La présente section fait la synthèse des résultats qui ont été publiés en anglais dans les articles des chapitres 3 à 6.

Chapitre 3 : Cycle de vie de l’omble chevalier anadrome à partir des savoirs inuits : une année en Ungava

Comme l'omble chevalier anadrome fait partie du mode de vie des Inuits du Nunavik depuis des temps immémoriaux le but de cette étude est de documenter leurs connaissances de cette espèce.

Pour ce faire, des entrevues semi-dirigées ont été réalisées avec des experts inuits dans les trois communautés de Kangiqsualujjuaq (n=5), Tasiujaq (n=3) et Kangirsuk (n=3). Neuf d’entre eux étaient des ainés et deux étaient des chasseurs moins âgés. Le travail a été inspiré du concept du « Two-eyed seeing » (Reid et al. 2021; Bartlett et al. 2012). Les savoirs partagés ont été mis à l’avant-plan et ont été mis en relation avec la littérature scientifique pour décrire le cycle de vie, les comportements et les habitats utilisés au fil des saisons.

Les schémas migratoires ont été décrits pour chacune des communautés. Ils comprennent la description des périodes de déplacement et des différentes vagues migratoires en fonction de la taille et du statu reproductif des poissons. Il est apparu que certains reproducteurs de l’année restent en rivière pendant l’été et ne migrent pas en milieu marin.

Les experts interrogés avaient des connaissances détaillées sur la période de reproduction, y compris sur les caractéristiques des sites de fraie. La période automnale est en effet une période de pêche populaire, alors que les ombles sont plus faciles à pêcher durant leur migration amont et qu’ils sont recherchés pour leurs œufs. Les sites de fraie décrits à Kangiqsualujjuaq et à Tasiujaq, où les ombles ont accès à des cours d’eau plus petits, ont des caractéristiques assez similaires. Les sites décrits à Kangirsuk étaient localisés dans de grandes rivières, près de la rive, dans des baies sableuses, à l’abri du courant principal mais montrant tout de même un écoulement. Ces différences dans les habitats de fraie sont liées à la géographie qui impacte la géomorphologie et l’hydrodynamique locale.

Des observations particulières et non documentées ont été faite par les experts inuits durant l'hiver. À Kangirsuk, des poissons ont été observés en banc dans des zones d'eau libre de glace en rivière en train de nager activement pour faire fondre la glace. Comme le phénomène observé en rivière était local et non récurrent, il pourrait s'expliquer par la formation barrages de frasil dans des rivières actives et qui trapperaient les poissons dans une zone restreinte.

Des observations un peu similaires mais plus récurrentes et en contexte lacustre ont été faites à la fin de l'hiver, dans plusieurs lacs de Kangiqsualujjuaq et dans une moindre mesure à Kangirsuk. Des agrégations importantes de poissons sont observées dans des zones d'eau libres ou de glace mince. Les poissons semblent aussi empêcher la glace de se former. Ce phénomène serait différent de celui observé ponctuellement en rivière puisqu'il n'y a pas de barrière physique à l'habitat. Une hypoxie des lacs au cours de l'hiver pourrait en être la cause.

La modification de l'environnent due aux changements climatiques est visible sur plusieurs aspects. Dans les trois communautés, la diminution des précipitations estivales et automnale a été constatée, ce qui génère une baisse du débit des rivières et des difficultés lors de la migration amont des poissons. Les hausses de températures estivales peuvent affecter les juvéniles dans les petits cours d'eau, comme il a été observé à Tasiujaq. La croissance rapide de la végétation en berge limite l'accès aux pêcheurs aux sites traditionnellement utilisés lors de la migration amont ou à l'automne à Kangiqsualujjuaq et Tasiujaq. De plus, l'augmentation de la végétation aquatique pourrait limiter le passage des poissons et modifier l'accès à leurs habitats comme il a été mentionné dans ces deux communautés. Dans les trois communautés, de plus en plus d'ours noirs sont observés et ils semblent être des prédateurs importants durant la saison de reproduction. La présence croissante du saumon Atlantique à Tasiujaq et Kangiqsualujjuaq est une source d'inquiétude, bien que son impact sur l'omble chevalier ne soit pas connu.

Les liens et la mise en parallèle des connaissances inuites et de la littérature scientifique ont permis d'avoir une compréhension plus holistique de l'écologie de l'omble chevalier. La présente étude a permis de mettre en lumière des pistes de recherche pertinentes sur l'écologie de cette espèce, pour des projets à codévelopper avec les communautés locales.

Chapitre 4 : Modélisation de l'habitat de fraie à partir des savoirs inuits, en utilisant la logique floue.

Comme les mêmes sites de fraie sont utilisés d'année en année, les Inuits ont une bonne connaissance de ces sites. Ainsi, les caractéristiques physiques des habitats de fraie en rivière ont pu être décrites à partir des variables de profondeur d'eau, de vitesse du courant et de granulométrie du substrat, lors des entrevues semi-dirigées réalisées à Kangiqsualujjuaq, Tasiujaq et Kangirsuk.

Selon les experts inuits interrogés, les habitats de fraie se situent principalement dans les rivières (incluant les sections de lac qui présentent un certain écoulement comme l'exutoire ou l'arrivée d'un tributaire). À l'échelle locale (0-10 m^2), les profondeurs les plus favorables sont comprises entre 0,6 m et 1,5 m et les vitesses sont supérieures à 0,1 m/s. Une large gamme de substrats de lit de rivière a été jugée appropriée tant que la plus petite classe de substrat est constituée de zones de gravier (à Kangiqsualujjuaq et Tasiujaq) ou de sable grossier (à Kangirsuk), selon la géomorphologie locale.

À partir de ces informations un modèle de prédiction de la qualité de l'habitat de fraie a été bâti. Il permet d'évaluer la qualité d'un site en fonction des valeurs locales des variables de profondeur, vitesse et substrat de la rivière. La logique floue a été utilisée pour coder les descriptions des variables caractéristiques provenant des entrevues, en une valeur numérique représentant l'indice de qualité de l'habitat (IQH) pour les frayères. Pour ce faire, les variables ont dû être catégorisées en ensembles flous. Par la suite, des règles décrivant chaque combinaison possible des variables par catégorie et la catégorie d'IQH en résultant (faible, moyen, élevé) ont été établies. Le modèle est une adaptation de la méthodologie déjà testée sur l'habitat de fraie du saumon, à partir d'experts scientifiques. Elle a été adaptée pour que les experts inuits n'aient pas à catégoriser les variables avec des valeurs numériques ni à décrire chacune des règles (combinaisons de variables). C'est l'analyste qui fait les entrevues qui bâti les règles à partir des informations recueillies, y compris les descriptions qualitatives des sites. Le modèle a été validé sur 15 sites dont les variables caractéristiques ont été mesurées sur le terrain dans les trois communautés. Six de ces sites étaient des sites de fraie.

Différents scénarios ont été testés, chacun construit à partir des informations de chacune des communauté seule, de Kangiqsualujjuaq et Tasiujaq ensemble puisque les descriptions étaient assez similaires et des trois communautés ensemble. Les différences locales, particulièrement concernant les catégories de variables non favorables, ont permis de rendre le modèle plus efficace en discriminant plus facilement les sites moins favorables, lorsque les règles étaient bâties à partir des informations provenant des trois communautés ensemble. Le modèle a ainsi pu prédire l'adéquation ou l'inadéquation de l'habitat de fraie de 14 sites de validation sur 15, à partir des valeurs de profondeur, de vitesse et de substrat, en tentant compte de l’information des trois communautés ensemble.

La méthodologie présentée est bien adaptée pour construire un modèle quantitatif basé sur la description d'observations locales et pourrait être appliquée à d'autres espèces animales ou végétales pour lesquelles des connaissances locales et/ou traditionnelles existent.

Chapitre 5 : Caractérisation de l'habitat hivernal et des frayères lacustres de l'omble chevalier anadrome en collaboration avec des pêcheurs Inuits.

L’habitat hivernal utilisé par les ombles anadromes est peu étudié, probablement pour les difficultés logistiques de travailler en Arctique l’hiver. Cependant, les Inuits pêchent les ombles chevaliers anadromes durant la saison hivernale, dans leur lacs d’hivernage, soit à l’aide de filets installés sous la glace, soit à l’hameçon (pêche sur la glace). Pour un même lac d’hivernage, ils connaissent les zones utilisées par les ombles et celles qui ne le sont pas. Ils ont également connaissance de la localisation de certaines zones de fraie dans les lacs d’hivernage. L’objectif de cette étude était de travailler en collaboration avec des pêcheurs Inuits pour caractériser les sites utilisés par les poissons et les comparer aux sites d’absence de poissons.

50 sites situés dans six lacs d’hivernage utilisés traditionnellement pour la pêche dans la région de Kangiqsualujjuaq, ont été caractérisés. Ce sont les pêcheurs collaborateurs qui ont identifié l’occupation de l’habitat (présence, absence et/ou fraie). La méthodologie est donc basée sur le principe que les sites de pêches traditionnels correspondent aux sites de « présence » des poissons et que les sites « d’absences » sont les zones où il n’y a jamais de pêche. Les sites identifiés ont été instrumentés par les pêcheurs, pendant leur pratique de pêche, pour faire leur

caractérisation physique à l’aide de la hauteur de neige, de la profondeur, d’un profil de température et d’un profil d’oxygène dissous. La distance du site par rapport à la rive et la pente du fond ont estimées à postériori à partir de cartes topographiques de leur localisation GPS. La plupart des mesures ont été faites à l’hiver 2020 et certaines ont réalisées lors des deux hivers subséquents.

La caractérisation a montré que les adultes matures et immatures (les poissons pêchés) utilisent la zone littorale des lacs d’hivernage, où la lumière atteint le fond du lac. À l’exception de l’utilisation de la zone littorale, les ombles de la région de Kangiqsualujjuaq n’ont pas montré de préférences d’habitat spécifiques en termes de température et d’oxygène. Ils ont été filmés en groupe, nageant lentement près du fond, comme observés régulièrement par les pêcheurs Inuits. Certains poissons ont même été vus couchés sur les enrochements du fond. Les poissons pourraient utiliser le fond du lac pendant cette période de métabolisme lent, tout en bénéficiant de la présence de lumière.

La caractérisation des zones de fraie a montré qu’elles étaient situées à des profondeurs moyenne de 3.0 m, significativement plus faibles que les sites d’absence de fraie (6,2 m). Bien que de façon non significative, les températures du fond étaient relativement plus chaudes (0,51°C contre 0,38°C). Ces caractéristiques suggèrent que les sites sélectionnés favorisent la survie des œufs en période d’incubation puisqu’ils seraient à l’abri du gel. Il a en effet été noté à quelques reprises, lors de l’instrumentation, que des profils de température peuvent être à 0°C jusqu’au fond du lac. La localisation des sites de fraie en zone littorale, serait également favorable aux alevins après leur éclosion qui se déroule à l’hiver. Un épisode d’éclosion a vraisemblablement été indirectement observé pendant les relevés effectués dans la rivière Koroc, au début du mois de mars. La zone littorale étant plus productive, elle est plus riche en zoobenthos et en particulier en larves de chironomides, principale source d’alimentation des alevins.

Chapitre 6 : Préférences d’habitat estival en rivière des ombles chevaliers anadromes juvéniles (alevins et tacons) au Nunavik

L'utilisation estivale de l'habitat par les juvéniles de la forme anadrome étant largement inconnue, la présente étude visait à caractériser les préférences d'habitat des alevins (jeunes de l'année) et des tacons (un an et plus) en rivière.

La présence et l'abondance des ombles chevaliers juvéniles a été déterminée lors de relevés de pêche électrique effectués dans 17 cours d'eau de la région de Kangiqsualujjuaq et 10 de la région de Tasiujaq à l'été 2019. L'habitat des juvéniles a été caractérisé à l'aide de la profondeur, de la vitesse, du diamètre médian du substrat, de son niveau d'imbrication, et de la température de l'eau. La modélisation a été faite à partir de méthodes statistiques à trois échelles, soit le microhabitat, l'échelle de la station (regroupement de microhabitat; 0-10 m^2) et l'échelle du mésohabitat (typiquement 10-100 m^2), caractérisé à partir des faciès géomorphologiques.

Les alevins ont montré certaines préférences d'habitats. À l'échelle du microhabitat ou de la station, ils ont montré une sélection des profondeurs inférieures à 20 cm et la majorité a été pêchés à des vitesses inférieures à 0,3 m/s, bien qu'aucune préférence de vitesse n'ait été trouvée. À l'échelle du mésohabitat, ils utilisent préférablement les seuils, et évitent les rapides et les biefs fluviaux uniformes.

Aucune préférence d'habitat n'a été détectée pour les tacons en fonction des variables et des sites analysés et ce, quelle que soit l'échelle analysée. Ils se montrent plastiques dans leur sélectivité d'habitat, tel qu'observé par les experts inuits interrogés. La taille des tacons était néanmoins positivement corrélée à la vitesse, qui s'est avérée être un facteur limitant pour l'utilisation de l'habitat par les juvéniles. Aucun juvénile n'a été pêché au-dessus de 0,6 m/s.

Cette première tentative de modélisation de l'habitat de l'omble chevalier anadrome juvénile montre l'importance des petits cours d'eau pour l'alevinage et leur vulnérabilité à un réchauffement potentiel de la température de l'eau.

Chapitre 7 : Engagement et réciprocité : Contribution aux bonnes relations entre chercheurs et Inuit et engagement

Travailler avec les savoirs Inuit implique d'avoir une pratique de recherche engagée de façon à bâtir des relations de réciprocité, qui font partie de la culture et de ce qu'incluent les savoirs inuits (Inuit Qaujimajatuqangit).

Le projet a évolué pour tenir compte plus largement des savoirs inuits par rapport à ce qui avait été initialement prévu. Des liens de confiance et de respect ont été bâtis au fil de ma pratique de suivi du travail et de mobilisation des connaissances auprès des communautés avec lesquelles je collaborais et au fil des visites de terrain. Mon apprentissage de la décolonisation scientifique s'est fait en même temps que ces liens se bâtissaient.

Plusieurs activités d'engagement ont été réalisées régulièrement. L'utilisation d'illustrations et de la vidéo comme outils a été très utile pour faciliter les communications. Mon engagement avec la communauté de Kangirsuk a mené à la réalisation d'un projet de recherche sur l'omble chevalier, mené par la communauté de Kangirsuk et intégré dans un principe de décolonisation de la recherche. Les méthodes scientifiques et les savoirs et savoir-faire inuits y sont mis en commun pour répondre en premier lieu aux intérêts de la communauté.

3 CYCLE DE VIE DE L'OMBLE CHEVALIER ANADROME À PARTIR DES SAVOIRS INUITS : UNE ANNÉE EN UNGAVA

Relevé des filets pour la pêche à l'omble chevalier à Ujarasutjulik (rivière Barnoin), Kangiqsualujjuaq, septembre 2019

Présentation du chapitre

Le présent chapitre fait une synthèse qualitative des entrevues réalisées avec des experts inuits dans les trois communautés de Kangiqsualujjuaq, Tasiujaq et Kangirsuk, situées dans la baie d'Ungava, au Nunavik. Les observations des experts inuits sur l'écologie de l'omble chevalier sont mises à l'avant-plan. L'objectif de ce chapitre est de faire des liens entre ces observations et la littérature scientifique pour bâtir une vision plus holistique des connaissances en considérant les deux systèmes de connaissances d'égale valeur. Il était important d'éviter d'utiliser la science pour confirmer les observations faites par les Inuits, comme si ces dernières avaient besoin d'être validées par une autorité supérieure. Le but était plutôt de démontrer la pertinence de jumeler les savoirs inuits et scientifiques pour incrémenter les connaissances sur l'espèce et pour alimenter la réflexion sur les connaissances scientifiques déjà établies. Le travail de mise en relation avec la littérature scientifique a également permis de mettre à jour des pistes de recherche, décrites à la fin du chapitre.

Ce chapitre sert de base au travail réalisé dans cette thèse sur l'étude des habitats en eau douce pour les différents stades de vie. En effet, la reproduction des ombles ayant été bien décrite lors des entrevues, une modélisation de ces habitats par la logique floue est présentée au chapitre 4 à partir de cette information. La méthodologie d'analyse des habitats d'hiver (chapitre 5) a été planifiée par suite des discussions sur l'utilisation des lacs et des pratiques de pêches.

Titre de l'article

Nunavik anadromous Arctic char life histories, behaviour and habitat use informed by both Inuit knowledge and western science: A year in Ungava Bay

Auteurs

Véronique Dubos[1], Peter May[2], Carole-Anne Gillis[3], André St-Hilaire[1,4], Normand Bergeron[1]

[1] Institut National de Recherche Scientifique (INRS), Québec, QC

[2] Nunavik Research Center, Kuujjuaq, QC

[3] Gespe'gewaq Mi'gmaq Resource Council, Listuguj, Qc

[4] Canadian Rivers Institute, Fredericton, N.B.

Publication

Dubos, V., Peter, M., Gillis, C.-A., St-Hilaire, A., Bergeron, N.E., 2023. Nunavik anadromous Arctic char life histories, behaviour and habitat use informed by both Inuit knowledge and western science: A year in Ungava Bay. **Arctic Science** (e-First). https://doi.org/10.1139/AS-2022-0019

Contribution des auteurs

J'ai contribué à la planification du guide d'entrevues. J'ai réalisé les entrevues et fait leur validation avec les participants. J'ai contribué à la conception, à l'analyse et à la rédaction de l'article. J'ai produit des synthèses, incluant la cartographie participative des sites d'intérêt pour chaque communauté.

PM a contribué à l'analyse et à la révision de l'article. CAG a contribué à l'interprétation et à la révision de l'article. ASTH a contribué à la conception du guide d'entrevues, à l'analyse et à la révision de l'article. NB a contribué à la conception du guide d'entrevues et à la révision de l'article.

Abstract

This study is a comprehensive documentation of anadromous Arctic char (*Salvelinus alpinus*) life history in Ungava Bay, Nunavik, Canada, through Inuit knowledge. Inuit experts shared their knowledge during semi-directed interviews and other occasions such as informal discussions and fieldwork. A contextualized synthesis of published western scientific literature is provided for the various life stages of Arctic char. The close year-round relationship Inuit have with Arctic char allows to set evidence of poorly described life history strategies in western literature and to reveal behaviours that, to the best of the authors' knowledge, have not been documented so far. The connections and paralleling of Inuit knowledge and published studies about Arctic char informs western science with a more holistic understanding of Arctic char ecology. By bringing Inuit knowledge of Arctic char to the foreground, the present study highlights relevant research avenues for co-developed projects on Arctic char ecology.

Key words: Arctic char migration; Knowledge co-production; Inuit Qaujimajatuqangit; Two-eyed seeing; Indigenous knowledge.

3.1 Contribution recognition

The present study was informed by knowledge holders from Kangiqsualujjuaq, Tasiujaq, and Kangirsuk communities, Nunavik, QC, Canada. We gratefully acknowledge their contribution, teachings, time and shared stories during the interviews and fieldwork. They are, for the interviews, in Kangiqsualujjuaq: Tommy Unatweenuk, Tivi Etok, Bobby Baron (D.), Kenny Angnatuk, Susie Morgan; in Tasiujaq: Moses Munick, Tommy Cain Sr. (D.), Willie Cain Jr.; and in Kangirsuk: Elijah Grey, Jeeka Kudluk, Mary Airo. Interviews in Kangiqsualujjuaq were arranged and interpreted by Thomas Edward Annanack. Interpreters were Susie Kudluk in Kangirsuk and Mary Annanack in Tasiujaq. For knowledge and stories shared *in situ* they are, in Kangiqsualujjuaq: Elijah Snowball, in Kangirsuk: Zebedee Annahatak and Mark Manic Carrier. The manuscript was provided to the municipal authorities and Local Nunavimmi Umajulivijiit Katujaqatigininga (LNUK, local hunters and fishers association) of the three communities for approval and validation, before being submitted.

3.2 Authors positionality

VD is a French immigrant graduate student, living in Quebec City, Canada. She has previously worked as a scientist and has been trained by an education system where cartesian science was presented as the only valid scientific point of view. She has a long-time interest in Inuit culture. Since her enrolment in her PhD program, she has followed numerous courses and training on Indigenous knowledge and has learn to acknowledge her own biases and those of western science towards Inuit knowledge. Time and regular communications were used to build trust and reciprocity with the involved communities. She has experienced Inuit lifestyle and ways of knowing and living in their environment. For the present study, she planned the interview guide, conducted the interviews, wrote, and edited the final documentation of interviews including maps, and conducted the validation process. PM is Inuk, born in Kuujjuaq and raised in Kangiqsuallujuaq and Kuujjuaq. He has worked at the Nunavik Research Center on various projects including Arctic char for 39 years, always integrating Inuit knowledge into his research. PM was involved in the project to provide an overview on the information gathered on Arctic char, given his significant experience doing research on this species, and to make sure the paper was respectful of Inuit knowledge. CAG is a settler inhabiting the 7th district of the unceded lands of the Mi’gmaq nation. Of western education with a PhD in water science, she is a biologist with 16 years of experience in the aquatic ecology of rivers, lakes, and migratory fishes. Since 2014, she has been working for the Gespe'gewaq Mi'gmaq Resource Council where each project carried out is based on the concept of Two-Eyed Seeing, whether for applied research projects, environmental monitoring, or habitat restoration. By unlearning and building reciprocity, she is honored to participate in the co-production of research with Indigenous communities. ASTH and NB are VD’s supervisor and co-supervisor, trained and practitioners in environment and fish ecology on a western science framework but learning the difference and importance of Indigenous knowledge. ASTH has worked in collaboration with First Nations communities (Mi'gmaq and Innu) on different research projects in which local and traditional knowledge was important to define sampling strategies. Previously, they implemented fuzzy logic models that allow for the inclusion of Inuit knowledge in habitat studies. They were the initiators of this project and provided western science insight for data analyses.

3.3 Introduction

Arctic char (*Salvelinus alpinus*) is an important food source for Inuit communities throughout the Canadian Arctic (Watts et al. 2017; Tremblay et al. 2020). In Nunavik, anadromous Arctic char is by far the most commonly consumed fish species (Watts et al. 2017; Blanchet and Rochette 2004). Year-round Arctic char fishing is part of the Inuit way of life since time immemorial. The continuum of extensive observations of the environment and interconnectedness integrated over time results in a deep comprehensive knowledge of fish behaviours and migration timing (Berkes 2018).

Arctic char biology and ecology was reviewed by Johnson (1980b) and Klemetsen et al. (2003), who described life histories and phenotypes. These detailed reviews dealt with the different morphs of Arctic char across its entire geographical distribution, with anadromous Arctic char being a small part of the general picture. A short updated synthesis of Arctic char life histories for the Canadian Arctic highlighted the importance of Arctic char fisheries for northern populations (Reist et al. 2018). However, Inuit knowledge was not included in any of these reviews, which were essentially informed exclusively by western studies on specific characteristics of this species life cycle. The importance of taking into account Traditional

Ecological Knowledge (TEK) in ecological studies is crucial, especially when the harvesters are impacted by management decisions (Huntington 2000). The ecology of several species has been studied through an Inuit knowledge lens and that allowed to further detail local ecology and bring complementary aspects on existing western knowledge, for example for polar bears (Laforest et al. 2018), Arctic terns (Henri et al. 2020), caribou (Gagnon et al. 2020), beluga (Breton-Honeyman et al. 2021; Ostertag et al. 2018) and Pacific salmon (Chila et al. 2021). For Arctic char, knowledge from Inuit fishers has been used to inform fisheries management (Berkes et al. 2005; Roux et al. 2019; Janjua et al. 2016) or to point out environmental change and char condition (Falardeau et al. 2022 ; Knopp et al. 2012). However, Inuit general knowledge on this species life histories has not yet been documented.

The aim of the present study is to document Inuit knowledge of the anadromous form of Arctic char in Ungava Bay during its entire life cycle and to weave published literature with this knowledge. The work was inspired by the concept of 'Two-eyed seeing' approach (Reid et al. 2021; Bartlett et al. 2012). The approach can be defined as "*learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of Western knowledges and ways of knowing, and to using both these eyes together, for the benefit of all*" (Bartlett et al. 2012). Our work was conducted so that both Inuit and scientific complementary perspectives interact without compromising each other and allow for a more comprehensive and holistic picture of overall anadromous Arctic char life histories, with respect for each knowledge system.

Inuit knowledge is presented under different themes. In the first four sections, the seasons used are divided according to adult fish behaviour, linked to northern climate, and as used by Inuit of Nunavik, instead of the usual western season dates (Figure 3.1). The following sections are related to juvenile rearing, interactions with other fish species, predators, and observed changes to the char environment. For each theme, Inuit knowledge is presented in the foreground and the scientific literature perspective is only presented in the "Discussion and links between Inuit knowledge and western scientific literature" section.

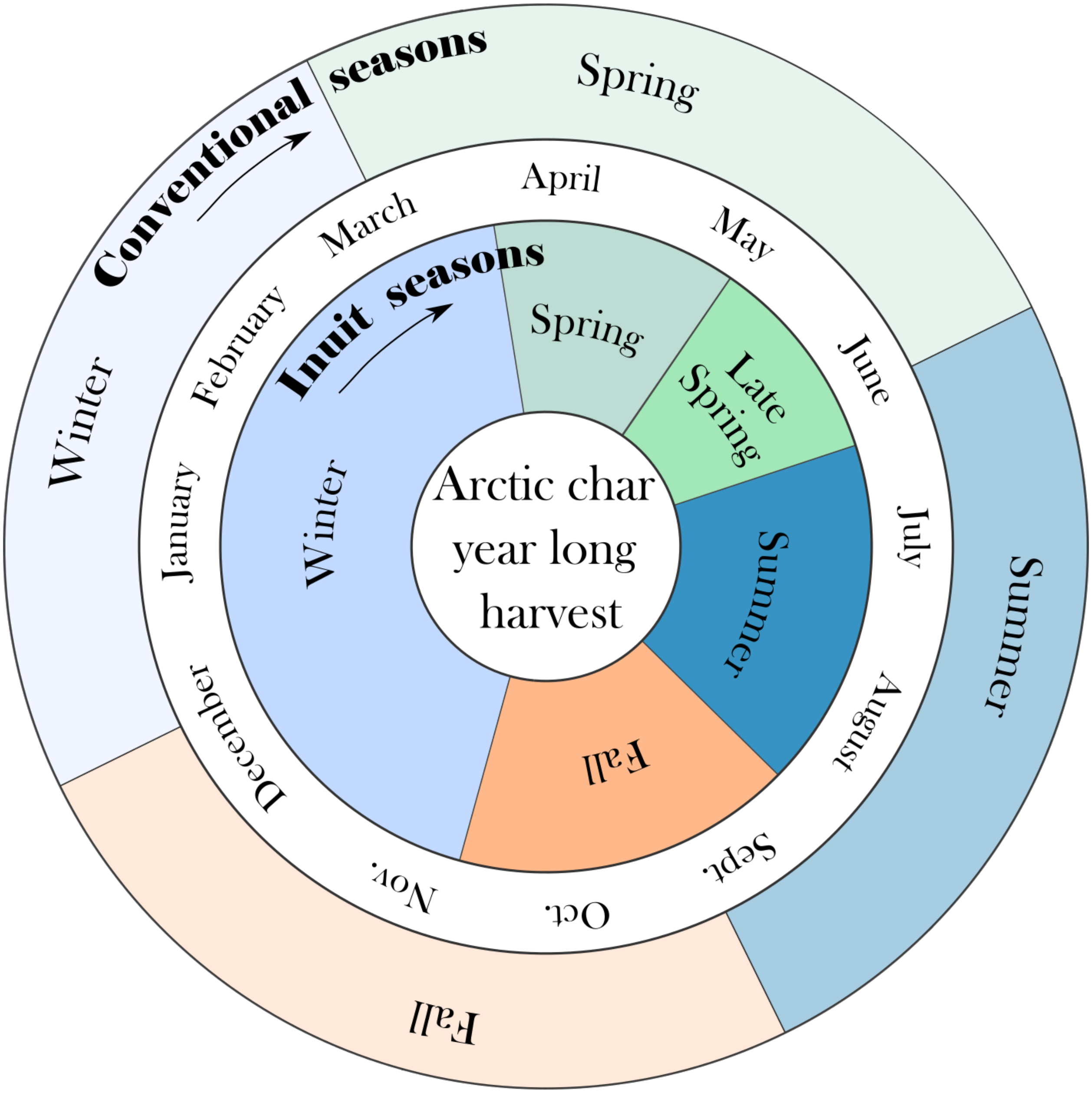


Figure 3.1 **Inuit seasons described in relation with rhythmic life of Arctic char in Nunavik (Inside colored wheel); Conventional western seasons (Outside colored wheel).**

3.4 Methods

3.4.1 Study background and design

The project followed local consultations led by Makivik Corporation on the state of Arctic char populations of Nunavik in a changing climate (Neelin 2021). Barriers to char migration due to various factors, especially to access their spawning areas, were mentioned as concerning in several communities. To have a better understanding of the local habitats used by char in fresh water and the potential impacts of climate change on these habitats, they had to be characterized first since they were poorly documented in the Nunavik region. This project was initiated by co-authors ASTH, NB and VD in collaboration with Makivik and Québec wildlife ministry (ministère des Forêts, de la Faune et des Parcs du Québec, MFFP). An interview framework was initially developed by VD, to address local habitat use and migration patterns. The study was conceived as a participatory mixed-method study, including participatory mapping (Creswell and Creswell 2018; Armitage and Kilburn 2015). Although, guided with fixed topics, the interview method allowed the participants to follow their ideas and associations. The different discussed topics were classified manually by main concordant themes which were linked to the seasons and fishing activities during the year. This highlighted the importance of seasonality and the different life histories through the lens of habitat use during the whole lifecycle, which is further described below under the form of a qualitative study. In addition, a quantitative analysis of the information gathered from the same interviews was being completed in parallel with the aim to specifically build predictive models of the spawning habitats. This quantitative component is not part of the current paper and is addressed in Chapter 4. Although the present study was initially built as a participatory project, in continuity to its results and for meaningful engagement and reciprocity as recommended in Wilson et al. (2020), we co-developed, with the community of Kangirsuk, a community-led project of Arctic char population assessment. This latter project was planned to build engagement from Inuit and southern researchers and is conducted following the ScIQ principles, meaning using scientific methods and tools but guided by the *Inuit Qaujimajatuqangit* (IQ) values and principles (Pedersen et al. 2020).

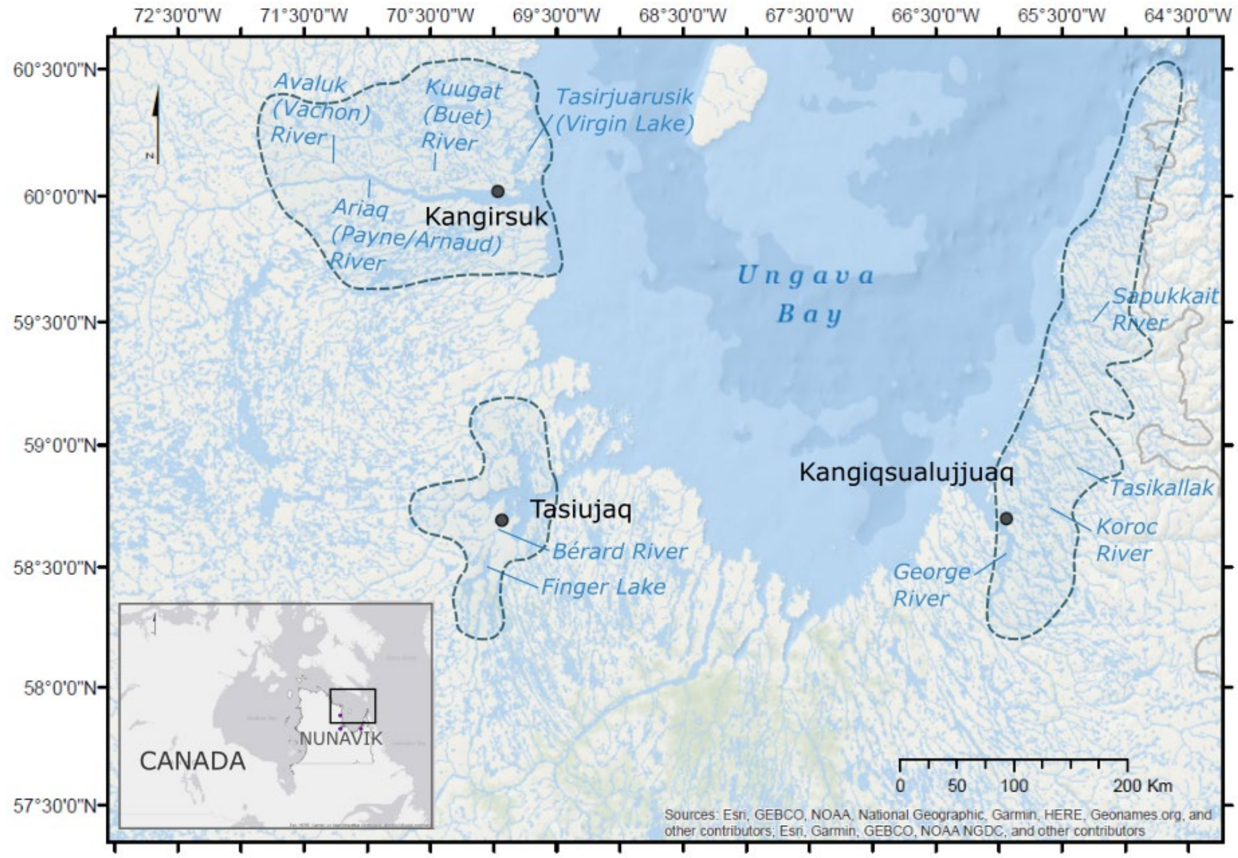


Figure 3.2 **Approximate location of the territories described for the purpose of this study around the villages of Kangiqsualujjuaq, Tasiujaq, and Kangirsuk (dashed lines). Several participants used larger territories not illustrated on the map. By no means the illustrated areas represent the extent of land use by Inuit, nor do they encompass the distribution of Arctic char of Ungava Bay. Map sources: Esri, "Ocean Basemap", GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors; and Esri, "Light Gray Canvas Map", DeLorme, HERE, MapmyIndia. Coordinate system: WSG_1984, Projection: Mercator Auxiliary Sphere.**

3.4.2 Interviews

Interviews were conducted during summer 2019 with elders and younger active hunters from three Nunavik villages located in the Ungava Bay: Kangiqsualujjuaq, Tasiujaq, and Kangirsuk (Figure 3.2). The term 'hunter' has a recognized social status among Inuit, and it is taken in its broader sense, which includes fish harvesting. A purposeful sampling (Coyne 1997) of the participants was completed by each LNUK (Local *Nunavimmi Umajulirijiit Katujjiqatigiinninga*, local hunters and fishers association) among knowledge holders from the community. Only one participant was member of a LNUK board, in Tasiujaq. They were chosen based on their recognized extensive knowledge of Arctic char, their availability and willingness to participate. The participants were considered as experts on this subject (Libakova and Sertakova 2015). A total of 11 participants were interviewed: two women and nine men. Nine of them were elders and two were middle-aged experienced hunters from Kangiqsualujjuaq and Tasiujaq. Most of the elders had experienced nomadic life before the settlement, and some of them were still active hunters (one in Kangirsuk and two in Kangiqsualujjuaq). As several participants explained, their knowledge *(IQ)* was acquired from their ancestors and by being on the land for fishing and other hunting activities with relatives. *IQ* has a larger meaning than the western use of the term 'knowledge' and incorporates relationships laws, culture, attitude and values (Nunavut Department of Education 2007). It should be considered as a way of being. The present study is based solely on the ecological knowledge embedded in *IQ*. Hence, the term 'Inuit knowledge' used throughout the study can be considered with a similar sense to the term 'Traditional Ecological Knowledge' (Berkes 2017; Usher 2000), although specific to Inuit culture and always evolving and adapting to a changing context. Despite the connotation of 'traditional', this knowledge can be contemporary (Tester and Irniq 2008).

Individual interviews were conducted in Kangiqsualujjuaq (n=5) and Tasiujaq (n=3) whereas in Kangirsuk, a group interview was conducted at the request of the participants (n=3). Semi-directive interviews were completed to allow for a relatively free conversation flow, albeit structured around fixed topics and questions, following an interview guide (Supplementary data). The interviews also included some specific questions about Arctic char habitat preferences for river characteristics. In addition, participants mapped several sites used by Arctic char, especially for reproduction and overwintering on 1: 50 000 scale maps. For each community, the territory identified covered several watercourses on portions of the territory traditionally used, and still today, for fishing (Figure 3.2). It was noticed by co-author VD, who conducted the interviews, that all participants were comfortable with specifying when they were unsure or did not have knowledge of certain aspects or specific sites. Except for the answers to specific questions, the information transmitted was in the form of stories and observations made during activities throughout the territory. Most of the interviews were conducted with the assistance of Inuktitut-English interpreters. No interpreter was required for the two youngest participants who were interviewed in English. Some minor loss on descriptions or nuances of terms may have happened due to the translation of the descriptive nature of the Inuktitut language. In addition, we acknowledge that a certain amount of subjectivity in the interpretation of the information is present. A *post hoc* validation of the information collected during the interviews was done with each participant, except for three of them who were not available (one in Kangiqsualujjuaq and two in Tasiujaq). This validation process was conducted with interpreters translating the English synthesis of information back to Inuktitut. It allowed to minimize misunderstandings that could have arisen from the translation and from the nature of knowledge transmitted. For each community, a synthesis of the information collected during the interviews, including maps of known habitat use and other sites of interest, was produced (in Inuktitut and in English), and transmitted for validation or comments to the participants, to the LNUK and the municipal office of each community and to the Nunavik Research Center. These reports remain confidential as required by the partner communities, due to the sensitive nature of the maps showing habitats used by the fish. Furthermore, some informal discussions with guides during fieldwork and with Inuit collaborators allowed to verify and support information. Hence, all the information presented in the current study was validated by other community members. The study, including informed consent and interviews protocol, was verified and approved by the INRS Ethics Committee (CER-19-517), based on INRS ethics policy for research involving humans, following the Tri-Council policy statement – Ethical Conduct for Research Involving Humans. Participants gave informed consent before participating in the study by signing a consent form. All participants gave their consent to be voice-recorded and to be named. They could withdraw at any point or decline to respond to any question.

4.3 Presentation of the results

To minimize any potential bias related to non-Inuit interpretation, except for the inevitable choice of which information would be presented, the subsections entitled 'Inuit knowledge' present only Inuit knowledge as it was transmitted during the interviews, unless explicitly stated otherwise. When community-specific knowledge was shared, the name of the community is mentioned. If the knowledge or observation(s) were shared among participants from different communities, then no specific community is identified. When a piece of information was not common to the majority, the number of participants that gave this information is specified (e.g., n=2). Nonetheless, the fact that the information was not mentioned by other participants did not mean that they disagree or that they did not have this specific knowledge. Indeed, each interview flow could lead to collecting information on different subjects or different stories. Citations between quotation marks from interviewees were attributed to their author. When the author of a citation was not a participant to the interviews, the mention 'pers. communication' was added to the author's name. Inuktitut names for fish are given in some sections to identify specific forms of Arctic char, as they are considered by Inuit of Nunavik (Table 1). Indeed, they use different names for different morphotypes. Commonly, the term *Arctic char* is used to identify anadromous Arctic char, called *Iqaluppik* in Nunavik Inuktitut. Landlocked or lake resident char are called *Nutillik* and are easily distinguishable from *Iqaluppik*. The Arctic char spawners are called *Aupalujaak* (or *Aupalujaalik* in Kangirsuk and Hudson Straight region), meaning red char.

Tableau 3.1 Inuktitut names of Arctic char with different life histories and reproductive strategies.

Inuktitut name	Life history	Physical description
Iqaluppik	Anadromous or sea-run Arctic char. They feed in the marine environment in summer.	The back is silver grey and can be greenish in summer when they are in the ocean. The belly is white when they are not spawning and can be pinkish for spent spawners. In the fall, spawners turn red in color and become *Aupalujaak* (or *Aupalujaalik*).
Aupalujaak or Aupalujaalik	Main reproducer, they are only found in fresh water. Some of them spend the summer in fresh water, without migrating to the marine environment.	Red color. Lean when they stay in rivers during summer.

Nutillik	Landlocked, lake-resident Arctic char.	Dark back and more orange belly.

3.5 Results and discussions

3.5.1 Preamble – Reflection on transmitted Inuit knowledge

Some questions of the interview framework were first formulated under the lens of western non-Inuit biological studies, which most often state hypotheses with the aim of answering one or many question(s) beginning by the word 'why'. However, it appeared rapidly that this question style was not appropriate as participants generally did not search to explain or justify fish behaviours. For example, when a participant was asked if he thought there would be a reason for a specific habitat choice, he stated that he could not answer the question because the fish were not talking to him. Another participant asked about some specific variable that could impact habitat selection, answered that "*It's really up to the fish, (…). That's the animal's choice*" (T. Etok, Kangiqsualujjuaq). The discomfort of participants questioned about animals intentions was also noted in Collings et al. (2018). The fish sentience, social intelligence and sense of self are generally excluded from the western scientific studies consulted, although they impact the fish behaviour (Brown 2015). Hence, questions regarding fish intentions about habitat selection were reformulated to be only descriptive and the flow of discussion gave more space to participants storytelling on fishing experience. In the present document, the authors attempted to respect the Inuit way of knowing about the environment and doing observations, for whom humans are strongly connected to all living things and an are integral part of the ecosystem (Nunavut Department of Education 2007).

3.5.2 Summer: Marine environment and upstream migration

3.5.2.1 Marine environment

<u>Inuit knowledge</u>

During the summer, Arctic char are feeding in estuaries of the main rivers, along the shores. They are harvested either using fishing rods or gillnets (usual mesh size: 8.8-10.0 cm), installed in the tidal zone, a few meters below the surface (Figure 3.3). Although the fish generally remain in coastal areas, some individuals can travel long distances. A participant from Kangiqsualujjuaq who had worked with Makivik researchers to tag fish in Sapukkait River, 70 km north of Kangiqsualujjuaq, told that one tagged individual was recaptured in Salluit, Nunavik, and another one in Siberia, Russia (B. Baron, Kangiqsualujjuaq). He had also knowledge about their displacement in the ocean and mentioned that when they are in the ocean and it is too cold west of Greenland and Hudson Strait, they are known to be found close to the coasts of Newfoundland. Another participant from Kangirsuk, who had also worked with researchers in the 1960's, told that a fish tagged in Kangirsuk during the summer was found in Iqaluit, Nunavut, during the fall of the same year (E. Grey, Kangiqsualujjuaq).

Figure 3.3 Example of traditional summer fishing area in the Koroc River estuary, near Kangiqsualujjuaq. Arctic char are caught by rod and gillnet. The picture was taken from the shore at low tide, on the 29th of June 2019 (Credit: Véronique Dubos). Map sources: Esri, "Ocean Basemap", GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors. Coordinate system: WSG_1984, Projection: Pseudo-Mercator.

3.5.2.2 Upstream migration

Timing and migration trigger (Inuit knowledge)

Some participants in Kangiqsualujjuaq (n=2) and Tasiujaq (n=1), mentioned that some fish start to migrate upstream in mid-July. In Kangirsuk, the migration starts later, i.e., in early or mid-August. The migration peak happens in late August in the three communities, but some fish can migrate upstream until late October (n=3 in Kangiqsualujjuaq, n=1 in Tasiujaq, n=3 in Kangirsuk).

During the fall, *"when there is strong wind and cold weather, some fish swim from the deep ocean* [back in the coastal area]*"* (S. Morgan, Kangiqsualujjuaq). When salt water is becoming too cold in the coastal area, they tend to stop feeding and start to move upstream. Some participants think the char have eaten enough (n=1 in Kangiqsualujjuaq, n=1 in Tasiujaq). During the fall season, there is heavy rainfall, and the river flows increase, helping the fish to move upstream. For each river, the upstream migration usually happens during the same period, from year-to-year. However, the exact dates could change depending on the weather and the water level. Sometimes, the upstream migration happens later because the rivers are too dry and the fish have to wait for the rain, *"they know they can climb the river as the water is deeper"* (W. Cain Jr., Tasiujaq) (n=3 in Kangiqsualujjuaq, n=1 in Tasiujaq). One participant in Kangiqsualujjuaq thinks it happens later in recent years. The fish wait for high tides to start going back in rivers. Especially when there is a waterfall to pass, they wait for the full moon to be able to climb the fall (E. Snowball, 2019, Kangiqsualujjuaq, pers. communication).

Going back and forth (Inuit knowledge)

In Kangiqsualujjuaq and Tasiujaq, it has been observed that the fish are not going straight from salt water to fresh water but are traveling back and forth between the two environments. For example, in Tasiujaq, they start to enter in the Bérard River at the beginning of August, then come back to salt water and they go back and forth between the estuary and the river, until the second week of August (n=1). They finally go up in the river during periods of high tides and heavy rain.

Behaviour according to size (Inuit knowledge)

Different waves of upstream migrations are observed according to the reproduction status and the fish size. In Kangirsuk, according to the three participants, the char who are going to spawn in the fall are the first to migrate in fresh water. The first wave migrates upstream during the latter half of August. The second wave of fish migrate from September to October. They are constituted by smaller individuals than the first wave or by mature non-spawners. The last fish coming in fresh water are the largest char, because they tend to migrate further out in the ocean. In Kangiqsualujjuaq, some spawners (*Aupalujaak,* red char) stay in rivers during the summer (n=3). The spawners are the first to go up tributaries, brooks, and smaller rivers to reach their spawning sites. They are already upstream while the smaller immature fish arrive in fresh water (n=2).

Discussion and links between Inuit knowledge and western scientific literature

Arctic char have preferences for estuarine environments in proximity to fresh water and especially for near shore habitat (Moore et al. 2016). Acoustic telemetry has confirmed fish movement between various estuaries and river systems using near shore habitat (Moore et al. 2016; Spares et al. 2015), where Inuit are harvesting them. As Arctic char have to prepare their re-entry in fresh water by acclimating, the observed back and forth movements are likely a part of the osmoregulation process (Jørgensen and Johnsen 2014).

In the published literature, several factors were mentioned as trigger of the upstream migration. Jørgensen and Johnsen (2014) proposed satiety as the main factor triggering this migration, as mentioned by some participants. However, several interviewees explained that the fish were waiting for a combination of high tides and higher river flow to move upstream. Tides are a factor affecting Arctic char movement in estuaries as measured by telemetry in Frobisher Bay (Nunavut, Canada) (Spares et al. 2015) and are likely impacting their movements even once in fresh water, up to the head of tides. In several rivers, the fish can be found at the base of waterfalls until advantageous tidal conditions occur. The importance of river flow for the upstream migration is highlighted with the example of the Nauyuk Lake system, Nunavut (Gilbert et al. 2016) where Arctic char have modified their migration patterns to adapt to a natural unsuitable river flow in fall that prevent them to access their spawning streams at that time. River length and mean slope is also a probable factor for earlier migration in the season, as Arctic char near Cambridge Bay (Nunavut, Canada) exhibit a shorter residence time in the ocean when they move to longer rivers (Moore et al. 2016). A combination of suitable water levels and required travel distances to favorable habitats are likely triggering the upstream migration.

The different waves of migration were recorded in Sapukkait and Sannirsariq systems, located north of Kangiqsualujjuaq, with large males (>700 mm fork length) caught at the end of the migration run (Boivin 1994). These larger fish likely benefit from this additional period at sea for feeding, thereby increasing their energetic reserve, as observed by interviewees that explained the last wave of migrants fed farther off the coast. It is indeed likely that large Arctic char use extended offshore geographic areas to feed, as shown from tracking experiments of congeneric Dolly Varden (*Salvelinus malma*) that traveled up to 152 km offshore (Gallagher et al. 2021). In addition, acoustic telemetry has shown that larger Arctic char use colder water than smaller ones (Mulder et al. 2019b), and thus may have more tolerance for the cooling temperature of the ocean in October.

3.5.3 Fall : Spawning

3.5.3.1 Migration strategies and spawning behaviour

Inuit knowledge

In the three communities, spawning occurs around mid to late September and can happen until October. Sometimes, fishers catch some red Arctic char (*Aupalujaak)* with eggs in late October. In the fall, when the char are spawning, the males turn very red, and their flesh turns to white. Females also turn red, but not as much as males. When the female spawners are in saltwater, the eggs that they bear are still small. Most of the maturation of eggs is done after the fish goes in fresh water, "*fresh water makes them bigger*" (T. Etok, Kangiqsualujjuaq) (n=2, Kangiqsualujjuaq).

In Kangiqsualujjuaq (n=3) and in a lesser extend in Kangirsuk (N. Eetook, 2022, Kangirsuk, pers. communication), it has been mentioned that some char who will spawn in the fall show a different life history with no summer migration in the ocean to feed. Indeed, some red char

(*Aupalujaak)* remain red all year long and stay in rivers even in summer, feeding in brackish water and freshwater, similar to some lake trout (*Salvelinus namaycush, Isiuralitaak*). These *Aupalujaak* are lean (LNUK meeting, 2019, Kangiqsualujjuaq). They feed on macroinvertebrates in rivers, but not in lakes (n=1, Kangiqsualujjuaq). They are still *Iqaluppik* and are different from landlocked char (*Nutillik*). A participant and a hunter from Kangiqsualujjuaq (E. Snowball, 2020, pers. communication) mentioned that the *Aupalujaak* that remain in fresh water have more eggs and are the main spawners. These *Aupalujaak* are waiting for the Arctic char spawners that have spent the summer in the ocean to go upriver for reproduction. While the silver, non-spawning char, are still in the lower river reaches near the mouth, the spawners have already moved further upstream. They use the smaller tributaries that flow into the main rivers to spawn. The non-spawning fish do not stay around the spawning fish, they are in different locations. At the spawning location, there is often a large number of fish together. Before spawning begins, they remain around the spawning bed, slightly moving their body with the current. "*Sometimes, females seem to climb on rocks, but it is to massage and soften their eggs*" (LNUK meeting, 2019, Kangiqsualujjuaq). The males are preparing the spawning ground. Each female has her own spawning site. The reproduction has been described in Kangirsuk as follows: "*The female fish is just there on the bed, never moving, but one male fish is always moving around the female fish to protect the eggs from other males. The male circles around the nest and moves upstream of the nest, so that the milt flows toward the female eggs with the current. After spawning, the males stay near the nests to protect the eggs and they become aggressive with other fish*" (M. Airo, Kangirsuk). One participant in Kangirsuk mentioned that, although spawned males are tempted to catch the fishing hook and bait, they avoid catching them, because they know the fish have to protect their eggs. Once they have spawned in a site, they swim back and they go further upstream to another stream to spawn again (n=2, Kangiqsualujjuaq). Once they have spawned in small tributaries, they go down the main river to reach their overwintering site. In Kangiqsualujjuaq, after the spawning, some *Aupalujaak* are slim and feeding occurs sporadically in the lakes until they gain some weight. This is the only time they feed in lakes (n=1).

<u>Discussion and links between Inuit knowledge and western scientific literature</u>

Interviews in Kangiqsualujjuaq highlighted different summer migration strategies during the year of reproduction. The slim *Aupalujaak* (the red char) staying in rivers in Kangiqsualujjuaq, is evidence that some reproducers do not migrate during the year of reproduction. This was assumed from summer sampling of Arctic char in an overwintering lake of the Sapukkait system, located on the east side of the Ungava Bay, where 76.2% (n=16) were in spawning color (Boivin 1994). A few cases of absence of marine migration during the year of reproduction have been documented. For example, Arctic char of the Hornaday River, Northwest Territories, remain in the river for almost two years before going back to the ocean (Harwood and Babaluk 2014). The absence of marine migration has also been observed in the Nauyuk system, in Nunavut, as the future spawning fish migrate upstream at the beginning of the summer, instead of swimming downstream to feed in the ocean (Johnson 1980b). Indeed, the local river hydrology does not allow an upstream migration to the spawning streams in the fall season. The forego of marine migration might be widespread in other Nunavik systems. Furthermore, as mentioned by participants, eggs are developing faster once in fresh water (Johnson 1980b), either due to the environment or to hormones level timing. The freshwater maturation and the absence of marine migration of some spawners, likely explain the low rate of fish with mature gonads caught near the river mouth with a counting fence during the upstream migration in Tasiujaq (10%) (Mainguy and Beaupré 2019a) and in Aupaluk (5.6% of females et 1.9% of male) (Mainguy and Beaupré 2019b). Hence, as several spawners might already be upstream, sampling in the lower reaches of a river might underestimate the actual fecundity rate. In other studies in which the fish were caught in various locations along the rivers but not near the river mouth, the proportions of spawners in total catch were estimated at 55% (Beddow et al. 1998) and 60% (Dempson and Green 1985).

In general, the spawning behaviour observed by participants was similar to what was documented in greater details by Brattli et al. (2018). Aggressive male behaviour with other fish during spawning act was also described by Johnson (1980b, citing Fabricius, 1953) for some individuals. A protective behaviour towards the eggs was observed by Frye et al. (2021) who also documented cannibalism on the eggs, increasing with male competition. Cannibalistic behaviour on the eggs was not mentioned by participants.

3.5.3.2 Spawning habitats physical characteristics

Characteristics of spawning habitats in Kangiqsualujjuaq and Tasiujaq (Inuit knowledge)

The spawning Arctic char can use several rivers to spawn, but the spawning sites are always at the same place. The riverbed is darker at the spawning sites (n=1, Kangiqsualujjuaq). They can spawn in any type of stream, but they often use small rivers that are narrow and most often not wadable, because it is easier for them to go upstream. The spawning sites can also be located in lakes, mainly at the inlet or at the outlet, where "*there's not much current but the water is flowing and it's on the gravel, just before the falls of the lake. Just above the falls*" (S. Morgan, Kangiqsualujjuaq). Three participants think they could spawn also in deeper areas of lakes but have never observed them spawning there (n=2 in Kangiqsualujjuaq, n=1 in Tasiujaq). In rivers, they spawn in flowing water with 'slow' or 'medium' current velocity (on a scale of null, slow, medium, and fast velocity), and even still water. "*When the current is strong, they use the side of the river, where there is less current*" (K. Angnatuk, Kangiqsualujjuaq). In the medium size rivers, they spawn in relatively shallow areas. The best suitable water depth at the spawning sites was described by the participants between 0.6 m (2 ft) and 1.5 m (5 ft) in Kangiqsualujjuaq (n=4) and between 0.6 m and 1.2 m (4 ft) in Tasiujaq (n=3). If they use shallower water, the spawning bed can be dewatered during dry periods. The fish in shallow water are not as protective as others (n=1, Kangiqsualujjuaq). All participants thought Arctic char spawn in small gravel or in a combination of gravel and cobble. They can also spawn beside big boulders (n=3 in Kangiqsualujjuaq; n=1 in Tasiujaq), but do not spawn in the sand (n=4 in Kangiqsualujjuaq; n=3 in Tasiujaq). In Kangiqsualujjuaq, a participant mentioned that sometimes, they build a redd in fine gravel and they move little rocks with their tail to surround their redd. However, they most frequently lay their eggs in unprotected areas on the bed and the current disperse them between the rocks.

Characteristics of spawning habitats in Kangirsuk (Inuit knowledge)

According to the participants of Kangirsuk, Arctic char spawn in rivers, never in lakes. They usually spawn along the rivers that have strong current, but they use some sandy little bays where there is less current. There are also spawning sites in the Payne River, located near rapids, downstream of small islands and hence, also protected from the current. The spawning sites are dominated by sand, with some gravel (n=3). In the fall, the copper brown spawning grounds contrast with the surrounding pale sandy riverbed. They do not spawn on pebbles or rocks. They spawn at a depth of 1.2 m (4 ft) to 1.8 m (6 ft) (n=3). Before laying their eggs, they build a redd in the sand and then they bring little rocks around it, "*it seems it is man hand done but it is done by the fish with their tail and head"* (M. Airo, Kangirsuk). Participants think that the rocks prevent the eggs from rolling out of the redd and drift downstream because of the current.

Discussion and links between Inuit knowledge and western scientific literature

The characteristics of habitat use is linked to the local hydrogeomorphology. The spawning habitats used in Kangiqsualujjuaq and in Tasiujaq were similarly described, with the use of slow flowing water, the presence of gravel bed and similar water depth. Few studies have described Arctic char spawning sites, but they showed similar characteristics of habitat use (Cunjak et al. 1986; Dempson and Green 1985). Spawning habitats described in Kangirsuk are rather different as they are located in calm bays along large fast flowing rivers, with little or no access to lakes and tributaries. In these bays, char use sandy substrate, which is rather unusual (Johnson 1980b). Local hydrodynamics and the presence of fluviatile surface deposits in Kangirsuk rivers (MRNF Québec 2004) explain the relative paucity of available spawning habitat and their peculiar characteristics.

3.5.3.3 Importance of water temperature

Inuit knowledge

All participants think that temperature is an important factor that can impact the spawning. The fish spawn when the water temperature is decreasing rapidly, but neither too cold nor too warm or the eggs will not survive (n=4). However, slightly warmer water at spawning sites leads to larger growth than cooler spawning sites (n=1). In Kuujjuaq, a hatchery operated by Nayumivik Landholding Corporation allows to stock the surroundings rivers with Arctic char fry. The project was led for several years by Allen Gordon. He was met outside of the regular interviews and explained that the eggs for the hatchery were collected in Tasiujaq a few years ago. He knew the fish were ready to spawn when the water temperature reached 6°C. If there were a few days with air temperature above 13°C-14°C, the spawning was stopped and re-initiated once the air temperature decreased again (A. Gordon, Kuujjuaq, 2020, pers. communication). All participants stated that fish can locate the suitable sites for spawning because the fish know the river will not freeze to the ground. The water temperature could also explain the difference in eggs coloration (LNUK meeting, 2019 Kangiqsualujjuaq). Indeed, the fish that are in rivers located further north have reddish eggs that differ in colour from those of southern Arctic char, that are more of the orange colour.

Discussion and links between Inuit knowledge and western scientific literature

All participants have pointed out that spawning is related to river temperatures as it triggers the beginning of the spawning season, and it can impact the eggs development. It has been shown in aquaculture that after at least a first week at an optimum maximum of 6°C, lowering the water temperature was not only non-detrimental to the eggs development (Jeuthe et al. 2016) but that mortality increased if the temperature did not decrease below 5°C during incubation (Jobling et al. 1993). From his work at Kuujjuaq hatchery, A. Gordon also established that in Tasiujaq, the same water temperature of 6°C was also associated to mature eggs (A. Gordon, Kuujjuaq, 2020, pers. communication). Observations of char spawning behaviour in other northern regions, coincided with temperatures below 7°C (Johnson 1980b; Beddow et al. 1998). River thermal regime is obviously a critical factor for anadromous Arctic char reproduction and warming waters due to climate change might impact the spawning timing and could affect eggs development.

The observed variation in egg coloration with latitude, mentioned during Kangiqsualujjuaq LNUK meeting, is likely linked to the latitudinal variation in prey availability, as egg pigmentation depends on the fish diet (Vuorinen et al. 1997) and thus might be indirectly linked to temperature and other factors such as oceanic currents.

Although all participants think that temperature is important for spawning, none of them had knowledge if spawning sites were located in areas of presence of underground spring, an established preference for congeneric Dolly Varden (Johnson 1980c; Stewart et al. 2010) or for a specific riverine population of Arctic char (Harwood and Babaluk 2014). Evidence of upwelling groundwater at location of redds was shown locally in the Koroc River, near Kangiqsualujjuaq (Cunjak et al. 1986). It is likely that several other spawning sites are located in upwelling groundwater areas or areas of high hyporheic flow that could help to locally regulate water temperature by preventing freezing of the eggs and by bringing cooler water later in the spawning season, as observed by Baxter and Hauer (2000) for bull trout (*Salvelinus confluentus*) in Montana.

3.5.4 Winter: Overwintering, trapped fish, and disappearance

<u>Overwintering (Inuit knowledge)</u>

At the beginning of the winter, after the spawning period, Arctic char gather to reach overwintering sites in accessible lakes and in some specific areas of rivers. Individuals of all sizes can be observed together, including adults and juveniles, spawners, and non-spawners. Participants mentioned that the Arctic char can spend the winter in deep water, but also in shallow water because the fish know the places where the water does not freeze to the bottom, "*they are aware of their environment, they know because they are moving constantly in the water*" (K. Angnatuk, Kangiqsualujjuaq). The anadromous Arctic char do not feed for the whole winter.

Arctic char use different sites to overwinter from one year to another, they do not always go back to the same river or lake (n=2, Kangiqsualujjuaq). Inuit participants do not think there is a particular purpose to the change of lake overwintering habitat, "*it's like visiting neighbors or going camping*" (S. Morgan, Kangiqsualujjuaq). Participants in Kangiqsualujjuaq have observed that some year they are abundant in a lake and the next year there could be hardly any. Alternatively, a cohort in a specific year may have smaller average size, in contrast with the cohort in the following year that is composed of larger individuals. One participant mentioned that it is something they have noticed more frequently in the last eight years than previously.

When they are in lakes they stay together, but not really aggregated because they have space. When they are in rivers, they get together very close. In Kangirsuk, overwintering sites are located mainly in rivers, and they remain in the same overwintering site for the whole winter.

<u>Trapped fish (Inuit knowledge)</u>

In Kangirsuk, when the ice is forming, fish can get trapped in some areas of the rivers as the ice formed around them from the bottom to the surface of the river. Participants have observed that the trapped fish stay alive all winter long by moving around to prevent the ice from forming, "*they're going to keep ice from freezing because they are all there, like a little city of char*." (E. Grey, Kangirsuk). One participant told that "*even if you fish in that hole whole day, all full day, you're not going to finish, it's full of fish (...). That's why people who go fishing in the winter, they do not find them as much* [in other locations]. *Because they are there"* (J. Kudluk, Kangirsuk). The fish have scratches on their sides from swimming so close of one another. They cannot escape until the ice breakup. One participant told that when he went back at this spot where the fish remained the whole winter, while they were gone in late spring, he could see the imprints of the fish in the ice, i.e., small cavities under the ice. Participants stated that the fish do not go back to the site where they got stuck because they know that there is a risk of getting trapped. It happens in different locations every winter.

Winter disappearance (Inuit knowledge)

In some large lakes used for overwintering in Tasiujaq (e.g., Finger Lake) and in Kangirsuk (Tasirjuarusik or Virgin Lake), observers mentioned that Arctic char seem to "disappear" during the winter as they become scarce and hardly fished. They "reappear" and become easy to fish in late spring.

Discussion and links between Inuit knowledge and western scientific literature

The low site fidelity of Arctic char to specific winter habitats has been established in the scientific literature, and contrast with their high fidelity to spawning hydrographic systems (Beddow et al. 1998; Kristofferson 2003; Moore et al. 2013; Gilbert et al. 2016). For western scientists, fish select the most easily accessible overwintering sites to minimize energy expenditure during migration, when they are not in a spawning year (Moore et al. 2017; Gilbert et al. 2016). Some participants view was rather that Arctic char use different overwintering lakes as a choice, to have some variety. Interannual variability in number and size of char observed by fishers is likely due to the broad diversity of life histories of Ungava Bay.

We did not find any documentation of Arctic char being trapped in restricted overwintering habitat with no ice cover although the phenomenon has been observed for other salmonids trapped in pocket of unfrozen upwelling groundwater (Power et al. 1999). It is however unlikely that the Arctic char observed in Kangirsuk schooled around a groundwater source as the location of trapped fish differs from one winter to another. The rivers used in Kangirsuk for overwintering are dynamic, with fast current, with the characteristics of rivers favoring the production of frazil and anchor ice (Brown et al. 2011). As anchor ice alters the usual hydrodynamic of rivers by the creation of anchor dams, the presence of this type of ice is likely one of the main reasons that the fish get trapped in small backwater areas, as observed by Inuit experts. The observed `imprints of the fish in the ice are similar to the domes created by northern pikes underneath the ice surface during an anoxia episode preceding a winterkill, as they stayed in proximity of the surface ice cover, where the highest concentration of dissolved oxygen were measured (Magnuson and Karlen 1970). The trapped Arctic char might thus exhibit the same survival behaviour. The observation that fish are not getting trapped again on the same site is likely due to the variability and unpredictability of frazil dam locations.

The Arctic char temporary winter "disappearance" in large lakes has not been documented and remains to be elucidated. The fish likely stay in the deep portions of the lake, where temperatures may be higher than near the surface and volumes are large enough to avoid anoxia (Clilverd et al. 2009). Fish tagging and lake monitoring is currently ongoing in Tasirjuarusik Lake in Kangirsuk (Dubos et al., *In prep.*).

3.5.5 Spring and late spring: schooling, increased activity, and downstream migration

3.5.5.1 Schooling

Inuit knowledge

During springtime, in many lakes of Kangiqsualujjuaq, participants and several fishermen have observed schools of Arctic char swimming around together and keeping locally ice-free the lake surface: "*When there are too many fish in one area, they melt the ice and they have a big hole there*" (T. Unatweenuk, Kangiqsualujjuaq). This behaviour is not observed at the same areas than winter fishing areas. Several fishermen have observed this phenomenon and told that there were so many fish that the water was not visible, "*they can be* [found all the way] *to the bottom. In this place, the ice is very thin*" (E. Snowball, 2020, Kangiqsualujjuaq, pers. communication). Some fish have scratches on their skin. Such schooling behaviour is seen regularly in Tasikallak Lake (Short Lake), north of Kangiqsualujjuaq, where a winterkill occurred in 2002.

<u>Discussion and links between Inuit knowledge and western scientific literature</u>

The increase of light intensity in ice free areas could explain fish aggregation, as it explained winter habitat selection for lake trout (Blanchfield et al. 2009). Another factor explaining the schooling of Arctic char associated with thin ice or open water, could be the presence of local groundwater springs, as it had been observed by Cunjak and Power (1986) with aggregation of brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) in rivers. However, this hypothesis remains to be verified in the case of Arctic char in lakes since the relative input of groundwater is small compared to the volume of surface water of a lake. Hence, the potential influence of groundwater on water temperature or dissolved oxygen content is likely to be less important than in a confined river. In the specific case of Tasikallak Lake, the observed schooling at a site of thin ice cover might be also explained by the risk of hypoxia/anoxia in the deeper zones of the lake, leading the fish to remain near the surface. Indeed, dissolved oxygen depletion was a possible cause of the winterkill that happened in 2002 (Côté 2002). The dissolve oxygen level of the lake was monitored during the winter 2021-2022 but did not decrease to critical values (Unpublished data). Whether the ice is melting because of the fish are swimming or if the fish are swimming in previously open water remains unsolved.

3.5.5.2 Increased activity and downstream migration

<u>Inuit knowledge</u>

In late spring, when the ice is starting to melt, the fish congregate near the surface of open water areas and are swimming actively. They also "reappear" from the lakes where they could hardly be caught in winter e.g., Finger Lake in Tasiujaq and Tasirjuarusik in Kangirsuk. A fisherman thought that during this period, they are trying to eat because they are easier to catch with hook than in winter (Anonymous, 2020, Kangirsuk).

When the ice cover of the overwintering lake starts breaking up and the river is flowing out of the lake, the char start their downstream migration to the marine environment. The downstream migration does not always happen the same exact date from year to year, it depends on the timing of the ice break (n=1 in Kangiqsualujjuaq). For instance, it starts between May and June in Kangiqsualujjuaq (n=2). The downstream migration persists during the months of June and July when the fish go down from the upper streams to the main rivers and then to brackish water and the marine environment (n=1 in Kangiqsualujjuaq).

<u>Discussion and links between Inuit knowledge and western scientific literature</u>

Acoustic telemetry has shown that some fish can start the downstream migration prior to sea-ice breakup (Hammer et al. 2021), probably to benefit from the rapid increase in primary (and consequently secondary) productivity in the spring (Druon 2017). Some fish even start their migration before river ice break-up (Smith 2020). An increase in appetite three to four weeks prior to downstream migration has been documented (Jørgensen and Johnsen 2014). The authors showed that the timing of increase of appetite seems controlled by endogenous factors, uncorrelated to temperature or food availability. This phenomenon is in adequation with the late spring ice-fishing period, when Inuit fishers observed that fish are active and are biting easily. A significant increase of anadromous Arctic char activity in lakes around the breakup period was also detected by telemetry (Mulder et al. 2019a). Although the authors pointed out that the increase of activity was correlated to water temperature, their measured temperature remained within the same range than in winter (<3°C). It is thus likely that the recorded increase of activity would be in open water areas preceding the ice breakup. Indeed, contrary to the sole interpretation of telemetry data, Inuit hunters can observe simultaneously the fish swimming behaviour and the ice cover conditions. That is how they have noticed that some areas with open water or thin ice are linked to fish schooling.

3.5.6 Rearing of juveniles

The exact date of hatching was not known among the participants, but five out of eleven participants thought they hatched at the beginning of winter, and they spend their first winter as fry. Through his work, author P. May observed that at the Kuujjuaq hatchery, where the water used comes from a nearby lake under natural thermal regime and is not heated, hatching happens in January.

<u>In Kangiqsualujjuaq and Tasiujaq (Inuit knowledge)</u>

In Kangiqsualujjuaq and Tasiujaq, according to all participants, juveniles do not remain in a specific habitat. In summer, "*they go everywhere*" (n=4, Kangiqsualujjuaq) "*they go with the current and feed*" (K. Angnatuk, Kangiqsualujjuaq). They can swim in any type of flows, except waterfalls. They can be found in shallow or deep water. However, a lot of small juveniles (presumably young of the year, fry) can be seen near spawning sites, in rivers and near lake outlets. Some participants (n=2 in Kangiqsualujjuaq; n=1 in Tasiujaq) thought they are more frequently found in lakes than in rivers, especially in the nearshore habitat. In mid-summer, they are found in shallow water, warmer than deeper zones. They always hide between rocks or behind boulders, in rivers and even in lakes (n=2 in Kangiqsualujjuaq; n=3 in Tasiujaq). They can be seen more easily at night with a flashlight (Elijah Snowball, 2019, Kangiqsualujjuaq, pers. communication) (Video: Dubos 2019).

Some participants have seen juveniles following the adults to the estuaries, in brackish water (n=4). There are also many individuals in river mouths, in the tidal zone. The smallest ones are around 100-120 mm length (n=2 in Kangiqsualujjuaq; n=1 in Tasiujaq). However, participants stated that if they were to migrate in a complete marine environment, they would die. One experienced fisher mentioned that for the first time in 2019, he saw small Arctic char swimming in a layer of fresh water at the surface of salt water and the fish were avoiding the deeper, more salty water (T. Etok, 2019, Kangiqsualujjuaq, pers. communication). Once they are around 250 mm in length, they follow the adults to the marine environment (n=2 in Tasiujaq). A participant in Kangiqsualujjuaq mentioned "*at the age of four years old, they will go to the sea. Before, they're feeding in the river.*" (B. Baron, Kangiqsualujjuaq). They come back to fresh water in the fall. In winter, juveniles can be seen in lakes. When ice fishing, participants see very small individuals. They can be found also in rivers where water depth is sufficient to avoid freezing (around 5 ft, or 1.5 m).

In Kangirsuk (Inuit knowledge)

In Kangirsuk, participants mentioned that after hatching, fry stay near the spawning sites. They remain in the same area where they were born, during the first winter, the next summer and the second winter. During this time, they avoid strong river current. They swim around small rocks, where current velocity is relatively low. They usually stay at the bottom of the river. As they grow bigger, they hide behind bigger rocks. One participant told: "*As I grew up along this river* [Ariaq/Payne] *as a child, (...) I was catching those fish* [±120-150 mm] *when the ice was starting to form (...), when the ice could get strong enough to hold me as a little girl, that's when I fished those little fish.*" (M. Airo, Kangirsuk).

During their second summer, the juveniles are bigger (around 150 mm), so they can swim in faster current. According to participants, juveniles do not spend many years in the river before doing their first migration to sea. "*They grow fast and, as soon as they are able, they follow the adults into brackish water*" (M. Airo, Kangirsuk). They can go to the salt water when their size is around 200 mm to 250 mm (n=3).

Discussion and links between Inuit knowledge and western scientific literature

From the literature, incubation was measured in hatchery between 280 and 420 degree-days for different populations, acclimation and incubation condition (Jobling et al. 1993; Granier 2013). In natural environment, Dolly Varden hatching time is between seven and nine months (Stewart et al. 2010). Author VD observed the presence of floating eggs in two different systems around Kangiqsualujjuaq, the Koroc River (2nd and 3rd of March 2020) and Tasikallak Lake (17th of March 2020), where water temperature was measured below 1°C (Video: Dubos 2020). Although eggs were not sampled, they were seen at sites identified by participants to be used by Arctic char for spawning and overwintering. The observation corresponded to approximately seven months after the spawning season and their presence were possibly due to the hatching of Arctic char eggs.

As for spawning habitats, fry (young of the year) habitat use was described differently in Kangirsuk than in other locations. Fry remain near the redds in calm bays along fast flowing rivers with a significant mean slope like for example Kuugat (Buet) and Avaluk (Vachon) rivers which have slope of 4.2 ‰ and 3.6 ‰ respectively for the first downstream 30 km. Nonetheless, it has been shown from electrofishing data from Kangiqsualujjuaq and Tasiujaq that fry have a preference for riffle type habitat (Dubos et al. 2022). Hence, the availability of this habitat type seems more limitative in Kangirsuk than near the other two communities where juveniles have access to various habitats and are able to show some site selectivity.

The juveniles of one year and more, called parr, are extensively using river mouths as summer habitat. Few of them were sampled using electrofishing in streams where fry were found in greater abundance (Dubos et al. 2022), suggesting the use of different habitat types, potentially including river mouths and estuaries. According to the size of the smallest parr observed in river mouths by participants (±100-120 mm), they are likely to be one year old (Mainguy and Beaupré 2019a). At that age, they were observed leaving their fry habitat in proximity to spawning grounds and swimming in the current in Kangirsuk.

The use of the estuarine surface layer by pre-smolt first migrant was recently measured by acoustic telemetry (Atencio et al. 2021). In this study, temperature or undefined environmental factors were proposed to be the selection factor for the surface position and the notion of thermohaline stratification was not mentioned (Drinkwater and Jones 1987). Nonetheless, the observed water stratification by an Inuk fisher is an explanation for the use of the surface layer by pre-smolts, allowing them to access more productive water in the estuary without being affected by salt water. In Kangirsuk, the minimum size at which some fish are able to fully cope with saltwater, was identified by participants to be between at 200 mm and 250 mm. A size of 200 mm would correspond to a two year-old fish whereas a size of 250 mm would correspond to a three year-old fish (Mainguy and Beaupré 2019a). Two years old was the minimum age measured near Kangiqsualujjuaq, although three years old fish were much more frequent (Boivin 1994). In Tasiujaq, two participants mentioned a minimum size of 250 mm, which would correspond to a three year-old fish (Mainguy and Beaupré 2019a). This size is comparable to the minimum size of 220 mm allowing hypo-osmoregulation capacity of Arctic char in an experimental settings (Schmitz 1995). In Kangiqsualujjuaq, Le Jeune (1967) mentioned, with some uncertainty, a first entry in ocean at the age of three or four years. Growth mostly occurs from the first entry in the ocean to the age of ten (Johnson 1980b; Le Jeune 1967).

3.5.7 Interactions with other fish species

Inuit knowledge

In several lakes used by anadromous Arctic char (*Iqaluppik*) during the fall and the winter, lake resident Arctic char (*Nutillik)*, and lake trout (*Isiuralitaak*) are also present. Although *Iqaluppik* and *Nutillik* are in sympatry, they do not use the same areas to spawn according to participants in Kangiqsualujjuaq. In Kangiqsualujjuaq and Kangirsuk, participants mentioned that lake trout and Arctic char can prey on each other and eat each other's eggs. Nonetheless, it has been mentioned in Kangiqsualujjuaq that lake trout and Arctic char are often seen together in fall and winter, "*like best friends*" (E. Snowball and S. Etok, 2019, Kangiqsualujjuaq, pers. communication). Some fishers even think that lake trout could help Arctic char to spawn as they have been seen around Arctic char during the spawning period. They sometimes find hybrid fish, that look like Arctic char, but with a lake trout tail. These hybrids are more frequent in the northern regions on the eastern side of Ungava Bay.

Brook trout (*Aanaak)* can be found in several streams also used by Arctic char. Both species use different spawning habitats, but brook trout will feed on the eggs of char when they are spawning (LNUK meeting, 2019, Kangiqsualujjuaq). However, participants think brook trout are not a problem for Arctic char populations. Author P. May has knowledge that they will also hybridize with char on occasion as he has seen quite a few hybrids in the George River, 100 miles inland from Kangiqsualujjuaq.

In Kangiqsualujjuaq, Atlantic salmon (*Salmo salar*, *Saamaak* in Inuktitut) is present in the George River and the Koroc River. In Tasiujaq, more and more Atlantic salmon are going up the Bérard River at the beginning of July (n=1, Tasiujaq). They did not use to go up the river. In both communities, participants think they did not seem to be a problem for Arctic char. Nonetheless, in Tasiujaq, they have been seen to scare the juvenile char (n=1, Tasiujaq).

In Kangiqsualujjuaq, some fishers mentioned that there was an increase of other fish species like brook trout, lake whitefish (*Coregonus clupeaformis*) and sucker species (*Catostomus* sp.) (LNUK meeting, 2019, Kangiqsualujjuaq). In Tasiujaq, one participant mentioned that sometimes people catch suckers in the Finger Lake with gillnets and use them for dog food. Suckers seem to eat the eggs of Arctic char.

Discussion and links between Inuit knowledge and western scientific literature

Studies have shown the hybridization of Arctic char with lake trout across Canadian Arctic (Hammar et al. 1989; Wilson and Hebert 1993). Evidence of Arctic char and brook trout hybrids was also documented in Labrador (Hammar et al. 1991). As the hybrids seem difficult to distinguish from brook trout, it may explain why no mention of these hybrids were made during the interviews. Brook trout were observed near spawning Arctic char by Cunjak et al. (1986), but were rather suspected to eat eggs. The presence of Atlantic salmon is increasing in some Nunavik rivers but its impact on Arctic char still remains unknown (Bilous and Dunmall 2020). However, they might feed on juvenile Arctic char, as a participant observed salmon scaring young char. Since 2017, new occurrences of pink salmon (*Oncorhynchus gorbuscha*) were documented in the Canadian Arctic, including one found in Kangirsuk in 2019 (McNicholl et al. 2021). Since then, three other specimens were confirmed in Ungava Bay (V. Nadeau, 2022, MFFP, Unpublished data). However, according to the interviewees, the communities do not see any significant impact due to competition, although these various species live in sympatry with Arctic char. In Northern Europe, competition and predation of brown trout on Arctic char parr have been observed (Heggenes and Saltveit 2007; Amundsen and Knudsen 2009), but the species is absent of the Canadian Arctic.

Cannibalism was observed in landlocked populations of Arctic char in Norway (Knudsen et al. 2016) or in Nunavut, in summer captures in Lake Hazen (Sinnatamby et al. 2012) or with a prevalence in winter in a lake of Cumberland Sound (Young et al. 2021). In contrast, from the captures in summer and winter at seven other sites in Cumberland Sound by Moore and Moore (1974), 10% of anadromous char showed some stomach content but none was identified as cannibalistic. Anadromous Arctic char not only does not have a cannibalistic behavior, but they actually do not really feed or really little in winter, as for example, on 409 individuals captured by Young et al. (2021), all had empty stomach in winter but one (fed on unidentified fish remains). In lakes north of Kangiqsualujjuaq, the 239 Arctic char captured along one winter all had empty stomach (Boivin and Power 1990).

3.5.8 Predators

Inuit knowledge

The main predators of Arctic char mentioned by participants are black bears (*Ursus americanus*). In the three communities, they are more and more frequently observed along the rivers when Arctic char are spawning. River otters (*Lontra canadensis*) are also predators of juvenile char. In Kangirsuk, participants mentioned that in a specific lake and a river area there have been a lot of otters for a long time, and, for this reason, they think that Arctic char might not spawn anymore in these locations. Nonetheless, they do not seem to impact the fish population in Tasiujaq or Kangiqsualujjuaq where they are also present. In Kangirsuk, falcons (*Falconidae* sp.), Osprey (*Pandion haliaetus*) and Bald eagles (*Haliaeetus leucocephalus*) have also been mentioned as predators and are more frequently seen in recent years than in the past.

Discussion and links between Inuit knowledge and western scientific literature

Inland predators of Arctic char like otters and black bears have been scarcely mentioned in the literature. Beddow et al. (1998) mentioned their potential impact to adult char in some Labrador rivers where black bear were also present. The northern limit of black bear distribution range overlaps the southern range of Arctic char distribution in Nunavik. However, black bears are more frequently observed further north than in the past decades (Cuerrier et al. 2015). By extending the overlapping territory with Arctic char, they could become significant predators, especially during the reproduction period when the fish are schooling in shallow rivers.

3.5.9 Observed changes in abiotic factors influencing habitat use

3.5.9.1 Decrease of size and catch

Inuit knowledge

In Kangiqsualujjuaq, participants mentioned that the mean size of Arctic char was decreasing and explained they had previously experienced that when the size gets smaller, the population decreases. Indeed, one participant told that in the 1960's, overfishing due to the commercial fishery supplying the community's co-op store led to an important decline of *Iqaluppik* population until the 1970's (B. Baron, Kangiqsualujjuaq). However, since the closure of the commercial fisheries in the late 1960's, two participants agree that the fish population has been partially restored and abundance is higher than it was 50 years ago. In Kangirsuk, fishers have observed that the quantity of catches is decreasing, and the Arctic char stock is thought to be declining.

Discussion and links between Inuit knowledge and western scientific literature

Commercial fisheries or overfishing can lead to a shift in size distribution through the selection of the larger and older fish (Johnson 1980b). This size truncation could be detrimental to population recruitment (Berkeley et al. 2004), as it was observed in Kangiqsualujjuaq in the 1960's-70's by participants and documented by Gillis et al. (1982). Furthermore, it was shown that Arctic char length and age increased with distance from the community while experimental commercial winter fisheries were in place since fishing was conducted mainly in the closest sites from the community (Boivin et al. 1989). Hence, the size reduction observed currently in Kangiqsualujjuaq likely indicates that the local stock is under pressure.

3.5.9.2 Lower hydrology, drought, and higher water temperature

Inuit knowledge

In recent years, participants from the three communities observed several changes in rivers, impacting fish habitats. Most participants mentioned that the lack of rain during summer and fall seasons can be a problem because the rivers are too dry for the fish (n=3 in Kangiqsualujjuaq; n=1 in Tasiujaq; n=3 in Kangirsuk). The upstream migration can be affected because of the low water level in rivers, and some fish even die. It has happened more frequently in the last decade and some participants mentioned that the difference in mean water level during the summer, compared to past decades, was important. Nonetheless, the impact does not show on the largest rivers which do not seem to be as affected. It has been mentioned in Kangiqsualujjuaq that for 10 to 15 years Arctic char habitat has changed substantially, water temperature is increasing, and char are looking for cold water refuges. The spawning sites identified by elders and visited by the previous generations of fishers might not be used anymore (Elder from Kangiqsualujjuaq, 2019, pers. communication). For example, a small lake, linked to the Koroc River is much less frequently used for spawning because aquatic plants have grown and are thought to block its outlet (Anguvigak meeting, 2019, Kangiqsualujjuaq). In Tasiujaq, in the last 5 to 10 years, rivers are much dryer in summer and fall and that is an impediment to fish passage in reaches where there was no problem before (n=1). Water temperature is also higher. Algae are now growing in areas of spawning habitats. Shrubs along the rivers are growing fast and one participant mentioned that their roots could also take more water from the river. Talking about a specific river branch, a participant mentioned: "*It has been really dry in the last five years. We used to go there fishing, there was lot of red char in the river. We barely see them. I do not think they really spawn much anymore.*" (W. Cain Jr., Tasiujaq). Also, in Tasiujaq, mortality of juveniles has been observed during a warm summer day (A. Gordon, Kuujjuaq, 2020, pers. communication). In Kangirsuk, in addition to the lack of rain during the fall, it has been mentioned by several fishermen that there is less snow in winter and that winds are stronger.

Discussion and links between Inuit knowledge and western scientific literature

Char growth has been linked, although weakly, to some environmental variables (Chavarie et al. 2018), especially rainfall for the adults and air temperature for the juveniles. Inuit observations on how a low hydrology can impact upstream migration and reproduction, as well as how high temperatures can affect the juveniles are direct and show a link between climatic variables and char condition. The lack of rain in summer and fall has been broadly observed in the three communities over the last decade and is likely a consequence of climate change. It has also been noted in Kangiqsujuaq (Cuerrier et al. 2015). This trend for summer and fall was not yet visible in historical climate simulations based on the climatic normal data before 2010 at the scale of the whole Nunavik region (Charron 2015), and a significant increase in precipitation is even observed from the historical data for the Ungava Bay before 2014 (1981-2010 reference period) (Barrette et al. 2020). The day-to-day observations of Nunavik Inuit were not yet recorded in historical data from the previously cited studies. The long-term future climate evolution (2041-2070) predicts also an increase in summer and fall precipitations, for both moderate and high emission scenarios (Ouranos 2021). The discrepancy between Inuit observations and long-term climate predictions could be either due to a local and temporary decrease trend, to scale discrepancies or to prediction uncertainties in regions with scarce data (Charron 2015). This highlights the need of more local meteorological and hydrometric data collection to monitor climate evolution and its impact on river hydrology. Predicted increase of mean temperature and of growing season is in accordance with Inuit observations.

3.5.9.3 Water level, thawing permafrost and erosion

Inuit knowledge

In Kangiqsualujjuaq, an experienced fisher mentioned that in some lakes, winter water levels are lower than in the past decades, as some boulders are now showing above the surface where it was only ice and snow in the past (E. Snowball, 2020, Kangiqsualujjuaq). Also, in Kangiqsualujjuaq fishers observed that "*Before, char were spawning under small rocks and now, there is sand covering all*" (LNUK meeting, 2019, Kangiqsualujjuaq). In Tasiujaq, it has been mentioned that "*the riverbed looks like the rocks are growing up.*" (W. Cain Jr., Tasiujaq). In addition to the lack of rain, permafrost thawing is thought to be the cause.

Discussion and links between Inuit knowledge and western scientific literature

In the interviews conducted in Nunavik by Cuerrier et al. (2015), permafrost thawing was also thought to be the reason of the decreasing level of lakes. In addition to a potential lake drainage from the bottom (although talik zone of unfrozen ground is already present), erosion of river banks and gullying lead to enlarged rivers and lakes outlet (Rowland et al. 2010; Vincent et al. 2017) (

Figure 3.4). Hence, for the same flow, water level of rivers and lakes tend to decrease. Landform and soil of Arctic region are the results of dynamic, relatively recent geological processes and are still active today (Allard 1996), leading to dynamic river bank erosion, which is also an important source of sediment input in the rivers, that could restrict fish passage. Post-glacial isostatic movements could be a factor of lower water level in coastal streams (Fracz and Chow-Fraser 2013).

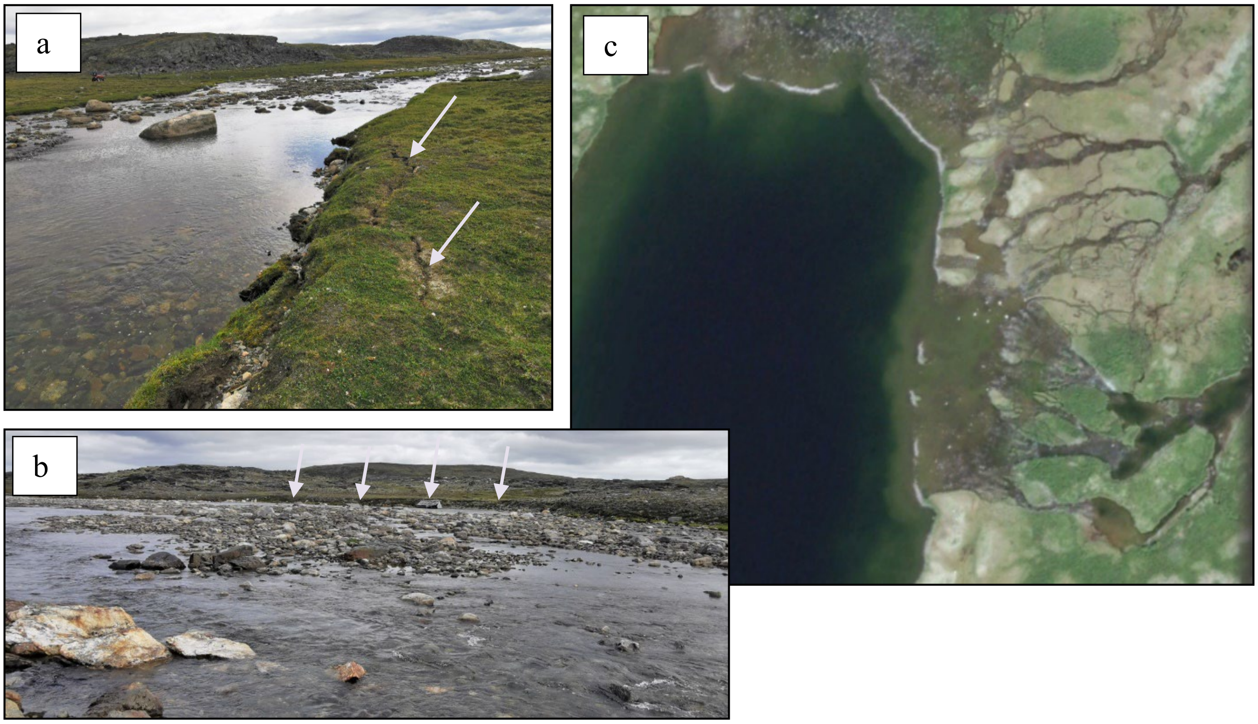


Figure 3.4 **a) and b) Riverbank erosion in Kangirsuk that has for consequence to enlarge river, decrease water depth, and increase sediment load in the river, impeding the fish passage. c) Lake outlet in Tasiujaq showing multiple channels and water tracks. The erosion and increase of these potential outlets lead to lower water level of the lake as the total potential flow output at the outlet of the lake increase (Credit for a and b: Véronique Dubos, August 2021; Source for c: Google Earth).**

3.6 Conclusions and future research directions

The strength of Inuit knowledge of Arctic char ecology lies in the detailed observations of the fish behaviour simultaneously done in conjunction with other environmental observations integrated over centuries. The life cycle and general behaviour of the fish described by Inuit knowledge holders were largely consistent with existing scientific studies, however, the contextualization of scientific literature in relation to this knowledge has made it possible to complement some western scientific findings and to highlight relevant avenues for research on Arctic char ecology:

- The forego of marine migration by the char who will reproduce during the fall has been scarcely described in the literature. In the Kangiqsualujjuaq region, there is evidence of a large number of spawners (*Aupalujaak*), identified as the main reproducers, that remain in rivers during the summer. Hence, there is a risk of underestimating fecundity rate by sampling the fish during the upstream migration in the lower section of rivers only. When the river system is used for subsistence fishing, it is recommended to ask local Inuit fishers for the potential presence of *Aupalujaak* in the rivers in summer. Further studies would be relevant to assess what is the extent of this behaviour in other regions. The existence of specific riverine populations has also to be differentiated from spawners of the anadromous form that skip summer migration.
- The the potential selectivity of spawning sites according to the presence of groundwater spring fed areas remains to be established for Arctic char.
- The winter schooling of Arctic char in open water areas or in locations with thin ice was, to our knowledge, undocumented by scientific literature. Whether the ice-free or thin ice conditions are due to the char swimming or on the contrary, whether the char are aggregating in thin ice or open water areas, for better oxygenation, still remains to be elucidated.
- Juvenile Arctic char are often observed by Inuit at river mouths and even in estuarine areas. The use of the freshwater surface layer by pre-smolt was confirmed by telemetry from the literature (Atencio et al. 2021). Thermohaline stratification is likely allowing them to reach estuarine and tidal environments at an early age.

- Scientists and Inuit knowledge holders agreed about the increase of mean temperature. However, the decrease in rain amounts observed during critical season for Arctic char, does not agree with the scientific analyses and model predictions (Charron 2015; Barrette et al. 2020). River flows are known to trigger upstream migration, according to Inuit observations, and a suitable water level is essential to access the reproduction sites. This highlights the importance of Inuit knowledge in hydrology and the need for more data collection in Arctic regions, especially in Nunavik regions where meteorological and hydrometric stations are scarce. The impact of changes in hydrology and temperature on spawning habitat could be addressed by future research.
- More information on the impact of black bear predation would be an asset.
- We recommend that all research, if not Inuit-led, should at least be co-developed with Inuit communities.

This study provided further insight into anadromous Arctic char ecology of Ungava Bay, with some inter-community specificities informed by Inuit knowledge holders. It also brought to light fish behaviour not yet documented (e.g., winter fish schooling), or documented punctually in other geographic areas such as the non-migrant spawners in Kangiqsualujjuaq. It also led to new explanations of some scientific observations and research avenues. This highlights how Inuit knowledge holders are of prior importance in ecological studies to increment existing documented knowledge.

Acknowledgements

We wish to thank the LNUK boards members from Kangiqsualujjuaq, Tasiujaq, and Kangirsuk for their interest and assistance. Véronique Dubos wishes to thank Mikhaela Neelin (McGill University) for her support to plan the first interviews. We are thankful for the comments of McCombie Annanack (Kangiqsualujjuaq). This project is supported by Makivik Corporation and MFFP (ministère des Forêts, de la Faune et des Parcs du Québec). The authors thank the editors and all the reviewers for their constructive comments.

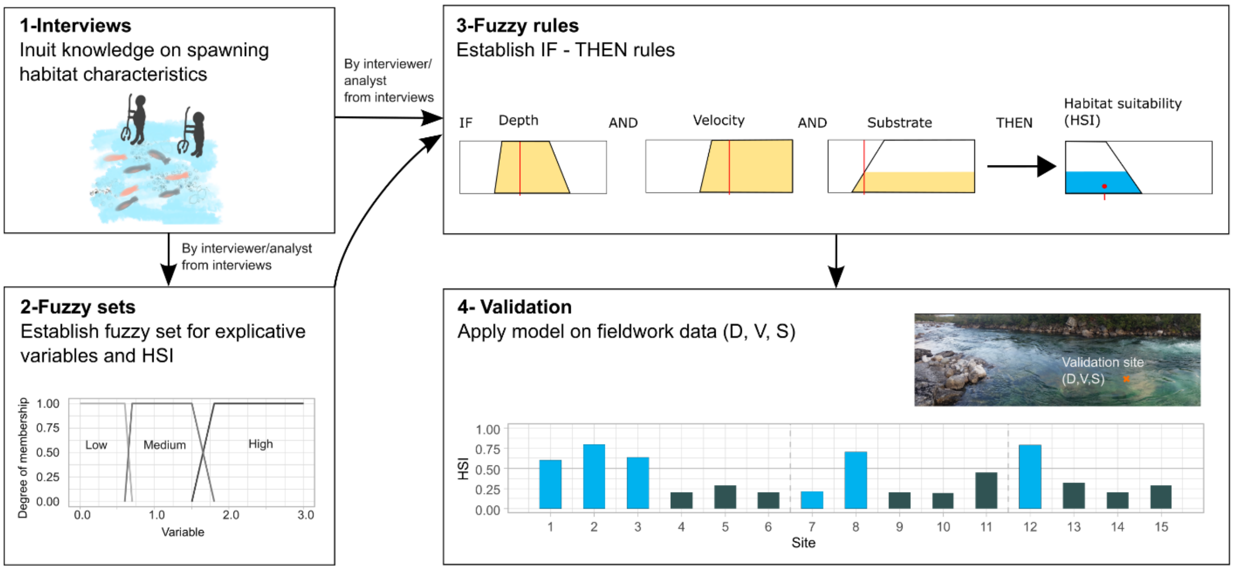
Competing interests

The authors declare there are no competing interests.

Data availability

Data generated or analyzed during this study are not publicly available due to the nature of this research. Each LNUK have ownership, control and possession of the data and permission regarding access or use of data would need to be directed to them or local authorities.

4 MODÉLISATION DE L'HABITAT DE FRAIE À PARTIR DES SAVOIRS INUIT, EN UTILISANT LA LOGIQUE FLOUE



Présentation du chapitre

Ce chapitre constitue le traitement quantitatif des résultats d'entrevues réalisées à Kangiqsualujjuaq, Tasiujaq et Kangirsuk. Il complémente l'analyse qualitative des résultats d'entrevues sur l'ensemble du cycle de vie, présentée au chapitre précédent. Comme les Inuits ont spécifiquement une connaissance détaillée des habitats de fraie, le but de ce chapitre est de présenter une méthode de modélisation basée uniquement sur les savoirs inuits, qui permet de prédire l'adéquation des sites de fraie en fonction des caractéristiques locales (0-10 m^2) de la rivière. La méthode est une adaptation de la modélisation d'habitat par la logique floue par des experts scientifiques (Mocq et al. 2013).

Titre de l'article

Fuzzy logic modelling of anadromous Arctic char spawning habitat from Nunavik Inuit knowledge

Auteurs

Véronique Dubos[1], André St-Hilaire[1,2], Normand E. Bergeron[1]

[1] Institut national de la recherche scientifique (INRS), Québec, Qc

[2] Canadian Rivers Institute, Fredericton, N.B.

Publication

Dubos, V., St-Hilaire, A., Bergeron, N.E., 2023. Fuzzy logic modelling of anadromous Arctic char spawning habitat from Nunavik Inuit knowledge. **Ecological Modelling** 477, 110262. https://doi.org/10.1016/j.ecolmodel.2022.110262

Contribution des auteurs

J'ai contribué à la planification du guide d'entrevues. J'ai réalisé les entrevues et fait leur validation avec les participants. J'ai contribué à établir à méthodologie spécifiques pour appliquer la logique floue aux experts inuits. J'ai contribué aux analyses et à la rédaction de l'article.

ASTH a contribué à la conception de l'étude, à la méthodologie pour appliquer la logique floue et à la révision de l'article. NB a contribué à la conception de l'étude, à l'analyse et à la révision de l'article.

Highlights

- Inuit experts provided new details on anadromous Arctic char spawning habitats in rivers.
- Based on this information, fuzzy logic was successful to predict habitat suitability.
- This is the first spawning habitat predictive model for Arctic char in river.
- This is the first fish habitat model built only from Inuit knowledge.
- The method can be applied to other species where local/traditional knowledge exists.

Abstract

Anadromous Arctic char (*Salvelinus alpinus, Iqaluppik*) and their freshwater habitats are vulnerable to the effects of climate change. Spawning habitats are critical to ensure the propagation of populations and the fisheries they support. However, detailed descriptions for river systems in the Canadian Arctic are limited, especially in the Nunavik region. As Arctic char is a traditionally important species for culture and subsistence of Inuit, some harvesters have a deep knowledge pertaining to habitat use, including optimal habitat conditions for spawning. Interviews of Inuit knowledge holders on Arctic char, were conducted in three communities of Nunavik, Canada: Kangiqsualujjuaq, Tasiujaq, and Kangirsuk. From the knowledge of Inuit experts, the most suitable spawning habitats were located in rivers, at depths between 0.6 m and 1.5 m with velocities > 0.1 m/s. A large range of riverbed substrate was deemed suitable as long as the smaller substrate size class showed some presence of gravel or coarse sand, depending on the local geomorphology. We used fuzzy logic to code natural language description provided by Inuit experts into a numerical value representing the Habitat Suitability Index for spawning sites. The model was able to predict the spawning habitat suitability or unsuitability of 14 out of 15 sites, given values of depth, velocity, and substrate. The methodology presented is well-suited to build quantitative model based on the description of local observations and could be applied for other animal or plant species for which local and/or traditional knowledge exists.

Keywords

Reproduction habitat, Arctic char habitat, Expert systems, Indigenous knowledge, Inuit qaujimajatuqangit, Fish habitat model, Arctic fish.

4.1 Contributorship of knowledge holders

The present study is based on the knowledge of the following Inuit experts who have participated to the interviews. We are grateful for the time and the knowledge they shared. They are, in Kangiqsualujjuaq: Tommy Unatweenuk, Tivi Etok, Bobby Baron (D.), Kenny Angnatuk, Susie Morgan; in Tasiujaq: Moses Munick, Tommy Cain Sr. (D.), Willie Cain Jr.; and in Kangirsuk: Elijah Grey, Jeeka Kudluk, Mary Airo. Interviews in Kangiqsualujjuaq were arranged and interpreted by Thomas Edward Annanack. Interpreters were Susie Kudluk in Kangirsuk and Mary Annanack in Tasiujaq,

4.2 Introduction

Arctic char (*Salvelinus alpinus*), and especially its anadromous form (*Iqaluppik* in Inuktitut), contributes to subsistence and is of social and economical importance for Inuit families and communities of Nunavik, Canada (Blanchet et al. 2002; Watts et al. 2017; Berkes 2018). Adult The fact that mean temperature anadromous Arctic char exclusively feed in marine environment during one to two summer months. They return to freshwater systems for reproduction and/or overwintering until the next downstream migration, during the ice breakup. The spawning period, between mid-September and mid-October (Cunjak et al. 1986; Johnson 1980b), is a popular fishing season. Hence, knowledge of reproduction habitat preferences is important for northern communities to protect critical Arctic char habitat, especially in the context of potential vulnerability such as low water level and bank erosion increasingly observed in Nunavik (Neelin 2021) and in other northern regions (Smart 2021). Local organisation of hunters, trappers, and fishers (Local Nunavimmi Umajulirijiit Katujjiqatigiinninga, LNUK) in Nunavik have concerns about the stocks of Arctic char that are perceived to have decreased in some communities of Ungava Bay. There are indeed more frequent observations from fishers that mature Arctic char have difficulties to access their spawning habitats during their upstream migration as they become more limited and/or disconnected, and even some watercourses which no longer sustaining char populations (LNUK meeting, Kangiqsualujjuaq, 2019, pers. communication; W. Cain Jr, Tasiujaq, 2019, pers. communication).

In Nunavik, anadromous Arctic char mainly spawn in rivers, from small streams to delimited areas of large rivers and areas of flowing water in lake inlets and outlets (Johnson 1980b; Reist et al. 2017; Dubos et al. 2023a). To our knowledge, no spawning habitat suitability model has been established for anadromous Arctic char in rivers. A few spawning sites used by anadromous Arctic char in rivers were described in the literature (Dempson and Green 1985; Johnson 1980b; Cunjak et al. 1986). However, their descriptions were not made in a perspective of detailed habitat characterization, and the information provided was not sufficient to infer preferred ranges of values for depth, velocity, and substrate, required to construct predictive models of spawning habitat.

Local or traditional knowledge holders can have a deep understanding of species distribution and behavior through the regular observation of animals, especially when they are part of subsistence or traditional country food (Mackinson and Nøttestad 1998; Berkes and Berkes 2009). Traditional ecological knowledge (TEK) is a qualitative knowledge and a way of knowing that derived from the experience and traditions of a particular group of people (Usher 2000). It is "*a cumulative body of knowledge, practice and belief, evolving by adaptative processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment.*" (Berkes 2017). TEK has been used to inform animals habitat studies, for instance for seals (Gryba et al. 2021), and in habitat modeling through cartographic description for caribou and moose (Polfus et al. 2014; Tendeng et al. 2016). Although increasingly used in habitat models, TEK remains rarely quantitatively integrated in scientific studies nor used as the main source of information (Roux et al. 2019; Stern and Humphries 2022). Inuit hunters are harvesting Arctic char since time immemorial and are traditional knowledge holders. Scientists studying fish population have worked advantageously with Inuit hunters for data collection (Bell and Harwood 2012) and Inuit knowledge is more and more considered in fisheries management (Moller et al. 2004; Snook et al. 2019). Since Inuit knowledge is accumulated from the past but also an evolving and current knowledge (Usher 2000), it allows to identify environmental change and trends, including changes in abundance when quantitative data are limited (Knopp et al. 2012; Janjua et al. 2016; Falardeau et al. 2022). However, Inuit knowledge has not been yet incorporated in the understanding of physical Arctic char habitat, though the fish use the same specific spawning sites year after year (Kristofferson 2003; Moore et al. 2017), and are regularly observed by Inuit harvesters.

Experts' systems have the faculty to model and represent human logic reasoning, using linguistic variables, i.e., by reasoning on imprecise data. Among them, Bayesian modelling (e.g., Tantipisanuh et al. 2014) or Fuzzy logic (Zadeh 1965) can be applied to predict habitat suitability. However, in Bayesian models, experts' knowledge is most often used to supplement quantitative field data, which are costly and challenging to acquire in Arctic remote environment. Indeed, the posterior distribution obtained in Bayesian models is often based on field data (see e.g.,Ellison 2004). Fuzzy logic is a method that allows the incorporation of the complex Indigenous knowledge in ecological modeling through qualitatively described observations (Berkes and Berkes 2009), without the need for quantitative input data. The fuzzy logic method consists of using reasoning through logic rules to get a numerical value representing a degree of truth, between 0 and 1. The method is suitable for modeling the behavior of living species from fishers knowledge since it allows one to consider the continuum that exists between descriptive variables and the uncertainty in associated ranges of variable values to categories (Mackinson and Nøttestad 1998). This method was successfully applied to assess habitat suitability of several fish species based on scientific experts' opinion (Mouton et al. 2007; Ahmadi-Nedushan et al. 2008; Mocq et al. 2013; Wegscheider et al. 2021). Nevertheless, the results of the model can be biased by the geographical origin of the experts who established the variables categories and logic rules as their observations were made in different environments (Mocq et al. 2015). Thus, using this finding positively, local or traditional knowledge rooted in specific regions can be expected to yield relevant information for regional fish habitat studies. Fuzzy logic modeling can thus be useful when applied in concert with Inuit knowledge.

Given the limited detailed scientific data pertaining to the physical characteristics of anadromous Arctic char spawning sites in Nunavik region, the overall goal of the study is to model and assess spawning habitat suitability based only on Inuit knowledge. Inuit knowledge (*Inuit Qaujimajatuqangit*) is a way of being and embraces all aspect of the Inuit traditional culture (Nunavut Department of Education 2007). In the present study, the term 'Inuit knowledge' is nonetheless restricted to the factual knowledge of the environment (Category 1, Usher 2000). Our specific objectives were to assess if (1) Inuit knowledge can describe accurately spawning habitat with the classical fish habitat model variables (water depth, velocity, and substrate) and if (2) Fuzzy logic was well-suited to use knowledge of Inuit hunters for quantitative analysis of Arctic char spawning sites. In the present study, spawning site suitability was assessed for rivers, including lake inlet or outlet where flowing water can be observed, but not in deeper areas or lakes. Building habitat suitability model for spawning sites will bring insight for river habitats and fisheries management by local communities.

4.3 Methods

4.3.1 Study area

The study was conducted in the three communities of Kangiqsualujjuaq, Tasiujaq, and Kangirsuk, located in the Ungava Bay (Nunavik, Quebec, Canada) (Figure 4.1). Regional climate is classified as polar with mean annual temperature of 5.7 °C and mean annual precipitation of 526 mm, with average snowfall of 257 cm/year (from Kuujjuaq A meteorological station). Kangiqsualujjuaq is located on the east side of the bay, on the shore of the George River, and the land is covered with shrub tundra with local forested tundra in valleys lowlands. Tasiujaq is located south of the west coast of Ungava Bay, on the shore of the Berard River, in shrub tundra zone. Kangirsuk lies on the west coast of Ungava Bay, along the Ariaq River (Payne/Arnaud River) and is at the edge of shrub tundra zone and herb tundra zone. The villages of Kangiqsualujjuaq and Tasiujaq lie both on widespread discontinued permafrost at the edge of continuous permafrost whereas Kangirsuk is on continuous permafrost zone (L'Hérault and Allard 2018). In Kangiqsualujjuaq and Tasiujaq, bed substrate consists mainly of shallow marine deposits (MRNF Québec 2004) with gravel size substrate inter-mixed among larger size boulders, and is more heterogenous than in Kangirsuk area. Around these two communities, Arctic char have access to a large variety of streams and lakes. In Kangirsuk, Arctic char spawning sites were mainly identified in large and fast flowing rivers such as the Kuugat (Buet) and Avaluk (Vachon) which have slopes of 4.2 ‰ and 3.6 ‰ respectively on their lowest 30 km, used locally by Arctic char for spawning. The rivers around Kangirsuk are flowing over fluviatile deposits (MRNF Québec 2004).

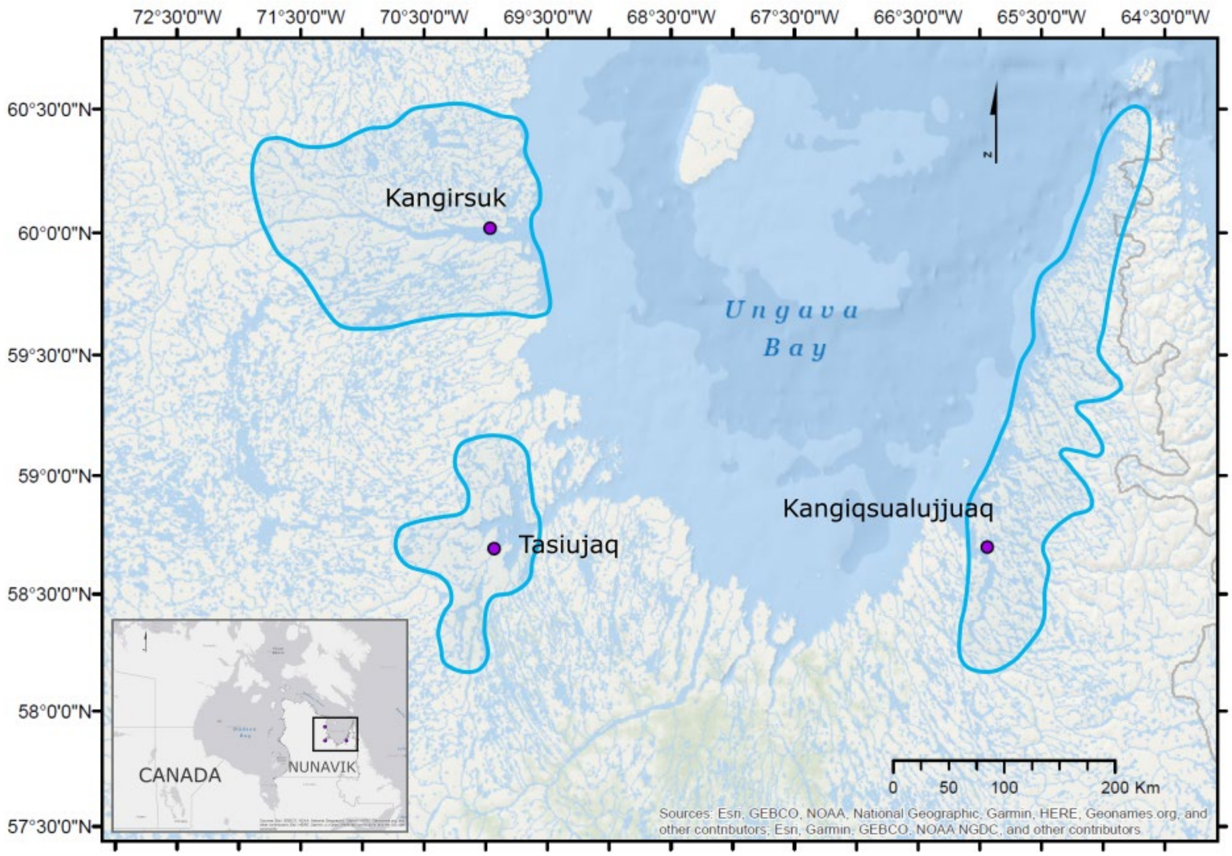


Figure 4.1 **Approximate limits of the territories described by the Inuit experts interviewed from the three communities about Arctic char habitat use (blue contour). Several participants used and had knowledge on larger territories not illustrated on the map. This delineation does not represent the extent of land use by Inuit, nor does it encompass the entire distribution of Arctic char in Ungava Bay.**

4.3.2 Interviews of Inuit experts

Interviews were conducted during summer 2019 with elders and younger active hunters from the Kangiqsualujjuaq, Tasiujaq, and Kangirsuk villages. Inuit hunters, who conduct both hunting and fishing activities, play an important role in Inuit communities as they provide country food and contribute to the maintenance of social relationships (Kishigami 2000). The participants were selected by the local Hunters and Trappers' Associations (Local *Nunavimmi Umajulirijiit Katujaqatigininga,* LNUK) for their knowledge of Arctic char and are herein referred to as experts of the Arctic char. A total of 11 experts were interviewed, among them, two were women and nine were men. Nine of the participants were elders and two were middle-aged experienced hunters. Elders were considered very knowledgeable in their communities and held in great respect. Interviews were conducted on an individual basis in Kangiqsualujjuaq (n=5) and Tasiujaq (n=3) although participants from Kangirsuk requested to be interviewed as a group (n=3). The interviews were conducted in semi-directed form, mainly under informal conversation, framed with fixed topics and questions (see Interview guide in Dubos et al. 2023a, Supp. material). All interviews were conducted by the first author, with the assistance of Inuktitut-English interpreters, except for the two youngest participants who were interviewed directly in English. It was noticed that all participants were comfortable specifying when they were unsure or did not have knowledge of certain aspects or sites. More detail on the interviews context and process and on the qualitative analysis is given in section 3.4.

Specific questions were asked about anadromous Arctic char river habitat preferences for spawning, with multiple choice answers based on photos and videos. For the present study, the habitat preferences were based on the information collected on water depth, velocity, and substrate type (later converted to median diameter) selected by Arctic char at the local scale (0-10 m^2), a slightly larger scale than typical microhabitat. These three variables correspond to classical fish habitat variables used as inputs in models (Bovee 1986). Five photos showing different substrate, with increasing range of mean diameter, and including different levels of heterogeneity (Figure 4.2), were presented to the participants who gave an opinion on the suitability of the substrate for spawning. To assess the suitable velocities, three videos of flowing rivers were presented, showing current velocities of 0.10 m/s, 0.27 m/s and 0.73 m/s as they appeared to be representative of the limits of categories of ‘Low’, ‘Medium’ and ‘High’ (Mocq et al. 2013a; Mouton et al. 2008) that could be expressed in natural language. Questions about depth used by the fish to spawn were simply answered by participants giving numerical values in feet although a measuring tape was available. Some spawning sites were also located on maps, independently of the site descriptions. Most of the spawning sites identified on maps were well known by the participants of the same community and by other collaborators, including our fieldwork guides.

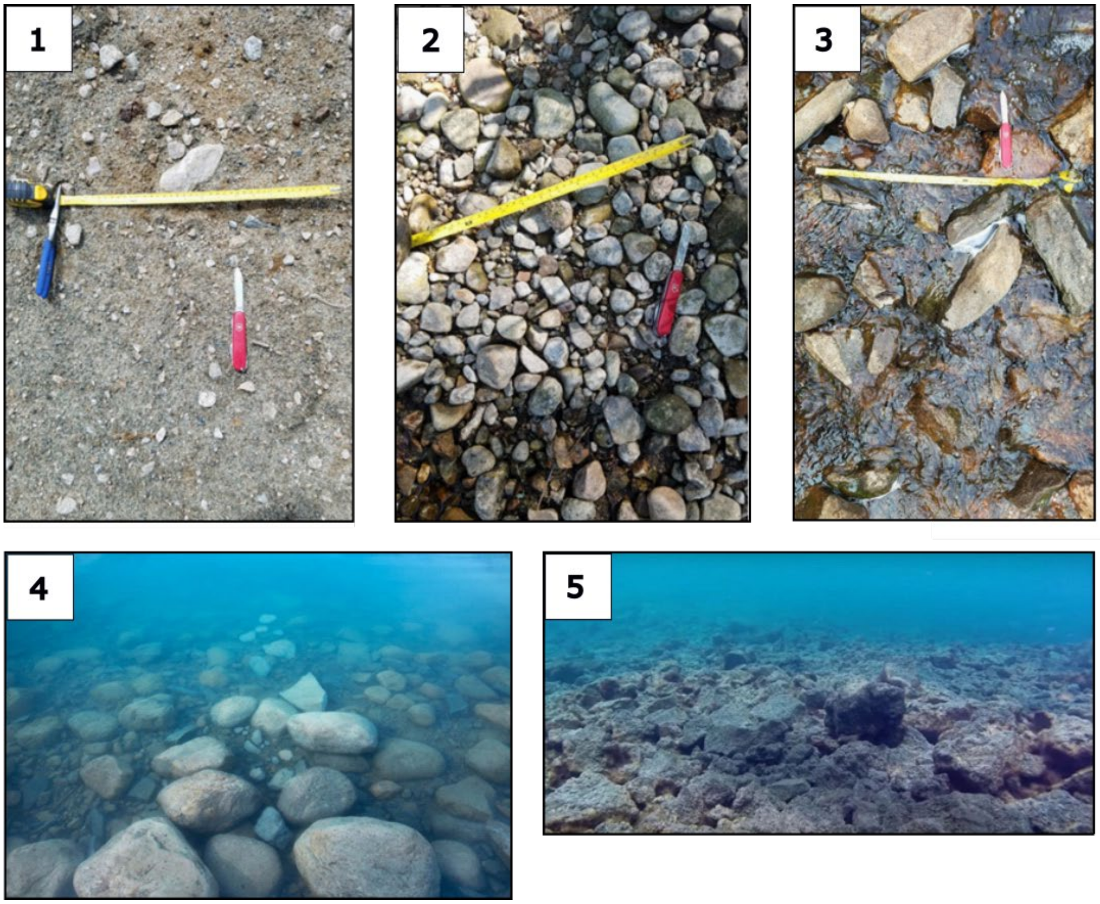


Figure 4.2 Photos of riverbed substrate presented during the interviews for the choice of suitable or unsuitable substrate grain size distribution for spawning habitat. Photos were initially chosen to represent a gradation in the predominant substrate, from sand to boulder with different level of heterogeneity.

A validation of the interview transcription was done by lead author with each participant, except for three of them who were not available, to ensure experts' opinion and interpretation were adequately reported and coded. This validation process was conducted with interpreters translating the English synthesis of information to Inuktitut to minimize misunderstandings/misinterpretations that could have arisen from translation. A synthesis of the information collected during the interviews was produced and provided to the participants, to the LNUK and the municipal office of each community, and to the Nunavik Research Center. Informed written consent was given by each participant. The location of spawning sites illustrated on maps during the interviews had to remain confidential. An ethics certificate for research involving humans was obtained from the Ethics Committee of Institut National de la Recherche Scientifique for the conduct of the interviews (CER-19-517).

4.3.3 Fuzzy logic model

Habitat suitability of spawning sites were modelled using fuzzy logic. The general principle of fuzzy logic is a mathematical method that handles unprecise (fuzzy) variables as input data and applies simple relations between these data, called logic rules (Zadeh 1965). The resulting combinations of these rules is a solution that represents a degree of truth (0: completely false, 1 completely true). In our case, the input variables were the local characteristics of the physical variables (river depth, velocity, and substrate) described during the interviews and the output was a Habitat Suitability Index (HSI). The fuzzy logic method was implemented with the Matlab Fuzzy toolbox (MathWorks 2018). A general description of the procedure and the definition of membership function is given in Mocq et al. (2013) and Beaupré et al. (2019). In our study, the following specific steps were applied:

1. Transform input variables (i.e., physical habitat variables: depth, velocity, and substrate) and model output (i.e., spawning habitat suitability index) into fuzzy sets (fuzzification). A fuzzy set is described by a range of values of a variable assigned to a category, to which is associated a membership function (0 = no membership, 1 = 100% membership in the specified category) (Figure 4.3). To incorporate the uncertainty about the boundaries of each category (the so-called fuzziness), each value of the specified variable can belong to one or more categories simultaneously. The limits of the categories were established according to interviews results (see section 4.4.2).

   For a given combination of input variables, the model output was a value of Habitat Suitability Index (HSI). Not to be confused with the membership function, the HSI also varies from 0 (habitat is inadequate) to 1 (habitat is fully adequate). The HSI fuzzy set was also chosen to have three categories, with “low” ($HSI<0.5$) meaning a poorly suitable habitat, “medium” ($0.3<HSI<0.7$) for moderate suitability and “high” ($HSI>0.5$) for good habitat suitability. It was not possible to determine a consensus in the literature on the standard limits for HSI categories. A triangular membership function was chosen for the “medium” category of the HSI fuzzy sets, to better differentiate between suitable or unsuitable sites, similarly to Ahmadi-Nedushan et al. (2008) and Zhang et al. (2016). The same fuzzy sets were used for each set of rules.

2. Establish logic rules for combinations of the variables and the implication on the suitability of the spawning sites, for instance: "IF the substrate is in the "coarse (high)" category AND the velocity is in the "medium" category AND the water depth belongs to the "medium" category, THEN HSI is in the "high" category (i.e., this site has good spawning habitat suitability). Rules were established from the interviews results, according to selected scenarios, to verify and consider inter-community differences and similarities (see section 4.4.2).

3. Run the model (apply the rules). The model was applied to field data for validation. The key habitat variables (depth, velocity, and substrate) of each validation site were measured. A membership value and a category were associated to each of the variable. A variable can belong to more than one category simultaneously (e.g., a velocity value of 0.25 m/s can belong in the “low” category with a membership of 0.5 and to the “medium” category with the same membership value, thereby representing the uncertainty or fuzziness). For this reason, several rules can be applied at the same time. Their association is called aggregation. In the present study, the "Maximum" method was applied for aggregation i.e., the combined resulting membership function value for HSI (Figure 4.4).

4. Defuzzify the aggregate fuzzy HSI to get a crisp numerical value of HSI between 0 and 1 (0 = unsuitability of habitat and 1 = maximum habitat suitability). Three defuzzification methods were tested (Figure 4.5): i) The “centroid”, for which the crisp value corresponds to the abscissa of the center of gravity of the aggregated HSI, ii) the “mom” which is the abscissa of the middle of the maximum aggregation and iii) the “lom”, which is the abscissa largest value of the maximum aggregation (Ouellet et al. 2021).

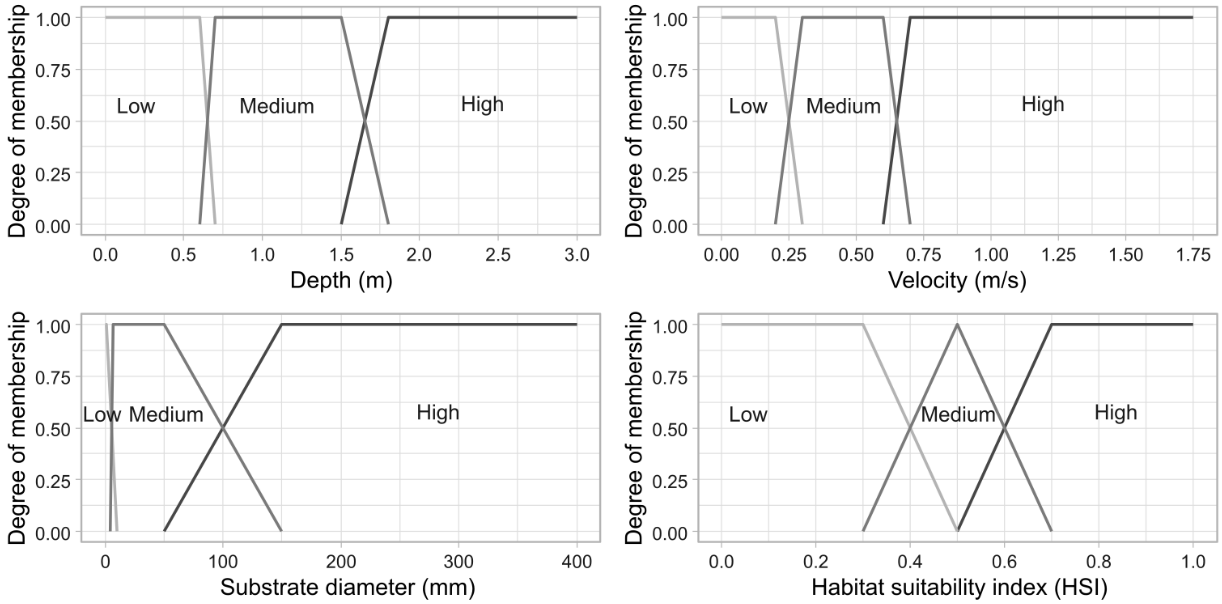


Figure 4.3 **Fuzzy sets showing membership functions for the input variables (depth, velocity, smallest class of substrate) and the fuzzy model output (HSI). For each variable, a given value belongs to at least one category (low, medium, or high) with a certain degree of membership. Boundaries overlap of the membership functions were established to be linked to the perception of the variable category and to the physical characteristic of the variable (see section 4.4.2.1).**

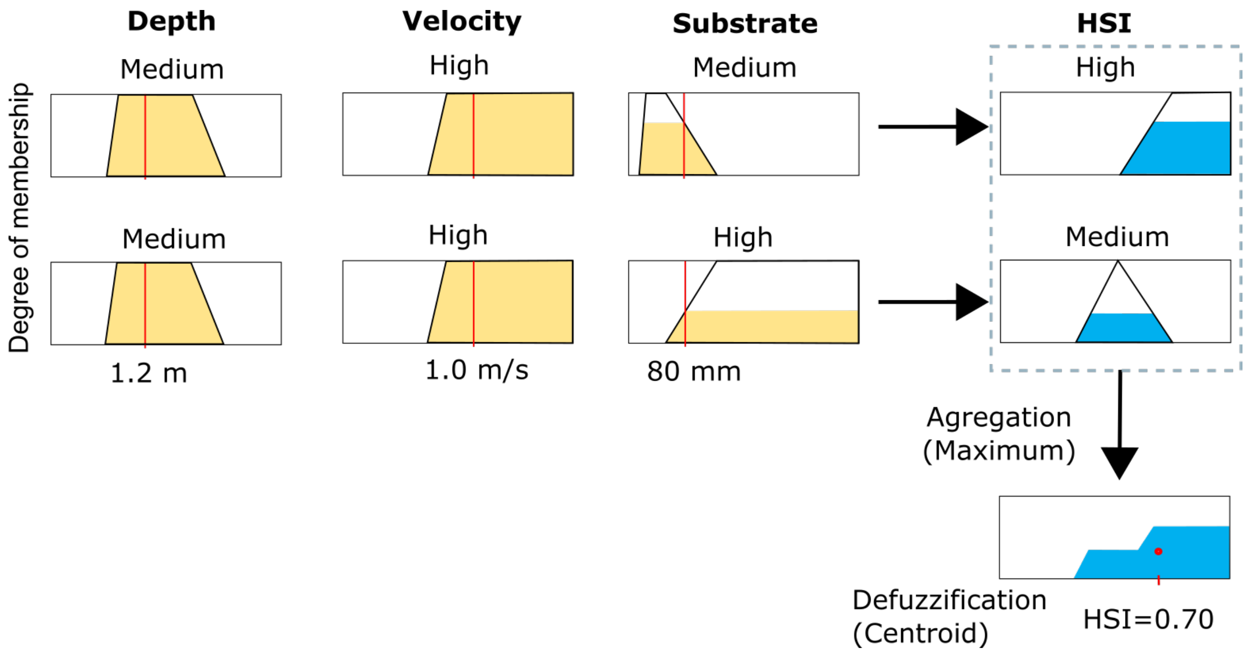


Figure 4.4 **Example of application of fuzzy rules and aggregation for a site (depth=1.2 m, Velocity=1.0 m/s; Substrate=80 mm). As substrate value belonged to two different categories (medium and high), two rules apply at the same time (see Table 4.2 for rules). The resulting fuzzy HSI corresponds to the aggregation of the HSI of each rule. The crisp or numerical value of the HSI is obtained by defuzzification with the "centroid" method and correspond to the abscissa value of the gravity center of the resultant HSI.**

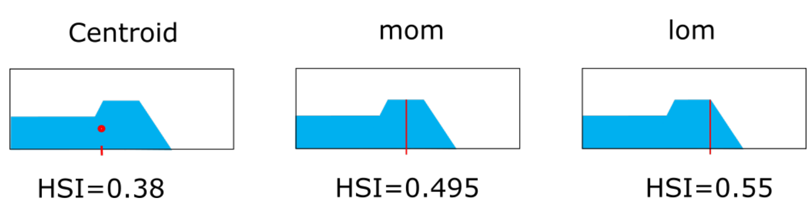


Figure 4.5 **Illustration of the defuzzification methods tested to obtain a crisp numerical value from the aggregate resultant HSI: Centroid, Middle of maximum (mom), Largest of maximum (lom).**

4.3.4 Intra-community similarities, inter-community differences and establishment of model scenarios

For a given community, the spawning site characteristics were described similarly, although some individual variations between responses were encountered (Figure 4.6 and Table S1, Supp. data). The small number of answers for variables categories did not allow us to apply distribution tests to compare potential inter-community differences as statistical power was too low ($1-\beta<0.1$). However, during the interviews, a discrepancy was noted between spawning site descriptions by the Kangirsuk experts and those from the other two communities (Kangiqsualujjuaq and Tasiujaq), which seemed qualitatively in agreement. In Kangirsuk, spawning sites were known to be specifically located in little bays along large rivers. The differences of suitable ranges of habitat variables were mostly noticeable regarding velocities and substrate. Hence, five spawning habitat models were built using different scenarios for input information:

- Model 1A, 1B and 1C: Rules from each community alone (respectively Kangiqsualujjuaq, Tasiujaq, and Kangirsuk).

  Model 2: Combined rules from the two communities of Kangiqsualujjuaq and Tasiujaq.
  Model 3: Combined rules from all the three communities of Kangiqsualujjuaq, Tasiujaq, and Kangirsuk.

4.3.5 Partial validation of the habitat suitability index (HSI)

4.3.5.1 Validation sites

The models built from Inuit knowledge were applied on 15 river sites (Table 4.1), located in the three communities. Validation sites were distributed in three different river systems in Kangiqsualujjuaq and two different systems in Tasiujaq. Sites in Kangirsuk were all in the Payne River. While in the same river, all sites were in different river sections, separated by a few hundred meters for the closest ones. The spawning sites were selected among the accessible sites located on maps during the interviews. Field guides also knew the exact location of those sites. Non-spawning sites were selected randomly during the fieldwork in areas known to not support spawning but connected to spawning areas and not showing obvious limitation for the fish. The sites were characterized in the field in September 2019, at or near the beginning of the spawning season. Arctic char in spawning color were observed in some identified spawning sites during the characterization, but their presence during the fieldwork could not be a criterion for the identification of sites as the spawning was not already started. No fish were seen at non-spawning sites. The measurements done at validation sites were representative of the local habitat (0-10 m^2). Water depth was measured with a weighed measuring tape, substrate mean diameter and the smallest class of substrate with at least ±15% of areal coverage, were estimated visually directly or using underwater camera. Mean surface velocity was estimated by measuring the time taken by a floating object to run through a distance from 1 m to 3 m. We chose to work with the surface velocity, as observed by Inuit from the shore or by boat. The resulting HSI of these sites were used for partial validation of the model's performance.

Tableau 4.1 Characteristics of the sites used to validate the models, measured in September 2019, close or at the beginning of spawning season. Sites were identified by multiple Inuit experts as being a spawning-site or a non-spawning site. The exact location of spawning sites remains confidential.

Site ID	Location	Spawning (1) / Non-spawning sites (0)	Depth (m)	Velocity (m/s)	Substrate (mm)
1	Kangiqsualujjuaq	1	1.8	0.4	150
2	Kangiqsualujjuaq	1	1.4	0.6	200
3	Kangiqsualujjuaq	1	1.5	0.0	5
4	Kangiqsualujjuaq	0	0.6	0.9	360
5	Kangiqsualujjuaq	0	2.0	0.0	5
6	Kangiqsualujjuaq	0	0.8	1.4	400
7	Tasiujaq	1	0.6	0.9	120
8	Tasiujaq	1	1.5	0.15	90
9	Tasiujaq	0	0.8	1.1	200
10	Tasiujaq	0	0.3	0.3	360
11	Tasiujaq	0	0.4	0.5	60
12	Kangirsuk	1	1.8	0.3	20
13	Kangirsuk	0	1.4	1.1	100
14	Kangirsuk	0	0.6	0.0	30
15	Kangirsuk	0	4.0	0.1	5

4.3.5.2 Results analysis

Each of these five models (see 4.3.4) were built using each different defuzzification methods. The Mann-Whitney U test (Mann and Whitney 1947), based on ranks, was used to compared the performance of the different models, according to the three defuzzification methods tested ("centroid", "mom", "lom"). The null hypothesis for Mann-Whitney test was that model mean HSI had similar distribution, whether it was calculated on sites with presence of spawning and on sites with absence of spawning. A rejection of the null hypothesis indicated that one of the mean HSI was significantly higher than the other.

The results agreement to the field data was assessed using Cohen's Kappa coefficient κ (Cohen 1960). The Kappa value is a measure of a true agreement of two data sets (in our case spawning/non-spawning and model prediction) beyond the 'by-chance' agreement, and is calculated from the following equation (Mouton et al., 2008):

$$\kappa = \frac{(a+d)-\left(\frac{(a+c)(a+b)+(b+d)(c+d)}{N}\right)}{N-\left(\frac{(a+c)(a+b)+(b+d)(c+d)}{N}\right)} \qquad (1)$$

where *a* is the number of true positive predictions, *b* is the number of false positive predictions, *c* is the number of false negative predictions, *d* is the number of true negative predictions and *N* is the number of data points. A positive value of κ implies that the model is in agreement with the data. The strength of agreement can be scaled between slight (0-0.2), fair (0.21-0.4), moderate (0.41-0.6), substantial (0.61-0.8) or almost perfect (0.81-1) (Landis and Koch 1977). In addition to the Kappa value, the model sensitivity and the specificity, respectively the proportion of truly positive prediction (suitable spawning prediction on all spawning site) and truly negative prediction (unsuitable prediction on all non-spawning sites), were calculated.

4.4 Results

4.4.1 Inuit knowledge about spawning sites characteristics

An interview synthesis of the information about the suitability of the physical variables for anadromous Arctic char spawning sites, is provided in Table S1 (Supp. data).

4.4.1.1 Depth suitability

There was a consensus on water depth suitability or unsuitability for spawning sites. All participants (100%) mentioned that depths between 0.6 m and 1.5 m were suitable for spawning (Figure 4.6). Water depth less than 0.6 m were deemed inappropriate by 78% of participants, for different reasons, such as the greater vulnerability to predators, and the risks of freezing in the winter or dewatering during low flows. Three participants indicated that depths higher than 1.5 m were also suitable (27%). One participant from Kangiqsualujjuaq declared that depths higher than 1.5 m as unsuitable, whereas participants from Kangirsuk (36%) declared depths between 1.2 m to 1.8 m the most suitable. Other participants did not express an opinion about the upper limit of depth preferences.

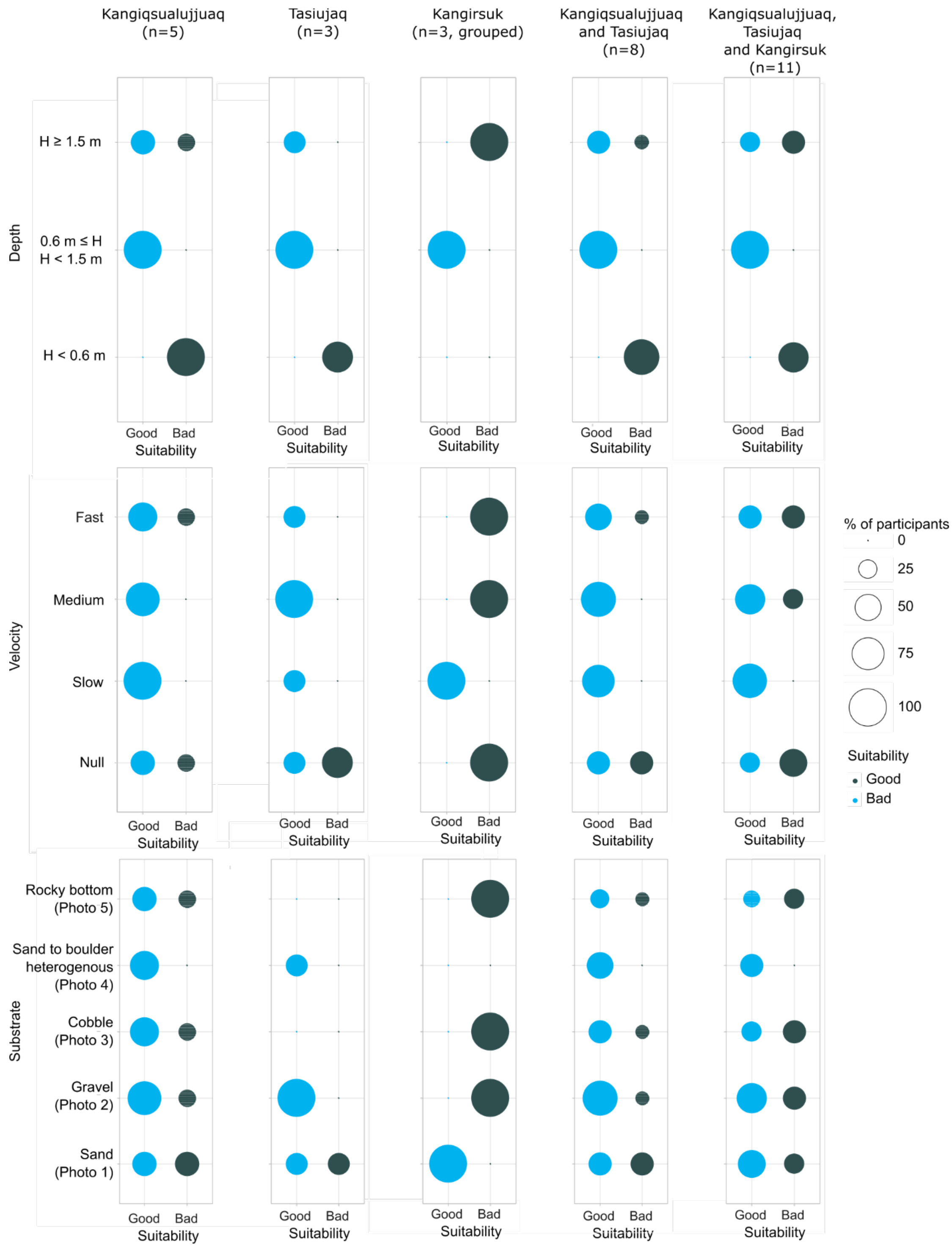


Figure 4.6 **Spawning habitat suitability of Arctic according to the Inuit experts for: 1 – Each community alone; 2- the two communities of Kangiqsualujjuaq and Tasiujaq; 3- the three communities together (Kangiqsualujjuaq, Tasiujaq, Kangirsuk). Velocity suitability was determined from videos and substrate suitability was determined from photos. Experts were allowed to express no opinion.**

4.4.1.2 *Velocity suitability*

73% of the experts indicated that spawning takes place only in rivers, including in areas located near outlet or inlet of lakes, where there is flowing water, and 27% think that some anadromous Arctic char can spawn in deeper area of lakes too. The presence of flowing water was considered an important variable for the choice of spawning site and a suitable velocity could be either slow or medium (0.10 m/s and 0.27 m/s videos). In Kangiqsualujjuaq and Tasiujaq, even fast velocity from the 0.73 m/s video was considered more suitable than unsuitable. Hence, the range of the suitable velocities was rather large. According to the experts of Kangiqsualujjuaq and Tasiujaq, the less suitable condition for anadromous Arctic char was null or near zero velocity. In Kangirsuk, where the rivers used by Arctic char to spawn are large and fast flowing, the suitable velocities were described as slow, and always associated with habitat located in side bays, protected from the current of the river main channel.

4.4.1.3 *Substrate suitability*

Substrate photos presented were initially planned to represent a range of substrate diameter, including different levels of heterogeneity (Figure 4.2). Nonetheless, the answers to these images indicated that any bed substrate could be good for spawning as long as there was the presence of gravel patches (in Kangiqsualujjuaq, Tasiujaq and Kangirsuk) or coarse sand (in Kangirsuk) (Table S1, Supp. data). Sand or finer sediment were declared unsuitable for spawning sites in Kangiqsualujjuaq and Tasiujaq. Hence, the model was built using the representative diameter of the smallest class of substrate.

4.4.2 Establishing fuzzy sets and logic rules

4.4.2.1 *Input variables fuzzy sets*

Fuzzy sets were defined by three categories (low, medium, high), associated to a range of values of each habitat variable by a membership function (Figure 4.3). The three categories of depth (D) were defined to correspond to the participants' description of habitat used by spawning char, inclusive of the three communities: low ($D<0.7$ m), medium ($0.5 \text{ m} \leq D < 1.9$ m) and high ($D \geq 1.5$ m). For velocity, the participants found the videos presented well-suited to correspond to the different categories of velocities (low: 0.1 m/s, medium between 0.27 m/s and 0.73 m/s, high: 0.73 m/s and more). The substrate categories were established from the experts' comments, according to the smallest class of bed substrate instead of the mean grain size of overall substrate (corresponding to the photos shown). Indeed, participants were discriminating photos showing riverbeds with presence of gravel or coarse sand for the suitable substrate diameter, independently of the presence of other larger substrate. The range of substrate diameter was implicitly associated to the following classes: sand (0.062 to <2 mm), gravel (2 to <64 mm), cobble (64 to <256 mm), boulder (≤256 mm) (Valentine 2019).

The boundaries and overlap of the membership functions were established to be simultaneously linked to the perception of the variable category and to the physical characteristic of the variable. A smaller overlap of membership functions was used when the experts could easily discriminate the categories, like for example, low and medium substrate linked respectively to sand and gravel. A larger overlap was used when the membership to a category was less consensual and allows to take into account the variability, like for example cobble substrate which could be classified as either medium or large.

4.4.2.2 Logic rules

Five sets of specific logic rules, and thus five fuzzy models, were established from the three scenarios of input information (see 4.3.4). The sets of rules described the implication of different combinations of variables on the suitability of a spawning site, from the interviews results (Table 4.2). Both the specific answers to the variables' suitability (Figure 4.6) and the conversational descriptions given during the interviews were used. The models were then applied on the validation sites.

Tableau 4.2 Fuzzy Logic rules for Arctic char spawning sites suitability (L=low, M=medium, H=high). The rules are on the form of the following example: IF depth is Medium AND velocity is High AND substrate is Medium, THEN HSI is Medium. The first three columns describe the combination of categories of habitat variables, combined with the operator AND. The other columns provide the resulting HSI category for: 1A, B, C - Each community alone; 2- The two communities of Kangiqsualujjuaq and Tasiujaq; 3- The three communities together (Kangiqsualujjuaq, Tasiujaq, Kangirsuk).

Depth	Velocity	Substrate	HSI				
			Model 1A Kangiqsualujjuaq	Model 1B Tasiujaq	Model 1C Kangirsuk	Model 2	Model 3
L	L	L	L	L	M	L	L
L	L	M	M	L	M	L	L
L	L	H	M	L	L	L	L
L	M	L	L	L	L	L	L
L	M	M	M	M	M	M	M
L	M	H	L	L	L	L	L
L	H	L	L	L	L	L	L
L	H	M	M	M	L	M	L
L	H	H	L	L	L	L	L
M	L	L	L	L	H	L	M
M	L	M	H	H	H	H	H
M	L	H	H	H	M	H	M
M	M	L	L	M	H	M	M
M	M	M	H	H	M	H	H
M	M	H	H	H	M	H	H
M	H	L	L	L	L	L	L
M	H	M	M	M	M	M	M
M	H	H	L	M	L	M	L
H	L	L	L	L	L	L	L
H	L	M	H	M	L	M	M
H	L	H	M	M	M	M	M
H	M	L	L	L	M	L	M
H	M	M	H	H	L	H	H
H	M	H	M	M	L	M	M
H	H	L	L	L	L	L	L
H	H	M	L	M	L	L	M
H	H	H	L	L	L	L	L

4.4.3 Fuzzy models result: Habitat Suitability Index (HSI)

4.4.3.1 Comparison of defuzzification method

The five fuzzy models (sets of rules) were tested with the 15 characterized validation sites, classified as spawning or non-spawning sites (Table 4.1). For each model, the resulting HSI were compared to the actual presence or absence of spawning. A sensitivity analysis was conducted for the three different defuzzification methods. The “centroid” defuzzification was the most discriminating method for sites suitability as the mean HSI were significantly higher for spawning sites than for non-spawning sites, for each of the five models (Mann-Whitney U test, Table 3). With the “centroid” method, the mean HSI calculated on identified spawning sites was above 0.5 and the mean HSI on non-spawning sites was below 0.5, except for model 1C, built with data from Kangirsuk only (Table 3). For this model (1C), the value of mean HSI for spawning sites (HSI=0.45) remained below 0.50, making it difficult to assess suitability of some sites. However, as for other models, the difference of mean HSI between spawning and non-spawning was significant (0.45 *vs*. 0.28). The largest difference was achieved for model 3 (information from the three communities together), with a mean HSI of 0.62 for spawning sites and of 0.26 for non-spawning sites.

When using “mom” and “lom” defuzzification methods, the difference between HSI calculated for spawning sites and HSI calculated for non-spawning sites decreased. With the “mom” methods, only the results for model 1A (information from Kangiqsualujjuaq only) and model 3 (information from the three communities together) showed a significant difference in HSI values between spawning and non-spawning sites (Table S2, Table S3 and Table S4 in Supp. data). With the “lom” methods, more models showed significant difference in HSI. However, the resultant HSI were not only higher at spawning sites, but also higher at non-spawning sites, often close or even above 0.5, which made it more difficult to discriminate suitable from unsuitable sites (Figure 4.7).

Tableau 4.3 Mean HSI for spawning and non-spawning sites and Kappa value, for the different scenarios of input information (5 models): Scenario 1: Each community alone (1A, 1B, 1C); Scenario 2: The two communities of Kangiqsualujjuaq and Tasiujaq; Scenario 3: The three communities together (Kangiqsualujjuaq, Tasiujaq, Kangirsuk). The centroid defuzzification method was applied.

	Model 1A Kangiqsualujjuaq	Model 1B Tasiujaq	Model 1C Kangirsuk	Model 2 Kangiqsualujjuaq, Tasiujaq	Model 3 Kangiqsualujjuaq, Tasiujaq, Kangirsuk
HSI Spawning sites	0.61 ± 0.22	0.61 ± 0.22	0.45 ± 0.25	0.61 ± 0.22	0.62 ± 0.21
HSI Non-spawning sites	0.33 ± 0.13	0.35 ± 0.14	0.28 ± 0.12	0.35 ± 0.14	0.26 ± 0.09
Mann-W. test, W	46.0	44.0	42.5	44.0	50.0
Mann-W. test, p-value	0.014	0.026	0.037	0.025	0.004
Kappa value, κ	0.53 (Moderate)	0.30 (Fair)	0.38 (Fair)	0.30 (Fair)	0.80 (Substantial)
Sensitivity	67%	67%	50%	67%	83%
Specificity	89%	67%	89%	67%	100%

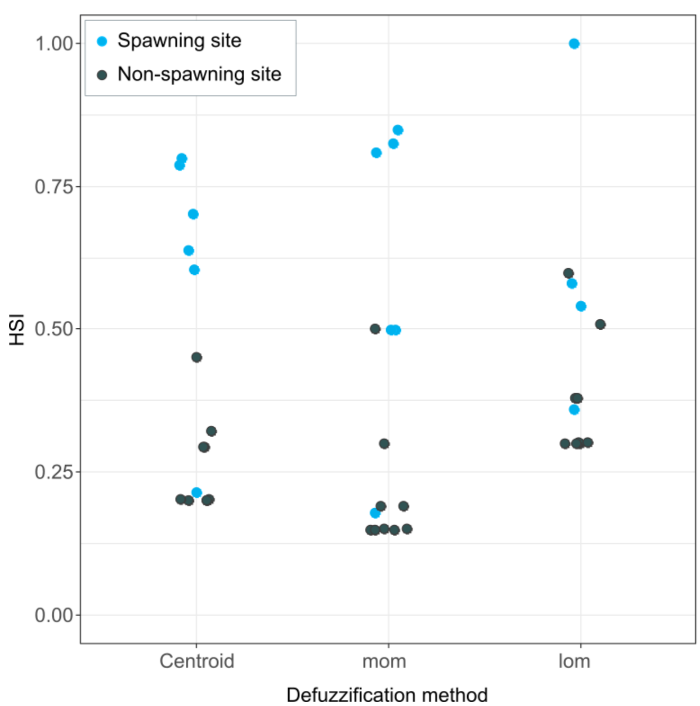


Figure 4.7 Comparison of HSI calculated from the three different defuzzification method for model 3.

4.4.3.2 *Comparison of model scenarios*

Compared to the results for scenario 1 or scenario 2, scenario 3 improved the ability to detect unsuitable spawning sites and to discriminate spawning and non-spawning sites with respectively a sensitivity of 83% and a specificity of 100%. The model agreement to the field data given by the Kappa value, was also the highest for model 3 (κ=0.80). This model successfully assessed the suitability of 14 of the 15 sites from the information given by all Inuit experts. The lowest Kappa value (κ=0.30) was obtained for model 1B and model 2, as these models gave HSI values inferior of 0.5 for two spawning sites and three HSI values of 0.5 for non-spawning sites (Figure 4.8). The three models of scenario 1, built with information from only one community, did not perform significantly better on validation sites from the same community (Table S5 in Supp. data). Models 1A and 1B perform similarly on all identified spawning sites but showed discrepancies on sites of absence. Model 1B (information from Tasiujaq only) gave higher HSI on non-spawning sites of Kangiqsualujjuaq and Tasiujaq, increasing the possibility of false positive, even on Tasiujaq sites. Model 1C gave the lowest mean HSI for both spawning and non-spawning sites, including on Kangirsuk validation sites.

Figure 4.8 Fuzzy model results: Habitat Suitability Index (HSI) on spawning sites and non-spawning sites from input information of scenario 1 with (a) Kangiqsualujjuaq alone, (b) Tasiujaq alone, (c) Kangirsuk alone, (d), scenario 2 with Kangiqsualujjuaq and Tasiujaq, and (e) scenario 3 with Kangiqsualujjuaq, Tasiujaq and Kangirsuk together. Sites 1 to 6 were located in Kangiqsualujjuaq, sites 7 to 11 were located in Tasiujaq and sites 12 to 15 were located in Kangirsuk. The centroid defuzzification method was applied.

4.5 Discussion

4.5.1 Inuit knowledge supports scientific literature on spawning sites

Examples of anadromous Arctic char spawning habitat characterization are relatively scarce in the literature, but some studies covering various geographic regions have described spawning sites characteristics that could be compared with the present study. The most suitable depth range given by the Inuit experts (0.6 m to 1.5 m /1.8 m) was slightly narrower but comparable to the ranges described in the literature where records indicate suitable depths between 0.2 m and 2 m (Johnson 1980b; Dempson and Green 1985; Cunjak et al. 1986; Beddow et al. 1998). The measured water velocities described in these studies were also variable (between 0.2 m/s and 0.8 m/s) but non-zero, similar to what was described by Inuit participants in the present study. Streams used by anadromous Arctic char to spawn in Nunavik and northern Labrador still flow during winter and the minimum depth to prevent freezing is about 0.6 m, as mentioned by Inuit experts. This stream use is contrasting to Canadian High Arctic where the rivers freeze to the bottom, preventing anadromous Arctic char to spawn in river unless some ground water feed the bottom (Harwood and Babaluk 2014).

Although some spawning sites described in the literature showed a predominance of gravel and pebble, char are known to use also heterogeneous substrates for spawning, consisting of a mix of coarse sand, gravel, pebble and boulders (Johnson 1980b; Cunjak et al. 1986; Beddow et al. 1998). Larger diameter substrate does not appear to hinder spawning. However, fine substrate (i.e., fine sand and silt) is typically not used for spawning, as described by Inuit experts. Char in the Fraser River, Labrador, exhibited two nesting strategies associated with the different type of substrate: either char dug redds when the substrate was dominated by coarse sand and gravel, or they dispersed eggs through the interstices of coarser substrate (Dempson and Green 1985). These two strategies were also described during the interviews as participants from Kangiqsualujjuaq and Tasiujaq mentioned that char usually do not build redds and the current rather disperses the eggs in the substrate, whereas in Kangirsuk, participants explained that char builds redds in the sand (Dubos et al. 2023a).

A potentially important finding from the analysis of our interviews is that substrate suitability for Arctic char spawning site is linked to the diameter of the smallest class of substrate instead of the mean diameter of substrate. The total proportion of this smallest class did not seem to be a factor determining the spawning site selectivity as long as there was a usable patch of suitable substrate. The minimal area of the patch is currently unknown. The importance of taking specifically into account small size substrate classes or substrate heterogeneity for fish spawning habitat studies has been known for a long time (Bain et al., 1985). Nonetheless in previous studies, a single value of mean, median or dominant substrate diameter was often included to model habitat suitability (for example in Ayllón et al. 2012; Garbe et al., 2016; Beaupré et al., 2019), probably because values describing the centre of substrate distribution are commonly used in hydraulic and physical habitat models. Granulometric indices have been widely used to integrate a level of substrate heterogeneity (Mocq et al., 2013; DFO, 2015). But when these indices are used, the dominant substrate classes are emphasized and the grain-size of the smallest substrate class is not specifically represented, although it could be of interest for spawning suitability, like in our study. This finding should be considered when describing substrate class for Arctic char and tested for other salmonids habitat suitability studies. The fine substrate could be considered from a threshold proportion, either by its diameter, like we did here, or by its proportion. Further work should be conducted to assess the minimum size of required substrate patch, which must be related to the stream size or order.

Experts interviewed expressed that a large variety of velocity and substrate can be suitable for Arctic char, which is in agreement with the known flexibility in niche selection of the species (Hammar 2014). Thus, in the present study, the characteristics they deemed unsuitable were also useful to establish rules and discriminate spawning and non-spawning sites.

4.5.2 Implication of the land-based knowledge of Inuit experts for sites characterization

4.5.2.1 Intra-community

Inuit experts generally agreed on the characteristics of suitable spawning sites, within each community. During the interviews, most participants from the same community located on maps the same spawning sites, since Arctic char show high spawning site fidelity. The knowledge of Inuit experts was gained from their own local use of territory, but also from other hunters, relatives, and ancestors. This shared knowledge leads to rich and tested information as their survival depends on it (Mackinson and Nøttestad, 1998; Berkes, 2017). As fuzzy logic is sensitive to the fuzzy rules, Ahmadi-Nedushan et al. (2008) recommended to combine several experts' opinion and ask them for a revision of their opinion in regards to what other participants thought. We presented interviews synthesis to the experts, following the Delphi method (Leite and Gasalla 2013). The validation of the interviews transcription did not result in changes in opinion from the experts about the spawning sites characteristics and the concordant intra-community opinion among Inuit experts limited the variability of results and was implicitly conducive to knowledge combination.

4.5.2.2 Inter-community

The different hydrographic and geomorphological features related to the geographic location of the communities could result in different inter-community perceptions of suitable variable categories for spawning habitats. For example, a velocity of 0.4 m/s in a small spawning stream of Tasiujaq could be described as “medium”, whereas the same value could be qualified as “low” in a side pool of a large rapid river in Kangirsuk, where Arctic char spawning sites were mainly identified. That might explain why “medium” velocities were considered suitable in Kangiqsualujjuaq and Tasiujaq but not in Kangirsuk. The difference of perception related to the type and size of rivers used by the fish was also one of the modelling challenges identified by Mocq et al. (2015), as the geographic origin of experts, from Europe and from North America, was a factor that partially explained discrepancies in estimation of suitable habitat. This is what was observed for the substrate suitability. Indeed, sand or finer sediment were deemed unsuitable for spawning sites in Kangiqsualujjuaq and Tasiujaq, where the riverbed substrate is more heterogenous, with gravel size substrate inter-mixed among larger size boulders, due to the geology (MRNF Québec 2004). In contrast, the reaches of rivers in the Kangirsuk region are flowing over fluviatile deposits. This explains the presence of sand in the slower reaches of the rivers, which are areas used by Arctic char to spawn according to the interviews. The substrate suitability discrepancies noticed between Kangirsuk and the two other communities was consistent with the different geologic characteristics. This highlights the importance of investigating the similarities/discrepancies of habitat characteristics among region/communities. The geologic characteristics and the type of surface deposits may be considered as additional model variables to discriminate the regions and established scenarios for the fuzzy rules.

In addition, the global size of streams used for spawning in each community, should be also considered. Indeed, the validation site 12 was the only spawning site characterized in Kangirsuk whereas the model 1C, from Kangirsuk experts’ information, performed the worst, giving a false negative. This site was located on the Payne River, whereas the discussion during the interviews was based mainly on the Kuugat (Buet) and Avaluk (Vachon), two tributaries that were of high importance in the past and still are. Their access in fall for fieldwork was not compatible with our logistic constraints. The difference of scale of the rivers might be in cause. Indeed, the depth of the validation site was 1.8 m, which falls in the 'high' depth category, while categories were established for all communities. High depth was nonetheless deemed 100% unsuitable habitat by Kangirsuk experts. A specific fuzzy set for Kangirsuk would have been more adapted, as the order of streams used by Arctic char was higher. Hence, in future work, fuzzy sets should be fitted to each region showing hydrogeomorphologic discrepancies.

4.5.3 Potential of fuzzy logic to evaluate spawning habitat suitability from Inuit knowledge

Fuzzy logic was a successful approach for the use of Inuit experts' knowledge and the models predicted spawning habitat suitability globally adequately for all models. Using "centroid" defuzzification method, all models exhibited significantly higher HSI for spawning sites than non-spawning sites. One of the validation spawning sites, the site 7, was evaluated as a poor spawning site by all five models. This site was located in a small rapid. Although it was indeed an identified spawning site (spawning was observed or at least highly suspected during the fieldwork), the hydraulic characteristics of this specific site were not in the range of highly suitable habitat with a depth of 0.6 m and velocity of 0.9 m/s. The fish might have selected other characteristics. Since, the site is on the downstream side of a large lake hydraulic control, it is likely that the presence of a hyporheic flow keep a suitable temperature for the eggs in winter, even with a low water depth. Despite this false negative, the agreement of model 3 (combined information from the three communities) to the field data is substantial, with a Kappa value of 0.80, showing the ability of the model to assess suitable spawning sites but also unsuitable sites. These results highlight the relative agreement in spawning habitat assessment among Inuit experts from different communities of the Ungava Bay region, compared to other studies using fuzzy logic with experts. For example, in Beaupré et al. (2019), scientific experts had to assess habitat suitability of Atlantic salmon (*Salmo salar*) parr from a combination of velocity, depth, substrate and temperature categories which lead to variable results and a stronger consensus about rivers originating from the experts region. In Mocq et al. (2015), the variability among scientific experts was found to be due to geographic origin, possibly also as fish can have specific and local preferences like it was established for brown trout (*Salmo trutta*; Mouton et al., 2009). The fact that Inuit experts used large territory likely gave them the opportunity to acquire knowledge covering a large range of sites specificities and, thus, allowed the fuzzy model to be representative of Ungava Bay Arctic char.

The fuzzy rules were established following the analysis of the interviews content, beyond the specific questions on habitat variables (depth, velocity, substrate), as the descriptions of spawning sites suitability or unsuitability were also included during the overall discussion which covered a larger scope. Hence, a certain degree of subjectivity is present and some differences in the interpretation of variables combination might depend on the person who is assessing the logic rules. However, given there was very few disagreements between experts from a same community on the suitable spawning sites characteristics, a consensus was generally quite naturally obtained on experts' opinion.

The low number of validation sites did not allow to optimize the model through the definition of variable categories and their range (Mouton et al. 2008). The validation was conducted on all the available validation sites, notwithstanding their location. In doing so, some knowledge that was specific to each community was not considered when applying the model to the variables of a site. The validation sites were also situated on rivers of various size which could have an impact on the relative characterization of variables. For example, in Kangirsuk, the three validation sites were located in the Payne River a major river whereas in Tasiujaq they were located on rivers less than 20 m large. This means that a depth of 0.8 m, that would be deemed suitable for spawning in rivers near Tasiujaq, would not be suitable in the Payne River. An increase of the number of validation sites would also allow to do a sensitivity study of the scenarios of input information applied on the different sites' regions. In addition, testing the model on sites outside of the Ungava Bay region would allow to assess its robustness in other Arctic regions. In the present study, the regional discrepancies were insufficient to truly affect model performance, as model 3 (i.e., using the information from all the three communities) provided the best performance in terms of spawning site identification.

Although specific values of the three variables (depth, velocity, and substrate) chosen to describe spawning sites could be associated to these sites, they lacked the hydrogeomorphologic context of the sites (e.g., little bay, side channel, …) and may not have been able to provide information that is site specific. For example, in Kangirsuk, participants described the river hydrodynamic characteristics at a broader scale than the local spawning habitat. The sites were indeed described as shallow, sandy little bays, in large and fast flowing rivers. It would be relevant to include mesoscale habitat information coupled with the fuzzy logic model. The use of remote sensing to extract predictive variables at the mesoscale (Hamann et al. 2014) may be a strong complement and should be considered in further studies. A difference in scale of analysis between western scientific and Indigenous knowledge can actually lead to more complete and improved habitat models (Polfus et al. 2014) and further, such studies would be relevant for Arctic char spawning habitats.

4.5.4 Other variables to be considered

According to the Inuit experts, water temperature triggers the spawning timing (Dubos et al. 2023a). Water temperature is also an important factor for the quality of eggs incubation (Jeuthe et al. 2016; Jobling et al. 1993). Nonetheless, Inuit experts could not describe temperature as an absolute variable. Since the char are in cold environment and the spawning is happening in fall, while water temperature is below a certain threshold, local temperature and warm thermal refuges could be of interest for the char. Indeed, regarding the habitat selectivity, presence of warm thermal refuges is a proxy for the presence of spring fed water source or hyporheic flow in the winter. Groundwater or hyporheic flow are important to the spawning sites for several char species, including Dolly Varden (Stewart et al. 2010), bull trout (Baxter and Hauer 2000) and brook trout (Curry and Noakes 2011). Upwelling of groundwater has also been associated with Arctic char spawning grounds near Kangiqsualujjuaq (Cunjak et al. 1986). Nonetheless, groundwater inflow through the riverbed is generally not visible from the surface and is seldom noticed unless the suspected upwelling site is instrumented. Hence, participants did not have any knowledge of the potential presence of underground springs in the rivers or associated to spawning sites. However, they mentioned that Arctic char were choosing sites where the water column was not freezing completely in the winter, which suggests the presence of upwelling ground water or hyporheic flow that increase the water temperature in winter. Further investigations are needed to test the hypothesis of spawning site selectivity according to the presence of groundwater inflow by anadromous Arctic char. Local temperature monitoring of spawning sites in winter could be a research avenue related to spawning selectivity.

Periphyton abundance can be positively associated to groundwater source (Hunt et al. 2006). During the fieldwork done to characterize the validation sites, periphyton was observed on the riverbed of several spawning sites and seemed absent from several non-spawning sites, although it was solely based on qualitative observations. Periphyton and biofilm constitute a source of food for benthic invertebrates including chironomids (Bégin et al. 2020), themselves sources of food for juvenile Arctic char (Moore and Moore, 1974; Sinnatamby et al., 2012). In addition, at a broader scale, the probability of occurrence of juvenile was associated to the streams with the highest density of benthic invertebrates (Danandeh Mehr et al. 2022). Hence, at a local scale, in addition to the presence of groundwater itself as a selectivity factor, the possibility of periphyton being a favorable biotic environment for early stage of fry should be considered in further research on spawning habitats and on connectivity with fry habitat.

Climate change have already had major impacts on hydrology and river erosion, and thus, on available habitat and on connectivity (Jeuthe et al. 2016). For example, one of the identified spawning sites on maps during the interviews is now seldom used by Arctic char because too many rocks and a low water level make the fish passage difficult. Hence, given the fast modification to the environment, it is important to make sure that spawning sites identified by elders are still up to date, which was the case of our validation sites. Regarding temperature, climate change can have an impact on the spawning timing, since the spawning act seems triggered by water temperature (Dubos et al. 2023a) and a post-spawning warming episode could be detrimental for the eggs and possibly on the eggs incubation (Jeuthe et al. 2016). However, climate change impact is still difficult to predict on the direct selectivity of spawning sites in a modelling perspective. In the present study, only abiotic physical variables were analysed. Nonetheless, during the interviews, biotic factors such as the presence of other fish species, the increasing abundance of algae or the presence of predators were mentioned by some Inuit experts as potential variables that could have an impact on spawning habitat and the presence or not of Arctic char on specific sites. Fish habitat studies would benefit from this traditional and local knowledge about specific sites.

4.6 Conclusion

Fuzzy logic was a successful approach to build a habitat model based on Inuit experts' knowledge. The model predicted spawning habitat suitability index in agreement with the field data for 14 of the 15 validation sites. The best results were achieved using the combined information of experts from the three communities of Kangiqsualujjuaq, Tasiujaq and Kangirsuk. The present study is, to our knowledge, the first fish habitat model based solely on Inuit knowledge and the first spawning habitat suitability model in river for anadromous Arctic char. The proposed model is intrinsically adapted to the Ungava Bay region, affected by changes in river hydrology and variation of Arctic char stock population, and can be a useful additional tool for fisheries and river management. For example, as local initiatives are occasionally conducted to improve fish passage and restore spawning site access to Arctic char, modelling spawning habitat can add information for river or site selection. Being able to have a quantitative habitat suitability index of vulnerable sites could serve as a tool for habitat protection by the communities, in a context of ongoing pressure for mining development on the territory.

Inuit experts interviewed had good knowledge of the physical characteristics of anadromous Arctic char spawning habitats and were able to describe the three classical variables of fish habitat models, depth, velocity, and substrate, associated to spawning sites. For a given community, Inuit experts generally agreed on the suitable and unsuitable characteristics of spawning sites however, discrepancies of spawning sites description were noted between communities and could be linked to the different local geology and geomorphology. The more suitable depths for spawning sites ranged between 0.6 m and 1.5 m and a large range of velocity was deemed suitable, as long as there was flowing water. Arctic char remains flexible in the selection of spawning habitats. Regarding the substrate, the analysis of the interviews highlighted the fact that substrate suitability for Arctic char spawning site was depended on the smaller class of substrate instead of the overall mean, median or dominant substrate diameter that is often used in fish habitat models. This finding should be considered when describing substrate class for further Arctic char habitat suitability.

It would be relevant for future work to add validation sites inside and outside the Ungava Bay region to assess the model robustness. Further research should also consider additional predictive variables of spawning site suitability, such as biotic factors as mentioned by some Inuit experts, the potential of groundwater inflow that could not be described by the visual observation of the experts, but could be established through local temperature, and considering mesoscale habitat through the use of remote sensing. These different perspectives highlight the advantages of braiding Indigenous knowledge and scientific knowledge and methods to increase global understanding of habitat selection.

The methodology presented in this study allows to formalize the description of local observations in a quantitative model and can be applied for other animal or plant species for which local and/or traditional knowledge exists. The prerequisite is that the predictive variables of the model can be categorized. Hence, the semi-directed interview method, including specific questions, is compatible with, and complementary to the scientific quantitative method applied.

Acknowledgements

We wish to thank the LNUK board members from Kangiqsualujjuaq, Tasiujaq and Kangirsuk for their interest and assistance and the guides for fieldwork: Elijah Snowball and Adam Annanack (Kangiqsualujjuaq), Daniel Annahatak (Tasiujaq) and Mark Manic Carrier (Kangirsuk). Véronique Dubos wishes to thank Mikhaela Neelin (McGill University) for her support to plan the first interviews. We are thankful to Carole Levesque (INRS) who commented on an early version of the manuscript. This project is supported by Makivik Corporation, NSERC and the *Institut Nordique du Québec*.

5 CARACTÉRISATION DE L'HABITAT HIVERNAL ET DES SITES DE FRAIE LACUSTRES DE L'OMBLE CHEVALIER ANADROME EN COLLABORATION AVEC DES PÊCHEURS INUITS

Illustration conceptuelle de la caractérisation de l'habitat hivernal.
Photo : Rivière Koroc, près de Kangiqsualujjuaq, Mars 2020

Présentation du chapitre

À l'automne, les ombles chevaliers anadromes rejoignent leurs lacs d'hivernage où ils passent la majorité de l'année sous le couvert de glace. Pour caractériser leur habitat hivernal, j'ai travaillé en collaboration avec des pêcheurs Inuits qui connaissaient les sites spécifiques utilisés par les ombles dans six lacs d'hivernage. L'étude est basée sur l'hypothèse que les sites de pêche traditionnels correspondent à des habitats utilisés par les poissons (sites de présence) et que les sites d'absence sont des sites où il n'y a pas de pêche. De plus, les pêcheurs connaissaient aussi certaines zones servant à la reproduction dans les lacs d'hivernage. Ainsi, des sites de présence et d'absence (pour les adultes et pour la fraie) ont été caractérisés. Comme les pêcheurs impliqués pratiquaient régulièrement une pêche de subsistance durant tout l'hiver, les relevés ont été adaptés pour qu'ils puissent les faire eux-mêmes lors de leur activité de pêche. Les variables mesurées ont été comparées afin de déterminer s'il y avait des différences entre les sites de présence et d'absence.

Titre de l'article

Characterization of anadromous Arctic char winter habitat and lake spawning areas in collaboration with Inuit harvesters

Auteurs

Véronique Dubos[1], André St-Hilaire[1,2], Isabelle Laurion[1,3], Normand E. Bergeron[1]

[1] Institut national de la recherche scientifique (INRS), Québec, Qc

[2] Canadian Rivers Institute, Fredericton, N.B.

[3] Centre for Northern Studies, Québec, QC

Titre de la revue

Article soumis à Arctic science le 9 février 2023.

Contribution des auteurs

J'ai contribué à la conception de l'étude. J'ai planifié, organisé et réalisé une partie des relevés de terrain et supervisé les relevés de terrain faits par les collaborateurs inuits. J'ai contribué aux analyses, à l'interprétation et la rédaction de l'article. J'ai présenté les résultats aux collaborateurs inuits et aux autorités municipales de Kangiqsualujjuaq pour vérifier l'interprétation.

ASTH a contribué à la conceptualisions de l'étude, aux analyses et à la révision de l'article. Il a contribué à la révision de l'article. NB a contribué à la révision de l'article

Highlights

- Anadromous Arctic char habitat occupancy was determined from Inuit knowledge.
- Site characterization was done with or by Inuit harvesters while they were fishing.
- Spawning areas had relatively shallow depths and warmer near-bottom temperature.
- Adult Arctic char used cold littoral zone where light reached the bottom.
- Sites of presence did not show other significant characteristics.

Abstract

In Nunavik, anadromous Arctic char spend more than six months under ice-covered habitats, mainly in lakes. Their winter habitats in this region have been scarcely studied due to the challenging logistics in the Arctic. In this study, we worked with Inuit hunters to characterize the winter habitat and spawning areas used by Arctic chars in six overwintering lakes. The collaborating hunters determined fish occupancy of certain areas (presence, absence, spawning) from their knowledge of fishing practices in the studied lakes. They also conducted measurements to characterize the sites, while performing their usual fishing activities. Measurements were planned to have a minimum impact on the fishing activities of the participating hunter, with adapted logistics and materials. The data showed that spawning areas were associated with shallower depths and warmer lake bottom temperatures than non spawning sites. Such attributes are beneficial for egg incubation. The productivity of these areas is also beneficial for fry that hatch during winter. On the other hand, adults and post-smolts habitats did not show any distinct characteristics but tended to be associated with cold littoral zone. The fish might use the lake bottom during this slow metabolism period while still benefiting from the presence of light. This exploratory study adds insights on the cryptic characteristics of the Arctic char winter habitat use, thanks to the Inuit hunters' expertise on the Arctic environment and their knowledge of fish movements.

Keywords

Overwintering, fish winter habitat, Inuit knowledge, Indigenous knowledge, winter fieldwork, Arctic fish.

5.1 Introduction

Anadromous Arctic char (*Salvelinus alpinus, Iqaluppik* in Inuktitut) is one of the northernmost distributed freshwater fish and has a circumpolar distribution (Klemetsen et al., 2003). Adults and non mature post-smolts anadromous Arctic char exclusively feed in marine environment during one to two summer months. They return to freshwater systems in fall, for reproduction and/or overwintering. Anadromous Arctic char typically use lakes to overwinter but can also use large river reaches that are not prone to freeze to the bottom (Boivin et al., 1989; Power and Barton, 1987; Smith et al., 2022). Although the overwintering period covers more than half of the year, this is the least studied part of the Arctic char life cycle, probably because conducting Arctic remote fieldwork in winter remains challenging and costly.

Recently, studies of winter habitat use have provided insight into winter behavior, activity level and movements of lake-resident Arctic char on a broad scale (Hawley et al. 2017), as well as anadromous char in their overwintering lakes (Mulder et al., 2018a, , 2019; Monsen, 2019) and overwintering rivers (Smith et al., 2022). The use of acoustic telemetry in these studies allowed to get a range of temperature used by the fish in winter. Since the water column in river was well mixed, the fish could not select thermal habitat. In lakes, the fish tended to use the upper water column, where water is colder (Mulder et al., 2018a). Depth and temperature were the only variables analyzed for habitat use. Recently, experimental gillnet sampling and simultaneous oxy-thermal measurements of lake water were conducted to assess habitat use of resident and anadromous Arctic char in Cumberland Sound, Nunavut. Although abundance of anadromous Arctic char was negatively correlated to pelagic area in the fall, no significant correlation was found between abundance and habitat variables in winter. The authors pointed out the necessity to assess the variability of its habitat use across its distribution range given the plasticity of the species (Klemetsen, 2010). To our knowledge, anadromous char winter habitat has not been characterized in Nunavik.

In Ungava Bay and particularly in Kangiqsualujjuaq, anadromous Arctic char is one of the few species caught year-round by the Inuit for subsistence fisheries. Winter is a good fishing season since fish are in specific areas known to harvesters, and access by snowmobile allows easier transportation than in other seasons (Boivin et al., 1989). Arctic char are usually harvested by gillnets installed under the ice for few hours or overnight, or by gigging with a hook (ice fishing). Both mature adults and non-mature (post-smolts) are caught. Knowledge of the sites used by fish is passed on from generation to generation of harvesters. Hence, traditional Inuit knowledge is a relevant source of information on Arctic char life cycle and habitat, especially in winter.

Given the paucity of scientific data on the physical characteristics of anadromous Arctic char winter habitat in Nunavik, during the presence of a stable ice cover, we collaborated with Inuit hunters to characterize Arctic char habitat during their traditional subsistence fishing activities. The idea was to use Inuit harvesters' knowledge of fishing sites in selected overwintering lakes to infer fish habitat use and then characterize it. The objectives of the study were to assess (1) if overwintering adults and post-smolts Arctic char select specific characteristics for their overwintering habitat and (2) if spawning areas (areas of incubation sites) identified in overwintering lakes showed different physical characteristics than non-spawning areas. Improved knowledge of the characteristics of habitats used by the adults and post-smolt will help to predict the impact of climate change and could be incorporated in fish habitat models. Moreover, some Nunavik communities consider increasing productivity with *in situ* hatchery in depleted rivers, where artificially fertilized eggs would be deposited. Hence, knowledge of the selected characteristics for spawning areas will be useful to select the potential incubation sites.

5.2 Methods

5.2.1 Study area

The study was conducted in in popular fishing lakes used by Arctic char to overwinter around Kangiqsualujjuaq, Ungava Bay, Nunavik, Québec, Canada. The ice cover in overwintering lakes is usually present from mid-November to the end of May. The mean annual temperature of the region is between -5°C and -6°C, and the total annual snow water equivalent varies from 300 to 400 mm, with a snow cover duration on the land between 241 to 260 days (Charron, 2015). The fishing sites were located in four different hydrographic systems. Three of them were located north-east of the village, Ujarasutjulik (Barnoin River), Koroc River and Tasikallak (Short Lake), while Tunnullik was located in the south-west portion of the territory (Figure 5.1). Ujarasutjulik (~2.5 km^2) and Ujarasutjuliup Qullinga (~10.7 km^2) are two consecutive fluvial lakes formed by a widening of the Barnoin River. Kuuurujuaq (~8.4 km^2) is also a fluvial lake formed by the Koroc River in its lower reach, while Koroc Allipaak is a lentic river reach of this river, about 25 km upstream. Tasikallak is a relatively small lake (~1.2 km^2) which flows directly into a fjord of the Ungava Bay through a short rapid stretch of 350 meters, while Tunnulik is also a small lake (~1.2 km^2) which flows into Ungava Bay through a lentic river of 4 km. In Tunnulik, the measured sites were located on its main tributary, at the lake entrance. Even if some studied sites were located in river reaches, the really low flow and the stable ice conditions makes them similar to lakes. Hence, for simplicity, the six sites are called overwintering 'lakes'.

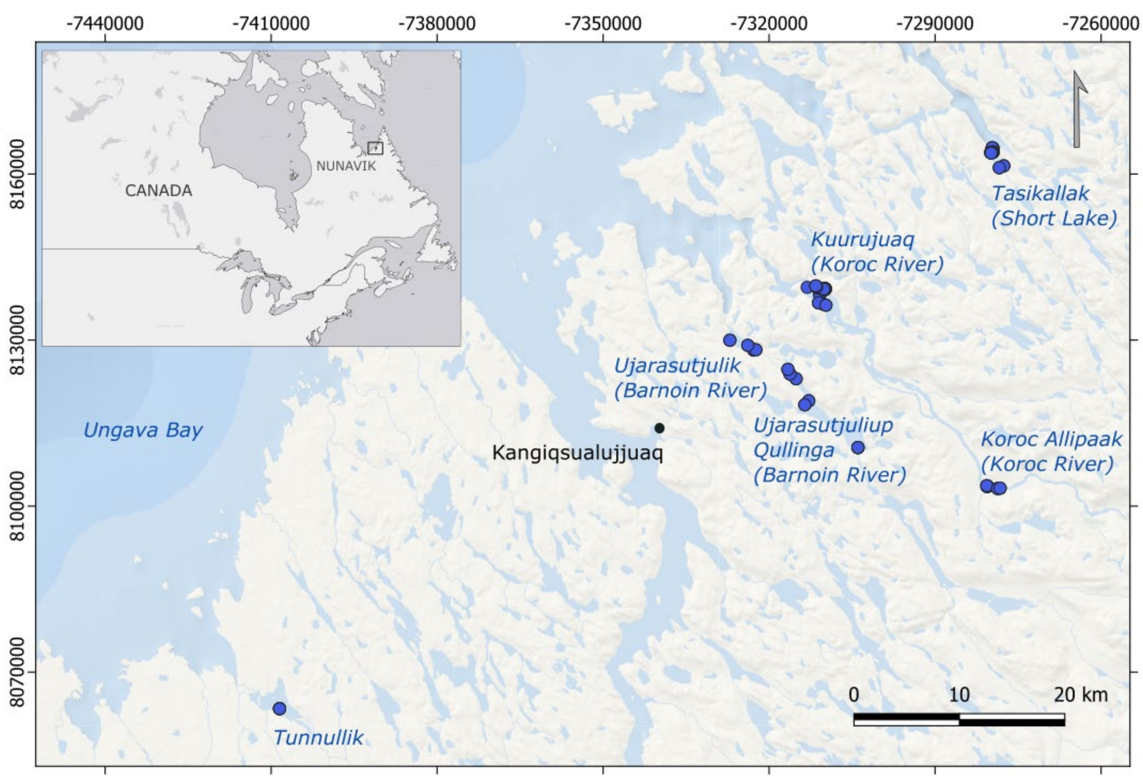


Figure 5.1 Location of the sampling sites. They are located in winter fishing areas that are popular with Kangiqsualujjuammiut. However, winter fishing is not limited to these areas. Map sources: Esri, "Ocean Basemap", GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other

contributors; and Esri, "Light Gray Canvas Map", DeLorme, HERE, MapmyIndia. Source: QGIS, Esri topo World. Coordinate references: EPSG:4326 - WGS 84, Projection: Pseudo-Mercator.

Anadromous Arctic char is the main fish species encountered in the studied lakes, but other salmonids are also present. Lake-resident Arctic char (*Nutillik* in Inuktitut), brook trout (*Salvelinus fontinalis; Aanaak*) and a few lake trout (*Salvelinus namaycush; Isiuralitaak*) are present in Ujarasujullik and Ujarasujuliup Qullinga. Brook trout, lake trout and Atlantic salmon (*Salmo salar*; *Saamaak)* are both using the Koroc River and thus, can be present in Kuuurujuaq and Koroc Allipaak. Tunnulik Lake also supports also brook trout and a whitefish (*Coregonus* sp.) was observed at this site, although they are do not seem to be a common species of the area.

5.2.2 Identification of site occupancy

According to the knowledge of experienced local hunters, Arctic char are generally harvested only in certain areas of the overwintering lakes, which can vary during the season. Hence, each lake has sites of fish 'presence' and 'absence'. Sites of 'presence' were defined as sites used for winter fishing during the sampling period, whereas sites of 'absence' were defined as all the other places where fishing was not practiced at any time of the year. In addition, some sites located in known spawning areas by the hunters were characterized and qualified as 'spawning' sites. The identified spawning areas were also mapped by elders who had spent a lot of time along the studied lakes and had observed the spawning (Dubos et al. 2023a). The sites not identified as spawning areas were analyzed as 'non-spawning' sites, although it is possible that some might just be unknown spawning site. Presence/Absence and Spawning/Non-spawning sites were analyzed independently as a spawning site could be either a winter habitat or a site of absence, and reciprocally. The type of occupancy was described qualitatively for each site characterized by the local hunters participating in the data collection and was confirmed by other knowledge holders from the community of Kangiqsualujjuaq during informal meetings. The characterized sites of absence were chosen randomly in areas never used for fishing. In addition to this Inuit knowledge, when fishing was carried out at the sites during the measurements, the occupancy of the sites was confirmed by catch or absence of catch. Underwater videos were also recorded from time to time to observe the presence or absence of fish, using GoPro Hero 3 and Hero 5 cameras attached to a stick.

5.2.3 Sites characterization

At each of the studied overwintering lake, some sites of ‘presence’ and ‘absence’ of fish or identified ‘spawning’ areas were physically characterized by drilling holes through the ice. A short in-person training was necessary for the use of the multiparameter instrument. The characterization was done at first with both researcher (author VD) and an Inuit hunter who subsequently did the measurements himself during his fishing activities. Due to a temporary incapacity, another hunter continued the measurements. He was also initially trained in-person by Makivik Research Center biologist. Hence, 43 measurements were conducted between January and May 2020, while snow and ice conditions allowed for safe access to the fishing areas. Five sites were sampled between March and April 2021, and two in May 2022. The principle of the method was that doing the measurements should have a minimum impact on the fishing activities of the participating hunters. The equipment provided for sampling was prepared to facilitate logistics; it had to be easy to handle in cold conditions and take up minimal space in a snowmobile sled. Instruments were selected so that they could be used through a fishing hole. The equipment included a chain of thermographs, and/or a thermometer and/or a YSI multiparameter probe (30 m cable); insulation materials and hand warmers to prevent the probe from freezing between two measurements; a weighted measuring tape (30 m) and an underwater GoPro camera mounted on a telescopic pole. Prepared notebooks were provided and were useful for the hunters to follow a standardized sampling.

At each site, fish occupancy, GPS location, ice depth, snow depth, water depth and oxy-thermal properties of the water column were collected. Snow depth and water depth were measured with the tape from the top of ice, that was equivalent to the lake water level. The ice depth was measured using a home-made wood stick that allowed to verify the ice bottom through the hole. Of the 50 vertical profiles conducted, 34 were obtained using a YSI multiparameter probe (either YSI 650 or YSI ProSolo) collecting temperature (accuracy ±0.15°C) and dissolved oxygen (DO; accuracy ±0.1%). The YSI instrument’s cable had a maximum length of 30 m, which was therefore the maximum length of the profiles for two sites with greater depths. For the other profiles, only temperature was measured, either with a Hanna thermometer (9 profiles, accuracy ±0.1°C) or with a vertical chain equipped of Hobo Pro V2 (±0.2°C) and Pendant (±0.5°C) thermographs positioned at different elevations (7 profiles). In most cases, the data produced were validated shortly after each day of measurements to ensure their quality. In addition to the *in situ* measured variables, the distance from the shore and the bed slope were estimated. The distance from the shoreline was derived from topographic maps. The mean bed slope was calculated as the ratio of the measured depth and the distance from the shoreline.

5.2.4 Data analysis

Pearson linear correlation and Spearman rank correlation were calculated for each pair of variables, for all locations pooled together. To assess if the measured variables were significantly different between lakes and between sites of presence and absence, the non-parametric Kruskal-Wallis statistical test was used as some data were not normally distributed (Shapiro-Wilk test). When a difference between lakes was significant, a post-hoc pair-wise Dunn test with Bonferroni correction was conducted to detect which location showed different characteristics. The Fligner-Killeen test was used to assess if the variance was significantly different between sites of presence and absence.

5.3 Results

5.3.1 Characteristics of overwintering lakes

A total of 50 sites were characterized in the six overwintering lakes, distributed as follows: Ujarasujullik (n=4), Ujarasujuliup Qullinga (n=7), Kuururjuaq (n=19), Koroc Allipaak (n=5), Tasikallak (n=13) and Tunnullik Lake (n=2) (see Table S3, and temperature and DO profiles in Annexe III). Water temperature of all sites remained in a restricted range (-0.04°C ≤ T ≤ 1.90°C, with a mean of 0.24°C) during the studied period. Regardless of site occupancy by Arctic char, the measured variables were significantly different by location for mean and bottom temperature (Kruskall-Wallis test, χ^2=13.80; p=0.017 and χ^2=12.61; p=0.027 respectively), water depth (χ^2=13.21; p=0.007) and shore distance (χ^2=12.84; p=0.025). However, pair-wise comparison with Dunn test for these variables did not show any significant differences between the compared lakes. This might be due to low statistical power, given the small number of sites in some lakes. The bottom temperature between Ujarasutjulik and Tasikallak was almost significantly different (p=0.053), with Tasikallak lake showing a warmer mean bottom temperature than Ujarasutjulik (0.64°C±0.36°C vs 0.10°C±0.18°C). All the characterized sites (presence / absence, spawning /

non-spawning) from the six overwintering lakes (Ujarasutjulik, Ujarasutjuliup Qullinga, Kuururjuaq, Koroc Allipaak, Tasikallak, and Tunnullik) were pooled since the number of sampled sites was too limited for some lakes to be analyzed on their own.

The sampled sites were located at depths varying between 0.7 m and > 30 m. Water depth was obviously correlated (linearly and with rank) with shore distance and consequently, with bed slope (Figure 5.2, values are given in supplementary information). Water depth was also correlated (linearly and with rank) with mean temperature. Recorded bottom temperatures varied between -0.03°C and 1.90°C, and vertically averaged temperature varied between -0.04°C and 1.1°C. Water temperature was negatively correlated with mean DO saturation [79,8%; 106.6%] and bottom DO values [67.4%; 107.1%]. Snow depth was negatively correlated with both mean and bottom DO with rank correlation, but linear correlation was not significant for any variable, including shore distance. Ice depth was not used for the analysis since measurements were done along the winter season and ice growth did not allow for site comparison.

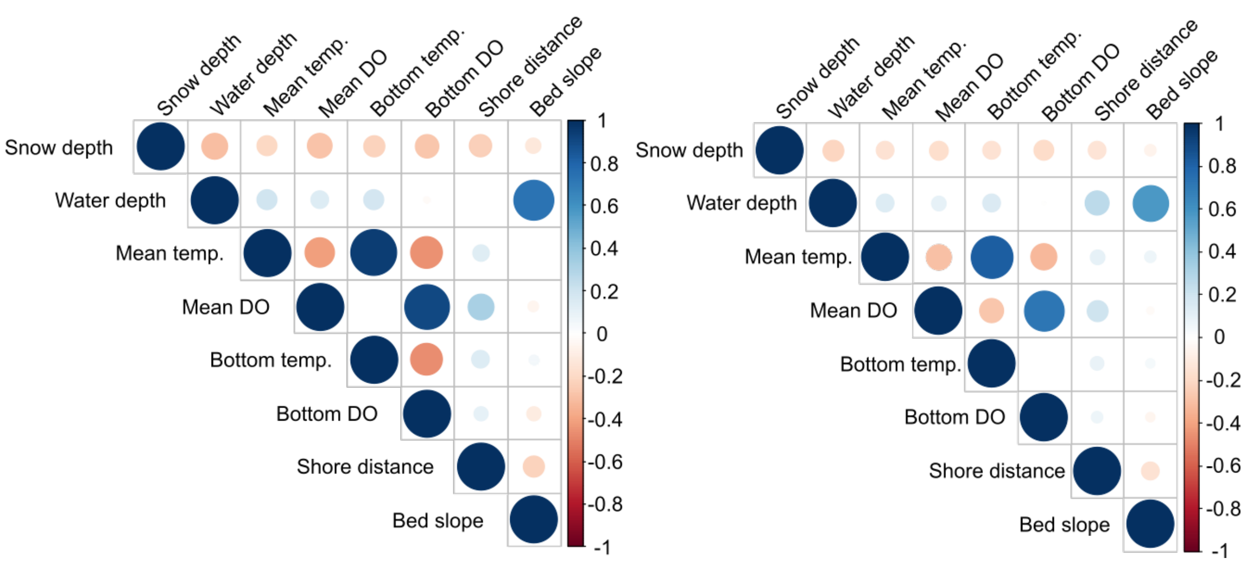


Figure 5.2 Correlation matrix of the measured variables according to a) Pearson linear correlation and b) Spearman rank correlation.

5.3.2 Characteristics of spawning areas in winter

The sites characterized as spawning areas showed a significantly shallower depths than non-spawning sites, with respectively a mean depth of 3.0 m and 6.2 m (χ^2=5.38; p=0.02) (Figure 5.3 and

Tableau 5.1). The median depth value of spawning sites was 2.4 m, whereas median depth of non-spawning site was 4.5 m. The depth of spawning areas [0.7 m; 8.4 m] showed a significantly smaller variance than non-spawning areas [0.9 m ; > 30 m] (χ^2=7.15; p=0.007). Even if they were located at shallower depths, spawning areas showed a mean bottom temperature of 0.51°C, which is higher than the mean bottom temperature of non-spawning areas (0.38°C), but the difference is not significant (χ^2=3.38; p=0.066). Bed slope variance was also significantly different on spawning areas than non-spawning sites (χ^2=2.70; p=0.010), with the former mainly located on slopes varying between 0.031 $m.m^{-1}$ and 0.045 $m.m^{-1}$ (first and third quartile). Other variables, including DO, did not show any statistically significant difference between spawning and non-spawning sites. However, spawning areas also tended to have lower snow depths (mean of 0.29 m) compared with non-spawning areas (mean of 0.35 m) and, as expected from the depth, they tended to be at a closer shore distance than non-spawning sites (mean distance of 83 m compared to 123 m).

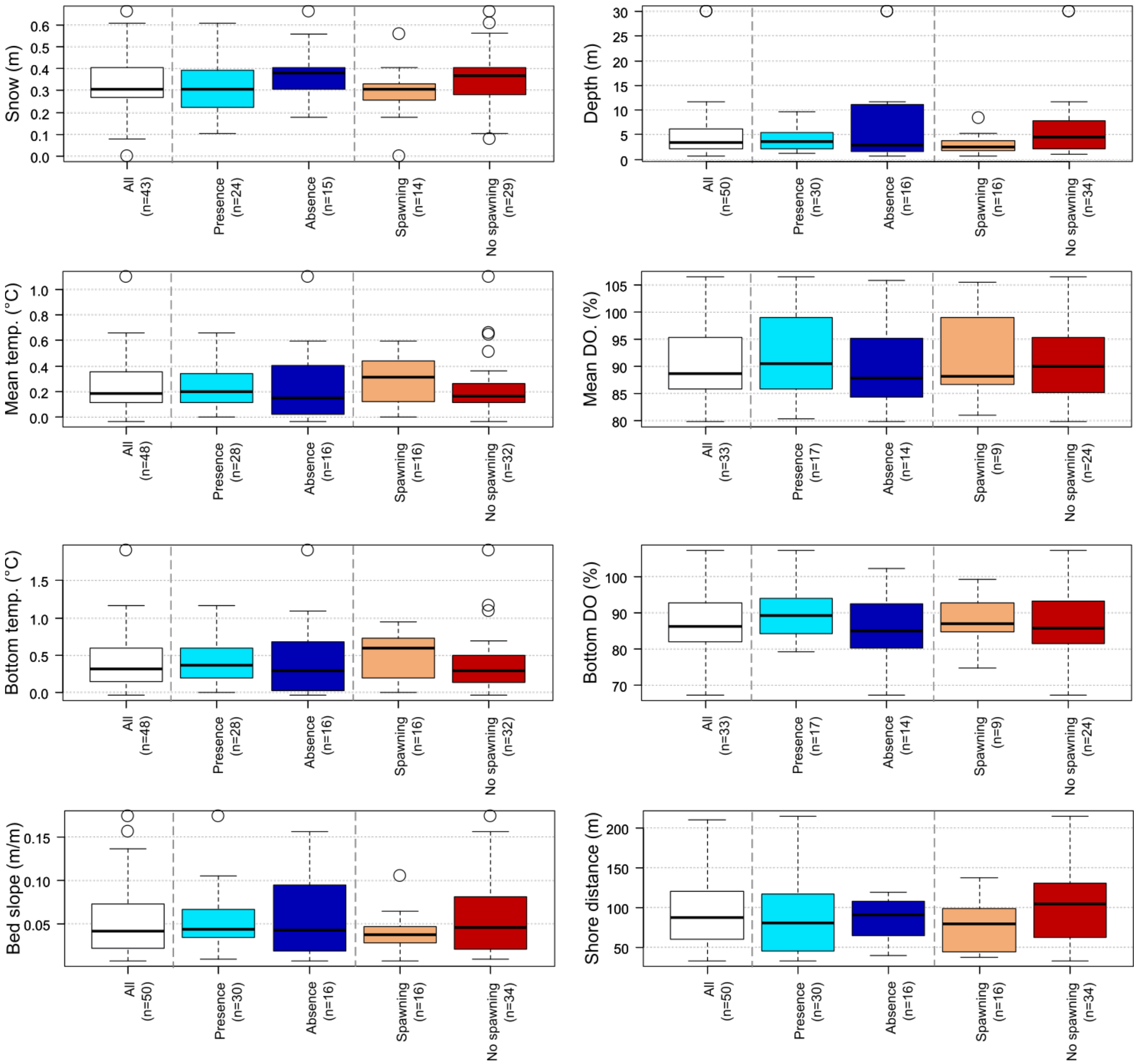


Figure 5.3 **Boxplot of the analyzed variables associated to the type of occupancy (blue tone: presence, absence; red tone: spawning, non-spawning). Black inbox line represent median, with box sides representing the first and third quantile.**

Tableau 5.1 Statistical comparison between characteristics from sites identified or not as a spawning site for the Arctic char. Significant p-values ($\alpha \leq 0.05$) are highlighted with asterisks and test statistic value is given in parenthesis. The sample size for each variable is given in parenthesis (N spawning / N non-spawning).

	Snow depth (N=14/29)	**Water depth (N=16/34)**	**Mean temp (N=16/32)**	**Mean DO (N=9/24)**	**Bottom temp (N=16/32)**	**Bottom DO (N=9/24)**	**Shore distance (N=16/34)**	**Bed slope (N=16/34)**
Kruskal-Wallis test on median value	0.121 (2.406)	0.020** (5.379)	0.108 (2.584)	0.968 (0.002)	0.066 (3.381)	0.716 (0.132)	0.100 (2.700)	0.279 (1.170)
Fligner test on variance	0.235 (1.413)	0.007** (7.149)	0.253 (1.309)	0.804 (0.062)	0.365 (0.820)	0.725 (0.124)	0.133 (2.260)	0.011** (6.489)

5.3.3 Characteristics of winter habitat use by adults and post-smolts

None of the variables used to characterize sites of presence of anadromous Arctic char was significantly different from sites of absence (Figure 5.3 and Tableau 5.2). Habitat used by the fish showed a mean vertical temperature of 0.25°C [0°C; 0.66°C] and a mean dissolved oxygen saturation of 91.9% [80.3%; 106.6%]. Although statistically not different, the mean depth of sites used by Arctic char was 4.1 m, whereas the mean depth measured at sites of absence was 7.7 m. The water depth variance was significantly lower (χ^2=3.83; p=0.050) at sites of presence, with depth used by fish varying between 1.3 m and 9.7 m, whereas depth of sites of absence was comprised between 0.7 m and > 30 m. Bed slope of sites used by Arctic char also tended to have a smaller variance than slope of sites of absence, with fish using mainly sites with a slope comprised between 0.034 $m.m^{-1}$ and 0.066 $m.m^{-1}$ (respectively for first and third quartile; χ^2=3.12; p=0.077). Sites of presence tended to have a lower snow accumulation than sites of absence (mean of 0.30 m compared to 0.38 m; χ^2=1.71; p=0.191), with a higher variance towards lower values of snow accumulation.

Tableau 5.2 Statistical comparison between characteristics from sites identified according to the presence or absence of adults and post-smolts anadromous Arctic char. Significant p-values (α ≤0.05) are highlighted with asterisks and test statistic value is given in parenthesis The sample size for each variable is given in parenthesis (N presence / N absence).

	Snow depth (N=24/15)	**Water depth (N=30/16)**	**Mean temp (N=28/16)**	**Mean DO (N=17/14)**	**Bottom temp (N=28/16)**	**Bottom DO (N=17/14)**	**Shore distance (N=30/16)**	**Bed slope (N=30/16)**
Kruskal-Wallis test on median value	0.191 (1.708)	0.926 (0.009)	0.428 (0.629)	0.475 (0.511)	0.435 (0.611)	0.211 (1.564)	0.604 (0.269)	0.854 (0.034)
Fligner test on variance	0.678 (0.173)	0.050** (3.833)	0.167 (1.906)	0.328 (0.956)	0.106 (2.610)	0.931 (0.008)	0.528 (0.398)	0.077 (3.124)

5.4 Discussion

In this study, we compared the physical characteristics of sites used by Arctic char with sites of absence, and spawning areas with non-spawning sites in six overwintering lakes of Nunavik. We worked in collaboration with Inuit harvesters to determine the habitat occupancy and conducted measurements while practicing traditional fishing activities using an evidence-based cumulative knowledge approach. The spawning areas identified by Inuit harvesters in the overwintering lakes were located at significantly shallower depths with higher bottom temperatures than sites not identified as spawning areas. On the other hand, the winter habitats used by adults and post-smolts anadromous Arctic char did not present significantly different characteristics than the sites of absence. However, winter habitats tended to be in the littoral zone of lakes, at depths less than 10 meters.

5.4.1 Spawning habitat

The location of the spawning areas at shallower depths and limited distance from the shore makes them favorable environments for egg incubation. Indeed, they might benefit from recirculating downslope density currents that comes from the ice surface with more oxygenated water, while the benthic zone undergoes a depletion of oxygen at the center of the lake during the winter (Jansen et al., 2020; Welch and Bergmann, 1985; Magnuson and Karlen, 1970). In addition, spawning sites are likely selected for their warmer bottom temperatures, possibly to prevent the eggs from freezing and improve the incubation conditions. Indeed, whereas In cold water (below 4°C), due to water density, bottom temperature usually increases with water depth, spawning areas were associated with warmer temperature despite their shallower depth than non-spawning areas. Among the non-spawning areas characterized, some temperature profiles even showed a null (0°C) temperature all along the depth that could be detrimental for egg incubation (Elliott and Elliott 2010). The presence of hyporheic or groundwater upwelling flow might explain the locally warmer temperature (Baxter and Hauer 2000). More detailed studies are needed to investigate the role of hyporheic flow in spawning areas of the Arctic char through the monitoring of local piezometric pressure and temperature as it was done for brook trout (Franssen et al. 2013).

Shallower depths used as spawning areas might likewise be selected as a favorable post-hatching environment for fry. Eggs are hatching in winter, between January and April depending on incubation conditions, while lakes are still covered with ice (Dubos et al. 2023a; Granier, 2013; Johnson 1980b). In our study, in addition to being at shallower depths, the spawning areas tended to have less snow accumulation (although not statistically significant). Snow depth has a critical impact on light penetration under the ice (Welch et al. 1987) and is thus related to productivity. Notably, the littoral zones are favorable for the development of macrophytes and periphyton, which are themselves associated with the growth of chironomid larvae (Jansen et al., 2020). During the winter, the littoral zones of high Arctic lakes were indeed associated with a high occurrence of zoobenthos, especially chironomid larvae, which are an important part of the diet of juvenile Arctic char (Svenning et al., 2007; Klemetsen et al., 2003). Although metabolic demand decreases at low temperatures, young-of-the-year need to feed in winter (Byström et al. 2006). Therefore, it is likely that shallower depths are selected as spawning areas for their increased productivity.

Due to the transitory nature of the reproduction period, the spawning areas identification is more difficult than the winter habitat of adults. Since spawning areas were in part associated with visual observation of spawning behavior, the identified sites might be at depths that allowed such observations. The identified spawning areas were also confirmed by the collaborating hunters who had already caught many individuals in spawning colours in these areas during the fall. Hence, the restricted range of depths associated with spawning areas may not be due to the identification method, but to a true habitat selectivity. A similar observation was done in shallow littoral zone of a Baffin Island lake by Young and Tallman (2021) who caught in the fall aggregated large Arctic char returning from migration. The fish were suspected to be in pre-spawning behavior, although their reproductive status or their colour was not specified.

5.4.2 Adult and post-smolt habitat use

None of the lakes in the present study showed the presence of an inverse stratification with bottom temperatures at 4°C as typically observed in more southern latitudes. The temperature in our overwintering lakes always remained below 1.90°C, and Arctic char occupied a narrow range of temperature [0°C-0.66°C]. This range of temperature is comparable with the body temperature of Arctic char from the Coppermine River, NWT, implanted with acoustic transmitters, ([-0.14°C-1.28°C], with over 98% of temperatures below 0.02°C) (Smith et al. 2022), the river being slightly cooler than the lakes studied here. In two subarctic lakes in Norway presenting a similar range of temperature than our study site, the large lake-resident Arctic char also used the cold water layer [0.2°C-0.7°C] located in the littoral zone (Klemetsen et al., 2003). The lake-resident char were thought to use the littoral for the presence of light and prey availability. However, according to Inuit observations and studies on stomach contents, anadromous Arctic char stop feeding or eat very little during the winter season (Dubos et al. 2023a; Young et al., 2021; Moore and Moore, 1974). In Tasikallak Lake, winter fasting has been confirmed by a sampling of 237 Arctic char which all had empty stomachs for, at least, several days (Boivin and Power 1990). Arctic char are highly tolerant to low temperatures and can even bear supercooling temperatures (Spares et al., 2012; Johnson 1980b; Scholander et al., 1957). As fish are fasting for several months in winter, the use of cold-water habitat is favorable to survival as it slows down their metabolic rate. Thus, anadromous Arctic char are not only adapted to the lower temperatures of Arctic lakes, but they generally seem to avoid higher temperature areas of these cold systems.

The DO saturation levels were well above the fish minimum requirements in all studied lakes (60%; Sæther et al., 2016). A minimum value of 67.4% was observed at a depth of 30 m at

Ujarasutjuliup Qullinga, at the end of March, but other lake areas were accessible. Therefore, DO cannot be considered a significant variable for winter habitat selection by fish, at least for the years covered by our study. Nonetheless, DO can vary from one site to another on the same lake but also from year to year because it depends on the concentration at the time of ice cover formation (Clilverd et al., 2009; Chambers et al., 2008). For example, during the winter 2021-2022 in Tasikallak, DO decreased constantly from 92% to 73% below the ice cover at a depth of 15 m (unpublished data). This same lake had experienced a major winter fish kill in 2002, possibly due to oxygen depletion (Côté 2002). DO depletion in the deepest areas of the lakes could explain the lack of fish (or fishing sites) in the pelagic zone. Telemetry studies showed that Arctic char do occasional incursions in deeper water but only for a limited time (Monsen, 2019; Hawley et al., 2017).

Adult Arctic char preferentially used the littoral zone in the present study (at depths < 10 m with a mean of 4.1 m), a behavior corroborated by other studies (Klemetsen et al., 2003; Svenning et al., 2007). Sites of presence showed slightly less snow accumulation, although differences were not significant. The study area in Nunavik is located at a latitude with daylight period of several hours in winter. The studied lakes are all clear and oligotrophic, with limited snow over the ice allowing the penetration of a certain amount of light in the water column, likely enough for fish with a good vision such as chars (Ali and Wagner 1980). However, since anadromous Arctic char do not feed in winter, other potential factors explaining this habitat selection must be considered. During the measurements, char were observed or filmed in shallow areas, swimming in group for most of them, but also laying on rocks or on the lake bottom for some of them (video accessible in Dubos and Snowball, 2020). One Inuit elder mentioned that «*at the beginning of the winter, all the char get together, the adults and the small. They are together but not always aggregate*» (Local fisher, Kangiqsualujjuaq 2019, pers. communication). Hence, the use of nearshore areas could allow them to use the substrate at the bottom of lakes during periods of slow metabolism, while benefiting from the available light for socialization. Although they show low activity in winter (Mulder et al., 2018b; Hawley et al., 2017), the fish have some daily movements as they are caught in fixed gill nets installed by Inuit harvesters for a few hours or for the night. Since these movements cannot be justified by the need of feeding, they might be explained by the need of socialising (Sneddon and Brown 2020) or the simple need or pleasure to move. Further study is needed to determine if other variables may impact the selectivity of winter habitat for these fish, such as the proximity to a tributary or the presence of a bay or irregular shorelines.

The habitats used by the fish were determined from the knowledge of hunters who seldom use the deepest lake areas to harvest fish. Thus, according to our results, depths greater than 10 m were not considered as used habitat as they are not fishing areas. It remains however possible that harvesters avoid the deepest areas for practical reasons regarding the length of ropes needed for setting nets at a suitable depth, which could result in a bias in the assignment of habitat based on fishing sites only. Nonetheless, during fieldwork, videos taken at sites of absence did not show any fish and attempts for fishing were unsuccessful, although they were of shorter duration than at fishing sites. We are confident in the validity of the hypothesis that Arctic char habitat use is correlated with known fishing sites since Inuit knowledge of hunters integrates hundreds of years of transmitted observations and practices, equivalent to extensive sampling (Berkes and Berkes 2009).

The usual fishing sites were located in specific areas of the lakes. For example, in Tasikallak, the sites of presence were delineated in four specific areas. Hence, it is likely that several fishing sites can exhibit similar characteristics and smaller variance, as observed. In addition, there were differences between lakes in sampling efforts; for example, only two sites were sampled in Tunnullik while 19 sites were sampled in Kuururjuaq , reflecting the hunters' practices. Future work would benefit from a more systematic sampling of sites in each lake, at least for sites of absence, and participation of more hunters, to increase characterization in undersampled lakes.

5.4.3 Specificities of the collaboration with Inuit hunters

The collaboration with Inuit hunters to sample the sites and get their insights on fish habitat occupancy was valuable since Inuit harvesters are going regularly on the land and are knowledgeable of the sites used by fish. This method allowed the efficient sampling of several lakes on a large territory, difficult to access for southern researchers in the winter season. A much larger number of sites were sampled than could be done by a team of southern scientists on one-time visits (Moller et al. 2004). A short in person-training of participating hunters was useful to improve their confidence in acquiring data and the level of details to be recorded, and to facilitate the transmission of collected data. Logistical or material considerations related to working in cold and sometimes harsh weather conditions were not always within the control of participating hunters, and the planning of the work was subject to different considerations between scientists and Inuit (Bates 2007). In addition, since we worked with hunters practicing subsistence fishery, their interest and timing was related to their need to provide food for their family or community. For these reasons, the lakes and the dates on which the measurements were to be made was chosen by hunters. But since the methodological approach was based on the goodwill of the hunters, following their agenda was the right way to proceed. The methodology and results intrinsically benefited from Inuit knowledge. For example, their knowledge of where and when fish are available has allowed for better timing with the fish presence in specific sites. The study was exploratory and proved to be relatively efficient. The study is an example of how traditional qualitative knowledge to locate fish habitats and science to characterize those habitats complement each other well. Reciprocally, the involvement of hunters in data collection during their traditional fishing activities motivated them to learn more about fish habitat characteristics and sparked their interest in the research process.

In addition to having knowledge of winter fish movements, Inuit hunters provided additional details on the study sites. For example, a site of absence in Kuururjuaq (not characterized) was a site of presence in the 1980s-1990s. The lower water level of the Koroc River was given as the reason explaining this habitat change of use. In addition, one site along this river, located in a bay, has ceased to be used as a spawning area, apparently because macrophyte growth is blocking fish passage to this area. This information therefore allows to relate fish occupancy to local environmental changes. Hence, traditional monitoring methods, used intuitively by Inuit harvesters, similar to catch-per-unit-effort (CPUE), should be considered more formally for assessing fish populations (Moller et al. 2004).

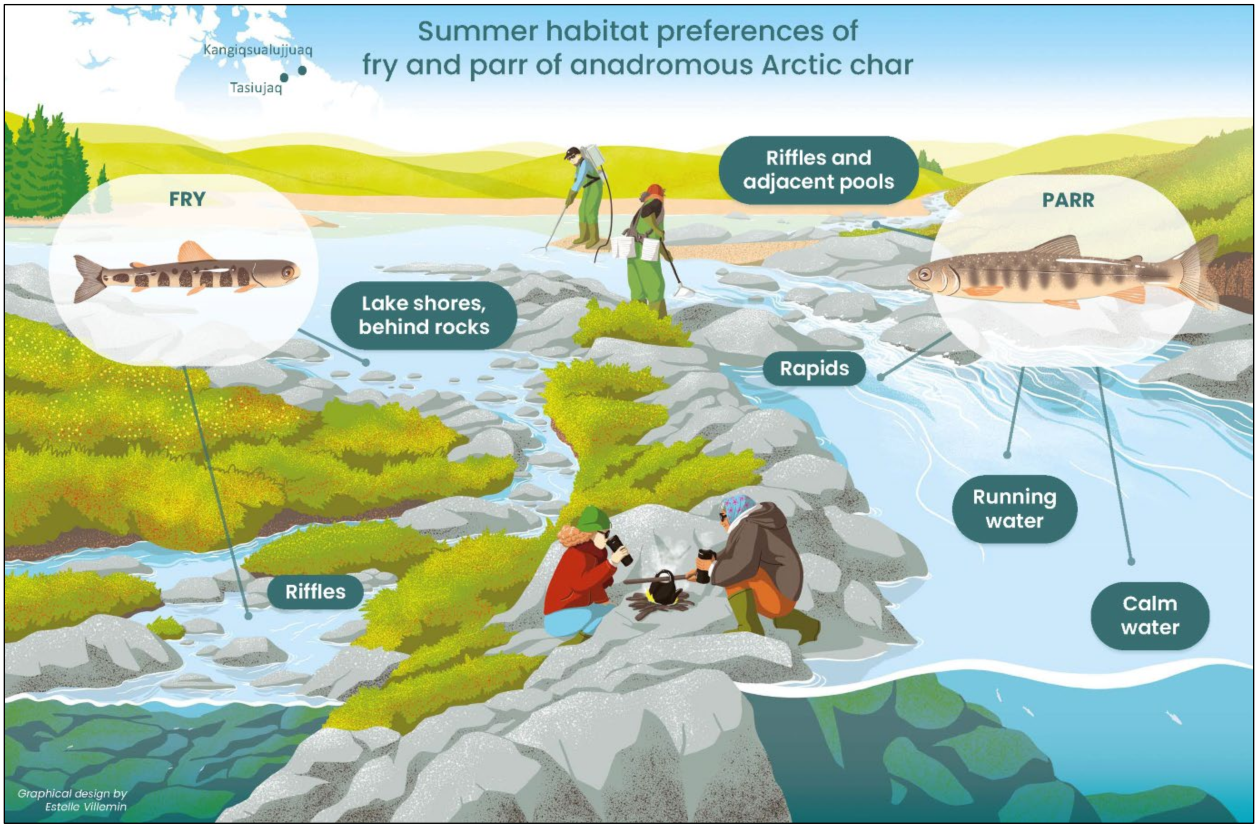
5.5 Conclusion

The study filled a gap in the knowledge of winter habitat use of anadromous Arctic char in Nunavik by showing that spawning areas have significantly different characteristics than non-spawning areas. Winter fish habitat was associated with the littoral zone, but the habitat used did not have significantly different characteristics than the sites of absence. Working with local harvesters has resulted in a recurrence of observations that surpasses the one-time observations that can be made by scientists alone in the field and has allowed investigation to study the close relationship between fish habitat use and traditional fishing sites. The study remains exploratory as the sites characterized depended on the availability, needs and practices of the collaborating hunters. Their active involvement in the measurements along with their fishing activities raised their interest in the study results. Combining the traditional fishing activities of Inuit hunters and their knowledge of site occupancy with simple measurements, is a promising approach to characterizing Arctic char habitat and learning on the winter ecology of this important species.

Acknowledgements

We are grateful for the active participation of Elijah Snowball and Elijah Eetook in this study. We would also like to thank Kangiqsualujjuaq Northern Village for its interest and support. This project was also supported by Makivik Corporation, Natural Science and Engineering Research Council of Canada, and the Institut Nordique du Québec.

6 PRÉFÉRENCES D'HABITAT ESTIVAL EN RIVIÈRE DES OMBLES CHEVALIER JUVÉNILES



Présentation du chapitre

Les habitats de fraie sont bien connus des Inuits, non seulement parce que les ombles chevaliers sont fidèles à leur site de reproduction, mais aussi parce que la saison de reproduction est une période importante pour la pêche puisque les œufs des femelles sont recherchés pour la consommation. En revanche, les experts inuits interrogés n'étaient pas en mesure de décrire l'habitat des juvéniles. Ces derniers ne sont pas pêchés et ils utilisent les lacs et rivières en été alors que les activités estivales de pêche sont concentrées en milieu marin, où les ombles adultes vont s'alimenter. Comme l'habitat estival utilisé par les juvéniles est de plus en plus vulnérable aux changements climatiques étant donné leur faible tolérance aux températures élevées, il est important de déterminer quels sont les habitats estivaux utilisés.

Le présent chapitre consiste à modéliser les préférences d'habitats des juvéniles en eau douce, avant la smoltification (alevins et tacons). Ces modèles ont été bâtis à partir de relevés de pêche électrique jumelés à de la caractérisation physique de l'habitat. Les résultats ont été néanmoins rapportés dans les communautés et corroborés par les observations des Inuits interrogés. Ce chapitre complète la caractérisation des différents habitats utilisés en eau douce.

Titre de l'article

Summer stream habitat preferences of Nunavik anadromous Arctic char (*Salvelinus alpinus*) fry and parr.

Auteurs

Véronique Dubos[1], André St-Hilaire[1,2], Normand E. Bergeron[1]

[1] Institut national de la recherche scientifique (INRS), Québec, Qc

[2] Canadian Rivers Institute, Fredericton, N.B.

Publication

Dubos, V., St-Hilaire, A., Bergeron, N.E., 2022. Summer stream habitat preferences of Nunavik anadromous Arctic char (*Salvelinus alpinus*) fry and parr. **Canadian Journal of Fisheries and Aquatic Sciences 79**(7): 1074-1085. https://doi.org/10.1139/cjfas-2021-0119

Contribution des auteurs

J'ai contribué au traitement des données de terrain, aux analyses et à la rédaction de l'article.

ASTH a contribué à la conception de l'étude, aux analyses et à la révision de l'article. NB a contribué à la conception de l'étude, aux relevés de terrain, aux analyses et à la révision de l'article.

Abstract

Arctic char is a fish species known to occupy diverse habitats within the Arctic region. However, summer habitat use during the juvenile stage of the anadromous form is largely unknown. The present study aims to characterize fry and parr summer habitat preferences. Surveys were conducted by electrofishing, associated with physical habitat characterization on several rivers of the Ungava Bay, Nunavik, Canada. At the microhabitat (4 m^2) and station scales (group of microhabitats, typically a few tenth of m^2), fry showed significant habitat preferences for shallow water and slow velocity. At the mesohabitat scale (typically 10-100 m^2), fry showed a significant habitat selectivity for riffles. This habitat selectivity implies that habitat models can be built to evaluate the potential of habitat suitability for Arctic char fry. However, no significant habitat selectivity was found for parr. Parr size was nonetheless positively correlated with velocity, which was found to be a limitative factor for juvenile habitat use. This first attempt at modeling juvenile anadromous Arctic char habitat in rivers emphasizes the importance of selecting an appropriate spatial scale and reiterates the fact that parr showed relatively high plasticity in stream habitat selection.

Key words

Juvenile Arctic char; anadromous Arctic char; Nunavik; fish habitat; mesohabitat.

6.1 Introduction

Arctic char (*Salvelinus alpinus*) are habitat generalists showing one of the most diverse ecology of fishes (Klemetsen et al. 2003a). Arctic char exhibit a wide flexibility in life history (Hammar 2014) and individuals of the anadromous form use different habitats throughout their life cycle. At the adult stage, feeding occurs in marine environment during summer, reproduction takes place in freshwater streams and lakes and overwintering generally occurs in lakes or deep river pools. Juveniles usually spend their first two to four years in freshwater streams or lakes, until they are ready for smoltification (Johnson 1980b; Le Jeune, 1967; Mainguy and Beaupré, 2019). Their adaptation to cold freshwater environments makes them more vulnerable to climate change impacts, which already affect the Arctic regions (Reist et al. 2006; Galappaththi et al. 2019). Indeed, mortality of juvenile Arctic char has been recently observed by an Inuit fisher in a small stream of the southern Ungava Bay area during an unusually warm summer period (A. Gordon, Kuujjuaq, pers. communication, 2020). Little is known about the habitat use of juvenile anadromous Arctic char owing to complex logistic associated with sampling in northern rivers, to the challenges associated with fry observation (Godiksen et al. 2012) and to their cryptic behavior (Heggenes and Saltveit 2007). As anadromous Arctic char are culturally important and a key resource to achieve food security for the Inuit of Canada (Watts et al. 2017; Dewailly et al. 2002), it is relevant to understand how juveniles might be vulnerable to climate change in their rearing habitats, specifically in streams prone to summer warming and/or low flows. The first step to assess this vulnerability is to understand the habitat use and preferences of juvenile Arctic char.

The literature on fry (young of the year, YOY) habitat is rather general and essentially based on the non-anadromous, lake resident form of Arctic char. Sandlund et al. (1988) found that they occupy near-shore environment when predators are present and tributaries are not available. The heterogeneity of substratum of near-shore habitat provides refuges and is a non-limitative source of benthic invertebrates, their main food source (Byström et al. 2004). Fry can also use pelagic habitat in the absence of predators (Langeland and L'Abée-Lund 1998). Sinnatamby et al. (2012) showed that when tributaries were accessible, lake resident Arctic char fry appeared to show a preference for the mouth of tributaries in slow velocity areas. Despite this observation, no physical characteristics of the environment could be significantly associated with fry habitat preferences. Observations of parr (> 1+ juveniles) showed that they are more mobile than fry, with presumed high movement towards river mouths at the end of summer, and they appear to occupy different habitat types such as lakes, deep pools or small, shallow (H < 0.20 m) stony streams (Gulseth and Nilssen 1999; Heggenes and Saltveit 2007; Witkowski et al. 2008). In an experimentation with parr enclosed in a tank on the shore of their native Koroc River (Ungava Bay), Adams et al. (1988) observed that juveniles had preferences for specific substratum depending on their diel level of activity. A larger substrate dominated by pebbles was selected as a shelter from predation at daylight, whereas a sandy substrate was used while active at night. In two rivers of northern Norway, Heggenes and Saltveit (2007) also found that the finest substrate was used at night, when parr were inactive as they only fed during the day. The authors also observed that most Arctic char were found aggregated in deep pools, in still water or with slow velocities, but that they also used riffles in one of the two rivers. However, only habitat use was analysed and no preference could be inferred as habitat availability was not measured. Additionally, Arctic char were in sympatry with Atlantic Salmon (*Salmo salar*) and brown trout (*Salmo truta*) and their habitat use were likely adapted to avoid these dominant species. Thus, the observed habitat use might not be representative of Arctic char parr in North America as brown trout are absent of their known territorial distribution and Atlantic salmon (*Salmo salar)* are still scarce.

Water temperature is known to have an impact on habitat selection of some salmonids (Wilbur et al. 2020; Boudreault et al. 2021). Juvenile Arctic char show temperature preferences between 9 °C and 11.8 °C from laboratory experiments (Larsson and Berglund 1998; Larsson 2005; Siikavuopio et al. 2014). Temperature higher than 16 °C is avoided by juveniles when they have access to colder refuges, as it is the lower bound of their higher critical range (Gilbert et al. 2020). Nonetheless, in the few studies conducted in natural environments, juveniles did not exhibit a clear preference for a specific temperature (Sinnatamby et al. 2012; Godiksen et al. 2012; Sinnatamby et al. 2013).

Fish habitat can be described and modelled at different spatial scales. At the local scale, microhabitat is often modelled with a limited number of variables, namely depth, velocity and substrate (Bovee 1986). For other salmonids, hydraulic characteristics have been complemented with water temperature (Boudreault et al. 2021) or cover availability (Armstrong et al. 2003). Mesoscale habitats can be defined using relatively homogenous reaches of a river, for which geomorphological features can be defined (Parasiewicz 2001). A combination of microhabitat and mesoscale habitat can be relevant to analyse juvenile preferences (Habersack et al. 2014). The present study aims to describe habitat use and attempts to model habitat preferences of Arctic char fry and parr at different spatial scales, from microhabitat to mesohabitat, in Nunavik (Canada) river systems. As the fitness of population is correlated to the size of fish and its variability is linked to habitat affinity (Polivka 2020), the relationship between the size of juveniles and specific habitats was also investigated.

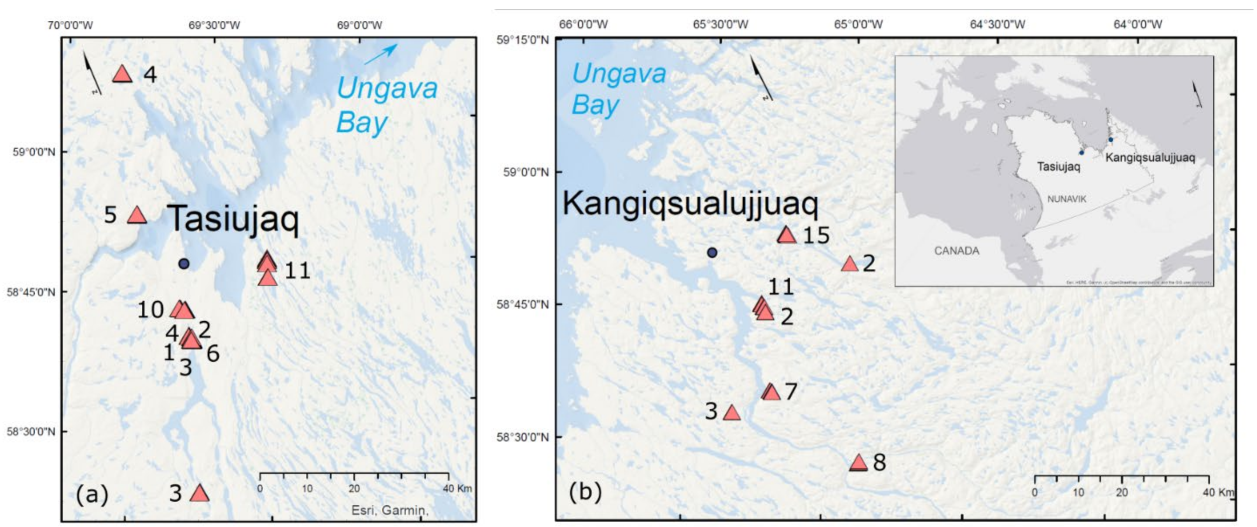


Figure 6.1 **Location of electrofishing sites and stations (red triangles) in the vicinity of (a) Tasiujaq and (b) Kangiqsualujjuaq (Nunavik, Canada). Numbers represent the number of fishing stations at each site. Details allowing site identification and exact location were omitted, as required by the two partner Inuit communities. Electrofishing was conducted between July 29th and August 4th 2019 in Kangiqsualujjuaq and between August 5th and 10th 2019 in Tasiujaq. Map sources: Esri, "Ocean Basemap", GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors, and Esri, "Light Gray Canvas Map", DeLorme, HERE, MapmyIndia.**

6.2 Methods

6.2.1 Study area and sites selection

Field work was conducted in rivers in proximity of two Nunavik communities, Kangiqsualujjuaq and Tasiujaq, Ungava Bay, Canada (Figure 6.1). Regional climate of both areas is classified as polar with moderate precipitations and a very short vegetation growing season of 90-119 days (Gérardin and McKenney 2001; Charron 2015). Fish sampling and habitat characterization were conducted between July 29th and August 4th, 2019 in Kangiqsualujjuaq and between August 5th and 10th, 2019 in Tasiujaq. Mean air temperatures of the combined months of July and August 2019 were 11.7 °C (s.d.= 3.3 °C) and 10.7 °C (s.d.= 3.2 °C) respectively in Kangiqsualujjuaq and Tasiujaq. A total of 17 streams were sampled with seven sites near Kangiqsualujjuaq (on the Barnoin River and tributaries of the George River) and ten sites in the Tasiujaq region (on the Bérard River and tributaries of Leaf Lake). Sampled streams varied in size, from a headwater stream with a drainage area of 28 km^2 to a larger river with a drainage area of 1580 km^2. On each stream, sampling sites were chosen downstream of known or suspected spawning areas according to Inuit experts (Kangiqsualujjuaq fishermen, fieldwork preparation meeting, pers. communication, 2019; Tasiujaq fishermen, fieldwork preparation meeting, pers. communication, 2019).

6.2.2 Fish sampling and river characterization

6.2.2.1 Electrofishing protocol

Single-pass electrofishing in open sections was completed at each sample site, including 1 to 15 electrofishing stations starting from downstream known or presumed spawning sites (Figure 6.2). Distance between stations was typically 50 m. Reaches with deep thalweg (i.e., not wadeable) were fished only in the wadeable portion. The sampling method thus exclude the analysis of deep sections that may also be part of selected habitat by juvenile. Each station consisted of six electrofishing points (4 m^2) distributed on a 2x3 pattern to cover the entire river width, except for two stations which had only three and five points. Two persons were using dip nets to catch fish on either side of the electrofisher. Each fish collected was identified (species), measured to fork length (hereafter referred to as "fish size") and released.

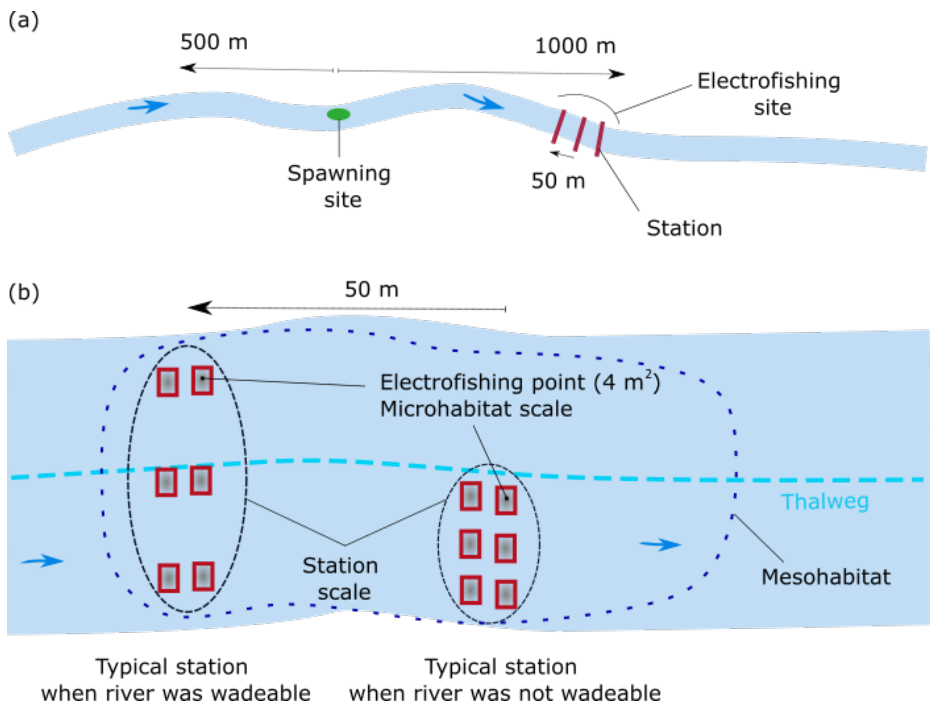


Figure 6.2 **Description of electrofishing protocol. (a) General location of stations for each fishing site. (b) Description and definition of the scales of analysis: microhabitat, station and mesohabitat (see**

Tableau 6.1 for mesohabitats identification). Each station except two, included six microhabitats.

6.2.2.2 Measured habitat variables and scale definition

The «microhabitat scale» is defined by the 4 m^2 area impacted by the electrical current of each electrofishing point. Regardless of the absence or presence of fish, the following habitat characteristics were measured at each sampled point: depth, mean velocity, substrate diameter (D_{50}), substrate embeddedness and water temperature. Hydraulic variables (depth and mean velocity) and temperature were measured at the center of each area. Velocity was measured with a Marsh McBirney Flo-mate 2000 flowmeter at 60% of depth for at least 30 s. Substrate diameter and embeddedness were estimated to be representative of the total microhabitat area. Substrate diameter was determined by measuring the B axis of rocks, which was used as an estimate of median diameter (D_{50}). Embeddedness of substrate was estimated visually on a scale of 0 to 3 (no interstice = 0). For each microhabitat, the Froude number (Fr), defined by the ratio of flow inertia to gravity, was calculated by the equation:

(1) $$Fr = V/\sqrt{(g.H)}$$

where V is the mean velocity (m/s) and H is water depth (m); g is the gravitational acceleration constant (m^2/s). Fr has been used as an indicator of habitat quality in various streams (Lamouroux and Jowett 2005).

The «station scale» (a few tenth of m^2), a broader scale than microhabitat, was defined to investigate habitat preferences using the number of sampled fish as an indicator. All fish sampled at the same station were pooled to get the fish number for each station. The microhabitat variables measured over a station were averaged to describe «station scale» characteristics.

The «mesohabitat» scale (typically 10-100 m^2) is defined by the geomorphological unit of the stream reach (

Tableau 6.1, Table S1 and Figure S1, Annexe IV). Mesohabitats were classified during sampling, at each station. In addition, three pictures were taken, showing transverse, upstream and downstream views. When identification of several adjacent stations was similar, they were considered to be part of the same mesohabitat. The number of fish was calculated for each distinct mesohabitat. Glides and runs were not discriminated and pools were classified with lentic mesohabitats. As only two lakeshore mesohabitats were sampled, they were not included in the analyses of selectivity. The mesohabitat classes were therefore riffle, rapid, run, lentic and backwater.

Tableau 6.1 Description of mesohabitats general characteristics (inspired from Malavoi and Souchon (2002) and Gosselin et al. (2012)) and study-specific mean flow characteristics. Although glides and pools are distinct mesohabitat types, they have been associated respectively with runs and lentic flows in the present study [a].

Mesohabitat	Depth	Mean depth (cm)	Velocity	Mean velocity (m/s)
Riffle	Very shallow, can show deeper pocket	30.1	Moderate with locally fast velocity, turbulent flow	0.20
Rapid	Shallow	28.5	Fast velocity, turbulent flow	0.26
Run	Moderately shallow	36.7	Moderate velocity, turbulent flow	0.24
Glide	Moderately shallow	-	Moderate velocity, non-turbulent flow	-
Lentic	Moderately shallow	35.9	Slow velocity	0. 11
Pool	Deep	-	Slow velocity	-
Backwater	Moderately shallow	48.8	Moderate or slow velocity. Can be an eddy zone	0.21

[a] See Table S1 in Supplementary data (Annexe IV) for more details on mesohabitat identification and Fig. S1 for more details on flow characteristics related to the mesohabitats.

6.2.3 Data analyses

6.2.3.1 Habitat selectivity from use-availability distribution

A G-test (McDonald 2014) was used for each spatial scale to test the null hypothesis that the distribution of habitat used was similar to the distribution of available habitat. In the case of a rejection of the null hypothesis, a *post-hoc* pair-wise comparison of each selected variable class (corresponding to specific range of values) was conducted to assess differences among classes. A Bonferroni correction was applied to the significance threshold (Manly et al. 1993).

Habitat selectivity was calculated using Jacobs' index (Jacobs 1974) for each habitat variables at the three spatial scales:

(2) $$J_i = \frac{r_i - p_i}{r_i + p_i - 2r_i p_i},$$

where J_i is the Jacobs' selectivity index for category i, r_i is proportion of habitat used or fish number and p_i is sampled proportion of category i or habitat availability. Values of Jacobs' index varies from -1 to 1 (-1=avoided habitat; 1=preferred habitat; 0 no selectivity).

6.2.3.2 Logistic regression for habitat model at microhabitat scale

The potential relationship between presence/absence of fish and microhabitat characteristics was analysed with a logistic regression model. As presence of fish in a microhabitat is a dichotomic variable (presence=1, absence=0), the probability of absence is given by the following equation:

(3) $$P(y = 0|X) = \frac{\exp(\beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n)}{1 + \exp(\beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n)}$$

where $X = [x_1 \ldots x_n]$ represents the vector of river characteristics used as predictors and β_i the regression coefficients. As the proportion of microhabitats showing fish presence was small, microhabitats with absence of fish were resampled to an equal proportion of presence and absence so that the model could converge. As the probability of use of the resampled data set was different than the probability of use of the reference sample, the logistic regression model provided a relative probability of presence that can be interpreted qualitatively to rank preferred habitat i.e. to evaluate qualitatively the relative importance of habitat variables (Keating and Cherry 2004). A boot-strap procedure was used to assess model performance. Each analysed sample was split in 2/3-1/3 proportion, respectively for model calibration and model validation. The procedure was iterated 1000 times and model evaluation was conducted on calibration samples and on validation samples separately to test predictability robustness. Model performance evaluation was based on the deviance (-2Log-Likelihood), and the Nagelkerke pseudo-R^2 (Walker and Smith 2016). Model sensitivity and specificity, which are respectively the probability of correct prediction of presence and of correct prediction of absence were also estimated. The area under the Receiver Operating Characteristic (ROC) curve, named AUC, was calculated. A 0.5 value of AUC corresponds to a random probability of presence and a value of 1.0 is a perfect predictive model. To compare model performances while accounting for the number of hydraulic variables that can be associated with fish presence, the smallest value of Akaike information criteria (AIC) was used for comparison (Boyce et al. 2002).

Generalized Additive Model (GAM) for habitat model at station scale and juvenile size at microhabitat scale

The number of juvenile fry and parr was assessed at each station where they were present. The relationship between the number of fish and the river characteristics at station scale was analysed using a Generalized Additive Model (GAM). GAM is a non-linear regression model that uses a smoothing function (splines were used in our model) to interpolate predictor variables (each river characteristic) and a transformation function to link the dependant variable (i.e., number of juveniles) with the predictors (Hastie and Tibshirani 1986):

(4) $$g(E(Y)) = \beta_0 + s_1(x_1) + s_2(x_2) \dots + s_n(x_n)$$

Where *E(Y)* is the expectation of the dependant variable *Y*, g is the link function (Poisson distribution as predictors are positive integers), x_i are the predictor variables, s_i the smooth functions (cubic splines) and β_0 is the intercept. GAM is well suited for quantity models as the relation between fish number and physical characteristics can be non-linear and the GAM predictors do not need to be independent (Hastie and Tibshirani 1986). Potential multicollinearity was not considered. A leave-one-out procedure was used and model parsimony was assessed using AIC and corrected AIC (AICc) because of the low number of data. Model performance was assessed using the adjusted-R^2, explained deviance and the deviance. GAM analyses were conducted in R (mgcv package).

The relationships between juvenile size and microhabitat habitat variables were also analysed with a GAM model. The Gaussian distribution was used. A leave-one-out procedure was carried out to assess model performance.

6.3 Results

6.3.1 Fish sampling

A total of 578 microhabitats and 97 stations were sampled. In the Kangiqsualujjuaq area, fish species included Brook trout (57%, n=128), Sculpin (*Cottidae* fam., undetermined species) (29%, n=66), Arctic char (8%, n=18), Stickleback (3%, n=7), Atlantic salmon (3%, n=6) and Whitefish (0.4%, n=1). In the Tasiujaq area, species included Brook trout (38%, n=166), Arctic char (31%, n=130), Sculpin (17%, n=74) and Stickleback (13%, n=57). A total of 105 Arctic char fry and 43 parr were recorded, located in 46 and 38 microhabitats respectively (Tableau 6.2).

Tableau 6.2 Number of sampled microhabitats, number of presence/absence and number of individuals for Arctic char fry and parr.

	Kangiqsualujjuaq		Tasiujaq		Total (pooled)	
	Presence of fish †	Total number of fish	Presence of fish †	Total number of fish	Presence of fish †	Total number of fish
Fry (0+)	4	4	42	101	46	105
Parr (>1+)	10	14	28	29	38	43
Total microhabitats	285		293		578	
Total station scale habitats	48		49		97	
Total mesohabitats	26		23		49	

† Number of microhabitats where Arctic chars were recorded. If there were several fish in one microhabitat, the count of presence remained 1 for this microhabitat.

The ranked size of the sampled juveniles showed a change in slope at 64 mm (Figure 6.3a). This threshold was used to differentiate fry (0+) from parr (> 1+ year). This length is in agreement with a former sampling conducted in Aupaluk, a community located near Tasiujaq, where fish age was determined from otoliths (Mainguy and Beaupré 2019a). All fish with size larger than 64 mm were considered parr. There was another relatively abrupt change in ranked size of sampled juveniles between 108 mm and 124 mm, that likely indicates the size limit between 1+ and 2+. This inference is comforted by the fairly similar size difference, i.e. 107 mm-126 mm between 1+ and 2+, measured in Aupaluk (Mainguy and Beaupré 2019a). Nevertheless, in the present study, no size segregation was done for parr because of the relatively small sample size. Spatial segregation of juveniles according to the threshold of 64 mm was noticeable, especially at sites showing a higher density of fry (TA003 and TA0010) (Figure 6.3b).

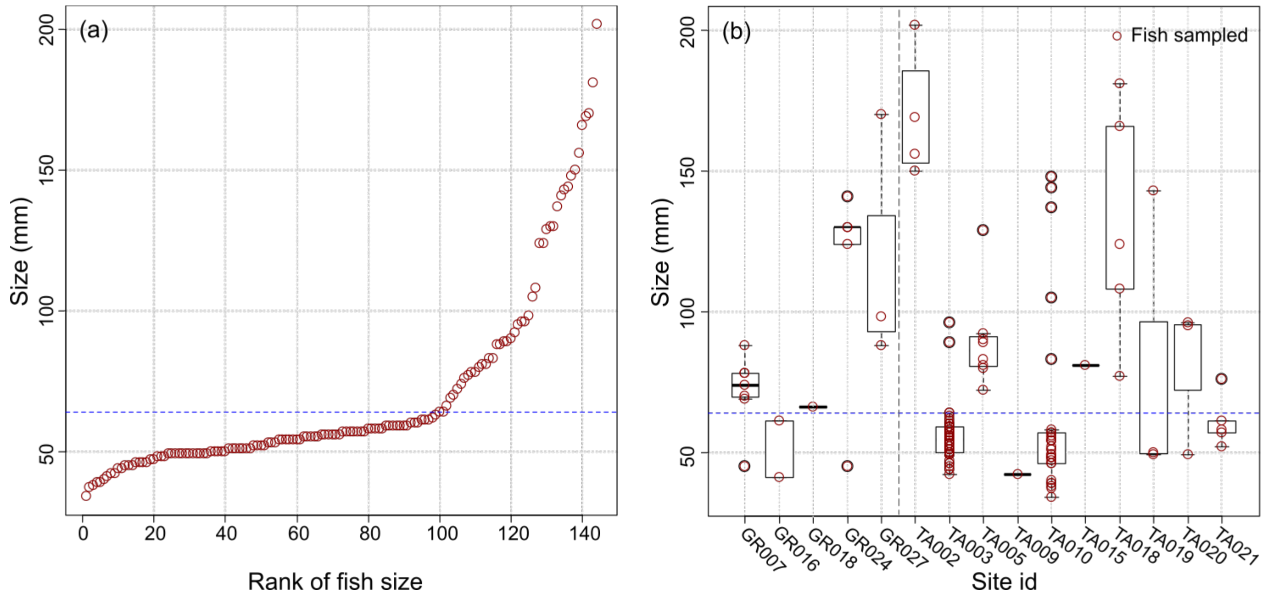


Figure 6.3 Size of all juvenile Arctic char sampled. (a) Ranked size. The length of 64 mm corresponds to a change of slope and is used to discriminate fry from parr (blue dashed line). A size disruption is observable between 108 mm and 124 mm, likely indicating the difference of sizes between 1+ and 2+ individuals. (b) Box plots of sizes sampled in the different streams of Kangiqsualujjuaq (GR site id) and Tasiujaq (TA site id).

6.3.2 Habitat preferences at microhabitat scale

6.3.2.1 Fry

Microhabitats used by fry showed significant difference from the overall available depths, velocities, substrate sizes and temperatures (Figure 6.4). From *post-hoc* G-test, fry showed a selectivity for shallow water below 20 cm, with Jacobs' index values of 0.74 and 0.59 for 0-10 cm and 10-20 cm depth classes respectively. They avoided depths higher than 20 cm. Substrate diameters larger than 300 mm were also significantly avoided. For temperature, the two different classes 7-9 °C and 15-17 °C showed significantly more occupation by fry. No significant selectivity was found for any velocity class, although 55% of fry were found at velocities below 0.1 m/s.

A logistic regression model was applied for fry presence/absence and microhabitat variables. Univariate logistic regression showed that depth and substrate were significant variables for fry presence/absence (p-values = 0.013 and 0.049 respectively). Multivariate logistic regression was applied to various combinations of the explicative variables. The set of variables showing the lowest AIC on the fitting sample was depth, velocity, substrate, Froude. However, Froude number add redundancy to depth and velocity and model Nagelkerke pseudo-R^2 was not improved with Froude. No correlation was detected between depth and velocity. Hence, the set of predictive variables that includes depth, velocity and substrate, which also showed the better Nagelkerke R^2 of 0.21 (Tableau 6.3a) a significant improvement from a non-informative model, was selected as the most appropriate model to predict fry presence. The model parameters are presented in the Supplementary data (Table S2, Annexe IV). Probability of presence of fry decreased with depth (Figure S2, Annexe IV), in agreement with the positive Jacobs' index value for low depth.

Tableau 6.3a Estimation of the performance of the multivariate logistic regression between presence of fry and river characteristics at the microhabitat scale. Parr presence did not show any significant relationship with any habitat variables at microhabitat scale.

Variables		R^2 Nagelkerke	Deviance	AIC
Depth, velocity, substrate, Froude	Fitting sample	0.16	57.9	67.9
	Validation sample	0.15	33.7	43.7
Depth, velocity, substrate	Fitting sample	0.21	64.2	72.2
	Validation sample	0.21	35.1	43.1
Depth, substrate	Fitting sample	0.17	68.5	74.5
	Validation sample	0.17	35.8	41.8
Null model	Fitting sample	0.00	142.6	153.5
	Validation sample	0.14	34.4	46.4

Tableau 6.3b Results of the frequency analysis between observed and predicted values of the multivariate logistic regression between presence of fry and river characteristics at the microhabitat scale.

Variables		Specificity	Sensitivity	Area under curve
Depth, velocity, substrate, Froude	Fitting sample	70.6	83.3	0.85
	Validation sample	67.2	80.7	0.82
Depth, velocity, substrate	Fitting sample	68.5	79.1	0.81
	Validation sample	65.6	77.0	0.79
Depth, substrate	Fitting sample	65.8	75.9	0.78
	Validation sample	64.6	74.1	0.77
Null model	Fitting sample	3.1	96.2	0.50
	Validation sample	67.4	79.9	0.81

6.3.2.2 Parr

The distribution of microhabitat used by parr showed no significant difference from the available microhabitat (Figure 6.4). Logistic regression model applied to parr presence/absence showed no significant relationship with any microhabitat variables nor any combination of these variables.

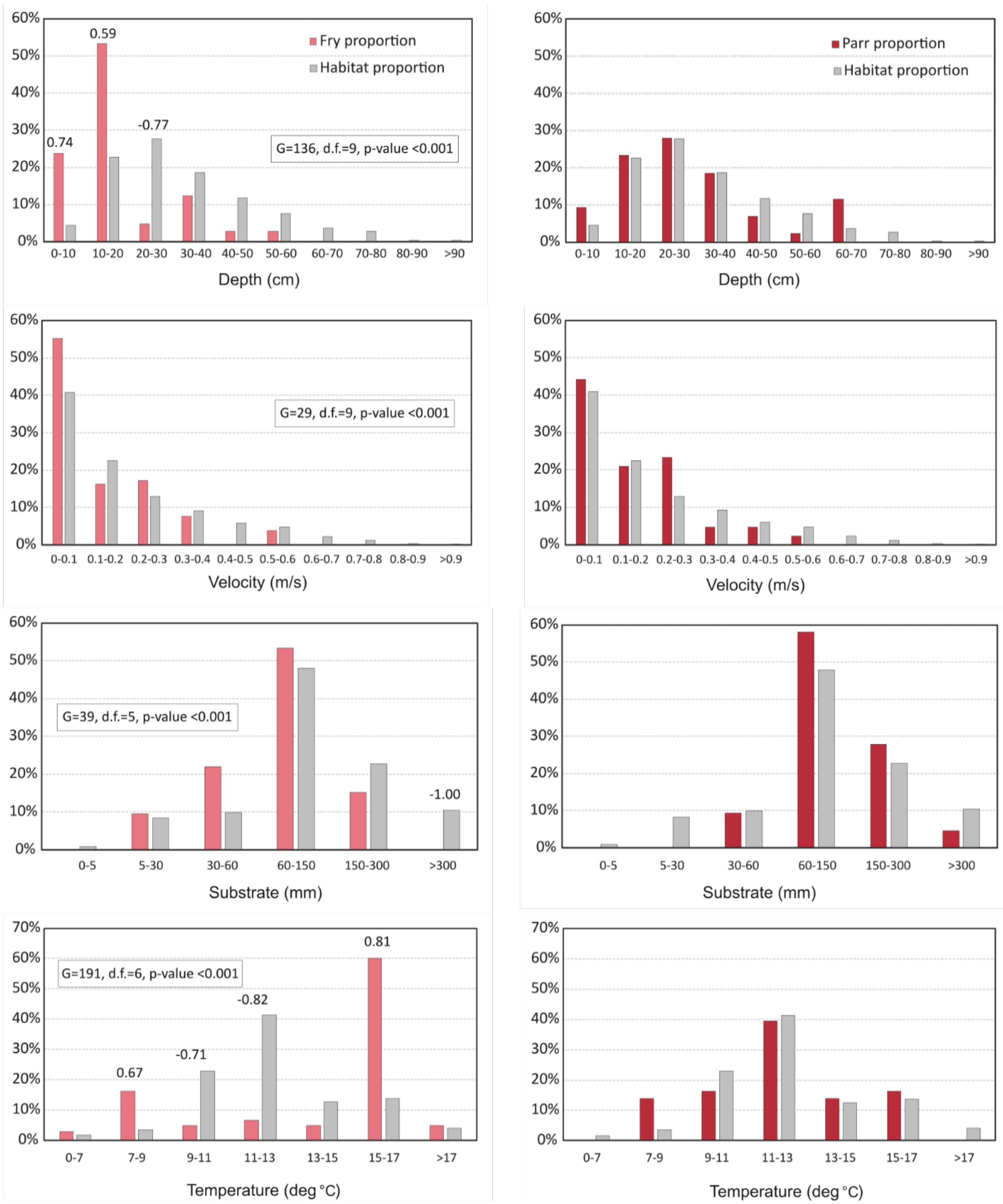


Figure 6.4 **Habitat use and availability for the microhabitat variables for fry (light red) and parr (dark red). Statistics are given for significantly different distributions. Numbers above use proportion correspond to the Jacobs' selectivity index (>0, selectivity; <0, avoidance), when a variable class use is significantly different than its availability.**

6.3.3 Habitat preferences at station scale

6.3.3.1 Fry

Fry number distribution was significantly different from the variable distribution at station scale, for depth, velocity, substrate and temperature. Results of the GAM model indicated a significant relationship between the number of fry and some river characteristics. At the station scale there was no variable collinearity detected, which can be explained by the fact the variables were averaged. Water temperature statistically explained 58% of deviance (Tableau 6.). The smallest AICc was obtained by adding depth to temperature. However, with a slight increase in AICc, adding velocity to depth and temperature lead to a substantial increase in R^2 and explained deviance. Adding Froude to the model increased the explained deviance to 92%, but significantly increased also the AICc. The most suitable set of variables to predict fry abundance was depth, velocity and substrate (Figure S3, Annexe IV). The highest fry quantity was predicted at depths lower than 30 cm and velocities around 0.2 m/s (Figure S4, Annexe IV). The quantity-temperature relationship was highly non-linear as most fry were found at the two sites TA003 and TA010. These sites were respectively at the lower (9°C) and higher (16.9°C) ends of the range of measured temperatures.

Tableau 6.4 Result of GAM for fry number vs habitat variables at station scale. Parr number did not show any significant relationship with habitat variables at station scale.

	R^2 (adj)	Deviance explained	Deviance	AIC	AICc
Depth, Velocity, temperature	0.73	89%	11.2	73.5	87.5
Depth, velocity, temperature, Froude	0.76	92%	8.9	73.6	103.6
Depth, velocity, substrate, temperature, Froude	0.78	92%	8.8	75.1	141.1
Depth, temperature	0.63	84%	16.5	75.4	81.4
Temperature	0.45	58%	44.4	99.9	101.9
Null model (intercept)	0.00	0.0%	105.3	156.8	157.1

6.3.3.2 Parr

Parr distribution did not show any significant difference from the distribution of station scale variables. When applying the GAM model to the number of parr, none of the combinations of habitat variables showed any significant relationship with parr number. Altogether, depth, velocity, temperature and Froude number constituted the best set of variables according to the AIC values, but explained only 8% of parr number deviance.

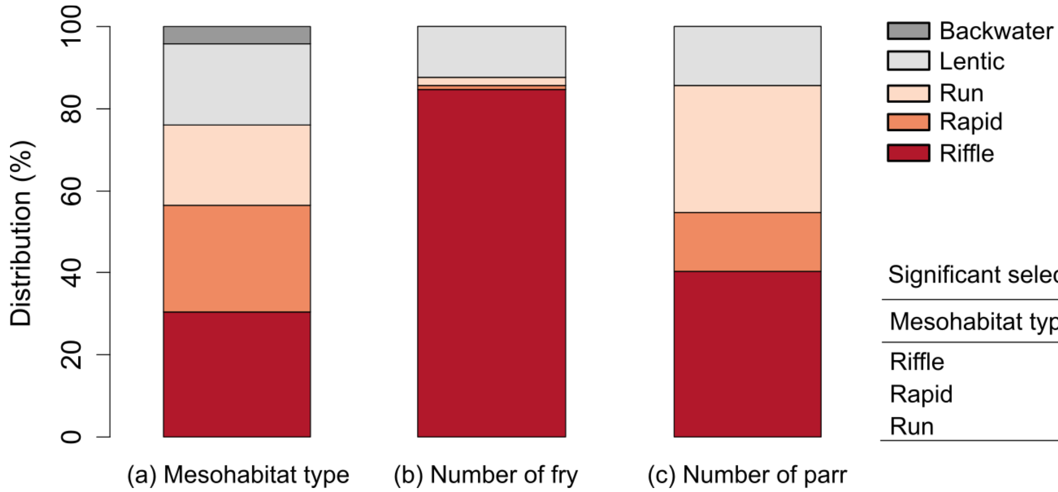
6.3.4 Habitat preferences at mesohabitat scale

6.3.4.1 Fry

The distribution of sites showing presence of fry is not significantly different from the distribution of all sampled mesohabitats (G-test=3.79, d.f.=5, p-value=0.58) (Figure S3, Annexe IV). The number of fry per mesohabitat, however showed a distribution significantly different than that of total mesohabitats sampled, revealing a selectivity (G-test=46.83, d.f.=5, p-value < 0.001) (Figure 6.5). Riffles were by far the habitats showing the highest number of sampled individuals, as 84% of fry were found in this type of mesohabitat. In order to discriminate which mesohabitat were selected for habitat use (positive selection or avoidance), a *post-hoc* G-test was conducted. The results showed that fry exhibit a significant positive selectivity for riffles (p-value<0.001), with a Jacobs' index value of 0.85 (Figure S5, Annexe IV). They also showed significant avoidance of runs and rapids (p-value<0.001). No significant selectivity for lentic environments nor backwater was found.

6.3.4.2 Parr

Although parr were found slightly more often in riffles and runs than in other mesohabitats (Figure 6.5), the general distribution of mesohabitats associated with presence of parr was not significantly different than the overall mesohabitat distribution (G-test=1.51, d.f.=5, p-value =0.95). Similarly, the distribution of the number of individuals was not significantly different (G-test=7.44, d.f.=5, p-value=0.28) (Figure S4, Annexe IV). Hence, according to these data, parr did not appear to show any mesohabitat preferences.



Significant selectivity for fry

Mesohabitat type	Jacobs' index
Riffle	0.85
Rapid	-0.95
Run	-0.85

Figure 6.5 Distribution of mesohabitat class for (a) total mesohabitats sampled, (b) total number of fry and (c) total number of parr. The number of fry per mesohabitat showed a significantly different distribution than the distribution of total mesohabitats sampled, revealing a selectivity. Fry showed a significant preference for riffles and significant avoidance for runs and rapids. Jacobs' indices are given for these mesohabitats. The distribution of the number of parr was not significantly different than the distribution of mesohabitats sampled.

6.3.5 Size as a dependant variable

6.3.5.1 Fry

The relationship between fry size and microhabitat variables was also modelled using a multivariate GAM. There was a significant relationship between fry size and water temperature as 17.6% of deviance was statistically explained by water temperature only. There was, however, a density dependence with size of fry with 13% of deviance in size statistically explained by their numbers, as 77% of fry were found in two streams (TA003 and TA010). TA003 site was warmer during the sampling period than TA010 (16.7 °C *vs*. 9 °C) and the size of fry from TA003 was significantly larger than fry from TA010 (p-value = 0.0006) (Figure 6.6). The size difference observed at these two locations likely explain the significant relationship between size and temperature. Other measured variables were not significant. Nonetheless, velocities used by fry showed a maximum threshold around 0.4 m/s, as only two individuals were found at higher velocity (0.6 m/s for both) (Figure S5, Annexe IV).

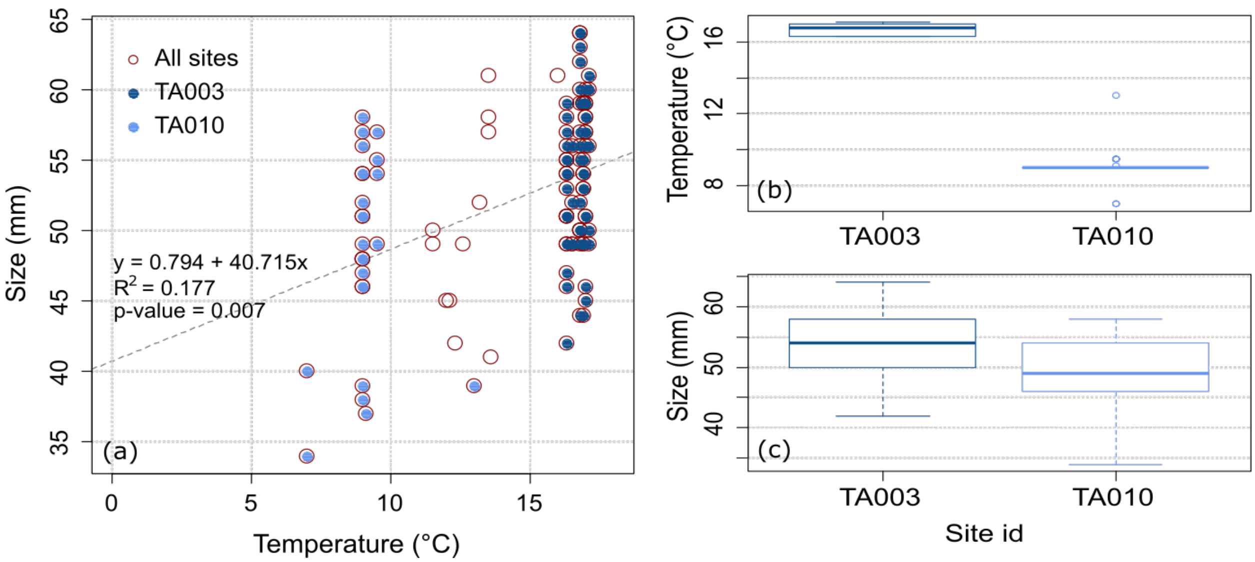


Figure 6.6 Size of fry vs. water temperature (a) for sampled microhabitats. (b) Box plots of temperature and (c) box plots of size for both TA003 and TA010 sites.

6.3.5.2 Parr

Distribution of parr lengths was best modeled using velocity, temperature and Froude number, the latter being dependant of water velocity, with an explained deviance of 40.3%. Velocity alone explained 24.7% of size deviance. When water temperature was added to the GAM model, 32.5% of size deviance was explained. There was a positive linear relationship between size of parr and velocity (R^2 = 0.22, p-value<0.001) (Figure S5, Annexe IV). Furthermore, only parr of more than 129 mm length were found at velocities above 0.35 m/s. These individuals were likely two years old and more. There was no significant relationship between size of parr and depth, substrate or number of fish.

6.4 Discussion

6.4.1 Fry habitat preferences

6.4.1.1 Microhabitat and station scale

The study demonstrated that at the microhabitat scale, Arctic char fry exhibited selectivity for shallow water with an increasing relative probability of fry presence when water depth was below 20 cm. At the station scale, the number of fry was predicted with a combination of depth, velocity, Froude number and temperature. Higher numbers of fry were predicted at depths below 30 cm, velocities around 0.2 m/s and low Froude numbers, i.e. below 0.1. These results are consistent with the habitat used by Dolly Varden fry (*Salvelinus malma malma*), a species closely related to Arctic char, which can be found in shallow areas (10-40 cm), near the river bed of gravel bars, backwaters of side or braided channels, or step pools (Stewart et al. 2010; Mochnacz et al. 2010). Substrate diameter larger than 300 mm were found to be avoided by Arctic char fry. Large substrate typically provides interstitial space that can be used by larger fish and potential predators of fry. The sampling method might also be less efficient to retrieve fish located in deeper interstices.

Although the GAM model was able to establish a statistical relationship between the quantity of fry and the temperature at station scale, it was not possible to infer any temperature preferences. Indeed, temperature variability was low for a given site, which precluded modelling of specific selectivity based on water temperature among available habitat. The high number of fry found in TA003 and TA010 (16.7 °C and 9.0 °C respectively) could be due to the circumstantial search of warmer habitat, which may lead fish to use shallow water (Nordahl et al. 2018). Indeed, fieldwork at these two sites was conducted on relatively warm sunny days and fry were likely reacting to local shifts in temperature. Nonetheless, the measured water temperature of 16.7 °C at TA003 site is at the lower limit of warm water avoidance for Arctic char. Either the fry had no access to colder refuges because of the shallow stream and potential physical barrier, or the relatively high measured water temperature was due to high direct solar radiation input. Maximum air temperature on this day was somewhat lower than that of the river, at 15.0 °C, which is in the optimal range of temperature to maximize juvenile char growth when food is abundant (Swift 1965; Jobling 1983; Larsson et al., 2005; Sæther et al., 2016). At the TA010 site, the measured temperature was in the range of juvenile thermal preference. Indeed, according to laboratory experiments, juveniles show preference for water temperature between 9 °C and 11.8 °C (Siikavuopio et al. 2014 ; Larsson, 2005), corresponding to the optimum for energetic efficiency (Larsson and Berglund 1998). As juvenile Arctic char live in low productivity environments, they show a preference for colder temperature than the value that maximises growth in laboratory. Further investigations are needed to understand fish behavior and preferences relative to water temperature.

6.4.1.2 Mesohabitat preference

The analysis at mesohabitat scale showed that fry had a significant preference for riffle habitat with a Jacobs' index value of 0.85. Riffles sections form the most heterogeneous landforms in reaches. Moreover, in high latitude regions, substrate size and river reach morphology, especially riffles, are not only constructed by hydraulic capacity, but also by freeze-thaw cycles (Reed and Bostock 1954) and river icing (Alekseev 2017). These cycles produce erosion, visible in several streams of the study area (Rowland et al. 2010 ; Jolivel and Allard, 2017). This implies that even in small streams, large size boulders can be found and act hydraulically as an obstacle to the flow, increasing the opportunity of heterogeneous flow and suitable habitat for fish.

Fry significantly avoided rapids and runs, likely because of velocities higher than their swimming capacity. No significant selectivity was found for lentic habitat in which 12 % of fry were found. Even if measured velocity was suitable, no fry was found in backwater habitat. Indeed, in the present study, backwater mesohabitats were characterized by the presence of eddies and were generally next to rapids. Hence, fry would have had to swim across the rapid to access the backwater zone. In the case where the backwater mesohabitat would be used as a spawning area, fry emerging at this location would likely be carried downstream with the current.

6.4.2 Size of fry depended on rearing site

As juvenile growth rate is positively correlated with water temperature (Larsson and Berglund 2005), it is a realistic assumption that larger size of fry observed in TA003 site was due to warmer water temperature than in TA010. Even if water temperature measures were spot measurements made during the sampling on two consecutive days, it is probable that direct solar radiation has had more warming effect on TA003 streams than on TA010 site, where the river takes its source form a large lake (Finger Lake), more difficult to warm. Larger size of fry in TA003 could also be due to food source availability, as stated by Godiksen et al. (2012) who did not find any clear correlation between mean temperature and growth of juvenile Arctic char from otolith analysis. Indeed, TA003 is a small tundra stream, fed by small ponds and marshes whereas TA010 constitutes one of multiple outlets of a large lake, which has less terrestrial particulate organic carbon input and thus more productivity. The presence of more resource for fry might explain why mature Arctic char spend energy to reach small streams for spawning, as some of them are remote from their overwintering areas. Size analysis indicates that there is a potential interest in looking at suitable habitat from perspectives other than a limited list of environmental variables, as suggested by Polivka (2020).

6.4.3 Parr did not appear to show habitat preferences

As Arctic char parr have better swimming capacities than fry, it was expected that parr would show higher habitat selectivity than fry. This is what is generally observed for juvenile salmon, indicating that motility allows them to get to their most favorable habitats (Hedger et al. 2004). On the contrary, in the present study neither presence nor number of parr could be related to the river physical variables, whether at microhabitat scale or station scale. Moreover, parr seemingly showed no preference for any specific mesohabitat based on reach geomorphology. Thus, from the data collected, parr habitat preferences could not be identified, based on streams physical characteristics. These results are supported by traditional Inuit knowledge. Indeed, knowledge holders on Arctic char from the Inuit communities of Kangiqsualujjuaq, Tasiujaq and Kangirsuk (Nunavik, Canada), who were asked about juvenile habitat, stated that parr did not have any preferences for a specific type of habitat(Figure S6, Annexe IV). According to some Inuit interviewed (three out of eleven), lakes are used by juvenile as much as rivers. Some also mentioned that juveniles follow the adults toward marine environment at an early age. The largest parr sampled was 202 mm and was likely three years old according to its size class (Mainguy and Beaupré 2019a). According to the literature, the mean size at first migration is around 180 mm (Johnson 1980b; Gulseth and Nilssen, 1999; Gilbert et al., 2016; Atencio et al., 2021). This size is corroborated for Ungava Bay by Inuit interviewed but it seems also that parr are found around river mouths, next to brackish water (Figure S6, Annexe IV). Hence, the decreasing number of parr with size might indicate that the majority of the largest juveniles had already migrated toward river mouths and the estuarine zones, which were not part of the sampled areas. It also should be noted that backpack electrofishing implies that deeper river sections, lake, larger rivers or tributary inlets/outlets were not sampled and could constitute significant parr habitat.

The well-known diversity in life history and flexibility in ecological niche use (Hammar 2014) is a consequence of individual flexible behavior, even at the early life stages. As they grow, Arctic char parr benefit from their increasing abilities to access more diverse habitats. As Arctic char is qualified as a generalist species, our results at reach scale tend to corroborate this notion, with flexible individual behavior of the juveniles.

6.4.4 Velocity is a limiting factor for juvenile Arctic char

Most fry were found at velocities below 0.30 m/s. They were likely sheltered from the current behind rocks and near the river bed, where they feed. The measured velocities in this study were representative of the whole microhabitat and not of the exact velocity at the nose of the fish. No relationship could be established between velocities and preference of parr, although only larger individuals were found at velocities higher than 0.35 m/s. Likewise, the majority of juvenile Arctic char observed by Heggenes and Saltveit (2007) at the end of summer, were aggregated in a deep side pool at a lower part of a river. The other parr used slow or still water, deeper than the habitat used by salmon parr, and preferably in a side channel. In our study, as larger individuals also used velocities lower than 0.35 m/s, we can speculate that higher velocities are not specifically a preferred habitat but that velocity just becomes less limitative with growing fish size.

6.4.5 Benefits of using multiple scales for habitat analysis

Microhabitat scale analysis, using hydraulic variables, relies on spot data measurements and are flow specific (Bovee 1982). They are useful for instream flow determination but, without the use of a hydraulic model, are limited to a specific condition. In addition, they do not allow for the incorporation of spatial variability of the surroundings for a given flow. The station scale used in this study was intended to account for such variability. Indeed, fish preference or selectivity can depend in part on a certain degree of suitability of the broader surrounding environment, even for different flows (Heggenes et al. 1996). Mesoscale habitat analysis from geomorphologic units allows to account for the patchiness of habitat. Using different scales of observations, and different factors, such as behavior or size can help with the understanding of habitat preferences (Heap et al. 2015). Investigating mesoscale habitat preferences based on geomorphological units allows also to explain the suitability of some sites with physical processes. For example, riffles are found in medium slope stream reaches (<1.5%), and their presence implies higher slope, lowering velocity in upstream pool (backwater) and increasing hydraulic roughness due to a variety of elements, reducing shear-stress on the river bed, and hence reducing sediment transport competence (Buffington et al. 2004). As a result, the periphery of riffles is subjected to gravel accumulation and can become suitable spawning habitat for salmonids. Nevertheless, as scale of rivers differs widely, mesohabitat identification bears some subjectivity. For example, a run in a small stream could present some of the same hydraulic characteristics as a pool in a larger river. Boulders and blocks can be found even in pools or lentic reaches. This means that fish are likely exposed to more variability between different mesohabitats as well as some heterogeneity within a mesohabitat. This structural complexity could be favorable for fish, but leads to difficulties in habitat identification.

It would be relevant to analyse habitat preferences at an even broader scale, taking into account site location in hydrographic and river dynamics context (Fausch et al. 2002). A downstream barrier to spawners passage could imply absence of juveniles without indicating unsuitability of local conditions upriver. This kind of limitative factor could be better identified by scaling-up and adding other habitat descriptive variables, like mean or maximum reach slope, heterogeneity level of mesohabitats or adding river bank typology (Cattanéo et al. 2014). Examining river order might also assist in better identification of sites used by parr. Indeed, although parr did not show any significant preference based on the hydraulic variables or mesohabitats, 18% of parr were found in small size streams, such as brooks or small anastomosed channels (one to a few meters wide). These small size streams formed only 5 % of microhabitats sampled. They usually show more spatial heterogeneity and hence, more variability in habitat availability within a smaller distance. Most other studies on anadromous char have focused on population dynamics and only general habitat use can be inferred. Parr of Dolly Varden are also known to use small streams in summer, different than their native and overwintering streams. They also use larger rivers as migration corridors and feeding habitats between tributaries or to estuaries (Craig and Poulin 1975; Stewart et al. 2010). It is likely that Arctic char parr exhibit similar stream use.

River order might also be important to consider for fry habitat preference. Small order streams are relatively frequent, but they are also more critical habitat for juvenile char than stated by Mochnacz et al. (2010) for Dolly Varden, which occupy mainly groundwater fed streams systems. In contrast, small shallow stream selection by fry of Arctic char in Nunavik makes them vulnerable to low flow and water warming during summer, more frequently observed by Nunavimmiut over the last years (Kangiqsualujjuaq local hunters' association (LNUK) meeting, June 2019; W. Cain Jr, Tasiujaq, 2019; fishermen, Kangirsuk, 2019 and A. Gordon, 2020, pers. communication). Fish are also more likely to get trapped in pockets of water at low flow condition. These conditions are likely to happen simultaneously in the middle and end of summer and can lead to juvenile mortality, given the important regional climate warming already observed in the Nunavik region.

6.4.6 Limitation of methodology and hypothesis

The prediction of fry number obtained with the GAM model was in large part influenced by the hydraulic and thermal characteristics of site TA003 where 66% of total fry individuals were found. As depth and temperature at this site, were not representative of the other sites (t-test, p-value < 0.001), a regional habitat selectivity model with pooled data may not be as representative as a local model (Hedger et al. 2004).

Backpack electrofishing shows better efficiency at low depth (<1 m) and relatively low velocity (1 m/s). Streams sampled showed a rather uniform range of hydraulic conditions (mean depth = 0.32 m, s.d. = 0.18 m; mean velocity = 0.20 m/s, s.d. = 0.16 m/s). Thus, the variability of habitats sampled is artificially reduced compared to actual available habitats, which is impacting selectivity index. Lakeshores were not included in the analysis of mesohabitat selectivity but some fry were observed in those mesohabitats during the night at the end of summer 2019 and in summer 2021, near Kangiqsualujjuaq. Furthermore, electrofishing conducted during the daytime tends to underestimate observed fish presence compared to snorkeling observations at night (Wegscheider et al. 2020), as juveniles can be more active during the night (Adams et al. 1988;

Stewart et al. 2007). Hence, microhabitats showing absence of fish might actually have been occupied by individuals that were simply missed (false absence) or fish that only occupy this habitat at night. This potential bias could lead to weaker relationship in the logistic regression when analysing absence/presence *vs* physical characteristics (Mouton et al. 2012) as the probability of detection of false absence were not assessed. Singled-pass electrofishing can also lead to biases on quantity measurement, especially when there is a low density of fish as it is the case of juvenile Arctic char (Hanks et al. 2018; Hedger et al. 2018).

The sampling showed that several species are present in the studied streams, and potential interaction between species were not considered. Among the species sampled, it is known that Stickleback could be prey for large juvenile Arctic char (i.e. ≥ 200 mm; Amundsen 1994; Dick et al. 2009). No known aggressive or predatory fish for juvenile Arctic char were found in the sampled rivers, unlike in northern Europe where brown trout and Arctic char can be in sympatry. However, the presence of other predators could affect the abundance of juvenile. Indeed, Inuit experts mentioned during interviews in Kangirsuk that river otters can affect char population in rivers when they are abundant (see section 3.5.8). In addition, in the recent years, predator birds like falcons, Osprey and Bald eagles have been also increasingly observed in this community.

6.5 Conclusion

The present study confirmed that Arctic char fry exhibit significant habitat selectivity. At the microhabitat scale, their presence could be linked to local depth, velocity, and substrate, with preferences for low depth and slow velocity and avoidance of the largest substrate. At the station scale, a slightly broader spatial scale of tens of square meters, depth, velocity and Froude number were significant predictors of fry abundance and habitat selectivity. They showed a preference for small depths, under 0.3 m, and velocities between 0.1 m/s and 0.2 m/s. At the mesohabitat scale, based on reach geomorphology identification, fry exhibited significant selectivity for riffles and avoid rapids and runs. This quantitative estimation of habitat selectivity for fry opens the path to building habitat preference models. Knowledge of fry preferences in terms of river reach morphology or hydraulic characteristics allows to assess the suitability of a given reach and thus, to identify importance of streams for juvenile Arctic char. But for management and conservation, site specific models would be more suitable than global models.

A complementary result was that size of fry depended on the rearing stream, either directly because warmer temperature fosters growth or indirectly because of sites resource availability. As growth is an indicator of population fitness, sites with better growth can be indicators of better suitable habitat for fry. Further research is needed to assess habitat preferences at the stream scale and the potential relation to water temperature. Data sampled did not allow to assess any local temperature selectivity. Long-term temperature measurements combined with juvenile observations would allow to better detect if habitat used are selected according to mean or sun-warmed temperature.

An unexpected finding of the study was that parr did not show any specific habitat selectivity in the context of the sampled data, leading to the impossibility to build a habitat preference model. Velocities are still a limitative factor for juveniles, depending on their size. Results were analogous at all scales and were consistent with the observation of Inuit who were interviewed. Larger size of parr have better motility, which allows them to use diversified habitats. This individual plasticity in their habitat use is likely a downscaling of the species known plasticity. Nonetheless, given that relatively few parr were sampled, their use of river mouths and estuaries, which were not sampled in the present study, is suspected. Further investigations are needed to assess a possible selectivity of these habitats as well as deeper areas (pools or lakes) of streams that were not part of the sampling protocol.

In the present study, use of various scales to analyse juvenile habitat preference allowed a more comprehensive understanding of juvenile Arctic char distribution in riverine ecosystems, as little was known about their rearing habitat selectivity. From qualitative observations, the suspected preference of small streams by juveniles in summer makes them vulnerable to experience low flows and a rise in water temperature in summer. Including stream size or order for habitat preference analysis would allow to better detect critical sites used by juveniles.

7 CHEMINEMENT DU PROJET, ENGAGEMENT ET RÉCIPROCITÉ

Baie de Tasikallak, région de Kangiqsualujjuaq, Août 2021

7.1 Évolution du projet et apprentissage de la décolonisation de la science

7.1.1 Projet initialement prévu

Le projet a été initié en discussion avec la société Makivik et le ministère de la Faune de la Forêt et des Parcs du Québec (MFFP). Il avait pour but de bâtir des modèles prédictifs pour l'habitat de fraie et l'habitat des juvéniles pour l'omble chevalier anadrome au Nunavik. Puisque les données de terrain étaient inexistantes et que les données de télédétection étaient peu précises dans le Nord, l'idée était d'utiliser un modèle de logique floue à partir des savoirs inuit, comme il avait déjà été fait pour le saumon avec des experts scientifiques (Mocq et al. 2013). Le projet a donc commencé comme un projet scientifique classique, à la différence près qu'il était localisé en territoire inuit et impliquait de collecter de l'information d'experts inuits, à travers des entrevues. Bien que les communautés eussent été approchées formellement en amont pour sonder leur intérêt et que l'omble chevalier était une espèce d'intérêt, il s'agissait d'une question de recherche établie par des chercheurs du sud, utilisant de façon sélective des informations spécifiques fournies dans un contexte d'entrevues formelles, avec peu d'application directe à court terme dans la gestion des pêches de chaque communauté. Dans un contexte de décolonisation de la science, le principe ce serait apparenté à de l'extractivisme (Tynan 2021) et risquait d'être non-acceptable du point de vue éthique.

7.1.2 La réalité du contexte

Le fait d'étudier l'omble chevalier, une espèce essentielle pour les communautés partenaires, a généré un intérêt de leur part et m'a ouvert des portes pour débuter le projet. Cependant, dès la première visite dans chacune des trois communautés, les collaborateurs Inuit m'ont mis au fait de la sursollicitation dont ils faisaient l'objet de la part des chercheurs. Cette « fatigue de la recherche » (*research fatigue*) a déjà été notée dans la littérature (Dufour-Beauséjour and Plante Lévesque 2020). De plus, j'ai été instruite par mes collaborateurs et certains ainés des pratiques de recherche peu éthiques qu'ils avaient subies (travail de guide sans salaire, travaux de recherche ayant un impact négatif sur la faune, chercheurs qui viennent très fréquemment dans la communauté sans prévenir et/ou sans faire de suivi de leurs résultats, …). Ils avaient clairement une méfiance envers l'attitude de certains chercheurs du sud qui profitent des Inuits et de leurs connaissances du territoire et sans qu'ils en aient les retombées. Ils m'ont explicitement demandé que (a) mon travail tienne compte des savoirs inuits, (b) les connaissances partagées et mes résultats ne puissent pas être utilisés au détriment des animaux ou de l'intégrité du territoire (par exemple, pour la collecte des œufs d'omble chevalier, quel qu'en soit le contexte); (c) mes résultats soient partagés aux communautés, (d) mon travail soit bénéfique pour la communauté. La connaissance des experts inuits ne pouvait pas être utilisée sans contrepartie, autre qu'une compensation financière pour leur participation.

7.1.3 Évolution du projet pour intégrer les savoirs inuits

Pour donner suite à ces discussions qui m'ont mise face au contexte historique et toujours colonialiste, il fallait que mon travail soit fait avec responsabilité et respect des personnes qui allaient partager leurs savoirs et, en premier lieu, tenir compte de ces savoirs lorsque c'était possible. Au cours des entrevues il a été constaté que beaucoup d'observations faites par les participants n'étaient pas documentées ou étaient complémentaires de la littérature scientifique. Ainsi, le savoir inuit a aussi été intégré de façon qualitative pour documenter le cycle de vie au complet de l'omble chevalier et faire des liens avec la littérature, bien que ce soit une pratique inhabituelle en sciences naturelles (chapitre 3). Pour l'étude des habitats, il est apparu que les experts inuits avaient effectivement beaucoup de connaissances sur les sites de reproduction des ombles, ce qui a permis d'appliquer un modèle de logique flou, tel que prévu (chapitre 4). Le contexte était cependant différent pour les juvéniles. En effet, mêmes s'ils étaient aperçus dans les cours d'eau, les participants n'avaient pas de connaissances spécifiques sur les caractéristiques de leurs habitats. La méthodologie planifiée initialement n'était donc pas applicable aux juvéniles. Cependant, le savoir inuit concernant les juvéniles a permis de valider les résultats du modèle par des chasseurs et des ainés (chapitre 6). Les relevés scientifiques auraient pu être les seules données, mais le fait de les voir corroborées a renforcé la confiance dans ces résultats. L'analyse de l'habitat d'hiver (chapitre 5) prend sa source des discussions faites lors des entrevues et avec des pêcheurs qui ont en effet expliqué que les poissons utilisent des zones spécifiques des lacs d'hivernage et qu'il y a des zones qu'ils n'utilisent pas. C'est ainsi, qu'est née l'idée de caractériser l'habitat hivernal utilisé par les ombles, en travaillant en partenariat avec des pêcheurs pour déterminer les sites de présence et pour faire les relevés. Cette méthode s'est avérée d'autant plus pertinente qu'à l'hiver 2020, période où les relevés ont débuté, il n'a plus été possible pour les scientifiques du sud d'aller faire des relevés dans le Nord à cause de l'épidémie de Covid19.

Durant les six séjours de travaux sur le terrain que j'ai complétés dans les différentes communautés ont été très utiles pour me familiariser avec la culture et les façons de faire et me permettre de bâtir et renforcer les liens de collaboration. Ces séjours et rencontres m'ont permis d'entrevoir la profondeur du savoir Inuit, bien qu'encore superficiellement.

7.2 Réciprocité et engagement auprès des communautés partenaires

7.2.1 Rapports synthèse d'entrevues

En ayant conscience que le projet aurait pu être plus collaboratif au départ, j'ai choisi d'avoir une pratique d'engagement et de dissémination des résultats proactive. Cette pratique a été faite pour répondre aux préoccupations qui m'avaient été partagées au début du projet et dans le but d'être dans une relation de réciprocité, sous-tendue par l'utilisation des savoirs inuits et respectant la culture inuite (Nunavut Department of Education 2007).

Ma pratique de dissémination des résultats a commencé en faisant un suivi régulier de mon travail, pour montrer qu'il était important pour moi que je partage les avancements puisque des ainés m'avaient fait confiance en me partageant leurs connaissances. La dissémination s'est concrétisée une première fois avec la distribution des rapports faisant la synthèse des entrevues dans chaque communauté (entrevues décrites au chapitre 3). Ces rapports m'avaient été demandés pour que l'information transmise par des ainés reste dans la communauté et ne disparaisse pas.

Pour chacune des trois communautés, un rapport faisant la synthèse des entrevues réalisées a été produit en anglais et Inuktitut. Les rapports comportaient également la cartographie des sites d'intérêts, relatifs à l'omble chevalier, localisés lors des entrevues. Le format a été choisi par les participants, préalablement aux entrevues. Les rapports ont été distribués aux participants, aux LNUK et/ou aux autorités municipales ainsi qu'au centre de recherche de Makivik, à Kuujjuaq. Ces rapports sont confidentiels étant donné que la localisation des sites de fraie est considérée comme une information sensible par les communautés.

7.2.2 Illustrations des résultats

Les résultats des pêches électriques réalisées à Kangiqsualujjuaq et à Tasiujaq ont également été cartographiés pour permettre un rendu visuel des espèces de poissons pêchées et de leur abondance respective (le chapitre 6 est basé sur les résultats de ces pêches électriques). Les rapports ont été distribués aux LNUK et/ou aux autorités municipales et au centre de recherche de Makivik, à Kuujjuaq.

Les rapports d'entrevues et de pêche électrique ont été fort appréciés et, à la suite de ces démarches de suivi et de vulgarisation, j'ai vu une plus grande ouverture dans la réception de mon travail. Voyant que l'illustration des résultats était utile pour ouvrir et faciliter la communication, j'ai postulé et obtenu la bourse Éric Dewailly, de la Chaire Littoral de l'Université Laval, qui permet de financer des produits de mobilisation des connaissances. J'ai ainsi pu faire réaliser des illustrations en collaboration avec une graphiste professionnelle, Estelle Villemin.

Un dépliant illustrant le cycle de vie de l'omble chevalier, basé sur les entrevues et personnalisant les participants a ainsi été réalisé. Pour illustrer les résultats de l'étude sur l'habitat des juvéniles, une illustration grand format montrant les préférences d'habitat a également été produite. Les illustrations ont été réalisées en français, anglais et Inuktitut (Annexe V).

7.2.3 Codéveloppement d'un nouveau projet de recherche à Kangirsuk, mené par la communauté et faisant suite à des problématiques soulevées durant les entrevues

Afin d'augmenter mon engagement envers les communautés partenaires, avec les capacités qui sont les miennes et parce que la réciprocité est un élément important de la culture inuite, j'ai proposé aux trois communautés de les accompagner pour chercher du financement permettant de résoudre d'éventuelles questions de recherches, quelque qu'elles soient, qui auraient pu les intéresser. Les communautés de Kangiqsualujjuaq et de Kangirsuk ont identifié des problématiques concernant l'omble chevalier et les changements climatiques. J'ai donc participé, en collaboration avec les LNUK des deux communautés à un appel de propositions pour le programme *Inuit Qaujisarnirmut Pilirijjutit: research by Inuit, for Inuit,* lancé par Inuit Tapiriit Kanatami et Arcticnet.

Le projet de Kangirsuk, qui consistait en un suivi communautaire des populations d'omble chevalier et un suivi par télémétrie acoustique en lac, a été sélectionné (https://arcticnet.ulaval.ca/fr/project/study-of-arctic-char-catches-and-stock-assessment-and-winter-disappearance-in-tasirjuarusik/). Il faisait suite à des problématiques soulevées lors des entrevues et à d'autres reprises lors de mes discussions sur place. Le projet a démarré à l'été 2021. Un financement de 137 000 $ a été octroyé directement au LNUK qui contrôle la recherche, la façon de travailler et les données. Il répond aux indicateurs permettant d'évaluer l'engagement d'un projet (David-Chavez et Gavin 2018) et aux cinq priorités de la stratégie de recherche inuite (Inuit Tapiriit Kanatami 2018) :

- Promouvoir la gouvernance inuite en matière de recherche;

- Améliorer l'éthique de la recherche;
- Harmoniser le financement en fonction des priorités de recherche des Inuits;
- Assurer l'accès, la propriété et le contrôle des Inuits relativement aux données et aux renseignements;
- Renforcer les capacités en recherche dans l'Inuit Nunangat.

Ainsi, en guise de réciprocité, mon projet de doctorat, a abouti sur un nouveau projet collaboratif, par et pour les Inuits, mené par la communauté de Kangirsuk.

7.2.4 Utilisation de la vidéo

Lors des relevés de terrain, j'ai commencé à filmer des ombles, à différents stades de leur cycle de vie. J'ai ainsi pu filmer des ombles en migration amont (Kangiqsualujjuaq, Ujarasutjulik), qui se groupaient quelques semaines avant de frayer (Kangiqsualujjuaq, Tasikallak), sur le point de frayer (Tasiujaq, rivière Bérard), des juvéniles visible pendant la nuit (Kangiqsualujjuaq, Ujarasutjulik), une éclosion hivernale en 2020 (Kangiqsualujjuaq, Tasikallak et rivière Koroc) et l'utilisation de l'habitat d'hiver (Kangiqsualujjuaq, Tasikallak). J'ai constaté que l'utilisation de la vidéo s'est avérée très utile pour éveiller l'intérêt de mes interlocuteurs inuits. J'ai donc continué à l'utiliser dans mes communications et pour faire le suivi régulier du projet.

J'ai également fait une vidéo montrant le terrain réalisé pour le projet de télémétrie acoustique à Kangirsuk. La vidéo avait comme objectif de montrer un exemple de projet collaboratif, mené par la communauté et avait été initialement prévue pour faire une présentation du projet dans le village, qui a finalement dû être annulée. Cependant, elle a été très appréciée à la fois par les participants au terrain qui ont été filmés, et par le LNUK de Kangirsuk qui voulaient la diffuser. La vidéo a également servi à faire des présentations dans des écoles :

- À Tasiujaq et à Kangirsuk, au niveau secondaire, pour parler du cycle de vie de l'omble chevalier et montrer comment les savoirs Inuit et la science peuvent travailler ensemble. L'objectif était de montrer que la science peut être intéressante et adaptée à leur environnement. Les participants au travail de terrain étaient connus des élèves à Kangirsuk ce qui a généré un intérêt supplémentaire.

- À l'école primaire de ma fille pour montrer aux enfants du sud ce que c'est que de faire de la science dans un environnement nordique et parler de la culture inuite

J'ai également utilisé cette vidéo pour des présentations dans des conférences scientifiques (Inuit Studies 2022 et Arcticnet 2022).

La version française a gagné le prix Coup de cœur du jury au concours vidéo de l'ACFAS en 2022. (https://www.acfas.ca/publications/magazine/2022/05/coup-de-pouce-coup-de-coeur-concours-vulgarisation-2021-2022-dubos-mysterieuse-disparition-ombles-chevaliers-lac-tasirjuarusik).

7.2.5 Apprentissage de l'Inuktitut

Mes travaux de terrain ont été immersifs, dans la mesure où j'étais la seule scientifique du sud accompagnée par un ou des Inuits. Cette immersion dans une culture et une langue très éloignée des miennes génère inévitablement de l'inconfort. Le fait de connaitre quelques notions d'Inuktitut a fini par me permettre de comprendre le contexte de discussion autour de moi, sans encore en comprendre le sens précis. De plus, montrer que je comprenais quelques mots a permis de blaguer un peu et a rendu le contexte de décalage culturel plus confortable. Surtout, l'apprentissage de cette langue très descriptive et liée à l'environnement m'aide à comprendre la culture, à comprendre comment les lieux sont nommés et surtout à un peu mieux percevoir le lien que les Inuits ont avec leur environnement. Au-delà de l'intérêt personnel, l'apprentissage de l'Inuktitut apporte un regard différent sur la culture et modifie le comportement mutuel.

8 DISCUSSION GÉNÉRALE ET CONCLUSIONS

8.1 Réalisation des objectifs et discussion

8.1.1 Objectif n°1 : Caractérisation des habitats

Le premier objectif de cette thèse était de caractériser et modéliser les habitats utilisés par l'omble chevalier anadrome pour ses différents stades de vie en eau douce. L'habitat de reproduction en rivière a été caractérisé à l'aide des savoirs inuits et a été modélisé à l'aide de la logique floue. Les habitats utilisés par les juvéniles en période estivale ont été caractérisés par la pêche électrique et ont été modélisés statistiquement. L'habitat d'hiver a été caractérisé à partir des sites de pêche traditionnels mais comme aucune relation avec les variables spécifiques analysées n'a été constatée, il n'a pas pu être modélisé. La figure 8.1 illustre les éléments de contribution de cette thèse (en vert) relativement au cycle de vie de l'omble anadrome du Nunavik.

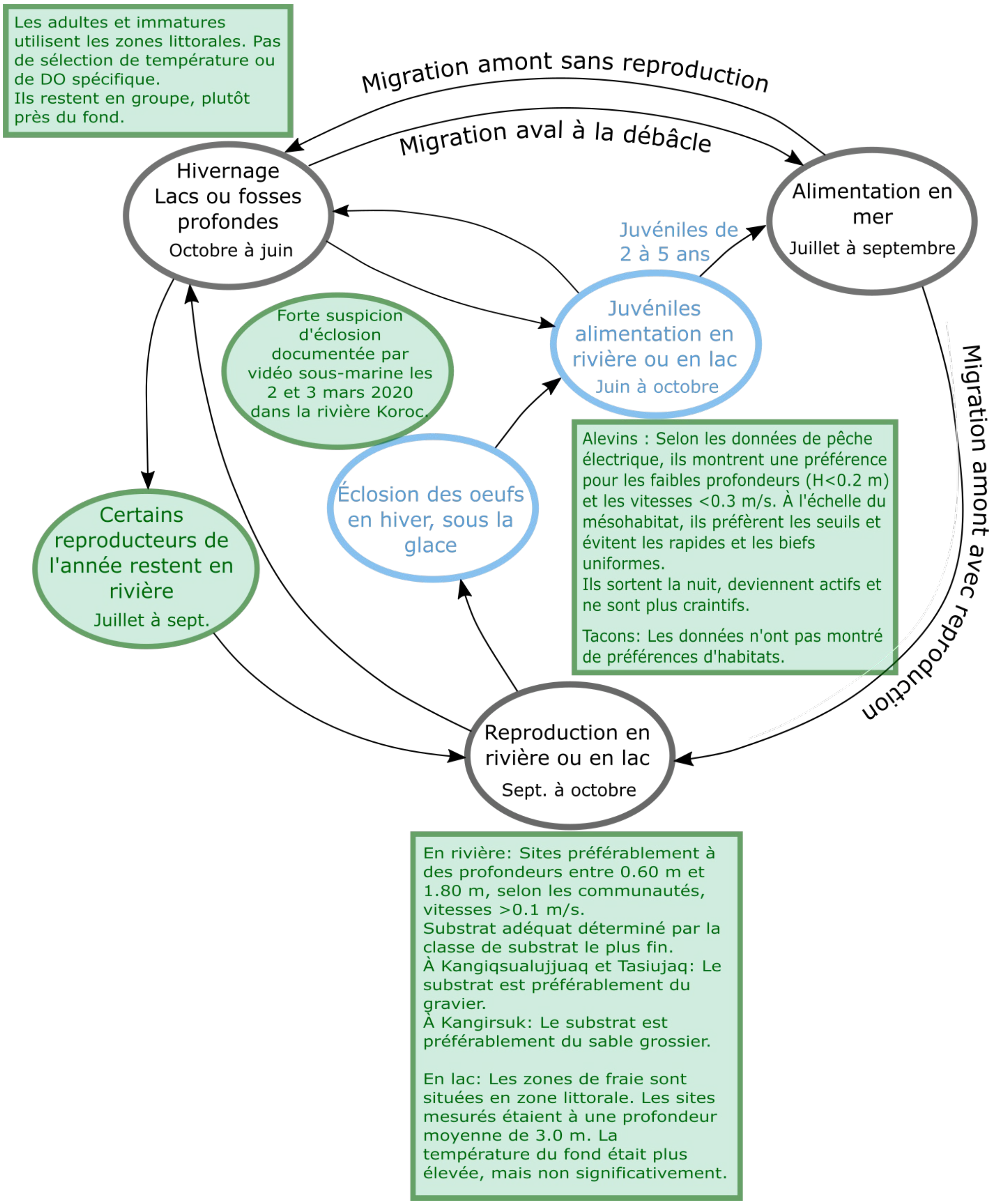


Figure 8.1 Éléments de contribution à la connaissance de l'écologie de l'omble chevalier anadrome (en vert). Les contours en boîtes décrivent les caractéristiques de l'habitat. Les stades de vie au contour gris concernent les adultes matures ou immatures. Les stades au contour bleu concernent les juvéniles avant smoltification.

8.1.1.1 Habitats de fraie en rivière

<u>*Caractérisation et modélisation*</u>

La baie d'Ungava est située à la limite méridionale de la distribution des ombles anadromes ce qui pourrait expliquer l'utilisation principale des rivières pour la fraie. En effet, les populations plus nordiques utilisent plutôt les lacs ou les fosses profondes des rivières importantes, possiblement parce que le risque de gel pour les œufs devient alors important à des profondeurs plus faibles (Johnson 1980b ; Harwood and Babaluk 2014). Les habitats de fraie en rivière ont pu être caractérisés à l'échelle locale (0-10 m^2), à partir des variables de profondeur d'eau, de vitesse du courant et de granulométrie du substrat, grâce aux connaissances détaillées d'experts inuits des trois communautés de Kangiqsualujjuaq, Tasiujaq et Kangirsuk, interrogés lors d'entrevues semi-dirigées (section 4.4.1).

Les préférences d'habitats décrites se sont avérées consensuelles à l'intérieur de chaque communauté. Les profondeurs jugées adéquates par les experts interrogés se situaient à des profondeurs comparables aux profondeurs mentionnées dans la littérature (voir tableau 8.1). Une assez grande plage de vitesses et de substrats pouvaient convenir à l'omble chevalier, ce qui est en accord avec la flexibilité connue dans la sélection de niche de l'espèce (Hammar 2014).

De plus, il a été constaté, en présentant des photos de substrat typiques lors des entrevues, que n'importe quel assemblage de substrat peut être utilisé pour la fraie pourvu que le substrat le plus fin soit constitué de gravier (à Kangiqsualujjuaq, Tasiujaq) ou de sable grossier (à Kangirsuk) et ce, en quantité suffisante. Le substrat à considérer est donc la plus petite classe de substrat plutôt qu'un substrat médian, moyen ou dominant comme il est souvent d'usage pour la description de l'habitat du poisson. Ces différences entre les communautés se sont avérées liées à la géographie et au type de géologie différente et les ombles se sont adaptés à la disponibilité des différents types d'habitats. Les caractéristiques décrites restent cependant cohérentes avec celles des sites en rivière décrits dans la littérature (Tableau 8.1), tout en illustrant la plasticité de l'espèce dans son adaptation locale.

Tableau 8.1 Contribution à la description des caractéristiques physiques des sites de fraie d'omble chevalier dans la Baie d'Ungava (en vert) et comparaison avec les sites décrits dans la littérature.

Substrat	Vitesse	Profondeur	Faciès géomorphologique	Localisation	Reference
Occasionnellement dans le sable.			Occasionnellement dans les rapides.	Salangen River, Norway	(Johnson 1980b)
Hétérogène mélange de sable grossier, gravier et quelques blocs.	0,2 m/s à 0,7 m/s			Rivers of Cumberland Sound, Baffin Island	(Johnson 1980b)
Gravier.	0,2 m/s à 0,8 m/s	0,2 m à 1 m		Yama et Yana River, east USSR	(Johnson 1980b)
Nids : sable fin à grossier jusqu'à des graviers de 4-5 cm. Dispersion des œufs sans nids : Blocs de 10-20 cm.		0,5 m à 1,5 m (rivière) 1,5 m à 2 m (lac)	Réseau de chenaux tressés secondaires Tête d'un petit lac, à l'arrivée d'un tributaire	Fraser River, Labrador	(Dempson et Green, 1985)
Hétérogène, de 1-15 cm de diamètre avec des blocs.	0,2 m/s à 0,5 m/s	0,6 m à 1,2 m	À l'amont d'un affleurement rocheux. Embouchure d'un tributaire.	Rivière Koroc, Nunavik	(Cunjak et al. 1986)
Hétérogène, 10% sable et gravier, 50% cailloux, 40% blocs.		1 m à 2 m approx.	Dans des fosses à l'aval de seuils ou à l'extrados d'un méandre.	Ikadlivik Brook, Labrador	(Beddow et al. 1998)
Peut être hétérogène, en autant que le substrat le plus fin est constitué de gravier ou petits Cailloux. Ils ne font généralement pas de nids.	**> 0,1 m/s**	**Profondeurs les plus favorables : 0,6 m à 1,5 m. Certains sont à des profondeurs plus grandes.**	**En rivière, incluant les zones de lacs montrant de l'écoulement comme l'amont des exutoires ou l'aval d'un tributaire. S'il y a des rapides, ils s'abritent du courant.**	**Kangiqsualujjuaq et Tasiujaq, Nunavik**	(Dubos et al. 2023b)
Sable grossier. Ils construisent des nids.	**Faible**	**Profondeurs les plus favorables : 1,2 m à 1,8 m.**	**Petites baies protégées du courant en rive de grandes rivières où le courant est fort. Ils peuvent aussi s'abriter derrière des îlots, où le courant est faible.**	**Kangirsuk, Nunavik**	(Dubos et al. 2023b)

Le modèle de logique floue basé sur les caractéristiques de ces trois variables (profondeur, vitesse, substrat) a donné des résultats satisfaisants en prédisant correctement l'adéquation (ou l'inadéquation) de 14 des 15 sites de validation. Ces résultats ont été obtenus en considérant les règles construites avec l'information des trois communautés ensemble et ce, malgré les différences inter-communautés. De fait, les catégories de variables jugées inadéquates pour la fraie ont été utiles au modèle pour mieux discriminer les sites non favorables.

Potentiel de la logique floue pour modéliser l'habitat à partir des savoirs locaux ou traditionnels

Le modèle de logique floue utilisé était basé sur une méthode établie pour des experts scientifiques qui devaient initialement compléter un long formulaire. Ce formulaire leur demandait d'établir les règles floues, c'est-à-dire toutes les combinaisons logiques des variables analysées et leurs conséquences sur la qualité de l'habitat (figure 4.4 et tableau 4.1). Les experts scientifiques, habitués à classifier et décortiquer l'effet des variables trouvaient eux-mêmes les formulaires fastidieux à remplir (Ouellet et al. 2021). Le protocole de combinaisons d'un jeu de variables fixes pour déterminer l'adéquation de l'habitat était culturellement inadapté pour les experts inuits, d'autant plus que la plupart étaient des ainés, peu confortables avec la communication écrite. Ils pouvaient cependant décrire les sites de fraie en détail. La méthodologie employée a donc consisté à utiliser les classifications des catégories de variables faites par les experts comme adéquates et non-adéquates pour bâtir moi-même les règles floues. Les descriptions qualitatives des sites faites pendant les entrevues ont été considérées pour déduire les interactions entre les variables. Pour ce faire, il a été utile d'avoir fait personnellement chacune des entrevues pour mieux comprendre le contexte descriptif des sites. Les ensembles flous (figure 4.3) ont été établis avec les experts inuits à partir d'éléments visuels (photos et vidéos) plutôt que de catégories numériques et ont été implicitement liés à leur utilisation par les poissons.

Ainsi, la logique floue s'est montrée adaptée pour bâtir des modèles prédictifs d'habitats de fraie à partir des savoirs inuits. La méthode a le potentiel d'être appliquée à d'autres espèces pour lesquels des savoirs locaux ou traditionnels existent et pour lesquelles l'habitat peut être déterminé par des variables fixes. Les règles doivent être alors bâties par l'analyste des entrevues en ayant des questions suffisamment spécifiques concernant les variables descriptives.

Impact potentiel du réchauffement climatique sur l'habitat de reproduction

Les changements climatiques ont déjà un impact sur la perte d'habitat, par la création de barrières à la migration vers les cours d'eau de plus faibles profondeurs. Ces barrières sont dues à la modification de l'hydrologie, à l'érosion importante des cours d'eau et/ou au drainage des cours d'eau par le fond dû à la fonte du pergélisol (voir section 3.5.9). De plus, dans les régions les plus septentrionales, la présence grandissante des castors et de leurs barrages limite l'accès à certains sites (Neelin 2021). Les impacts hydrologiques directs sur les conditions hydrauliques et les habitats restent cependant à définir à cause du manque de données climatiques en région nordique.

L'augmentation de la température de l'eau pourrait avoir un impact sur le moment de la fraie qui pourrait être retardée, puisqu'elle semble déclenchée par la température (Dubos et al. 2023a). Un épisode de réchauffement après la fraie pourrait être préjudiciable à l'incubation des œufs (Jeuthe et al. 2016).

La prédation grandissante par les ours noirs durant la fraie est l'un des impacts indirects des changements climatiques déjà observé. Les sites sont en effet situés en eau relativement peu profonde pour un ours.

8.1.1.2 Habitat hivernal des adultes matures et immatures

L'habitat hivernal des ombles adultes a été caractérisé en combinant les connaissances des sites de pêche par des pêcheurs expérimentés et l'instrumentation des caractéristiques physiques des sites. La prémisse de l'étude est que les sites de présence des poissons correspondent aux sites de pêche et que les sites où aucune pêche n'est pratiquée, ne constitue pas un habitat utilisé par les poissons. Elle est basée sur la pratique régulière de la pêche des collaborateurs inuits et la transmission intergénérationnelle des savoirs.

Les ombles adultes utilisent la zone littorale des lacs d'hivernage, où la lumière atteint le fond du lac. Aucune des variables de l'habitat testées ne s'est montrée significativement différente des sites d'absence, y compris la température et l'oxygène, comme il a également été constaté dans un lac de l'île de Baffin (Young and Tallman 2021). Des études par télémétrie ont montré que les ombles utilisaient une profondeur constante pendant une longue période en hiver, et que certains individus faisaient des incursions ponctuelles en eau plus profonde (Monsen, 2019; Mulder et al., 2018b). Considérant que les ombles ont été filmés nageant lentement en groupe (Dubos and Snowball 2020), près du fond, comme ils sont observés régulièrement par les pêcheurs inuits, on peut supposer que la profondeur constante mise en évidence par la télémétrie est en réalité une localisation constante, près du fond, à une profondeur donnée, généralement en zone littorale. Lorsque les poissons font des incursions en zones plus profondes, ils se déplaceraient vers la zone pélagique, mais ces déplacements seraient ponctuels. Ils seraient non-vitaux et limités à quelques individus plus aventureux (Hawley et al. 2017). Les poissons pourraient donc choisir d'utiliser utiliser le fond du lac en zone littorale, pour bénéficier de la présence de lumière. Il semble aussi y avoir un aspect social dans leur occupation de l'habitat qui n'est pas abordé dans la littérature mais qui a été observé pour d'autres poissons (Sneddon and Brown 2020).

Cette étude était exploratoire et permettait également de vérifier la faisabilité des mesures par les pêcheurs collaborateurs. L'utilisation d'instruments non invasifs, adaptés aux activités traditionnelles des pêcheurs, faciles d'utilisation ou de déploiement, a permis d'instrumenter de nombreux site à un coût avantageux. L'utilisation de caméras GoPro sous la glace a également permis de faire des observations sur le comportement des poissons qui permettent à tout le moins d'apporter des hypothèses sur la sélectivité des habitats.

Les mesures n'ayant pas été systématiques, les sites de présence sont surreprésentés par rapport aux sites d'absence. Ces derniers ont été choisis aléatoirement sur le lac à une certaine distance des sites de pêche. De plus, comme les poissons utilisent des zones spécifiques dans les lacs, la proximité relative des différents sites de présence dans un même lac est susceptible de donner un poids relatif à certaines variables en créant de la redondance. Il serait pertinent d'effectuer des relevés plus systématiques, à tout le moins pour les sites d'absences.

8.1.1.3 Caractéristiques hivernales de l'habitat de fraie en lac

La caractérisation de zones de fraie localisées dans les lacs d'hivernage a permis de montrer que ces zones étaient situées à une profondeur moyenne de 3,0 m, soit des profondeurs significativement plus faibles que les sites où il n'y avait pas de fraie identifiée (section 5.3.2). Les profondeurs des site caractérisés sont comparables à celles de sites de fraie observés entre

3,0 m et 6,0 m, dans le lac Willow, dans le haut Arctique Canadien (Johnson 1980b). De plus, notre étude a montré que les zones de fraie étaient situés à des températures du fond du lac plus chaudes, bien que la différence ne soit pas statistiquement significative à α=0.05 (0,51°C contre 0,38°C pour les sites d'absence, p=0.06). Ces caractéristiques suggèrent que les zones sélectionnées par les poissons pour la fraie favorisent la survie des œufs en période d'incubation puisqu'ils seraient à l'abri du gel. Il a en effet noté à quelques reprises lors de l'instrumentation des lacs que des profils de température peuvent être à 0°C jusqu'au fond du lac.

De plus, les sites de fraie sont localisés en zone littorale, montrant une productivité primaire plus élevée, ce qui serait également favorable aux alevins lorsqu'ils débutent leur alimentation. Il se nourrissent en effet de zoobenthos et majoritairement de larves de chironomides (Svenning et al., 2007; Klemetsen et al., 2003) qui se retrouvent plus fréquemment associés aux macrophytes et au périphyton, présents en zone littorale (Jansen et al., 2020).

La motivation derrière la caractérisation thermique des sites de fraie en hiver était de déterminer la présence potentielle de source d'eau souterraine, plus chaude que l'eau du lac. Étant donné l'important volume d'eau (le lac), les relevés ponctuels n'ont pas permis d'établir la présence de résurgence d'eau souterraine. L'hypothèse reste cependant valide puisque la température était plus chaude que le milieu environnant. Une instrumentation thermique hivernale du fond du lac dans les zones de fraie et à proximité, comme réalisé par Franssen et al. (2013) pour les sites de fraie d'omble de fontaine, permettrait d'avoir plus de certitude.

À ma connaissance, il n'y a pas eu d'autres études hivernales de l'habitat de fraie des ombles chevaliers et il s'agirait d'une première caractérisation. Cependant, les sites caractérisés correspondaient à des zones identifiées comme étant des zones de fraie, mais aucun site spécifique ou nids n'a été identifié avec précision. Ainsi, les résultats prometteurs sur la température et le soupçon de résurgence d'eau souterraine associées à ces zones de fraie pourraient être validés ou invalidés en localisant plus précisément les sites de fraie, ce qui nécessiterait au préalable une identification automnale.

8.1.1.4 *Éclosion*

L'utilisation des vidéos sous-marines, jumelée à la caractérisation des sites, a mené à l'observation fortuite de nombreux œufs éclos ou non viables, flottant dans la colonne d'eau dans deux lacs de la rivière Koroc, les 2 et 3 mars 2020 (Dubos 2020). Il s'agit d'un fort soupçon d'épisode d'éclosion d'œufs d'ombles chevalier puisque ces observations ont été faites dans des zones utilisées très majoritairement par les ombles (Kuururjuaq et Koroc Allipaak). Dix jours plus tard, il n'y avait plus aucune trace de l'évènement au lac Kuururjuaq. Les 16 et 17 mars 2020, quelques rares œufs flottants ont été observés au lac Tasikallak, qui ne comporte que des ombles chevaliers, laissant penser à une fin d'éclosion. Une éclosion autour de début avril a été mentionnée par Gillis et al. (1982) pour une incubation entre 0 et 2.2°C mais elle n'est pas référencée et ne semble pas avoir été observée directement par les auteurs. Une plage assez large de durée d'incubation a été documentée dans la littérature (entre 280 and 420 degrés-jours; Jobling et al. 1993; Granier 2013). Ces durées d'incubation ont été obtenues à des températures plus chaudes que les températures expérimentées par les œufs en milieu naturels au Nunavik, à partir de données d'aquaculture ou de laboratoire. Comme elle survient l'hiver, sous la glace, l'éclosion en milieu naturel n'est généralement pas observée, y compris par les Inuits. Ainsi, l'observation réalisée est importante puisqu'étant donné les basses températures enregistrées à l'hiver 2020, elle confirmerait, en milieu naturel, que le nombre de degrés-jours requis pour l'incubation diminue avec la température (Koops and Tallman 2004), c'est-à-dire que le taux de développement des œufs n'est pas linéairement proportionnel à la température sur toute la plage de température, illustrant l'adaptation des populations locales aux températures froides.

8.1.1.5 *Habitat des juvéniles*

Des relevés de pêche électrique effectués dans les environs de Kangiqsualujjuaq et Tasiujaq ont permis de caractériser et modéliser les habitats des ombles chevaliers juvéniles. Seules les mesures de terrain ont été utilisées puisque les experts inuits pouvaient décrire les comportements des juvéniles mais par leurs habitats de façon détaillée. Les alevins (jeunes de l'année) ont montré des préférences pour les faibles profondeurs et les faibles vitesses à l'échelle du microhabitat. La modélisation à l'échelle du mésohabitat a montré des préférences pour les seuils et un évitement des rapides et des biefs fluviaux uniformes. À l'échelle locale (microhabitat ou station), la recherche de chaleur de radiation pourrait expliquer la présence importante des alevins à faible profondeur (<0,2 m) puisque les relevés dans les cours d'eau montrant les plus fortes densités ont été effectués lors de journées ensoleillées. Les sites ayant montré des densités importantes étaient possiblement situés à proximité des frayères où ils ont éclos, en supposant qu'ils se déplacent peu durant le premier été, comme les alevins de Dolly Varden (Mochnacz et al. 2010).

Les relevés de pêche électrique ont été réalisés à gué, limitant la gamme de conditions rencontrées. Il est donc possible que les alevins utilisent aussi des milieux plus profonds en rivière puisque les sites de fraie sont situés généralement à des profondeurs comprises entre 0,6 m et 1,5 m (chapitre 4). Les rives de lacs semblent être aussi des habitats favorables, possiblement pour les alevins qui ont éclos dans ces mêmes lacs (Gulseth and Nilssen 1999).

Pour les tacons (1 an et plus) en revanche, aucune préférence d'habitat n'a été détectée en fonction des variables et des sites analysés et ce, quelle que soit l'échelle analysée. Les relevés ont cependant montré que la vitesse était un facteur limitant pour les juvéniles qui n'ont pas été pêchés dans des zones où la vitesse dépasse 0,6 m/s. La flexibilité des tacons dans la sélection d'habitat a été confirmée par les Inuits interrogés qui ont mentionné que les tacons peuvent utiliser n'importe quel habitat. Cependant, comme les zones plus profondes, les lacs et les embouchures de rivières n'ont pas été échantillonnés, ces habitats pourraient constituer des habitats préférentiels.

La température de l'eau a été identifiée comme une variable statistiquement significative pour expliquer l'abondance des alevins par le modèle GAM. Ces résultats sont plutôt circonstanciels puisque les sites montrant les plus fortes densités d'alevins étaient à la fois le cours d'eau le plus froid (8,9°C en moyenne, TA010) et le cours d'eau le plus chaud (16,9°C en moyenne, TA003). Il est probable que les fortes densités rencontrées ponctuellement dans ces deux cours d'eau s'expliquent plutôt par la proximité de sites de fraie.

Importance de la productivité sur la taille des juvéniles

Une relation significative entre la taille et la température, essentiellement due aux échantillons et caractéristiques des deux cours d'eau TA003 et TA010, a été constatée. Dans ce cas, en plus de la température qui joue un rôle sur le métabolisme et la croissance des poissons (Jobling, 1983; Larsson et Berglund 1998; Thyrel et al. 1999), mais dont le lien direct sur la croissance n'a pas été montré en milieu naturel (Godiksen et al. 2012), la productivité potentielle pourraient également expliquer les différences. En effet, une modélisation à l'échelle d'un bassin versant de la rivière Teno, située entre la Norvège et la Finlande, a montré que l'abondance d'invertébrés benthiques était le premier facteur expliquant la présence des ombles dans les petits cours d'eau (Danandeh Mehr et al. 2022). La présence des invertébrés benthiques est également liée aux caractéristiques de l'environnement. TA003 est un petit cours d'eau, alimenté par des marécages et de petits étangs, tandis que TA010 constitue l'un des multiples exutoires d'un grand lac, générant possiblement moins d'apports de carbone organique terrestre. Or, en milieu oligotrophe, la présence de marécages implique un apport de matière organique, qui favorise la productivité de l'écosystème et par conséquent l'abondance des invertébrés benthiques. La taille plus élevée des alevins de TA003 s'expliquerait donc par une plus grande productivité du cours d'eau. Pour la rivière TA010, l'abondance des juvéniles malgré une productivité potentiellement moindre qu'à TA003, pourrait être due à sa facilité d'accès et au fait que le lac l'alimentant est un lac d'hivernage.

Impact potentiel du réchauffement climatique sur l'habitat des juvéniles

Les communautés de Tasiujaq et Kangiqsualujjuaq sont situées à la limite de la zone subpolaire qui connait de plus en plus d'épisodes de plus chaleurs atteignant la plage de température critique pour les juvéniles. Le suivi thermique réalisée en continu à l'été 2021 dans le lac Finger Lake à Tasiujaq, et dans un bras de la rivière Bérard, qui constitue son exutoire, a montré que la rivière est à une température optimale de croissance des juvéniles d'omble chevalier pendant l'été (voir Figure S3 à l'annexe VI). Cependant, la température s'est approchée régulièrement de la température maximale de croissance de 16°C. La rivière Bérard est pourtant alimentée par le grand lac Finger Lake (58,9 km^2), qui a un rôle d'atténuation sur les variations ponctuelles de températures estivales (Woolway et al. 2016). Par conséquent, les petits cours d'eau, prenant leur source dans des lacs de plus petite dimension ou des marécages, comme le site TA003, risquent de subir une plus grande influence des hausses de température de l'air et risquent par conséquent de devenir plus vulnérables aux changements climatiques.

Les changements climatiques favoriseraient aussi l'apparition d'autres espèces comme le saumon Atlantique (Bilous and Dunmall 2020) ou le saumon rose (*Oncorhynchus gorbuscha*) (McNicholl et al. 2021). Le saumon rose est une espèce envahissante qui a été observée ponctuellement au Nunavik depuis 2019 (V. Nadeau, 2022, MFFP, Unpublished data). L'augmentation importante de la présence du saumon Atlantique a été notée à Kangiqsualujjuaq et à Tasiujaq par certains participants aux entrevues et d'autres collaborateurs. L'impact du saumon sur les juvéniles d'omble chevalier est inconnu.

8.1.2 Objectif n°2 : Travail avec les savoirs Inuit

8.1.2.1 Bénéfice de l'apport des savoirs inuits au travail scientifique

Le deuxième objectif de cette thèse était de voir comment le savoir traditionnel Inuit pouvait appuyer les méthodes scientifiques occidentales pour permettre la caractérisation et la modélisation des habitats de l'omble chevalier anadrome.

En mettant les savoirs inuits à l'avant-plan, j'ai voulu souligner à quel point ils étaient significatifs pour la connaissance de l'écologie de l'omble chevalier anadrome. Les savoirs inuits ont été intégrés de différentes manière en fonction des connaissances partagées et selon les différents contextes d'analyse des stades de vie des poissons. Ils ont permis d'informer qualitativement des aspects non documentés du cycle de vie et des habitats et, mis en lien avec la littérature scientifique, ont permis de mettre en contexte certains résultats (chapitre 3). Ils ont été utilisés de façon quantitative grâce aux connaissances locales des sites de fraie pour pouvoir développer un modèle d'habitat (chapitre 4). L'utilisation ancestrale des mêmes sites de pêche a permis de déterminer les sites de présence des poissons pour étudier l'habitat d'hiver (chapitre 5) et d'avoir accès à des sites de fraie pour la validation du modèle de logique floue ou pour la caractérisation hivernale en lac. La logistique et les décisions sur les meilleures façons de faire ont été laissées aux guides, tous chasseurs, qui ont également partagés leurs connaissances des différents sites sur le terrain, tel que recommandé pour bénéficier des savoirs Inuit (Pedersen et al. 2020).

Utilisation qualitative des savoirs inuits

Le savoir qualitatif a été très important pour les descriptions des différentes histoires de vie, pour déterminer les parcours migratoires des poissons et les périodes de montaisons et dévalaisons locales, liées aux conditions environnementales. Le travail a notamment permis de mettre en lumière un schéma de migration spécifique de certains reproducteurs de l'année qui restent en rivière pendant l'été, non documenté au Nunavik, bien que déjà soupçonné par la présence d'ombles matures en été dans un lac au Nord de Kangiqsualujjuaq (Boivin 1994). Ce comportement peut avoir un impact lors de l'estimation du taux de fertilité lorsqu'il est estimé sur les migrateurs en mer. Il pourrait être lié à une adaptation au régime hydrologique local.

Les études d'habitats du poisson sont généralement basées sur des données quantitatives. Cependant, la présente étude a montré que les données qualitatives pouvaient être importantes dans la caractérisation de l'habitat. Non seulement de façon directe, pour décrire les variables caractérisant l'habitat, tel qu'utilisé dans le modèle de logique floue (chapitre 4), mais aussi de façon plus spécifique, comme la connaissance des sites utilisés par les poissons durant les différentes saisons, ou d'observations particulières comme l'abandon de l'utilisation d'un habitat local pour des raisons environnementales. Pour bénéficier de ces informations, il faut cependant accepter de travailler avec des données qui sont qualitatives, et parfois empreintes d'une certaine incertitude, ce qui ne les rend pas moins pertinentes. Ainsi, travailler avec les savoirs inuits implique, pour un scientifique, de reconnaitre qu'on est influencé par notre éducation cartésienne et de « réapprendre » qu'il n'y a pas que les données objectives, numériques ou quantifiables qui comptent ou qui sont exactes.

Considérations sur l'aspect local des savoirs inuits

Les savoirs traditionnels sont parfois définis comme très locaux (Berkes 2017; Stern et Humphries, 2022). De fait, les caractéristiques des habitats de fraie décrites par les experts inuits se sont avérées consensuelles à l'intérieur de chaque communauté. Cette constatation découle vraisemblablement du fait que les connaissances des experts provenaient de leur propre utilisation locale du territoire, mais aussi d'autres chasseurs, parents et ancêtres qui avaient utilisés et vécu sur ce territoire. Cependant, bien que l'expression 'locale' soit utilisée pour différencier les territoires décrits relatifs à chaque communauté, ce sont de grands territoires qui s’étendent sur quelques centaines de kilomètres autour des villages actuels. Ces connaissances partagées entre plusieurs individus et générations portent des informations riches et vérifiées (Mackinson et Nøttestad, 1998; Berkes, 2017).

Des différences inter-communautés sont apparues dans les descriptions des sites de fraie par les experts de Kangirsuk et celles des deux autres communautés (Kangiqsualujjuaq et Tasiujaq). Dans le cas de la présente étude, les descriptions des sites de fraie étaient plutôt similaires à Kangiqsualujjuaq et à Tasiujaq, mais différaient à Kangirsuk. Dans le cas des sites de fraie, où la géomorphologie locale détermine le type de substrat et l’hydrodynamique des cours d’eau et, par conséquent, le type d’habitat disponible, l’aspect de description locale est un élément important.

8.1.2.2 Relations de réciprocité

Cette façon de lier et intégrer les savoirs inuits et scientifiques a été possible par des efforts conscients de communication et d’échanges, pour bâtir et entretenir des liens de confiance et de collaboration. Le travail avec les savoirs inuits impliquait implicitement de bâtir des relations de réciprocité (Pedersen et al. 2020). L’évolution du projet pour une prise en compte plus globale des savoirs inuits, et non seulement pour la description des variables caractéristiques des sites de fraie, ainsi que l’engagement croissant envers les communautés partenaires, a fait partie d’un processus d’apprentissage de décolonisation de la science.

L’engagement réalisé auprès des communautés partenaires, à divers degrés en fonction des demandes et des réactions, a rendu le travail de collaboration de plus en plus facile au fil du temps. Dans le but de bâtir une relation de réciprocité, ce projet de doctorat a mené sur un nouveau projet par et pour les Inuits dans la communauté de Kangirsuk. Le fait que le financement et les décisions soit gérés directement par le LNUK a changé la dynamique de travail.

Ma façon de communiquer s’est aussi adaptée et améliorée. La communication écrite par courriel n’était pas la méthode à privilégier, les différents collaborateurs inuits n’ayant accès à des ordinateurs et à leurs courriels que ponctuellement, ou pas du tout pour certaines personnes. Les communications par téléphone étaient préférables. Comme les collaborateurs n’avaient pas toujours de bureau, il fallait utiliser leur téléphone personnel à la maison, ce qui pouvait être un peu intimidant. De plus, l'anglais était une deuxième langue pour nous et les différences d'accent pouvaient rendre les conversations téléphoniques difficiles. Le fait d'avoir fait plusieurs visites sur place (5 à Kangiqsualujjuaq, 4 à Tasiujaq et 6 à Kangirsuk) a permis de bâtir des liens plus humains. Les relevés de terrain et autres activités sur le territoire ont également été très utiles pour apprendre à se connaître. Ces visites, jumelées à l'intégration de plus de visuels dans mes communications pour faire le suivi du travail, a généré un intérêt grandissant de la part des communautés.

En retour, ces relations ont facilité mon travail, par exemple pour avoir des informations, planifier des rencontres ou trouver des personnes-ressources. En effet, la disponibilité des personnes-ressources a été une considération récurrente, en particulier pour la planification des différents relevés de terrain, ainsi que pour la caractérisation hivernale. Les trois communautés avec lesquelles j'ai travaillé sont petites (de 300 à 900 habitants environ). Les collaborateurs du projet avaient aussi d'autres responsabilités et d'autres priorités et n'avaient pas toujours la disponibilité souhaitée, en particulier lorsque la pandémie a frappé. Le fait d'être à distance des communautés a limité aussi ma compréhension de ce qui pouvait se passer sur place.

Des séjours plus longs auraient été bénéfiques, en particulier avant de réaliser les entrevues. Une acclimatation culturelle m'aurait possiblement permis d'être plus à l'aise. Une présence plus longue dans les communautés aurait peut-être aussi permis de réaliser des entrevues pendant les activités de pêche, ce qui aurait apporté plus de profondeur aux discussions. Ces longs séjours n'ont cependant pas été possibles, ni budgétairement ni familialement.

Les partenaires Inuit locaux (LNUK, guides, et/ou autorités municipales) ont été consultés régulièrement au long des étapes du projet, y compris en phase d'interprétation des résultats. Cependant, le travail, bien qu'inspiré par le concept du « *Two-eyed seeing* » (Bartlett et al., 2012; Reid et al., 2021), n'a pas suivi ce principe puisque l'interprétation des résultats n'a pas été faite en parallèle par les Inuits. De plus, bien que la planification des méthodes d'analyses ait été adaptée, il aurait été plus approprié d'intégrer les partenaires locaux dans la planification du questionnaire d'entrevue et les méthodes d'analyses. Pour ce faire, un budget prévoyant des séjours dans le Nord plus fréquents et du temps supplémentaire pour réaliser le travail doit être prévu.

8.2 Contribution originale à l'avancement des connaissances

Le travail réalisé dans cette thèse apporte une meilleure compréhension de l'habitat et du cycle de vie de l'omble chevalier anadrome au Nunavik. Il a permis de caractériser les habitats de fraie en rivière, les habitats de fraie en lac durant l'hiver, l'habitat hivernal des adultes et l'habitat estival en rivière des juvéniles, alevins et tacons. Un modèle prédictif des habitats de fraie en rivière a été élaboré en utilisant la logique floue. Les savoirs inuits ont été intégrés par des méthodes qualitatives et quantitatives aux méthodologies scientifiques conventionnelles en habitat du poisson, comme la modélisation pour prédire la qualité de l'habitat par logique floue, l'échantillonnage par pêche électrique, et l'analyse statistique. Les contributions de cette thèse à l'avancement des connaissances sont décrites par chapitre et sont les suivantes :

Chapitre 3 : Cycle de vie de l'omble chevalier anadrome à partir des savoirs inuits : une année en Ungava

a) Reconnaissance de la valeur des savoirs inuits et production d'une synthèse globale des savoirs inuits concernant l'écologie de l'omble chevalier anadrome au Nunavik.
b) Mettre en relation la littérature scientifique existante, sans chercher à confirmer ou appuyer les observations venant des savoirs inuits, mais plutôt en combinant les systèmes de savoirs de façon à apporter de nouveaux éclairages, ouvrant sur des avenues de recherches. Le travail a notamment permis de mettre en lumière :
    1. Un schéma de migration spécifique de certains reproducteurs de l'année qui restent en rivière pendant l'été, non documenté au Nunavik. Cette stratégie peut impacter les études scientifiques de populations qui sont faites aux embouchures des rivières lors de la migration des poissons.
    2. Certains comportements hivernaux des ombles, comme les agrégations liées à des zones d'eau libres ou de glace mince.
    3. Les multiples impacts de la modification de l'environnent des ombles due aux changement climatiques tels que la diminution des précipitations estivales et automnale et par conséquent la baisse du débit des rivières au moment de la migration amont, les hausses de températures estivales pouvant affecter les juvéniles dans les petits cours d'eau, la croissance de la végétation en berge qui limite l'accès des

pêcheurs aux sites de pêches traditionnels lors de la migration amont ou à l'automne, la croissance de la végétation aquatique qui pourrait limiter le passage des poissons et modifier l'accès à leurs habitats, la présence de plus en plus notable de certains prédateurs comme les ours noirs durant la saison de reproduction.

Chapitre 4 : Modélisation de l'habitat de fraie à partir des savoirs inuits, en utilisant la logique floue.

a) À partir des entrevues avec les experts inuits, mise en évidence des préférences d'habitats de fraie en rivière à l'échelle locale (0-10 m^2), en fonction des variables classiques d'habitat du poisson: profondeur, vitesse et substrat.
b) Mise en évidence de l'importance des classes de substrat plus fins pour la sélectivité des sites de fraie, plutôt qu'un substrat médian, moyen ou dominant, utilisés classiquement pour d'autres espèces.
c) Adaptation de la méthodologie de modélisation par logique floue qui était jusqu'à présent appliquée à des experts scientifiques, de façon à pouvoir l'appliquer à des experts inuits. Le modèle développé est le premier modèle d'habitat basé uniquement sur le savoir Inuit. Le modèle pourrait être utilisé pour prédire l'impact d'une modification de l'environnement sur l'adéquation des sites de fraie, dans le contexte des changements climatiques, mais également dans un contexte de développement minier, puisque les régions de Kangirsuk et Kangiqsualujjuaq sont considérées comme ayant un potentiel pour l'exploitation minière. La méthode pourrait être appliquée à d'autres espèces dont les habitats sont caractérisés par des variables spécifiques, et pour lesquelles des savoirs locaux ou traditionnels existent.

Chapitre 5 : Caractérisation de l'habitat hivernal et des frayères lacustres de l'omble chevalier anadrome en collaboration avec des pêcheurs inuits.

a) Planifier une méthodologie de caractérisation simple en collaboration avec des pêcheurs inuits. Le travail est basé sur le principe qu'à travers leur pratique de pêche ancestrale, les pêcheurs connaissent la localisation des sites utilisés par les ombles en hiver et les zones des lacs qu'ils n'utilisent pas. Ainsi, les savoirs inuits ont servi à identifier l'utilisation de l'habitat et ces habitats ont été instrumentés pour faire la caractérisation physique. Les mesures ont tout d'abord été faites avec les pêcheurs qui les ont poursuivies seuls au cours de l'hiver 2020 et des deux hivers subséquents.

b) Montrer qu'en condition hivernale, les zones de fraie situées dans les lacs d'hivernage sont localisées en plus faible profondeur et ont des températures du fond relativement plus chaudes que les sites non utilisés pour la fraie. Ces caractéristiques sont favorables à l'incubation des œufs. La localisation des sites de fraie en zone littorale, plus productive, est également favorable aux alevins après éclosion. Comme certaines communautés qui voient les stocks d'ombles chevaliers diminuer envisagent d'intervenir en faisant de l'aquaculture pour la fertilisation artificielle et l'incubation de œufs ou de l'incubation en milieux naturels. La connaissance de ces caractéristiques permettrait de déterminer des sites adaptés dans le cas où des œufs fertilisés étaient déposés en milieu naturel.

c) Montrer que les adultes matures et immatures utilisent la zone littorale des lacs d'hivernage où de la lumière peut pénétrer jusqu'au fond. Confirmer qu'à l'exception de l'utilisation de la zone littorale, les ombles de la région de Kangiqsualujjuaq n'ont pas de préférences d'habitat spécifiques, dans la gamme des valeurs mesurées, y compris en termes de température et d'oxygène, comme il avait été constaté dans un lac de l'île de Baffin (Young and Tallman, 2021).

d) Observer un épisode vraisemblable d'éclosion des œufs d'ombles chevaliers dans la rivière Koroc (Kuururjuaq et Koroc Allipaak) les 2 et 3 mars 2020. Cette observation est importante puisqu'elle confirmerait en milieu naturel que le nombre de degrés-jours requis pour l'incubation diminue avec la température (Koops and Tallman 2004), illustrant l'adaptation des populations locales aux températures froides.

Chapitre 6 : Préférences d'habitat estival en rivière des ombles chevaliers anadromes juvéniles (alevins et tacons) au Nunavik

a) Montrer que les alevins sélectionnent certains habitats en rivière : à l'échelle du microhabitat ou de la station (regroupement de microhabitats; 0-10 m^2) ils sélectionnent des profondeurs inférieures à 0,2 m et se retrouvent à des vitesses inférieures à 0,3 m/s. À l'échelle du mésohabitat (typiquement 10-100 m^2), ils utilisent préférablement les seuils, et évitent les rapides et les biefs fluviaux uniformes.

b) Montrer que les tacons sont plastiques dans la sélectivité d'habitat et que la vitesse d'écoulement est un facteur limitant en fonction de leur taille.

Chapitre 7 : Engagement et réciprocité : Contribution aux bonnes relations entre chercheurs et Inuit et engagement

Mon engagement avec la communauté de Kangirsuk a conduit au financement et au démarrage d'un nouveau projet intégré dans un principe de décolonisation de la recherche, qui répond aux attentes du protocole de la recherche en territoire Inuit (Inuit Tapiriit Kanatami 2018). Le projet de recherche sur les populations locales d'ombles chevalier est mené par le LNUK de Kangirsuk. Les méthodes scientifiques et les savoirs et savoir-faire inuits sont mis en commun pour répondre aux intérêts de la communauté.

8.3 Conclusions et perspectives de recherche futures

Le présent travail a montré l'importance de la collaboration avec les Inuits à divers niveaux pour la caractérisation des habitats de l'omble chevalier anadrome et pour une meilleure connaissance de son écologie. Cette façon de lier les savoirs inuits et scientifiques a été possible par des efforts conscients de communication et d'échanges, pour bâtir et entretenir des liens de confiance et de collaboration.

Comme peu d'études sur les habitats existaient et comme le savoir inuit n'avait pas été considéré pour décrire l'écologie de l'omble chevalier, plusieurs pistes de recherche future ont été soulevées et sont décrites ci-après.

Habitat de fraie

Le travail réalisé dans cette thèse a permis de caractériser et modéliser l'habitat de fraie en rivière, mais le travail de modélisation pourrait être approfondi avec les éléments suivants :

- Augmenter le nombre de sites de validation du modèle de logique floue. La validation pourrait être faite sur des habitats plus variés à l'intérieur et en dehors de la Baie d'Ungava pour vérifier sa robustesse. Un nombre de sites plus important permettrait éventuellement d'utiliser des sites pour calibrer les limites des ensembles flous.
- Utiliser l'imagerie satellite pour extraire les données de vitesse, profondeur et substrat d'une rivière. Le modèle pourrait ainsi servir à bâtir des cartes d'habitats potentiels.
- Associer les sites de fraie en rivière à l'échelle du mésohabitat. La géomorphologie locale pourrait expliquer physiquement les écoulements hyporhéiques.

Certaines caractéristiques hivernales de l'habitat de fraie lacustre laissent penser que les sites pourraient être sélectionnés en fonction de la température du fond, que ce soit pour l'incubation elle-même ou pour la productivité après éclosion. Pour valider cette hypothèse :

- Poursuivre l'instrumentation thermique des sites de fraie de façon plus systématique pour vérifier l'hypothèse de la présence d'un écoulement hyporhéique associé aux sites de fraie.

Éclosion

Il semble que la période d'incubation (degrés-jours) soit moins longue en milieu naturel où la température de l'eau est froide (<2°C):

- Vérifier *in situ* la période d'incubation des œufs par un suivi communautaire par vidéo sous-marine. La collecte des œufs flottants à l'aide d'un fin filet permettrait de confirmer hors de tout doute qu'il s'agit bien d'œufs d'ombles chevaliers.

Habitat hivernal

La caractérisation de l'habitat hivernal utilisé par les adultes pourrait être complétée :

- Vérifier si l'habitat pourrait être lié à d'autres variables telle que la proximité de tributaires ou la présence de reliefs topographiques locaux spécifiques (rive irrégulière, baies, …).
- Caractériser les sites d'absences de façon plus systématique sur la surface des lacs.
- Étendre la caractérisation réalisée à Kangiqsualujjuaq à des sites d'hivernage situés en rivière dans la région de Kangirsuk ou d'autres communautés.

L'observation des ombles qui semblent nager afin d'empêcher, à des endroits spécifiques, la formation d'un couvert de glace durant l'hiver reste une observation intrigante faite par plusieurs personnes à des contextes divers (en rivière et en lac) :

- Documenter ce phénomène lorsqu'il survient. Cela permettrait éventuellement de relever des évènements environnementaux connexes (par exemple phénomène d'hypoxie ou début de la fonte). Étant donné le phénomène ponctuel de ces évènements, la participation des communautés serait essentielle. L'instrumentation de ces sites reste cependant difficile, d'abord par l'imprévisibilité des observations et pour des raisons de sécurité (glace mince).

Juvéniles

Les relevés de pêche électriques ont permis de montrer des préférences d'habitats pour les alevins, mais les données étaient limitées à des sites accessibles à gué. Pour compléter l'analyse des préférences d'habitats en rivière :

- Analyser l'habitat estival des alevins dans des sites de plus grandes profondeurs. Vérifier la mobilité des alevins par rapport aux sites de fraie.

Lors de l'analyse des résultats de pêche électrique il a été observé une corrélation entre la taille des alevins et la température de deux cours d'eau différents mais ces relevés étaient ponctuels :

- Poursuivre cette analyse en instrumentant les deux cours d'eau où une forte densité d'alevins ayant des tailles différentes a été trouvé (TA003 et TA010 près de Tasiujaq) ou des cours d'eau avec des caractéristiques similaires. L'instrumentation permettrait de confirmer la différence de température sur une plus longue période, et permettrait de comparer leur productivité.

Les tacons, qui n'ont pas montré de préférence d'habitat selon l'échantillonnage effectué, semblent aussi effectuer des migrations saisonnières (Craig and Poulin 1975; Gulseth and Nilssen 1999; Young and Tallman 2021) qui restent méconnues :

- Faire un suivi par télémétrie permettrait d'analyser leurs déplacements, y compris durant l'hiver. De la pêche au filet expérimental dans les lacs d'hivernage permettrait également de vérifier si l'utilisation de l'habitat des juvéniles est similaire à celui des adultes, avec ou sans présence de prédateurs (touladis et ombles chevaliers résidents).

<u>*Cyle de vie*</u>

Au-delà de l'utilisation des habitats, les stratégies migratoires restent à comprendre :

- Documenter plus précisément le schéma de migration des ombles reproducteurs qui restent en rivière pendant l'été. Il pourrait être lié à des facteurs hydrologiques.
- Comprendre l'étendue géographique de ce comportement.
- Déterminer les facteurs déclenchant les migrations aval et amont.

Changements climatiques

Au regard des inquiétudes sur l'impact des changements climatiques sur la pérennité des populations d'omble chevalier, les points suivants devraient être considérés :

- Augmenter l'instrumentation de données climatiques pour préciser les changements climatiques locaux qui ne semblent pas se faire dans le sens des prédictions de changements climatiques au Nunavik.
- Instrumenter les débits/niveaux et températures des lacs et rivières à moyen et long terme pour comprendre l'évolution de l'hydrologie et l'impact que cette évolution peut avoir sur le passage des poissons et leur habitat.
- Faire un suivi des populations d'omble chevalier et des pêches faites dans les communautés pour dissocier les impacts anthropiques et environnementaux sur les variations de populations.
- Documenter l'impact potentiel des prédateurs comme l'ours noir durant la période de fraie ou d'autres prédateurs sur les juvéniles (les loutres de rivière, oiseaux, …).

Les futures recherches doivent être réalisées en partenariat avec les communautés pour le bénéfice mutuel des scientifiques et des communautés.

RÉFÉRENCES

Abu, R., Reed, M.G., and Jardine, T.D. 2020. Using two-eyed seeing to bridge Western science and Indigenous knowledge systems and understand long-term change in the Saskatchewan River Delta, Canada. Int. J. Water Resour. Dev. **36**(5): 757–776. Routledge. doi:10.1080/07900627.2018.1558050.

Adams, N.J., Barton, D.R., Cunjak, R.A., Power, G., and Riley, S.C. 1988. Diel patterns of activity and substrate preference in young Arctic char from the Koroc River, northern Quebec. Can. J. Zool. **66**(11): 2500–2502. doi:10.1139/z88-370.

Ahmadi-Nedushan, B., St-Hilaire, A., Bérubé, M., Ouarda, T.B.M.J., and Robichaud, É. 2008. Instream flow determination using a multiple input fuzzy-based rule system: a case study. River Res. Appl. **24**(3): 279–292. doi:10.1002/rra.1059.

Alekseev, V.R. 2017. Aufeis areas in river valleys: engineering development problems. Earths Cryosphere **XXI**(6): 56–64.

Ali, M.A., and Wagner, H.-J. 1980. Vision in charrs: a review and perspectives. *In* Charrs: salmonid fishes of the genus Salvelinus. E. K. Balon. Dr. W. Junk Publishers. The Hague, The Netherlands. pp. 391–422.

Allard, M. 1996. Geomorphological Changes and Permafrost Dynamics: Key Factors in Changing Arctic Ecosystems. An Example from Bylot Island, Nunavut, Canada. Geosci. Can. Available from https://journals.lib.unb.ca/index.php/GC/article/view/3916 [accessed 10 December 2021].

Amundsen, P.-A. 1994. Piscivory and cannibalism in Arctic charr. J. Fish Biol. **45**(sA): 181–189. doi:10.1111/j.1095-8649.1994.tb01092.x.

Amundsen, P.-A., and Knudsen, R. 2009. Winter ecology of Arctic charr (*Salvelinus alpinus*) and brown trout (*Salmo trutta*) in a subarctic lake, Norway. Aquat. Ecol. **43**(3): 765–775. doi:10.1007/s10452-009-9261-8.

Armitage, P., and Kilburn, S. 2015. Conduct of Traditional Knowledge Research - A Reference Guide - North Slope Science Catalog. Wildlife Management Advisory Council North Slope • Whitehorse, Yukon. Available from https://catalog.northslopescience.org/gl/dataset/2303 [accessed 3 June 2022].

Armstrong, J.D., Kemp, P.S., Kennedy, G.J.A., Ladle, M., and Milner, N.J. 2003. Habitat requirements of Atlantic salmon and brown trout in rivers and streams. Fish. Res. **62**(2): 143–170. doi:10.1016/S0165-7836(02)00160-1.

Atencio, B.J., Thorstad, E.B., Rikardsen, A.H., and Jensen, J.L.A. 2021. Keeping close to the river, shore, and surface: the first marine migration of brown trout (*Salmo trutta*) and Arctic charr

(*Salvelinus alpinus*) post-smolts. J. Fish Biol. **99**(2): 462–471. doi:https://doi.org/10.1111/jfb.14737.

Ayllón, D., Almodóvar, A., Nicola, G.G., Elvira, B., Ayllón, D., Almodóvar, A., Nicola, G.G., and Elvira, B. 2012. The influence of variable habitat suitability criteria on phabsim habitat index results. River Res. Appl. **28**(8): 1179–1188. doi:10.1002/RRA.1496.

Bain, M.B., Finn, J.T., and Booke, H.E. 1985. Quantifying Stream Substrate for Habitat Analysis Studies. North Am. J. Fish. Manag. **5**(3B): 499–500. doi:10.1577/1548-8659(1985)5<499:QSSFHA>2.0.CO;2.

Barrette, C., Brown, R., and Way, R. 2020. Chapter 2: Nunavik and Nunatsiavut regional climate information update. *In* In Ropars P, Allard M, Lemay M (eds.), Nunavik and Nunatsiavut: From science to policy, an integrated regional impact study (IRIS) of climate change and modernization, second iteration. ArcticNet Inc, Québec, Canada. p. 58.

Bartlett, C., Marshall, M., and Marshall, A. 2012. Two-Eyed Seeing and other lessons learned within a co-learning journey of bringing together indigenous and mainstream knowledges and ways of knowing. J. Environ. Stud. Sci. **2**(4): 331–340. doi:10.1007/s13412-012-0086-8.

Bates, P. 2007. Inuit and Scientific Philosophies about Planning, Prediction, and Uncertainty. Arct. Anthropol. **44**(2): 87–100. University of Wisconsin Press. doi:10.1353/arc.2011.0065.

Baxter, C.V., and Hauer, F.R. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout. Can J Fish Aquat Sci **57**: 12.

Beaupré, J., Boudreault, J., Bergeron, N.E., and St-Hilaire, A. 2019. Inclusion of water temperature in a fuzzy logic Atlantic salmon (*Salmo salar*) parr habitat model. J. Therm. Biol.: 102471. doi:10.1016/j.jtherbio.2019.102471.

Beddow, T.A., Deary, C., and McKinley, R.S. 1998. Migratory and reproductive activity of radio-tagged Arctic char (*Salvelinus alpinus L.*) in northern Labrador. *In* Advances in Invertebrates and Fish Telemetry. *Edited by* J.-P. Lagardère, M.-L.B. Anras, and G. Claireaux. Springer Netherlands, Dordrecht. pp. 249–262. doi:10.1007/978-94-011-5090-3_29.

Bégin, P.N., Rautio, M., Tanabe, Y., Uchida, M., Culley, A.I., and Vincent, W.F. 2020. The littoral zone of polar lakes: inshore–offshore contrasts in an ice-covered High Arctic lake1. Arct. Sci. Canadian Science Publishing1840 Woodward Drive, Suite 1, Ottawa, ON K2C 0P7. doi:10.1139/as-2020-0026.

Bell, R.K., and Harwood, L.A. 2012. Harvest-based Monitoring in the Inuvialuit Settlement Region: Steps for Success. ARCTIC **65**(4): 421–432. doi:10.14430/arctic4240.

Berkeley, S.A., Hixon, M.A., Larson, R.J., and Love, M.S. 2004. Fisheries Sustainability via Protection of Age Structure and Spatial Distribution of Fish Populations. Fisheries **29**(8): 23–32. doi:10.1577/1548-8446(2004)29[23:FSVPOA]2.0.CO;2.

Berkes, F. 2017. Sacred Ecology (4th ed.). Routledge, New York. doi:10.4324/9781315114644.

Berkes, F. 2018. Arctic Fish, Northern Cultures, and Traditional Ecological Knowledge. *In* Marine Fishes of Arctic Canada. *Edited by* B.W. Coad and J.D. Reist. University of Toronto Press, Toronto. pp. 57–60. doi:10.3138/9781442667297-010.

Berkes, F., and Berkes, M.K. 2009. Ecological complexity, fuzzy logic, and holism in indigenous knowledge. Futures **41**(1): 6–12. doi:10.1016/j.futures.2008.07.003.

Berkes, F., Huebert, R., Fast, H., Manseau, M., and Diduck, A. (*Editors*). 2005. Breaking Ice: Renewable Resource and Ocean Management in the Canadian North. University of Calgary Press. doi:10.2307/j.ctv6gqvp5.

Bilous, M., and Dunmall, K. 2020. Atlantic salmon in the Canadian Arctic: potential dispersal, establishment, and interaction with Arctic char. Rev. Fish Biol. Fish. **30**(3): 463–483. doi:10.1007/s11160-020-09610-2.

Blanchet, C., Dewailly, E., Chaumette, P., ED, N., Bjerregaard, P., T, P., J, L., Furgal, C., and Proulx, J.-F. 2002. Diet profile of Circumpolar Inuit. *In* Sustainable Food Security in the Arctic. Vol 1. Quebec: Canadian Circumpolar Institute Press, chapter 2. GÉTIC, Université Laval, 2000. pp. 47–60.

Blanchet, C., and Rochette, L. 2004. Nutrition and Food Consumption among the Inuit of Nunavik. Nunavik Inuit Health Survey 2004, Qanuippitaa? How are we? Quebec: Institut national de santé publique du Québec (INSPQ) & Nunavik Regional Board of Health and Social Services (NRBHSS). Available from https://www.inspq.qc.ca/pdf/publications/774_ESISurveyHighlights.pdf. [accessed 3 February 2023].

Blanchfield, P.J., Tate, L.S., Plumb, J.M., Acolas, M.-L., and Beaty, K.G. 2009. Seasonal habitat selection by lake trout (*Salvelinus namaycush*) in a small Canadian shield lake: Constraints imposed by winter conditions. doi:10.1007/s10452-009-9266-3.

Boivin, T. 1994. Biology and commercial exploitation of anadromous Arctic charr (*Salvelinus alpinus*) in eastern Ungava Bay, Northern Québec 1987-1992, Ministère de l'Environnement et de la Faune, Ministère de l'Agriculture, des Pêcheries et de l'Alimentation, and Makivik Corporation.

Boivin, T., Olpinski, S., and May, P. 1989. The Arctic charr (*Salvelinus alpinus*) experimental-commercial winter fishery in Kangiqsualujjuaq, Québec, November, 1988-April, 1989. Makivik Corporation, Kuujjuaq, Quebec.

Boivin, T.G., and Power, G. 1990. Winter condition and proximate composition of anadromous arctic charr (*Salvelinus alpinus*) in eastern Ungava Bay, Quebec. Can. J. Zool. **68**(11): 2284–2289. doi:10.1139/z90-319.

Boudreault, J., St-Hilaire, A., Chebana, F., and Bergeron, N.E. 2021. Modelling Fish Physico-Thermal Habitat Selection using Functional Regression. J. Ecohydraulics **6**(2).

Bovee, K.D. 1982. A Guide to Stream Habitat Analysis Using the Instream Flow Incremental Methodology. Western Energy and Land Use Team, Office of Biological Services, Fish and Wildlife Service, U.S. Department of the Interior.

Bovee, K.D. 1986. Development and Evaluation of Habitat Suitability Criteria for Use in the Instream Flow Incremental Methodology. National Ecology Center, Division of Wildlife and Contaminant Research, Fish and Wildlife Service, U.S. Department of the Interior.

Boyce, M.S., Vernier, P.R., Nielsen, S.E., and Schmiegelow, F.K.A. 2002. Evaluating resource selection functions. Ecol. Model. **157**(2): 281–300. doi:10.1016/S0304-3800(02)00200-4.

Brattli, M.B., Egeland, T.B., Nordeide, J.T., and Folstad, I. 2018. Spawning behavior of Arctic charr (*Salvelinus alpinus*): Spawning synchrony, vibrational communication, and mate guarding. Ecol. Evol. **8**(16): 8076–8087. doi:10.1002/ece3.4277.

Breton-Honeyman, K., Huntington, H.P., Basterfield, M., Campbell, K., Dicker, J., Gray, T., Jakobsen, A.E.R., Jean-Gagnon, F., Lee, D., Laing, R., Loseto, L., McCarney, P., Jr, J.N., Palliser, T., Ruben, L., Tartak, C., Townley, J., and Zdor, E. 2021. Beluga whale stewardship and collaborative research practices among Indigenous peoples in the Arctic. Polar Res. **40**. doi:10.33265/polar.v40.5522.

Brooke, L.F. 1993. The Participation of Indigenous Peoples and the Application of their Environmental and Ecological Knowledge in the Arctic Environmental Protection Strategy, Vol. 1. Inuit Circumpolar Conference, Ottawa.

Brown, C. 2015. Fish intelligence, sentience and ethics. Anim. Cogn. **18**(1): 1–17. doi:10.1007/s10071-014-0761-0.

Brown, R., Hubert, W., and Daly, S. 2011. A Primer on Winter, Ice, and Fish: What Fisheries Biologists Should Know about Winter Ice Processes and Stream-Dwelling Fish. Fisheries **36**: 8–26. doi:10.1577/03632415.2011.10389052.

Buffington, J.M., Montgomery, D.R., and Greenberg, H.M. 2004. Basin-scale availability of salmonid spawning gravel as influenced by channel type and hydraulic roughness in mountain catchments. Can. J. Fish. Aquat. Sci. 6111 2085-2096 **61**(11): 2085–2096.

Byström, P., Andersson, J., Kiessling, A., and Eriksson, L.-O. 2006. Size and Temperature Dependent Foraging Capacities and Metabolism: Consequences for Winter Starvation Mortality in Fish. Oikos **115**(1): 43–52. [Nordic Society Oikos, Wiley].

Byström, P., Andersson, J., Persson, L., and Roos, A.M.D. 2004. Size-dependent resource limitation and foraging-predation risk trade-offs: growth and habitat use in young arctic char. Oikos **104**(1): 109–121. doi:10.1111/j.0030-1299.2004.12759.x.

Cattanéo, F., Grimardias, D., Carayon, M., Persat, H., and Bardonnet, A. 2014. A multidimensional typology of riverbank habitats explains the distribution of European grayling (*Thymallus thymallus L.*) fry in a temperate river. Ecol. Freshw. Fish **23**(4): 527–543. doi:10.1111/eff.12106.

Chambers, M.K., White, D.M., Lilly, M.R., Hinzman, L.D., Hilton, K.M., and Busey, R.C. 2008. Exploratory Analysis of the Winter Chemistry of Five Lakes on the North Slope of Alaska1. JAWRA J. Am. Water Resour. Assoc. **44**(2): 316–327. doi:10.1111/j.1752-1688.2007.00164.x.

Charron, I. 2015. Élaboration du portrait climatique régional du Nunavik. Ouranos. Ouranos, Montréal, 86pp.

Chavarie, L., Reist, J.D., Guzzo, M.M., Harwood, L., and Power, M. 2018. Influences of environmental variation on anadromous Arctic charr from the Hornaday River, NWT. Hydrobiologia. doi:10.1007/s10750-018-3828-0.

Chila, Z., Dunmall, K.M., Proverbs, T.A., Lantz, T.C., Aklavik Hunters and Trappers Committee, Inuvik Hunters and Trappers Committee, Sachs Harbour Hunters and Trappers Committee, Olokhaktomiut Hunters and Trappers Committee, and Paulatuk Hunters and Trappers Committee. 2021. Inuvialuit knowledge of Pacific salmon range expansion in the western Canadian Arctic. Can. J. Fish. Aquat. Sci.: 1–14. NRC Research Press. doi:10.1139/cjfas-2021-0172.

Clilverd, H., White, D., and Lilly, M. 2009. Chemical and Physical Controls on the Oxygen Regime of Ice-Covered Arctic Lakes and Reservoirs1. JAWRA J. Am. Water Resour. Assoc. **45**(2): 500–511. doi:10.1111/j.1752-1688.2009.00305.x.

Cohen, J. 1960. A Coefficient of Agreement for Nominal Scales. Educ. Psychol. Meas. **20**(1): 37–46. doi:10.1177/001316446002000104.

Collings, P., Pearce, T., and Kann, J. 2018. “We don’t know anything about whales”: ecological knowledge and ways of knowing in Ulukhaktok, Northwest Territories, Canada. Arct. Sci. **4**(3): 223–241. NRC Research Press. doi:10.1139/as-2017-0030.

Conallin, J., Boegh, E., and Jensen, J.K. 2010. Instream physical habitat modelling types: an analysis as stream hydromorphological modelling tools for EU water resource managers. Int. J. River Basin Manag. **8**(1): 93–107. doi:10.1080/15715121003715123.

Côté, I. 2002. Massive fish-fill at lake Tasikallak, Nunavik. Final report. Makivik Research, Kuujjuaq.

Coyne, I.T. 1997. Sampling in qualitative research. Purposeful and theoretical sampling; merging or clear boundaries? J. Adv. Nurs. **26**(3): 623–630. doi:10.1046/j.1365-2648.1997.t01-25-00999.x.

Craig, P.C., and Poulin, V.A. 1975. Movements and Growth of Arctic Grayling (*Thymallus arcticus*) and Juvenile Arctic Char (*Salvelinus alpinus*) in a Small Arctic Stream, Alaska. J. Fish. Res. Board Can. **32**(5): 689–697. doi:10.1139/f75-088.

Creswell, J.W., and Creswell, J.D. 2018. Research design: qualitative, quantitative, and mixed methods approaches. *In* Fifth edition. SAGE, Los Angeles.

Cuerrier, A., Brunet, N.D., Gérin-Lajoie, J., Downing, A., and Lévesque, E. 2015. The Study of Inuit Knowledge of Climate Change in Nunavik, Quebec: A Mixed Methods Approach. Hum. Ecol. **43**(3): 379–394.

Cunjak, R.A., and Power, G. 1986. Winter Habitat Utilization by Stream Resident Brook Trout (*Salvelinus fontinalis*) and Brown Trout (*Salmo trutta*). Can. J. Fish. Aquat. Sci. **43**(10): 1970–1981. doi:10.1139/f86-242.

Cunjak, R.A., Power, G., and Barton, D. R. 1986. Reproductive habitat and behaviour of anadromous arctic char (*Salvelinus alpinus*) in the Koroc River, Quebec. Nat. Can. (113): 383–387.

Curry, R.A., and Noakes, D.L.G. 2011. Groundwater and the selection of spawning sites by brook trout (*Salvelinus fontinalis*). Can. J. Fish. Aquat. Sci. NRC Research Press Ottawa, Canada. doi:10.1139/f95-765.

Danandeh Mehr, A., Erkinaro, J., Hjort, J., Torabi Haghighi, A., Ahrari, A., Korpisaari, M., Kuusela, J., Dempson, B., and Marttila, H. 2022. Factors affecting the presence of Arctic charr in streams based on a jittered binary genetic programming model. Ecol. Indic. **142**: 109203. doi:10.1016/j.ecolind.2022.109203.

David L. G., N. 1980. Social behavior in young charrs. *In* Balon, E.K., ed. The Hague: Dr. W. Junk Publishers. Available from https://noclegikobylanka.pl/bibliographies2wam/charrs-salmonid-fishes-of-the-genus-salvelinus-148.html [accessed 12 December 2019].

David-Chavez, D.M., and Gavin, M.C. 2018. A global assessment of Indigenous community engagement in climate research. Environ. Res. Lett. **13**(12): 123005. IOP Publishing. doi:10.1088/1748-9326/aaf300.

Dempson, J.B., and Green, J.M. 1985. Life history of anadromous arctic charr, *Salvelinus alpinus* , in the Fraser River, northern Labrador. Can. J. Zool. **63**(2): 315–324. doi:10.1139/z85-048.

DFO. 2015. Review of the applicability of Habitat Suitability Index (HSI) Model and Habitat Assessment Tool (HAT) for assessment of Westslope Cutthroat Trout habitat characteristics and associated productivity. DFO Can. Sci. Advis. Sec. Sci. Resp. 2015/034.

Dick, T.A., Gallagher, C.P., and Yang, A. 2009. Summer habitat use of Arctic char (*Salvelinus alpinus*) in a small Arctic lake, monitored by acoustic telemetry. Ecol. Freshw. Fish **18**(1): 117–125. doi:10.1111/j.1600-0633.2008.00330.x.

Drinkwater, K.F., and Jones, E.P. 1987. Density stratification, nutrient and chlorophyll distributions in the Hudson Strait region during summer and their relation to tidal mixing. Cont. Shelf Res. **7**(6): 599–607. doi:10.1016/0278-4343(87)90025-2.

Druon, J.-N. 2017. Ocean Productivity index for Fish in the Arctic: First assessment from satellite-derived plankton-to-fish favourable habitats. EUR 29006 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-77299-3, doi:10.2760/28033, JRC109947.

Dubos, V. 2019. Young arctic char at night on the shore of Ujarasutjullik Lake. [Video file]. YouTube. Available from https://youtu.be/I_iYiRiMab8 [accessed 3 January 2023].

Dubos, V. 2020. Fish eggs floating in Koroc River (Kuururjuaq). [Video file]. YouTube. Available from https://youtu.be/FkfalluL3gw [accessed 3 January 2023].

Dubos, V., Peter, M., Gillis, C.-A., St-Hilaire, A., and Bergeron, N.E. 2023a. Nunavik anadromous Arctic char life histories, behaviour and habitat use informed by both Inuit knowledge and western science: A year in Ungava Bay. Arct. Sci. Just In. doi:10.1139/AS-2022-0019.

Dubos, V., and Snowball, E. 2020. Arctic char under ice at night in Tasikallak (Short Lake). [Video file]. YouTube. Available from https://youtu.be/0bnawtOkTV4 [accessed 3 January 2023].

Dubos, V., St-Hilaire, A., and Bergeron, N.E. 2022. Summer stream habitat preferences of Nunavik anadromous Arctic char (*Salvelinus alpinus*) fry and parr. Can. J. Fish. Aquat. Sci. **79**(7): 1074–1085.

Dubos, V., St-Hilaire, A., and Bergeron, N.E. 2023b. Fuzzy logic modelling of anadromous Arctic char spawning habitat from Nunavik Inuit knowledge. Ecol. Model. **477**: 110262. doi:10.1016/j.ecolmodel.2022.110262.

Dufour-Beauséjour, S., and Plante Lévesque, V. 2020. Our practice of outreach during the Ice Monitoring project in Nunavik: an early-career researcher perspective. FACETS **5**(1): 123–137. doi:10.1139/facets-2019-0021.

Dunbar, M.J., Alfredsen, K., and Harby, A. 2012. Hydraulic-habitat modelling for setting environmental river flow needs for salmonids. Fish. Manag. Ecol. **19**(6): 500–517. doi:10.1111/j.1365-2400.2011.00825.x.

Durkalec, A., and Breton-Honeyman, K. 2022, June. Taking the lead: An integrated plan for research management in Nunavik. Polynia Consulting Group. Available from https://nunavikresearch.ca/wp-content/uploads/bsk-pdf-manager/2022/07/NRRA-Integrated-Plan_2022-06-28_FINAL_low-res-1.pdf. [accessed 1 March 2023].

Elliott, J.M., and Elliott, J.A. 2010. Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. J. Fish Biol. **77**(8): 1793–1817. doi:10.1111/j.1095-8649.2010.02762.x.

Ellison, A.M. 2004. Bayesian inference in ecology. Ecol. Lett. **7**(6): 509–520. doi:10.1111/j.1461-0248.2004.00603.x.

EPTC. 2014. Énoncé de politique des trois Conseils - éthique de la recherche avec des êtres humains / [publié conjointement par] Conseil de recherches en sciences humaines du Canada, Conseil de recherche en sciences naturelles et en génie du Canada, Instituts de recherche en santé du Canada. : RR4-2/2014F-PDF - Publications du gouvernement du Canada - Canada.ca. Available from http://publications.gc.ca/site/fra/9.644092/publication.html [accessed 24 February 2019].

Fabricius, E. 1953. Aquarium observations on the spawning behaviour of the char, *Salmo alpinus*. Rep Inst Freshw. Res Drottningholm **37**: 14–48.

Falardeau, M., Bennett, E.M., Else, B., Fisk, A., Mundy, C.J., Choy, E.S., Ahmed, M.M.M., Harris, L.N., and Moore, J.-S. 2022. Biophysical indicators and Indigenous and Local Knowledge reveal climatic and ecological shifts with implications for Arctic Char fisheries. Glob. Environ. Change **74**: 102469. doi:10.1016/j.gloenvcha.2022.102469.

Fausch, K.D., Torgersen, C.E., Baxter, C.V., and Li, H.W. 2002. Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream FishesA Continuous View of the River is Needed to Understand How Processes Interacting among Scales Set the Context for Stream Fishes and Their Habitat. BioScience **52**(6): 483–498. Oxford Academic. doi:10.1641/0006-3568(2002)052[0483:LTRBTG]2.0.CO;2.

Fracz, A., and Chow-Fraser, P. 2013. Impacts of declining water levels on the quantity of fish habitat in coastal wetlands of eastern Georgian Bay, Lake Huron. Hydrobiologia **702**(1): 151–170. Springer.

Franssen, J., Pépino, M., Lapointe, M., and Magnan, P. 2013. Alternative tactics in spawning site selection by brook trout (*Salvelinus fontinalis*) related to incubation microhabitats in a harsh winter environment. Freshw. Biol. **58**(1): 142–158.

Frye, M., Egeland, T.B., Nordeide, J.T., and Folstad, I. 2021. Cannibalism and protective behavior of eggs in Arctic charr (*Salvelinus alpinus*). Ecol. Evol. **11**(21). doi:10.1002/ece3.8173.

Gagnon, C.A., Hamel, S., Russell, D.E., Powell, T., Andre, J., Svoboda, M.Y., and Berteaux, D. 2020. Merging indigenous and scientific knowledge links climate with the growth of a large migratory caribou population. J. Appl. Ecol. **57**(9): 1644–1655. doi:10.1111/1365-2664.13558.

Galappaththi, E.K., Ford, J.D., Bennett, E.M., and Berkes, F. 2019. Climate change and community fisheries in the arctic: A case study from Pangnirtung, Canada. J. Environ. Manage. **250**: 109534. doi:10.1016/j.jenvman.2019.109534.

Gallagher, C.P., Courtney, M.B., Seitz, A.C., Lea, E.V., and Howland, K.L. 2021. Ocean-entry timing and marine habitat-use of Canadian Dolly Varden: Dispersal among conservation, hydrocarbon exploration, and shipping areas in the Beaufort Sea. Estuar. Coast. Shelf Sci.: 107609. doi:10.1016/j.ecss.2021.107609.

Garbe, J., Beevers, L., and Pender, G. 2016. The interaction of low flow conditions and spawning brown trout (*Salmo trutta*) habitat availability. Ecol. Eng. **88**: 53–63. doi:10.1016/j.ecoleng.2015.12.011.

Gérardin, V., and McKenney, D. 2001. Une classification climatique du Québec à partir de modèles de distribution spatiale de données climatiques mensuelles : vers une définition des bioclimats du Québec. Contribution du service de la cartographie écologique. No 60.

Gilbert, M.J.H., Donadt, C.R., Swanson, H.K., and Tierney, K.B. 2016. Low Annual Fidelity and Early Upstream Migration of Anadromous Arctic Char in a Variable Environment. Trans. Am. Fish. Soc. **145**(5): 931–942. doi:10.1080/00028487.2016.1173095.

Gilbert, M.J.H., Harris, L.N., Malley, B.K., Schimnowski, A., Moore, J.-S., and 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. Conserv. Physiol. **8**(1). Oxford Academic. doi:10.1093/conphys/coaa036.

Gillet, C. 1991. Egg production in an Arctic charr (*Salvelinus alpinus L.*) brood stock: effects of temperature on the timing of spawning and the quality of eggs. Aquat. Living Resour. **4**(2): 109–116. doi:10.1051/alr:1991010.

Gillis, D.J., Allard, M., and Kemp, W.B. 1982. Life history and present status of anadromous Arctic char (*Salvelinus alpinus L.*) in northern Quebec with case studies on the George, Payne and Kovik rivers, Kativik Regional Government, Kuujjuaq. 1982. Available from https://pubs.aina.ucalgary.ca// [accessed 3 January 2023].

Godiksen, J.A., Power, M., Borgstrøm, R., Dempson, J.B., and Svenning, M.A. 2012. Thermal habitat use and juvenile growth of Svalbard Arctic charr: evidence from otolith stable oxygen isotope analyses. Ecol. Freshw. Fish **21**(1): 134–144.

Gosselin, M.-P., Maddock, I., and Petts, G. 2012. Mesohabitat use by brown trout (*Salmo trutta*) in a small groundwater-dominated stream. River Res. Appl. **28**(3): 390–401. doi:10.1002/rra.1464.

Granier, S. 2013, May. Alimentation, réserves énergétiques et qualité des oeufs chez l'omble chevalier (*Salvelinus alpinus*) et le doré jaune (*Sander vitreus*). phd, Université du Québec à Rimouski, Rimouski, Québec. Available from https://semaphore.uqar.ca/id/eprint/958/ [accessed 6 July 2022].

Gryba, R., Huntington, H.P., Von Duyke, A.L., Adams, B., Frantz, B., Gatten, J., Harcharek, Q., Olemaun, H., Sarren, R., Skin, J., Henry, G., and Auger-Méthé, M. 2021. Indigenous Knowledge of bearded seal (Erignathus barbatus), ringed seal (Pusa hispida), and spotted seal (Phoca largha) behaviour and habitat use near Utqiaġvik, Alaska, USA. Arct. Sci. **7**(4): 832–858. NRC Research Press. doi:10.1139/as-2020-0052.

Gulseth, O.A., and Nilssen, K.J. 1999. Growth Benefit from Habitat Change by Juvenile High-Arctic Char. Trans. Am. Fish. Soc. **128**(4): 593–602. doi:10.1577/1548-8659(1999)128<0593:GBFHCB>2.0.CO;2.

Habersack, H., Tritthart, M., Liedermann, M., and Hauer, C. 2014. Efficiency and uncertainties in micro- and mesoscale habitat modelling in large rivers. Hydrobiologia **729**(1): 33–48. doi:10.1007/s10750-012-1429-x.

Hamann, E.J., Kennedy, B.P., Whited, D.C., and Stanford, J.A. 2014. Spatial Variability in Spawning Habitat Selection by Chinook Salmon (*Oncorhynchus tshawytscha*) in a Wilderness River. River Res. Appl. **30**(9): 1099–1109. doi:https://doi.org/10.1002/rra.2704.

Hammar, J. 2014. Natural resilience in Arctic charr *Salvelinus alpinus*: life history, spatial and dietary alterations along gradients of interspecific interactions. J. Fish Biol. **85**(1): 81–118. doi:10.1111/jfb.12321.

Hammar, J., Dempson, J.B., and Sköld, E. 1989. Natural hybridization between arctic char (*Salvelinus alpinus*) and lake char (*S. namaycush*): Evidence from Northern Labrador. Nord. J Freshw. Res **65**: 54–70.

Hammar, J., Dempson, J.B., and Verspoor, E. 1991. Natural Hybridization between Arctic Char (*Salvelinus alpinus*) and Brook Trout (*S. fontinalis*): Evidence from Northern Labrador. Can. J. Fish. Aquat. Sci. **48**(8): 1437–1445. NRC Research Press. doi:10.1139/f91-171.

Hammer, L.J., Hussey, N.E., Marcoux, M., Pettitt-Wade, H., Hedges, K., Tallman, R., and Furey, N.B. 2021. Arctic char enter the marine environment before annual ice breakup in the high Arctic. Environ. Biol. Fishes. doi:10.1007/s10641-021-01099-3.

Hanks, R., Kanno, Y., and Rash, J. 2018. Can Single-Pass Electrofishing Replace Three-Pass Depletion for Population Trend Detection? Trans. Am. Fish. Soc. **147**. doi:10.1002/tafs.10061.

Harwood, L.A., and Babaluk, J.A. 2014. Spawning, Overwintering and Summer Feeding Habitats Used by Anadromous Arctic Char (*Salvelinus alpinus*) of the Hornaday River, Northwest Territories, Canada. ARCTIC **67**(4): 449–461.

Hastie, T., and Tibshirani, R. 1986. Generalized Additive Models. Stat. Sci. **1**(3): 297–310. Institute of Mathematical Statistics.

Hawley, K.L., Rosten, C.M., Haugen, T.O., Christensen, G., and Lucas, M.C. 2017. Freezer on, lights off! Environmental effects on activity rhythms of fish in the Arctic. Biol. Lett. **13**(12): 20170575. Royal Society. doi:10.1098/rsbl.2017.0575.

Heap, S.M., Stuart-Fox, D., and Byrne, P.G. 2015. Reduction in site fidelity with smaller spatial scale may suggest scale-dependent information use. Behav. Ecol. **26**(2): 543–549. Oxford Academic. doi:10.1093/beheco/aru230.

Hedger, R.D., Diserud, O.H., Sandlund, O.T., Saksgård, L., Ugedal, O., and Bremset, G. 2018. Bias in estimates of electrofishing capture probability of juvenile Atlantic salmon. Fish. Res. **208**: 286–295. doi:10.1016/j.fishres.2018.08.005.

Hedger, R.D., Dodson, J.J., Bergeron, N.E., and Caron, F. 2004. Quantifying the effectiveness of regional habitat quality index models for predicting densities of juvenile Atlantic salmon (*Salmo salar L.*). Ecol. Freshw. Fish **13**(4): 266–275. doi:10.1111/j.1600-0633.2004.00069.x.

Heggenes, J., Bremset, G., and Brabrand, Å. 2010. Groundwater, Critical Habitats, and Behaviour of Atlantic Salmon, Brown Trout and Arctic Char in Streams. Norwegian Institute for Nature Research. NINA report 654.

Heggenes, J., and Saltveit, S.J. 2007. Summer stream habitat partitioning by sympatric Arctic charr, Atlantic salmon and brown trout in two sub-arctic rivers. J. Fish Biol. **71**(4): 1069–1081. doi:10.1111/j.1095-8649.2007.01573.x.

Heggenes, J., Saltveit, S.J., and Lingaas, O. 1996. Predicting Fish Habitat Use to Changes in Water Flow: Modelling Critical Minimum Flows for Atlantic Salmon, *Salmo Salar*, and Brown Trout, *S. Trutta*. Regul. Rivers Res. Manag. **12**(2–3): 331–344. doi:10.1002/(SICI)1099-1646(199603)12:2/3<331::AID-RRR399>3.0.CO;2-E.

Henri, D.A., Martinez-Levasseur, L.M., Weetaltuk, S., Mallory, M.L., Gilchrist, H.G., and Jean-Gagnon, F. 2020. Inuit knowledge of Arctic Terns (*Sterna paradisaea*) and perspectives on declining abundance in southeastern Hudson Bay, Canada. PLOS ONE **15**(11): e0242193. Public Library of Science. doi:10.1371/journal.pone.0242193.

Hunt, R.J., Strand, M., and Walker, J.F. 2006. Measuring groundwater–surface water interaction and its effect on wetland stream benthic productivity, Trout Lake watershed, northern Wisconsin, USA. J. Hydrol. **320**(3): 370–384. doi:10.1016/j.jhydrol.2005.07.029.

Huntington, H.P. 2000. Using traditional ecological knowledge in science: methods and applications. Ecol. Appl. **v. 10**(5): 5–1274.

Inuit Tapiriit Kanatami. 2018. National Inuit Strategy on Research.

Jacobs, J. 1974. Quantitative measurement of food selection : A modification of the forage ratio and Ivlev's electivity index. Oecologia **14**(4): 413–417. doi:10.1007/BF00384581.

Janjua, M.Y., Etuangat, J., Sudlovenick, E., Martin, Z., Tallman, R.F., Friesen, M., and Carmichael, T. 2016a. Results of a traditional ecological knowledge study on Arctic char in Qikiqtarjuaq (Nunavut) fishing areas. Can. Manuscr. Rep. Fish. Aquat. Sci. 3090. Fisheries and Oceans Canada.

Jansen, J., MacIntyre, S., Barrett, D., Chin, Y.P., Cortes, A., Forrest, A., Hrycik, A.R., Martin, R., McMeans, B.C., Rautio, M., and Schwefel, R. 2021. Winter limnology: how do hydrodynamics and carbon biogeochemistry shape unique ecosystems under ice? **126**(6): B018-0015.

Jeuthe, H., Brännäs, E., and Nilsson, J. 2016. Effects of variable egg incubation temperatures on the embryonic development in Arctic charr *Salvelinus alpinus*. Aquac. Res. **47**(12): 3753–3764. doi:10.1111/are.12825.

Jobling, M. 1983. Influence of body weight and temperature on growth rates of Arctic charr, *Salvelinus alpinus (L.)*. J. Fish Biol. **22**(4): 471–475. doi:10.1111/j.1095-8649.1983.tb04767.x.

Jobling, M., Jørgensen, E.H., Arnesen, A.M., and Ringø, E. 1993. Feeding, growth and environmental requirements of Arctic charr: a review of aquaculture potential. Aquac. Int. **1**(1): 20–46. doi:10.1007/BF00692662.

Johnson, D. 1980a. The Comparison of Usage and Availability Measurements for Evaluating Resource Preference. USGS North. Prairie Wildl. Res. Cent. Available from https://digitalcommons.unl.edu/usgsnpwrc/198.

Johnson, L. 1980b. The arctic charr, *Salvelinus alpinus*. *In* Charrs: salmonid fishes of the genus Salvelinus., E. K. Balon. Dr. W. Junk Publishers. The Hague, The Netherlands. pp. 15–98.

Johnson, L. 1980c. Analysis of the dolly varden charr, Salvelinus malma, of northwestern North America and northeastern Siberia. *In* Charrs: salmonid fishes of the genus *Salvelinus*., E. K. Balon. Dr. W. Junk Publishers. The Hague, The Netherlands. Available from https://noclegikobylanka.pl/bibliographies2wam/charrs-salmonid-fishes-of-the-genus-salvelinus-148.html [accessed 12 December 2019].

Johnson, N., Pearce, T., Breton-Honeyman, K., Etiendem, D.N., and Loseto, L.L. 2020. Knowledge co-production and co-management of Arctic wildlife. Arct. Sci. **6**(3): 124–126. NRC Research Press. doi:10.1139/as-2020-0028.

Jolivel, M., and Allard, M. 2017. Impact of permafrost thaw on the turbidity regime of a subarctic river: the Sheldrake River, Nunavik, Quebec. Arct. Sci. **3**(2): 451–474. NRC Research Press. doi:10.1139/as-2016-0006.

Jørgensen, E.H., and Johnsen, H.K. 2014. Rhythmic life of the Arctic charr: Adaptations to life at the edge. Mar. Genomics **14**: 71–81. doi:10.1016/j.margen.2013.10.005.

Keating, K.A., and Cherry, S. 2004. Use and Interpretation of Logistic Regression in Habitat-Selection Studies. J. Wildl. Manag. **68**(4): 774–789. doi:10.2193/0022-541X(2004)068[0774:UAIOLR]2.0.CO;2.

Kishigami, N. 2000. Contemporary Inuit Food Sharing and Hunter Support Program of Nunavik, Canada. Senri Ethnol. Stud. (53): 171–192. doi:10.15021/00002848.

Klemetsen, A. 2010. The Charr Problem Revisited: Exceptional Phenotypic Plasticity Promotes Ecological Speciation in Postglacial Lakes. Freshw. Rev. **3**(1): 49–74. doi:10.1608/FRJ-3.1.3.

Klemetsen, A., Amundsen, P.-A., Dempson, J.B., Jonsson, B., Jonsson, N., O'Connell, M.F., and Mortensen, E. 2003a. Atlantic salmon *Salmo salar L.*, brown trout *Salmo trutta L.* and Arctic charr *Salvelinus alpinus (L.)*: a review of aspects of their life histories. Ecol. Freshw. Fish **12**: 1–59. doi:10.1034/j.1600-0633.2003.00010.x@10.1111/(ISSN)1600-0633.Editors-Choice-2011.

Klemetsen, A., Knudsen, R., Staldvik, F., and Amundsen, P.-A. 2003b. Habitat, diet and food assimilation of Arctic charr under the winter ice in two subarctic lakes. J. Fish Biol. **62**: 1082–1098. doi:10.1046/j.1095-8649.2003.00101.x.

Knopp, J.A., Furgal, C.M., Reist, J.D., Babaluk, J.A., Sachs Harbour Hunters and Trappers Committee, and Olokhaktomuit Hunters and Trappers Committee. 2012. Indigenous and Ecological Knowledge for Understanding Arctic Char Growth. *In* Fishing People of the North: Cultures, Economies, and Management Responding to Change. *Edited by* C. Carothers, K.R. Criddle, C.P. Chambers, P.J. Cullenberg, J.A. Fall, J.P. Johnsen, N.S. Kimball, and C.R. Menzies. Alaska Sea Grant, University of Alaska Fairbanks. pp. 177–191. doi:10.4027/fpncemrc.2012.14.

Knudsen, R., Gjelland, K.Ø., Eloranta, A.P., Hayden, B., Siwertsson, A., Amundsen, P.-A., and Klemetsen, A. 2016. A specialised cannibalistic Arctic charr morph in the piscivore guild of a subarctic lake. Hydrobiologia **783**(1): 65–78. doi:10.1007/s10750-015-2601-x.

Koops, M., and Tallman, R. 2004, August 1. Adaptive variation in the development and mortality of Arctic char eggs. International Congress on the Biology of Fish.

Kristofferson, A.H. 2003. Identification of Arctic char stocks in the Cambridge Bay area, Nunavut Territory, and evidence of stock mixing during overwintering. (PhD thesis), University of Manitoba, Winnipeg, Canada.

Laforest, B.J., Hébert, J.S., Obbard, M.E., and Thiemann, G.W. 2018. Traditional Ecological Knowledge of Polar Bears in the Northern Eeyou Marine Region, Québec, Canada. Arctic **71**(1): 40–58. Arctic Institute of North America.

Lamouroux, N., and Jowett, I.G. 2005. Generalized instream habitat models. Can. J. Fish. Aquat. Sci. **62**(1): 7–14. doi:10.1139/f04-163.

Landis, J.R., and Koch, G.G. 1977. The Measurement of Observer Agreement for Categorical Data. Biometrics **33**(1): 159–174. doi:10.2307/2529310.

Langeland, A., and L'Abée-Lund, J.H. 1998. An experimental test of the genetic component of the ontogenetic habitat shift in Arctic charr (*Salvelinus alpinus*). Ecol. Freshw. Fish **7**(4): 200–207. doi:10.1111/j.1600-0633.1998.tb00187.x.

Larsson, S. 2005. Thermal preference of Arctic charr, *Salvelinus alpinus*, and brown trout, *Salmo trutta* – implications for their niche segregation. Environ. Biol. Fishes **73**(1): 89–96. doi:10.1007/s10641-004-5353-4.

Larsson, S., and Berglund, I. 1998. Growth and food consumption of 0+ Arctic charr fed pelleted or natural food at six different temperatures. J. Fish Biol. **52**(2): 230–242. doi:10.1111/j.1095-8649.1998.tb00795.x.

Larsson, S., and Berglund, I. 2005. The effect of temperature on the energetic growth efficiency of Arctic charr (*Salvelinus alpinus L.*) from four Swedish populations. J. Therm. Biol. **30**(1): 29–36. doi:10.1016/j.jtherbio.2004.06.001.

Larsson, S., Forseth, T., Berglund, I., Jensen, A.J., Näslund, I., Elliott, J.M., and Jonsson, B. 2005. Thermal adaptation of Arctic charr: experimental studies of growth in eleven charr populations from Sweden, Norway and Britain: Thermal adaptation of Arctic charr. Freshw. Biol. **50**(2): 353–368. doi:10.1111/j.1365-2427.2004.01326.x.

Le Jeune, R. 1967. L'omble chevalier anadrome du Kagnersoualoudjouark. Bulletin 10. Service de la Faune. Available from https://diffusion.mern.gouv.qc.ca/public/Biblio/Mono/2016/07/0878825.pdf [accessed 3 February 2023].

Leite, M.C.F., and Gasalla, M.A. 2013. A method for assessing fishers' ecological knowledge as a practical tool for ecosystem-based fisheries management: Seeking consensus in Southeastern Brazil. Fish. Res. **145**: 43–53. doi:10.1016/j.fishres.2013.02.013.

L'Hérault, E., and Allard, M. 2018. Production de la 2ième approximation de la carte de pergélisol du Québec en fonction des paramètres géomorphologiques, écologiques, et des processus physiques liés au climat.

Libakova, N.M., and Sertakova, E.A. 2015. The Method of Expert Interview as an Effective Research Procedure of Studying the Indigenous Peoples of the North. J. Sib. Fed. Univ. Humanit. Soc. Sci. **8**(1). Available from https://core.ac.uk/download/pdf/38643859.pdf [accessed 26 May 2021].

Long, R.A., Muir, J.D., Rachlow, J.L., and Kie, J.G. 2009. A Comparison of Two Modeling Approaches for Evaluating Wildlife-Habitat Relationships. J. Wildl. Manag. **73**(2): 294–302. doi:10.2193/2008-052.

Lotspeich, F.B., and Everest, F.H. 1981. A new method for reporting and interpreting textural composition of spawning gravel. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. doi:10.2737/PNW-RN-369.

Lyytikäinen, T., Koskela, J., and Rissanen, I. 1997. Thermal resistance and upper lethal temperatures of underyearling Lake Inari Arctic charr. J. Fish Biol. **51**(3): 515–525. doi:10.1111/j.1095-8649.1997.tb01509.x.

Mackinson, S., and Nøttestad, L. 1998. Combining Local and Scientific Knowledge. Rev. Fish Biol. Fish. **8**(4): 481–490.

Magnuson, J.J., and Karlen, D.J. 1970. Visual Observation of Fish Beneath the Ice in a Winterkill Lake. J. Fish. Board Can. (27): 1059–1068. NRC Research Press Ottawa, Canada. doi:10.1139/f70-122.

Mainguy, J., and Beaupré, L. 2019a. Establishment of a reference state for Arctic charr population(s) in Aupaluk. Ministère des Forêts, de la Faune des Parcs, Gouvernement du Québec. Available from https://mffp.gouv.qc.ca/our-publications/arctic-charr-populations-in-aupaluk/?lang=en [accessed 3 February 2023].

Mainguy, J., and Beaupré, L. 2019b. Établissement d'un état de référence pour la population d'omble chevalier de la rivière Berard à Tasiujaq. Ministère des Forêts, de la Faune des Parcs, Gouvernement du Québec. Available from https://mffp.gouv.qc.ca/nos-publications/omble-chevalier-tasiujaq/ [accessed 3 February 2023].

Malavoi, J.R., and Souchon, Y. 2002. Description standardisée des principaux faciès d'écoulement observables en rivière : clé de détermination qualitative et et mesures physiques. Bull. Fr. Pêche Piscic. (365–366): 357–372. EDP Sciences. doi:10.1051/kmae:2002040.

Manly, B.B., Manly, B.F.J., McDonald, L., and Thomas, D. 1993. Resource Selection by Animals: Statistical Design and Analysis for Field Studies. Springer Science & Business Media.

Mann, H.B., and Whitney, D.R. 1947. On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other. Ann. Math. Stat. **18**(1): 50–60. Institute of Mathematical Statistics.

MathWorks. 2018. MATLAB Fuzzy Logic Toolbox. User's Guide. Natick, MA, USA. Available from https://www.mathworks.com/help/fuzzy/index.html?s_cid=doc_ftr.

Mcdonald, J.H. 2014. G–test of goodness-of-fit. *In* Handbook of Biological Statistics, 3rd ed., Sparky House Publishing, Baltimore, Maryland. pp. 53–58. Available from http://www.biostathandbook.com/gtestgof.html [accessed 6 October 2020].

McGregor, D. 2018. From 'Decolonized' To Reconciliation Research in Canada: Drawing From Indigenous Research Paradigms. ACME Int. J. Crit. Geogr. **17**(3): 810–831.

McNicholl, D.G., Harris, L.N., Loewen, T., May, P., Tran, L., Akeeagok, R., Methuen, K., Lewis, C., Jeppesen, R., Illasiak, S., Green, B., Koovaluk, J., Annahatak, Z., Kapakatoak, J., Kaosoni, N., Hainnu, B., Maksagak, B., Reist, J.D., and Dunmall, K.M. 2021. Noteworthy occurrences among six marine species documented with community engagement in the Canadian Arctic. Anim. Migr. **8**(1): 74–83. De Gruyter Open Access. doi:10.1515/ami-2020-0113.

Mochnacz, N.J., Ghamry, H.K., Enders, E.C., Watkinson, D.A., Gallagher, C.P., and Reist, J.D. 2020. Flow and spawning habitat relationships for Dolly Varden: Understanding habitat–population dynamics in the Canadian Western Arctic. River Res. Appl. **36**(1): 68–78. doi:10.1002/rra.3547.

Mochnacz, N.J., Schroeder, B.S., Sawatzky, C.D., and Reist, J.D. 2010. Assessment of Northern Dolly Varden, *Salvelinus malma malma* (Walbaum, 1792), Habitat in Canada. Manuscr. Rep. Fish. Aquat. Sci. 2926: vi + 48 p.

Mocq, J., St-Hilaire, A., and Cunjak, R.A. 2013. Assessment of Atlantic salmon (*Salmo salar*) habitat quality and its uncertainty using a multiple-expert fuzzy model applied to the Romaine River (Canada). Ecol. Model. **265**: 14–25. doi:10.1016/j.ecolmodel.2013.05.020.

Mocq, J., St-Hilaire, A., and Cunjak, R.A. 2015. Influences of Experts' Personal Experiences in Fuzzy Logic Modeling of Atlantic Salmon Habitat. North Am. J. Fish. Manag. **35**: 271–280.

Moir, H.J., and Pasternack, G.B. 2008. Relationships between mesoscale morphological units, stream hydraulics and Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat on the Lower Yuba River, California. Geomorphology **100**(3): 527–548. doi:10.1016/j.geomorph.2008.02.001.

Moller, H., Berkes, F., Lyver, P.O., and Kislalioglu, M. 2004. Combining Science and Traditional Ecological Knowledge: Monitoring Populations for Co-Management. Ecol. Soc. **9**(3). Resilience Alliance Inc. Available from https://www.jstor.org/stable/26267682 [accessed 7 June 2021].

Monsen, G.-J. 2019. Behavioral study of coexisting populations of anadromous brown trout and arctic char that overwinter in a subarctic lake (Master thesis). Nor. Univ. Life Sci. NMBU. Norwegian University of Life Sciences, Ås. Available from https://nmbu.brage.unit.no/nmbu-xmlui/handle/11250/2633868 [accessed 30 May 2020].

Moore, J.-S., Harris, L.N., Kessel, S.T., Bernatchez, L., Tallman, R.F., and 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. Can. J. Fish. Aquat. Sci. **73**(9): 1434–1445. doi:10.1139/cjfas-2015-0436.

Moore, J.-S., Harris, L.N., Luyer, J.L., Sutherland, B.J.G., Rougemont, Q., Tallman, R.F., Fisk, A.T., and 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. Mol. Ecol. **26**(24): 6784–6800. doi:10.1111/mec.14393.

Moore, J.-S., Harris, L.N., Tallman, R.F., and Taylor, E.B. 2013. The interplay between dispersal and gene flow in anadromous Arctic char (*Salvelinus alpinus*): implications for potential for local adaptation. Can. J. Fish. Aquat. Sci. NRC Research Press. doi:10.1139/cjfas-2013-0138.

Moore, J.W., and Moore, I.A. 1974. Food and growth of arctic char, *Salvelinus alpinus (L.)*, in the Cumberland Sound area of Baffin Island. J. Fish Biol. **6**(1): 79–92. doi:10.1111/j.1095-8649.1974.tb04525.x.

Mouton, A.M., Dillen, A., Van den Neucker, T., Buysse, D., Stevens, M., and Coeck, J. 2012. Impact of sampling efficiency on the performance of data-driven fish habitat models. Ecol. Model. **245**: 94–102. doi:10.1016/j.ecolmodel.2012.03.003.

Mouton, A.M., Jowett, I., Goethals, P.L.M., and De Baets, B. 2009. Prevalence-adjusted optimisation of fuzzy habitat suitability models for aquatic invertebrate and fish species in New Zealand. Ecol. Inform. **4**(4): 215–225. doi:10.1016/j.ecoinf.2009.07.006.

Mouton, A.M., Schneider, M., Depestele, J., Goethals, P.L.M., and De Pauw, N. 2007. Fish habitat modelling as a tool for river management. Ecol. Eng. **29**(3): 305–315. doi:10.1016/j.ecoleng.2006.11.002.

Mouton, A.M., Schneider, M., Kopecki, I., Goethals, P.L.M., and Pauw, N.D. 2006. Application of MesoCASiMiR: Assessment of Baetis rhodani Habitat Suitability. : 7.

Mouton, A.M., Schneider, M., Peter, A., Holzer, G., Müller, R., Goethals, P.L.M., and De Pauw, N. 2008. Optimisation of a fuzzy physical habitat model for spawning European grayling (Thymallus thymallus L.) in the Aare river (Thun, Switzerland). Ecol. Model. **215**(1): 122–132. doi:10.1016/j.ecolmodel.2008.02.028.

MRNF Québec. 2004. Cartes numériques des dépôts de surface. Québec : Ressources naturelles et Faune. Division des inventaires forestiers. Available from http://mffp.gouv.qc.ca/les-forets/inventaire-ecoforestier/ [accessed 30 July 2022].

Mulder, I.M., Dempson, J.B., Fleming, I.A., and Power, M. 2019a. Diel activity patterns in overwintering Labrador anadromous Arctic charr. Hydrobiologia **840**(1): 89–102. doi:10.1007/s10750-019-3926-7.

Mulder, I.M., Morris, C.J., Dempson, J.B., Fleming, I.A., and Power, M. 2018a. Winter movement activity patterns of anadromous Arctic charr in two Labrador lakes. Ecol. Freshw. Fish **27**(3): 785–797. doi:10.1111/eff.12392.

Mulder, I.M., Morris, C.J., Dempson, J.B., Fleming, I.A., and Power, M. 2018b. Overwinter thermal habitat use in lakes by anadromous Arctic char. Can. J. Fish. Aquat. Sci. **75**(12): 2343–2353. doi:10.1139/cjfas-2017-0420.

Mulder, I.M., Morris, C.J., Dempson, J.B., Fleming, I.A., and Power, M. 2019b. Marine temperature and depth use by anadromous Arctic Char correlates to body size and diel period. Can. J. Fish. Aquat. Sci. doi:10.1139/cjfas-2019-0097.

Neelin, M.N. 2021. Arctic char in a changing climate: Community priorities and recommendations. Makivik Corporation, Kuujjuaq, Quebec. 91 p.

Nordahl, O., Tibblin, P., Koch-Schmidt, P., Berggren, H., Larsson, P., and Forsman, A. 2018. Sun-basking fish benefit from body temperatures that are higher than ambient water. Proc. R. Soc. B Biol. Sci. **285**(1879): 20180639. Royal Society. doi:10.1098/rspb.2018.0639.

Nunavut Department of Education. 2007. Inuit Qaujimajatuqangit. Education Framework for Nunavut Curriculum. Nunavut Department of Education, Curriculum and School Services Division, ISBN 1-55015-031-5. 61 p.

Ostertag, S.K., Loseto, L.L., Snow, K., Lam, J., Hynes, K., and Gillman, D.V. 2018. "That's how we know they're healthy": the inclusion of traditional ecological knowledge in beluga health monitoring in the Inuvialuit Settlement Region. Arct. Sci. **4**(3): 292–320. NRC Research Press.

Ouellet, V., Mocq, J., El Adlouni, S.-E., and Krause, S. 2021. Improve performance and robustness of knowledge-based FUZZY LOGIC habitat models. Environ. Model. Softw. **144**: 105138. doi:10.1016/j.envsoft.2021.105138.

Ouranos. 2021. Portraits climatiques. Available from https://portclim.ouranos.ca/#/regions/14 [accessed 22 December 2021].

Parasiewicz, P. 2001. MesoHABSIM: A concept for application of instream flow models in river restoration planning. Fisheries **26**(9): 6–13. doi:10.1577/1548-8446(2001)026<0006:M>2.0.CO;2.

Pedersen, C., Otokiak, M., Koonoo, I., Milton, J., Maktar, E., Anaviapik, A., Milton, M., Porter, G., Scott, A., Newman, C., Porter, C., Aaluk, T., Tiriraniaq, B., Pedersen, A., Riffi, M., Solomon, E., and Elverum, S. 2020. ScIQ: an invitation and recommendations to combine science and Inuit Qaujimajatuqangit for meaningful engagement of Inuit communities in research. Arct. Sci. doi:10.1139/AS-2020-0015.

Petrou, Z.I., Kosmidou, V., Manakos, I., Stathaki, T., Adamo, M., Tarantino, C., Tomaselli, V., Blonda, P., and Petrou, M. 2014. A rule-based classification methodology to handle uncertainty in habitat mapping employing evidential reasoning and fuzzy logic. Pattern Recognit. Lett. **48**: 24–33. doi:10.1016/j.patrec.2013.11.002.

Polfus, J.L., Heinemeyer, K., Hebblewhite, M., and Taku River Tlingit First Nation. 2014. Comparing traditional ecological knowledge and western science woodland caribou habitat models: TEK Caribou Habitat Models. J. Wildl. Manag. **78**(1): 112–121. doi:10.1002/jwmg.643.

Polivka, C.M. 2020. Habitat affinity and density-dependent movement as indicators of fish habitat restoration efficacy. Ecosphere **11**(6): e03166. doi:https://doi.org/10.1002/ecs2.3166.

Power, G., and Barton, D.R. 1987. Some Effects of Physiographic and Biotic Factors on the Distribution of Anadromous Arctic Char (*Salvelinus Alpinus*) in Ungava Bay, Canada. Arctic **40**(3): 198–203. doi:http://dx.doi.org/10.14430/arctic1767.

Power, G., Brown, R.S., and Imhof, J.G. 1999. Groundwater and fish—insights from northern North America. Hydrol. Process. **13**(3): 401–422. doi:10.1002/(SICI)1099-1085(19990228)13:3<401::AID-HYP746>3.0.CO;2-A.

Reed, J.C., and Bostock, H.S. 1954. Research in Geology and Geomorphology in the North American Arctic and Subarctic. ARCTIC **7**(3 and 4): 129–140. doi:10.14430/arctic3837.

Reid, A.J., Eckert, L.E., Lane, J.-F., Young, N., Hinch, S.G., Darimont, C.T., Cooke, S.J., Ban, N.C., and Marshall, A. 2021. "Two-Eyed Seeing": An Indigenous framework to transform fisheries research and management. Fish Fish. **22**(2): 243–261. doi:10.1111/faf.12516.

Reist, J.D., Dempson, J.B., Dunmall, K., Harris, L.N., Power, M., and Swanson, H.K. 2018. Family Salmonidae – Trouts and Salmons, Truites et Saumons. *In* Marine Fishes of Arctic Canada. *Edited by* B.W. Coad and J.D. Reist. University of Toronto Press, Toronto. pp. 248–301. doi:10.3138/9781442667297-043.

Reist, J.D., Wrona, F.J., Prowse, T.D., Power, M., Dempson, J.B., King, J.R., and Beamish, R.J. 2006. An Overview of Effects of Climate Change on Selected Arctic Freshwater and Anadromous Fishes. AMBIO J. Hum. Environ. **35**(7): 381–387. doi:10.1579/0044-7447(2006)35[381:AOOEOC]2.0.CO;2.

Rikardsen, A.H., Amundsen, P.-A., and Bodin, P.J. 2003. Growth and diet of anadromous Arctic charr after their return to freshwater. Ecol. Freshw. Fish **12**(1): 74–80. doi:10.1034/j.1600-0633.2003.00001.x.

Roux, M.-J., Tallman, R.F., and Martin, Z.A. 2019. Small-scale fisheries in Canada's Arctic: Combining science and fishers knowledge towards sustainable management. Mar. Policy **101**: 177–186. doi:10.1016/j.marpol.2018.01.016.

Rowland, J.C., Jones, C.E., Altmann, G., Bryan, R., Crosby, B.T., Hinzman, L.D., Kane, D.L., Lawrence, D.M., Mancino, A., Marsh, P., McNamara, J.P., Romanvosky, V.E., Toniolo, H., Travis, B.J., Trochim, E., Wilson, C.J., and Geernaert, G.L. 2010a. Arctic Landscapes in

Transition: Responses to Thawing Permafrost. Eos Trans. Am. Geophys. Union **91**(26): 229–230. doi:10.1029/2010EO260001.

Sæther, B.-S., Siikavuopio, S.I., and Jobling, M. 2016. Environmental conditions required for intensive farming of Arctic charr (*Salvelinus alpinus (L.)*). Hydrobiologia **783**(1): 347–359. doi:10.1007/s10750-015-2572-y.

Saltveit, S.J., and Brabrand, Å. 2013. Incubation, hatching and survival of eggs of Atlantic salmon (*Salmo salar*) in spawning redds influenced by groundwater. Limnologica **43**(5): 325–331. doi:10.1016/j.limno.2013.05.009.

Sandlund, O.T., Malmquist, H.J., Jonsson, B., Skúlason, S., Snorrason, S.S., Jónasson, P.M., Gydemo, R., and Lindem, T. 1988. Density, length distribution, and diet of age-0 arctic charrSalvelinus alpinus in the surf zone of Thingvallavatn, Iceland. Environ. Biol. Fishes **23**(3): 183–195. doi:10.1007/BF00004909.

Schmitz, M. 1995. Seasonal changes in hypoosmoregulatory ability in landlocked and anadromous populations of Arctic charr, *Salvelinus alpinus*, and Atlantic salmon, *Salmo salar*. Environ. Biol. Fishes **42**(4): 401–412. doi:10.1007/BF00001471.

Schneider, M., and Jorde, K. 2003. Fuzzy-Rule Based Models for the Evaluation of Fish Habitat Quality and Instream Flow Assessment. Int. IFIM Users' Workshop Fort Collins Colo.

Scholander, P.F., Dam, L. van, Kanwisher, J.W., Hammel, H.T., and Gordon, M.S. 1957. Supercooling and osmoregulation in arctic fish. J. Cell. Comp. Physiol. **49**(1): 5–24. doi:10.1002/jcp.1030490103.

Siikavuopio, S.I., Sæther, B.-S., Johnsen, H., Evensen, T., and Knudsen, R. 2014. Temperature preference of juvenile Arctic charr originating from different thermal environments. Aquat. Ecol. **48**(3): 313–320. doi:10.1007/s10452-014-9485-0.

Sinnatamby, R.N., Babaluk, J.A., Power, G., Reist, J.D., and Power, M. 2012. Summer habitat use and feeding of juvenile Arctic charr, *Salvelinus alpinus*, in the Canadian High Arctic. Ecol. Freshw. Fish **21**(2): 309–322. doi:10.1111/j.1600-0633.2012.00552.x.

Sinnatamby, R.N., Shears, M., Dempson, J. Brian, and Power, M. 2013. Thermal habitat use and growth in young-of-the-year Arctic charr from proximal fluvial and lacustrine populations in Labrador, Canada. J. Therm. Biol. **38**: 493–501.

Smart, J. 2021. Inuit knowledge and observations of changes in Arctic char (*Salvelinus alpinus*) and implications for subsistence livelihoods in Unlukhaktok, Northwest Territories, Canada. (Master thesis). University of Northern British Columbia, Prince George, Canada.

Smith, R., Hitkolok, E., Loewen, T., Dumond, A., Kristensen, K., and Swanson, H. 2022. Overwintering ecology and movement of anadromous Arctic char (*Salvelinus alpinus*) in a large, ice-covered river in the Canadian Arctic. J. Fish Biol. **100**(6): 1432–1446. doi:10.1111/jfb.15054.

Smith, R.L. 2020. Migration timing and overwintering habitat of anadromous Arctic Char (*Salvelinus alpinus*) near Kugluktuk, Nunavut. (Master thesis), University of Waterloo, Canada.

Sneddon, L.U., and Brown, C. 2020. Mental Capacities of Fishes. *In* Neuroethics and Nonhuman Animals. *Edited by* L.S.M. Johnson, A. Fenton, and A. Shriver. Springer International Publishing, Cham. pp. 53–71. doi:10.1007/978-3-030-31011-0_4.

Snively, G., and Williams, W.L. 2016. Knowing Home: Braiding Indigenous Science with Western Science, Book 1. *In* Edited by Gloria. University of Victoria. Available from https://ecampusontario.pressbooks.pub/knowinghome/ [accessed 20 June 2020].

Snook, J., Akeeagok, J., Palliser, T., Cunsolo, A., Hoover, C., Bailey, M., Basterfield, M., Dale, A., and Giles, A. 2019. Enhancing fisheries co-management in the Eastern Arctic. Northern Public Affairs, Nov. 2019. : 70–74.

Spares, A.D., Stokesbury, M.J.W., Dadswell, M.J., O'Dor, R.K., and Dick, T.A. 2015. Residency and movement patterns of Arctic charr *Salvelinus alpinus* relative to major estuaries. J. Fish Biol. **86**(6): 1754–1780. doi:10.1111/jfb.12683.

Spares, A.D., Stokesbury, M.J.W., O'Dor, R.K., and Dick, T.A. 2012. Temperature, salinity and prey availability shape the marine migration of Arctic char, *Salvelinus alpinus*, in a macrotidal estuary. Mar. Biol. **159**(8): 1633–1646. doi:10.1007/s00227-012-1949-y.

Steel, E.A., Jensen, D.W., Burnett, K.M., Christiansen, K., Firman, J.C., Feist, B.E., Anlauf, K.J., and Larsen, D.P. 2012. Landscape characteristics and coho salmon (*Oncorhynchus kisutch*) distributions: explaining abundance versus occupancy. Can. J. Fish. Aquat. Sci. **69**(3): 457–468. doi:10.1139/f2011-161.

Stern, E.R., and Humphries, M.M. 2022. Interweaving local, expert, and Indigenous knowledge into quantitative wildlife analyses: A systematic review. Biol. Conserv. **266**: 109444. doi:10.1016/j.biocon.2021.109444.

Stewart, D.B., Mochnacz, N.J., Reist, J.D., Carmichael, T.J., and Sawatzky, C.D. 2010. Fish life history and habitat use in the Northwest Territories: Dolly Varden (*Salvelinus malma*). Can. Manuscr. Rep. Fish. Aquat. Sci. 2915. Fisheries and Oceans Canada.

Stewart, D.B., Mochnacz, N.J., Sawatzky, C.D., Carmichael, T.J., and Reist, J.D. 2007. Fish life history and habitat use in the Northwest Territories: bull trout (*Salvelinus confluentus*). Can. Manuscr. Rep. Fish. Aquat. Sci. 2801. Fisheries and Oceans Canada.

Svenning, M.-A., Klemetsen, A., and Olsen, T. 2007. Habitat and food choice of Arctic charr in Linnévatn on Spitsbergen, Svalbard: The first year-round investigation in a High Arctic lake. Ecol. Freshw. Fish **16**(1): 70–77. doi:10.1111/j.1600-0633.2006.00183.x.

Swift, D.R. 1965. Effect of Temperature on Mortality and Rate of Development of the Eggs of the Windermere Char (*Salvelinus alpinus*). J. Fish. Res. Board Can. **22**(4): 913–917. doi:10.1139/f65-086.

Tagalik, S. 2012, January. Inuit Qaujimajatuqangit: The role of Indigenous knowledge in supporting wellness in Inuit communities in Nunavut. National Collaborating Centre for Indigenous Health.

Tantipisanuh, N., Gale, G.A., and Pollino, C. 2014. Bayesian networks for habitat suitability modeling: a potential tool for conservation planning with scarce resources. Ecol. Appl. **24**(7): 1705–1718. Wiley.

Tendeng, B., Asselin, H., and Imbeau, L. 2016. Moose (*Alces americanus*) habitat suitability in temperate deciduous forests based on Algonquin traditional knowledge and on a habitat suitability index. Écoscience **23**(3–4): 77–87. Taylor & Francis. doi:10.1080/11956860.2016.1263923.

Tester, F.J., and Irniq, P. 2008. Inuit Qaujimajatuqangit: social history, politics and the practice of resistance. Arctic **61**(4): S48–S48. Arctic Institute of North America of the University of Calgary.

Thyrel, M., Berglund, I., Larsson, S., and Näslund, I. 1999. Upper thermal limits for feeding and growth of 0+ Arctic charr. J. Fish Biol. **55**(1): 199–210. doi:10.1111/j.1095-8649.1999.tb00669.x.

Tonina, D., and Buffington, J.M. 2009. Hyporheic Exchange in Mountain Rivers I: Mechanics and Environmental Effects. Geogr. Compass **3**(3): 1063–1086. doi:https://doi.org/10.1111/j.1749-8198.2009.00226.x.

Tremblay, R., Landry-Cuerrier, M., and Humphries, M. 2020. Culture and the social-ecology of local food use by Indigenous communities in northern North America. Ecol. Soc. **25**(2). The Resilience Alliance. doi:10.5751/ES-11542-250208.

Truth and Reconciliation Commission of Canada. 2015. Truth and Reconciliation Commission of Canada: Calls to Action. Truth and Reconciliation Commission of Canada, Winnipeg, Manitoba. Available from https://nctr.ca/records/reports/, https://nctr.ca/records/reports/ [accessed 7 February 2023].

Tynan, L. 2021. What is relationality?: Indigenous knowledges, practices and responsibilities with kin. Cult. Geogr. **28**(4): 597–610. doi:10.1177/14744740211029287.

Usher, P.J. 2000. Traditional Ecological Knowledge in Environmental Assessment and Management. ARCTIC **53**(2): 183–193. doi:10.14430/arctic849.

Valentine, P.C. 2019. *In* Sediment classification and the characterization, identification, and mapping of geologic substrates for the glaciated Gulf of Maine seabed and other terrains, providing a physical framework for ecological research and seabed management. USGS Numbered Series, U.S. Geological Survey, Reston, VA. doi:10.3133/sir20195073.

Vincent, W.F., Lemay, M., and Allard, M. 2017. Arctic permafrost landscapes in transition: towards an integrated Earth system approach. Arct. Sci. **3**(2): 39–64. NRC Research Press. doi:10.1139/as-2016-0027.

Vuorinen, P.J., Paasivirta, J., Keinänen, M., Kositinen, J., Rantio, T., Hyötyläinen, T., and Welling, L. 1997. The M74 syndrome of baltic salmon (*Salmo salar*) and organochlorine concentrations in the muscle of female salmon. Chemosphere **34**: 1151–1166. doi:10.1016/S0045-6535(97)00415-3.

Walker, D.A., and Smith, T.J. 2016. Nine Pseudo R2 Indices For Binary Logistic Regression Models. J. Mod. Appl. Stat. Methods **15**(1): 848–854. doi:10.22237/jmasm/1462078200.

Watts, P., Koutouki, K., Booth, S., and Blum, S. 2017. Inuit food security in canada: arctic marine ethnoecology. Food Secur. **9**(3): 421–440. doi:10.1007/s12571-017-0668-0.

Wegscheider, B., Linnansaari, T., Ndong, M., Haralampides, K., St-Hilaire, A., Schneider, M., and Curry, R.A. 2021. Fish habitat modelling in large rivers: combining expert opinion and hydrodynamic modelling to inform river management. J. Ecohydraulics. Taylor & Francis. doi:10.1080/24705357.2021.1938251.

Wegscheider, B., Linnansaari, T., Wall, C.C., Gautreau, M.D., Monk, W.A., Dolson-Edge, R., Samways, K.M., and Curry, R.A. 2020. Diel patterns in spatial distribution of fish assemblages in lentic and lotic habitat in a regulated river. River Res. Appl. **n/a**(n/a). John Wiley & Sons, Ltd. doi:10.1002/rra.3615.

Welch, H.E., and Bergmann, M.A. 1985. Water Circulation in Small Arctic Lakes in Winter. Can. J. Fish. Aquat. Sci. **42**: 506–520. NRC Research Press Ottawa, Canada. doi:10.1139/f85-068.

Welch, H.E., Legault, J.A., and Bergmann, M.A. 1987. Effects of Snow and Ice on the Annual Cycles of Heat and Light in Saqvaqjuac Lakes. Can. J. Fish. Aquat. Sci. **44**(8): 1451–1461. NRC Research Press. doi:10.1139/f87-174.

Wilbur, N.M., O'Sullivan, A.M., MacQuarrie, K.T.B., Linnansaari, T., and Curry, R.A. 2020. Characterizing physical habitat preferences and thermal refuge occupancy of brook trout (*Salvelinus fontinalis*) and Atlantic salmon (*Salmo salar*) at high river temperatures. River Res. Appl. **36**(5): 769–783. doi:https://doi.org/10.1002/rra.3570.

Wilson, C.C., and Hebert, P.D.N. 1993. Natural Hybridization between Arctic Char (*Salvelinus alpinus*) and Lake Trout (*S. namaycush*) in the Canadian Arctic. Can. J. Fish. Aquat. Sci. **50**(12): 2652–2658. NRC Research Press. doi:10.1139/f93-288.

Wilson, K.J., Bell, T., Arreak, A., Koonoo, B., Angnatsiak, D., and Ljubicic, G.J. 2020. Changing the role of non-Indigenous research partners in practice to support Inuit self-determination in research. Arct. Sci. **6**(3): 127–153. NRC Research Press. doi:10.1139/as-2019-0021.

Witkowski, A., Kotusz, J., Popiolek Marcin, and Kusznierzznierz Jan. 2008. Summer dynamics of density and biomass of the Arctic charr, *Salvelinus alpinus (L.)*, in a polar stream (SW Spitsbergen). Pol. Polar Res. **29**(3): 237–243.

Wong, C., Ballegooyen, K., Ignace, L., Johnson, M.J. (Gùdia), and Swanson, H. 2020. Towards reconciliation: 10 Calls to Action to natural scientists working in Canada. FACETS **5**(1): 769–783. Canadian Science Publishing. doi:10.1139/facets-2020-0005.

Woolway, R.I., Jones, I.D., Maberly, S.C., French, J.R., Livingstone, D.M., Monteith, D.T., Simpson, G.L., Thackeray, S.J., Andersen, M.R., Battarbee, R.W., DeGasperi, C.L., Evans, C.D., Eyto, E. de, Feuchtmayr, H., Hamilton, D.P., Kernan, M., Krokowski, J., Rimmer, A., Rose, K.C., Rusak, J.A., Ryves, D.B., Scott, D.R., Shilland, E.M., Smyth, R.L., Staehr, P.A., Thomas, R., Waldron, S., and Weyhenmeyer, G.A. 2016. Diel Surface Temperature Range Scales with Lake Size. PLOS ONE **11**(3): e0152466. Public Library of Science. doi:10.1371/journal.pone.0152466.

Young, A.L., and Tallman, R.F. 2021. The comparative lake ecology of two allopatric Arctic Charr, *Salvelinus alpinus*, populations with differing life histories in Cumberland Sound, Nunavut. Arct. Sci. **7**(2). doi:10.1139/AS-2019-0037.

Young, A.L., Tallman, R.F., and Ogle, D.H. 2021. Life history variation in Arctic charr (*Salvelinus alpinus*) and the effects of diet and migration on the growth, condition, and body morphology of two Arctic charr populations in Cumberland Sound, Nunavut, Canada. Arct. Sci.: 1–18. NRC Research Press. doi:10.1139/as-2019-0036.

Zadeh, L.A. 1965. Fuzzy sets. Inf. Control **8**(3): 338–353. doi:10.1016/S0019-9958(65)90241-X.

Zadeh, L.A. 1975. The concept of a linguistic variable and its application to approximate reasoning—I. Inf. Sci. **8**(3): 199–249. doi:10.1016/0020-0255(75)90036-5.

Zhang, H., Sun, T., Shao, D., and Yang, W. 2016. Fuzzy logic method for evaluating habitat suitability in an estuary affected by land reclamation. Wetlands **36**(Suppl. 1): 19–30. doi:10.1007/s13157-014-0606-2.

ANNEXE I – DOCUMENTS SUPPLÉMENTAIRES DU CHAPITRE 3 (CYCLE DE VIE)

Note: The following interview framework was meant to be used as a guide during the interviews. The order of the themes addressed could be modified to follow the flow of the interview and encourage interviewees to share their knowledge via storytelling.

Necessary Materials

- A large scale map of the river basin
- Clear plastic sheets for each participant to draw on the map
- Pictures of adult Arctic Char: both anadromous and resident
- Pictures of juvenile Arctic Char; is there a visual difference between anadromous and resident?
- Pictures of different geomorphological unit (shallow bank (juvenile), pool with a visible gentle slope, pool with undercut bank (overwintering habitat), riffle, run)
- Pictures of (5) different typical substrate sizes
- Measuring tape
- Short video clips of (3) different flow velocities
- Voice recorder
- Consent forms.

Workflow of interviews

1) Thank the participant for his/her presence and collaboration
2) Briefly introduce team members that are present and their role in the project
3) Explain project goal
4) Describe how the interview will be conducted and give an estimate of how long it should take

SECTION 1 : SEA-RUN ARCTIC CHAR SPAWNING GROUNDS

General Location (use of maps)

1. Which river or area are you familiar with ?

2. Do you know which river or lake is used by sea-run arctic char?
   a. Name
   b. Locations on map

3. Do you know if they overwinter in the river or in an upstream lake? (see map)

Spawning

4. Do you know of locations where iqaluppik lay their eggs?

   a. Are these spawning grounds in lakes? rivers? both?

5. Can you show location(s) of spawning sites (nests for the eggs) on the map?

6. Could you describe the characteristics of the river at these spawning sites? (what does it look like?)

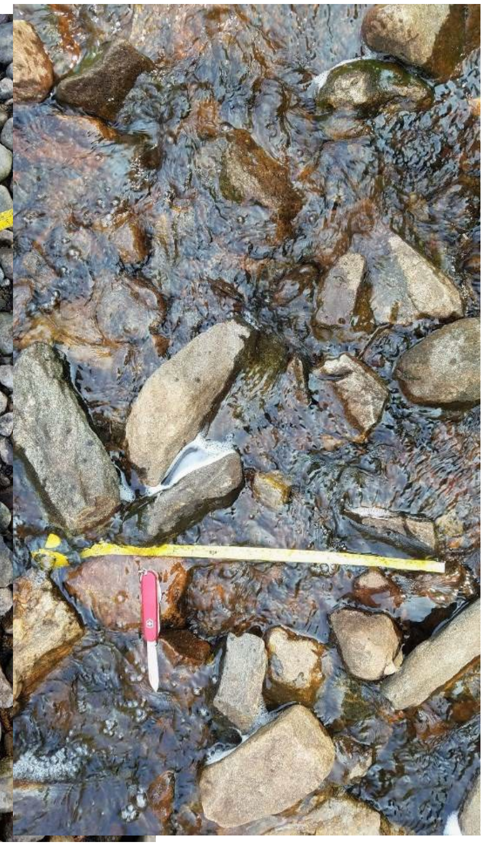
Local spawning sites characteristics (with videos, photos)

7. What do you think is most important for the spawning of Arctic char?
   - Bed material size
   - Water depth
   - Flow velocity
   - Temperature (Local groundwater inflow, sun or shade)
   - Other:

8. Do you think riverbed material (river floor /ground) is important for spawning chars?

1. If yes, is there one of these pictures that could be the best bed material? (pick the preferred repartition and size of rocks)
   (each picture in individual large print)





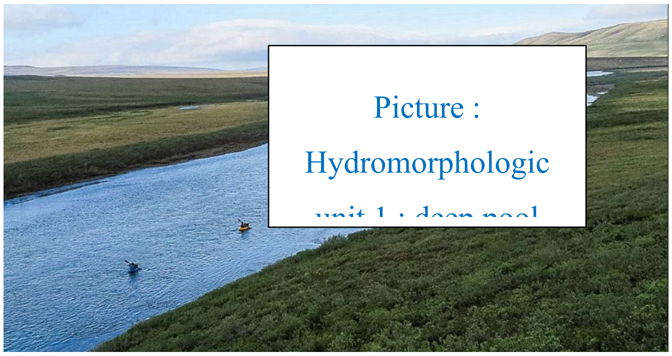

2. Do you think chars prefer a certain water velocity for spawning?
    a. Is there one of these video that could be the best velocity for char spawning?
    b. Is there one of these velocity that's not a good velocity for spawning? (show video)

Video 1: low or no velocity	Video 2 : Medium velocity	Video 3: High Velocity

3. Have you an idea of which water depth could be the best for spawning? (measuring tape)

River geomorphology

4. Do you think one of these pictures could be a good location for char spawning? (each pictures in individual large print)



Picture :
Hydromorphologic
unit 1 : deep pool

Groundwater:

5. Do you know if there is groundwater (water coming from the ground, through the riverbed) coming in the river?

    a. If yes, can you describe the river at this location?
    b. If yes, can you show location on the map?

6. Do you think sites where groundwater comes in the river could be important for char spawning? (do you think the char is looking for groundwater springs to spawn?)

7. Have you noticed some spots where the river freezes later? (it could be a sign of groundwater spring)
    a. If yes, can you show location?

8. During winter, are there some spots where the water doesn't freeze all the way to the bottom? Or where there is open ice ?

9. Have you already noticed these kinds of icing? (multiple layers of ice)




a. If yes, can you show where on the map?
b. Do you think it can be linked to the presence or not of arctic char spawning ground? (maybe upstream of icings)
c. Do you think it can be linked to the wintering habitat of adult or juvenile? (maybe upstream of icings)

SECTION 2: JUVENILE ARCTIC CHAR HABITAT

10. Have you ever seen juvenile arctic chars? (the young immature, which hasn't yet migrated) (photo)

    a. If yes, are there some spots where you can always find them? in River / in lake?

11. Can you show location(s) of juvenile preferred sites on the map?

12. Which size are the fish you see/have seen?

13. Could you describe those sites?

Micro-habitat characteristics

14. Is there one of this picture that could be the best bed material for juvenile char? (pick the preferred repartition and size of rocks)
(each picture in individual large print)





Do you think juvenile chars have a preference for a certain water velocity?

a. Is there one of these video that could be the best water velocity for juvenile char?
b. Is there one of these video that's not a good velocity for juvenile? (show video)

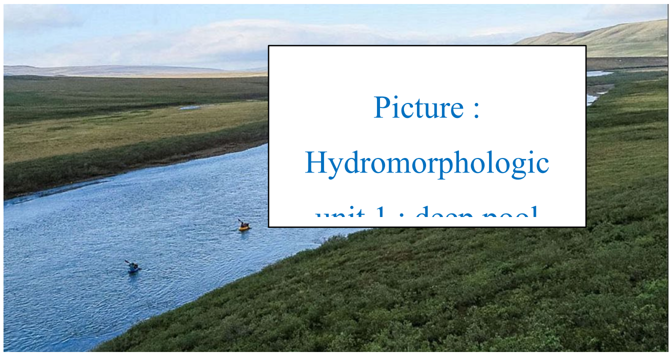
Video 1: low or no velocity	Video 2 : Medium velocity	Video 3: High Velocity

15. Have you an idea of which water depth could be preferred by juvenile? (measuring tape)

<u>River geomorphology</u>

16. Is there one of these pictures that could be a good site for juvenile chars?

a. Is there one of these pictures that's not a good spot?



Picture :
Hydromorphologic
unit 1 : deep pool

17. Do you think the juveniles could prefer sites where groundwater comes in the river?

    (Ask only if participant has a suspicion/hint of groundwater location – From questions on spawning)

18. Do you think the juveniles prefer warmer or colder water temperature in summer?

19. In summer, do you think that juveniles char could occupy smaller tributaries mouth?

20. Do you know the predators of juvenile arctic char?

    (birds, bigger chars 4+, bears, other species, …)

21. Are there any other fish species in the river? Can they be a problem for Iqaluppit ?

SECTION 3: OVERWINTERING SITES OF SEA-RUN ARCTIC CHAR

22. During winter, do you know if there are there some spots where you can always find adult arctic char? Are locations changing from one day to another?

    a. Are they only in lakes? or also in rivers?

23. Can you show location(s) of adults sites during winter on the map/satellite picture?

Groundwater:

Only if participant has information related to groundwater spring from spawning questions

If positive for spawning, then ask :

24. Do you know if adults stay on the same sites where water freeze later?

SECTION 4: TRIGGER OF UPSTREAM MIGRATION OF SEA-RUN ARCTIC CHAR

25. Do you have an idea of how the fish know it's time to go back to freshwater (from the sea)? Or What do you think triggers the beginning of upstream migration at the end of the summer?

    (Air temperature? Freshwater temperature? Sea temperature? river discharge? Tide / moon? day light duration?)

26. Does the upstream migration, from sea to freshwater occur always around the same date or period?

27. Have you noticed any modifications in recent years?

Timing of spawning

28. What is the approximate time of the year when char spawning occurs? (for temperature or flow)

29. Have you observed any changes in the timing of char spawning in the past decades?

SECTION 5: PROBLEMS FOR ARCTIC CHAR

30. Do you have knowledge of problems for Arctic char ?

ANNEXE II – DOCUMENTS SUPPLÉMENTAIRES DU CHAPITRE 4 (LOGIQUE FLOUE)

Table S1 - Spawning habitat characterisation from interviews of eleven Inuit knowledge-holders from three communities: Kangiqsualujjuaq (participants A,B,C,D,E), Tasiujaq (participants F,G,H), Kangirsuk (participants I,J,K). Interviews were conducted in June and September 2019. In Kangirsuk, the three participants I, J, K were interviewed together. Empty cases mean the expert did not express an opinion.

	Substrate (see pictures below)					Velocity				Depth			Miscellaneous
Experts	1	2	3	4	5	0	Low (0.1 m/s Video)	Medium (0.27 m/s Video)	Fast (0.73 m/s Video)	D<2 ft	2 ft<D<5 ft	D>5 ft	
A	Yes	Not sure, because doesn't see the small gravel	No, it needs gravel	Yes, because of the fine and gravel between big rocks	no	All are good				No	5 ft in the river.		
B	All are good					All are good				All are good, but in shallow water they might dry			Spawning sites are always at the same place. It can be any type of stream, it could be in the gravel or not, it could be faster or not. They follow up the narrow river, because it is easy to go upstream.
C		Yes, maybe a little bit smaller gravel					Yes, smooth water		No	No, eggs will freeze	Yes	Yes, in lake >15ft (but didn't know exact spawning sites in lake, just presence of char)	The fish spawn in the medium size river, it is kind of shallow, not too deep, and it is in the gravel area.
D	no	All are good, hide eggs between rocks					All are good			No, because of predators	Yes	No, not in lakes	Eggs are hidden behind rocks. They only spawn in the creeks and rivers. They use the main river (George) tributaries.

E	No	Yes	Yes, but less than 2	doesn't have knowledge of. Probably too much sand and boulders too big	Doesn't have knowledge of. Could be OK to hide the eggs	Not in lake	Yes			No	Yes, less than 5 ft, not really deep		They spawn in gravel bed, where there is some current, even slow (not in lakes). If the current is strong, they spawn in the side of the river, where there is less current. Sometimes, they spawn in gravel surrounded by little bits of rocks that they are able to move with their tail.
F	Yes, in the gravel	Yes				Not in lake		Yes		No, 2 ft too low depth	Yes		Water is always flowing at spawning sites. They do not spawn in lakes.
G		Yes		Was hesitant. Said it was for the adults to hide		Not in lake		Yes		No	Yes, 4 ft		They spawn mostly in rivers (Do not have knowledge of spawning site in lake). Do not do redd, they lay their eggs in the gravel.
H	No, too fine	Yes, in the small gravel		Yes could be good also		Think probably spawn in lake too.	All are good. Told nonetheless that everytime there is spawning, there is not much current. The medium velocity was his/here favorite, even if the other could also be suitable.				Yes 3 ft to 2 ft	Yes, probably in lake (do not know exactly but think they are)	Spawn in slow water, in the rocks.
I J K	Yes, they do a nest in the sand	No	No		No	Not in lake	Yes	No	No, much too fast		Yes, 4 ft, 5 ft, 6 ft	No, do not spawn in deep water, nor lake.	They spawn in a rivers with strong current, in little bays or behind islands where the current is very slow. The riverbed is sandier and copper-brown. They build nests in the sand.

Note: The following pictures were presented to assess substrate preferences:

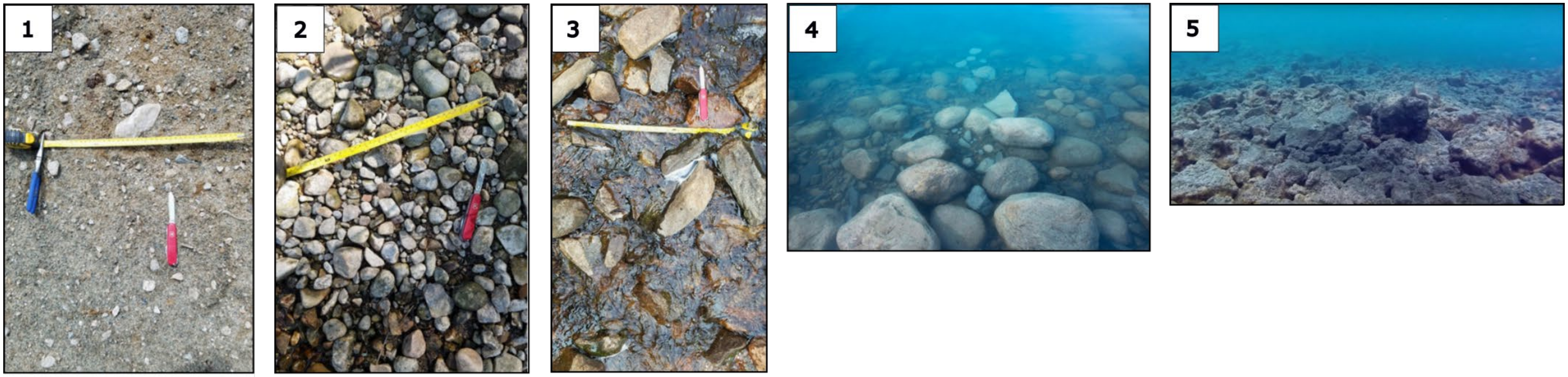

1
2
3
4
5

Table S2 Mean Habitat Suitability Index (HSI) modeled on spawning sites and non-spawning, according to different defuzzification methods and for the three scenarios of input information: Model 1 (A, B, C) - Each community alone; Model 2 - The two communities of Kangiqsualujjuaq and Tasiujaq; Model 3 - The three communities together (Kangiqsualujjuaq, Tasiujaq, Kangirsuk). In grey: difference between presence and absence is non-significant according to Mann-Whitney test ($\alpha<0.05$) (Table S4).

	Model 1A Kangiqsualujjuaq		Model 1B Tasiujaq		Model 1C Kangirsuk		Model 2		Model 3	
Method	Spawning sites	Non-spawning sites	Spawning sites	Non-spawning sites	Spawning sites	Non-spawning sites	Spawning sites	Non-spawning sites	Spawning sites	Non-spawning sites
Centroid	0.61	0.33	0.61	0.35	0.45	0.28	0.61	0.35	0.62	0.26
mom	0.56	0.25	0.56	0.31	0.44	0.25	0.56	0.31	0.61	0.21
lom	0.71	0.40	0.71	0.42	0.59	0.40	0.71	0.42	0.75	0.37

Table S3 Mann-Whitney U test according to different defuzzification methods, for the three different scenarios of input information: Model 1 (A, B, C) - Each community alone; Model 2 - The two communities of Kangiqsualujjuaq and Tasiujaq; Model 3 - The three communities together (Kangiqsualujjuaq, Tasiujaq, Kangirsuk). In grey: difference between spawning and non-spawning is not significant ($\alpha<0.05$).

	Model 1A Kangiqsualujjuaq		Model 1B Tasiujaq		Model 1C Kangirsuk		Model 2		Model 3	
Method	W	p-value	W	p-value	W	p-value	W	p-value	W	p-value
Centroid	44.0	0.025	42.0	0.043	42.5	0.037	43.0	0.034	50.0	0.004
mom	42	0.042	37.5	0.111	37.0	0.128	40.0	0.066	47.0	0.010
lom	41	0.054	39.0	0.085	35.5	0.170	41.0	0.054	48.0	0.007

Table S4 Kappa value according to different defuzzification methods, for the three different scenarios of input information: Model 1 (A, B, C) - Each community alone; Model 2 - The two communities of Kangiqsualujjuaq and Tasiujaq; Model 3 - The three communities together (Kangiqsualujjuaq, Tasiujaq, Kangirsuk). In grey: difference between spawning and non-spawning is not significant according to Mann-Whitney test (α<0.05) (Table S4).

Method	Model 1A Kangiqsualujjuaq	Model 1B Tasiujaq	Model 1C Kangirsuk	Model 2	Model 3
Centroid	0.53 (Moderate)	0.30 (Fair)	0.38 (Fair)	0.30 (Fair)	0.80 (substantial)
mom	0.43 (Moderate)	0.24 (Fair)	0.27 (Fair)	0.24 (Fair)	0.68 (substantial)
lom	0.33 (Fair)	0.24 (Fair)	0.16 (Slight)	0.24 (Fair)	0.56 (Moderate)

Table S5 sensitivity and specificity according to different defuzzification methods, for the three different scenarios of input information: Model 1 (A, B, C) - Each community alone; Model 2 - The two communities of Kangiqsualujjuaq and Tasiujaq; Model 3 - The three communities together (Kangiqsualujjuaq, Tasiujaq, Kangirsuk). In grey: difference between spawning and non-spawning is not significant according to Mann-Whitney test (α<0.05) (Table S4).

	Method	Model 1A Kangiqsualujjuaq	Model 1B Tasiujaq	Model 1C Kangirsuk	Model 2	Model 3
Sensitivity	Centroid	67%	67%	50%	67%	83%
	mom	80%	80%	50%	80%	83%
	lom	80%	80%	50%	80%	83%
Specificity	Centroid	89%	67%	89%	67%	100%
	mom	70%	50%	78%	50%	89%
	lom	60%	50%	67%	50%	78%

Table S5 Comparison of mean HSI calculated on spawning and non-spawning sites for scenario 1, for each community. The results corresponding to the same community than the set of rules are highlighted in blue.

	Sites of Kangiqsualujjuaq		Sites of Tasiujaq		Sites of Kangirsuk	
Model	Spawning	Non-spawning	Spawning	Non-spawning	Spawning	Non-spawning
1A-Kangiqsualujjuaq	0.61	0.28	0.52	0.29	0.79	0.42
1B-Tasiujaq	0.61	0.33	0.52	0.38	0.79	0.33
1C-Kangirsuk	0.51	0.21	0.46	0.29	0.26	0.35

CODES MATLAB UTILISÉS POUR LA LOGIQUE FLOUE

```
%%%%%%%%%%
%  Application de la logique floue
%  Le programme appelle une sous-routine qui contient les FIS
%  Les fichiers FIS ont été fait avec le module logique floue de MAtlab (mais peut être fait à la main)
%%%%%%%%%%


clear;
%Lecture du fichier de données brutes frayères (Avec absences et
%présences)
[data,headings]=xlsread('Frayères.xlsx');

H=data(:,3);
V=data(:,4);
S=data(:,5);

input=[S,V,H];     %Paramètres H,V,S mesurés aux sites de validation

result_centroid = NaN(length(H),5);
result_mom = NaN(length(H),5);
result_lom = NaN(length(H),5);

HSI_GR_Tas_Kangirsuk_centroid = readfis('HQI_GR-Tas-Kangirsuk_HVS_centroid');    %Lecture du fuzzy set - Defuzification centroid
HSI_GR_Tas_centroid = readfis('HQI_GR-Tas_HVS_centroid.fis');   %Lecture du fuzzy set -  Defuzification centroid
HSI_Kangirsuk_centroid = readfis('HQI_Kangirsuk_HVS_centroid.fis');    %Lecture du fuzzy set -  Defuzification centroid
HSI_GR_centroid = readfis('HQI_GR_HVS_centroid.fis');   %Lecture du fuzzy set -  Defuzification centroid
HSI_Tas_centroid = readfis('HQI_Tas_HVS_centroid.fis');   %Lecture du fuzzy set -  Defuzification centroid

HSI_GR_Tas_Kangirsuk_mom = readfis('HQI_GR-Tas-Kangirsuk_HVS_mom');   %Lecture du fuzzy set -  Defuzification mom
HSI_GR_Tas_mom = readfis('HQI_GR-Tas_HVS_mom.fis');   %Lecture du fuzzy set -  Defuzification mom
HSI_Kangirsuk_mom = readfis('HQI_Kangirsuk_HVS_mom.fis');   %Lecture du fuzzy set -  Defuzification mom
HSI_GR_mom = readfis('HQI_GR_HVS_mom.fis');   %Lecture du fuzzy set -  Defuzification mom
HSI_Tas_mom = readfis('HQI_Tas_HVS_mom.fis');   %Lecture du fuzzy set -  Defuzification mom

HSI_GR_Tas_Kangirsuk_lom = readfis('HQI_GR-Tas-Kangirsuk_HVS_lom');    %Lecture du fuzzy set -  Defuzification lom
HSI_GR_Tas_lom = readfis('HQI_GR-Tas_HVS_lom.fis');   %Lecture du fuzzy set -  Defuzification lom
HSI_Kangirsuk_lom = readfis('HQI_Kangirsuk_HVS_lom.fis');   %Lecture du fuzzy set -  Defuzification lom
HSI_GR_lom = readfis('HQI_GR_HVS_lom.fis');   %Lecture du fuzzy set -  Defuzification lom
HSI_Tas_lom = readfis('HQI_Tas_HVS_lom.fis');   %Lecture du fuzzy set -  Defuzification lom

output3_centroid = evalfis(input,HSI_GR_Tas_Kangirsuk_centroid)
output2_centroid = evalfis(input,HSI_GR_Tas_centroid)
output1_centroid = evalfis(input,HSI_Kangirsuk_centroid)
output1GR_centroid = evalfis(input,HSI_GR_centroid)
output1Tas_centroid = evalfis(input,HSI_Tas_centroid)
```

```
output3_mom = evalfis(input,HSI_GR_Tas_Kangirsuk_mom)
output2_mom = evalfis(input,HSI_GR_Tas_mom)
output1_mom = evalfis(input,HSI_Kangirsuk_mom)
output1GR_mom = evalfis(input,HSI_GR_mom)
output1Tas_mom = evalfis(input,HSI_Tas_mom)

output3_lom = evalfis(input,HSI_GR_Tas_Kangirsuk_lom)
output2_lom = evalfis(input,HSI_GR_Tas_lom)
output1_lom = evalfis(input,HSI_Kangirsuk_lom)
output1GR_lom = evalfis(input,HSI_GR_lom)
output1Tas_lom = evalfis(input,HSI_Tas_lom)

result_centroid(:,1)=output3_centroid;
result_centroid(:,2)=output2_centroid;
result_centroid(:,3)=output1_centroid;
result_centroid(:,4)=output1GR_centroid;
result_centroid(:,5)=output1Tas_centroid;
Tcentroid=table(result_centroid);
writetable(Tcentroid,'result_centroid.xlsx');

result_mom(:,1)=output3_mom;
result_mom(:,2)=output2_mom;
result_mom(:,3)=output1_mom;
result_mom(:,4)=output1GR_mom;
result_mom(:,5)=output1Tas_mom;
Tmom=table(result_mom);
writetable(Tmom,'result_mom.xlsx');

result_lom(:,1)=output3_lom;
result_lom(:,2)=output2_lom;
result_lom(:,3)=output1_lom;
result_lom(:,4)=output1GR_lom;
result_lom(:,5)=output1Tas_lom;
Tlom=table(result_lom);
writetable(Tlom,'result_lom.xlsx');
```

%%%%%%
%% Exemple de fichier FIS pour le modèle 3
%% C'est le fichier qui donne les limites des variables floues
%% et les règles
%% Le fichier a été généré par le module Logique floue de Matlab, mais il peut être généré à la main
%%%%

```
[System]
Name='HQI_GR-Tas-Kangirsuk_HVS_centroid'
Type='mamdani'
Version=2.0
NumInputs=3
NumOutputs=1
NumRules=27
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='Substrat'
Range=[-1 500]
NumMFs=3
MF1='Fine':'trapmf',[0 0 1 10]
MF2='Gravel':'trapmf',[4 7 50 150]
MF3='Cobble_boulder':'trapmf',[50 150 1500 3000]

[Input2]
Name='Vitesse'
Range=[0 3]
NumMFs=3
MF1='Medium':'trapmf',[0.2 0.3 0.6 0.7]
MF2='Fast':'trapmf',[0.6 0.7 3 5]
MF3='Slow':'trapmf',[0 0 0.2 0.3]

[Input3]
Name='Profondeur'
Range=[0 3]
NumMFs=3
MF1='Shallow':'trapmf',[0 0 0.6 0.7]
MF2='Medium':'trapmf',[0.6 0.7 1.5 1.9]
MF3='Deep':'trapmf',[1.5 1.9 4 10]

[Output1]
Name='HQI'
Range=[0 1]
NumMFs=3
MF1='Mauvais':'trapmf',[0 0 0.3 0.5]
MF2='Moyen':'trapmf',[0.3 0.5 0.5 0.7]
MF3='Bon':'trapmf',[0.5 0.7 1 1]
```

[Rules]
1 1 1, 1 (1) : 1
1 1 2, 2 (1) : 1
1 1 3, 2 (1) : 1
1 2 1, 1 (1) : 1
1 2 2, 1 (1) : 1
1 2 3, 1 (1) : 1
2 1 1, 2 (1) : 1
2 1 2, 3 (1) : 1
2 1 3, 3 (1) : 1
2 2 1, 1 (1) : 1
2 2 2, 2 (1) : 1
2 2 3, 2 (1) : 1
3 1 1, 1 (1) : 1
3 1 2, 3 (1) : 1
3 1 3, 2 (1) : 1
3 2 1, 1 (1) : 1
3 2 2, 1 (1) : 1
3 2 3, 1 (1) : 1
1 3 1, 1 (1) : 1
1 3 2, 2 (1) : 1
1 3 3, 1 (1) : 1
2 3 1, 1 (1) : 1
2 3 2, 3 (1) : 1
2 3 3, 2 (1) : 1
3 3 1, 1 (1) : 1
3 3 2, 2 (1) : 1
3 3 3, 2 (1) : 1

ANNEXE III – DOCUMENTS SUPPLÉMENTAIRES DU CHAPITRE 5 (HABITAT D'HIVER)

Table S1 Pearson correlation coefficient between variables. Green data show significant value ($\alpha \leq 0.05$)

	Snow depth (m)	Ice thickness (m)	Water depth (m)	Mean temp (deg)	Mean DO (%)	Bottom temp (deg)	Bottom DO (%)	Distance to shore (m)	Slope
Snow depth (m)	1.00	-0.12	-0.06	-0.13	-0.26	-0.12	-0.24	-0.06	-0.10
Water depth (m)	-0.06	0.21	1.00	0.36	-0.08	0.34	-0.32	0.66	0.55
Mean temp (deg)	-0.13	-0.23	0.36	1.00	-0.36	0.93	-0.51	0.02	0.30
Mean DO (%)	-0.26	0.46	-0.08	-0.36	1.00	-0.35	0.83	0.11	-0.09
Bottom temp (deg)	-0.12	-0.12	0.34	0.93	-0.35	1.00	-0.52	0.03	0.25
Bottom DO (%)	-0.24	0.38	-0.32	-0.51	0.83	-0.52	1.00	0.07	-0.25
Distance rive	-0.06	0.06	0.66	0.02	0.11	0.03	0.07	1.00	-0.11
Pente fond	-0.10	0.25	0.55	0.30	-0.09	0.25	-0.25	-0.11	1.00

Table S2 Spearman rank correlation coefficient between variables. Green data show significant value ($\alpha \leq 0.05$)

	Snow depth (m)	Ice thickness (m)	Water depth (m)	Mean temp (deg)	Mean DO (%)	Bottom temp (deg)	Bottom DO (%)	Distance to shore (m)	Slope
Snow depth (m)	1.000	-0.198	-0.196	-0.163	-0.285	-0.160	-0.275	-0.192	-0.031
Water depth (m)	-0.196	0.391	1.000	0.279	0.086	0.174	-0.115	0.480	0.693
Mean temp (deg)	-0.163	-0.205	0.279	1.000	-0.370	0.895	-0.387	0.134	0.201
Mean DO (%)	-0.285	0.502	0.086	-0.370	1.000	-0.390	0.896	0.208	-0.028
Bottom temp (deg)	-0.160	-0.089	0.174	0.895	-0.390	1.000	-0.393	0.078	0.102
Bottom DO (%)	-0.275	0.413	-0.115	-0.387	0.896	-0.393	1.000	0.040	-0.120
Distance rive	-0.192	0.084	0.480	0.134	0.208	0.078	0.040	1.000	-0.170
Pente fond	-0.031	0.313	0.693	0.201	-0.028	0.102	-0.120	-0.170	1.000

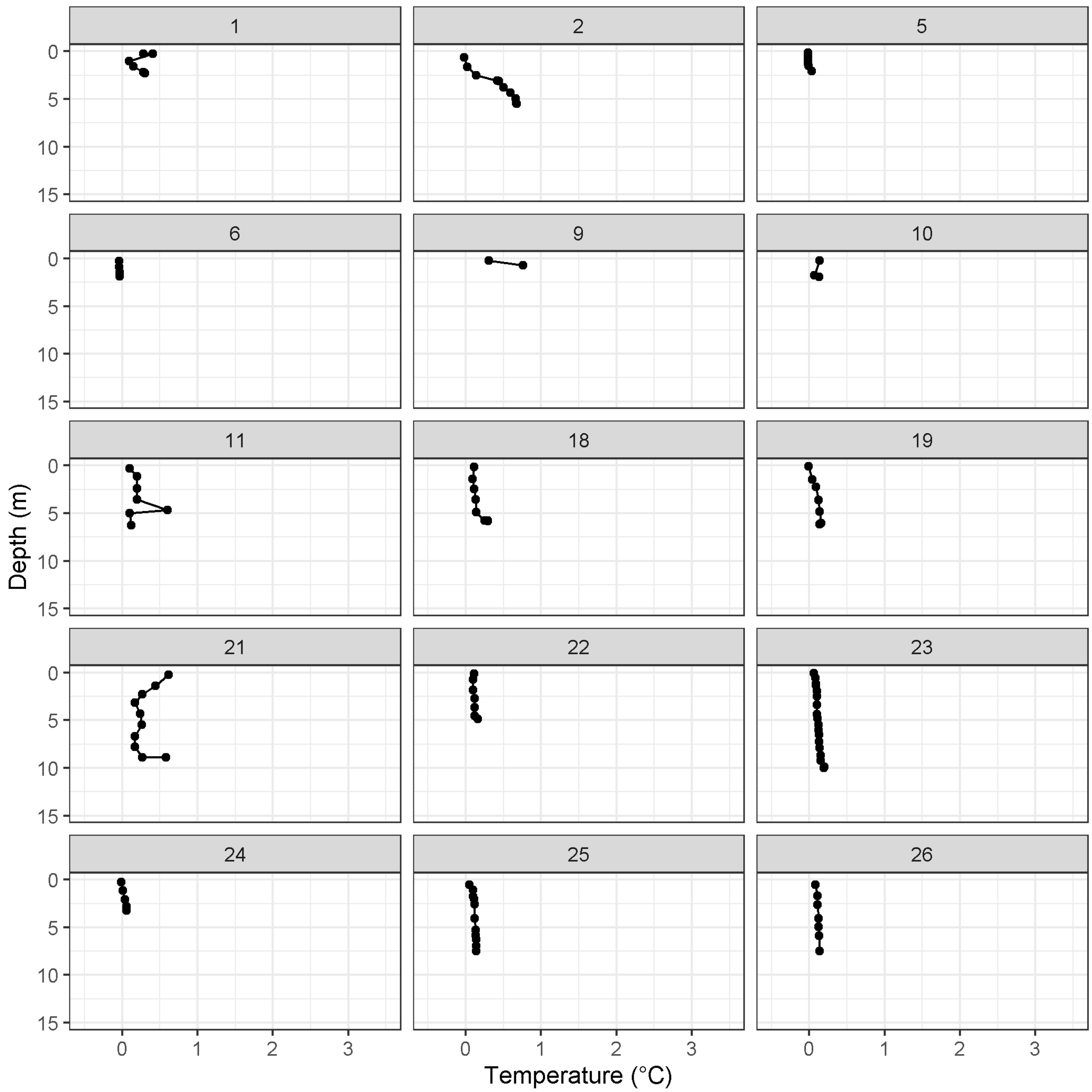
Table S3 Sites characterization on six overwintering lakes around Kangiqsualujjuaq. The GPS location of the sites were kept confidential.

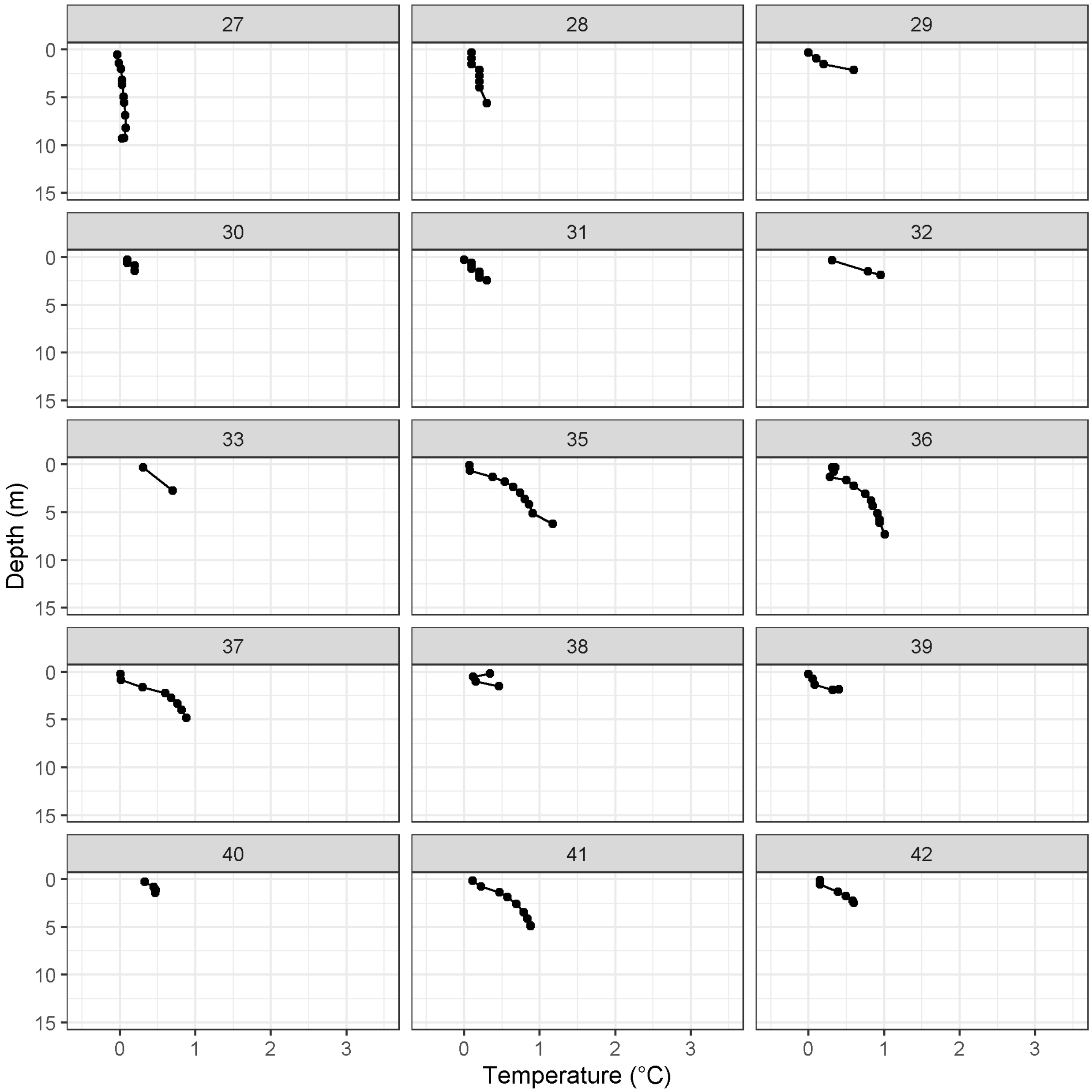
Site #	Location	Date	Type	Type	Ice depth (m)	Snow depth (m)	Water depth (m)	Mean temp. (°C)	Mean DO (%)	Bottom temp. (°C)	Bottom DO (%)	Distance rive (m)	Slope ($m.m^{-1}$)
2	Ujarasutjuliup Qullinga	29/02/2020	Presence	Spawning	0.81	0.18	5.33	0.29	98.99	0.68	92.70	88	0.061
3	Ujarasutjuliup Qullinga	08/04/2020	Presence	Spawning	0.93		3.45	0.22		0.60		79	0.044
4	Ujarasutjuliup Qullinga	08/04/2020	Presence	Spawning	0.97		3.94	0.33		0.85		79	0.050
51	Ujarasutjuliup Qullinga	25/03/2021	Presence	Spawning	0.79	0.33	2.90	0.00	88.73	0.00	99.00	45.2	0.064
1	Ujarasutjuliup Qullinga	29/02/2020	Presence	No_Spawning	0.81	0.37	2.18	0.21	106.05	0.30	107.10	254	0.009
53	Ujarasutjuliup Qullinga	06/04/2021	Presence	No_Spawning	0.91	0.11	3.28	0.19	106.55	0.50	101.10	214	0.015
52	Ujarasutjuliup Qullinga	25/03/2021	Absence	No_Spawning	0.74	0.41	30.00	1.10	86.21	1.90	67.40	192	0.156
50	Ujarasutjulik	06/04/2021	Presence	Spawning	0.91	0.18	8.43	0.25	99.76	0.20	99.10	80	0.105
5	Ujarasutjulik	29/02/2020	Absence	No_Spawning	0.74	0.38	2.08	-0.01	95.19	0.03	92.40	119	0.018
6	Ujarasutjulik	29/02/2020	Absence	No_Spawning	0.79	0.38	1.88	-0.04	105.84	-0.03	102.30	94	0.020
56	Ujarasutjulik	06/04/2021	Absence	No_Spawning	0.91	0.18	11.00	0.16	99.32	0.30	96.50	106	0.104
9	Koroc - Allipaak	02/03/2020	Absence	Spawning	0.53	0.29	0.69	0.46	80.93	0.76	74.90	98	0.007
10	Koroc - Allipaak	02/03/2020	Presence	No_Spawning	0.89	0.30	2.11	0.11	95.40	0.13	94.00	85	0.025
11	Koroc - Allipaak	02/03/2020	Presence	No_Spawning	0.46		5.00	0.24	93.33	0.12	89.20	57	0.088
12	Koroc - Allipaak	25/02/2020	Absence	No_Spawning	0.48	0.30	1.37	0.00		0.00		72	0.019
19	Kuurujuaq	03/03/2020	Presence	Spawning	0.89	0.30	2.11	0.09	105.50	0.14	89.40	100	0.021
14	Kuurujuaq	15/01/2020	N/A	Spawning	0.56	0.00	2.11	0.14		0.23		137	0.015
13	Kuurujuaq	15/01/2020	Presence	No_Spawning	0.51		3.66	0.29		0.45		127	0.079
15	Kuurujuaq	25/02/2020	Presence	No_Spawning	0.89	0.46	8.76	0.17		0.34		131	0.067
17	Kuurujuaq	03/03/2020	Presence	No_Spawning			9.73	0.64	85.80	0.69	84.20	120	0.081
20	Kuurujuaq	03/03/2020	Presence	No_Spawning	0.99	0.10	6.21					80	0.078
22	Kuurujuaq	03/03/2020	Presence	No_Spawning	0.69	0.46	4.88	0.11	90.52	0.16	85.10	113	0.043
23	Kuurujuaq	03/03/2020	Presence	No_Spawning	0.69	0.38	4.88	0.12	87.72	0.19	84.70	169	0.029

Table S3 (continued)

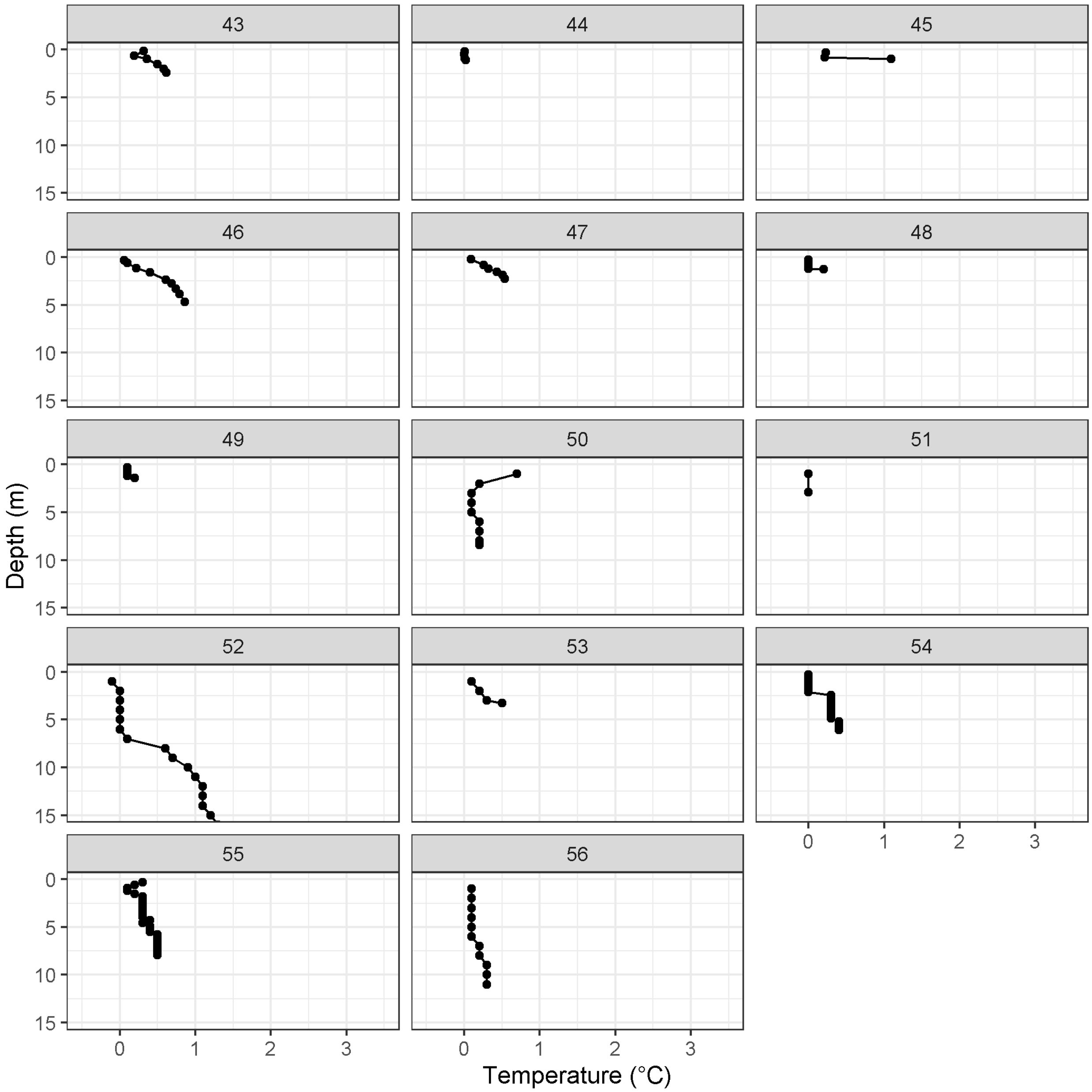
Site #	Location	Date	Type	Type	Ice depth (m)	Snow depth (m)	Water depth (m)	Mean temp. (°C)	Mean DO (%)	Bottom temp. (°C)	Bottom DO (%)	Distance rive (m)	Slope (m.m^{-1})
25	Kuurujuaq	13/03/2020	Presence	No_Spawning			4.04	0.11	80.48	0.14	79.20	117	0.035
28	Kuurujuaq	12/04/2020	Presence	No_Spawning	0.97	0.56	5.61	0.18		0.30		109	0.051
29	Kuurujuaq	13/04/2020	Presence	No_Spawning	0.89	0.56	2.11	0.17		0.60		33	0.064
30	Kuurujuaq	15/04/2020	Presence	No_Spawning	0.91	0.61	1.42	0.15		0.20		40	0.036
54	Kuurujuaq	13/01/2022	Presence	No_Spawning	0.64	0.08	6.10	0.21	91.52	0.40	91.80	180	0.034
55	Kuurujuaq	27/03/2022	Presence	No_Spawning	1.07	0.15	7.90	0.35	93.30	0.50	91.20	130	0.061
31	Kuurujuaq	15/04/2020	N/A	No_Spawning	0.94	0.28	2.59	0.13		0.30		156	0.017
16	Kuurujuaq	25/02/2020	Absence	No_Spawning	0.79	0.37	2.36	0.22		0.34		50	0.047
18	Kuurujuaq	03/03/2020	Absence	No_Spawning	0.81	0.41	30.00	0.13	89.60	0.29	88.00	726	0.041
21	Kuurujuaq	03/03/2020	Absence	No_Spawning	0.89	0.25	11.15	0.28	84.19	0.58	81.10	87	0.128
24	Kuurujuaq	03/03/2020	Absence	No_Spawning	0.84	0.56	3.43	0.03	98.39	0.06	93.90	40	0.086
26	Kuurujuaq	13/03/2020	Absence	No_Spawning	0.84		8.71	0.12	90.50	0.14	83.50	102	0.085
27	Kuurujuaq	13/03/2020	Absence	No_Spawning	0.94	0.30	11.76	0.04	84.40	0.03	78.40	86	0.137
32	Tasikallak	09/02/2020	Presence	Spawning	0.56	0.30	1.87	0.57		0.95		44	0.043
33	Tasikallak	09/02/2020	Presence	Spawning	0.61	0.30	2.74	0.48		0.70		76	0.036
40	Tasikallak	17/03/2020	N/A	Spawning	0.66	0.41	1.50	0.41	82.49	0.47	82.10	40	0.037
41	Tasikallak	17/03/2020	N/A	Spawning	0.66	0.33	4.83	0.59	87.37	0.88	84.70	110	0.044
42	Tasikallak	17/03/2020	N/A	Spawning	0.66	0.56	2.36	0.36	88.23	0.60	87.00	67	0.035
43	Tasikallak	17/03/2020	N/A	Spawning	0.56	0.30	2.49	0.41	86.66	0.62	85.40	210	0.012
39	Tasikallak	17/03/2020	Presence	No_Spawning	0.69	0.38	1.91	0.08	80.31	0.40	82.10	54	0.035
47	Tasikallak	18/03/2020	Presence	No_Spawning	0.71	0.30	2.26	0.36	81.42	0.54	80.30	110	0.021
34	Tasikallak	2020-03-16 et17	Presence	No_Spawning	0.79	0.34	6.10					35	0.174
35	Tasikallak	2020-03-16 et17	Presence	No_Spawning	0.74	0.19	5.44	0.66	86.71	1.17	86.29	75	0.072
44	Tasikallak	17/03/2020	Absence	No_Spawning	0.64	0.66	1.09	0.01	87.13	0.02	85.20	62	0.018
45	Tasikallak	18/03/2020	Absence	No_Spawning	0.69	0.41	0.97	0.51	79.83	1.09	80.20	60	0.016
48	Tunnullik	24/04/2020	Presence	Spawning	0.86	0.25	1.27	0.00		0.20		37	0.034
49	Tunnullik	24/04/2020	Presence	Spawning	0.74	0.30	1.40	0.11		0.20		37	0.038

Profils de temperature relevés



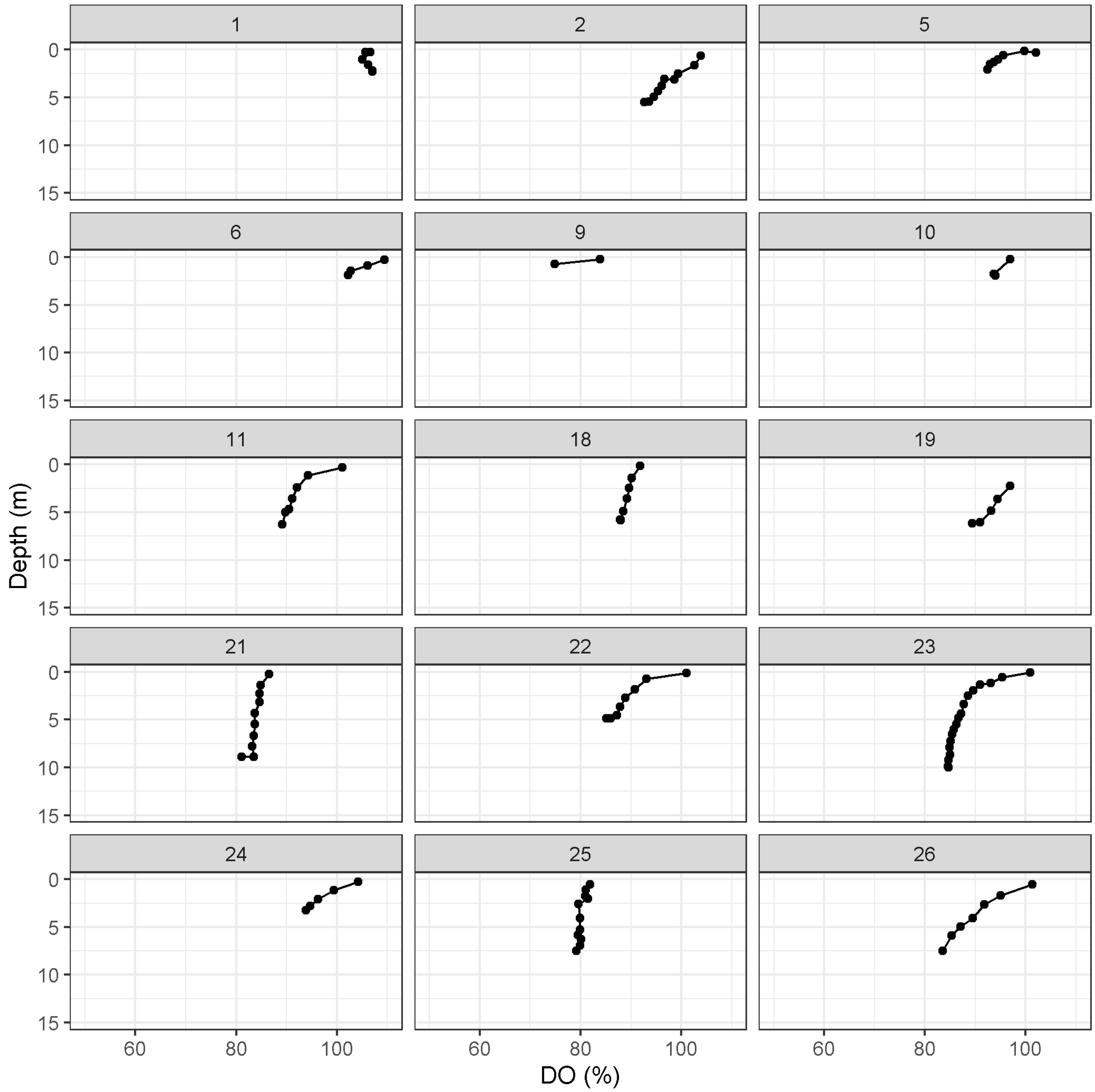


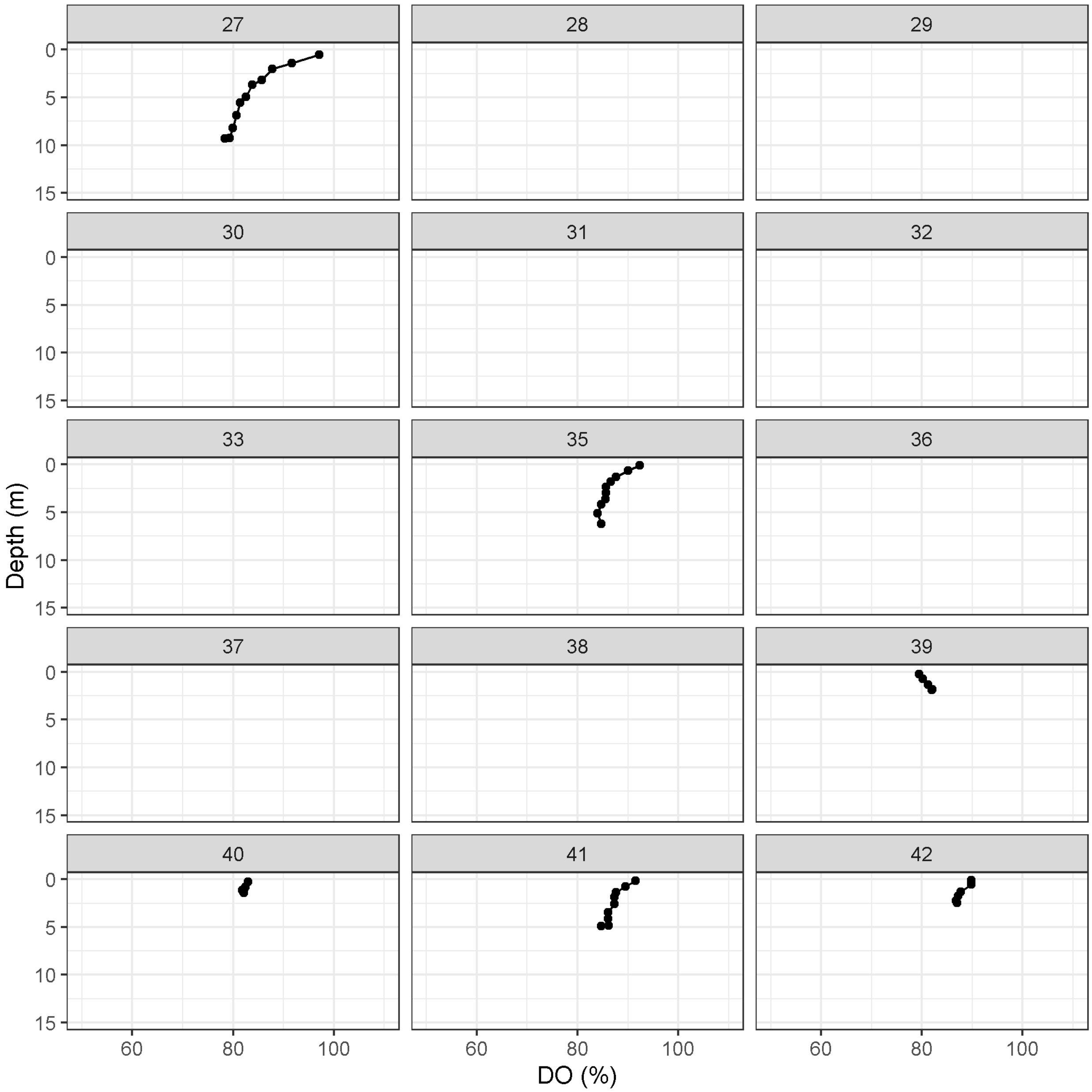
27
28
29
30
31
32
33
35
36
37
38
39
40
41
42
Depth (m)
0
5
10
15
0
1
2
3
Temperature (°C)

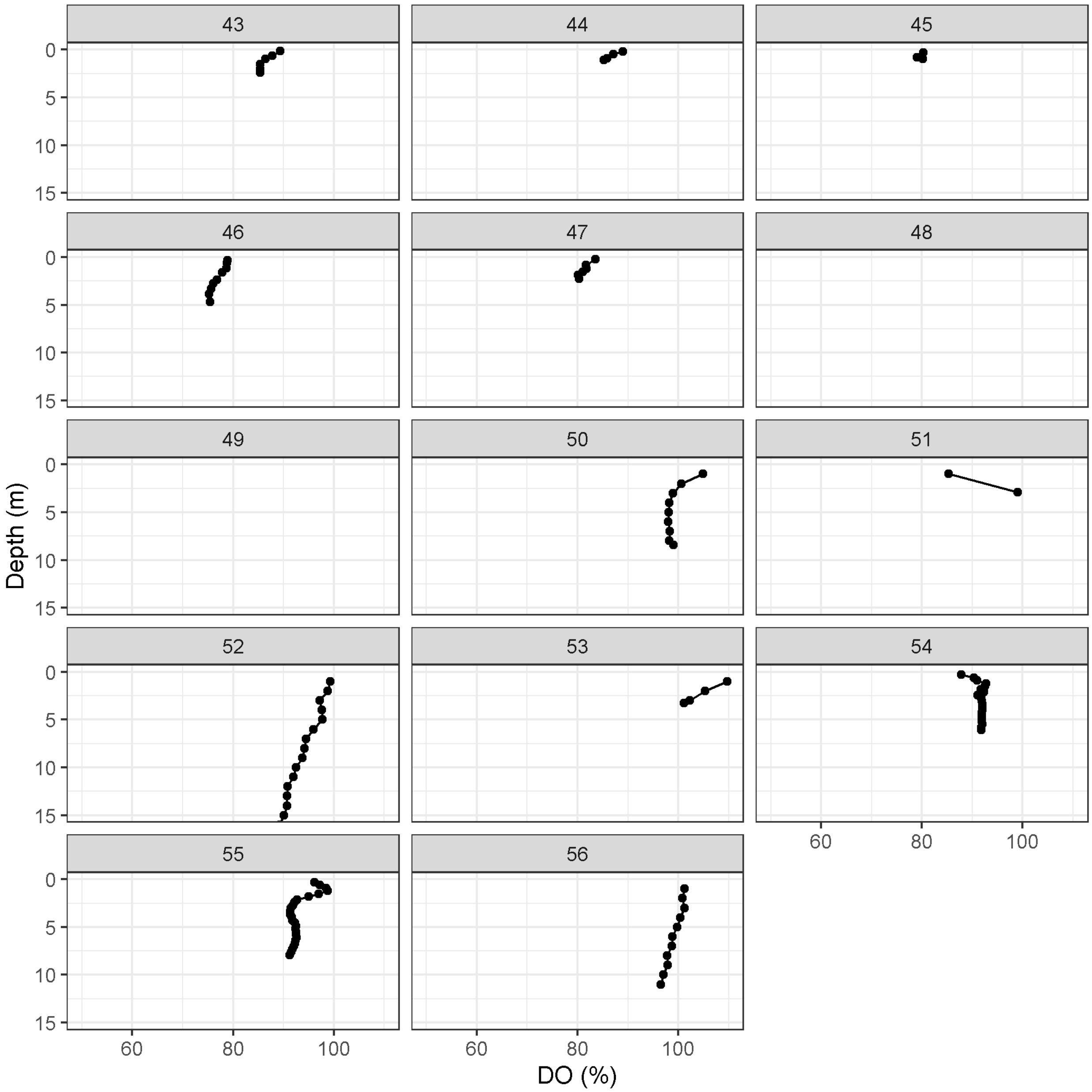


43
44
45
46
47
48
49
50
51
52
53
54
55
56
Depth (m)
0
5
10
15
0
1
2
3
Temperature (°C)

Profils d'oxygène dissous relevés




27
28
29
30
31
32
33
35
36
37
38
39
40
41
42
Depth (m)
DO (%)
0
5
10
15
60
80
100



43
44
45
46
47
48
49
50
51
52
53
54
55
56
Depth (m)
0
5
10
15
60
80
100
DO (%)

ANNEXE IV – DOCUMENTS SUPPLÉMENTAIRES DU CHAPITRE 6 (HABITAT DES JUVÉNILES)

Table S1 Description of mesohabitat characteristics, including associated river flow profile (inspired from Malavoi and Souchon (2002) and Gosselin et al. (2012)) and examples from the studied streams.

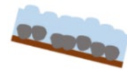
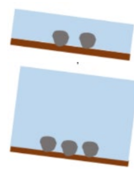
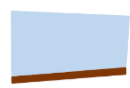
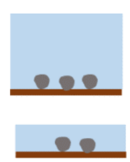
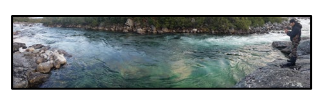
Mesohabitat	Depth	Velocity	Example of flow
Riffle	Very shallow, can show deeper pocket	Moderate with locally fast velocity, turbulent flow	 
Rapid	Shallow	Fast velocity, turbulent flow	 
Run	Moderately shallow	Moderate velocity, turbulent flow	 
Glide	Moderately shallow	Moderate velocity, non-turbulent flow	 
Lentic	Moderately shallow	Slow velocity	 
Pool	Deep	Slow velocity	 
Backwater	Moderately shallow	Moderate or slow velocity. Can be a eddy zone	

Table S2 Multivariate logistic regression model parameters associated between presence of fry and river characteristics at the microhabitat scale. Associated p-value are given in parenthesis.

Variables	β_0 Intercept	β_1 Depth	β_2 Velocity	β_3 Substrate	β_4 Froude
Depth, velocity, substrate, Froude	-1.927	0.007	35.238*	0.088	-42.455
	(0.153)	(0.514)	(0.047)	(0.119)	(0.081)
Depth, velocity, substrate	-3.350	0.064*	4.181	0.088	-
	(0.449)	(0.027)	(-0.103)	(0.439)	-
Depth, substrate	-2.656**	0.061*	0.093	-	-
	(0.004)	(0.022)	(0.073)	-	-

Table S3 Distribution of mesohabitat types, presence and number of fry.

Mesohabitat type	Total habitat type sampled		Mesohabitat with presence of fry		Number of fry	
	Number	Proportion	Number	Proportion	Number	Proportion
Riffle	14	30%	4	36%	88	85%
Rapid	12	26%	1	9%	1	1%
Run	9	20%	2	18%	2	2%
Lentic	9	0%	4	36%	13	13%
Backwater	2	4%	0	0%	0	0%
	46	100%	11	100%	104	100%

Table S4 Distribution of mesohabitat types, presence and number of parr.

Mesohabitat type	Total habitat type sampled		Mesohabitat with presence of parr		Number of parr	
	Number	Proportion	Number	Proportion	Number	Proportion
Riffle	14	30%	6	30%	17	41%
Rapid	12	26%	4	20%	6	14%
Run	9	20%	5	25%	13	31%
Lentic	9	0%	4	20%	6	14%
Backwater	2	4%	0	0%	0	0%
	46	100%	19	100%	42	100%

Table S5 Significance of mesohabitat type selectivity and Jacobs's index from fry numbers. No significant selectivity was found for parr.

Mesohabitat type	p-value	Modified p-value for Bonferroni correction	Selectivity significance †	Jacobs' index
Riffle	3.3E-16	1.7E-15	Yes	0.85
Rapid	5.1E-09	2.5E-08	Yes	-0.95
Run	1.1E-05	5.5E-05	Yes	-0.85
Lentic	0.163	0.817	No	-0.26
Backwater	0.012	0.058	No	-1.00

† Significance is determined at a level of 0.01 and includes Bonferroni correction on p-value for pairwise comparisons.

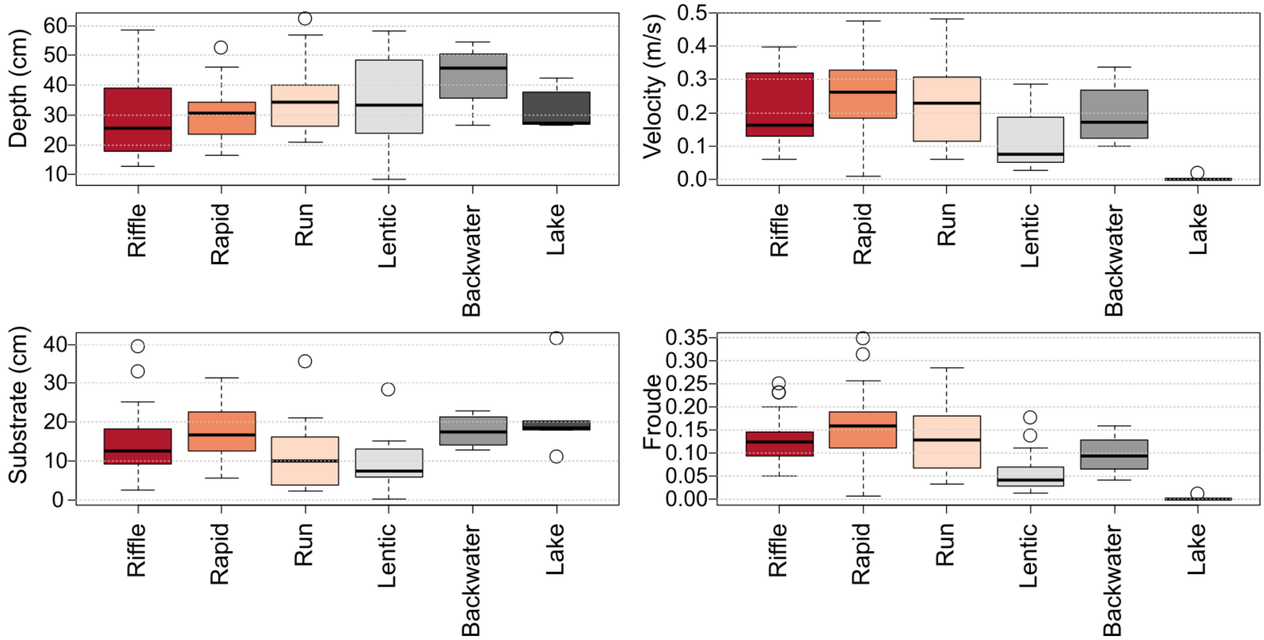


Fig. S1 Distribution of measured river depth, velocity, substrate and Froude number at station scale for the mesohabitats identified in the present study.

Key flow variables were tested for differences between mesohabitats. Velocity and Froude number were significantly different (Kruskall-Wallis, df=5, p-value<0.001). A posteriori Wilcoxon pair-wise comparison showed that rapid, riffle and lentic mesohabitats could be discriminated using velocity or Froude number. For example, Froude number was generally > 0.09 for riffle and <0.08 for lentic mesohabitat.

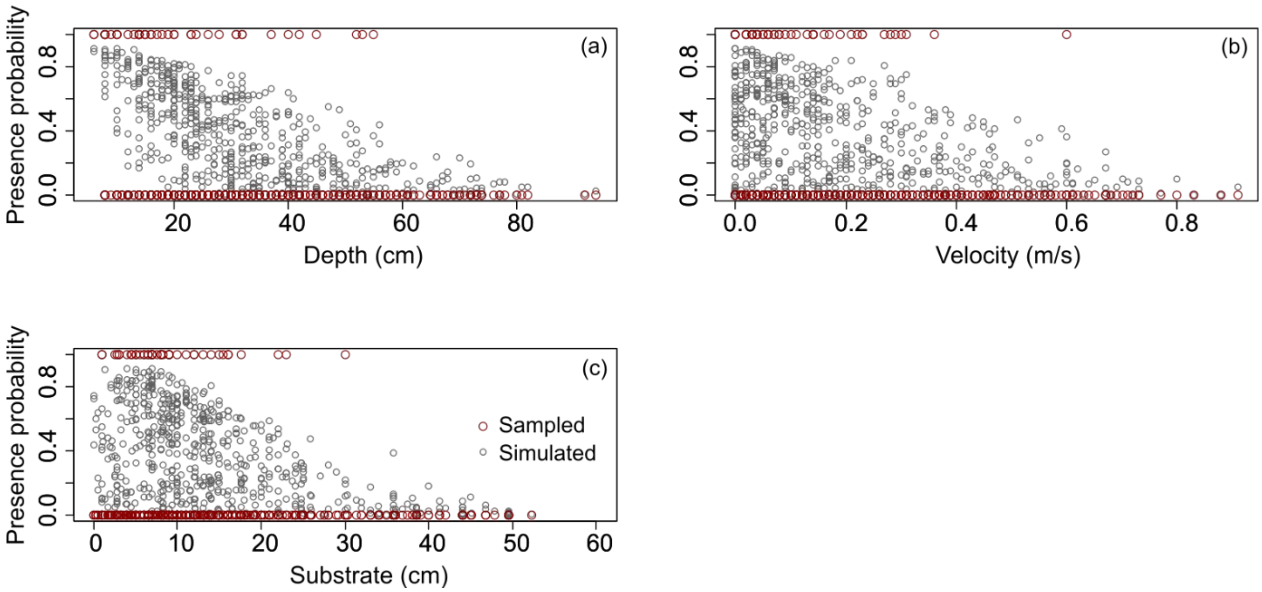


Fig. S2 Measured presence and absence (dark red) at microhabitat scale and modelled relative probability of use (grey) for each sampled microhabitat estimated by multivariate logistic regression with (a) depth, (b) velocity and (c) substrate diameter as predictors.

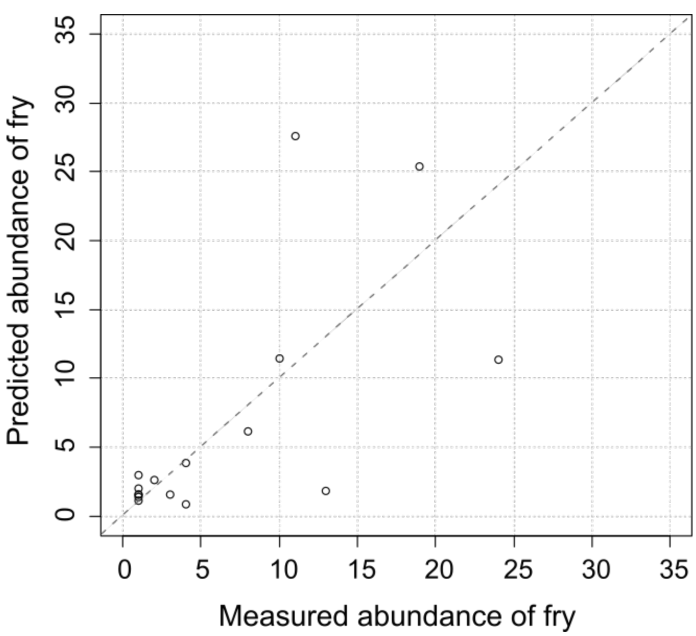


Fig. S3 Number of fry (0+) predicted with GAM model vs number of sampled fry, using depth, velocity and temperature as predictive variables, at station scale.

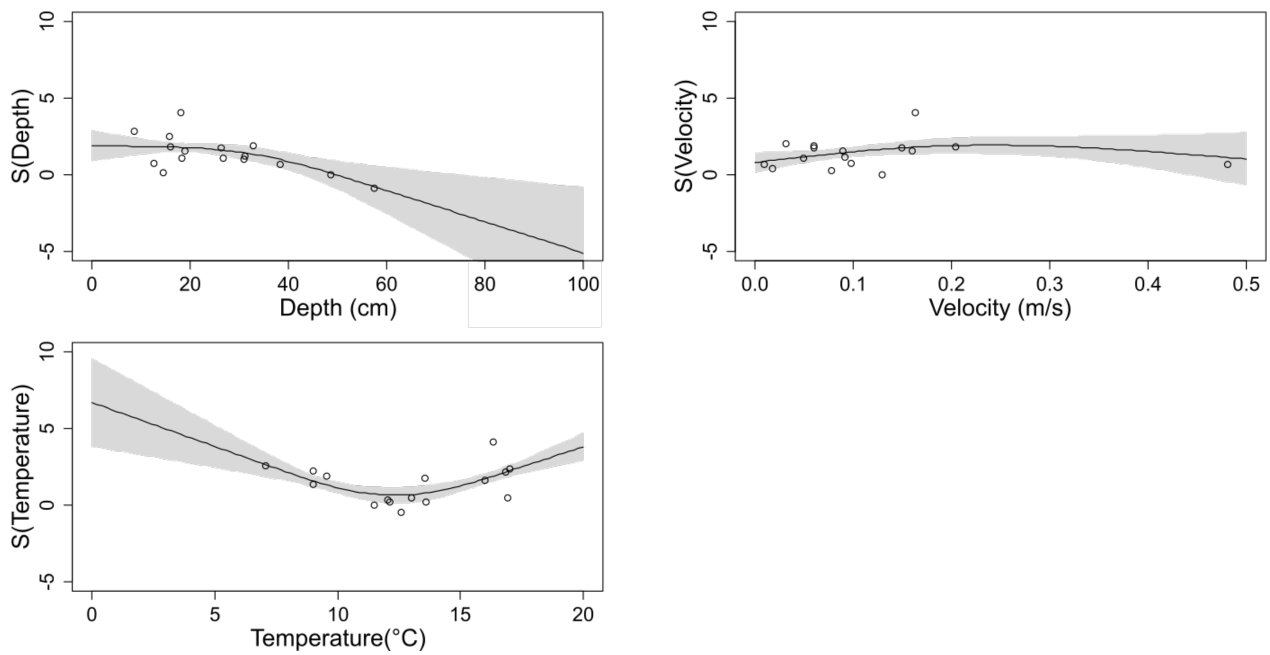


Fig. S4 GAM model fitting for abundance of fry (0+) with depth, velocity and temperature as predictive variables at station scale. The function *g* of total predicted abundance of fry corresponds to the sum of each variable fitting/the log of the sum of each s function.

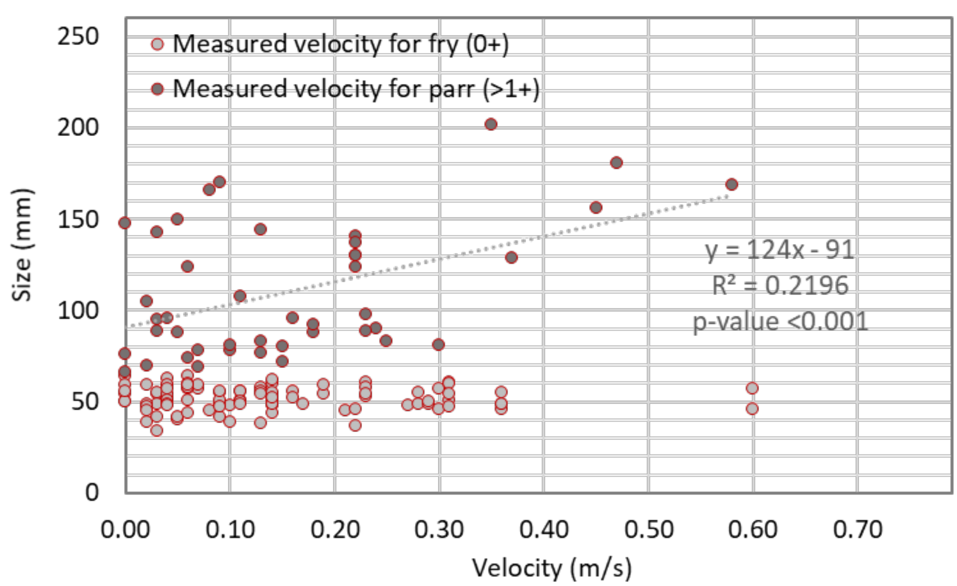


Fig. S5 Size of fry and parr vs measured velocity. The linear regression between size and the measured velocity for parr is illustrated with the dashed line.

Table S6 - Juvenile habitat use characterisation from interviews of eleven Inuit knowledge-holders from three communities: Kangiqsualujjuaq (participants A,B,C,D,E), Tasiujaq (participants F,G,H), Kangirsuk (participants I,J,K). Interviews were conducted in June and September 2019. In Kangirsuk, the three participants I, J, K, were interviewed together. The interviews methodology is described hereafter.

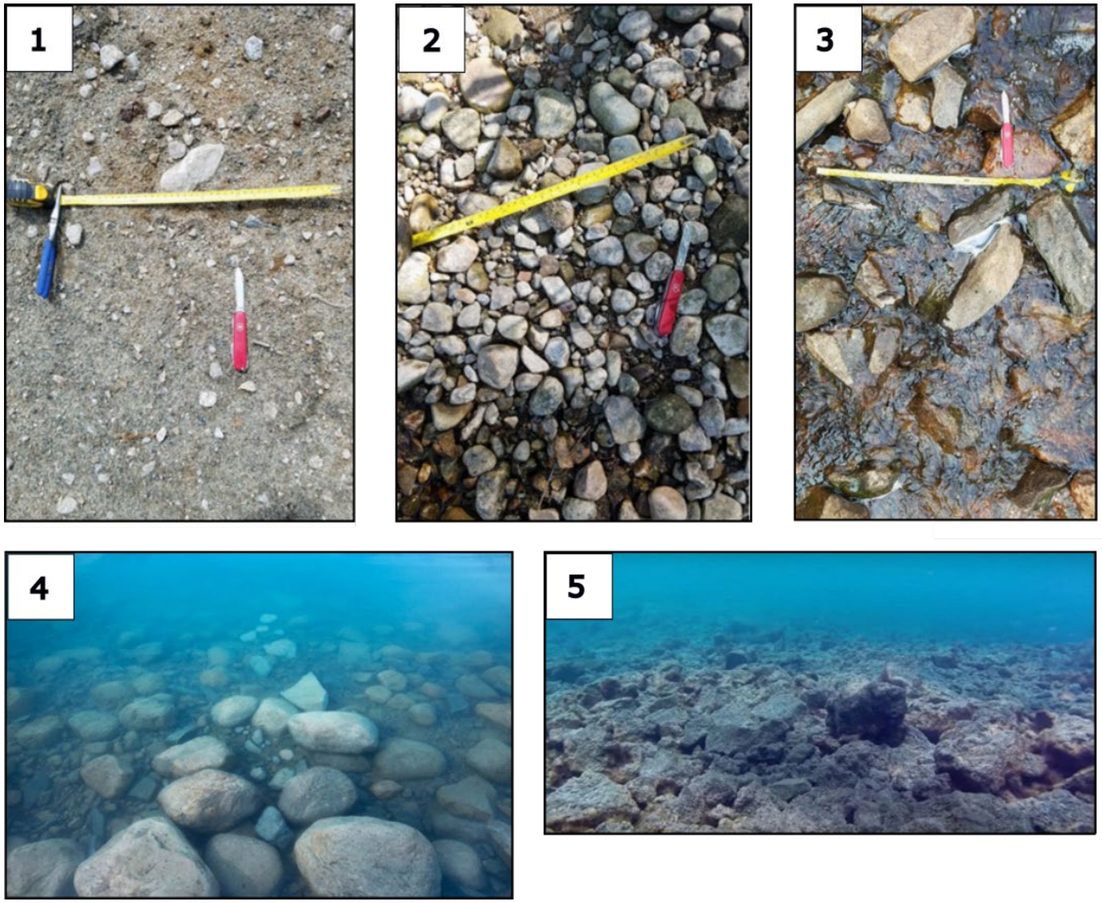
	Substrate (see pictures below)					Velocities				Depth			Other
Participant	1	2	3	4	5	0	Low	Medium	Fast	H<2'	2'<H<5'	H>5'	
A	They go everywhere, hide between rocks during the day												Juvenile (+/-10 cm) can go to the estuary. They find them on the bay beach.
B	They go everywhere					They go everywhere				They go everywhere			The smaller one are everywhere along the lakes and streams. They are in lakes before

										going to the river.
C						They go everywhere	Mid-summer, warmer			Small fish can be at shallow areas of lakes (in a specific location). They don't stay near the spawning sites, they move with the current and feed.
D				Yes, they always hide under the boulders		They follow the current. Can swim all velocities.	They go everywhere			Small fish can be in lakes outlet. The young (+/-20 cm) are going to the sea, following the adults. At the migration, the

													spawning adult go first and after the young follow.
E	They go everywhere					They go everywhere and can swim all velocities							Around 20 cm they follow the adults in salt water
F		Yes	Yes (depends on fish size)	Yes (depends on fish size)	Yes (depends on fish size)	No. Not in lakes.	All seem to be good				5', not too deep.		
G		Yes, to hide		Yes									Many young > 12 cm go around salt water in summer.
H		Yes		Yes, to hide	No.	All are good							They go near salt water when they are

													10-15 cm length.
I J K		Yes, to hide	Yes, to hide	Yes, to hide			Yes	Yes	Not the smallest. When they are large enough (15 cm), they go everywhere.				When they are small, for their first summer, they are usually at the same area than the spawning sites. When they are 'teenagers' and they're able, they follow the adults to the sea (might have 1+ year old according to participants).

Note: The following pictures were presented to assess Arctic char substrate preferences:


1
2
3
4
5

CODES MATLAB UTILISÉS POUR LE MODÈLE DE RÉGRESSION LOGISTIQUE

```
%%%%%%%%%%%%%%%%%%%%%%%%
% Régression logistique multiple : HVS
% Input: Présence/absence vs prof, vit, temp, etc.
% Échantillonne le 2\3-1\3 des présences
% Réduit les absences sur le même nombre de présences
% Fitte les paramètres sur le 2\3
% Valide le modèle sur le 1\3
% Vérifie le modèle par plusieurs estimateurs (LL, pseudo-R2, AIC)
%%%%%%%%%%%%%%%%%%%%%%%

close all;
clear all;
iteration=1000;     %nbre de fois qu'on applique le modèle avec un nouvel échantillon aléatoire, idéalement 1000
k=1;
result_multi = NaN(iteration,17);

%[data_all,headers]= xlsread('data_all_unplus.xlsx'); % lire les données
[data_all,headers]= xlsread('data_all_zeroplus.xlsx'); % lire les données

%Standardisation des données
% moyenne=mean(data_all,'omitnan');  %vecteur de la moyenne de chaque variable
% ecart=std(data_all,'omitnan');  %vecteur de la moyenne de chaque variable
% standard=(data_all-moyenne)./ecart;
% data_all_standard(:,1)=data_all(:,1);
% data_all_standard(:,2:6)=standard(:,2:6);

for k=1:iteration        % On itère le modèle 1000 fois (boot-strap) pour faire une moyenne des résultats et avoir une idée de la robustesse du modèle
   k
   %reformate les données de terrain pour avoir un nbre d'absence identique au nbre de présence
   %data_reduit=reduction_absence(data_all_standard);
   data_reduit=reduction_absence(data_all);
   %sépare l'échantillon en 2\3-1\3
   [data,data_valid]=tirage_tiers(data_reduit);

   %%
   %%%%%% modèle reg log pour la PROFONDEUR  + vitesse + Substrat   %%%%%%
   %
   X=[data(:,2),data(:,3),data(:,4)];
   y=categorical(data(:,1));   %Nécessaire si on utilise le modèle 'nominal' au lieu de 'hierarchical'
   [Bmulti,DEVmulti,STATSmulti] = mnrfit(X, y, 'model', 'hierarchical')
   logcotes=Bmulti(1)+Bmulti(2).*data(:,2)+Bmulti(3).*data(:,3)+Bmulti(4).*data(:,4);  %cote = ratio entre probabilité que l'événement se produise et probabilité qu'il ne se produise pas.
   %Proba absence

zero_model=exp(Bmulti(1)+Bmulti(2).*data(:,2)+Bmulti(3).*data(:,3)+Bmulti(4).*data(:,4))./(1+exp(Bmulti(1)+Bmulti(2).*data(:,2)+Bmulti(3).*data(:,3)+Bmulti(4).*data(:,4)));  %Proba d'une absence modélisée
   presence_model=1-zero_model;    % Proba d'une présence modélisée   (sert à calculer les courbes ROC)

   %spécificité (% d'absence prédites correctement corrects)
   seuilabsence=0.5;
   indice_absence_data=find(data(:,1)==0); %indices des valeurs d'absence mesurées
   indice_absence_modele=find(zero_model>seuilabsence); %indices des valeurs modélisées d'absence (si la proba > seuil, on considère que c'Est une prédiction d'Absence)
```

```
    correspondance_absences=intersect(indice_absence_data,indice_absence_modele);%Indices des absences qui correspondent
    nbre_absence_data=length(indice_absence_data);
    nbre_absence_bienpredites=length(correspondance_absences);
    specifitemulti=nbre_absence_bienpredites/nbre_absence_data*100

    %sensitivité (% d'absence prédites correctement corrects = Taux de vrai positif )
    indice_presence_data=find(data(:,1)==1); %indices des valeurs de presences mesurées
    indice_presence_modele=find(zero_model<seuilabsence); %indices des valeurs modélisées de presence (si la proba d'absence < seuil, on considère que c'Est une prédiction de presence)
    correspondance_presences=intersect(indice_presence_data,indice_presence_modele);%Indices des presences qui correspondent
    nbre_presence_data=length(indice_presence_data);
    nbre_presence_bienpreditesmulti=length(correspondance_presences);
    sensitivitemulti=nbre_presence_bienpreditesmulti/nbre_presence_data*100  % True positif
    fauxpositif=1-specifitemulti;

    %
    %%%%%%% Vérification du Receiver operating characteristic (ROC) curve   %%%%%%%
    %
    % Permet d'évaluser les faux positif vs vrai positif. Calcule une
    % surface sous la coube : 1 = parfait, 0.5 = aléatoire
    %
    [X_ROC_multi,Y_ROC_multi,T_ROC_multi,AUC_multi] = perfcurve(data(:,1),presence_model,1);

    result_multi(k,1)=STATSmulti.beta(1);
    result_multi(k,2)=STATSmulti.beta(2);
    result_multi(k,3)=STATSmulti.beta(3);
    result_multi(k,4)=STATSmulti.beta(4);
    result_multi(k,5)=STATSmulti.p(1);
    result_multi(k,6)=STATSmulti.p(2);
    result_multi(k,7)=STATSmulti.p(3);
    result_multi(k,8)=STATSmulti.p(4);
    result_multi(k,9)=specifitemulti;
    result_multi(k,10)=sensitivitemulti;
    result_multi(k,11)=AUC_multi;    %Aire sous la courbe ROC

    %%%%% Maxvraisemblance, G et R2 Cox & Snell et autres critères (Tchantchane, 2009)
    %
    % Vraisemblance
    LLmodel_multi=sum(log(binopdf(data(:,1),ones(length(y'),1),presence_model))) % binomial proba density function
    % Vraisemblance modèle non informatif
    modelebeta0_multi=exp(Bmulti(1))/(1+exp(Bmulti(1)))*ones(length(y'),1);             %ce que donnerait le modèele non informatif
    LLbeta0_multi=sum(log(binopdf(data(:,1),ones(length(y'),1),1-modelebeta0_multi)));
    % %critère de comparaison -2LL et G^2,
    MoinsdeuxLLbeta0_multi=-2*LLbeta0_multi;
    MoinsdeuxLL_multi=-2*LLmodel_multi;
    Gdeux_multi=-2*(LLbeta0_multi-LLmodel_multi)
    pvaluemodel_multi=1-cdf ('chi2',Gdeux_multi, length(Bmulti)-1);

    % % r2 cox et snell
    Rcoxsnell_multi=1-(LLbeta0_multi/LLmodel_multi)^(2/length(y'));
    nagelkerke_multi=Rcoxsnell_multi/(1-(-2*LLbeta0_multi)^(2/length(y')));

    % % AIC
    AIC_multi=-2*LLmodel_multi+2*length(Bmulti);
```

```
    result_multi(k,12)=LLmodel_multi;
    result_multi(k,13)=LLbeta0_multi;
    result_multi(k,14)=pvaluemodel_multi;
    result_multi(k,15)=Rcoxsnell_multi;
    result_multi(k,16)=nagelkerke_multi;
    result_multi(k,17)=AIC_multi;


    % %
    %%%%%%% Validationsur l'échantillon de 1/3
    %
    %
    validation_HVS=reglogdicho_multi_HVS_validation(data_valid,Bmulti);
    result_multi_valid(k,:)=validation_HVS(:);

end

%Calcul des statistiques : moyenne et écart-type d'une loi normale de
%chacun des paramètres  = LEs 2 dernières lignes du fichier de résultats

k=k+1;
for b=1:13
    pdprof(b) = fitdist(result_multi(:,b),'Normal');
    result_multi(k,b)=pdprof(b).mu;
    result_multi(k+1,b)=pdprof(b).sigma;
end

% Tprof=table(result_multi);
% writetable(Tprof,'result_model_unplus_multi_HVS.xlsx');
%
% Tprof_valid=table(result_multi_valid);
% writetable(Tprof_valid,'result_valid_unplus_multi_HVS.xlsx');

Tmulti=table(result_multi);
writetable(Tmulti,'result_model_zeroplus_multi_HVS.xlsx');

Tprof_valid=table(result_multi_valid);
writetable(Tprof_valid,'result_valid_zeroplus_multi_HVS.xlsx');
```

```
function [result]=reglogdicho_mnrfit_validation(data,beta)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% validation du modèle
% Input:
%   Échantillon de 1\3, déja réduit : Présence/absence vs prof, vit, temp, etc.
%   Paramèetre du modèele èa valider
%   Colonne correspondant èa la variable explicative
% Fitte les paramètres sur le 2\3
% Valide le modèele sur le 1\3
% Vérifie le modèle par plusieurs estimateurs (LL, pseudo-R2, AIC)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%

result = NaN(1,17);
y=categorical(data(:,1));   %Nécessaire si on utilise le modèle 'nominal' au lieu de 'hierarchical'


%%
%%%%%%% modèle reg log pour la PROFONDEUR et le SUBSTRAT   %%%%%%%
% %
%
%Vérif du modèele en fonction de la variable
zero_model=exp(beta(1)+beta(2).*data(:,2)+beta(3).*data(:,3)+beta(4).*data(:,4))./(1+exp(beta(1)+beta(2).*data(:,2)+beta(
3).*data(:,3)+beta(4).*data(:,4)));  %Proba d'une absence modélisée
presence_model=1-zero_model;    % Proba d'une présence modélisée   (sert à calculer les courbes ROC)
%
%figure
% on veut trier la matrice selon l'ordre de la variable explicative pour le
% graphique
%zerotri_model=exp(Bprof(1)+Bprof(2).*sort(data(:,2)))./(1+exp(Bprof(1)+Bprof(2).*sort(data(:,2))));      %Idem, mais sur la
variable triée pour graphique
%     [~,idx] = sort(data(:,2)); % sort just the first column
%     sortedmat = data(idx,:);   % sort the whole matrix using the sort indices
%     plot(sortedmat(:,2),sortedmat(:,1),'o');
%     hold
%     title('Présence de >1+ vs Profondeur')
%     xlabel('Profondeur (cm)')
%     ylabel('Présence/Absence >1+')
%     plot(sortedmat(:,2),1-zerotri_model);

%
%%% spécificité (% d'absence prédites correctement corrects)
seuilabsence=0.5;
indice_absence_data=find(data(:,1)==0); %indices des valeurs d'absence mesurées
indice_absence_modele=find(zero_model>seuilabsence); %indices des valeurs modélisées d'absence (si la proba > seuil, on
considère que c'Est une prédiction d'Absence)
correspondance_absences=intersect(indice_absence_data,indice_absence_modele);%Indices des absences qui
correspondent
nbre_absence_data=length(indice_absence_data);
nbre_absence_bienpredites=length(correspondance_absences);
specifite=nbre_absence_bienpredites/nbre_absence_data*100

%sensitivité (% d'absence prédites correctement corrects = Taux de vrai positif )
indice_presence_data=find(data(:,1)==1); %indices des valeurs de presences mesurées
indice_presence_modele=find(zero_model<seuilabsence);  %indices des valeurs modélisées de presence (si la proba
d'absence < seuil, on considère que c'Est une prédiction de presence)
correspondance_presences=intersect(indice_presence_data,indice_presence_modele);%Indices des presences qui
correspondent
```

```
nbre_presence_data=length(indice_presence_data);
nbre_presence_bienpredites=length(correspondance_presences);
sensitivite=nbre_presence_bienpredites/nbre_presence_data*100  % True positif
fauxpositif=1-specifite;

%
%%%%%%% Vérification du Receiver operating characteristic (ROC) curve   %%%%%%%
%
% Permet d'évaluser les faux positif vs vrai positif. Calcule une
% surface sous la coube : 1 = parfait, 0.5 = aléatoire
%
[X_ROC,Y_ROC,T_ROC,AUC] = perfcurve(data(:,1),presence_model,1);

%     %figure
%     plot(X_ROC_prof,Y_ROC_prof);
%     title('Courbe ROC pour : Présence de 0+ vs Profondeur')
%     xlabel('Fausse prédiction de présence')
%     ylabel('Vrai prédiction de présence')


result(1,9)=specifite;
result(1,10)=sensitivite;
result(1,11)=AUC;    %Aire sous la courbe ROC

%%%%% Maxvraisemblance, G et R2 Cox & Snell et autres critères (Tchantchane, 2009)
%
% Vraisemblance
LLmodel=sum(log(binopdf(data(:,1),ones(length(y'),1),presence_model))) % binomial proba density function
% Vraisemblance modèle non informatif
modelebeta0=exp(beta(1))/(1+exp(beta(1)))*ones(length(y'),1);
LLbeta0=sum(log(binopdf(data(:,1),ones(length(y'),1),modelebeta0)));
% %critère de comparaison -2LL et G^2,
MoinsdeuxLLbeta0=-2*LLbeta0;
MoinsdeuxLL=-2*LLmodel;
Gdeux=-2*(LLbeta0-LLmodel);
pvaluemodel=1-cdf ('chi2',Gdeux, length(beta));

% % r2 cox et snell
Rcoxsnell=1-(LLbeta0/LLmodel)^(2/length(y'));
nagelkerke=Rcoxsnell/(1-(-2*LLbeta0)^(2/length(y')));

% % AIC
AIC=-2*LLmodel+2*length(beta);

result(1,12)=LLmodel;
result(1,13)=LLbeta0;
result(1,14)=pvaluemodel;
result(1,15)=Rcoxsnell;
result(1,16)=nagelkerke;
result(1,17)=AIC;

end
```

```
%%%%%%%%%%%%%%%%%%%%
%% Réduit le nombre d'absences d'un échantillon en tirant aléatoirement
%% (uniforme) un nombre d'absences similaire au nombre de présences
%%
%% Intrant : Échantillon total (présences + absences) vs prof, vit, temp, etc.
%% Sortant : Échantillon réduit : Présences totales +absences réduites au même nbre vs prof, vit, temp, etc.
%%%%%%%%%%%%%%%%%%%%%5

function [data_all_reduit]=reduction_absence(data_all)

indice_presence_data=find(data_all(:,1)==1); %indices des valeurs de presences mesurées
indice_absence_data=find(data_all(:,1)==0); %indices des valeurs d'absence mesurées
nbre_presence=length(indice_presence_data);

%Tirage aléatoire des absences en tirant les indices sans remise)
copie_absence=indice_absence_data;  %indices des absence - Ce vecteur va être diminué au fur et à mesure du tirage pour ne pas qu'il y ait de répétition
for i=1:nbre_presence
    i_alea=randi(length(copie_absence)); %indice tiré
    absence_reduit(i)=copie_absence(i_alea); %construction du nouveau vecteur d'incice
    copie_absence(i_alea)=[];  % on enlève l'indice d'absence déja utilisé et on réduit le vecteur pour ne pas le tirer de nouveau
end

data_all_reduit_presence=data_all(indice_presence_data,:);
data_all_reduit_absence=data_all(absence_reduit,:);
data_all_reduit=cat(1,data_all_reduit_presence,data_all_reduit_absence);

% T=table(data_all_reduit);
% %writetable(T,'data_all_reduit_deuxtiers.xlsx');
% %writetable(T,'data_all_reduit_unplus.xlsx');
% writetable(T,'data_all_reduit_zeroplus.xlsx');
end
```

```
%%%%%%%%%%
%%  Fonction pour séparer l'échantillon en 1/3-2/3
%%%%%%%%%%

function [data_all_deuxtiers,data_all_tiers]=tirage_tiers(data_all)

% Sépare l'échantillon des présences en deux sous échantillons de 1/3-2/3
% (sert à faire le modèle sur le 2/3 et la validation sur le 1/3)
%
% Intrant : Échantillon modifié (nbre d'absence = nbre de présence)
% Sortant : Échantillon 2/3 présences et échantillon 1/3 présences complémentaires

%[data_all,headers]= xlsread('data_all_unplus.xlsx'); % lire les données
%[data_all,headers]= xlsread('data_all_zeroplus.xlsx'); % lire les données

indice_presence_data=find(data_all(:,1)==1); %indices des valeurs de presences mesurées
indice_absence_data=find(data_all(:,1)==0); %indices des valeurs d'absences
mesurées_data=find(data_all(:,1)==1); %indices des valeurs de presences mesurées
nbre_presence_data=length(indice_presence_data);
nbre_absence_data=length(indice_absence_data);

%Calcul du tiers des présences
tiers_presence=floor(nbre_presence_data/3); %Taille échantillon validation

%Tirage aléatoire du tiers des présences en tirant les indices sans remise
copie_presence=indice_presence_data;  %indices des presences - Ce vecteur va être diminué au fur et à mesure
du tirage pour ne pas qu'il y ait de répétition
for i=1:tiers_presence
   i_alea1=randi(length(copie_presence)); %indice tiré
   presence_tiers(i)=copie_presence(i_alea1); %construction du nouveau vecteur d'incice
   copie_presence(i_alea1)=[];  % on enlève l'indice de presence déja utilisé et on réduit le vecteur pour ne pas le
tirer de nouveau
end

%Calcul du tiers des absences
tiers_absence=floor(nbre_absence_data/3); %Taille échantillon validation

%Tirage aléatoire du tiers des présences en tirant les indices sans remise
copie_absence=indice_absence_data;  %indices des absences - Ce vecteur va être diminué au fur et à mesure
du tirage pour ne pas qu'il y ait de répétition
for ii=1:tiers_absence
   i_alea2=randi(length(copie_absence)); %indice tiré
   absence_tiers(ii)=copie_absence(i_alea2); %construction du nouveau vecteur d'incice
   copie_absence(i_alea2)=[];  % on enlève l'indice de absence déja utilisé et on réduit le vecteur pour ne pas le
tirer de nouveau
end

presence_tiers=presence_tiers' ;   %vecteur d'indice
presence_deuxtiers=copie_presence; %vecteur d'indices
absence_tiers=absence_tiers' ;   %vecteur d'indice
absence_deuxtiers=copie_absence; %vecteur d'indices

vect_indice_tiers=[presence_tiers;absence_tiers] ;
vect_indice_deuxtiers=[presence_deuxtiers;absence_deuxtiers] ;

data_all_deuxtiers=data_all(vect_indice_deuxtiers,:);
data_all_tiers=data_all(vect_indice_tiers,:);
end
```

ANNEXE V – VULGARISATION DES TRAVAUX DE RECHERCHE ET ACTIVITÉS D'ENGAGEMENT

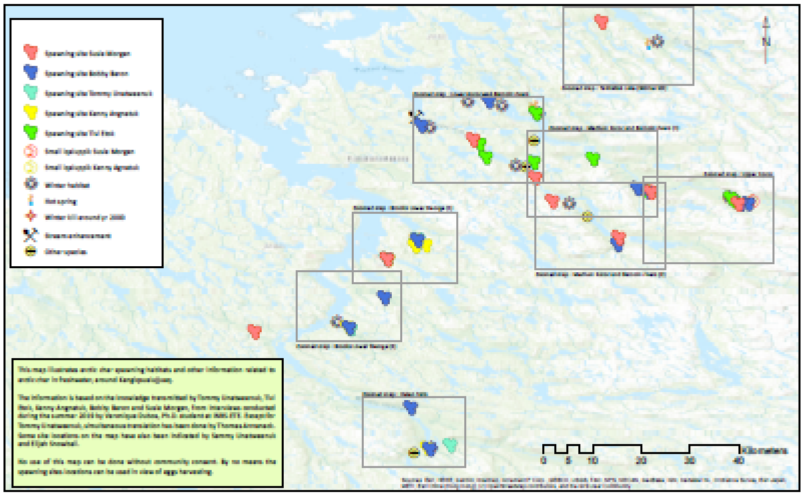
Parmi les produits de dissémination de la recherche réalisée, cette section présente un aperçu des rapports faisant la synthèse des entrevues pour chacune des communautés, en incluant des cartes détaillées des sites d'intérêts reliés à l'omble chevalier. Comme les communautés ont choisis de garder ses cartes confidentielles, seul un aperçu de la carte principale est fourni ici, ne permettant pas d'identifier les sites. Les synthèses ont été produites en anglais et en Inuktitut.

Les résultats des pêches électriques faites à Kangiqsualujjuaq et à Tasiujaq ont également été cartographiés pour permettre un rendu visuel des espèces de poissons pêchées et de leur abondance respective.

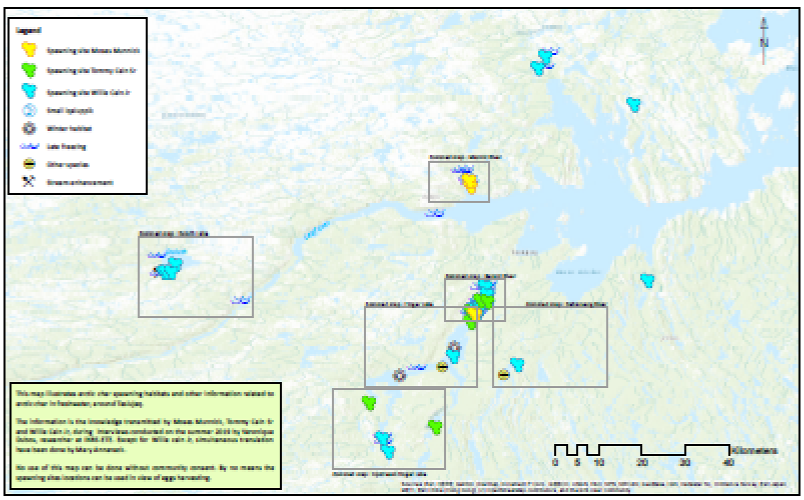
Des illustrations grand format ont également été réalisées en collaboration avec une graphiste, Estelle Villemin, dans le cadre de la bourse Éric Dewailly, de la Chaire Littoral de l'Université Laval. La bourse permettait de financer des produits de mobilisation des connaissances. Une illustration grand format du cycle de vie de l'omble chevalier, basé sur les entrevues et personnalisant les participants a été produite. Pour illustrer les résultats de l'étude sur l'habitat des juvéniles, une illustration grand format montrant les préférences d'habitat a également été produite. Les illustrations ont été réalisées en français, anglais et Inuktitut.

A- Rapports synthèse des entrevues, incluant des cartes des sites d'intérêt reliés à l'omble chevalier

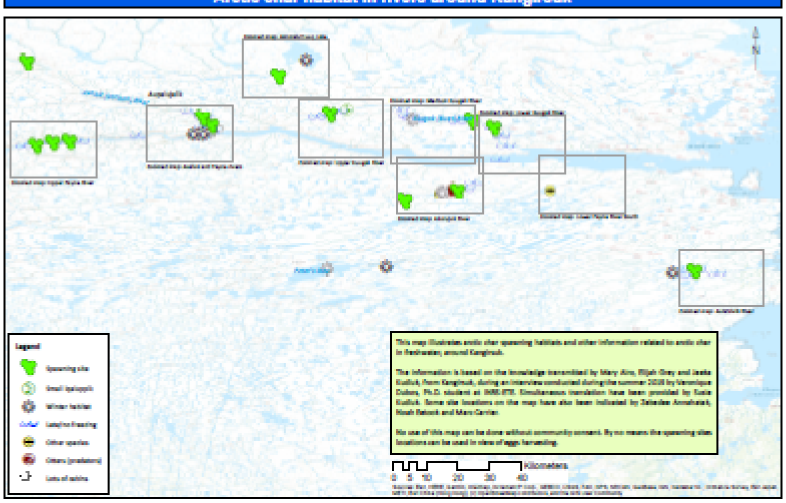
Arctic char habitat in rivers around Kangiqsualujjuaq



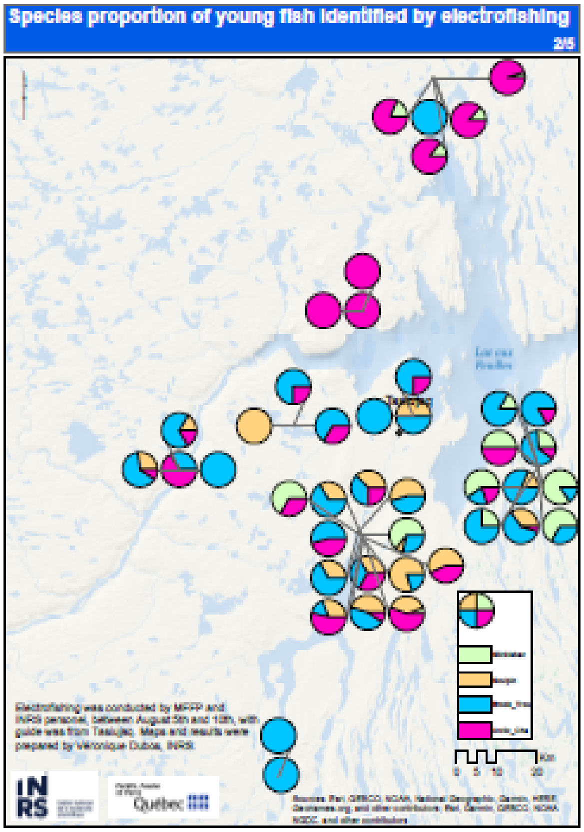
Arctic char habitat in rivers around Tasiujaq

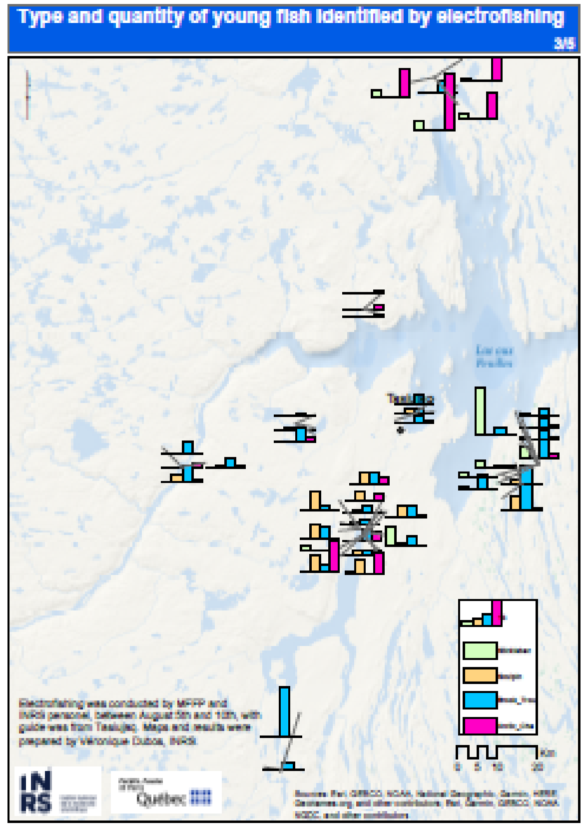


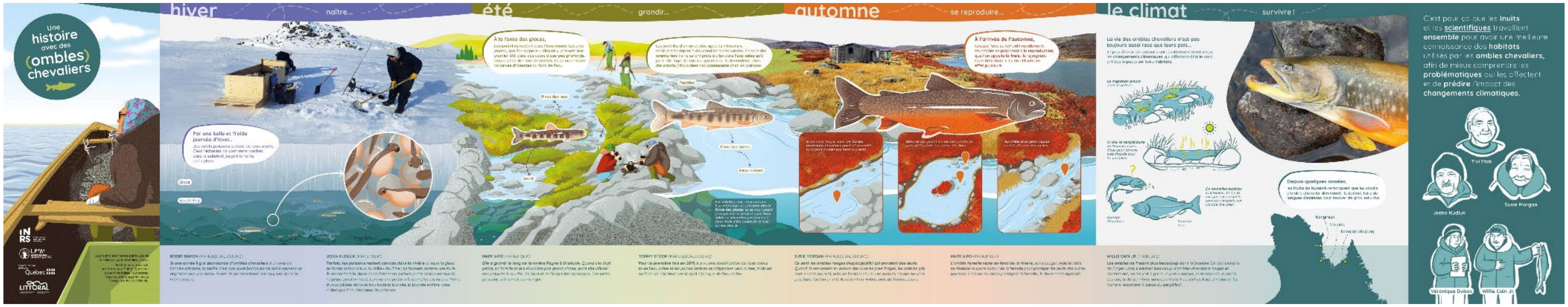
Arctic char habitat in rivers around Kangirsuk

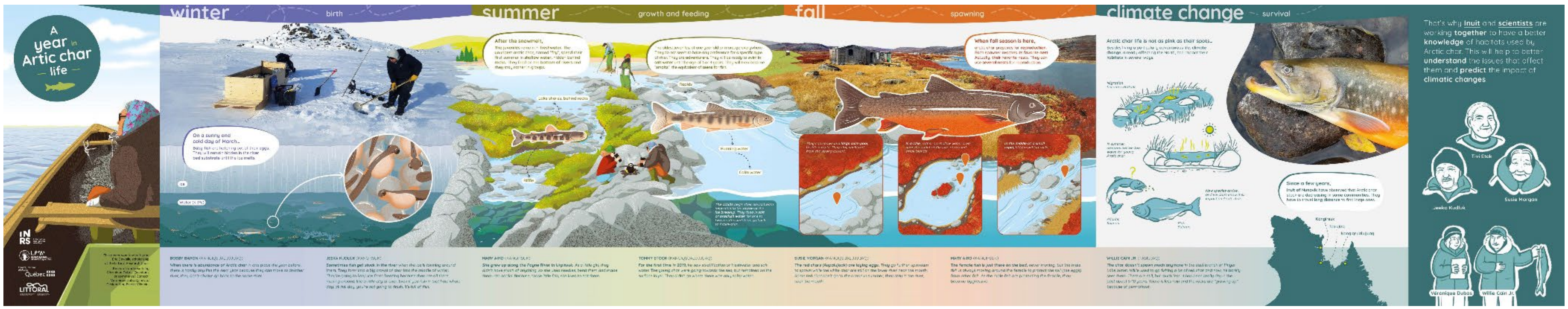


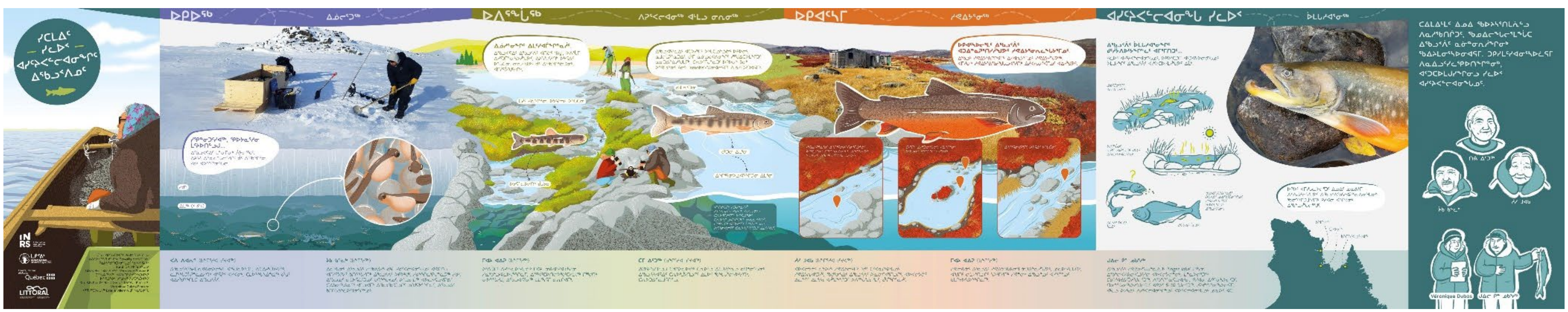
B- Exemple d'illustration des résultats de pêche électrique fournis aux communautés de Kangiqsualujjuaq et Tasiujaq

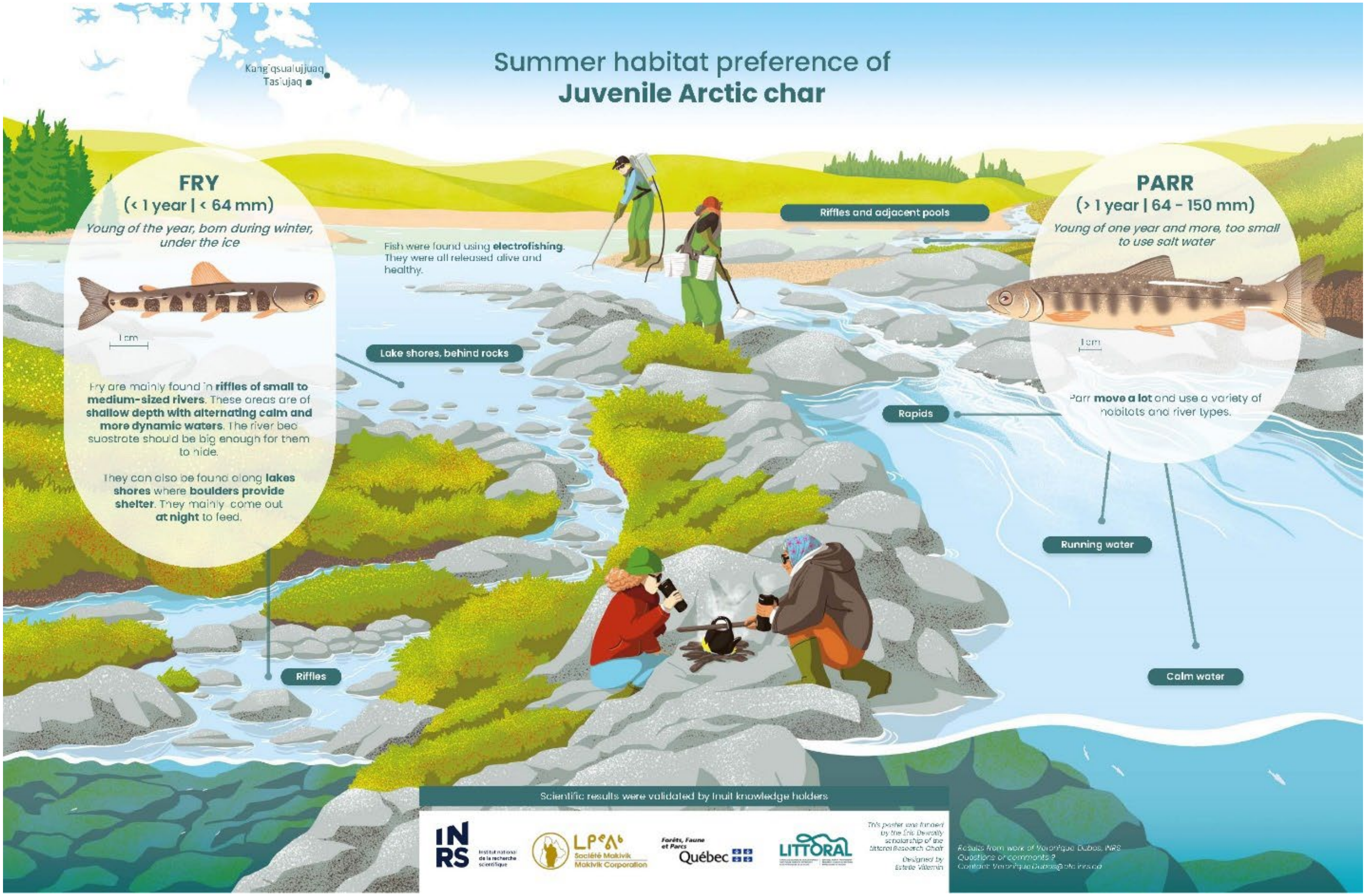

Species proportion of young fish identified by electrofishing
2/5
Electrofishing was conducted by MFFP and INRS personel, between August 5th and 10th, with guide was from Tasiujaq. Maps and results were prepared by Véronique Dubos, INRS.
Km
0 5 10 20
INRS
Québec
Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors, Esri, Garmin, GEBCO, NOAA NGDC, and other contributors


Type and quantity of young fish identified by electrofishing
3/5
Electrofishing was conducted by MFFP and INRS personel, between August 5th and 10th, with guide was from Tasiujaq. Maps and results were prepared by Véronique Dubos, INRS.
Km
0 5 10 20
INRS
Québec
Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors, Esri, Garmin, GEBCO, NOAA NGDC, and other contributors


Une histoire avec des (ombles) chevaliers
hiver
naître...
été
grandir...
automne
se reproduire...
le climat
survivre !
C'est pour ça que les Inuits et les scientifiques travaillent ensemble pour avoir une meilleure connaissance des habitats utilisés par les ombles chevaliers, afin de mieux comprendre les problématiques qui les affectent et de prédire l'impact des changements climatiques.
Tivi Etok
Jeela Kudluk
Susie Morgan
Véronique Dubos
Willie Cain Jr.
LITTORAL


A year in Artic char life
winter
birth
summer
growth and feeding
fall
spawning
climate change
survival
That's why Inuit and scientists are working together to have a better knowledge of habitats used by Arctic char. This will help to better understand the issues that affect them and predict the impact of climatic changes.
Tivi Etok
Jeela Kudluk
Susie Morgan
Véronique Dubos
Willie Cain Jr.
LITTORAL


Véronique Dubos
LITTORAL



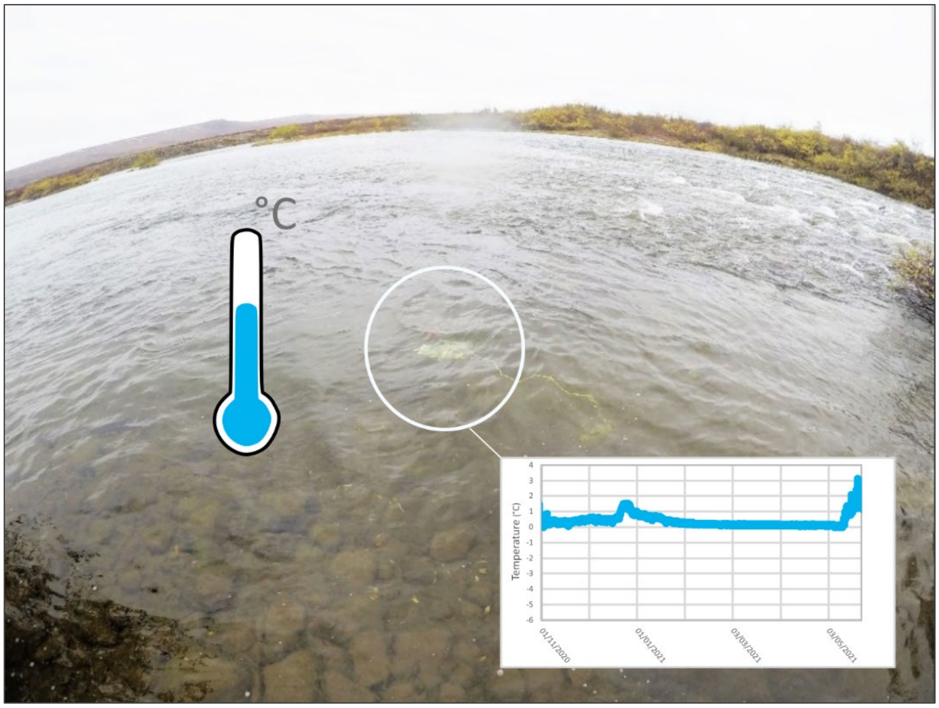
Kangiqsualujjuaq
Tasiujaq
Summer habitat preference of
Juvenile Arctic char
FRY
(< 1 year | < 64 mm)
Young of the year, born during winter, under the ice
1 cm
Fry are mainly found in riffles of small to medium-sized rivers. These areas are of shallow depth with alternating calm and more dynamic waters. The river bed substrate should be big enough for them to hide.
They can also be found along lakes shores where boulders provide shelter. They mainly come out at night to feed.
Fish were found using electrofishing. They were all released alive and healthy.
Riffles and adjacent pools
Lake shores, behind rocks
Rapids
Riffles
Running water
Calm water
PARR
(> 1 year | 64 - 150 mm)
Young of one year and more, too small to use salt water
1 cm
Parr move a lot and use a variety of habitats and river types.
Scientific results were validated by Inuit knowledge holders
INRS
Société Makivik
Makivik Corporation
Forêts, Faune et Parcs
Québec
LITTORAL
This poster was funded by the Éric Dewailly scholarship of the Littoral Research Chair
Designed by Estelle Villemin
Results from work of Véronique Dubos, INRS
Questions or comments ?

En plus des activités décrites plus précédemment, j'ai participé à la rédaction de deux articles dans le magazine Taqralik, distribué dans les 14 communautés du Nunavik en anglais et en Inuktitut :

- Véronique Dubos, Johnny Nassak, Noah Eetook, 2023-01. *Tracking the tagged Arctic char of Kangirsuk, the first results.* Popularized science article in Tarqalik Magazine #130, Nunavik Research fact N°60, p35-36, January 2023. (pdf version: https://www.makivik.org/magazine/issue130/)

- Véronique Dubos, 2022-11. *Tagging Arctic char in Tasirjuarusik, Kangirsuk*. Popularized science article in Tarqalik Magazine #127, Nunavik Research fact sheet N°57, p35-36, November 2021. (pdf version: https://www.makivik.org/magazine/issue127/?fbclid=IwAR2YFxc-OUMAe4F7592j3ZNL6BfBisH80AzgsiqGphy51ZaP6-zfla9NR0M#34

ANNEXE VI – SUIVI THERMIQUE À TASIUJAQ



Suivi thermique d'un site de fraie dans la rivière Bérard, Tasiujaq, septembre 2020

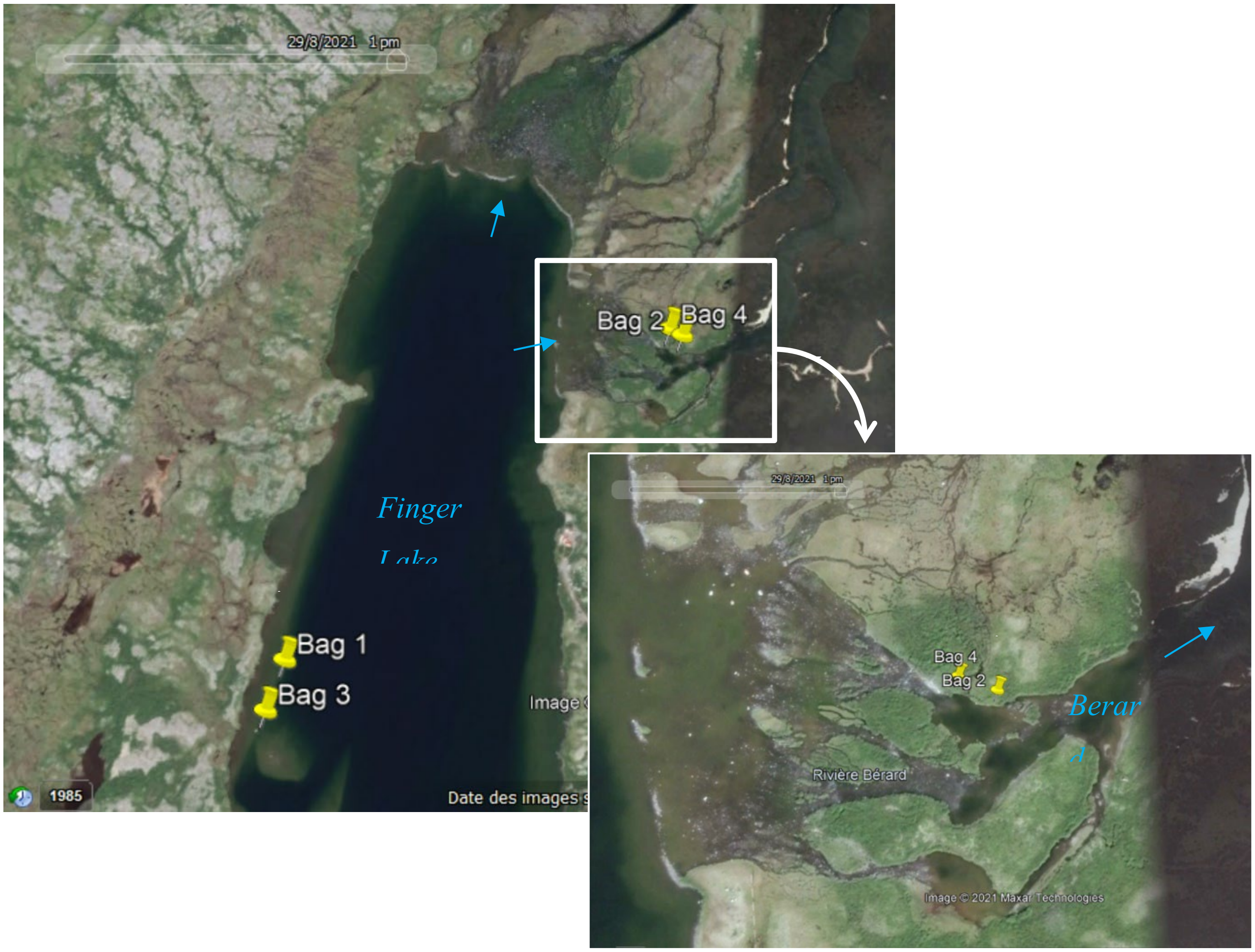


Figure S1. Localisation des thermographes dans le lac Finger Lake et dans la rivière Bérard. Les thermographes ont été installés le 2020-10-06 et récupérés le 2021-08-14 par Willie Cain Jr (Tasiujaq).

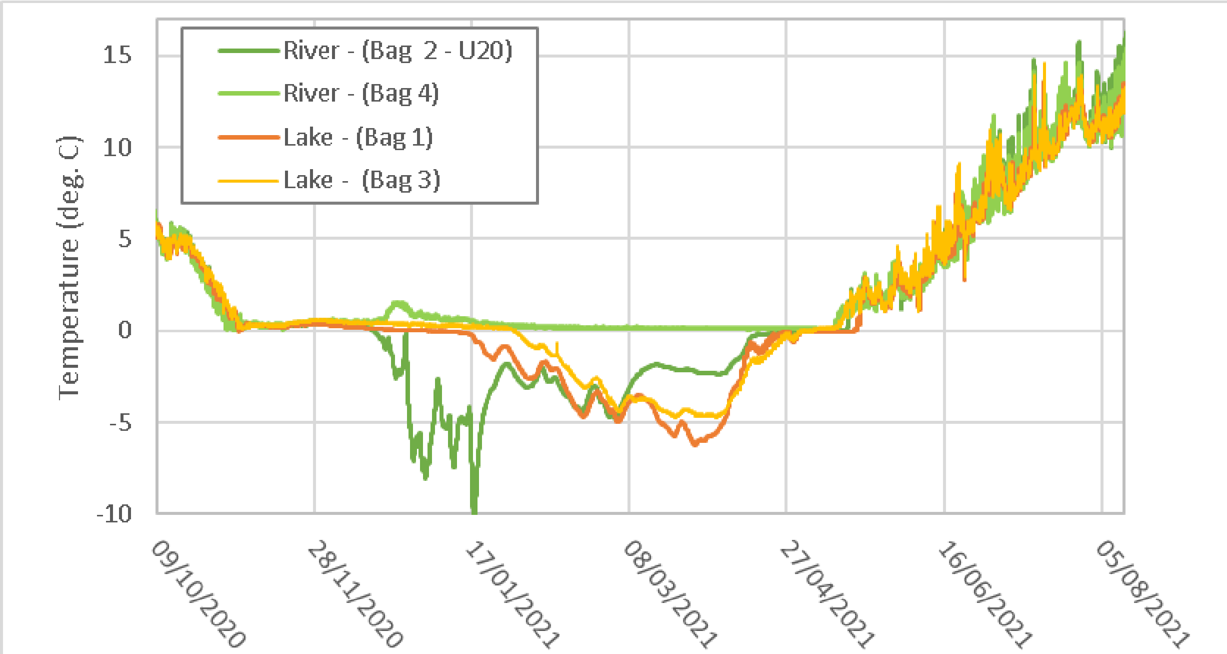


Figure S2. Température de l'eau dans le lac Finger Lake et dans la rivière Bérard durant la période d'installation.

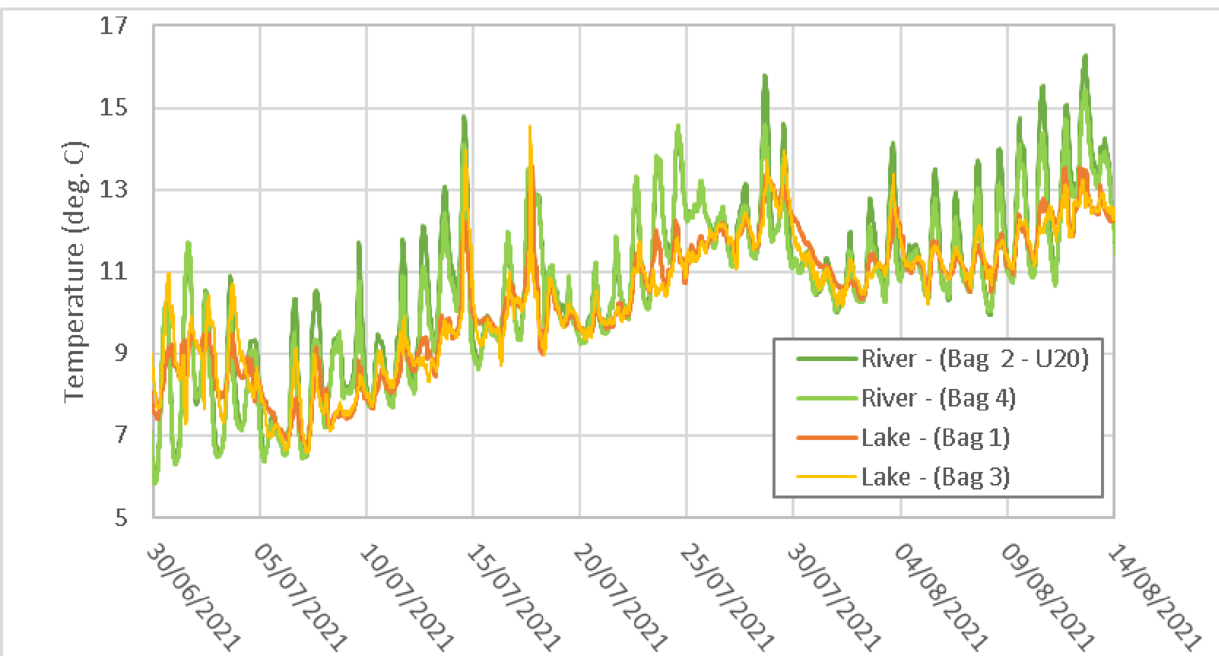


Figure S3. Température de l'eau durant l'été dans le lac Finger Lake et dans la rivière Bérard.

<u>Observation</u>

En juillet et en août, les mois les plus chauds de l'année, la température de la rivière montre une amplitude quotidienne significativement plus élevée que celle du lac. La température de la rivière peut être de 4°C plus élevée le jour que la nuit. Dans le lac, la différence moyenne entre le jour et la nuit est d'environ 1°C. Le volume d'eau du lac provoque une inertie qui limite l'augmentation de la température.

Conséquences sur les ombles chevaliers juvéniles

Tant que la température de l'eau reste inférieure à 16°C, la croissance des juvéniles est favorisée par une température de l'eau plus chaude, c'est-à-dire que plus la température de l'eau est élevée, plus les juvéniles grandissent rapidement. Ainsi, la température plus chaude de la rivière pourrait expliquer la forte présence de juvéniles dans la rivière Bérard, tel qu'observé par les Inuits (d'après les entrevues, été 2019).

Dans le cas de la rivière Bérard, comme l'eau provient du lac Finger Lake, la température demeure sous la limite thermique acceptable de 16 °C pour l'omble chevalier, car le lac a une inertie thermique.

Néanmoins, les données montrent que même si la rivière est alimentée par l'eau relativement froide du lac, elle se réchauffe d'environ 4°C pendant la journée. Ainsi, pour les autres petits cours d'eau non alimentés par les grands lacs, les juvéniles en croissance peuvent être plus vulnérables à l'épisode de réchauffement de l'eau durant l'été.