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Inclusion of water temperature in a fuzzy logic Atlantic salmon (*Salmo salar*) parr habitat model

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Abstract

As water temperature is projected to increase in the next decades and its rise is clearly identified as a threat for cold water fish species, it is necessary to adapt and optimize the tools allowing to assess the quantity and quality of habitats with the inclusion of temperature. In this paper, a fuzzy logic habitat model was improved by adding water temperature as a key determinant of juvenile Atlantic salmon parr habitat quality. First, salmon experts were consulted to gather their knowledge of salmon parr habitat, then the model was validated with juvenile salmon electrofishing data collected on the Sainte-Marguerite, Matapedia and Petite-Cascapedia rivers (Québec, Canada). The model indicates that when thermal contrasts exist at a site, cooler temperature offered better quality of habitat. Our field data show that when offered the choice, salmon parr significantly preferred to avoid both cold areas (<15 °C) and warm areas (> 20.5 °C). Because such thermal contrasts were not consistently present among the sites sampled, the model was only validated for less than 60% of the sites. The results nevertheless indicate a significant correlation between median Habitat Quality Index and parr density for the Sainte-Marguerite River (R^2 = 0.38). A less important, albeit significant (F-test; p=0.036) relationship was observed for the Petite-Cascapedia river (R^2 = 0.14). In all instances, the four-variable (depth, velocity, substrate size and temperature) model provided a better explanation of parr density than a similar model excluding water temperature.

Keywords: Fuzzy logic, Habitat quality model, Atlantic salmon, parr, water temperature

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1. INTRODUCTION

Anticipated water temperature increase in rivers linked to climatic and anthropic changes is a threat to aquatic ecosystems (Isaak *et al.*, 2018). In the recent past summers, water temperature in many Eastern Canadian rivers exceeded critical thermal thresholds for many cold water fish species, such as Atlantic salmon (*Salmo salar*) (i.e. >27.8°C; Gendron, 2013; Jeong et al., 2013). Even if Atlantic salmon is commonly recognized as a relatively thermally tolerant species (Garside, 1973; Jonsson *et al.*, 2009), it is known that juvenile salmon parr become thermally stressed when water temperature exceeds 23°C (Breau *et al.*, 2011; Elliott, 1991). A continuous exposure to extreme temperatures can cause massive mortalities or alter considerably the health of ectotherm fishes (Garside, 1973; McCullough, 1999). Despite the relative paucity of river thermal information available for North America, predictions suggest a general increase of river temperature, which depends in part on latitudinal position (Morrill *et al.*, 2005; van Vliet *et al.*, 2013).

In this context, habitat models are key tools to optimize management and conservation programs. In habitat modelling, classical approaches determine the quantity and quality of area potentially useful for a species' life stage or guild based either on expert knowledge or on observed habitat use and physical data (Yi *et al.*, 2017). Classical variables used in habitat model for juvenile Atlantic salmon include flow velocity, water depth and substrate size (Table 1). When the model is based on habitat use solely (i.e. not taking into account habitat availability), univariate Habitat Suitability Indices (HSI) are defined from field measurements of presence-absence or abundance/density of fish in sampling parcels. A composite HSI is calculated by combining the

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univariate HSIs, using different methods (additive function, arithmetic mean, lowest HSI, etc.). The most commonly used method thus far has been the geometric mean. A HSI of 0 describes a poor habitat, while a HSI of 1 describes an optimal habitat. Multiplying the composite HSI by the surface area on which it applies provides a Weighted Usable Area (WUA). This approach is often used in combination with hydraulic models to provide estimates of usable areas at difference river discharges (e.g. Instream Flow Incremental Methodology Bovee *et al*., 1998; DeGraaf *et al*., 1986; Morantz *et al.*, 1987).

Combining univariate HSIs usually rely on two assumptions. First, that habitat variables are independent, and second, that they exert an equal influence on habitat selection (Ahmadi-Nedushan *et al.*, 2008). However, those assumptions cannot be validated in most cases, as some habitat variables (e.g. depth and velocity) are clearly interdependent, and some variables are more important than others in the habitat selection decision. Furthermore, classical methods based on field data typically require large amounts of data that are costly to acquire. They are also generally obtained from a relatively small area (e.g. a single river or catchment), which makes the model poorly transferable to rivers other than the one which served for calibration (Guay *et al.*, 2003; Millidine *et al.*, 2016).

To overcome these gaps, Ahmadi-Nedushan *et al.* (2008) and Mocq *et al.* (2013) worked with fuzzy systems inspired by the work of Jorde *et al.* (2001) who developed the Computer Aided Simulation Model for Instream Flow Requirements (CASIMIR) habitat model. Those authors developed salmonids fuzzy habitat models considering the classical habitat variables of water depth, flow velocity and substrate size. Ahmadi-Nedushan *et al.* (2008) tested the models for two Atlantic salmon life stages - spawning adults and parr - and conducted a sensitivity analysis of the fuzzy rules of the system based on six expert opinions. Their suggestion was to further validate the model, increase the number of experts and add other habitat variables. Mocq *et al.* (2013) improved the model by adding a life stage (young of the year) and a considerable amount of experts (30 experts in total) with European and North American experience. The authors partially validated their model and compared the output to a classical habitat model (Ayllón *et al.*, 2012; Bourgeois *et al.*, 1996; Gibbins and Acornley, 2000) based on Weighted Usable Areas. Both models were used to assess the variation of WUA as a function of discharge and uncertainty around the relations were estimated using a bootstrap method. The results indicated that relations of WUA as a function of discharge were similar on both instances, even though the fuzzy model was based on expert knowledge only. Mocq *et al.* (2015) also showed that the geographical origin of the experts influenced the uncertainty associated with the delimitation of the categories and they hypothesized that experts from different countries were mostly drawing their knowledge from their experience from local rivers. The fuzzy logic approach also offers other advantages: 1) it helps describe imprecise processes through qualitative knowledge and human interpretation, 2) it is unimpaired by dependence between variables, and 3) it allows the easy addition of new predictors or expert knowledge to the model.

Beyond the shortcomings of classical habitat models that could be addressed by fuzzy logic, there are other deficiencies in current Atlantic salmon habitat models. One such deficiency is that models generally neglect water temperature despite its importance for the physiology and phenology of the salmon. Indeed, water temperature has rarely been included in habitat models of this species (but see Stanley et al., 1995) and when it was included, it was through approximation from air temperature (Caron *et al.*, 1999). Although this deficiency was probably due in the past to the lack of suitable water temperature data, there are now monitoring networks of river temperature existing in the Pacific Northwest and in Eastern Canada (RivTemp, www.rivtemp.ca; Boyer *et al.*, 2016), which offer the opportunity to improve salmon habitat models by adding water temperature.

The aim of this paper is to improve Atlantic salmon parr habitat modelling in Eastern Canada using a fuzzy logic approach. First, a multi-expert model that includes water temperature is developed to infer juvenile salmon parr habitat quality. The model is then partially validated by comparing values of habitat suitability obtained from the model with parr density data collected in thermally contrasted river reaches.

2. METHODOLOGY

2.1 Multi-experts model

2.1.1 Fuzzy sets and rules

In the context of juvenile salmon habitat modelling, fuzzy logic is used to codify experts' knowledge regarding the role of flow velocity, water depth, substrate size and water temperature salmon parr habitat quality.

The first step in designing a fuzzy model is called "fuzzification". The purpose of this step is to divide each input variable into categories. In this case, input and output variables were classified as "low", "medium" or "high". As an example, flow velocity was categorized as either "slow", "medium" or "fast". The fuzzyfication was completed by interviewing experts on the selected habitat variables and their impact on the suitability of parr habitat. The experts were ask to divide the range of possible values of each variable into three categories using more or less precise

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ranges of values. The separation of variables into categories is done by assigning a membership degree to the values, thereby creating a membership function (Figure 1). A habitat variable (e.g. velocity) value with a membership degree of 0 means that it does not belong to the category. Conversely, a membership degree of 1 means that this habitat variable value belongs totally to the category. For each variable, the experts targeted ranges of values for which they were certain of full membership (i.e., membership degree =1) in the categories.

As working with nominal categories leads to uncertainties, the experts were given the opportunity to leave a range of values that can belong to two categories, thereby representing the uncertainty (or fuzziness) of the expert on the definition of boundaries between categories (e.g. for velocity, 0.3-0.5 m/s; 0.7-0.9 m/s; Figure 1). The uncertain intervals are called the “fuzzy zones”. It is possible to model a value in a fuzzy zone by attributing it proportionally to two categories at the same time. To help the expert delineate the categories, we asked them to think about parr habitat in a context of survival. We did not predetermine upper boundary values for the variables. The experts had to fix them themselves according to their experience.

Once the categories were delimited, the experts had to qualify the habitat resulting from the combination of each category of variables. The fuzzy rules are all constructed using the following format: IF the substrate size is large, AND IF velocity is medium AND IF depth is low AND temperature is warm THEN habitat suitability is... either "poor", "medium" or "high" according to experts. Considering three categories for each of the four variables, there are a total of 81 combinations and their consequences (habitat suitability) are defined based on the experience of the respondent. Some habitat variables combinations are not found or are very rare in nature and therefore, are rarely used in the model. For example, if an expert determined that a fast velocity is greater than 2 m/s and a small substrate is less than 2mm. All the rules involving a fast velocity and a small substrate would be unrealistic because in rivers, the water flowing at such high velocity would most likely flush out such fine substrate.

2.1.2 Experts selection

From April to October 2017, we interviewed experts with a concrete knowledge of Atlantic salmon parr habitat in order to gather and codify this knowledge (Mocq et al., 2015). We gathered the opinions of 22 experts through meetings of which 18 answered the questions on their own. Two teams of two were also counted as one expert each. Among the participants, 17 work in the public sector, while five are in the private sector. Public organizations include teaching and research institutions (8), government departments (5) and non-profit organizations (5). There were eight technicians, three professors, eleven managers and three graduate students. Some of them occupied more than one position. Our primary criterion for selecting an expert was that the person had at least one year of hands-on experience with Atlantic salmon parr in Eastern Canada to optimize the model for this region, as the origin of the expert has been shown to influence the model outcome (Mocq *et al.*, 2015). The geographic origin of the expert's experience has been separated into seven different groups: Saguenay (15 experts; Qc), North Shore (10 experts; Qc), Ungava (3 experts; Qc) and Québec City area (1 expert; Qc) which are located on the north shore of the St. Lawrence River. Lower-St.Lawrence (6 experts; Qc), Gaspésie (10 experts; Qc) and New-Brunswick (3 experts; NB) are located south of the St. Lawrence River. Their knowledge about habitat preferences could come either from literature or field experience. We did not measure their level of expertise, however experts were asked to rate their level of confidence in their response from 1 (low confidence) to 10 (high confidence). We also contacted some of the experts who had already done a similar exercise with Mocq *et al.* (2013).

2.2 Field sampling

2.2.1 Sites selection and description

The second specific objective of the project was to validate whether the experts' opinion was consistent with what we could observe in the river. Site selection was based on three main criteria. The first was presence of parr in the site area. The second criterion refers to the initial hypothesis of the study, i.e. that water temperature influences the quality of parr habitat as defined by the expert and that it influences habitat selection. Thus, we looked for sites where there was a potential thermal contrast such as a confluence of a river with a colder or warmer tributary. Since the hypothesis guiding the study was temperature-related, we defined the two compared areas as the "warm area" and the "cold area". To better understand the sampling protocol, Figure 2 illustrates the definition of what is considered in this project as a site, an area (cold or warm) and a patch. The last criterion to choose the site was that similar habitats (depth, velocity and substrate size) exist in the warm and the cold areas. Comparing similar habitat types in both areas is an attempt to isolate the effect of water temperature.

The warm and the cold areas had to be more than two meters wide and no less than 40 m^2 each. The sampled area could be located directly in the tributary, in the tributary plume downstream of the confluence, upstream or downstream in the main channel, as long as the temperature was different and the other variables were comparable. According to those criteria, four sites were selected. The A and B sites are in the Sainte-Marguerite River (SMA). This 100 km long river is

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in a mainly forested area between Chicoutimi and Sacré-Coeur on the Quebec North shore, Canada. The salmon population for this river was about 360 spawning adults in 2016 (MFFP, 2017) and the regional average summer air temperature for the last ten years is about 20.8 °C. The C and D sites are in the Matapedia River catchment on the Quebec South shore, Canada. Mean summer air temperature is about 21.6 °C. Spawning adult population on this river was about 1940 in 2016 (MFFP, 2017). Figure 3 gives more details about the geographic position of the sites. In total 12 surveys were completed, which consist of electrofishing and habitat characterization.

2.2.2 Electrofishing protocol

A field campaign was undertaken from July 20^{th} to September 26^{th} 2017. We sampled five times site A, three times site B, three times site C and one time site D to compare parr densities in two thermally contrasted areas (see Figure 3). Only a partial validation was performed since, as previously explained, it is not the full suite of 81 fuzzy rules that were found to apply when using variable values measured in the field during the sampling campaign. Furthermore, the electrofishing method restricted the sampling areas to relatively shallow reaches with relatively slow flowing water. We could not fish in an area deeper than hip height or when the water velocity was greater than 1.5 m/s with water depth higher than the knees.

When arriving at a fishing site, the area was scanned using the Seek Thermal Compact XR device to visualize water temperature spatial variability. Figure 4 shows a typical site picture taken with the thermal camera. This infrared camera picture was assessed against spot measurements of temperature using a digital thermometer. Depending on the availability of contrasted habitat

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observed by thermal camera, warm and cold areas were delimited to form fishing zones, each with an area between 50 and 150 m^2 (Figure 2). In a designated site, we tried to compare areas with roughly the same surface area. Habitat use was evaluate by electrofishing in groups of three people. The team included one person handling the electrofisher (Smith-Root LR-42 model) accompanied with two catchers holding a net. The electrofisher parameters (voltage, frequency, duty cycle) were programmed in “Direct Current” and according to water conductivity with the automatic “Quick set-up” option in the menu. The voltage was adjusted in increments of 20 V until the optimum fish response was achieved, that is, galvanotaxi (e.g. involuntary swimming towards the anode) followed by a vigorous recovery in the following 20 seconds. The electrofisher holder was placed upstream and perpendicular to the catchers to perform a large sweeping gesture with the anode (“M” shaped motion) in front of them, shocking an area of approximately 0.80 m^2. The electrofishing was repeated and carried out to cover the entire delimited area.

When a parr was caught, its location was identified with a tag, the temperature was measured and the fish was placed in a container. The captured specimens were all weighed and measured. If two individuals were captured in the same 0.5 m radius patch (Keeley *et al.*, 1995; Lindeman *et al.*, 2015), they were associated with the same habitat measurements. Once the measurements were made, fish were returned to the river, downstream of the sampling area. The electrofishing was made from downstream to upstream while taking care never to trample the patches before fishing. The same exercise was performed in the cold and the warm area. We noted the total fishing time in each thermally contrasted area to ensure a constant fishing effort and the number of parr caught in each area have been used to calculate a density over a surface of 100 m^2.

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2.2.3 Habitat

In the sampling areas, habitat variables were also surveyed in at least ten patches where no fish was caught or observed. While performing the electrofishing, patches were selected in a stratified random manner, so that the range of available velocities, depth and substrate were covered in the samples. The selected patches for characterization were also identified with tags. Temperature was measured instantly because it is a variable that can change over the fishing period. Once electrofishing was completed in the areas, the other habitat variables were measured at each location. The diameter (B-axis) of the dominant substrate was evaluate out of the 0.79 m^2 window around the tag. Depth and velocity at 40% of the total depth of the water column from the bed (Marsh McBirney flowmeter) was taken at the focal location of the tag. Sampling tags (placed for fishing and/or characterisations) were never located in the same 0.79 m^2 habitat patch. At every site, two temperatures sensors (Hobo Pendant Temperature/Light Data Logger) were also placed, one in the main channel and one in the tributary. Water temperature ± 0.5 °C was recorded every 15 minutes from July 4th to September 20th 2017 to characterize the plume at sites A and B and to assess the thermal contrast between the receiving river and the tributary at sites C and D.

2.3 Model application

All field measurements were used as inputs in the fuzzy logic model to calculate Habitat Suitability Indices (HSI) using the Fuzzy logic toolbox in Matlab R2016b software. The toolbox is used for the construction of fuzzy sets using linear functions defined by the experts. The rules defining how each combination of habitat variables lead to different HIS categories are also

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entered. Like Mocq *et al.* (2013) and Ahmadi‐Nedushan *et al.* (2008), the Mamdani inference was used to calculate HSI of patches sampled in the summer of 2017. This implies that when two fuzzy sets are combined in a rule, with specific membership function values, the minimum is used to quantify the membership function value of the HSI. When more than one rule is needed to describe the combination of habitat variables, the resulting fuzzy set is a sum of the HSI membership functions.

The two main steps in the fuzzy inference used to calculate HSI are called the implication and the defuzzification. This latter step allows to convert a fuzzy HSI set to a real HSI value. Those operations were completed for all sampled habitat patches, considering individual expert fuzzy sets and rules separately. When the values of all the habitat variables in the patch have a full membership to their respective category (membership degree of 1), a single fuzzy rule is involved. In this case, the conclusion function is defined by the full range of the consequence of the rule determined by the expert (low, medium or high habitat quality). As illustrated in Figure 5, considering a substrate of 12 mm, a velocity of 0.1 m/s, depth: 1.4 m and a temperature of 10°C, an expert model would considerer that his patch has a small substrate, low velocity, high depth, medium temperature and the consequence of this combination is low HSI. Since all the variables in the parcel have a membership degree (MD) of 1, the minimum of the conclusion function (implication) is also 1 or 100%. The numerical HSI of the patch will be determined by defuzzifying using the center of gravity of the area under the curve of the conclusion function.

Sometimes, many rules are necessary to describe a patch. Depending on the expert, the number of fuzzy rules applying to a habitat patch can vary between one to a maximum of 16. For instance, if

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the values of three variables (out of four) in the patch are in a fuzzy zone (i.e. having membership in two categories), eight rules will be needed to describe the patch. As seen on Figure 5, when one value is in the fuzzy zone, two rules are necessary to describe the patch. Supposing a patch with a median substrate diameter of 100 mm, a velocity of 0.5 m/s, a depth of 1.2 m and a temperature of 6 °C (in the fuzzy zone). According to this expert this patch has a small substrate, low velocity, high depth. Temperature belongs partly to the medium and partly to the high categories and the consequence of this combination is an aggregation of medium and high habitat quality. As the minimum membership degree (MD) among the variables for the first rule is 0.4, the membership of the partial conclusion function is also 0.4 and it is 0.6 for the second rule. Making an aggregation, by combining the fuzzy sets representing the conclusion functions of each rule, provides the total conclusion set. The center of gravity of the area under the curve of this resulting aggregated fuzzy set becomes the numerical value of the HSI.

2.4 Model validation

2.4.1 Validation in a thermal contrast

The partial validation of the model was completed for every electrofishing and habitat survey (one day, one site), considering all experts' fuzzy models separately. A HSI was calculated for each sampled habitat patch, in presence and in absence of parr. Then, a non-parametric Kruskal-Wallis test was used to verify the null hypothesis that the median HSI of the warm and cold areas of a fishing survey were equal with a confidence level α=0.05. To facilitate the description of the results, we identified so-called "significant experts" when the experts' model rejected the null hypothesis for an electrofishing survey, i.e. the model showed a significant difference in HSI values between thermally contrasted habitats. The global model was considered validated when the majority of the significant experts express a higher HSI in the area where higher parr density was measured.

2.4.2 Validation of observed densities

A second partial model validation was conducted using a different data set from field surveys undertaken during summer 2017 between July 27th and September 16th on the Sainte-Marguerite (previously described in Section 2.2.1) and the Petite-Cascapedia rivers located in the Gaspésie region (Eastern Québec). See Figure 6 for rivers location. On these rivers, various sites were surveyed to cover a wide heterogeneity of salmon habitat. In total, 30 sites were surveyed on the Petite-Cascapedia River whereas 27 sites were surveyed on the Sainte-Marguerite River. These sites were at least separated by 500 m along watercourse to ensure independence between sites. At each site, 30 equally spaced 4 m^2 patches along 5 transects (6 patches per transect) were electrofished and physically characterized as illustrated on Figure 6. The same physical habitat variables were measured at each of those patches (depth, velocity, substrate size and water temperature). The only difference is that the velocity and temperature were measured using an acoustic velocity meter (Sontek Flow Tracker 2) on the Petite-Cascapedia River. After all measurements were completed in all patches, the mean value of these measurements was used as an input for the expert's models to obtain a HSI value for each of the sites. Finally, electrofishing was conducted using also the Smith-Root LR24 Electrofisher at each of these 30 patches. The parr density for a site was then obtained by summing the individual parr densities at each patch within the site. Hence, the relation between the HSI given by the experts and the relative parr density at each site can be investigated as another validation of the developed expert model.

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3. RESULTS

3.1 Experts based model

All 20 experts had to design fuzzy sets for each of the four input variables (temperature, velocity, depth and substrate) with three categories (low, medium, high). Table 2 shows the medians and ranges (maximum and minimum) of selected limits for fuzzy sets defining the categories of habitat variables. It can be seen that typically the variability (median/range) is between 0.2 and 2 %. For instance, experts defined roughly the "low" category for temperatures between 0 and 8 °C, "medium" category between 12 and 18 °C and "high" category over 22 °C.

The 20 experts had to assign a consequent Habitat Suitability (poor, medium or high) for each combination of velocity, depth, substrate and temperature categories. Like Mocq et al. (2013), we identified the most frequently selected consequent HSI category as the "consensus" response and we calculated how many experts were part of this consensus. Considering the 81 rules, experts have a mean consensus of 63.7 %. In others words, about 13 experts out of 20 generally agree on rules consequence. Experts attributed a poor habitat for 64% of the rules, with a consensus of 68%. For half of those rules, there is about 11% of the experts that conclude, conversely, that these same rules lead to a high habitat quality. About 25 % of the rules have "medium" HSI as consequence, with a consensus of 53%. Only 9% of the rules have been associated with a "high" HSI and about 56% of experts were part of this consensus. For 71 % of the rules with a high HSI consequence, a minority (2.8 %) of the experts concluded the opposite, i.e. that habitat was of poor quality. Two rules have no consensus, i.e. different consequent categories were selected by an equal number of experts.

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3.2 Habitat characterization

During the summer, water temperature was measured every 15 minutes for July 7th to September 20th. The average summer water temperature in the main channel and in the tributary as well as the maximum temperature reached for study sites are compiled in Table 3. For all surveys, physical habitat variables measurements were taken. Median values measured for the velocity ranged from 0.11 to 0.76 m/s, depths ranged from 0.11 to 0.38 m and substrate sizes ranged from 85 to 190 mm. Median temperatures ranged from 13.1 °C to 19.5 °C in the cold areas and from 16.1 °C to 21.8 °C in the warm areas. The thermal contrasts (median temperature differences) between cold and warm areas varied from 1.4 °C to 6.0 °C. For all electrofishing surveys completed, this thermal difference was statistically significant (Kruskal-Wallis; $p < 0.05$). Despite efforts to sample areas with similar values for habitat variables other than temperature, for four electrofishing surveys, there were two significantly different habitat variables including water temperature and three surveys had three significantly different variables between cold and warm areas, when the Kruskall-Wallis test was applied. Table 4 gives more details about the median values of the variables sampled for each electrofishing survey..

We characterized a total of 451 patches. From these measurements, a HSI value was calculated for each of the 20 experts. The analysis of the 451 patches also generated 21 031 applications of 66 different rules. The other 15 rules were never used. The most frequently used rule (3 798 times) is when the values of the four variables belong the medium category, represents 18% of uses and 80% of experts agree on the consequent HSI for this rule (high HSI). The seven most frequently used rules are shown in Table 5. They represent 63% of rule applications, with a mean

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expert consensus of 60%.

As already stated, HSI for each of the 20 experts were calculated for each sampled habitat patch. The mean standard deviation for HSI was 0.18 (HSI varies between 0 and 1). Only expert models that expressed a significant difference between median habitat quality in the colder and the warmer area were considered to partially validate the model. As shown in Table 6, four experts expressed significant differences for more than 90% of the fishing surveys, two experts never expressed significant differences and two other expressed differences for less than 10 % of fishing surveys. For 50% of the surveys, experts that concluded to significant differences were unanimous to determine that the colder area had the highest habitat quality. For 17% of the surveys, opinions were more split. Respectively for site A day 269 and site B day 201 (Table 5), 56% and 57% of the significant experts agreed that the cold area was of better quality compared to 44% and 43% who said the opposite. For the other surveys, over 70% of the experts agreed on the model conclusion.

3.3 Electrofishing

For our analysis, we considered only the specimens with fork length >55 mm as parr. A total of 226 parr (1+ and 2+), in 201 different patches were captured or clearly observed during the summer. For all the electrofishing surveys, we standardized the number of fish that we caught in each area (colder vs warmer) by prorating densities for an area of 100 m^2. As seen in Table 4, among all the electrofishing surveys, the highest density of fish was found in median temperature ranges of 15.2 to 20.2 °C, which is in agreement with the known temperature optimum for parr feeding (15 to 19 °C according to the literature; DeCola, 1970; Elliott, 1991; Elson, 1969; Stanley *et al.*, 1983). We did not find any fish in the warmest area (21.8°C). Moreover, when the warm areas exceeded 20.9 °C, 42% more fish were caught in the colder area. We also saw that when the colder area offers temperatures lower than the feeding optimum range (<15.0 °C), parr were mostly found (48% more) in the warm area.

3.4 Model application and validation

3.4.1 Validation in a thermal contrast

As indicated in Table 4, the model was partially validated seven times and was shown to be inconclusive five times. As already explained, validation was conclusive when the highest fish density was found in the area with the highest modelled HSI values for a majority of experts. Every time the model was not validated, most of experts predicted a better quality of habitat in the cooler area while the highest parr density was in the warmer area. For site A, the model was validated three times out of five surveys. When the model was not validated for this site (day 214 and 229; table 4), the temperatures of the cold area were respectively 14.2 and 13.1 °C. For day 214, we note that the velocity and the substrate size were also significantly different between the two areas (lower velocity and larger substrate in the warm area). For site B, the model was always validated. At that site, temperature values were always in a range that is adequate for parr (15.2-20.9 °C). For day 201, depth was significantly higher in the warm area (0.21 vs 0.33 m) than in the colder area and for day 209, the substrate was significantly larger in the colder area (100 vs 140 mm) than in the warmer area. At site C, the model was invalidated for the first two electrofishing surveys. In the first case, the temperature of the cold area was 13.9 °C while temperature in the warm area was 19.2 °C. Also, the velocity and the substrate size were significantly higher in the cold area than in the warm area. In the second case, the temperature of the cold area was 16.1 °C while the temperature of the warm area was only 19.3 °C. The velocity

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was also significantly faster in the cold area. The model was validated for the third electrofishing survey at this site while the temperature in the warm area was 21.1 °C and 16.2 °C in the cold area. The depth was also significantly greater in the warm area (0.11 vs 0.17 m) and the substrate was larger in the cold area (90 vs 105 mm). Finally, for site D, the model has not been validated for the only electrofishing survey that was completed at that site. The temperatures in the warm and cold areas were respectively 18.3 °C and 16.5 °C.

3.4.2 Validation of observed densities

Validation of the model with the additional dataset collected on Sainte-Marguerite and Petite-Cascapedia River is shown in Figure 7. This figure illustrates the link between the logarithmic transformation of parr density (1+ and 2+) at each site and predicted HSI from the model considering only depth, velocity and substrate size (a) vs our expert's model including the same three variable and water temperature (b). Our model explains respectively 37% and 15 % of the parr density for Sainte-Marguerite and Petite-Cascapedia rivers while the model without water temperature explains respectively 18% and 1%. Based on a F-test comparing the model that includes HSI to explain log density to a simpler model that includes only an intercept, the p-value of 0.036 means that the model that includes HSI is significantly different than an intercept-only model.

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4. DISCUSSION

The main objective of this project was to include water temperature in an expert based model to better quantify and qualify habitat preferences for Atlantic salmon parr. This main objective was achieved by completing two steps. The first one was to codify the knowledge of selected experts on four habitat variables: water temperature, depth, velocity and substrate size. These experts also had to qualify the Habitat Suitability Index resulting from the different combinations of these variables. The second step was to perform a partial validation of the model by putting field data into the model in order to obtain a numerical HSI, and compare it against parr density with and without a thermal contrast at different sites. This work therefore presents an improvement from the models developed by Ahmadi-Nedushan *et al.* (2008) and Mocq *et al.* (2013).

We selected 20 professionals with an Eastern Canadian experience to optimise the model for this region. The model has been validated for 58 % of the surveys. Considering that it is the first fuzzy model that includes water temperature for Atlantic salmon parr, and considering that sampling was completed in a summer with relatively low temperature contrasts (i.e. no heat waves or sustained warm periods) this result is promising and constitutes an important advancement.

The first validation method aimed to compare habitat quality between cold and warm areas. When the model was not validated, it predicted that higher quality habitat would be in a cold area, whereas parr were mostly in warm areas. We suspect that the main cause explaining why 42% of the electrofishing surveys did not agree with the model is that the summer 2017 in Quebec was not particularly warm and hence, cold water temperature refuges in the sampled rivers were often not necessary for parr. The temperature sensors placed at the sites under study revealed that the hottest temperature of the water during the summer period, all sites combined, was 25.8°C which is not close to the upper incipient lethal temperature for parr (27.8 °C; death of 50% of fish after 7 days). When this temperature was reached, it generally lasted for less than two hours. For sites A, B and C there was respectively 19, 7 and 18 days where temperature exceeded 22 °C. This temperature represents the upper critical range where normal metabolic functions cease, but parr can still survive for a long period of time at that temperature (Jonsson and Jonsson, 2009). However, 22 °C exceedances never persisted for more than 12 hours. At night, the temperature generally decreased below 20 °C. This might give a respite to fish by recreating the effect of a thermal refuge. Nonetheless, at site D, there were 31 days where temperature exceeded 23 °C and rarely cooled down below 20 °C. There was a particular warm period between day 195 and day 207 (from July 17 to July 23) where the average daily water temperature remained above 22 °C. The maximum temperature reached during this period was 25.8 °C while the minimum never went below 20.6 °C, which is considerably high for a prolonged period. Even if Site D was the warmest, our only electrofishing survey at this site was completed during a cooler period and we suspect that is the reason why the model was not validated for this survey. Furthermore, among all the surveys, it was common to compare two areas whose average temperatures were both in the tolerable, almost optimal range for parr. Such ranges generally do not trigger movement to cold refugia (Breau *et al.*, 2011).

We also attempted to test and compare the proposed model on a different, larger dataset, which is an approach suggested by many authors (Fukuda, 2009; Kampichler *et al.*, 2000; Mouton *et al.*, 2008). We can see on Figure 7 that in both cases, our four-variable model explains better parr densities then the three-variable model, and this, for every site. This suggests that adding a variable such as water temperature improves the predictability of the model. The correlation between the median HSI and the density of parr is weaker for Petite-Cascapedia (R^2 = 0.15) than for Sainte-Marguerite data (R^2 = 0.37). This could be explained by the low heterogeneity of the habitats studied on the former river. In fact, the lowest HSI model assigned in the Petite-Cascapedia River was 0.4, which is generally considered an average value, according to most experts. Thus, the patches sampled were all of considerable interest for parr and relatively similar. It goes without saying that all the parcels cannot be occupied, thus leaving several interesting habitat patches vacant. Although the concept of transferability is not accepted by all (Groshens and Orth, 1993; Leftwich *et al.*, 1997; Strakosh *et al.*, 2003), the correlations revealed by these linear regressions allow us to be enthusiastic about the possibility of transferring this model to several rivers. Although some authors have tested the transferability of regional models, the correlation that we obtained on the Sainte-Marguerite River has not, to our knowledge, been previously equaled (e.g. R^2 = 0.02 to 0.31; Guay et al., 2003, Hedger *et al.*, 2004). The fact that the correlation is considerably higher for the Sainte-Marguerite River raises new questions about the possible bias of the experts, some of whom may have never seen rivers such as the Petite-Cascapédia. In fact, it is possible to note that the expertise of our respondents comes mainly from the north shore of Quebec (60%). Thus, perhaps the model could be better optimized for cooler rivers considering that the specific adaptations of juveniles in the north and south may be different (Glozier et al., 1997, Hedger et al., 2004).

Even if the proposed model is less parsimonious than its predecessors, it is still a simplification of a complex system that influences parr habitat selection. It includes only four physical variables, but excludes many important ones for habitat selection such as habitat connectivity (Bardonnet *et al.*, 2000), biomass cover and food abundance (Wilzbach, 1985), circadian and seasonal cycle (Cunjak, 1996; Mäki-Petäys *et al.*, 2004), density dependent relationship (Jonsson *et al.*, 1998; Lindeman *et al.*, 2015), etc. As habitat selection by parr is based on many biotic and abiotic factors (Armstrong *et al.*, 2003; Klemetsen *et al.*, 2003), it has been shown many times that HSI and WUA are ambiguous concepts because it is often hard to link them to fish abundance and density (Bourgeois *et al.*, 1996; Milhous *et al.*, 1989). Even in the case where a large number of good habitat patches exist on a river, parr could actually use few of them. Conversely, it is also possible to find parr in habitats of poor quality with little or no explanation for their presence.

Globally, our expert models suggest that a cooler temperature would offer a better habitat quality, which is probably more exact during warmer periods but less accurate when both sections offer a tolerable range of temperature or a contrast that is not optimal, e.g. an area that is too cold vs a tolerable warm area. We did see that when the warm area was hotter than 20.8 °C, the model is always validated and parr were mostly in the cold area as predicted by the experts. This systematic validation for higher temperatures suggests that the model is adequate when limiting temperatures are reached (Breau *et al.*, 2007; Elliott and Elliot, 2010; Jonsson *et al.*, 2009).

On the other hand, even if parr can survive near 0° C and still feed at 3.8 °C (Elliott, 1991), growth is largely linked to feeding (Storebakken *et al.*, 1987) and it starts being suboptimal below 15 °C (DeCola, 1970). Despite this, for some electrofishing surveys, the majority of significant experts indicated that 14.2 °C, 13.1 °C and 13.9 °C would offer respectively better habitat quality than 20.2 °C, 16.1 °C and 19.5 °C. Our electrofishing results suggest that this may not be accurate. In that context, it would be beneficial to review with the experts, the parameters assigned for the temperature categories, and the consequent HSI category (de Little *et al.*, 2018).

Especially considering that a part of the model bias could come from an incomplete understanding of the instructions to prepare the fuzzy model for the expert or from a misinterpretation between the interlocutors. For this model, we suspect that questioning the expert in a feeding context rather than in a survival context would provide a better setting when discussing parr preferences.

Also, several experts verbally testified during the exercise that having four categories instead of three for the output variable (habitat quality) would facilitate the attribution of consequences to the rules. These categories could be poor, medium, high and very high HSI. Unlike adding a category to input variables, adding an output category would not affect the number of rules to answer by experts. This modification could be done during a new consultation with the experts.

As many other studies on habitat model there is still a need for further validation to prove that this model could be an effective management tool (Ahmadi-Nedushan *et al.*, 2008; Bargain *et al.*, 2018; Guay *et al.*, 2000; Lamouroux *et al.*, 2002; Mocq *et al.*, 2013). Even if multiple-experts based model have been identified as potentially highly exportable (Annear *et al.*, 2002) It would be important to gather data from other studies on parr from different river types and different thermal regimes for further validation. Additional validation should include sites within a river that are separated by a distance that is sufficient to minimize the risk of movement of individual fish from the warm to the cold area during sampling.

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Acknowledgments

The authors would like to thank the partners and the funding organizations: Mitacs Accelerate, the Atlantic Salmon Conservation Foundation as well as la Fondation Saumon for their generosity. We also want to thank all the technicians, colleagues and interns who help accomplish fieldwork as well as the scientific support provided by members of the research groups of A. St-Hilaire and N. Bergeron. Warm thanks to all the experts who participated in building the model.

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Tables

Table 1: Preferred parr physical habitat variables ranges found in the literature

	Depth (m)	Velocity (m/s)	Substrate (mm)	Reference
1+ parr*				
	0.10-0.40	0.00-0.20	16-256	Heggenes et al., 1999
	0.16-0.28	0.10-0.30	-	Gibson, 1993
	0.10-0.35	0.15-0.60	25-125	Scruton and Gibson, 1993
	0.1-0.50	0.00-0.60	Gravel-pebbles	Jonsson and Jonsson, 2011
	0.20-0.40	0.20-0.60	20-200	Finstad et al., 2011
2+ parr**				
	0.17-0.76	0.35-0.80	200-300	Armstrong et al., 2003
	< 0.50	0.0-0.25	Small gravel and cobble	Gibson, 1993
	0.20-0.60	0.03-0.25	64-512	Heggenes et al., 1999
	0.19-0.31	0.11-0.29		Gibson, 1993
	0.10-0.55	0.10-0.70	30-200	Scruton and Gibson, 1993
	0.10-0.80	0.0-0.80	Gravel, pebble, cobble	Jonsson and Jonsson, 2011
	0.20-0.70	0.00-0.90	25-450	Finstad et al., 2011

* Second summer of growth in river
**Third summer of growth in river

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Table 21: Medians and ranges (maximum and minimum) of selected limits for fuzzy sets defining the categories of habitat variables.

	Substrate size (mm)				Velocity (m/s)				Depth (m)				Temperature (°C)			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Minimum	5	10	45	64	0.05	0.2	0.45	0.55	0.02	0.15	0.35	0.4	4	8	16	19

Median	20	50	240	300	0.15	0.28	0.6	1	0.15	0.3	0.73	1	8	12	18	22
Maximum	100	200	700	1000	0.6	0.8	1.3	1.8	0.3	0.5	2	5	19	22	25	30

Where A represents the upper limit values fully belonging to the low category, B and C the limits of the values fully belonging to the medium category and D the lower limit of the values fully belonging to the high category. See Figure 1

Table 3: Average summer water temperature in the main stem and in the tributary for study sites from July 4th to September 20th 2017

	Main stem temperature	Tributary temperature	Maximum temperature*
	(°C)		
Site A	17.3	10.7	25.2
Site B	16.5	14.8	23.5
Site C	17.7	15.4	25.3
Site D	14.8*	20.7*	25.8

*experienced at the site

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Table 4: Median values for each sampled variable and parr density (standardized on 100m^2) in the different areas (warm and cold) for each electrofishing survey.

	Day of the year	Depth (m)		Velocity (m/s)		Substrate size (mm)		Temperature (°C)		Fish density		Model validation
		Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold	Warm	
A	**201**	0.29	0.38*	0.29	0.42	110	145	17.6	21.8*	14	0	Yes
	208	0.20	0.28	0.21	0.25	150	150	16.1	21.2*	16	8	Yes

	214	0.23	0.20	0.24*	0.13	115	175*	14.2	20.2*	9	28	No
	229	0.22	0.26	0.20	0.11	150	140	13.1	16.1*	7	11	No
	269	0.24	0.28	0.27	0.40	85	88	17.1	20.1*	7	6	Yes
B	**201**	0.21	0.33*	0.48	0.71	90	120	19.5	20.9*	5	3	Yes
	209	0.28	0.34	0.76	0.74	140*	100	15.2	18.1*	13	1	Yes
	215	0.27	0.29	0.68	0.63	120	120	17.0	19.2*	7	0	Yes
C	**206**	0.32*	0.20	0.52*	0.42	165	190	13.9	19.5*	4	22	No
	212	0.19	0.22	0.33*	0.24	110	130	16.1	19.3*	9	20	No
	234	0.11	0.17*	0.26	0.36	105*	90	16.2	21.1*	16	13	Yes
D	**206**	0.22	0.25	0.43	0.52	100	95	16.5*	18.3*	6	14	No

(*) indicates that the median was significantly higher.

Table 5: The most frequently used fuzzy rules

Rule	Substrate	Velocity	Depth	Temperature	Number of applications
41	Medium	Medium	Medium	Medium	3798
42	Medium	Medium	Medium	Warm	2047
29	Medium	Slow	Low	Medium	1927
32	Medium	Slow	Medium	Medium	1789
68	large	Medium	Medium	Medium	1379
50	Medium	Fast	Medium	Medium	1162
33	Medium	Slow	Medium	Warm	1074

Table 6 : Median HSI for both warm and cold areas of each site, according to the 20 experts

			Experts																			
Sites	**Day of the year**	**Sections**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
A	201	cold	0.57	0.68	0.59	0.64	0.33	0.54	0.64	0.65	0.53	0.77	0.56	0.53	0.81	0.86	0.48	0.72	0.70	0.37	0.52	0.43
		warm	0.38	0.34	0.29	0.80	0.30	0.63	0.78	0.87	0.55	0.80	0.33	0.59	0.36	0.29	0.50	0.55	0.73	0.13	0.54	0.48
	208	cold	0.60	0.64	0.69	0.56	0.31	0.54	0.51	0.57	0.38	0.49	0.67	0.51	0.61	0.88	0.50	0.60	0.62	0.47	0.29	0.20
		warm	0.38	0.54	0.36	0.51	0.30	0.59	0.55	0.55	0.19	0.77	0.33	0.48	0.39	0.54	0.50	0.60	0.61	0.13	0.44	0.37

	214	cold	0.66	0.70	0.69	0.55	0.30	0.54	0.43	0.53	0.40	0.54	0.68	0.51	0.64	0.87	0.50	0.60	0.59	0.48	0.24	0.26
		warm	0.38	0.62	0.46	0.52	0.30	0.53	0.44	0.49	0.18	0.46	0.33	0.50	0.42	0.87	0.50	0.61	0.59	0.12	0.17	0.17
	229	cold	0.79	0.75	0.69	0.61	0.30	0.56	0.41	0.58	0.55	0.63	0.68	0.51	0.75	0.87	0.50	0.64	0.64	0.48	0.23	0.27
		warm	0.77	0.62	0.69	0.53	0.35	0.56	0.35	0.57	0.54	0.41	0.68	0.52	0.54	0.87	0.50	0.67	0.69	0.47	0.15	0.17
	269	cold	0.61	0.63	0.50	0.49	0.32	0.54	0.47	0.60	0.52	0.68	0.59	0.51	0.73	0.86	0.50	0.68	0.64	0.38	0.37	0.43
		warm	0.38	0.66	0.40	0.80	0.31	0.53	0.70	0.78	0.52	0.80	0.33	0.63	0.52	0.86	0.31	0.70	0.68	0.13	0.52	0.52
B	201	**cold**	**0.42**	**0.64**	**0.43**	**0.58**	**0.29**	**0.53**	**0.60**	**0.65**	**0.52**	**0.77**	**0.42**	**0.52**	**0.59**	**0.63**	**0.40**	**0.79**	**0.59**	**0.12**	**0.52**	**0.47**
		warm	**0.38**	**0.88**	**0.40**	**0.38**	**0.31**	**0.53**	**0.78**	**0.56**	**0.55**	**0.80**	**0.33**	**0.58**	**0.45**	**0.50**	**0.50**	**0.67**	**0.63**	**0.13**	**0.65**	**0.52**
	209	cold	0.80	0.88	0.69	0.38	0.35	0.54	0.76	0.57	0.88	0.80	0.85	0.70	0.85	0.49	0.75	0.82	0.63	0.68	0.56	0.58
		warm	0.56	0.88	0.61	0.39	0.36	0.52	0.73	0.57	0.66	0.78	0.52	0.88	0.81	0.50	0.35	0.82	0.67	0.34	0.74	0.63
	215	cold	0.66	0.88	0.69	0.49	0.35	0.54	0.73	0.59	0.74	0.78	0.63	0.67	0.84	0.50	0.69	0.82	0.63	0.44	0.52	0.58
		warm	0.46	0.88	0.51	0.59	0.32	0.53	0.78	0.59	0.59	0.78	0.44	0.81	0.65	0.50	0.50	0.81	0.64	0.13	0.52	0.58
C	206	cold	0.80	0.88	0.69	0.63	0.33	0.54	0.52	0.60	0.88	0.80	0.85	0.57	0.85	0.55	0.59	0.78	0.64	0.49	0.52	0.54
		warm	0.42	0.72	0.49	0.55	0.29	0.53	0.54	0.57	0.27	0.58	0.40	0.52	0.61	0.87	0.50	0.76	0.59	0.12	0.52	0.46
	212	cold	0.75	0.80	0.69	0.72	0.32	0.54	0.70	0.74	0.55	0.76	0.80	0.51	0.85	0.87	0.50	0.73	0.62	0.47	0.52	0.47
		warm	0.44	0.73	0.52	0.63	0.30	0.53	0.71	0.59	0.26	0.62	0.43	0.52	0.62	0.87	0.50	0.69	0.61	0.13	0.37	0.34
	234	cold	0.49	0.71	0.69	0.60	0.27	0.54	0.52	0.51	0.33	0.50	0.72	0.51	0.83	0.87	0.50	0.63	0.53	0.46	0.30	0.34
		warm	0.36	0.53	0.36	0.61	0.28	0.53	0.58	0.56	0.36	0.66	0.33	0.46	0.43	0.61	0.40	0.55	0.58	0.12	0.44	0.46
D	206	cold	0.69	0.88	0.69	0.58	0.33	0.54	0.69	0.60	0.76	0.78	0.68	0.52	0.85	0.86	0.50	0.76	0.61	0.46	0.52	0.49
		warm	0.52	0.74	0.50	0.48	0.31	0.53	0.58	0.57	0.58	0.72	0.50	0.51	0.76	0.50	0.43	0.81	0.62	0.31	0.52	0.47

The boxes in gray indicate a significant difference between cold and warm areas. The light gray boxes indicate that a majority of significant experts who established that habitat quality was better in the cold area than in the warm area for this electrofishing survey. In dark grey boxes, the experts established that habitat quality was significantly better in the warm area.

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Figures

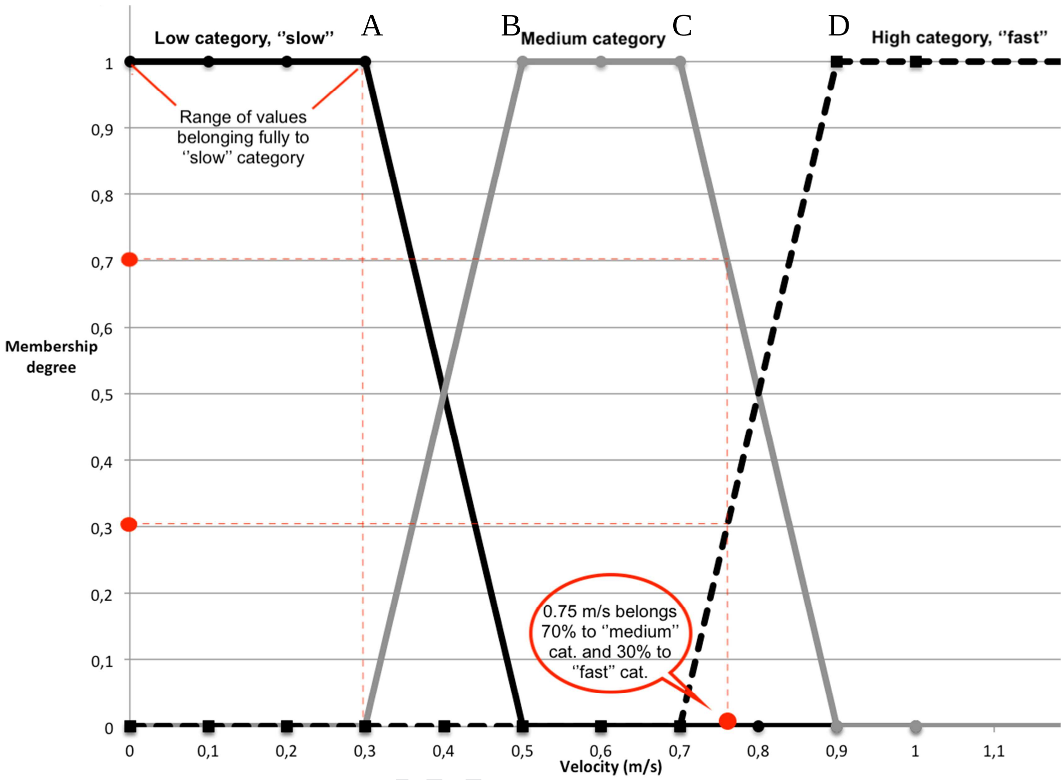


Figure 1 : Example of fuzzy sets defined by an expert for the velocity.

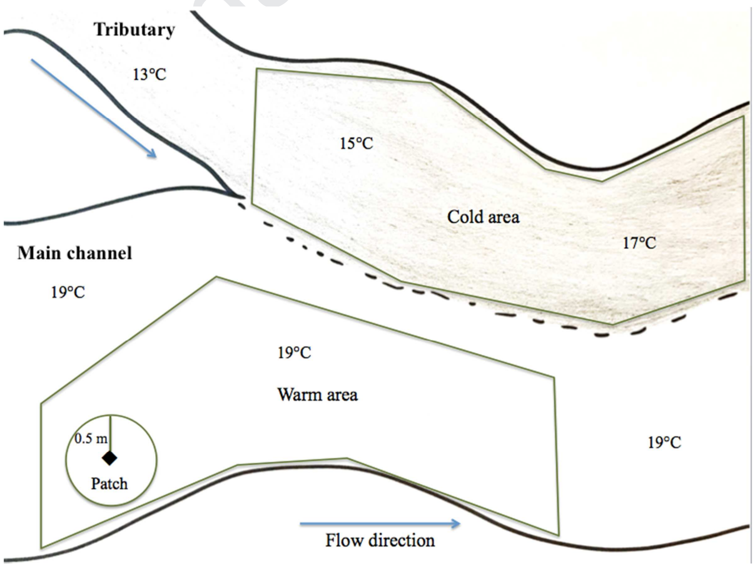


Figure 2 : Fictitious site to represent the sampling model. A site is composed of a cooler area usually generated by the inflow of a tributary and a corresponding warmer area, with roughly the same size. In both areas, several patches with an area of 0.79 m^2 are sampled for depth, velocity, substrate size and temperature, in presence and absence of fish.

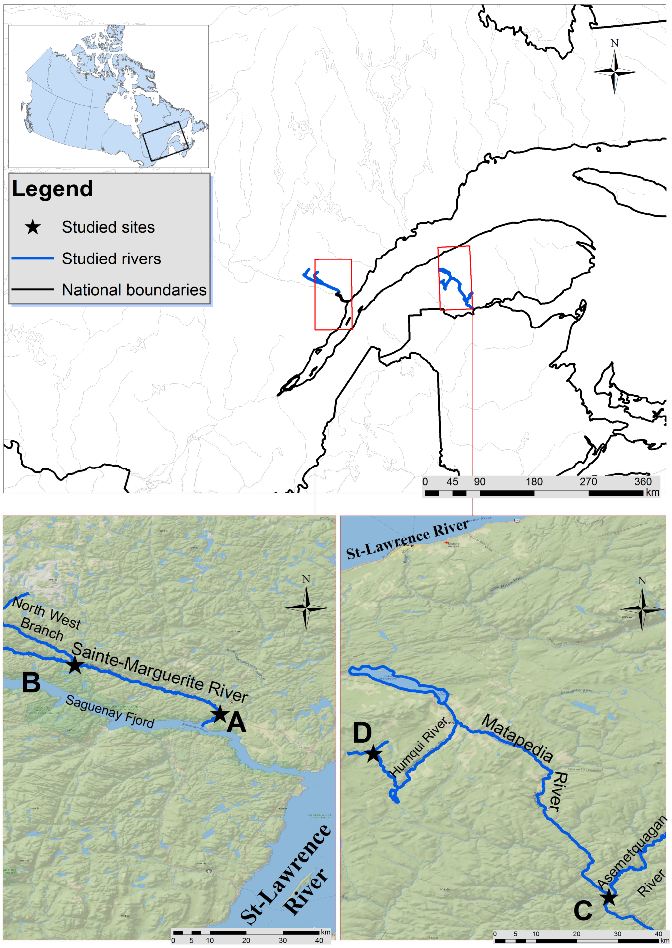


Figure 3 : Sites map

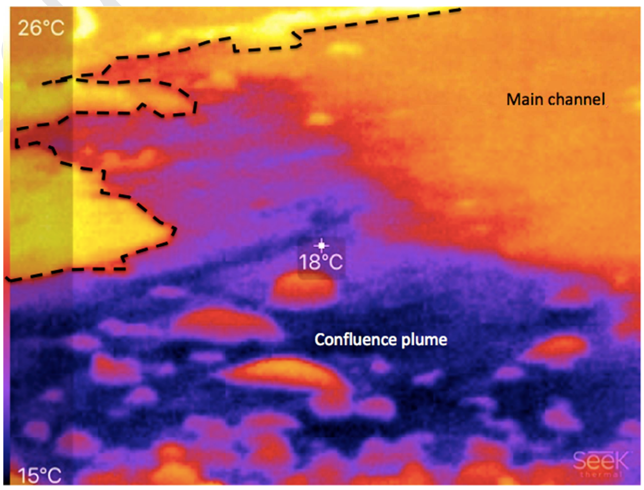
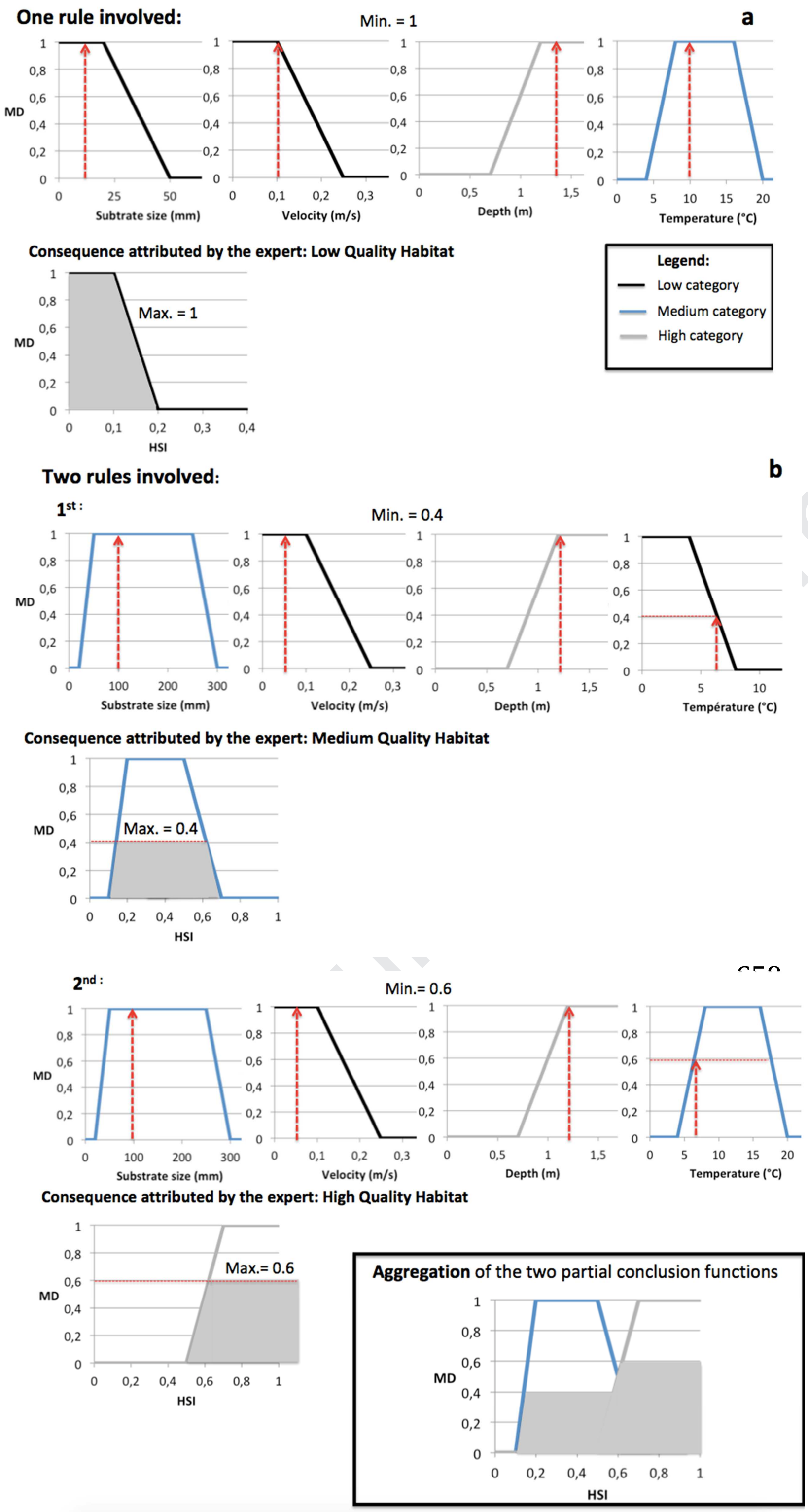


Figure 4 : Site A Infrared picture taken from upstream of the confluence of a cold tributary and the Sainte-Marguerite river with the Seek thermal XR© device. Left of the dotted line is the river bank. The purple area is the cold water plume caused by the tributary water emptying in the main stem, while warmer main stem water is shown in orange: warm area.



667 *Figure 5 : a) Application of a unique fuzzy rule. Fuzzy sets are shown for all four habitat variables. Arrows indicated*
668 *the value of each habitat variable. Grey area show the fuzzy set of the associated HSI b) Implication and*
669 *aggregation of two conclusion functions associated with two rules.*

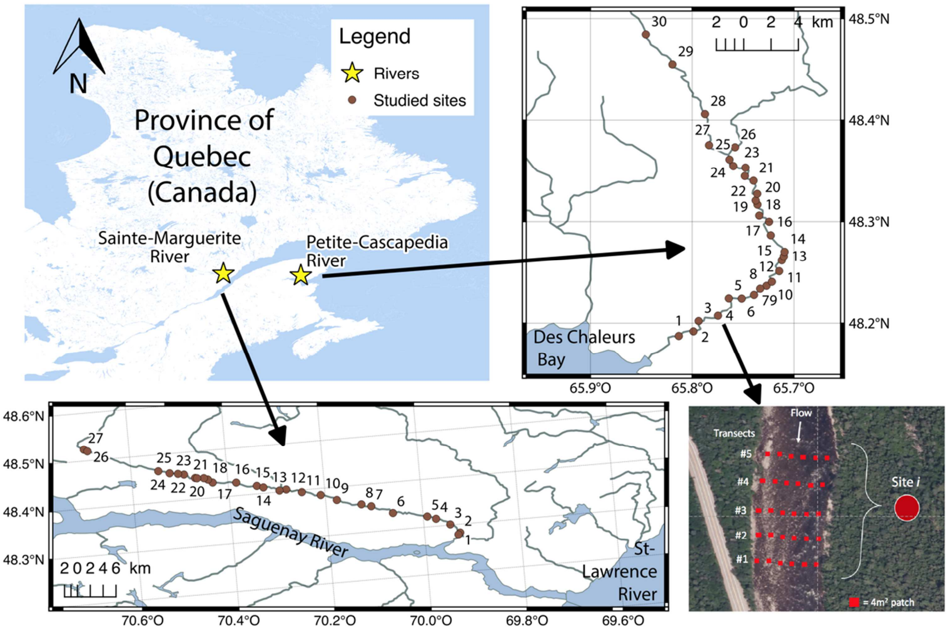


Figure 6 : Sites map for the second data set on Sainte-Marguerite and Petite-Cascapedia Rivers. Red dots on transects indicate the typical distribution of points where physical habitat variables were measured within a site.

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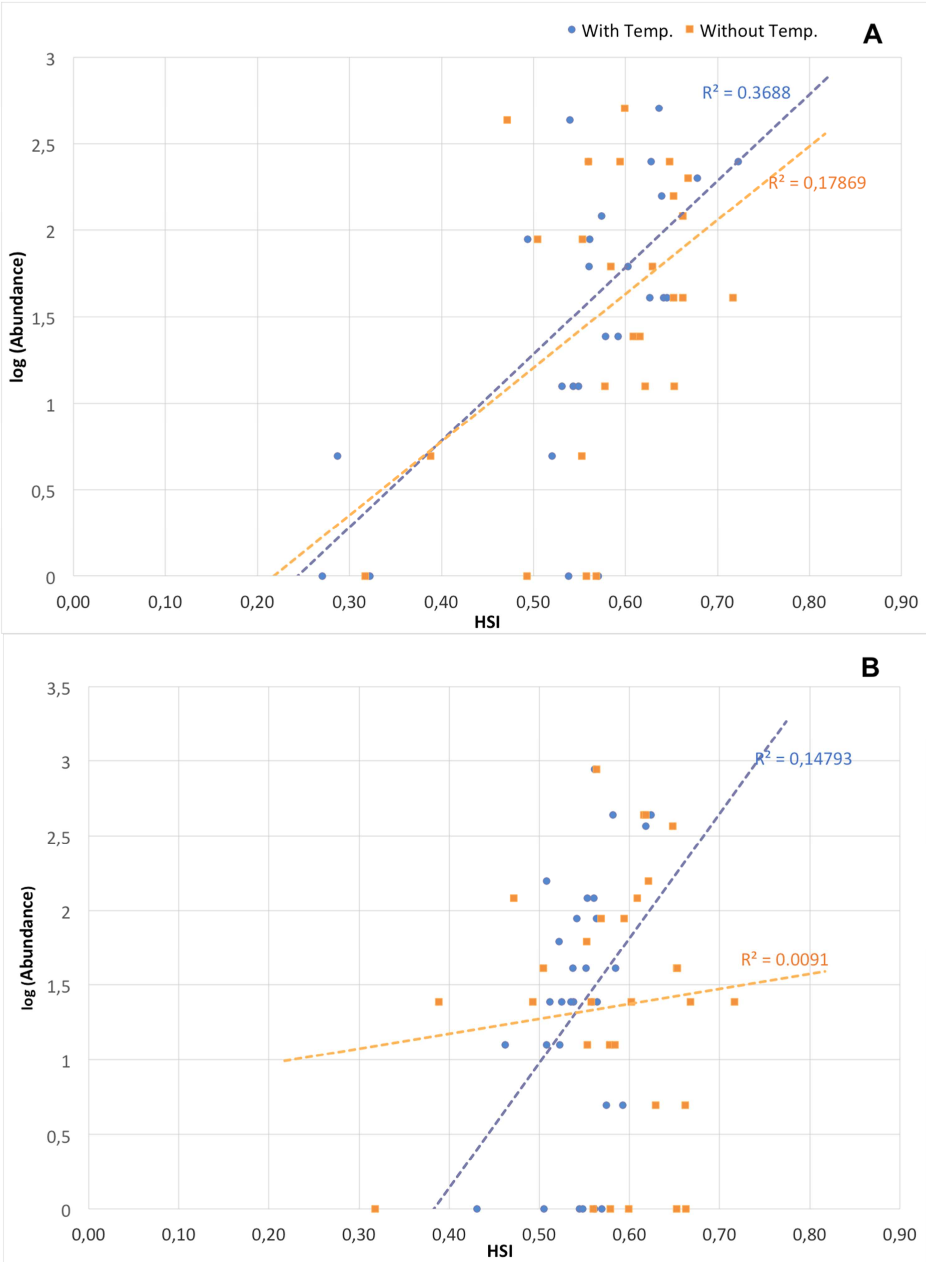

Figure 7 : : Link between density and HSI for the model with temperature (blue) and without temperature (orange) for the Sainte-Marguerite River (a) and the Petite-Cascapédia River (b)

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Highlights:

- A fuzzy rules-based model was developed for Atlantic salmon parr habitat that includes water temperature.
- A multi-expert approach was used to build the model.
- The model was partially validated by conducting electrofishing surveys in thermally contrasted areas.
- Mutational processes similar in primary and relapse; radiotherapy can damage genome
- Significant correlations between median Habitat Quality Index and parr density were found in multiple rivers in Québec, Canada.
- The four-variable (depth, velocity, substrate size and temperature) model provided a better explanation of parr density than a similar model excluding water temperature.

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