RAPPORT FINAL (EXTRAIT)

Critical thermal refugia for Atlantic salmon and brook trout populations of eastern Canadian rivers

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Public Summary of Outcomes and Benefits to Canada

Climate warming is a threat to cold water salmonid populations at the southern limit of their range. This project acquired a high spatial resolution, comprehensive understanding on the distribution and various types of thermal refugia for salmonids in rivers in Quebec and New Brunswick. We also modelled the future (mid-century) relative importance and fate of key type of thermal refugia in the context of climate warming.

Our partner, Hydro Quebec requires up to date knowledge concerning the resilience of salmonid habitat to ongoing climate changes and thermal alterations associated with dam operation, which this study provided. Specifically, this project identified how types and spatial distribution of thermal refugia vary with geomorphic river type and how climate change is likely to affect these key habitats. The work also provides design suggestions on technical means to enhance such habitats.

The project has 3 integrated components:

1. thermal refugia detection and characterisation along rivers;
2. fish use of refugia unfer thermal stress conditions and
3. the future fate of key types of thermal refugia in a climate change context.

Each component included multiple projects. The most significant results will be summarized below.

Seven research labs participanted in the project, based at McGill University, Université de Montréal, INRS-Ete and University of New Brunswick. Study river systems were located in Quebec (Ouelle River, St Marguerite River and Matapedia Restigouche system) and New Brunswick (Little South-West Miramichi river).

Under project component 1. refugia detection and characterisation, a high resolution (10cm) helicopter based Thermal Infrared Imagery (TIR) platform was developped at INRS-Ete. Over 300 km of riverine thermal data was acquired using this platform, including repeated coverage in some systems under varying seasonal climate regimes. A GIS and Matlab based georeferencing and refugia type classification system was also developped, from which statistics were extracted on the linear density (refugia per river km) of the various types of refugia and how this distribution varied with river and valley geomorphic type. It was discovered that the linear density and persistence of refugia along a given system increased with total spring and early summer runoff volumes, a proxy for annual groundwater recharge.
Other projects under this component investigated the geomorphic and hydrological controls on the main types of refugia (cool tributary plumes, lateral seeps and cold, channel margin alcoves). Larger alcoves with sandy-silt beds and those situated alongside higher river banks are more likely to hold cooler water and were observed to serve as thermal refugia under heat stress conditions. Along thalweg alluvial pools in study gravel bed rivers almost never stratify significantly, but the deepest bedrock pools can. The largest individual refugia are cool trib plumes. Hydraulic modelling revealed that cool tributaries create more refugia habitat when they flow into lower slope, slower mainstem reaches. The hydraulic modelling further shows that it is technically feasable to create temporary cool plume refugia for thousands of salmonid juveniles by

pumping stream bank groundwater using a solar pannel powered, temperature trigerred, low discharge (l/s scale) submersible pump.

Component 2 investigated Pit tagged salmon and trout behavior, displacements and temperature thresholds for refugia use during heat spells, in reaches with and without known refugia.

358 Atlantic salmon parr were individually tagged with Passive Integrated Transponders (PIT tags) in early June in three river reaches of Little Southewest Miramichi River (LSWM). Two of the river reaches provided various types of cold water refugia (point source seeps and tributary plumes) whereas one river reach served as a control without any adjacent cold water source. The tagged fish were monitored using active tracking surveys before, during and after thermally stressing events. In addition, stationary PIT monitoring systems were established in two cold-water refugia to provide continuos data on fish aggregation times. Of the tagged fish, 46 % were re-located in a cold water refugia during a high temperature event. Spatial distribution of the fish was collected also before and after the fish aggregated in to cold water refugia.
Stationary PIT monitoring systems were also established around two known trbutary plume refugia in the River Ouelle, Quebec, and 250 salmon parr were tagged in order to collect data on aggregation thresholds in this river system (similarly to LSWM in 2010). This is important to be able to compare the similarities and differencies in salmon parr behaviour between the river systems.
Aggregations of Atlantic salmon parr were observed in all of the monitored cold water refugia during thermal events in 2010 when water temperature exceeded 30 ^{o}C. Different cold water refugia supported variable numbers of fish (ranging from 50 to over 5000 salmon parr) depending of the amount of cold water flow. There was some indication that carrying capacity of the smaller refugia was exceeded causing between refugia movements during the thermal stress period. Large scale mortalities in all age groups (incl. adult salmon) were observed throughout the monitored area during the warmest part of the 2010 event. The collected data was used to build a logistic regression threshold model for LSWM.
Aggregations of YOY parr were observed when water temperature exceeded 28 ^{o}C, and the temperature conditions during the previous night were not below 23 ^{o}C. Movements to locate cold water refugia occurred in both up- and downstream directions. Fish were able to find refugia located on the opposite side of the river from the initial fish location. Largest detected movements were > 8 km. The control reach with no cold water refugia was void of fish during thermally stress event and tagged with from this area were observed approximately 4 km away (both up- and downstream)

Component 3 modelled the mid-century fate of cool tributary and groundwater fed spring refugia, given of a range regional climate warming scenarios.

Mainstem and refugia water temperatures in future climate scenarios. The persistence of thermal refugia may be of capital importance for the survival of salmon populations in many Canadian rivers. This work focused on three important salmon rivers of eastern Canada, two of which (Ouelle and Little Southwest Miramichi) warm up to temperatures higher than the Atlantic salmon lethal limit (>28°C) repeatedly most summers. Water temperature was monitored at 53 sites on the three basins during 2 to 18 summers (June to September), with about half of these sites (27) being known or potential thermal refugia (usually cold tributaries). Site-specific statistical models predicting water temperature were developed using air temperature and precipitation, in order to assess how many of these sites provided potential thermal refugia between 1970 and 1999 based on historical meteorological conditions, and how many will remain cool enough to serve as refugia in the future (2046-2065), based on ten different climate scenarios. Results indicate that according to a range of ten thermal stress temperature metrics (describing mean daily values, weekly maximum values and occurrence, duration and timing of high temperature events), the thermal regimes of all three rivers will be significantly affected by climate changes and mainstem fish habitat will be consequently reduced. The persistence of thermal refugia could thus become critical for the sustainability of salmonid populations in South-eastern Canada. The majority of refugia modeled remain at least 1C cooler than local mainstems during future stress periods However, in the most extreme future scenarios, the resultant refugia temperatures may in many places still become too warm, in absolute terms, for some salmonids, based on their current tolerance ranges.

Groundwater Modelling

This project component was focused on groundwater-sourced thermal refugia in the Little Southwest (LSW) Miramichi River in central New Brunswick. The transport of groundwater and heat in two aquifer-stream systems with contrasting geometries (i.e. Otter Brook, a shallow spring fed stream, and a deeper seated, river terrace groundwater seepage area) was simulated with numerical models. Downscaled, regional climate model results were used to define the temporal recharge boundary conditions for the groundwater flow and heat transport

models. At the two sites modeled, shallow groundwater temperatures were increased with global climate warming, especially by mid-late-summer in the case of shallow aquifers, although they are increased less than air temperatures as significant winter snowpack decreases cool ground temperatures in winter. Due to increased winter snowmelt and spring precipitation totals, groundwater recharge was not decreased and indeed increased according to some future climate scenarios. The results suggest that spring fed refugia issuing from deeper and larger aquifers are better buffered against climate warming and may become particularly important for salmonid fish populations.

Dissemination of Research Results

Refereed Journal Articles Submitted :	2
Refereed Journal Articles Accepted or Published:	7
Conference Presentations/ Posters:	15
Other (Technical Reports, Non-Refereed Articles, etc.):	3
How many of the publications, conference presentations, etc. identified above were co-authored with a non-academic partner?	0

Refereed Journal Articles, Submitted

Kurylyk, B.L., K.T.B. MacQuarrie, J.M. McKenzie (In Review), Projecting climate change impacts on groundwater and soil temperature: Previous studies and emerging methods, *Earth-Science Reviews*.

Kurylyk, B.L., K. Watanabe (In Review), Review: The mathematical representation of freezing and thawing processes in variably-saturated, non-deformable soils, *Advances in Water Resources*.

Papers in preparation (in order of expected completion)

Gendron, JF and M. Lapointe (in prep.) Thermally stratified thermal refuges for salmonids in two Quebec salmon rivers: occurrence, dynamics and implications for summer survival of stream salmonids
To be submitted to *Environmental Hydrology*

Kurylyk, B.L., K.T.B. MacQuarrie, C.I. Voss (In prep.) Impact of climate change on the magnitude and temperature of groundwater discharge from shallow aquifers, intended for *Water Resources Research*.

ST-HILAIRE, A., A. DAIGLE, M. LAPOINTE, D. CAISSIE. 2012.Modelling of Future Water Temperature And Extreme Events In Catamaran Brook. To be submitted to the *Canadian Water Resources Journal.*

Corey, E., Dugdale, S.J., Gendron, J-F., Linnansaari, T., Franssen, J., Bergeron, N., Lapointe, M., Cunjak, R.A. Environmental thresholds and behavioural thermoregulation of juvenile Atlantic salmon (*Salmo salar)* in two Eastern Canadian rivers.

Corey, E., Linnansaari, T., Cunjak, R.A. Movement patterns of juvenile Atlantic salmon (*Salmo salar)* in relation to cool water refugia.

Corey, E., Breau, C., Linnansaari, T., Cunjak, R.A. Predicting the aggregation response in juvenile Atlantic salmon (*Salmo salar)*; a model-based approach.

Corey, E., Linnansaari, T., Cunjak, R.A. Juvenile Atlantic salmon (*Salmo salar)* in warming rivers; does the presence of cool water alter wide-scale distribution patterns?

Corey, E., Currie, S., Linnansaari, T., Cunjak, R.A. Fish in hot water; examining the effects of multiple day heat stress on the physiology of juvenile Atlantic salmon (*Salmo salar).*

Refereed Journal Articles, Accepted or Published

Beauregard, David, Eva Enders, and Daniel Boisclair. (in press 2013. Consequences of circadian fluctuations in water temperature on the standard metabolic rate of Atlantic salmon parr (Salmo salar). Can. J. Fish. Aquat. Sci.

Dugdale S, Bergeron NE, St-Hilaire ASH. 2013. Temporal variability of thermal refuges and water temperature patterns in an Atlantic salmon river, Remote Sensing of Environment **136**: 358–373.

Kurylyk, B.L. and K.T.B. MacQuarrie (2013), A new analytical solution for assessing projected climate change impacts on subsurface temperature, *Hydrological Processes*. Published Online, doi:10.1002/hyp.9861.

Kurylyk, B.L. and K.T.B. MacQuarrie (2013), The uncertainty associated with estimating future groundwater recharge: A summary of recent research and an example from a small unconfined aquifer in a northern climate, *Journal of Hydrology*, 492 (7), 244-253, doi:10.1016/j.jhydrol.2013.03.043.

Kurylyk, B.L., C.P. -. Bourque, and K.T.B. MacQuarrie (2013), Potential surface temperature and shallow groundwater temperature response to climate change: an example from a small forested catchment in east-central New Brunswick (Canada), *Hydrology and Earth System Sciences Discussions*, 10, 3283-3326, doi:10.5194/hessd-10-1-2013 (Accepted for *HESS*).

Monk, W.A., N. Wilbur, R.A. Curry, and R. Faux. 2013. Using landscape-scale geospatial information to predict summer, cold water refugia in rivers. J. Environ. Mgt. 118:170-176.

JEONG, D.I., A. DAIGLE, A. ST-HILAIRE. 2012. Development of a Stochastic Water Temperature Model And Projection of Future Water Temperature And Extreme Events In The Ouelle River Basin In Québec, Canada. *River Research and Applications* DOI: 10.1002/rra.2574

Other (Technical Reports, Non-Refereed Articles, etc.)

Theses

David Beauregard. 2012. Mémoire de maîtrise. Conséquences de l'acclimatation à différents régimes thermiques sur les taux métaboliques standards des tacons du saumon de l'Atlantique (Salmo Salar). Université de Montréal. Département de sciences biologiques, Faculté des arts et des sciences. 76 pp.

Corey, E. (PhD thesis in prep., anticipated completion 2014) The effects of warming rivers on juvenile Atlantic salmon. Department of Biology, University of New Brunswick, Fredericton, NB.

Kurylyk, B.L. (These In prep.) Simulated effects of climate change on future subsurface thermal and hydraulic regimes. PhD, Department of Civil Engineering, University of New Brunswick, Fredericton.

Wilbur, N. (2012), Characterizing thermal refugia for brook trout (*Salvelinus fontinalis*) and Atlantic salmon (*Salmo salar*) in the Cains River, New Brunswick, Canada. MScE, Department of Civil Engineering, University of New Brunswick, Fredericton.

Dugdale SJ (PhD thesis in prep., anticipated completion 2014) Riverscape scale distribution of cold water refugia in Atlantic salmon rivers, Institut National de la Recherche Scientifique, Centre Eau Terre et Environnement

Gendron, Jean-François, 2013, MSc Thesis. Physical controls on summer thermal refuges for salmonids in two gravel-cobble salmon rivers with contrasting thermal regimes: the Ouelle and Ste-Marguerite Rivers. Department of Geography. McGill University

Research reports

Dugdale, SJ, Clerc, C, Bergeron, N. 2013. *Acquisition of airborne optical and thermal infrared (TIR) imagery, Restigouche River watershed project, year 2*. Rapport preliminaire, Février 2013. Institut National de la Recherche Scientifique, Quebec, Canada

Conference Presentations

Dugdale S, Bergeron NE. 2011. Detection of Multi-Scale Salmonid Thermal Refugia from Airborne Thermal Infrared (TIR) Imagery. *Symposium on Riverscape Ecology: Theory and Application for Understanding and Conserving*

Lotic Fishes. American Fisheries Society 141st Annual Meeting, Seattle, Washington, Sept 4-8 2011.

Dugdale S, Bergeron NE, Rousseau, M. 2011. Detection of salmonid thermal refugia from airborne thermal infrared (TIR) imagery. European Workshop for Doctoral Fellows on Salmo salar and Salmo trutta research, NoWPaS Salmonid Research Network. Gotein-Libarrenx, France, 17 – 20 March.

Dugdale S, Bergeron N, Rousseau M. 2011. L'utilisation des images aériennes infrarouges pour détecter les refuges thermiques des salmonidés. 14ème colloque annuel du Centre Interuniversitaire de Recherche sur le Saumon Atlantique (CIRSA), Université Laval, Québec. 5 – 6 Mai

Dugdale S, Bergeron N, Rousseau M. 2010. Détection des refuges thermiques des salmonidés basée sur la télédétection aérienne. 13ème colloque annuel du Centre Interuniversitaire de Recherche sur le Saumon Atlantique (CIRSA), Université Laval, Québec. 27 – 28 Avril

Dugdale S, Bergeron N, Rousseau M. 2010. Detection of salmonid thermal refugia from airborne thermal infrared (TIR) imagery. Gravel Bed Rivers 7, Tadoussac, Québec. 5 – 10 September

Dugdale S, Bergeron N, Rousseau M. 2010. Detection of salmonid thermal refugia from airborne thermal infrared (TIR) imagery. American Geophysical Union (AGU) Fall Meeting, San Fransisco, USA, 13 – 17 December

Knowledge and Technology Transfer

Briefly describe these outcomes

Because of our research, Hydro-Quebec is more aware of the role of thermal refugia in supporting salmon and trout populations , more aware of the effects of damming and flow chnages on the importnace and distribution of these refugia and will be able to acquire and interpret Thermal Infrared imagery to understand these patterns in river's of interest for damming or modifications to flow regimes . Our research also proposed mitigation and refugia enhancement techniques for rivers where refugia are lacking.

Knowledge and Technology Transfer

Describe any environmental or social benefit that resulted or could result in the future from this research

Our research will allow salmonid resource managers to priorise for intervention and conservation in the context of climate warming, fish populations for which thermal refugia are not overly rare (low resilince populations) or where refugia habitat enhancement is possible.