THE IMPACT OF DAMS ON THE WINTER THERMAL REGIME OF STREAMS:

PROGRESS REPORT

THE IMPACT OF DAMS ON THE WINTER THERMAL REGIME OF STREAMS: PROGRESS REPORT

RAPPORT DE RECHERCHE # R1506

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INTRODUCTION

Fisheries and Oceans' Center of Expertise on the Effects of Hydropower on Fish and Fish Habitat (CHIF) is conducting research in partnership with the HYDRONET NSERC (Natural Science and Engineering Research Council) network (http://www.hydronet.umontreal.ca/accueil.htm). As part of this partnership, researchers from the Gulf Region (D. Caissie) and INRS-ETE (A. St-Hilaire, A. Maheu) are involved in investigating the potential impact of dams on the thermal regime of rivers.

The overall objectives of the project are:

1) to monitor both regulated and natural (reference) HYDRONET sites for comparison purposes and assess the degree of thermal modifications, with an emphasis on summer extremes and winter thermal conditions

2) to study the spatial variability of thermal conditions immediately downstream of dams and to define thermal indices that characterize this variability.

3) to identify important meteorological and streamflow characteristics that can predict the influence (or the degree of change) in river thermal conditions.

The present project, which was funded in part by CHIF, deals specifically with objective 1 and aims at characterizing the potential impact of dams on the winter thermal regime of streams. To achieve this objective, the thermal regime of streams was described for four pairs of rivers in Eastern Canada, each pair made-up one regulated river reach and one natural reference or control reach.

SECTION 1: METHODOLOGY

Water temperature was monitored at four pairs of rivers in Eastern Canada: one regulated river and a reference unregulated river. Rivers pairs were selected by HydroNet according to the following criteria: accessibility, wadeable rivers, study reach ranging between 5 and 10 km and the presence of a dam for at least 15 years. Among the HydroNet sites, the four pairs of rivers that were selected in the present study are shown in Figure 1. Among the study sites, two rivers were regulated by run-of-the river dams (St-Jean and Etchemin) and two rivers were located downstream of a storage reservoir dam (Fourchue and Dee). This site selection allowed to contrast the influence of dams on the winter regime according to the dam type.

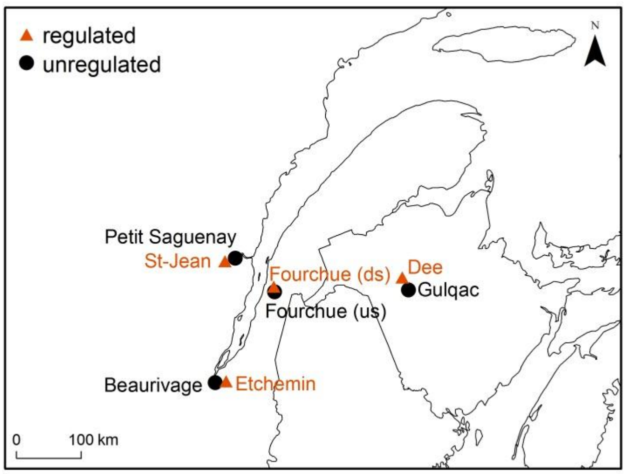

Figure 1. Location of study sites in Eastern Canada (us=upstream and ds=downstream)

Water temperature was monitored by deploying between two and ten water temperature loggers longitudinally downstream of the dam. The longitudinal distance between monitored sites varied according to the estimated impact of the dam, i.e. a smaller distance for run-of-the river dams and a longer distance for storage dams with reservoirs.

In the regulated rivers, water temperature loggers were deployed according to a stratified design. The studied reach was divided into three strata: the first stratum was located near the foot of the dam, the second stratum was in the mid-portion of studied reach and the third stratum was located where the thermal impact from the dam was expected to be minimal. According to the stratified design, 50% of water temperature loggers were deployed in the first stratum, 30% of loggers in the second stratum and 20% in the third stratum.

In the unregulated rivers, water temperature loggers were deployed in a systematic way and loggers were deployed at a relatively equal distance one from another, as accessibility allowed it. The total longitudinal distance covered was comparable to the length of the studied regulated reach.

The thermal regime of streams was characterized for the period of October 1st to June 1st. To describe the thermal regime, a series of metrics was calculated at each site. Metrics describing the magnitude of the thermal regime were computed: the monthly mean, minimum and maximum daily water temperatures. The rate of change was also described by computing the mean rate of decrease in water temperatures between October 1st and the onset of the ice cover (i.e. when water temperature was below 0.5 °C) as well as the mean rate of increase from the onset of positive water temperature and June 1st. The start of the ice cover period was identified as the first period where water temperature was below 0.5 °C for five consecutive days. The end of the ice cover period was defined according to the methodology defined by Daigle et al. (2010):

i. Find the last period of five consecutive days with water temperatures equal to 0 °C. This date corresponds to *min_onset*, which is the end of the frost period and earliest possible date for the end of the ice cover period.

ii. From the end of the frost period, find the day at which cumulative degree-days exceed 10 °C. This date corresponds to *max_onset*, which is the latest possible date for the end of the ice cover period.

iii. The end of the ice cover period corresponds to the earliest date in the [*min_onset*, *max_onset*] interval at which water temperature exceeds 0.5 °C.

Timing was described by calculating the Julian day of year (e.g. January 1st = 1 and December 31st = 365) for the start and end of the ice cover period. Diel variability at each site was also described with the monthly mean daily range where the daily range corresponded to the daily maximum minus the daily minimum. The number of days where the daily range exceeded 0.1 °C was quantified as well.

SECTION 2 – The St-Jean and Petit Saguenay Rivers

The St-Jean and Petit Saguenay rivers are located on the north shore of the St-Lawrence River near the town of L'Anse-Saint-Jean, Québec. Both rivers are tributaries of the Saguenay River and their watershed are contiguous (Figure 2). Forest is the dominant land cover in both watersheds, although housing development is present along both rivers. Atlantic salmon can be found in both streams and recreational fishing is an important part of the local economy.

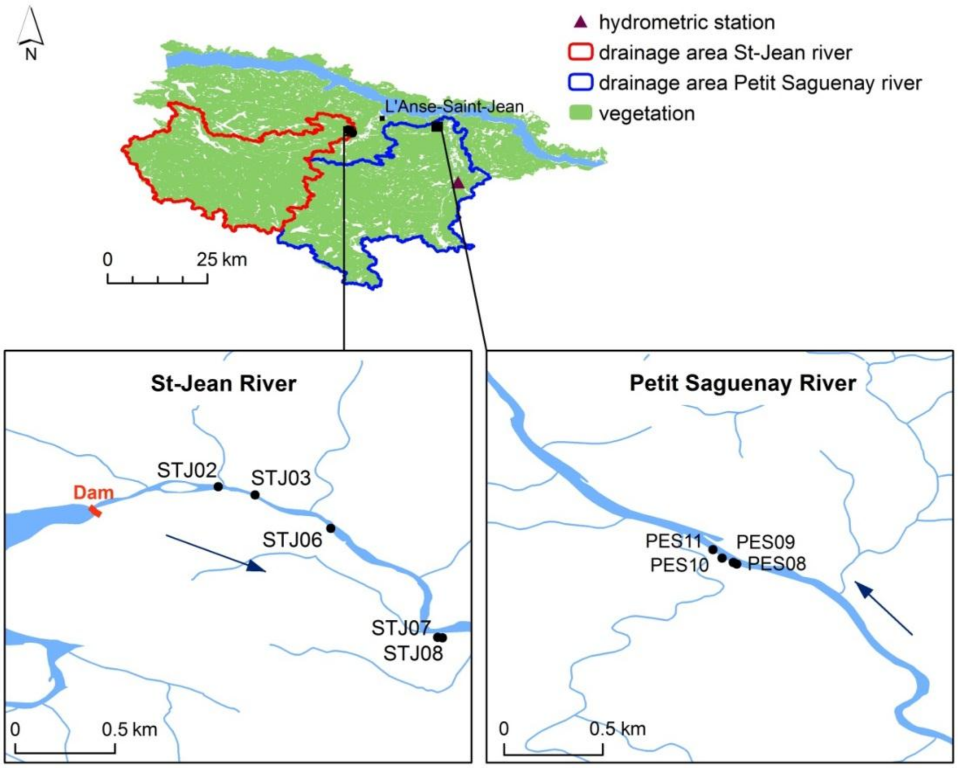

Figure 2. Location of study sites in the St-Jean and Petit Saguenay rivers, winter 2012-13

St-Jean River (regulated)

The Anse-Saint-Jean dam is a 13.2 m-high by 68 m-large concrete gravity dam on the Saint-Jean River. The dam has a capacity of 0.45 MW. This run-of-the-river dam has a small storage capacity which reaches a maximum of 285,575 m³ (CEHQ, 2014). The small reservoir upstream of the dam has an area of 57,000 m². The drainage area upstream of the dam is 647.5 km².

For the winter period, UA-002 Hobo^{TM} pendant water temperature loggers (accuracy of ± 0.5 °C and resolution of 0.1 °C) were deployed over a distance of 6.5 km downstream of the dam. Unfortunately, the most downstream loggers were lost during the spring freshet and the winter thermal regime was monitored for a distance of 1.6 km downstream of the dam (Figure 2).

Petit Saguenay River (natural)

The Petit Saguenay River is an unregulated river. The studied reach was located at about 15 km east of the Anse-Saint-Jean dam. The most upstream point of the studied reach corresponded to a drainage area of 712 km².

For the winter period, UA-002 Hobo™ water temperature loggers (accuracy of ± 0.5 °C) were deployed over a 4.3 km reach. Unfortunately, the most upstream and downstream loggers were lost during the spring freshet and the winter thermal regime was monitored only over a 100m reach (Figure 2).

A hydrometric station operated by the Centre d'expertise hydrique du Québec (station 060102) is located about 25 km upstream of the studied reach. Mean annual flow at the hydrometric station is 10.7 m³/s (1999-2013). Figure 3a illustrates the flow regime during the winter period. In the early autumn of 2012 mean daily flows were low at about 12 m³/s. Toward the end of October, the flow increased drastically and reached 111 m³/s on November 1st, 2012. Flow then decreased and remained at about 3 m³/s for the rest of the winter. After April 20, 2013, the spring freshet started and a maximum flow of 100 m³/s was reached on May 5, 2013. This event was followed by decreasing flows to 30 m³/s and then increased again in late May to then reach 71 m³/s on June 1st (Figure 3a).

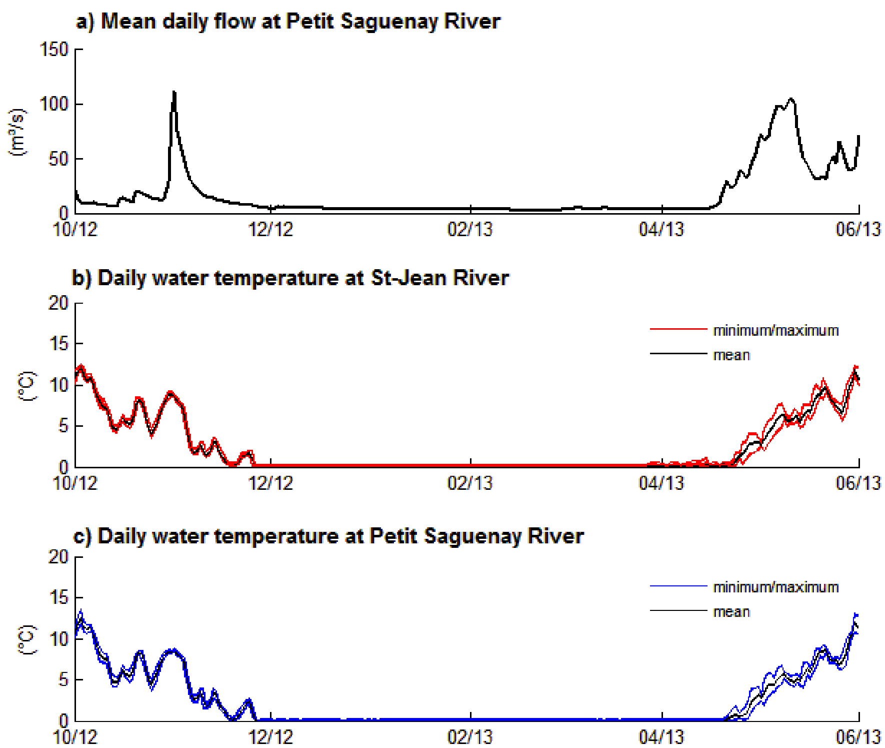

Figure 3. Flow and water temperature from 2012-10-01 to 2013-06-01 at St-Jean (regulated) and Petit Saguenay (natural) rivers

Comparison of winter thermal regimes between rivers

The two studied reaches on the St-Jean and Petit Saguenay rivers shared very similar annual thermal regimes (Figure 3b and 3c). In the fall, mean daily water temperature decreased at a mean rate of -0.18 °C/day for both rivers between October 1st and freeze-up occurred, which occurred around November 30th at both rivers. Water temperatures remained close to 0 °C until the end of March due to the isolating effect of the ice cover. Ice breakup occurred around April 24th, 2013 as mean daily water temperatures raised above 0.5 °C at both rivers. Between ice break up (April 24th) and June 1st, mean daily water temperature increased at a mean rate of 0.25 °C/day at the St-Jean river and 0.27 °C/day at the Petit Saguenay river.

Overall, the Anse-Saint-Jean dam did not have a measurable effect on the winter thermal regime of the St-Jean River, as the magnitude and timing of the annual water temperature cycle were not significantly different between the St-Jean and Petit Saguenay rivers. Longitudinal water temperature profiles were also similar at the two rivers and no longitudinal gradient in water temperature was identified downstream of the dam. Two minor differences were observed between the two studied river reaches.

First, during the ice cover period (i.e. period where water temperatures remained below 0.5 °C), a difference in diel variability was observed across studied sites. Figure 4 shows the number of days where the daily water temperature range was greater than 0.1 °C at each site. At the Petit Saguenay River, the daily range was null or close to zero at the three most upstream sites. Less than 150 m downstream, small diel fluctuations were recorded for more than 25 days at the site PES11. In January, the greatest variability was observed at the foot of the dam on the St-Jean River. In February, variability was also greater at the most upstream site (STJ02) but null about 150 m downstream at STJ03.

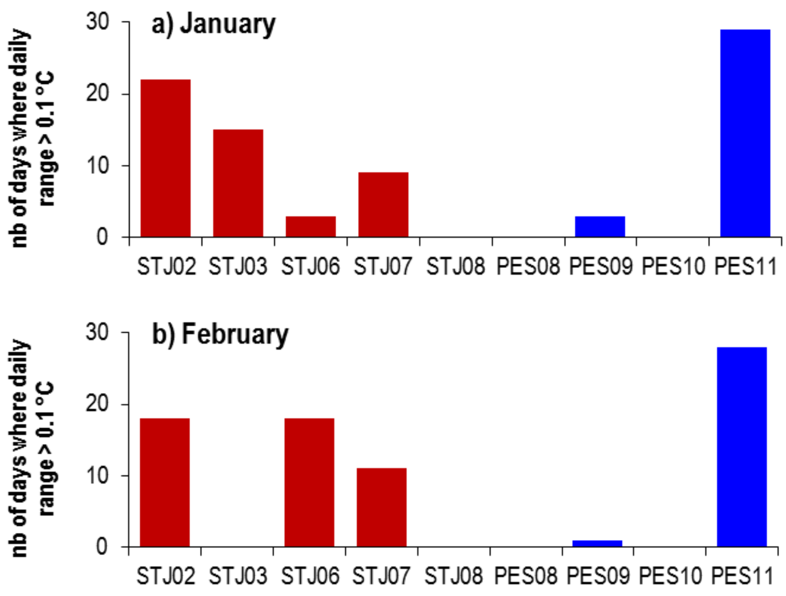

Figure 4. Number of days where the daily water temperature range was greater than 0.1 °C on the St-Jean (STJ) and Petit Saguenay (PES) rivers

Differences in diel variability across sites could be due to different river ice formation processes, a hypothesis that unfortunately cannot be validated given that ice cover data (e.g. thickness and areal coverage) were not collected in the winter 2012-13. A partial ice cover with open water in the middle of the channel could lead to greater diel fluctuations in water temperatures than under a fully developed insulating ice cover. For example, in the winter 2013-14, only a partial ice cover developed below the dam at STJ02 (Figure 5) and such river ice formation could also have occurred in the winter 2012-13. Linkages between river ice formation and water temperatures will be further explored when the winter 2013-14 data are available. As such, water temperature loggers with a greater precision were deployed as well as two cameras to capture ice cover information at both rivers.

Although only a partial ice cover was observed below the dam in the winter 2013-14, this distinctive feature could be due to the local topography and morphology of the river where the dam is located rather than an effect of the dam structure itself. For example, dams tend to be built at sites of high gravitational potential energy and thus flow turbulence could explain the potentially distinct ice cover formation below the dam compared to the Petit Saguenay River. Apart from turbulence, difference in variance during the ice cover period could also be due to groundwater flow which can exhibit important spatial variation at the reach level (Evans et al., 1995; Brown et al., 2005).

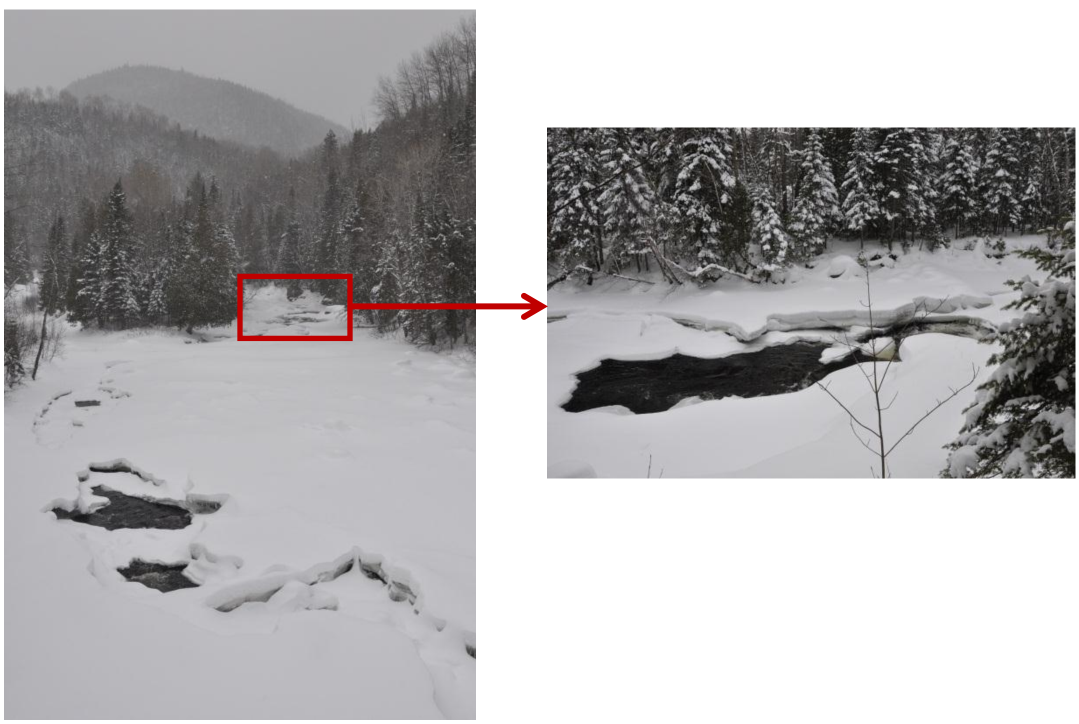

Figure 5. Partial ice cover at STJ02 on the St-Jean River (2014-02-16)

However, the hypothesized difference in ice covers did not influence the onset of positive temperature at the foot of the dam. At the Petit Saguenay River, the onset of positive water temperatures occurred around April 24th, 2013 and the onset of positive water temperatures for sites STJ02 to STJ06, located in the 900 m-reach downstream of the Anse-Saint-Jean dam, occurred around the same date. However, water temperature rose above 0.5 °C about 14 days earlier at the two sites located 1600 m downstream of the dam (STJ07 and STJ08). As such, a slightly earlier ice breakup may have occurred further downstream of the dam. Still, the spring warming rate was similar at all St-Jean sites (0.25 °C/day) and was comparable to Petit Saguenay River (0.27 °C/day).

Secondly, larger maximum water temperatures were recorded at the Petit Saguenay River compared to the St-Jean River as demonstrated by the left-hand portion of the temperature duration curve (Figure 6c). In early fall (2012/10/03) and in late spring (2013/05/31), maximum water temperature reached 13 °C at the Petit Saguenay River while maximum water temperature did not exceed 12.5 °C at the St-Jean River. Differences in maximum water temperatures at St-Jean and Petit Saguenay rivers will be further examined when the summer thermal regime is analyzed in details.

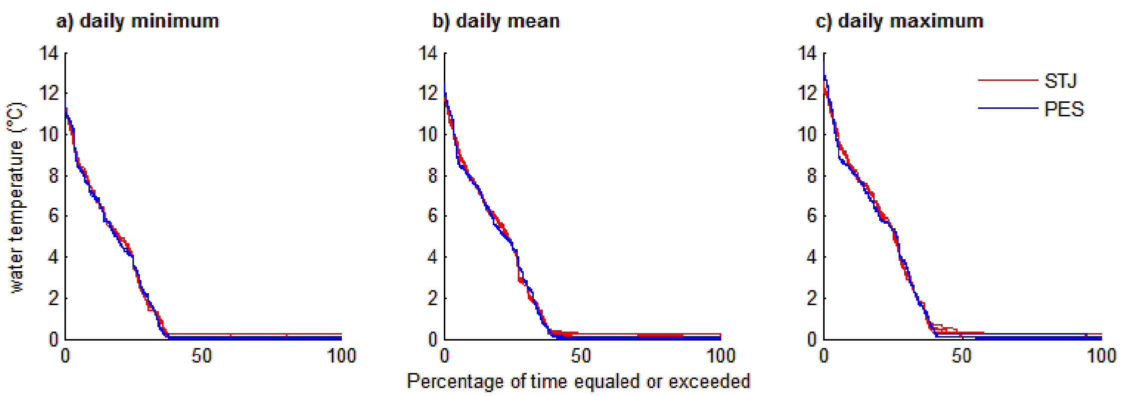

Figure 6. Daily water temperature duration curves at the St-Jean (STJ) and Petit Saguenay (PES) rivers from October 1st, 2012 to June 1st, 2013.

SECTION 3 – The Etchemin and Beaurivage Rivers

The Etchemin and Beaurivage rivers are located on the south shore of the St-Lawrence River, about 10 km from the town of Lévis, Québec (Figure 7). The Chaudière River separates the two drainage basins and about 15 km separate the two study reaches.

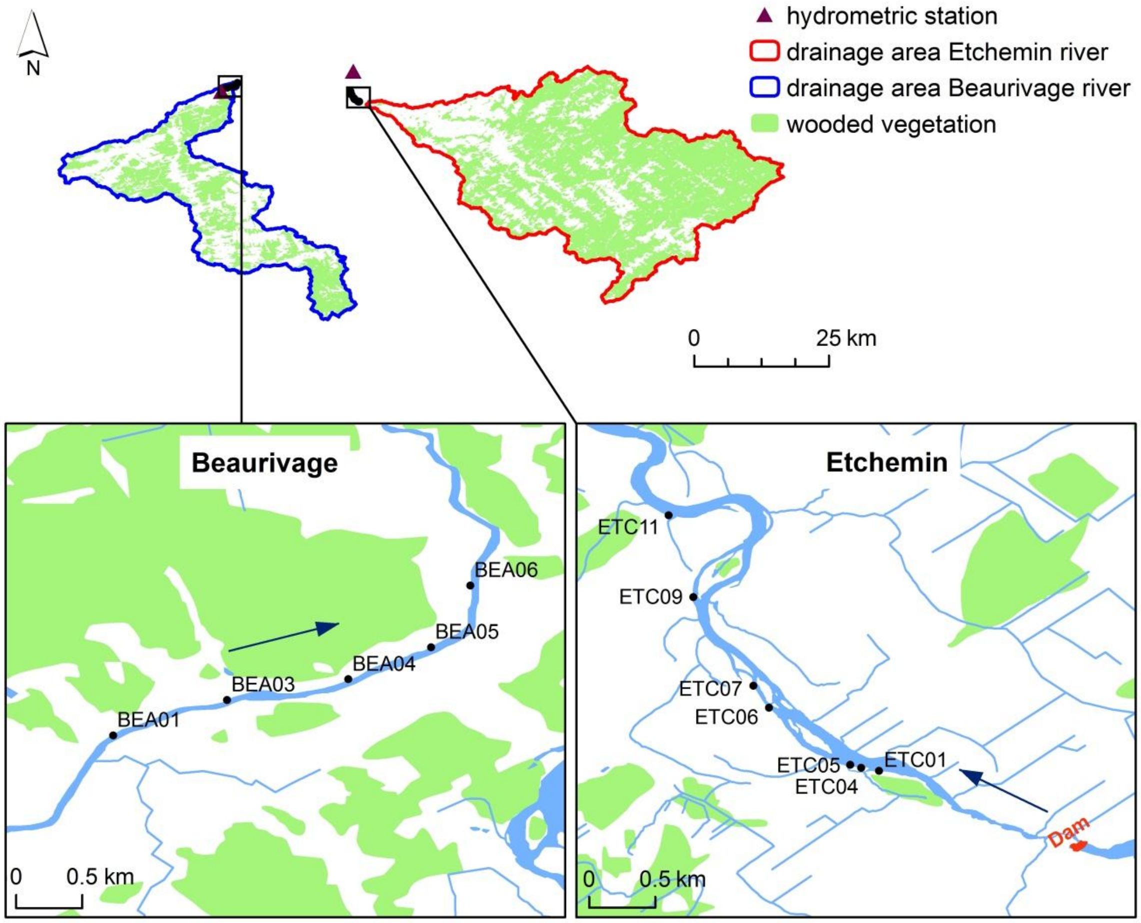

Figure 7. Location of study sites on the Etchemin and Beaurivage rivers, winter 2012-13

Etchemin River (regulated)

The studied reach of the Etchemin River was located in an agricultural area and riparian vegetation was generally sparse or absent on the banks. The substrate of the river was mainly cobbles and boulders and the downstream portion of the studied reach comprised mainly of bedrock.

The Jean-Guérin dam is a run-of-the-river dam built in 1911 at a 23-m high waterfall on the Etchemin River. Historically, the dam has been used to regulate the river levels and for hydroelectricity production and in 1998, a new run-of-the-river power station was built with an annual capacity of 5.9 MW. The Jean-Guérin dam is a 17.5 m-high by 66 m-large concrete gravity dam on the Etchemin River. The water intake is located near the surface. This run-of-the-river dam has a very small storage capacity (maximum of 166 400 m^3) and the reservoir area upstream of the dam is only 80 000 m^2 (CEHQ, 2014).

A hydrometric station operated by the CEHQ is located 9 km downstream of the Jean-Guérin dam (station 023303). The drainage area at the hydrometric station is 1152 km^2. Mean annual flow at the hydrometric station was 16.0 m^3/s (1981-2013). Figure 8a illustrates the flow regime during the winter period 2012-13. In fall 2012, flows were between 9.8 and 61.6 m^3/s. Thereafter, flow decreased in early November to reach a minimum of 4.1 m^3/s on December 1st. During the winter, flow was generally low and stable, ranging between 5.9 and 11.5 m^3/s, with a few occasional small peaks (Figure 8a). For example, flow raised above 30 m^3/s on December 6 (31.4 m^3/s), January 15 (35.4 $^3/s$) and February 1st (55.3 m^3/s). The spring freshet started around March 12 and during this period, the spring flow was highly variable, ranging from 16.5 m^3/s (March 26) to a peak value of 222.3 m^3/s (May 26).

For the winter period, seven UA-002 Hobo™ pendant water temperature loggers (accuracy of ± 0.5 °C and resolution of 0.1 °C) were deployed over a distance of 4.3 km downstream of the dam (Figure 6). Figure 8b illustrates the winter thermal regime at the Etchemin River from October 1st, 2012 to June 1, 2013. In October, the monthly mean water temperature was 9.4 °C at the seven sites of the studied reach. In the fall, mean water temperatures decreased at a rate of -0.19 °C/day until an ice cover formed around November 29th, 2012. From that date, water temperatures remained stable and varied between 0.1 and 0.2 °C until ice break up. In December and January, the mean daily standard deviation was smaller than 0.01 °C in the first 2 kilometers below the dam (ETC01 to ETC06 on Figure 7) and slightly superior (0.03-0.04 °C) in the downstream portion of the studied reach (ETC07 to ETC11 in Figure 7). Ice break up occurred around April 10th, 2013 in the first 1.5 kilometers downstream of the dam (ETC01 to ETC05) and about 4 to 5 days later in the downstream portion of the studied reach (ETC06 to ETC11). Between ice break up and June 1st, mean daily water temperatures increased at a rate of 0.31 °C/day in the first 1.5 kilometers downstream of the dam and at a rate of 0.33 °C/day in the most downstream portion of the studied reach. On June 1st, cumulated degree-days reached 478 °C-days in the first 1.5 kilometers downstream of the dam and 473 °C-days in the downstream section.

Beaurivage river (natural)

The Beaurivage River is an unregulated river and the main land use within the watershed is agriculture. The study reach is located 18 km from the Jean-Guérin dam, in a residential portion of the watershed. As a result of the agricultural land use, riparian vegetation was generally sparse or absent from banks.

A hydrometric station operated by the CEHQ is located 470 m upstream of the studied reach (station 023401) and has a drainage area of 708 km^2. Mean annual flow at the hydrometric station was 14.3 m^3/s (1926-2013). Figure 8c illustrates the flow regime during the winter period (October 2012 to June 2013). In the fall 2012, a series of rainfall event led to rapid increases in flow, reaching maximum values ranging from 24 to 72 m^3/s. In November, flow decreased and a minimum flow was reached on December 1st (2.1 m³/s). During the winter, flows were generally low, ranging from 2 to 6 m³/s. Flow raised above these values on three occasions : December 5 (10.3 m³/s), January 15 (32.4 m³/s) and February 1st (45.4 m³/s). The spring freshet occurred around March 14th, with flows reaching 125 m³/s. During the spring, flows were highly variable and varied between 5.2 m³/s (May 8) and 183.8 m³/s (May 26).

For the winter period, UA-002 Hobo™ pendant water temperature loggers (accuracy of ± 0.5 °C and resolution of 0.1 °C) were deployed over a distance of 4.5 km. However, the most downstream loggers were lost during the spring flood and winter water temperature data were available over a 2.6 km reach (Figure 7). Figure 8d illustrates the winter thermal regime at the Beaurivage River from October 1st, 2012 to June 1, 2013. In October, the monthly mean water temperature was 9.4 °C and mean daily water temperature decreased at a mean rate of -0.16 °C/day until the formation of an ice cover. The date of river ice formation varied from December 1st at the most downstream site of the study reach (BEA06) to December 10th at sites BEA01 and BEA05. Mean daily water temperature varied between 0.1 and 0.3 °C between December and March. In January and February, the mean daily standard deviation was 0 °C, except for the most downstream site (BEA06) where it was 0.05 °C. The onset of water temperature above 0.5 °C occurred around April 15, 2013 at all five sites and mean daily water temperatures increased at a mean rate of 0.37 °C/day. On June 1st, an average of 554 °C-days had been accumulated in the Beaurivage River.

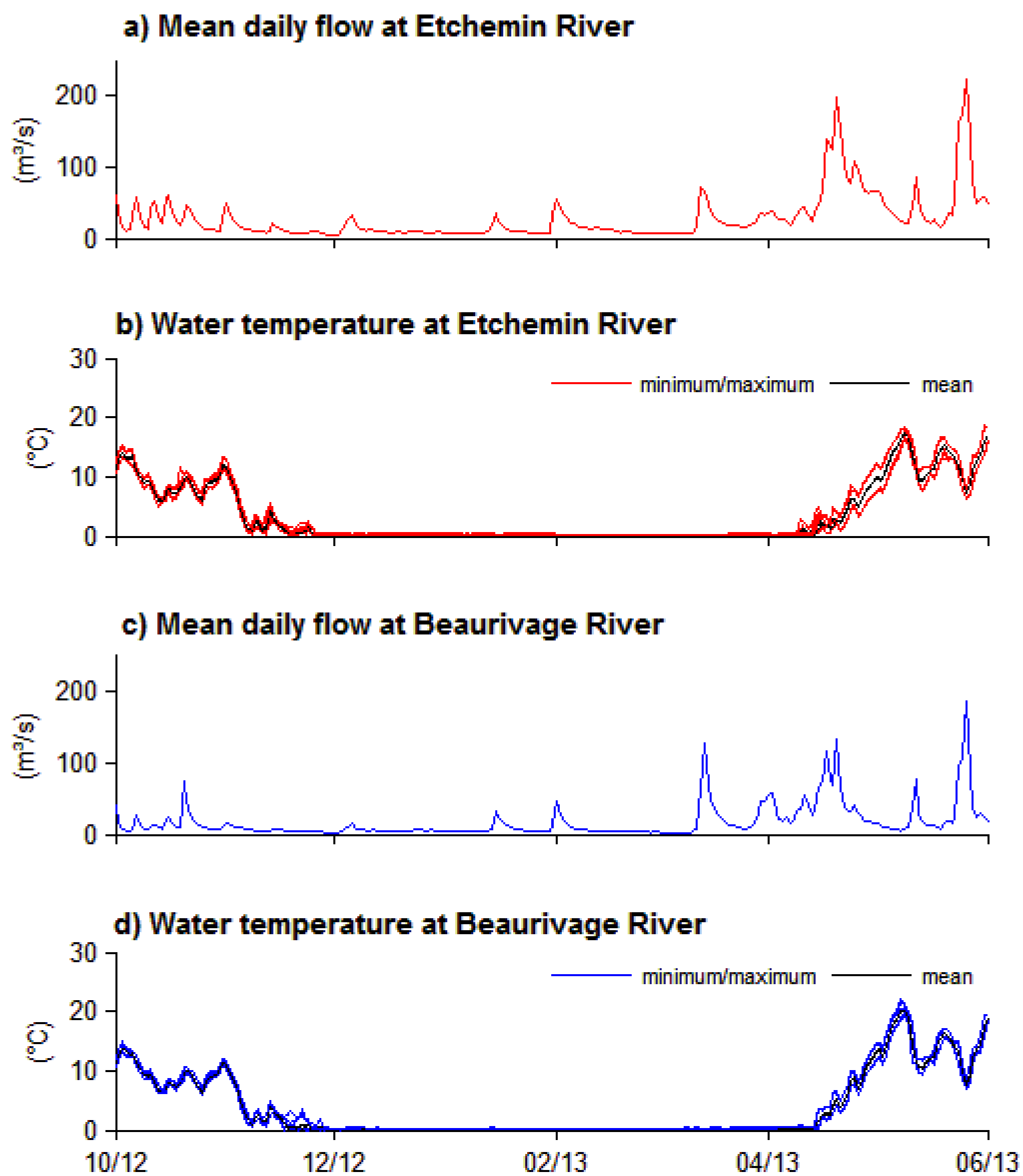

Figure 8. Flow and water temperature from 2012-10-01 to 2013-06-01 at Etchemin (regulated) and Beaurivage (natural) rivers

Comparison of winter thermal regimes between rivers

In the fall, the magnitude and rate of change of water temperatures were comparable between the Etchemin and Beaurivage rivers. Mean monthly water temperatures were not significantly different between the two rivers from October to December (Kruskal-Wallis test, $p<0.05$ combined with multiple comparison test showing differences larger than the instrument accuracy). Water temperatures also decreased at a mean rate of -0.2 °C/day at both reaches from October 1st to the onset of the ice cover. The timing of river ice formation occurred slightly later in the upstream portion of the Beaurivage river reach (between December 5 and 10, 2012) compared to the Etchemin river (November 29-30, 2012).

In the winter, the thermal regime of the Etchemin and Beaurivage rivers were very similar. Ice covers developed over both river reaches and water temperatures remained between 0 and 0.3 °C between December 2012 and March 2013. During that period, water temperatures were stable and the monthly standard deviation remained below 0.1 °C. Variance during the ice cover period was very similar between the two reaches (Figure 9). The most upstream sections of the studied reaches exhibited little diel variance during the ice cover period, with less than three days where the diel range exceeded 0.1 °C in January and February. Even at the foot of the Jean-Guérin dam, the diel range was 0 °C in January and February. During the winter 2013-14, an ice cover developed on top of the dam itself which could explain the lack of diel variance downstream of the dam (Figure 10). The downstream section of the studied river reaches presented more important diel variability, with more than 25 days where the daily range exceeded 0.1 °C. The onset of water temperatures above 0.5 °C occurred first at the foot of the Jean-Guérin dam (April 10th, 2013), while it occurred about five days later in the downstream portion of the Etchemin river as well as on the Beaurivage river (April 15, 2013).

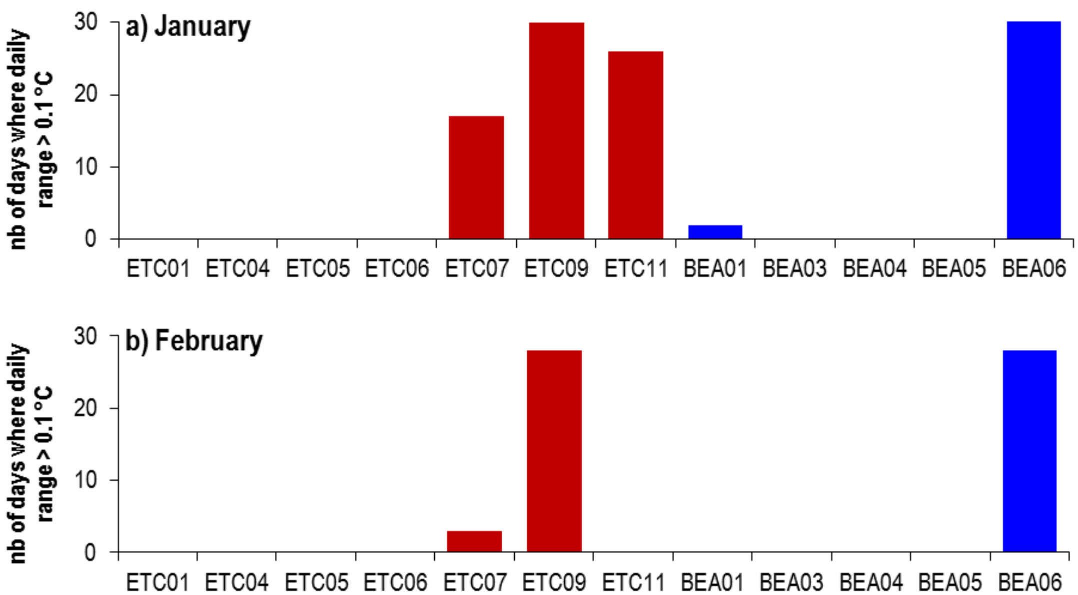

Figure 9. Number of days where the daily water temperature range was greater than 0.1 °C on the Etchemin (ETC) and Beaurivage (BEA) rivers

a)

b)

Figure 10. a) Jean-Guérin dam and b) site ETC06, 2 km downstream of the Jean-Guérin dam (2014-02-11).

The main difference between the two river reaches was observed in the spring. The Beaurivage River warmed up more quickly than the Etchemin River. Between the onset of water temperature above 0.5 °C and June 1st, water temperatures increased at a mean rate of 0.4 °C/day at the Beaurivage River compared to 0.3 °C/day at the Etchemin River. In May, the mean monthly water temperature reached 13.0 °C at the Beaurivage River compared to 11.0 °C at the Etchemin River. As a result, on June 1st, the Beaurivage River had accumulated 554 degree-days compared to 402 degree-days at the Etchemin River. Temperature duration curves also illustrate the warmer water temperatures in the spring at the Beaurivage river compared to the Etchemin River (most noticeable for minimum and mean; Figure 11b). Although the onset of water temperature above 0.5 °C occurred five days earlier at the foot of the Jean-Guérin dam compared to the Beaurivage River, it did not translate into a more rapid warming of the Etchemin River. On the contrary, the Beaurivage River warmed up more quickly in the spring 2013. This difference in the warming rate of the river could be due to the drainage basin size and flow magnitude. Between April 10th and June 1st, the mean flow was 26.9 m³/s at the Etchemin River compared to 14.4 m³/s at the Beaurivage River. With a greater volume of water is associated a greater thermal capacity and more energy will be required to warm up the Etchemin River compared to the smaller Beaurivage River. In the fall, the flow difference was smaller between the two rivers with a mean flow of 25.0 m³/s at Etchemin River and 20.9 m³/s at Beaurivage River between October 1st and December 1st, 2012. As such, the cooling rate of the two rivers were comparable for this period (-0.2 °C/day).

Differences in diel variability were also observed between the two river reaches in the fall and in the spring. In October, the mean daily range was significantly greater at the Etchemin River (1.7 °C) compared to the Beaurivage River (1.2 °C) (Kruskal-Wallis test and multiple comparison test, $p<0.05$). In November, the mean daily range was not significantly different between the two rivers (Kruskal-Wallis test, $p>0.05$). The mean daily range in November ranged between 1.2 and 1.4 °C at the two rivers. In the winter, no significant difference was observed in the magnitude of diel variability between the two river reaches (Kruskal-Wallis test, $p<0.05$ combined with multiple comparison test showing differences larger than the instrument accuracy). In spring, diel variability was greater at the Etchemin River than at the Beaurivage River. In April, the mean daily range varied from 2.1 °C at the foot of the dam to 1.7 °C at 4.3 km downstream of the dam. During the same month, the mean daily range was 1.4 °C at the Beaurivage River. A similar pattern was observed in May where the mean daily range varied from 3.2 °C at the foot of the dam and only 2.8 °C at 4.3 km downstream on the Etchemin River. Meanwhile, the mean daily range was 2.3 °C at the Beaurivage River in May. Differences in diel variability can also be observed on temperature duration curves (Figure 11). For example, maximum daily water temperature rose above 21 °C at the Beaurivage River while it reached a maximum of 18.4 °C at the Etchemin River (Figure 11c).

Overall, diel variability was greater at the Etchemin River in October, April and May compared to the Beaurivage River. The difference in diel variability in the spring can be explained by the smaller flow experienced in the Beaurivage River in the spring (mean flow of 26.9 m³/s on the Etchemin River vs. mean flow of 14.4 m³/s on the Beaurivage River between April 10th and June 1st).

However, diel variability decreased in the downstream direction of the dam at the Etchemin River in the spring. For about 800m downstream of the dam, the Etchemin River can be considered narrow (40 m) as well as being characterized by an important entrenchment. The Etchemin River then widens and reaches a mean width of 110 m at ETC01, which remains relatively constant along the rest of the study reach, although a few islands modify width locally. The width and entrenchment of the river below the dam could explain the longitudinal gradient in diel variability. As a stream widens, diel variability generally increases given the streams is more exposed to meteorological conditions (Caissie, 2006). As such, this distinctive pattern on the Etchemin River could be associated with physiography rather than with the presence of the dam itself.

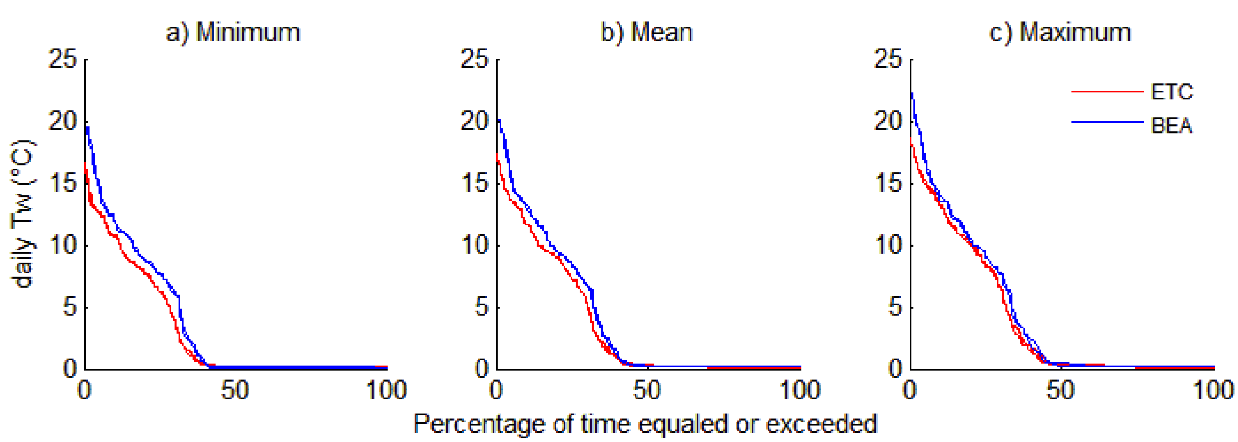

Figure 11. a) Minimum, b) Mean and c) Maximum daily water temperature duration curve at the Etchemin (ETC) and Beaurivage (BEA) rivers.

SECTION 4 – The Dee and Gulqac Rivers

The Dee and Gulqac rivers are located in northern New Brunswick, about 50 km east of Grand Falls. The drainage basins of the two rivers are contiguous and the two rivers are sub-basins of the Tobique river drainage basin, which is a tributary of the Saint John river (Figure 12).

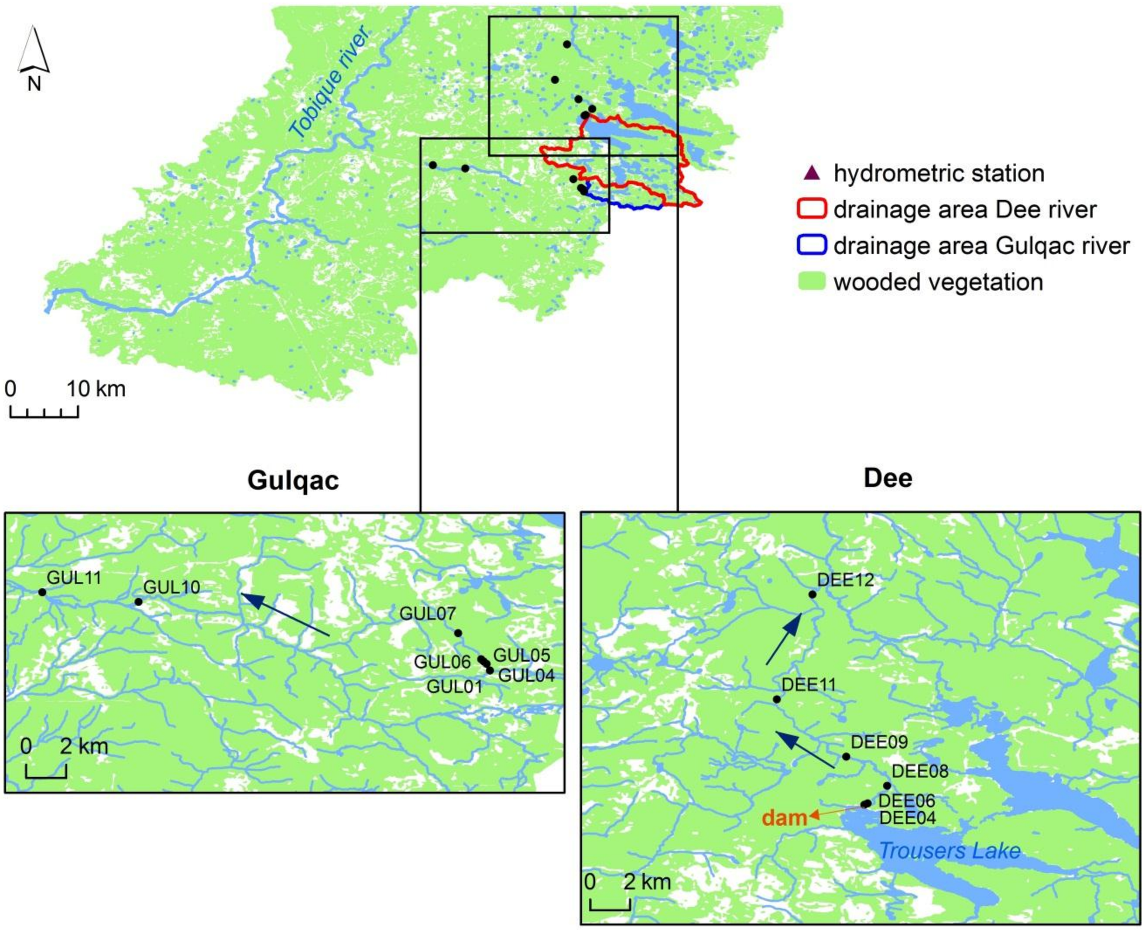

Figure 12. Location of study sites in the Dee and Gulqac rivers, winter 2012-13

Dee River (regulated)

The Dee River is located downstream of the Trousers Lake reservoir (10.8 km²). This reservoir is one of the four headwater storage reservoirs upstream of the Tobique Narrows generating station. These reservoirs are used to store spring runoff and release flows during low flow periods such as winter (Washburn and Gillis, 1996 in Flanagan, 2003). For the winter period, six UA-002 Hobo™ water temperature loggers (accuracy of ± 0.5 °C) were deployed over a 16 km reach (Figure 12).

Figure 13a illustrates the flow regime at the foot of the dam. On October 1st and 2nd, the flow released was respectively 6.1 and 3.9 m³/s. Thereafter, flow remained below 1m³/s until January 8th. During the month of January until mid-February, flows remained above 3 m³/s and peaked at

9.6 m³/s on January 29th. Between February 18 and March 3rd, flows decreased and remained below 1 m³/s. Flows increased again and peaked at 13.1 m³/s on March 5th. Thereafter, flow decreased and remained below 1.5 m³/s between April 4th and June 1st.

Figure 13b illustrates the thermal regime at DEE04 located 120 m downstream of the dam. In the fall, mean daily temperature decreased from a weekly average of 13.5 °C during the first week of October to a weekly average ranging from 6.2 °C (DEE09) to 8.0 °C (DEE04) during the first week of November. In October, mean daily water temperature was on average 0.7 °C warmer at DEE04 (120 m downstream) than DEE09 (4.3 km downstream of dam) and this longitudinal gradient was exacerbated in November with a mean difference of 1.6 °C between the two sites. At the foot of the dam (DEE04), mean daily water temperature decreased at a mean rate of 1.3 °C/day and stabilized around 2 °C around November 27, 2012. For the remaining of winter, mean daily water temperature oscillated between 1.4 and 3.0 °C at the foot of the dam (DEE04). During this period, mean daily water temperature varied between 0 and 2.8 °C at DEE09 (4.3 km downstream of dam) and varied similarly at DEE12 (16 km downstream of the dam), i.e. between 0.2 and 3.3 °C. After March 31st, the mean daily water temperature departed from the winter regime with increasing temperatures as well as increasing diel variability. During the winter period (November 27 – March 31), the mean daily range (i.e. daily maximum minus daily minimum) ranged from 0.4 °C at DEE04 to 0.8 °C at DEE12. In contrast, the mean daily range ranged from 1.2 °C at DEE04 to 3.5 °C at DEE12 in the first week of April. From April 1st to June 1st, mean daily water temperature increased at a mean rate of 2.5 °C at all sites. On June 1st, mean daily water temperatures ranged between 12.5 and 13.1 °C below the dam on the Dee River.

Gulqac River (natural)

The study reach is located 3 km downstream of the Gulqac Lake with an area of approximately 2 km². At the lake outlet, the Gulqac River is wide, reaching approximately 50 m in width and narrows down approximately 10m at the beginning of the study reach. For the winter period, seven UA-002 Hobo™ water temperature loggers (accuracy of ± 0.5 °C) were deployed over a 21 km reach (Figure 12).

Mean daily water temperature from a weekly average of 11.8 °C in the first week of October to a weekly average of 5.5 °C in the first week of November (Figure 13). The ice cover probably formed around November 30th, and water temperature remained below 0.5 °C until April 19, 2013. From the ice breakup around April 23 to June 1st, mean daily water temperature increased at a mean rate of 0.8 °C/day at most sites. Water temperatures were generally comparable across the reach and little differences were observed between the study sites with the exception of the site GUL01. Mean daily water temperature was on average 1.6 °C warmer in the spring at GUL01 which is located upstream of a tributary of the Gulqac River.

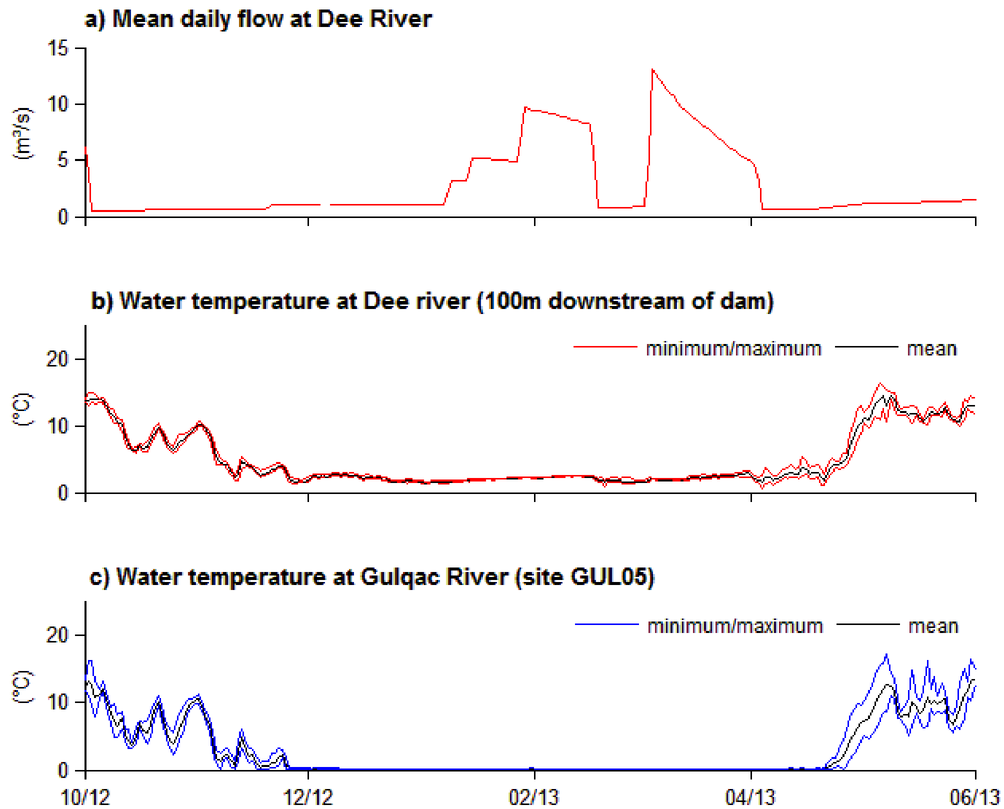

Figure 13. Flow and water temperature from 2012-10-01 to 2013-06-01 at Dee (regulated) and Gulqac (natural) rivers

Comparison of winter thermal regimes between rivers

In terms of magnitude, the Dee River reach had a considerably warmer winter regime compared to the Gulqac River (Figure 14). At 100m downstream of the dam (DEE04), mean daily water temperature remained above 1.4 °C for the entire winter period. At 1.7 km downstream of the dam (DEE08), freezing conditions (mean daily water temperature below 0.3 °C) were only reached for 7 days or 2.5 % of the period. At 4.3 km downstream of the dam (DEE09), freezing conditions were reached for 37 days or 15 % of the study period. In comparison, freezing conditions were observed between 41 % (GUL07) and 60 % (GUL01 and GUL05) of the study period at the Gulqac River.

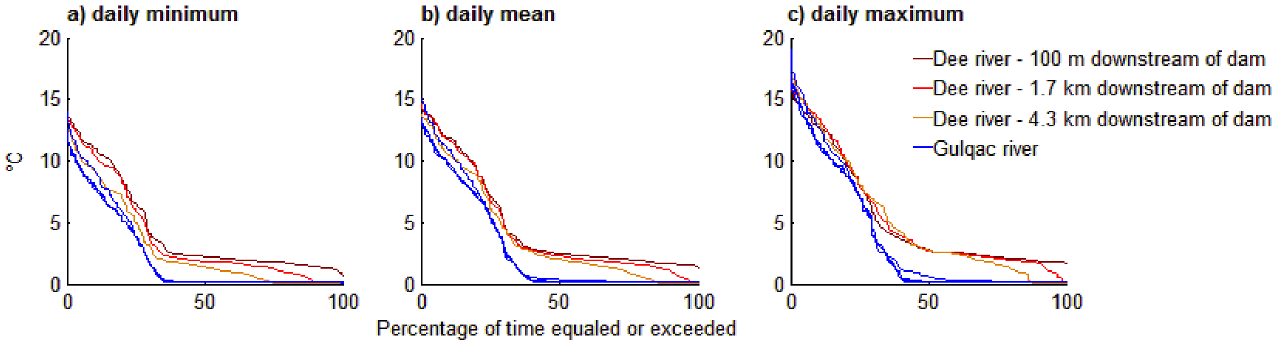

Figure 14. Mean daily water temperature duration curve at the Dee and Gulqac rivers

A clear warming effect due to the dam flow release was observed on the Dee River which was not observed on the Gulqac River. The zone of influence (i.e. the longitudinal impacted distance below the dam) varied throughout the winter in terms of the warming effect. Figure 15 shows the longitudinal profile for the mean monthly water temperature over a distance of 16 km downstream of the dam on the Dee River (in blue). Individual study sites are represented by a dot. Also plotted is the mean monthly water temperature across all study sites at the Gulqac River (solid line) and its variability across the river reach (dotted line represents one standard deviation around the mean).

In October, the Dee River was on average 1.8 °C warmer in the first 2 km downstream of the dam compared to the Gulqac River. At 4 km downstream of the dam, the mean October water temperature reached 8.8 °C which is comparable to GUL01, the warmest sites across the studied reach on the Gulqac River. Data were not available further downstream on the Dee River for the month of October.

In November, the monthly mean water temperature for the first 1.7 km downstream of the dam on the Dee River was between 1 and 1.7 °C warmer than on the Gulqac River. At about 4 km downstream of the dam, the mean November water temperatures were comparable between the two rivers. At about 8 km downstream of the dam, the mean November water temperature reached 0.1 °C which is 2.3 °C cooler than on the Gulqac River for the same period. Therefore, the dam had a warming effect on the first 1.7 km downstream of the dam in November. In December, the dam had a similar zone of influence. The mean December water temperature was 2.2 °C at the foot of the dam and cooled down to 0.4 °C at 4 km downstream, conditions which were similar to the Gulqac River with a mean December water temperature of 0.2 °C. From January to April, the dam has a considerably longer zone of influence on the Dee River. During January and February, mean monthly water temperature remained below 0.3 °C on the Gulqac River. In January, the dam had a significant warming effect on the first 8 km of the river Dee and prevented the formation of an ice cover on that section of the river. In February and March, the zone of influence of the dam extended further and prevented the formation of an ice cover on at least 16 km. In April, the dam had a warming effect on at least 16 km and the mean April water temperature was on average 2.6 °C warmer on the Dee River compared to the Gulqac River. In May, the zone of influence of the dam was reduced to the first 1.7 downstream. In that section of the Dee River, the mean May water temperature was on average 2.5 °C warmer than on the Gulqac River. Figure 17a summarizes the longitudinal distance for which mean daily water temperature on the Dee River were warmer than on the Gulqac River.

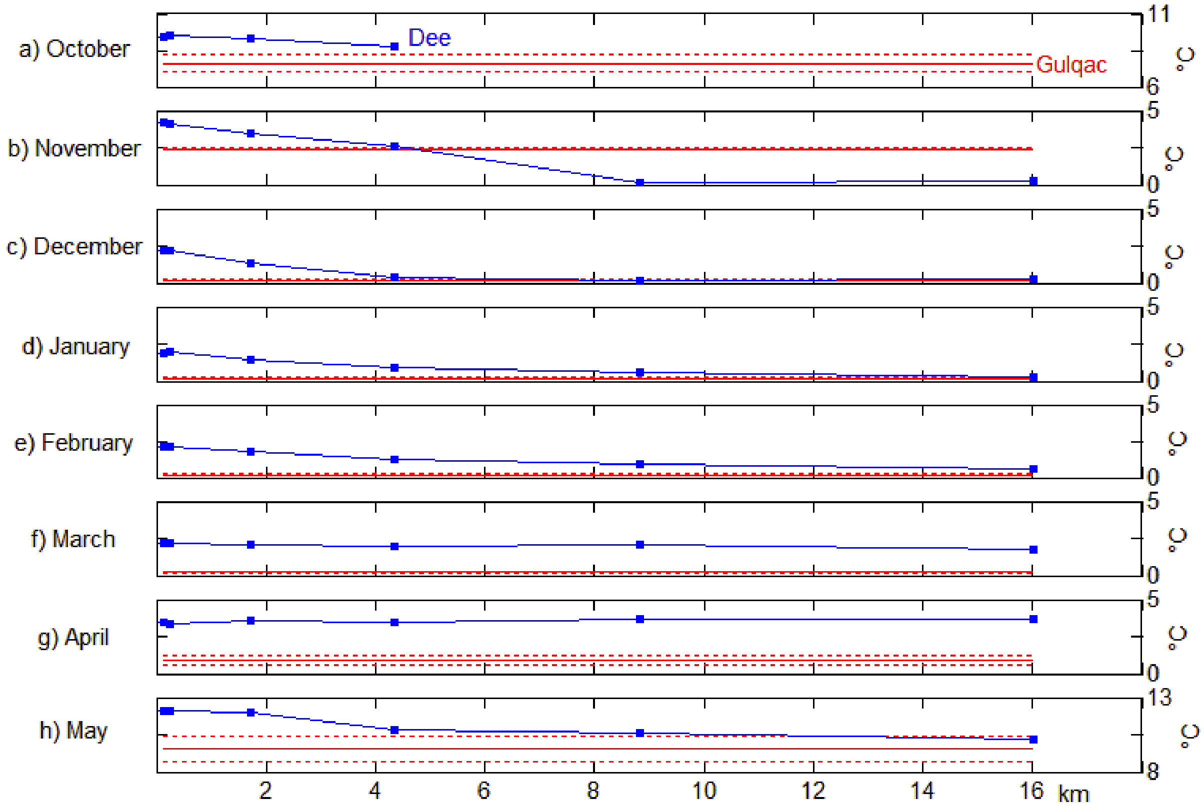

Figure 15. Longitudinal profile of monthly mean water temperatures downstream of the dam on the Dee River (blue). The red line shows monthly mean water temperatures for the Gulqac River (solid red line) ± 1 standard deviation (dashed red line).

In addition to the warming effect of the dam, the impoundment also modified the diel variability on the Dee River (Figure 16). The longitudinal distance downstream of the dam for which diel variability was modified varied throughout the winter period (Figure 17b). In the fall (October and November) and spring (May), diel variability was greater on the Gulqac River than on the Dee River. In October, the daily range varied between 1.1 and 1.7 °C in the first 1.7 km downstream of the dam on the Dee River while it was on average 2.4 °C on the Gulqac River. The difference was less in November where the daily range was 0.9 °C in the first 300 m downstream of the dam and then reached 1.5 °C at 1.7 km downstream of the river, which was comparable with diel variability on the Gulqac River (1.4 °C).

As the ice cover developed on the Gulqac River, the mean daily range was generally below 0.1 °C from December to March. On the Dee River where the dam prevented the formation of an ice over certain sections, the mean monthly daily range ranged between 0.2 and 2.2 °C between December and March. On the river Dee, diel variability was generally lowest at the foot of the dam and increased downstream during the winter. In the spring, diel variability was greater on the regulated river in April and the situation was reversed in May where diel variability was greater on the unregulated reach. The mean April daily range varied between 1.6 to 5.1 °C downstream of the dam, compared to an average mean daily range of 1.2 °C on the Gulqac River. In May, diel variability was inferior for the 1.7 km reach downstream of the dam (2.0 to 3.1 °C) compared to the Gulqac River (4.7 °C). At 4 km downstream of the dam, the mean May daily range was 4.6 °C, which represents conditions comparable to the Gulqac River.

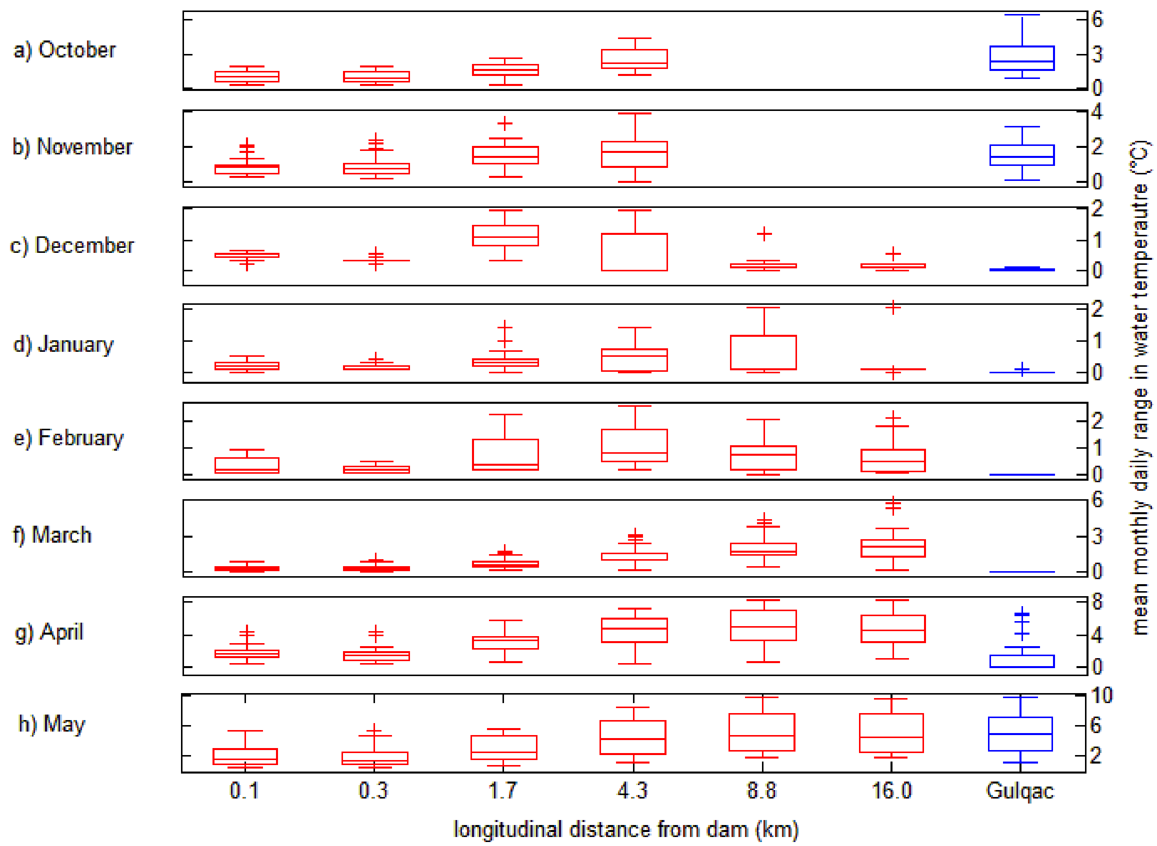

Figure 16. Mean monthly daily range in water temperature in the Dee River (red) and Gulqac River (blue), winter 2012-2013.

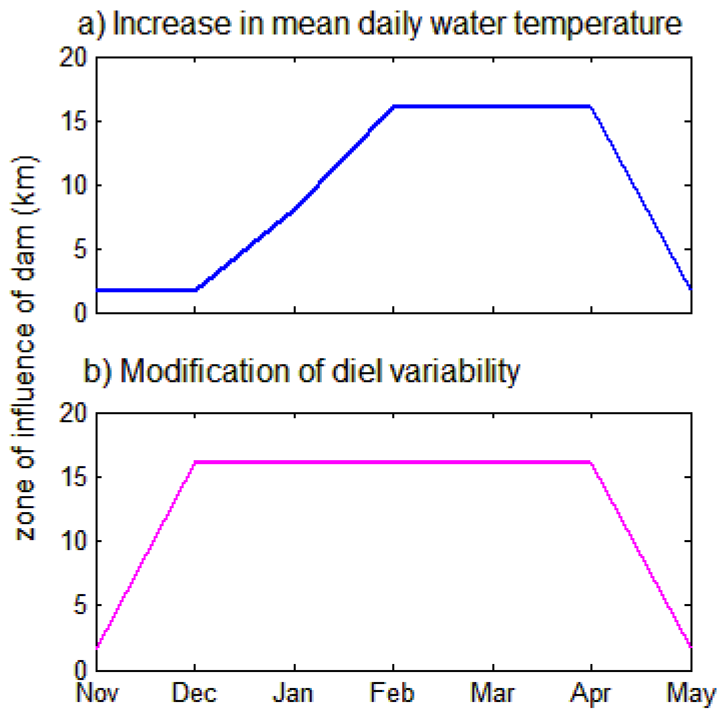

Figure 17. Temporal variation in the minimum longitudinal distance for which the dam modified water temperature conditions on the Dee River, November 2012 to May 13.

SECTION 5 – The Fourchue River

The Fourchue River is located on the south shore of the St. Lawrence River, near the town of St-Alexandre-de-Kamouraska, Québec. The watershed of the river is little developed and is mainly forested, with the exception of the most downstream section, which intersects with agricultural land. As opposed to comparing two different river systems, water temperatures were compared for reaches upstream and downstream of the dam.

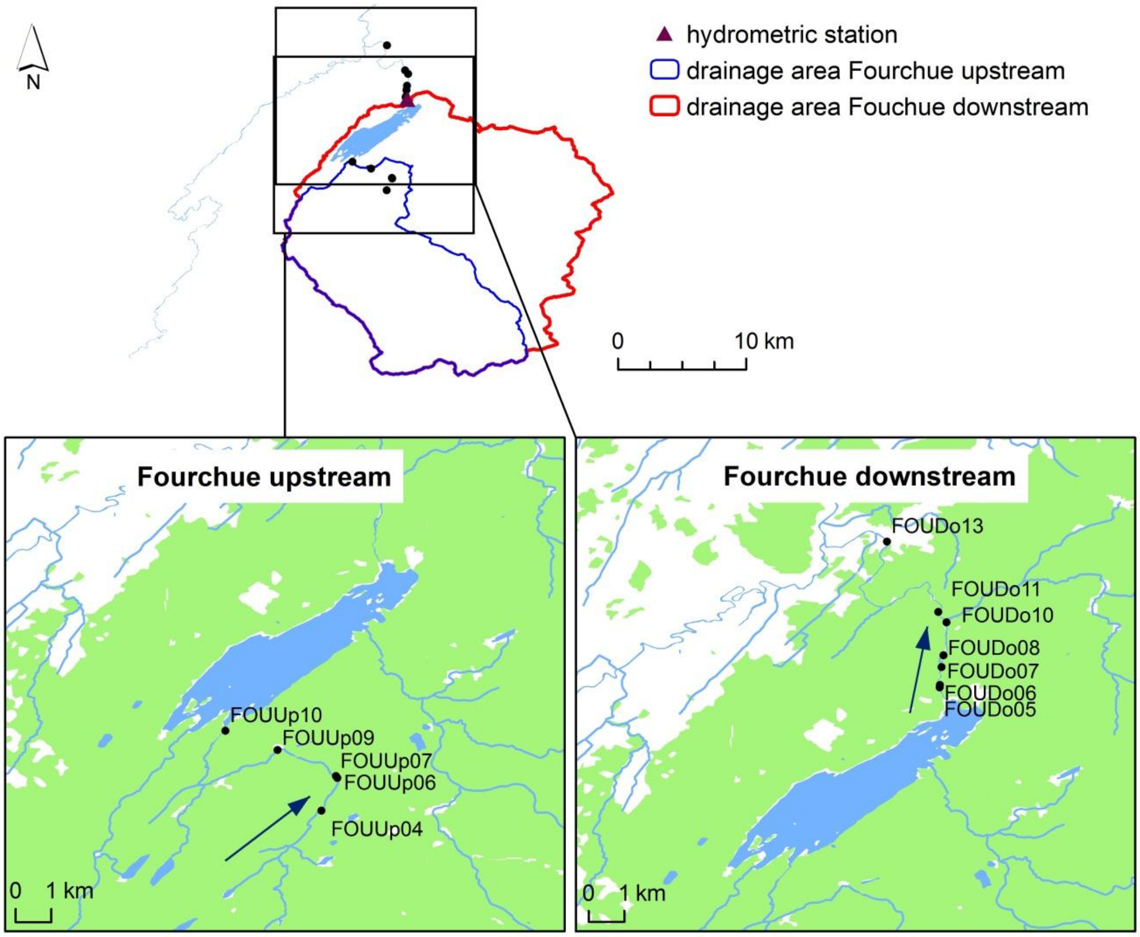

Figure 18. Location of study sites in the Fourchue River, winters 2011-12 and 2012-13

Fourchue River (regulated)

The downstream reach of the Fourchue River is regulated by the Morin dam, which is a 16.3 m-high by 198 m-large concrete gravity dam. Upstream of the dam is Lake Morin, a 6.8 x 10^6 m² reservoir. The water intake at the dam is located near the bottom of the dam. The main purpose of the dam is to store water and release it during low flow periods such as summer and winter to raise water levels in the Du Loup River, of which the Fourchue River is a tributary. At the dam, the drainage area is 261 km².

For the winter 2011-2012, two Pro-v2 Hobo™ water temperature loggers (accuracy of ± 0.2 °C) were deployed over a 7 km reach downstream of the Morin dam (FOUDo 06 and 13 on Figure

18). Water temperature loggers were deployed mid-November 2011 and retrieved in March 2012, before the spring flood. For the winter 2012-13, six Pro-v2 Hobo™ water temperature loggers (accuracy of ± 0.2 °C) were deployed over a 7 km reach upstream of the Lake Morin reservoir (FOUDo 05, 07, 08, 10 11 and 13; Figure 18).

A hydrometric station operated by the Centre d'expertise hydrique du Québec (station 022505) is located 200 m downstream of the Morin dam on the Fourchue River. Figure 19a and 20a illustrate the flow regime between the winters 2011-12 and 2012-13. During both winters, a steady flow ranging between 1 and 6 m^3/s was released from October until spring. In 2012, flow increased to 35 m^3/s on March 21st, and then decreased to 1.3 m^3/s. The flow increased again to reach a peak value of 48 m^3/s on April 25, 2012. Thereafter, flows generally decreased in May and reached a flow of 4 m^3/s in the beginning of June. In 2013, flow remained below 6 m^3/s until April 30, 2013. Maximum flow was reached later in 2013, around May 27th (38 m^3/s; Figure 19a).

Fourchue River (natural)

A 6-km reach of the Fourchue River upstream of the Lake Morin was used as a reference reach to assess the thermal modification of the Fourchue River downstream of the Morin dam. This upstream portion of the river was not gauged and flow information was not available. For the winter 2011-2012, two Pro-v2 Hobo™ water temperature loggers (accuracy of ± 0.2 °C) were deployed over a 1.5 km reach upstream of the Lake Morin reservoir (FOUUp 07 and 09 on Figure 18). Water temperature loggers were deployed mid-November 2011 and retrieved in March 2012, before the spring flood. For the winter 2012-13, four Pro-v2 Hobo™ water temperature loggers (accuracy of ± 0.2 °C) were deployed over a 6 km reach upstream of the Lake Morin reservoir (FOUUp 04, 06, 09 and 10 on Figure 18).

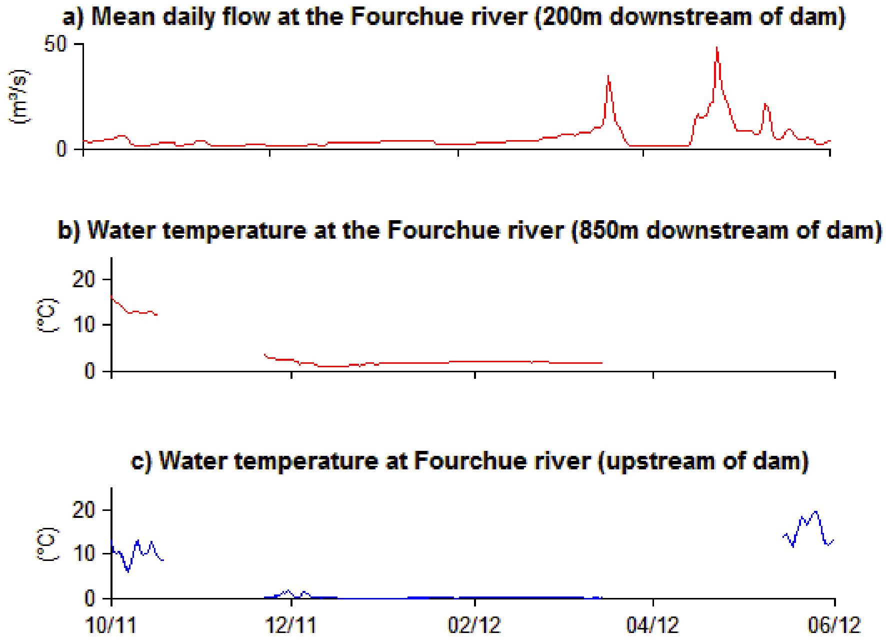

Figure 19. Flow and water temperature from 2011-10-01 to 2011-06-01 downstream and upstream of the dam on the Fourchue River.

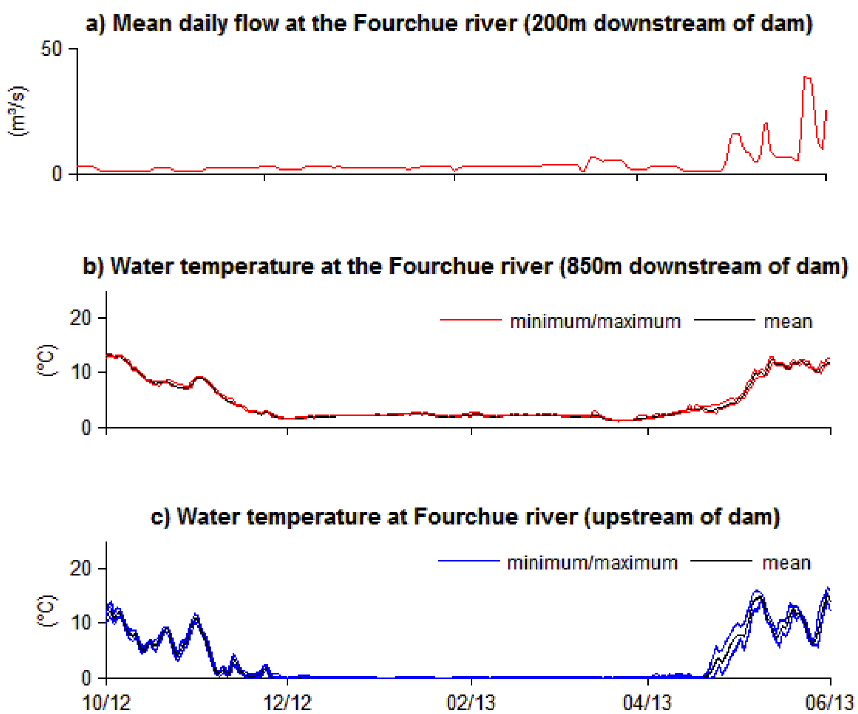

Figure 20. Flow and water temperature from 2012-10-01 to 2013-06-01 downstream and upstream of the dam on the Fourchue River

Comparison of winter thermal regimes between rivers

During both winters, the dam had a warming effect on the Fourchue River downstream reach. Figure 21 shows the longitudinal profile downstream of the dam for the winter 2012-13. Over the winter period, the dam significantly modified the thermal regime of the Fourchue River from October to April. In October and November 2012, the monthly mean temperature was warmer by 1.9 °C and 2.4 °C at 262 m downstream of the dam for each month respectively. At 7.1 km downstream of the dam, the warming effect was still significant although lessened: the October and November monthly mean water temperature was warmer by 1.3 and 1.2 °C respectively compared to the upstream reach.

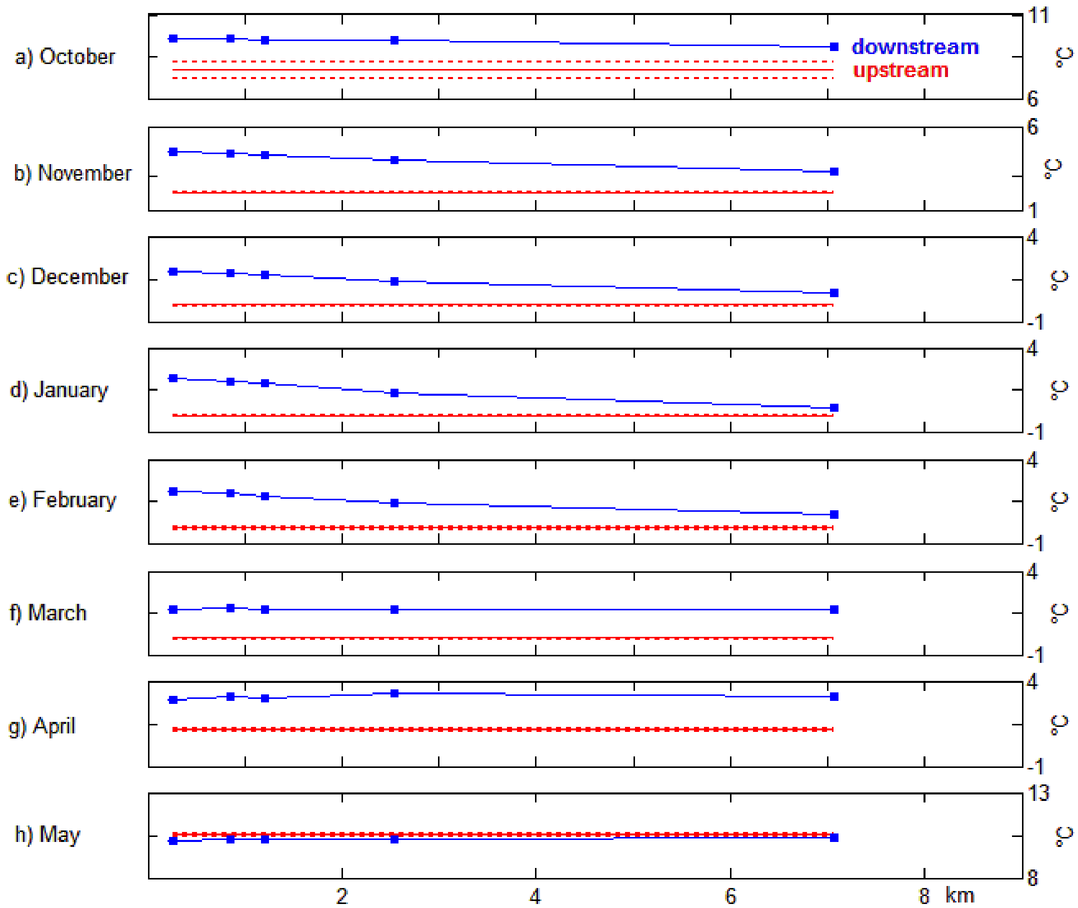

Figure 21. Longitudinal profile of monthly mean water temperatures during the winter 2012-13 downstream of the dam on the Fourchue River (blue). The red line shows monthly mean water temperatures for the upstream reach of the Fourchue River (solid red line) ± 1 standard deviation (dashed red line).

From December to March, the monthly mean water temperature was below 0.5 °C in the unregulated reach during both winters. Compared to the unregulated reach, the monthly mean water temperature was 1.6 °C warmer at about 300 m downstream of the dam and 0.5 °C warmer at 7.1 km downstream of the dam from December 2011 to February 2012. The warming effect was similar in the winter 2012-13 and the monthly mean water temperature was on average 2.1°C warmer at about 300 m downstream of the dam and 0.7 °C warmer at 7.1 km downstream of the dam. In the winter 2012-13, the release of warm water from the reservoir completely prevented the formation of an ice cover over at least the first 2.5 km downstream of the dam (Figure 22b). At 7.1 km downstream of the dam, freezing conditions occurred for 19 % of the monitoring period compared to 61 % for the natural upstream reach of the Fourchue River in the winter 2012-13. In the winter 2011-12, the dam completely prevented the formation of an ice cover for at least the first 300 m downstream of the dam. Data were not available at 2.5 km for the winter 2011-12 (Figure 22a).

In March 2013, the warming effect was comparable across the entire 7.1 km reach downstream of the dam and no longitudinal gradient was observed regarding the warming effect. While the mean monthly water temperature remained at 0°C in the unregulated reach, the monthly mean in the regulated reach was 1.5 °C in 2012 and 1.7 °C in 2013. In April 2013, the monthly mean water temperature was 1.2 °C in the unregulated reach, while it ranged from 2.4 °C to 3.3 °C downstream of the dam. The smallest warming effect (1.2 °C difference) was observed immediately downstream of the ruisseau Carrier, a tributary of the Fourchue River located 2.5 km downstream of the Morin dam. For fall 2012 and winter 2013, the tributary did not significantly moderate the warming influence of the dam on the mean monthly water temperature.

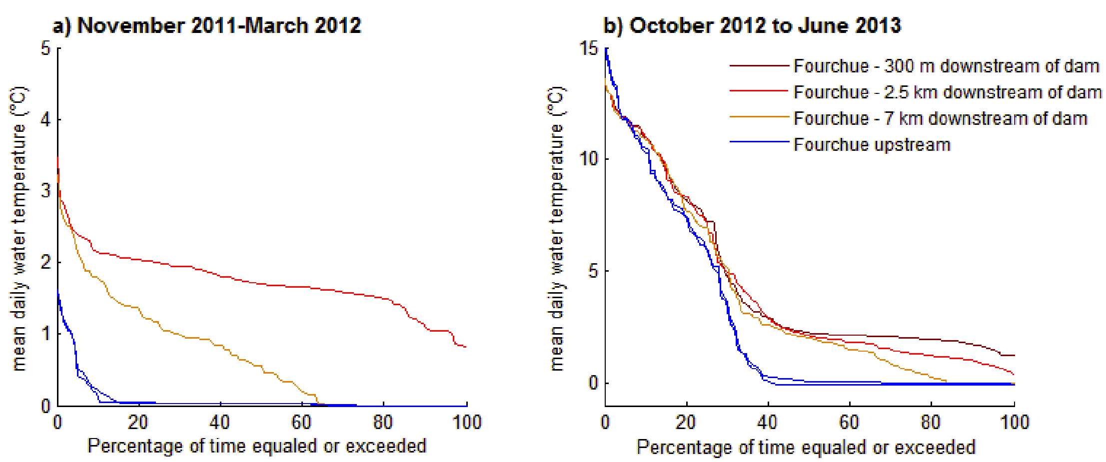

Figure 22. Mean daily water temperature duration curve at the Fourchue River, upstream and downstream of the Morin dam a) from November 2011 to March 2012 and b) from October 2012 to June 2013

In addition to the increase in mean daily water temperature downstream of the dam, it also modified the diel variability of water temperature in the Fourchue River (Figure 23). In October 2012, the mean daily range at 300 m downstream of the dam was smaller than at the unregulated reach. Over the next 2 km, the mean daily range in the regulated and unregulated reaches was comparable. At 7 km downstream of the dam, the mean daily range was greater than at the unregulated reach. A similar longitudinal pattern was observed in November 2012. From December 2012 to March 2013, the absence of an insulating ice cover downstream of the dam led to increased diel variability for 7 km downstream of the dam compared to the unregulated reach. For example, in February 2013, the mean daily range was 0.3 °C at the foot of the dam and reached 1.0 °C at 7 km downstream of the dam. Meanwhile, the mean monthly daily range varied between 0.0 and 0.1 °C at the unregulated reach. In April, diel variability was greater downstream of the dam compared to the unregulated reach. Between 850 m and 7 km downstream of the dam, the median daily range varied between 1.7 °C to 3.2 °C in April while it only 0.4 °C in the unregulated reach. The opposite effect was observed in May and diel variability was greater in the unregulated reach: the median daily range was 2.3 °C in the unregulated reach and ranged between 0.8 and 2.3 °C downstream of the dam.

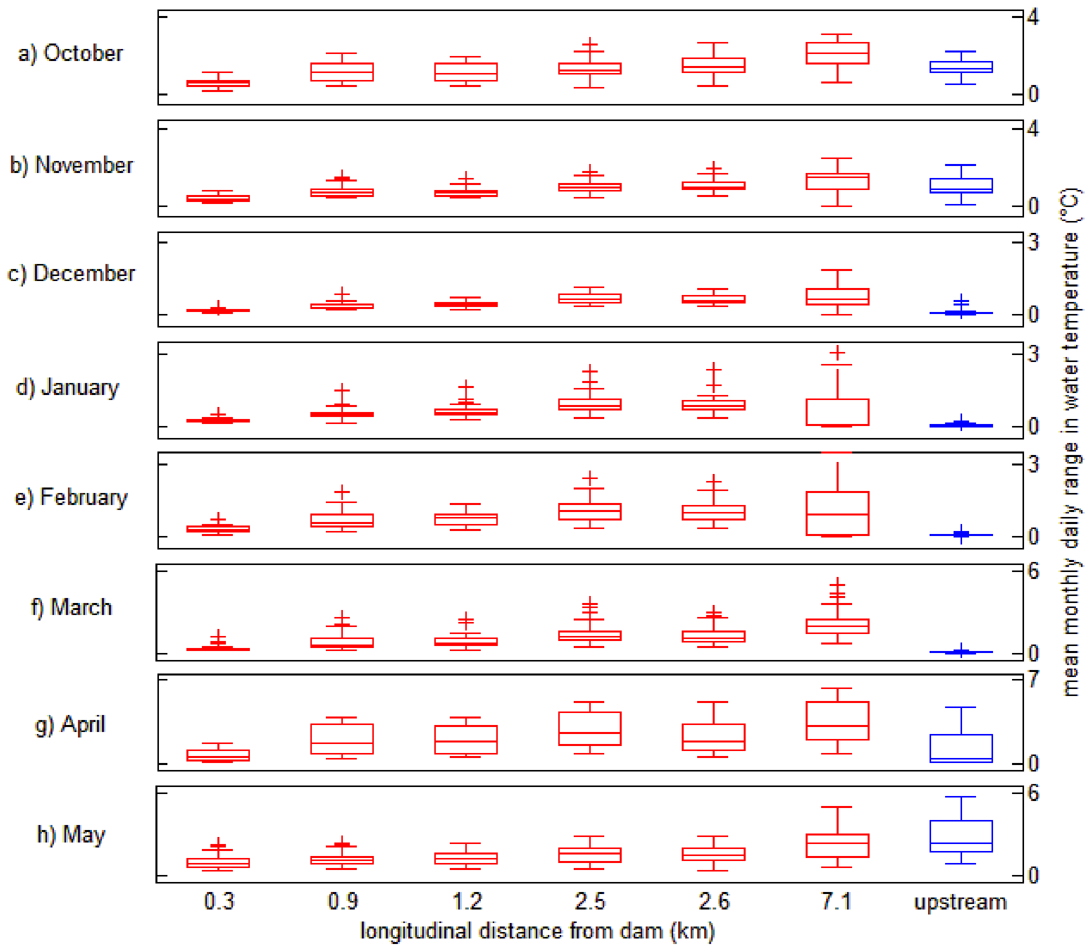

Figure 23. Mean monthly daily range in water temperature in the regulated (red) and unregulated (blue) reaches of the Fourchue River, winter 2012-2013

Overall, the longitudinal zone of influence of the dam varied in time as well as with the type of modification of the thermal regime. From October 2012 to April 2013, the dam had a significant warming effect on the Fourchue River and the mean daily water temperatures were comparable between the regulated and unregulated reaches (Figure 24sa). In the fall, the modification of diel variability by the dam was limited to the first 300 m downstream of the dam while diel variability was modified for the entire study reach (7 km) in the winter and spring (Figure 24b).

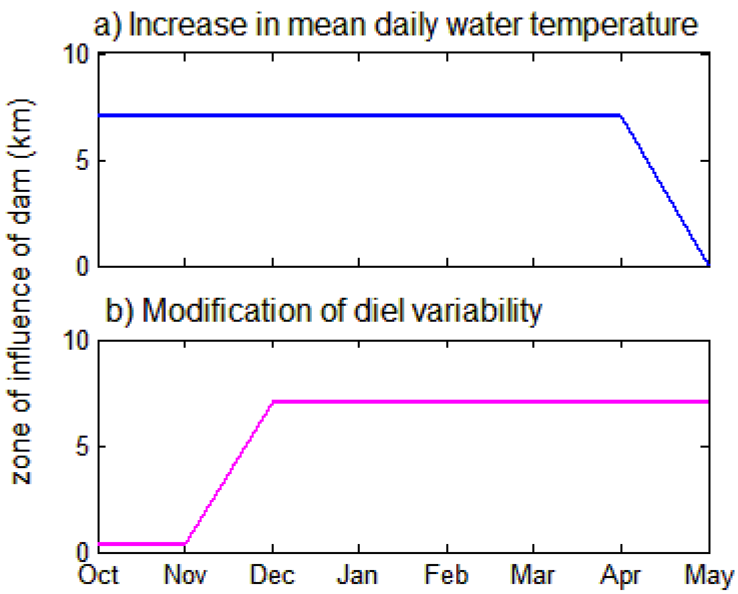

Figure 24. Temporal variation of the minimum longitudinal distance where the dam modified water temperature conditions on the Fourchue River, October 2012 to May 2013.

The impact of the dam on the magnitude and diel variability of the thermal regime of the Fourchue River was comparable between years. The magnitude of differences between the unregulated and regulated reaches was the same for the monthly mean water temperature from December to February. Interannual differences of the dam influence were not assessed in the fall and spring given no data was available in the 2011-12 study period. Similarly, interannual differences of the dam influence on the timing and duration of the ice cover period could not be assessed due to missing data. Interannual differences on the dam influence will be evaluated when loggers from the winter 2013-14 are retrieved in the summer 2014.

CONCLUSION

In this study, the influence of two different types of dam on the winter thermal regime of rivers was investigated: run-of-the-river dams (St-Jean and Etchemin rivers) and storage dams (Dee and Fourchue rivers).

Run-of-river dams

The two run-of-river dams in the present study did not have a significant effect on the winter thermal regime of rivers. Both the magnitude and timing of the winter water temperature cycle were comparable between the regulated and unregulated reaches. Very small differences in diel variability have been noted between certain reaches, but these differences were likely associated with different river ice formations rather than an effect of the dam itself.

Storage dams

In the present study, both dams had a significant effect on the thermal regime of streams. The two storage dams modified different aspects of the thermal regime of streams, namely the magnitude and the diel variability in water temperatures. The two dams completely eliminated freezing conditions for 1.7 km downstream of the Dee River and for 2.5 km downstream of the Fourchue River. Impoundment also considerably reduced the period of freezing conditions for 4.3 km on the Dee River and 7.1 km on the Fourchue River.

The two storage dams also modified diel variability. In the fall, diel variability was greater on the Gulqac River than on the Dee while it was comparable between the unregulated and regulated reaches of the Fourchue River. In the winter, the two regulated experienced more important diel fluctuations in the absence of an insulating ice cover. In April, diel variability was greater on the unregulated Gulqac River compared to the Dee River, while it was greater in the regulated reach of the Fourchue River compared to the upstream unregulated reach. In May, diel variability was not significantly modified on the Dee River while the diel variability was smaller on the regulated reach of the Fourchue River compared to its unregulated pair.

The impact of the storage dams on the thermal regime varied both spatially and seasonally. The longitudinal zone of influence downstream of the dams varied according to the type of impact (i.e. magnitude vs. diel variability). For example, while diel variability was reduced for about 300 m downstream of the Fourchue River dam in the fall, the magnitude of the thermal regime was modified for 7 km downstream of the dam. The impact of dams also varied through time and autumn and spring were generally associated with smaller longitudinal zones of influences compared to the winter period.

Further work

In conclusion, future work will explore the different seasonal impacts of these types of dams. For example, the accumulation of heat in the spring starts earlier downstream of storage dams but energy input tends to be reduced during the summer when cool hypolimnetic water is release from the dam. The implications of this tradeoff will be further explored. The role of atmospheric conditions and flow in the variation of the longitudinal zone of influence will be further analyze to better understand how the thermal modification of stream varies in time as well as between different systems.

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