Water Temperature Variability in the St. Lawrence River Near Montreal

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Water Temperature
Variability in the St. Lawrence River
Near Montreal

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Abstract

Information on water temperature is essential to the interpretation of biological data. The objectives of this study were to characterize the variability of St. Lawrence River water temperatures and to examine the linkages between temperature and flow regime as a result of the confluence of the St. Lawrence and Ottawa rivers in the Montreal area.

Transversal differences in conductivity and temperature were observed year-round at a cross-section of the river located downstream of the confluence of the St. Lawrence (flowing along the south shore) and Ottawa rivers (flowing along the north shore). From April to July, St. Lawrence River waters originating from Lake Ontario were up to 3.5°C colder than those coming from the Ottawa River. During the first two weeks of August, the two water masses were within 0.5°C of each other. From mid-August to the end of March, however, waters from Lake Ontario were systematically 2 to 3.5°C warmer than water from the Ottawa River. This pattern likely resulted from the considerably large volume of water originating from Lake Ontario, which is slow to warm up in spring and summer and slow to release stored heat through the fall and winter.

Water hardness values from five water filtration plants in the Montreal area revealed their exposure to different water masses, even though some of the intakes were in close proximity. Water hardness values were generally high at the Charles-J. Des Baillets (DB), Atwater (AW) and Longueuil (LO) plants, corresponding to the predominant, year-round influence of waters originating from Lake Ontario. In contrast, the John Labatt (JL) and Pointe Claire (PC) plants were periodically exposed to Ottawa River waters, as shown by lower and seasonally-variable hardness values. The water temperature at each plant was consistent with the seasonal pattern of exposure to either water mass.

Multiple regression models ($r^2 = 0.89$) predicting daily water temperature based on environmental variables were developed for the three plants with intakes in waters originating from Lake Ontario (LO, DB and AW). Models included air temperature, season, Ottawa river discharge and the ratio of Ottawa to total river discharge. Water temperature did not differ significantly between LO and DB; temperature recorded at both plants was warmer (by 0.6°C) than at the AW plant.

Over the years, mean annual water temperature increased at three of the plants, showing rates of 0.5 °C (JL, 1978-2001), 0.7°C (DB, 1981-2001) and 1.2°C (LO, 1992-2002) per 10-year period. No long-term trend in water temperature was detected at AW (1919-2001), owing to the presence of alternating warm and cold water years. However, none of the 10 coldest years and 4 of the 9 warmest years of the series occurred since 1980. For terrestrial plants (air temperature), no significant temporal trends were observed in the dates of the beginning, end or duration of the growing season. For aquatic organisms, growing season calculated for 5, 10, 15 and 20°C thresholds generally indicated a later water cooling in the fall and an increase in the duration of the growing season.

The average annual water temperature at the AW plant was negatively related ($p < 0.05$) to levels for both the pre- (1919-1957) and post- (1960-2001) regulation periods. On a monthly basis, the effect of low levels were particularly important in May, June and September, with > 1 °C increase in mean monthly temperature for each 1-m decrease in average level (DB, JL). Years of low discharge coincided with a precocious warm-up in the spring and a late cooling in the fall, yielding a higher cumulative number of degree-days and a longer growing season.

Résumé

La température de l'eau est une variable essentielle à l'interprétation des données biologiques. Les objectifs de cette étude sont de caractériser la variabilité de la température de l'eau du Saint-Laurent et d'examiner les liens complexes entre la température et le débit résultant de la confluence du Saint-Laurent avec la rivière des Outaouais dans la région de Montréal.

Des différences de conductivité et de température ont été observées pendant toute l'année à une section transversale située en aval de la confluence du Saint-Laurent (dont les eaux coulent le long de la rive sud) et de l'Outaouais (dont les eaux coulent le long de la rive nord). D'avril à juillet, les eaux du Saint-Laurent provenant du Lac Ontario étaient jusqu'à 3,5^{o}C plus froide que celles provenant de l'Outaouais. Au cours de la première moitié du mois d'août, la température des deux masses d'eau était semblable à 0,5^{o}C près. De la mi-août à la fin mars, cependant, les eaux provenant du Lac Ontario étaient de 2 à 3,5^{o}C plus chaudes que celles de l'Outaouais. Ce patron proviendrait du volume considérablement plus élevé des eaux du Lac Ontario, qui tardent à se réchauffer au printemps et en été, mais se refroidissent plus lentement au cours de l'automne et l'hiver.

L'examen des valeurs de la dureté de l'eau à cinq stations de filtration de la région de Montréal a révélé l'influence de différentes masses d'eau, même si certains des sites de pompage étaient avoisinants. La dureté de l'eau était généralement élevée à Charles-J. Des Baillets (DB), Atwater (AW) et Longueuil (LO), correspondant à l'influence prédominante, tout au long de l'année, des eaux provenant du Lac Ontario. Par ailleurs, les stations John Labatt (JL) et Pointe-Claire (PC) étaient périodiquement exposées aux eaux de la rivière des Outaouais, tel que démontré par de faibles valeurs de dureté affichant des variations saisonnières marquées à ces stations. La température de l'eau enregistrée à chaque station était cohérente avec leur patron d'exposition saisonnier à l'une ou l'autre des masses d'eau.

Des modèles ($r^2 = 0,89$) de régressions multiples permettant de prédire la température journalière de l'eau à partir de variables environnementales ont été développés pour les trois stations de filtration influencées par les eaux provenant du Lac Ontario. Les modèles comprenaient la

température de l'air, la saison, le débit de l'Outaouais et la fraction du débit de l'Outaouais sur le débit total. La température de l'eau ne différait pas significativement entre LO et DB ; la température enregistrée à ces deux stations était plus chaude (de 0,6°C) qu'à AW.

Au cours des années, la température moyenne annuelle de l'eau s'est accrue à trois des stations, affichant un taux de 0,5 °C (JL, 1978-2001), 0,7°C (DB, 1981-2001) et 1,2°C (LO, 1992-2002) par période de 10 ans. Aucune tendance à long terme ne fut détectée à AW (1919-2001), en raison de l'alternance d'années d'eau chaude et froide. Notons cependant qu'aucune des 10 années les plus froides et que 4 des 9 années les plus chaudes ont été enregistrées depuis 1980. Pour les plantes terrestres (température de l'air), aucune tendance temporelle n'a été observée dans les dates de début, de fin et de durée de la saison de croissance. Pour les organismes aquatiques, la saison de croissance calculée pour des seuils de 5, 10, 15 et 20°C indiquaient généralement un refroidissement plus tardif à l'automne et un accroissement de la durée de la saison de croissance.

La température moyenne annuelle de l'eau à AW était négativement reliée au niveau ($p < 0,05$), autant pour la période pré- (1919-1957) que post- (1960-2001) régularisation (AW). Sur une base mensuelle, les effets des bas niveaux étaient particulièrement marqués au mois de mai, juin et septembre avec une hausse de > 1 °C de température moyenne mensuelle pour chaque mètre de diminution de niveau moyen (DB, JL). Les années de bas niveau coïncident avec un réchauffement hâtif au printemps et un refroidissement tardif à l'automne, générant une saison de croissance plus longue et un nombre accru de degrés-jours de croissance.

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Acknowledgments

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Summary Table

Introduction

Water temperature is a critical variable in limnology since it defines the rate at which a number of physical, chemical and biological processes take place. In temperate systems, the water temperature follows a seasonal cycle of between 0 and 25°C, thus defining the growing season of plants and animals. Depending on climatic conditions, the timing, duration and intensity vary from year to year, resulting in inter-annual differences in productivity, recruitment and survival of a wide variety of organisms. In spite of its importance, however, long-term information on water temperature and growing season duration are not available for the St. Lawrence River. One of our objectives was thus to examine long-term data series of St. Lawrence River water temperature, from which growing season variability can be characterized.

In addition to the strong signal introduced by seasonal air-temperature variations, water temperature can be further modulated by hydrological factors. In small streams, changes in flow regime are often associated with changes in water temperature (Ward 1974; Short and Ward 1980; Rørslett 1988). Small river temperatures are more sensitive to instream flow rate, upstream inflow temperature, air temperature, humidity and solar radiation than to other parameters, such as wind speed and channel geometry and morphology (Gu and Li 2002). For large river systems, however, relationships between temperature and flow have been less well documented, likely because they have unique individual properties (Melack 1992). In addition, most large rivers have been subjected to impoundment and regulation, which are also susceptible to altering their temperature regime. The relationships between water temperature and river discharge and level were examined on an annual basis, to contrast pre and post-regulation conditions, as well as on a monthly (seasonal) basis.

The confluence of the Ottawa River with the St. Lawrence largely determines the hydrological conditions near Montreal. The St. Lawrence River (average of 7800 $m^3 s^{-1}$ at Cornwall) is sourced in Lake Ontario, which acts as a huge reservoir and sedimentation basin, lying in part on ancient lacustrine clay and silt deposits (Environment Canada 1987). St. Lawrence River waters are very clear for a river of its size, since they contain low suspended particulate matter (SPM) and dissolved organic carbon (DOC) concentrations (Fraser *et al.* 1995). In contrast, the Ottawa

River (average of 1900 $m^3 s^{-1}$ at the Carillon dam) drains a multitude of small and large lakes and tributaries flowing on the granite formations of the Canadian Precambrian Shield, with surface deposits of glacial tills (Bobée et al. 1977). Ottawa River waters carry higher SPM and DOC loads, which explain its characteristic turbidity and brown colour. Owing to these differences in morphology, the Ottawa and St. Lawrence rivers follow different patterns of seasonal discharge and possess a distinct physical and chemical signature by which to quantify their relative proportions during mixing.

We hypothesized that the relative importance of each water mass could affect the water temperature regime in the Montreal area. We examined this hypothesis by comparing water temperature at 10 stations across the St. Lawrence River, about 5 km downstream of the confluence of the St. Lawrence and Ottawa rivers (Hudon 2000). This information allowed us to compare, over the same period, the average temperature recorded in waters from the south shore (main river channel), which is under the predominant influence of Lake Ontario, with waters flowing along the north shore, under the influence of the Ottawa River.

Water filtration plants are an invaluable source for historical records on water temperature and water quality. For some of these plants, the confluence of the Ottawa and St. Lawrence rivers has practical consequences in terms of the variability of raw water quality over time, as a function of the location of their intake systems and the seasonal and inter-annual variations in river discharge. These differences are superimposed to the effects of plant infrastructures and monitoring frequency, which represent an additional element of background variability.

Once the confounding effects of water mass and plant infrastructure have been accounted for, the time series can be examined in terms of historical trends or environmental interactions. For example, long-term water temperature records and growing season characteristics may reflect the effects of the general warming of air temperatures observed over the last decade. Such information is the first step in documenting the wide-ranging effects of climate change on aquatic ecosystems (Magnuson et al. 1997; Schindler 2001). Finally, we examined the linkages among discharge and water-level variations with water temperature, through predictive models of water temperature based on environmental variables. This information should be useful to assessing the biological consequences of flow management in the St. Lawrence-Ottawa River systems.

Objectives

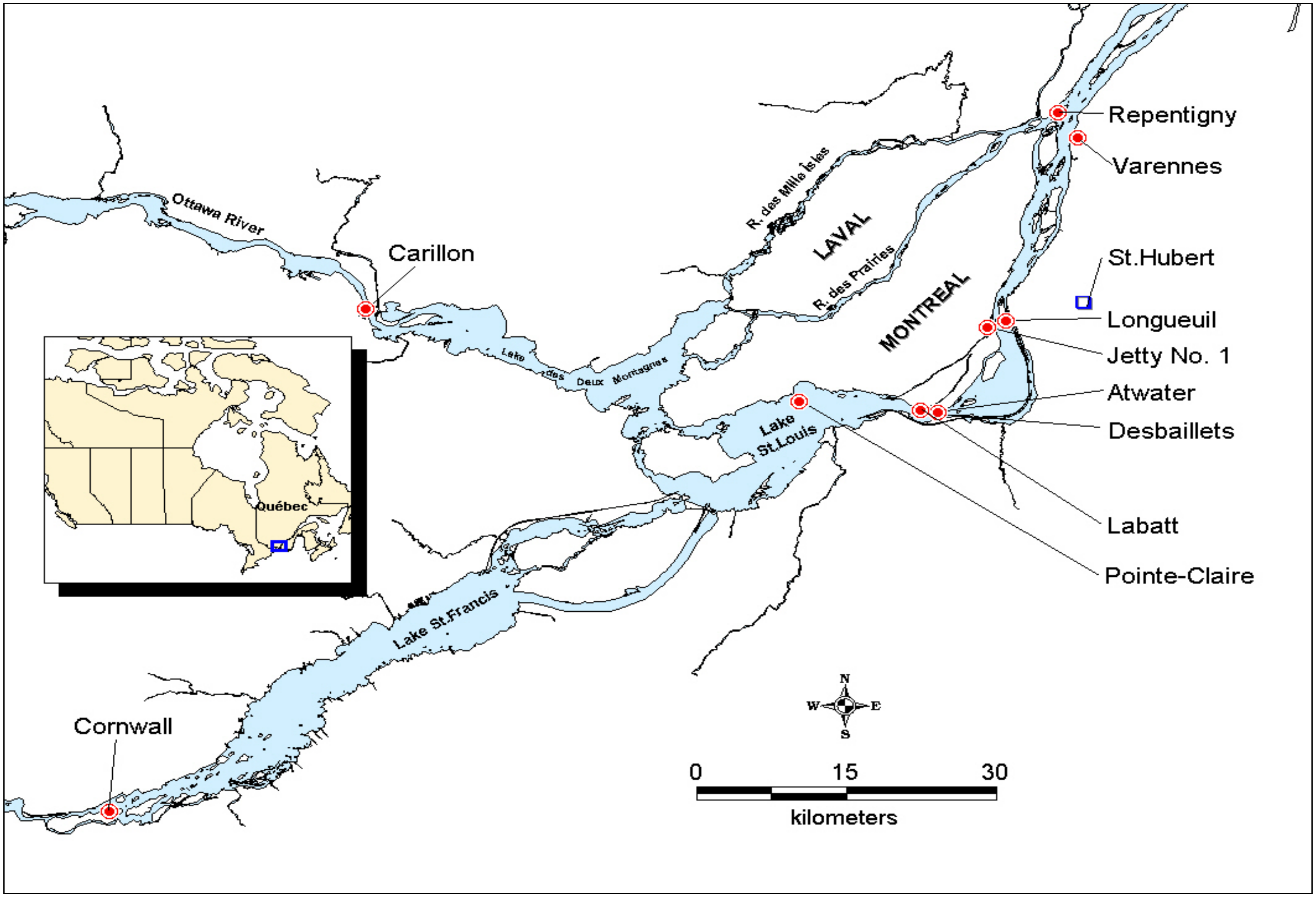
The objectives of this report are to characterize the variability of St. Lawrence River water temperatures in the Montreal area and examine the linkages between temperature and flow regime. More specifically, this study will

1. Contrast the seasonal variations in water masses primarily influenced by the St. Lawrence and Ottawa rivers prior to their complete mixing.
2. Characterize the relative importance of each water mass component at five filtration plants.
3. Quantify the temperature differences due to infrastructure by comparing three plants with intake points always under the influence of Lake Ontario waters.
4. Model the daily river water temperature from discharge, proportion of Ottawa River waters, season and air temperature.
5. Examine the temporal trends in water temperature and growing season characteristics.
6. Assess the effects of variations in level and discharge on water temperature.

Study Area

The study area is located in the Greater Montreal area (3 million residents), at the confluence of the St. Lawrence and Ottawa rivers (Fig. 1). The main stem of the St. Lawrence River flows from Lake Ontario and upper River through the Moses-Saunders dam (Cornwall) into lakes St. Francis and St. Louis. Water from the Ottawa River enters the St. Lawrence in part through Lake St. Louis and flows along the south shore of Montreal Island. The rest of the Ottawa River's discharge enters the St. Lawrence downstream of the island of Montreal, via the des Mille-Îles and des Prairies rivers. Downstream of the confluence, St. Lawrence waters flow along the south

Figure 1. Map of the study area, showing the location of sampling stations with respect to the confluence of the St. Lawrence and Ottawa rivers near Montreal



shore, whereas waters from the Ottawa River transit along the north shore. A zone of partially mixed waters is found in the central area, which varies in location and size depending on the discharges of both rivers.

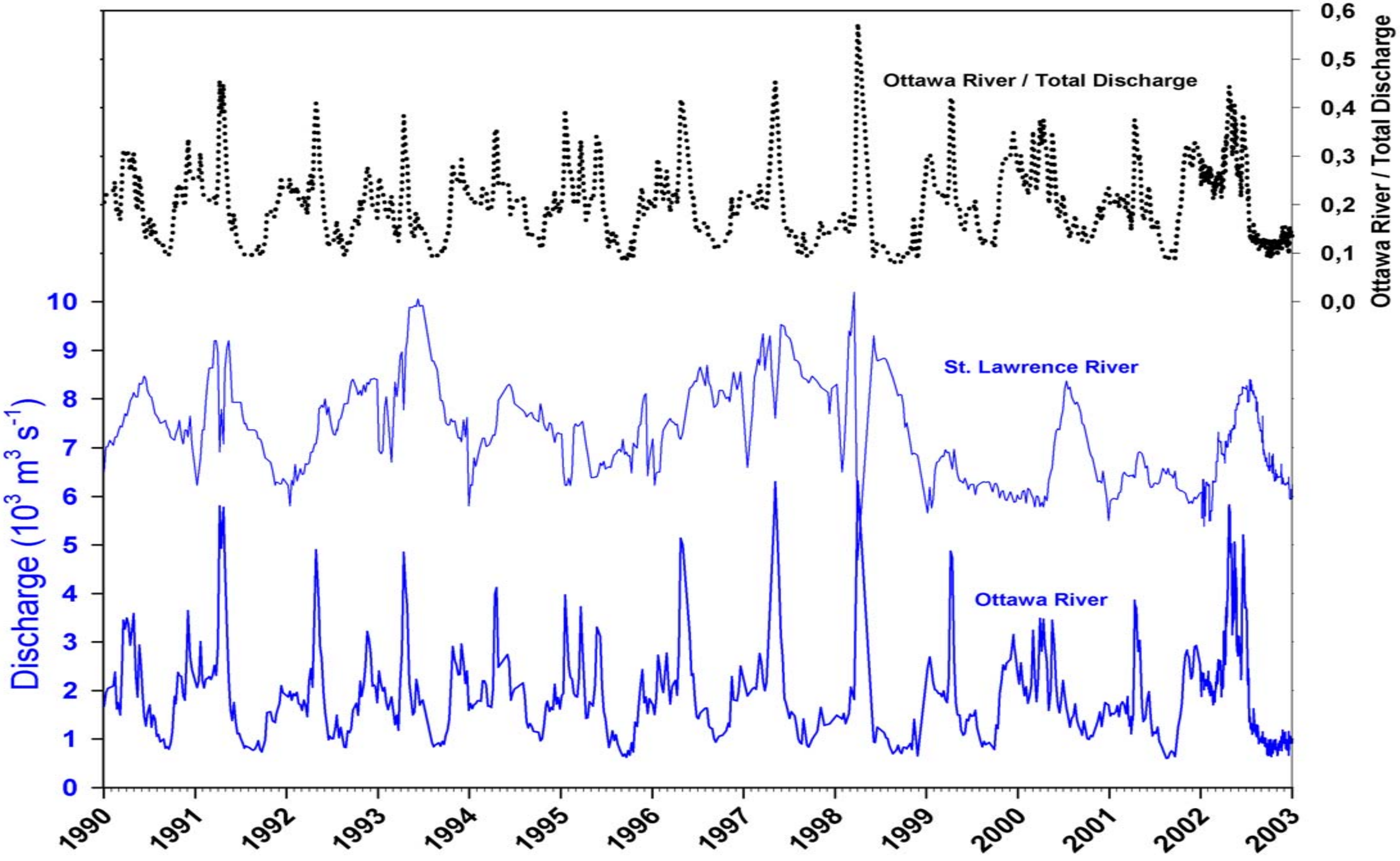
Physical and chemical characteristics of the St. Lawrence and Ottawa rivers

Upstream of their confluence, the physical and chemical characteristics of the St. Lawrence and Ottawa rivers differ markedly owing to the geological and morphological settings of their watersheds. Water from the St. Lawrence originates from the outflow of Lake Ontario, whose watershed lies over relatively soluble sedimentary rock formations, corresponding to waters of moderately high conductivity, hardness, alkalinity and pH (Table 1). The lake itself acts as a sedimentation basin, which results in waters of low turbidity and colour. In contrast, the Ottawa River drains the granite rocks of the Precambrian Canadian Shield via a very large number of small and large lakes and rivers; this river, as well as other tributaries discharging on the north shore of the St. Lawrence, exhibits higher colour and turbidity and lower conductivity, hardness, alkalinity and pH values than St. Lawrence River waters (Rondeau 1993; Primeau 1996) (Table 1). These water quality variables thus constitute the “signature” of each water mass and conservative constituents such as water hardness, conductivity and alkalinity can be used to calculate mixing.

Seasonal and interannual variations in the discharge of the St. Lawrence and Ottawa rivers

The discharge of the St. Lawrence (average annual discharge 1973-2001 at Cornwall : 7800 $m^3 \bullet s^{-1}$) and Ottawa (average annual discharge 1973-2001 at the Carillon dam: 1900 $m^3 \bullet s^{-1}$) rivers vary both seasonally and on an interannual basis (Fig. 2). The discharge of the St. Lawrence River shows relatively small seasonal fluctuations yet demonstrates large interannual fluctuations among years, ranging from 6922 in 2001 to 9079 m^3 s^{-1} in 1986. In contrast, the Ottawa River shows a three-fold range in seasonal discharge variations, with a spring flood and low discharge values in late summer and fall. For the 1973-2001 period, the discharge in April and September averaged 3590 and 1053 m^3 s^{-1}, respectively. The mean annual discharge of the Ottawa River ranges from 1934 (in 1978) to 2524 m^3 s^{-1} (in 1974). As a result of fluctuations in both rivers, the Ottawa River represented, on average, 19% (s.d. 7%) of total discharge in the Montreal area, ranging on average from 6% (in

Figure 2. Daily discharge of the St. Lawrence (at Cornwall) and Ottawa (at Carillon dam) rivers (1990-2002) and proportion of Ottawa River to total discharge.



September) to 58% (in April) of the total discharge in the Montreal area (Fig. 2).

Methods

Daily mean air temperature data for the St. Hubert airport (1928-2002) were obtained from Environment Canada (2002). Daily discharge values (1973-2001) for the St. Lawrence River (Cornwall) and the Ottawa River (Carillon dam) upstream of their confluence were obtained from Environment Canada (Ontario Region) and Hydro-Quebec (2002), respectively. These values were used to calculate the proportion of Ottawa River water to total river discharge in the Montreal area. Daily water levels (1918-2002) measured at Montreal (Montreal Harbour Jetty No. 1, gauging station No. 15520, 5.564 m above sea level) were obtained from the Department of Fisheries and Oceans (2002).

Temperature and conductivity gradients across the St. Lawrence River downstream of its confluence with the Ottawa River were documented at a transect between Varennes (south shore) and Repentigny (north shore) (Fig. 1). Spatial gradients were monitored at a frequency ranging from weekly to monthly between May 1994 and May 1996 (Hudon and Sylvestre 1998; Hudon 2000), thus allowing us to assess the seasonal differences in water temperature in each water mass, identified from conductivity values.

Time series of water temperature and hardness data for the Montreal area were obtained from four municipal (Atwater, AW; Charles-J. Des Baillets, DB; Pointe-Claire, PC and Longueuil, LO) and one industrial (John Labatt Brewery, JL) water filtration plants (Fig. 1). These plants monitor temperature and raw water quality parameters on a daily to weekly basis to optimize drinking water production. Historical records (1918-1980) were gathered from annual operating reports at AW plant; other plants provided data records for the last 10-25 years. Site characteristics, data acquisition and validation were fully documented in Armellin *et al.* (2003).

Comparisons among plants were necessary to reconstitute the longest time series of water temperature with the highest possible resolution while accounting for other sources of variability, such as the effects of water masses and plant infrastructure. The water mass influencing the five filtration plants was determined by examining seasonal variations in water hardness (mg $CaCO_3$ l^{-1}) and hardness-temperature diagrams at each plant over the 1990-2001 period. The relative quantity of Ottawa and St. Lawrence river water at each filtration plant was determined from characteristic hardness values of Lake Ontario and Ottawa River waters drawn from previous studies (Rondeau 1993, Primeau 1996) and an Environment Canada data base (Pierre Gagnon, Environment Canada - Quebec Region, St. Lawrence Centre, 105 McGill St., 7th floor, Montreal, Canada, H2Y 2E7; personal communication).

Water temperature differences resulting from infrastructure, measuring equipment, precision and methodology (background variability) were assessed by comparing water temperatures from three filtration plants pumping waters originating primarily from Lake Ontario (AW, DB, LO). Two of these (DB, AW) plants have the same water intake but differ markedly in terms of their infrastructures, whereas LO's intake is located in the same water mass, about 15 km downstream (Fig. 1). Water temperature measurements made over the same time interval (1993- 98) at AW, DB and LO were compared using ANOVA (Statsgraphics), with plant, season and year as factors. More detailed comparisons among the five plants were made by examining residual values of paired measurements of water temperature made on the same day at each pair of plants; DB was chosen as the reference for comparison.

The subset of environmental variables predicting best daily water temperatures was determined from multiple regressions (SAS) for the three plants pumping waters under the influence of Lake Ontario waters. Data from plants influenced by Ottawa River waters was excluded to avoid the effect of a different water mass on daily water temperature. Environmental variables included daily average air temperature (Saint-Hubert airport), season, daily discharge at Carillon dam and Cornwall, and the proportion of Ottawa River water to total (Carillon + Cornwall) discharge. Season was a surrogate binary variable, defined as follows: summer (21 June to 20 September), fall (21 September to 20 December), winter (21 December to 20 March) and spring (21 March to 21 June).

Growing season characteristics include the first and last day of the year above a given temperature threshold; these were used to calculate its duration, as the total number of days included in the interval. For terrestrial plants, the growing season was defined as the day of the year on which the average daily air temperature was above 5.5^{o}C for 5 days out of 7 (Grandtner 1966), calculated from daily average air temperature data from Saint-Hubert airport. For aquatic organisms, growing season characteristics were calculated for water temperature thresholds of 5, 10, 15 and 20°C (5 days out of 7), since different aquatic organisms exhibit different responses to water temperature. This calculation was made for the four water filtration plants and the intervals for which daily temperature values were available (AW, LO, JL and PC). Growing season characteristics were compared among plants, using multi-factor ANOVA (Statsgraphics), by plant and year to test for the effects of water mass and time interval, which differed among plants. Temporal trends in growing season characteristics were tested using linear regressions (Sigma Plot) and Pearson *r* parametric correlations (Excel) between each variable and year. Given the high number of relationships involved (4 plants x 14 variables = 56), it was assumed that a certain number of the significant values would arise by chance alone (3 out of 56 correlations at the 0.05 probability level).

The relationship between mean monthly water level and water temperature was determined for the months of April to September at two water filtration plants characterized by water originating from Lake Ontario (DB, 1981- 2001) and mixed waters (JL, 1977- 2001), using linear regressions (Statsgraphics and Sigma Plot).

Results and Discussion

1. Temperature and conductivity gradients across the St. Lawrence River downstream of the confluence with the Ottawa River

As they flow through the Greater Montreal area to their complete merger at the Repentigny–Varennes site, the waters of both rivers are progressively mixed together in the central portion of the river, while retaining their individual identities along either shore. Strong transversal differences in conductivity were observed on all sampling dates, with high values along the south shore and low values along the north shore, coinciding with waters originating from Lake Ontario and the Ottawa River, respectively (Fig. 3). Transversal temperature gradients were also recorded. From April to

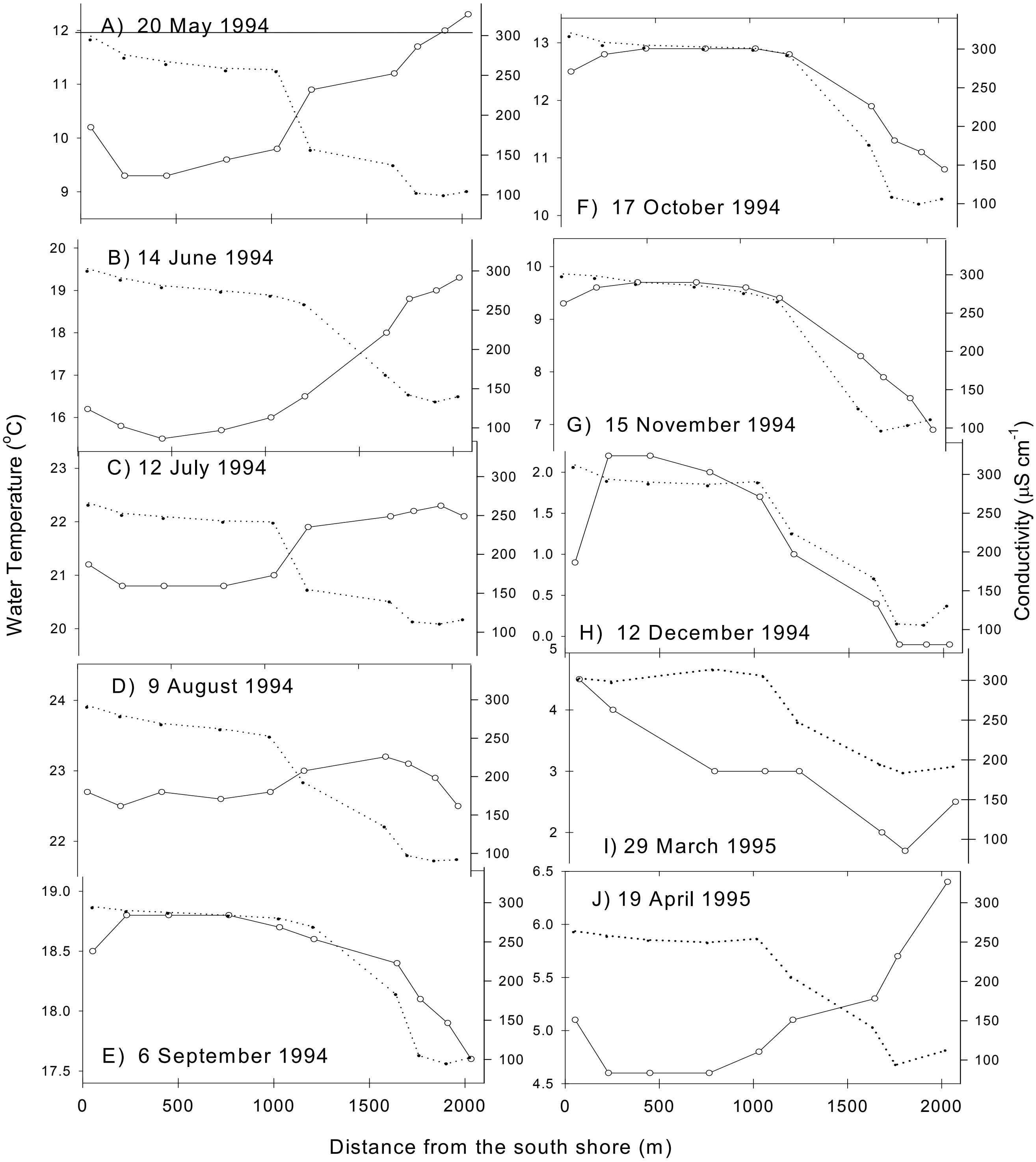
July, waters flowing along the south shore were up to 3.5^{o}C colder than along the north shore. By early to mid-August, temperature differences across the river were down to 0.5^{o}C. From mid-August to the end of March, however, waters flowing along the south shore were warmer than water from the Ottawa River. This systematic difference in temperature equaled 2-3.5^{o}C in the fall and throughout the winter. This pattern likely results from the considerably larger volume of water originating from Lake Ontario, which takes more time to warm up in the spring and summer, but retains heat in the fall and winter in contrast to the Ottawa River and the north shore tributaries.

An examination of the average water temperature across the river over the warmest months (June to October) showed Ottawa River waters to be consistently warmer than Lake Ontario water by about 1^{o}C, both in 1994 and 1995 (Table 2). In comparison with 1994, the water temperature was warmer by about 0.5^{o}C at all stations in 1995, coinciding with a 12% discharge reduction (from 9054 m^3 s^{-1} in 1994 to 7932 m^3 s^{-1} in 1995) at the Carillon dam and Cornwall from June to October.

2. Influence of water masses at Montreal area filtration plants

Differences in water hardness values measured at the five filtration plants in the Montreal area revealed their exposure to different water masses (Fig. 4, Table 3). Water hardness values were generally high (median 120-125 mg $CaCO_3$ l^{-1}) at DB, AW and LO, corresponding to the predominant influence of waters originating from Lake Ontario (Table 1). A slight drop of about 10% in water hardness was observed at the three plants over the ten-year period (Fig. 4). In contrast, hardness values at PC and JL plants were lower (48-75 mg $CaCO_3$ l^{-1}) and showed a 5-fold range (between 20 and 125 mg $CaCO_3$ l^{-1}), which varied seasonally. The lowest hardness values (< 60 mg $CaCO_3$ l^{-1}) were observed in spring whereas the highest values (> 80 mg $CaCO_3$ l^{-1}) were observed in summer and fall, revealing the seasonal influence of Ottawa River flood waters.

Figure 3.



Monthly temperature (--O--) and conductivity (··········) gradients across the St. Lawrence River downstream from the confluence with the Ottawa River, at a transect between Varennes (south shore) and Repentigny (north shore)

An examination of temperature-hardness diagrams at JL and PC plants showed a spring decrease in hardness concurrent with the rise in water temperature, with a characteristic counter-clockwise temporal progression (Fig. 5). Hardness values remained stable and high throughout the year at the LO, AW and DB plants. Data for 1996 are shown (Fig. 5) because that year was characterized by discharge and water-level conditions close to the 30-year average; a largely similar pattern was observed for the years 1993-2000 (not shown). Although both JL and PC plants were periodically exposed to Ottawa River waters, their occurrence at the PC plant appeared to be more intense (Table 3), more frequent (Fig. 4) and less regular over time (Fig. 5) than at the JL plant.

At JL, the presence of a large inflow of Ottawa River water in the spring explains the systematically warmer waters at that plant contrast to AW and DB (Fig. 6), despite the close proximity of all three plant intakes to each other (< 500 m distance) (Fig. 1). Spring is the period during which the largest discrepancies were recorded between JL and DB (as well as between LO and AW), which was confirmed by examining paired residuals by season (Fig. 7). The pattern of decreasing water temperatures in the fall did not differ markedly among the JL, AW and DB plants (Fig. 6).

In contrast, PC appeared to be under the partial influence of the Ottawa River at all times, but to varying degrees. Accordingly, temperature differences between PC and DB were the most wide-ranging overall, with the most pronounced differences in spring (5-95% percentile ± 2^{o}C) and fall (5-95% percentile -1 to -5^{o}C) (Fig. 7). Fall temperatures were colder by an average 2.8^{o}C at the PC plant, consistent with the continuous influence of Ottawa River waters, which cool faster than the Lake Ontario waters found at DB, AW and LO plants. Such subtle differences among Montreal filtration plants located close to one another point up the need to characterize the water masses at each site prior to examining long-term water temperature trends.

3. Influence of filtration plant infrastructure within the same water mass

A comparison of the daily water temperatures recorded at LO, AW and DB plants over the 1993-98 period revealed insignificant differences between plants (ANOVA F ratio = 1.07, $p = 0.34$)

and highly significant differences among years and seasons (ANOVA F ratio of 7.02 and 3344.65,

Figure 4.

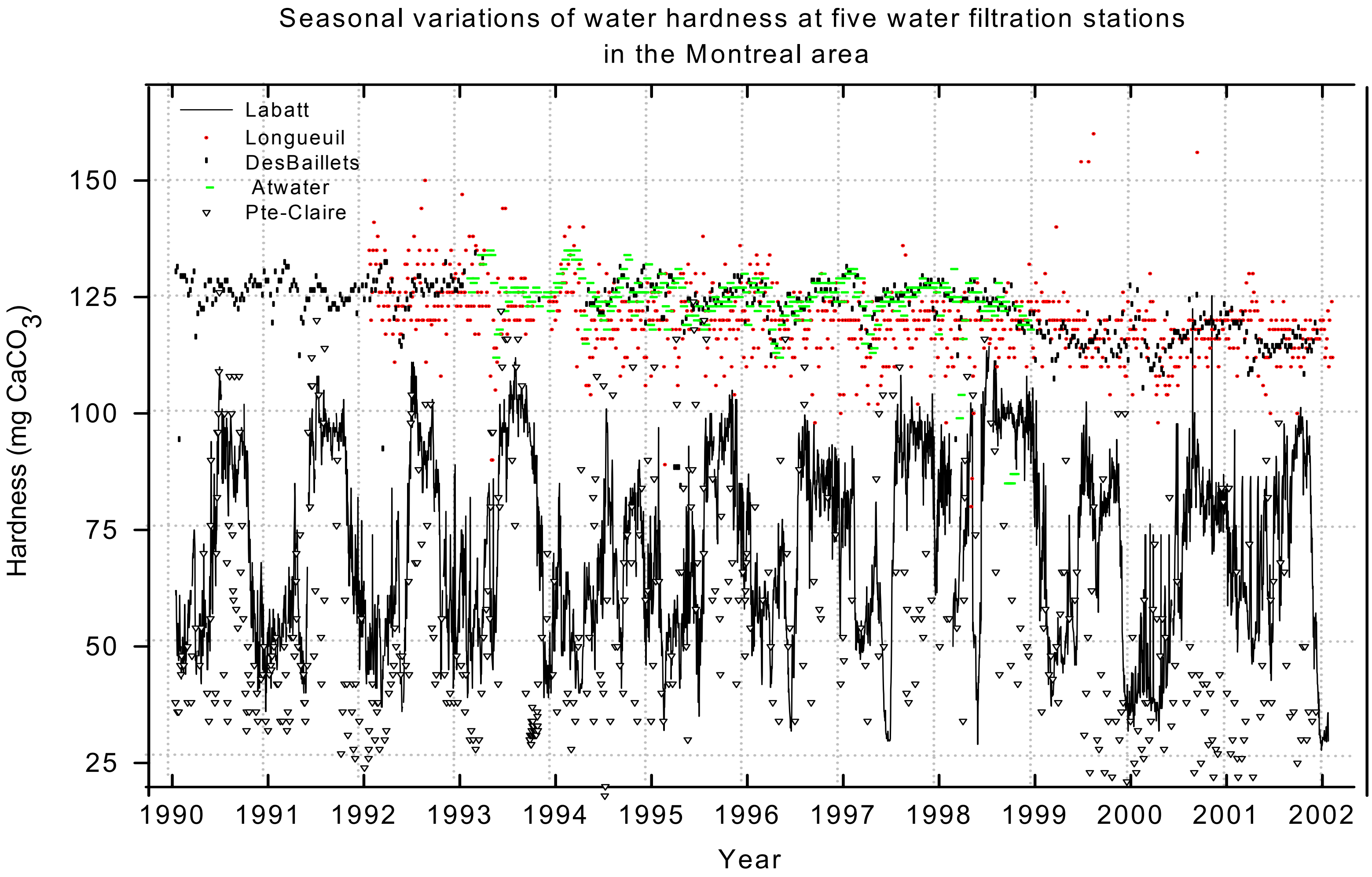
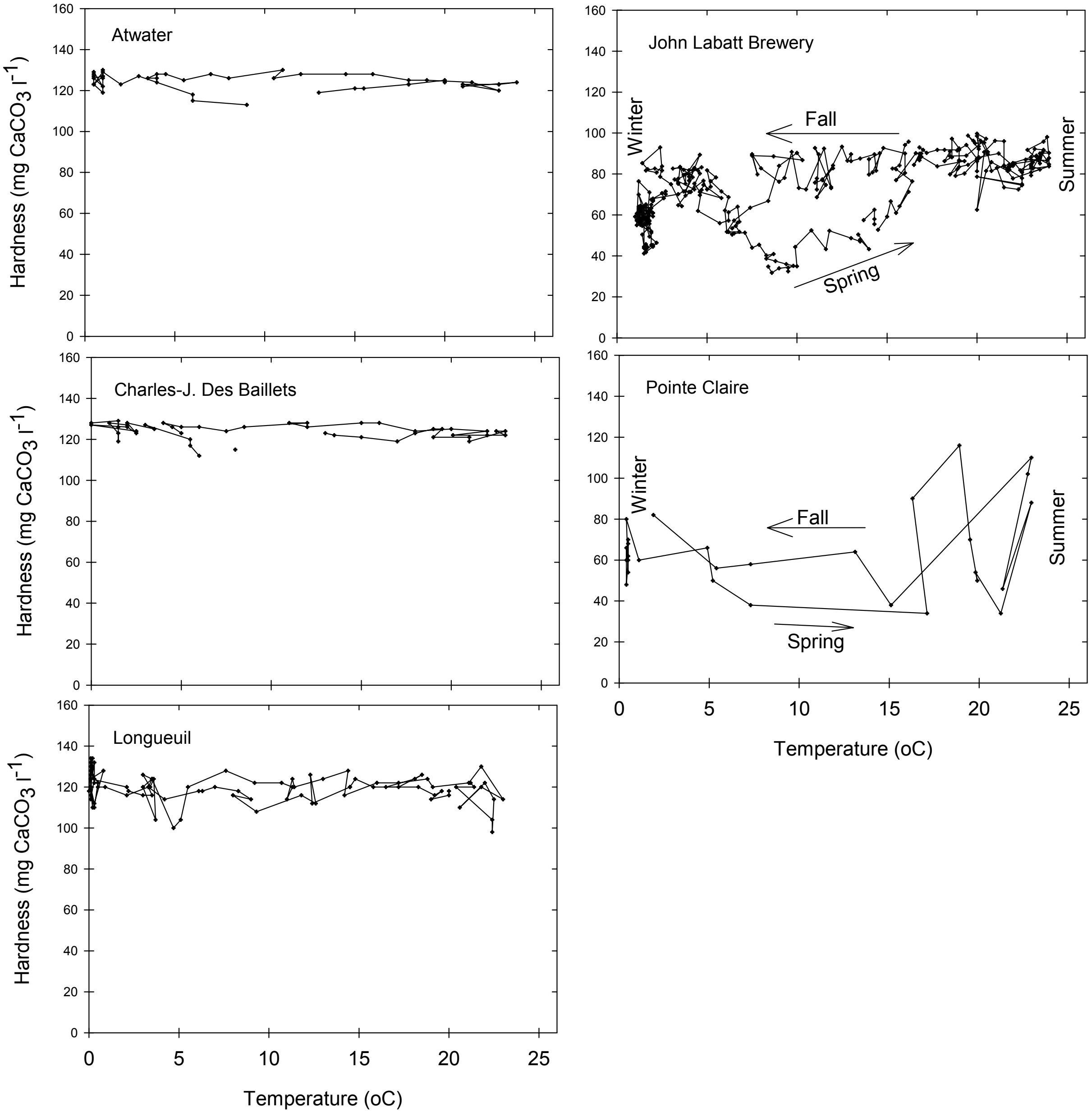
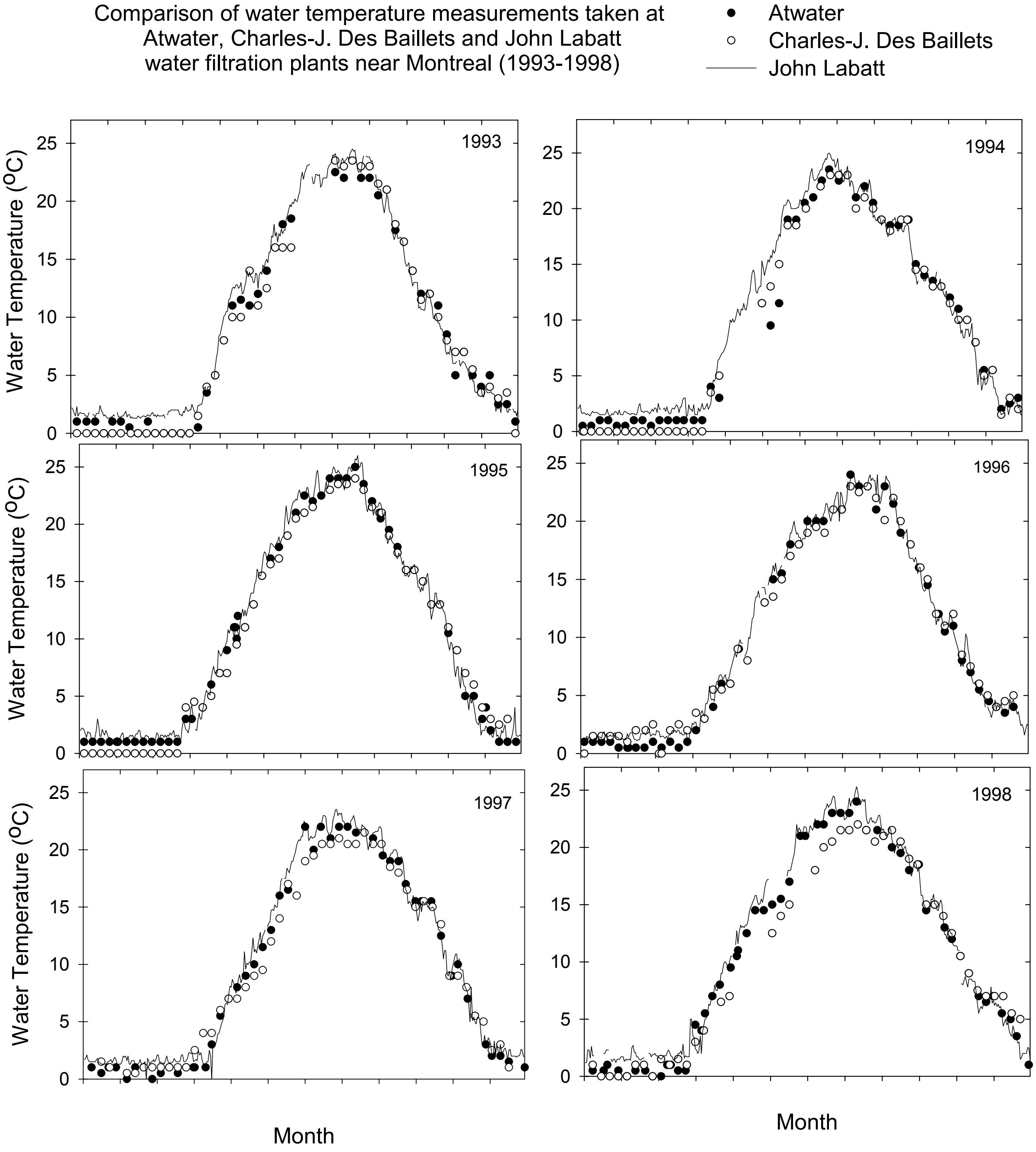

Seasonal variations of water hardness at five water filtration stations
in the Montreal area
Labatt
Longueuil
DesBaillets
Atwater
Pte-Claire
Hardness (mg CaCO$_3$)
150
125
100
75
50
25
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
Year

Figure 5



Comparison of the temperature-hardness diagrams at the water filtration stations influenced by water originating from Lake Ontario (Atwater, Charles-J. DesBaillets, Longueuil) and by a mixture of Ottawa River waters (John Labatt brewery, Pointe Claire) for 1996

Figure 6.


Comparison of water temperature measurements taken at Atwater, Charles-J. Des Baillets and John Labatt water filtration plants near Montreal (1993-1998)

respectively, $p < 0.0000$). The average annual water temperature at all three plants was within 0.3°C of each other.

A more detailed assessment of seasonal differences among plants was carried out on daily paired temperature differences between DB and the other two plants. AW and DB share the same water intake, but differ markedly in terms of their infrastructures and water transit time to the plants. Average seasonal deviations between AW and DB were < 1°C. The largest differences between AW and DB were recorded in summer, during which temperatures at AW were higher than at DB by an average 0.5°C, with 95% percentile and maximum differences of 2.5°C and 3°C, respectively.

In contrast, LO and DB have transit times in the same range, but use river water intakes that are about 15 km apart. Average seasonal deviations between LO and DB were < 1°C. The largest differences between LO and DB were recorded in the fall, when temperatures at LO were lower than at DB by about 0.9°C on average, with 95% percentile and maximum differences of +0.2°C and 3.7°C, respectively. Overall, the range of differences is smallest between LO and DB (Fig. 7).

4. Predictive models of water temperature based on environmental variables

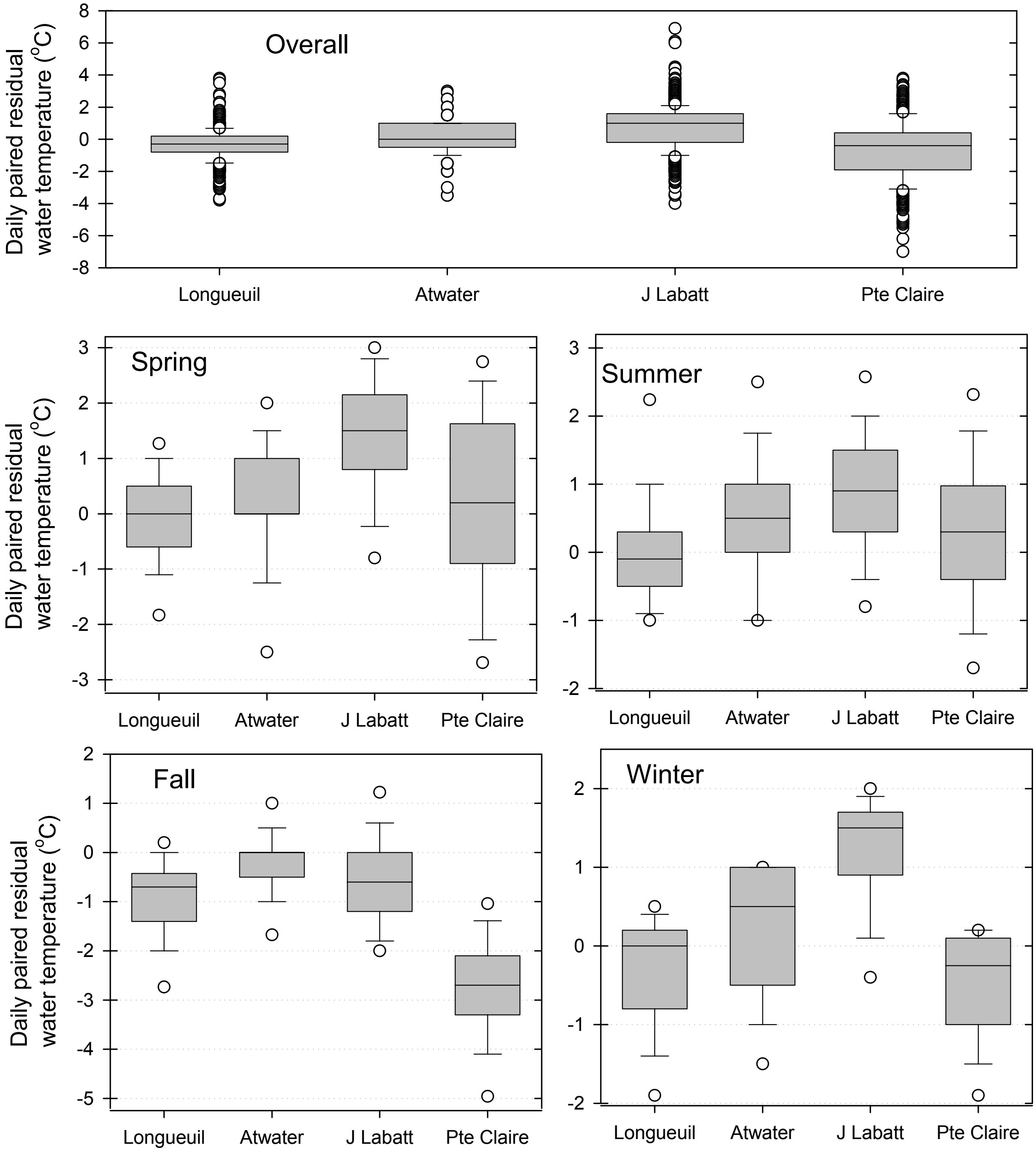
Multiple regressions predicting the water temperature at the three filtration plants pumping waters originating from Lake Ontario generated models explaining 89% of the total variance in water temperature (Table 4). Air temperature, season, discharge at Carillon and the ratio of Ottawa River to total discharge yielded very highly significant regression coefficients. All coefficients were positive except for the ratio of Ottawa River to total discharge. Seasonal effects were accounted for by different intercept values. Regression equations for LO and DB did not differ significantly, however, seasonal coefficients were slightly (by 0.5°C), but significantly lower for AW plant. This difference could result from the inclusion of data from the 1970's at AW (1973-1998) in contrast with the more recent temperature record from LO (1992-2002) and DB (1980-2001) (see next section for more details).

5. Temporal trends in water temperature and growing season

Annual mean water temperatures showed similar, nearly parallel, inter-annual variations for the AW, DB, JL and LO plants, for which mean annual temperature values were available only for the past 10-25 years (Fig. 8). For a given year, values for plants DB, JL and LO differed by about

Figure 7.

Distribution of daily residual water temperature differences between Des Baillets
the remaining four filtration stations. All outliers are identified in the overall distribution.
Seasonal plots show 5-95% percentile distribution only.



1.0°C. The PC plant also followed the same temporal pattern, but exhibited broader inter-annual variations.

Significant, positive trends in annual water temperatures over time were observed for the DB, LO and JL plants, characterized by the following regression equations:

$T_{DB} = -124.48 + 0.07$ year $r^2 = 0.41$ $n = 13$ $p < 0.05$ (1981-2001)
$T_{LO} = -226.22 + 0.12$ year $r^2 = 0.44$ $n = 11$ $p < 0.05$ (1992-2002)
$T_{JL} = -84.46 + 0.05$ year $r^2 = 0.39$ $n = 24$ $p < 0.01$ (1978-2001)

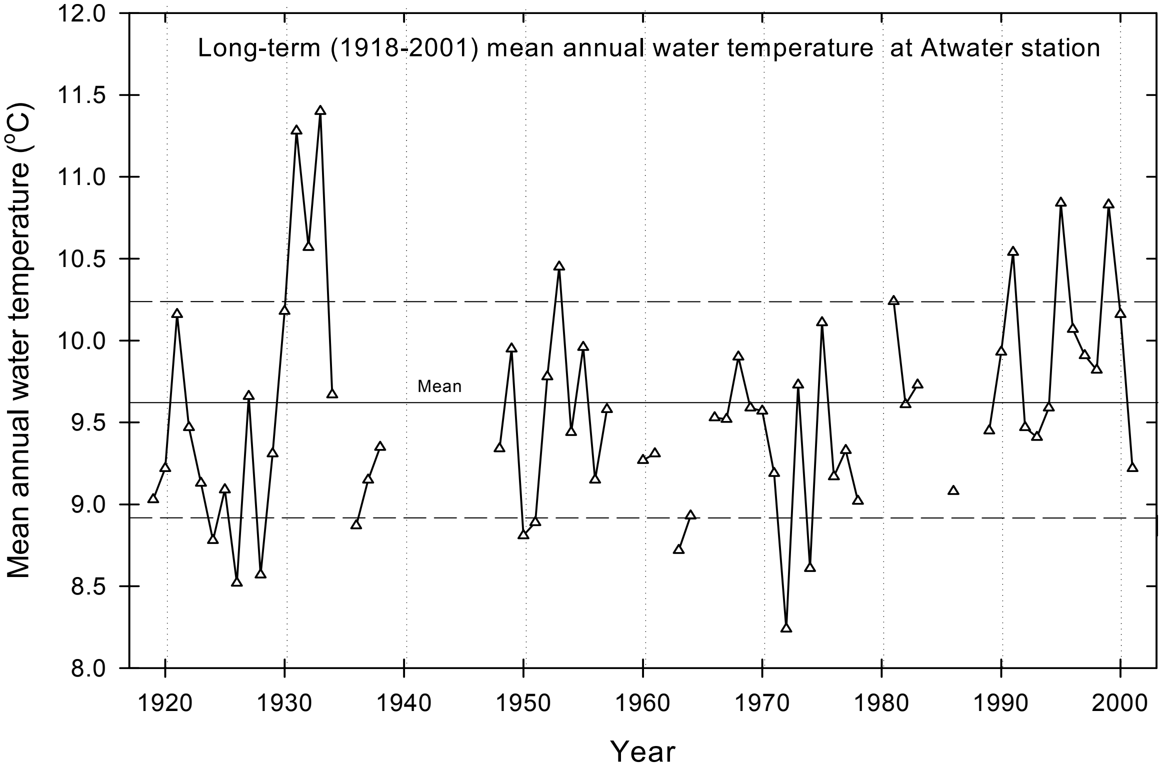
The slope of these equations indicates an average increase of 0.5 (JL) to 1.2°C (LO) in annual average water temperature over the past 10 years.

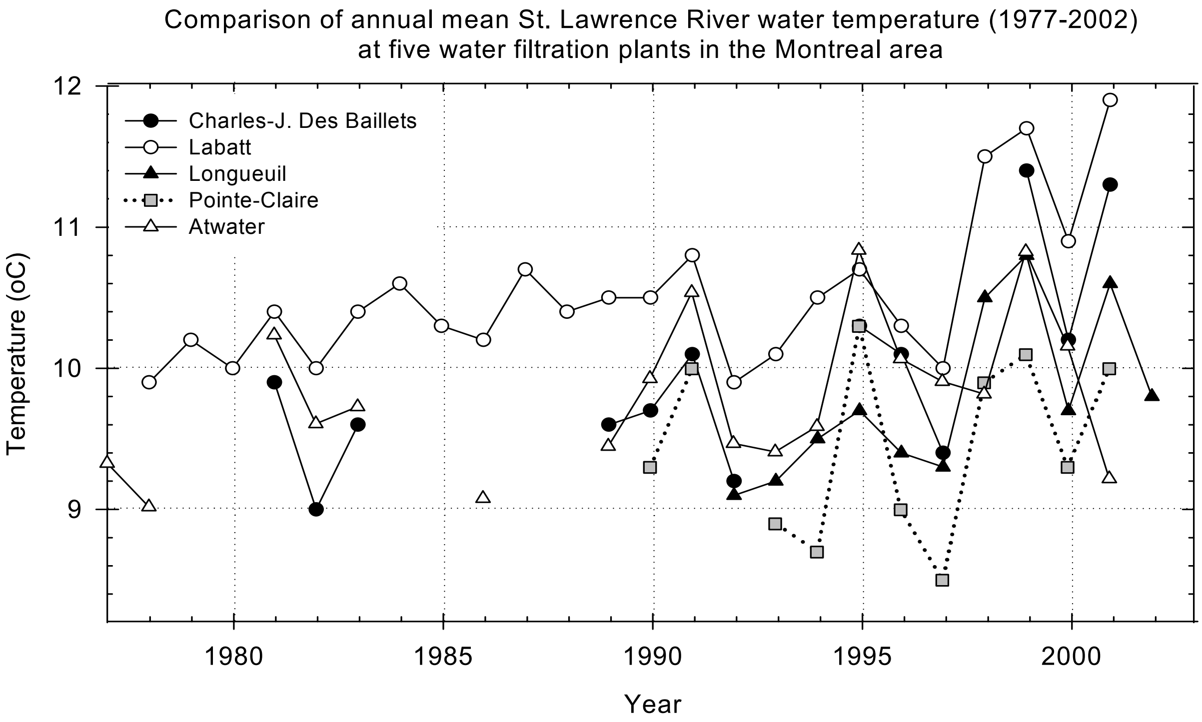
Mean annual water temperature values could be calculated for AW for the periods the 1919-1938 and 1948-2001, a total of 63 years (Fig. 8). No long-term trend in water temperature could be detected at AW, owing to the apparent alternating of warm and cold water years. Years of warmest (11.4°C in 1933) and coldest (8.3°C in 1972) average water temperatures differed by 3.1°C (overall mean = 9.56 ± 0.65). The highest water temperatures were recorded in the early 1930s, corresponding with the Prairie Dust Bowl period of low levels and dry and warm weather conditions (Rosenzweig and Hillel 1993, Changnon 1994). Nine years of noticeably warm (> 10.21°C = mean + 1 s.d.) water temperatures were recorded in 1930-33, 1953, 1981, 1991, 1995 and 1999. Ten years of cold water temperatures (< 8.92°C = mean – 1 s.d.) were observed in 1924, 1926, 1928, 1936, 1950-51, 1963-64, 1972 and 1974. In spite of the lack of a temporal trend, it is noteworthy that none of the cold years and four of the nine warm years have occurred since 1980.

On average (1930-2001), the terrestrial plant growing season (air temperature > 5.5°C) starts on April 14 (± 8 days) and ends on October 20 (± 9 days). The most precocious onset was observed on March 21 (in 1987), the latest occurred on April 29 (in 1956). The date at which the growing season ended the earliest was September 28 (in 1974); the latest end was recorded on November 9 (in 1975). The growing season for terrestrial plants lasts 189 days on average (± 12 days, minimum 156 days, maximum 211 days). There were no temporal trends in the dates of beginning, end or duration of the growing season for terrestrial plants.

Figure 8. Mean annual water temperature at AW (1919-1998) (Top panel) and at the five water

filtration plants in the Montreal area (1977-2002) (Bottom Panel).





To account for the specific needs of a variety of aquatic organisms, the growing season assessed from water temperature was divided into 5°C intervals between 5 and 20°C (Table 5). Values computed from four different water filtration plants for which daily water temperature values were available yielded very similar results, which occasionally showed significant differences among plants. Whether the differences were due to opposing temporal trends (e.g. relatively colder conditions at AW over the period 1948-1978) or variable proportions of water masses (at JL and PC plants) could not be ascertained. Significant correlations ($p < 0.05$) between years and dates of beginning, end or duration of the growing season were observed in 11 cases out of a maximum possible number of 56 (4 stations x 14 variables = 56); most (9 out 11) were positive, generally indicative of a later water cooling in the fall and an increase in the duration of the growing season, although no single temperature threshold could be clearly identified.

Overall, the rise in spring temperature was initiated on April 20 (± 2.5 days), rose to 10°C on May 10 (± 5 days), 15°C on June 2 (±4.5 days), 20°C on July 2 (± 8 days) and reached its maximum temperature (24.1°C) on August 4 (± 8 days). The fall decrease to 20°C was initiated on September 17 (± 1 day) and dropped to 15°C on October 2 (± 5 days), 10°C on October 28 (± 8 days) and 5°C on November 22 (± 8 days). Water temperatures were > 5°C for 217 days (± 12.5 days), > 10°C for 172 days (± 4 days), > 15°C for 123 days (± 4.5 days) and > 20°C for 58 days (± 7.5 days) on average.

6. Relationships between water temperature and levels in the St. Lawrence River near Montreal

River discharge is the best hydrological variable to describe the relationship between the origin of water mass and water temperature, because it relates directly to their volume and heat retention-transfer capacity. However, downstream of their confluence in the Montreal area, our results have shown that the two water masses do not mix entirely and largely retain their physical, chemical and thermal characteristics, although their discharge is cumulated. From the standpoint of many aquatic and riparian plants and faunal species, however, water levels represent a more meaningful hydrological variable than discharge. Water levels and depth determine the light intensity available for plants, as well as access to the floodplain and availability of littoral areas for faunal species. In addition, historical variations in water levels include the cumulative effects of shoreline and river bed alterations, which are not accounted for by total discharge.

Water temperatures were thus examined in relation to water level variations in the Montreal area, to ascertain whether the inverse relationships identified with discharge of the St. Lawrence and Ottawa rivers (Table 4) would remain perceptible once they were cumulated and translated into water level downstream of the confluence. As anticipated, a negative relationship ($p < 0.05$) was observed between average annual water temperature (T) at AW plant and mean annual level at Montreal Harbour (Jetty No. 1), described by the equation:

$T = 10.13 - 0.38$ Level $r^2 = 0.09$ $p < 0.05$ $n = 64$ (1919-1964)

When the data series was divided between the pre- (1919-1957) and post- (1960-2001) regulation periods (Fig. 9), it became apparent that the range of water levels of the two periods only partially overlapped, showing the lower average annual water levels in the post-regulation period. The computation of separate relationships for pre- and post-regulation periods revealed that both the slopes and intercepts differed among periods, so that, for a given water level, water temperature was higher in the pre-regulation period than post-regulation. This difference visibly resulted from the very high water temperatures recorded in the 1930-33 period, which coincided with prolonged drought conditions in the Prairies (Rosenzweig and Hillel 1993, Changnon 1994).

An examination of the relationship between monthly average water level and temperature for the Montreal area (JL and DB plants) revealed significant, negative correlations for the months of May to September (Figures 10-11, Tables 6-7). For both plants, the effect of low levels was highest in May, with a 1.45-degree increase in mean monthly temperature for each 1-m decrease in average level. The results indicate that years of low discharge coincide with a precocious warm-up in the spring and a late cooling in September. These conditions should add up to a longer growing season and higher cumulative number of degree-days during sustained low-level periods. It is noteworthy that the maximum monthly temperature values recorded in 1995, 1999

Figure 9. . Relationships between the mean annual temperature of the St. Lawrence River at the AW plant and water levels (Montreal Harbour Jetty No. 1) for the pre (1919-1957) and post (1958-2001) regulation periods.

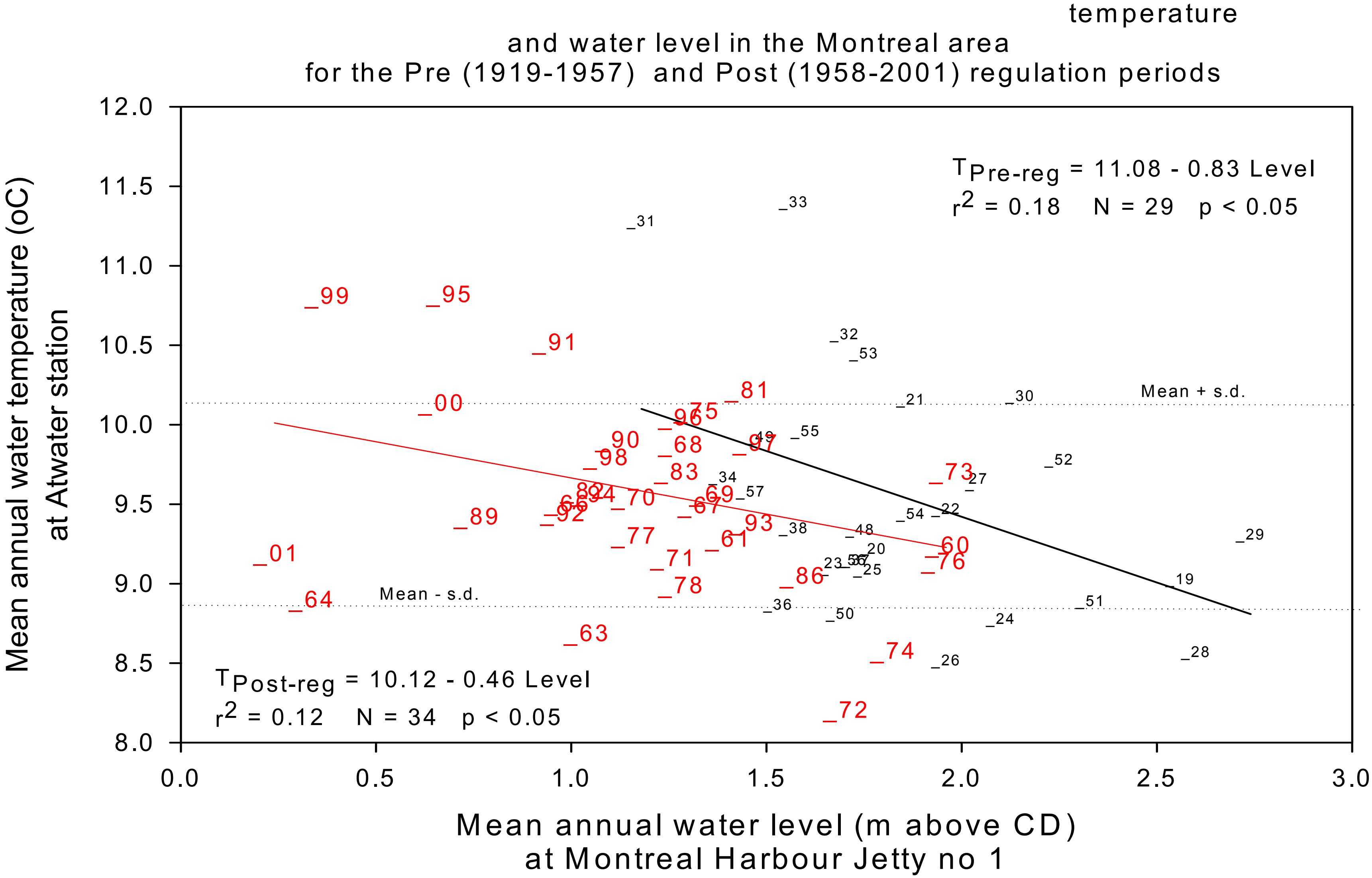


Figure 10. Relationship between mean monthly water level (m above CD) and mean monthly water temperature at the Charles-J. Des Baillets water filtration plant for the years 1981-2001. Full lines identify significant linear relationships; dotted lines are not significant.

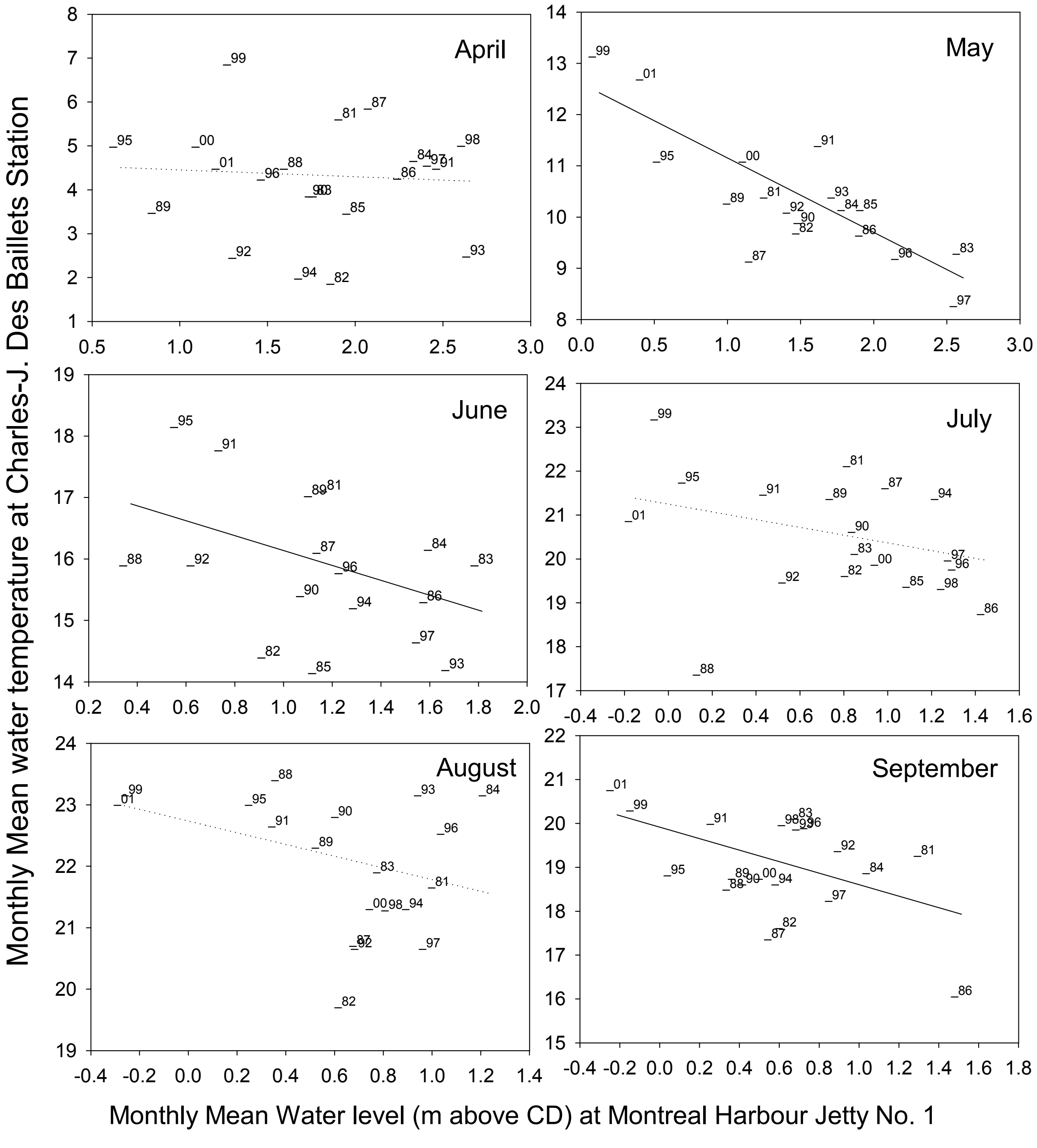
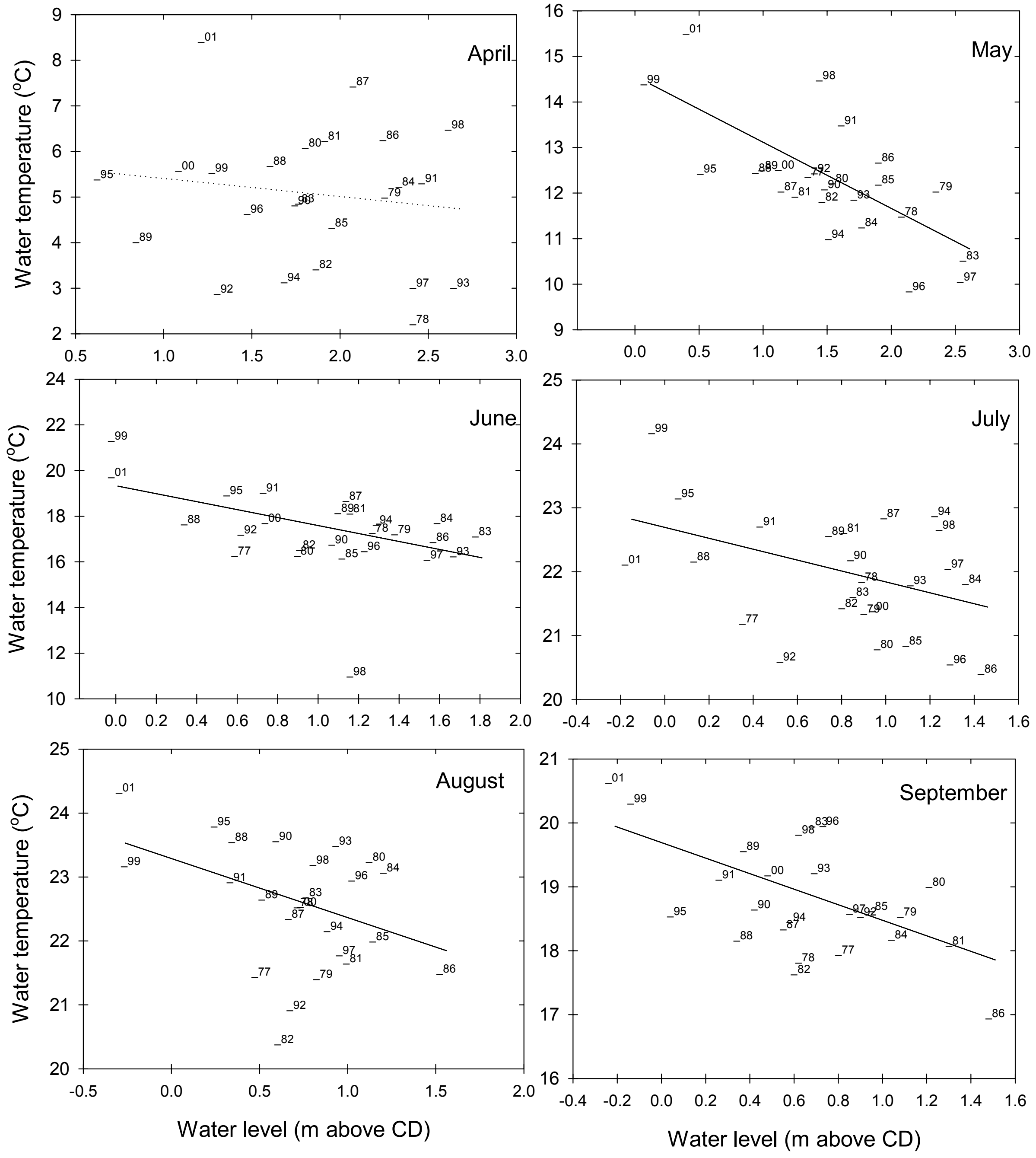


Figure 11. Relationship between mean monthly water level (m above CD) and mean monthly water temperature at the John Labatt water filtration plant for the years 1977-2001. Full lines identify significant linear relationships; dotted regression lines are not significant.



and 2001 are always the highest of the 20-year time series, coinciding with record-low levels in the Montreal area.

Conclusion

This study explored the links between temperature and flow regime resulting from the confluence of the St. Lawrence and Ottawa rivers in the Montreal area. As a function of volume, waters originating from Lake Ontario are slow to warm in the spring and summer but retain their heat in the fall and winter much longer than the waters originating from the Ottawa River. The influence of each water mass is perceptible in the seasonal temperature recorded at water filtration plants in the Montreal area. Differences induced by water masses are greater than those resulting from plant infrastructure. The discharges of both rivers and water levels downstream of their confluence were negatively correlated with water temperature, at all temporal scales, showing that years of high discharge and levels coincide with years of low water temperatures, and vice versa. Although long-term time series (1919-2001) showed an alternation between warm and cold years, shorter series (1977-2001) revealed a trend towards warmer water temperatures. This warming trend likely resulted from the combination of the natural (climatic) variability in climate (air temperature and water supply) and regulation of discharge.

St. Lawrence flow reduction and air temperature increases in recent years (1999-2001) are within the expected range forecast by climate change scenarios (Lofgren et al. 2002, NRC 2002). Recent years of low discharge coincide with a precocious warm-up in the spring and a late cooling in September, adding up to a longer growing season and higher cumulative number of degree-days during sustained low-level periods. Although the water temperature differences recorded are small in absolute terms, they represent potentially important changes for aquatic organisms.

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Table 1
Physical and chemical characteristics of waters originating from Lake Ontario and the Ottawa River

	Waters originating from Lake Ontario				Waters originating from Ottawa River				
	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum	References
Temperature (°C)	14.1	6.5	7	24	11.7	9.1	0	26	Annex 3.5[e] in Rondeau 1993
Apparent colour (Pt-Co units)	11	6	2	24	64	25	32	147	Annex 3.2[e] in Rondeau 1993
True colour (Hazen units)					25	5	17.0	48.0	Annex 2.1.20 in Primeau 1996
Turbidity (NTU)	1.3	0.6	0.4	2.5	4.2	3.0	1.2	17.0	Annex 3.3[e] in Rondeau 1993
	0.67	0.35	0.2	1.5	5.9	6.4	1.8	38	Gagnon (pers. comm.)[f]
Light extinction coefficient	0.31[c]	0.04			1.32[d]	0.03			Hudon 2000
Hardness (mg L^{-1} $CaCO_3$)	124.8	4.3	115.8	131.7	32.1	5.5	23.6	47.2	Annex 3.8[e] in Rondeau 1993
Alkalinity (mg L^{-1} $CaCO_3$)	89.8	3.7	81.5	95.7	22.2	4.5	15.7	36.5	Annex 3.7[e] in Rondeau 1993
pH	8.2	0.1	7.9	8.6	7.7	0.5	7.0	8.9	Annex 3.6[e] in Rondeau 1993
	7.6	0.39	6.6	8.2	6.8	0.44	6.0	8.0	Gagnon (pers. comm.)[f]
Conductivity (µS cm^{-1})	295.0[a]	16			95[b]	21			Hudon 2000
	307	15	278	344	90	16	52	118	Annex 3.1[e] in Rondeau 1993
	298	20	263	360	92	21	62	132	Gagnon (pers. comm.)[f]

Measurement site

[a] Wolfe Island (Lake Ontario)

[b] Carillon

[c] Lake Saint-François

[d] Lake des Deux Montagnes

[e] 1985-1990 period. For Lake Ontario waters: buoy 9205 located in Lake St. Francis in the navigation channel south of Cornwall Island. For Ottawa River waters: buoy 9002 located in Sainte-Anne channel.

[f] Data provided by Pierre Gagnon (15 January 2003), extracted from RISQUE data base (Répertoire Informatisé pour le Suivi de la QUalité de l'Eau) covering the 1996-97 period ; For Lake Ontario waters: Cornwall, Moses-Saunders dam; for Ottawa River waters: Carillon dam.

Table 2. Average water temperature (between May 30 and October 5, 1994 and 1995) at ten stations located between Varennes (south shore) and Repentigny (north shore), downstream of the confluence of the Des Prairies and Des Mille-Iles rivers (Ottawa R.) with the St. Lawrence

Station (m from south shore)	**Major influences**	**1994 Conductivity Mean (s.d.) n = 18**	**1995 Conductivity Mean (s.d.) n = 8-12**	**1994 Temperature Mean (s.d.) n = 18**	**1995 Temperature Mean (s.d.) n = 10**
1 (53)	South shore tributaries and Upper St. Lawrence River	294.4 (8.5)	292.3 (5.7)	19.20 (3.11)	19.79 (3.07)
2 (230)	Navigation channel, Upper St. Lawrence River	283.3 (10.3)	282.3 (5.4)	18.99 (3.19)	19.48 (3.12)
3 (450)	Upper St. Lawrence River	277.6 (10.8)	n.a.	19.07 (3.13)	n.a.
4 (765)	Upper St. Lawrence River	272.2 (12.0)	277.9 (7.7)	19.07 (3.14)	n.a.
5 (1030)	Upper St. Lawrence River, Montreal wastewater treatment plant	268.6 (13.4)	273.4 (17.0)	19.29 (3.29)	19.79 (3.07)
6 (1210)	Mixed waters	213.0 (39.0)	236.8 (50.2)	19.75 (3.01)	20.10 (2.98)
7 (1645)	Mixed waters	147.0 (24.6)	160.2 (29.3)	19.97 (2.90)	20.49 (3.18)
8 (1767)	Ottawa River, pleasure boating channel	116.2 (17.8)	137.8 (23.2)	20.07 (2.90)	20.62 (3.27)
9 (1910)	Ottawa River	107.0 (17.8)	n.a.	20.09 (2.89)	n.a.
10 (2032)	Ottawa and l'Assomption rivers, north shore tributaries	114.4 (16.5)	132.5 (18.4)	20.02 (2.85)	20.75 (3.31)
All	Excluding stations 3-4-9	205.3 (79.3, 7)	216.5 (70.9, 7)	19.61 (0.13, 7)	20.10 (0.15, 7)

Note: The water mass and environmental influences are outlined for each station (for more information, see Hudon and Sylvestre 1998). n.a. not available.

Table 3. Comparison of water hardness (mg $CaCO_3$ L^{-1}) values recorded at the five water filtration plants in the Montreal area (modified from Armellin *et al.* 2003). For each plant, the number of records (N), average number of days between measurements (Frequency), minimum (Min), 5, 50 and 95% percentile and maximum (Max) values are indicated. Values recorded for waters originating from Lake Ontario and Ottawa River are indicated as reference (from table 1).

Plant (period)	**N**	**Frequency (days)**	**Min**	**5% percentile**	**Median**	**95% percentile**	**Max**
Atwater (1993-98)	304	7.2	85.0	115.2	125.0	132.9	135.0
Charles-J. Des Baillets (1980-2001)	1 113	7.1	81.0	88.0	123.0	130.0	174.0
Longueuil (1992-2003)	1 069	3.8	80.0	108.0	120.0	132.0	160.0
John Labatt (1977-2001)	7 825	1.1	11.0	56.2	75.0	91.8	171.5
Pointe-Claire (1992-2001)	521	8.4	18.0	28.0	48.0	108.0	126.0
Lake Ontario water			115.8		124.8		131.7
Ottawa River water			23.6		32.1		47.2

Table 4. Models predicting daily St. Lawrence River water temperature at three water filtration plants under the influence of water from Lake Ontario, in the Montreal area. Regression coefficients (± standard error) for each environmental variables are indicated: Average daily air temperature (Dorval airport), daily Ottawa River discharge at Carillon, daily ratio of Ottawa River to total river discharge (at Cornwall + Carillon).

	Plants primarily influenced by Lake Ontario waters		
	Longueuil (1992-2002)	**Charles-J. Des Baillets (1980-2001)**	**Atwater (1973-1998)**
Intercept in Summer	16.1 ± 0.26	15.9 ± 0.26	15.5 ± 0.26
Intercept in Autumn	10.7 ± 0.26	10.6 ± 0.26	10.1 ± 0.26
Intercept in Winter	6.8 ± 0.26	6.7 ± 0.26	6.2 ± 0.26
Intercept in Spring	8.7 ± 0.26	8.6 ± 0.26	8.1 ± 0.26
Air temperature (^{o}C)	0.36 ± 0.006	0.36 ± 0.006	0.36 ± 0.006
Ottawa River Discharge ($m^3 s^{-1}$)	0.00048 ± 0.0001	0.00048 ± 0.0001	0.00048 ± 0.0001
Ratio of Ottawa River to total discharge	-20.55 ± 2.207	-20.55 ± 2.207	-20.55 ± 2.207
r^2	0.89	0.89	0.89

Note: For each plant, the interval covered is specified. For each variable entered in the equation, the associated coefficient is indicated with its level of significance. The proportion of the total explained variance (r^2) is indicated for each regression equation. All terms are very highly significant ($p < 0.001$).

Table 5. Comparison of growing season characteristics recorded at filtration plants influenced by Lake Ontario (Atwater and Longueuil) and Ottawa River (John Labatt and Pointe Claire) waters using ANOVA.

				Lake Ontario waters		**Ottawa River waters**	
Variable	**Effect of plant F^{p}**	**Effect of years F^{p}**	**Overall mean n = 74**	**AW 1948-1978 n = 29**	**LO 1992-2001 n = 11**	**JL 1977-2001 n = 25**	**PC 1990-2001 n = 12**
> 5°C							
Spring	1.42 $^{n.s.}$	0.24 $^{n.s.}$	110.3	110.7^{a}	109.1 ^{a}	108.4 ^{a}	112.9 ^{a}
Fall	12.03***	0.86 $^{n.s.}$	326.1	329.6 ^{a}	332.2 ^{a}	327.3 ^{a}	315.2 ^{b}
Duration	2.81*	0.58 $^{n.s.}$	217.6	226.9 ^{a}	222.7 ^{a}	218.7 ^{a}	201.9 ^{b}
> 10°C							
Spring	5.17**	0.00 $^{n.s.}$	130.5	135.7 ^{a}	132.6 ^{ab}	125.6 ^{bc}	128.1 ^{c}
Fall	4.56*	6.49***	301.3	308.0 ^{a}	301.8 ^{b}	302.8 ^{b}	292.7 ^{c}
Duration	3.73*	1.88 $^{n.s.}$	170.8	172.3 ^{a}	169.2 ^{ab}	177.2	164.5 ^{b}
> 15°C							
Spring	4.42**	0.05 $^{n.s.}$	153.7	158.2 ^{a}	156.7 ^{a}	149.8 ^{b}	150.0 ^{b}
Fall	2.84*	3.39 $^{n.s.}$	275.5	280.5 ^{a}	275.0 ^{bc}	276.0 ^{b}	270.7 ^{c}
Duration	0.87 $^{n.s.}$	7.38 **	128.6	122.7 ^{a}	129.4 ^{b}	131.6 ^{b}	130.8 ^{b}
> 20°C							
Spring	2.92*	0.46 $^{n.s.}$	183.3	192.6 ^{a}	182.2 ^{b}	177.4 ^{b}	180.8 ^{b}
Fall	0.13 $^{n.s.}$	1.44 $^{n.s.}$	250.1	250.5 ^{a}	249.7 ^{a}	251.0 ^{a}	249.4 ^{a}
Duration	1.92 $^{n.s.}$	0.01 $^{n.s.}$	66.9	58.1 ^{a}	67.4 ^{ab}	73.6 ^{b}	68.6 ^{ab}
Max Temperature	3.59*	0.30 $^{n.s.}$	24.1	23.1 ^{a}	24.1 ^{b}	24.7 ^{b}	24.5 ^{b}
Day of maximum temperature	2.03 $^{n.s.}$	3.82 $^{n.s.}$	216.5	227.5 ^{a}	213.9 ^{b}	213.9 ^{b}	210.9 ^{b}

Note: The effects of years and plants are tested on the day of the year at which a given temperature is reached in the spring and the fall as well as on the number of days (duration) above each water temperature threshold. Overall mean (n = 74) and means per plant are provided, with letters indicating groups of stations bearing significantly different means. The F values and significance (*p*) are indicated for each effect: n.s. non-significant, * $p < 0.05$, ** $p < 0.01$, ***, $p < 0.001$.

Table 6. Linear regressions between the mean monthly water level (L, m above chart datum) (Montreal Harbour Jetty No. 1) and the mean monthly water temperature (T, ^{o}C) at Montreal (Charles-J. Des Baillets water filtration plant), between 1981 and 2001

Month	Equation predicting mean monthly temperature	Mean 1981-2001 (s.d.)	n	r^2 (p)
April	$4.61–0.16\ L_{\text{April}}$	4.33 (1.26)	21	0.005 n.s.
May	$12.60–1.45\ L_{\text{May}}$	10.46 (2.29)	18	0.656***
June	$18.29–2.00\ L_{\text{June}}$	16.20 (1.52)	21	0.462***
July	$21.25–0.88\ L_{\text{July}}$	20.55 (1.37)	19	0.096 n.s.
August	$22.73–0.95\ L_{\text{August}}$	22.11 (1.10)	19	0.123 n.s.
September	$19.92–1.31\ L_{\text{September}}$	19.12 (1.13)	20	0.250*

Note: For each regression equation, the number of monthly mean values available for each regression (n), the fraction of the total variance explained (r^2) and the significance level of associated probability *(p)* are indicated: * $p < 0\ .05$; ***, $p < 0.001$; n.s., non significant.

Table 7. Linear regressions between the average monthly water level (L, m above chart datum) (Montreal Harbour Jetty No. 1) and the average monthly water temperature (T, °C) at Montreal (John Labatt Brewery water filtration plant), between 1977 and 2001

Month	**Equation predicting mean monthly temperature**	**Mean 1977-2001 (s.d.)**	**n**	r^2 **(p)**
April	$5.80–0.40\ L_{April}$	5.07 (1.52)	24	0.02 n.s.
May	$14.57–1.45\ L_{May}$	12.34 (1.28)	25	0.504***
June	$19.33–1.74\ L_{June}$	17.51 (1.81)	25	0.221*
July	$22.70–0.85\ L_{July}$	21.99 (0.92)	25	0.176*
August	$23.29–0.92\ L_{August}$	22.61 (0.97)	25	0.160*
September	$19.69–1.21\ L_{September}$	18.87 (0.89)	25	0.325**

Note: For each regression equation, the number of monthly mean values available for each regression (n), the fraction of the total variance explained (r^2) and the significance level of associated probability (*p*) are indicated: * $p < 0\ .05$; ***, $p < 0.001$; n.s., non-significant.