Water Qual. Res. J. Can. 2010 · Volume 45, No. 1, 47–57

Frequency Analysis as a Tool for Assessing Adverse Conditions During a Massive Fish Kill in the St. Lawrence River, Canada

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During the summer of 2001, the largest fish kill in the recorded history of the St. Lawrence River occurred. More than 25,000 dead carp were recovered. Preliminary analyses suggested hydroclimatic factors may have triggered the fish kill. Long time series of hydroclimatic variables were available upstream and downstream from the study area. In order to investigate if hydroclimatic conditions were extreme during the summer of 2001, frequency analyses were performed on time series of air and water temperature, water level, and solar radiation. During this period, the daily maximum water temperature was abnormally high (return period of 47 years) relative to other years. Air temperature was also high (return period of 22 years) and water level was very low (return period of 67 years). Results showed that hydroclimatic forcings were acting at two different time scales. First, short-term extremes are more likely to have direct impacts on ecosystems, such as lethal stress caused by oxygen depletion in shallow areas. Long-term extremes have indirect effects, which are more difficult to detect, such as immunosuppression. These results reiterate the importance of water temperature in aquatic habitat, particularly in the present context of global warming and climate change.

Key words: **fish kill, water temperature, physiological stress, St. Lawrence River, frequency analysis**

Introduction

Water temperature is one of the most fundamental parameters for assessing suitable conditions for fish (Sinokrot et al. 1995; Mohseni et al. 2003; Cooke et al. 2004). Temperature has an important effect on fish life history characteristics such as survival, growth, spawning date and reproduction, egg incubation, habitat selection, distribution, and migration (Mortsch and Quinn 1996; Bergstedt et al. 2003; Brodeur et al. 2004; Cooke et al. 2004; Gillet and Péquin 2006; Ham et al. 2006; Mingelbier et al. 2008). Although water temperature may not always be the direct driving factor or main stressor leading to mortality, it is often an indirect factor involved in a wide number of physical and physiological processes linked to fish mortalities.

Massive fish kills are defined as events that affect a large number of individuals across relatively large aquatic areas. They are often triggered by adverse environmental conditions. This phenomenon may occur in marine or freshwater environments and may involve one or many fish species (Herman and Meyer 1990). Such events may be related to a broad range of factors, such as high population density, spawning stress, reduced food abundance, excessive or sudden water temperature changes, and bacterial or fungal infections (Herman and Meyer 1990; Bartholow 1991; FWC 2006; MDE 2006).

The St. Lawrence River and the Great Lakes have been the site of a number of fish kills of various scales, but related documentation on them is scarce. A review of provincial and federal reports did not reveal any official mention of massive fish kills, until 2001. The fish kill observed during the summer of 2001 may be the largest event of its kind in the last decades or even the past century on the St. Lawrence River (Monette et al. 2006). Most of the mortality observed during the summer of 2001 occurred in the freshwater reaches of the St. Lawrence River between Montréal and Québec City. During the first part of the event, from June 28 to July 5, 8,127 carcasses were found between Sainte-Anne-de-Bellevue and Québec City (Fig. 1). During the second part, July 6 to July 13, 11,397 dead fish were counted in the same reaches but also in the upstream part of Deux-Montagnes Lake and in the Sorel archipelago. Within this stretch of the St. Lawrence River, the distribution of carcasses did not reveal any spatial or temporal correlation, which indicates that dead fish were not originating from one specific area. During the third period, July 14 to July 31, 6,440 carcasses were collected, mostly in the lower reaches of the study area, between Donnacona and Québec.

The bulk of the dead fish collected were carp but other fish were also found, including: Catostomidae, Anguillidae, Acipenseridae, Ictaluridae, Esocidae, Percidae, and Centrarchidae. About 25,000 dead carp (*Cyprinius carpio*) were collected along the St. Lawrence River (Mingelbier et al. 2001). This is believed to be a conservative estimate because the carp were only recovered in inhabited areas. The dead carp were mainly large adults and no biological sampling was performed on collected carcasses, except for abundance.

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Many hypotheses were reviewed by Mingelbier et al. (2001) to explain the massive fish kill of 2001 in the St. Lawrence River. No toxic spills were reported in St. Lawrence River and its tributaries during the summer of 2001. Analyses for heavy metals and other contaminants showed normal concentrations for the period between April and July 2001, which negated the hypothesis of contamination (Mingelbier et al. 2001).

However, spot measurements of water temperatures as high as 34°C were reported in the area of Lake Saint-Pierre (Mingelbier et al. 2001), which is considered very high for most of the fish of the St. Lawrence River. It is important to mention that during the same period, a similar fish die-off occurred in the neighbouring Lake Champlain area (Vermont, U.S.A.), but for other fish species (Mingelbier et al. 2001). This led to the hypothesis that regional environmental factors may have affected a large area at the same time. Adverse hydrometeorological conditions could therefore be a potential cause of mortality.

Surprisingly, carp was the species mostly affected by the conditions during the summer of 2001. Carp is an opportunistic species that can tolerate many adverse conditions, such as high temperatures, low concentrations of dissolved oxygen, and poor water quality, with a lethal temperature limit between 36 and 41°C (Cooper 1987). The spawning period for carp is triggered when spring or early summer water temperature reaches 17°C. Monette et al. (2006), who examined the dead fish, concluded that the ultimate cause of mortality was opportunistic bacterial infection by *Aeromonas hydrophila* and *Flavobacterium sp.* The gills and the other internal organs presented with infections by these bacteria. Moreover, lesions were observed in the digestive system and on the gills. Such type of infection only leads to mortality when the fish present internal lesions. Since these bacteria do not usually lead to mortality when fish are healthy, it is believed that the fish were immunodeficient because of physiological stress that could have been induced by spawning energy demand and by high water temperature.

Environmental conditions (mostly related to the thermal regime) are suspected to be one of the causes (direct or indirect) of mortality. Therefore, this paper investigates the hydroclimatic conditions during the summer of 2001. The objective is to determine whether extreme conditions that may have been conducive to environmental stress for fish occurred. To achieve this objective, historical water and air temperature series as well as solar radiation and water level historical time series were analyzed using frequency analysis for different durations (1 to 41 days). We aimed to verify if those four variables exhibited extreme values during the summer of 2001. Air temperature, solar radiation, and water levels were selected because they are known to have an impact on water temperature. The relation between air temperature and water temperature is well known and used in numerous studies to predict water temperature by regression (Cluis 1972; Crisp and Howson 1982; Jourdonnais et al. 1992; Stefan and Preud'homme 1993;

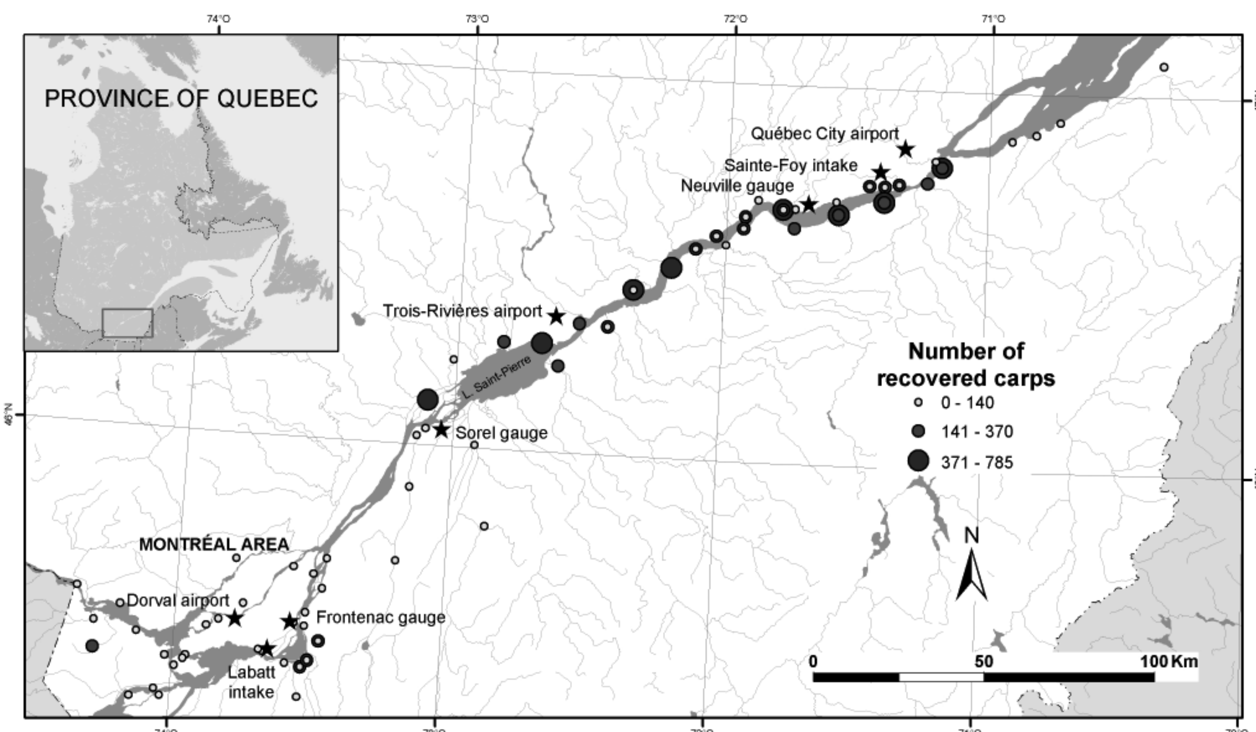

Fig. 1. Study area: St. Lawrence River and all the localities where dead fish were observed during the fish kill of 2001. Stars indicate location of measurement stations used for the frequency analyses.

Caissie et al. 1998; Mohseni and Stefan 1999). Lack of local data precluded the use of such a relationship to model water temperature where mortality occurred. Therefore, the preferred tool to examine the hydroclimatic conditions was frequency analysis of relatively long time series at stations located in the vicinity of the study area. Extremes of different durations (i.e., 1 to 41 days) from May to August were analyzed.

Material and Methods

Study Area

The St. Lawrence River, located in Québec, is one of the largest rivers in North America. It flows for more than 1,000 km, from the Greats Lakes to the Atlantic Ocean (Fig. 1). Its drainage area covers 1,344,200 km^2, and the mean annual discharge at Sorel is 10,333 m^3/s (Morin and Bouchard 2001). The fish kill occurred in the freshwater portion of the St. Lawrence River. The morphology of this section is highly variable. Downstream from Montréal the flow is mainly concentrated in the navigation channel, which has a minimum depth of 12 m and a width of 250 m (Triboulet et al. 1977). The mean width of the section between Montréal and Québec City is about 2.5 km, except in Lake St. Pierre, which is a widening of the river (approximately 15 km in width) where the mean depth is about 3 m. It takes approximately three to four days for water to flow from Montréal to Québec City.

Data

The only spot measurements available during the event originated from the monthly water quality data of the Banque de données sur la qualité du milieu aquatique (BQMA) (MDDEP 2008). This routine monitoring was not specifically targeting the fish kill conditions. In 2001, a total of 15 variables were monitored, including chlorophyll *a*, nitrates and nitrites, total nitrogen, dissolved oxygen, pH, total dissolved and suspended phosphorus, and turbidity. The data are presented in Table 1, but only for the parameters that were measured for the entire summer period. Spot measurements showed no abnormal variation of the water chemistry. However, the sampling frequency (monthly) of this monitoring effort did not permit us to fully assess the prevailing conditions. It should be noted that the temperatures in Table 1 show a maximum value of 24°C at the monitoring station, which is close to the all-time maximum (25°C).

Long-term time series of air and water temperatures as well as water levels and global solar radiation were used to quantify how extreme the meteorological and aquatic conditions were during the summer of 2001. The stations used in this study were selected for their relative proximity to the study area, the length of the time series, and whether the series included 2001 (Table 2).

Frequency Analysis

Frequency analyses were performed on temperature (air and water), water level, and solar radiation time series. The daily air temperature ranges, which are the differences between maximum and minimum temperature, were also examined. Frequency analysis is a statistical approach that relates the magnitude of events, e.g., extreme temperature, to a probability of exceedance for a given duration. A return period is calculated based on the probability that the event will be equalled or exceeded in any given year. The return period is defined in equation (1):

$$T(x_t) = \frac{1}{1 - F(x,\theta)} \quad (1)$$

where $T(x_t)$ is the return period associated with a given event, x_t; $F(x,\theta)$ is the probability distribution of x with n observation ($x=\{x_1,...,x_n\}$); and θ represents the vector of the parameters of the probability distribution F. Hence, a statistical distribution is fitted to annual or seasonal extremes and this model is used to calculate probabilities

TABLE 1. Spot measurements of water quality variables in 2001 (MDDEP 2008)

Variables	*2001-05-15*	*2001-06-12*	*2001-07-09*	*2001-08-13*	*Median*	*Maximum*	*Minimum*
Active chlorophyll *a* (mg/m^3)	3.05	3.35	1.68	1.60	2.37	3.35	1.60
Aluminum (mg/L)	0.02	0.07	0.06	0.05	0.06	0.07	0.02
Ammoniacal nitrogen (mg/L)	0.01	0.03	0.06	0.02	0.03	0.06	0.01
Conductivity (µS/cm)	247.17	238.33	252.00	264.33	249.59	264.33	238.33
Dissolved oxygen (mg/L)	10.6	9.49	7.94	8.37	8.93	10.6	7.94
Fecal coliforms (CFU/100mL)	1,130	3,190	1,490	1,210	1,350	3,190	1,130
Nitrates and nitrites (mg/L)	0.32	0.36	0.24	0.15	0.28	0.36	0.15
Organic carbon (mg/L)	3.22	3.67	3.10	3.07	3.16	3.67	3.07
pH	7.98	8.10	8.22	8.40	8.16	8.40	7.98
Pheophytin (mg/m^3)	1.15	1.02	0.57	0.78	0.90	1.15	0.57
Suspension solids (mg/L)	9.83	6.67	5.83	6.33	6.50	9.83	5.83
Temperature (°C)	13.22	19.05	20.65	24.08	19.85	24.08	13.22
Total dissolved phosphorus (mg/L)	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total suspended phosphorus (mg/L)	0.02	0.01	0.01	0.01	0.01	0.02	0.01
Turbidity (NTU)	5.47	3.47	1.63	3.07	3.27	5.47	1.63

TABLE 2. Time series and station specifications

Time series	*Location*	*Record length (years)*
Air temperature	Dorval Airport (Montréal)	59
	Québec City Airport	30
Water temperature	Labatt brewery intake (Montréal)	15
	Ste-Foy intake (Québec City)	24
Water level	Frontenac gauge station (Montréal)	69
	Sorel gauge station (Lake Saint -Pierre)	73
	Neuville gauge station (30 km upstream of Québec City)	45
Solar radiation	Trois-Rivières Airport	11
	Québec City Airport	11

of exceedance for different return periods. The complete theory and detailed description of frequency analyses are described in many books, such as Rao and Hamed (2001).

Time series of daily data were extracted and moving averages with different time periods were calculated for the period of interest (May to August). As described earlier, there were strong indications that the 2001 mortality event was directly caused by abnormal meteorological conditions. These peculiar conditions were likely initiated in the weeks prior to the onset of the first mortalities (i.e., the second week of June) and may have lasted for a portion of July, for a total of more than 30 days. However, it is also possible that stressful or lethal temperatures were exceeded for a shorter period, and subsequent mortalities were observed for weeks after, even if temperatures had returned to more normal values. For this reason, moving averages were calculated with duration windows of 1, 3, 7, 15, 31, and 41 days in order to assess the event duration. Frequency analyses were performed on seasonal (May to August) maxima and minima of the times series of moving averages. For temperature minimum, we selected for analysis the highest minimum values because they are indicative of continued potential stressful events (i.e., the temperature remained high throughout the day). With this approach, quantiles for different return periods (e.g., 2, 5, 10, 50, 100 years) and different durations were estimated. Intensity-duration-frequency curves can thus be built to provide graphical representations of the probability that a given event, x_t, of a duration of 1 to 41 days will occur (Rao and Hamed 2001; Khaliq et al. 2005; Meylan et al. 2007). Extreme events are quantified in terms of duration and frequency.

Frequency analysis is based on three hypotheses: homogeneity, stationarity, and independence of the time series. The following three statistical tests were used in this study: 1) the Wilcoxon test for homogeneity (Wilcoxon 1945); 2) the Kendall test for stationarity (Mann 1945); and 3) the Wald-Wolfowitz test for randomness (Wald and Wolfowitz 1943).

A total of eight distributions were tested and compared for goodness of fit on each series: four two-parameter and four three-parameter distributions. Each time, the distribution that showed the best fit was chosen to calculate $T(x_t)$. These distributions and their probability density functions are presented in Table 3.

The parameters of each fitted distribution can be estimated using different approaches. In the present study, the maximum likelihood method was used. This method has the advantage of producing the smallest variance in estimating the parameters and the quantiles (Meylan et al. 2007).

The adequacy of the fit of each statistical distribution to the observations was examined using different methods: the Chi-squared test was used to verify the hypothesis that the selected distribution can be considered as the parent distribution of the sample. In addition, the Akaike criterion (AIC) (Akaike 1974) and Bayesian Information Criterion (BIC) (Schwartz 1978) were also used to compare the goodness of fit of different distributions. The distribution with the best fit is the one with the lowest criteria values. The BIC tends to be more severe than the AIC, and generally the BIC is the first selection criterion. All frequency analyses were performed with HYFRAN software.

Results

Time Series Analysis

Correlation between air and water temperatures was calculated for different lags using daily data. It reached maximum values (median of 0.9) for concomitant series (i.e., a lag of 0 between air and water temperature) and decreased with an increasing lag, but remained greater than 0.5 up to a lag of ±2 and greater than 0.4, up to a lag of ±3 (Fig. 2). This suggests that water and air temperatures followed the same temporal pattern, with little delay between the two extremes. Hence, an analysis of air temperature may provide insight into the prevailing water conditions.

The analysis of empirical probabilities for daily air temperature during the period from 1970 to 2000 revealed that the maximum values recorded from early May 2001 (29°C) exceeded the 95th percentile (Mingelbier et al. 2001). Such extreme temperatures occurred during three days in May 2001. Higher maximum values were also recorded twice: in mid-June (33°C; >99%) and late

TABLE 3. Probability distribution functions used in the frequency analysis

Name	*Probability density function*	*Domain*	*Number of parameters*
Gamma	$f(x)=\frac{\alpha^{\lambda}}{\Gamma(\lambda)}x^{\lambda-1}e^{-\alpha x}$	$x > 0$	2
GEV[a]	$f(x)=\frac{1}{\alpha}\left[1-\frac{k}{\alpha}(x-u)\right]^{\frac{1}{k}-1}\exp\left\{-\left[1-\frac{k}{\alpha}(x-u)\right]^{1/k}\right\}$	$x > u + \alpha/k$ if $k<0$ $x < u + \alpha/k$ if $k>0$	3
Gumbel	$f(x)=\frac{1}{\alpha}\exp\left[-\frac{x-u}{\alpha}-\exp\left(\frac{x-u}{\alpha}\right)\right]$	$-\infty < x$ $x < +\infty$	2
Log-normal 2 parameters	$f(x)=\frac{1}{x\sigma\sqrt{2\pi}}\exp\left\{-\frac{(\ln x-\mu)^2}{2\sigma^2}\right\}$	$x > 0$	2
Log-normal 3 parameters	$f(x)=\frac{1}{(x-m)\sigma\sqrt{2\pi}}\exp\left\{-\frac{[\ln(x-m)-\mu]^2}{2\sigma^2}\right\}$	$x > m$	3
Log-Pearson Type 3	$f(x)=\frac{\alpha^{\lambda}}{x\Gamma(\lambda)}(\ln x-m)^{\lambda-1}e^{-\alpha(\ln x-m)}$	$X > e^{m}$	3
Pearson Type 3	$f(x)=\frac{\alpha^{\lambda}}{\Gamma(\lambda)}(x-m)^{\lambda-1}e^{-\alpha(x-m)}$	$x > m$	3
Weibull	$f(x)=\frac{c}{\alpha}\left(\frac{x}{\alpha}\right)^{c-1}\exp\left[-\left(\frac{x}{\alpha}\right)^{c}\right]$	$x > 0$	2

[a] GEV = generalized extreme value.

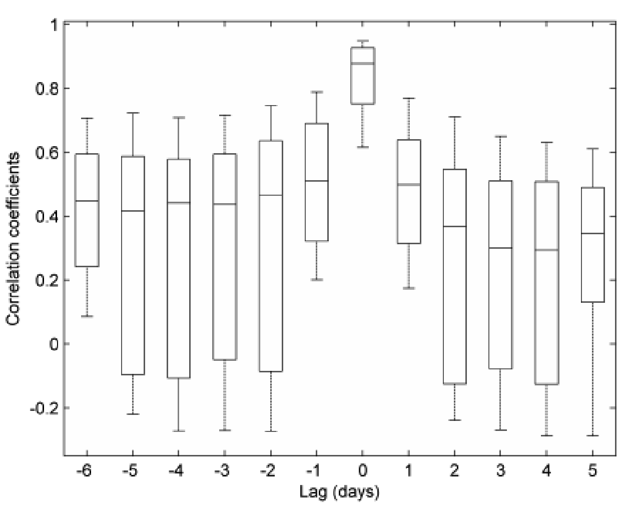

Fig. 2. Box plots of annual correlation coefficients between air temperature (Dorval Airport) and water temperature (Labatt Brewery intake) for different lags; the median value is indicated by a horizontal line inside the box.

June (29°C; >95%). In addition, relatively low daily minimum temperatures were observed in early June, about eight days before the highest daily air temperature maximum peak. Early in May, air temperature at Dorval remained above 28°C for three days. The same pattern was observed in Québec City (Fig. 3).

Water temperature in the upstream portion of the study area remained above 20°C throughout the summer after June 9. Downstream, at the Sainte-Foy pumping station, water temperature reached 20°C by mid-June and remained above this threshold for the rest of the summer (Fig. 4). Spot measurements in June revealed water temperatures as high as 34°C in the Lake Saint-Louis and Lake Saint-Pierre areas (Mingelbier et al. 2001).

During the same period, water levels were constantly decreasing from May to mid-August, exhibiting extremely low values: 4.95 m at the Frontenac station (compared with the interannual mean of 6.35 m for the same period), 3.61 m at the Sorel station (interannual mean = 4.93 m), and 0.51 m for the Neuville station (interannual mean = 1.17 m) (Fig. 5).

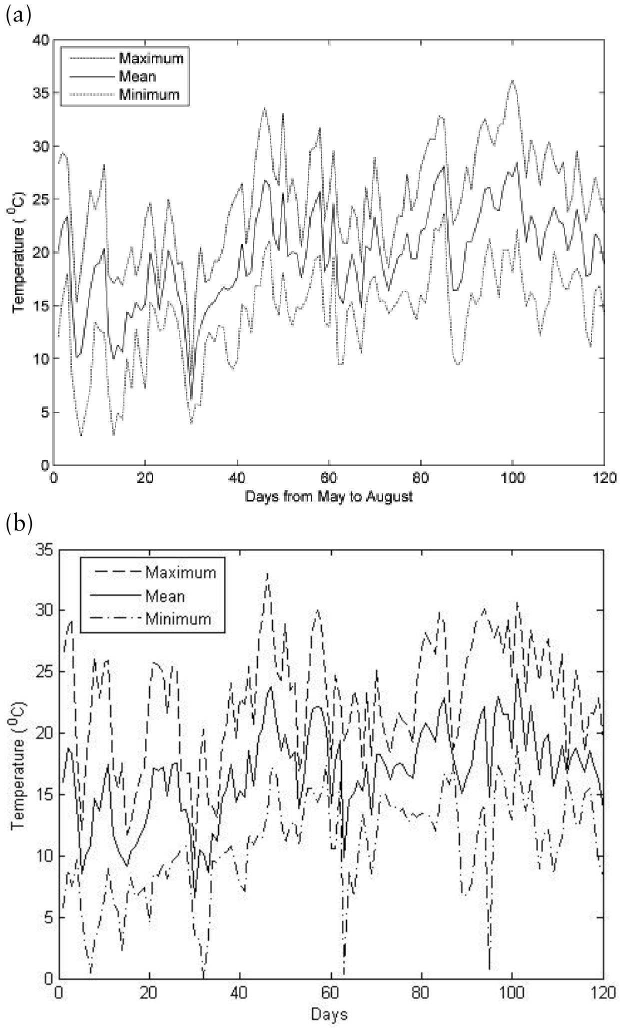

Fig. 3. Air temperatures between May 1 and August 31, 2001 from climatologic stations of (a) Dorval Airport (Montréal) and (b) Québec City Airport.

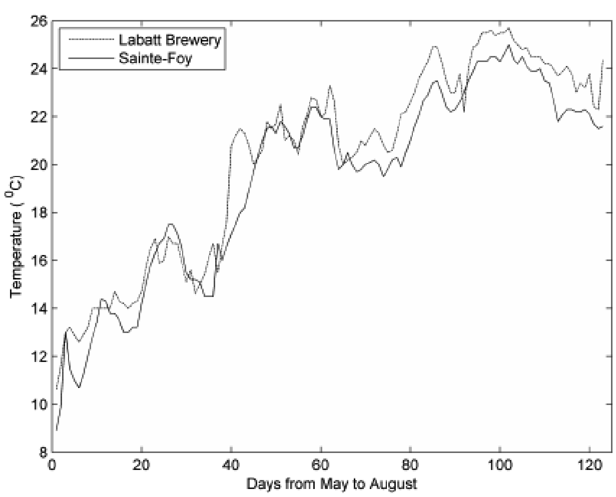

Fig. 4. Water temperatures between May 1 and August 31, 2001 from water supply installations of the Labatt Brewery (Montréal) and Sainte-Foy.

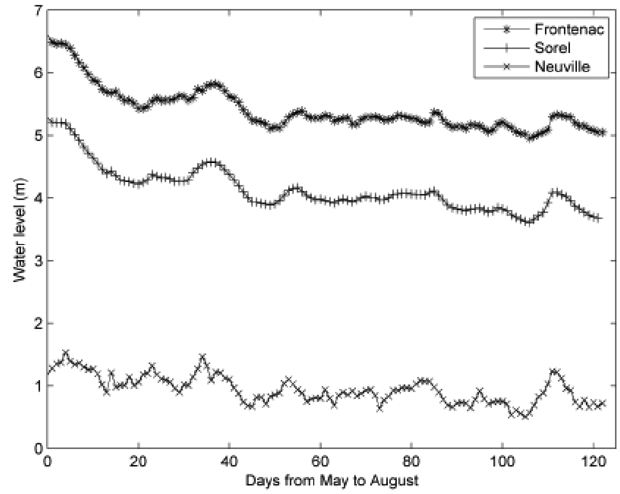

Fig. 5. Water levels between May 1 and August 31, 2001 from the Frontenac (Montréal), Sorel (Lake Saint-Pierre), and Neuville (near Québec City) stations.

Frequency Analysis

All series were tested for homogeneity, stationarity, and independence with a significance level of 0.05. Only one time series, the daily temperature range time series with a duration of 41 days, failed the test of independence and was therefore excluded from the analysis. For the majority of tested series (nine), the most adequate statistical model was a Weibull distribution. The remaining four cases were adjusted with two-parameter log-normal, three-parameter log-normal, gamma, and generalized extreme value (GEV) distributions.

The intensity-duration-frequency (IDF) curves are similar for the Dorval and Québec stations. Therefore, only those for Dorval are presented (Fig. 6 and Fig. 7). Using these IDF curves, it is possible to calculate the return period for 2001 for events of durations of 1, 3, 7, 15, 31, and 41 days. This is presented in Table 4. At Dorval Airport, temperature maximums in 2001 had a high return period for shorter durations (one and three days), with a maximum of 22 years. For longer durations, the return periods decreased slowly to reach a value of 15 years (duration 15 days). The return period for durations of 31 and 41 days are less than two years, showing that the extreme warm event in air temperature lasted between 15 and 31 days. Results for the Québec meteorological station were quite different with almost all T_{max} return periods equal to two years or less for 2001. The only exception was for the one-day duration maximum temperature, which had a return period of six years.

Extreme low daily air temperatures were not relevant for this study. High minimum values would indicate that fish were not submitted to colder spells during which they could recuperate from the high maxima. To investigate this hypothesis, frequency analysis was performed on the maximum values of T_{min}. For air temperatures, all return

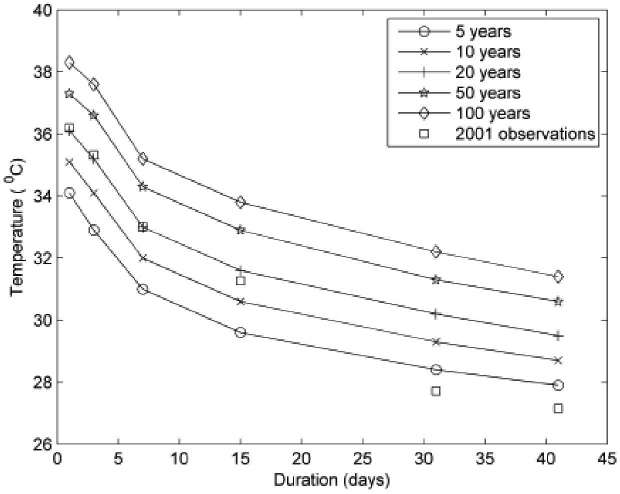

Fig. 6. IDF curve for the maximum air temperature at the Dorval station.

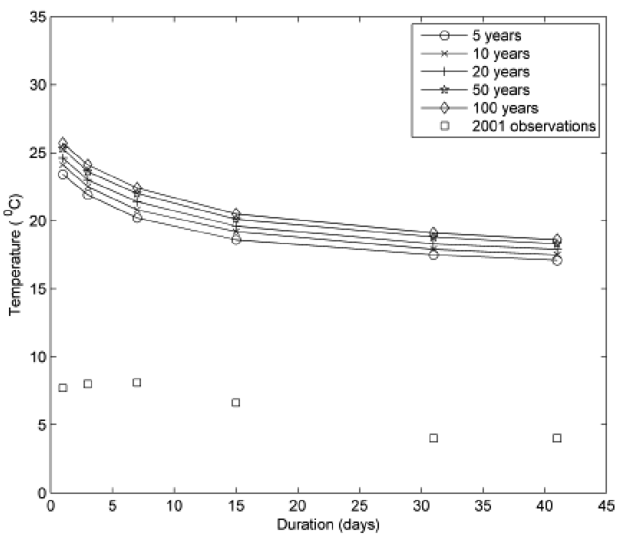

Fig. 7. IDF curve for the minimum air temperatures at the Dorval station.

periods for the $T_{\min}$ maxima in 2001 were less than two years for all durations and for both stations.

The IDF curves for the water temperature time series are again presented for only one of the two stations (Labatt) because of similarities in the results (Fig. 8 and Fig. 9). These results were calculated for durations of 1, 3, 7, 15, 31, and 41 days. The return periods for 2001 were extracted from these curves and are summarized in Table 4. For the Labatt station, the return period calculated for the shortest duration was about eight years and increased for longer durations: up to $T(x_t)$ = 19 years for an event duration of 15 days and a $T(x_t)$ = 17 years for a durations of 7 and 31 days. The return period decreased to less than two years for the longer (41 days) duration. This confirms that the high water temperatures of the summer of 2001 were not commonly observed. The low return period for the 41 day duration is an indication that the high temperature event was not sustained for such a long interval. At high minimum water temperatures, high return periods for short durations were seen (e.g., a return period of 47 years for a duration of three days); the return period decreased to seven years for a duration greater than 15 days. This indicates that minimum water temperatures were occasionally unusually high during the study period.

For the Sainte-Foy station, the estimated return periods were higher than those of the Labatt station (Table 4). For the shortest duration, the return period was 15 years and increased in duration to a maximum return period of 48 years for a duration of 31 days. When event duration was further increased to 41 days, return periods were found to be lower than two years. This again highlights the fact that the warm event was shorter than 41 days, i.e., the total duration was probably in the order of one month. Minimum temperatures showed similar results, with an event duration of approximately one month and the highest return period for a duration of 15 days (21 years).

For both the Labatt and Sainte-Foy stations, the daily temperature ranges were also examined for the same durations. In all cases the return periods calculated were shorter than two years. It seems that the daily

TABLE 4. Return period in years computed for the different time series of different durations in days during the summer of 2001[a]

	Air temperature (°C)				*Water temperature (°C)*				*Water level (m)*		
	Dorval		*Québec*		*Labatt*		*Sainte-Foy*		*Frontenac*	*Sorel*	*Neuville*
Duration	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	*Level*	*Level*	*Level*
1	22	≤2	6	≤2	8	14	15	5.5	≤2	4	≤2
3	22	≤2	≤2	≤2	10	47	17	20	≤2	4	≤2
7	20	≤2	≤2	≤2	17	27	20	12	23	34	50
15	15	≤2	≤2	≤2	19	31	34	21	19	31	67
31	≤2	≤2	≤2	≤2	17	7	48	17	14	21	20
41	≤2	≤2	≤2	≤2	≤2	7	≤2	≤2	13	18	20

[a] $T_{\max}$ is maximum temperature, $T_{\min}$ is minimum temperature, and water levels are the minimum values.

water temperature ranges were not abnormal. There was an upward shift in all water temperatures, but the difference between the maximums and minimums were not atypical.

For water levels, an example of the IDF curve is shown for the Sorel station (Fig. 10), and information on the exact return periods of the 2001 event is presented in Table 4. For the three stations, Frontenac, Sorel, and Neuville, the return periods calculated for different durations indicate that the event of 2001 was extreme. For the Frontenac (Montréal) water level station, the return period for a five-day duration was 23 years and for a duration of 41 days, it was 13 years (Table 4). The return periods obtained in Lake Saint-Pierre were greater: 31 years for a five-day duration and 18 years for an event duration of 41 days. For the Neuville water level station, the return periods calculated for the same set of durations were, respectively, 46 and 20 years. The tidal signal is present at Neuville. This may explain the return period of 67 years that was calculated for a duration of 15 days since it is possible that the low discharge was associated with the spring fortnightly tidal cycle to produce extremely low levels.

Analysis for global solar radiation (not shown) indicated that the maximum and minimum global solar radiation were normal during the summer of 2001. All of the estimated return periods were less than 5 years. It seems that the high water temperatures observed in 2001 were not the consequence of high radiation inputs associated with long periods of low cloud cover.

Discussion

Extremes of hydroclimatic variables can be characterized by frequency analysis which is a useful tool for determining the return period of a specific event. In the present study, results showed that the St. Lawrence River experienced unusually high water temperatures associated with elevated air temperatures and low water levels during the summer of 2001. It is important to mention that these events and the mortality have not only temporal concordance, but also a concordance in the duration of the events; this suggests that there is a link between the extreme hydroclimatic conditions and fish mortality.

Water temperatures in 2001 exhibited abnormal return periods of 47 years for short and long durations; these results are mostly representative of temperatures in the deeper channel. In fact, heating processes differ between the deep and shallow areas. Shallow water areas in the St. Lawrence River, where carp usually spawn in early June, are exposed to rapid heating effects. Hence, it is possible that the extreme values with similar or even greater return periods in shallow water occurred, and that they were associated with higher quantile values.

Similarly, extreme values of air temperatures (maximum return period of 22 years) and water levels (maximum return period of 67 years) occurred during the summer of 2001. Abnormally high air temperatures

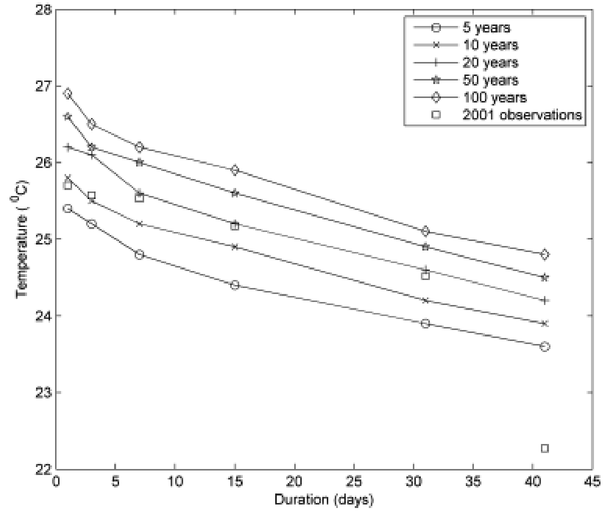

Fig 8. IDF curve for the maximum water temperature of the Labatt Brewery station.

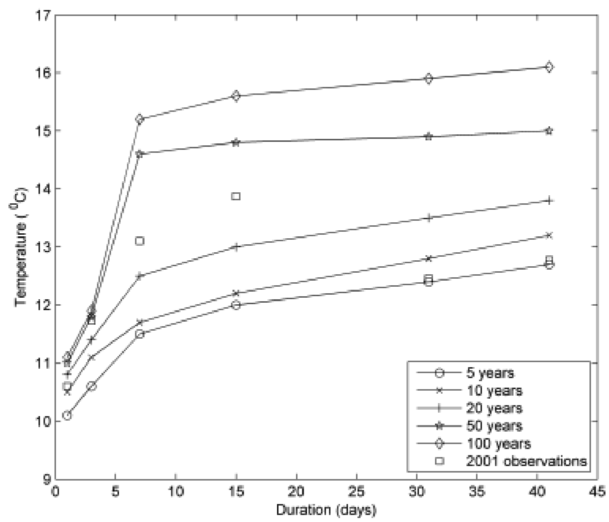

Fig. 9. IDF curve for the minimum water temperature of the Labatt Brewery station.

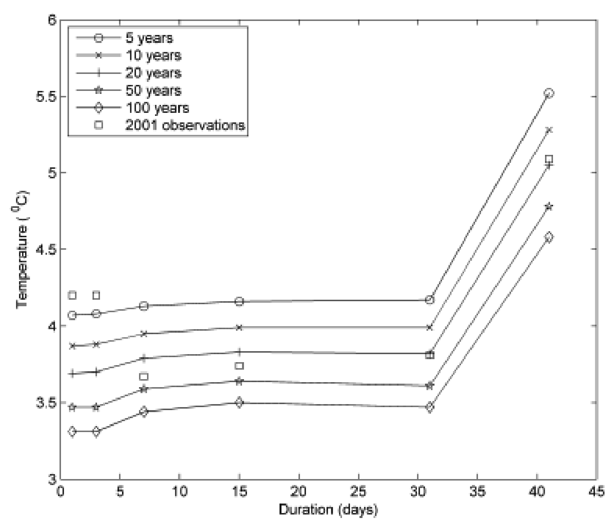

Fig. 10. IDF curve for the minimum water level at the Sorel station (Lake Saint-Pierre).

combined with exceptionally low water levels most likely explained the resulting high water temperatures. It is important to note that these two phenomena act in synergy but not at the same time scale.

Abnormal air temperatures, compared with the past decades, were recorded before and during the period of high mortality (Mingelbier et al. 2001). During this time of the year, the temperature gradient between air and water is particularly high and usually results in very efficient heat exchange between air and water. Air temperature is an indirect proxy for solar radiation but it also influences sensible heat transfer and incoming longwave radiation. The influence of air temperature on water temperature is most important for short time periods of several hours to a few days, as indicated by the greatest return periods of air temperature for durations of one or three days. These quick rises in air temperature are sufficient to induce high water temperatures, especially in shallow areas with slow currents. Also, changes in water levels were occurring for longer durations (more than three days). For these longer durations and at extreme low levels, water can be more easily and more progressively warmed because of the smaller volume of water that is heated. Spot measurements of water temperatures of 34°C (Mingelbier et al. 2001) in the area of Lake Saint-Pierre are examples of these phenomena.

Extreme water temperatures may have been associated with mortality in two different ways. First, at short time scales, extremely high water temperature can have direct effects on mortality if the lethal threshold is reached (Bennett et al. 1998; Beitinger and Bennett 2000). Without time to adapt or to seek thermal refugia, fish cannot support high temperatures for long periods of time and can eventually die of direct physiological consequences. Such high temperatures can interfere with enzyme production, respiration, and numerous other metabolic functions (von Bertalanffy 1960; van der Have and de Jong 1996; Plante et al. 1998).

On a longer time scale, high water temperatures are known to have indirect effects, such as oxygen depletion in the shallow waters where fish spawn. Such conditions can lead to immunosuppression in fish, thereby increasing their susceptibility to a large number of parasites, bacteria, or other organisms (Herman and Meyer 1990; Engel et al. 1999; Bermingham and Mulcahy 2004; Monette et al. 2006). The mechanism by which high water temperatures lead to immunosuppression in fish is still unknown, but it is certain that affecting various metabolic functions and energy demands will greatly perturb fish metabolism and the immune system.

In the present case, many fluctuations of temperature were recorded before and after the temperature extremes measured. Sharp rises in temperature leave no period of adaptation for fish. Beitinger and Bennett (2000) have studied the importance of this adaptation period in temperature tolerance of fish. As an example, the sheepshead minnow (*Cyprinodon variegates*) has temperature tolerance limits from intrinsic levels that increase from 19.3 to 27.9°C if the fish is given time to adapt.

Carp are known to be resistant fish, but during the spawning period their resistance to adverse environmental conditions may be lower because most of their energy is used for reproduction activities, which diminishes their ability to fend off infections or other metabolic requirements (Sandström et al. 1997; Beer and Anderson 2001). Moreover, the lethal limit for carp, which is between 36 and 41°C, was nearly reached during the summer of 2001, with the temperature measured at 34°C. There is little literature on the joint effect of bacterial and environmental stressors, and more research on these complex interactions is required to gain better a understanding of the processes.

Multiplication of bacteria such *A. hydrophila* and *Flavobacterium sp*. and the resulting infections are mostly driven by water temperature (Nematollahi et al. 2003). These bacteria are harmful pathogens widely known to impact freshwater fish (Decostere et al. 1999; Suomalainen et al. 2005). In this case, it is hypothesized that infection was spread by frequent contacts between individual fish during spawning. In the case of *Flavobacterium sp*., a high water temperature increases the growth of the bacteria, facilitates the attachment of the bacteria to gill arches, and the rate of mortality of fish is known to increase when water temperature rises, which may result in up to 100% mortality at temperatures above 20°C (Suomalainen et al. 2005). The mortality rate with *A. hydrophila* could be greater because this bacterium has the possibility of producing a number of potential virulence factors, including cytotoxin, haemolysin, and enterotoxin. The optimal temperature for the growth of this bacterium is 30°C (Sautour et al. 2003). Such extreme high water temperatures were observed in some areas of the St. Lawrence River during the summer of 2001.

Conclusion

Frequency analysis indicated, through high return periods for water temperature and water levels, that the summer of 2001 was subjected to abnormal events that only occur once in more than thirty years on average. Moreover, these extreme events were concomitant with fish mortality. High temperature events had similar durations as the mortality event, i.e., a maximum of 31 days and a probable mean close to 15 days. The available data on air and water temperature as well as water levels suggested that this particular fish kill was most likely driven by hydroclimatic conditions, and that the thermal conditions caused high stress; this may have been a sufficient factor for potential mortality.

It is suspected that carp were mostly affected because they are one of the species that reproduce the latest in the spring. Also, they only spawn once a year and therefore invest much more energy in single seasonal reproduction than multiple spawners do. Energy and oxygen expenditures are also more important for large fish, which may explain why carp were more affected by such drastic changes in abiotic variables than other fish species that may have been using similar habitat during this period.

Massive fish kills have great Impacts on the ecosystem and on the economy. For the aquatic ecosystem, a massive fish kill such as the event of 2001 in the St. Lawrence River has led to a loss of perhaps more than one cohort for a species (carp) and perhaps other species as well. This could have many impacts on the food web. Impacts for the ecosystem can be catastrophic if dead fish are not recovered. Decomposing carcasses could be a vector of diseases or lead to a temporary depletion of oxygen as a consequence of the decomposition. When the species affected is an economically important species, the consequences can be disastrous for fisheries. The massive depletion of fish biomass can lead to poor captures for many years, depending on ecosystem recovery time. It is therefore important to study fish kills in order to understand the phenomena that could lead to such events and attempt to prevent them or mitigate their impacts.

It is possible that in the future, hydroclimatic conditions such as those observed during the summer of 2001 will occur more frequently or during other periods of the year. Therefore, it is important to increase our knowledge on how future water temperature changes could affect fish and lead to mortality. But also, there is a need for further investigations into the role of thermal refugia for fish adaptation and survival. Numerous questions can be raised on the use of thermal refugia by fish with respect to the definition of threshold temperatures, their location, and how fish use them. There is also a need to have a better understanding of processes occurring in shallow water, where fish spawn. Moreover, this study also highlights the importance of gaining a better understanding of combined stressors on organisms like fish. In the case studied here, neither spawning nor water temperature alone could have led to a massive fish kill. Rather, it appears that the high mortality was the result of the combined effects and that water temperature was a driving factor. These interactions are complex and need to be thoroughly studied in the future.

Some answers may be provided by developing and using spatially explicit habitat models, which can link biological, physical, and hydrological variables. These are useful tools to understand the spatiotemporal variability of such habitat characteristics, and there is a need to implement them in the context of climate change.

Acknowledgments

The authors are indebted to P. Gachon (Environment Canada) for providing insightful advice and facilitating meteorological data acquisition. Funding for this project was provided by FQRNT, NSERC, Environment Canada, and Québec's Department of the Ministry of Natural Resources and Wildlife.

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Received: 16 December 2008; accepted: 16 October 2009.