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Adaptive management strategies to protect Atlantic salmon (*Salmo salar*) under environmentally stressful conditions

Stratégies de gestion adaptative pour protéger le saumon atlantique (*Salmo salar*) durant des périodes de conditions environnementales stressantes

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ABSTRACT

There is an overall concern for Atlantic salmon (*Salmo salar*) under stressful conditions associated with extreme climatic events. In-season management measures have been introduced to reduce the impact of recreational fishing on Atlantic salmon during periods of warm water and low water levels. Fisheries closures have occurred as a response to high temperatures but these were not based on pre-determined temperature triggers. The proposed threshold temperature for in-season fishery closures was established based on fish physiology. Water temperatures below 20°C are required for fish to recover physiologically from metabolic byproducts produced as a result of anaerobic metabolism associated with high water temperatures. A minimum water temperature threshold was set to establish criterion for fisheries closures and openings. If the minimum water temperatures (T_{min}) over two successive days exceed 20°C, a fishing closure is initiated. The condition for reopening consists of two successive days when the minimum water temperatures (T_{min}) are less than 20°C. The number of closures and the duration of closures based on the proposed criterion were assessed using historic water temperature data.

RÉSUMÉ

Il y a des préoccupations générales pour le saumon atlantique (*Salmo salar*) soumis aux conditions stressantes dues à des évènements extrêmes du climat. Des mesures de gestion durant la saison ont été utilisées pour réduire les conséquences des pêches récréatives sur le saumon atlantique durant des périodes de température d'eau élevées et de faibles écoulements. Les fermetures des pêches qui ont eu lieu n'ont pas été établies avec des déclencheurs de températures pré-déterminés. Le seuil de température proposé pour déclencher des fermetures de pêches durant la saison a été établi sur des critères de physiologie des poissons. Des températures de l'eau inférieures à 20°C sont nécessaires pour permettre aux poissons de rétablir un équilibre physiologique. Le poisson doit se débarrasser des produits métaboliques accumulés durant le métabolisme anaérobie qui se manifeste durant les périodes de températures élevées. Le seuil de température pour déclencher des fermetures et des ouvertures des pêcheries est établi sur un critère de température minimale. Si la température minimale de l'eau (T_{min}) durant deux journées successives est supérieure à 20°C, une fermeture de la pêche est déclenchée. Les conditions pour la réouverture de la pêche sont similaires, au moins deux journées successives avec une température minimale de l'eau inférieure à 20°C. Les nombres de fermetures et les durées des fermetures selon les critères proposés sont évalués en utilisant les séries historiques disponibles de températures de l'eau.

INTRODUCTION

There is an overall concern for Atlantic salmon (*Salmo salar*) under stressful conditions associated with extreme climatic events. The water temperatures in portions of the Miramichi River can in the summer approach and exceed lethal temperatures (25 to 28ºC) for all life stages of Atlantic salmon (Caissie et al. 2013; Elliott 1991). The effects of warm water conditions on the physiology and behaviour of salmon have been discussed in Breau (2013). Cooler water temperatures that would allow the physiological recovery of salmon are critical for fish survival.

Some jurisdictions have used inseason interventions to manage impacts of fisheries during warm and low water events. The Montana Department of Fish and Parks (http://fwp.mt.gov/news/drought/closurepolicy.html, accessed June 2012) and the Big Hole River Foundation (see http://www.bhrf.org/drought_mngt.htm, accessed June 2012) have developed closure policies for recreational fisheries to address drought and warm water conditions. In Newfoundland, the Atlantic salmon recreational fishery management plan previously indicated that angling closures would be considered when the water temperature measured in mid-afternoon equaled or exceeded 22ºC on two consecutive days (Porter 1997). This resulted in a large number of rivers being closed and a high proportion of the potential angling days lost due to warm water and low water conditions, especially during the 1995 to 1999 period (Dempson et al., 2001). In addition, rivers with catch and release fishing only are closed when water temperature exceeds 18°C (Dempson et al. 2002).

In-season recreational fisheries closures have been used in the Miramichi River (New Brunswick) to reduce the impact of excessive mortality from catch and release recreational fishing on Atlantic salmon during periods of warm water and low water levels (Chaput et al. 2000). Modifications to fisheries management plans are made via variation orders which define geographically and temporally the aspects of the regulations being modified. Variation orders, which identify fisheries closures resulting from low and warm water conditions, are legal documents of public record.

A threshold temperature for in-season fishery closures of Atlantic salmon recreational fisheries was recently developed based on principles from fish physiology (Breau 2013). The threshold temperature was a minimum daily water temperature of 20°C to ensure physiological recovery. The elaboration of the threshold temperature was the first step in the development of the management framework. The purpose of this document is to quantify, based on historical water temperature data, the implications of using the intervention triggers.

MATERIALS AND METHODS

Water temperatures were measured at two sites on the Miramichi River located on the Little Southwest Miramichi River (LSWM) and on the Doaktown (SWMira). The station on the Little Southwest began monitoring in 1992 but data are missing for 1994 due to equipment malfunction. The Southwest Miramichi River at Doaktown began monitoring in 2002; however, data were missing in 2006 to 2008 (due to a combination of datalogger malfunction and low water conditions which prevented good water temperature representation).

Water temperature was recorded hourly using VEMCO™ minilogs (VEMCO Minilog8-TR) that have a typical accuracy of ±0.2°C within the range of -5 to 35°C. Only water temperatures from July 1st to August 31st were considered in the analysis, temperatures corresponding to the time period of high temperature events.

The management interventions examined were based on the following rules:

a. If the minimum water temperature (T_{min}) over two consecutive days exceeded 20°C, a fishery closure was triggered.

b. It takes one day (day 3) for a variation order to be processed so at minimum it takes three days before the fishery can be closed.

c. Once closed, the fishery may (or not) remain closed for a minimum number of days, ranging from 0 days (i.e., continuous monitoring of water temperatures and based only on closing and opening triggers, but constrained by the implementation time, three days minimum) to 14 days. For the 14 days scenario, once closed, the fishery will remain closed for a minimum of 14 days before considering reopening.

d. Monitoring of river temperatures was continuous. After the minimum number of closure days was met as described in c), a reopening can occur if the minimum water temperature (T_{min}) during two consecutive days was less than 20°C.

e. It takes one day for a variation order to be processed to reopen a fishery

Management implications were quantified as:

1. Total number of interventions (closure/opening) in a year,

2. Total number of days closed in a year, and

3. Minimum number of days between interventions in a year.

Retrospective analyses were done for the years 1992 to 2011 (excluding 1994) for the station in the Little Southwest Miramichi River and for 2001 to 2011 (excluding 2006 to 2008) for the Southwest Miramichi River station at Doaktown.

RESULTS

Seasonal patterns of water temperatures were similar at the SWMira station and at the LSWM monitoring station (Fig .1). Water temperatures were generally slightly warmer at the SWMira compared to LSWM. As such, the number of days (annually) when minimum daily temperatures exceeded 20ºC were generally more frequent in a given year and in more years at the SWMira station compared to the LSWM station (Fig. 2).

The scenario of no minimum number of days for each closure period (0 day) implies that the closures and openings would be based on water temperature triggers only. Under these conditions, two days are required to intervene with variation orders (one day each to communicate the closure and the reopening). The results of the number of closures initiated annually for this scenario ranged from 0 to 5 during 1992 to 2011 based on monitoring at LSWM (Table 1). For the SWMira monitoring station, the number of closures ranged from 1 to 5 during 2001 to 2011 (Table 2). The total number of days closed per year ranged from 0 to 24 for the LSWM and 9 to 31 for SWMira (Tables 1 and 2). During 2002 to 2011, closures would have been similar in two years (2003, 2009) irrespective of the location (Fig. 3). During other years, closures were not predictable based on the location with the SWMira site initiating more closures in some years. The total duration of closures would have been more based on the SWMira site for the majority of years (except 2006 to 2008, missing data) (Fig. 3; Tables 1 and 2). At the LSWM station, no closures would have been initiated in 1992, 1997, 2000, 2008 and 2011 whereas closures would have occurred every year based on the SWMira station (Tables 1 and 2).

As the minimum number of days during each closures increases, the total number of interventions decreases (Figs. 4 and 5). Figure 4 shows that for a minimum of 2-day closure, the average number of closures per year over a 19-year period would have been 1.95 (or 37 closures in total) using the data from the LSWM. For this example, when the closing trigger would be initiated, then the closure would be for a minimum of two days before considering reopening, regardless of water temperatures. The corresponding duration for the 2-day minimum closure was calculated at 8.79 days per year (or a total of 167 days for the 19 years of data). The years with most closures were 1999 (5 closures), 1995 (4) and 2006 (4) whereas the years with the longest duration would have been recorded in 2010 (24 days), 1999 (23 days) and 2006 (18 days).

If the minimum number of days increases from 2 days to 3 days, the mean number of closures per year is reduced to 1.89 with a corresponding duration of 9.79 days per year (Figs. 4 and 5). The results indicate that the mean number of closures per year decreases and the duration increases as the closure period increases. The objective of having a minimum number of days for each closure is to prevent too many closures in a given year.

When temperature data from the SWMira were used, there were some differences in the number of closures and the durations. The results of this analysis are shown in Figure 6 for the mean number of closures per year and Figure 7 for the corresponding durations. Figure 6 shows that for a minimum of 2-day closure, the average number of closures per year over an 8-year period would have been 3 (or 38 closures in total). The corresponding duration for the 2-day minimum closure was calculated at 30 days per year (or a total of 402 days for the 8-year dataset). The years with the most closures initiated were 2002 and 2011 (5 closures), 2001, 2004, 2005 and 2010 (4 closures) whereas the years with the longest duration of closures were 2004 and 2002 (31 days), 2010 (30 days) and 2003 (26 days). If the minimum number of days increases from 2 days to 3 days, the mean number of closures per year decreases to 3.63 closures with a corresponding duration of 24.5 days per year (Figs. 6 and 7). As for the LSWM, the mean number of observed closures per year decreased (Fig. 6) and the duration increased with an increase in the minimum number of days per closure (Fig. 7).

Longer duration of closures results in fewer interventions and therefore fewer short duration management interventions (Table 1). The duration between closures varied between 2 and 40 days depending on the year. Years 2004, 2005 and 2010 were the most recent warm water years and the proposed inseason closures based on T_{min} exceeding 20°C are shown in Figure 8. This figure shows a response time of three days before a closure, based on the 2-day trigger and 1-day communication. A 1-day response time is also required for communicating the reopening.

DISCUSSION

Since 1962, there have been six in-season interventions (1987, 1995, 1999, 2001, 2005 and 2010) implemented in the Miramichi River. These interventions have varied from closures of specific pools or stretches of river, time of day closures to closures of the entire river. The closures corresponded to the years where discharge conditions were low, generally when the daily discharge in the Southwest Miramichi River was less than 20 m^3/s. There was no closure in place during some low flow years, in particular 1991 and 1994.

The consequences to fisheries of management scenarios can be assessed retrospectively, as was done in this study. Ultimately management has to decide on the acceptable trade-off between frequent and short interventions, less frequent but longer interventions, or no intervention at all. Consequences to fisheries access of closures is discussed by Dempson et al. (2001).

The effectiveness of closures on incidental mortalities of Atlantic salmon are difficult to assess because there is no systematic monitoring of mortalities, either before during or after temperature events. The mortality related to hook and release during episodes of high temperatures is also difficult to quantify because the fish are released and not subsequently tracked.

The large and diverse physical characteristics of the Miramichi River provide an additional challenge to managers. Mean daily water temperatures in summer within the Miramichi River can differ by as much as 5ºC between the main stem and stretches in the headwaters of the river (Caissie 1997). Caissie et al. (2013) demonstrated that basin-wide interventions may restrict fisheries but mean temperatures are not highly different across the geographical region. It may be possible to categorize a large river like the Miramichi based on water temperature differences. The mean water temperature at the various sites in Miramichi and Restigouche rivers indicate that at the most, the rivers could be divided into main stems and tributaries (Caissie et al. 2013). For example, Caissie et al. (2013) showed that the Topogonops and the NW Branch of the Northwest Miramichi River could be classified as cooler sites than the main stem. On warm days, the main river is warm throughout the system and on warm water days, nighttime water temperature at Bridge Pool (above Crown reserve stretches on the NW Miramichi) remained warm (Breau 2013).

At the local spatial scale, pool closures protect fish aggregating in pools but not those located in warm water conditions or fish that use small patches of cool water. Hyporheic exchange and groundwater seeps create small patches of cooler water and adult salmon use them. Juvenile salmon and brook trout are also struggling during these warm water events and these life stages and species can also benefit from reductions in disturbance.

The biggest uncertainty in using any inseason management triggers associated with water temperature is the unpredictability of forecasting water temperatures even on a time scale of days. Consequently, we have to accept that there will be occasions when the fishery will be closed unnecessarily or vice versa.

The cumulative physiological stress response associated with high temperatures is not well known under both constant controlled conditions and that much less under fluctuating temperatures. Therefore, it is currently not possible to determine the amount of stress accumulated over a time period and the time required for physiological recovery.

However, we do know that at temperatures exceeding 20°C, survival rate decreases rapidly when fish are angled.

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Table 1. Retrospective assessment of consequences to fisheries access of applying the 20°C thresholds for closing or opening fisheries based on temperatures at the Little Southwest Miramichi River (LSWM) station.

			Duration of individual closures			Time between closures (days) (for 3 or more closures)		
Year	Number of closures	Total duration (days)	Min	Max	Mean	Min	Max	Mean
Minimum number of days during each closure (0 day)								
1992	0	0	NA	NA	NA	NA	NA	NA
1993	1	3	NA	NA	NA	NA	NA	NA
1995	4	14	3	5	3.5	2	13	7.7
1996	1	3	NA	NA	NA	NA	NA	NA
1997	0	0	NA	NA	NA	NA	NA	NA
1998	2	6	3	3	NA	NA	NA	NA
1999	5	23	3	8	4.6	5	30	17
2000	0	0	NA	NA	NA	NA	NA	NA
2001	3	13	3	5	4.3	11	30	NA
2002	3	14	3	8	4.7	5	30	NA
2003	3	12	3	5	4	3	9	NA
2004	2	8	3	5	NA	NA	NA	NA
2005	3	12	3	6	4	16	17	NA
2006	4	18	3	6	4.5	2	7	4.7
2007	2	9	3	5	NA	NA	NA	NA
2008	0	0	NA	NA	NA	NA	NA	NA
2009	1	8	NA	NA	NA	NA	NA	NA
2010	3	24	3	17	8	12	40	NA
2011	0	0	NA	NA	NA	NA	NA	NA
Minimum number of days during each closure (7 days)								
1992	0	0	NA	NA	NA	NA	NA	NA
1993	1	7	NA	NA	NA	NA	NA	NA
1995	3	22	7	8	7.3	4	11	NA
1996	1	7	NA	NA	NA	NA	NA	NA
1997	0	0	NA	NA	NA	NA	NA	NA
1998	2	14	7	7	NA	NA	NA	NA
1999	4	38	7	17	9.5	4	26	18.3
2000	0	0	NA	NA	NA	NA	NA	NA
2001	3	21	7	7	7	9	28	NA
2002	2	23	7	16	NA	NA	NA	NA
2003	2	18	7	11	NA	NA	NA	NA
2004	2	14	7	7	NA	NA	NA	NA
2005	3	21	7	7	7	12	16	NA
2006	3	27	7	13	9	3	5	NA
2007	1	11	NA	NA	NA	NA	NA	NA
2008	0	0	NA	NA	NA	NA	NA	NA
2009	1	8	NA	NA	NA	NA	NA	NA
2010	3	31	7	17	10.3	8	40	NA
2011	0	0	NA	NA	NA	NA	NA	NA

Table 1 (continued).

			Duration of individual closures			Time between closures (days) (for 3 or more closures)		
Year	Number of closures	Total duration (days)	Min	Max	Mean	Min	Max	Mean
Minimum number of days during each closure (14 days)								
1992	0	0	NA	NA	NA	NA	NA	NA
1993	1	15	NA	NA	NA	NA	NA	NA
1995	2	31	14	16	NA	NA	NA	NA
1996	1	15	NA	NA	NA	NA	NA	NA
1997	0	0	NA	NA	NA	NA	NA	NA
1998	2	30	14	14	NA	NA	NA	NA
1999	3	49	16	17	16.3	NA	NA	NA
2000	0	0	NA	NA	NA	NA	NA	NA
2001	2	36	14	14	NA	NA	NA	NA
2002	2	31	14	16	NA	NA	NA	NA
2003	2	30	14	14	NA	NA	NA	NA
2004	1	15	NA	NA	NA	NA	NA	NA
2005	3	45	14	14	14	5	9	NA
2006	2	30	15	15	NA	NA	NA	NA
2007	1	15	NA	NA	NA	NA	NA	NA
2008	0	0	NA	NA	NA	NA	NA	NA
2009	1	15	NA	NA	NA	NA	NA	NA
2010	2	47	14	32	NA	NA	NA	NA
2011	0	0	NA	NA	NA	NA	NA	NA

Mean values were only calculated for years when there were at least three closures.
NA represent years with less than three observations.

Table 2. Retrospective assessment of consequences to fisheries access of applying the 20°C thresholds for closing or opening fisheries based on temperatures at the Southwest Miramichi River (SWMira) Doaktown station.

			Duration of individual closures			Time between closures (days) (for 3 or more closures)		
Year	Number of closures	Total duration (days)	Min	Max	Mean	Min	Max	Mean
Minimum number of days during each closure (0 day)								
2001	4	23	3	9	5.8	6	14	10.7
2002	5	31	3	10	6.2	2	15	7.3
2003	3	26	4	13	8.7	6	9	*NA*
2004	4	23	3	10	5.8	2	7	4
2005	4	23	4	8	5.8	2	15	8.3
2009	1	9	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
2010	4	30	3	18	7.5	5	21	10.7
2011	5	15	3	3	3	3	23	10
Minimum number of days during each closure (7 days)								
2001	4	33	7	9	7.8	6	12	9.3
2002	4	40	7	15	9.5	3	15	7.3
2003	3	32	7	13	9.7	6	9	*NA*
2004	2	27	7	10	*NA*	*NA*	*NA*	*NA*
2005	4	32	7	8	7.5	2	11	6
2009	1	9	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
2010	3	36	7	18	11.7	6	22	*NA*
2011	3	25	7	9	8	4	24	*NA*
Minimum number of days during each closure (14 days)								
2001	3	53	14	14	14	3	12	*NA*
2002	3	46	14	16	15	5	15	*NA*
2003	3	47	14	14	14	4	5	*NA*
2004	2	34	14	19	*NA*	*NA*	*NA*	*NA*
2005	3	45	14	14	14	5	8	*NA*
2009	1	15	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
2010	3	48	14	18	15.3	6	18	*NA*
2011	2	35	14	16	*NA*	*NA*	*NA*	*NA*

Mean values were only calculated for years when there were at least three closures.
NA represent years with less than three observations.

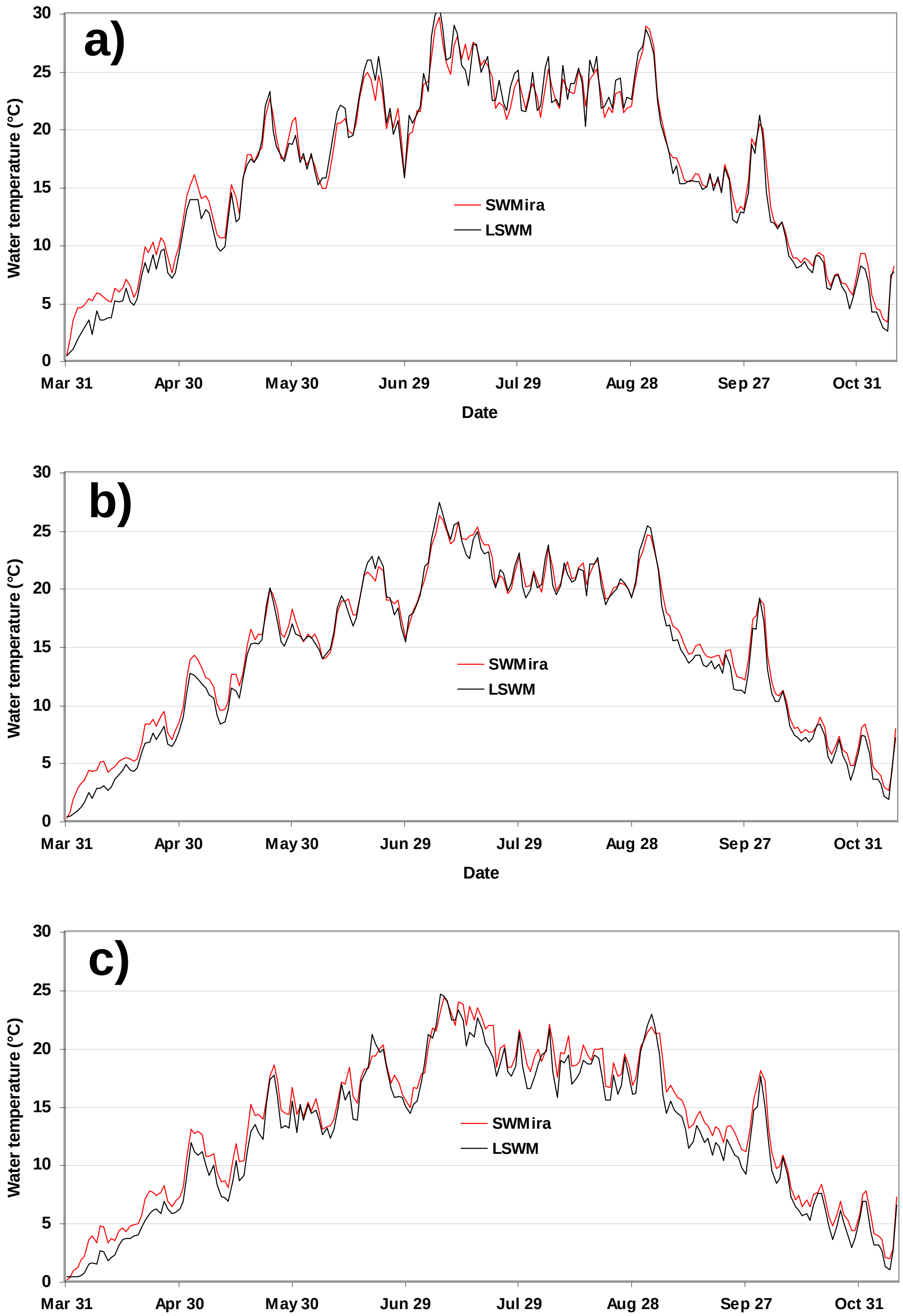

Figure 1. Time series of a) maximum, b) mean and c) minimum water temperature in 2010 for the Southwest Miramichi River (SWMira) at Doaktown and the Little Southwest Miramichi River (LSWM).

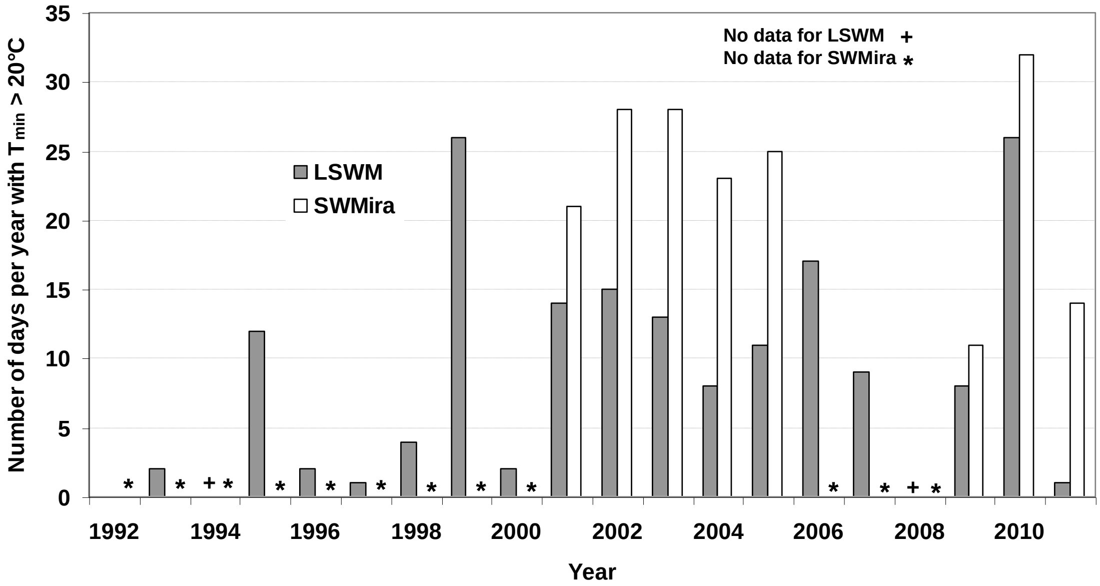

Figure 2. Number of days per year with Tmin exceeding 20°C between 1992 and 2011 for the Southwest Miramichi River (SWMira) at the Doaktown site and the Little Southwest Miramichi River (LSWM). Symbols indicate years with missing data for both rivers.

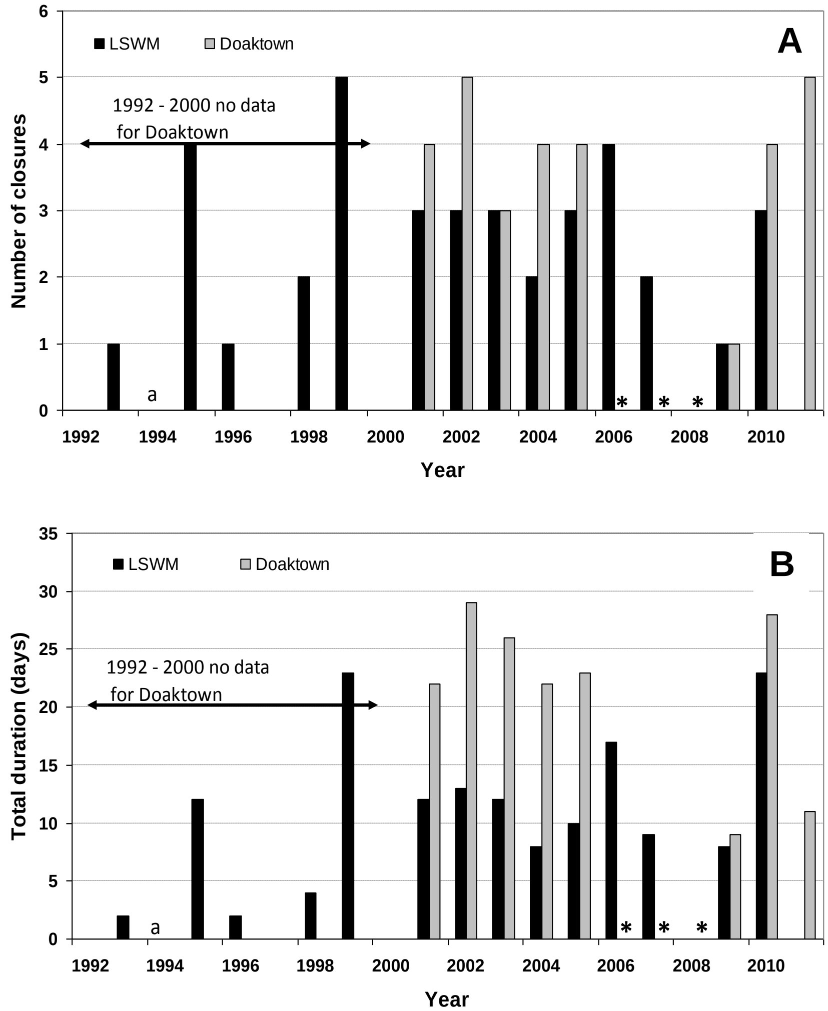

Figure 3. A comparison of a) the number of closures and b) the total duration of these closures based on water temperature in the Little Southwest Miramichi River (LSWM; 1992-2011) and Southwest Miramichi River at Doaktown (SWMira; 2002-2011; with missing data in 2006, 2007 and 2008).

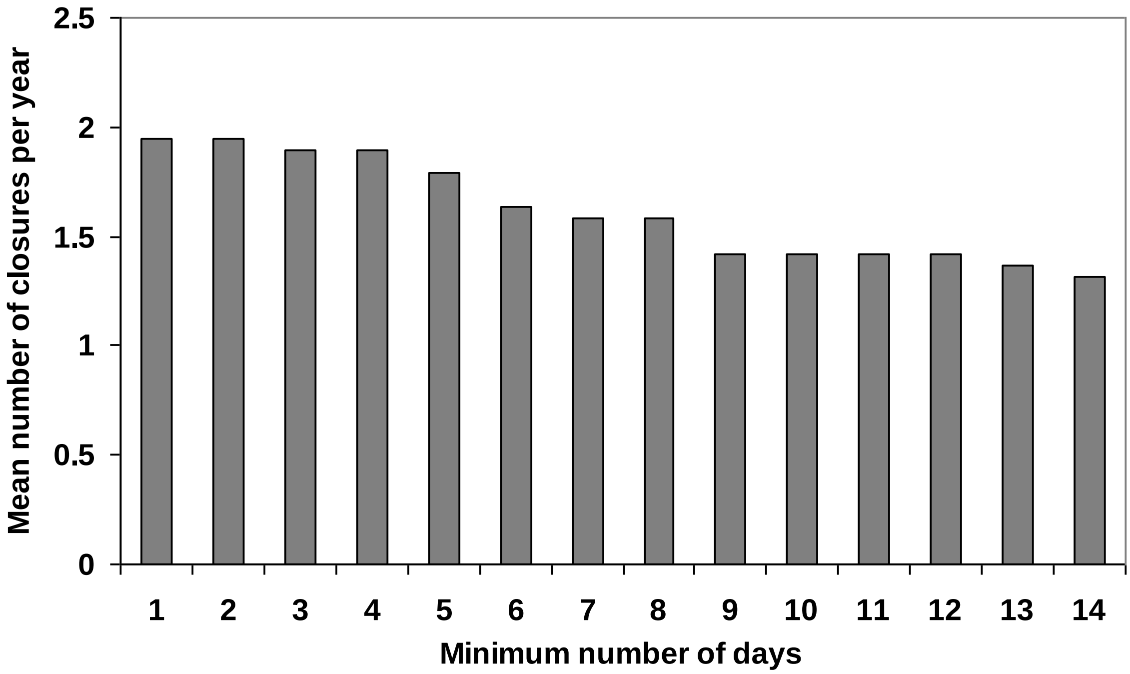

Figure 4. Mean number of closures per year (19 years of data) relative to the minimum number of days during each closure. Results based on water temperatures in July and August at Little Southwest Miramichi River (NB).

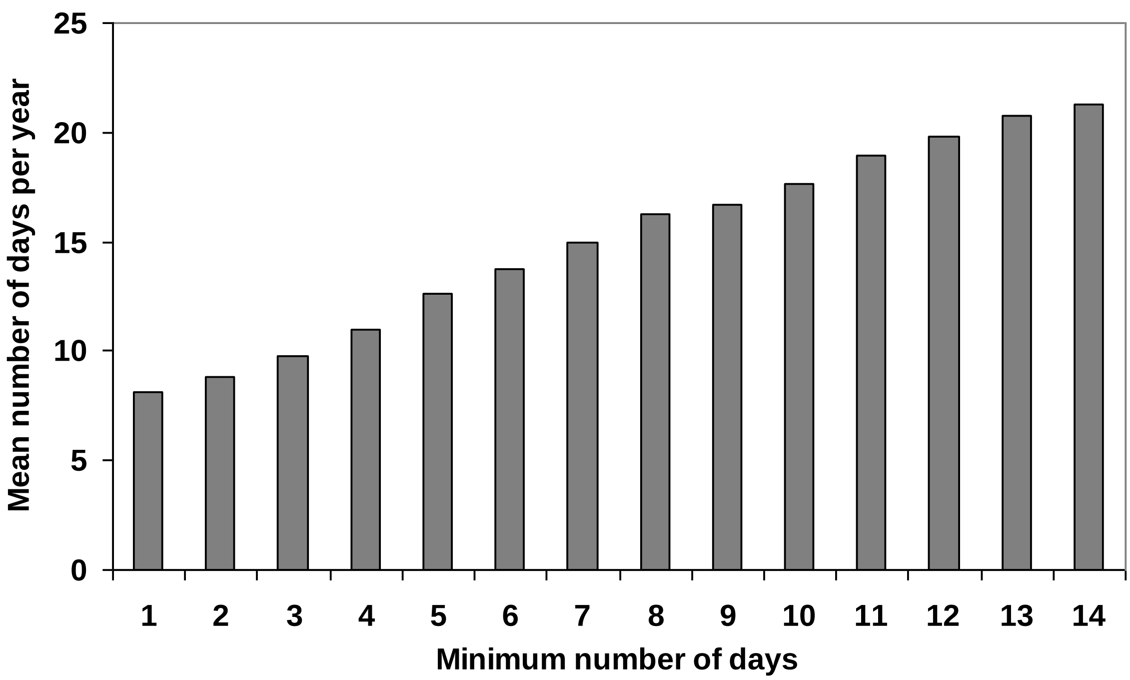

Figure 5. The mean duration of individual closures (number of days per year) as a function of the minimum number of days during each closure. Results based on water temperatures in July and August at Little Southwest Miramichi River (NB).

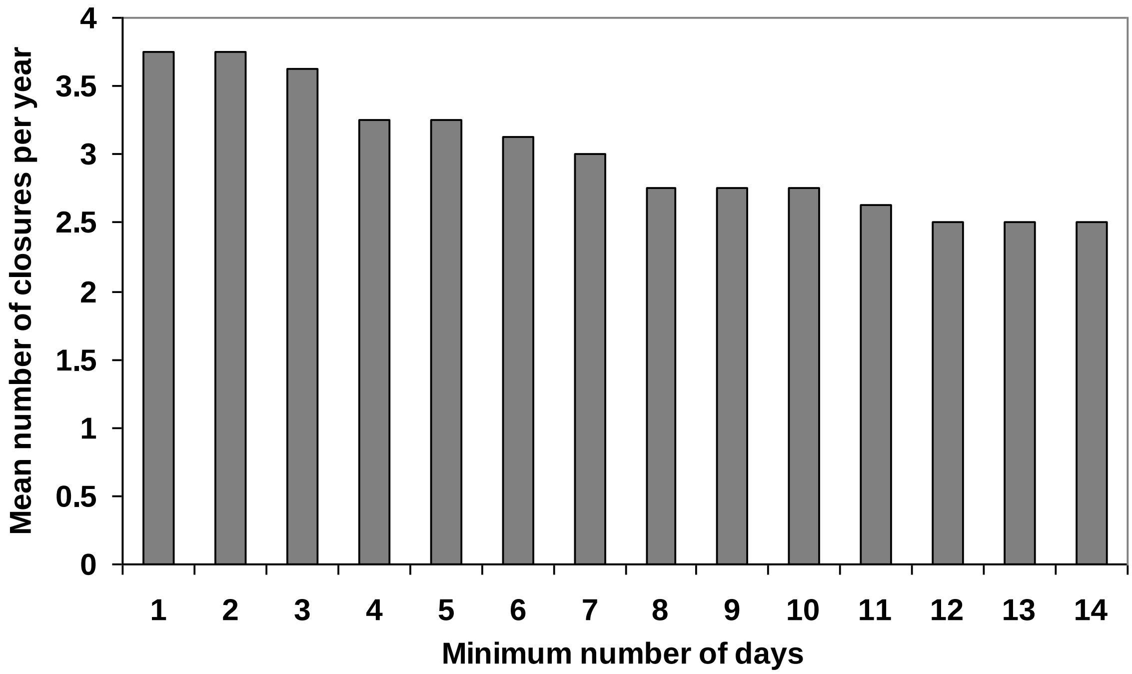

Figure 6. Mean number of closures per year (8 years of data) relative to the minimum number of days during each closure. Results based on water temperatures in July and August at the Southwest Miramichi River at the Doaktown site (NB).

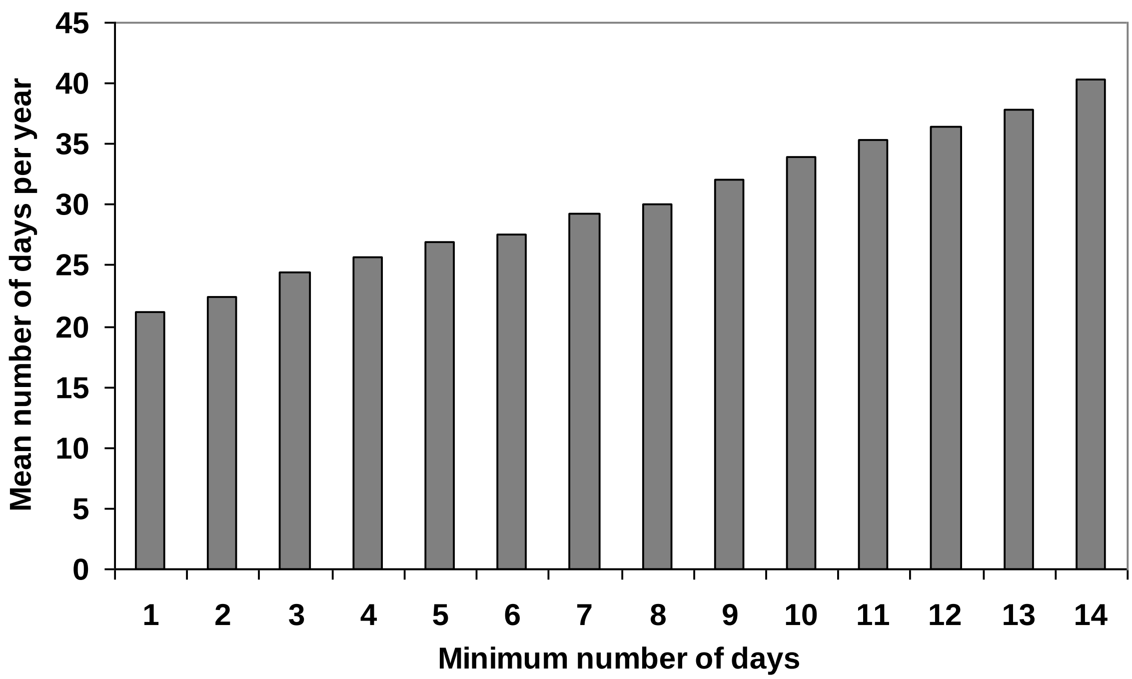

Figure 7. The mean duration of individual closures (number of days per year) as a function of the minimum number of days during each closure. Results based on water temperatures in July and August at Southwest Miramichi River at the Doaktown site (NB.).

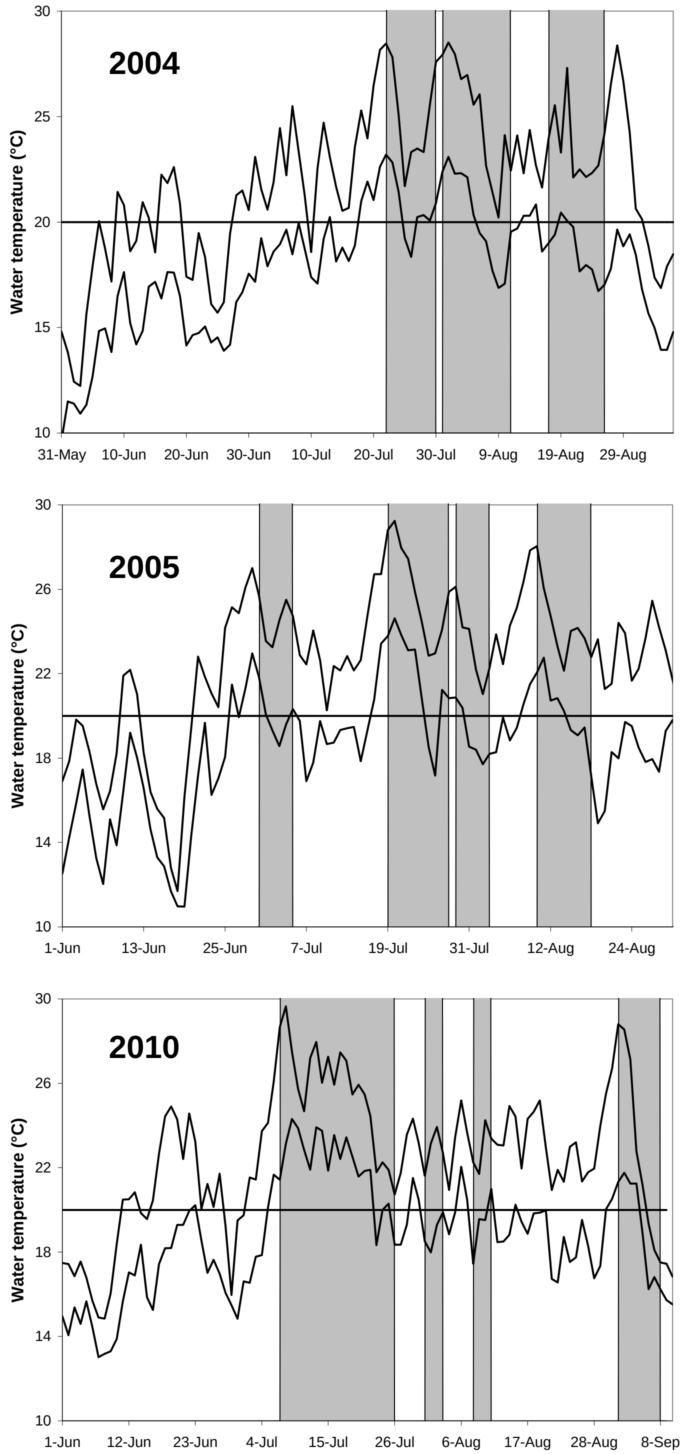

Figure 8. The daily minimum and maximum water temperatures for the Southwest Miramichi River (Doaktown station) for most recent years with high temperature events (2004, 2005 and 2010). The shaded areas represent management closures based on the present study threshold temperature (T min ≥ 20°C for closing and T min < 20°C for two consecutive days for opening the fishery, including periods for implementation using variation orders). 20°C is shown by the horizontal line.