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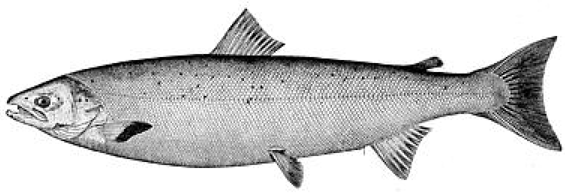
Science Sciences
Gulf Region
Canadian Science Advisory Secretariat
Science Advisory Report 2012/019

TEMPERATURE THRESHOLD TO DEFINE MANAGEMENT STRATEGIES FOR ATLANTIC SALMON (*SALMO SALAR*) FISHERIES UNDER ENVIRONMENTALLY STRESSFUL CONDITIONS



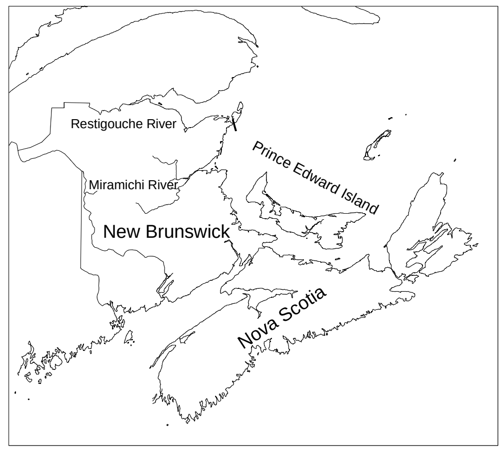


Figure 1: The Maritime provinces of Canada showing locations of the Miramichi and Restigouche rivers.

Context :

*High summer water temperatures along with low water/reduced flow conditions frequently occur in Atlantic Salmon (*Salmo salar*) rivers in the Maritimes: together they pose an environmental stress that is particularly severe for early-run salmon in the Miramichi and Restigouche Rivers in New Brunswick. During July and August, water temperatures in rivers of the southern Gulf of St. Lawrence can exceed 25°C. In the summer of 2010, the Miramichi and Restigouche rivers experienced both warm water and low water conditions leading to thermal stress and fish mortality. Over the past fifty years, there have been five inseason fishery closures in the Miramichi River 1987, 1995, 1999, 2001 and 2010. These closures corresponded to extremely low discharge conditions and high water temperatures. In those years, selected pools or locations were closed to angling due to concerns related to illegal fishing activities.*

Criteria used for management closures in the Miramichi River have been ad hoc which leads to delays in management response and reduced benefits to the resource. DFO Fisheries and Aquaculture Management Gulf Region has requested advice on environmental thresholds for the management of Atlantic salmon fisheries. A Regional Science peer review meeting was conducted March 15, 2012. Participants included DFO scientists and fishery managers from Gulf, Maritimes, Newfoundland and Labrador, and Central and Arctic Regions, from provincial governments, university experts, Aboriginal organizations, as well as watershed organizations and conservation groups.

SUMMARY

- Temperature tolerance in Atlantic salmon is size-specific with adult salmon less tolerant of high temperatures than juveniles.
- There is limited information on optimal temperatures and critical temperatures that define the aerobic scope for adult Atlantic salmon and inferences are made based on evidence from juvenile life stages of Atlantic salmon and other species.
- The temperature thresholds proposed are based on bioenergetic considerations. A daily minimum water temperature (T_{min}) of 20ºC is proposed to be most important for physiological recovery and survival of Atlantic salmon.
- The proposed closure trigger is if the minimum water temperature (T_{min}) during each of two consecutive days equals or exceeds 20°C.
- The proposed opening trigger is if the minimum water temperature (T_{min}) during each of two consecutive days is less than 20°C.
- Mean water temperatures show spatial structure within the Miramichi River and the Restigouche River based on main stem or tributary sites and distance from the estuary.
- The management performance of the proposed closing and opening triggers can be assessed by retrospective evaluation using criteria such as the number of closures and the duration of the closures.
- The number of salmon vulnerable to mortality from angling activities during warm water conditions is not known. In river mortalities of adult Atlantic salmon are not systematically documented in either the Miramichi or Restigouche rivers and angling statistics at a temporal scale sufficient for assessing the potential impacts of angling during warm water periods are not available.
- Other human activities can displace fish and contribute to stress on Atlantic salmon during warm water events including wading in streams, swimming in pools, boat traffic, as well as scientific activities.

INTRODUCTION

Inseason management measures have been introduced in the past to reduce mortality of Atlantic salmon (*Salmo salar*) captured in catch and release recreational fisheries during periods of warm and low water levels. In some areas of eastern Canada, there has been an increased frequency of recreational closures as a direct result of these environmental events.

The management decision to intervene inseason must be timely. There is overwhelming evidence that incidental mortality from catch and release angling increases with water temperatures above 20ºC. Mortality resulting from displacement of salmon from cool water seeps, burst of high energy swimming, and general unease is expected to increase with increasing temperatures.

DFO Fisheries and Aquaculture Management Gulf Region requested advice on the following questions:

- What environmental thresholds could be used to trigger management actions to open or close Atlantic salmon fisheries?

- Given the size of the rivers (Miramichi and Restigouche), what are the options available for managing Atlantic salmon fisheries during environmentally stressful conditions?

In response, this advisory report was developed considering the following points:

- Information on physiology and metabolic rates of Atlantic salmon and associations with the level and duration of stress (warm water) and the cause(s) of mortality.
- Possible temperature benchmarks associated with increased risk/probabilities of mortality that could be used to trigger management interventions (protocols) under environmentally stressful conditions for Atlantic salmon.
- Environmental (temperature, discharge/water level) characteristics (spatial and temporal) of the Miramichi and Restigouche rivers.
- Evidence that Atlantic salmon are susceptible to angling during warm water events and that interventions could be used to manage incidental catch mortality in these fisheries.
- Evaluation of fishery management options for the Miramichi and Restigouche rivers considering the frequency and duration of management interventions.

ANALYSIS

Fish Bioenergetics

In fish, temperature governs metabolic processes such as cardio-vascular functions. Basal metabolic rate (BMR) is a measure of the energy expenditure required to sustain vital life supporting functions such cardio-vascular activity. BMR is measured when an animal is at rest. BMR is aerobic, which means that energy is generated by combining food with oxygen. BMR increases non-linearly with increasing water temperature to a maximum level known as AMR: active metabolic rate (Fig. 2). The difference between BMR and AMR is termed the aerobic scope which is the energy available for additional life cycle functions including swimming, feeding, and growth, among others. The aerobic scope is specific to the species and life stage, with the aerobic capacity and thermal tolerance in fishes being lower for adults than juveniles.

The optimal temperature (T_{opt}) is defined as the temperature that provides the greatest aerobic scope and as a result the highest level of energy available for metabolism. T_{crit} is the temperature corresponding to the complete collapse of the aerobic scope. As water temperature increases from T_{opt} to T_{crit}, aerobic scope decreases. During this phase, anaerobic metabolism, in which energy is generated without combustion with oxygen, contributes increasingly to meeting the energy requirements of the fish (Fig. 2). Beyond T_{crit} survival is time-limited because the metabolic requirements exceed the aerobic capacity. Anaerobic metabolism is energetically costly and leads to the production of potentially damaging cellular metabolic byproducts such as lactic acid. Only a return to conditions under which there is aerobic scope will allow the organism to breakdown the byproducts of anaerobic metabolism.

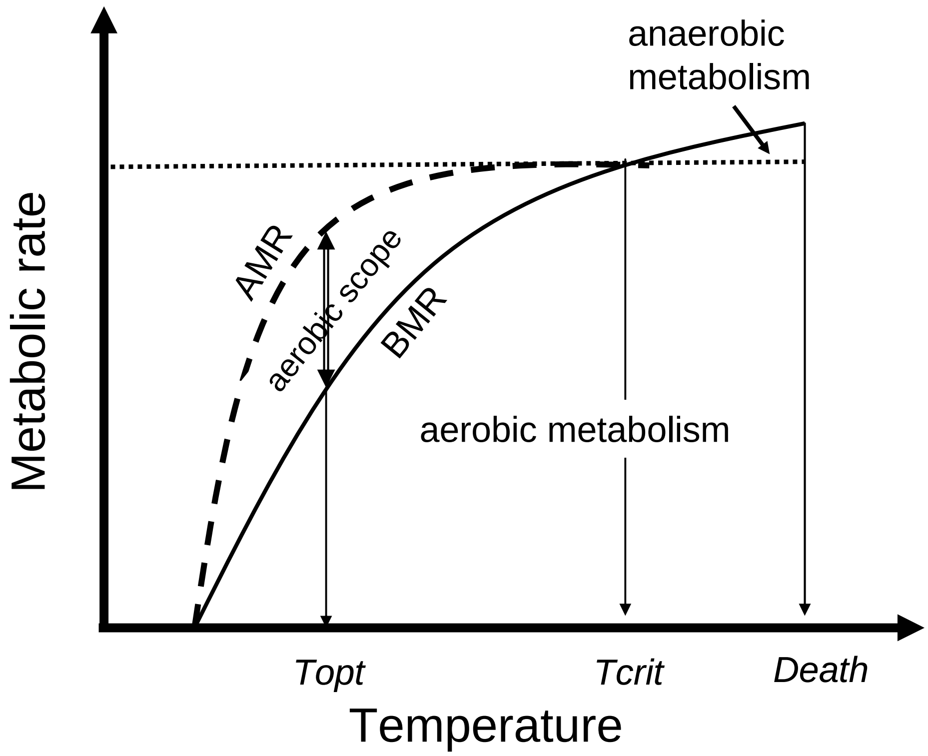


Figure 2: Simplified diagram of the relationship between basic metabolic rate (BMR), active metabolic rate (AMR), and aerobic scope relative to water temperature for fish. T_{opt} is the temperature at which the aerobic scope (AMR – BMR) is maximum. T_{crit} is the temperature at which AMR = BMR (aerobic scope is null). All metabolic energy requirements below maximum AMR can be attained by aerobic metabolism. All metabolic energy requirements above maximum AMR, when temperature is higher than T_{crit}, must be realized by anaerobic metabolism.

Temperature tolerances for Atlantic salmon

Salmonids (trout, salmon, charr) have generally the lowest thermal tolerance of many fish groups. For Atlantic salmon juveniles, the incipient lethal temperature, defined as the temperature which the fish can tolerate for a long period (usually taken as seven days), is 27.8ºC (Elliott 1991). The ultimate lethal temperature for juveniles, defined as the temperature which the fish cannot tolerate even for short periods of time (usually taken as 10 minutes), is in the range of 30 to 33ºC. Thermal sensitivity is size-specific such that adult salmonids prefer lower temperatures and are less tolerant of high temperatures than juveniles (Fowler et al. 2009). As such, incipient lethal temperature and ultimate lethal temperature of adult Atlantic salmon are expected to be lower than the values for juveniles and therefore; the incipient lethal temperature for adult salmon is likely near 25°C.

Adult Atlantic salmon acclimated to 23°C survived for at least three days and 70% of the fish were able to recover post-exhaustive exercise when held at that acclimation temperature (Wilkie et al. 1997). However, adult Atlantic salmon only survived temperatures of 24 to 27°C for a short time period (Huntsman 1946). Since the adult salmon held above 24°C were not able to recover from the effects of exhaustive exercise and anaerobic metabolism, this infers that these temperatures are above the critical temperature (T_{crit}). Since some of the adult salmon were able to recover from exhaustive exercise at 23°C, this infers that 23°C is very near the level for T_{crit}.

Temperature-related stress in juvenile Atlantic salmon has been associated with behavioural changes such as abandonment of feeding territories and aggregations at cool-water seeps (Breau et al. 2007, 2011). Juvenile and adult salmon have been observed aggregating at sources of cool water when the minimum nighttime temperature remained above 20°C for two consecutive nights. Active feeding also ceased under these warm water conditions.

The optimum temperature for growth has been equated to the temperature which provides the maximum aerobic scope. The optimum temperature for growth of juvenile salmon is in the range of 16 to 20ºC (Elliott and Elliott 2010). Adult anadromous Atlantic salmon do not feed in freshwater and the optimum temperature for growth in wild salmon at sea has been equated with the temperatures corresponding to the highest catch rates at sea, in the range of 4 to 10ºC (Reddin and Friedland 1993). For some Pacific salmon species and populations, the optimum temperature for migration corresponds to the water temperatures which the populations have experienced during their upriver migration (Farrell et al. 2008). Adult Atlantic salmon return to rivers in eastern Canada over a range of river water temperatures with river migration seemingly favoured at water temperatures in the range of 14 to 20°C.

Proposed Temperature Thresholds

Proxies for T_{crit} for adult Atlantic salmon

Based on laboratory studies of fish obtained in the wild, T_{crit} (where BMR=AMR and aerobic scope is null) for 2-year old juvenile Atlantic salmon was estimated to be 24°C (Breau et al. 2011). T_{crit} for adult Atlantic salmon has not been measured but the aerobic capacity and thermal tolerance of adults are lower than in juveniles so T_{crit} for adult Atlantic salmon is undoubtedly lower than 24°C. In studies of the recovery rate of adult Atlantic salmon acclimated and subjected to exercise to exhaustion at 18°C, 20°C and 23°C, it was shown that most of the physiological endpoints returned to pre-exhaustion (resting) levels after four hours or more although recovery to resting levels for these endpoints took longer than 4 hours when fish were exercised to exhaustion at 20ºC (Wilkie et al. 1996, 1997). In these studies, there was a delayed mortality, with 40% of the adult salmon dying when held at 20°C and 23°C. Based on the range observed in other salmonid species, a T_{crit} value of less than 24ºC could be assumed.

Proxies for T_{opt}

In salmonids, the temperature range differential T_{crit} and T_{opt} was estimated to be 6 to 7°C. T_{opt} for Pacific salmon was shown to correspond to the range of water temperatures experienced during upriver migration. On that basis, a proxy for T_{opt} for adult Atlantic salmon could be estimated based on the median water temperature experienced during the migration period of June and July. For the Miramichi River, the median temperature in the river from June 1 to July 31 over a six year period (2005 to 2010) was 19°C (Fig. 3). Over the same period for the Restigouche River, the median water temperature at migration over the same months and years was cooler, at a median water temperature of 17°C (Fig. 3). This suggests that T_{opt} may be at a lower temperature for adult salmon in the Restigouche River than it is for adult salmon in the Miramichi River.

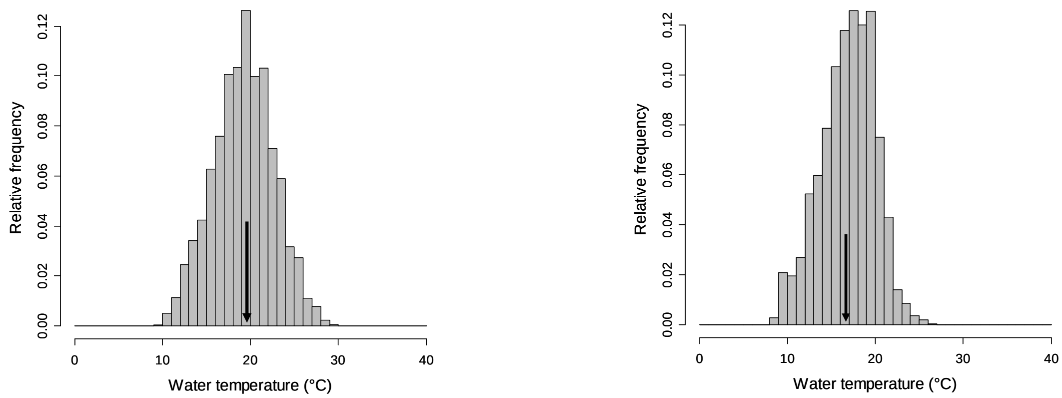


Figure 3: Mean daily water temperature distribution between June 1 and July 31, the period corresponding to the migration period of early-run Atlantic salmon, for the years 2005 to 2010, in the Miramichi River (left panel) and the Restigouche River (right panel). Temperature distributions were defined based on records from two sites in each river. Solid arrows indicate the median temperatures of the distributions.

Minimum temperature (T_{min}) as a management threshold

The scope for activity of adult Atlantic salmon at temperatures just below 23ºC is considered to be very small and anaerobic metabolism is required to sustain activities at temperatures above 23ºC. Recovery is more rapid at temperatures close to T_{opt}. Daily fluctuations in temperatures can subject adult Atlantic salmon to temperature stress resulting in the accumulation of anaerobic byproducts. Although potentially exposed to temperatures that exceed 23ºC during the day, Atlantic salmon can recover if temperatures overnight decline to values closer to T_{opt} for even short periods of time, for example for four hours. After exercise to exhaustion, at 23ºC, fish at rest can survive for days and in some instances are able to recover to resting state after exercise to exhaustion.

Threshold proposals are based on observed changes in behaviour of Atlantic salmon both in the wild and in experiments with measured physiological responses of adult salmon exposed to exercise at high water temperatures. A daily minimum water temperature rather than a maximum temperature (within the thermal tolerance limits of salmon) is proposed to be the appropriate indicator of physiological recovery and survival. Juvenile Atlantic salmon in the Little Southwest Miramichi form aggregations at cool water sites when T_{min} exceeded 20°C for two consecutive nights. Consequently, a T_{min} value of 20ºC is proposed as the threshold temperature for assessing physiological stress in Atlantic salmon.

Water Temperature Characteristics of the Miramichi and Restigouche rivers

Water temperature varies on temporal scales of hours, days, seasons and years. In addition, water temperature conditions can be spatially heterogeneous and associated with river size, depth, discharge and other physical features (e.g. elevation, stream exposure, slope, etc). Water temperature characteristics of the Miramichi and Restigouche rivers were described based on data collected at over three dozen monitoring sites in these rivers.

There is a well defined seasonal pattern of water temperatures (daily minimum, mean and maximum) with peak values for each on about July 30 (Fig. 4). The highest water temperatures are consistently recorded in the months of July and August and coinciding with low water levels in summer.

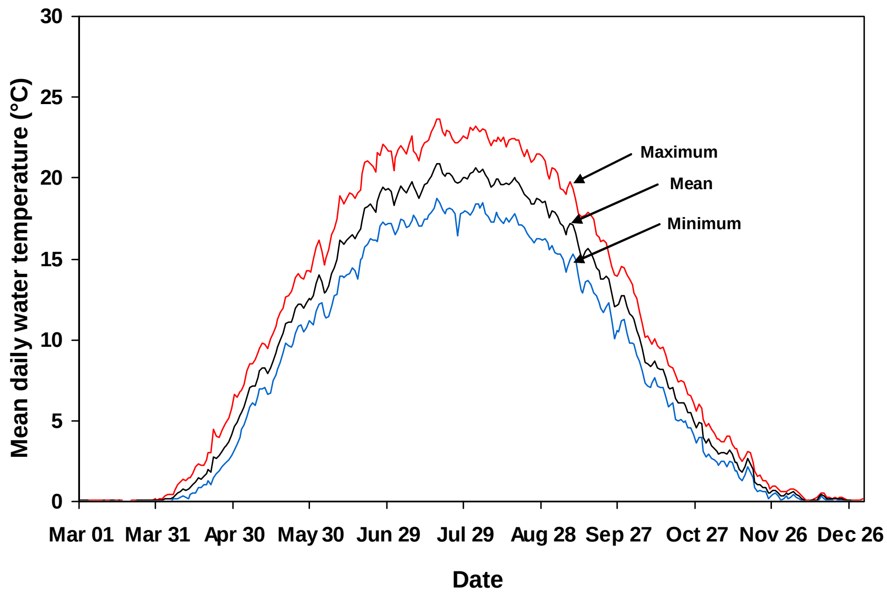


Figure 4: Mean daily water temperature (minimum, maximum and mean by date) at the Little Southwest Miramichi River monitoring site for the years 1992 to 2011.

In terms of the diurnal temperature cycle, the minimum water temperature generally occurs in the morning at around 9:00 AM (DST) and at this index site (Little Southwest Miramichi River) is on average 2.7°C cooler than the mean value for the day (Fig. 5). The mean daily water temperature was observed around 1:00 PM and the maximum water temperature was observed around 7:00 PM, the maximum was on average 2.8°C warmer than the daily mean temperature. The diel variability pattern may vary daily, seasonally and annually as well as among sites.

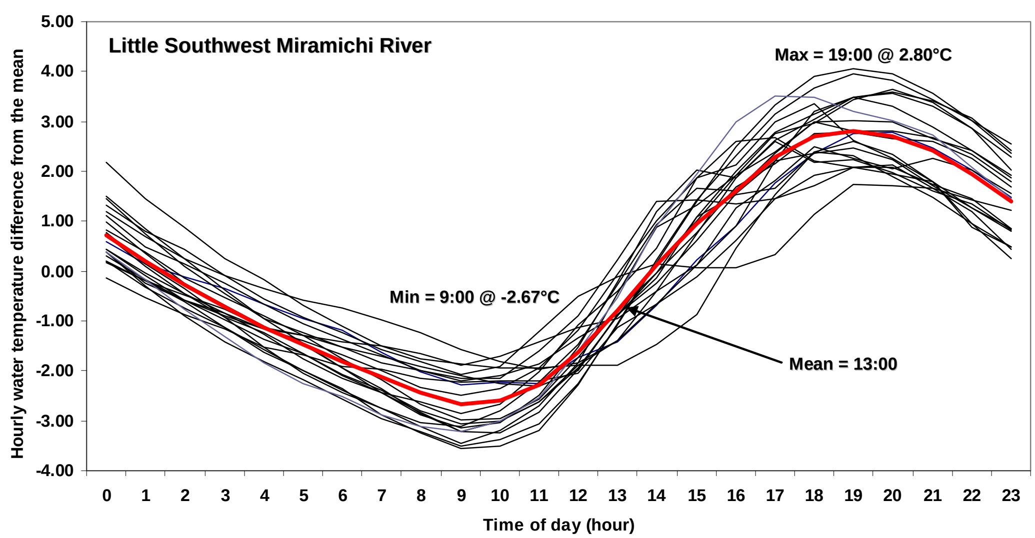


Figure 5: Diel water temperature variability at the Little Southwest Miramichi River monitoring site. The solid red line is the mean value over all days and the individual black lines are for each day between July 3 to July 25, 1995 (during a period of high water temperature).

There is important spatial heterogeneity in the temperature profiles within and among sites of the Miramichi and Restigouche rivers (Fig. 6). The mean summer (July and August) water temperatures among sites varied between 16.5°C and 18.0°C in the Miramichi River whereas mean summer water temperatures were lower among sites the Restigouche River, varying between 14.2°C and 18.0°C (Fig. 6). The difference between the minimum and maximum water temperature ranged from 2.8 to 6.3ºC on the Miramichi River and variation was less for the Restigouche River (2.1 to 4.3ºC).

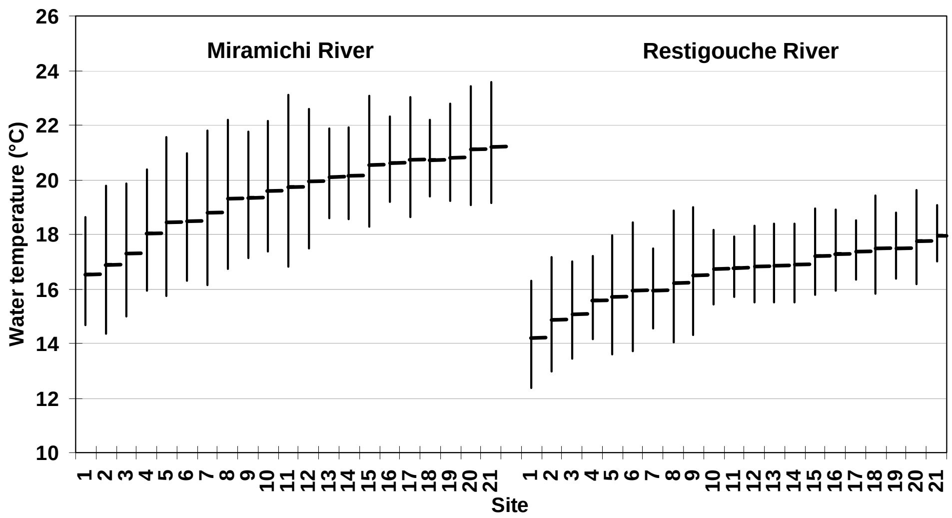


Figure 6: Site-specific variations in temperatures (minimum to maximum range, mean) in the Miramichi and Restigouche rivers. Sites are ordered from coolest to warmest within each river.

Mean water temperatures show spatial structure within each river associated with whether they are main stem or tributary sites and distance (or elevation) from the estuary (Fig. 7). Water temperatures were much warmer in the Miramichi River, with the majority of main stem sites (Southwest Miramichi, Renous, Northwest Miramichi and Little Southwest Miramichi) characterized by mean water temperatures exceeding 20ºC (Fig. 7). Moderate temperature sites (18 to 20ºC) were located in the upper portions of the main stem sites and tributary sites whereas the few cool water sites (< 18ºC) were located in the upper headwaters of tributaries. In contrast, mean water temperatures in the Restigouche are less than 18ºC (except at the lowest sites in the main stem) with the coolest sites in the headwater and tributary areas.

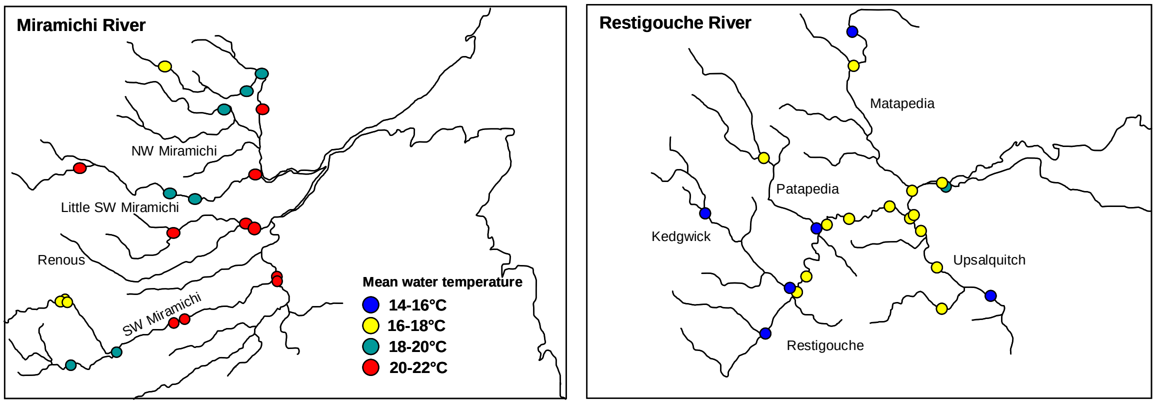


Figure 7: Mean summer (July and August) water temperature at monitored sites in the Miramichi River and Restigouche River. Number of years varies among sites but the overall period of coverage is 1992 to 2010.

Given the narrow aerobic scope for activity of adult Atlantic salmon at 23ºC, the number of days per year in which the daily maximum water temperature (T_{max}) exceeded 23°C was examined for two main river stem sites; for the Little Southwest Miramichi River over the years 1992 to 2011 and the Restigouche River at Two Brooks for the years 2003 to 2011. There was a marked difference in the number of days with temperatures >23°C at the Little Southwest Miramichi site compared to the Restigouche River (Fig 8a). With one exception, the year 2008, the temperature at the Little Southwest Miramichi site exceeded 23ºC at least once during the summer months and the number of days per year was as high as 50 to 60 days. In contrast at the Restigouche River site, there were generally fewer than five days and most often zero days in which 23ºC was exceeded (Fig. 8a).

A T_{min} value of 20ºC is proposed as the threshold temperature for assessing physiological stress in Atlantic salmon. Also shown in Figure 8 (panel b) are the number of days per year in which the daily minimum water temperature (T_{min}) exceeded 20°C for the Little Southwest Miramichi River and the Restigouche River (at Two Brooks). he minimum daily temperature remained above 20ºC in every year except 2008 in the Little Southwest Miramichi River, and it lasted over a period of 25 days in 1999 and 2010 (Fig. 8b). At the Restigouche River site, the minimum daily temperature exceeded 20ºC in 4 of the 9 years and the maximum number of days per year was 8 in 2005 (Fig. 8b). In 2010, warm water conditions noted at the Little Southwest Miramichi site were substantially less severe at the Restigouche River site.

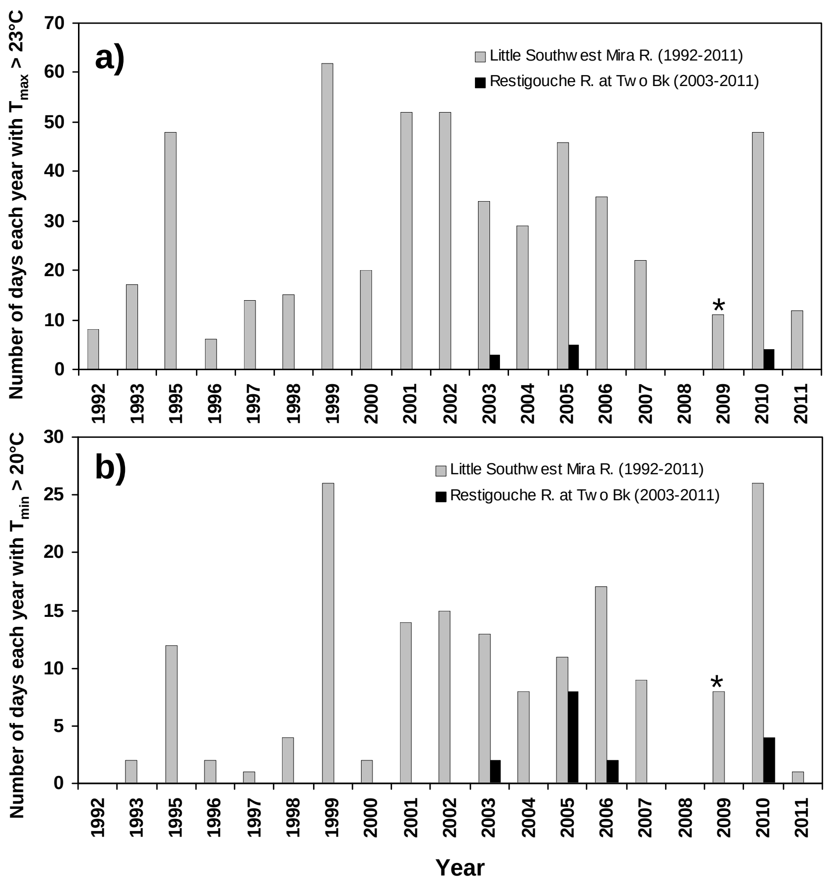


*Figure 8: Number of days per year in which (a) the daily maximum water temperature (T_{max}) exceeded 23°C and (b) the daily minimum water temperature (T_{min}) exceeded 20°C for the Little Southwest Miramichi River (years 1992 to 2011, excluding 1994) and the Restigouche River at Two Brooks (years 2003 to 2011). The * indicates a year (2009) with incomplete data.*

Evaluation of management scenarios based on historical data

To minimize physiological risk to fish from environmental stress, the proposed temperature threshold consists of a temperature and a duration.

The proposed closure trigger is:

- The minimum water temperature (T_{min}) over each of two consecutive days equals or exceeds 20°C.

The proposed opening trigger is:

- The minimum water temperature (T_{min}) over each of two consecutive days is less than 20°C.

The justification for the choice of a threshold minimum temperature has been provided above. The choice of two days as an indication of a physiologically stressful condition for Atlantic salmon is guided by the studies on behavioural responses to warm water conditions. Thus, two days in which the minimum temperature always exceeds 20ºC alters behaviour in juvenile Atlantic salmon who move away from active defence of feeding territories to seek coolwater refuge. Although these aggregations generally breakup overnight, a minimum water temperature that falls below 20ºC over two consecutive days following the physiologically stressful condition is proposed for fish recovery.

The performance of the proposed decision rules was assessed retrospectively by evaluating the number of closures and the duration of the closures based on historical temperature data from two monitoring locations in the Miramichi River. The two monitoring sites were the Southwest Miramichi station (at Doaktown) for the years 2001 to 2011 and the Little Southwest Miramichi River site (above Catamaran Brook) for the years 1992 to 2011. It was assumed that one full day would be required to effect and communicate a closure once the closure trigger is activated and one full day would be required for a re-opening once the opening trigger is activated. Monitoring for minimum temperatures was continuous and as a result the minimum closure time once initiated was two days.

Based on the temperature data from the Little Southwest Miramichi River (LSWM), between 1992 and 2011 (excluding 1994 with no data), there would have been at least one closure in 14 of 19 years (Fig. 9). The number of closures annually ranged from one to five (for 1999). The total number of days under closure ranged from a low of 2 days in 1993 to a high of 23 days in 1999 and 2010. Water temperatures at the Southwest Miramichi River station (Doaktown) were warmer than in the Little Southwest Miramichi. Based on the Southwest Miramichi River monitoring site, there would have been closures in all eight years with monitoring data (2001 to 2005, 2009 to 2011) and the number of closures per year would have ranged from one to five (in 2011). The total days closed in those years would have ranged from a low of 9 days to 29 days (in 2002). Because temperatures at the Southwest Miramichi River monitoring station were warmer than those of the Little Southwest Miramichi River, there would have been more annual closures, more closures per year and closures overall of longer duration when the Southwest Miramichi River monitoring site is used. Over years with comparable data, the closure interventions in 2011 differed most between the two sites with the Southwest Miramichi River data triggering five closures but no closures based on the Little Southwest Miramichi monitoring site.

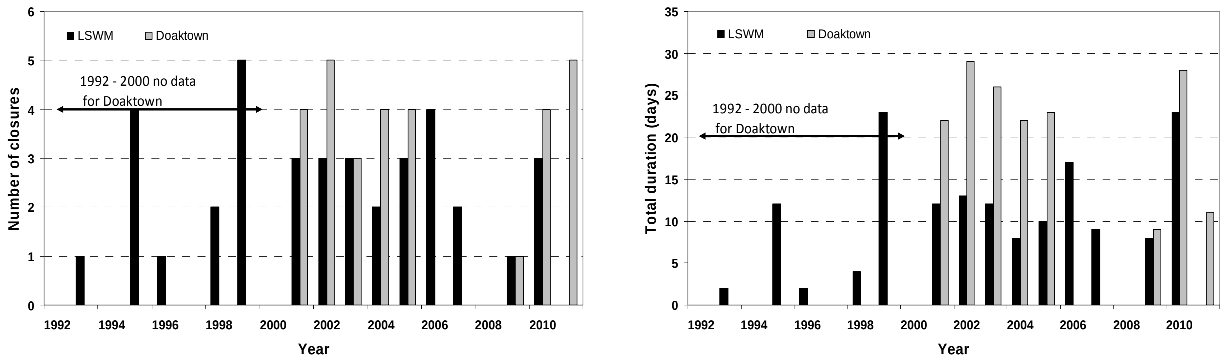


*Figure 9: Number of closures (left panel) and total number of days closed based on closure trigger of two days, opening trigger of two days and management lag of one day for closing and opening. No data at Doaktown from 1992 to 2000. * indicates years with no data at Doaktown station and "a" indicates years with no data at LSWM.*

In addition, one performance measure of interest is the duration between closure interventions within a year. The management interventions in 2005 and 2010 based on water temperature monitoring data from the Southwest Miramichi River station are shown in Figure 10. In 2005, there were four interventions initiated with a brief two day opening between successive closures in late July (Fig. 10). In 2010, there were also four closures but with the exception of the first closure which lasted 18 days, the second and third closures were short (2 days each) and spaced over 6 days apart. Note that the number of interventions and the duration within and between interventions could be examined retrospectively to inform management if frequency of closures and duration are factors of interest.

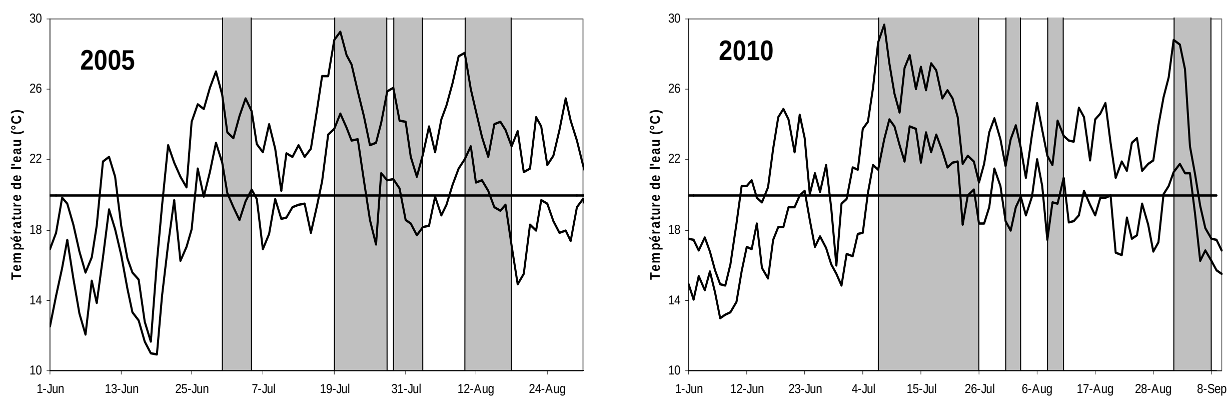


Figure 10: The daily minimum and maximum water temperatures at the Southwest Miramichi River (Doaktown) station for 2005 (left panel) and 2010 (right panel). The shaded areas represent the days when a management intervention would have taken place based on the closing and opening triggers defined in text. The solid horizontal line is 20°C.

Angling success for Atlantic salmon during warm water temperature events

For Atlantic salmon, 20ºC appears to be the inflection point beyond which mortality from angling increases rapidly with at increasing temperatures (Dempson et al. 2002). Generally catch rates are lower at higher temperatures (Fig. 11), but salmon are captured (Fig. 12), as evidenced from creel reports from NB Crown Reserve angling stretches and corresponding temperature data from nearby monitoring sites in both the Miramichi and Restigouche rivers. Even though catch per unit effort was lower on those days, many adult Atlantic salmon were caught.

The loss of Atlantic salmon associated with increased catch and release mortality in these warm water periods cannot be assessed because the angling data are not collected at an adequate spatial and temporal scale annually. Constant catch and release mortality rates of 3% and 6% are applied to the annual catch and release estimates of the Miramichi River and Restigouche River, respectively. The values are based on general considerations of run timing, angling activities within the season and seasonal variations in water temperature. A higher value is used for the Restigouche River because this population is also affected by furunculosis which may itself contribute to mortality under warm water stress conditions but may be exacerbated by catch and release activities.

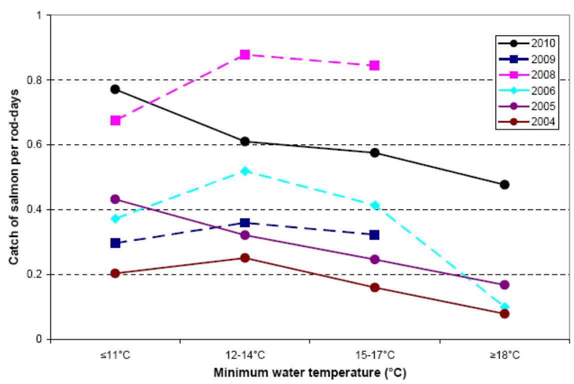


Figure 11. Catch of Atlantic salmon (size groups combined) per rod day of effort from New Brunswick Crown Reserve angling stretches of the Northwest Miramichi River as recorded on creel record forms for the years 2004 to 2010 (excluding 2007) relative to minimum nighttime water temperature recorded at the continuous temperature data logger upstream of these angling streches. The temperature monitoring site (Northwest Miramichi Bridge Pool) has the coolest water temperature in the Miramichi River.

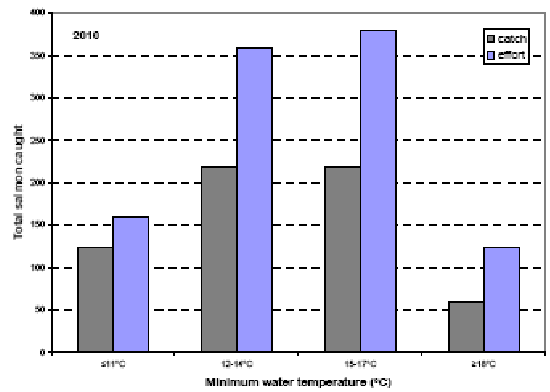


Figure 12: Catch of Atlantic salmon (size groups combined) and effort in NB Crown Reserve stretches (Adams, Charlie's Rock, Groundhog Landing and Squirrels Falls) of the Northwest Miramichi River in 2010 relative to minimum nighttime water temperatures recorded at the coolest water monitoring site (Northwest Miramichi Bridge Pool) of the Miramichi River. These angling stretches are located in a section of river where temperatures are warmer than those recorded at Bridge Pool site.

Sources of Uncertainty

The temperature thresholds proposed are based on bioenergetic considerations of salmonids. There is limited information on optimal temperatures and critical temperatures that define the aerobic scope for adult Atlantic salmon and inferences have been made based on evidence from juvenile life stages of Atlantic salmon and other species. An examination of the water temperatures at migration of adult Atlantic salmon has been used as a proxy for T_{opt}. This provides some support for the choice of 20ºC as a threshold temperature that promotes recovery of bioenergetic endpoints which are critical for survival. Dedicated research to determine T_{opt} and T_{crit} for adult Atlantic salmon is required to confirm that 20ºC is appropriate.

A single temperature threshold value has been proposed. Evidence from Pacific salmon populations migrating in the Fraser River at different times of the year indicate that run timing may be adaptive and associated with water temperatures that match population-specific T_{opt} values. The median temperature at migration in the Restigouche River is 2ºC cooler than that for the Miramichi River. The proposed 20ºC threshold for Atlantic salmon is a close match to the median temperature at migration for the Miramichi River. This threshold may be too high for salmon from the Restigouche River. Mortalities of adult salmon have been noted in the Restigouche River in some years. Although these mortalities were most often attributed to disease, the pathogen may have been a secondary stress that took hold following bioenergetic constraints that weakened the fish. Population-specific research would address this uncertainty.

Laboratory studies of adult Atlantic salmon exercised to exhaustion indicate that recovery can occur within four hours for fish at rest in water of constant temperature. The opportunity for recovery of salmon in the wild may be reduced because thermal refuge habitat may be limiting and fish behaviour in the wild imposes energetic demands not considered in laboratory studies. The post-thermal stress recovery process of Atlantic salmon in the wild has not been studied.

The proposed two day period where water temperature exceeds 20ºC as the minimum temperature for a closure trigger is based on observations of behavioural changes in Atlantic salmon juveniles associated with warm water temperature stress. Adult Atlantic salmon also behaviourally respond to warm water events manifested over similar or shorter duration.

Similarly, it is proposed that the trigger for opening be based upon two consecutive days in which the minimum temperature is less than 20ºC. This opening trigger requires that there would have been at least one hour per day over two consecutive days when the minimum temperature was less than 20ºC. The minimum number of hours required to recover fully to aerobic metabolism, particularly as temperature fluctuates, is not known. Recovery is most rapid when fish can find temperatures which are closest to their optimal temperature. This value can vary with the acclimation temperature, the size of the animal and the maturity state. The role of these factors has not been tested in adult Atlantic salmon.

The association between diel cycling of temperatures and the rates of anaerobic byproduct accumulation and assimilation is not known. Refined thresholds and triggers could be developed if the functional relationship between these could be defined; for example whether the rate of anaerobic byproduct accumulation is a linearly increasing function of temperature above T_{crit} and similarly if the rate of byproduct assimilation is a linear but inverse function of temperature between T_{crit} and T_{opt}. As presently defined, the re-opening trigger assumes that one hour at any temperature below 20ºC has an equivalent value for recovery and no consideration is given to the anaerobic debt associated with time spent at temperatures above T_{crit}.

Warm water temperature events can vary in duration and frequency but the consequences of the cumulative stress associated with multiple events on Atlantic salmon life processes including migration, reproductive success, and survival have not been shown empirically.

Water temperatures are currently monitored at selected location sites within the Miramichi and Restigouche rivers. The temperature recorders are not located in known salmon holding pools and it is unknown if temperatures to which salmon are directly exposed are similar to those recorded at the monitoring stations. Adult salmon can sense and move to cool water seeps, a behaviour similar to juvenile salmon aggregations around such refugia. There are localized variations in water temperatures due to small cool water stream inputs and groundwater seeps but with few exceptions, the spatial scales of these cool water refugia are poorly known. It is most likely that the temperatures recorded at the shallow water monitoring sites are warmer in general than the temperatures where adult Atlantic salmon occur. However temperatures are generally uniform between the top and bottom of the water column within the main stems and large tributaries of the Miramichi and Restigouche rivers and when salmon are displaced from limited cooler water sources, they can be exposed to the prevailing warmer water of the river. Consequently, these monitoring sites represent the worst conditions which adult salmon may face during their occupancy and migration in these rivers. The locations and characteristics of adult salmon thermal refuges, particularly in main stem reaches, needs to be investigated and documented.

The number of salmon vulnerable to mortality from angling activities during warm water conditions is not known. Inriver mortalities of adult Atlantic salmon are not systematically documented in either the Miramichi or Restigouche rivers and angling statistics at a temporal scale suitable to assess the potential angling impacts are not collected. In the past, inseason management closure intervention was in response to reported salmon mortalities in certain stretches of river and concerns for illegal activities when water levels were low. Reported mortalities in the Miramichi River associated with warm water and low water conditions reached highs between 200 and 500 in a localized stretch (~ 40m stretch) of river in 1999 and 2001.

CONCLUSIONS

The scope for activity of adult Atlantic salmon at temperatures just below 23ºC is considered to be very small and anaerobic metabolism is required to sustain activities at temperatures above 23ºC. Based on observed changes in behaviour of Atlantic salmon in the wild and laboratory studies of measured physiological responses of adult salmon exposed to exercise at high water temperatures, a daily minimum water temperature (T_{min}) of 20ºC is proposed as the threshold temperature for assessing physiological stress in Atlantic salmon. This is the first of two conditions for defining threshold triggers.

To define the two triggers for recreational management purposes, duration of the temperature event was evaluated with respect to period of fish exposure and exhibited behavioural response. The closure trigger is proposed as a two day period where minimum temperature exceeds the 20ºC and is based on observations of dramatic behavioural changes in juvenile Atlantic salmon, away from active defence of feeding territories to aggregating at coolwater seeps.

Following the physiologically stressful condition that produced the closure, a minimum water temperature that falls below 20ºC over two consecutive days is proposed for the opening trigger to ensure that there is at least one hour per day in two successive days at which temperatures would be closer to T_{opt} for adult Atlantic salmon. A proxy for T_{opt} for adult Atlantic salmon from the Miramichi River and the Restigouche River was estimated based on the median water temperature experienced during the migration period in of June and July. For the Miramichi River, the median temperature in the river was 19°C. For the Restigouche River, the median water temperature was 17°C. This suggests that T_{opt} may be at a lower temperature for adult salmon in the Restigouche River compared to those in the Miramichi River and requires further research.

There is a well defined seasonal pattern of water temperatures in rivers with the highest water temperatures consistently recorded in the months of July and August. Mean water temperatures show spatial structure within each river associated with whether they are main stem or tributary sites; and distance (or elevation) from the estuary. Water temperatures were overall much warmer in the Miramichi River, with the majority of main stem sites characterized by mean water temperatures exceeding 20ºC and moderate temperature sites (18 to 20ºC) located in the upper portions of the main stem sites and tributary sites. In contrast, mean water temperatures in the Restigouche are overall less than 18ºC with the coolest sites in the headwater and tributary areas.

Main stem sites in the Miramichi River would be expected to meet the warm temperature thresholds sooner in the year and more often than the sites in the upper portion of that river. Few locations in the Restigouche River would be expected to exceed the 20ºC T_{min} threshold in any given year.

The management performance of the proposed opening and closing triggers was assessed by retrospective evaluation of the number of closures and the duration of the closures over the 1992 to 2011 period. Based on the temperature data from the Little Southwest Miramichi River monitoring site, there would have been at least one closure in 14 of 19 years between 1992 and 2011 and the number of closures annually would have ranged from one to five. The total number of days closed ranged from a low of 2 days in 1993 to a high of 23 days in 1999 and 2010. Another criterion for evaluating the proposed decision rules could consider the number of interventions and the duration within and between interventions if frequency of closures and duration are factors of interest. Management options can be assessed retrospectively to determine which ones best fit the desired objectives.

Impacts of angling during warm water events were considered as the mortality rate from catch and release angling increases sharply at temperatures above 20ºC. Other human activities can displace fish and contribute to stress on Atlantic salmon during warm water events including wading in streams, swimming in pools, boat traffic, as well as scientific activities.

SOURCES OF INFORMATION

This Science Advisory Report is from the Fisheries and Oceans Canada, Canadian Science Advisory Secretariat, regional peer review meeting of March 15, 2012 on the development of Environmental Thresholds to Define Management Strategies for Atlantic Salmon Fisheries under Environmentally Stressful Conditions. Additional publications from this process will be posted as they become available on the DFO Science Advisory Schedule at http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

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