An analysis of water temperatures on the Rainy River in relation to critical fish spawning periods, with recommendations on peaking restrictions

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1 Introduction

The Rainy River is a large international river that drains a vast area of Minnesota and Ontario (Figure 1). The river begins at Rainy Lake where a dam is in place to control the outflow. The operation of two hydropower facilities that exist at this site (H2O Power in Ontario and Boise Inc. in Minnesota) affect downstream water levels and flows.

Water levels and flow rates on the Rainy River have been a concern of the Minnesota Department of Natural Resources (DNR) and the Ontario Ministry of Natural Resources and Forestry (MNRF) since the mid-1980s. At that time, a study of lake sturgeon revealed that flow conditions were such that fish were unable to access their spawning habitat and some sites were completely dewatered. In response to this and concerns voiced at public meetings, a group named the 'Peaking Committee' was established in 2002 by the International Rainy Lake Board of Control (IRLBC) and the International Rainy River Water Pollution Board (IRRWPB). The mandate of this committee was to examine the environmental effects of peaking on the aquatic resources and habitat of the Rainy River and propose solutions.

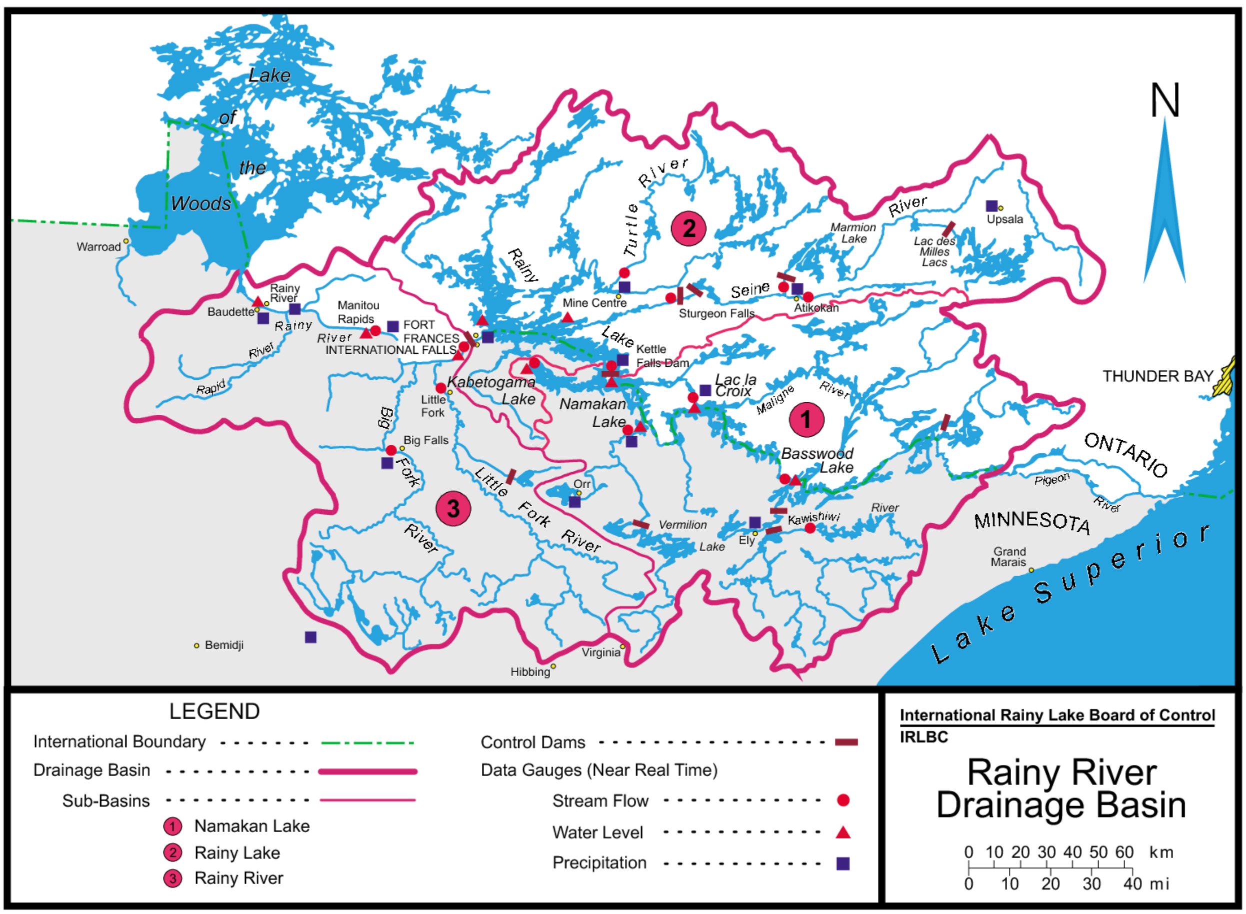

Figure 1. Map of Rainy River basin illustrating major drainage systems within the Rainy River basin.

The Peaking Committee suggested that no peaking should occur during the spring fish-spawning season, which would be the time period from April 15 to June 30 under typical conditions (IJC 2005). This position was supported by the Boards, although they suggested that the actual period during which peaking is restricted should be verified by updated field observations (IRLBC/IRRWPB 2005).

In this report, this issue is reexamined to determine an alternative to simple date restrictions to peaking operations by hydropower facilities on the Rainy River. To accomplish this, a review was made of the critical spawning periods for walleye and lake sturgeon, two species of particular concern within this system. Water temperature data collected at different monitoring stations were then examined to determine temporal and spatial trends at different reaches in the river. Air temperature surrogates and the cumulative temperature unit concept were examined for their efficacy in this endeavor. Lastly, a scientifically defensible alternative to date restrictions for peaking operations is proposed.

1.1 Impacts of hydropower water usage on fish reproduction

Generally, there are two basic operating regimes at hydroelectric facilities: "run-of-river" and "peaking". A run-of-the-river operation is based on constant flows through the facility that are equivalent to natural flows being received from upstream. Little or no storage of water is involved in this type of operation. In contrast, a peaking operation is one in which water is stored in the reservoir for a period of time and then spilled through the turbines to produce electricity when the demand is the highest. This results in a dramatic reduction in downstream flows for a period of many hours, which has often been attributed to lowered biological diversity downstream of these sites (Cushman 1985). Hydropower operations at Fort Frances - International Falls have employed peaking operations for many years.

Altered hydrologic regimes associated with impoundment operations have been identified as a leading threat to imperiled fish fauna (Richter et al. 1997; World Wildlife Fund 2009). Cushman (1985), Stokes et al. (1999), and Steele and Smokorowski (2000) provide reviews of this issue. In particular, disruption of flows during the spawning period has been found to have negative effects on recruitment, size structure and health of spring spawning populations, notably for lake sturgeon and walleye (Auer 1996).

For lake sturgeon, water temperatures and discharge initiate the spawning movement, with a gradual warming and increase in discharge preferred (Koroshko 1972; Kempinger 1988). The amount and quality of spawning habitat (depth, velocity, and substrate) are largely a function of discharge, and the continued suitability of habitat for developing eggs is heavily influenced by the rate of change of discharge (Koroshko 1972). The alteration of flows outside of natural variability has a pronounced impact on sturgeon as constant water flows trigger reproductive cues and allow large fish to migrate upstream (Auer 1994, 1996). Nocturnal flows are also required to ensure the downstream drift of sturgeon larvae, which occurs predominantly at night.

In addition to lake sturgeon, other species of interest use shallow riffles and shoreline substrate to spawn. In the Rainy River, these include walleye, sauger, smallmouth bass, and northern pike. Dewatering of these areas could lead to the stranding of eggs and affect the reproductive success of these species as well.

The relationship between discharge and habitat was studied at two sites on the Rainy River (IJC 2005). Physical habitat data were examined at Manitou Rapids and Long Sault Rapids, two of the primary riffle/rapid areas along the Rainy River (O'Shea 2005). A 10% fluctuation in the daily mean flow was found to reduce habitat by approximately 10% for mussel species and spawning lake sturgeon. Walleye spawning appeared to be much more sensitive to flow fluctuations than other species. At the 10% fluctuation of daily flows, approximately 25% of their available habitat is lost; this could be increased to 71% of available habitat if daily flows fluctuated by 30% (IJC 2005).

Such loss of habitat could have severe repercussions for the fisheries not only on Rainy River, but also on Lake of the Woods. Long Sault Rapids supports a large spawning population of walleye and tag returns indicate that almost all of these fish spend the rest of the year in Lake of the Woods (DNR 2014). Similarly, Rusak and Mosindy (1997) found that all lake sturgeon tagged in Lake of the Woods moved into the Rainy River to spawn, with the International Falls dam site being a preferred location. Loss of production of these stocks could have considerably social and economic costs to the Lake of the Woods fishery.

2 Critical reproductive periods for walleye and lake sturgeon

2.1 Walleye

Across their range, walleye spawn in lakes, rivers, and small tributaries in the spring (April-June), just after ice-out, at temperatures ranging between 4.0 - 11.1 ^{o}C (Scott and Crossman 1973; Kerr et al. 1997; Lyttle 2008; Bozek et al. 2011). Spawning temperatures can be quite variable, as walleye are known to delay spawning in years with early, warm springs and advance spawning in years with late, cold springs (Hokanson 1977; Summerfelt et al. 2011). In Lac la Ronge, Saskatchewan, it was found that walleye spawned at colder temperatures (3.3 - 7.2 $^{\circ}$C) when spawning was delayed by cold weather, and at higher temperatures (7.2 - 11.1 $^{\circ}$C) in years when there was an early spring (Rawson 1957).

A recent study of food webs and critical spawning habitat in the upper Rainy River was carried out during 2012-2013 by Smith (2014) (Figure 2). She found that walleye spawning occurred at temperatures ranging from 2.0 to 9.7 $^{\circ}$C (Figure 3), with eggs found from mid-April to mid-May in 2012 and throughout May in 2013.

Figure 2. Location of the spawning study in the upper Rainy River. Cross-sections 1-3 and 4-6 denote lake sturgeon spawning locations. Cross-sections 1-3, 15-17 and 18-19 denote walleye spawning locations. (Smith 2014).

Serendipitously, the years of 2012 and 2013 demonstrated great contrast in early spring warming. In the spring of 2012, record warm temperatures were enjoyed in this part of the continent, resulting in extremely early ice-out in Rainy Lake and other upstream lakes. In contrast, 2013 experienced an extended period of cold winter weather, and ice-out on area lakes and streams occurred weeks later than the previous year.

In the warm spring of 2012, Smith (2014) observed walleye spawning in the Rainy River as early as April 11 at water temperatures of 4 $^{\circ}$C and continuing until temperatures reached 10 $^{\circ}$C on May 8. In contrast, in 2013 spawning did not begin until May 3 (2 $^{\circ}$C) and continued until May 26 (9 $^{\circ}$C). Walleye were also observed to spawn at a late date and at colder than normal temperatures in other locations in northwestern Ontario which experienced this cold spring weather. For example, in 2013 in the Namewaminikan River on the east side of Lake Nipigon, walleye spawning occurred from May 11 - 18 with water temperatures ranging from 3 – 6 $^{\circ}$C (Marshall 2013).

The time required for walleye hatch is dependent on accumulated thermal units (TU), which are the sum of the mean daily water temperatures above 0 $^{\circ}$C (Leitritz and Lewis 1976; Bozek et al. 2011). The incubation interval is typically 21 days, although this can range from 12 - 31 days post-spawn, depending on water temperature (Summerfelt et al. 2011). The newly hatched larvae then concentrate near the bottom for approximately 3 - 5 days prior to downstream dispersal (Scott and Crossman 1973; Kerr et al. 1997; Bozek et al. 2011).

In the Rainy River, Smith (2014) reported the first instance of walleye larval drift to occur in mid-May in 2012, while this did not happen until mid-June in 2013. Eggs were found to remain at the spawning sites for approximately 29 days in 2012, with water temperatures ranging from 4-10 ˚C, and 39 days in 2013, with water temperatures ranging from 2-14 ˚C (Smith 2014). The downstream drift of fry may not have been complete for another 4-5 days, at which time temperatures would have climbed to about 16 ˚C.

Based on these two contrasting years of study, it can be then be concluded that in the upper reaches of Rainy River the critical reproductive period for walleye encompasses water temperatures ranging from 2 -16 ˚C.

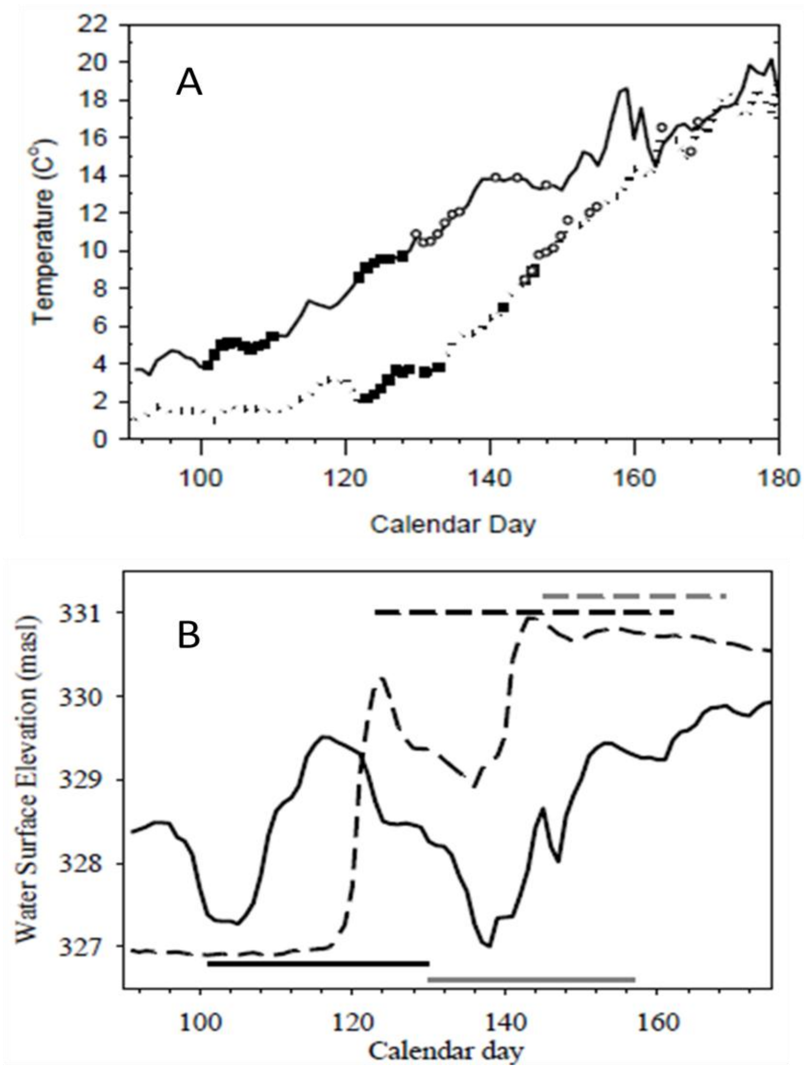

Figure 3. A) Instances of walleye spawning (black squares) and lake sturgeon spawning (white circles) in relation to Julian date and water temperatures for 2012 (solid line) and 2013 (dotted line) in the upper Rainy River. B) Periods where walleye adults, eggs or larvae were present at spawning sites are indicated in black for 2012 (solid) and 2013 (dashed) while lake sturgeon is indicated by grey lines for 2012 (solid) and 2013 (dashed). Water surface elevations are also illustrated for 2012 (solid line) and 2013 (dotted line) (Smith 2014). [Note: A conversion table for Julian day is provided in Appendix 1]

2.2 Lake Sturgeon

Lake sturgeon is the largest fish found in both Ontario and Minnesota waters. They are an old-lived fish and their mean age at maturity in this area is greater than that of humans, at 16.8 years for males and 25.8 years for females (Mosindy and Rusak 1991). In the Rainy River, populations were devastated by overharvesting for meat and caviar during the late 1800s and early 1900s. Following this, pollution from pulp and paper mills at International Falls and Fort Frances, in addition to municipal discharges during the late 1800s to mid-1900s, caused water quality and nursing and spawning habitats in the Rainy River to deteriorate drastically.

Since the passage of the US Clean Water Act in 1972 and Canada's Fisheries Act revisions of 1976, along with subsequent legislation in Ontario involving limits on lake sturgeon harvest, water quality in the Rainy River has improved and sturgeon recovery has been slow and gradual (Mosindy and Rusak 1991; Stewig 2005). Today, in Minnesota lake sturgeon are listed as a species of special concern and in Ontario as a threatened species under the Ontario Endangered Species Act.

There are currently at least two discrete populations of sturgeon in Lake of the Woods and the Rainy River: one that remains within the lake and the other that migrates to the river in the winter months (Rusak and Mosindy 1997). These two populations use the same spawning grounds located at Long Sault Rapids, Manitou Rapids, just below International Falls on the Rainy River, and additional sites upstream on major tributaries such as the Big and Little Fork Rivers in Minnesota (Rusak & Mosindy 1997).

Lake sturgeon spawn in late spring-early summer with the onset of spawning cued by thermal conditions, although photoperiod may also have an influence (Cech and Doroshov 2004). Water temperatures are usually between 11.5 – 16 ^{o}C during peak spawn (Bruch and Binkowski 2002), but this can vary considerably. For example, at the well-studied Pointe du Bois GS spawning location on the Winnipeg River (which warms slowly due to its large volume), the primary spawning period typically occurs at water temperatures of 9.5 – 11 °C during late May to mid June; however, spawning behaviour has been observed to commence as early as 8 °C and continue until 13 °C in some years (Gillespie and MacDonell 2013). At the much smaller Weir River (lower Nelson River tributary which tends to warm quickly due to its small volume), spawning has been observed over a wider temperature range (8 – 18 °C) during early to mid-June (Ambrose et al. 2008). The rate of water temperature increase prior to spawning appears to influence the actual temperature that spawning begins (Bruch and Binkowski 2002).

In the Rainy River, lake sturgeon spawning has been observed over a wide range of temperatures and dates; from as low as 9 $^{\circ}$C and as high of 17.7 $^{\circ}$C, and as early as April 28th to as late as the first week of June (Table 1). The sequence of first spawning in Rainy River generally follows an upstream movement of activity. Spawning is initiated first at Long Sault Rapids, followed by Manitou Rapids, and lastly at the Fort Frances/International Falls dam (Van den Broeck 2007).

In 2007, Van den Broeck (2007) observed lake sturgeon spawning in the upper Rainy River over a four day period, from May 16 to May 19, under stable flow conditions and at temperatures of 12.6 $^{\circ}$C to 13.4

˚C. In her more recent study of critical spawning habitat at the same location, Smith (2014) found that spawning occurred at temperatures ranging from 8.5 - 16.5 ˚C, with eggs found from mid to late May in 2012 and late May to mid-June in 2013 (Figure 3). In the very warm spring of 2012, spawning began early (May 10 - 29) and took place within a relatively narrow temperature window (10.0 - 14.0 ˚C). The much colder year of 2013 experienced a later and longer spawning period (May 26 - June 19) over a wider temperature range (8.2 - 16.9 ˚C).

Table 1. Water temperatures and dates associated with lake sturgeon spawning at various Rainy River sites, from observations and anecdotal accounts (Van den Broeck 2007)

ID#	YEAR	DATA TYPE	LOCATION	TEMPERTURE	DATE	SOURCE
T1	1988	Telemetry	Long Sault Rapids	13.5	May 3-5	Mosindy and Rusak 1991
T2	1989	Telemetry	Long Sault Rapids	13 °C	May 14-16	Mosindy and Rusak 1991
T3	1990	Telemetry	Long Sault Rapids	11 to 13 °C & 13-14 °C	June 1-3	Mosindy and Rusak 1991
OS1	1997	Observed Spawning	Fort Frances Dam	9 to 10°C*	May 24	resident/MNR
OS2	2000	Observed Spawning	Fort Frances Dam	13.9 °C*	May 19 -20	ACCC
OS3	2004	Observed Spawning	Sturgeon River	12.7-13.3 °C	May 19 -24	DNR/MNR
OS4	2005	Observed Spawning	Sturgeon River	17.7°C	Jun 1-3	DNR/MNR
OS5	2005	Reported Spawning	Rapid River	12.2 -15 °C	May 2-9	DNR
OS6	2005	Reported Spawning	Little Fork River	unknown	May 7-8	Resident/DNR
OS7	2006	Observed Spawning	Little Fork River	12.7 °C	April 28	Burri, 2006
RS8	2006	Reported Spawning	Fort Frances Dam	12 to 13°C	May 17-23	ACCC/MNR
OS9	2006	Observed Spawning	Sturgeon River	12.8°C	Apr 28	DNR
OS10	2006	Observed Spawning	Off site near Emo	15.6°C	May 26 -27	MNR
OS11	2007	Observed Spawning	Little Fork River	12 to 13°C	Apr 30- May 1	Resident/DNR
SS12	2007	Observed Spawning	Little Fork River	17°C	May 9-11	Resident/DNR
RS13	2007	Observed Spawning	Long Sault Rapids	unknown	May 3	RRFN
SS14	2007	Suspected Spawning	Fort Frances Dam	12.6-13.4 °C	May 15 May 17 -19th	DNR(SS) ACCC(RS)
SS15	2007	Suspected Spawn	Rapid River	13.5 °C	May 30	DNR
RS16	2007	Reported Spawning	Manitou Rapids	16 °C	May 7	RRFN

* Treatment plant data

Lake sturgeon can have two separate spawning events during a season, which is believed to be primarily influenced by water temperature (Kempinger 1988; Bruch and Binkowski 2002). This spawning behaviour has been documented in several locations including the Kaministiquia River where spawning occurs at temperatures of approximately 13 ˚ C (usually the last week in May) and then again at 16 ˚ C (Friday 2004, 2005, 2014). Bruch and Binkowski (2002) noted that sudden declines in water temperatures after the onset of spawning activity can result in this second, delayed spawning run. Smith (2014) provided evidence that this may have occurred in 2013 in the Rainy River. Initial spawning occurred in late May (8.0 - 12.0 ˚C) followed by a second spawning event approximately 10 days later in

June (15.0 - 16.0 ˚C). This coincided with a cooling period and a rapid drop in water temperature from about 18.5 ˚C to 14.0 ˚C.

Following spawn, lake sturgeon eggs incubate for approximately 5 to 14 days depending on water temperature (Scott and Crossman 1973; Kempinger 1988; Smith 2003; Johnson et al. 2006). Once their yolk sac is absorbed larval sturgeon emerge and begin a “swim-up” phase where they drift downstream in congregations with the current. Downstream drift occurs predominantly at night (D’Amours et al. 2001), between 1000 hours and 0100 hours, and is often associated with a minimum water temperature of 16 ˚C (Smith and King 2005; Peterson et al. 2007). Depending upon the length of interval between separate spawning episodes, there can be more than one larval drift period (Auer and Baker 2002).

In the Rainy River, Smith (2014) reported the first instances of lake sturgeon drift to occur in early June in 2012 and mid-June in 2013, with eggs remaining at the spawning sites for approximately 27 days in 2012, with water temperatures ranging from 10 – 15 ˚C, and 24 days in 2013, with water temperatures ranging from 8 - 17 ˚C. Friday (2014) found that in the Kaministiquia River larval drift took an average of 37 days to complete, measured from the date of first spawning. Applying this to the Rainy River, in 2012 downstream drift would have continued until about June 17, when water temperatures were at 16 ˚C. Because of the later spawning start date in 2013, in that year drift would have continued until about July 2 with water temperatures at 21 ˚C. Friday (2014) recommends that cumulative temperature units be used as a tool to predict these key dates.

Based on these two contrasting years of study, it can then be concluded that in the Rainy River the critical reproductive period for lake sturgeon encompasses water temperatures ranging from at least 8 – 21 ˚C.

3 Water temperature measurements

3.1 Water temperature monitoring stations

The monitoring of water temperature in the Rainy River has been a collaborative effort. A number of monitoring stations have come on-stream over the past few years, with their operation and maintenance the responsibility of different companies or agencies (Table 2).

There are three primary monitoring sites on the river (Figure 4). The first of these is at the tailrace of the H2O Power generating station immediately below the dam at Fort Frances/International Falls, with the sensor measuring near surface water temperatures. An additional station exists at this site in the headwater above the generating station operated by Boise Inc. Together, these stations have provided a continuous data stream that has been available to us since June 23, 2009.

The second site is at Manitou Rapids, 57 km downstream from the dam. This site is maintained by the US Geological Survey and our records also go back to June 23, 2009. The sensor measures temperatures at about 1 m depth. The third monitoring station is located at the town of Rainy River opposite Baudette

(Minnesota), 112 km downstream from the dam. This site was established August 1, 2010 by the Water Survey of Canada (WSC). The sensor is anchored to the bottom at a depth of 2.4 m, as measured on July 21, 2014. A complete series of water temperature values is available from the three primary monitoring stations for the years 2011-2014.

Two additional monitoring stations have recently been established by the US Geological Survey. One of these is at the International Falls boat launch 4 km below the dam. The other is near the outflow of the Rainy River into Lake of the Woods at Wheeler's Point, 131 km below the dam. These sites did not come on-stream until May 2014, so are of limited use for this analysis.

Table 2. Water temperature monitoring stations in the Rainy River.

Station Name	Proponent	Start Date of Data series	Distance Downstream from Dam (km)	Latitude	Longitude	Specific Location
Int'l Falls PH	Boise Inc.	23/06/2009	0.00	48°36'29"N	93°24'17"W	Headwater above dam at generating station, just below surface
Fort Frances Tailwater	H2O Power	17/02/2011	0.00	48°36'32"N	93°24'09"W	Tailrace of generating station, at 1.2 m depth
RR BL Blw IF	USGS	15/05/2014	3.94	48°35'32"N	93°26'48"W	Out from boat launch, anchored at bottom ~3.0 m deep
Manitou Rapids	USGS	23/06/2009	56.79	48°38'04"N	93°54'47"W	Along south bank ~6.0 m from shore and ~1.0 m deep
Rainy River / Baudette	WSC	01/08/2010	112.43	48°43'00"N	94°34'05"W	Along north bank ~10.0 m from shore and ~2.4 m deep
Wheeler's Point	USGS	21/05/2014	131.35	48°50'13"N	94°41'57"W	Along south bank ~6.0 m from shore and ~1.5 m deep

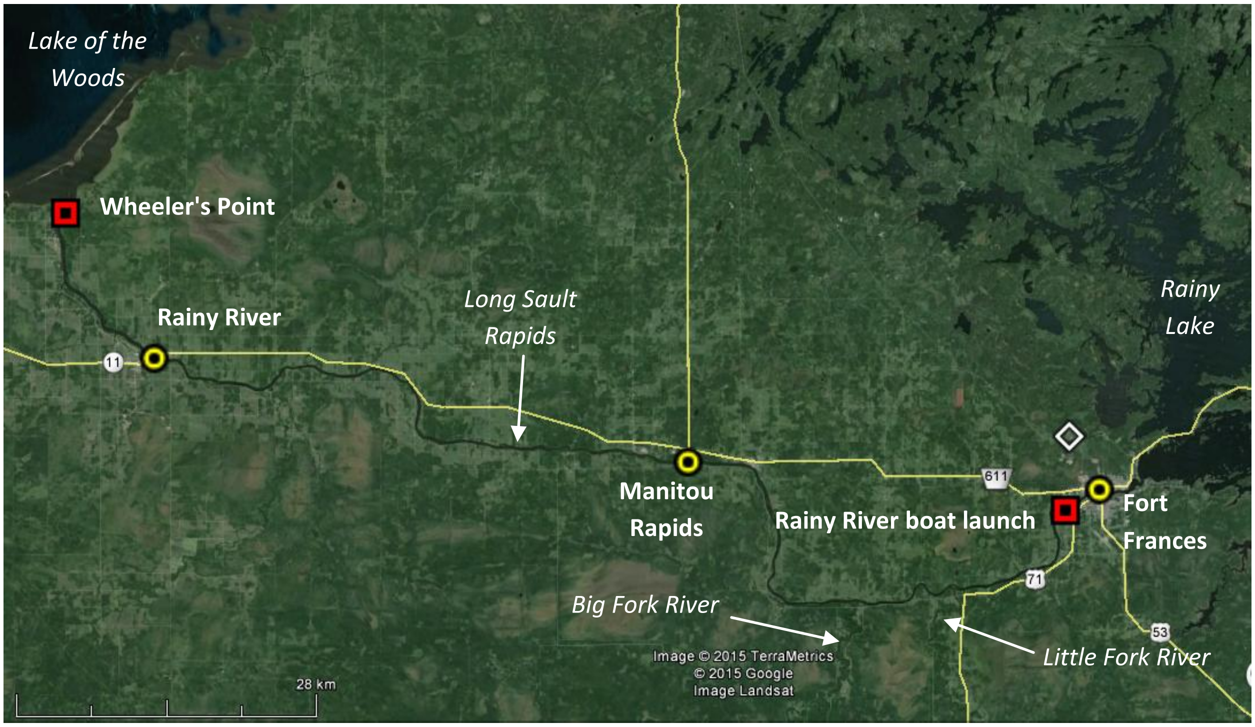

Figure 4. The location of the water temperature monitoring stations within the Rainy River. The yellow dots indicate the three primary stations: Fort Frances tailwater (also the location of the International Falls powerhouse), Manitou Rapids, and town of Rainy River. Two addition stations have recently been added: below the boat launch at International Falls and at Wheeler's Point (red squares). The white triangle indicates the location of the weather station at the Fort Frances airport.

3.2 Spatial and temporal trends in water temperature

The Rainy River experiences a lengthy period of partial ice cover, with water temperatures at about 0.5 ˚C for approximately 115 days of the year. Temperatures begin to rise above 1 ˚C during the third week of March in typical years, while the decline back to near zero temperatures occurs during the last week of November (Figure 5). Temperatures reach their maximum in July and August, with water temperatures normally exceeding 20 ˚C during this period and occasional days experiencing 25 ˚C or higher.

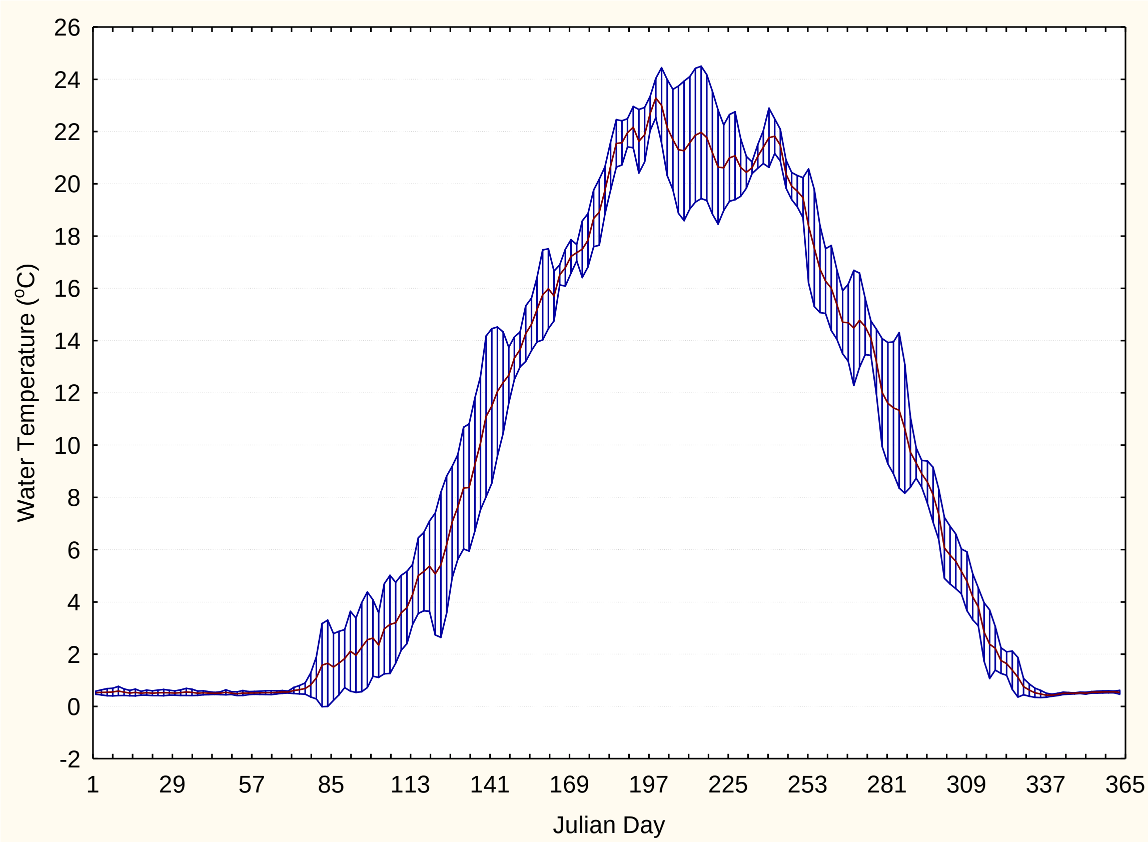

Figure 5. Mean annual water temperature for the period of 2011-2014, averaged across the three monitoring stations. The outer envelope represents the 95% confidence interval of values.

There is a notable difference in spring-early summer warming at the three monitoring stations (Figure 6; 7). The first sign of spring warming is evident at the downstream site of Rainy River/Baudette which towards the last week in March usually becomes ice-free with water temperatures rising above 2 °C. Temperatures then drop briefly by month end as cold water descends from upstream reaches that experience a later spring melt. The upper river site (Fort Frances tailwater) is consistently the coldest portion of the river through the spring-summer period. This is as expected, as locations immediately below reservoirs frequently experience colder temperatures than normally found downstream (Palmer and O'Keefe 1989). Additionally, the significant inflows from the warmer Big Fork and Little Fork rivers (Figure 1; 4) and other tributaries would moderate the temperature at downstream locations during this early period. By mid July, temperatures have reached their peak, with no detectable differences between sites.

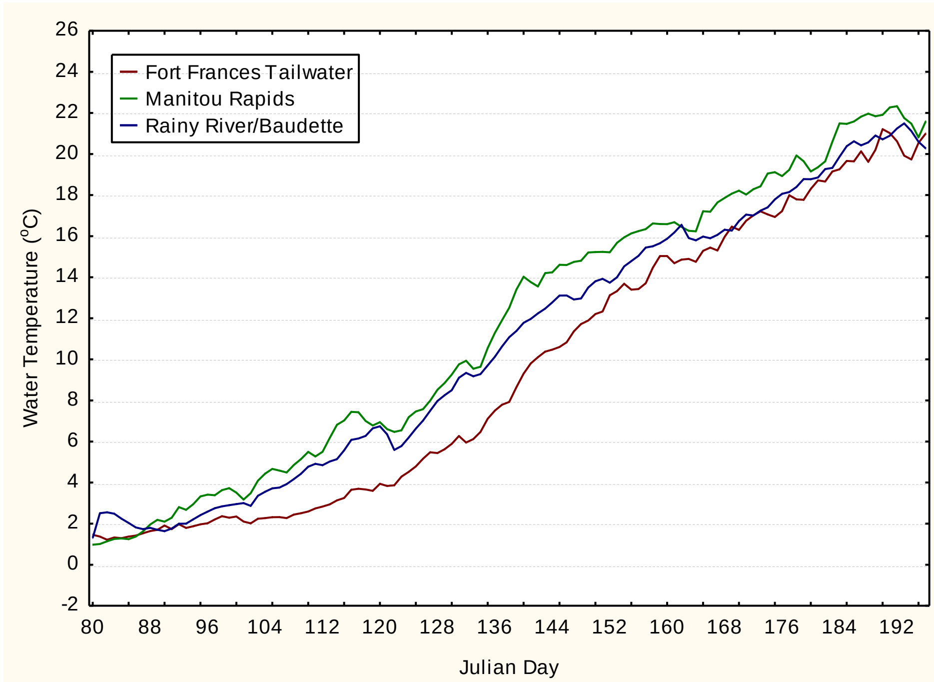

Figure 6. Patterns of change in mean water temperature at the three monitoring sites during the period of spring-early summer warming (2011-2014).

Manitou Rapids experiences slightly warmer but much more variable temperatures than Rainy River through most of the early season (Figure 6;Figure 7). This contrasts with the findings of Van den Broeck (2007) where water temperatures at Emo, located slightly upstream of Manitou Rapids, were consistently lower than Rainy River/Baudette throughout this period. The water temperature data in his study was obtained at the intakes of water treatment plants. The location of the temperature sensors at the currently used monitoring sites may have some bearing on this, as the sensor at Manitou Rapids is situated at a shallower depth (~1.0 m) than the one at Rainy River/Baudette (~2.4 m).

Spring warming through the period of April 1 to June 30 can be modeled through linear regression as follows:

MDWT = -19.7501 + 0.2173 * Julian Day; R^2 = 0.8754, F (1,343) = 2416.9, p <0.001

where MDWT is mean daily water temperature, averaged across the three monitoring sites for the years 2011-2014. This model explains 87.6% of the variance in water temperature. It predicts an average daily increase in water temperature of 0.217 $^{\circ}$C throughout this three month period.

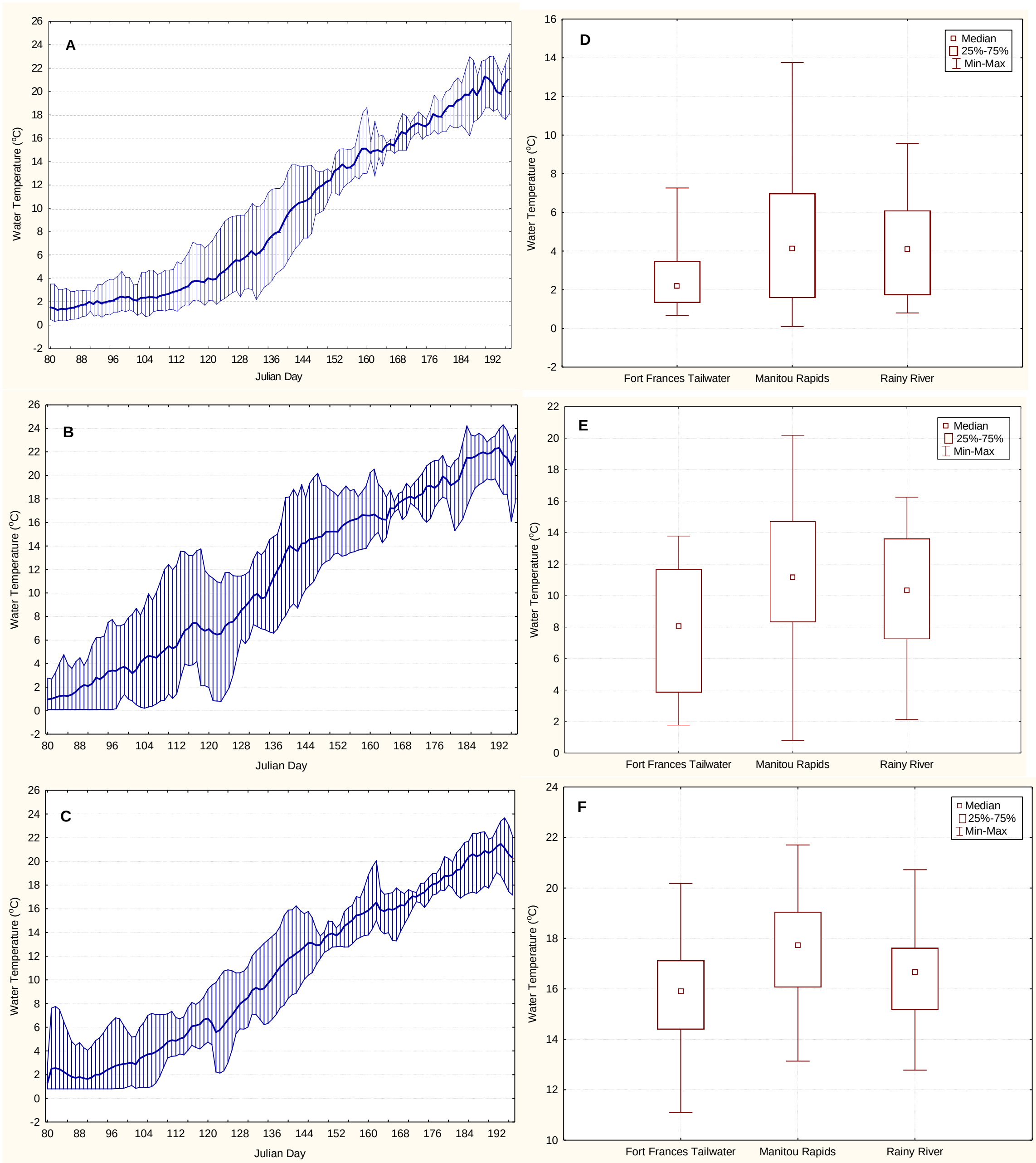

Figure 7. Graphs on the left illustrate variance in spring-early summer water temperatures at A) Fort Frances tailwater, B) Manitou Rapids, and C) Rainy River/Baudette. Mean temperature at each site for 2011-2014 is indicated by the solid line, while the vertical bars indicate the range of values observed. The box plots on the right reveal differences between these sites specific to the months of D) April, E) May, and F) June.

3.3 Air-water temperature relationships

Air and water temperatures are always highly correlated because of the joint dependence of these two variables on solar radiation. As such, simple linear regression models are often applied for predicting or simulating water temperature from air temperate data at daily, weekly, or longer time steps (Smith 1981; Crisp and Howson 1982; Mackey and Berrie 1991). The relationship between the two becomes stronger as the time interval of the data increases from hourly to daily to weekly means (Stephan and Preud'homme 1993; Webb et al. 2003; Benyahya et al. 2007).

Webb et al. (2003) found that the sensitivity and explanatory power of these models improved by incorporation of a lag, which increased with catchment size. They also showed that water temperature was inversely related to discharge for all catchments and time-scales. Similarly, Stephan and Preud'homme (1993) demonstrated that water temperatures responded to air temperatures with time lags ranging from a few hours for small streams to seven days for large rivers up to five meters in depth. The greatest improvement in the standard error of prediction was from 4.42 °C to 3.96 °C when a 5-day time lag was included for the longest river they investigated (Mississippi River). The study also found that the correlations became markedly better when weekly average temperatures were used instead of daily values.

Pilgrim et al. (1995) performed simple regression analysis of air and water temperature for 43 Minnesota streams, one of which was the Rainy River. Water temperature records were collected from 1980 - 1983 at Manitou Rapids, while air temperature measurements were obtained from Babbitt, MN, about 230 km distance. They found that at the Manitou Rapids site, air temperature explained 72.2 % of the variation in water temperature at the daily scale of measurement, 87.0 % at the weekly scale, and 94.7 % at the monthly scale. Time lags were not incorporated into their calculations.

As part of the current study, air-water temperature relationships were re-examined for the Rainy River. Various time lags were considered, from none, to a single day, to the mean of the five previous days (Table 3). For daily data, same day air temperature explained from 61 - 77 % of the variance in water temperature at the three sites. Applied on a weekly scale, explained variance was improved to 72 – 85%. For the Manitou Rapids site that was jointly compared, these results are quite similar to the findings of Pilgrim et al. (1995).

In every instance, model precision increased for daily estimates with lengthier time lags (Table 3; Figure 8), as predicted by Stephan and Preud'homme (1993). Air temperature averaged over the previous five days explained from 77 – 87 % of the variance in water temperature at the different locations. The tightest fit was always with the Manitou Rapids site. The weakest correlations were with the upstream, coldwater site (Fort Frances tailwater).

Table 3. Correlation matrix showing relationship between air temperature (Fort Frances Airport) and water temperature at the three Rainy River sites, incorporating different periods of time lag.

Location	Daily Data						Weekly Data
	No lag	1 day lag	1-2 day lag	1-3 day lag	1-4 day lag	1-5 day lag	No lag
Fort Frances Tailwater	0.78	0.80	0.83	0.85	0.86	0.88	0.85
Manitou Rapids	0.88	0.88	0.90	0.91	0.92	0.93	0.94
Rainy River/Baudette	0.84	0.86	0.88	0.90	0.92	0.93	0.91

A better model fit between air and water temperature was found at all three Rainy River sites when data were applied on a weekly scale, as follows:

a) MWAT = 3.1436 + 0.8881*x; R^2 = 0.7301
b) MWAT = 3.1579 + 0.9564*x; R^2 = 0.8764
c) MWAT = 3.8114 + 0.8773*x; R^2 = 0.8331

where MWAT is the mean weekly air temperature and x is the mean weekly water temperature at a) Fort Frances tailwater, b) Manitou Rapids, and c) Rainy River/Baudette.

However, in all instances this metric was not sensitive enough to changes in water temperature to be of benefit as an alternative to date restrictions for peaking operations

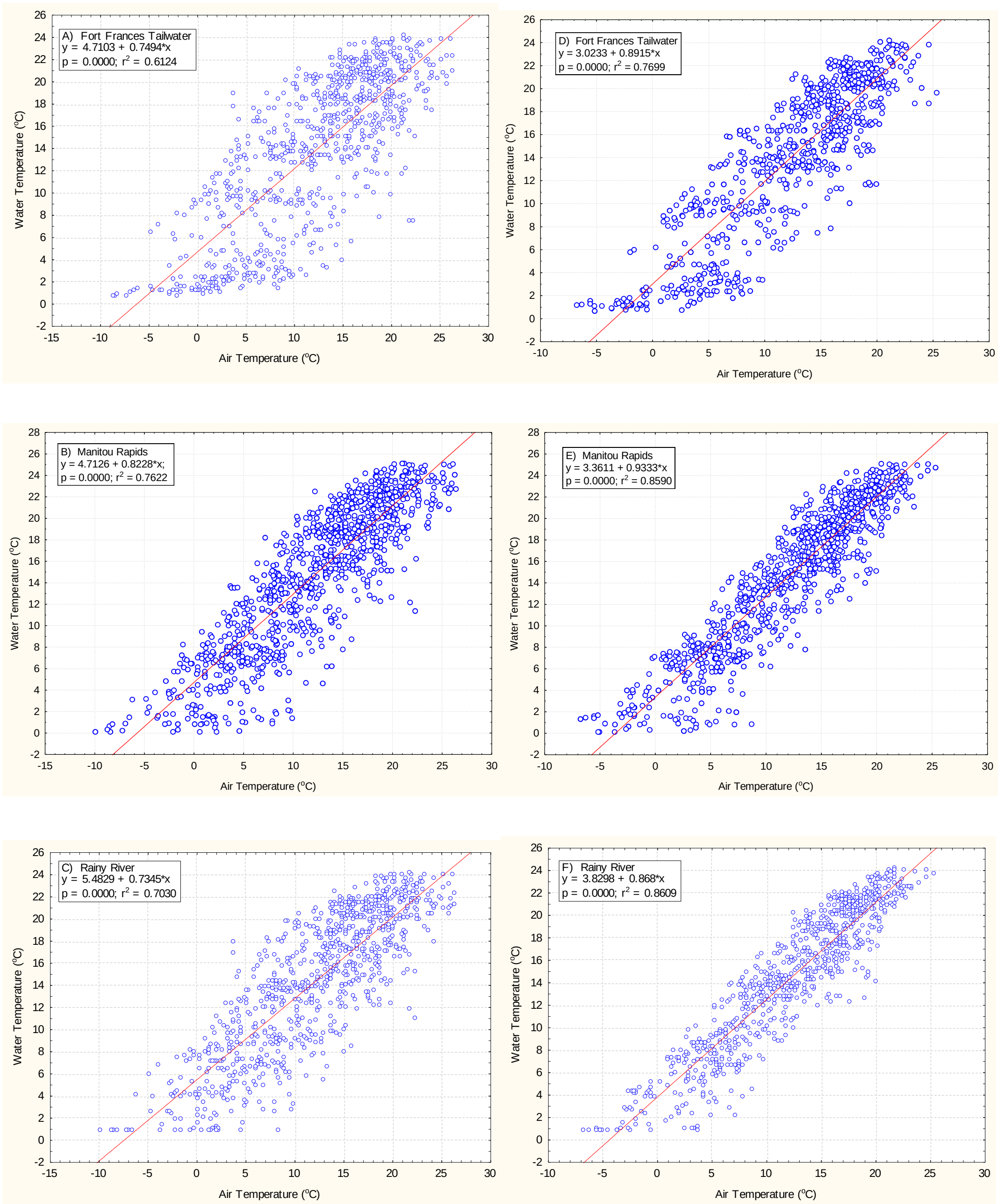

Figure 8. Daily air-water temperature relationships for A) Fort Frances tailwater, B) Manitou Rapids, and C) Rainy River/Baudette using current day data, and, respectively, with a time lag representing the previous 1-5 day mean temperature (D-F).

3.4 Cumulative temperature units

The early stages of lake sturgeon development, including egg incubation period and start and duration of larval drift are related to cumulative thermal units (CTU) (Wang et al. 1985; Kempinger 1988; Smith and King 2005). Kempinger (1988) defined this as

$$\text{CTU} = \sum_{i=1}^{n} (x_i - K)$$

where K = the constant (5.8 °C), xi = mean daily water temperature (°C) for day i calculated from real time data, and n = number of days from spawning to end of drift.

Friday (2014) quantified the relationships between CTU and various stages of lake sturgeon development in the Kaministiquia River in northwestern Ontario. At that location spawning typically occurs when water temperatures are between 11 and 13 °C. Over a ten year period of study, the start of larval drift consistently occurred at a CTU value of 150 (Figure 9). Similarly, a mean value of 400 CTU defined the end of larval drift in all but two years. In these years, a late, second spawning event occurred, which delayed the end of drift until the accumulation of about 565 CTU.

We can apply these values to predict sturgeon developmental stage in the Rainy River for the five years that water temperature data were available at the Fort Frances tailwater site (Table 4; Figure 10). The date of first spawn was arbitrarily declared as 13 °C for all years, as suggested by Friday (2014) and which was in the range of that found in 2012 and 2013 field study by Smith (2014) and reported by Van den Broeck (2007) for the Rainy River (Table 1). This reveals that in most years, the end of the critical period for lake sturgeon fry would be July 2 (400 CTU), although this could be delayed to about July 13 in occasional years in which a late, second spawning event occurred (565 CTU).

Table 4. Dates related to critical reproductive stages for lake sturgeon in the Rainy River as predicted using the CTU concept.

Year	Date of 1st Spawn (13 °C)	Start of Drift (150 CTU)	Normal End of Drift (400 CTU)	Delayed End of Drift (565 CTU)
2010	May 18	June 2	June 23	July 5
2011	May 21	June 8	July 2	July 13
2012	May 20	June 7	June 28	July 7
2013	June 8	June 23	July 11	July 21
2014	June 1	June 19	July 7	July 23

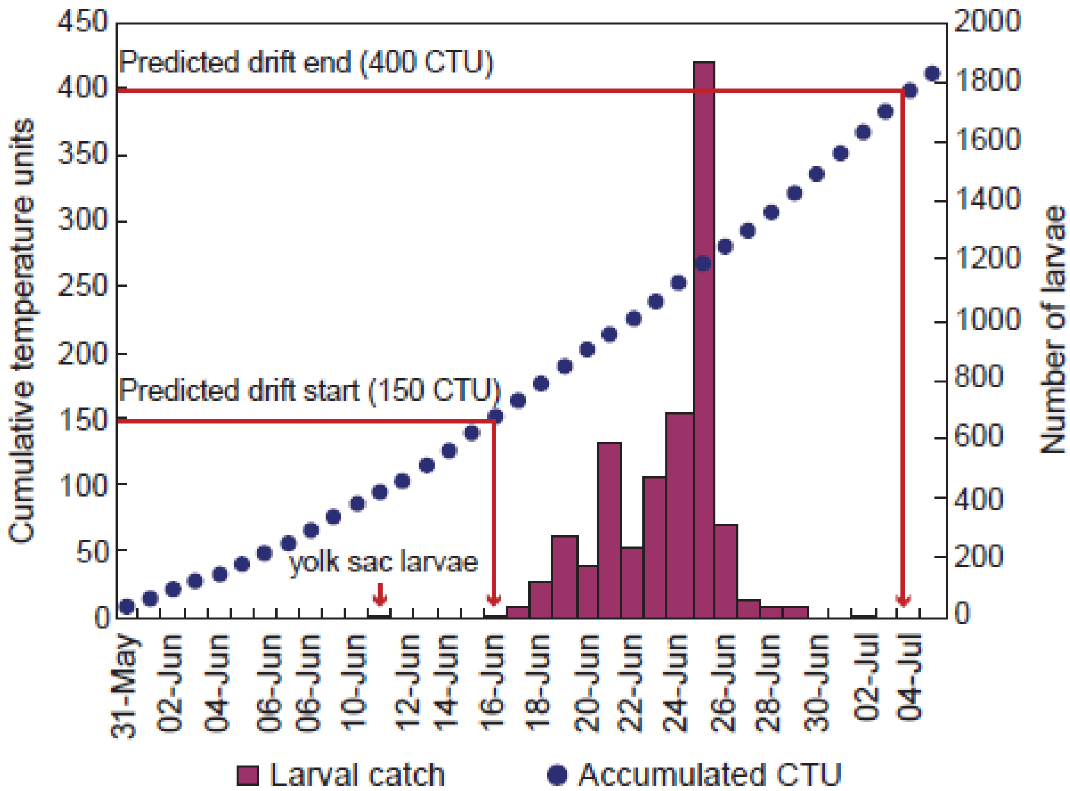

Figure 9. Relationship between CTU and lake sturgeon larval drift in the Kaministiquia River in 2013. Initial spawning occurred on May 31 (Friday 2014).

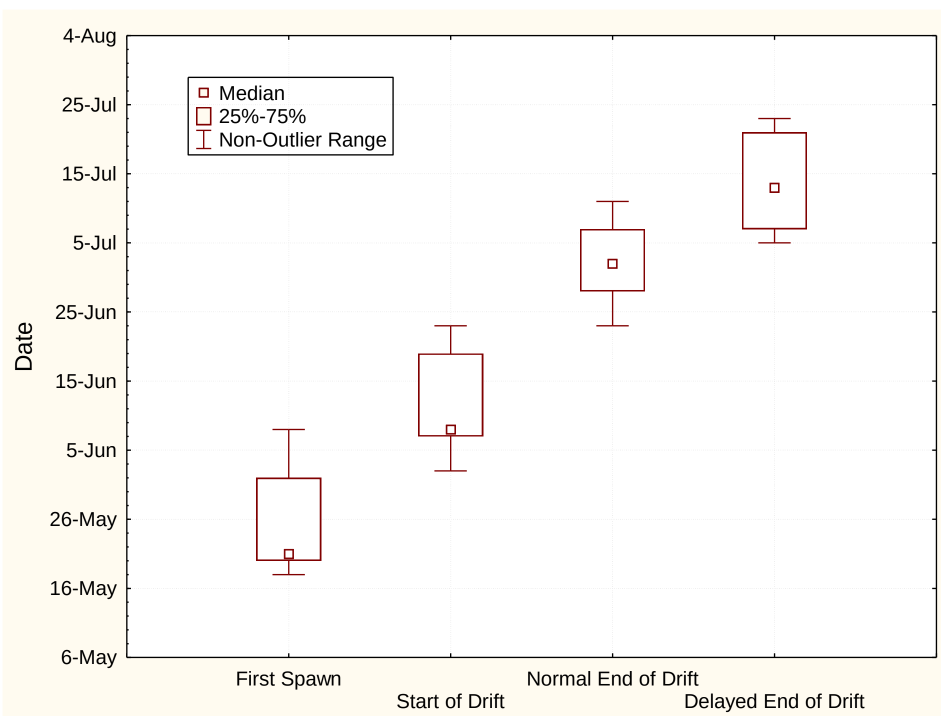

Figure 10. Median and range of dates related to lake sturgeon reproductive stages in the Rainy River (2010 – 2014), as inferred through CTUs.

4 Recommendations

As an alternative to date restrictions for peaking operations at the Fort Frances/ International Falls hydropower facilities, we suggest that a process be applied that uses water temperature data that is readily available from the monitoring stations. This would include applying cumulative temperature units (CTU) as a tool for water management planning as recommended by Friday (2014).

This would be a two stage process, as follows:

1. Initially, spring water temperatures would be monitored at Manitou Rapids as temperatures warm here more rapidly than elsewhere in the river. Restrictions to peaking operations would begin when water temperatures reached 4 ˚C which would ensure protection of walleye for the entirety of their spawning period at all points in the river. Normally, this would occur about April 12. Alternatively, temperatures in the upper river could be used as a surrogate for Manitou Rapids. If this were the case, peaking restrictions would begin when temperatures measured at Fort Frances tailwater (H2O Power) reached 2 ˚C.

2. Water temperatures would continue to be monitored in the upper river, as this is the coldest portion of the river. Once water temperature reached 13 ˚C, CTUs would be calculated daily using the formula of Kempinger (1988), as described in the previous section. Restrictions to peaking operations would be lifted when 400 CTU was reached, which would ensure the protection of larval sturgeon to the end of larval drift in normal years. Alternatively, if a higher level of protection was desired, restrictions would remain in place until 565 CTU was reached. This higher level of protection is recommended. This would provide a natural flow of water for larval sturgeon even in years when late second spawning events occurred. On average, 400 CTU would accumulate by July 2, while 565 CTU would accumulate by July 13.

This strategy should provide adequate protection for the two primary species of interest (walleye and lake sturgeon) during their reproductive phases, especially if the higher level of protection was implemented (565 CTU). If adopted, it is recommended that monitoring be carried out to judge the effectiveness of this approach, at least during the first years of operation.

Peaking operations may continue to affect other fish species whose reproductive activities are not encompassed by this timing window (e.g., lake whitefish; smallmouth bass and other centrarchids; various cyprinids) and invertebrate species within this riverine system. Research studies should be undertaken to quantify the level of impact on these species related to the manipulation of water levels and flows in the Rainy River at all times of the year.

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Appendix 1. Julian day calendar for non leap years.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365