DEPARTMENT OF NATURAL RESOURCES

Assessment of instream temperatures in Little Rock Creek near Sartell Wildlife Management Area

1/26/2021

Table of Contents

DEPARTMENT OF NATURAL RESOURCES

DEPARTMENT OF NATURAL RESOURCES

Executive Summary

Little Rock Creek is a designated trout stream that straddles the border between Morrison and Benton counties. In 2013, the Minnesota Pollution Control Agency (MPCA) listed Little Rock Creek as impaired for dissolved oxygen, nitrate, and temperature. The focus for the temperature impairment was concentrated on effects on water temperature from groundwater withdrawals and the effects that the water control structure and impoundment have on water temperatures around the Sartell Wildlife Management Area (WMA). The TMDL report suggests a combination of reductions in groundwater use and the creation of a more "free flowing system" at the WMA impoundment to minimize thermal impacts (Barr Engineering, 2015). This report investigates the available water temperature data in this study area to evaluate the suggested implementation strategies from the TMDL.

Monitoring data collected by the Minnesota Department of Natural Resources (DNR) shows that seasonal and daily water temperatures are distinctly warmer at sites that are downstream of the Sartell WMA impoundment. In the spring season, all sites vary by less than 1 degree Celsius, but as the summer progresses, temperatures differ by more than 3 degrees Celsius between sites upstream of the impoundment where water is cooler and downstream of the impoundment where water is warmer. Water temperature criteria that the MPCA used in determining the impairment for temperature continue to be exceeded at the monitoring sites downstream of the impoundment. There are also strong correlations between air temperature and water temperature at all sites evaluated in this study, indicating that weather is a primary factor in influencing water temperatures in this area. These correlations further indicate a difference between air-water relationships at sites upstream of the WMA impoundment and sites downstream of the impoundment. It is likely that differences in temperature between sites are a result of the impoundment increasing residence times in the WMA by more than 10 hours under low flow conditions and greatly increasing surface area at the impoundment, both of which result in increased solar warming in the WMA and downstream. The results from the time of travel studies and removal of the dam in 2019 show that modifying operations at the impoundment has the potential to cool water temperatures at sites downstream of the dam, but doesn't appear to totally decrease impairment criteria to levels observed upstream. It is likely that dam modifications targeted during the warmest weeks of the summer will result in decreased water temperatures at the sites downstream of the dam, but there remains a good chance that temperatures at the downstream sites will remain somewhat elevated.

1. Introduction

1.1. Background and Purpose

In this report, several hydrologic datasets are evaluated to quantify the impact that the impoundment at the Sartell Wildlife Management Area (WMA) has on the water temperatures of Little Rock Creek. The Minnesota Pollution Control Agency (MPCA) lists both Little Rock Creek and Bunker Hill Creek as impaired waters (Figure 1). One of the indicators identified in the Little Rock Creek Total Maximum Daily Load (TMDL) report is a lack of cold-water sport or commercial fish and aquatic life. The three impairments found were dissolved oxygen, nitrate, and temperature. Even though the temperature impairment is attributed to the entire trout stream as designated, the focus of the temperature impairment in the TMDL report is on monitoring sites downstream of the Sartell WMA impoundment. To address the temperature impairment, the MPCA recommends a 1% reduction in thermal loading across all thermal sources to meet temperature criteria (Barr Engineering, 2015). To achieve reduction in water temperature, the TMDL report suggests a combination of two implementation strategies: 1) reductions in groundwater use and 2) the creation of a "more free flowing system…to improve connectivity and temperature issues during critical conditions described in this report" (i.e. removing the impoundment at the Sartell WMA). An analysis of water temperature records at these locations assesses historic conditions in the study area and the differences in stream temperatures with and without the impoundment. Four time of travel studies were conducted on Little Rock Creek to quantify the differences in travel time and stream dynamics when the impoundment is in place as well as when the impoundment is removed.

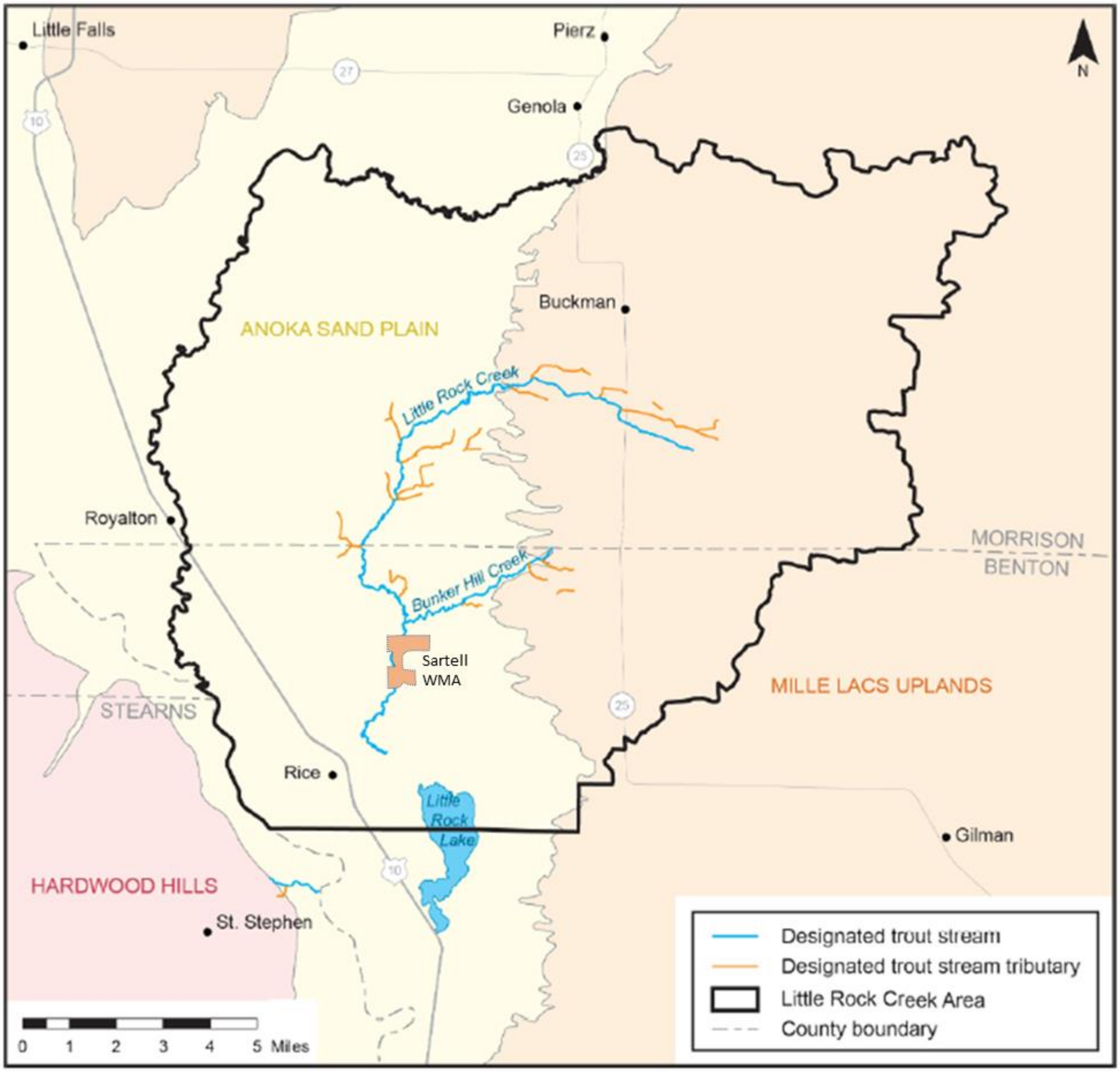

Figure 1. Study area of the Little Rock Creek watershed and Sartell WMA

1.2. Study Area

Little Rock Creek is a designated trout stream in Benton and Morrison Counties in central Minnesota (Figure 1). The creek begins in the drumlin hills south of Buckman and flows west, then south toward the town of Rice. Bunker Hill Creek is the main tributary to Little Rock Creek with several small, unnamed tributaries also contributing. Before draining into Little Rock Lake, Little Rock Creek flows through the Sartell WMA, where the creek's only impoundment is managed for waterfowl habitat. The Division of Fish and Wildlife manage the levels of this impoundment and keep thorough records of water levels and bird counts with each field visit. The control structure at the WMA was installed in 1978. It is a sheet pile dam with a 48 foot wide crest and a series of stop logs that are used to control water levels. When filled, the impoundment is a little over 20 acres in area with water depth ranging from 0.5 to 3 feet. On occasion, the impoundment is drained in an attempt to establish regrowth of vegetation.

Monitoring locations for this report are shown in Figure 2. The DNR collects continuous streamflow data at County Road 26 (CR 26), 15th Ave NW field road, County Road 40 (CR 40), and County Road 12 (CR 12). The streamflow record at 15th Ave NW field road has the longest continuous record in the watershed and is used for streamflow statistics and analyses in other reports (Minnesota Department of Natural Resources, 2020). The DNR also collects water temperature data during summer months, generally April-September, at each of the sites listed above as well as at a location just downstream of the WMA impoundment, 15th Ave NW downstream of dam. The lengths of these temperature records vary by site and are summarized in Table 1. For this report, temperature data are only analyzed near the Sartell WMA. Several of the upstream sites listed in Table 1 are not reviewed in detail in this report. Long-term weather data is collected at the Little Falls/Morrison County Airport. There is also a more recent climate record that is collected at a weather station located near Rice, MN (Minnesota Department of Agriculture, 2020).

Table 1. Period of record for water temperature monitoring collected by DNR Fisheries.

Stream	DNR Station Name	Date Ranges (seasonal monitoring generally occurs from April-September)
Little Rock Cr	CR 12	2009, 2012-2020
Little Rock Cr	15th Ave NW downstream of dam	2015-2020
Little Rock Cr	CR 40	2009-2020
Little Rock Cr	15th Ave NW field road	2015-2019
Little Rock Cr	CR 26	2007-2020
Little Rock Cr	Twp 234	2008-2020
Little Rock Cr	230th Ave	2008, 2012, 2014-2020
Bunker Hill Creek	Bunker	2017-2020

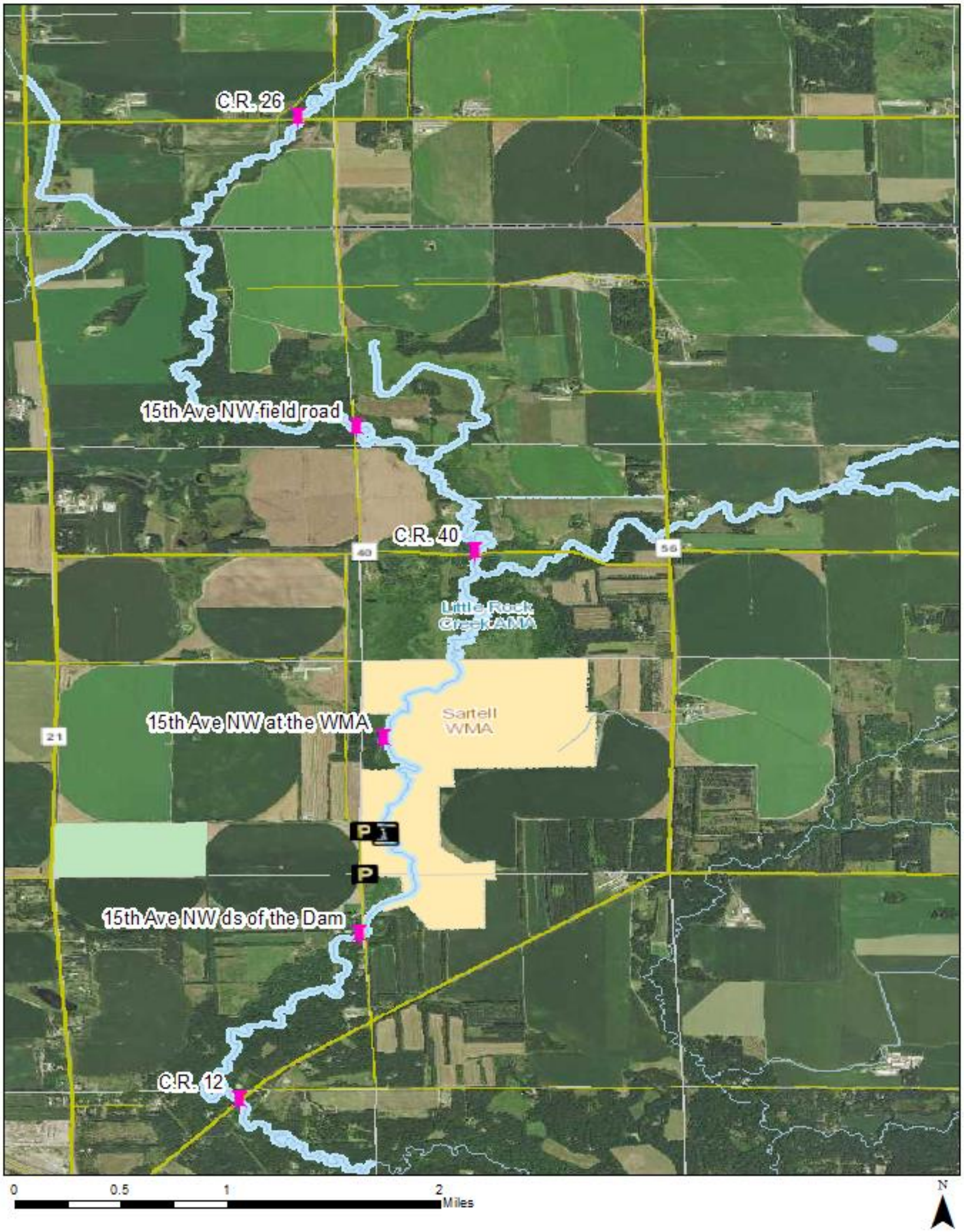

Figure 2. Site locations and names for temperature monitoring and time of travel studies.

2. Assessment of water temperature monitoring

2.1. Annual and seasonal water temperatures at study sites

An analysis of water temperature data shows that the sites downstream of the impoundment are consistently warmer than the sites upstream of the impoundment. This deviation occurs in mid-May and persists until late September. Graphs of water temperatures at three sites around the WMA for the 2019 monitoring season shown in Figures 3 and 4 demonstrate these differences in temperatures between sites upstream and downstream of the impoundment. Water temperatures in the spring start out cool as the snow melts. As the season progresses surface heating intensifies due to increased air temperatures and solar angles, which results in warmer water temperatures in the creek (Figure 3). In July, the upstream location at CR 40 is consistently cooler than the two locations downstream of the impoundment by 2-3 degrees Celsius (Figure 4). Proximity to the impoundment also affects water temperatures. Daily maximum temperatures at the site immediately downstream of the impoundment, 15th Ave NW downstream of the dam, are consistently greater than temperatures at the site at CR12 further downstream indicating that water temperatures are warmest near the impoundment.

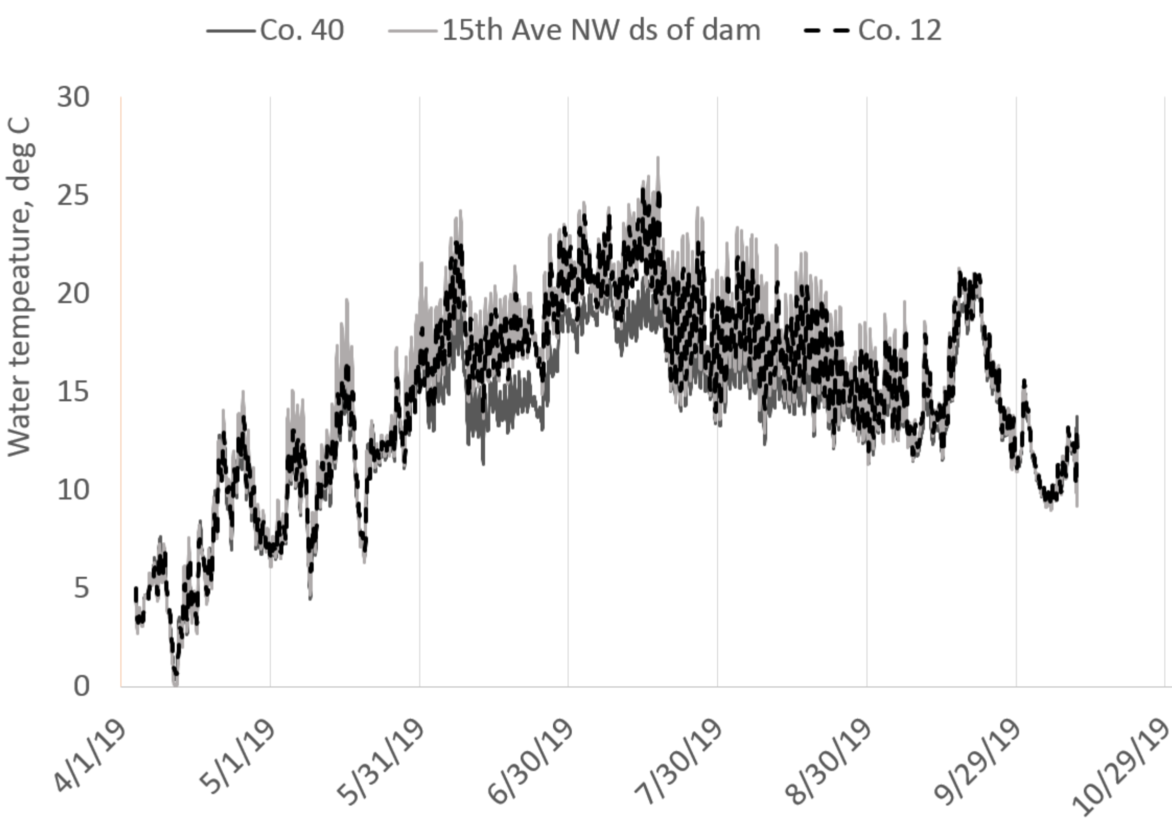

Figure 3. Observed water temperatures at three Little Rock Creek monitoring locations during 2019

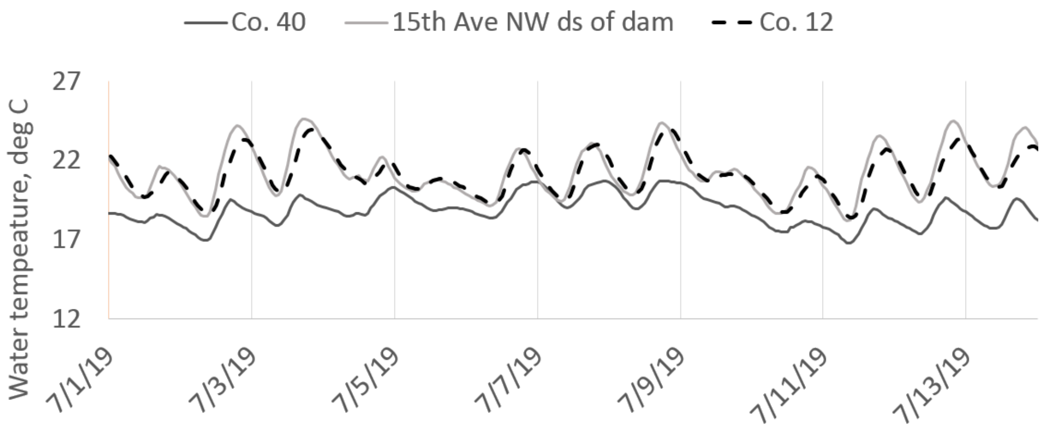

Figure 4. Observed water temperatures at three Little Rock Creek monitoring locations for two weeks in July 2019.

2.2. Differences in correlation of air and water temperature

Water temperatures in a stream are dependent on a variety of factors within the watershed and in the atmosphere. Several of the influencing factors include weather variables (air temperature, solar radiation, cloud cover, wind, humidity), channel dimensions (water depth, channel width), point discharges (drain tiles, tributaries, power plant discharges, etc.), groundwater inflow, and streambank vegetation (shade, wind protection, insulation). Of all of these parameters, air temperature, especially on weekly and monthly time scales, is a good indicator of stream temperature (Erickson et al, 2000). A linear equation that relates stream temperature with air temperature can be defined as:

$$T_w=BT_a+A.$$

where T_w and T_a are the mean stream temperature and air temperature, respectively. The constants A (degrees C) and B (dimensionless) are the fitted parameters from a linear least squares regression. The parameters A and B for each reach are impacted by the physical parameters of the watershed and weather variables. An increase in B indicates an increase in importance of air temperature as a predictor of water temperature. Groundwater inflow elevates parameter A and decreases parameter B.

Figure 5 shows the correlation between mean monthly air temperatures at the Little Falls/Morrison County Airport with the mean monthly water temperature at four monitoring locations in the study area for the period of record that is available at each site. Each of the four sites exhibit a strong correlation of water temperature and air temperature. The linear models for the sites that are upstream of the impoundment have parameters that are distinct from those models from sites that are downstream of the impoundment, most notably in the B-parameters and coefficient of determination (R^2 value) (Table 2). The two sites that are upstream of the impoundment, CR 40 and CR 26, have B parameters that are less than the two sites downstream of the impoundment, CR 12 and 15th Ave NW downstream of the dam. Linear regression analysis shows that 93% of the variation in monthly water temperature at 15th Ave NW downstream of dam is explained by changes in monthly air temperature, clearly the largest R^2 value for the four sites that are analyzed.

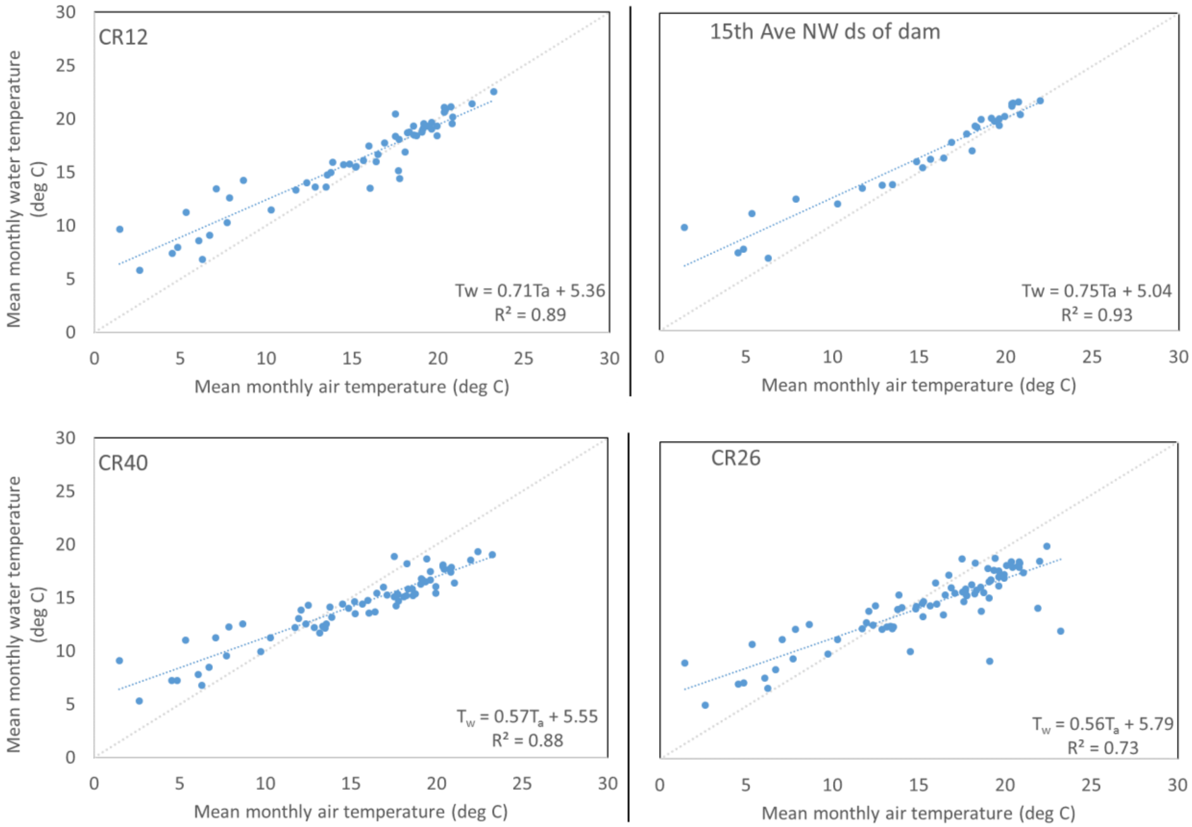

Figure 5. Correlations on mean monthly air temperature and mean monthly water temperature at 4 monitoring stations on Little Rock Creek

The difference between these linear models upstream and downstream of the dam point to the average monthly water temperatures at the upstream sites being less heavily influenced by monthly air temperatures than at the downstream sites. There are several influencing factors at these upstream sites that contribute to this difference. High air temperatures are commonly correlated with clear, sunny, and long summer days. The upstream sites have channel widths of 10-15 meters, which are typical for Little Rock Creek. The channel banks at the upstream sites are also fully vegetated, covering most of the channel in shade. These two factors combine to maintain cooler temperatures in the stream, primarily through limiting the impacts from solar radiation that are common during the months when air temperatures are at their highest. At the impoundment, the channel width is more than 200 meters wide with vegetation that provides little shade to the water. These locations measure water that is much warmer, because it has absorbed more solar radiation at the impoundment.

Table 2. Parameters from linear regression models for four Little Rock Creek water temperature monitoring stations.

Site	B	A (degrees C)	R^2	Se	Sd
CR12	0.71	5.36	0.89	0.54	4.11
15th Ave NW ds of dam	0.75	5.04	0.93	0.82	4.56
CR40	0.57	5.55	0.88	0.38	3.22
CR26	0.56	5.79	0.73	0.38	3.38

Se = Standard error of estimate of stream temperature.
Sd= Standard deviation of stream temperature.

2.3. Evaluation of water temperature monitoring for TMDL criteria

In 2015, the MPCA published the Total Maximum Daily Load Report for the Little Rock Creek Watershed (Barr Engineering, 2015). In the report, three water quality impairments are explained and allocations for each impairment are defined. Two criteria are applied in the assessment of the water temperature impairment—chronic and acute temperature criteria for trout. The chronic temperature criterion is set at 19 degrees Celsius and is defined as the maximum weekly average temperature for trout growth. The acute temperature criterion is set at 24 degrees Celsius and is defined as the daily maximum temperature for survival of trout for short-term exposure. These criteria are evaluated with average and maximum daily temperatures, respectively.

The DNR has collected water temperature data at eight monitoring locations in the streams dating back to 2007 at some sites. These data were analyzed at five sites surrounding the WMA, both upstream and downstream. The average number of days in the months of June, July, and August from 2015-2020 that exceed both chronic and acute criteria for five monitoring sites in the study area are presented in Table 3. In the TMDL impairment report, the MPCA reported that temperatures for the 2008 growing season exceeded the chronic criteria 60 times at the most downstream location at CR12. Additional data from 2015-2020 are consistent with the 2008 results from the TMDL report. On average, from 2015-2020 the chronic temperature criterion is exceeded at CR 12 53 times in the 92-day period from June through August. This accounts for 57% of the time from June-August. The location just downstream of the impoundment, 15th Ave NW downstream of the dam, is warmer still. From 2015-2020, daily average temperatures at this site exceed the chronic criterion an average of 61 days per summer (more than 60% of the season) and exceeds the acute criterion an average of 13 days per summer (14% of the season). The three sites upstream of the impoundment do not record temperatures that are nearly as warm. Figures 6 and 7 show that the sites CR40, 15th Ave NW field road, and CR26 average 0 days that exceed the acute criterion and all three sites have many fewer days that exceed the chronic criterion.

DEPARTMENT OF NATURAL RESOURCES

Table 3. Average frequency of daily average water temperature exceeding TMDL defined chronic criteria of 19 degrees C and acute criteria of 24 degrees C during the 92 days of June, July, and August from 2015-2020. Sites are tabulated from downstream locations on the left to upstream locations on the right.

	CR 12	15th Ave NW ds of dam	CR 40	15th Ave NW field road	CR26
	days	days	Days	days	Days
Average summer days exceeding chronic criterion	53	61	12	15	19
Average summer days exceeding acute criterion	5	13	0	0	0

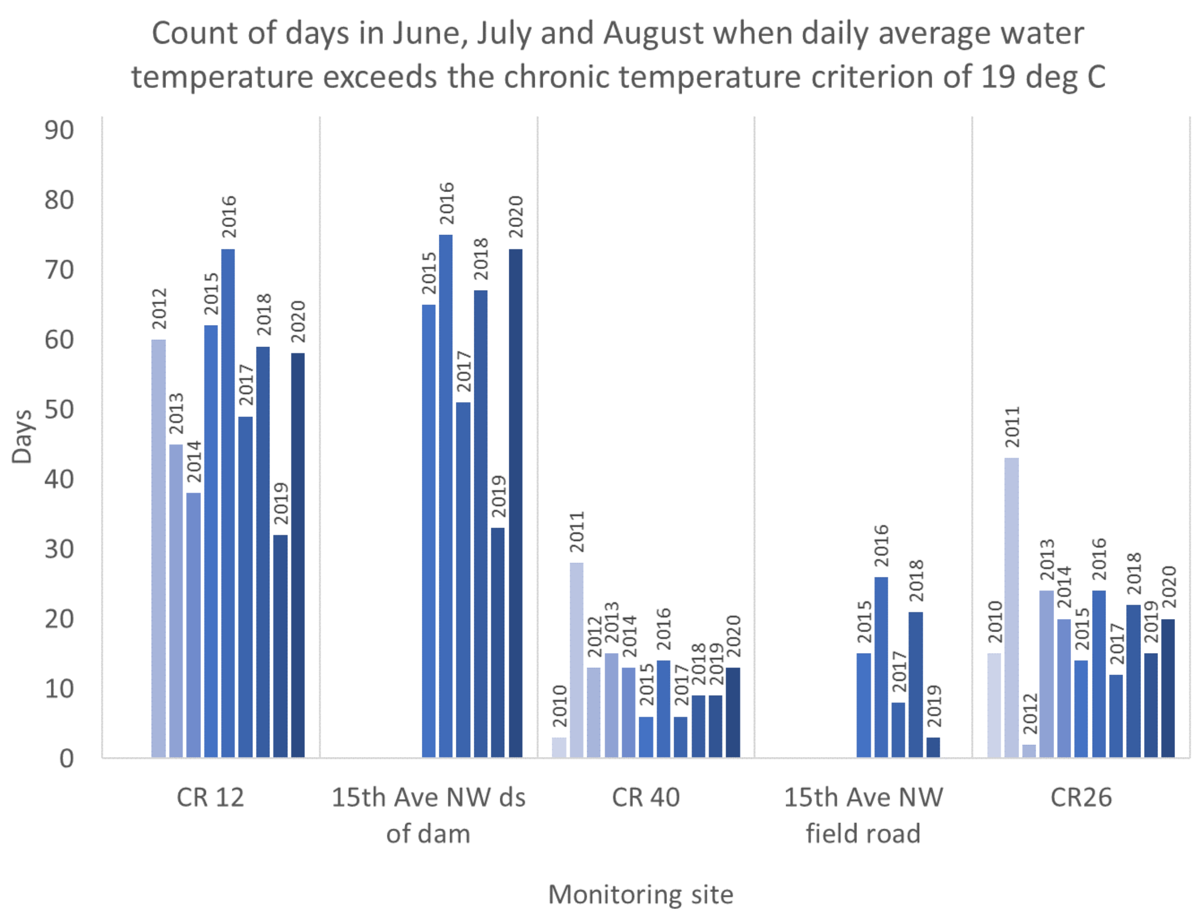

Figure 6. Count of days that exceed the chronic temperature criterion at five monitoring sites near the Sartell WMA.

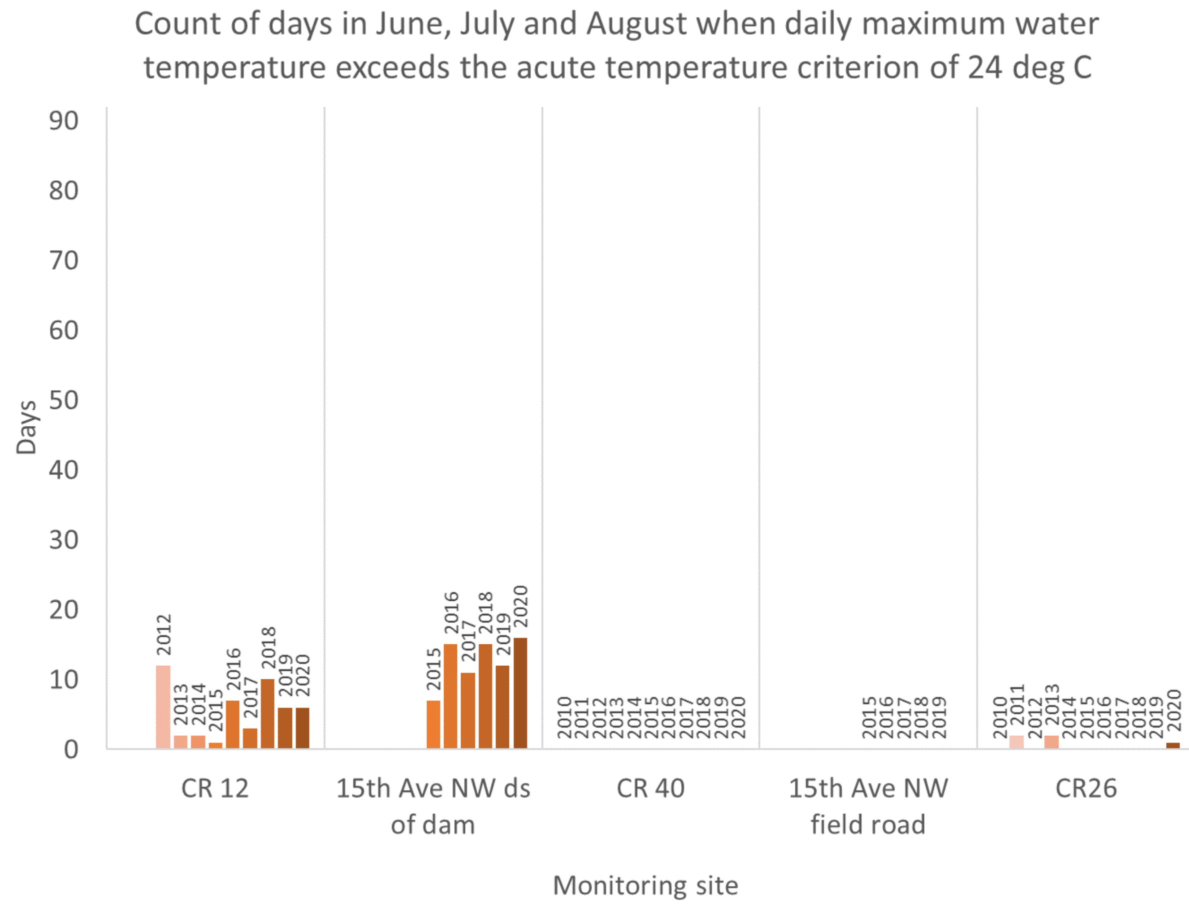

Figure 7. Count of days that exceed the acute temperature criterion at five monitoring sites near the Sartell WMA.

Additional analysis of the chronic and acute criteria help to explain the relationship between discharge, time of the year, and warm water temperatures in the stream. Not only are chronic temperatures exceeded much more frequently at sites downstream of the dam, but also the chronic and acute exceedances occur earlier in the summer and last longer into the summer at the two downstream sites than at sites upstream. Tables 4 and 5 show the dates of the year when chronic and acute temperatures are most commonly observed at four sites from 2015-2020. For the two sites downstream of the dam, 25% of the observed chronic exceedances occurred before June 26 at the site nearest the impoundment. The sites upstream of the impoundment do not exceed the chronic criterion at this 25% amount until July 7. There was only one acute exceedance at all of the three upstream sites during 2015-2020. Acute exceedances at the site immediately downstream of the dam occur six days earlier than at the CR12 site that is further downstream from the impoundment.

Table 4. Date of the year when chronic exceedances have occurred from 2015-2020

Date of the year when chronic exceedances have occurred from 2015-2020				
	25%	50%	75%	100%
CR 12	Jun-29	Jul-14	Aug-2	Sep-23
15th Ave NW ds of dam	Jun-26	Jul-14	Aug-2	Sep-23
CR 40	Jul-7	Jul-15	Jul-22	Sep-21
CR 26	Jul-6	Jul-15	Jul-26	Sep-21

Table 5. Date of the year when acute exceedances have occurred from 2015-2020

Date of the year when acute exceedances have occurred 2015-2020				
	25%	50%	75%	100%
CR 12	Jul-5	Jul-11	Jul-17	Jul-24
15th Ave NW ds of dam	Jun-29	Jul-8	Jul-15	Jul-28
CR 40	NA	NA	NA	NA
CR 26	NA	NA	NA	NA

There is also a distinct difference between the relationship between temperature exceedance and discharge for sites downstream of the impoundment and sites upstream. Figure 8 shows the percentage of recorded chronic exceedances from 2015-2020 with respect to discharge as recorded at CR40. For both sites downstream of the impoundment, more of the chronic exceedances occur during periods of low flow. At the sites upstream of the impoundment, it appears that more chronic exceedances occur during moderate to high discharges. For example, both sites downstream of the impoundment record over 60% of the chronic exceedances at discharges that are less than or equal to the median discharge recorded at CR40. The upstream sites record only 15% and 38% of the chronic exceedances under the same flow regimes. At these sites upstream of the impoundment, the majority of chronic exceedances occur during discharges that are above the median flow for CR40. Table 6 shows the total counts of the chronic exceedances at each of the four sites for the respective flow durations recorded at CR40.

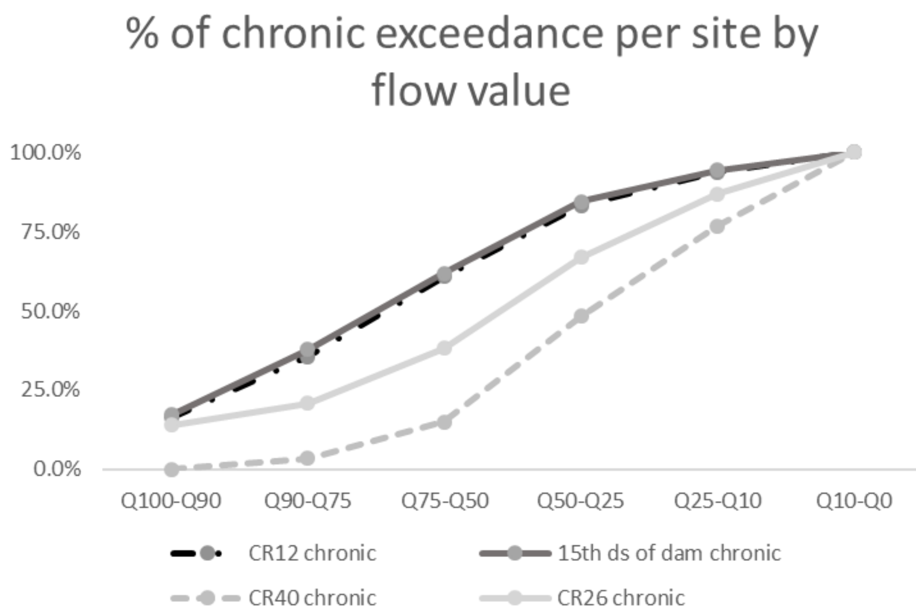

Figure 8. Cumulative percentage of chronic temperature exceedances from 2015-2020 at four sites with respect to discharge as observed at CR40.

Table 6. Count of chronic exceedance from 2015-2020 at four stream locations with observed discharge amounts.

CR40 Percentile Range	CR40 flow (cfs)	CR12 chronic	15th ds of dam chronic	CR40 chronic	CR26 chronic
Q100-Q90	<10.8	59	67	0	16
Q90-Q75	14.4	70	80	2	8
Q75-Q50	21.4	91	94	7	20
Q50-Q25	38.4	81	88	20	33
Q25-Q10	87.23	38	39	17	23
Q10-Q0	>237.51	23	22	14	15
Total		362	390	60	115

2.4. Dye tracing to measure impoundment impacts to channel width/depth, travel time, and water temperature

The water temperature data acquired since publication of the TMDL shows that the two locations downstream of the impoundment often exceed chronic temperature criteria and infrequently exceed acute temperature criteria. These updated datasets support the conclusions from the TMDL report that "[s]tation 13 (i.e. CR 12), which is the only monitoring station downstream of the WMA impoundment, should be the focus of the heat load mitigation activities". To address this focus on sites downstream of the impoundment, the TMDL report suggests the creation of a "more free flowing system…to improve connectivity and temperature issues during critical conditions described in this report".

In an attempt to quantify the impact that the impoundment has on water temperatures in the creek, DNR completed four time of travel studies in 2018 and 2019 to collect estimates of travel times and mixing parameters under different flow conditions with the impoundment in place and with the impoundment removed. Fluorescent dye was injected at CR 26 and concentration of the dye was measured at downstream locations. The results from these dye traces were analyzed to estimate travel times through reaches and the mixing parameters under each flow and impoundment scenario. The reaches for these dye traces are listed in Table 7.

Table 7. Reach lengths and river miles for the stations used in the time of travel studeis.

Site name	upstream river mile	downstream river mile	reach length (mile)
CR26 (injection point)		11.1	
15th Ave NW field road	11.1	7.9	3.2
CR 40	7.9	6.7	1.2
15th Ave NW at the WMA	6.7	5.5	1.2
15th Ave NW downstream of dam	5.5	4.3	1.1
CR12	4.3	2.9	1.4

The duration of a tracer response at a section is the difference between the slowest trailing time of the dye and the fasted leading time (Kilpatrick and Wilson, 1989). It is calculated by subtracting the time when the dye arrived from the time when the dye concentrations returned to background levels. The duration that dye was observed at 15th Ave NW downstream of the dam for each time of travel study is shown in Table 8.

Removing the dam decreased durations at 15th Ave NW downstream of the dam by 10-12 hours. Removing the dam also significantly modifies the width and depth of the channel that flows through the WMA. Air photos of the WMA with the impoundment in place in 2017 and with the impoundment drained in 2003 demonstrates these changes (Figure 9). Figures 9i and 9ii show the extent of the impoundment with the dam in place. Water is stopped by the dam, which impounds an area more than 20 acres with a width of more than 200 meters in places. Under these conditions, bankside vegetation provides very little shading in relation to the amount of the impoundment that is exposed. Figures 9iii and 9iv show the results of the drawdown of the impoundment that took place in 2003. When the stop logs are removed and the impoundment is drained, the width of the channel is decreased by an order of magnitude to 20-30 meters wide. This results in a large decrease in duration time of water in the WMA. Without the stop logs, water is moving through the impoundment considerably faster and with a much smaller surface area exposed to solar radiation. Both of these changes result in less warming in the WMA.

Table 8. Durations of dye at 15th Ave NW downstream of dam for four dye traces.

	flow at 15th Ave NW field road/15029001 during arrival (cfs)	Duration of dye at 15th Ave NW ds of dam/ H15031005 (hrs)
WMA dam in place		
2018 low flow #3	9	26
2018 low flow #2	10	24
2018 moderate flow	19	13
Stop logs removed and basin drained		
2019 low flow	13	14

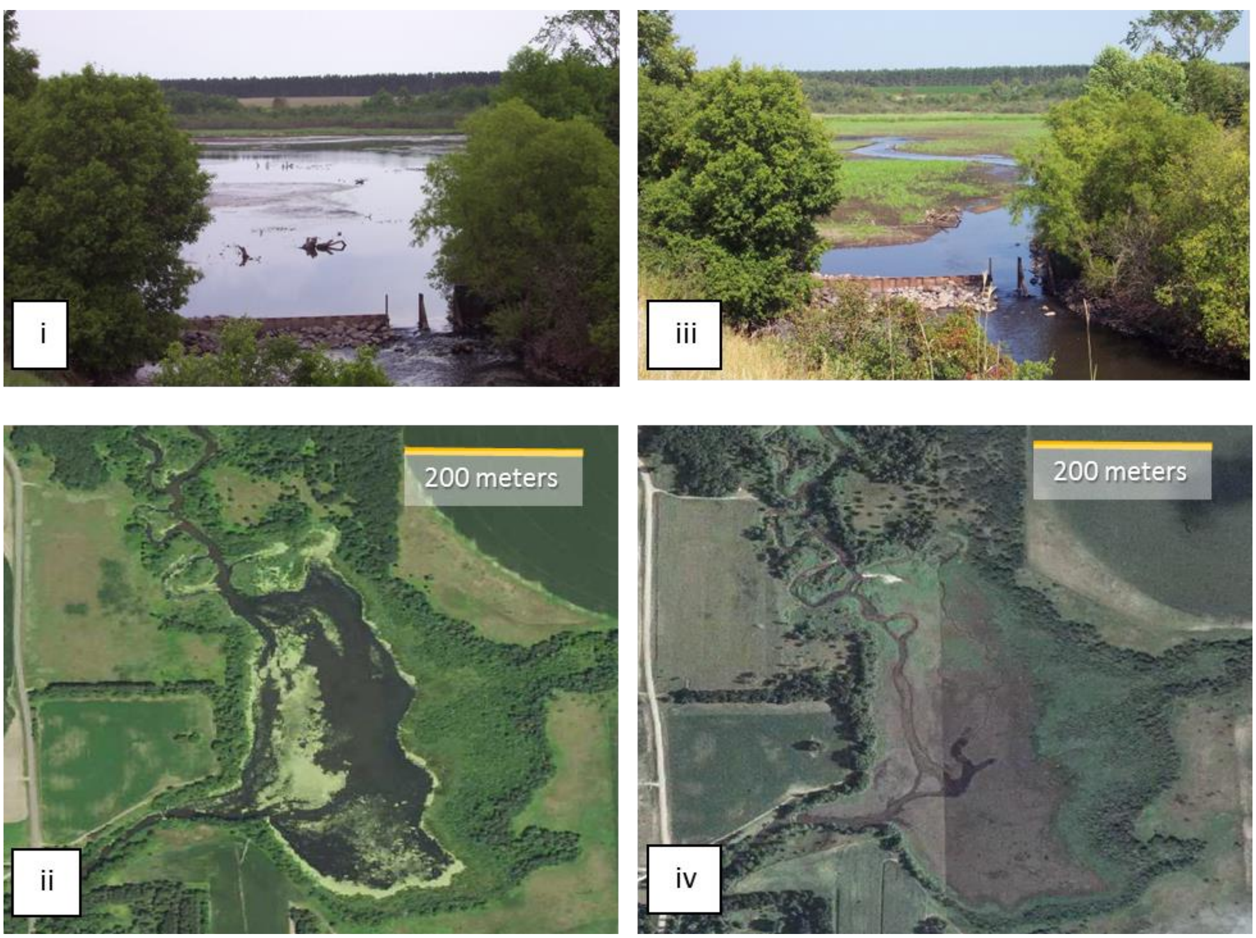

Figure 9. On-site and air photos showing the differences in channel geometry at the 15th Ave NW ds dam site with the impoundment in place in 2017 (i and ii) and with the impoundment removed in 2003 (iii and iv)

Removing the impoundment also impacted water temperatures at the site downstream of the dam. Figure 10 shows the observed water temperatures at the 15th Ave NW downstream of the dam for the year 2015-2019. The vertical lines denote when the impoundment began draining, when the drawdown a finished, and when the impoundment began filling up again in 2019. It is evident in Figure 10 that water temperatures in 2019 prior to the drawdown were warm and near temperatures from previous years. Temperatures gradually decreased in the days after the drawdown began and remained uniformly below most historic temperatures for the duration of the drawdown. Once the impoundment is filled again in September and the drawdown is complete, water temperatures return to average and above over several days. The only period when 2019 water temperatures were higher than a previous year occurred in the first week of August when 2017 air temperatures dropped well below average and were the lowest for the entire period of all five years analyzed. Otherwise, average air temperatures during July-September for 2019 were within 0.2 degrees of the previous years. Even with similar air temperatures in 2019 compared with previous years, the difference in average water temperatures during the drawdown in 2019 with the 4-year historic average is 2.4 degrees C cooler. Furthermore, the number of chronic exceedances for 2019 when the stop logs were removed were the lowest in the period of record for both sites downstream of the impoundment (Figure 6).

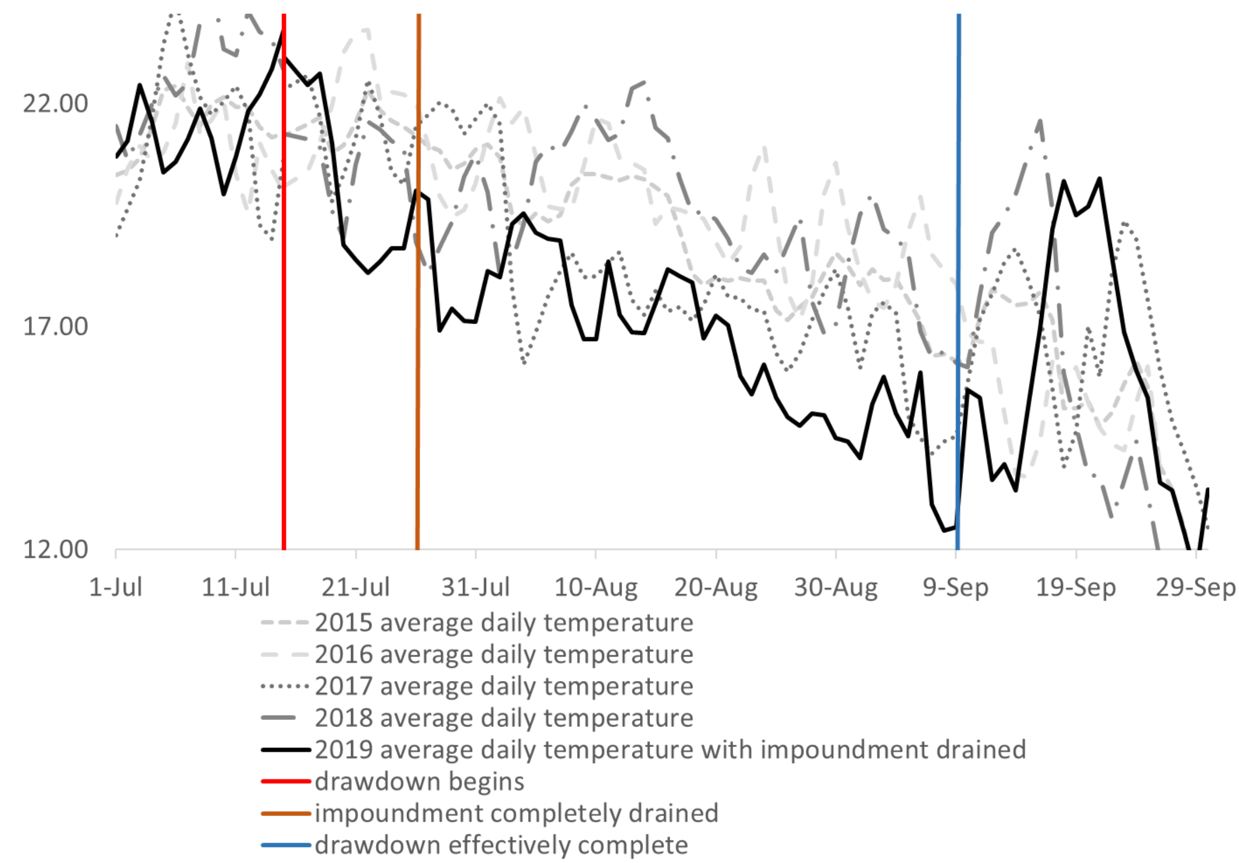

Figure 10. A graph of daily average water temperatures at 15th Ave NW downstream of the dam for the 2019 drawdown against the average daily water temperature from 2015-2018 when the impoundment is in place

The impoundment does not appear to have a significant impact on travel times and water temperatures at sites upstream of the impoundment. The time of travel results at CR 40 were not collected for all studies, but at the site immediately upstream of CR40, durations of dye at 15th Ave NW field road indicate that impacts to durations from the impoundment at the WMA do not spread upstream. Table 9 shows the durations that dye was observed at 15th Ave NW on the field road (Site H15029001). At this location, removing the dam does not change travel times as was observed at the location downstream of the dam—7-8 hours with the dam and 8 hours without the dam. There were also no observed changes in channel width or depth at this site with the impoundment and without the impoundment. Also, water temperatures at this site during the impoundment drawdown only differed from the average of the period by -0.4 degrees C.

Table 9. Duration of dye at 15th Ave NW field road for four dye traces

	flow at 15th Ave NW field road/15029001 during during arrival (cfs)	Duration of dye at 15th Ave NW field road/ H15029001 (hrs)
WMA dam in place		
2018 low flow #3	9	7
2018 low flow #2	10	8
2018 moderate flow	19	11
Dam removed and basin drained		
2019 low flow	13	8

3. Conclusion

Water temperature data from four sites in Little Rock Creek were analyzed to evaluate the impacts that the impoundment at the Sartell WMA might have on the temperature impairment identified by the MPCA in 2014. It is evident that water temperatures observed at two sites downstream of the WMA impoundment are consistently warmer than the temperatures observed at sites upstream of the impoundment. These differences begin in mid-May, peak in late June, and converge in late September. Proximity to the impoundment also affects water temperatures. Daily maximum temperatures at the site immediately downstream of the impoundment, 15th Ave NW downstream of the dam, are consistently greater than temperatures at the site further downstream (Figure 4). Each of the four sites exhibits a strong correlation of water temperature and air temperature, but the linear models for the sites that are upstream of the impoundment have parameters that are distinct from those models from sites that are downstream of the impoundment. The model parameters for sites upstream indicate that water temperatures are not as heavily influenced by air temperatures as the two downstream sites and that groundwater contribution might play a larger role in the upstream temperatures. Finally, additional temperature data from 2015-2020 are consistent with the 2008 results from the TMDL report that concluded a temperature impairment in the Creek. On average, the chronic temperature criterion is exceeded 56 times a summer at CR 12 and 61 days per summer at 15th Ave NW downstream of the dam. These chronic exceedances are 4-5 times greater than what are recorded at the upstream sites. The acute criterion is exceeded an average of 6 days days per summer at CR 12 and 13 days per summer at 15th Ave NW downstream of the dam. There is only one instance of an acute exceedance at any of the three upstream sites over the same time period. Chronic and acute temperatures also occur earlier in the summer and last longer into the summer at the two downstream sites than at sites upstream.

Additional investigations were conducted around the WMA by monitoring travel times and temperatures around these sites with the impoundment in place and with the impoundment drained. Results from the time of travel studies showed that removing the dam decreased durations at 15th Ave NW downstream of the dam by 10-12 hours. Removing the dam also significantly modifies the width and depth of the channel that flows through the WMA. Without the dam, water is moving through the impoundment faster and with a much smaller surface area exposed to solar radiation. Both of these changes result in less warming in the WMA. A comparison of water temperatures at the 15th Ave NW downstream of the dam site shows that with similar air temperatures in 2019 compared with previous years, the difference in average water temperatures during the drawdown in 2019 with the 4-year historic average for the same days of the year is 2.4 degrees C cooler. Furthermore, the number of chronic exceedances for 2019 when the dam was removed were the lowest in the period of record for both sites downstream of the impoundment (Figure 6). The impoundment does not appear to have a significant impact on travel times and water temperatures at sites upstream of the impoundment.

The results from the time of travel studies and removal of the dam in 2019 show that modifying operations at the impoundment has the potential to cool water temperatures at sites downstream of the dam. The drawdown in 2019 lasted for 57 days and likely resulted in nearly half as many chronic temperature exceedances for that year. Temporary drawdowns every year might not decrease temperature exceedances to levels that are similar to upstream sites, but it is likely that dam modifications targeted during the warmest weeks of the summer will result in decrease water temperatures at the sites downstream of the dam.

4. References

Barr Engineering, 2015, Little Rock Creek Watershed Total Maximum Daily Load Report – Dissolved Oxygen, Nitrate, Temperature, and Fish Bioassessment Impairments: Prepared for Benton Soil and Water Conservation District and Minnesota Pollution Control Agency, 55p. with appendices.

Erickson, Troy R. and Stefan, Heinz G., 2000. Air/Water Temperature Correlation for Streams During Open Water Periods. Journal of Hydrologic Engineering. July

Kilpatrick, F.A., and J.F. Wilson, Jr., 1989. Measurement of time of travel in streams by dye tracing. U.S. Geological Survey Techniques of Water-Resources Investigations, Bk.3, Chap. A9, 27p.

Minnesota Department of Agriculture. 2020. Central Minnesota Ag Weather Network Database. Accessed October 2020.

Minnesota Department of Natural Resources. 2020. Minnesota Department of Natural Resources. Groundwater Flow and Groundwater/Stream Interaction in the Little Rock Creek Area. Minnesota Department of Natural Resources (MN DNR) Report, St. Paul, MN, USA.