Trend Analysis of Water Temperatures Relative to Air Temperatures and Flow in the Big Hole River

Final Report

Big Hole Watershed, SWMT
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SYNOPSIS

A primary focus in the Big Hole watershed has been to improve water quality and water quantity. Specific attention is given to mediating low flows and high stream temperatures when conditions threaten the wellbeing of the Big Hole River fishery. This focus has facilitated partnership efforts to benefit Arctic grayling (*Thymallus arcticus)* and other species throughout the Big Hole River. Extensive restoration work and management actions have been implemented by federal and state agencies, private landowners, and non-profit organizations since the mid-1990s to meet desired objectives. It is presumed the sum of restoration actions should improve channel configuration and riparian vegetation to an extent that temperature extremes would be ameliorated at some level. This analysis was designed to provide a "first look" assessment of trends in Big Hole River temperatures over the last 17-years and how they are influenced by air temperatures and stream flow patterns at Wisdom and Melrose during that period. The tendency for high water temperatures to occur, at which the fishery was stressed or threatened, was a particular analysis we used to describe fisheries conditions over the 17-year period. We found that hourly water temperatures that exceed 70°F are frequent at both locations, but with twice as many hours occurring at Wisdom. There is a strong indication that the thermally, "critical" periods for Big Hole River fisheries are from June 25th to August 18th at Wisdom, and from July 5th to August 18th at Melrose. The frequency of occurrence of water temperatures greater than 70°F increases steadily with increasing daily maximum air temperatures, but is not confined to lower flow levels at either location. We believe that solar radiation is a major variable influencing the likelihood of high water temperatures (>70°F). With more time, more intensive data collection, and proper statistical analysis, indications of improvements to water quality in the Big Hole may be measurable in the future.

This report is in accordance to the contract agreement between the Big Hole Watershed Committee and the Beaverhead Deerlodge National Forest. Funding was provided by Montana Department of Environmental Quality 319 program and the Big Hole Watershed Committee.

ACRONYMS

BHWC	Big Hole Watershed Committee
CCAA	Candidate Conservation Agreement with Assurances
DEQ	Montana Department of Environmental Quality
DMP	Drought Management Plan
DNRC	Montana Department of Natural Resource and Conservation
J,A,S	July, August, and September
MTFWP	Montana Fish, Wildlife and Parks
TMDL	Total Daily Maximum Load
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

TABLE OF CONTENTS

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INTRODUCTION

A primary focus in the Big Hole watershed is to improve water quality and quantity, especially by mediating the occurrence of high water temperatures and low flows which threaten the wellbeing of the Big Hole River fishery. This focus has facilitated partnership efforts to benefit Arctic grayling (*Thymallus arcticus)* and other fish throughout the Big Hole River. Extensive restoration work and adaptive management actions have been implemented since the mid – 1990s, to augment streamflows and limit angling impacts when conditions threaten maintenance of this world renowned fishery. Cooperators working toward common goals include federal and state agencies, private landowners, and non-profit organizations. It is presumed that the entirety of this remediation work should improve channel structure and riparian vegetative vigor to an extent that maximum water temperatures will be ameliorated at some level.

Big Hole Restoration Actions and Management Plans

High water temperatures in the Big Hole have been a concern for fisheries managers for some time. Low flows, which contribute to high water temperatures, are also tied to the decline of Arctic grayling in the Big Hole River (Lamothe and Magee, 2004). Four prominent programs are in place to restore habitat and mitigate against conditions stressful to fish during times of drought and high water temperatures. They are:

- The Big Hole River Drought Management Plan (DMP)
- The Candidate Conservation Agreement with Assurances (CCAA)
- Upper and North Fork Big Hole Planning Area TMDLs and Water Quality Restoration Approach
- Middle and Lower Big Hole Planning Area TMDLs and Water Quality Improvement Plan

The Big Hole DMP was adopted in 1997 to mitigate the effects of low streamflows and lethal water temperatures for fisheries through a voluntary effort from landowners. When flows or temperatures meet certain trigger levels, a voluntary reduction of irrigation, stock water diversions, municipal water use, and angling is initiated (BHWC, 1997). If these efforts are not enough and harmful flow levels and water temperatures are exceeded, then Montana Fish Wildlife and Parks (MTFWP) will close parts of the river to fishing until flow levels and water temperatures maintain an acceptable level.

Table 1- The Drought Management Plan (version 2012) for Wisdom and Melrose during July, August, and September.

Wisdom Gaging Site DMP Temperature Trigger levels from July 15th to September 1st		
Water Temperatures	Average daily Flows	Action
Exceed 70° > 8hr/day for 3 consecutive days	Above 30 cfs	Notification to encourage anglers to seek other destinations to fish.
Exceed 70° > 8hr/day for 3 consecutive days with evidence of thermally induced fishery occurs	Between 25-30 cfs	Upper river is closed to angling until water temperatures do not exceed 70°F for 8hr/day for 3 consecutive days and until flows increase to >30 cfs.
Exceed 70° > 8hr/day for 3 consecutive days	Less than 25 cfs	Upper river is closed until water temperatures do not exceed 70°F for 8hr/day for 3 consecutive days and until flows increase to >30 cfs.

Melrose Gaging Site DMP Temperature Trigger levels from July 15th to September 1st		
Water Temperatures	Average daily Flows	Action
Exceed 70° at 8hr/day for 3 consecutive days	Above 250 cfs	Notification to encourage anglers seek other destination to fish
Exceed 70° at 8hr/day for 3 consecutive days with evidence of thermally induced fishery occurs	Between 150-200 cfs	Lower reach A of river is closed until water temperatures do not exceed 70°F for 8hr/day for 3 consecutive days and until flows increase to >200 cfs for 7 consecutive days.
Exceed 70° at 8hr/day for 3 consecutive days	Below 150 cfs	Lower reach A of river is closed until water temperatures do not exceed 70°F for 8hr/day for 3 consecutive days and until flows increase to >200 cfs for 7 consecutive days.

The Big Hole CCAA was formed in 2006 between the U.S. Fish and Wildlife Service (USFWS) and non-Federal entities in order to secure and enhance the population of fluvial Arctic grayling within the upper reaches of the Big Hole watershed. Non-federal property owners are voluntarily managing their land and waters to remove threats to grayling and have received assurances against further regulatory requirements should the species be listed under the Endangered Species Act (CCAA Agreement, 2005). The CCAA addresses those threats with projects that increase streamflows, repair riparian habitat and remove barriers for fish migration. Since the mid-2000s, most restoration actions have occurred in the upper Big Hole watershed in conjunction with the CCAA.

In 2009, the Upper/North Fork, and Middle/Lower Big Hole TMDLs and Water Quality Improvement Plans were released, which have many congruent water quality goals and conservation measures to the CCAA (Cayer, et al 2012). A stream segment temperature model done by the DEQ was used in the analysis of the TMDLs to assess water quality. The model results showed that: 1) increasing flow rates could significantly lower daily maximum water temperatures, 2) improving riparian vegetation could decrease mean and maximum daily water temperatures, 3) and reducing stream channel width-to-depth ratios could reduce maximum daily water temperatures; and subsequently in combining these scenarios, the river could return to a more natural thermal regime (Upper TMDL, 2009). TMDLs for water temperatures were written for water body segments throughout the upper, middle, and lower Big Hole Watersheds. To attain water quality targets for these areas, the improvement plans focused on riparian shade and canopy density, channel width-to-depth ratio, irrigation water management, and instream flows.

Table 2- Timeline for implementation of management plans and restoration actions in the upper and middle Big Hole watershed.

YEAR	RESTORATION/MANAGEMENT
1995	Big Hole Watershed Committee started
1997	Big Hole River Drought Management Plan (DMP)
2005	Candidate Conservations Agreement with Assurances (CCAA)
2009	Upper & North Fork Big Hole River Planning Area TMDLs and Framework Water Quality Restoration Approach
2009	Middle and Lower Big Hole Planning Area TMDLs and Water Quality Improvement Plan
2006-2012	CCAA restoration activities: Infrastructure improvements and upgrades, riparian fencing, willow planting, etc.

Considering the extensive work that has been done over the last 15 years, there has been limited evaluation of broader benefits that may have occurred. It would help managers to know the influence restoration and management efforts have had on fisheries conditions in the Big Hole River. We hypothesize restoration and flow management actions will tend to reduce the occurrence of water temperatures exceeding 70° F. This analysis specifically evaluates whether Big Hole River temperatures have changed across broader stream reaches relative to air temperatures and streamflows. For this purpose, data from two locations; Wisdom and Melrose, were analyzed. They are approximately 70 river miles apart (Figure 1) and have USGS gaging stations with readily available water temperature and flow data since 1996. Wisdom is closer to where most of the restoration actions have been implemented; which include riparian fencing, channel reconstruction, improvements in irrigation infrastructure, and willow planting.

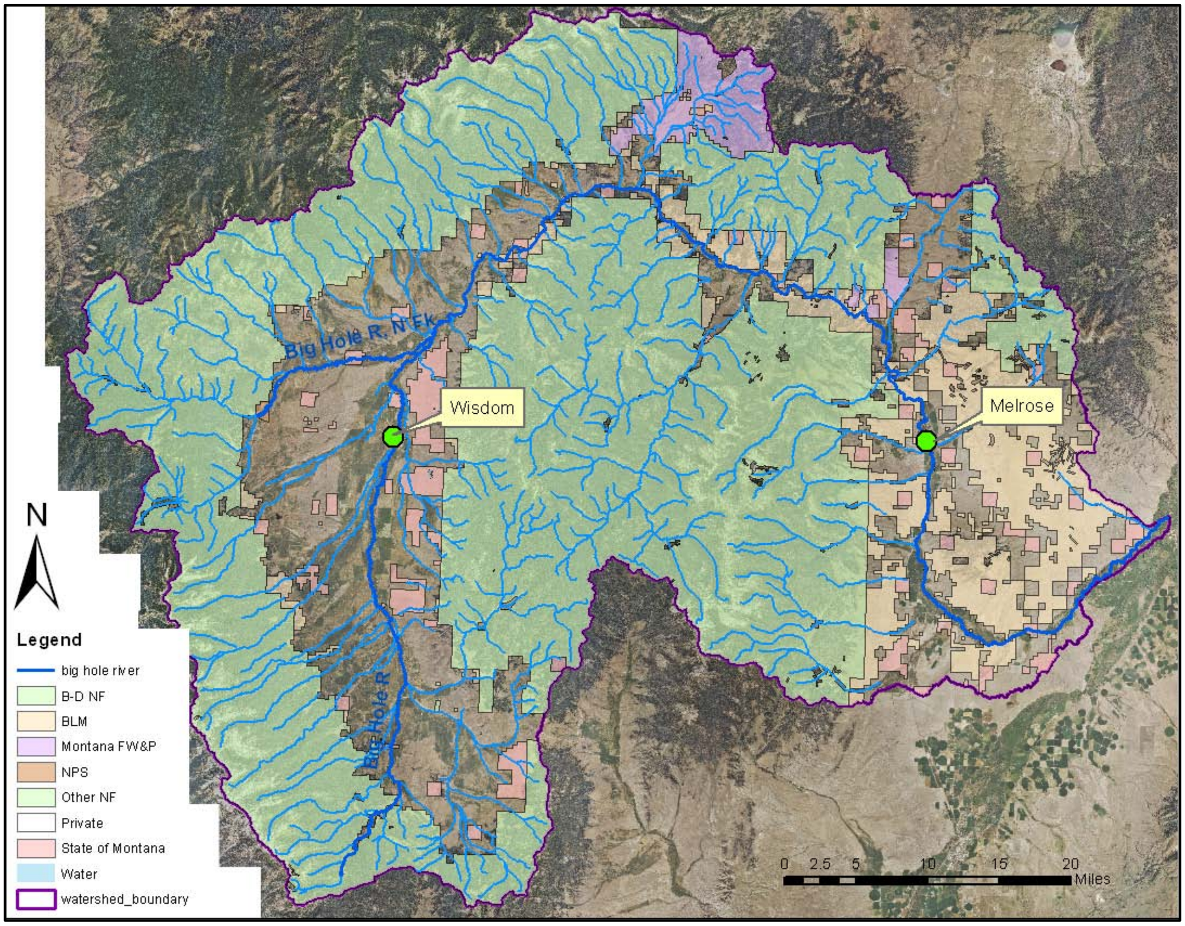

Figure 1- Big Hole Gaging Stations where stream temperatures and flow temperatures were collected.

Analysis Objectives

1. Describe air temperatures, stream flows and Big Hole water temperatures trends over the last 17-years; at Wisdom and Melrose.
2. Define warmer and cooler years based on air and stream temperatures.
3. Define higher and lower stream flow years.
4. Describe any apparent relationships between stream temperature and air temperature patterns.
5. Describe any apparent relationships between stream temperatures and stream flow patterns.
6. Make recommendations for the future.

METHODS

Data Collection

Air temperature data was collected from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center for Wisdom and Divide. Because air temperature data were not available at Melrose, information from Divide (~10 miles north) was used. Daily maximum and minimum air temperatures were accessed at http://www.ncdc.noaa.gov/cdo-web/#t=secondTabLink.

Water temperature and discharge data were collected from two gaging stations; USGS Station-06024450 near Big Lake Creeks confluence with the Big Hole river near Wisdom and USGS Station-06025500 at Kalsta Bridge downstream of Melrose. Daily maximum, minimum and mean daily stream temperatures were available from 1996 through 2012; as were mean daily discharges (streamflows). The data were readily accessed from http://waterdata.usgs.gov/nwis. Hourly stream temperature data were collected for both locations upon request by emailing the USGS Montana Water Science Center in Helena, MT.

Temperature and flow data were assembled for a 17-year period, from 1996-2012. Because fishery concerns are related to high water temperatures and low flows, we limited our assessment to July through September for each of those years -- the 3 month period when those conditions are most likely to occur simultaneously.

Data used in this analysis included:

- Hourly Big Hole River temperatures during July, August and September; from 1996 - 2012
- Daily air temperatures during July, August and September; from 1996 - 2012
- Hourly Big Hole River flows during July, August and September; from 1996 -2012

Quality Control/ Quality Assurance

The amount of information assembled for analysis was substantial. Some gaps and outliers exist within the datasets. While we attempted to deal with each occurrence carefully and appropriately, time-frames for this project were too short to ensure all outliers were found and dealt with. Available data from the gaging sites are identified as "provisional" and there were instances where the certain data points seemed "suspect". The "suspect" data that we noticed included uncharacteristically high water temperatures and air temperature data that were mislabeled. Obviously inaccurate data were corrected or excluded, but we lacked the time and resources to investigate all the data points thoroughly. None-the-less, for the temporal and spatial scales over which this analysis was done, we believe the patterns and relationships represented by the data are supportable.

Analysis

Many factors influence water temperature, but the primary determinants are climatic drivers, such as air temperature, solar radiation, and wind speed (Poole and Berman, 2001). As such, daily maximum and minimum air temperatures were analyzed at Wisdom and Melrose to consider patterns and relationships relative to water temperatures.

Air temperatures were analyzed for the months of July, August and September, from 1996-2012. The seventeen year average of daily maximum and minimum air temperatures were calculated for each location. The extent to which daily maximum and minimum air temperatures (for individual years) deviated from the 17-year averages was used to describe “warmer” and “colder” years.

Streamflow data were analyzed similarly to air temperatures. The 17-year average of mean daily discharges was defined for the same period of time. Average daily stream discharge for individual years was evaluated against this average to define “higher” and “lower” flow years. Deviations above and below this mean were quantified for each year to help indicate possible patterns consistent with water temperatures.

Water temperatures were analyzed over the same period of time as air temperatures and flows, at Wisdom and Melrose. Mean daily stream temperatures were calculated for each year at each location by averaging hourly temperatures, and the 17-year averages of mean daily temperatures were calculated for both locations. The extent to which mean daily stream temperatures (for individual years) deviated from the 17-year averages was used to describe “warmer” and “colder” years.

The frequencies that hourly temperatures exceeded 70°F and 77°F were also quantified allowing comparison between years. These temperatures were selected because they represent important thresholds for managing salmonids. Temperatures above 70°F are generally considered stressful for trout (BHWC, 1997) and 77°F represents the upper incipient lethal temperature for grayling (Cayer, Titus, Bias, & Anderson, 2012). The occurrence of 70°F stream temperatures is also a target used to determine when drought management actions should be initiated. Patterns for temperatures meeting/exceeding these limits were summarized to understand their tendencies for occurring during July, August and September, and to see if changes have occurred in recent years.

RESULTS

Maximum Air Temperature Tendencies at Wisdom & Melrose (1996-2012)

The general tendency for maximum daily air temperatures at Wisdom, over the last 17-years is a pattern of warming through July before peaking about the last week of the month, then cooling slowly through the end of September. More specifically, mean (for the 17-year period) maximum daily air temperatures ranged from 55-82 °F on July 1st, 79-94 °F around July 24th, before declining slowly to 45-85 °F at the end of September (Figure 2). The number of days in which maximum daily air temperature is over 80°F is 28 days and commonly occurs from July 11th to August 10th (Table 3).

Because Melrose lacked air temperature data for the period of analysis, air temperatures from Divide (~10 miles north) were used. From this point forward, we refer to the Divide air temperatures as Melrose air temperatures for ease of discussion.

The general tendency for maximum daily air temperatures at Melrose is comparable to what occurs at Wisdom. They display a similar pattern of warming through July, peaking near the end of July, and cooling slowly through the end of September. Mean (for the 17-year period) maximum daily air temperatures ranged from 59-88 °F on July 1st, 76-98 °F around July 24th then, decline slowly to temperatures commonly between 42-80 °F at the end of September (Table 3). The number of days in which maximum daily air temperature is over 80 °F is 49 days, 21 days more than at Wisdom, and commonly occurs from July 11th to August 15th.

Table 3- Summary statistics for maximum daily air temperatures at Wisdom and Melrose.

Location	Avg. of Maximum Daily Air Temps °F on July 1st	Peak Temps for Avg. of Maximum Daily Air Temps °F	Date of Peak Avg. for Maximum Daily Air Temps °F	# Days that Avg. of Maximum Daily Air Temps Exceed 80°F	Avg. of Maximum Daily Air Temps °F on Sept. 30th	Avg. of Std. Dev. °F (July, Aug., Sept.)	Range of Std. Dev. °F (July, Aug., Sept.)
Wisdom	74.0	84.4	7/23	28	69.7	7.4	4.1-12.8
Melrose	78.9	85.6	7/24	49	70.3	8.3	3.9-14.2

Comparison of the averages of maximum daily air temperatures between Wisdom and Melrose demonstrate a similar pattern except that Melrose is typically warmer (Figure 2). Only 10 days have warmer maximum daily air temperatures at Wisdom ranging from 0.1--2.2 °F, and mostly occur in September. For the 17-year period, standard deviations show that there is a larger range in temperatures from the means of maximum daily air temperatures at Melrose.

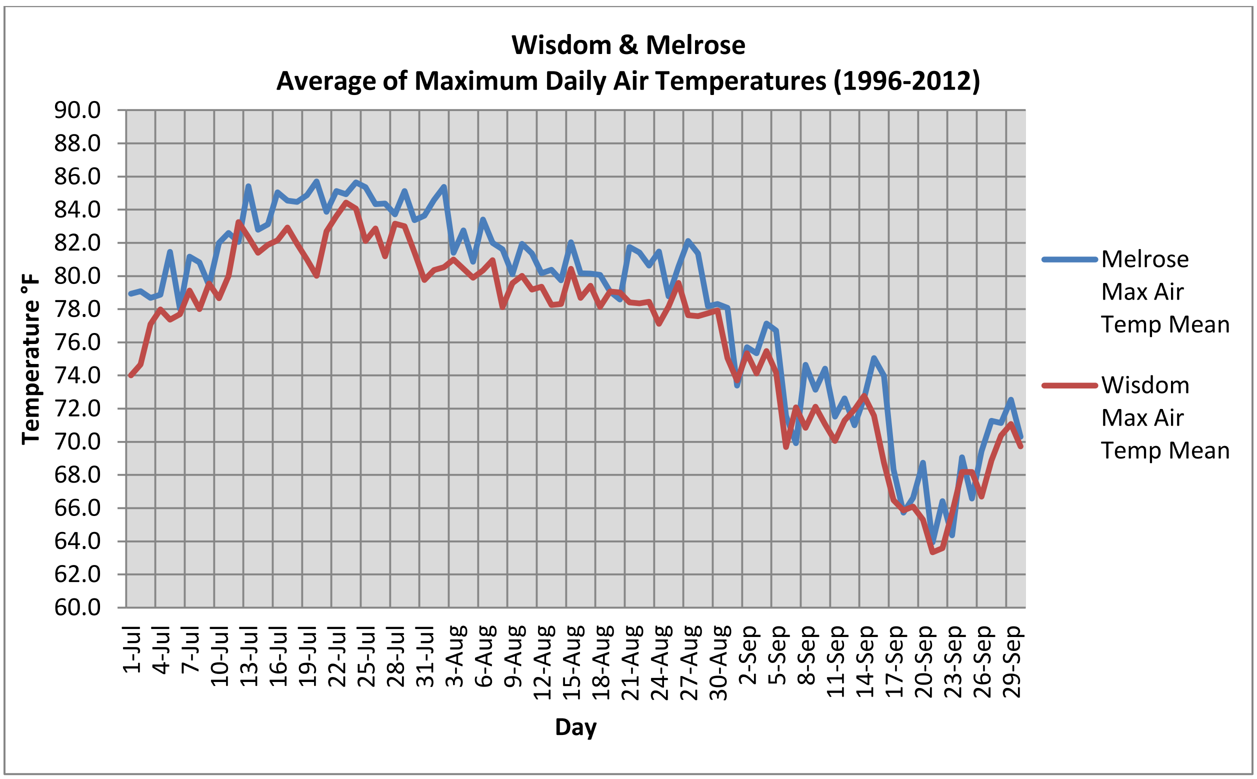

Figure 2- Comparison of average maximum air temperatures for the last 17-years. Melrose air temperatures are collected from Divide, MT (approximately 10 miles north) representing the closest site with suitable air temperature data.

See Appendix A for individual years graphed against these means at each location.

Minimum Air Temperature Tendencies at Wisdom & Melrose (1996-2012)

The general tendency for minimum daily air temperatures at Wisdom, over the last 17-years, is a pattern of slight warming through July, before hitting the highest point sometime in the last two weeks of the month and cooling slowly through the end of September. More specifically, mean (for the 17-year period) minimum daily air temperatures range from 30--44 °F on July 1st, increase a to 32--53 °F around July 17th then, decline slowly to temperatures commonly ranging between 10--45 °F at the end of September (Figure 3). The number of days over 38 °F is 24 and occurs between July 1st and August 2nd.

The general tendency for minimum daily air temperatures at Melrose is comparable to what occurs at Wisdom. They display a similar pattern of slight warming through July, before hitting the highest points in the last two weeks of July and cooling slowly through the end of September. Mean (for the 17-year period) minimum daily air temperatures ranged from 35--51 °F on July 1st, before slightly increasing to between 35--60 °F around the 26th then, declining slowly to temperatures commonly between 25--45 °F at the end of September (Figure 3). The number of days over 38 °F is 30 days occurring from July 11th to August 10th.

Table 4- Summary statistics for minimum daily air temperatures at Wisdom and Melrose.

Location	Avg. of Minimum Daily Air Temps °F on July 1st	Peak Temps for Avg. of Minimum Daily Air Temps °F	Date of Peak Avg. for Minimum Daily Air Temps °F	# Days that Avg. of Minimum Daily Air Temps Exceed 38°F	Avg. of Minimum Daily Air Temps °F on Sept. 30th	Avg. of Std. Dev. °F (July, Aug., Sept.)	Range of Std. Dev. °F (July, Aug., Sept.)
Wisdom	38.1	39.5	7/16	19	23.4	6.0	3.3-9.7
Melrose	44.8	48.9	7/29	92	40.1	6.0	3.6-9.3

Direct comparison of the averages of minimum daily air temperatures between Wisdom and Melrose illustrate the similarity of general temperature patterns except that Wisdom is considerably cooler than Melrose (Figure 3). For the 17-year period, standard deviations show that there is virtually the same range in temperatures from the means of minimum daily air temperatures at both locations.

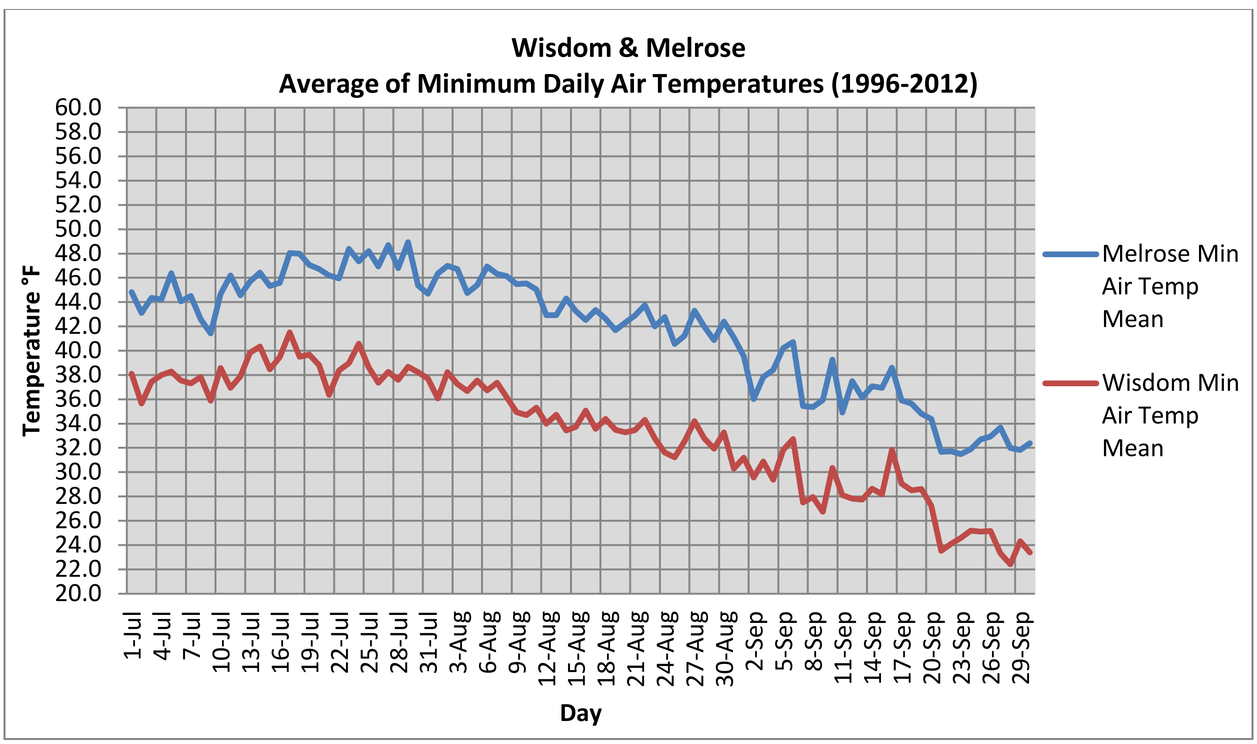

Figure 3- Comparison of average minimum air temperatures for the last 17-years. Melrose air temperatures are collected from Divide, MT (approximately 10 miles north) representing the closest site with suitable air temperature data.

See Appendix B for individual years graphed against these means at each location.

Flow Tendencies at Wisdom & Melrose (1996-2012)

Over the 17-year period evaluated, streamflows at Wisdom tend to spike multiple times, coinciding with periods of accelerated snowmelt, during a period of general decline through the first three weeks of July. During lower flow years, base flow levels are achieved by the end of August (Figure 4). In years where flows are higher, base flows are achieved early to mid-September. The 17-year average of mean daily flows at Wisdom is 386 cfs on July 1st, declining steadily until they fall below 100 cfs on August 1st (Table 5). From August 22nd to September 9th, the lowest average of mean daily flows is below 40 cfs for 17 days.

Table 5- Summary statistics for average of mean daily flows at Wisdom and Melrose from 7/1 to 9/30.

Location	Avg. of Mean Daily Flow cfs on July 1st	Peak Flows for Mean Daily Flow cfs	Date of Peak Avg. of Mean Daily Flow cfs	# Days that Avg. of Mean Daily Flow Below 40 cfs	Avg. of Mean Daily Flow cfs on Sept. 30th	Avg. of Std. Dev. cfs (July, Aug., Sept.)	Range of Std. Dev. cfs (July, Aug., Sept.)
Wisdom	386	386	7/1	42	46	20	19-538
Melrose	2262	2262	7/1	0	339	410	97-1734

At Melrose, all years are at their highest flows during the first week of July. The average of mean daily flow stays between 2200 and 500 cfs from July 1st to August 3rd and flows remain below 500 cfs through September. The lowest flows are seen between August 21st and September 16th where the average of mean daily flow is less than 300 cfs.

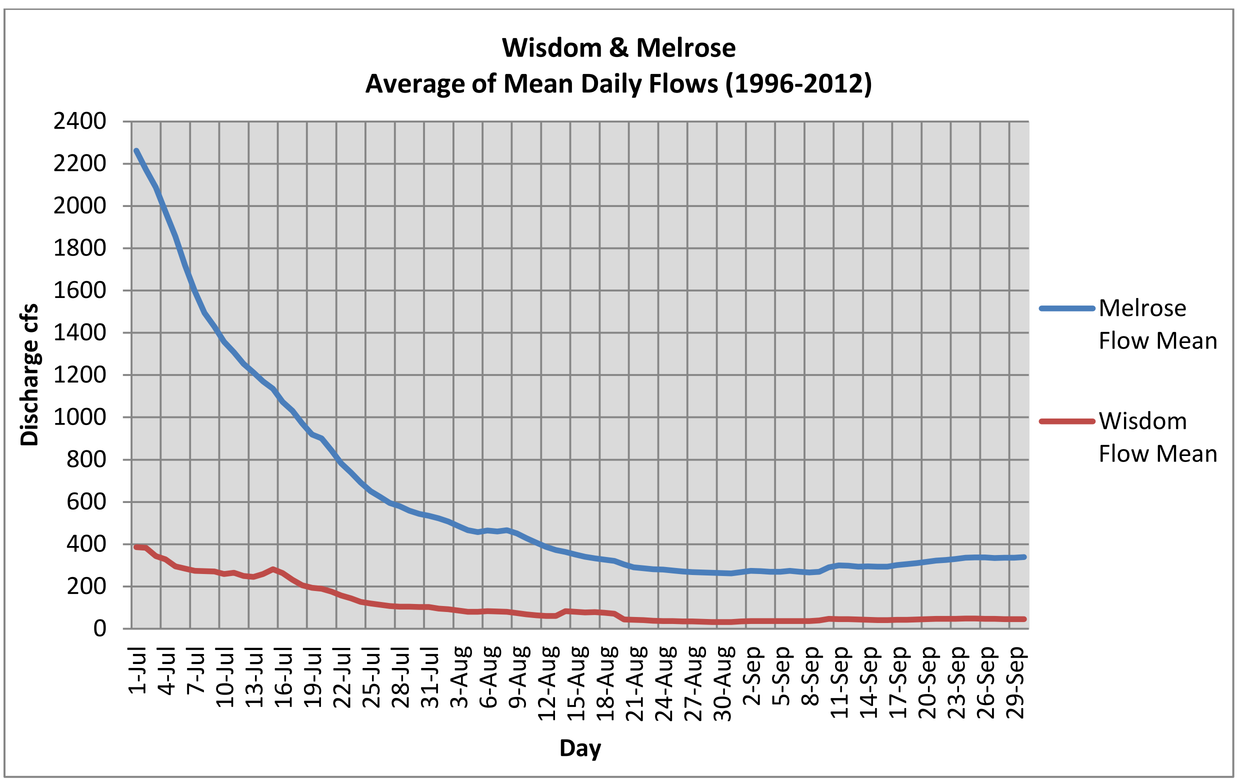

Figure 4- Comparison of the average mean daily flows for 17-years at Wisdom and Melrose.

In general, flows are highest early July and steadily decrease to their lowest values around the 1st of September, and then increase very slightly at the end of September. As to be expected, flows at Wisdom are much lower than at Melrose. For the 17-year period, standard deviations show that there is a significantly wider range in discharge from the mean of average daily flow at Melrose (Table 5).

See Appendix C for individual years graphed against these means at each location.

Water Temperature Tendencies at Wisdom & Melrose (1996-2012)

The general tendency for mean daily river temperatures at Wisdom, over the last 17-years, is a pattern of moderate warming through July, before peaking the last week of the month and cooling slowly through the end of September. More specifically, the mean (for the 17-year period) average daily water temperatures range from 54--67 °F on July 1st increasing a few degrees to between 59--71 °F around the 24th, then decline slowly to temperatures between 45--55 °F at the end of September (Figure 5). The number days over 65 °F is 11 and largely occur from July 15th to July 27th.

The general tendency for mean daily river temperatures at Melrose is comparable to what occurs at Wisdom. They display a similar pattern of moderate warming through July, before peaking near the end of July and cooling slowly through the end of September. Mean (for the 17-year period) average daily water temperatures ranged from 54--68 °F on July 1st, 60--71 °F around July 25th then, decline slowly to temperatures between 45--56 °F at the end of September (Figure 5). The number days over 65 °F is 8 and occurs from July 21st to July 29th.

Table 6- Summary statistics for mean daily water temperatures at Wisdom and Melrose.

Location	Avg. of Mean Daily Water Temps on July 1st	Peak Temps for Mean Daily Water Temps	Date of Peak Avg. of Mean Daily Water Temps	# Days that Avg. of Mean Daily Water Temps Exceed 65°F	Avg. of Mean Daily Water Temps on Sept. 30th	Avg. of Std. Dev. (July, Aug., Sept.)	Range of Std. Dev. (July, Aug., Sept.)
Wisdom	62.9	65.9	7/24	11	50.1	3.0	1.7-4.6
Melrose	61.6	65.7	7/23	8	51.8	2.7	1.7-3.9

Comparison of the averages of mean daily water temperatures between Wisdom and Melrose illustrate the similarity of general water temperature patterns (Figure 5). The mean of average daily water temperatures is about 0.5--1.6 °F cooler at Melrose until converging on July 21st, where temperatures remain closely the same until approximately August 10th. From here, temperatures diverge and Melrose water temperatures tend to become slightly warmer than Wisdom by about 0.5--2.2 °F. The difference of this divergence increases marginally from a 0.5°F to 1.7° by end of September. For the 17-year period, standard deviations show that there is a slightly larger range in temperature from the mean of average daily water temperature at Wisdom (Table 6).

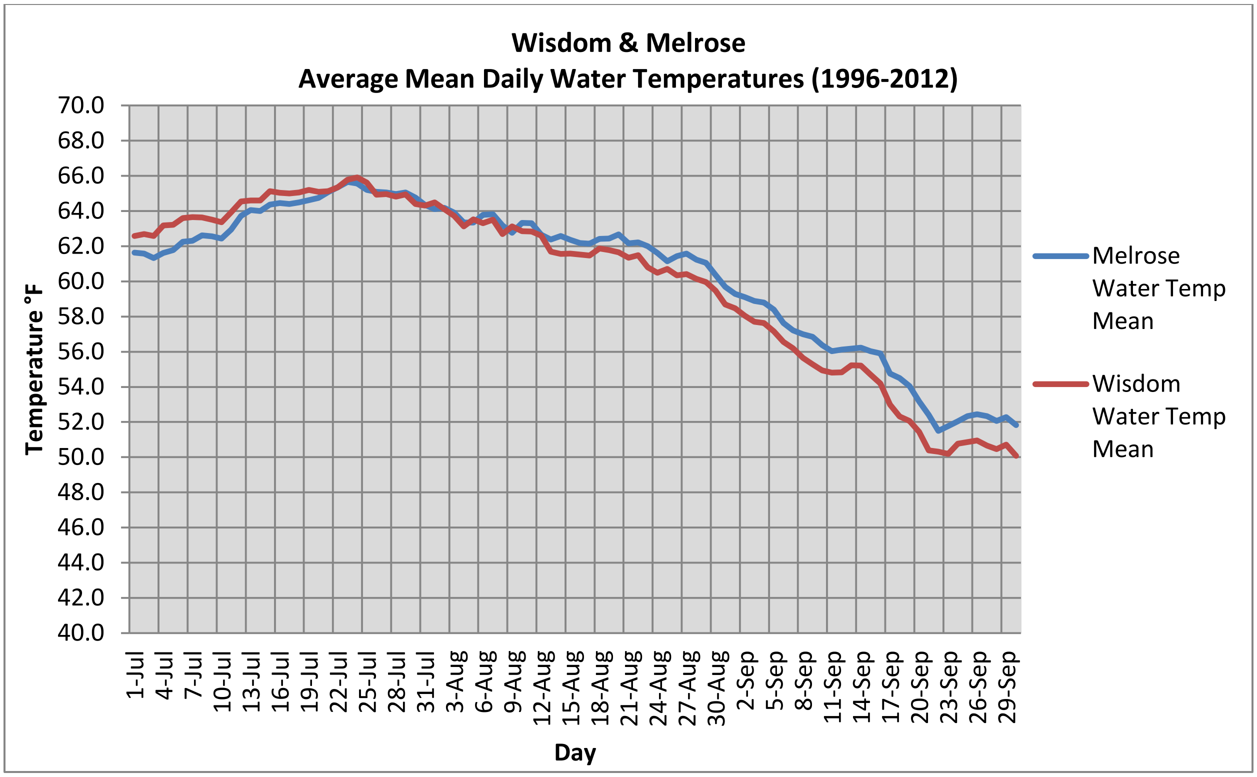

Figure 5- Comparison of average mean daily water temperatures for 17-years at Wisdom and Melrose.

See Appendix D for individually graphed years against these means for each location.

Occurrences of Hourly Water Temperatures Exceeding 70°F & 77°F at Wisdom & Melrose (1996-2012)

One of the primary goals of the DMP and restoration efforts is to minimize stress on fisheries by preventing stream temperatures from exceeding two critical temperature thresholds (BHWC, 1997). Total hours exceeding 70°F and 77°F were tallied annually for the 17-year period along with the number of occurrences where temperatures exceeded 70°F for 8 hours a day for 3 consecutive days. The numbers of occasions are partially inflated when more than three days occurred consecutively. For instance, in the case that there were 4 consecutive days with water temperatures that exceeded 70°F for 8 hours a day, then 2 occasions would have been tallied through our analysis (using the logic function in Excel).

Data gaps from 1998 at Wisdom and from 1996 and 1997 at Melrose may have caused our analysis to indicate fewer hours exceeding 70°F or 77°F than actually occurred.

Hourly Occurrences by Year with Water Temperatures Exceeding 70°F and 77°F

At Wisdom, water temperatures exceeded 70°F every year in the 17-year period evaluated. During eight of the years, over 200 hours of 70°F plus temperatures were recorded (Figure 6). Five of the years also had water temperatures over 77°F, but at relatively low frequencies. The lowest numbers of 70°F water temperatures occurred in 1997 and 2011, where total hours recorded were 42 and 21, respectively.

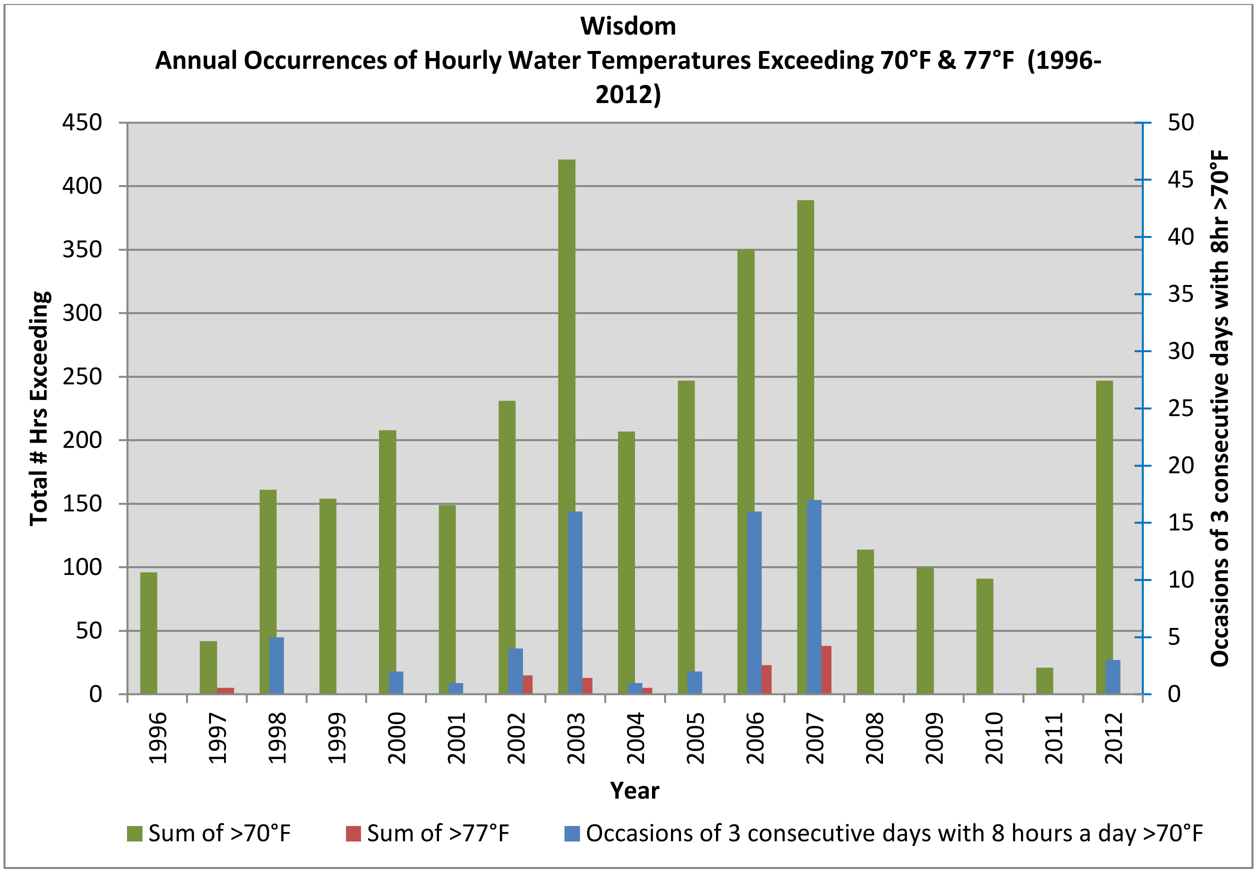

Figure 6- Annual occurrences of water temperatures exceeding 70°F and 77°F from June through September at Wisdom. [The scale for green and red bars is on the left axis of the graph and the scale for blue bars is on the right axis.]

Three consecutive days with 8 hours a day of water temperatures greater than 70°F occurred during 10 of the 17-years evaluated. The frequency of occurrence was highest during 2003, 2006 and 2007 (16-17 times). These years had the warmest water temperatures with each having more than 350 hours exceeding 70°F and 16-38 hours exceeding 77°F. Three consecutive days with 8 hours a day of water temperatures greater than 70°F occurred only once in 2001 and 2004; and twice in 2000 and 2005. Water temperatures exceeded 70°F for at least 150 hours during each of the 10 years noted.

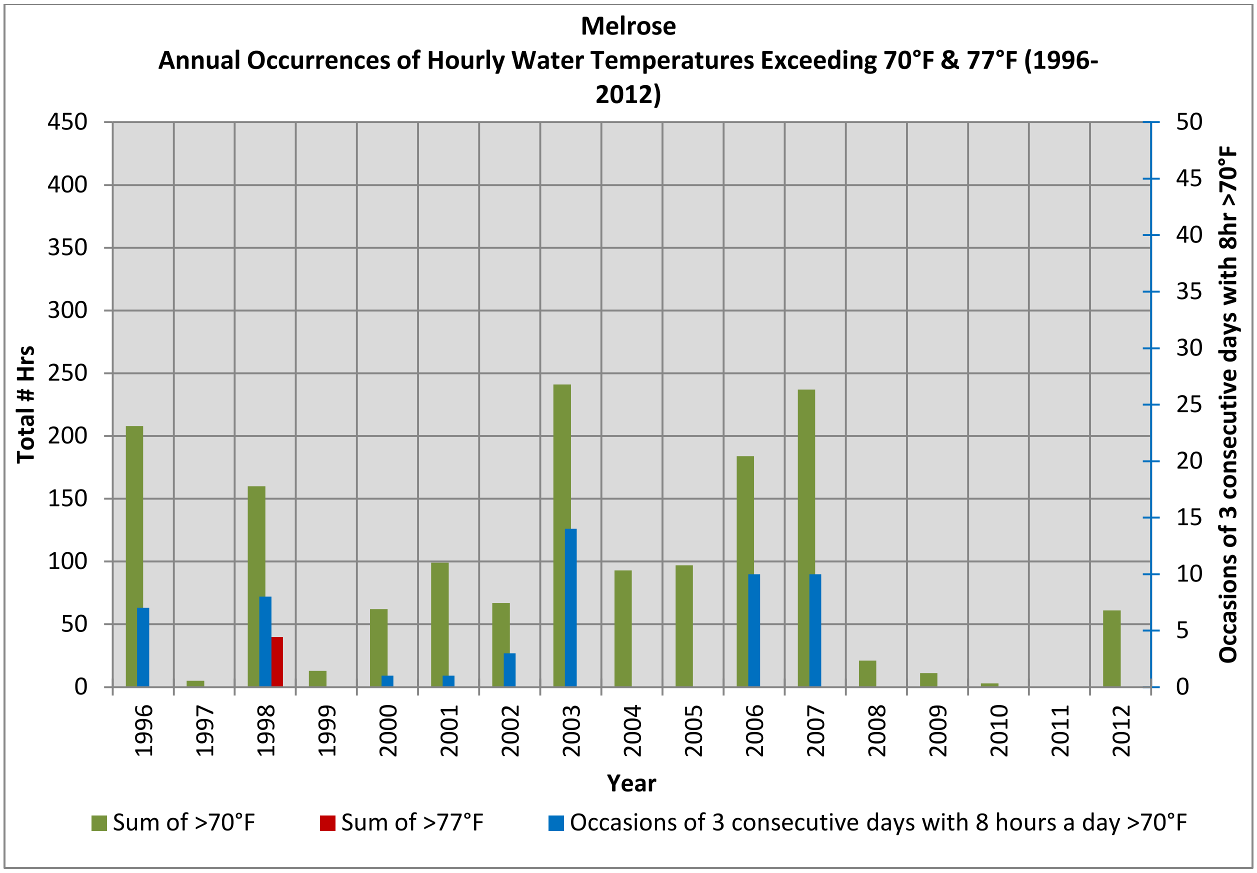

Figure 7- Annual occurrences of water temperatures exceeding 70°F and 77°F from June through September at Melrose. [The scale for green and red bars is on the left axis of the graph and the scale for blue bars is on the right axis.]

At Melrose water temperatures exceeded 70°F every year within the 17-years evaluated except 2011, which was a year of significantly high runoff (Figure 7). While the occurrence of high temperatures was common from year to year, total hours were less than half of what occurred at Wisdom. Three of the 17-years: 1996, 2003, 2007 had over 200 hours with water temperatures greater than 70°F.

Extreme temperatures were uncommon, with greater than 77°F recordings only in 1998. The total number of hours that year (40) however, was substantially greater than the highest number of hours seen at Wisdom (17, 2007) during the evaluation period.

Low numbers of greater than 70°F water temperatures were recorded in 1997, 1999, 2008, 2009 and 2010, where total hours ranged from 3 to 21. Eight of 17-years had occasions of three consecutive days with 8 hours a day with water temperatures over 70°F. These occasions occur in years that have over 60 total hours exceeding 70°F. The highest number of occurrences happened in 2003, 2006, and 2007, ranging from 10-14 times. The total hours exceeding 70°F, for those years ranged from 184-241.

Hourly Frequencies by Month and Day for Water Temperatures Exceeding 70°F and 77°F

We analyzed the frequencies of hourly water temperatures exceeding 70°F and 77°F by month and day for the 17-year evaluation period. While the majority of this report focuses on information from July through September, we found water temperatures that exceeded 70°F during June in some years. For this reason, we included June water temperatures in this part of the analysis to fully understand the pattern of occurrence for high water temperatures.

At Wisdom high water temperatures occurred as early as June 1st and as late as September 25th. However, they primarily tended to occur with notable frequencies between the 3rd week in June and the end of August (Figure 8). The frequencies of greater than 70°F water temperatures at Wisdom are approximate to a normal distribution with a peak on July 21st (Figure 8). We found that 90% of the greater than 70°F temperatures (distributed evenly on both sides of the peak) occurred between June 25th and August 18th (Figure 8). These data suggest that before June 25th and after August 18th, the circumstances which cause high water temperatures are less frequent.

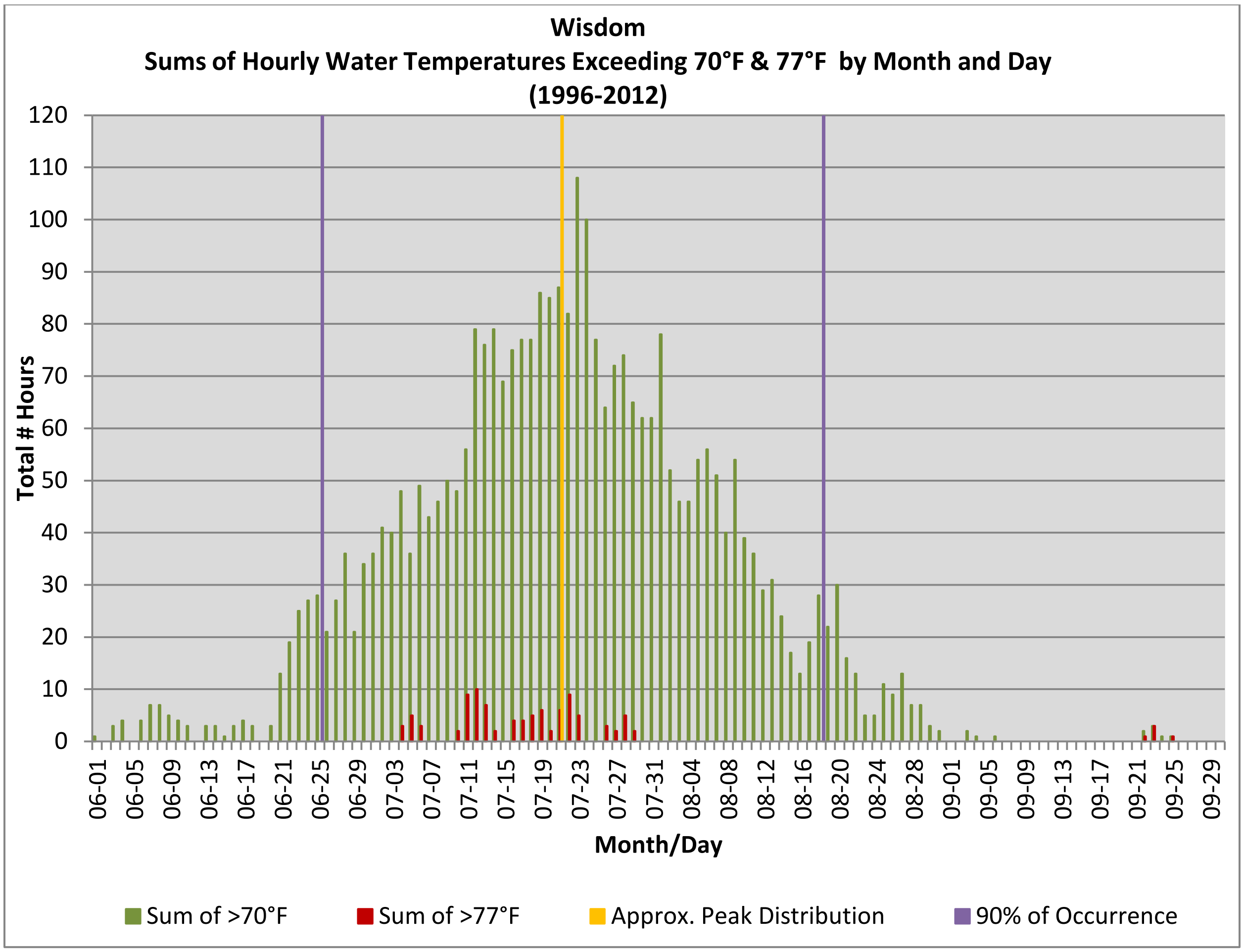

Figure 8- Sums of hourly water temperatures exceeding 70°F and 77°F by month and day at Wisdom from June through September.

Water temperatures tend to exceed 77°F mostly between July 4th and July 29th, but occur infrequently. The 77°F temperatures depicted at the end of September all occurred in 1997. It is our opinion that this data is incorrect, but we were unable to determine for certain this inaccuracy or if extremely uncommon circumstances were the cause.

The most common period of the day for water temperatures exceeding 70°F is from 2pm to midnight, and the most common time for temperatures exceeding 77°F is from 5pm to 9pm. Occurrences of temperatures greater than 70°F between 2am and noon seem to occur very rarely.

At Melrose, high temperature data from the month of June was also analyzed. In 1996, there was an uncharacteristically high concentration of hourly water temperatures greater than 70°F recorded throughout June; an occurrence which was not observed again in the following 16 years. While the data may have been accurate (or not) it tended to be an outlier when assessed against all the other years analyzed. As such it strongly skewed our assessment of general tendency for the analysis period. For this reason, the June-1996 data were excluded from this segment of our analysis- the frequencies of hourly water temperatures exceeding 70°F and 77°F at Melrose. However, to reduce this bias, graphs were developed to show the cumulative days that occurred with water temperatures exceeding 70°F and 77°F over the 17-year period for both locations. These did not exclude data points and as such, still resulted in virtually the same distribution found in Figures 8 and 9. See Appendix G.

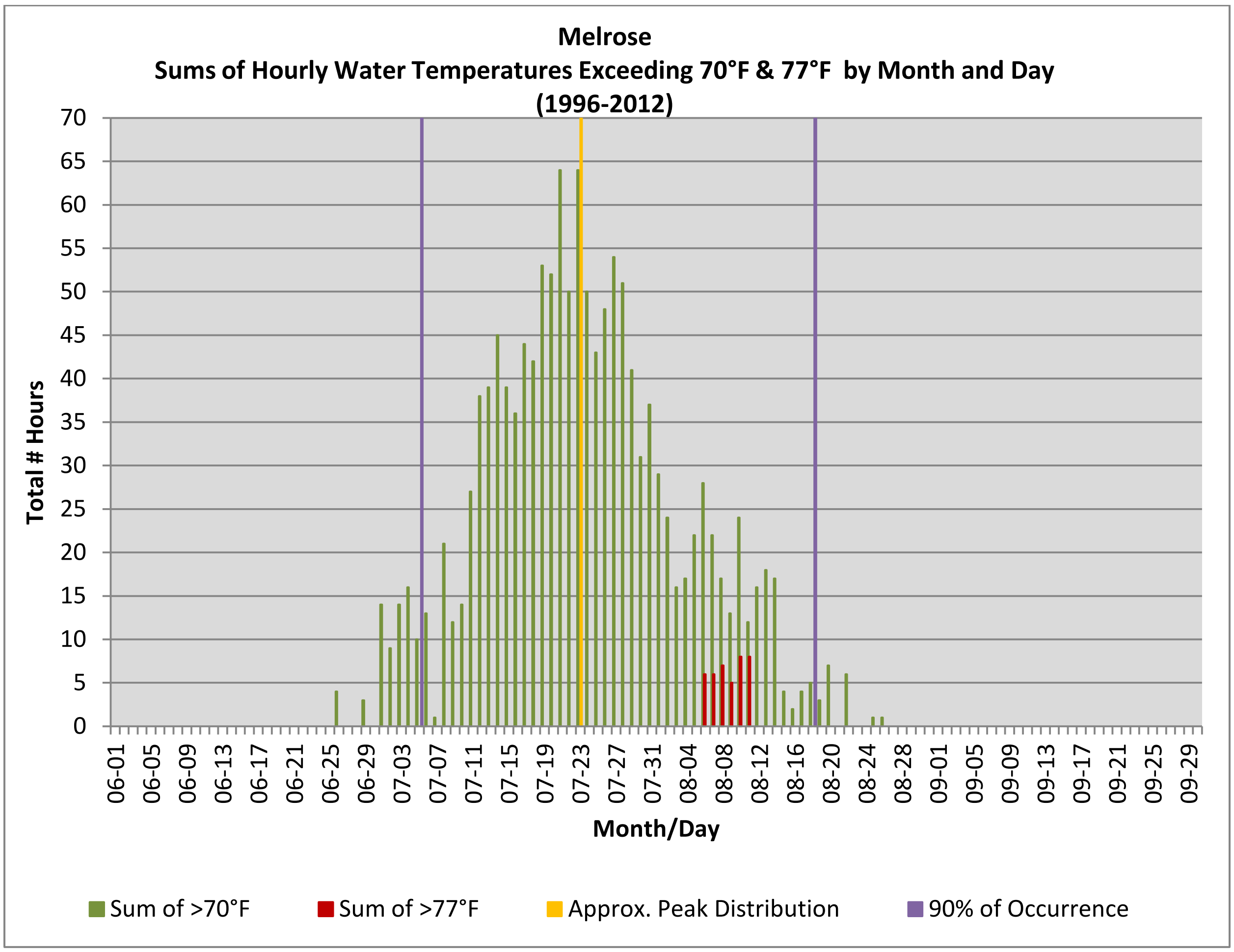

Figure 9- Sums of hourly water temperatures exceeding 70°F and 77°F by month and day at Melrose from June through September.

At Melrose water temperatures in excess of 70 °F began to occur on June 26th, a few days later than at Wisdom; and occurred as late as August 28th (Figure 9). However, they primarily occurred with notable frequencies between July 1st and August 13th. Similar to what was observed at Wisdom, the frequencies of 70°F water temperatures approximate a normal distribution, which peaks between July 21st and the 23rd (Figure 9). Using July 23rd as the peak, we found that 90% of the 70°F temperatures (distributed evenly on both sides of the peak) occurred between July 5th and August 18th (Figure 8). These data suggest that outside this time period, the circumstances which cause high water temperatures occur less commonly.

Water temperatures at Melrose exceeded 77°F between August 5th and August 11th, but only occurred during one year; in 1998.

The most common period of the day for water temperatures to exceed 70°F is from 3pm to midnight, with some occurrences from 1am to noon. In 1998, temperatures exceeded 77°F, between 1pm and 7pm.

Comparing the tendencies for high water temperatures between the two sites, Melrose exhibits a tendency for 70°F plus water temperature occurrences to peak at about the same time as Wisdom (between July 21st and July 23rd). Also, the timeframe representing the period of greatest likelihood for high water temperatures tends to end at the same time (August 18th). However, it begins about 11 days later at Melrose than at Wisdom (July 5th vs. June 25th).

The period of most common 70°F plus temperatures shared by both locations is from about July 1st to August 18th. For the remainder of our analysis, we focused on data within this period in an attempt to better understand the relationships between high water temperatures, air temperatures and flows.

See Appendix E for individually graphed frequencies of hourly water temperatures over 70°F and Appendix F for yearly graph of hourly water temperatures over 77°F.

Annual Deviations from the 17-Year Average of Daily Maximum and Minimum Air Temperatures (1996-2012)

In order to evaluate air temperature differences between years, daily maximums and minimums were evaluated against the 17-year averages. Daily temperature deviations (plus or minus from the 17-year average) were summed, and then totaled for a six week period between July 1st to August 18th (which represents the period of greatest tendency for water temperatures to exceed 70°F at both Wisdom and Melrose). Summed totals that are positive indicate a general tendency for air temperatures to be warmer than an average year and those which are negative indicate a colder than average year. The magnitude of difference between totals provides a general scale to compare warm and cold years. Some daily air temperature data are missing from both locations in most years, and occur randomly. At Wisdom, missing data were more common from 2002 to 2012 and at Melrose, data gaps tended to occur more from 1996-2003.

Daily Maximum Air Temperatures

As might be expected, maximum air temperature data generally indicate a tendency for conditions to be similarly warmer or colder at Wisdom and Melrose during the same year (Figure 10). This was not necessarily the case in years where temperatures were close to the 17-year average (1996, 2002, and 2005). However, the differences in deviation, from the 17-year average, between the two locations during those years were not substantially different from what occurred during other years (1997, 2007, 2010 and 2011).

At Wisdom, 9 of the 17-years had daily maximum air temperatures that were warmer than the 17-year average (Figure 10). Years 2003 and 2007 were substantially warmer than all other years at both locations. Years 1997 and 2009 were the coldest years at Wisdom. Years 2009 and 2010 were the coldest on average at Melrose.

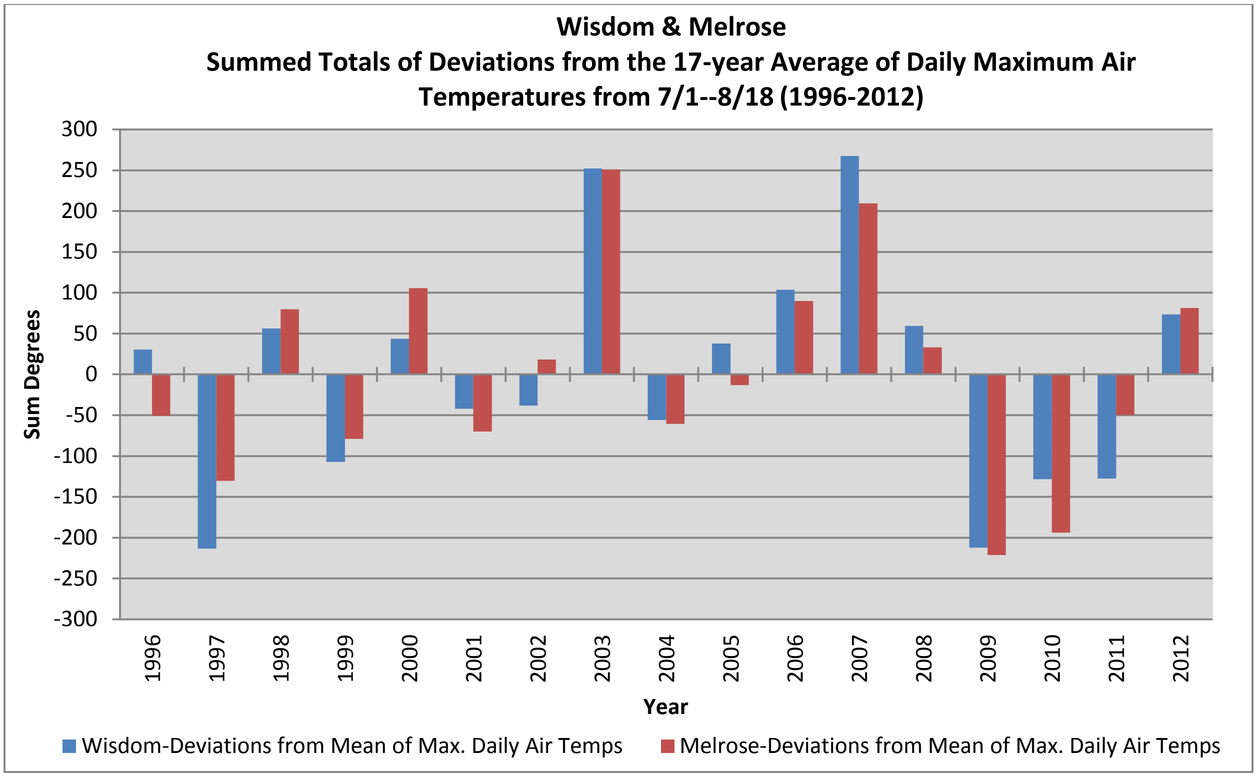

Figure 10- Annual deviations (summed °F) from the 17-year averages of daily maximum air temperatures at Wisdom and Melrose.

Daily Minimum Daily Air Temperatures

As with maximum air temperatures, data generally indicate a tendency for minimum air temperatures to be similarly warmer or colder at both locations during the same year, except in some instances when they were near the 17-year average (Figure 11). One notable difference, however, is the tendency for total deviation (from the 17-year average) in minimum air temperatures to vary more substantially in magnitude between locations (years 1998, 2007, and 2012).

At Wisdom, 7 of the 17-years had warmer minimum daily air temperatures than the 17-year average; while at Melrose, 6 of the 17-years were warmer (Figure 11).

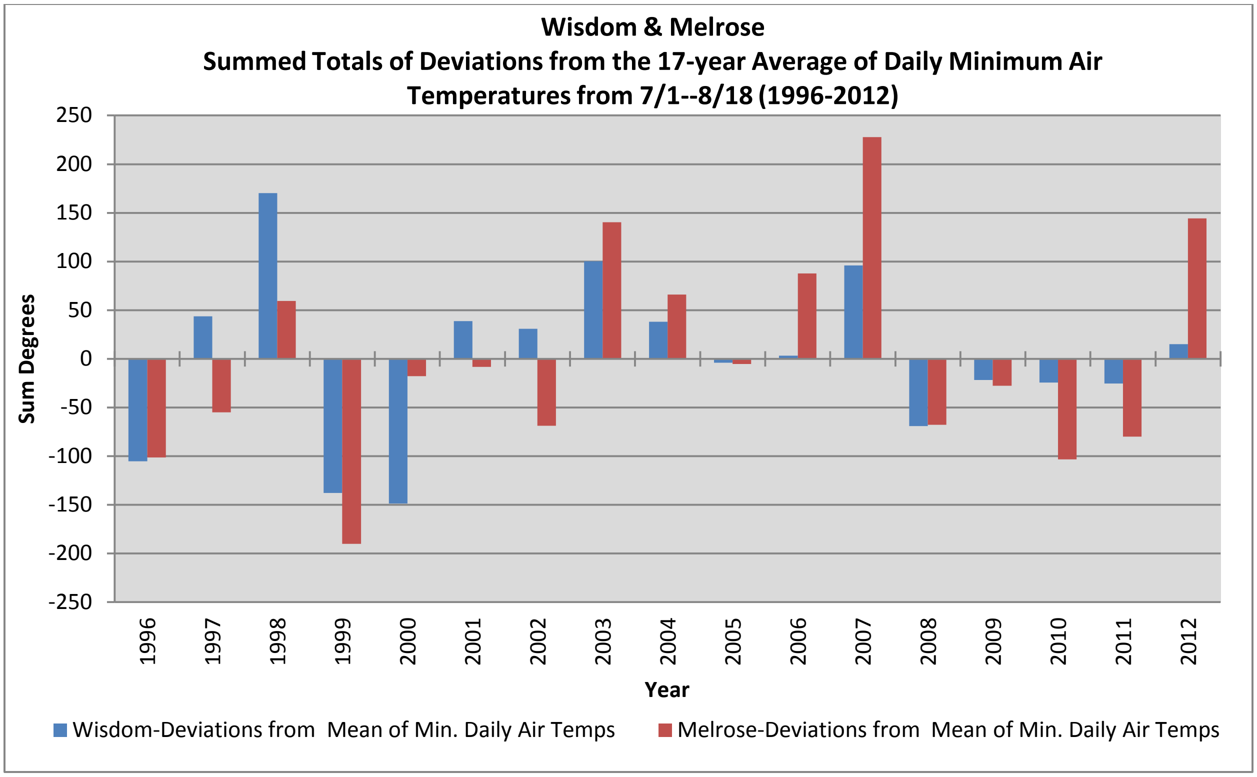

Figure 11- Annual deviations (summed °F) from the 17-year averages of daily minimum air temperatures at Wisdom and Melrose.

The three warmest years at Wisdom were in 1998, 2003, and 2007. The three warmest at Melrose were 2003, 2007, and 2012. In years where both locations had warmer minimum temperatures than average, they were warmer at Melrose except in 1998 when Wisdom has considerably warmer minimum daily air temperatures. In recent warm years since 2003, Melrose appears to have had much warmer minimum daily air temperatures than Wisdom.

Annual Deviation from the 17-Year Averages of Mean Daily Streamflows (1996-2012)

In order to evaluate streamflow differences between years, mean daily discharges were evaluated against the 17-year averages. Daily deviations (plus or minus) from the average were summed, and then totaled for a six week period between July 1st to August 18th (which represents the period of greatest tendency for water temperatures to exceed 70°F at both Wisdom and Melrose). Summed totals that are positive indicate occurrence of flows that were higher than an average year and those which are negative indicate flows lower than average. The magnitude of difference between totals provides a general scale to compare low flow versus high flow years.

As would be expected, there is a tendency for flows at Melrose to deviate from the 17-year average with greater magnitude than occurs at Wisdom (Figure 12). This is primarily because flows there are usually orders of magnitude greater than those upstream. Thus, a 5% change in flow at Melrose would result in substantially more cfs than a 5% change at Wisdom.

At Wisdom, 12 of the 17 had below average flows. However, for two of those years (2008 and 2009), they were only marginally below the average (Figure 12).

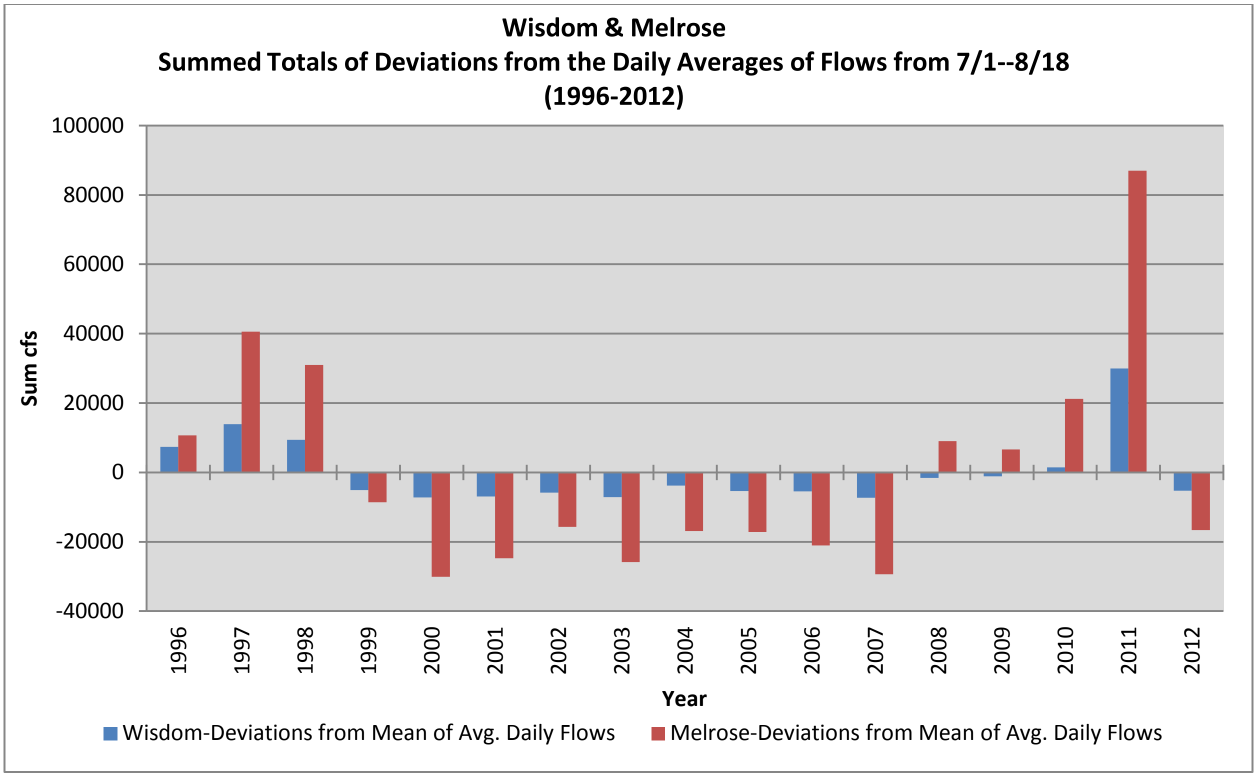

Figure 12- Annual deviations (summed cfs) from the 17-year averages of daily average flows at Wisdom and Melrose.

The greatest deviation from average flows occurred in 2011 for both locations. The years 1996, 1997, 1998 and 2011 were the only years where stream flows at Wisdom were substantially better than average. At Melrose those same years represented better flow years along with 2010 (Figure 12). In 2008 and 2009, when Wisdom was slightly below average, Melrose had flows that were above average.

Annual Deviation from the 17-Year Averages of Mean Daily Water Temperatures (1996-2012)

In order to evaluate differences between years, mean daily water temperatures were evaluated against the 17-year averages. Daily deviations (plus or minus) from the average were summed, and then totaled for a six week period between July 1st to August 18th (which represents the period of greatest tendency for water temperatures to exceed 70°F at both Wisdom and Melrose). Summed totals that are positive, indicate occurrence of temperatures that were higher than an average year and those which are negative indicate temperatures lower than average. The magnitude of difference between totals provides a general scale to compare warm water temperature years versus cooler water temperature years.

At Wisdom, 8 of 17-years exhibited warmer than average water temperatures. This was also the case at Melrose during 9 of the 1- years evaluated (Figure 13).

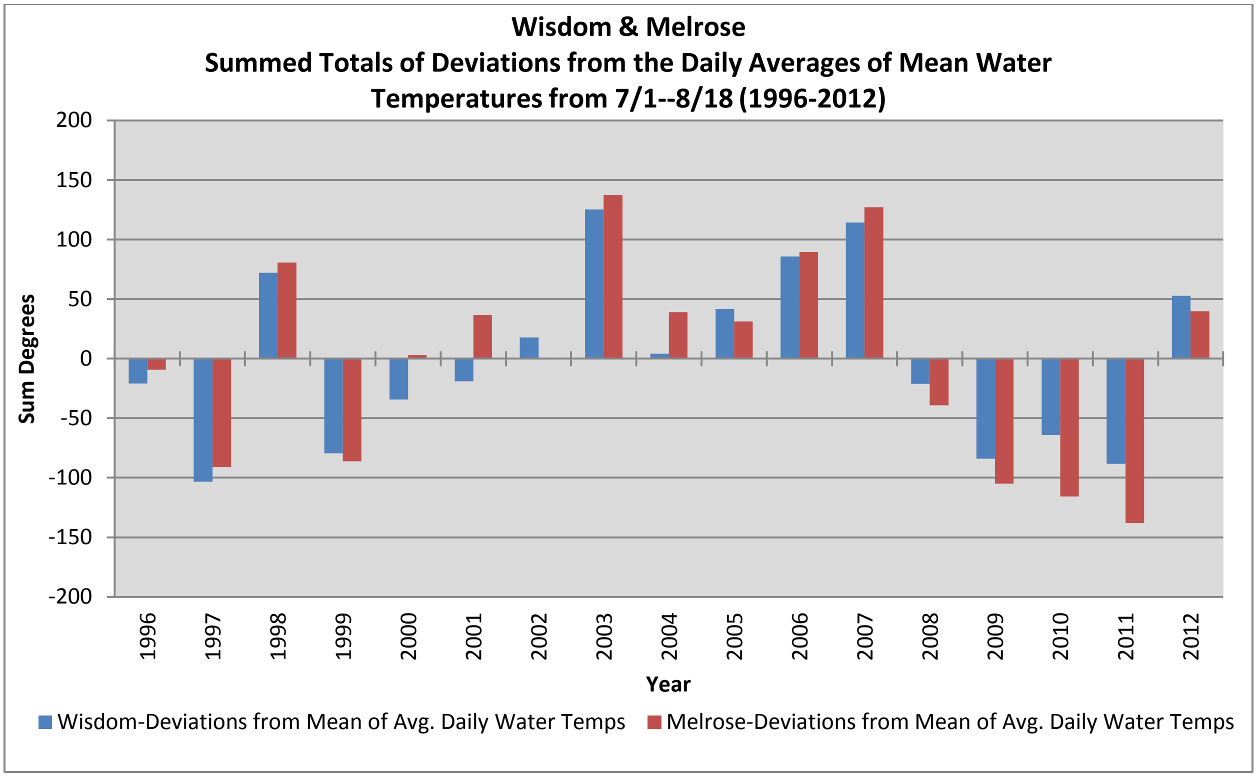

Figure 13- Annual deviations (summed °F) from the 17-year averages of mean daily water temperature at Wisdom and Melrose.

As might be expected, water temperature data generally indicates a tendency for conditions to be similarly warmer or colder at Wisdom and Melrose during the same year (Figure 13). This was, however, not always the case. In 2000 and 2001, Wisdom was cooler than the 17-year average while Melrose was warmer. However, in 2002, the situation was reversed where Wisdom was warmer than the 17-year average while Melrose was essentially equal to the 17-year average. The magnitude of difference between sites was greatest for 2001, 2010 and 2011. The reason for this is not fully understood. Also, water temperatures at Melrose tended to deviate somewhat more from the average than those at Wisdom.

The four warmest years are the same for both locations; they were 1998, 2003, 2006, and 2007. Five of the years evaluated were notably cooler than the average for both sites. They were 1997, 1999, 2009, 2010 and 2011.

Comparing Annual Patterns for Water Temperatures, Air Temperatures and Stream Flows (1996 – 2012)

For comparison, the patterns of deviation from the 17-year averages for mean daily water temperature, maximum and minimum daily air temperatures, and average daily streamflow are displayed together (Figures 14 and 15) for Wisdom and Melrose.

Annual tendencies at Wisdom

There are no obvious or strongly indicated tendencies between mean daily water temperature, maximum and minimum daily air temperatures, or average daily flow at Wisdom. However, it appears that mean daily water temperatures are more consistently correlated with daily air temperatures than any other variable evaluated

(Figure 14). Inconsistencies tended to be most common when conditions were near the 17-year averages. Mean daily water temperatures seemed to have tendencies similar to minimum daily air temperatures except in 1997 and 2001.

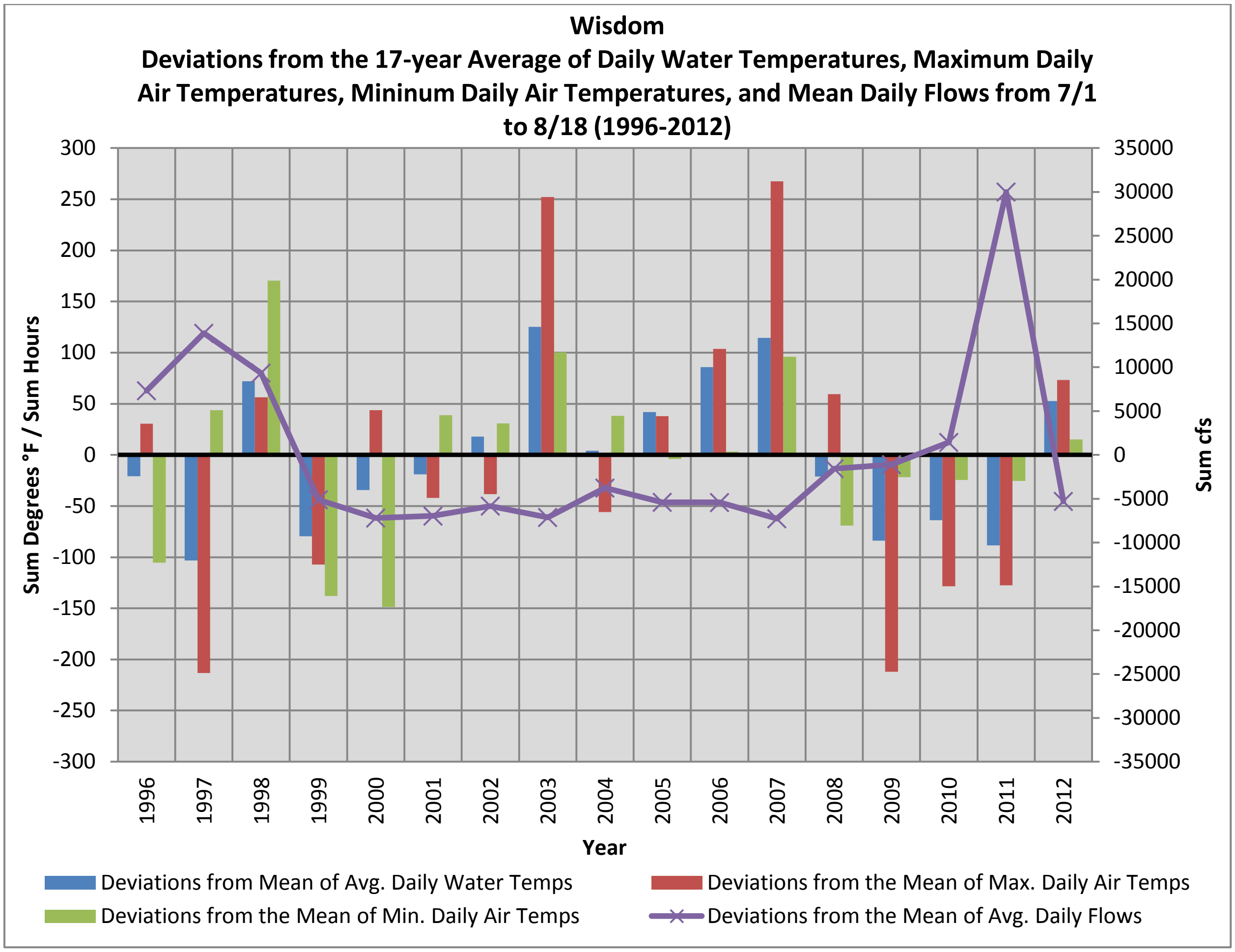

Figure 14- Annual comparison of mean daily water temperature, maximum and minimum daily air temperatures, and mean daily flows from a 17-year period at Wisdom.

Comparisons between annual tendencies for mean daily flows and mean daily water temperatures failed to reveal any obviously consistent relationships (Figure 14). As might be expected, water temperatures were warmest in 2003, 2006 and 2007, when streamflows between 7/1 and 8/18 were substantially below the 17-year average. However, low flow conditions observed in 2000, 2001, and 2002 were similar to 2003, 2006 and 2007, but water temperatures remained near the average. In 1999, flows were well below average conditions, but so were water temperatures. In 1998 streamflows were well above average as were water temperatures; however we cautiously note that data gaps in water temperatures occurred frequently that year. However, data gaps did not occur in Melrose (Figure 15) during 1998 and the pattern of deviation closely resembles what occurred at Wisdom.

Annual Tendencies at Melrose

Similar to Wisdom, there are no obvious or strongly indicated tendencies between mean daily water temperature, maximum and minimum daily air temperatures, or average daily flow at Melrose. However, mean daily water temperatures were more consistently correlated with daily maximum air temperatures than any other variable evaluated; especially when water temperatures were substantially warmer or colder than the 17-year average (Figure 14). Inconsistencies tended to be most common when conditions approached the averages. Similarities in the patterns for mean daily water temperatures and minimum daily air temperatures seemed to be fewer than at Wisdom (Figure 14).

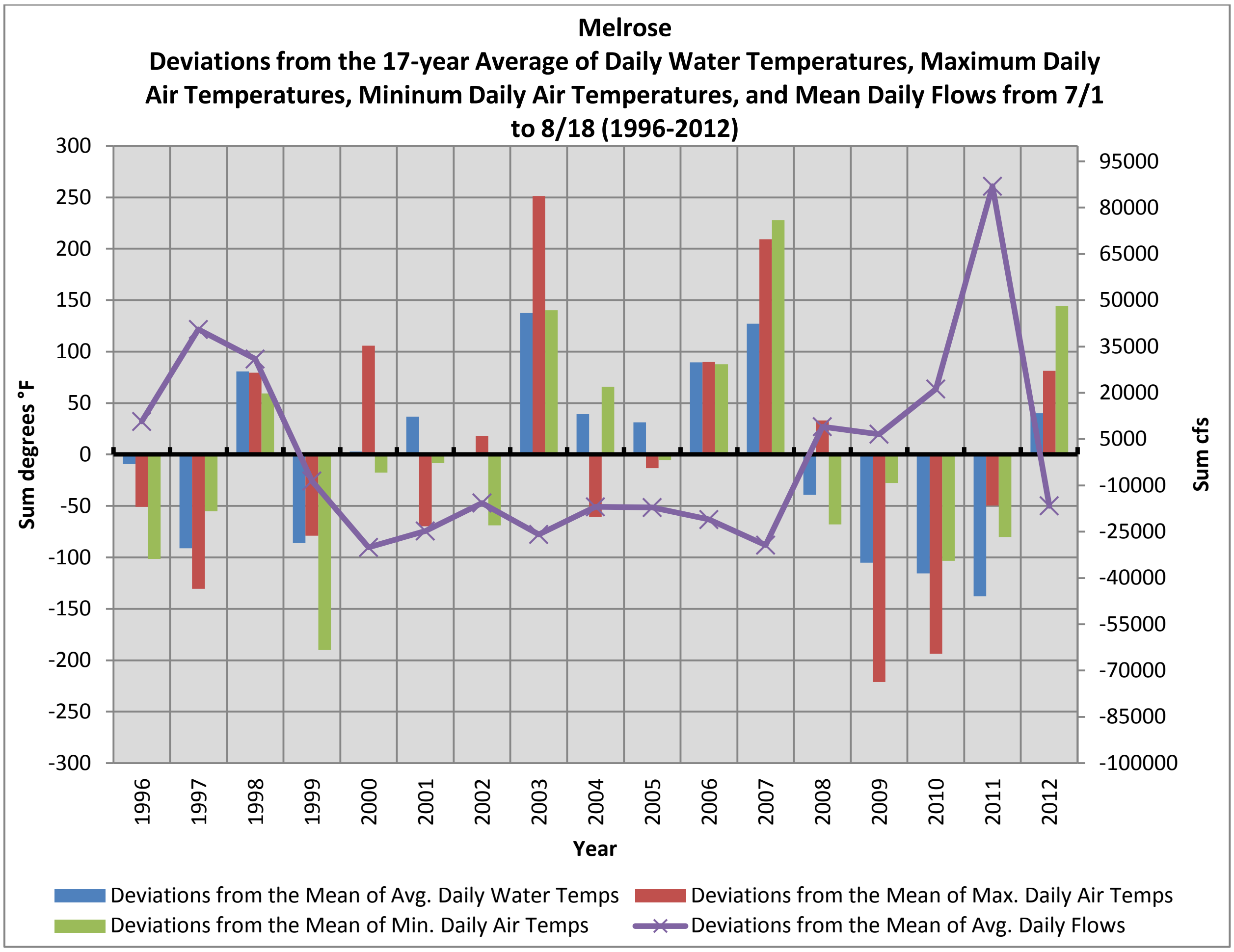

Figure 15- Annual comparison of mean daily water temperature, maximum and minimum daily air temperatures, and mean daily flows from a 17-year period at Melrose.

Direct comparisons between annual tendencies for mean daily flows and mean daily water temperatures failed to reveal any obviously consistent relationships at Melrose (Figure 15). Similar to Wisdom, water temperatures were warmest in 2003, 2006 and 2007, when streamflows were substantially below the 17-year average. However, low flow conditions observed in 2001, 2002 and 2004 were similar to 2003, 2006 and 2007, but water temperatures remained near the average. In 1998 streamflows were well above average when stream temperatures were also warmer than average. In 1999 flows were below average conditions, when stream temperatures were notably cooler than average. These data show a lack of correlation between flow and temperature patterns where data are analyzed at a coarse scale (e.g. annually).

In 2000, 2001 and 2004, water temperatures were especially inconsistent with what we'd expect, based on streamflow and maximum air temperatures. In 2000, flows were well below average and maximum air temperatures were well above average, but water temperatures were essentially at the 17-year average. In 2001 and 2004, stream flows and maximum daily air temperatures were well below average, but stream temperatures were above average (Figure 15). Frequent data gaps occurred in 2001 daily air temperatures (see Appendix A) and may be portraying an inaccurate picture of conditions; however tendencies for these variables were very nearly the same between 2000 and 2004 where the data were more complete.

A more specific look at the annual tendencies for water temperatures over 70°F, streamflow, maximum air temperatures and the deviations from the 17-year average for mean daily water temperatures are provided in Table 7. We note that hourly water temperatures exceed 70°F even during summers when mean daily water temperatures were below (e.g. cooler than) the 17-year average. During those years, the average number of hours over 70°F at Wisdom and Melrose were 96 and 13, respectively during a 6 week period from 7/1 to 8/18.

During years when mean daily flows were higher, there tended to be fewer hours with water temperatures exceeding 70°F, but high flows did not prevent high water temperatures. In 2011, which was a year of significantly high snowpack and the highest flow year in our period of analysis, there were no hourly occurrences with water temperatures greater than 70°F recorded from 7/1 to 8/18 at Melrose; however 21 hours of 70°F plus temperatures occurred at Wisdom. Interestingly, they occurred from July 3rd to July 6th when the average daily flows approximated 1350 cfs. During this period, a spike in maximum and minimum daily air temperatures occurred, which seemed to correlate with the warm water temperatures. Another possible contribution to warm water temperatures, especially where it is prominently practiced in the upper watershed, may be from heated surface irrigation return; however, this is extremely difficult to quantify and we did not have data to analyze this possibility. Still, this suggests that under extreme climate conditions, streamflow has a limited capacity to buffer against high stream temperatures. Information in Table 7, suggest that years with higher frequencies of water temperatures exceeding 70°F often tend to have low flows and warm maximum daily air temperatures.

Table 7- Cumulative number hours each year (1996-2012) in which water temperatures exceeded 70°F between July 1st and August 18th at Wisdom and Melrose.

Wisdom from 7/1 to 8/18					Melrose from 7/1 to 8/18				
Summed # of Hours with Water Temperatures >70°F	Year-	Average of Mean Daily Flow cfs	Average of Daily Maximum Air Temperatures °F	Deviation from the 17 yr. average for Mean Daily Water Temperature °F	Summed # of Hours with Water Temperatures >70°F	Year-	Average of Mean Daily Flow cfs	Average of Daily Maximum Air Temperature °F	Deviation from the 17 yr. average for Mean Daily Water Temperature °F
354	2003	23	86.2	Above	**237**	2007	292	86.7	Above
326	2007	20	86.3	Above	**232**	2003	363	88.8	Above
293	2006	58	83.1	Above	**180**	2006	461	84.2	Above
228	2005	58	81.4	Above	**160**	1998	1523	85.0	Above
222	2012	60	82.8	Above	**97**	2005	541	82.1	Above
201	2002	49	79.5	Above	**94**	2001	386	79.9	Above
184	2004	91	79.2	None	**93**	2004	545	81.1	Above
171	2000	21	81.1	Below	**67**	2002	571	82.9	None
159	1998	359	81.4	Above	**62**	2000	277	85.3	None

Wisdom from 7/1 to 8/18					Melrose from 7/1 to 8/18				
Summed # of Hours with Water Temperatures >70°F	**Year-**	**Average of Mean Daily Flow cfs**	**Average of Daily Maximum Air Temperatures °F**	**Deviation from the 17 yr. average for Mean Daily Water Temperature °F**	**Summed # of Hours with Water Temperatures >70°F**	**Year-**	**Average of Mean Daily Flow cfs**	**Average of Daily Maximum Air Temperature °F**	**Deviation from the 17 yr. average for Mean Daily Water Temperature °F**
122	2001	26	79.5	Below	**61**	2012	552	84.1	Above
112	1999	64	78.1	Below	**33**	1996	1110	81.3	Below
99	2008	136	81.6	Below	**21**	2008	1075	83.1	Below
87	2010	197	77.1	Below	**9**	1999	716	79.6	Below
79	2009	146	75.3	Below	**8**	2009	1026	77.9	Below
71	1996	318	80.9	Below	**5**	1997	1718	78.6	Below
33	1997	452	75.7	Below	**3**	2010	1325	78.4	Below
21	2011	780	77.5	Below	**0**	2011	2665	81.4	Below

These data indicate that air temperatures and water temperatures seem to have some relationship, especially at Wisdom. With significantly higher volumes of average daily flow, high mean daily water temperatures may be buffered to some extent. Clarifying how air temperatures and water temperatures relate, along with how flow levels and water temperatures relate would be valuable knowledge in answering if a trend in water temperature is improving. Fully defining these relationships may be beyond the capability of the data at this point.

Common Tendencies between Daily Maximum Air Temperatures and 70°F Water Temperatures (1996-2012)

Over the 17-year evaluation period we analyzed the tendencies for high stream temperatures to increase as maximum daily air temperatures increased. The data indicated that water temperatures began to exceed 70°F with some level of consistency when maximum daily air temperatures reached 75°F.

Maximum Daily Air Temperatures and 70°F Water Temperatures

In Figure 16, the percentage of days occurring with water temperatures over 70°F are binned in ranges of maximum daily air temperatures from 75°F to >91°F. Both Wisdom and Melrose show a steadily increasing occurrence of water temperatures >70°F as maximum daily air temperatures increase.

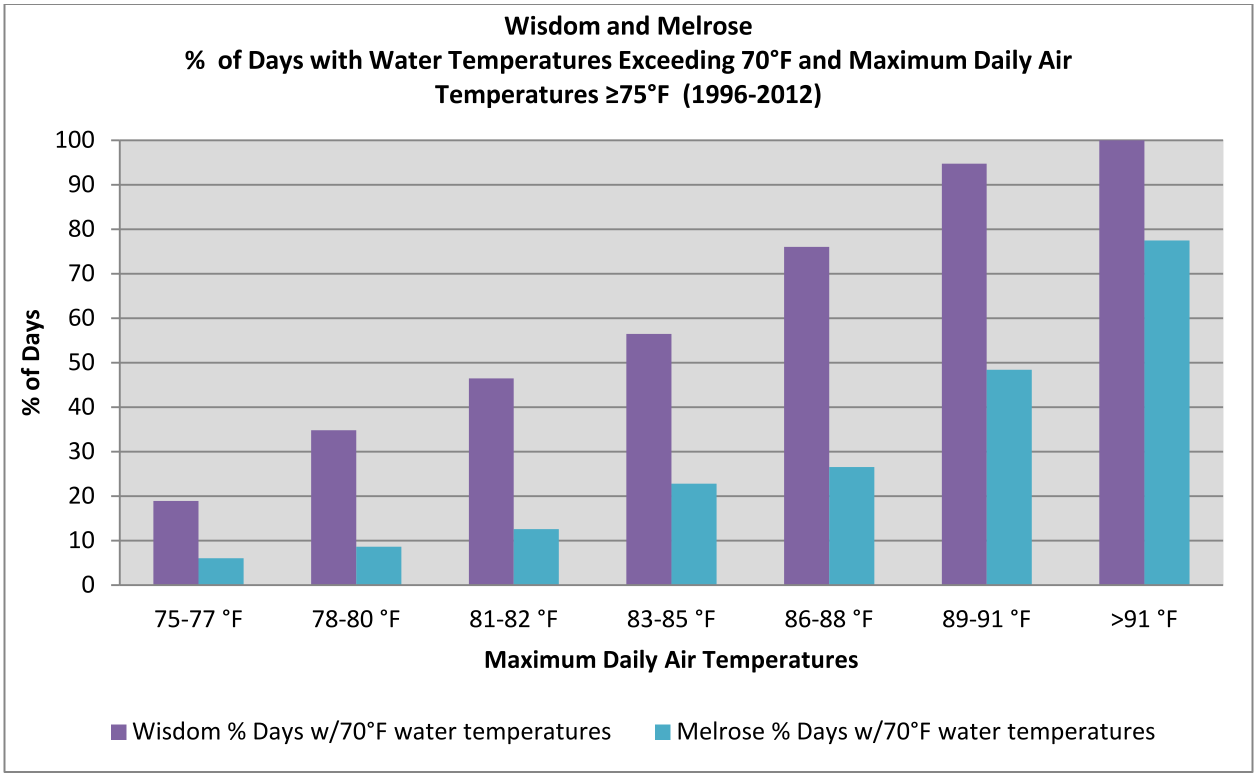

Figure 16- Changes in the likelihood of having water temperatures that exceed 70°F at Wisdom and Melrose as maximum daily air temperatures increase.

The likelihood of occurrence for 70°F water temperatures at Wisdom approached 100% whenever maximum daily air temperatures were 89°F or higher (Figure 16). At Melrose, the likelihood was lower, but still approached 80% when maximum air temperatures were > 91°F.

Table 8 presents a break-down, by month, of the data summarized above in Figure 16. At Wisdom, a total of 438 days with maximum daily air temperatures ≥75°F also have occurrences of water temperatures exceeding 70°F in July, August, and September over the last 17-years (Table 8). At Melrose, we also found the highest occurrence of warm air temperatures days are in July. Of the 407 days with maximum daily air temperatures over 75°F that took place in the last 17-years, 154 days also have occurrences with water temperatures over 70°F (Table 8). September had the fewest occurrences of maximum daily air temperatures ≥75°F totaling 173 days over the last 17-years. Only four of these days had water temperatures exceeding 70°F (Table 8). This data shows that the likelihood for high water temperatures declines substantially from July to August; and again from August to September, at both locations. When maximum daily air temperatures were greater than 75°F at Wisdom, the occurrence of 70°F water temperatures was 69%, 43% and 2% for July, August and September, respectively. For Melrose the occurrence of high water temperatures was 38%, 15% and 0% for the same months.

Table 8- Number of days by month with and without water temperatures over 70°F at Wisdom and Melrose from 1996-2012.

# of Days	Wisdom July	Wisdom August	Wisdom Sept.	Wisdom TOTAL	Melrose July	Melrose August	Melrose Sept.	Melrose TOTAL
With 70°F water temps; when Max air temps are 75-77°F	22	11	1	**34**	5	3	0	**8**
Without 70°F water temps; when Max air temps are 75-77°F	31	46	69	**146**	27	37	61	**125**
With 70°F water temps; when Max air temps are 78-80°F	59	50	0	**109**	15	6	0	**21**
Without 70°F water temps; when Max air temps are 78-80°F	52	81	71	**204**	81	76	65	**222**
With 70°F water temps; when Max air temps are 81-82°F	35	24	0	**59**	10	8	0	**18**
Without 70°F water temps; when Max air temps are 81-82°F	18	34	16	**68**	37	59	29	**125**
With 70°F water temps; when Max air temps are 83-85°F	43	30	1	**74**	19	9	0	**28**
Without 70°F water temps; when Max air temps are 83-85°F	15	37	5	**57**	33	43	19	**95**
With 70°F water temps; when Max air temps are 86-88°F	52	37	0	**89**	31	12	0	**43**
Without 70°F water temps; when Max air temps are 86-88°F	2	18	8	**28**	39	62	18	**119**
With 70°F water temps; when Max air temps are 89-91°F	41	11	2	**54**	49	13	0	**62**
Without 70°F water temps; when Max air temps are 89-91°F	2	1	0	**3**	31	31	4	**66**
With 70°F water temps; when Max air temps are >91°F	17	2	0	**19**	25	6	0	**31**
Without 70°F water temps; when Max air temps are >91°F	0	0	0	**0**	5	4	0	**9**
Total Days when Max air Temps are ≥75°F	389	382	173	**944**	407	369	196	**972**
Total Days when Max air Temps are ≥75°F with Water Temps Exceeding 70°F	269	165	4	**438**	154	57	0	**211**
% Days when Max air Temps are ≥75°F with Water Temps Exceeding 70°F	69%	43%	2%	**46%**	38%	15%	0%	**22%**

Figure 17 displays the likelihood of high water temperatures by month, as maximum daily air temperatures increase at Wisdom. Note that the tendency for high water temperatures (>70°F) is substantially lower in August than in July until maximum air temperatures reach 89°F or higher. In September, there is a much lower tendency to achieve greater than 70°F water temperatures until maximum air temperatures are 89 °F or higher. Maximum air temperatures of 86-88 °F occur with greater than 70°F water temperatures 96% of the time in July; however, there are no water temperatures greater than 70°F that occurred in September during this air temperature range.

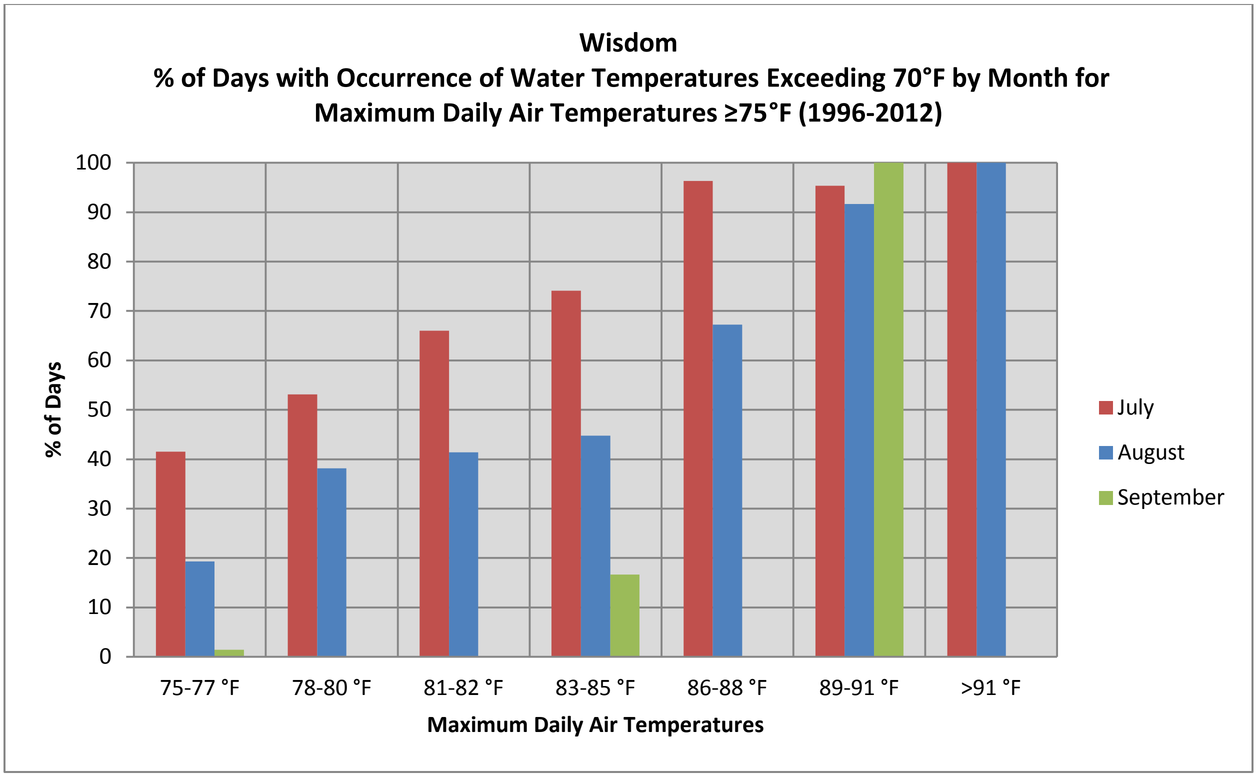

Figure 17- Changes in the likelihood of having water temperatures that exceed 70°F at Wisdom as maximum daily air temperatures increase.

Figure 18 displays the likelihood of high water temperatures by month, as maximum daily air temperatures increase at Melrose. The percentage of days increases steadily with increasing maximum daily air temperatures, and when air temperatures range from 89-91 °F, a 56% occurrence of days with water temperatures over 70°F result (Figure 18). Furthermore, when days with air temperatures greater than 91°F occur, there are 83% of days occurring with water temperatures exceeding 70°F water temperatures.

In August, only 57 days with air temperatures greater than 75°F occur also with water temperatures exceeding 70°F. The percentage of days with water temperatures exceeding 70°F stays below 20% when the maximum daily air temperatures ranged from 75-91 °F. However, when maximum air temperatures are greater than 91°F, there is a 60% chance of days occurring with water temperatures over 70°F.

No days occur with water temperatures greater than 70°F in September when maximum daily air temperatures are greater than 75°F.

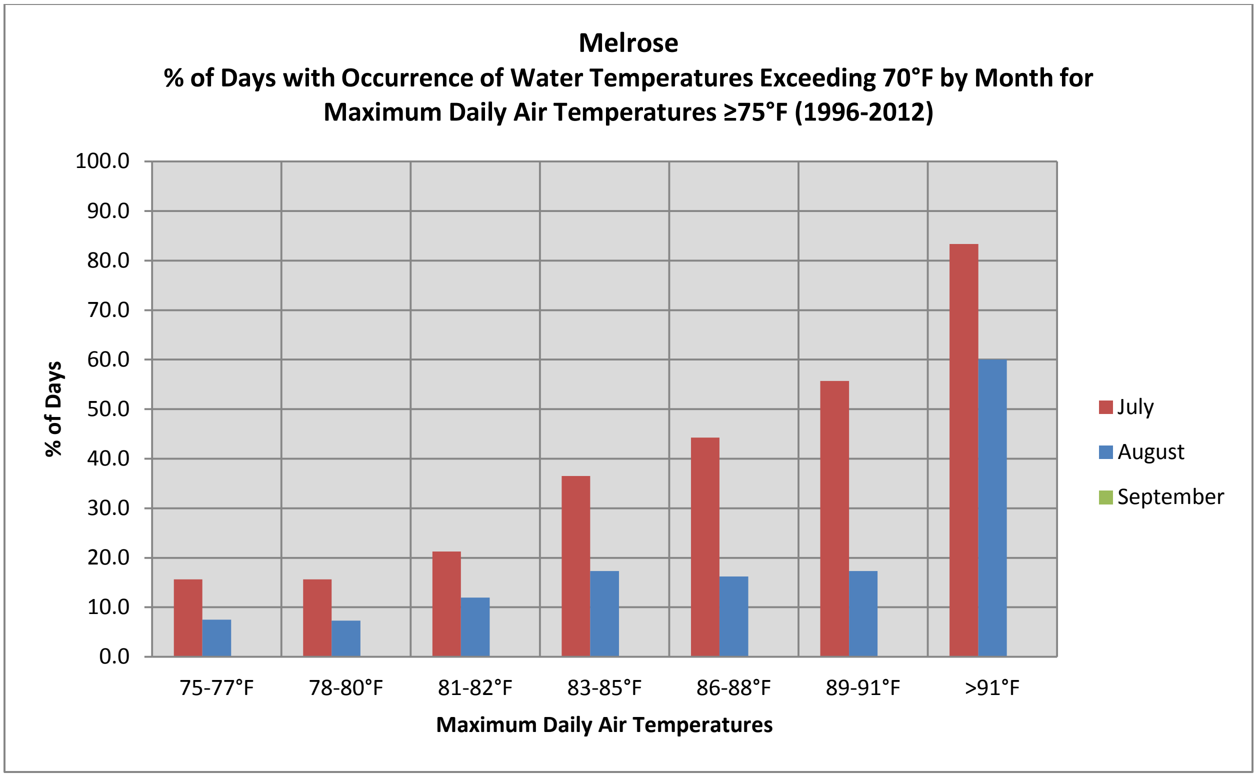

Figure 18- Changes in the likelihood of having water temperatures that exceed 70°F at Melrose as maximum daily air temperatures increase.

A much stronger relationship between high maximum daily air temperatures and high water temperatures is observed at Wisdom than at Melrose. At Wisdom, our data for the past 17-years show that when maximum daily air temperatures are greater than 91°F, water temperatures always exceed 70°F. However, at Melrose this tendency is not as strong. We know that flows are generally much higher at Melrose and that there are fewer days with water temperatures exceeding 70°F. In an attempt to determine how higher volumes of flow influence water temperatures, we analyzed the percentage of days with water temperatures exceeding 70°F at different flows regimes during the summer.

Average Daily Flows and 70°F Water Temperatures

Figures 19 and 20 display the tendency for high stream temperatures to occur as streamflow increases, by month, at Wisdom and Melrose.

At Wisdom, 497 days occur with water temperatures over 70°F (Table 9). The majority of these days happen between 0-125 cfs (Figure 19). Most days with high water temperatures happen during July, and the highest percentage of these days (25%), occurs between 26-50 cfs. Nonetheless, there were still occurrences of high water temperatures when flows increased to as high as to 550 cfs.

In August, 183 of 344 days had water temperatures over 70°F with 52% of these days occurring when flows are from 0-25 cfs. However, these high temperatures continue to result when flows are as high as 350 cfs.

In September there were only 7 days with water temperatures greater than 70° and occurred with flow levels that ranged from 0-100 cfs; four of these seven days occur between 76-100 cfs.

Table 9- Total of days, by month, with and without water temperatures that exceed 70°F for all maximum daily air temperatures.

	Wisdom July	Wisdom August	Wisdom September	WISDOM TOTALS	Melrose July	Melrose August	Melrose September	MELROSE TOTALS
# of Days Occurring with Water Temp >70°F	307	183	7	497	171	69	0	240
# of Days Occurring without Water Temps >70°F	220	344	503	1067	356	458	510	1324
Totals	527	527	510	1564	527	527	510	1564

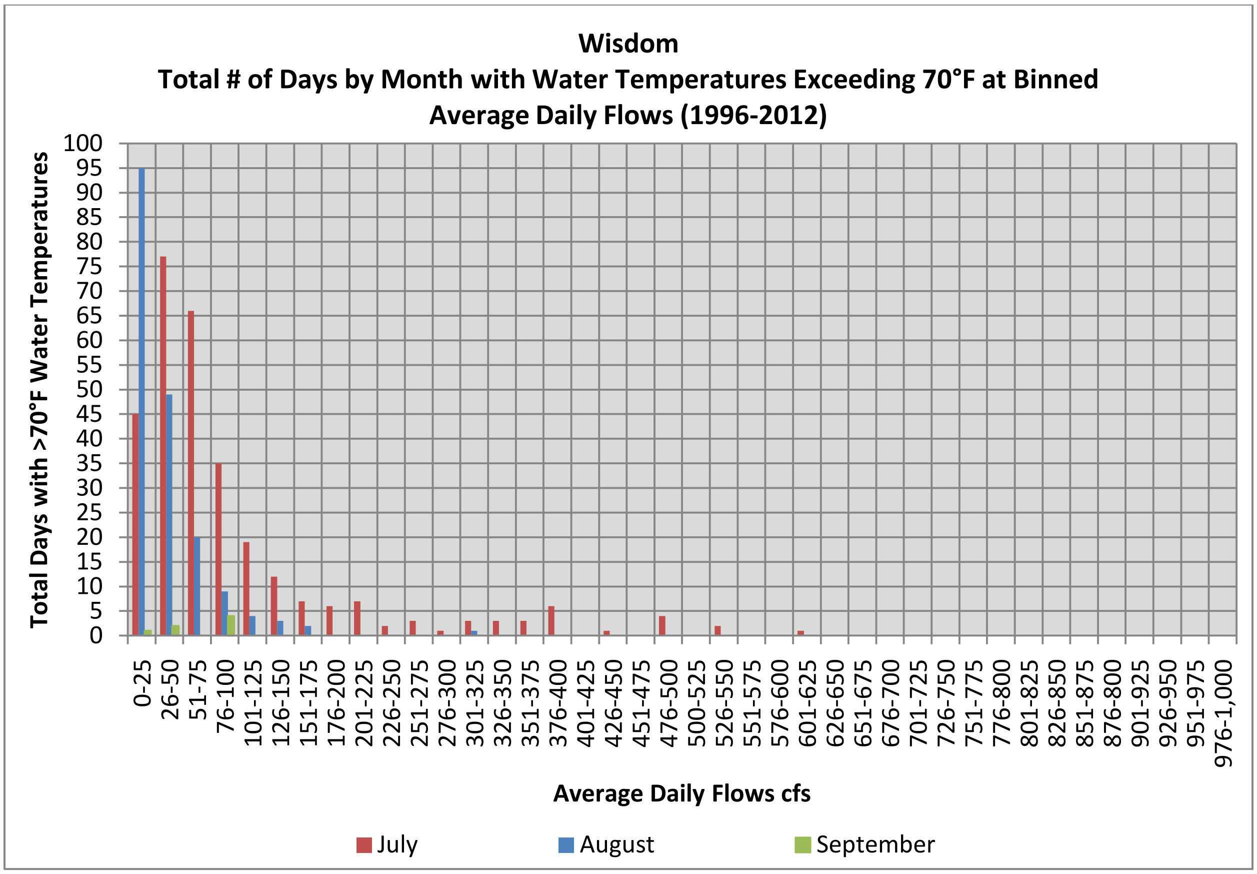

Figure 19- The number of days with water temperatures exceeding 70°F at different streamflows at Wisdom for the months of July, August, and September.

At Melrose, 240 days had water temperatures exceeding 70°F (Table 9). The range of flows for these days was from 176 to 975 cfs. Most days occurred when flows were between 176-450 cfs (Figure 20). Most days with high water temperatures occurred in July (171 days). And, the highest percentage of these days (8%) occurred between 301-325 cfs.

In August, there were fewer than 70 days that had water temperatures over 70°F. They occurred between 151 and 850 cfs with 19% happening from 201-225 cfs. No 70°F temperatures occurred in September.

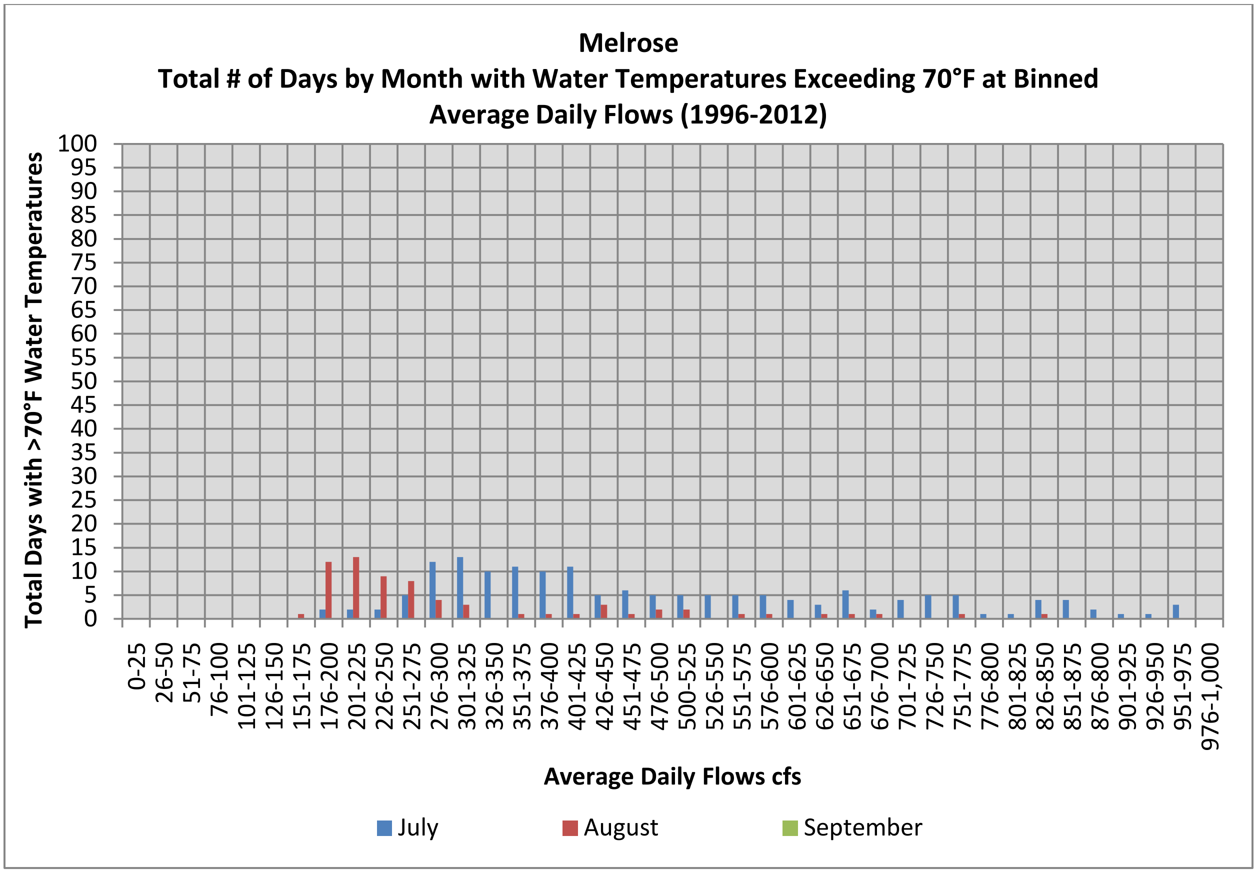

Figure 20- The number of days with water temperatures exceeding 70°F at different streamflows at Melrose for the months of July, August, and September.

While high water temperatures tend to occur more commonly during low flows, the relationship between streamflow and water temperatures appears to be complicated and is not fully understood. For all of the flows with days that water temperatures exceeded 70°F, there were also days that water temperatures greater than 70°F that were not observed at both locations.

The information in Figures 19 and 20 display days with high water temperatures during high streamflows have greatest tendency to occur in July.

Trend of Yearly Conditions between July 1st and August 18th at Wisdom and Melrose from 1996 to 2012

The averages of maximum and minimum daily air temperatures, mean daily flows, and mean daily water temperatures were calculated for each year from July 1st to August 18th (Tables 10 and 11). Averages of mean daily water temperatures fluctuate across the 17-year period, but essentially appear to show a static trend.

The influence that microclimate effects or hourly fluctuations have on the occurrence of water temperatures exceeding 70°F are not fully understood in these averages. Analysis between water and air temperatures and streamflow at the same recorded interval may explain trends in the future.

Table 10- Average annual values from 7/1 to 8/18 for mean daily water temperatures, maximum and minimum daily air temperatures, mean daily flows, and the total hours of water temperatures exceeding 70°F at Wisdom.

Wisdom	Averages from 7/1 to 8/18				
Year	Mean Daily Water Temps °F	Maximum Daily Air Temps °F	Minimum Daily Air Temps °F	Mean Daily Flows cfs	# of Hrs. of Water Temps >70°F
1996	63.4	80.9	35.1	318	71
1997	61.7	75.7	38.2	452	33
1998	66.0	81.4	40.8	359	159
1999	62.2	78.1	34.5	64	112
2000	63.1	81.1	34.3	21	171
2001	63.4	79.5	38.1	26	122
2002	64.2	79.5	38.2	49	201
2003	66.4	86.2	39.6	23	354
2004	63.9	79.2	38.3	91	184
2005	64.6	81.4	37.2	58	228
2006	65.5	83.1	37.5	58	293
2007	66.1	86.3	39.3	20	326
2008	63.4	81.6	35.8	136	99
2009	62.1	75.3	36.6	146	79
2010	62.5	77.1	36.6	197	87
2011	62.0	77.5	36.8	780	21
2012	64.9	82.8	37.8	60	222
Average	**63.85**	**80.39**	**37.34**	**168.12**	**162.47**

Table 11- Average annual values from 7/1 to 8/18 for mean daily water temperatures, maximum and minimum daily air temperatures, mean daily flows, and the total hours of water temperatures exceeding 70°F at Melrose.

Melrose	Averages from 7/1 to 8/18				
Year	Mean Daily Water Temps °F	Maximum Daily Air Temps °F	Minimum Daily Air Temps °F	Mean Daily Flows cfs	# of Hrs. of Water Temps >70°F
1996	63.4	81.3	43.1	1110	33
1997	61.7	78.6	43.9	1718	5
1998	65.2	85.0	47.3	1523	160
1999	61.8	79.6	39.1	716	9
2000	63.6	85.3	45.1	277	62
2001	64.3	79.9	45.2	386	94
2002	63.5	82.9	43.7	571	67
2003	66.4	88.8	49.0	363	232
2004	64.3	81.1	46.8	545	93
2005	64.2	82.1	45.4	541	97
2006	65.4	84.2	47.3	461	180
2007	66.1	86.7	50.1	292	237
2008	62.7	83.1	44.1	1075	21
2009	61.4	77.9	44.9	1026	8
2010	61.2	78.4	43.3	1325	3
2011	60.7	81.4	43.9	2665	0
2012	64.4	84.1	48.5	552	61
Average	**63.55**	**82.38**	**45.34**	**890.94**	**80.12**

DISCUSSION

The 17-year averages of mean daily water temperatures (1996 – 2012) indicate Big Hole River temperatures tend to be slightly warmer (about 1°F) at Wisdom, than at Melrose, during the first 3 weeks of July. For the three week period from July 21st to August 11th, average temperatures at both locations were comparable. From August 12th to the end of September, mean daily water temperatures at Wisdom tended to be slightly cooler (about 1°F) than at Melrose. Over the long-term, average temperatures peaked within one day of each other- July 24th and July 23rd at Wisdom and Melrose, respectively.

Water temperatures exceeding 70°F (stressful temperature to trout) occurred every year at both locations except in 2011 (a year with significantly high snowpack) at Melrose. Cooler than average air and water temperatures were observed at Wisdom and Melrose that year, but they weren't notably different from other years. Stream flows, however, were twice those of the next highest flow year (1997). While water temperatures still exceeded 70°F at Wisdom in 2011, they happened at only half the frequency observed in 1997 (year with the 2nd fewest occurrences).

Hourly water temperatures that exceeded 77°F (the upper incipient lethal temperature for grayling) over the 17-year period tended to occur at Wisdom only during very warm summers. These were last recorded in 2007. At Melrose, greater than 77°F water temperatures were observed in only 1998.

When hourly water temperatures greater than 70°F were summed by day for the 17-year period, the occurrences peaked around August 21st at Wisdom, and August 23rd at Melrose. The frequency of occurrence for these water temperatures approximated a normal distribution at both locations. Ninety percent of the total hours that exceeded 70°F happened from June 25th to August 18th at Wisdom, and from July 5th to August 18th at Melrose. These periods represent thermally, "critical" periods for Big Hole River fisheries. We considered the critical period most common to both locations to be between July 1st and August 18th.

Analysis of the occurrence of these hourly water temperature exceedences identified thermally, "critical" periods for Big Hole River fisheries to be from June 25th to August 18th at Wisdom, and from July 5th to August 18th at Melrose. These dates represent when 90% of the total hours with water temperatures greater than 70°F over the 17-year period occurred for each location. We considered the average period critical to both locations was between July 1st to August 18th and that guided us to focus our analysis on data within that timeframe.

The occurrence of high water temperatures was not confined to low flow levels at either location. The 17-year averages of mean daily flow indicate that base flows tend to be achieved after August 20th at Wisdom, and after August 29th at Melrose. Thus, water temperatures that exceed 70°F tend to be most common before base flow conditions are achieved. In fact, the data indicated high temperatures (>70°F) sometimes coincided with stream flows as high as 500cfs at Wisdom, and 900cfs at Melrose. High water temperatures sometimes occurred during hot days at high flow levels in July and August, but not during hot days in September at base-flows. While it seems apparent that stream flows can moderate the occurrence of high stream temperatures, it appears not to be the dominant factor of influence.

High water temperatures tended to correlate most closely with maximum daily air temperatures. When maximum daily air temperatures were 75°F and warmer was when greater than 70°F water temperatures tended to occur. The frequency of occurrence for high water temperatures increased steadily as maximum air temperatures rose. At Wisdom, high water temperatures (>70°F) occurred 100% of the days when maximum daily air temperatures were greater than 91°F. At Melrose, high water temperatures occurred 77.5% of those days.

Water temperatures exceeding 70°F are most common in July and August, especially as maximum daily air temperatures increase. Interestingly, there is a much less likelihood of water temperatures exceeding 70°F in September, even when maximum air temperatures are equally as warm as those that occur in July and August. This suggests day length (solar radiation) is an important variable influencing the likelihood of high water temperatures. Sunlight hours decline by approximately 4 hours between July 1st and September 30th (http://aa.usno.navy.mil/data/docs/RS_OneYear.php).

While it is logical that warmer days result in warmer water temperatures, air temperature is probably not the driving factor behind high water temperatures. Johnson (2003) demonstrated, that transfer of heat energy from warmer air to cooler stream water, was only a small portion of the energy exchange that occurs. Solar radiation is the primary influence on both air and water temperatures. The correlation between maximum daily air temperatures and high water temperatures occurs because they are similarly influenced by solar radiation.

The dominant influence of solar radiation on water temperature helps explain the declining tendency for water temperatures to exceed 70°F from late July through September, as day length declines and the angle of the sun becomes less direct. On summer equinox (June 21st), the length of daylight in the Big Hole is around 15 hours and 45 minutes. One month later on July 21st, which is at the peak frequency for hourly water temperatures to be over 70°F; daylight is 15 hours and 10 minutes (http://aa.usno.navy.mil/data/docs/RS_OneYear.php). On August 21st, the length of day is about 13 hours and 40 minutes, and at the end of September, it decreases to 12 hours and 10 minutes. Minimal occurrences of water temperatures over 70°F happened in September at Wisdom and none occurred in Melrose when flows are typically around their lowest. There is also nearly 2 hours less daylight.

Given our outcomes, the influence that solar radiation appears to be having on water temperatures in the Big Hole River is important. If air and water temperatures, along with stream flow represent the range of conditions we can expect in the future, and solar radiation is the factor most significantly driving high water temperatures, then the Big Hole River will probably display a similar "pattern" of high water temperatures (>70°F) in the future (i.e. occurring from early July through the 3rd week in August; and peaking around July 23rd). However, they wouldn't have to occur with the same frequency as they have in the past.

Information gained through this analysis verifies the appropriateness of the restoration actions that are ongoing in the watershed. The only way to reduce solar influence on water temperatures is to reduce the exposure. This can be accomplished by restoring riparian areas with restored vegetation and appropriate stream channel shape. There is a possibility that management and restoration efforts could already be influencing water temperatures in the Big Hole. This may be demonstrated in the fact that 77°F water temperatures were last observed at Wisdom in 2007. And, high water temperatures (>70°F) may occur less frequently at Melrose because of naturally cold groundwater and tributary inputs near Wise River and Dewey, and where the canyon walls provide topographical shading (Middle-Lower TMDL, 2009). Much taller riparian vegetation (cottonwood trees) around Melrose also provides a buffer against solar radiation.

Over time, the influence of management and restoration actions on Big Hole River water temperatures is most likely to be demonstrated by comparing the frequency of hourly water temperature greater than 70°F occurring (at specific locations) during periods of similar climate conditions. We postulate that high water temperatures (>70°F) are most likely to be eliminated, during periods when the conditions promoting them are marginal (i.e. from late June to mid-August when maximum air temperatures range from 75-80°F). Also, the frequency of high water temperatures occurrences may be reduced or become less continuous in late July.

Analysis of the data presented in this report was not adequate to demonstrate water temperature changes that might occur, or have already occurred in the Big Hole River, or its tributaries. For example, maximum daily air temperature data were only available from Divide (approximately 20 miles from the gaging station near Melrose). We recommend expanding data collection to at least include solar radiation and air temperature at selected gaging stations, with the recording frequency being standardized (i.e. every ½ hour).

We recognize the need for temperature data collection which is specific to individual stream segments, in conjunction with information that may answer questions over longer reaches of the Big Hole River. Considering this, we recommend that where ever stream temperature data is being recorded, air temperature data should be recorded at the same location and recording frequency. This may allow the correlations between solar radiation and air temperatures at a gaging station to be extrapolated to nearby locations in the watershed; which could then be evaluated against water temperature patterns. We foresee, in time, restructuring and standardizing data collection in this way, will help demonstrate changes in restored stream reaches and across broader reaches of the Big Hole River.

Key Findings:

- Hourly occurrences with water temperatures greater than 70°F occurred every year over the last 17-years at both locations with the exception of 2011 (a year of significantly high snowpack) at Melrose. Twice as many hours exceeded 70°F water temperatures at Wisdom, as compared to Melrose.
- Hourly water temperatures that exceeded 77°F were most common over the 17-year period at Wisdom during very warm summers, but last occurred in 2007. Water temperatures greater than 77°F only occurred one year in 1998 at Melrose.
- Seventeen years of data indicate that the thermally, "critical" periods for the Big Hole River fishery are from June 25th to August 18th at Wisdom, and from July 5th to August 18th at Melrose.
- The frequency of occurrence for water temperatures greater than 70°F increased steadily with increasing daily maximum air temperatures (>75°F). However, the occurrence of greater than 70°F water temperatures was not confined to lower flow levels at either location.
- Solar radiation is a major variable influencing the occurrence of high water temperatures (>70°F).
- There is a reasonable likelihood that management and restoration efforts are influencing stream temperatures in the Big Hole, but current data is limiting our ability to describe it.
- More time, more intensive data collection, and proper statistical analysis, will likely describe successful improving water quality in the Big Hole.

FUTURE RECOMMENDATIONS

Some of the datasets used for this analysis are coarse and limit our potential to understand tendencies and relationships that influence water temperatures. This is exemplified in the fact that water temperatures and flows are measured throughout the day, but the only air temperature data available is a single point (daily maximum or minimum). We recommend that correlations can be better described by increasing the intensity of data collection from June through September. It may also help to monitor more sites with water temperature data. We recommend that air temperature data loggers be deployed wherever there are water temperature data loggers (at least at the gaging stations that collect water temperature) and measure in 30 minute intervals to more closely compare to how water temperature and streamflow data is collected. This shorter recording interval of time would allow more investigation into the influence of daily events, longer and shorter warm periods during the day and the lag time response for water temperatures and how that may influence 70°F water temperatures.

We've come to believe that understanding the relationship between incoming solar radiation and high water temperatures is essential in order to detect changes that are occurring from management and restoration actions; primarily because improvements in water temperature are likely incremental and most likely to be observed during environmental conditions that "inconsistently" result in high water temperatures (i.e. high daily temperatures of 75°F during June). The greatest ability to correlate high water temperatures with daily influences is to measure the variable that is having the most direct influence. And to measure it at the same location and intensity as the other data collected.

It appears that incoming solar radiation may be the most prominent factor driving water temperatures in July and August, and is not necessarily limited to only affecting water temperatures when flow is low and shallow. Having a clearer understanding of the influence that direct solar radiation has on water temperatures would improve the likelihood that managers could document and track incremental improvements.

We recommend that a remote weather station be installed at each gaging station, which has the capability to monitor daily climate conditions including ½ hour measurements of solar radiation. We also recommend, if feasible, that some measurement of solar radiation data be consistently collected at specific locations between Wisdom and Melrose to supplement other data and allow information from the gaging stations to be extrapolated to reaches between the two locations. Information regarding the types of instrumentation can be pursued by contacting Campbell Science equipment (http://www.campbellsci.com/), or Onset Hobo data loggers (http://www.onsetcomp.com/).

Understanding the effects of extensive restoration actions and the implementation of the Big Hole River Drought Management Plan are having on water temperature is important for managers in addressing fisheries concerns and water quality in the Big Hole River. Because there is dedicated and far-ranging participation between private and public land managers committed to achieving improvement, it will be valuable to answer competently what trend conditions are relevant to mitigation effects. To determine the effectiveness of the DMP to mitigate water temperature, we recommend that more detailed documentation be kept for all the levels of implementation. We also recommend that a spatial dataset of all the extensive restoration actions and monitoring sites taking place be developed.

Key Recommendations to Identify Trend in the Future:

1. **1.** Analyze climate, water temperature, air temperature, and streamflow from June 1st to September 30th annually at monitoring sites.
   - → It is important to measure these variables mentioned above when water temperatures are stressful to the fishery. Our findings show that hourly water temperatures have exceeded 70°F in June and September.

2. **2.** Establish consistency in the recording interval of data collection for all the measured variables (e.g. at half hour intervals) at all monitoring sites.
   - → Measuring the variables at a half hour or hour intervals will allow for better analysis and understanding of influences and relationships between the variables.

3. **3.** Add monitoring sites at current gaging stations that are collecting flow data, and instate the collection of air temperature and water temperature.
   - → At minimum, a monitoring site should be located in each sub-watershed area (upper, middle, and lower) that measures water temperature, air temperature, and streamflow with the same recording interval from June 1st to September 30th.

4. **4.** Establish permanent weather stations with the capability to monitor solar radiation at Wisdom, Melrose, and at least one other in the lower watershed.
   - → Ideally, solar radiation should be collected at monitoring sites in each sub-watershed at the same recording interval as the other variables from June 1st to September 30th. May consider having more installed as expenses permit.

5. **5.** Consider strategic placement of temporary air and water temperature monitoring sites tied specifically to restoration sites (above and below the site). If current monitoring is occurring, consider adding an air temperature monitoring device at each location with the same recording interval.
   - → Monitoring temperatures at each restoration sites will allow for a more direct trend analysis of water temperature improvement. If localized improvement is occurring, it is likely that benefits are extending throughout the river.

6. **6.** Record each level of implementation of the drought management plan (DMP) annually.
   - → Maintaining a detailed record of implementation will be useful to monitor the effectiveness of the DMP.

7. **7.** Develop a spatial dataset through ArcGIS to display the type and the location of all restoration actions completed since the CCAA program (since around 2005).
   - → A spatial display of the restoration activities will help the all parties involved in the Big Hole watershed to understand where it is most likely that water temperature will show improvement.

8. Develop a spatial dataset through ArcGIS to display the location of all water temperature collected in the Big Hole River and its tributaries.
    - → The dataset should specify the coordinates of each location, the period of data recording, and the agency collecting the data. Ideally, all water temperature data collected to date would be analyzed and summarized to display mean, maximum, and minimum daily temperatures.

9. Should any new water temperature monitoring sites be established (short-term or permanently), that air temperature monitoring occur concurrently at the same recording interval.
    - → Our findings indicate that there is a strong correlation between water temperature and air temperature. Monitoring air temperature will provide a way to measure water temperature improvement relevant to climatic condition.

CONCLUSION

It was our assumption that if extensive restoration activities and enhanced management efforts have been sufficient in improving conditions in the Big Hole River, then improvements will be detectable when suitable conditions are most critical to the fishery. We completed a series of analyses to assess water temperature trend relative to air temperature and flow, but did not find any overwhelming indication that water temperature is improving. While broadly defined tendencies and relationships with water temperature, air temperature, and flow from the last 17-years (1996-2012) at Wisdom and Melrose gaging stations emerged through this assessment, it was revealed that more intensive data collection is needed to fully comprehend if successful improvement in water temperature is occurring. In addition, we believe that solar radiation plays a significant role in the influence of high water temperatures (>70°F) and consider it to be a vital "piece of the puzzle" in assessing water temperature trend. Furthermore, we feel that the appropriate mitigation actions to buffer against the influence of solar radiation is concurrent with the existing restoration approaches to improve water quality through increasing riparian vegetation (which increases shading), narrowing channel width, and increasing channel depth. To further ameliorate water temperatures we suggest expanding these efforts to other reaches of the Big Hole that are over widened, shallow, and lacking vegetation.

Ultimately, with more intensively collected data and proper statistical analysis, we believe that indication of improvement in Big Hole river temperatures will be identified.

APPENDICES

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