UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
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Analysis of Stream Temperature Data from Miller Creek, Duluth, MN

by

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Abstract

This report summarizes an analysis of stream temperature and associated climate data for Miller Creek, a trout stream in Duluth, MN. The study was undertaken in support of an MPCA-mandated temperature TMDL. The main goals of the analysis were 1) to characterize the spatial and temporal variations of stream temperature and 2) to determine the main drivers of stream temperature exceedances in Miller Creek. Stream temperature and flow data from 1997-98, 2003-05, and 2007-08 were analyzed at hourly to annual time scales. Included were water temperature data from the main stem of Miller Creek, its tributaries, and from storm sewer outlets to Miller Creek.

Stream temperature in Miller Creek was found to be highly correlated to air temperature from the Duluth Airport at daily to annual time scales. Temperature exceedances (T > 20 ºC) were found to be caused mainly by strong atmospheric heat transfer to the stream due to low channel shading in the middle reaches of Miller Creek. Only 5 to 10% of all temperature exceedances appear to be associated with surface runoff from rainfall events, and even fewer are associated solely with surface runoff. Little evidence was found that lower stream flow leads to increased stream temperature and more frequent temperature exceedances. In mid summer tributaries of Miller Creek are typically at a lower temperature than the main stem of Miller Creek. The tributary at Chambersburg Ave. appears to measurably lower the temperature of the main stem, up to several degrees Celsius. The roles of groundwater and wetlands in the water (flow) and heat budgets of Miller Creek can not be quantified based on the available stream temperature records

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1. Introduction

The report summarizes an analysis of observed stream temperature data for Miller Creek in Duluth, MN, in order to characterize Miller Creek water temperatures and their dependence on other hydrologic and climate parameters, as part of the MPCA temperature TMDL process. The stream temperature data were collected in 1997, 1998, 2003 – 2005, and 2007 – 2008 by the South St. Louis SWCD, the Minnesota DNR, and the Minnesota Pollution Control Agency. Temperature data were collected using 1) the three flow gaging stations using the temperature sensors integrated with the stage measurement pressure sensors, and 2) with temperature loggers (1997 1998, 2007, and 2008 only). The available stream temperature data coverage for the main stem is summarized in Table 1.1. The locations of the measurements in the Miller Creek watershed are shown in Figures 1.1 and 1.2, for the 1997/1998 and 2008/2008 periods, respectively, and Table 1.2. Temperature data from DNR sites was collected using Onset Hobo V2 loggers, temperature data collected by the South St. Louis SWCD used Onset Tidbit loggers, and temperature data from the flow logging sites utilized temperature sensors integral to the pressure sensors used to measure stage. Flow data from Miller Creek were previously analyzed, as summarized in Herb and Stefan 2008. Temperature data from Miller Creek were previously analyzed by the South St. Louis SWCD (2001).

Table 1.1. Summary of stream temperature data available for Miller Creek, 1997 – 2008. The data intervals range from 15 to 60 minute at the flow gaging stations and 5 to 15 minutes for the Onset temperature loggers.

	Main Stem Flow Gaging Sites			Temperature Loggers			
	Dates			Number of Points			Dates
	Lower	Middle	Upper	Main Stem	Tribs	Storm water	
1997	5/1-11/10	7/15-11/15	4/1-5/27, 6/20-11/30	11	0	0	6/18-10/23
1998	4/1-11/23	4/1-11/23	4/1-4/29, 7/11-11/23	11	1	0	7/17-10/7
2003	6/28-11/7	7/2-7/23, 8/4-11/14	6/6-8/8, 8/14-11/14	0	0	0	-
2004	4/1-12/3	4/1-11/23	4/1-11/23	0	0	0	-
2005	4/21-8/9	4/1-7/17	4/1-11/18	0	0	0	-
2007	3/20-7/23 10/19-12/31	4/2-9/1, 10/19-21/31	3/20-11/30	15	6	3	5/8-9/14
2008	1/1-12/3	6/25-10/13	5/1-10/23	15	8	2	5/23-10/14

Table 1.2. Summary of stream temperature measurement sites for 1997/98 and 2007//08. Sites labeled "Trib" are tributaries, sites labeled "SW" are stormwater inlets. All other sites are on the main stem of Miller Creek. The Trinity 97/98 station is not in the same place as the 07/08 Trinity station, and the 97/98 Anderson station is very close to the 07/08 Chambersburg DNR station.

1997/98 Stream Temperature Sites

Sta. Num.	Name	Station Mile	Station Km
1	Swan Lake	7.1	11.43
2	Wal-mart	6.25	10.06
3	U-haul	5.86	9.43
4	Sunby	5.22	8.40
5	Beaver Pond	5.13	8.26
6	Kohls upstream	5.07	8.16
8	Kohls, DS	5.04	8.11
9	Kohls Trib	5.04	8.11
7	Upper Flow SIte (Kohl's)	4.95	7.97
10	Village Mall	4.61	7.42
11	Miller Hill Mall	4.31	6.94
12	Middle Flow Site (Chambersburg)	3.59	5.78 0.00
13	Anderson	3.57	5.75
14	Trinity	1.97	3.17
15	Lower Flow Site (26th)	0.39	11.43

2007/08 Stream Temperature Sites

Sta. Num.	Name	Station Mile	Station Km
32	Ridgewood	9.15	14.73
31	Airport-Haines	7.66	12.33
30	Airpark Trib	7.36	11.85
29	Swan Lake	7.07	11.38
28	Ralston	6.38	10.27
26	Arrowhead-Airbase	6.45	10.38
25	Walmart	6.04	9.72
24	Uhaul	5.79	9.32
23	Haines 53	5.62	9.05
22	Sundby Trib (DNR)	5.61	9.03
21	Kohl's Upstream	5.19	8.36
20	Superone Trib	5.02	8.08
19	Haines Trib	5.02	8.08
18	Upper Flow (Kohls)	4.95	7.97
17	Mall Dr Target	4.84	7.79
16	Mall Dr SW	4.71	7.58
14	Firestone Trib	4.50	7.25
13	Middle Flow Site (Chambersburg)	3.59	5.78
12	Chambersburg Trib	3.56	5.73
11	Chambersburg (DNR)	3.56	5.73
10	Lake Superior College	2.22	3.57
9	Trinity	1.88	3.03
8	Springvale Trib	1.57	2.53
6	LP 10SW	1.22	1.96
4	LP 5 SW	0.86	1.38
2	Lower Flow Site (26th)	0.39	0.63

Figure 1.1. Miller Creek watershed and stream temperature logging sites in 1997/1998.

Figure 1.2. Miller Creek stream temperature logging sites in 2007/2008.

2. Climate Data for the Miller Creek Watershed

To help understand stream temperature variability, climate data for the Duluth area was obtained and analyzed. The primary source of climate data for the Miller Creek watershed is the Duluth International Airport (DLH), which reports air temperature, humidity, precipitation, wind speed, and wind direction at 1 hour intervals. These data were obtained for 1997-2008 from the National Climate Data Center (http://www.ncdc.noaa.gov/oa/climate/isd/index.php). Simulated hourly solar radiation data for the Duluth International Airport were obtained from the National Renewable Energy lab for 1997-2005 (http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005); these data are based mainly on observed cloud cover data combined with models for clear weather solar radiation. Hourly observed solar radiation data for 2008 were available from a new station at Lincoln Park Middle School, near the lower end of the watershed. These data were supplied by the Duluth MPCA. Precipitation data was measured at the upper (Kohl's) flow gaging station in 1997 through 2005. In 2008, air temperature and humidity measurements were made at all three flow gaging stations in Miller Creek (Upper, Middle and Lower sites at Kohl's, Chambersburg. and 26th Avenue, respectively). These data were included with the flow data obtained from the South St. Louis SWCD.

Air temperature, precipitation, and solar radiation data are summarized in Table 2.1 for all years with available data for Miller Creek: 1997-1998, 2003-2005, and 2007-2008. On average, July is the warmest month, while August is the driest. 2003 and 2007 were relatively warm years in July and August, while 1997 and 2007 were relatively dry years. The correlations of stream temperature to varying air temperature, precipitation and stream flow is examined in the next section at several time scales. The years with simulated solar radiation data (1997-1998, 2003-2005) seem to be consistent with the observed data from 2008 (Table 2.1).

Synoptic air temperature and humidity measurements taken at multiple sites in the Miller Creek watershed in 2008 provide an opportunity to examine climate gradients in the Miller Creek watershed which extends from elevation 610 ft to 1422 ft amsl at Duluth International Airport. Monthly average air and dew point temperatures from four sites are summarized in Table 2.2 and weekly average temperatures are shown in Figure 2.1 and 2.2. Air temperatures at the lower flow site are consistently higher than the other sites, largely because the daily minimum air temperature is higher (Figure 2.1). Average dew point temperatures vary less between the sites than air temperature (Figure 2.2, Table 2.2). The airport is the farthest from the lake, consistently has the lowest dew point temperature, while the lower station has the highest average dew point temperature in most months.

The data suggest that gradients in air temperature and humidity exist in the Miller Creek watershed. Previous analysis of flow and precipitation data also showed spatial variation in precipitation in the Miller Creek watershed (Herb and Stefan 2009). It can be assumed, however, that climate conditions in the upper part of the watershed are the most important in determining stream flow and stream temperature, because 1) the watershed is wider towards the top and 2) the channel slope is lower in the upper part of the watershed, so that the water has a longer residence time. The higher stream slope and associated higher flow velocities in the lower part of the watershed give the stream less time to respond to local climate conditions.

Table 2.1. Summary of monthly-average air temperatures, monthly total precipitation, and monthly-average solar radiation for 1997-1998, 2003-2005, and 2007-2008, for data from Duluth International Airport. Solar radiation is averaged over full 24-hour periods.

	1997	1998	2003	2004	2005	2007	2008	Average all years	Standard Dev.
Average Air Temperature (°C)									
May	7.7	13.3	10.8	8.2	9.2	12.3	9.3	10.1	2.1
June	17.0	14.7	15.6	14.2	16.7	17.0	15.7	15.9	1.1
July	17.8	18.9	19.2	17.8	19.5	19.9	18.3	18.8	0.8
August	16.2	19.2	19.6	14.9	18.2	18.6	18.2	17.8	1.7
September	14.0	14.9	12.9	14.6	15.5	13.9	13.4	14.2	0.9
All Months	14.5	16.2	15.6	13.9	15.8	16.3	15.0	15.3	0.9
Total Precipitation (cm)									
May	4.9	9.0	9.0	9.1	11.3	8.6	7.4	8.5	1.9
June	12.6	15.4	8.8	5.3	13.9	5.7	10.9	10.4	3.9
July	4.7	4.4	12.3	9.4	2.8	4.1	11.3	7.0	3.9
August	3.4	6.6	7.7	4.4	5.9	1.0	6.2	5.0	2.3
September	4.4	8.5	8.9	13.0	9.3	9.9	12.2	9.5	2.8
All Months	30.1	43.8	46.8	41.3	43.1	29.4	48.0	40.4	7.6
Average Solar Radiation (W/m^2)									
May	211	286	286	205	189		227	234	42.1
June	261	214	214	259	235		221	234	21.6
July	222	262	262	246	268		253	252	16.5
August	180	222	222	191	215		228	210	19.5
September	155	177	177	152	154		137	159	15.6
All Months	206	232	232	211	212		213	218	11.5

Table 2.2. Comparison of monthly-average air and dew point temperatures observed at Duluth International Airport and at the three Miller Creek flow gaging stations.

Average Air Temp (°C)					Average Dew Point Temp (°C)			
	Airport	Upper	Mid	Lower	Airport	Upper	Mid	Lower
May	9.4	9.2	8.8	10.2	1.0	1.8	1.3	2.4
Jun	15.7	15.7	14.7	17.0	8.7	9.9	9.6	10.0
Jul	18.2	18.3	17.4	19.7	11.9	13.1	13.2	13.1
Aug	18.1	18.5	17.1	20.2	12.2	13.4	13.6	14.3
Sep	12.8	13.2	11.9	14.5	8.5	9.8	9.7	10.7
Oct	8.6	9.0	8.8	10.2	4.1	5.3	6.7	6.3
All	13.8	14.0	13.1	15.3	7.7	8.9	9.0	9.5
Average Daily Max Air Temp (°C)					Average Daily Min Air Temp (°C)			
	Airport	Upper	Mid	Lower	Airport	Upper	Mid	Lower
May	14.9	16.3	15.3	15.6	4.0	2.1	1.8	5.2
Jun	20.8	22.1	20.3	22.3	10.6	9.4	8.7	11.7
Jul	23.2	24.6	22.5	25.0	12.6	11.6	11.2	14.1
Aug	23.7	25.4	23.0	25.7	12.5	11.7	10.8	15.0
Sep	17.6	18.6	16.5	19.4	8.0	8.0	7.1	10.5
Oct	12.6	13.7	12.9	14.1	4.0	3.8	4.2	5.9
All	18.8	20.1	18.4	20.4	8.6	7.8	7.3	10.4

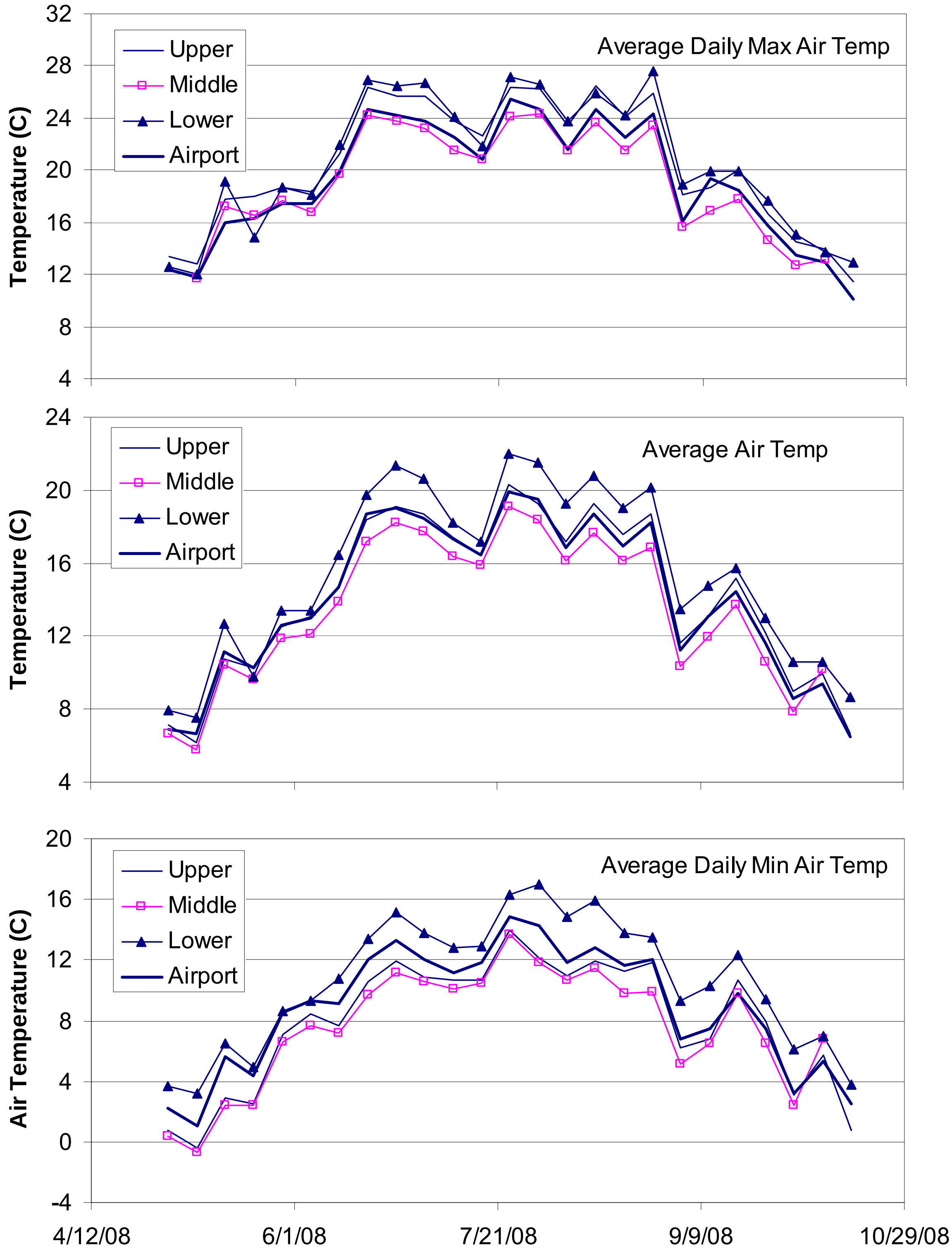


Figure 2.1. Weekly averages of air temperature, daily maximum air temperature, and daily minimum air temperature recorded at Duluth International Airport and at the three (Upper, Middle and Lower) Miller Creek flow gaging stations, May – October, 2008.

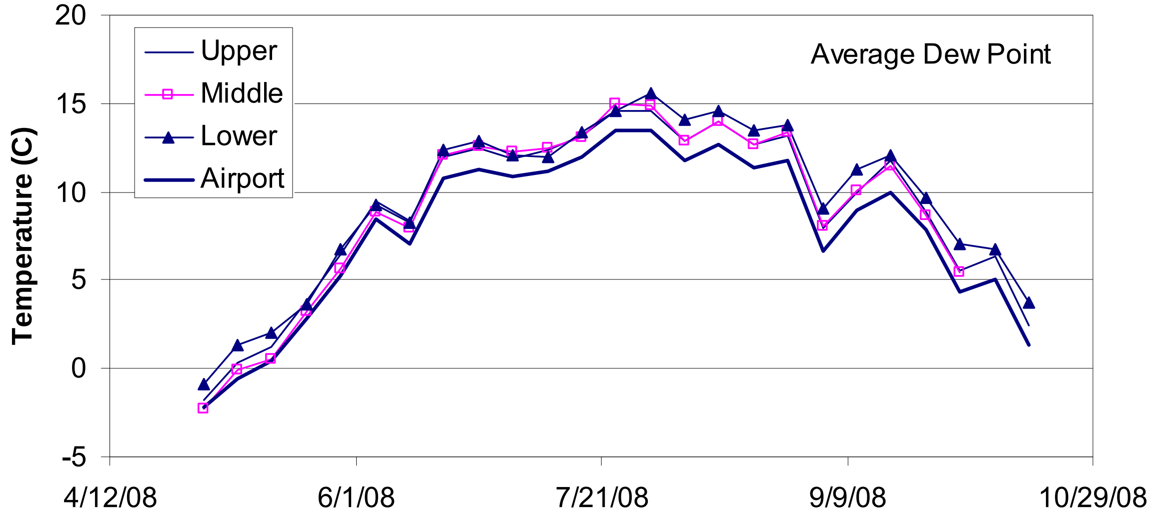


Figure 2.2 Weekly-average dew point temperature at Duluth International Airport and at the three (Upper, Middle and Lower) Miller Creek flow gaging stations, May – October, 2008.

3. Relationships of Stream Temperature to Air Temperature, Precipitation and Streamflow

3.1 Relationships of Stream Temperature to Air Temperature

Air temperature can be a good predictor of stream temperature at daily to monthly time scales (Mohseni et al. 1998). At seasonal time scales, stream temperature in Miller Creek follows the trend of air temperature, although air temperature goes through much more variation at hourly and daily time scales (Figure 3.1). The relationship of stream and air temperature at seasonal time scales can be more effectively shown by averaging the data at weekly and monthly intervals, as exemplified in Figure 3.2 for 2008 stream temperature data from the lower (26^{th} Ave) gaging station. Year to year variations in monthly averaged air temperature lead to similar variations in monthly averaged stream temperature (Figure 3.3). Corresponding stream and air temperature statistics are summarized in Table 3.1 for the seven years of stream temperature data available for the lower gaging site. On average, July and August have the highest stream temperature, 18.2 ºC. August has relatively high variability for air (SD=2.1 ºC) and stream temp (SD=1.8 ºC) compared to June and July.

The seasonal maximum daily stream temperature can exceed 20 ºC in Miller Creek from approximately June 15 to September 15 (Figure 3.4), but with substantial day to day variations. At daily time scales, both maximum daily stream temperature and average daily stream temperature were found to be well correlated to average daily air temperature (r^2=0.82, Figure 3.5). Average daily air temperature was a better predictor of maximum daily stream temperature compared to maximum daily air temperature. This is not surprising, since air temperature goes through much higher fluctuations at hourly time scales compared to stream temperature (Figure 3.1). At weekly time scales, the relationship between stream temperature and air temperature becomes even stronger (Figure 3.6), with higher r^2 (0.91), lower intercept (2.9 ºC) and a slope closer to 1 (0.81) compared to the daily averaged relationships given in Figure 3.5.

The slope of the relationship between stream temperature and air temperature for Miller Creek is relatively high, e.g. 0.7 at daily time scales (Figure 3.5). Stream temperature – air temperature relationships for Miller Creek can be compared to data for a tributary of the Vermillion River (South Branch) in Figure 3.7. South Branch drains approximately 20 sq. miles (compared to 10 sq miles for Miller Creek), and has relatively strong groundwater inputs and a relatively undeveloped watershed. For South Branch, the slope of the stream temperature / air temperature relationship is about 0.5, substantially less than the slope for Miller Creek (0.7). Groundwater inputs provide a thermal buffer that reduces the influence of air temperature on stream temperature, so that the temperature characteristics of Miller Creek suggest low groundwater inputs.

3.2 Relationships of Stream Temperature to Precipitation and Streamflow

Precipitation was not found to have a significant effect on the relationships between stream temperature and air temperature at daily time scales. Separate regression relationships for wet and dry days are shown in Figure 3.8 for stream temperature data from all three flow gaging sites. Note that the regression for the upper gaging site has a somewhat higher slope (0.82 to 0.83) than the middle and lower flow sites (0.67 to 0.77). This could indicate a stronger influence of climate conditions in the flatter, upper part of the watershed (upstream of Kohl's). Maximum daily stream temperature was not found to be well correlated with the amount of precipitation at a daily time scales (Figure 3.9), although there is some indication that on days with high precipitation (> 3 cm) stream temperatures moderate, tending towards 15 ºC.

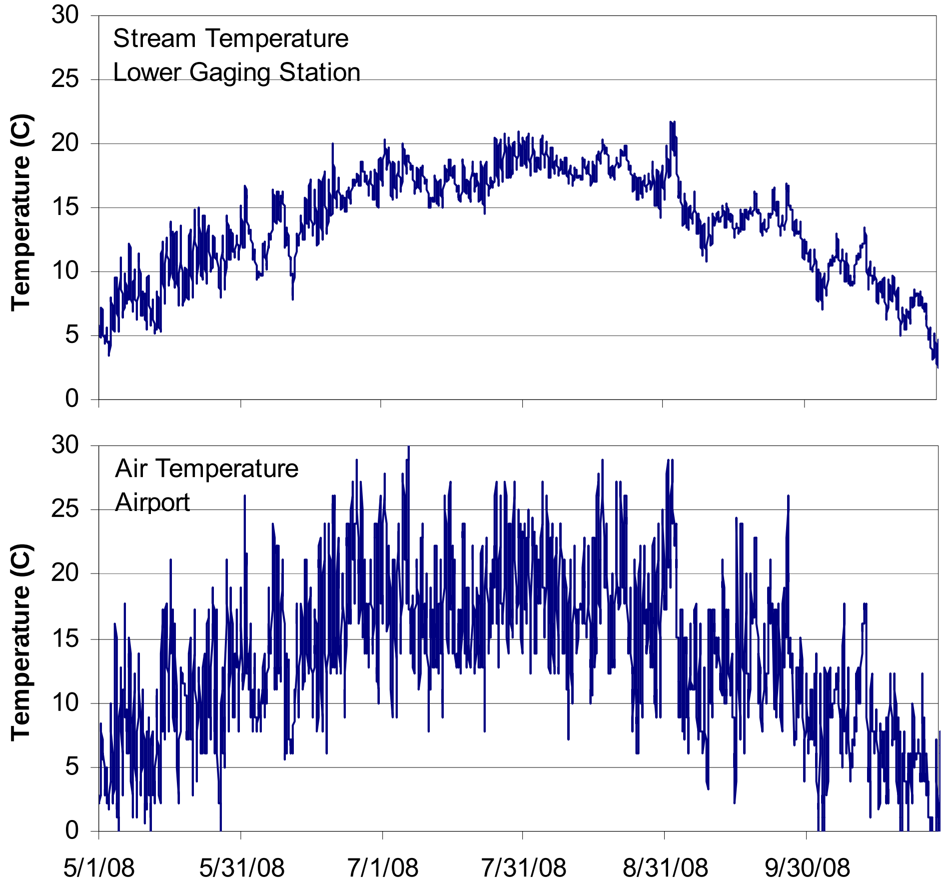
Maximum daily stream temperature was not found to be well correlated to stream flow at a daily time scale (Figure 3.10); distributions of stream temperature maxima with flow were similar at all three stream sites for wet or dry days alike. The relationship was explored further by multi-variable linear regression analysis of stream temperature with air temperature and stream flow. Using stream flow and temperature data from 1997, 1998, 2007, and 2008, a significant relationship was found between daily maximum stream temperature, daily average air temperature, and daily average stream flow, as summarized in Table 3.2. Including all days, the regression coefficient for flow was -0.025 °C/cfs. The regression coefficient systematically increases at lower flows to -0.25 °C/cfs for flows less than 10 cfs and to -0.75 °C/cfs for flows less than 2 cfs (Table 3.2). This suggests that stream temperature is more sensitive to stream flow at low flows. The coefficient may be even higher for flows less than 1 cfs, but insufficient data were available to give a significant relationship.

Table 3.1 Average monthly air and stream temperatures at the lower Miller Creek flow gaging station for 7 years of temperature observations. The standard deviation gives the year to year variability of the temperatures in each month.

	Air Temp (°C)		Stream Temp (°C)	
	Average	Standard Dev.	Average	Standard Dev.
May	9.9	2.3	10.3	1.7
Jun	15.9	1.2	15.1	0.8
Jul	18.7	0.9	18.2	0.7
Aug	17.6	2.1	18.2	1.8
Sep	14.1	0.9	15.0	0.7
Oct	7.5	0.8	8.7	0.5

Table 3.2. Summary of regression results for least-squares fitting of daily maximum stream temperature (T_{max}) to daily average air temperature (T_a) and daily average stream flow (Q): $T_{max} = c0 + c1 \cdot Q + c2 \cdot T_a$.
The standard errors of the coefficients are given in parenthesis.
P-values were all < 0.0005.

	All Flows	0-10 cfs	0-2 cfs
R^2	0.767	0.761	0.708
Adjusted R^2	0.766	0.760	0.705
Observations	475	396	198
c0 (°C)	7.046 (0.299)	8.355 (0.36)	9.64 (0.564)
c1 (°C/cfs)	-0.025 (0.005)	-0.249 (0.036)	-0.748 (0.203)
c2 (°C/°C)	0.682 (0.018)	0.641 (0.02)	0.59 (0.029)



3.1. Hourly stream temperatures at the lower Miller Creek stream gauging station and air temperatures at Duluth International Airport for May 1 – Oct 31, 2008.

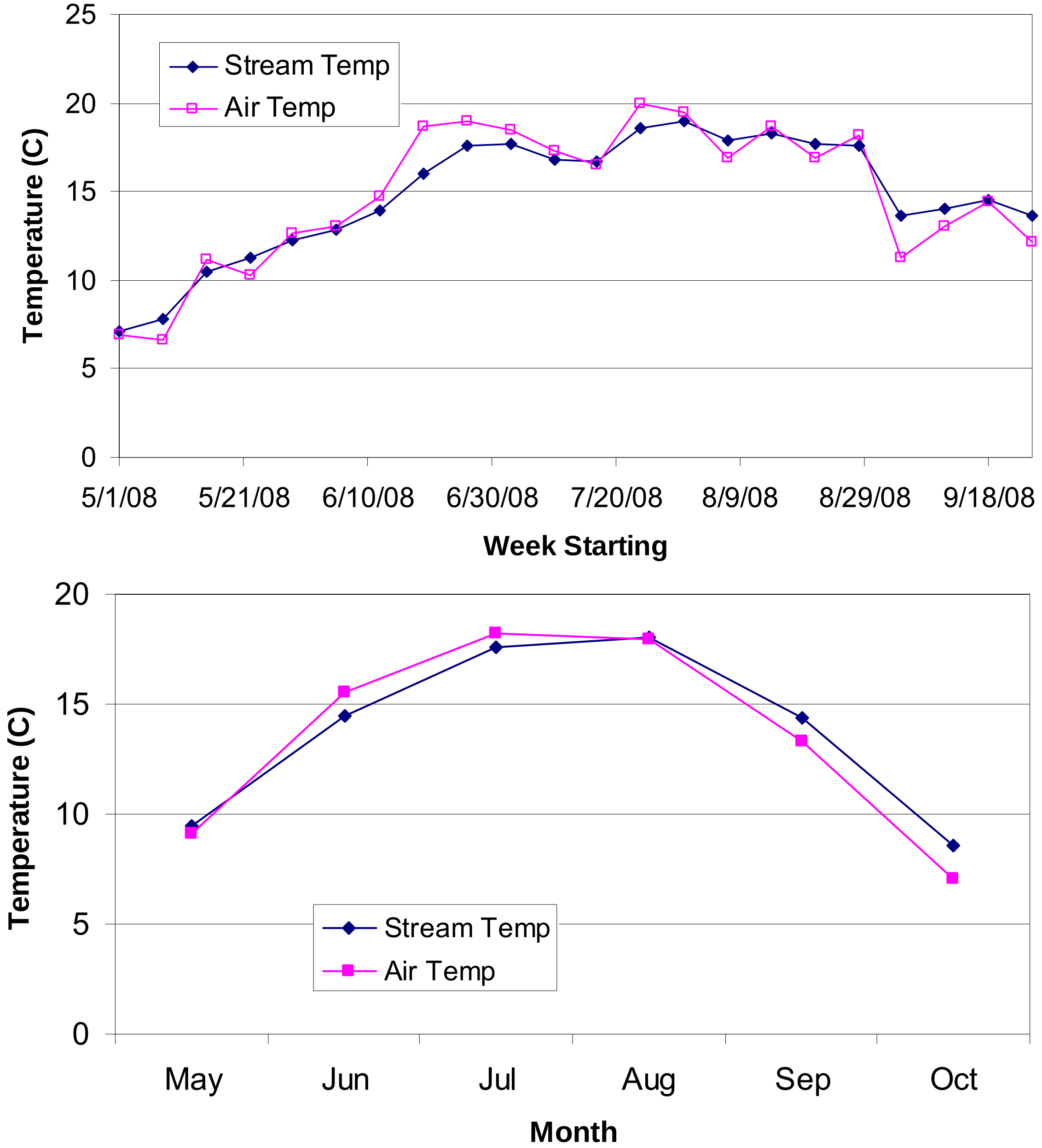


Figure 3.2. Weekly (upper panel) and monthly (lower panel) average stream temperatures at the lower Miller Creek flow gaging station and air temperatures at Duluth International Airport for 2008.

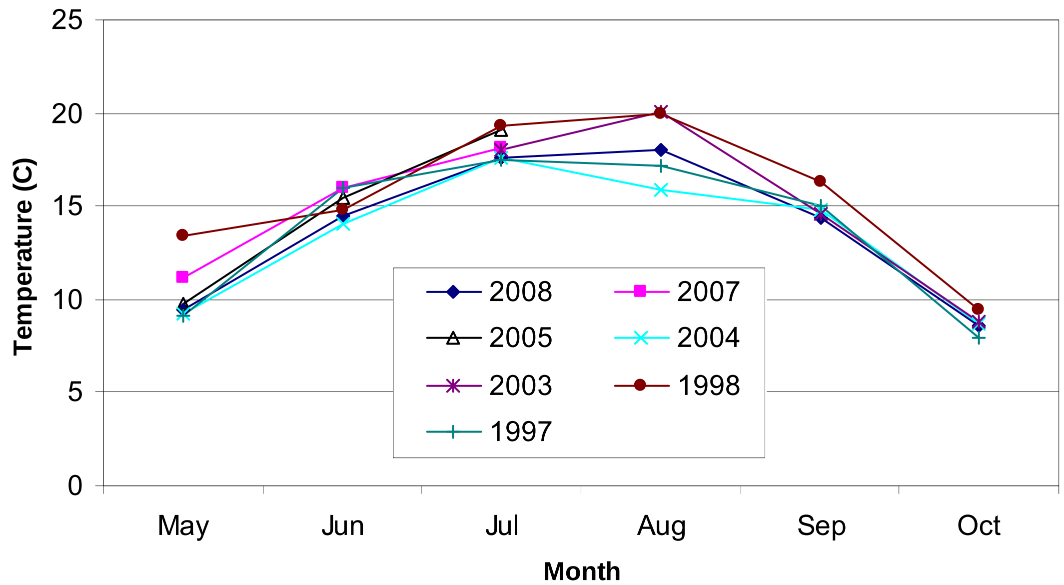


Figure 3.3. Monthly average stream temperatures at the lower Miller Creek flow gaging station for 7 years of observations.

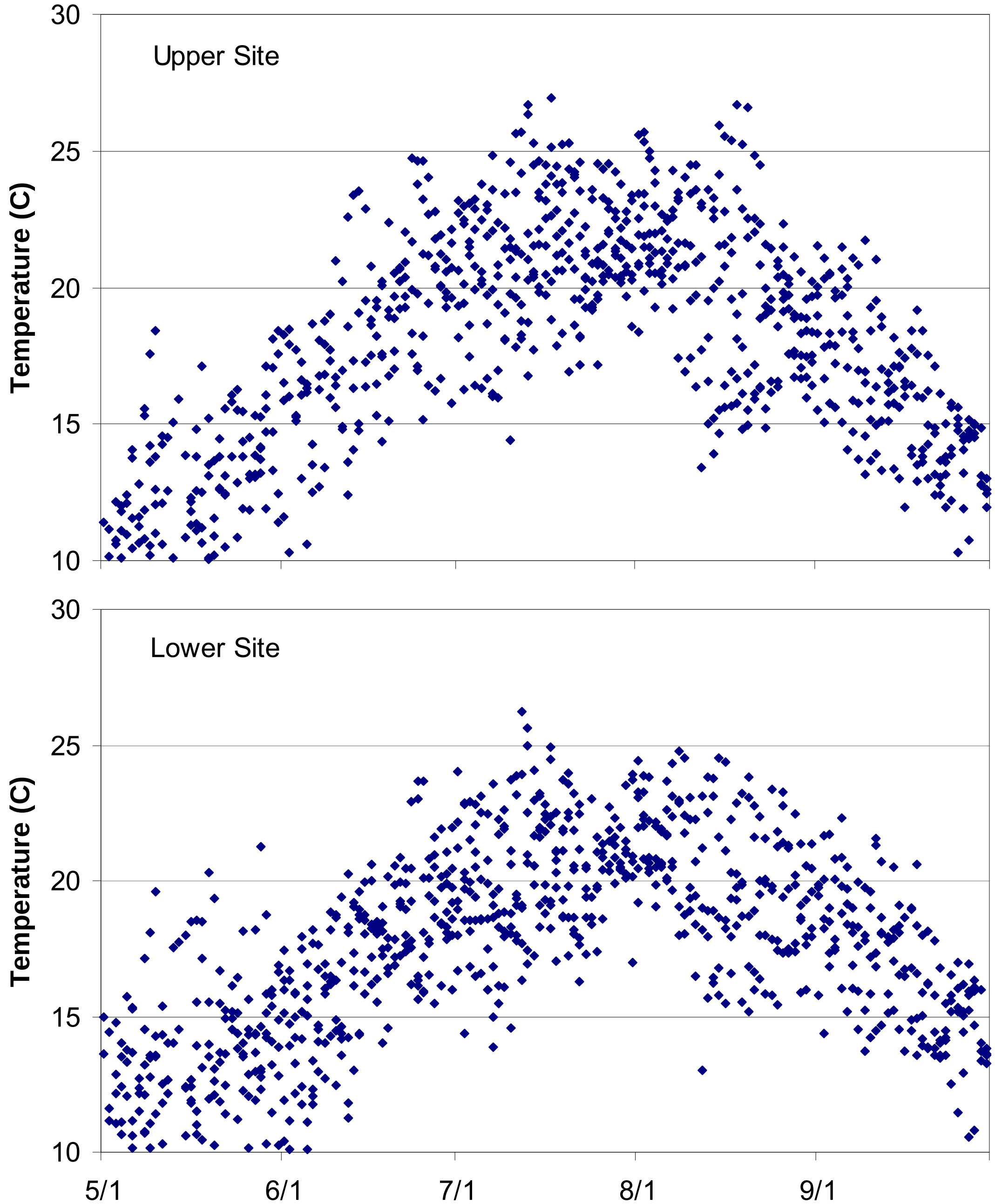


Figure 3.4. Seasonal distribution of maximum daily stream temperature at the lower and upper Miller Creek flow gaging stations for 1998-1999, 2003-2005, and 2007-2008.

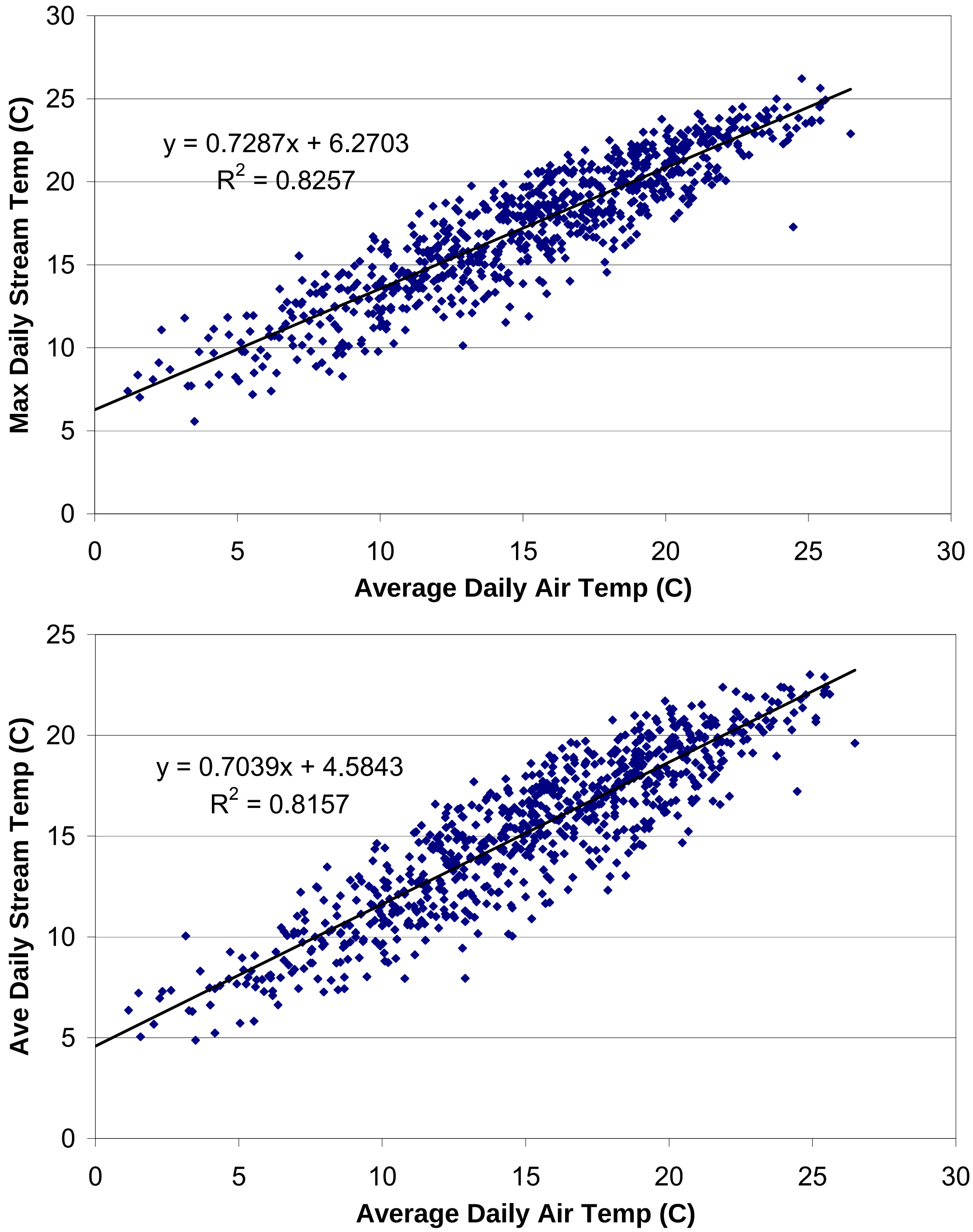


Figure 3.5. Maximum (top) and average (bottom) daily stream temperatures vs. average daily air temperatures at the lower Miller Creek flow gaging station, May through October, 1997-2008.

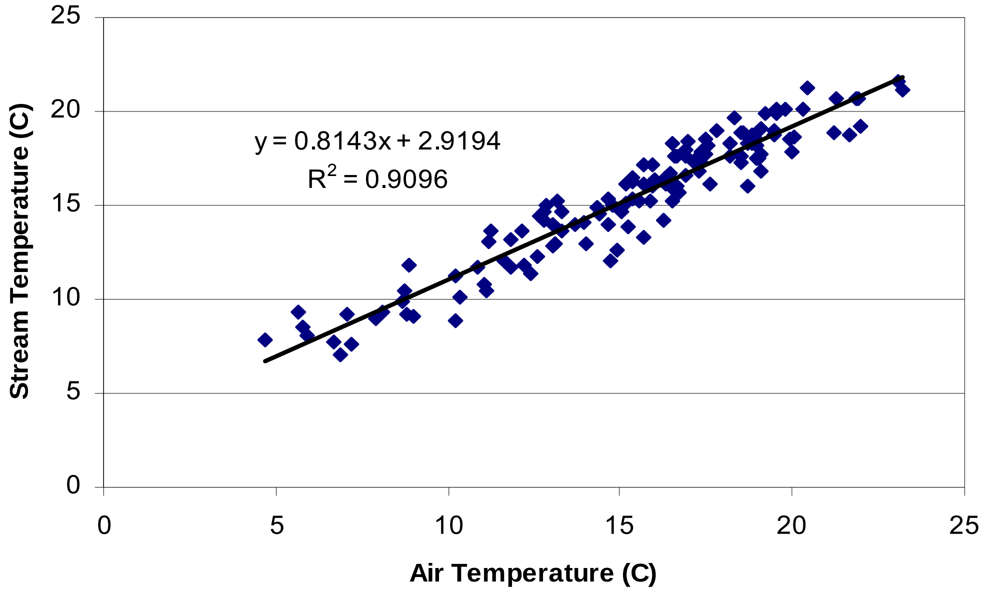


Figure 3.6. Weekly average stream temperature vs. average daily air temperatures at the lower Miller Creek flow gaging station (26th Ave) vs. air temperature at Duluth International Airport for May through October, 1997-2008.

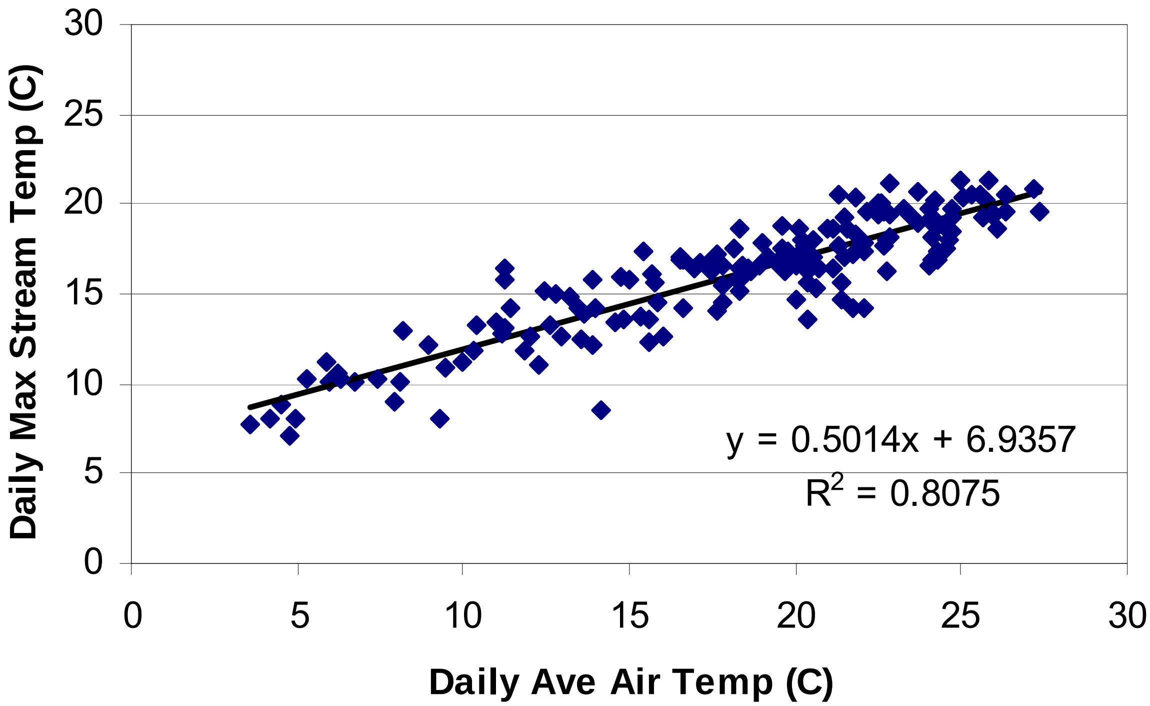


Figure 3.7. Daily average stream temperature vs. daily average air temperature for the South Branch of the Vermillion River, Minnesota, May – October, 2007.

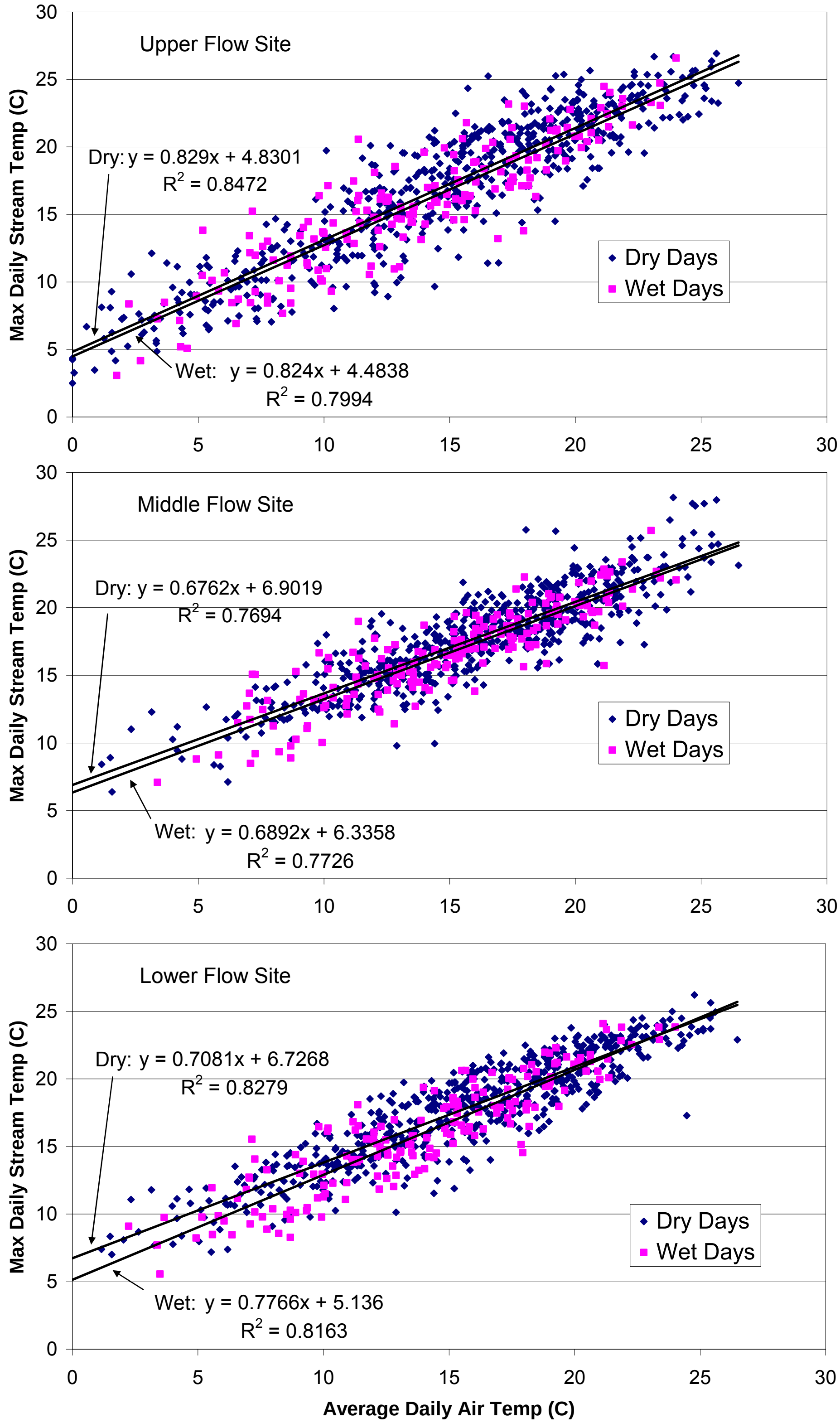


Figure 3.8. Max daily stream temperature at the lower, middle, and upper Miller Creek flow gaging sites vs. average daily air temperature at Duluth International Airport for all data 1997-2008,

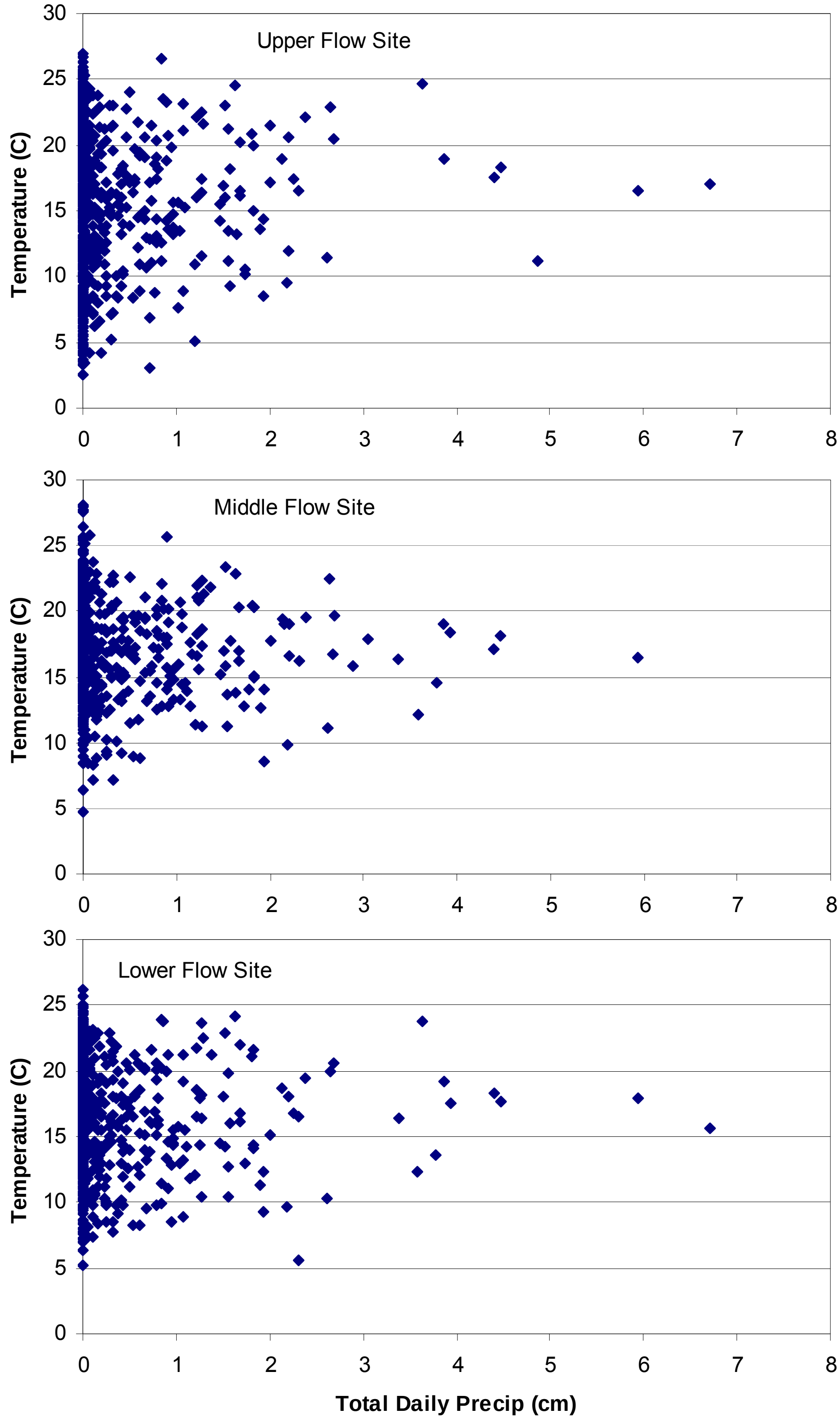


Figure 3.9. Maximum daily stream temperature at the lower (26th Ave), middle (Chambersburg), and upper (Kohl's) Miller Creek flow gaging sites. vs. total daily precipitation for all data 1997-2008,

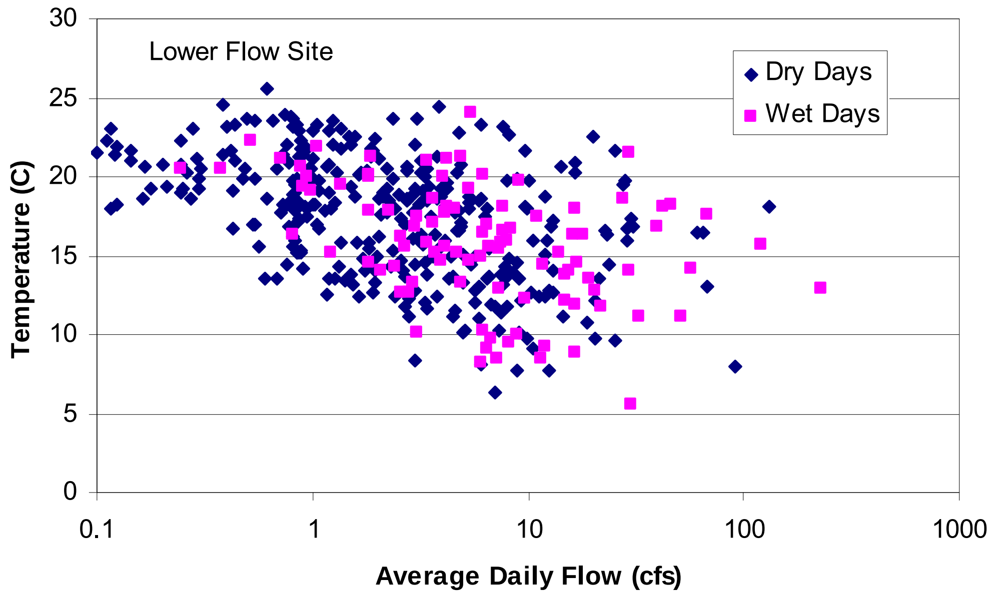


Figure 3.10. Maximum daily stream temperature vs. average daily flow from the lower (26th Ave.) Miller Creek flow gaging station for all data 1997, 1998, 2007 and 2008.

4. Spatial Variability of Stream Temperature in the Miller Creek Main Stem

The many temperature measurements made along the Miller Creek main stem and tributaries in 1997/98 and 2007/08 (Locations in Figures 1.1 and 1.2 and distance (miles) in Table 1.1) can be used to examine spatial (longitudinal) variability of stream temperature. Overall, there is a trend of increasing water temperature with distance in downstream direction. There are also local temperature decreases due to tributary inflows. This longitudinal temperature pattern is a similar to that previously found for the Vermillion River (Herb and Stefan 2008), although the Vermillion is a hydrogeologically very different trout stream system.

Stream temperature data were processed by month to determine average daily stream temperatures, average daily maximum stream temperatures, and average diurnal temperature change (max – min). These averaged data are plotted for July and August in 1997, 1998, 2007 and 2008 in Figures 4.1 to 4.5. The analysis focuses on July and August, because 1) these are critical months for trout habitat and 2) data is more consistently available for these two months.

In all years and in general water temperatures increase from the upstream monitoring points (Ridgewood Rd., RS 9.1) to Kohl's (RS 5.1), although localized increases and decreases variable by month and year also exist.
A distinct cold spot at RS 5.1 in July 1997 (Figure 4.1) was observed below a beaver dam. It is likely that the pool upstream of the beaver dam was stratified and was discharging relatively cool subsurface water. The dam was removed later in 1997, and the August measurements at the same point are more consistent with upstream and downstream measurements from then on.

The reach downstream of the intersection of Haines Rd. and Highway 53 and upstream of Kohl's has increasing temperatures and high diurnal temperature amplitudes, suggesting a lack of shading in the channelized wetland area upstream of Kohl's.
The measurements at Swan Lake Rd (RS 7.1) in August of 2008 (Figure 4.4) had exceptionally low diurnal variations; the temperature sensor may have been partially buried in the sediment during this time.

In 1997 and 1998, temperature loggers were placed in the main stem upstream and downstream of the confluence with the tributary at Kohl's. Inflow of this tributary gave temperature decreases in the main stem of 0.12 to 0.65 ºC (Figures 4.1, 4.2, Table 4.1), although in 1998, the measured temperature of Kohl's tributary was higher than that of the main stem (Figure 4.2), as will be discussed in Section 5. In 2007 and 2008 the change in temperature of the main stem due to the tributary at Kohl's varied from a 3.3 ºC decrease to a 0.83 ºC increase. The largest decrease in temperature due to the Kohl's tributary coincides with the highest upstream main stem temperature of 22.4 ºC; the largest increase coincides with the lowest upstream main stem temperature of 17.2 ºC. Hence, the tributary appears to have an increasing cooling effect on the main stem as the main stem temperature increases.

The Miller Creek main stem reach between Kohl's (RS 5.1) and Miller Hill Mall (RS 4.3) is highly impacted by development. In 1997 and 1998, this stream reach typically saw a temperature increase of 0.3ºC to 0.5ºC, followed by a comparable temperature reduction from Miller Hill Mall to Chambersburg Ave., a relatively well shaded reach. The 2007/08 data do not include a monitoring point at Miller Hill Mall, but the existing data show an overall small decrease in temperature from the Mall Drive monitoring point (RS 4.8) to Chambersburg.

In all years, tributary inflow at Chambersburg Ave. gave a significant temperature decrease from 0.1ºC to 5.1ºC in the main stem (Figures 4.1- 4.5, Table 4.1). Unlike the tributary and Kohl's, There is, however, no relationship between the temperature of the main stem and the temperature reduction provided by the Chambersburg tributary, as had been found for the main stem and the tributary at the Kohl site.

The Miller Creek reach from Chambersburg Ave. to 26th Ave. shows a temperature increase in most cases, ranging from 0.2 ºC in July 1997 to 5.5 ºC in July 1998 (Figures 4.1 to 4.5), with the temperature at 26th Ave. reaching a monthly mean of up to 20 ºC.

Table 4.1. Monthly average main stem temperature (T_{ave}) and average change in main stem temperature (ΔT) due to tributary inflows at Kohl's and Chambersburg Ave.

	Kohl's		Chambersburg	
	T_{ave} (^oC)	ΔT (^oC)	T_{ave} (^oC)	ΔT (^oC)
Jul 1997	19.0	-0.12	19.0	-1.7
Aug 1997	17.4	-0.44	16.4	-0.69
Jul 1998	20.1	-0.65	18.8	-5.1
Aug 1998	19.8	-0.48	18.2	-3.3
Jul 2007	22.4	-3.3	18.9	-2.0
Aug 2007	17.2	0.83	16.8	-2.8
Jul 2008	18.6	-0.66	17.4	-0.10
Aug 2008	18.6	-0.96	17.0	-0.69

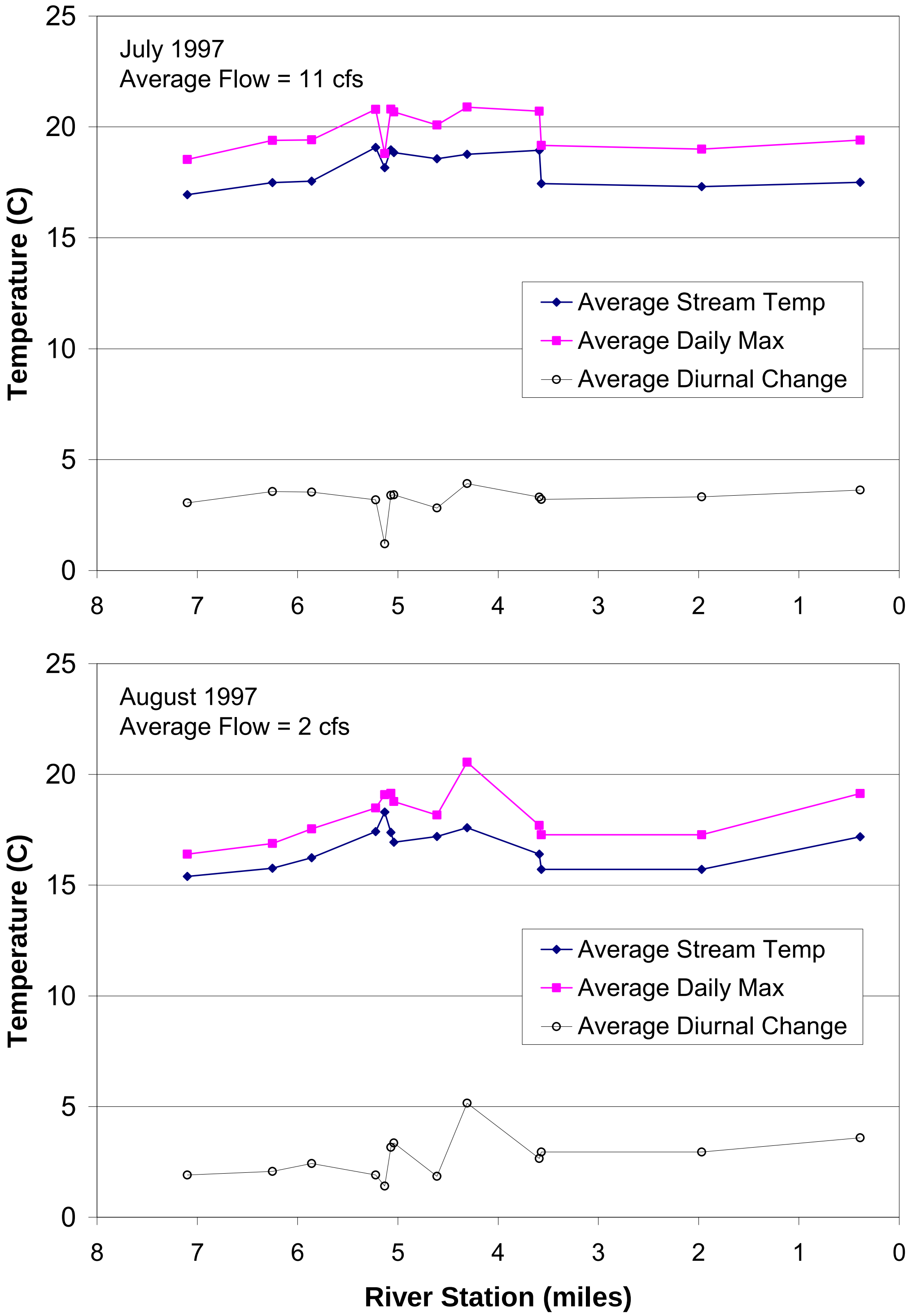


Figure 4.1. Longitudinal variability of ave daily max, and diurnal change in stream temp from the Wal-mart location (RS 6.25) to the 26th Ave gaging site (RS 0.39) in July and Aug of1997.

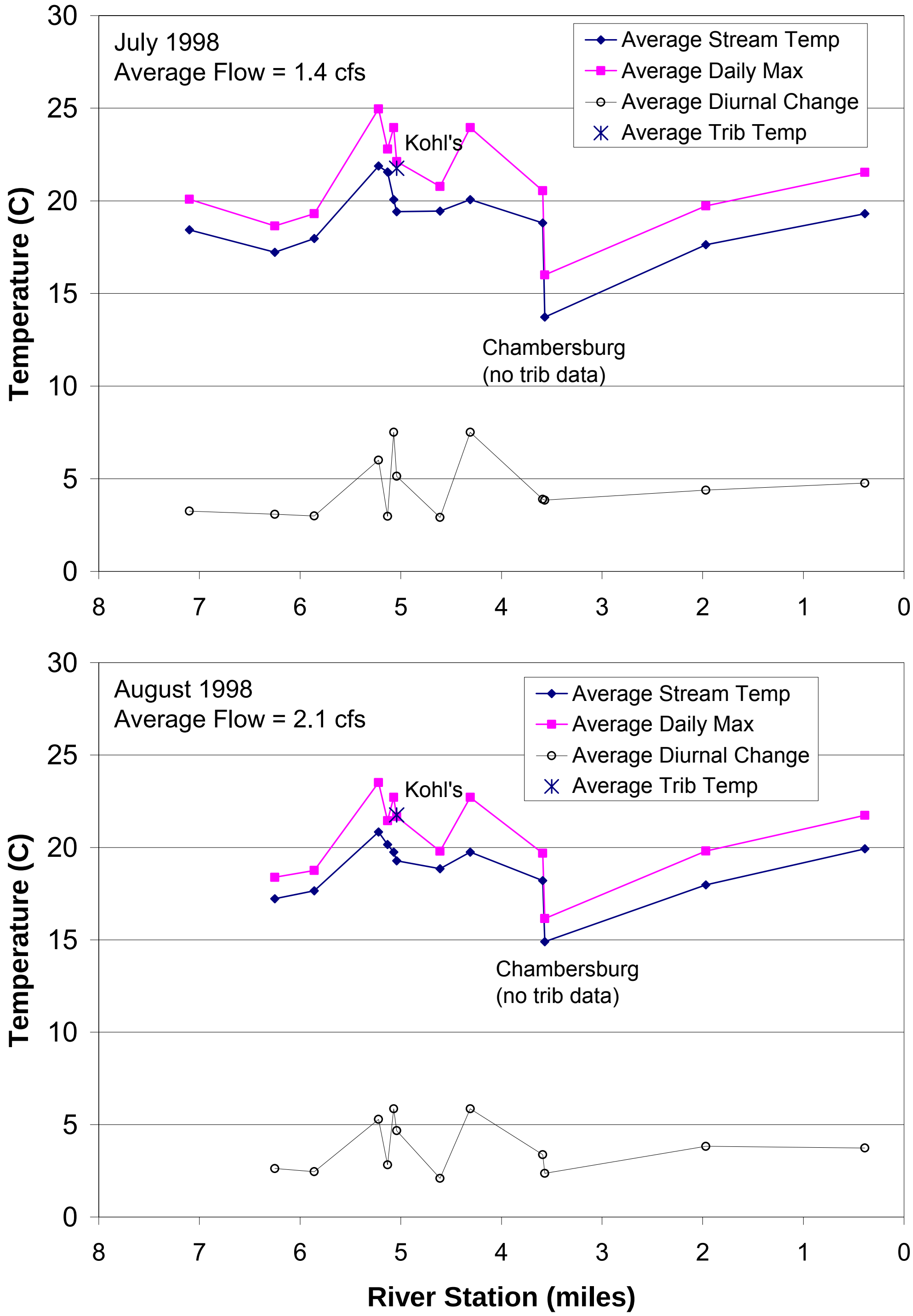


Figure 4.2. Longitudinal variability of average daily maximum stream temperature, and diurnal change in stream temperature from the Wal-mart location (RS 6.25) to the 26th Ave gaging site (RS 0.39) in July and August of 1998.

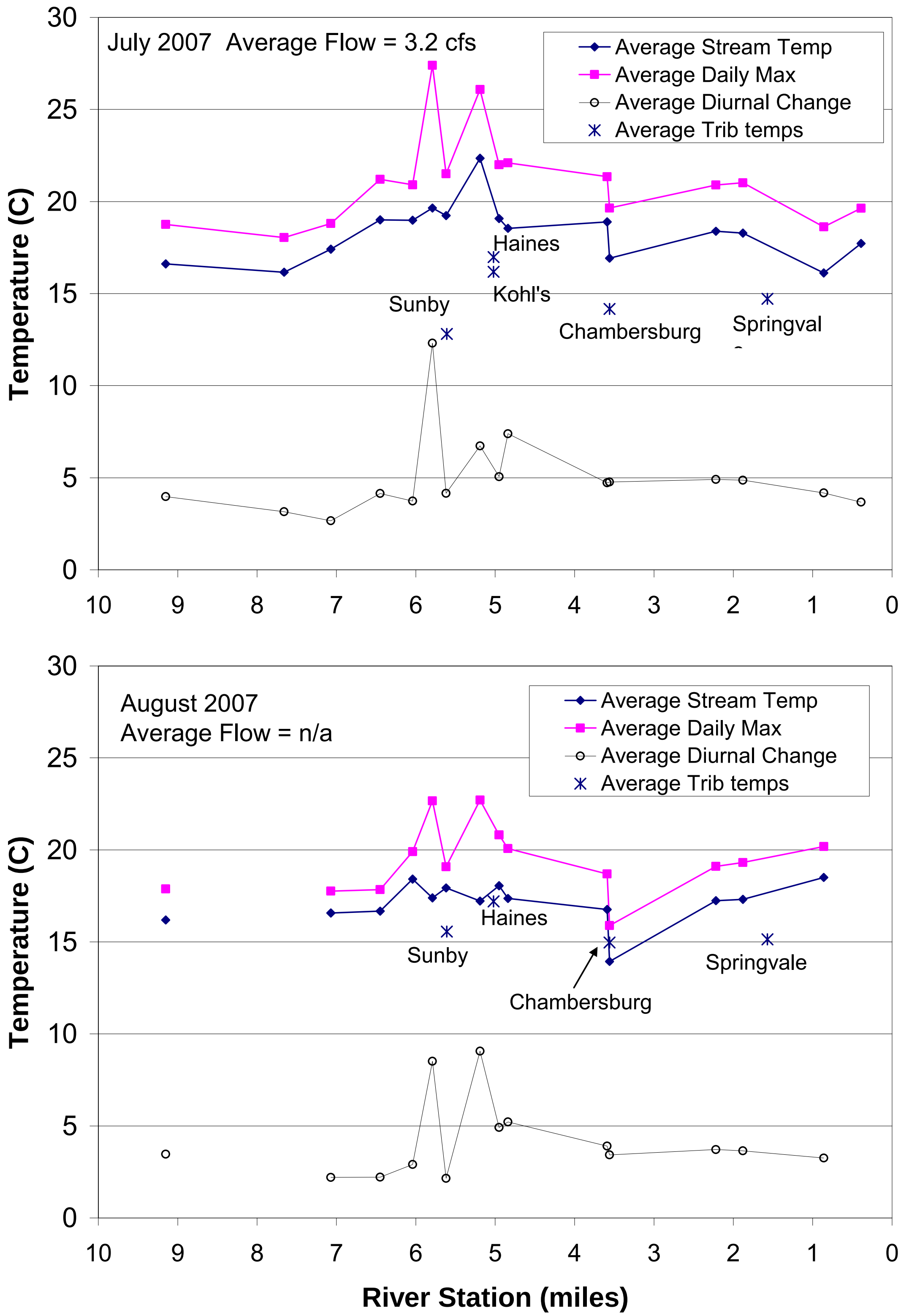


Figure 4.3. Longitudinal variability of average, daily maximum, and diurnal change in stream temperature from the Ridgewood Rd. location (RS 9.15) to the 26th Ave gaging site (RS 0.39) in July and August of 2007.

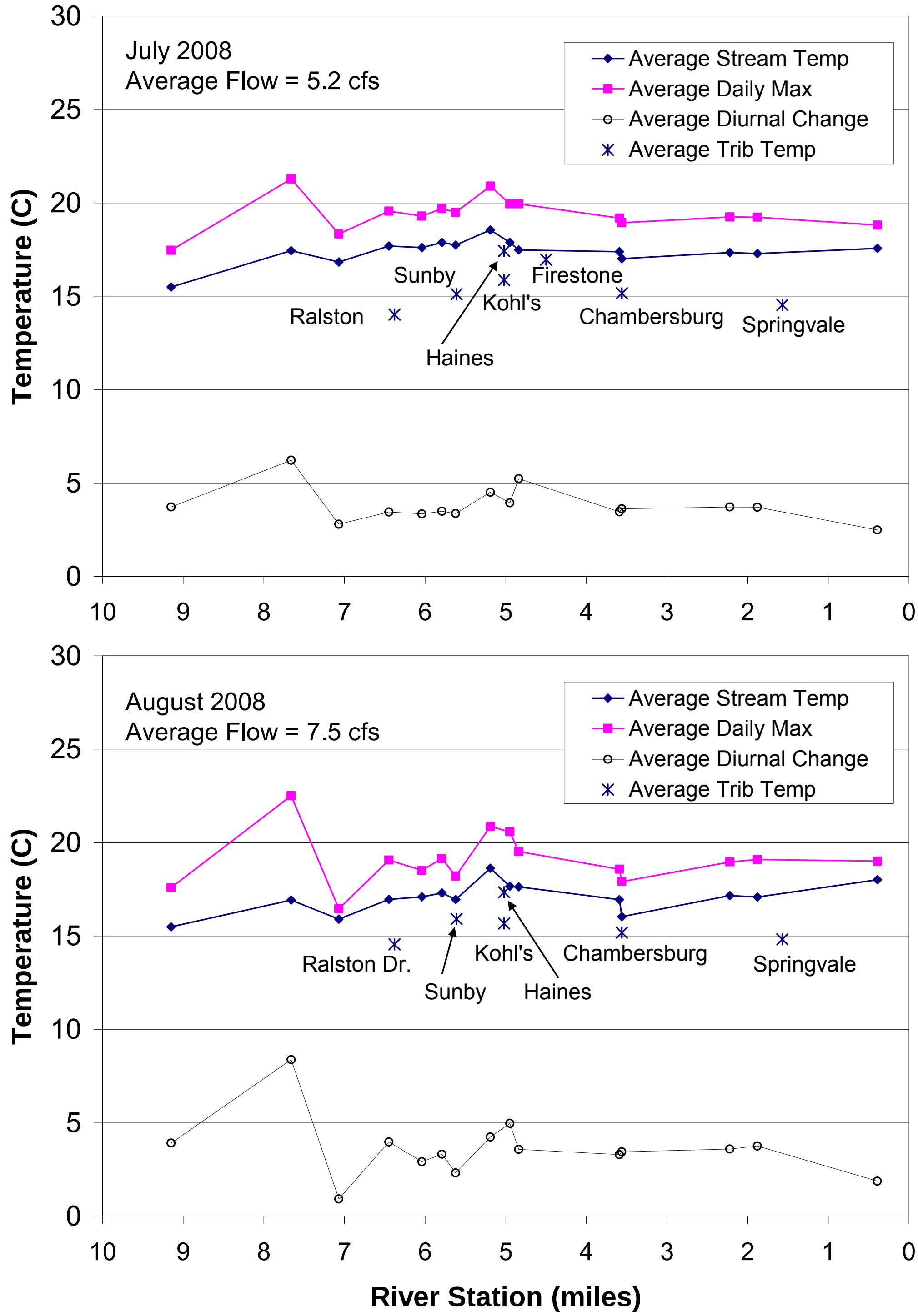


Figure 4.4. Longitudinal variability of average, daily maximum, and diurnal change in stream temperature from the Haines location (RS 7.66) to the 26th Ave gaging site (RS 0.39) in July and August of 2008.

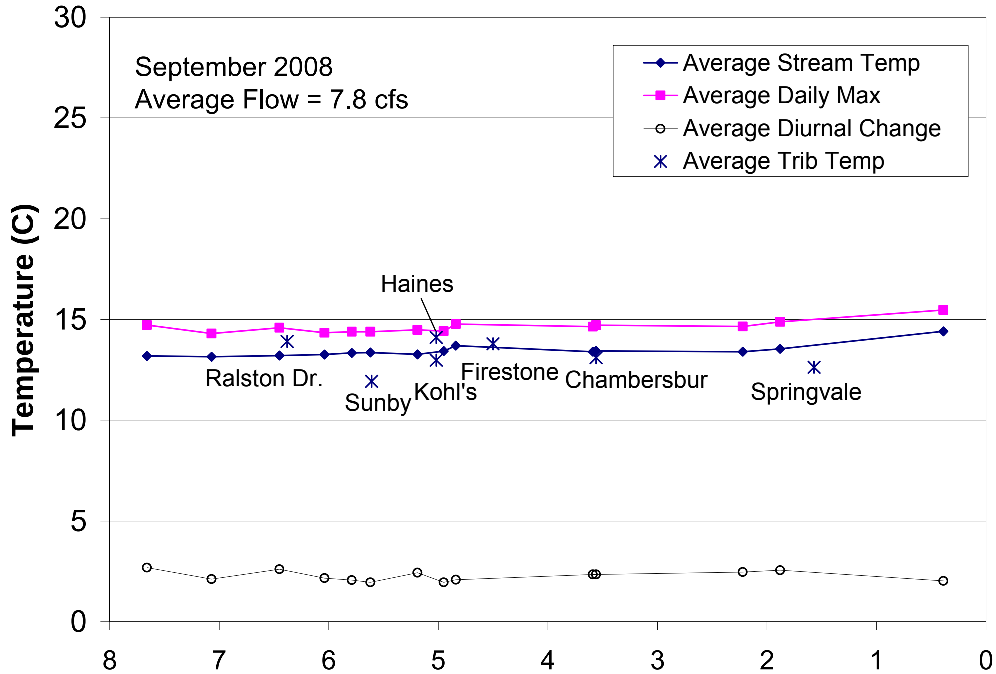


Figure 4.5. Longitudinal variability of average, daily maximum, and diurnal change in stream temperatures from the Haines location (RS 7.66) to the 26th Ave gaging site (RS 0.39) in August 1998 and September 2008.

5. Temperatures of Miller Creek Tributaries and Stormwater Inlets

5.1 Tributary Temperatures

The 2007/2008 Miller Creek stream temperature data set includes temperature measurements of 8 tributaries in 2007 and 7 tributaries in 2008 (Table 1.2). Data are plotted in Figure 5.1 and average temperatures are given in Table 5.1. In addition, 3 stormwater inlets were instrumented in 2007 and 2 in 2008. The Kohl's tributary was the only tributary instrumented in 1998 (Figure 5.2), and no tributaries were instrumented in 1997.

Time series of tributary and nearby main stem temperatures at Kohl's and Chambersburg Ave. are given in Figures 5.1 and 5.2 for the years 2007, 2008 and 1998. In 2007 and 2008, the tributaries have lower mean temperatures and lower diurnal amplitudes compared to the main stem. Monthly average temperatures for the combination of all tributaries and all main stem measurement sites are given in Table 5.1.

The Kohl's tributary has a lower mean temperature and lower diurnal temperature change compared to the main stem in July and August of 2007 and 2008. Earlier (June) and later (September) in the season the tributary temperatures more closely match the main stem temperatures. In 2007, the tributary exhibits relatively high diurnal amplitude in August and

September (Figure 5.1), suggesting that the inflow of groundwater to the tributary was minimal in this period. Overall, the main stem experienced a temperature reduction due to Kohl's tributary. This was also true in 2008, and in July of 2007. In July of 2008, the main stem increases in average temperature from upstream to downstream of Kohl's tributary, likely because there was little or no flow in the tributary due to dry weather.

In 1998, temperature observations from Kohl's creek are markedly different, with a higher mean temperature than the main stem and higher diurnal amplitude compared to other years (Figure 5.2, Table 5.1). However, the main stem still experiences a temperature reduction from upstream to downstream of Kohl's tributary in 1998 (Figure 4.2). This may indicate a problem with the temperature measurement in Kohl's creek in 1998.

Temperature measurements upstream and downstream of the SuperOne wetland provide the opportunity to determine if the wetland is providing temperature mitigation. Rainfall events in both 2007 and 2008 were identified (Figure 5.3) where the wetland does appear to give a temperature reduction from upstream to downstream. There is some indication that the thermal buffering capacity of the SuperOne wetland can be overwhelmed by larger rainfall, such as the 0.9 cm event on July 20, 2008, that was preceded by rainfall totaling 4.7 cm in the five days prior. Of 47 rainfall events between June 15 and Sept. 15, 2008, there were 20 rainfall events with a distinct temperature increase at the Haines station and an attenuated temperature increase at the SuperOne station. The relative flows are not known, so that the corresponding heat energy reductions due to the wetland are not known.

The Chambersburg tributary has a lower mean temperature as the main stem at this point, but a similar diurnal temperature change (Figure 5.4), suggesting the presence of a cold groundwater source and some influence of atmospheric heat transfer. Plots of the main stem temperature show a decrease from upstream to downstream of this tributary of 0.5 to 2 ºC (Figures 4.3, 4.4), indicating that the Chambersburg tributary flow is a significant fraction of the main stem. Stormwater inflows through the Chambersburg tributary increased temperatures, but the inflows did not exceed 20ºC in any case.

Overall, the tributary temperatures were lower than nearby main stem temperatures by 1.1 to 3.1 ºC in 2007 and 2008 (Table 5.1), and all tributaries were found to be colder than neighboring main stem reaches in July and August (Figure 4.2 –4.5). The relative importance of each tributary on the overall Miller Creek heat budget will be difficult to determine, because no spatially detailed flow data is available.

Tributaries can show a distinct response to stormwater inputs, since baseflow in tributaries can be quite small and baseflow temperatures in tributaries are typically lower than those of the main stem. The tributaries at Haines Road and Firestone (near Miller Hill Mall) both show relatively strong response to stormwater inputs for multiple events in 2007 and 2008; temperature increases are rapid, and maximum temperatures exceed 20ºC.

In 2007, storm events led to temperature spikes exceeding 20ºC five times in the Haines tributary (Figure 5.3) and eight times at the Firestone tributary (Figure 5.5). 2008 data showed similar responses, although the temperature record at the Firestone station was incomplete due to lack of flow. Other tributaries such as the Chambersburg tributary (Figure 5.6) showed less temperature response to storm events, and few or no temperature spikes exceeding 20ºC were attributable to storm runoff.

5.2 Storm Sewer Discharge Temperatures

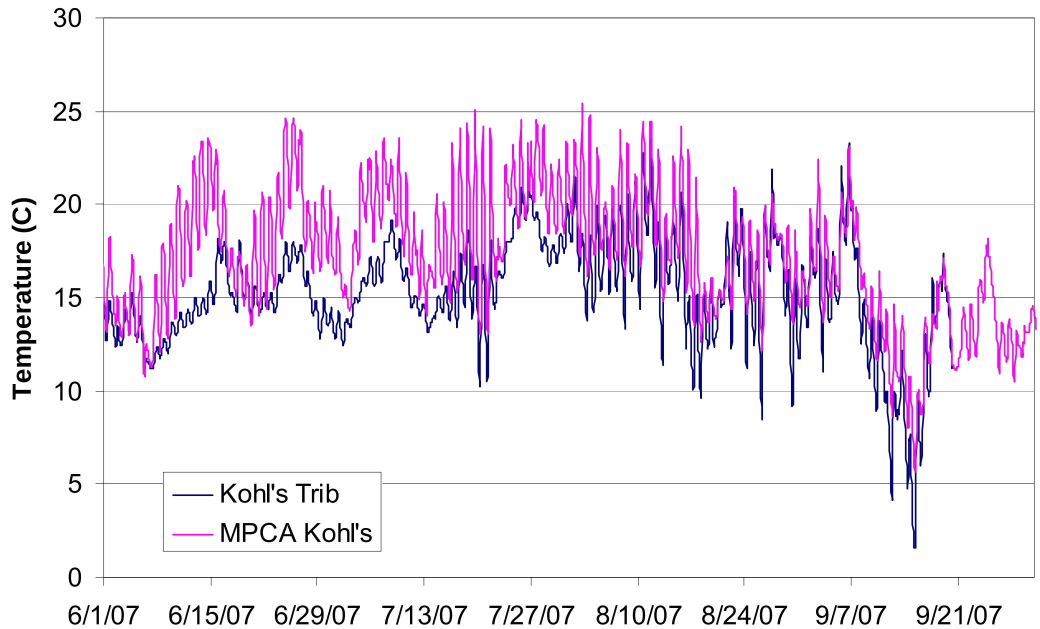
The 2007/2008 data set also includes temperature measurements at several storm sewer discharge points; 3 in 2007 (LP-5SW, LP-10SW, and Mall Drive SW), and 2 in 2008 (LP-10SW and Mall Drive SW). The locations of these stormwater inputs to the main stem are shown in Figure 1.2. Time series of observed water temperatures at the stormwater inputs are given in Figures 5.7 and 5.8, along with total precipitation and average dew point temperature for each storm. Dew point temperature is an estimate of rainfall temperature, and, therefore, an estimate of minimum runoff temperature for cases where warming of the runoff on pavements is absent, such as at night and in early morning when pavements are not heated by sunshine prior to rainfall. In those cases runoff temperature should be close to dew point temperature.

The Mall Drive stormwater input shows the strongest temperature response to rainfall events in 2007 and 2008, with inflow temperatures exceeding 20ºC eight times in 2007 and four times in 2008 (Figure 5.7, 5.8). Some, but not all, of the events exceeding 20ºC are associated with rainfall events with relatively high dew point temperature, e.g. June 26, July 26, and September 6, 2007. The June 11, 2008 event shows influx of colder water (8.1ºC) due to a low dew point temperature (5ºC). The event on July 5, 2007 gave a relatively high storm water temperature (23.9 ºC), despite a relatively low dew point temperature (12.8 ºC), which may be an indication of runoff heated by pavement. Using dew point temperature from the Duluth airport, the observed temperatures at the Mall Drive stormwater discharge are almost all higher than the observed dew point temperature. However, if 2008 dew point temperature data from the flow gaging stations are used, the inlet temperatures at Mall Drive are more in line with dew point temperatures (Figure 5.8). On average, dew point temperatures from the Miller Creek flow gaging stations during rainfall events are about 1ºC higher than dew point temperatures from the airport.

The stormwater outlet at LP-10SW showed relatively moderate discharge temperatures compared to the Mall Drive location, with only one event exceeding 20ºC in 2007 (Figure 5.7) and one event in 2008 (not shown). At both the Mall Drive and LP-10SW locations, the observed temperature during dry weather is relatively low and invariant compared to air and stream temperature, which could indicate a continuous leak of groundwater into the stormwater systems. The temperature record for LP-5SW in 2007 is incomplete, and the recorded temperatures have higher diurnal variation during dry weather compared to the other stormwater sites, perhaps indicating more influence of the stream temperature at this location. Several temperature increases due to storm events are visible in Figure 5.7, including one event exceeding 20ºC on July 5, 2007.

Table 5.1 Monthly average stream temperatures of all Miller Creek main stem sites and all tributary sites.

	June		July		August		September	
	Main Stem (°C)	Tribu-taries (°C)	Main Stem (°C)	Tribu-taries (°C)	Main Stem (°C)	Tribu-taries (°C)	Main Stem (°C)	Tribu-taries (°C)
1997	16.9		17.6		15.7		13.4	
1998	15.1		18.9	21.8	18.7	20.7	15.1	16.1
2007	15.5	13.5	17.6	14.5	17.3	15.3	14.3	13.8
2008	15.0	12.5	16.6	14.9	16.4	15.3	13.0	13.5



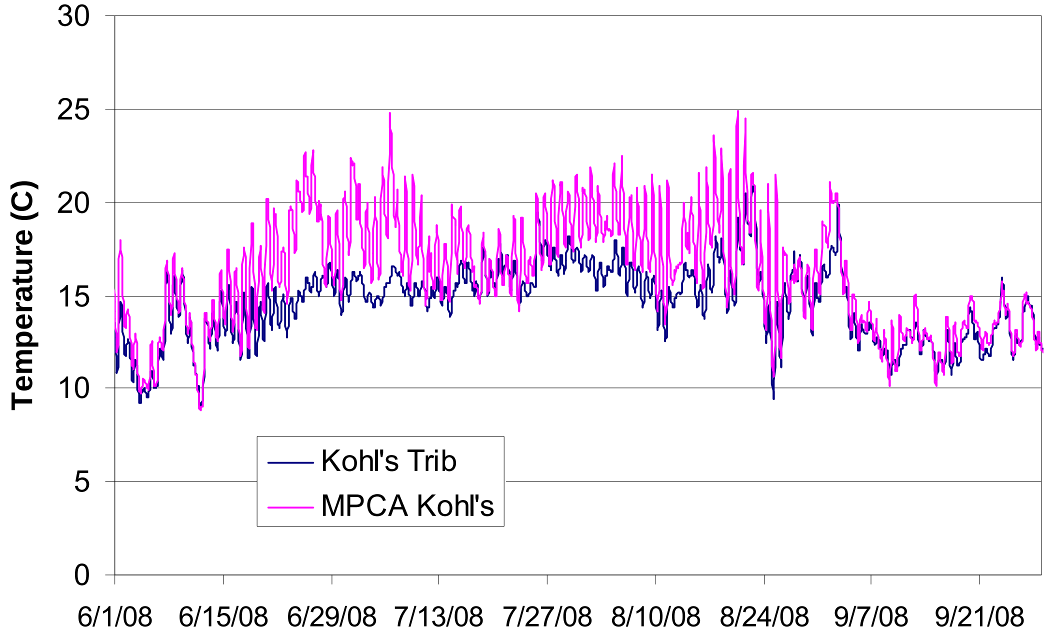


Figure 5.1. Miller Creek main stem and tributary temperatures at the Kohl's stream flow gaging station in 2007 and 2008.

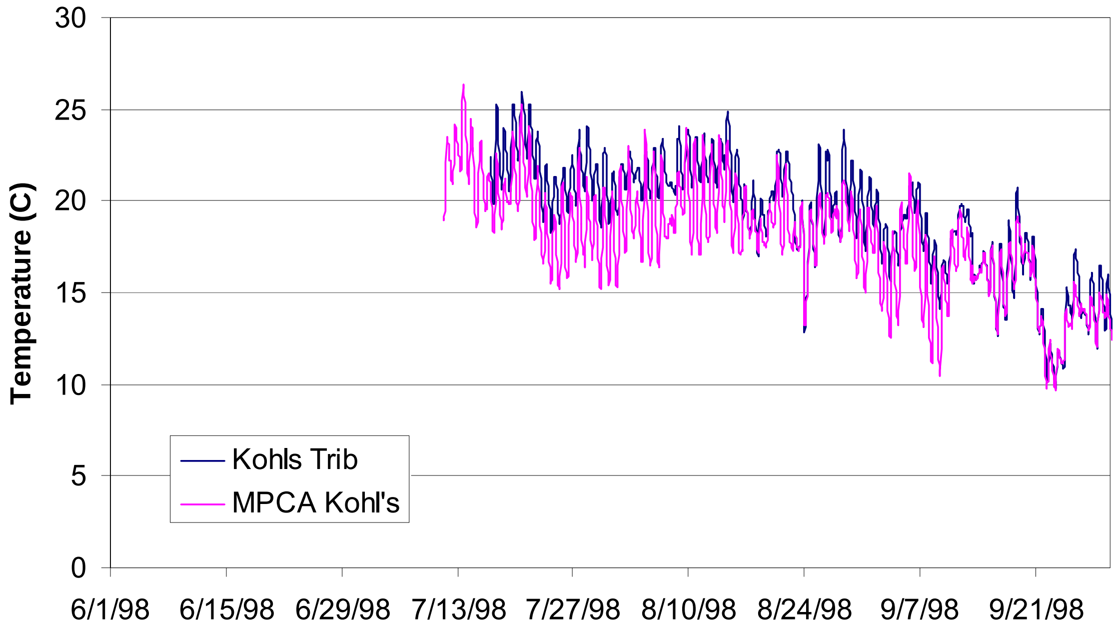
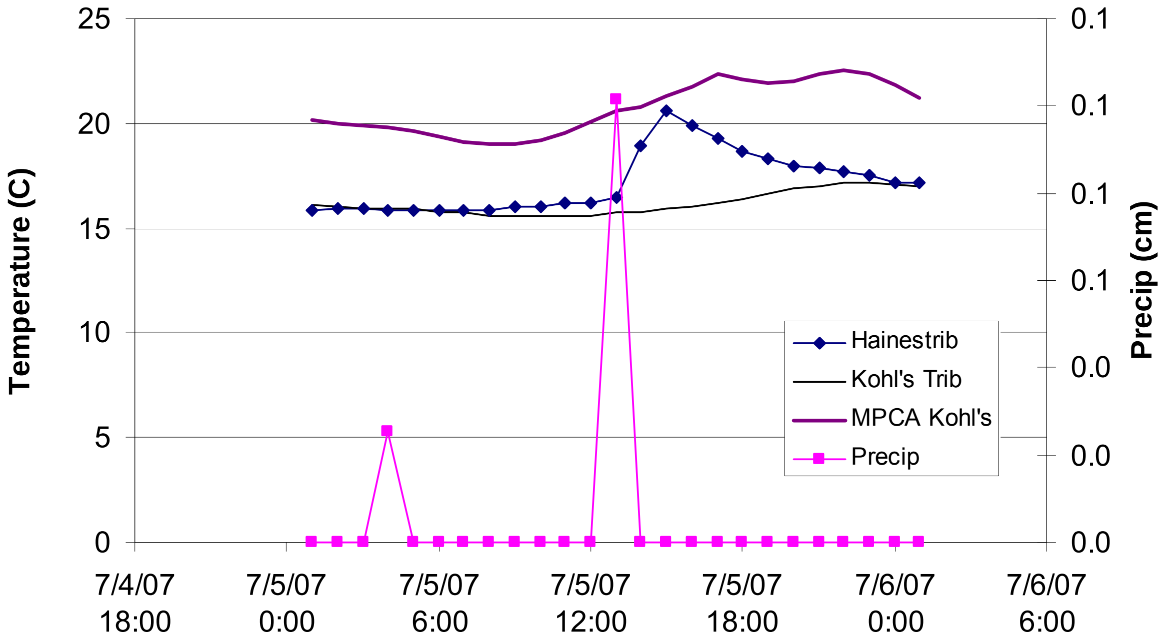


Figure 5.2. Miller Creek main stem and tributary temperatures at the Kohl's stream flow gaging station in 1998.



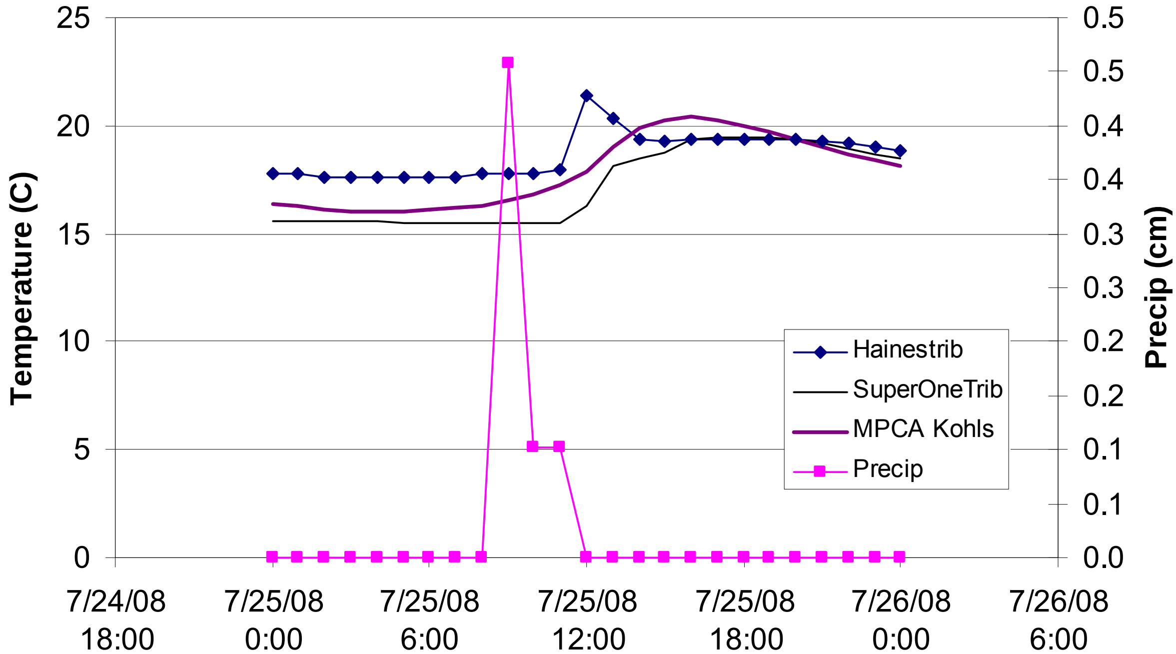


Figure 5.3. Hourly temperatures of the Haines and SuperOne tributaries and the Miller Creek main stem at the MPCA Kohl's stream flow gaging station, just downstream of the confluence with the SuperOne tributary on July 5 and July 25, 2007.

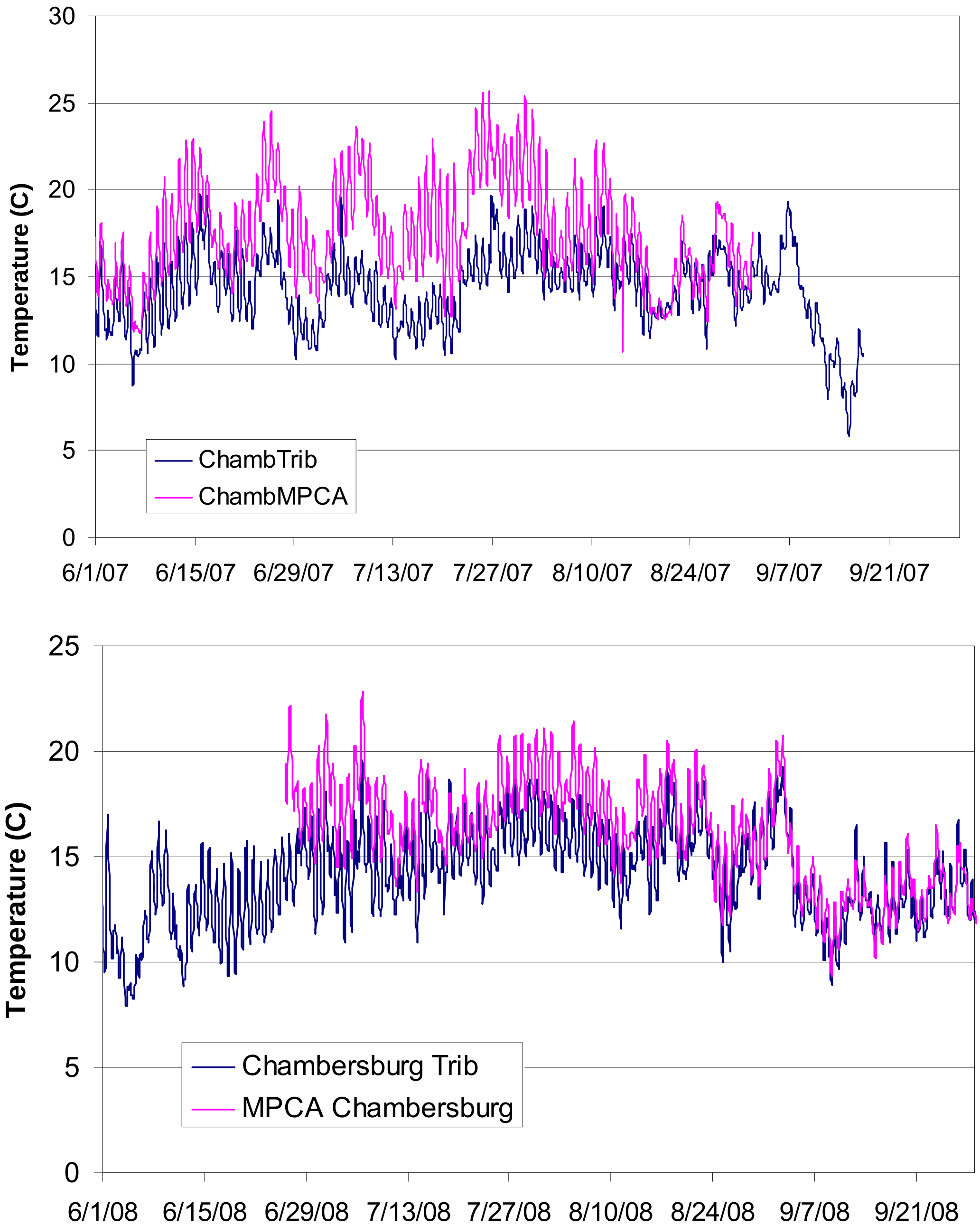


Figure 5.4. Miller Creek main stem and tributary temperatures at Chambersburg Ave. in 2007 (upper panel) and 2008 (lower panel).

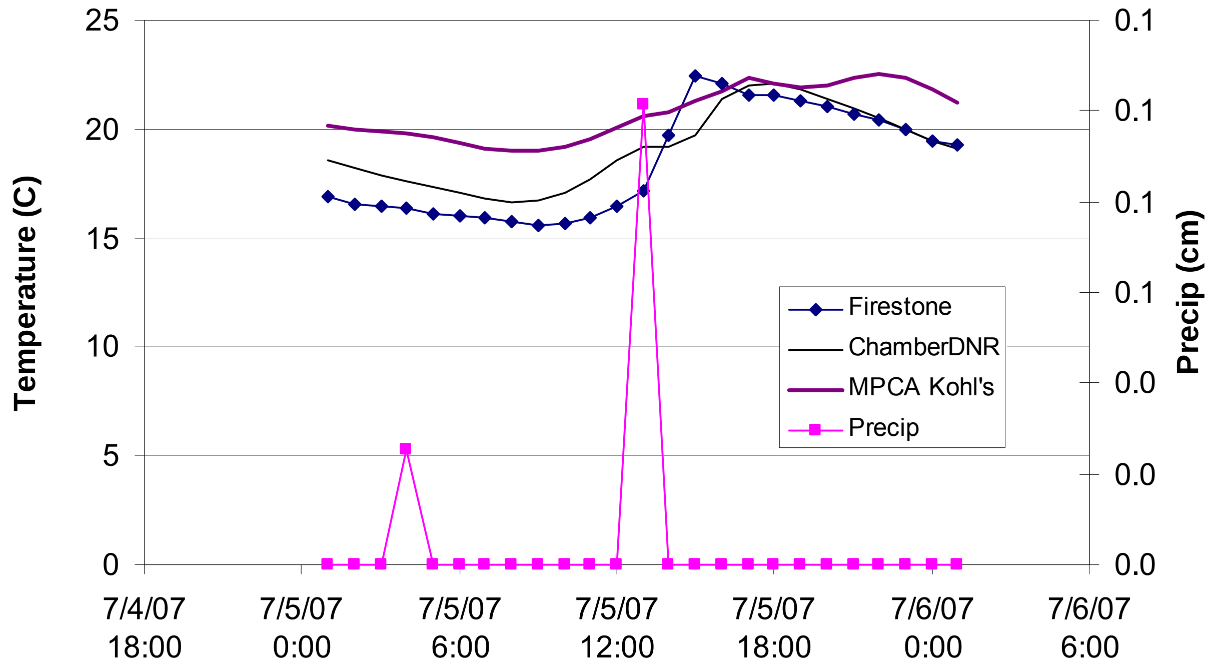


Figure 5.5. Hourly temperatures of the Firestone tributary and Miller Creek main stem at the MPCA Kohl's and Chambersburg Ave. flow gaging stations on July 5, 2007.

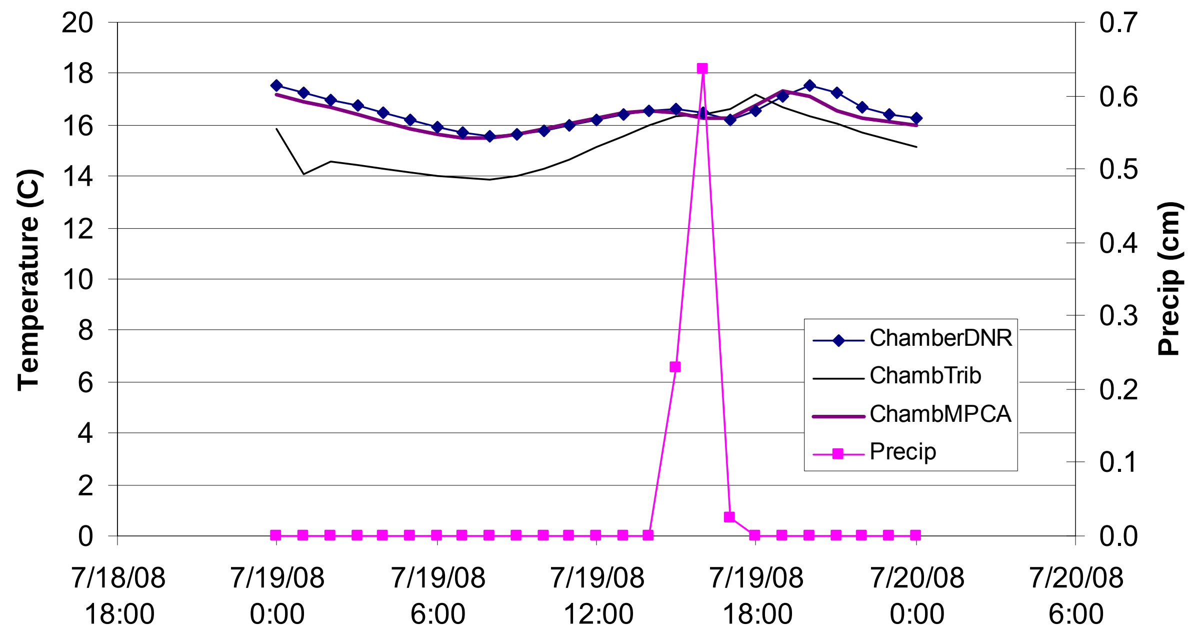


Figure 5.6. Hourly temperatures of the Chambersburg tributary and Miller Creek main stem upstream (Chambersburg MPCA) and downstream (Chambersburg DNR) of the tributary on July 19, 2007.

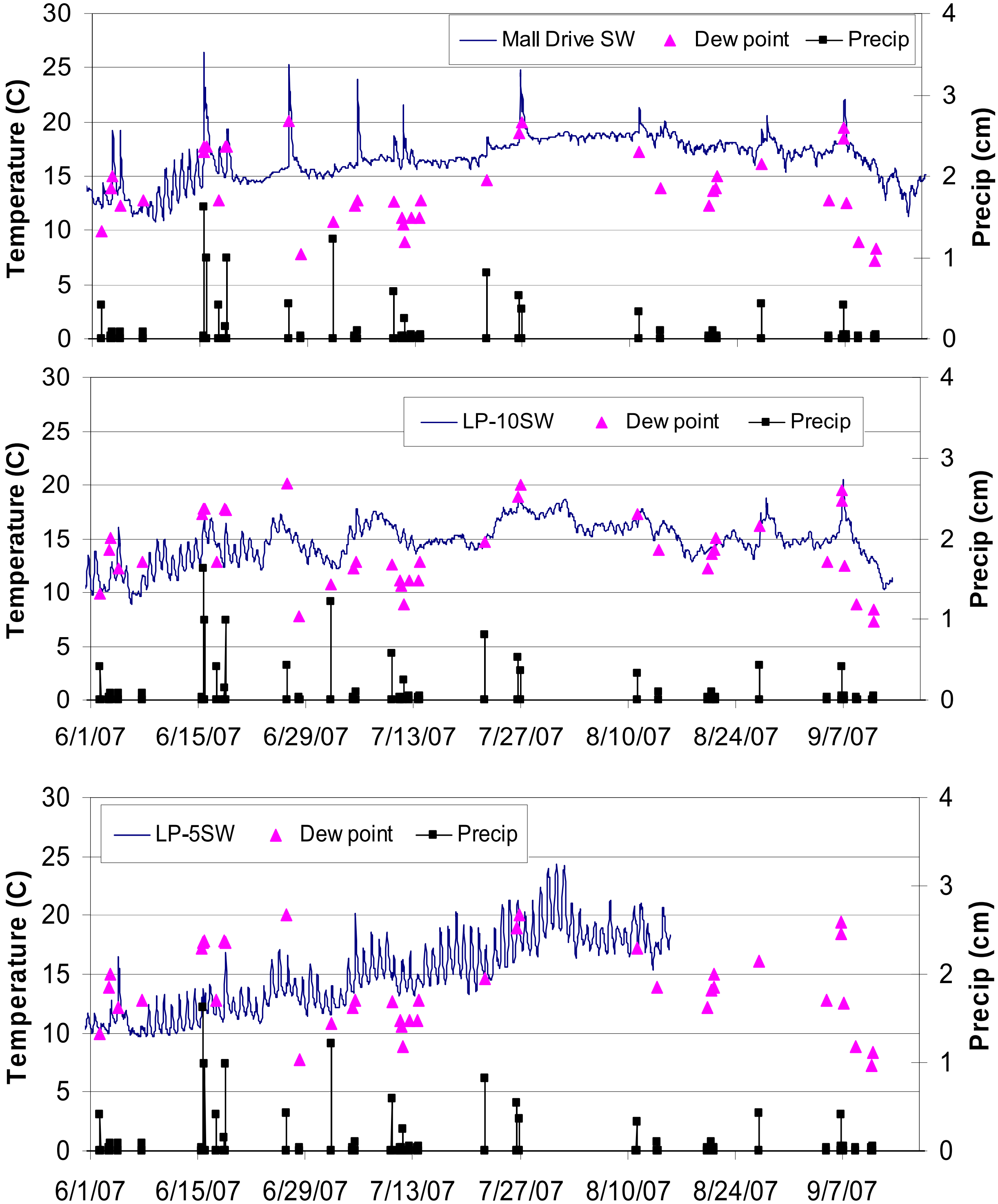


Figure 5.7. Hourly inflow temperatures at 3 stormwater inflow points (Mall Drive SW, LP-10SW and LP-5SW) to Miller Creek in 2007. Total precipitation for rainfall events and storm-averaged dew point temperatures are also shown.

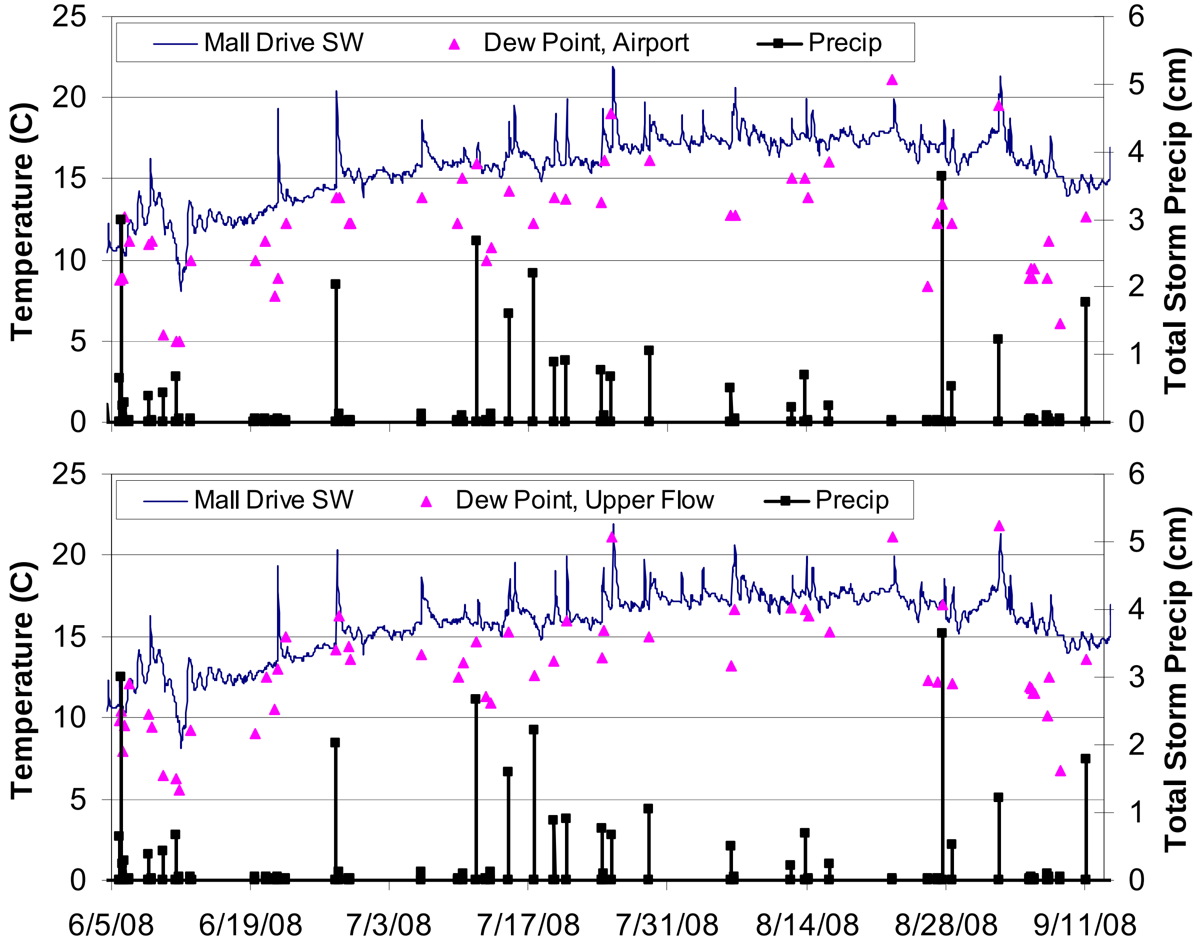


Figure 5.8. Hourly inflow temperatures at the Mall Drive SW stormwater input to Miller Creek in 2008. Total precipitation for rainfall events and storm-averaged dew point temperatures from the airport (upper panel) and the upper gaging station (lower panel) are also shown.

6. Analysis of Stream Temperature Exceedances

Maximum daily stream temperature in Miller Creek can exceed 20 ºC (68 ºF) from approximately June 15 to September 15 (Figure 3.4). Stream temperature data from this 92 day period were analyzed to compile the number of days when stream temperature exceeded 20 ºC or 24 ºC (75 ºF). Temperature exceedances events, e.g. continuous periods of time where stream temperature exceeded 20 ºC were also counted. 20 ºC represents a chronic temperature limit for trout, while 24 ºC represents a lethal temperature limit (South St. Louis SWCD 2001).

Figures 6.1 to 6.4 give overall statistics for 20 ºC and 24 ºC temperature exceedance on all Miller Creek main stem stations in 1997, 1998, 2007, and 2008, respectively. These plots are similar to those given in the Miller Creek Diagnostic and Implementation Study Plan (South St. Louis SWCD 2001) for 1997 Miller Creek temperature data. For stations with incomplete records for the period June 15 to September 15, the total number of observed exceedance days was multiplied by the factor (92/n), where n is the actual number of measurement days. This adjusted value is an estimate for the number of exceedances for a complete measurement record.

Overall, temperature exceedances are both more numerous and longer in duration in the middle reaches of Miller Creek, between the Highway 53/Haines Rd. intersection and Miller Hill Mall. 1997 and 2008 had relatively few exceedances, but even in these years, some sites in Miller Creek exceeded 20 ºC on over half of all measurement days (Figure 6.1, Figure 6.4). In 1998, 76 days (80% of all measurement days) exceeded 20 ºC at the sites upstream of Kohl's and at Miller Hill Mall (Figure 6.2), and 33 days exceeded 24 ºC at each of these two sites.

Seven years of stream temperature data are available from the three Miller Creek flow gaging sites at Kohl's, Chambersburg Ave. and 26th Ave. These data give an opportunity to examine year to year variations in temperature exceedances. The number of days with stream temperatures exceeding 20 ºC in the seven years of available data are plotted in Figure 6.5. Exceedance days for each station follow the same trend from year to year, which appears to largely driven by year to year variations in air temperature. Of the three sites, the upper station (Kohl's) has the highest number of exceedance days in all years except 1998. 2005 has the highest number of exceedance days at all stations, with 78 out of 92 days exceeding 20 ºC at the upper station. The values given in Figure 6.5 are listed in Table 6.1, along with average durations and corresponding statistics.

Stream temperature exceedances can also be analyzed as events, rather than by day, since some exceedance events last longer than 24 hours. Temperature exceedance events can be associated with 1) stormwater runoff, 2) atmospheric heat transfer during warm, dry weather, or 3) both stormwater and atmospheric heat transfer.

An example of stream temperature time series is given in Figure 6.6, which shows a temperature exceedance on July 26, 1997 associated with a runoff event, followed by an exceedance event on July 27, 1997 associated with atmospheric heat transfer. Compared to the exceedance due to atmospheric heat transfer, the exceedance due to runoff has more rapid changes in stream temperature, a shorter duration, more spatial variability in the magnitude of the response, and a time lag in the response between stations. The temperature spike due to runoff is highest near Miller Hill Mall.

Temperature exceedance events (20 ºC) are compiled in Table 6.2 for stream temperature data from the three Miller Creek flow gaging sites. The flow gaging site at Kohl's has the highest number of exceedance events (226) and the lowest number of exceedance events associated with runoff (8). Note that the average stream flow for exceedance events (3.5 to 4.1 cfs) is only slightly lower than the average stream flow for the measurement period (5.4 cfs). Many of the exceedance events associated with runoff also include substantial contribution from atmospheric heat transfer, either prior to or after the runoff event, yielding exceedance events with very long durations, e.g. the August 20, 2005 event given in Figure 6.7. As a result, statistics for event duration are not given for runoff associated events in Table 6.2.

Several EPA-approved temperature TMDLs that focus on cold water salmon rivers use the running 7-day average of daily maximum stream temperature as a metric for evaluating temperature exceedances (e.g. Oregon DEQ, 2001 and USEPA, 2000). The seven day average tends to de-emphasize transient events such as stormwater inflows, and emphasizes the more consistent, repeated heating process of atmospheric heat transfer. For Miller Creek, the relative number of 7-day average exceedance days between the lower, middle, and upper flow stations is similar to the unaveraged exceedances given in Table 6.1, with the upper station having the highest number of exceedances (54 days per year) and the middle station the least (28 days per year), as given in Table 6.3. There were no instances of the 7-day running average exceeding 24 ºC. The temperature records of all three stations include continuous, multi-week periods when the 7-day average maximum temperature exceeded 20 ºC (Figure 6.8).

The distribution of high stream temperatures in Miller Creek can also be characterized using temperature duration curves. A temperature duration curve is constructed by counting the number of days on which stream temperature exceeds a certain value, e.g. 16 ºC, 18 ºC , or 20 ºC. The number of exceedance days is then normalized to the total number of observations, to give a fraction or percent of exceedance days for each temperature. Temperature duration curves for four locations in Miller Creek are given in Figure 6.9. The duration curves show that the Kohl's site has a notably higher number of higher temperature days than the other sites (Lake Superior College, Chambersburg, 26th Ave.), with Kohl's exceeding 20 ºC on 32% of the observation days compared to 12% for the 26th Ave monitoring site.

The temperature duration curve for the 26th Ave site on Miller Creek is compared to stream temperatures from the flow gaging sites on Chester Creek and Tischer Creek in Figure 6.10. Stream temperatures in Miller Creek at 26th Ave are only slightly higher than temperatures in Chester Creek or Tischer Creek. Further comparisons of the stream temperature of Miller Creek to other North Shore streams are given in Appendix I for 2009 data.

Table 6.1. Number of days and duration of 20 ºC stream temperature exceedances at the lower, middle and upper Miller Creek flow gaging stations (Kohl's; Chambersburg Ave. and 26th Ave., respectively) for seven years of record between 1997 and 2008.

	Lower		Middle		Upper	
Year	Days	Duration (hours)	Days	Duration (hours)	Days	Duration (hours)
1997	29	9.1	20	12.1	33	11.3
1998	63	11.2	36	9.6	43	10.3
2003	54	11.4	47	9.9	64	10.3
2004	24	7.1	18	6.1	31	8.1
2005	65	12.0	62	14.7	78	12.4
2007	37	10.8	44	12.1	64	10.6
2008	15	6.3	16	5.8	45	7.1
Mean	41.0	9.7	34.8	10.0	51.0	10.0
St Dev	20.0	2.2	17.6	3.3	17.7	1.8

Table 6.2. Stream temperature exceedances above 20 ºC for the 621 measurement days common to all 3 Miller Creek stream flow gaging sites in 1997-1998, 2003-2005, and 2007-2008. Flows are for the lower stream gaging site (26th Ave). The average flow for all measurement days is 5.4 cfs.

	All Temperature Exceedances			Runoff Exceedances	
Station	Total Number Events	Average duration (hours)	Average Flow (cfs)	Total Number Events	Average Flow (cfs)
26th Ave	170	11.0	4.1	21	4.7
Chambersburg	135	11.5	4.0	10	4.7
Kohl's	226	11.0	3.5	8	2.5

Table 6.3. Number of days per year when the 7-day running average of daily maximum stream temperature exceeds 20 ºC or 24 ºC at the Miller Creek lower, middle and upper flow gaging stations. For incomplete records, the observed number of exceedance days has been adjusted, as described in the text.

	Number of 20 ºC Exceedance Days			Number of 24 ºC Exceedance Days		
Year	Lower	Middle	Upper	Lower	Middle	Upper
1997	24	25	35	0	0	0
1998	63	30	68	0	0	0
2007	36	52	69	0	0	0
2008	8	7	46	0	0	0
Mean	33	28	54	0	0	0
St Dev	23	19	17			

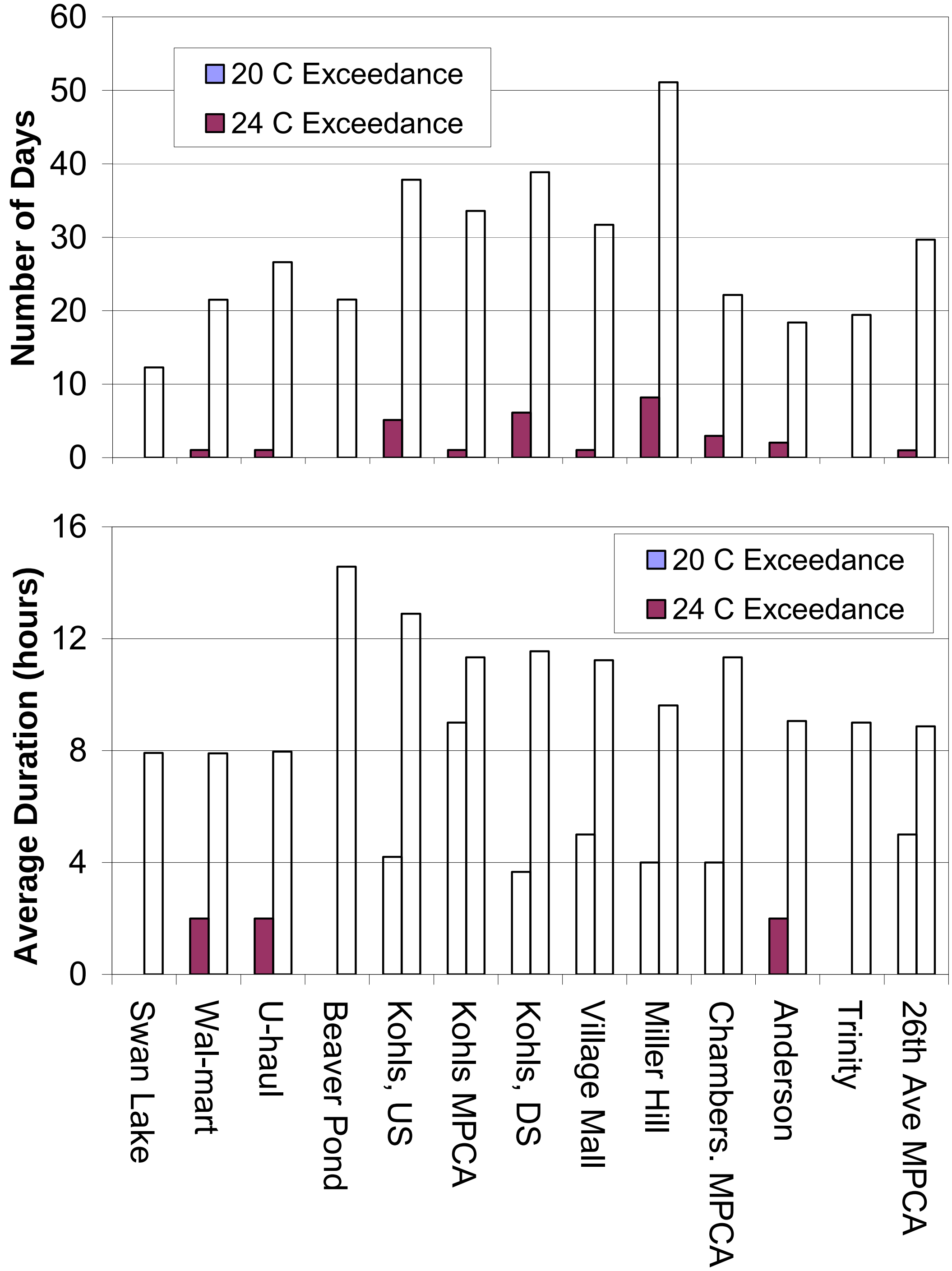


Figure 6.1. Temperature exceedance statistics for Miller Creek in 1997: number of days with temperature exceedances above 20 ºC or 24 ºC, and average duration of the temperature exceedances.

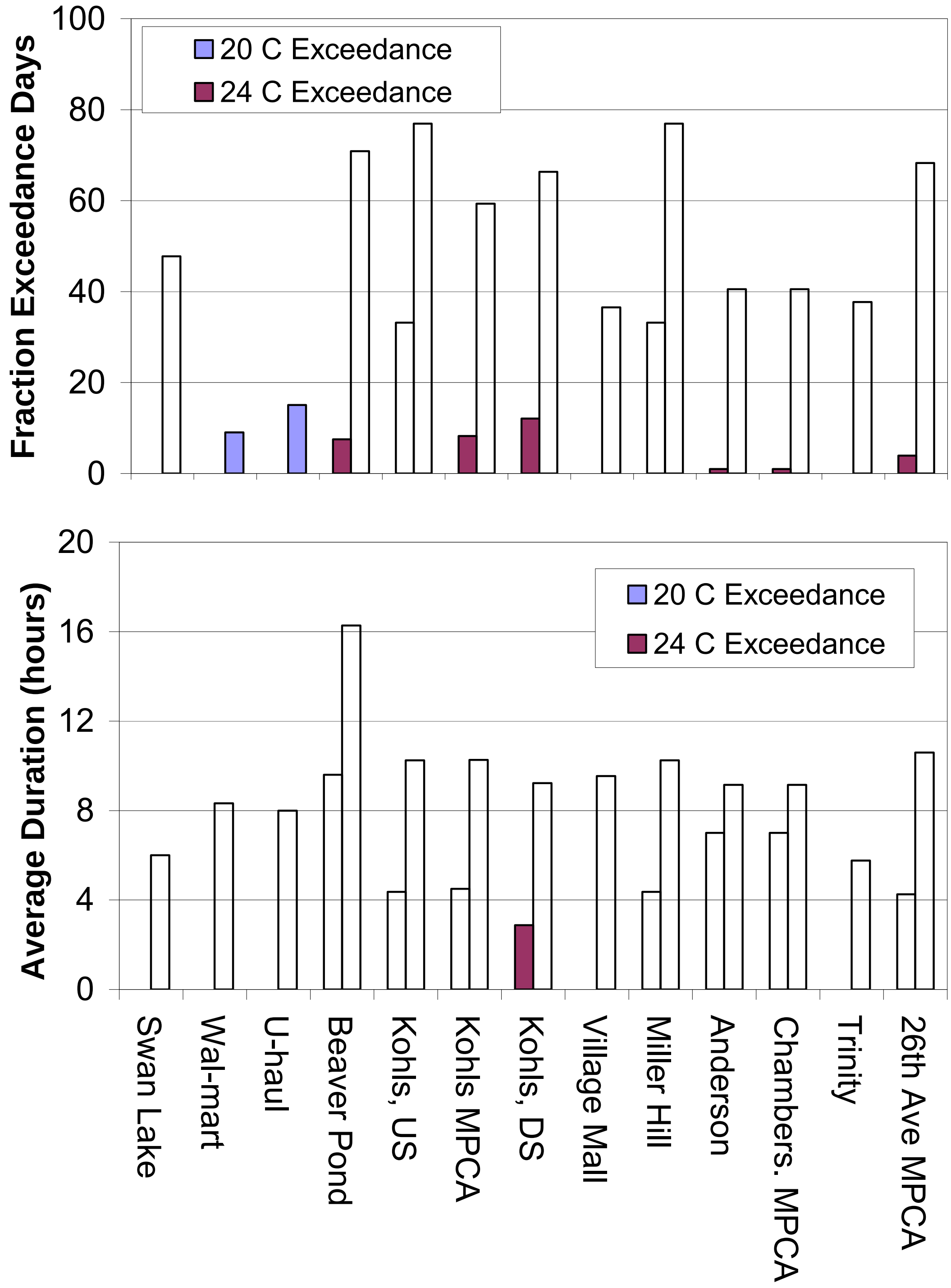


Figure 6.2. Temperature exceedance statistics for Miller Creek in 1998: number of days with temperature exceedances above 20 ºC or 24 ºC, and average duration of the temperature exceedances.

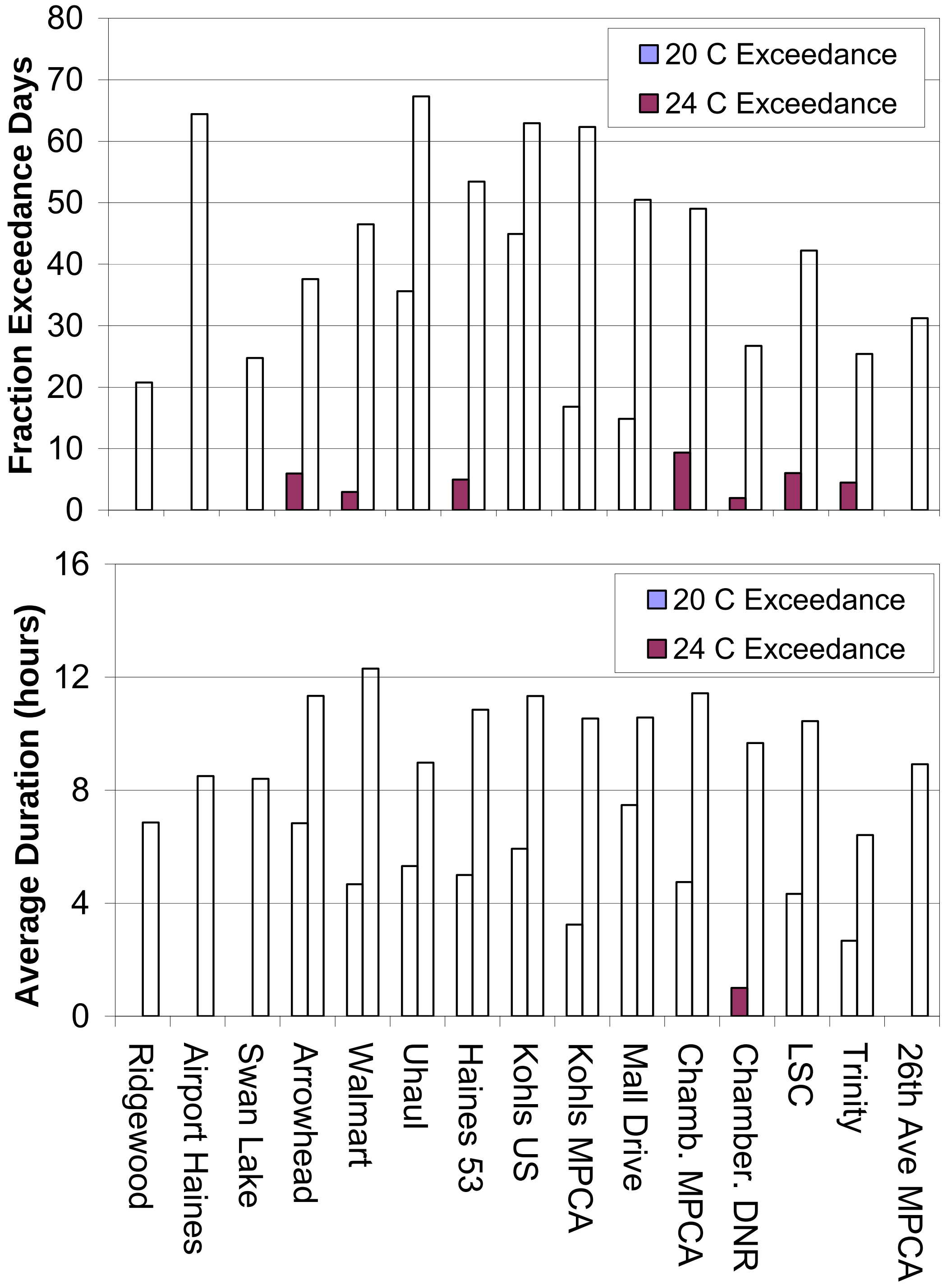


Figure 6.3. Temperature exceedance statistics for Miller Creek in 2007: number of days with temperature exceedances above 20 ºC or 24 ºC, and average duration of the temperature exceedances.

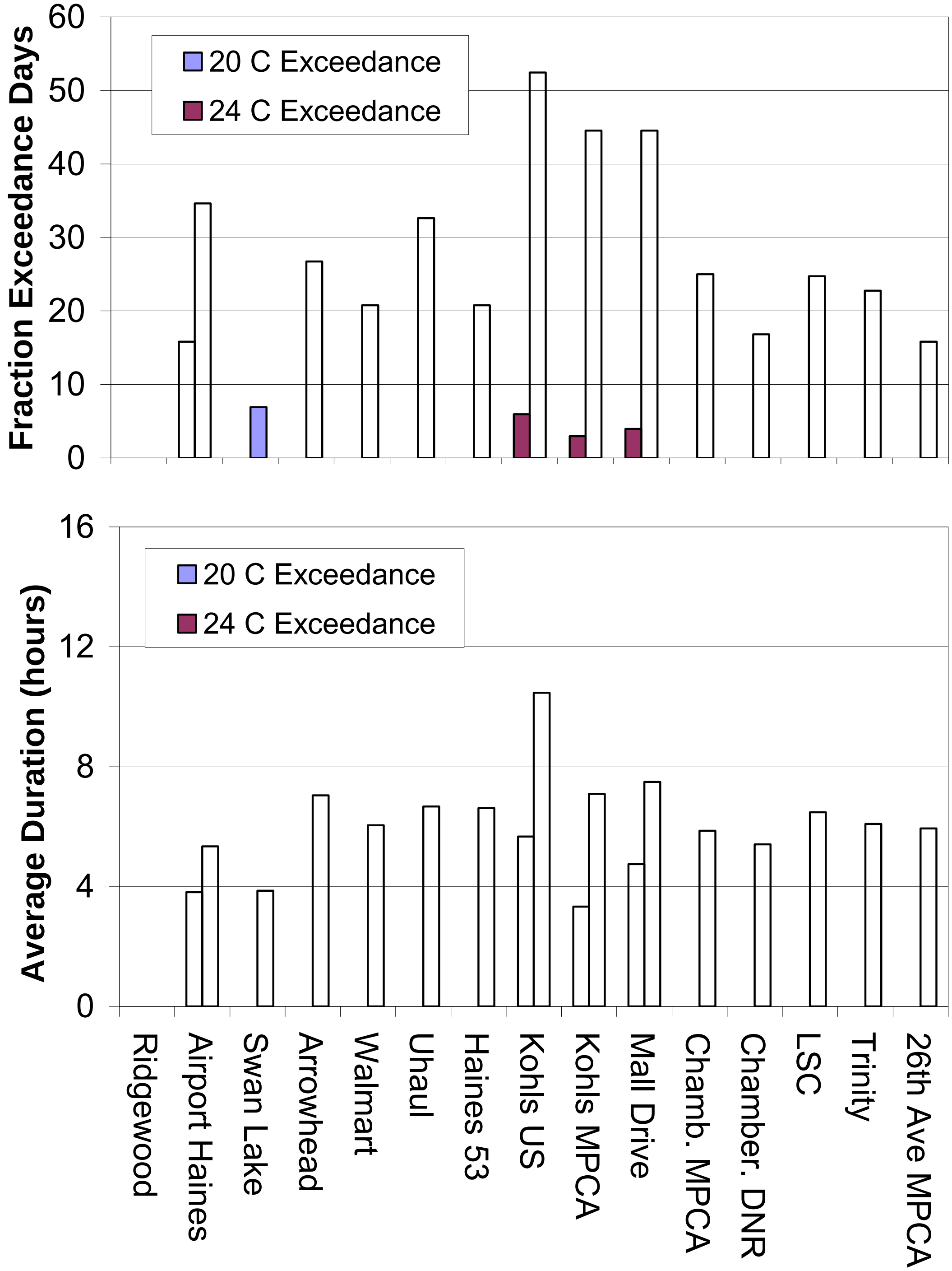


Figure 6.4. Temperature exceedance statistics for Miller Creek in 2008: number of days with temperature exceedances above 20 ºC or 24 ºC, and average duration of the temperature exceedances.

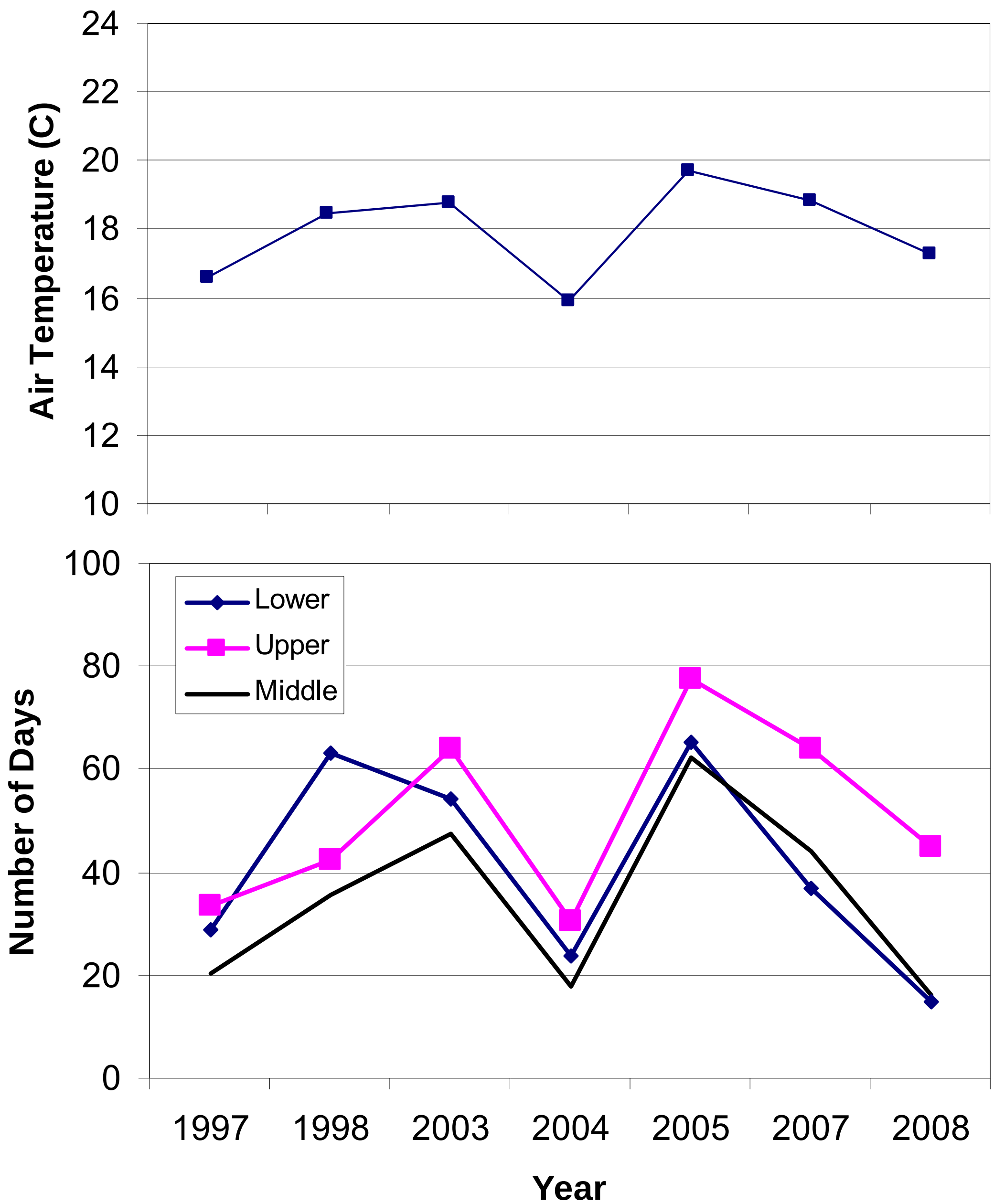
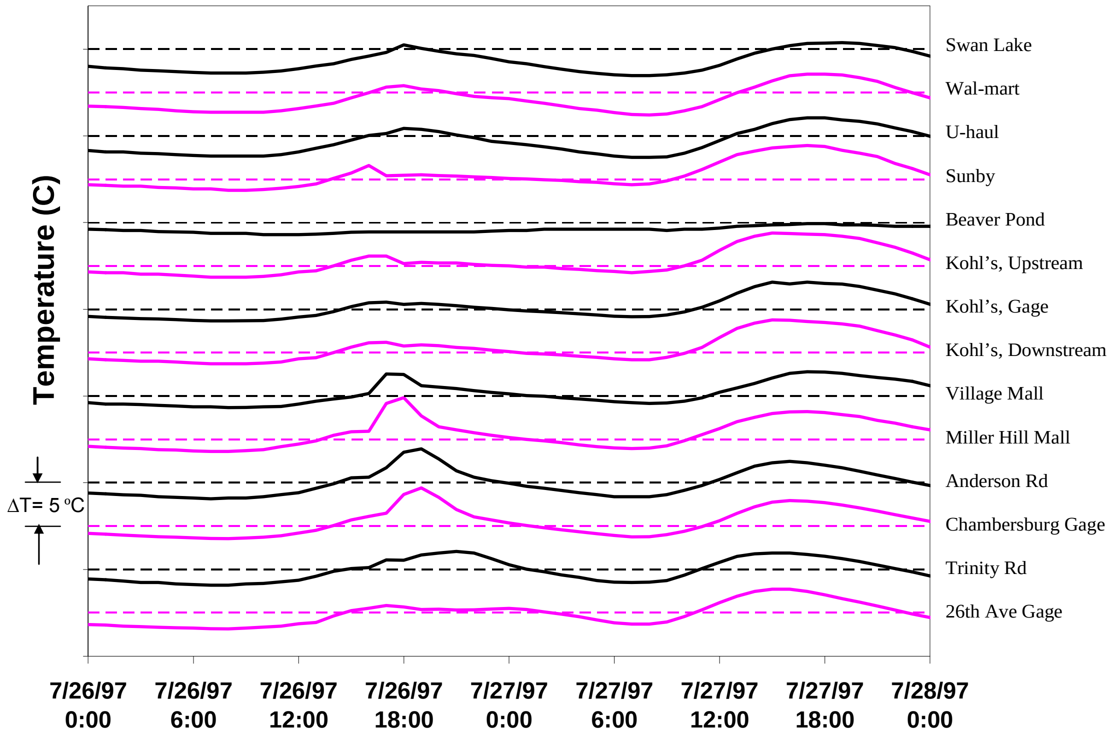


Figure 6.5. Number of days when stream temperatures exceed 20 ºC at the lower, middle, and upper Miller Creek flow gaging stations (Kohl's, Chambersburg Ave. and 26th Ave, respectively) in 1997 – 2006 (lower panel), and average air temperature for the period June 15 to September 15 in each year (upper panel). The number of exceedance days was adjusted for incomplete records, as needed, as described in the text.



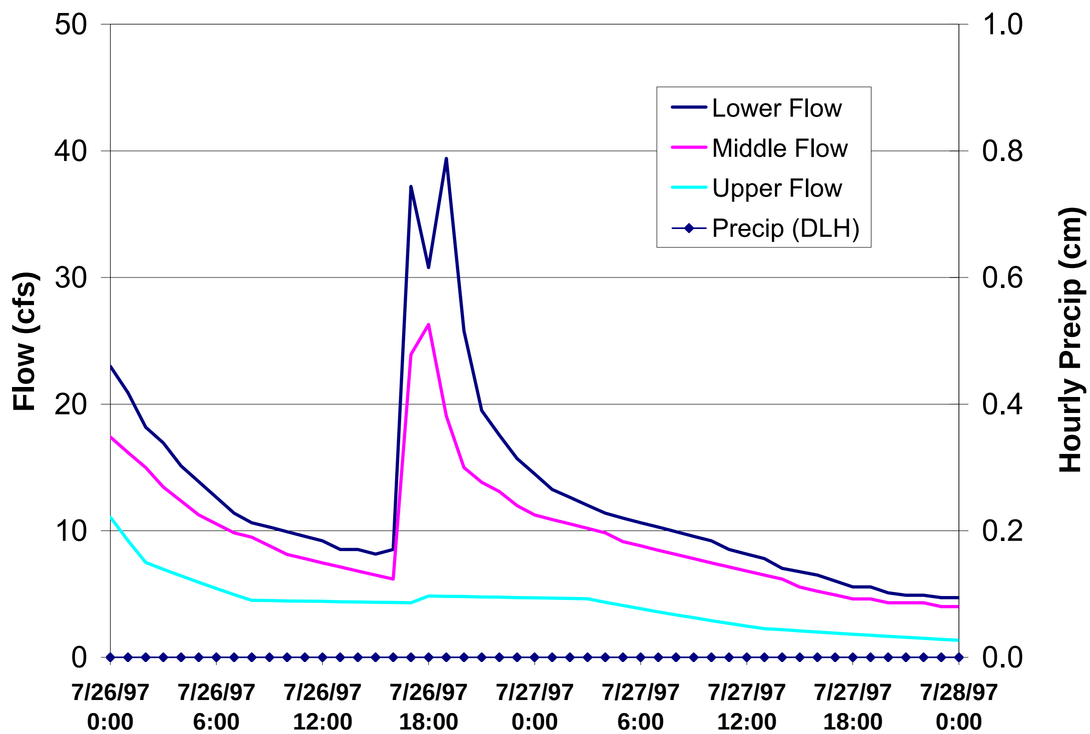
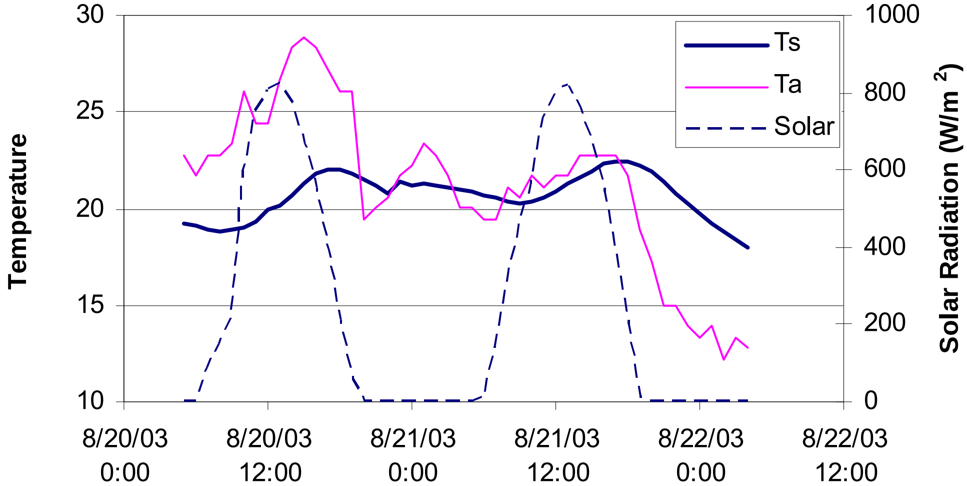


Figure 6.6. Stream temperatures (upper panel) and stream flow (lower panel) in Miller Creek on July 26 and 27, 1997. The temperature scale includes a 5 ºC offset between stations to separate the time series for the 14 stations. The dashed lines in the upper panel are 20 ºC reference lines for each temperature time series. Note that for the runoff event on July 26, no precipitation was recorded at the Duluth International Airport.



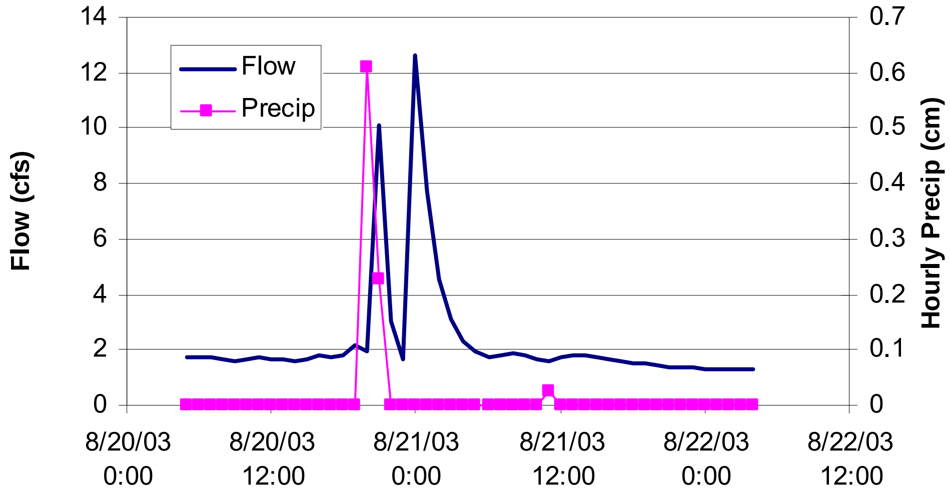


Figure 6.7. Stream temperatures from the Chambersburg Ave stream flow gaging station (T_s), air temperatures (T_a), solar radiation, hourly precipitation, and stream flow at the 26th Ave stream flow gaging station on August 20 - 22, 2003.

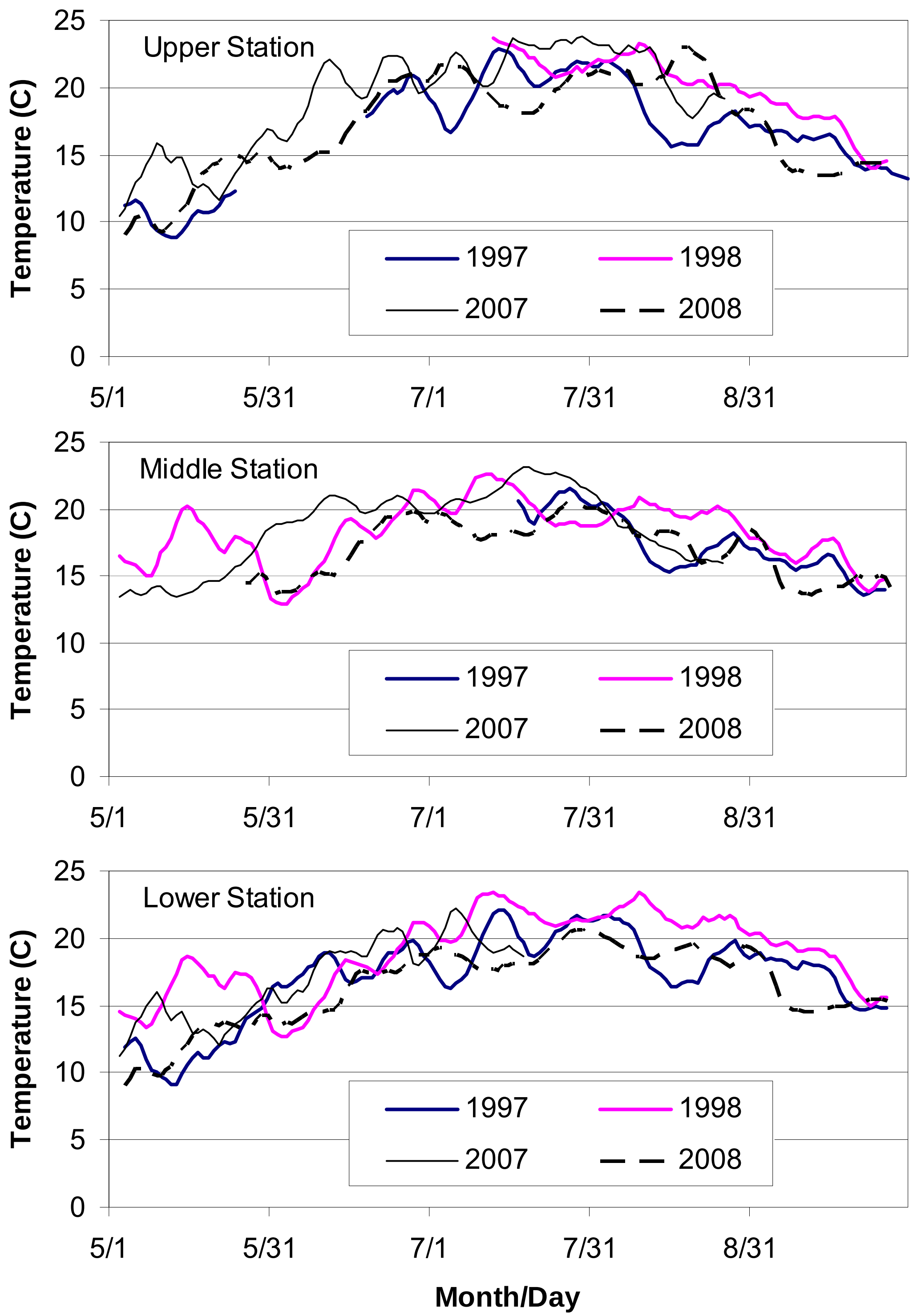


Figure 6.8. 7-day running average of maximum daily stream temperatures for the lower (26th Ave), middle (Chambersburg Ave) and upper (Kohl's) stream flow gaging stations for 1997, 1998, 2007, and 2008.

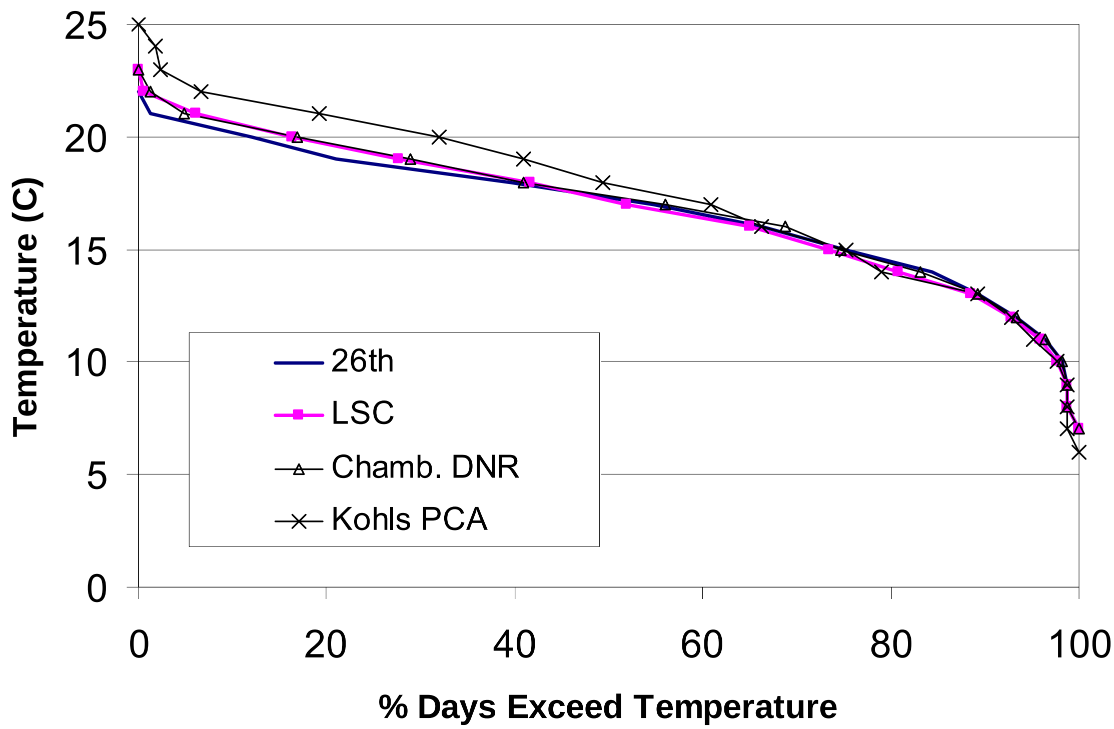


Figure 6.9. Stream temperature duration curves for Miller Creek at four locations, using 2007/2008 stream temperature data.

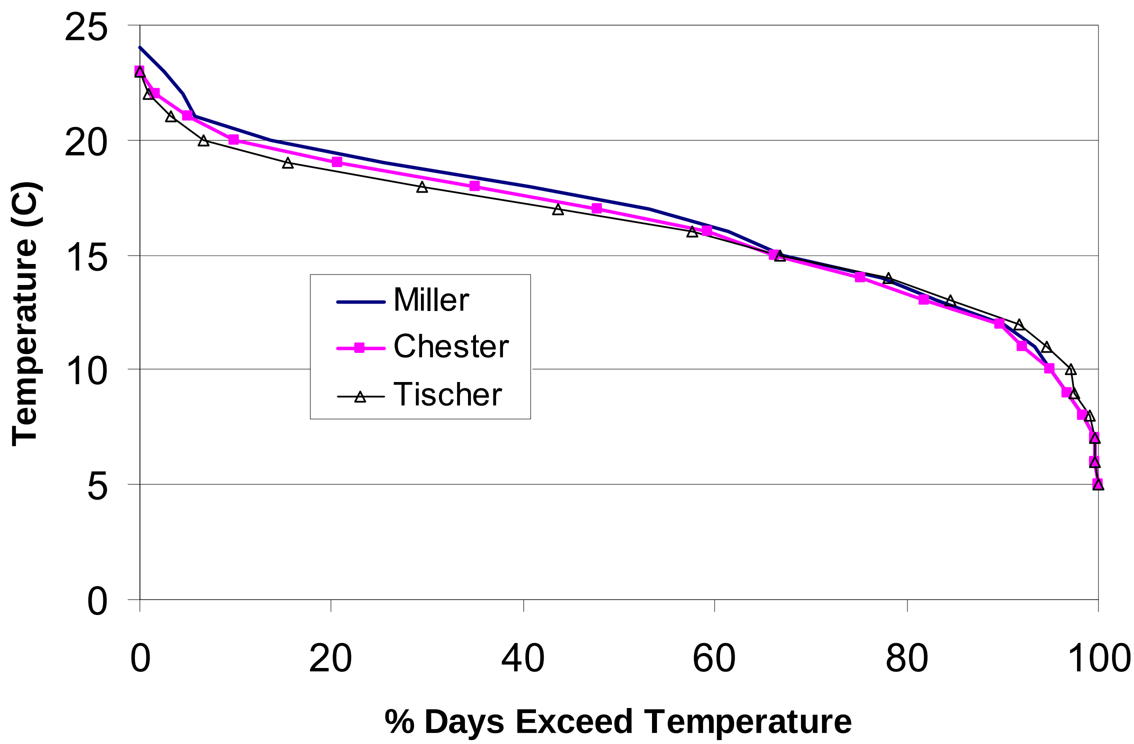


Figure 6.10. Stream temperature duration curves for Miller Creek (26th Ave), Tischer Creek, and Chester Creek using 2007/2008 stream temperature data.

7. Conclusions

Various analyses of Miller Creek stream temperature data described in this report lead to the following conclusions:

1) Stream temperature in Miller Creek is highly correlated to air temperature at the Duluth Airport at daily to annual time scales. Multi-parameter linear regressions of stream temperature to additional parameters (wind speed, solar radiation, stream flow) did not markedly improve the prediction of stream temperatures compared to regressions using air temperature alone. However, the relationship between stream temperature and stream flow was found to become stronger as stream flows become lower (< 5 cfs).

2) Temperature exceedances above 20 °C occur everywhere in the main stem of Miller Creek, but are most numerous in the middle reaches, centered on the highly commercialized area from Kohl's to Miller Hill Mall.

3) Temperature exceedances above 20 °C are mainly caused by strong heat transfer from the atmosphere to the stream especially due to low channel shading in the middle reaches of Miller Creek, such as the channelized wetland upstream of Kohl's.

4) Stormwater runoff does cause some temperature exceedances, but only 5 to 10% of all temperature exceedances appear to be associated with surface runoff due to rainfall, and even fewer are caused exclusively by runoff. If shading of Miller Creek is increased in the future to reduce dry weather stream temperatures, stormwater runoff inputs may become more influential in the temperature record.

5) Little evidence was found that lower stream flow leads to increased stream temperature and more numerous temperature exceedances, except for extremely dry conditions approaching zero stream flow (<< 1 cfs). However, issues with the stream flow data, including an apparent temperature sensitivity of the pressure sensors used to measure water levels (stage) in Miller Creek, may, in part, have tainted the available data.

6) In mid summer tributaries are typically at a lower temperature than the main stem of Miller Creek. The inflow of the tributary at Chambersburg Ave. lowers the temperature of the main stem by up to several degrees Celsius. Other tributaries also have relatively low temperatures, but there is little evidence in the temperature records that they lower the stream temperature in the main stem significantly, and there are no data on how much flow they contribute.

7) The roles of groundwater and wetlands in the flow and heat budgets of Miller Creek are not yet quantified. There is some evidence that a wetland in relatively good condition (i.e. well shaded) can provide thermal mitigation, and that channelizing wetlands can raise stream temperatures due to lower shading.

8) Reaches of Miller Creek that are less impacted, e.g. downstream of Lake Superior College, have water temperatures that are comparable to other Duluth area streams and even Grand

Marais area trout streams. The spatial variability of water temperature in both impacted streams (Miller Creek) and relatively pristine streams (Mud Creek, Appendix I) requires that multiple monitoring locations are needed to do good evaluations and comparisons of trout habitat between streams.

The stream flow and temperature models currently under development at SAFL will provide additional information on the flow and thermal budget of Miller Creek, particularly for runoff events. Additional data on runoff temperatures from different types of land use will be needed to adequately characterize the heat exchange processes and the resulting thermal budget during wet weather. To characterize baseflow conditions in Miler Creek in response to development and climate variations, more information will be required on the water sources, e.g. the temperatures of the wetlands in the upper part of the watershed and the extent and contribution, if any, of the shallow groundwater.

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Appendix I: Comparisons of 2009 Stream Temperature near Duluth and Grand Marais.

Stream temperature data were obtained for several trout streams near Grand Marais, MN from the Minnesota DNR Grand Marais office. 2009 data were selected from streams evaluated by the DNR to have good Brook Trout populations: Little Devil's Track Creek, Mud Creek, and Elbow Creek. Little Devil's Track, Mud Creek and Elbow Creek are all tributaries to Devil's Track River, between the city of Grand Marais and the Grand Marais/Cook County Regional airport.

2009 air temperature data were obtained from this airport, the Duluth International airport, and from the Devil's Track MDNR hatchery. Air temperature data are plotted as weekly averages in Figure A1.1. In general, air temperature readings are 1 -2 °C lower at Grand Marais compared to Duluth, except for the week of June 14, when the air temperatures were slightly higher at the Grand Marais airport compared to Duluth.

Weekly average stream temperatures and weekly average daily maximum stream temperatures are given in Figure A1.2 and A1.3, respectively. Although the Grand Marais area streams (Mud, Elbow, Little Devil's Track) are support good Brook Trout populations and are in a slightly cooler climate than Duluth, stream temperatures at these sites are similar to or higher than the Duluth area streams (Miller, Tischer, Chester, Amity). With the exception of Tischer and Chester creeks, all streams have weekly average temperatures that meet or exceed 20 °C. The warmest average stream temperatures were in Mud Creek; the reach of Mud Creek that was monitored for temperature in 2009 has a series of Beaver ponds, which may increase stream temperature if the ponds are not well shaded. Note that Miller Creek (at 26th Ave) is intermediate in temperature compared to the other streams, suggesting that some reaches of Miller Creek are not temperature impaired compared to other trout streams in the region.

This limited analysis suggests that even relatively pristine North Shore trout streams have water temperatures that are higher than optimum for trout. However, a better evaluation could be made if multiple temperature monitoring locations were available for each stream, with measurements in both ponded and free flowing reaches. The heterogeneous characteristics of North Shore streams, with wetland areas, beaver dams, and free flowing reaches make evaluation of trout thermal habitat characteristics from a single measurement difficult, because heterogeneous hydrology and morphology lead to heterogeneous water temperatures. In Mud Creek, two sites were monitored for temperature in 2009 (Figure A1.4). The location at river mile 0.45 was downstream of a beaver dam, while the 2.75 river mile location was in a low velocity marsh area with springs and floating vegetation mats. The mile 2.75 measurement appears to be in a stratified pool – the temperature logger was placed at ~1.5 ft depth. Quantifying these sorts of temperature heterogeneity in North Shore stream temperatures will be an important step in predicting the response of trout habitat to future development and climate change.

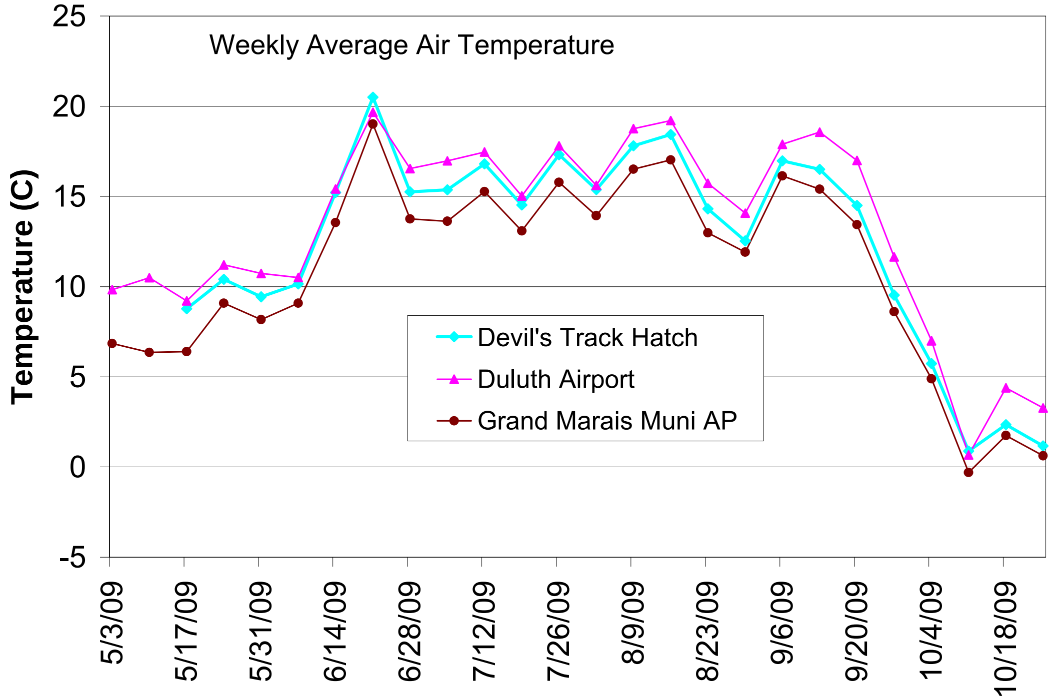

Figure A1.1. 2009 weekly average air temperature time series for data from Duluth International airport, the Grand Marais regional airport, and DNR measurements at the Devil's Track hatchery.

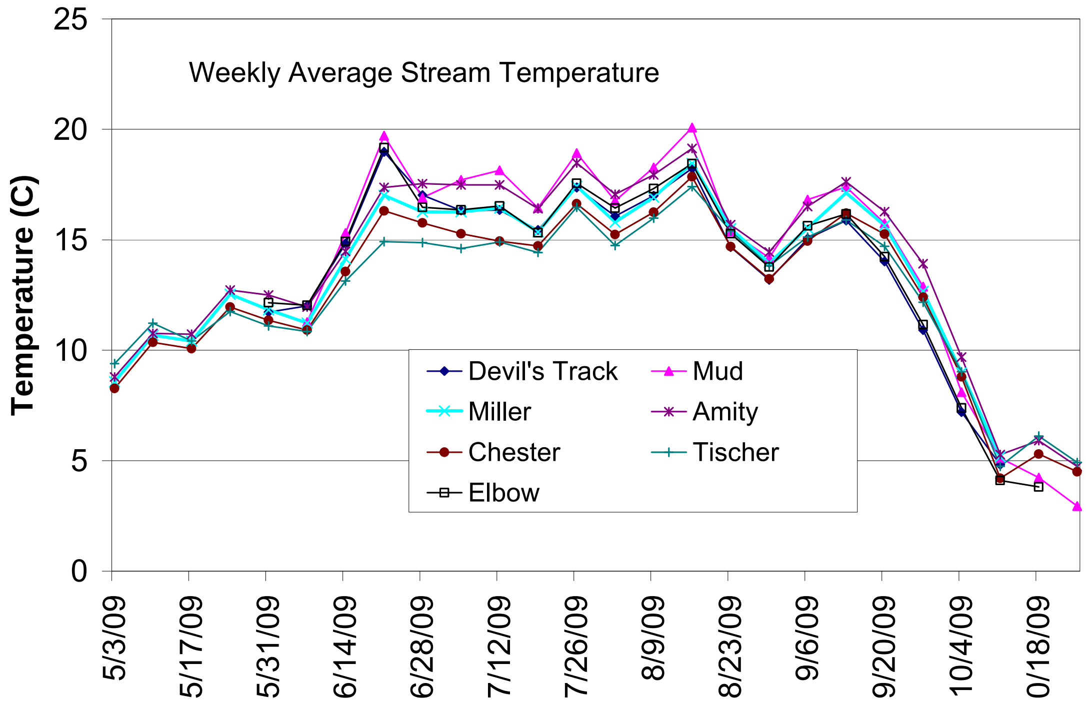

Figure A1.2. 2009 weekly average stream temperature time series for trout streams in Duluth (Miller, Tischer, Chester) and Grand Marais (Little Devil's Track, Mud, Elbow).

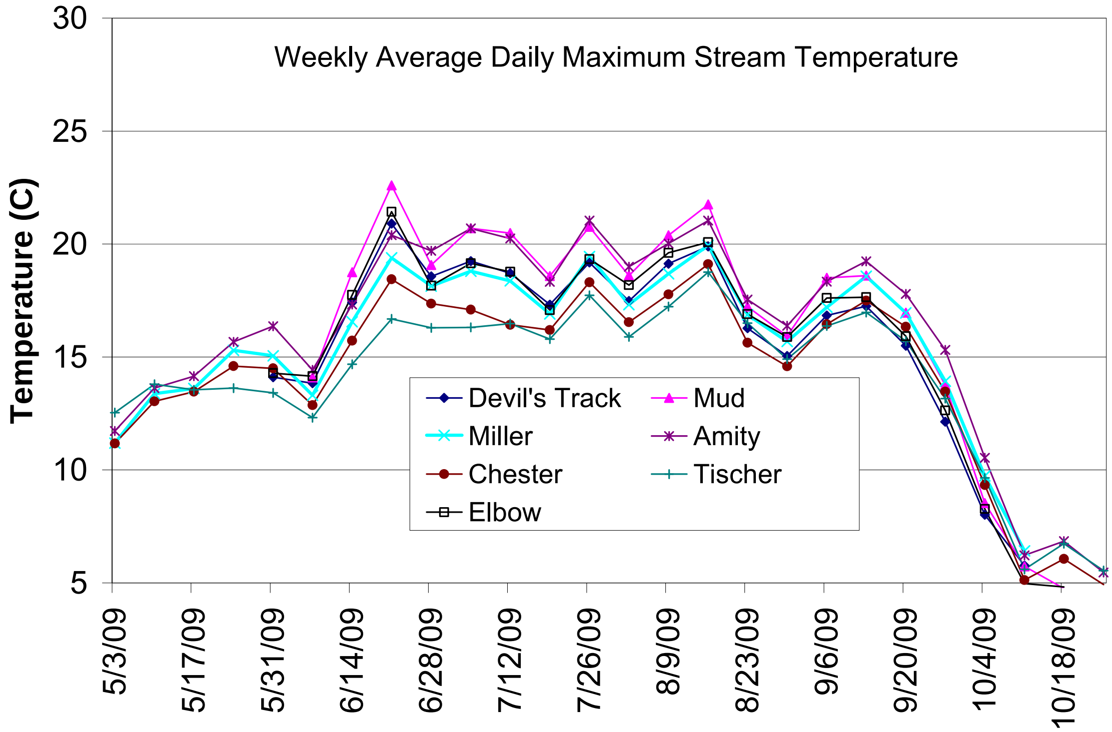

Figure A1.3. 2009 weekly average daily maximum stream temperature for trout streams in Duluth (Miller, Tischer, Chester) and Grand Marais (Little Devil's Track, Mud, Elbow).

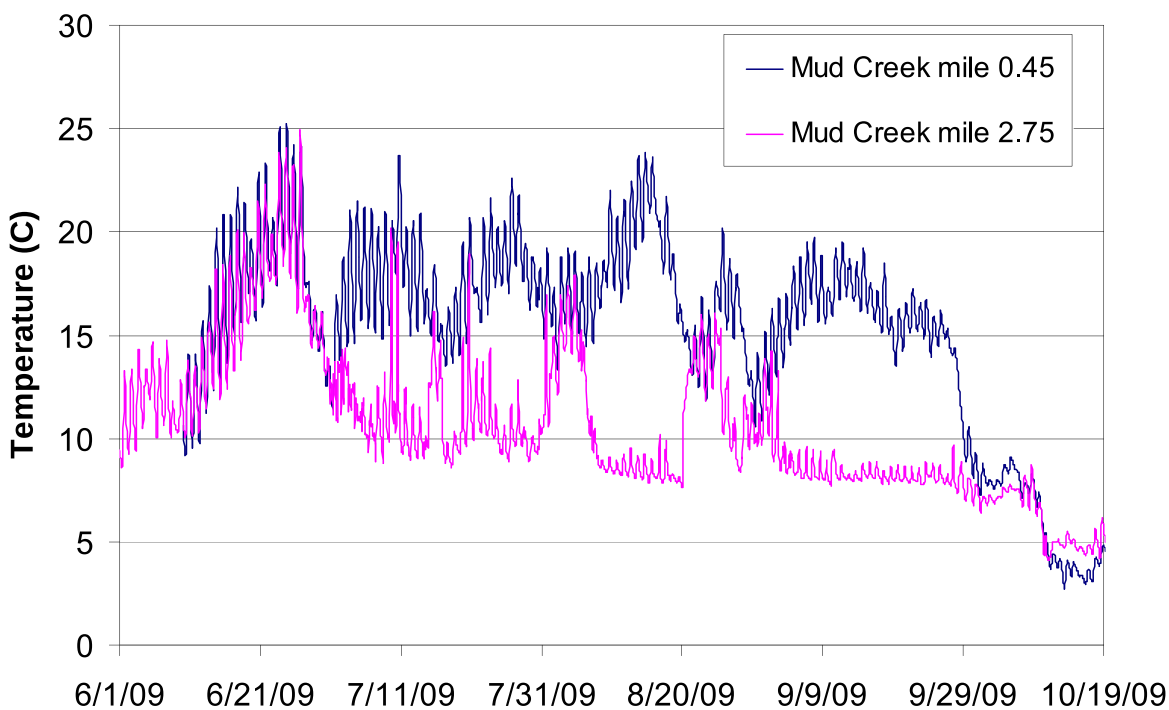

Figure A1.4. 2009 hourly stream temperatures for Mud Creek at mile 0.45 and 2.75.