UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 552

Characterization of Stream Temperature and Heat Loading for Miller Creek, Duluth, Minnesota

by

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Prepared for
South St. Louis Soil and Water Conservation District
Duluth, Minnesota

August 2011
Minneapolis, Minnesota

I. Introduction

This report summarizes a study of heat loading and stream temperature in Miller Creek in support of the MPCA Miller Creek temperature TMDL. The work described here builds on previous work done at St. Anthony Falls Lab (Erickson et al. 2009, Herb and Stefan 2009a, 2009b, 2009c.) to include 2009 monitoring data and to characterize temperatures and heat inputs based on both daily and weekly temperature standards.

II. Temperature Data Analysis

Three years of stream temperature monitoring data (2007, 2008, 2009) were analyzed along with air temperature data from Duluth International Airport, which is at the upper end of the Miller Creek watershed. Air temperature and precipitation data provides important background information for analyzing stream temperatures. Monthly air temperature data for the three monitoring years are shown in Figure 1 along with the 30 year normals (1971-2000). Figure 1 shows that 2007 had above average air temperatures in May through October, while 2008 had near normal temperatures and 2009 had cooler than normal air temperatures in July and August but a warm September. Figure 1 (lower panel) shows 2007 was a dry summer, with precipitation totals in June through August (10.9 cm) much lower than normal (32.8 cm). 2009 was also drier than normal, with 20.7 cm of precipitation in July through September compared to a normal total of 42.7 cm. Overall, 2008 is an example of a typical climate year and 2007 is an example of a year with warmer and drier climate compared to normal. As is the case for most rivers and streams, Miller Creek water temperatures are correlated to air temperatures at daily time scales and longer. The relationship of weekly running average air and stream temperatures in Miller Creek is given in Figure 2 for 2007-2009 data at the 26th Ave site.

Two temperature standards for stream temperature were considered in this study: a weekly average temperature of 19 °C (i.e. a chronic temperature standard) and a daily maximum temperature of 24 °C (i.e. an acute temperature standard). To align with these standards, the analysis of Miller Creek temperature and flow data given in this report is based on both daily and weekly time scales. Weekly averaged temperatures were calculate as a running-average, i.e. a temperature for each day was calculated based on data from that day and the previous 6 days. Figure 3 gives the resulting weekly average temperatures for several monitoring stations in Miller Creek. It can be seen that the weekly average temperatures exceeded 19 °C on a number of das in 2007 and relatively few days in 2008 and 2009. The relatively high number of exceedances in 2007 is expected, given that 2007 was a warm year (Figure 1) and that stream temperature are well correlated to air temperatures (Figure 2).

Figure 4 gives data on daily maximum stream temperature in 2007, 2008 and 2009 for several monitoring stations. Again, the 2007 data shows more temperature exceedances (daily average temperature exceeding 24 °C), but there are exceedances in all three years. A more complete summary of the number of temperature exceedances is given in Figure 5 and Tables 1 and 2.

Note that the number of temperature observations for each station varies from year to year (Table 1), based on the availability of monitoring data. 2007 temperature data from the Kohl's Upstream and U-haul stations were omitted from the analysis, as these temperature sensors appeared to be tracking air temperature for some or all of the record. The Walmart, Chambersburg PCA, and Kohl's PCA sites were not monitored in 2009.

Spatially, the temperature exceedances occur mainly in the middle reaches of Miller Creek, from the station upstream of Kohl's to the Mall Drive Target station (Figure 5). It is quite possible that the reach immediately downstream of the Mall Drive Target station, e.g. to Miller Hill Mall, also has numerous temperature exceedances, but monitoring data are not available for this reach in 2007-2009. Table 2 summarizes the number of temperature exceedances at each station by month and year. No temperature exceedances were recorded in September of any year, even though September was warmer than average in 2009 (Figure 1).

The daily maximum temperature exceedance data were further analyzed to segregate the data into wet and dry days, to determine the number of exceedances associated with stormwater inputs (wet days) and solar radiation inputs (dry days). The results are summarized in Table 3, which gives the total number of exceedances over the three year period for each station, the number of exceedances that occurred on dry days (no precipitation) and wet days (measureable precipitation).

The occurrence of a temperature exceedance on a wet day does not necessarily imply that the temperature exceedance was caused by stormwater inputs. Figure 6 gives time series of hourly stream temperature at the MPCA Kohl's site and precipitation for June 26 and August 11, 2007. For the event on June 26, the daily maximum stream temperature occurred shortly after the afternoon precipitation event, and it is likely that by stormwater inflows contribute to the temperature high stream temperatures. For the event on August 11, the precipitation event occurs early in the morning while the stream temperature maximum occurs in mid-afternoon. So, although August 11 has precipitation, it is unlikely that stormwater had a major contribution to the stream temperature maximum. Overall, the data suggest that stormwater caused less than 10% of the observed temperature exceedances in Miller Creek.

Table 1. Compilation of weekly running average (T> 19 °C) and daily maximum (T> 24 °C) stream temperature exceedances for 14 monitoring stations on the main stem of Miller Creek. #Observ. = number of observations, #Exceed = number of exceedances.

Weekly running average exceedances (T>19 °C)						
	2007		2008		2009	
Station	# Observ.	# Exceed	# Observ.	# Exceed	# Observ.	# Exceed
26th Ave	77	3	178	5	178	2
Trinity	94	12	149	0	137	3
LSC	122	16	149	0	139	2
Chambersburg DNR	97	5	149	0	141	0
Chambersburg MPCA	118	20	128	1		
Mall Drive Target	106	20	149	8	141	10
Kohl's PCA	164	37	175	9		
Upstream of Kohls			148	37	126	17
Haines 53	134	32	149	1	126	3
Uhaul			149	5	141	5
Walmart	133	28	149	0		
Arrowhead Airbase	135	17	151	0	141	2
Swan Lake	134	7	149	0	141	0
Ridgewood	143	6	151	0	138	0

Daily maximum exceedances (T>24 °C)						
	2007		2008		2009	
Station	# Observ.	# Exceed	# Observ.	# Exceed	# Observ.	# Exceed
26th Ave	83	0	184	0	184	0
Trinity	100	6	143	0	131	0
LSC	128	6	143	0	125	0
Chambersburg DNR	103	1	143	0	135	0
Chambersburg MPCA	124	7	128	0		
Mall Drive Target	112	15	143	4	135	3
Kohl's PCA	170	17	174	3		
Upstream of Kohls			142	4	120	12
Haines 53	140	5	143	0	120	1
Uhaul			143	0	135	0
Walmart	139	2	143	0		
Arrowhead Airbase	141	6	145	0	135	3
Swan Lake	140	0	143	0	135	0
Ridgewood	149	0	145	0	132	0

Table 2. Compilation of weekly (T>19 °C) and daily (T>24 °C) stream temperature exceedances by month, for 14 monitoring stations on the main stem of Miller Creek. No temperature exceedances were recorded in September.

Weekly running average exceedances (T>19 °C)									
	2007			2008			2009		
Station	June	July	Aug	June	July	Aug	June	July	Aug
26th Ave	0	3		0	0	5	0	0	2
Trinity	0	6	6	0	0	0	0	0	3
LSC	0	9	7	0	0	0	0	0	2
Chambersburg DNR	0	5	0	0	0	0	0	0	0
Chambersburg MPCA	4	10	6	1	0	0			
Mall Drive Target	3	9	8	0	1	7	5	0	5
Kohl's PCA	9	12	16	0	2	7			
Upstream of Kohls				5	13	19	8	4	5
Haines 53	4	12	16	0	1	0	3	0	0
Uhaul				0	5	0	5	0	0
Walmart	0	11	17	0	0	0			
Arrowhead Airbase	0	11	6	0	0	0	2	0	0
Swan Lake	0	4	3	0	0	0	0	0	0
Ridgewood	0	3	3	0	0	0	0	0	0

Daily maximum exceedances (T>24 °C)									
	2007			2008			2009		
Station	June	July	Aug	June	July	Aug	June	July	Aug
26th Ave	0	0		0	0	0	0	0	0
Trinity	0	5	1	0	0	0	0	0	0
LSC	0	4	2	0	0	0	0	0	0
Chambersburg DNR	1	0	0	0	0	0	0	0	0
Chambersburg MPCA	1	5	1	0	0	0			
Mall Drive Target	2	9	4	3	1	0	1	2	0
Kohl's PCA	3	8	6	0	1	2			
Upstream of Kohls				2	2	0	4	8	0
Haines 53	0	5	0	0	0	0	1	0	0
Uhaul				0	0	0	0	0	0
Walmart	0	1	1	0	0	0			
Arrowhead Airbase	0	5	1	0	0	0	3	0	0
Swan Lake	0	0	0	0	0	0	0	0	0
Ridgewood	0	0	0	0	0	0	0	0	0

Table 3. Compilation of weekly (T>19 °C) and daily (T>24 °C) stream temperature exceedances by station and precipitation conditions (wet/dry day).

	Weekly Standard (T>19 °C)	Daily Standard (T>24 °C)		
Station	Total	Total	Dry	Wet
26th Ave	10	0	0	0
Trinity	15	6	5	1
LSC	18	6	5	1
Chambersburg DNR	5	1	1	0
Chambersburg MPCA	21	7	6	1
Mall Drive Target	38	22	21	1
Kohl's PCA	46	20	17	3
Upstream of Kohls	54	16	15	1
Haines 53	36	6	6	0
Uhaul	10	0	0	0
Walmart	28	2	1	1
Arrowhead Airbase	19	9	8	1
Swan Lake	7	0	0	0
Ridgewood	6	0	0	0

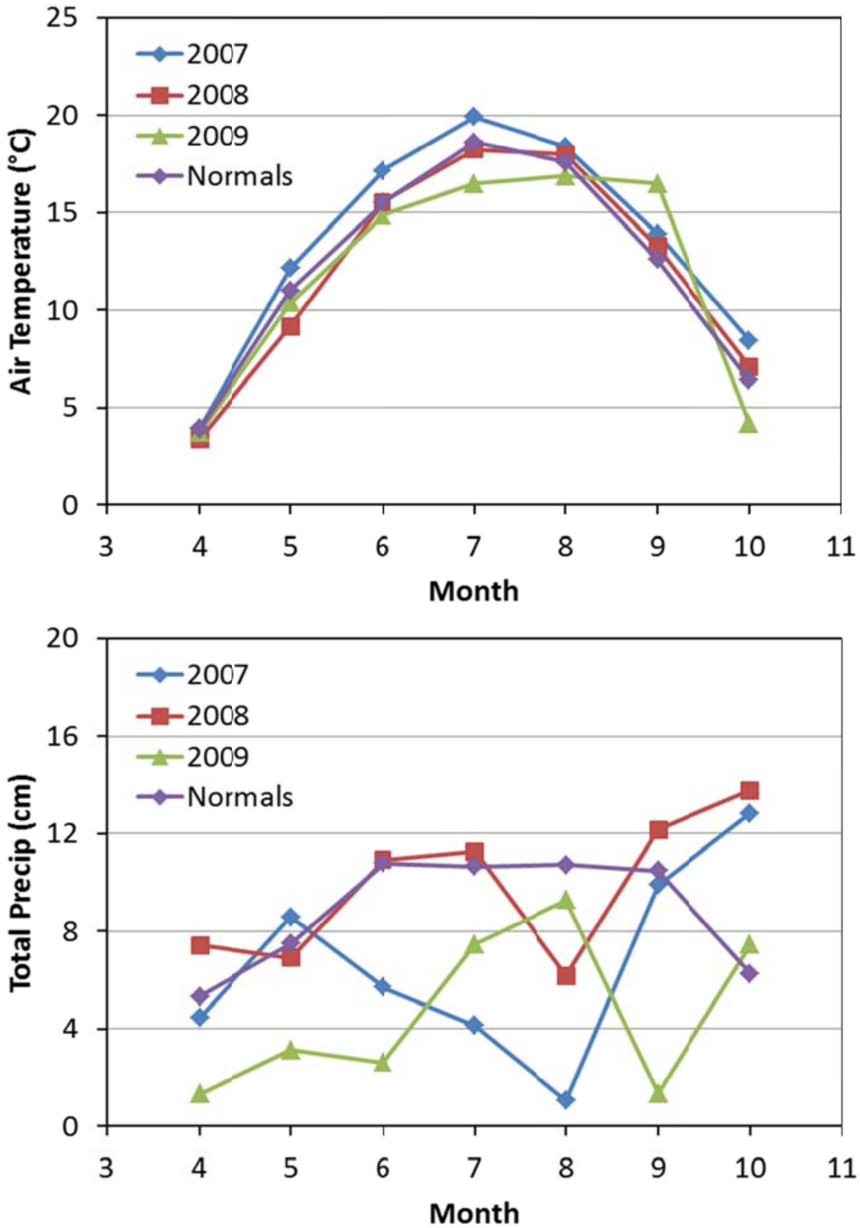

Figure 1. Monthly average air temperature and total precipitation observed at Duluth International Airport along with monthly normals (1970-2000).

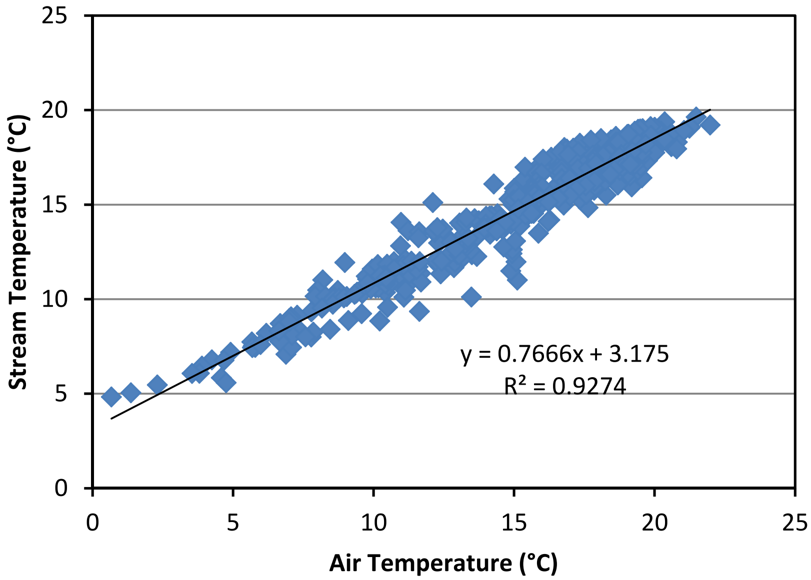

Figure 2. Weekly running average stream temperature at 26th Ave. vs. weekly running average air temperature at Duluth International Airport for 2007, 2008, and 2009 data.

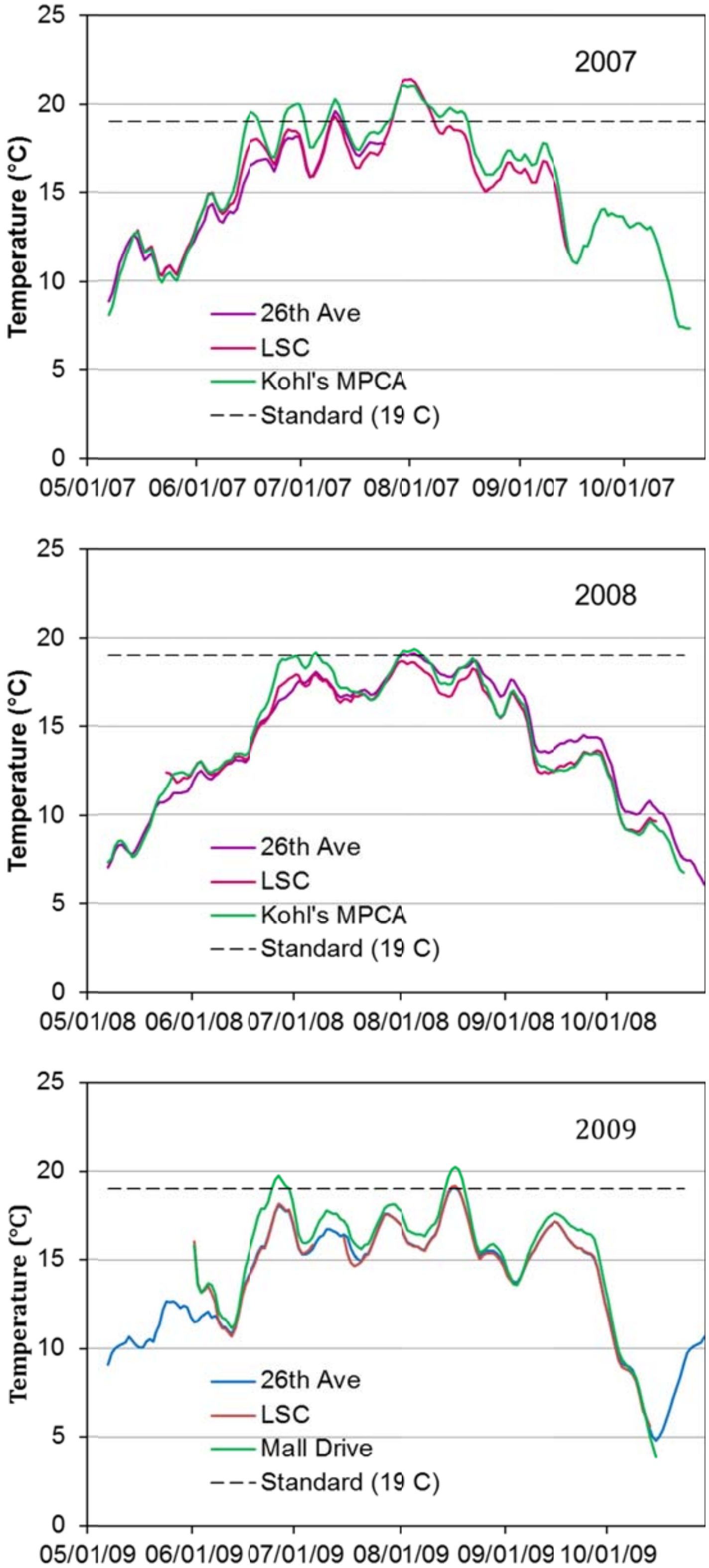

Figure 3. Time series of weekly running average stream temperature at select locations in Miller Creek in 2007, 2008, and 2009.

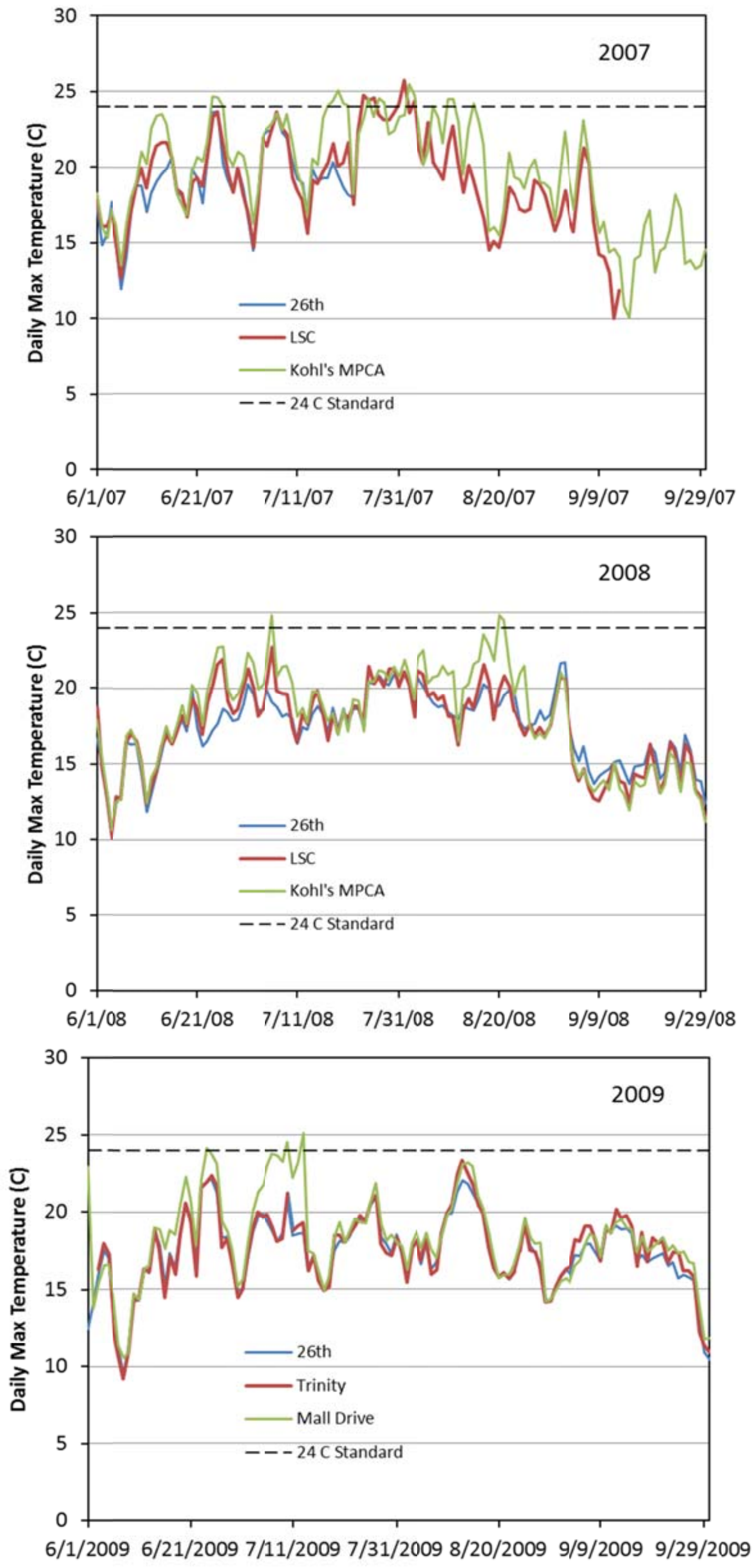

Figure 4. Time series of daily maximum stream temperature at select locations in Miller Creek in 2007, 2008, and 2009.

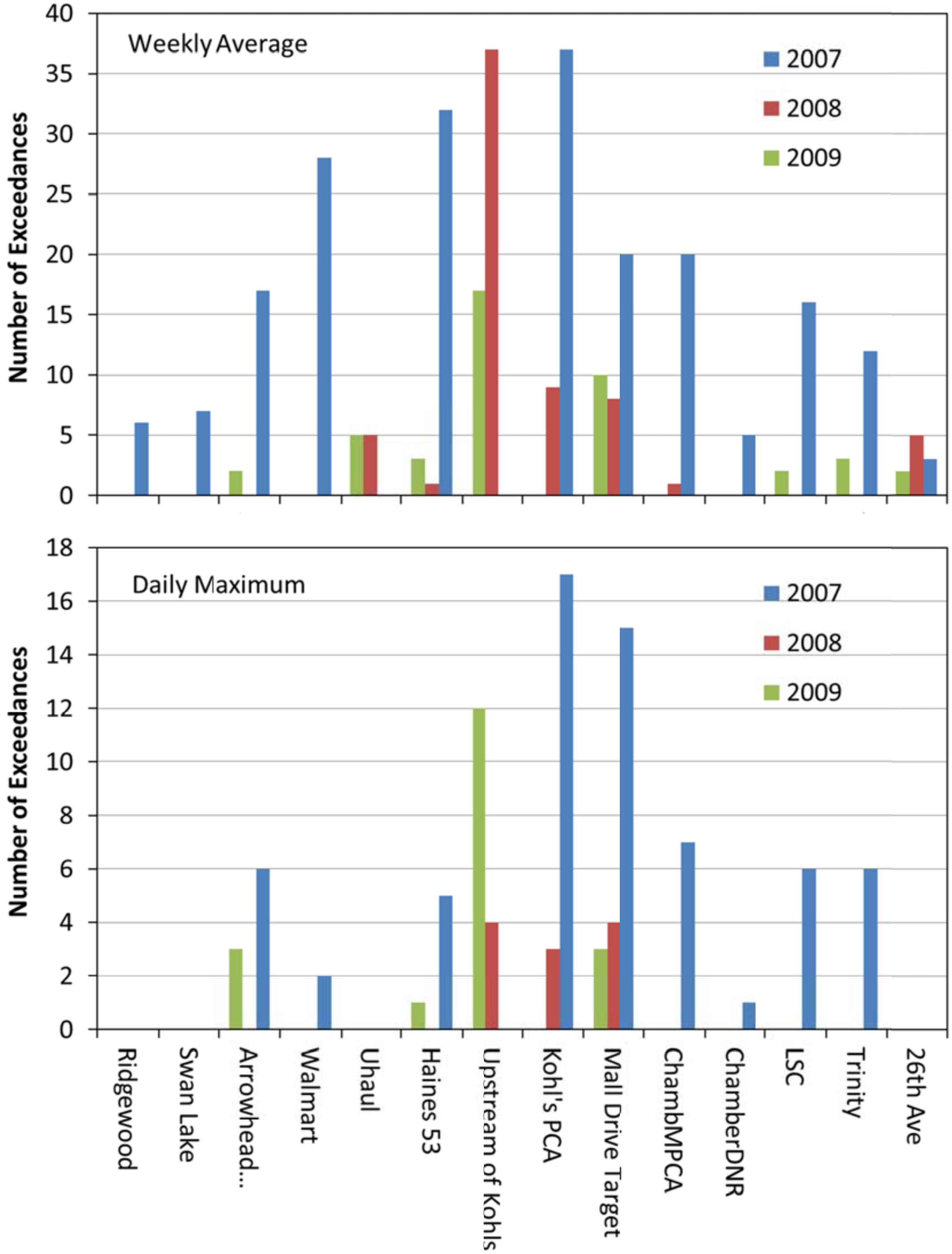

Figure 5. Number of weekly average temperature exceedances (T>19 °C, upper panel) and daily maximum temperature exceedances (T>24 °C, lower panel) at main stem monitoring locations in Miller Creek in 2007, 2008, and 2009. Temperature data from 2007 at Uhaul and Upstream of Kohl's appeared to be erroneous and were omitted. The Walmart, Chambersburg PCA, and Kohl's PCA sites were not monitored in 2009.

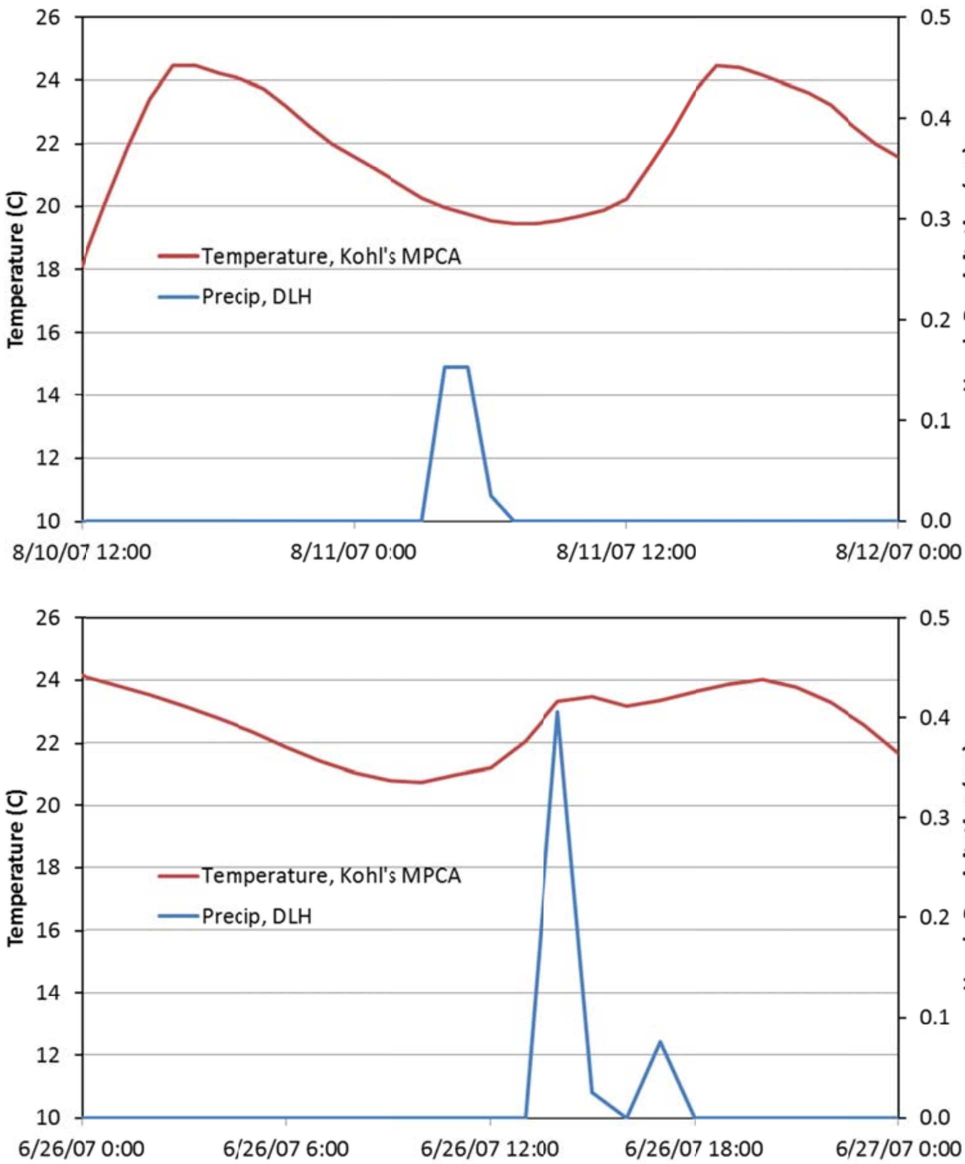

Figure 6. Hourly time series of precipitation and stream temperature at the MPCA Kohl's site for daily maximum temperature exceedance events on days with precipitation: June 26 and August 11, 2007.

III. Heat Loading Analysis

Temperature is, in effect, a measure of the concentration of heat in a stream or lake. One difference between temperature and other stream water quality parameters, such a phosphorus concentration, is that typical measures of temperature have inconsistent zero values, e.g. 0 °C ≠ 0 °F. As a result, the heat loading to a stream needs to be defined with respect to a reference temperature. For comparing actual and allowable heat loadings to a stream, the value of the reference temperature is not crucial, but using a consistent value of reference temperature in all heat calculations is important. In this report, 0 °C is chosen as the reference temperature.

Heat can enter a stream from atmospheric heat transfer, heat conduction through the sediment, and by inputs of surface water or groundwater. The total heat loading, in joules of energy, to a stream reach (H) over some time period (Δt) can be calculated as:

$$H = \rho C_p \, \Delta t \, \left(Q_1 T_1 - Q_0 T_0\right) \quad \text{(Joules)} \qquad (1)$$

where ρC_p is the product of density and specific heat for water, Q is the stream flow, T is the stream temperature, and the 1 and 0 subscripts indicate values of flow and temperature at the downstream and upstream ends of the reach, respectively. If the upstream end of the reach has negligible flow so that $Q_1T_1 >> Q_0T_0$, the upstream heat input can be neglected, the expression for total heat loading can be simplified to:

$$H = \rho C_p \, \Delta t \, Q_1 T_1 \quad \text{(Joules)} \qquad (2)$$

H is the total heat required to cause the downstream end of the reach at flow Q_1 to be at temperature T_1. If T_1 and Q_1 are the observed stream temperature and flow, e.g. averaged over 1 day, then the calculated H is the actual (observed) heat input for that day. If, instead, T_1 is taken to be temperature criteria to be applied to the stream, then the calculated heat is the allowable heat input for that day. Note that:

1) In both cases, the observed stream flow at the downstream end of the reach is used in the heat loading calculation, and that the heat loadings needed to produce a particular downstream temperature T_1 increase linearly with flow rate.

2) There is a direct relationship between temperature exceedances and heat loading exceedances, i.e. if the stream temperature exceeds the criteria on a given day, then the actual heat input to the stream exceeds the allowable heat input on that day.

In Miller Creek, the highest temperatures typically occur in the middle sections, e.g. between the station upstream of Kohl's and the Chambersburg MPCA station (Figure 5). If heat inputs are calculated over the entire length of the main stem (Ridgewood to 26^{th} Ave), the actual heat inputs will rarely exceed the allowable heat inputs, because stream temperatures at 26th Ave rarely exceed the criteria (19 °C). Therefore, to effectively characterize the problem heat inputs to the

Miller Creek, actual and allowable heat loadings at intermediate monitoring points need to be calculated.

The observed (actual) heat input over a short section of a stream reach, e.g. between 2 monitoring stations, can be calculated from Equation 1, if the upstream and downstream flows and temperatures are available. However, the allowable heat input for a section of a reach needs to be defined. The approach take here is as follows:

- As with the actual heat input, the observed upstream and downstream flows are used.
- The downstream temperature is taken to be the allowable temperature (19 °C)
- The upstream temperature is taken to be the lesser of the 1) observed stream temperature and 2) the allowable temperature.

In this way, a downstream reach is allowed to add additional heat the stream if the upstream temperatures are below the allowable, and a downstream reach is not required to cool an upstream reach during periods where upstream temperatures exceed the allowable.

To better characterize heat inputs to Miller Creek, the main stem was split into an upstream and downstream section, with the Mall Drive Target monitoring station as the mid-point separating the two reaches. For the downstream reach, the observed (H_o) and allowable (H_a) heat inputs were calculated using Equations 3 and 4, respectively:

$$H_a = \rho C_p \, \Delta t \, \left(Q_2 T_c - Q_1 \cdot \min(T_1, T_c)\right) \qquad \text{(Joules)} \qquad (3)$$

$$H_o = \rho C_p \, \Delta t \, \left(Q_2 T_2 - Q_1 T_1\right) \qquad \text{(Joules)} \qquad (4)$$

For the upstream reach, the flow at the upstream end (Q_0, Figure 7) is assumed to be negligible, and the observed (H_o) and allowable (H_a) heat inputs were calculated using Equations 5 and 6, respectively:

$$H_{o,i} = \rho C_p \, \Delta t \; Q_1 T_1 \qquad \text{(Joules)} \qquad (5)$$

$$H_{a,i} = \rho C_p \, \Delta t \; Q_1 T_c \qquad \text{(Joules)} \qquad (6)$$

where T_c is the allowable temperature and T_1, T_2, Q_1, and Q_2 are the observed stream temperature and flows, respectively, as shown in Figure 7. Equations 3 - 6 can be applied at daily and weekly time scales to obtain information for the daily and weekly temperature standards, respectively.

Figure 7. Monitoring stations used to delineate Miller Creek into an upper section and a lower section.

III.1 Actual and Allowable Heat Inputs for Weekly Temperature Standard

For the weekly average temperature standard (19 °C), heat loading calculations were performed for weekly averaged stream temperature and flow rates in 2007, 2008, and 2009.

Calculation of heat loadings for the Miller Creek upper and lower reach requires flow data for the Mall Drive Target monitoring point. Stream flows were calculated for that site based on the 1) observed flow at the 26th Ave station and a regression equation for stream flow at each site based on the SWMM model previously developed for Miller Creek (Erickson et al. 2009). An example of a regression equation to estimate flow at the Kohl's MPCA site based on observed flow at the 26th Ave site is given in Figure 8.

Figures 9 and 10 give actual (observed) and allowable heat inputs to Miller Creek upper and lower reaches, plotted as a function of stream flow as load-duration curves. In each figure, the lower panel gives the values of observed and allowable heat inputs on a log scale, the center panel gives the difference between the observed and allowable (excess heat), and the upper panel gives the % difference between the observed and allowable. The center and upper panels are scaled such that only positive values are shown (observed > allowable). Note that the highest actual heat inputs are quite close to the allowable heat inputs over a wide range of flow conditions – this implies that the highest weekly average stream temperatures are close to 19 °C over a wide range of flow conditions and monitoring stations. As expected, actual heat inputs exceed the allowable most commonly at monitoring sites with the most temperature exceedances (Figure 5), e.g. Kohl's MPCA and upstream of Kohl's. The relatively low number of heat input exceedances in the lower reach implies that excess heat inputs to Miller Creek in the upper reaches are partially mitigated in the lower reach by improved shading, underground reaches, and cold water inputs from the Chambersburg tributary and other sources. It is evident in Figures 9 and 10 that most exceedances are at lower flows, e.g. flows corresponding to a duration interval > 50%. Tables 4a and 4b summarize the data in Figures 9 and 10, giving actual and allowable heat inputs to Miller Creek for five flow ranges. The upper half of Miller Creek has more heat exceedances (26) than the lower half (7), with most of the exceedances occurring during mid-range and dry conditions. For both the upper and lower reaches, the highest heat exceedance (%) occurs at low flows (90-100% flow percentile), but there are more exceedance events for dry conditions (60-90% flow percentile).

Table 4a. Miller Creek, Lower Half (Mall Drive Target– 26th Ave)

Flow Condition	Flow Percentile	Flow Range (cfs)	Average Allowable (GJ/day)	Average Actual (GJ/day)	Number of Exceedances	Highest Exceedance (%)
High	0-10%	<17.5	5521.3	3491.5	0	-
Moist	10-40%	5.5-17.5	1302.5	681.6	0	-
Mid-range	40-60%	3.1-5.5	574.0	321.8	0	-
Dry	60-90%	0.75-3.1	233.6	163.0	6	3.2
Low	90-100%	0.09-0.75	33.2	26.7	1	4.8

Table 4b. Miller Creek, Upper Half (Ridgewood - Mall Drive Target)

Flow Condition	Flow Percentile	Flow Range (cfs)	Average Allowable (GJ/day)	Average Actual (GJ/day)	Number of Exceedances	Highest Exceedance (%)
High	0-10%	<11.8	3843.4	2708.5	0	-
Moist	10-40%	3.1-11.8	1152.5	877.8	2	2.9
Mid-range	40-60%	1.5-3.1	427.3	354.4	6	5.8
Dry	60-90%	0.28-1.5	167.9	150.9	15	6.5
Low	90-100%	0.07-0.28	39.1	35.1	3	9.6

III.2 Actual and Allowable Heat Inputs for Daily Temperature Standard

To evaluate heat inputs to Miller Creek corresponding to the daily maximum temperature standard (24 °C), heat calculations were made using Equations 3 - 6 using daily average stream flow and daily maximum stream temperature. Figures 11 and 12 give actual (observed) and allowable heat inputs to the Miller Creek upper and lower reaches, respectively, plotted as a function of stream flow as load-duration curves. In general, there were fewer exceedances of the daily maximum temperature standard compared to the weekly average temperature standard (Figure 5), so there are correspondingly exceedances of heat loading for the daily maximum standard (Figures 11-12) compared to the weekly average standard (Figures 9-10). For the lower reach, there were no days in the data set where the observed daily maximum heat input exceeded the allowable. The Mall Drive Target location (Figure 14) had the highest exceedances as a percent of allowable, with exceedances approaching 30%. As with the weekly exceedances, most of the daily exceedances are at lower flows, e.g. flows corresponding to a duration interval > 50%.

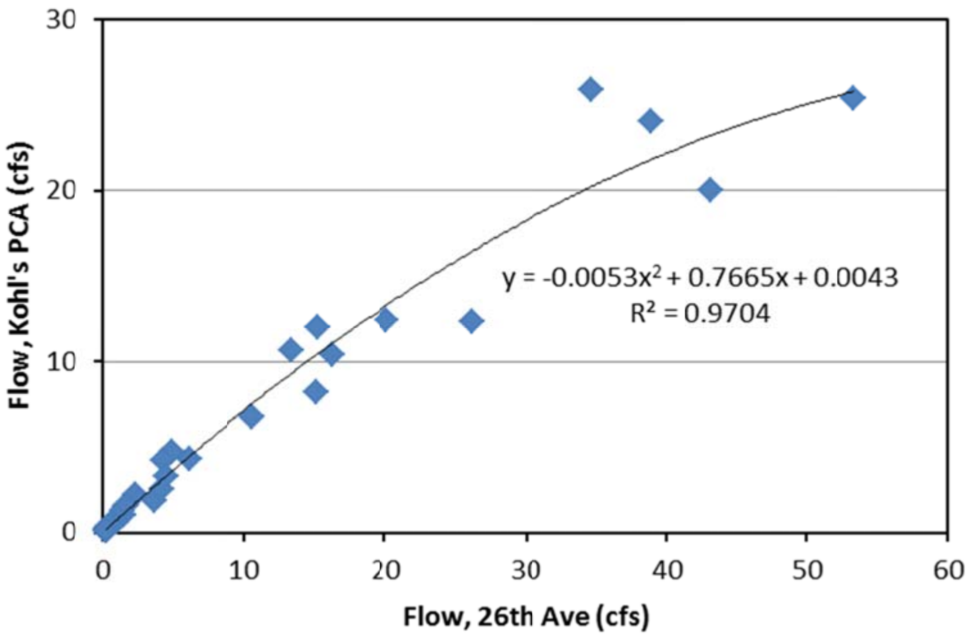

Figure 8. Regression equation to predict flow at the Kohl's MPCA site based on observed flow at the 26th Ave site, based on SWMM simulated stream flow in 2008.

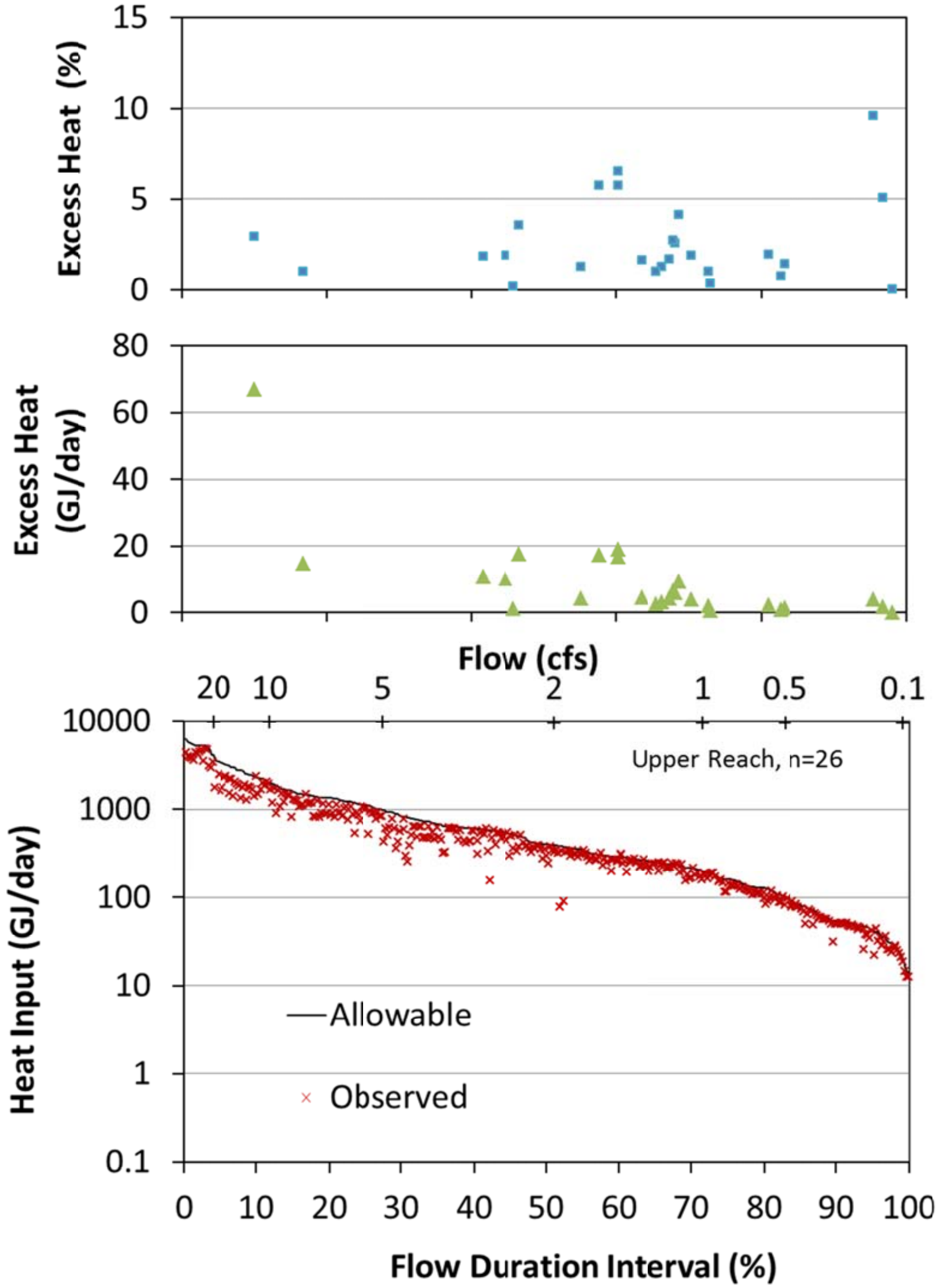

Figure 9. Actual (observed) and allowable <u>weekly</u> heat loadings vs. flow duration interval for the Miller Creek upper reach based on 2007, 2008, and 2009 data. The upper panel gives the difference between the actual and allowable heat inputs for days where the actual exceeded the allowable.

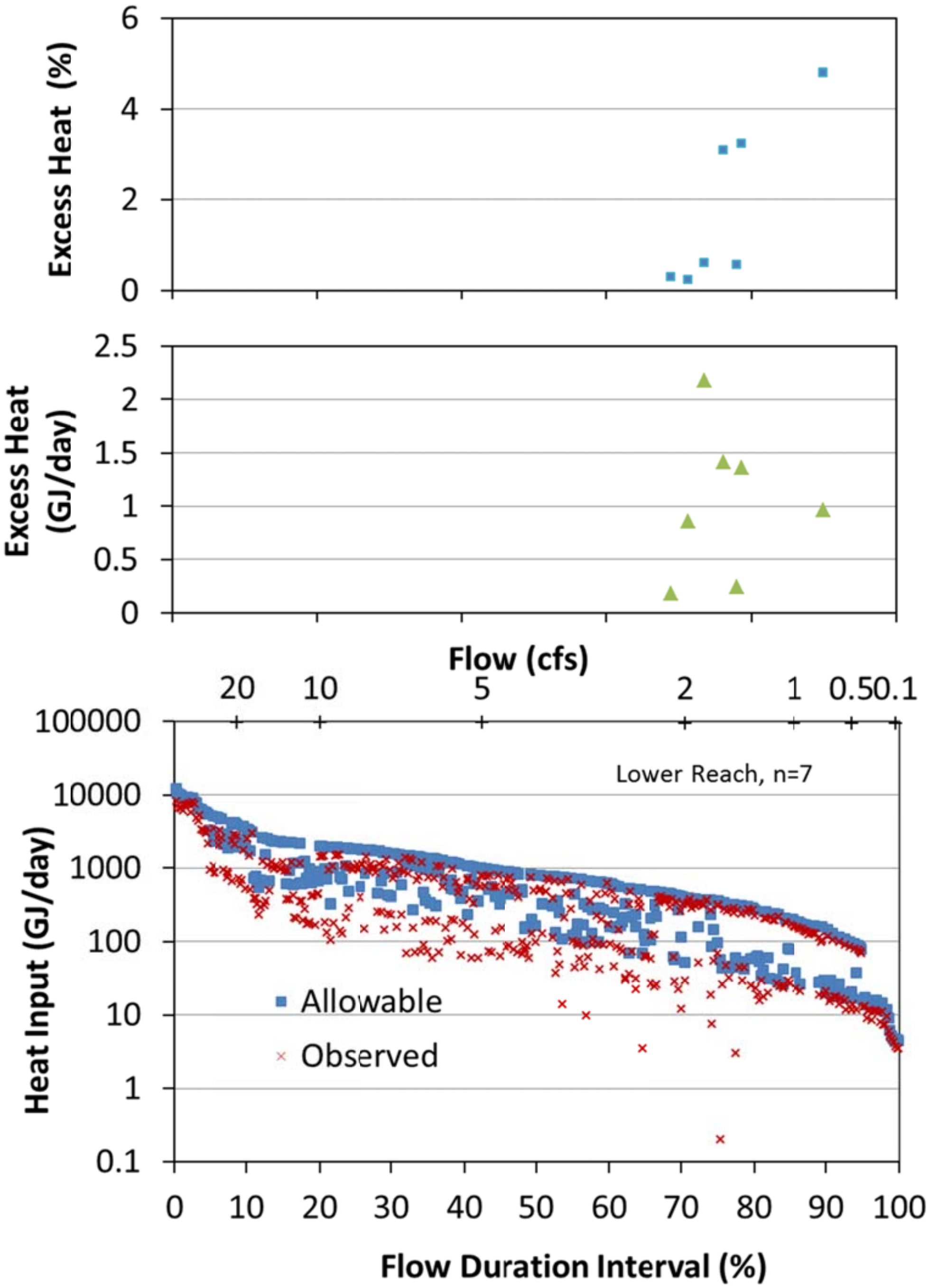

Figure 10. Actual (observed) and allowable weekly heat loadings vs. flow duration interval for the Miller Creek lower reach based on 2007, 2008, and 2009 data.

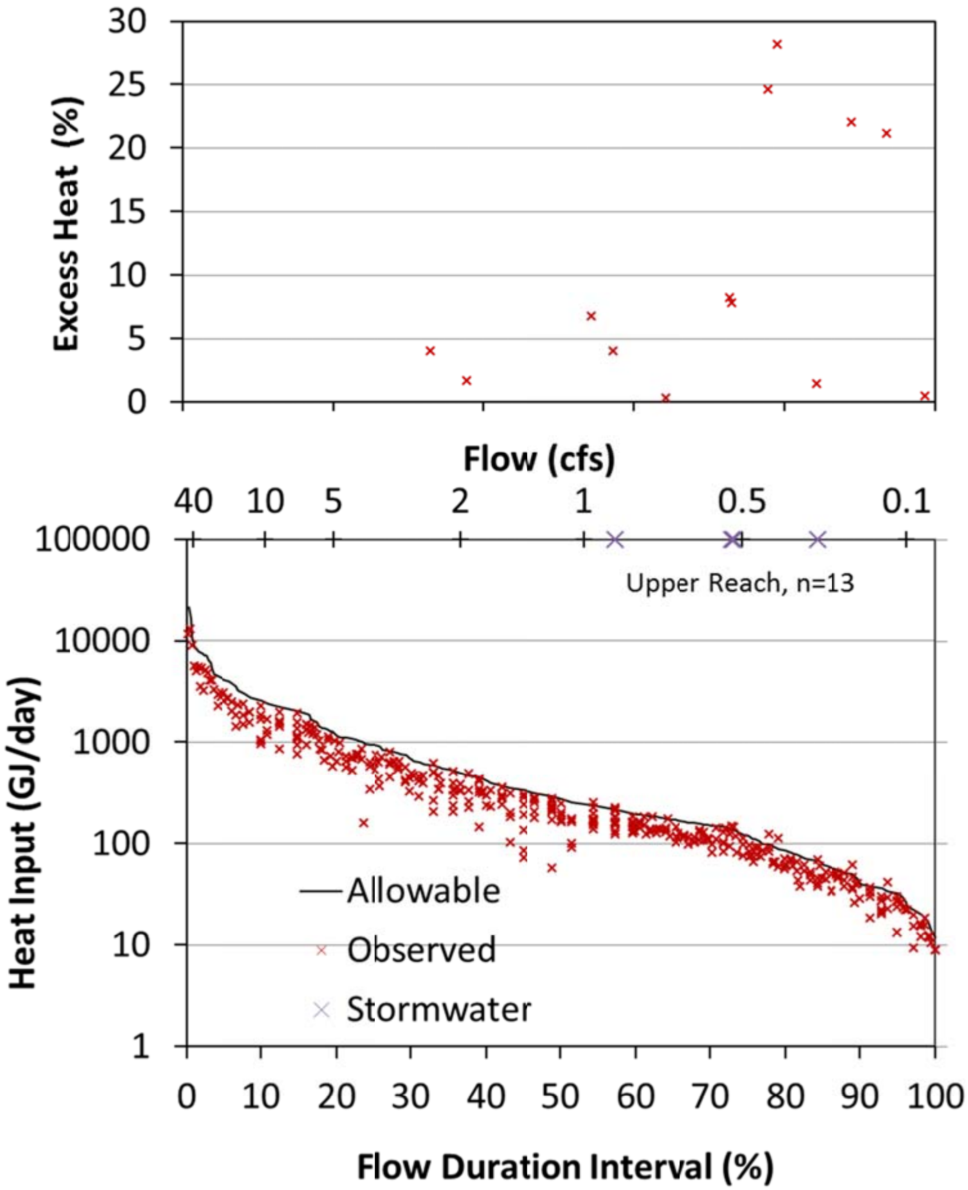

Figure 11. Actual (observed) and allowable <u>daily</u> heat loadings vs. flow duration interval for Miller Creek upper reach based on 2007, 2008, and 2009 data.

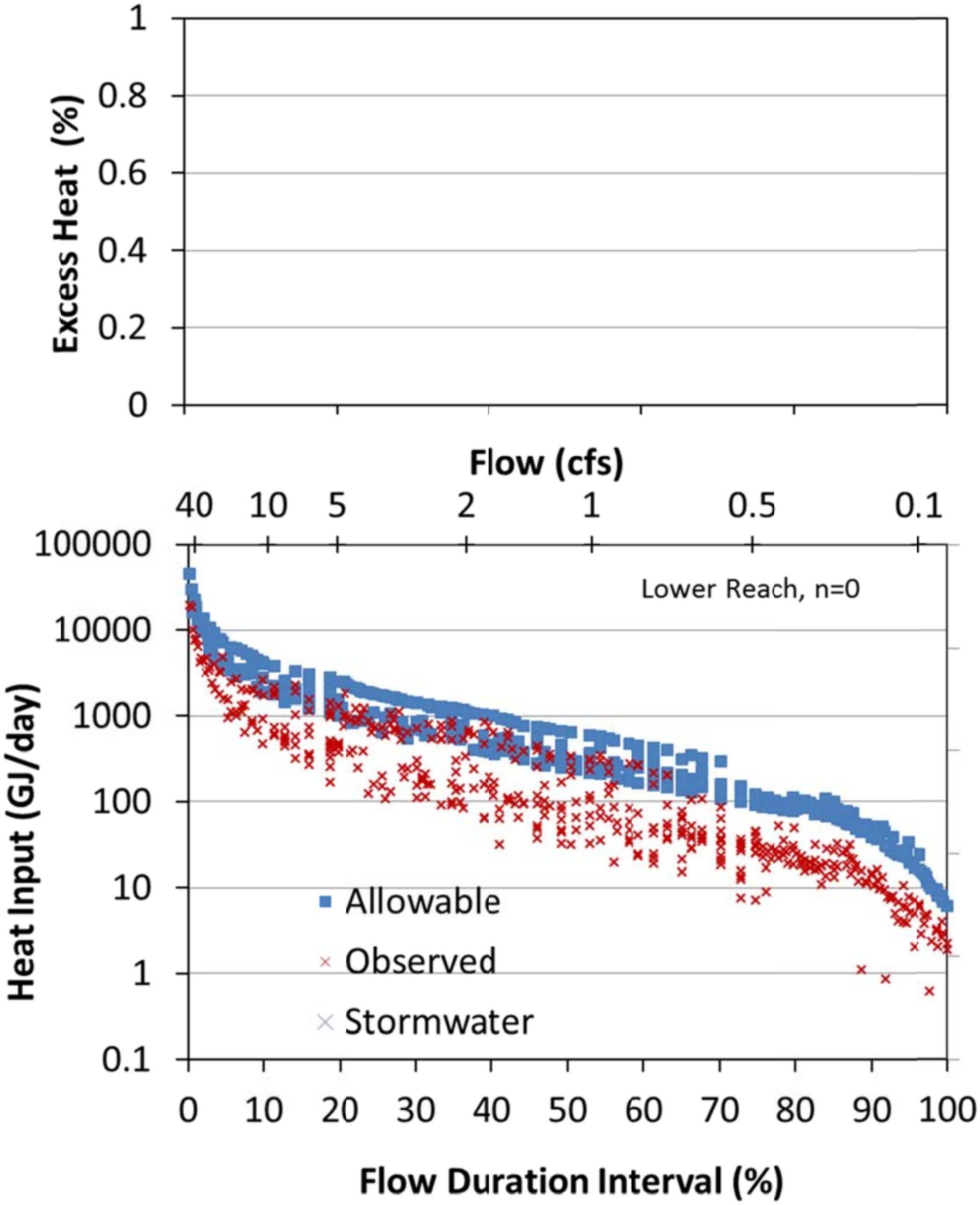

Figure 12. Actual (observed) and allowable daily heat loadings vs. flow duration interval for the Miller Creek lower reach based on 2007, 2008 and 2009 data.

III.3 Relative Contribution of Stormwater to Total Heat Inputs

For purposes of allocating heat reductions, it is necessary to estimate the relative contribution of stormwater to the total heat input budget for Miller Creek. The heat allocation reductions presented here focus on heat inputs calculated at a weekly running average, corresponding to the weekly average temperature standard, because the weekly average standard is violated more commonly in Miller Creek. Calculations were made for the 26th Ave site integrate heat inputs over the entire main stem of Miller Creek. Stormwater heat input calculations were made for 2008 only, because 2008 was the only year where simulated stormwater inflow temperatures were available (Herb and Stefan 2009c). Similar calculations for 2007 would likely give different results, since 2007 was warmer and drier than 2008.

The weekly average stream temperature standard integrates the effect of dry and wet days over 7 day time increments, and the total heat input data gives no information on the relative contribution of stormwater to weekly heat inputs. Since no stormwater inflow volume data was collected in Miller Creek, estimates of stormwater inputs need to be made. Stormwater heat inputs require estimates of both inflow rates (or volumes) and temperatures:

$$H_{sw} = \rho C_p \, \Delta t \;\; Q_{sw} T_{sw} \qquad \text{(Joules)} \qquad (7)$$

where Q_{sw} and T_{sw} are the stormwater inflow rate and temperature. While stormwater input temperatures were measured at several stations at Miller Creek in 2007-2009, no corresponding discharge data were collected. Runoff temperatures for different land uses were therefore estimated using the MINUHET simulation tool (Herb and Stefan 2009c). Two methods were used to estimate stormwater input volumes at daily and weekly time scales:

1) Simulated runoff data from the SWMM model developed and calibrated for Miller Creek (Erickson et al. 2009).

2) Baseflow extraction techniques (Arnold and Allen 1999) were used to partition the observed streamflow data into surface runoff and baseflow components.

While the SWMM model was calibrated for the period June 1 to October 1, 2008, the total stream discharge predicted be the SWMM model at the 26th Ave gaging site can be substantially off for certain daily and weekly time periods (Figure 13). As a result, it was concluded that it is inadvisable to compare stormwater heat inputs calculated using the SWWM results to actual or allowable heat inputs calculated using observed stream flows.

Two methods were used to compare stormwater heat inputs to total stream heat inputs. Method 1 uses simulated stormwater inputs and streamflow from the SWMM model, while method 2 relies on observed streamflow data:

Method 1

- Calculated stormwater heat inputs based on SWMM runoff volumes and MINHUET runoff temperatures
- Calculate actual stream heat input based on SWMM simulated streamflow and observed stream temperatures
- Calculate allowable stream heat input based on SWMM simulated streamflow and temperature standard (19 °C)
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Method 2:

- Calculate total stormwater input using baseflow extraction (Arnold and Allen 1999).
- Partition stormwater runoff to catchments based on the fraction of impervious area
- Calculated stormwater heat inputs based on these estimated runoff volumes and MINHUET runoff temperatures
- Calculate actual stream heat input based on observed streamflow and observed stream temperatures
- Calculate allowable stream heat input based on observed streamflow and temperature standard (19 °C)

For the period June 15 to September 15, 2008, the SWWM model simulations (method 1) predicted stormwater runoff volume to be 88% of total the streamflow volume at the 26th Ave gaging site. For the same period, stormwater volumes derived from baseflow separation (method 2) predicted stormwater runoff volume to be 75% of total the streamflow volume at the 26 Ave gaging site. The higher fraction of stormwater input predicted by method 1 leads to correspondingly higher predicted stormwater heat inputs.

Overall (all flows and all dates), method 1 predicted that stormwater contributed 103% of the actual heat input to Miller Creek in 2008, while method 2 predicted that stormwater contributed about 70% of the actual heat input. Stormwater heat estimates using method 1 predict that total stormwater heat inputs in 2008. While it is possible for stormwater heat inputs to exceed the actual stream heat, if atmospheric heat transfer for the period is negative, this is unlikely for long periods of time, e.g. a week or longer. A more likely explanation is that the stormwater heat input calculations using method 1 are systematically over-predicted. Therefore, stormwater heat input results using method 2 were used for this study.

Stormwater and actual heat inputs calculated using method 2 are given for five ranges of stream flow (flow duration intervals) in Table 4. Overall, the fraction of total heat inputs due to stormwater increase with increasing stream flow, as expected. At very high stream flows (flow duration < 10%), the fraction of stormwater heat input drops off, but there are only 3 data points for this flow range in 2008. For all flow ranges, it was found that the fraction of stormwater heat tracked very closely to the fraction of stormwater volume (Figure 14) in 2008. Figure 14 also gives the fraction of stormwater volume versus flow duration interval based on three years of streamflow data (2007-2009). Using three years of monitoring data, the stormwater volume fraction consistently and smoothly increased with stream flow smoothly, as would be expected.

Based on the results given in Figure 14, the 2007-2009 volume fraction relationship was used to represent the heat input fraction due to stormwater for Miller Creek. These values are given in the far right column of Table 5 for the five flow duration intervals.

Since most temperature exceedances occur at low and mid-range flows (50-100% flow duration interval), heat contributions of stormwater in this flow regime are more relevant for the TMDL. While heat contributions from stormwater can be quite high at high flows, these heat contributions generally do not result in temperature exceedances. From Table 5, stormwater contributes 58% of the total heat input for mid-range flows (40-60% flow duration interval), 44% of the total heat input for moist conditions (60-90% flow duration interval), and 35% of the total heat input for low flows (>90% flow duration interval). The remaining heat input is assumed to come from non-point, atmospheric sources (solar radiation, etc.).

Table 5. Summary of weekly average stormwater and actual heat inputs to Miller Creek in 2008 calculated using method 2. Heat values are given by flow duration range.

SW Heat Fraction = (stormwater heat/actual heat).

Flow Duration Range (%)	Flow Range (cfs)	Average Actual (GJ)	Average SW (GJ)	SW Heat Fraction (2008)	SW Volume Fraction (2007-2009)
0 -10	>17.5	2593.5	1099.3	0.42	0.81
10 - 40	5.5-17.5	1603.6	1333.6	0.83	0.74
40 - 60	3.1-5.5	662.0	454.8	0.69	0.58
60 - 90	0.75-3.1	343.2	196.6	0.57	0.44
90 - 100	<0.75	71.3	25.4	0.36	0.35

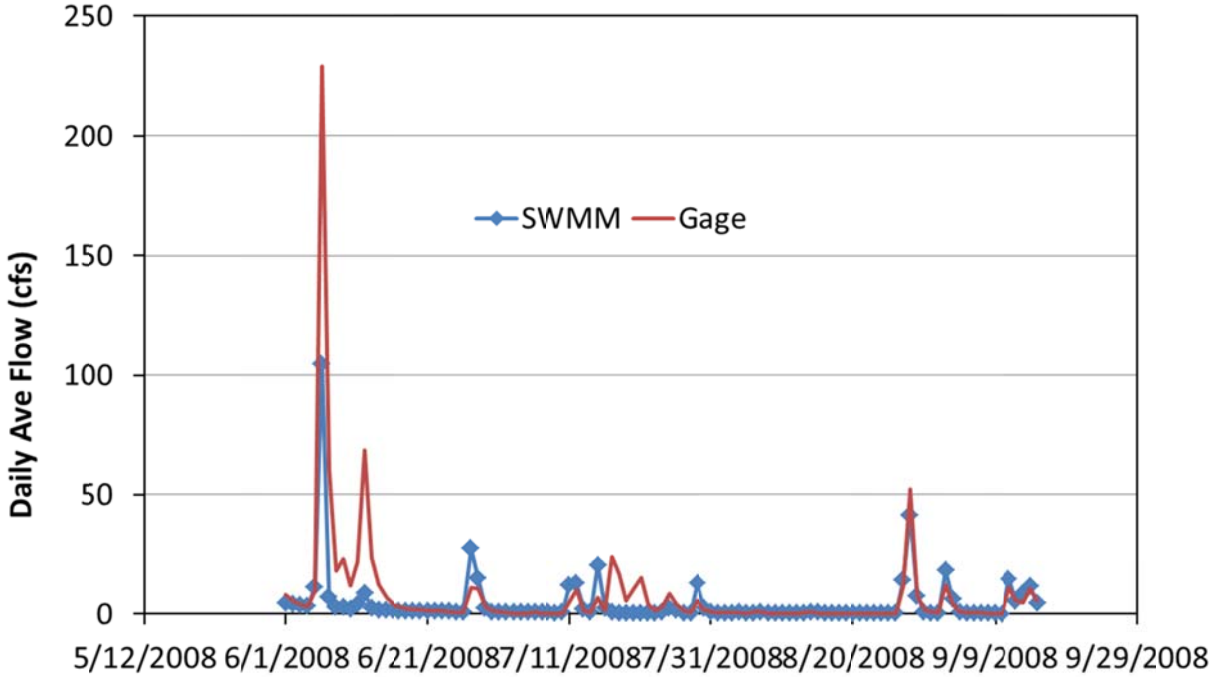

Figure 13. Time series of daily average flow rates at the 26th Ave gaging site for gage observations and SWMM simulations.

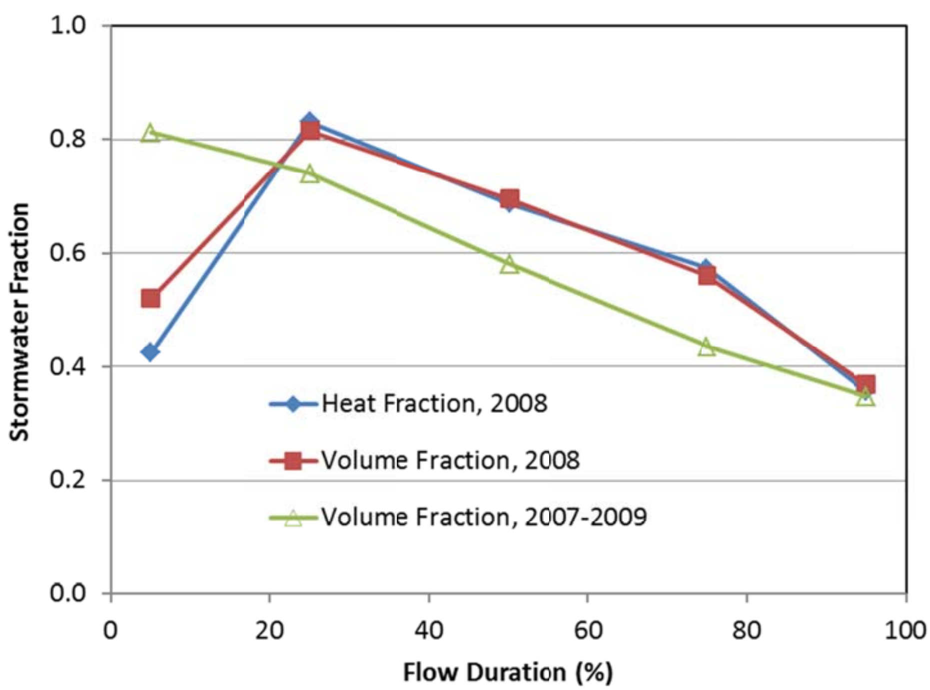

Figure 14. Fraction of total heat and volume due to stormwater versus flow duration for Miller Creek at the 26th Ave station.

IV. Stormwater Heat Loading Allocations (WLA) by MS4

Since separate stormwater monitoring data were not available the MS4s, the relative contribution of each MS4 to the total thermal loading to Miller Creek was estimated for the upper and lower reaches of Miller Creek based on impervious area, i.e. it was assumed that each MS4 contributed heat to Miller Creek in proportion to the total impervious area contained in each MS4. The total impervious area for each MS4 was estimated in GIS (ESRI ArcMap) using the 2006 NLCD impervious layer (Figure 15). The Duluth MS4 was divided into sections contributing to the upper and lower half of Miller Creek, with the Mall Drive Target as the dividing point (Figure 16). Impervious areas for roads and highways were estimated using GIS estimates of the total road lengths in each section. Total areas were then estimated assuming a typical width (Table 6). Impervious areas for Lake Superior College (LSC) and the Natural Resources Research Institute (NRRI) were also estimated separately using the 2006 NLCD impervious layer (Figure 16, Table 7). The impervious areas for the Duluth and Hermantown MS4s were reduced to take into account impervious areas already included in the MNDOT, County, LSC, and NRRI MS4s, to avoid double counting. Based on this analysis, the total fraction of impervious area for each MS4 was determined for the regions of land contributing stormwater to the upper and lower reaches of Miller Creek (Table 8).

Combing these results with results in previous sections for 1) the total heat loading and 2) the fraction of total heat loading attributable to stormwater, the allowable heat loadings (TMDL) to Miller Creek were then calculated for each MS4 as follows:

$$H_{wla} = H_{a,tot} \cdot f_{sw} \cdot f_{imp} \qquad (8)$$

where $H_{a,tot}$ is the total allowable heat for a particular flow regime (Table 4), f_{sw} is the fraction of the total heat loading due to stormwater (Table 5), and f_{imp} is the fraction of impervious area for a particular MS4 (Table 8). The remaining heat load allocation for atmospheric sources (LA) is estimated as:

$$H_{la} = H_{a,tot} \cdot (1-f_{sw}) \qquad (9)$$

H_{la} was not broken down by MS4, since these loadings are related more to riparian shading and channel conditions, not to general land use in the watershed. The calculated TMDLs for each MS4 are summarized in Tables 9a and 9b for the upper and lower section of Miller Crek, respectively.

Table 6. Impervious road areas in the Miller Creek watershed

Road Type	Length (m)	Assumed Width (m)	Area (m^2)	Area (acres)
State Highway	8700	30	260800	64.5
County Highway	15100	15	225900	56.0
County Road	4350	12	52200	12.9

Table 7. Impervious areas in the Miller Creek watershed. The adjusted impervious areas for the Duluth and Hermantown MS4s were reduced to take into account impervious areas included in the MNDOT, County, LSC, and NRRI MS4s, to avoid double counting.

Watershed Region	Total Area (m^2)	Total Area (acres)	Fraction Impervious	Impervious Area (acres) Unadjusted	Impervious Area (acres) Adjusted
Duluth-Lower	8928400	2206.7	0.24	520.8	457.9
Duluth-Upper	8953200	2212.8	0.19	413.8	380.9
Hermantown	5895700	1457.2	0.23	339.5	285.9
NRRI	29700	7.3	0.54	4.0	4.0
LSC	101700	25.1	0.49	12.2	12.2

Table 8. Contribution fraction of each MS4 to total impervious area in upper and lower regions of the Miller Creek watershed.

Region	Upper Half	Lower Half
Duluth-Lower	n/a	0.88
Duluth-Upper	0.506	n/a
Hermantown	0.380	n/a
MnDOT	0.048	0.05
County	0.062	0.043
NRRI	0.005	n/a
LSC	n/a	0.02

Table 9a. Heat Load Allocation (TMDL) Table for Miller Creek, upstream of the Mall Drive Target station.

Miller Creek, Upper Section					
Flow Duration Range (%)	0-10	10-40	40-60	60-90	90-100
Flow Range (cfs)	>11.8	3.1-11.8	1.5-3.1	0.28-1.5	< 0.28
Total Heat (GJ/day)	3843.4	1152.5	427.3	167.9	39.1
LA Fraction	0.19	0.26	0.42	0.56	0.65
WLA Fraction	0.81	0.74	0.58	0.44	0.35
Total LA Heat (GJ/day)	720.3	299.0	179.3	94.9	25.5
Total WLA Heat (GJ/day)	3123.1	853.5	248.0	73.1	13.6
WLA - Duluth, Upper (GJ/day)	1580.3	431.8	125.5	37.0	6.9
WLA - Hermantown (GJ/day)	1186.8	324.3	94.2	27.8	5.2
WLA - MnDOT (GJ/day)	149.9	41.0	11.9	3.5	0.7
WLA - County (GJ/day)	193.6	52.9	15.4	4.5	0.8
WLA - NRRI (GJ/day)	15.6	4.3	1.2	0.4	0.1

Table 9b. Heat Load Allocation (TMDL) Table for Miller Creek, downstream of the Mall Drive Target station.

Miller Creek, Lower Section					
Flow Duration Range (%)	0-10	10-40	40-60	60-90	90-100
Flow Range (cfs)	>17.5	5.5-17.5	3.1-5.5	0.75-3.1	<0.75
Total Heat (GJ/day)	5521.3	1302.5	574.0	233.6	33.2
LA Fraction	0.19	0.26	0.42	0.56	0.65
WLA Fraction	0.81	0.74	0.58	0.44	0.35
Total LA Heat (GJ/day)	1034.8	338.0	240.9	132.0	21.7
Total WLA Heat (GJ/day)	4486.5	964.5	333.1	101.6	11.5
WLA - Duluth, Lower (GJ/day)	3948.1	848.8	293.2	89.4	10.1
WLA - MnDOT (GJ/day)	192.9	41.5	14.3	4.4	0.5
WLA - County (GJ/day)	89.7	19.3	6.7	2.0	0.2
WLA - LSC (GJ/day)	15.6	4.3	1.2	0.4	0.1

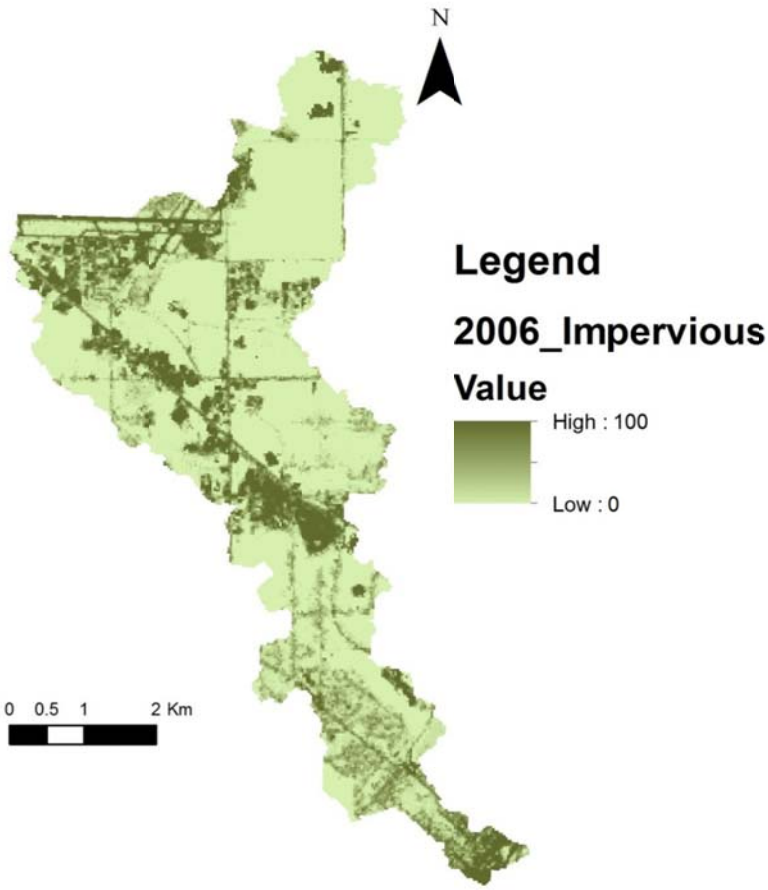

Figure 15. Map of imperviousness (0-100%) in the Miller Creek watershed based on the 2006 NLCD analysis.

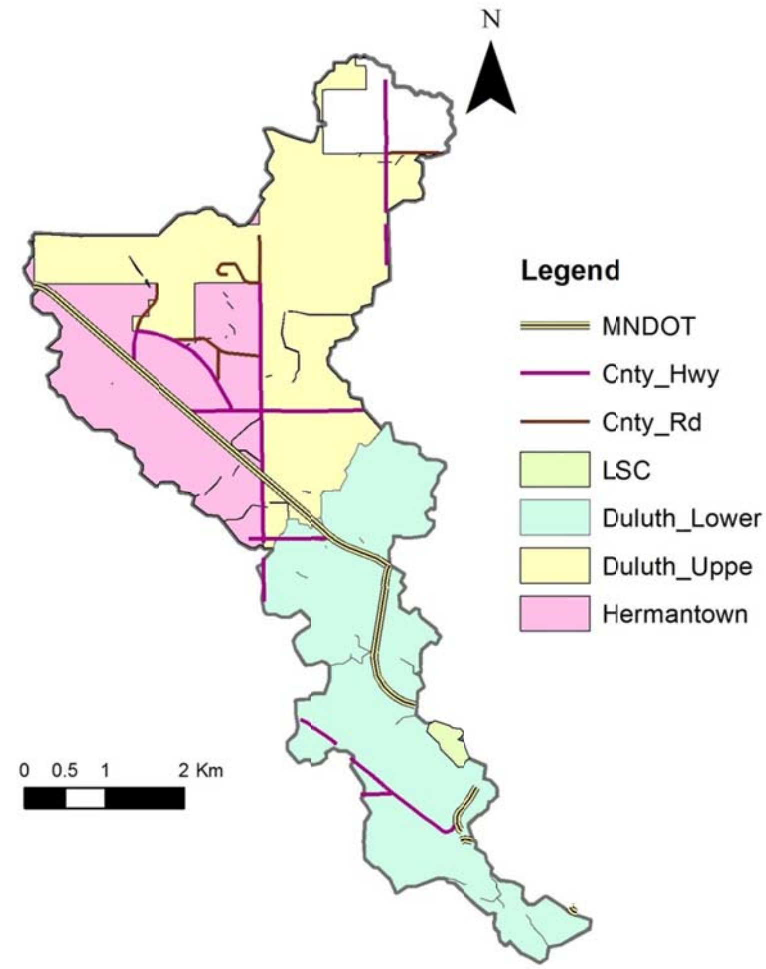

Figure 16. Delineation of the Miller Creek watershed into MS4 areas, with Duluth split into areas above and below the Mall Drive Target monitoring station.

V. Heat Reduction Allocations

Observed heat inputs to Miller Creek exceed allowable heat inputs only slightly during time periods with temperature exceedances. For the upper reach of Miller Creek in 2007-2009, for the 26 days that weekly average stream temperature exceeded 19 °C, actual heat inputs exceeded allowable heat inputs by an average of about 10 GJ, or about 2% of the allowable heat. The highest heat exceedances at the Mall Drive Target location approached 10% of allowable (Table 4). Based on these numbers, a 10% reduction in overall heat input should eliminate the majority of temperature exceedances in the upper reach of Miller Creek. The lower reach of Miller Creek has fewer temperature and heat exceedances, and the maximum heat exceedance for the 2007-2009 study period was about 5% of allowable (Table 4b).

While heat input exceedance were larger based on the daily temperature standard (24 °C), up to 30% of allowable (Figure 11), both the temperature data analysis and the heat input calculations suggest that stormwater has a lesser role in violations of the 24 °C standard compared to the 19 ° weekly average standard.

Based on the stormwater heat input results given in Table 5, about 40% of total heat input is attributable to stormwater in the low flow regime (60-90% flow percentile) that most commonly has temperature and heat input exceedances (Table 4). Therefore, 40% of the required reduction in total heat loading is assigned to the WLA (stormwater), with the remainder allocated to reduction in the LA (non-point, atmospheric heat inputs). Overall, stormwater heat inputs then need to be reduced by 4% in the upper portion of Miller Creek and 2% in the lower portion to satisfy the heat loading criteria, as summarized in Table 9. Based on the results given in Table 4, stormwater hear reductions should be focused on the mid-range, dry, and low flow regimes.

For the upper reach of Miller Creek, the Duluth and Hermantown MS4s account for about 90% of all stormwater loading (Table 8). Therefore, Duluth and Hermantown should each strive to reduce stormwater loading by 4% in the upper watershed. For the lower reach of Miller Creek, the Duluth MS4 accounts for about 88% of all stormwater loading (Table 8). Therefore, Duluth should each strive to reduce stormwater loading by 2% in the lower watershed, with emphasis on the commercialized areas between the Mall Drive Target site and Miller Hill Mall.

Table 9. Summary of required reductions in heat inputs for Miller Creek.

Reach	Overall Heat Reduction	Reduction in WLA (stormwater)	Reduction in LA (atmospheric)
Upper	10%	4%	6%
Lower	5%	2%	3%

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