UNIVERSITY OF MINNESOTA
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Stream Temperature Modeling of Miller Creek, Duluth, Minnesota

by

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Abstract

This report summarizes a modeling study of heat loading and stream temperature in Miller Creek in support of the MPCA Miler Creek temperature TMDL. The MINUHET surface runoff modeling tool was used to characterize runoff temperatures for typical residential and commercial watersheds for the continuous period June 15 to September 15, 2008. These results were then generalized to the entire Miller Creek watershed using runoff volumes from a SWMM model developed at SAFL. These simulated runoff temperatures and volumes were then used to estimate point source heat loadings to Miller Creek for the same time period.

Separate models for wet detention ponds, infiltration basins, and underground stormwater vaults were used to estimate possible reductions in heat loading from surface runoff. Standard wet ponds were found to increase overall heat inputs, but reduce peak heat loading rates and maximum stream temperature increases due to stormwater. The use of wet ponds with bottom outlet structures and underground vaults gave some reductions in effluent temperature for smaller rainfall events (< 1 cm), but were of little benefit for larger events. Infiltration practices give the greatest benefit in reducing temperature impacts of runoff, by direct reduction in runoff volume, however, widespread implementation of infiltration practices in the Miller Creek watershed may be difficult.

In tandem with the runoff models, several stream temperature models for Miller Creek were developed based on the USGS SNTEMP modeling package. The stream temperature models were used to characterize atmospheric (non-point source) heat inputs to Miller Creek for current riparian shading conditions and for several mitigation scenarios with increased shading. Reductions of up to 1 ºC in maximum daily stream temperature were predicted for increasing shading levels in impacted areas from the wetland upstream of Kohl’s to Miller Hill Mall.

Stream temperatures in Miller Creek were modeled with a focus on low flow (baseflow) conditions when trout habitat becomes critical. Both the stream temperature models used in this study and previous studies of the relationship of stream temperature to stream flow suggest, however, that increasing baseflow, by itself, will not necessarily lead to reductions in stream temperature. The temperature of Miller Creek was found to be relatively sensitive to air temperature, i.e. a 1 ºC increase in air temperature led to a 0.6 ºC increase in stream temperature. This sensitivity is likely due to low groundwater inputs, which tend to buffer diurnal and seasonal changes in air temperature. This suggests that Miller Creek, and perhaps North Shore streams in general, may be particularly sensitive to climate change.

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1. Introduction

Miller Creek is a trout stream which originates near Duluth International Airport, flows through the cities of Hermantown and Duluth, MN and discharges into St. Louis Bay of Lake Superior. Despite a highly urbanized watershed, Miller Creek has a naturally reproducing Brook Trout fishery. Prominent hydrologic features of the 9.4 square mile watershed include relatively high levels of impervious surfaces (22%) and extensive wetlands in the upper portion of the watershed (Figure 1.1) that are believed to supply much of the hydrologic storage for the watershed. Miller Creek is temperature impaired and was recently put on the list of impaired waters by the Minnesota Pollution Control Agency (MPCA).

Temperature impairment of a stream implies that the stream is receiving excessive loading of heat energy for particular climate and flow conditions. The main sources of heat energy for a stream include atmospheric heat transfer (solar radiation, long wave radiation, evaporation, convection), surface runoff and local inputs, e.g. of treatment effluent. Previous temperature TMDLs for Pacific Northwest salmon rivers (e.g. USEPA 2000) have treated atmospheric heat transfer as a non-point source of heat and local inputs of treatment effluent as point sources of heat. Atmospheric heat inputs are further classified into natural and anthropogenic sources, based on existing and attainable levels of riparian shading. Although groundwater inputs can be a (negative) source (sink) of heat energy for streams, heat inputs from groundwater have typically not been directly addressed in temperature TMDLs.

Heat loading to a stream from stormwater runoff has also been previously considered in a temperature TMDL (Iowa DNR, 2007). In that study a watershed model (SWMM) was constructed to determine stormwater runoff volumes from each part of the McCloud Run watershed. Runoff temperatures based on the TURM model (Dane County 2005) were then combined with the runoff model to estimate heat loadings to the stream for a 2 year return period storm under current conditions. Heat loadings were calculated based on existing areas and MS4 stormwater permits. Existing heat loadings were then compared to allowable heat loadings for each MS4 area, where the allowable heat loading was calculated based on a State of Iowa temperature standard for trout streams: change in stream temperature due to (anthropogenic) heat inputs less than 3°C and less than 1°C per hour.

The work described in this report and three related supporting reports follows a similar strategy for stream temperature analyses as used in the previous EPA-approved temperature TMDLs. The supporting reports give analyses of streamflows and stream temperatures observed in Miller Creek (SAFL project reports #522 and #529, Herb and Stefan 2009a and b, respectively) and were used to determine 1) the quantity and quality of available flow, temperature, and climate data, 2) typical summer low flows 3) spatial extent and frequency of stream temperature impairments, and 4) mechanisms responsible for temperature impairments. In SAFL Project Report #529, it was concluded that atmospheric heat transfer to the stream is the dominant mechanism for temperature impairments in Miller Creek, with the reach from Kohl’s department store to Miller Hill Mall the most impaired.

As in previous temperature TMDLs, a calibrated stream temperature model is the most important component of the study. A stream temperature model was developed for Miller Creek based on the USGS SNTEMP model (USGS 2008), as described in Section 3. The SNTEMP model was calibrated for current conditions (June – September 2008), and is able to predict daily average and daily maximum stream temperature with an accuracy of 1-2°C. In the temperature calibration process current riparian shading conditions for Miller Creek were quantified; lower shading levels were found in the impacted wetland upstream of Kohl’s and the commercial region between Kohl’s and Miller Hill Mall. The sensitivity of stream temperatures to different parameters in the SNTEMP model was assessed (Section 3), including riparian shading, climate parameters, and streamflow. The sensitivity of stream temperature to riparian shading is explored in more detail in Section 5.2, where several scenarios for reductions in stream temperature are explored.

The MINUHET model (Herb et al. 2009) was used to predict stormwater runoff temperatures for this study. Although MINUHET can also predict runoff volumes, it is not designed to model entire watersheds. To quantify stormwater volume inputs to Miller Creek for the whole watershed, a model for the watershed was constructed (SAFL project report #536, Erickson et al. 2009) using SWMM (USEPA 2005), based on a previously developed model for Miller Creek (Schomberg et al. 2000). The SWMM model was calibrated to observed streamflow data, and then used to generate daily runoff volumes for each of 41 sub-watersheds of Miller Creek for the period June 1, 2008 to October 10, 2008.

Runoff temperatures were simulated using MINUHET for a commercial and residential development in Miller Creek, and calibrated to observed stormwater discharge temperatures in 2008, as described in Section 2. In Section 4, these runoff temperatures are generalized for the entire watershed, based on the level of impervious land use, and combined with the volumes determined by the SWMM model to give the resulting heat loading due to stormwater for the entire watershed. Runoff volumes and heat loadings from stormwater were calculated for a continuous period (June 15 to September 15, 2008), so that the heat loading from a variety of storms over the period is captured. The simulated runoff volumes and temperatures from each sub-watershed were then used to estimate stormwater heat inputs to Miller Creek from the MS4 permit areas (Section 4.2). These estimated heat loadings did not, in general, take into account possible best management practices (BMPs) of stormwater. The effect of stormwater BMPs such as wet ponds, infiltration practices, and underground vaults on heat loading is examined for a commercial development in Section 5.1. At the time of this report draft, allowable stormwater heat loadings have not been calculated, because the temperature standard to be used for the TMDL has not been finalized.

Finally, conclusions are given in Section 6 for managing stream temperature impairments in Miller Creek. There are several pressing issues to resolve for the Miller Creek temperature impairment. Low levels of riparian shading from upstream of Kohl’s to Miller Hill Mall lead to much of the current stream temperature impairments. If shading is improved, then stormwater inputs may give more noticeable impacts of stream temperature. While infiltration practices are the most effective means to reduce stormwater heat loading, rate control practices (wet ponds, underground vaults) slow down the flow water and heat energy, and reduce the magnitude of stream temperature spikes. Increasing summer baseflow in Miller Creek through, e.g., wetland restoration will likely improve trout habitat, but baseflow increases may not, alone, give substantial reductions in stream temperature. Beyond this TMDL study, the high sensitivity of stream temperature to air temperature in Miller Creek makes future climate change effects a major concern.

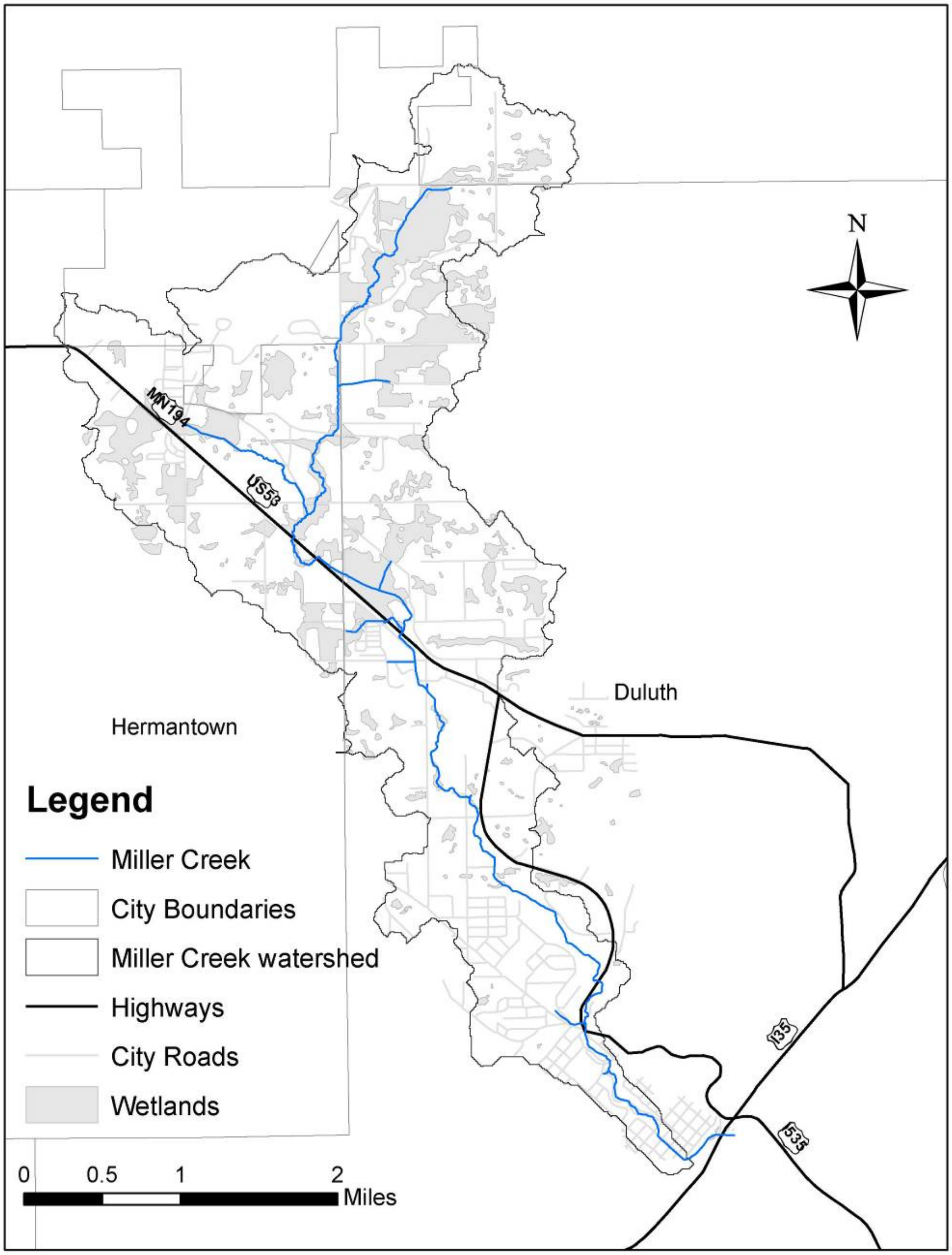


Figure 1.1. Map of the Miller Creek watershed, including wetland delineations.

2. Runoff temperatures in the Miller Creek watershed

Stormwater runoff is an important process in the Miller Creek watershed, because on average about 22% of the watershed area is impervious. Runoff temperatures were simulated for two purposes: 1) as inputs to the stream temperature model and 2) to estimate point source heat loadings to Miller Creek. The MINUHET tool (Herb and Stefan 2009) was used to perform continuous simulations of runoff temperature for the period June 15, 2008 to September 15, 2008. Simulations were first made for two specific sub-watersheds to verify that MINUHET could reproduce runoff temperatures observed at Miller Creek stormwater inlets (Section 2). Runoff temperature simulations were then made for typical residential and impervious areas, and the results were applied to the entire watershed to give total loadings to the stream (Section 4)

The ability of MINUHET to accurately simulate runoff temperature was evaluated for commercial and residential sub-watersheds using available 2008 temperature observations from stormwater inlet pipes to Miller Creek. A commercial sub-watershed that drains into Miller Creek at Maple Grove Road was chosen as the first test case (Figure 2.1). The sub-watershed includes a Target and Best Buy, with substantial roof and parking lot areas, and minimal stormwater mitigation practices.

Climate data required for simulating runoff temperatures include air and dew point temperature, wind speed, precipitation, and solar radiation. Available climate data for the Miller Creek watershed are summarized in Figure 2.2. For simulating runoff from the commercial sub-watershed, precipitation data from the upper MPCA gaging station near Kohl's was used. The only available solar radiation data were taken at Lincoln Park Elementary School, about 5 km from the commercial sub-watershed. Examination of the precipitation and solar data showed some questionable observations of high solar radiation at Lincoln school during precipitation events at Kohl's. Such precipitation/solar radiation data tends to produce artificially high simulated runoff temperatures. To rectify this problem, the solar radiation during rainfall events was adjusted, based on relationships previously developed for precipitation and solar radiation data from MnROAD (Albertsville, MN), given in Figure 2.3. The fitted equations for solar radiation for during and prior to precipitation events were used to set an upper limit on the observed solar radiation values from Lincoln school.

Runoff temperature from the commercial site was modeled based on a previously developed MINUHET model for a Wal-mart facility in Hastings, MN (Herb 2008a). Since detailed plans for the Miller Creek commercial developments were not obtained, a comparison of the relatively complex MINUHET model developed for the Wal-mart to a simplified model with single sub-watersheds for rooftops, pavements and pervious areas was performed. This study is summarized in Appendix I, and led to the conclusion that the simplified model results are comparable to complex model results where the complex models include multiple sub-watersheds for pavements and roofs, and complete representation of the stormwater drainage network. The simplified model was used for further analysis of the commercial sub-watershed.

A summary of the simplified commercial sub-watershed areas and runoff volumes is given in Table 2.1 and Figure 2.4. Simulation results for the simplified MINUHET Wal-mart model are compared to observed temperature data from the Mall Drive stormwater inlet in Figure 2.5. During rainfall events, the observed and simulated temperatures give the runoff temperature, but during dry periods, these temperatures represent the internal temperature of the inlet pipe. The temperature algorithm used by MINUHET to represent pipe temperature (Herb and Stefan 2009) does a reasonable job of estimating the pipe temperature during dry periods, although there is more discrepancy with observed temperatures in late August and September. Simulated and observed runoff temperatures during wet weather are compared more directly in Figure 2.6. The RMSE (root-mean-square error) of the runoff temperature simulation is 1.3 ºC. These runoff temperature simulation results and those given in Appendix I suggest that it is feasible to use simplified, generic models to simulate runoff temperatures from developed areas.

A similar analysis was performed for a primarily residential sub-watershed that drains to Miller Creek at W 10th Street (the SWCD LP-10SW monitoring point). An aerial photo of this sub-watershed is given in Figure 2.7, along with the sub-watershed boundaries from the SWMM model and major stormwater pipes. The drainage network is a mix of pipes and ditches, with small drainage networks of stormwater pipes collecting runoff from subdivisions of houses, which are then routed through drainage ditches to Miller Creek. Overall, observed stormwater temperature at the LP-10SW site are lower than the Mall Drive site (Figure 2.8). Lower temperatures are probably due to 2 factors: 1) more shading of impervious surfaces (streets) in the residential watershed and 2) a higher fraction of pervious area, with sufficient slope to produce runoff.

A summary of the MINUHET model used for the residential sub-watershed is given in Table 2.1 and Figure 2.4. As with the simplified commercial development, the details of the watershed were not modeled, but represented as a total area of pavement, rooftop, and pervious surfaces. A simple network of piping was used to combine the runoff from the separate surfaces, and then routed through a 200 m long pervious ditch to mimic the actual drainage network (Figure 2.7). 30% of the impervious area was routed to pervious areas, e.g. 30% disconnected. The soil hydraulic properties were set equal to those used in the SWMM model, with a hydraulic saturated conductivity of 7.8 x10^{-6} m/sec. The relatively low hydraulic conductivity along with the relatively high mean slope (6.8%) of the sub-watershed resulted in significant runoff volume from pervious areas.

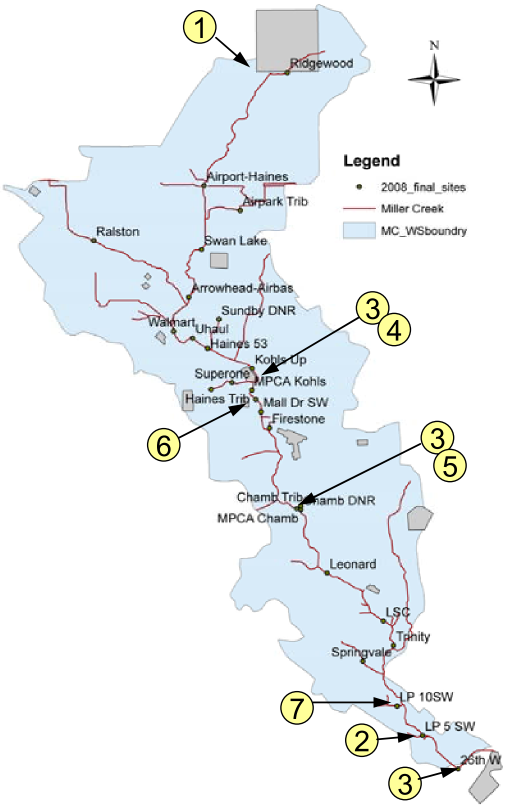
The residential MINUHET reproduced runoff temperatures quite well (Figures 2.9, 2.10). The observed pipe temperatures between rainfall events showed more variability than at the commercial site. This could be due to small flows of groundwater through the open ditch or interaction of air with the temperature sensor. The RMSE of the runoff temperature simulation for the residential site was 1.1 ºC.

The runoff temperature simulations for the residential and commercial sub-watersheds summarized in this section demonstrate that is it possible to use simplified representations of land uses and routing and still obtain good results. These simulations can form the basis for estimating heat inputs from stormwater runoff to Miller Creek in the entire watershed.

Table 2.1. Summary of pavement, roof, and pervious areas used in the commercial and residential MINUHET test cases, and the runoff volumes for the simulation period (June 1 to Sept. 15, 2008). Total rainfall depth for the analysis period = 38.9 cm.

	Commercial	Residential
Total Area, hectares (acres)	12.3 (30.5)	40.0 (98.8)
Impervious Area, hectares (acres)	8.7 (21.4)	6.4 (15.8)
Impervious (%)	70.0	21.5
Pavement Area (hectares)	6.7	3.8
Roof Area (hectares)	2.0	2.6
Total Runoff Volume (m^3)	30,500	66,470
Impervious Volume (m^3)	27,200	20,310
Runoff Depth (cm)	24.8	16.7
Mean Runoff Temperature (ºC)	15.7	15.1

Figure 2.1. Commercial sub-watershed at Maple Grove Rd. The red arrow shows the drainage inlet to Miller Creek and the light-colored lines between black dots show the drainage system.



1 hour air temp, humidity, wind, precip from Duluth Airport
1 hour solar radiation from Lincoln Park Elementary School
15 min air temp and humidity from upper, middle and lower flow gaging sites
15 min precip from upper gaging site (after 7/22 only)
5 min air temp, humidity, wind, precip and pavement temp from RWIS station
5 min water temperature in storm sewer outlet to Miller Creek (Mall Drive SW)
5 min water temperature in storm sewer outlet to Miller Creek (LP 10 SW)

Figure 2.2. Locations of climate and stream temperature monitoring sites and measurements used in the MINUHET analysis.

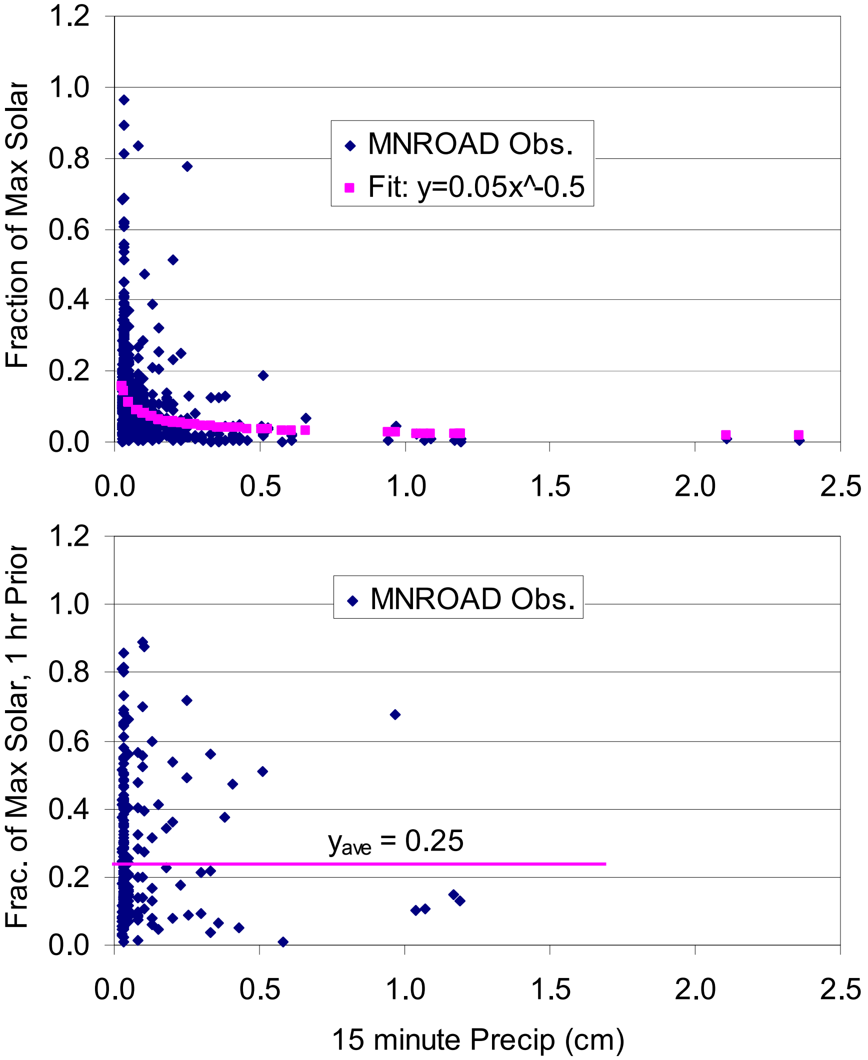


Figure 2.3. Relationships between precipitation depth and solar radiation using six years of 15 minute precipitation and solar radiation data from MnROAD (Albertsville, MN). The upper panel gives solar radiation during precipitation, the lower panel gives solar radiation 1 hour prior to each precipitation event.

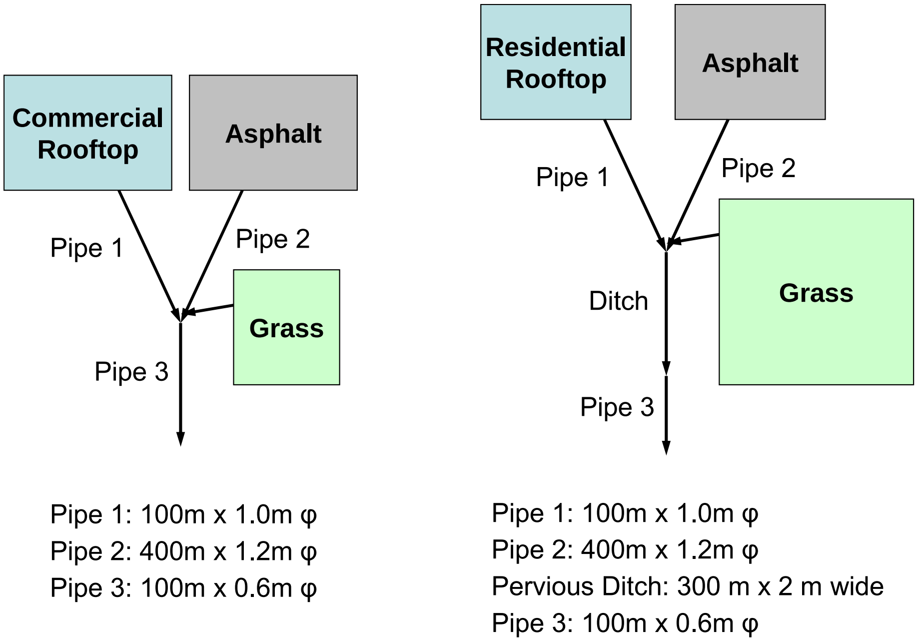


Figure 2.4. Schematics of the simplified runoff models used for the commercial sub-watershed (left) and residential sub-watershed (right).

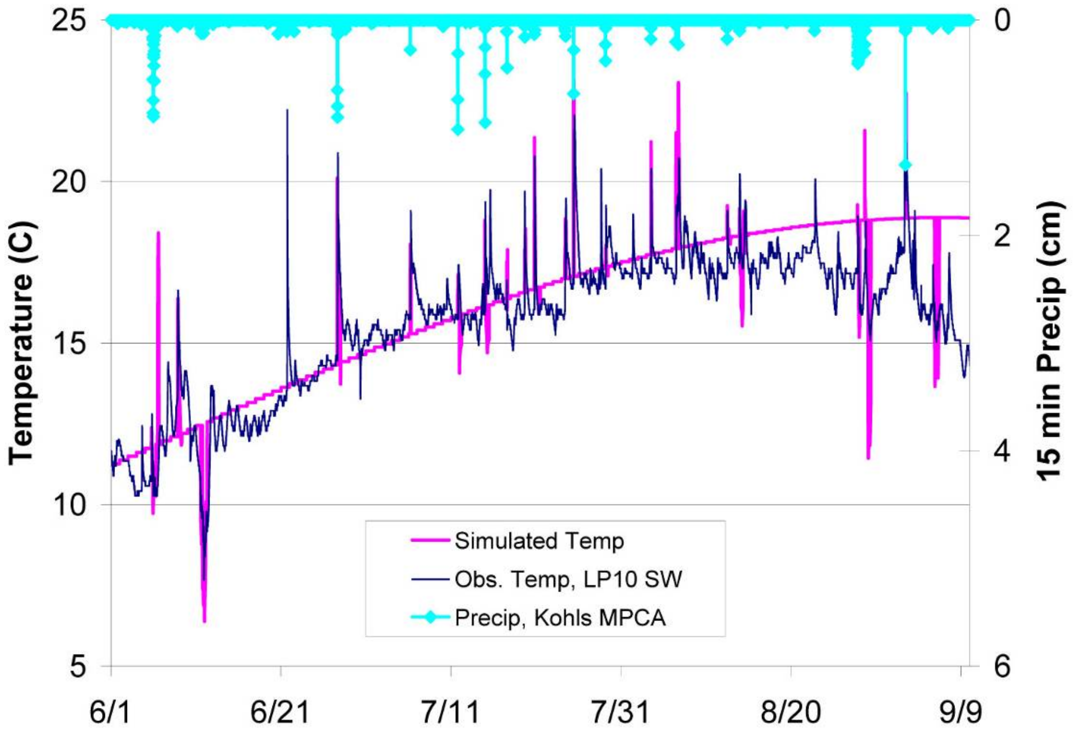


Figure 2.5. Time series of observed and simulated runoff temperatures at the Mall Drive stormwater inlet from June 1 to August 30, 2008.

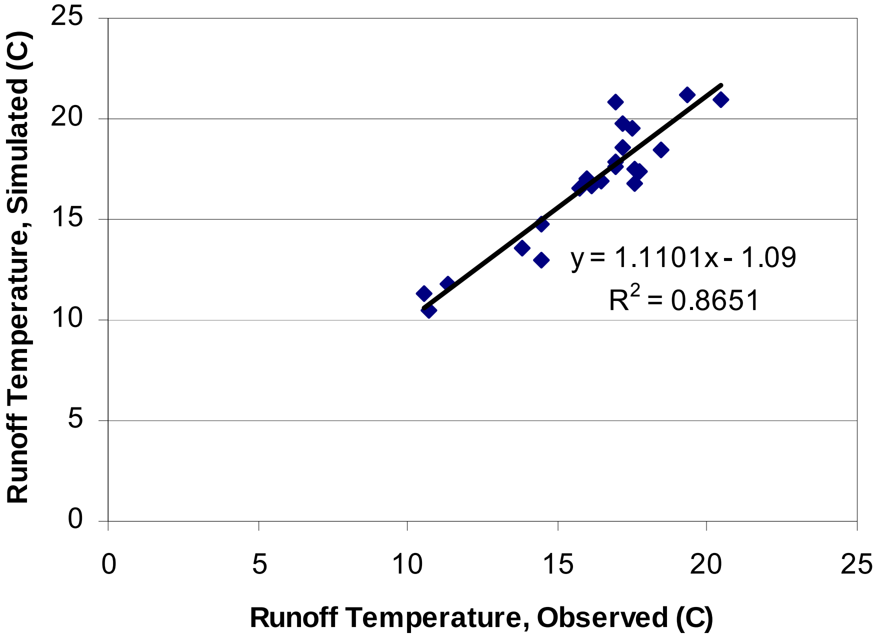


Figure 2.6. Simulated runoff temperature vs. observed runoff temperature at the Mall Drive site for 22 rainfall events from June 1 to September 15, 2008.

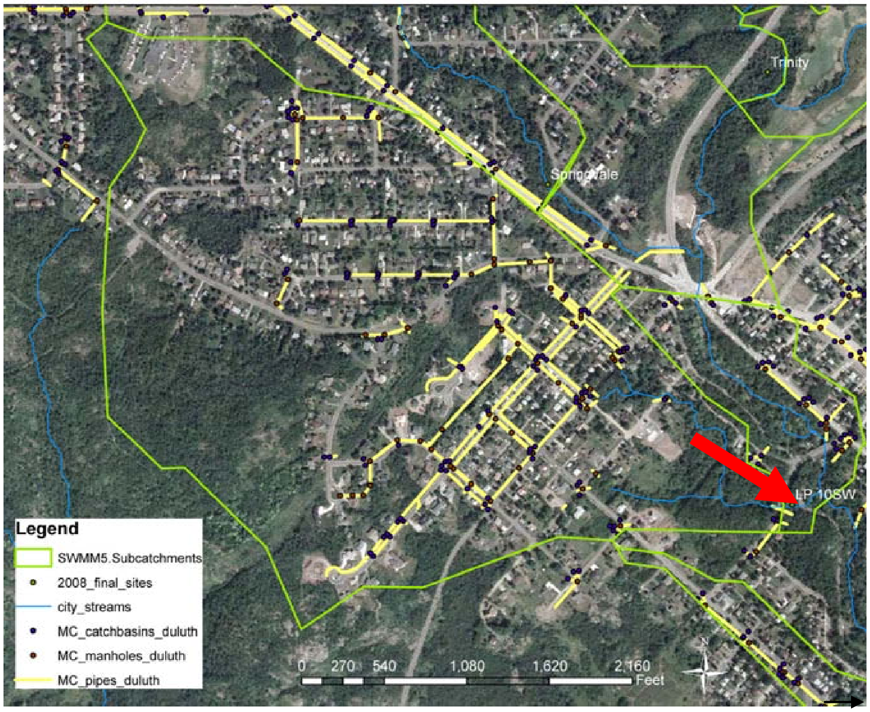


Figure 2.7. Residential sub-watershed at W 10th Street.
The red arrow indicates the drainage inlet to Miller Creek and the light-colored lines show the drainage system.

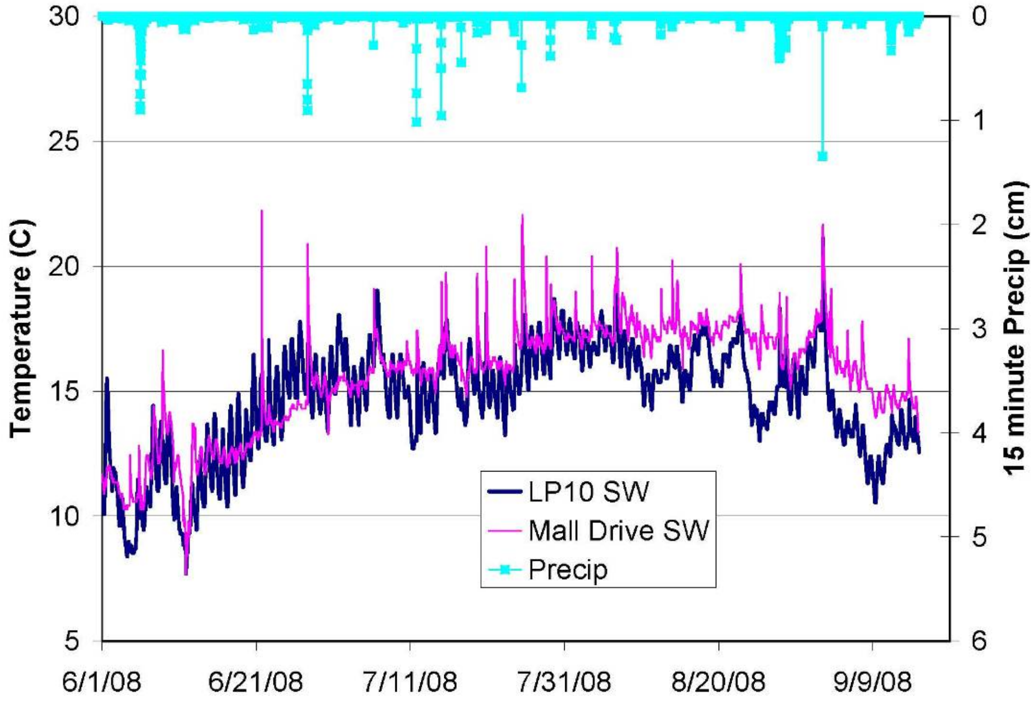


Figure 2.8. Comparison of observed stormwater temperatures at the W 10th Street inlet (LP10 SW) and the Mall Drive stormwater inlet at Maple Grove Rd from June 1 to Sep 30, 2008.

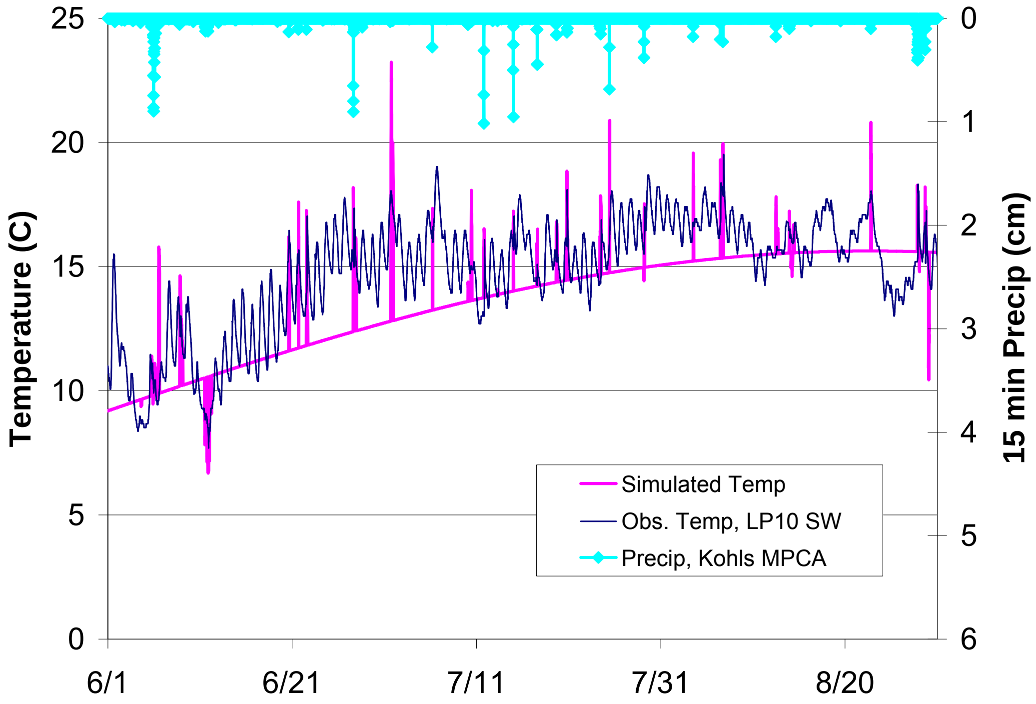


Figure 2.9. Time series of observed and simulated runoff temperature at the W 10th Street inlet (LP10 SW) from June 1 to Aug 30, 2008.

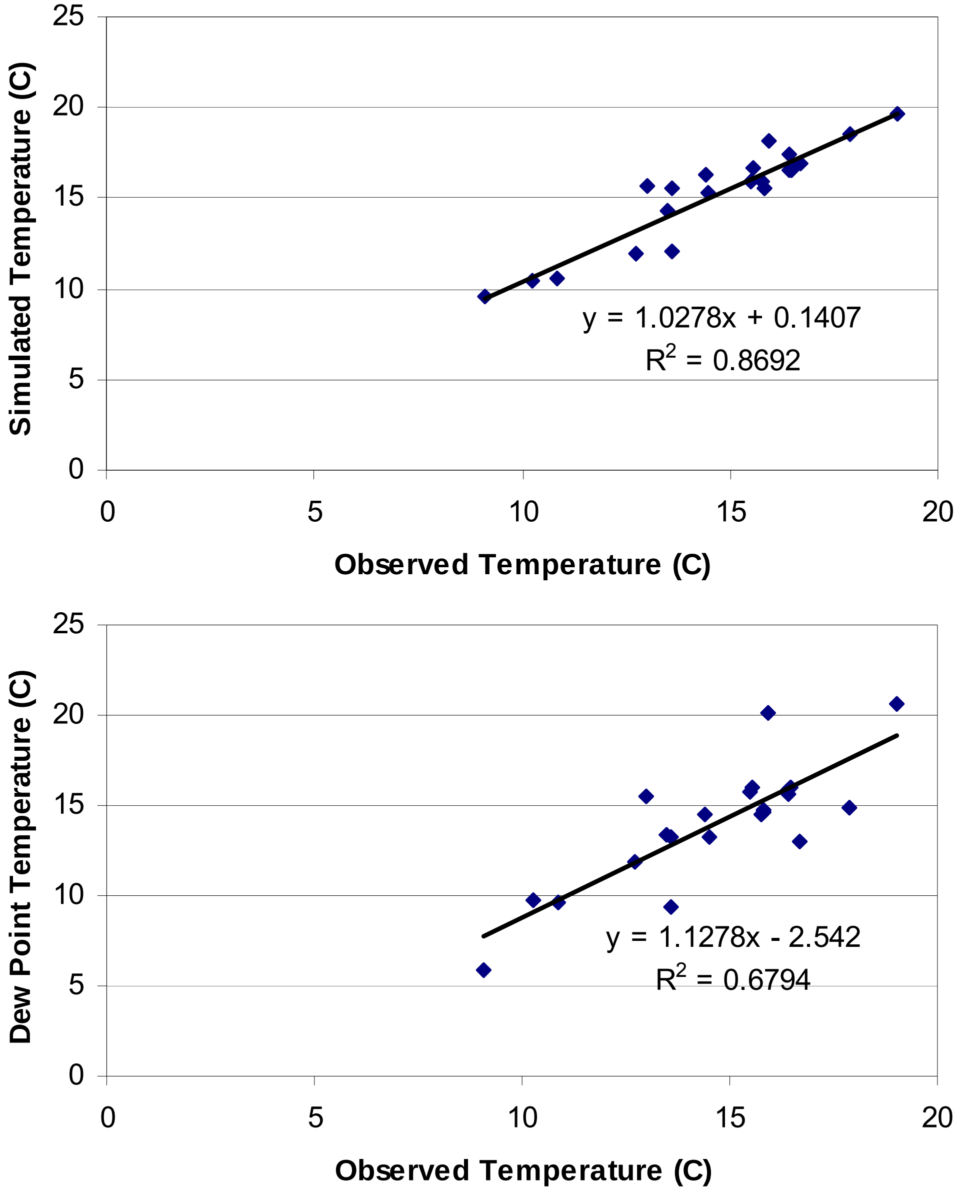


Figure 2.10. Simulated runoff temperature (upper panel) and dew point temperature (lower panel) vs. observed runoff temperature at the W 10th St. site (LP-10SW) for 22 rainfall events from June 1 to Sep 15, 2008. The RMSE of the simulation is 1.1 ºC.

3. Stream temperature model for Miller Creek

A stream temperature model was created and calibrated for Miller Creek including point source and non-point source heat inputs for present conditions, to assess future temperature mitigation strategies. The stream temperature model is based on the SNTEMP model (USGS 2008), which has been previously used for EPA-approved river temperature TMDL studies (State of New Mexico 1999). The 1-D SNTEMP model predicts daily average and daily maximum stream temperatures versus streamwise distance as function of discharge, climate, channel geometry, riparian shading, and groundwater inputs. Several model versions were created to test different configurations for tributary and groundwater inputs, to obtain the best match of simulated stream temperatures to observed stream temperatures. Results from SNTEMP were also compared to another stream temperature model developed at SAFL (Herb and Stefan 2008), which calculates stream temperature with much higher temporal resolution, e.g. 15 minutes.

In all cases, the SNTEMP model was restricted to the main stem of Miller Creek. Tributaries were not modeled, because 1) available flow and channel geometry information on the tributaries were very limited, and 2) observed temperatures for the major tributaries were available for much of 2007 and 2008. Two final SNTEMP model versions that gave good results are documented in this report, and summarized in Table 3.2 and Figures 3.1 and 3.2. Model nodes are specified for tributary inputs, points used to specify changes in shading or stream channel geometry, and points where the stream temperature needs to be predicted, i.e. temperature monitoring points. The main difference between the SNTEMP version 1 and 2 models was the method for specifying tributary and stormwater inflows.

The channel geometry (length, width, slope, roughness) between each pair of model nodes was specified using values from the SWMM model (Erickson et al. 2009). These values are listed for model version 1 and 2 in the SNTEMP geometry files given in Appendix IV.

The SNTEMP models use daily averaged climate parameters as input: air temperature, wind speed, relative humidity, and fraction of clear sky solar radiation. Internal algorithms in SNTEMP estimate maximum clear sky solar radiation based on the calendar day, latitude, and altitude. Weather data input files were created for 2008 using air temperature, wind speed, and humidity from Duluth International Airport and observed solar radiation values from a station on the roof of Lincoln Park Elementary School. Weather data files for 2007 were similar, except that in lieu of observed solar radiation, daily solar radiation estimates for Duluth were obtained from the Minnesota State Climatology office. The lack of observed solar radiation data in 2007 is a major limitation for stream temperature simulations in 2007.

Most of the Miller Creek temperature simulations were therefore made for the weather conditions that occurred from June 1 to September 15, 2008. Overall, this summer period had typical air temperatures and precipitation compared to mean values for the period 1971-2000 (Table 3.1). August 2008 had less precipitation (6.2 cm) than average (7.9 cm), while September 2008 had more precipitation (12.2 cm) than average (10.5 cm).

Table 3.1. Monthly average air temperature and average monthly total precipitation for Duluth International Airport in 2008 and for the period 1971-2000.

	Period	June	July	August	September
Air Temperature (°C)	1971-2000	15.5	18.6	17.7	12.6
	2008	15.5	18.2	18.0	13.3
Precipitation (cm)	1971-2000	10.8	10.7	7.9	10.5
	2008	10.9	11.3	6.2	12.2

3.1 Comparison of SNTEMP and SAFL stream temperature models

The SNTEMP stream temperature model is essentially a steady state model, and is primarily intended to simulate daily average stream temperature, but also can be used to simulate daily maximum temperature. For the purposes of this study, daily maximum stream temperatures are important. To evaluate the ability of SNTEMP to give good predictions of daily maximum stream temperatures, an SNTEMP model was set up for a 3 km long lower reach of Miller Creek, from the Chambersburg DNR station to Trinity Rd. A model for the same reach was also set up using the stream temperature model developed at SAFL (Herb and Stefan 2008) – this model performs full, unsteady stream temperature analysis at, e.g 15 minute time increments. Streamflow was specified as a constant 6 cfs, roughly the average observed streamflow at the 26th Ave stream flow gaging site for the simulation period from July 1 to Aug 30, 2008. Both models predicted daily average and daily maximum stream temperature with less than 1 ºC RMSE (Figure 3.1) over the simulation period. A similar analysis for an upstream reach of Miller Creek (Wal-mart to Kohl's) showed more difference between the models (Figure 3.1, but both models were less accurate for the upstream reach compared to the Trinity Rd. lower reach. The lower simulation accuracy for the upstream reach is probably due to lower and more intermittent streamflow. Based on these results, it was concluded that the SNTEMP model is adequate for simulating daily average and maximum stream temperatures in Miller Creek.

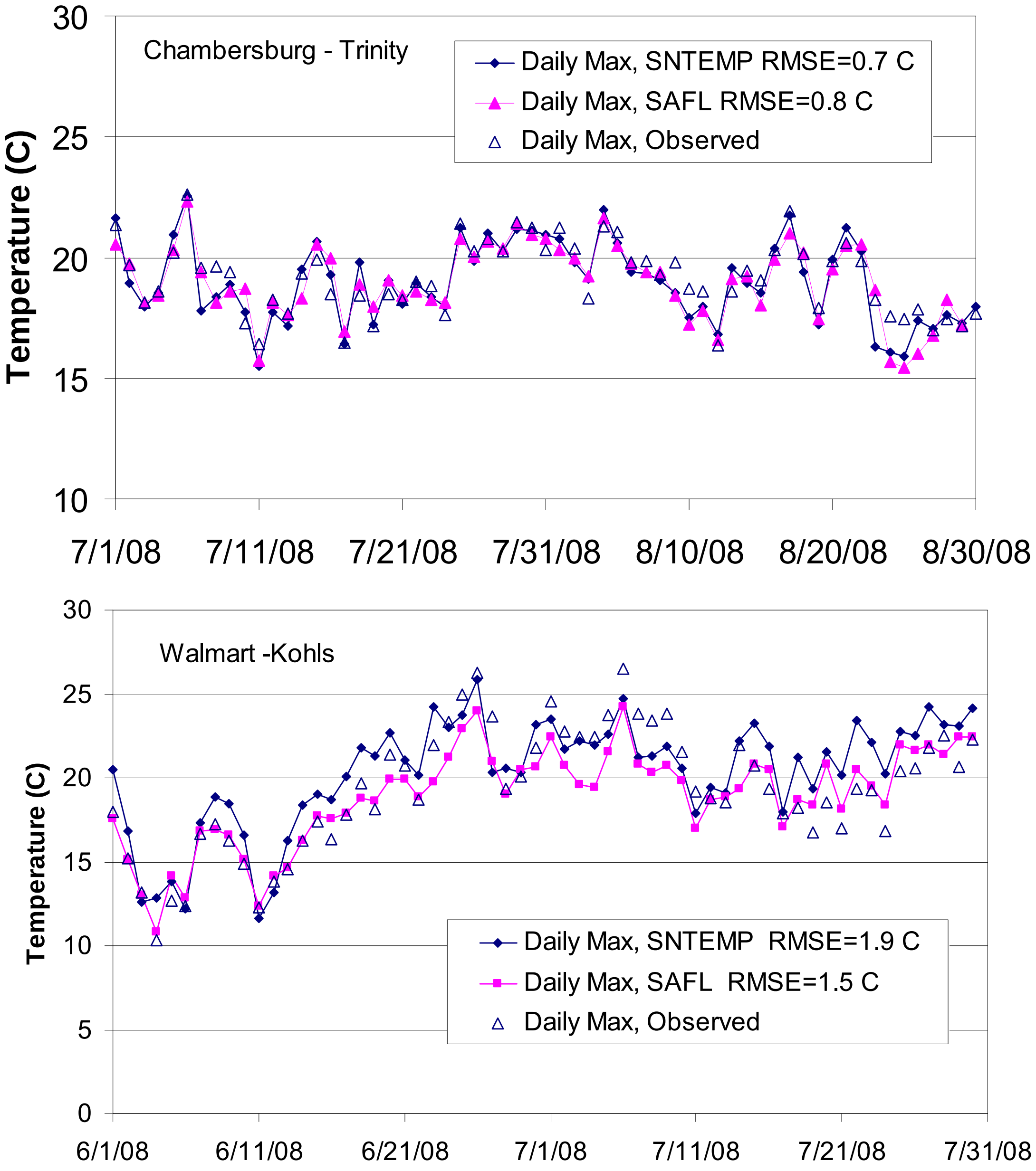


Figure 3.1. Comparison of simulated stream temperatures predicted by the SNTEMP and the SAFL stream temperature models with observed values for two stream reaches of Miller Creek ending at Trinity Road and at Kohl's, respectively

3.2 SNTEMP model Version 1

The SNTEMP model Version 1 was developed mainly to simulate stream temperatures in Miller Creek during baseflow conditions. Tributary and stormwater inflows are specified as a constant fraction of the observed daily average flow at the lower gaging station (26th Ave) (Table 3.2).

Inflow temperatures are specified as model input based on 2008 observed tributary temperatures. In addition to the tributary inflows, three additional inflows were specified to represent the release of water from wetlands to Miller Creek. These inflow points are labeled GWinput 1, 2 and 3 in Figure 3.2. The inflow rates were specified as a constant fraction of the total streamflow (Table 3.2), and the inflow temperatures were set equal to the observed temperature at the Ridgewood site, which is in a large wetland. Most tributaries were set to be a relatively small fraction of the total flow (5%), based on the baseflow measurements made by the South St. Louis SWCD in 2009 and on the SWMM simulation results. The Chambersburg tributary was set higher (15%) based on the observed change in main stem stream temperature upstream and downstream of the tributary. The remaining flow was distributed between the three wetland/groundwater inputs (Table 3.2). Since the SNTEMP model is steady-state (no water or heat storage terms), no attempt was made to introduce time leads/lags in the flows between upstream and downstream points.

The main calibration parameter for the SNTEMP model was channel shading. Channel shading was adjusted for each reach to best fit observed daily average and daily maximum stream temperature. The channel shading parameter for SNTEMP varies from 0 to 1, with 0 representing no shading (all solar radiation reaches the water surface) and 1 representing full shading (no solar radiation hits the water surface). The distribution of shading along Miller Creek obtained by model calibration is shown in Figure 3.3. The lowest shading is along the stream reach in the channelized wetland upstream of Kohl’s. 2008 tree canopy measurements made by the South St. Louis SWCD are also shown. The calibrated shading coefficient for Miller Creek upstream of Kohl’s is higher than the tree canopy measurement, suggesting that shading of the upper reaches is available not only from tree canopies, but also includes tall grasses and other wetland vegetation. In the lower reaches (below Kohl’s), the calibrated channel shading parameter is comparable to the tree canopy observations. There is disagreement between measured and calibrated shading values at the Lake Superior College site, which may be due to the relatively short distance (100 m) over which the tree canopy was measured.

Examples of time series of simulated and observed stream temperatures are given in Figures 3.4 and 3.5 for the Lake Superior College site and the site upstream of Kohl’s, respectively. The corresponding distribution of temperature simulation errors (RMSEs) is given in Figure 3.6. In general, upstream reaches were more difficult to simulate than downstream reaches, probably due to lower and more intermittent flows. The observed temperatures of the outflow from the upstream reach was the most difficult to simulate. Although the model was developed mainly to simulate stream temperatures during baseflow conditions, the temperature simulation errors were similar for all days including days with flows less than 2 cfs, (Figure 3.6).

In 2008, several stations had temperature observations that were inconsistent with temperature observations at neighboring monitoring sites as well as simulated temperatures for that site. Much of the observed temperature record for the Swan Lake site and some of the record for the Airport-Haines site (Figure 3.7) fell into that category. These anomalous temperature data were not included in the model calibration process.

Table 3.2. Tributary inflow as a constant fraction of total stream flow at 26th Ave for the SNTEMP model Version 1

Input	Fraction
Ridgewood	0.05
Airpark Trib	0.05
GW Input 1	0.18
GW Input 2	0.18
Kohls Trib	0.05
Firestone Trib	0.05
GW Input 3	0.18
Chamb. Trib	0.20
LP10-SW	0.05

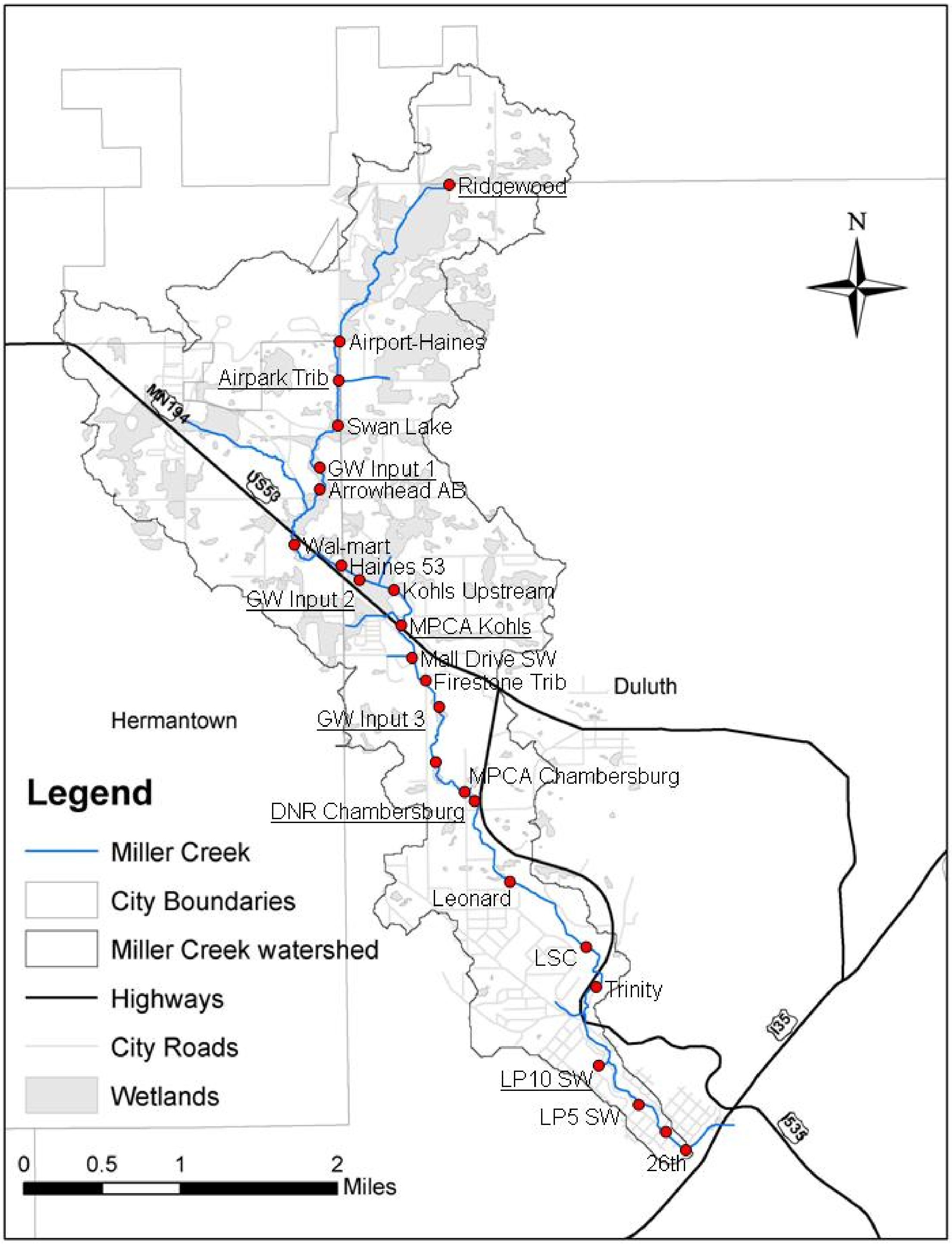


Figure 3.2. Model nodes for the SNTEMP model Version 1. Inflow rates and inflow temperatures are specified at points with underlined labels.

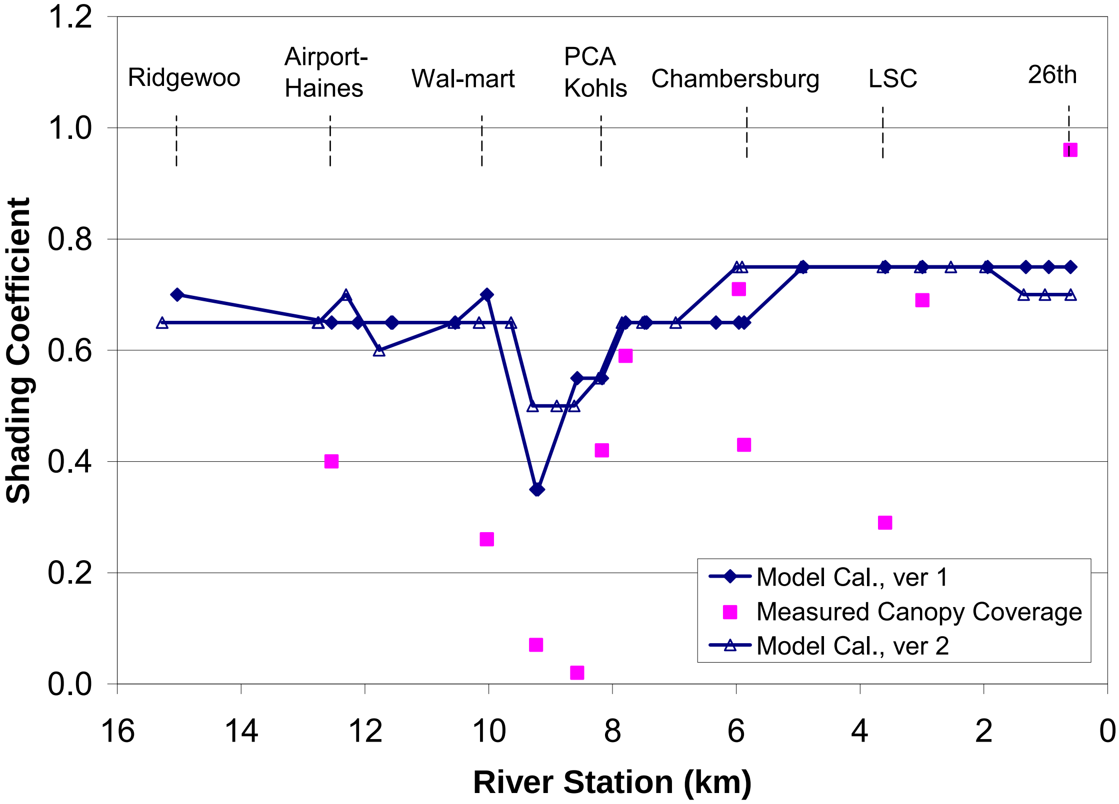


Figure 3.3. Spatial variation of the calibrated shading coefficients from the SNTEMP models Version 1 and Version 2. Measurements of tree canopy coverage by the South St. Louis SWCD in 2009 are also shown.

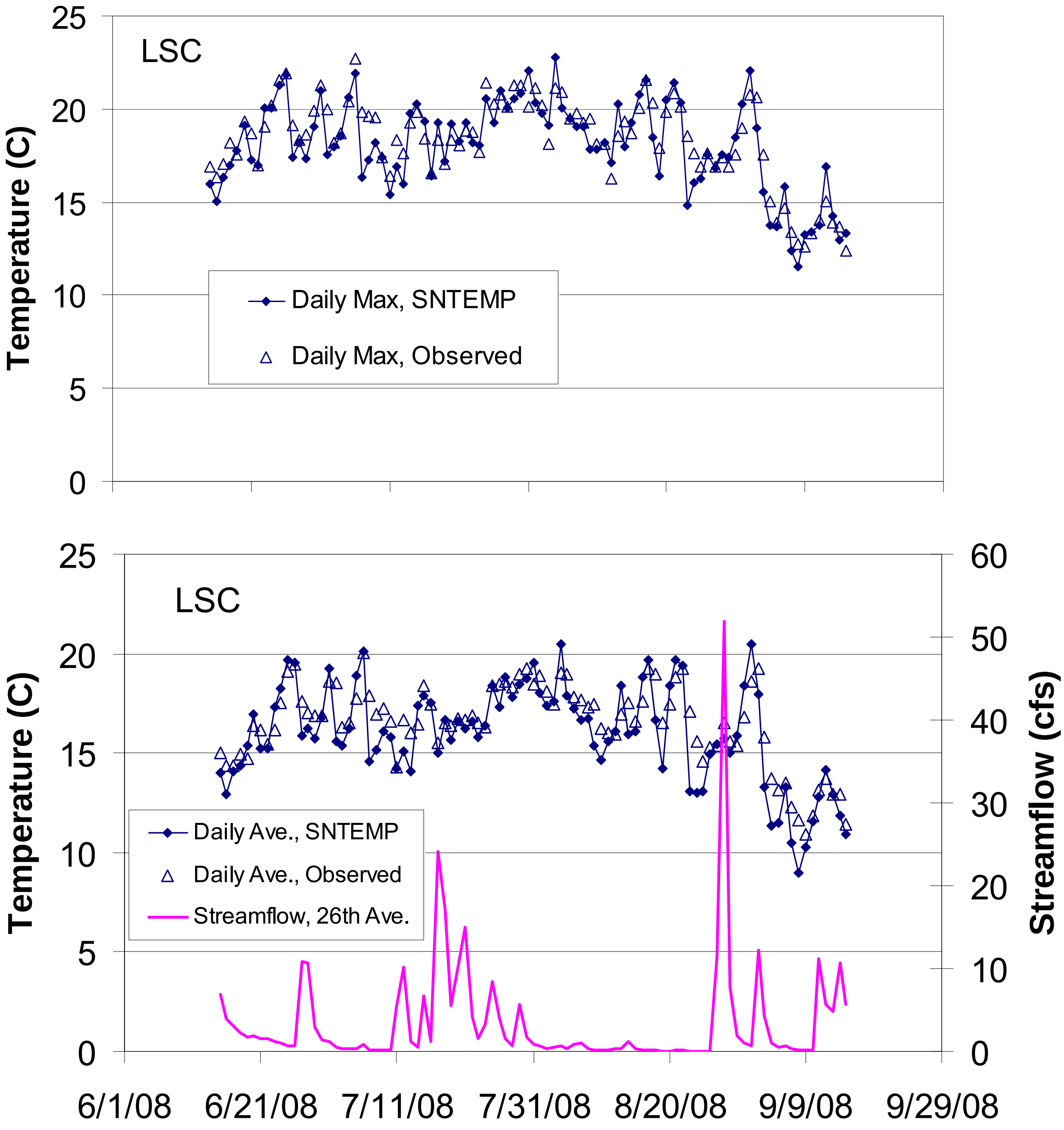


Figure 3.4 Simulated and observed daily maximum (upper panel) and daily average (lower panel) stream temperatures of Miller Creek at Lake Superior College. The RMSE for daily maximum and daily average stream temperature is 1.1 and 1.3 °C, respectively. Streamflow at the 26th Ave. gage is given for reference.

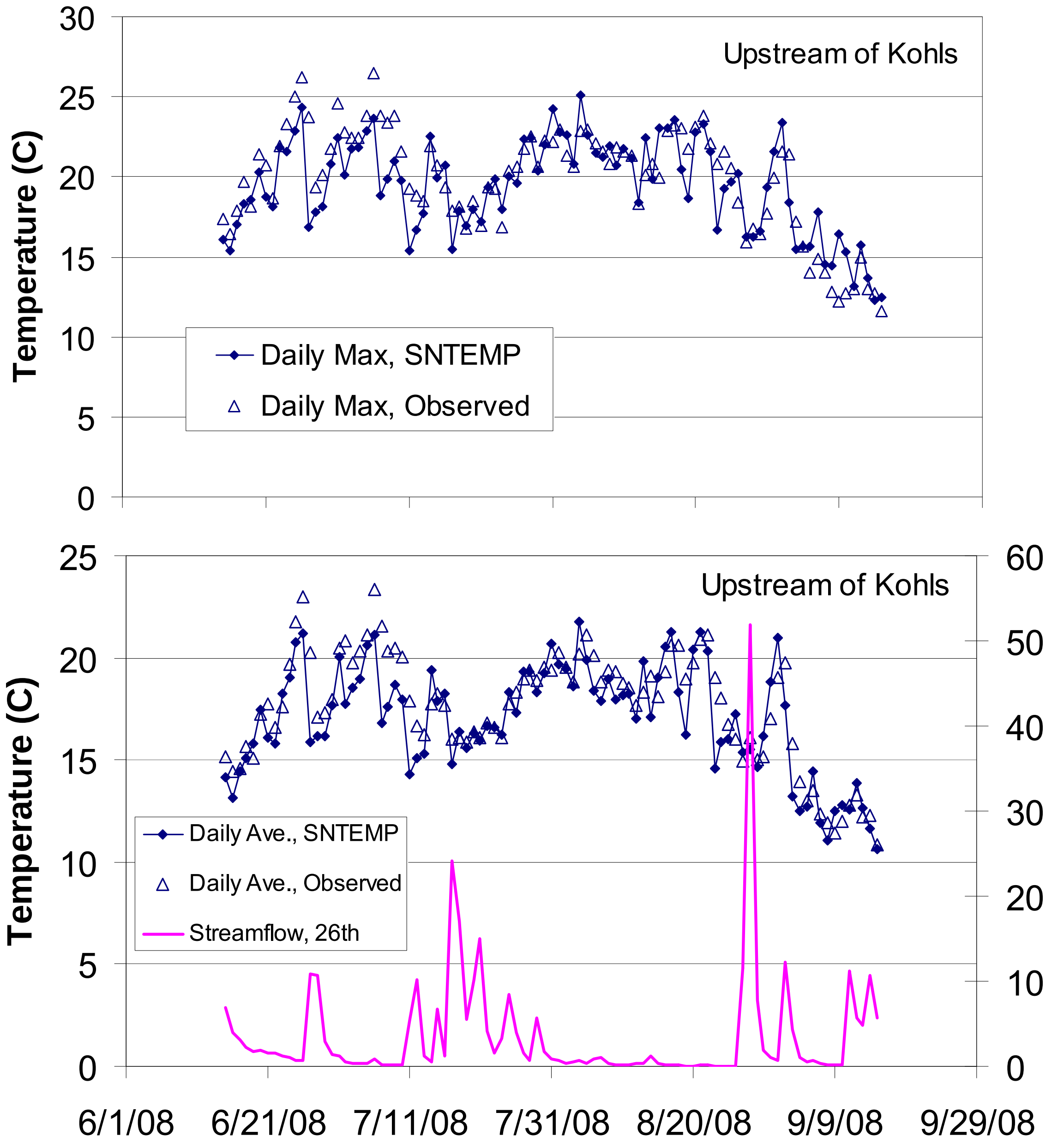


Figure 3.5. Simulated and observed daily maximum (upper panel) and daily average (lower panel) stream temperatures of Miller Creek upstream of Kohl's at Lake Superior College. The RMSE for daily maximum and daily average stream temperatures is 1.8 and 1.5 ºC, respectively. Streamflow at the 26th Ave. gage is given for reference.

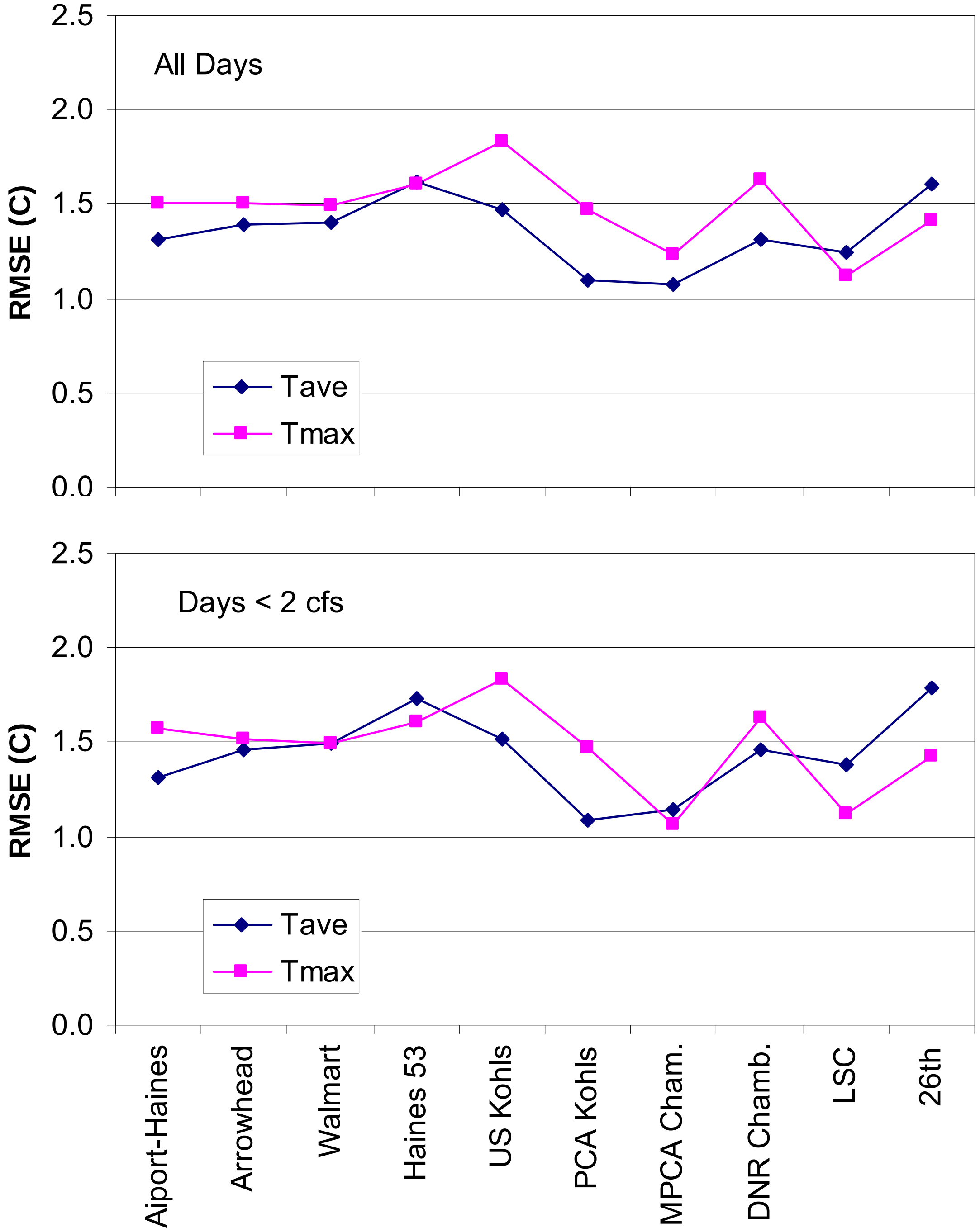


Figure 3.6. Root-mean-square error (RMSE) of the temperature simulations at different points in Miller Creek for all days from June 15 to Sept. 15 (upper panel) and for days with average flows < 2 cfs (lower panel).

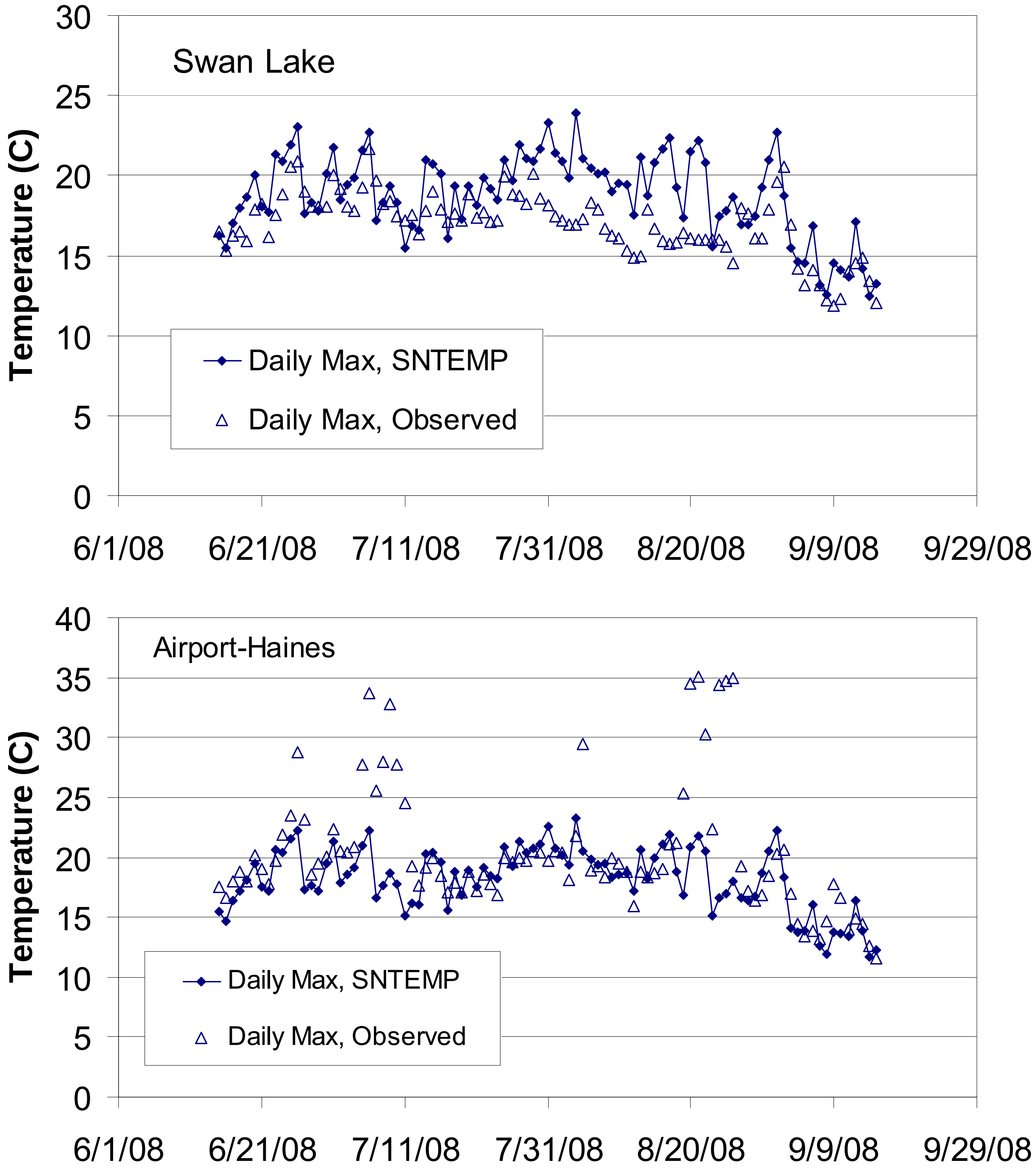


Figure 3.7. Simulated and observed daily maximum stream temperatures at the Airport-Haines and Swan Lake sites.

3.3 Sensitivity analysis

To quantify the accuracy and uncertainty of the temperature simulations, the sensitvity of simulated stream temperature to several basic model parameters was investigated using the SNTEMP model Version 1. The sensitivity was quantified as the change in the mean stream temperature and the mean daily maximum stream temperature over the simulation period (June 15 – Sept. 15, 2008). The results are summarized in Table 3.3. Stream temperature is shown to be relatively sensitive to changes in air temperature (stream temperature change is about 60% of the air temperature change), and to shading coefficients (10% decrease in shading causes a 0.3 ºC increase in daily average temperature and a 0.6 ºC increase in daily max stream temperature). This is consistent with results found by analysis of observed stream and air temperatures (Herb and Stefan 2009b). The temperature specified for tributary and wetland storage inputs had a moderate effect on stream temperatures (mean and daily max stream temperature increase 0.24 ºC and 0.21 ºC, respectively, for a 1 ºC inflow temperature change) Stream temperature was found to be insensitive to stream width, stream flow, the partitioning of inflows, and to Manning's' roughness coefficient, which is used to determine stream flow velocities. Further analyses on the sensitivity of stream temperature to shading are given in Section 5.

Table 3.3. Summary of stream temperature sensitivity to SNTEMP model input parameters and variables.

Parameter or Variable	Change in Parameter	Change in Mean Stream Temperature (ºC)	Change in Daily Maximum Stream Temperature (ºC)
Air Temperature	+ 1 ºC	0.61	0.59
Shading Coefficient	- 10%	0.33	0.61
Tributary Inflow Temperature	+ 1 ºC	0.24	0.21
Stream Width	+ 50%	0.06	0.12
Stream Flow	+ 20%	-0.03	-0.06
Tributary Fraction of Flow	see table below	0.01	-0.01
Manning's Roughness	+ 50%	0.00	-0.08

Fraction of Input Flow	Nominal Fraction	Modified Fraction
Ridgewood	0.05	0.05
Airpark Trib	0.05	0.1
GW Input 1	0.20	0.15
GW Input 2	0.20	0.15
Kohls Trib	0.05	0.1
Firestone Trib	0.05	0.1
GW Input 3	0.20	0.15
Chamb. Trib	0.15	0.15
LP10-SW	0.05	0.05

3.4 SNTEMP model Version 2

The SNTEMP model Version 1 uses observed streamflows and temperatures as inputs, while the SNTEMP model Version 2 uses simulated flows from the SWMM (Erickson et al. 2009) to specify inflow rates at a total of 16 sites (Table 3.4). This model version is needed to estimate total heat input to Miller Creek from surface runoff (stormwater). The temperatures of the inflows are based on simulated runoff temperatures for different classes of land use in the watershed.

Based on current aerial photos and a 1993 land use map for the Miller Creek watershed from the USGS Gap Analysis Program (GAP), the impervious area within each subwatershed was placed into one of two categories, roughly corresponding to commercial and residential land uses (Figure 3.9). The sub-watersheds used in the SWMM are shown in Figure 3.10. Impervious surfaces within areas mapped as ‘high intensity urban development’ in the GAP study were treated as commercial areas, while impervious areas within low intensity and mixed development areas were treated as residential areas. MINUHET was used to simulated runoff temperatures for commercial impervious areas (75% pavement, 25% roof, 100% connected, no shading) and for residential impervious areas (60% pavement, 40% roof, 30% shading, 30% disconnected). These simulations were very similar to the verification simulations described in Section 2, except that pervious areas were not included. A simulation of runoff from pervious areas (short grass, C type soil, 4% slope) was done separately. The underlying assumption was that some runoff occurs from pervious areas only in the steeper (higher slope) portions of the watershed, whereas no runoff occurs from low slope pervious and wetland areas.

Simulated runoff temperatures for the commercial impervious surfaces were the highest (16.1 ºC), followed by the residential impervious surfaces (15.4 ºC) and the pervious surfaces (14.5 ºC) (Table 3.5). The runoff depths were even more variable, with seasonal totals for impervious commercial, impervious residential, and pervious surfaces of 29.1, 33.6 and 11.3 cm (June 15 to Sept 15), respectively. For the watershed as a whole, stormwater mitigation was not included. The effect of stormwater mitigation on heat loading are addressed in Section 5.

The SNTEMP model Version 2 was then run for 2008 (June 15 to Sept 15) using simulated daily runoff volumes and temperatures from 41 sub-watersheds as inputs at the 16 inputs points, as summarized in Table 3.4. The overall average volume fraction of each of the 16 inputs is also given in Table 3.4. The Version 2 model was then calibrated to observed stream temperatures from 2008 by adjusting the shading coefficients for each station. The resulting calibrated 2008 shading is similar, but not identical to, to the Version 1 model, as shown in Figure 3.3. An example of the resulting simulated stream temperatures is given in Figure 3.11 for the Lake Superior College location. The simulation RMSEs for each station are given in Figure 3.12. Overall, the SNTEMP model Version 2 gave very similar results to the Version 1 model. In the sensitivity analysis, the SNTEMP stream temperature model had been found to be only moderately sensitive to inflow rate and inflow temperatures (Table 3.3). It is therefore not surprising that the two strategies used to create inflows for the Version 1 and 2 models gave similar results.

Table 3.4. Tributary inflow as a variable fraction of total stream flow at 26th Ave for the SNTEMP model Version 2 (average of time varying fraction)

Input	Fraction
Ridgewood	0.021
Airport-Haines	0.132
Airpark Trib	0.016
Swan Lake	0.040
Arrowhead/Ralston	0.235
Sunby Trib	0.068
Kohls Trib	0.068
Mall Drive SW	0.052
Firestone	0.007
Miller Hill Mall	0.075
Chambersburg Trib	0.025
Leonard	0.056
Trinity	0.062
LP10 SW	0.054
LP5 SW	0.035
Above 26th	0.056

Table 3.5. Simulated total runoff depth and mean runoff temperature from commercial (high intensity) impervious, residential (low intensity) impervious, and pervious surfaces in the Miller Creek watershed in 2008. September numbers are through the 15th only.

	Precip (cm)	Total Runoff Depth (cm)			Mean Runoff Temperature (^{o}C)		
		High	Low	Pervious	High	Low	Pervious
June	14.2	11.07	11.51	5.38	12.5	12.1	12.7
July	11.6	8.76	11.70	4.08	17.4	16.3	15.8
August	7.4	5.33	5.73	1.83	18.2	17.5	17.0
September	5.3	3.96	4.31	0.00	18.4	17.7	
Overall	39.0	29.1	33.3	11.3	16.1	15.4	14.5

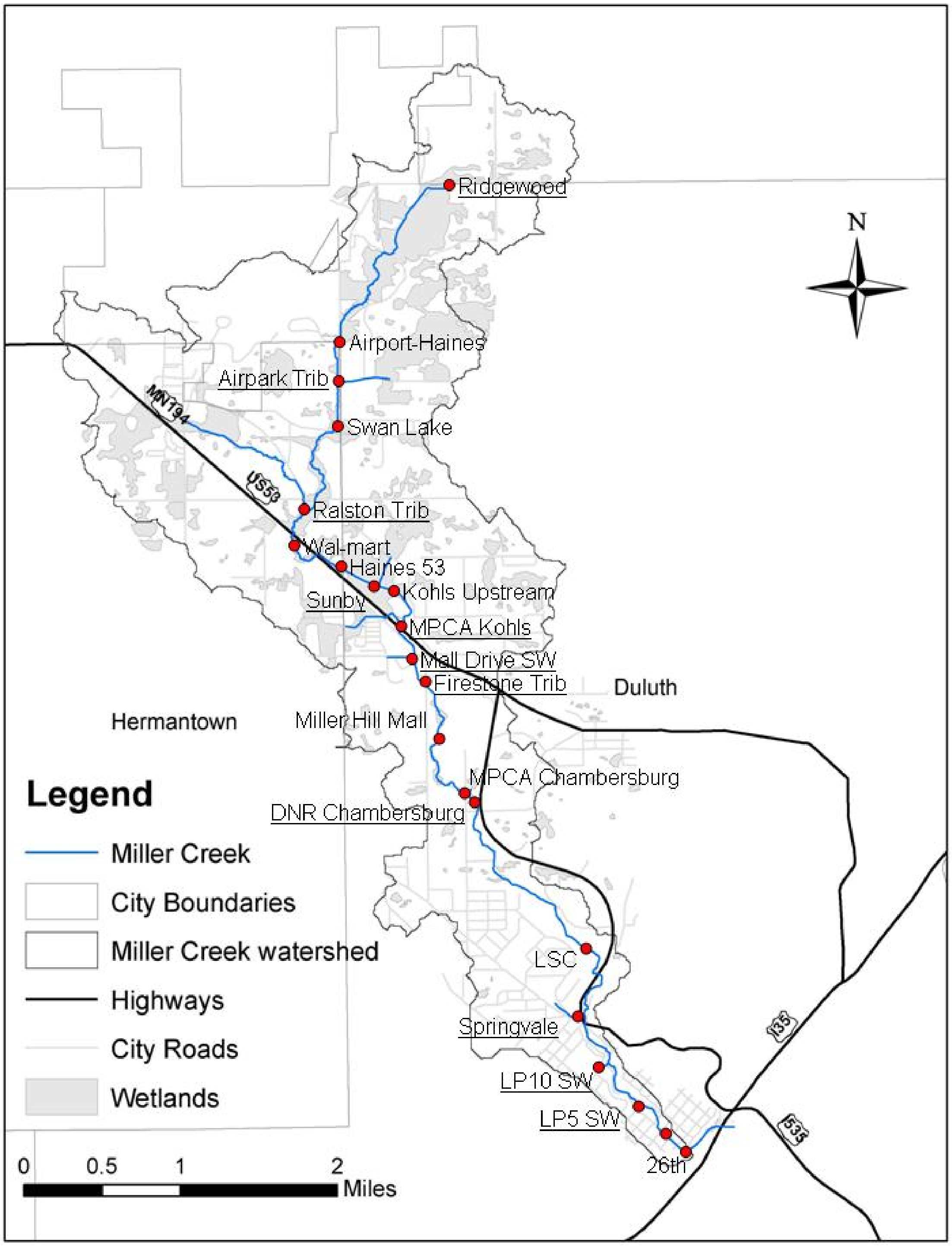


Figure 3.8. Model nodes for the SNTEMP model Version 2. Inflow rates and inflow temperatures are specified at points with underlined labels.

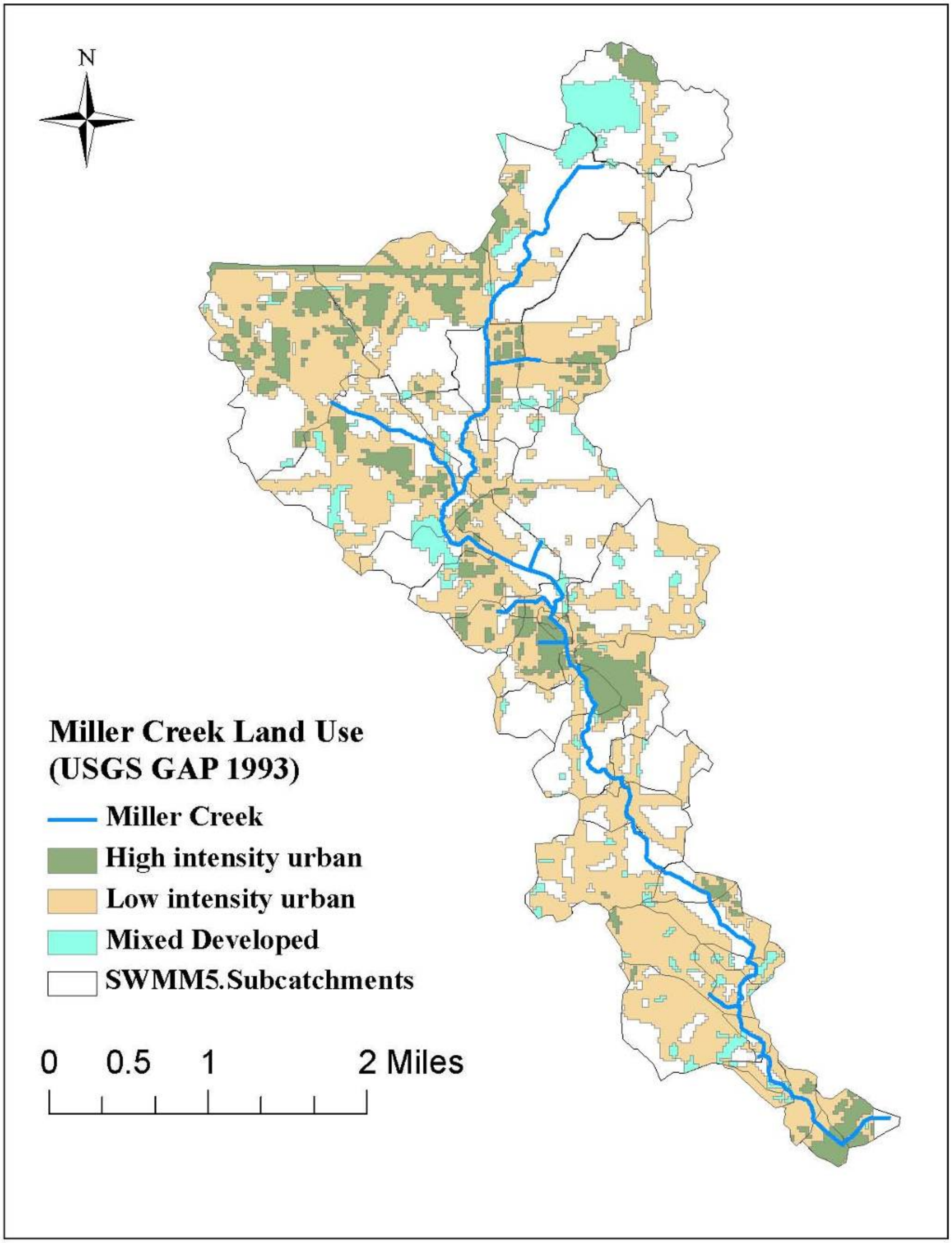


Figure 3.9. Land use classifications in 1993 from the USGS Gap Analysis Program (GAP).

Figure 3.10. Sub-watersheds (41) of the SWMM model (Erickson et al. 2009).

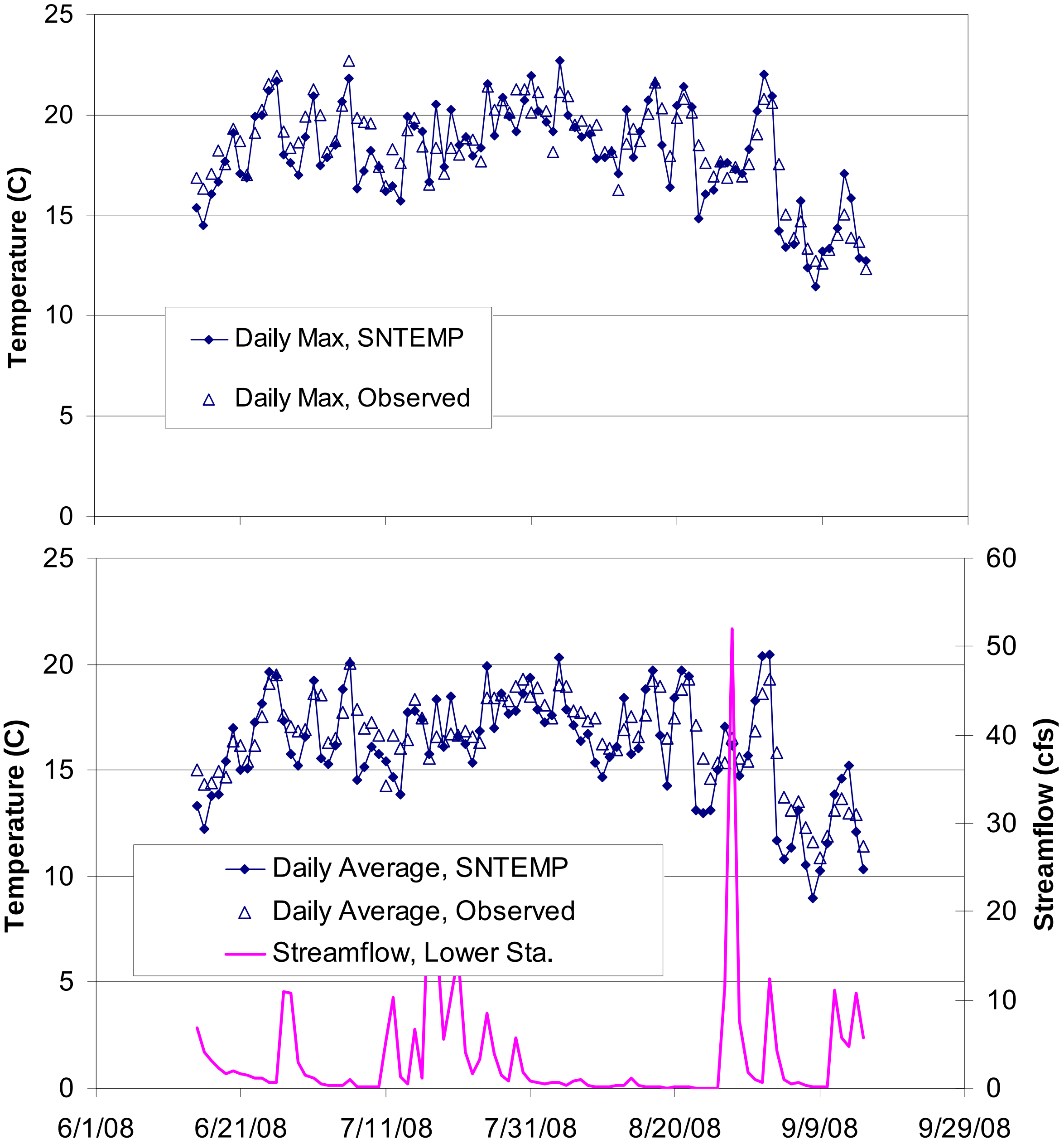


Figure 3.11. Simulated and observed daily maximum (upper panel) and daily average (lower panel) stream temperatures of Miller Creek at Lake Superior College. Simulations were performed with the SNTEMP model Version 2. The RMSE for daily maximum and average stream temperatures is 1.2 and 1.4 ºC, respectively. Streamflow at the 26th Ave. gage is given for reference.

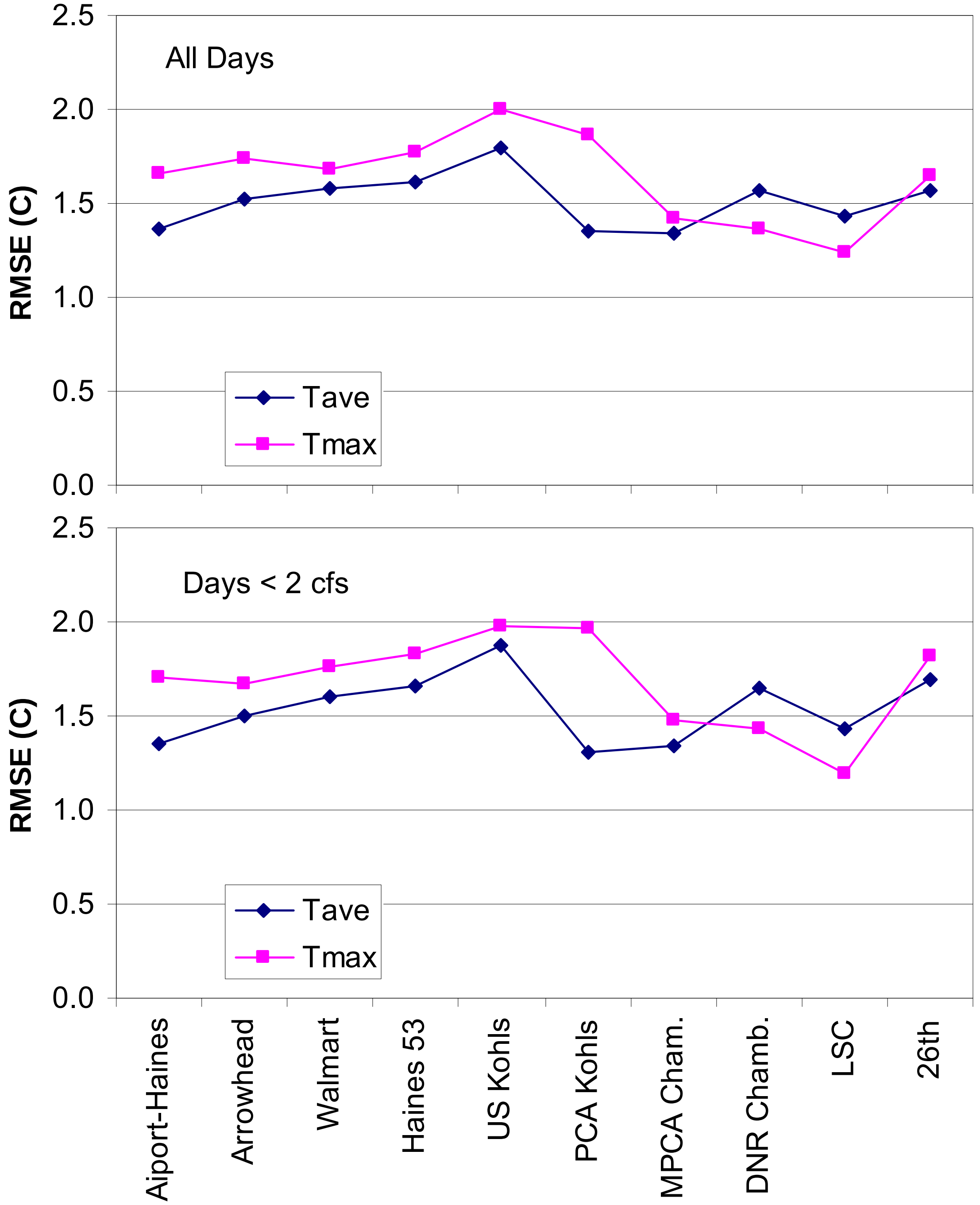


Figure 3.12. Root-mean-square error (RMSE) of the SNTEMP model Version 2 stream temperature simulation at different points in Miller Creek for all days June 15 to Sept. 15 (upper panel) and for days with average flow < 2 cfs (lower panel).

4. Heat inputs to Miller Creek from the atmosphere and stormwater .

The goal of the analysis presented in this section is to estimate the relative magnitudes of point source (stormwater) and non-point source (atmospheric) heat inputs to Miller Creek, which cause the stream temperature to change from the upstream end (Ridgewood) to the downstream end (26th Ave, Figure 4.1). The upstream temperature (T_o) is then the reference temperature for heat input calculations; net positive heat input from the atmosphere or from surface runoff increases stream temperature above the upstream reference temperature. In calculating heat input to a stream in this way, atmospheric and surface runoff heat inputs can be found even for a completely undeveloped stream.

4.1 Stormwater runoff and atmospheric contributions to total heat input for Miller Creek.

The total heat input to a stream can be found from the changes in stream temperature with distance and time, starting at the upstream end. The equation used to calculate net total heat input (H_{tot}, Joules) to a stream reach based on either simulated or observed stream temperatures is:

$$H_{tot} = \rho C_p \, \Delta t \; Q_i \left(T_i - T_o \right) \qquad (4.1)$$

where T_o and T_i are the upstream and downstream temperatures, Q_i is the downstream flow, and Δt is the timestep over which the heat input is calculated, e.g. 1 hour or 1 day. The net heat input (H_{in}) due to lateral inflows (tributaries, stormwater) can be calculated separately as:

$$H_{in} = \rho C_p \, \Delta t \sum_j Q_j \left(T_j - T_o \right) \qquad (4.2)$$

where Q_j and T_j are flow rates and temperatures of all discrete surface inputs upstream of point i. The cumulative upstream atmospheric heat input (H_{atm}) for any point i in the stream can then be found as the difference between H_{tot} and H_{in}:

$$H_{atm} = \rho C_p \, \Delta t \left(Q_i T_i - \sum_j Q_j T \right)_j \qquad (4.3)$$

where Q_j and T_j are flow rate and temperature of the jth inflow. If the calculation is performed using daily average stream temperature, then the resulting heat inputs are also daily average. For this analysis, the simulated stream temperatures, stream flows, and surface runoff inputs associated with the SNTEMP model Version 2 were used for the heat input calculations, since this model should give the most complete representation of surface runoff inputs from the Miller Creek watershed. Heat input calculations were done for the period June 15 to September 15, 2008.

Calculated total heat input, heat input from surface inflow, and atmospheric heat inputs are given in Figure 4.2 for Miller Creek in 2008. Heat inputs are greatest on days with high rainfall and streamflow, and most of the heat energy comes from surface runoff. The streamwise distribution of heat inputs is plotted in Figure 4.3 for a day with high precipitation, in Figure 4.4 for days with low precipitation, and in Figure 4.5 for days with no precipitation.

On a day with high precipitation (June 27, 3.6 cm), heat inputs due to surface inflows dominate atmospheric inputs, and are very high because precipitation and flow are high (40 cfs at the 26th Ave stream flow gage). On this day stream temperatures are mainly determined by runoff temperatures.

On a day with low precipitation (August 3, 0.4 cm), heat inputs due to surface inflows and atmospheric inputs are both important. Runoff temperatures are relatively high (~21 ºC), giving positive heat inputs to the stream, while atmospheric heat transfer has a cooling effect.

On a day with no precipitation (August 21), heat inputs due to surface inflows are zero and atmospheric heat inputs are positive (adding heat to the stream). Note that although stream temperatures are relatively high, heat inputs are relatively small compared to wet days. For low stream flow conditions, very little heat input is required to produce warm temperatures. Total surface inflow and atmospheric heat inputs over 2 week periods are given in Table 4.1 for current conditions.

4.2 Runoff heat inputs by MS4 permits

MS4 stormwater permits have been given to the cities of Duluth and Hermantown plus several smaller stormwater dischargers: The University of Minnesota NRRI, Lake Superior College, MNDOT (State Highway 53), and St. Louis County (county roads). Appropriate runoff volumes and temperatures for the Duluth and Hermantown MS4 permits were estimated in this study as follows:

- Each sub-watershed was placed in the Duluth or Hermantown sub-watershed using GIS.
- For sub-watersheds with areas in both cities, the fraction of impervious area in each city was determined. The total runoff volume for the sub-watershed was then divided between the two cities by the impervious fractions.
- For sub-watersheds with areas in both cities, runoff temperatures for each fraction of runoff were determined based on the amount of high and low intensity impervious areas.

The low and high impervious area classifications include roads. For the MNDOT and St. Louis County MS4 permits, pavement areas and runoff volumes were separately estimated, and these areas and runoff volumes were subtracted from the Duluth and Herman town MS4s. Pavement areas for county and state roads in the watershed were estimated by finding total lengths in GIS and multiplying by width, based on aerial photos. Highway 53 was assumed to be 34 m wide in four lane sections and 16 m wide in 2 lane sections. County roads were assumed to be an average of 20 m wide. With these assumptions, Highway 53 and county roads have total paved areas of 61.5 acres and 88.5 acres, respectively, in the Miller Creek watershed. Road runoff was routed through open vegetated ditches. MINUHET simulations for a 500 x 20 m segment of road with a vegetated ditch (type "C" soil) gave a 22% reduction in runoff volume compared to untreated pavement runoff, but with very similar runoff temperatures to low intensity (residential) development (Table 3.5).

The surface runoff heat loadings were then determined for each MS4 based on the runoff volumes and temperatures for each day. The results are summarized in Table 5.2. NRRI runoff volumes and heat loadings were estimated separately assuming 3800 m^2 of commercial roof area and 10,800 m^2 of pavement, with no stormwater mitigation. Overall, Duluth and Hermantown contribute about 70% and 18%, respectively, of the total heat energy from surface runoff to Miller Creek.

Table 4.1. Two-week average air temperature, total precipitation, total heat input due to atmospheric heat transfer (H_{atm}) and surface runoff (H_{inf}) for Miller Creek for current conditions

Period		Air Temp	Precip	Current Conditions	
Start	Stop	(C)	(cm)	H_{inf} (GJ)	H_{atm} (GJ)
6/15/08	6/30/08	17.66	4.47	1186.35	290.29
7/1/08	7/14/08	18.04	4.99	623.76	88.80
7/15/08	7/31/08	18.41	6.57	773.02	615.65
8/1/08	8/16/08	18.07	1.55	108.57	23.87
8/15/08	8/30/08	17.92	5.82	3361.91	232.61
9/1/08	9/15/08	13.04	5.87	4119.47	-448.15
6/15/08	9/15/08	17.22	29.27	10173.07	803.07

Table 4.2. Two-week average air temperature, total precipitation, total runoff volume, and total heat input due to surface inflows (H_{inf}) for the Duluth., Hermantown, MNDOT, and St. Louis County MS4 permits.

Period		Air Temp	Precip	Duluth		Hermantown	
Start	Stop	(C)	(cm)	Volume (10^4 m^3)	H_{inf} (GJ)	Volume (10^4 m^3)	H_{inf} (GJ)
6/15/08	6/30/08	17.66	4.47	7.51	757.48	3.18	185.79
7/1/08	7/14/08	18.04	4.99	4.34	405.29	1.87	95.36
7/15/08	7/31/08	18.41	6.57	11.68	318.97	4.43	61.48
8/1/08	8/16/08	18.07	1.55	1.11	78.84	0.86	32.80
8/15/08	8/30/08	17.92	5.82	15.56	2224.86	5.30	649.49
9/1/08	9/15/08	13.04	5.87	17.19	3065.58	5.21	747.35
6/15/08	9/15/08	17.22	29.27	57.38	6851.01	20.86	1772.27

Period		MDOT		St. Louis County		NRRI	
Start	Stop	Volume (10^4 m^3)	H_{inf} (GJ)	Volume (10^4 m^3)	H_{inf} (GJ)	Volume (10^4 m^3)	H_{inf} (GJ)
6/15/08	6/30/08	0.69	78.65	0.99	113.08	0.05	5.64
7/1/08	7/14/08	0.51	40.93	0.73	58.85	0.03	3.78
7/15/08	7/31/08	1.51	137.17	2.17	197.22	0.09	10.69
8/1/08	8/16/08	0.00	0.00	0.00	0.00	0.01	1.05
8/15/08	8/30/08	1.09	145.38	1.57	209.02	0.07	10.10
9/1/08	9/15/08	0.65	76.41	0.94	109.86	0.06	7.46
6/15/08	9/15/08	4.44	478.55	6.39	688.03	0.32	38.73

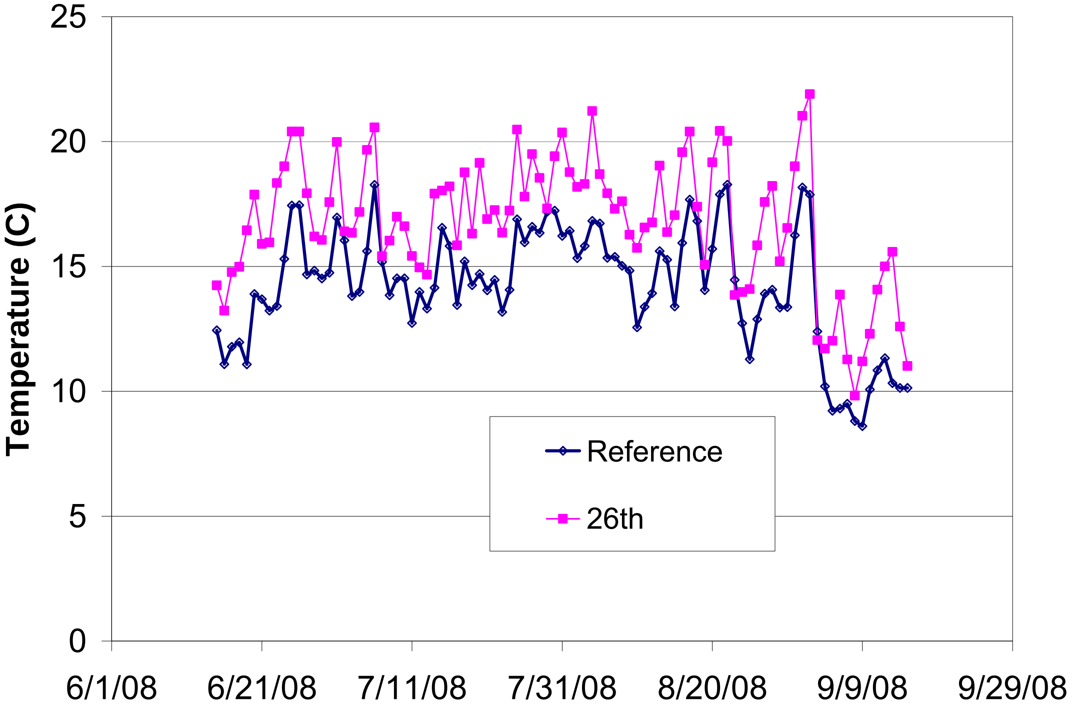


Figure 4.1. Daily average temperature at the upstream end of Miller Creek (Ridgewood monitoring point) and the downstream monitoring point (26thAve).

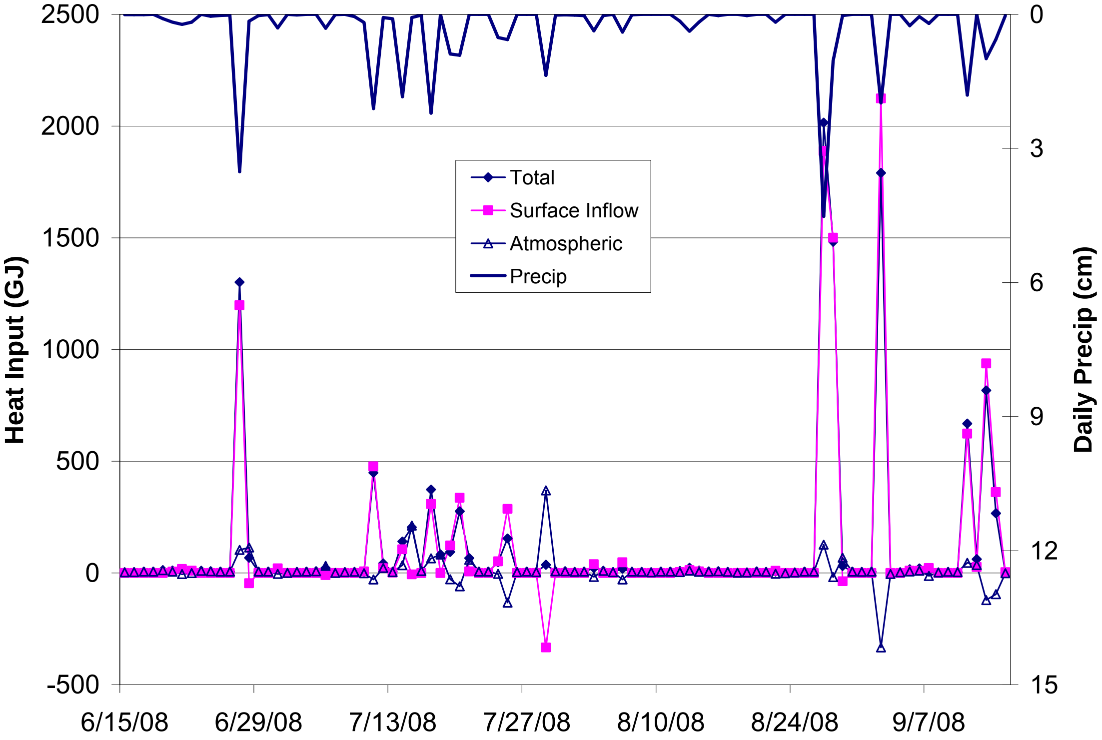


Figure 4.2. Daily total heat input summed over Miller Creek from Ridgewood to 26th Ave, in units of GJ (10^9 Joules).

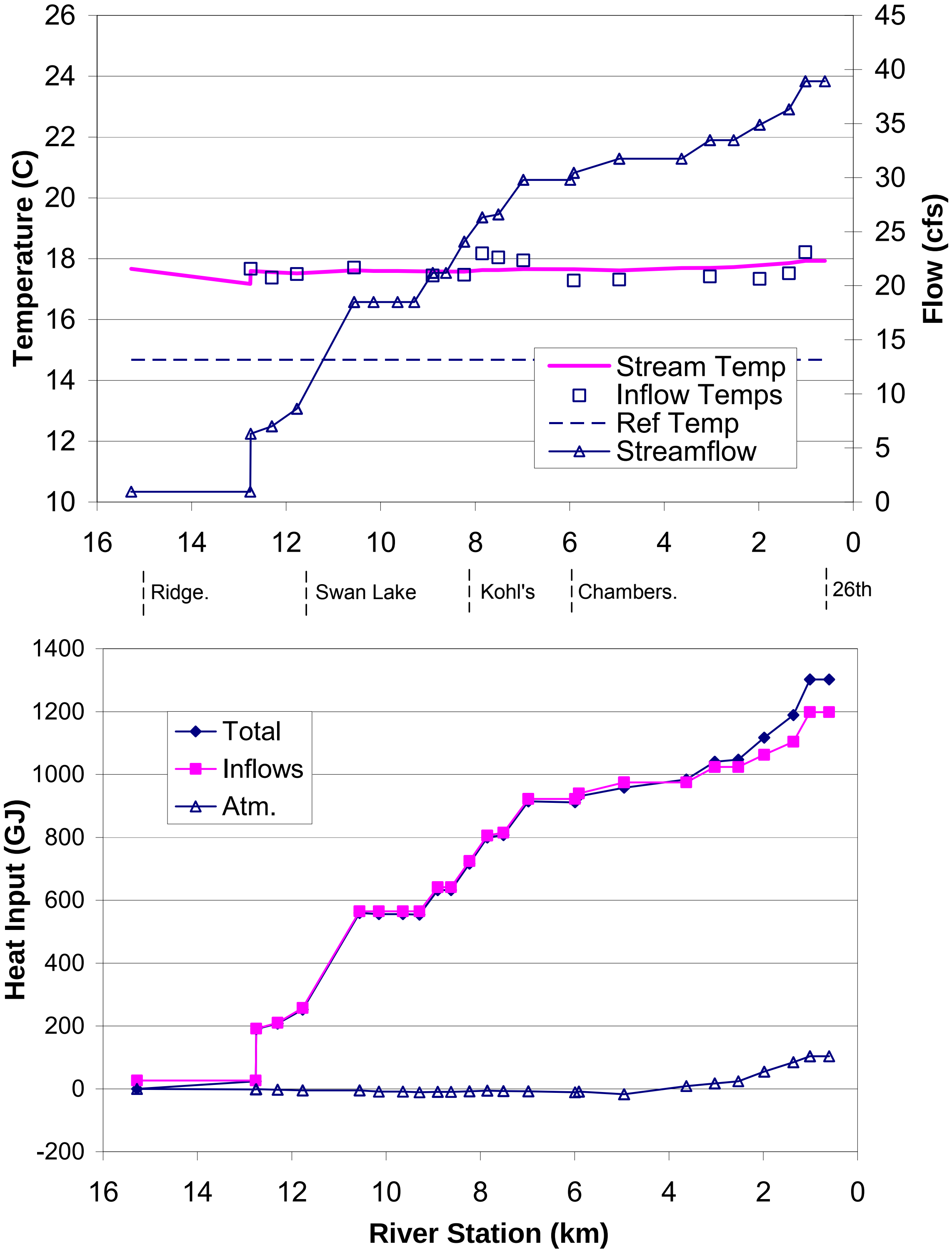


Figure 4.3. Cumulative heat input over distance (lower panel) and streamwise distribution of stream flow and stream temperature (upper panel) for Miller Creek on a day (June 27, 2008) with high precipitation (3.6 cm).

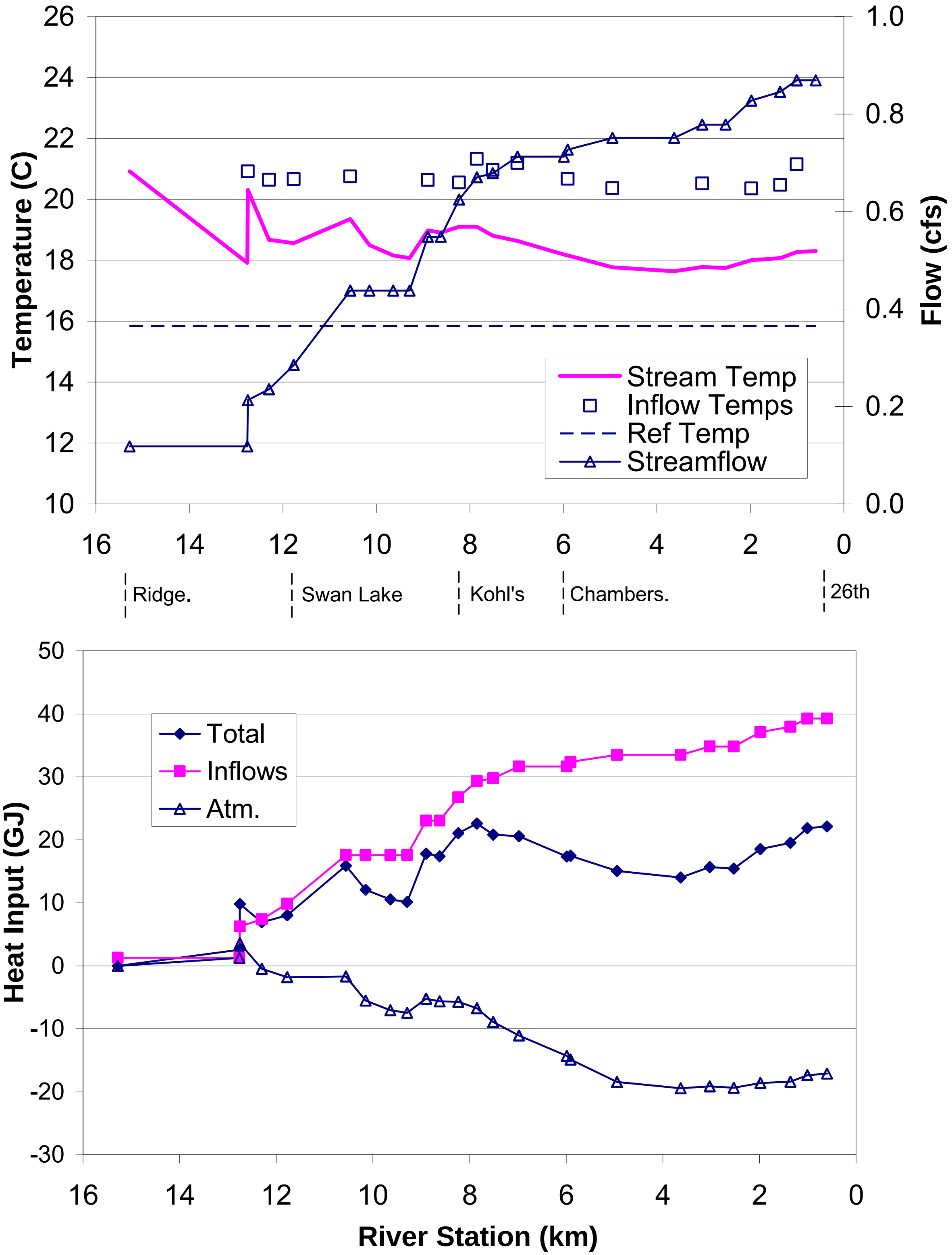


Figure 4.4. Cumulative heat input (lower panel) and stream flow and stream temperature (upper panel) over distance for Miller Creek on a day (Aug 3, 2008) with low rainfall (0.4 cm) that produced warm surface runoff.

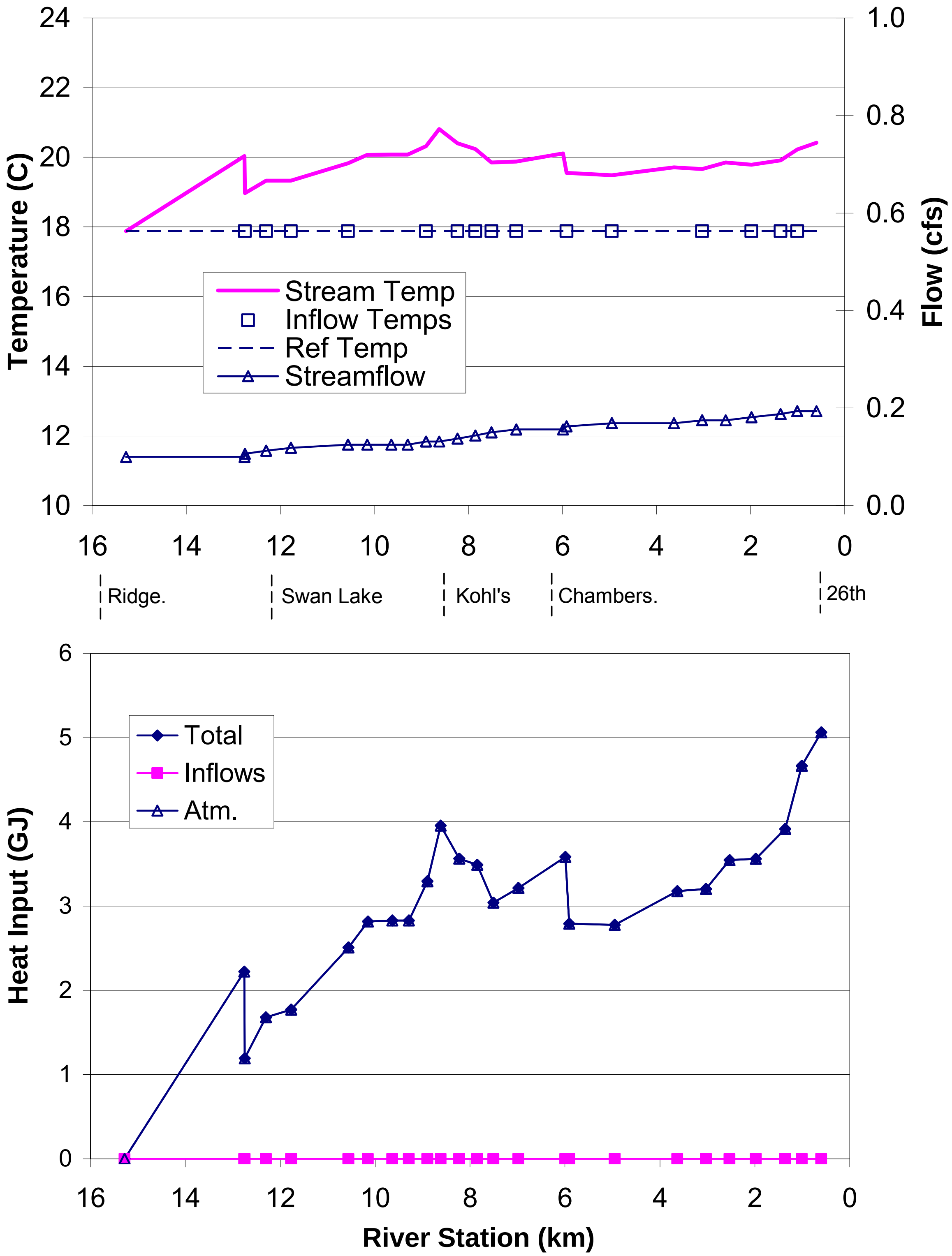


Figure 4.5. Cumulative heat input (lower panel) and stream flow and temperature (upper panel) over distance for Miller Creek on a dry day (August 21, 2008). Since there is no runoff, the total and atmospheric heat inputs are identical.

5. Temperature mitigation for Miller Creek

Two methods for temperature mitigation have been explored: increased riparian shading and stormwater best management practices.

5.1 Effect of stormwater management on heat loading and stream temperature

Stormwater management techniques explored here can be categorized into rate and volume controls. Rate controls include wet detention ponds and underground storage vaults. Previously developed models for these devices were used to quantify their effect on stormwater flow rates and temperatures. Temperature and level observations taken by the South St. Louis SWCD at several sites with stormwater BMPs (stormwater best management practices) in the Miller Creek watershed were available from 2008 to help verify the model results. Stormwater heat input calculations were made at a 1-day time scale, but some information was also obtained for shorter time scales (15 minutes) to evaluate the effect of stormwater on peak stream temperatures. Overall, it was found that heat inputs can be characterized at daily time scales, as described in Appendix II.

Stormwater rate controls, e.g. wet ponds, can reduce heat loading by reducing the peak flow rate. Some change in temperature can also be expected and explored with models and temperature observations. The outlet structure type (surface outlet, bottom outlet) influences pond outlet temperature. Some wet ponds can been installed in the Miller Creek watershed with bottom outlets as a temperature mitigation measure. A MINUHET model for a 0.5 acre wet pond with a bottom outlet was assembled and run using Duluth climate data for the period June 1, 2008 to Sep 15, 2008. Observed inlet and bottom temperatures from this MNDOT pond were available for comparison for the period Aug 1, 2008 to Aug 12, 2009. The observed inlet temperatures are 1 to 2ºC lower than the simulated pond surface temperatures (Figure 5.1). Since the temperature logger was not mounted near the center of the pond, edge shading may have led to the lower observed temperature. The observed and simulated outlet temperatures are both close to 20ºC for the measurement period.

With some evidence that the MINUHET pond model simulations match observations for Duluth, the entire simulation record was analyzed and compared to similar simulations made for a more standard surface outlet. Impervious runoff inflows were generated from an area of 22 acres, such that the wet pond had a water quality treatment volume corresponding to 1 inch of runoff. For both the surface and bottom outlet cases, the pond outlet had a diameter of 0.15 m (6 in) that gave approximately a 24 hour drawdown time. Daily time series of inflow (runoff) temperature and outflow temperature for surface and bottom outlets are given in Figure 5.2. The bottom outlet gives lower temperatures mainly for days with precipitation less than 1 cm (Figure 5.3). When averaged over 2-week periods, the bottom outlet temperature is 0.08 to 1.2 ºC lower than the surface outlet temperature (Table 5.1). Note, however, that the pond bottom outlet temperature, averaged over the entire period (June 15 to Sep 15, 2008) is nearly equal to the inlet temperature. The heat energies associated with the inflows and outflows were also calculated using a seasonally varying wetland reference temperature (Figure 4.1). Overall, the surface outlet ponds added more heat energy to the runoff (297 GJ to 410 GJ) compared to the bottom outlet pond (297 GJ to 354 GJ) (Table 5.2).

Heat energies calculated at daily and longer time scales do not consider the reductions in peak runoff rate and heat export rate afforded by the detention ponds. Figure 5.4 plots time series of simulated 15-minute heat export rates for untreated runoff and outflows from detention ponds with surface and bottom outlets. The peak heat export rates for both ponds are lower than the untreated runoff, due to the reduction in peak runoff rate.

An example of the changes in stream temperature associated with treated or untreated runoff are given in Figure 5.5; the runoff is assumed to enter Miller Creek at the Kohl's site. The temperatures for the treated runoff are substantially reduced compared to the untreated runoff. However, the treated runoff gives temperature changes of longer duration, reflecting the slow release of water from a detention pond.

Underground stormwater vaults are expected to have temperature mitigation properties similar to wet ponds, because they also provide a rate control. Vaults designed with substantial long term retention of water may have an advantage over wet ponds, because the retained water may be cooler, on average, than surface water retained in a wet pond. To examine the effect of a stormwater vault on heat export, a model was constructed and calibrated based on 2008 data from the Gander Mountain facility in the Miller Creek watershed (Appendix III). The stormwater vault at Gander Mountain has a 0.18 acre wet pond for pre-treatment.

The simulated response of the stormwater vault at the Gander Mountain facility shows that some temperature and heat mitigation is obtained. Overall, the temperature of standing water in the vault is similar to the temperature at the pond bottom (Figure 5.6). Note that the vault temperature gets relatively warm later in the year, due to the delayed response of soil temperatures to seasonal heating. The daily average outflow temperatures from the vault were lower than the pond outflow temperatures, by up to several degrees for smaller rainfall amounts (Figure 5.7). When averaged over 2-week periods, the vault heat outflows were lower than those of the pond in June through August, but slightly higher in September (Table 5.3).

Volume controls, e.g. infiltration practices, give direct reductions in heat loading by reducing runoff volume. The effect of adding infiltration capacity equal to 1 inch of runoff was investigated. A model for an infiltration basin was added to the previously studied commercial parking lot with a wet pond, since wet ponds are usually used as pre-treatment for infiltration basins. The infiltration basin has an area of 4.3 acres and an assumed infiltration rate of 8.3 cm/day. The wet pond and infiltration basin designs are based on a treatment system designed for a commercial site in Hastings, MN (Herb 2008).

The infiltration pond provided substantial reductions in heat loading, mainly by reducing runoff volume (Table 5.2). The infiltration pond only discharged on August 28 and 29, 2008, after daily precipitation totals of 3.0 and 1.1 cm on August 27 and 28, 2008, respectively. For most rainfall events, the infiltration capacity was not exceeded, and no flow or heat discharged from the pond. Note that the effect of underdrains has not been considered.

Table 5.1. Summary of inflow and outflow temperatures for various stormwater BMPs over 2-week periods (6/15/08-9/15/08).

Period	Total Precip (cm)	T_a (C)	Average Temperature (^{o}C)			
			Untreated Runoff	Surface Outflow	Bottom Outflow	Vault Outflow
6/15 – 6/30	2.54	17.48	18.06	18.62	18.38	18.22
7/1 – 7/15	3.07	18.05	16.78	17.05	16.98	16.76
7/15-7/31	8.18	18.42	17.93	19.47	18.36	18.38
8/1 – 8/15	1.45	18.18	20.35	21.15	19.93	20.28
8/15 – 9/1	4.72	17.63	17.51	18.20	17.63	17.91
9/1 – 9/15	3.86	13.82	17.71	17.40	17.20	18.11
6/15 - 9/15	23.83	17.26	18.06	18.65	18.08	18.28

Table 5.2. Summary of inflow and outflow volumes and heat energies over 2-week periods, (6/15/08-9/15/08), for a hypothetical wet pond and infiltration pond treatment system. The heat energies were calculated using the seasonally varying wetland reference temperature.

Period	Total Volume (m^3)			Total Heat (GJ)			
	Untreated Runoff	Pond Outflow	Infiltration Outflow	Untreated Runoff	Pond Surface Outflow	Pond Bottom Outflow	Infiltration Outflow
6/15 – 6/30	3525.8	3485.8	0.0	41.01	59.54	56.03	0.00
7/1 – 7/15	2528.5	2179.4	0.0	29.11	29.25	28.59	0.00
7/15-7/31	6541.6	6832.4	0.0	81.80	123.95	91.92	0.00
8/1 – 8/15	645.5	520.2	0.0	12.62	12.19	9.55	0.00
8/15 – 9/1	5148.0	5138.8	938.3	72.64	99.74	87.28	8.91
9/1 – 9/15	4542.6	4398.2	0.0	60.07	84.94	81.13	0.00
6/15 - 9/15	22932.1	22554.8	938.3	297.27	409.59	354.51	8.91

Table 5.3. Summary of untreated runoff, wet pond outflow, and stormwater vault heat energy outputs over 2-week periods for the Gander Mountain treatment facility. Mean Duluth air temperature (T_a) is also given. The heat energies were calculated using the seasonally varying wetland reference temperature.

Period	Total Precip (cm)	Total Heat (GJ)		
		Untreated Runoff	Pond Outflow	Vault Outflow
6/15 – 6/30	2.54	16.04	89.43	15.69
7/1 – 7/15	3.07	11.07	24.51	8.34
7/15-7/31	8.18	33.99	81.60	36.95
8/1 – 8/15	1.45	5.23	5.07	4.54
8/15 – 9/1	4.72	30.72	131.39	31.09
9/1 – 9/15	3.86	25.82	38.73	31.46
6/15 - 9/15	23.83	122.88	370.74	128.07

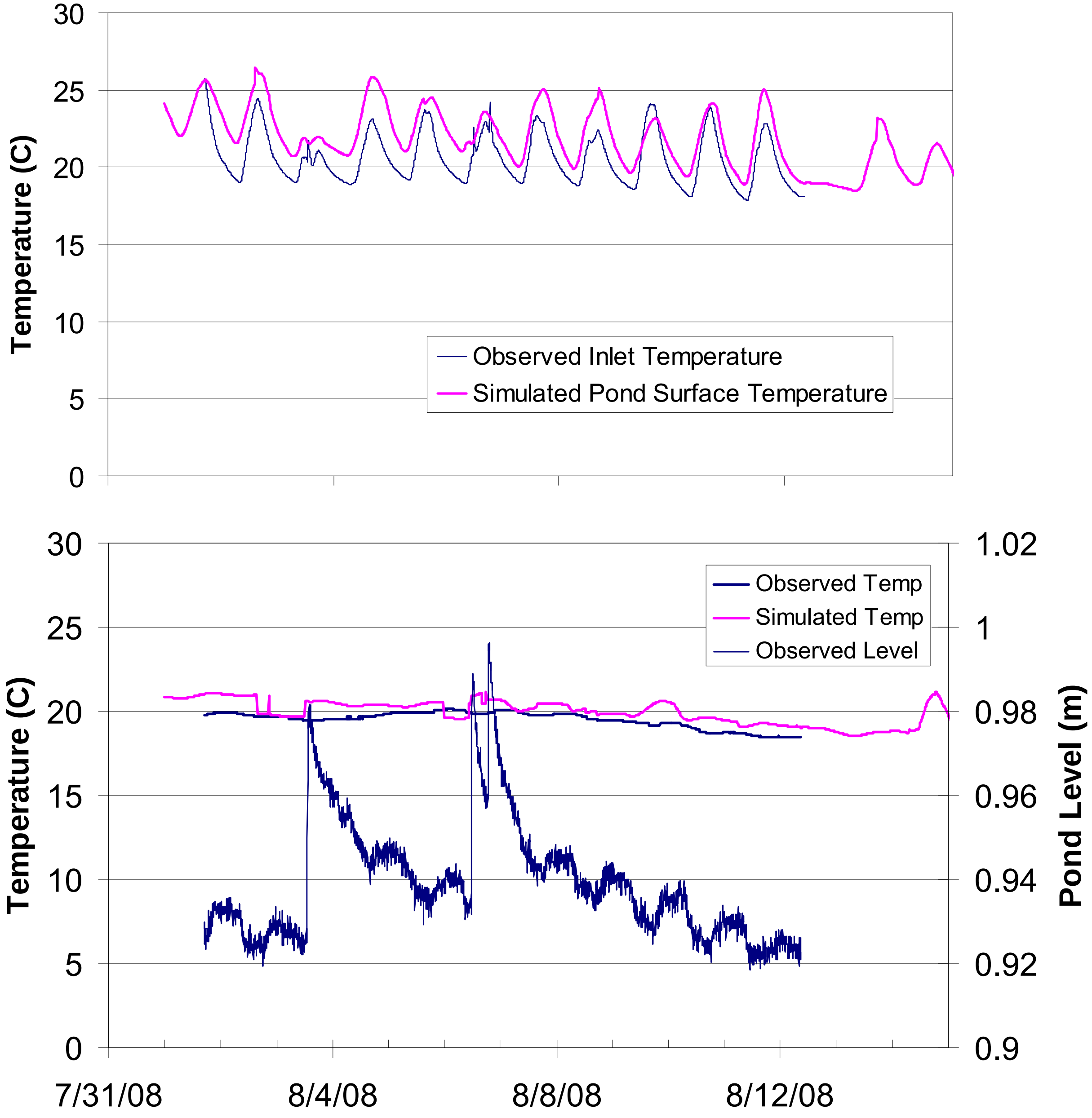


Figure 5.1. Simulated and observed inlet temperature (upper panel) and outlet temperature (lower panel) for a wet pond with a bottom outlet structure. Temperature and pond level observations taken from the MNDOT pond at Highway 53 and Trinity Rd.

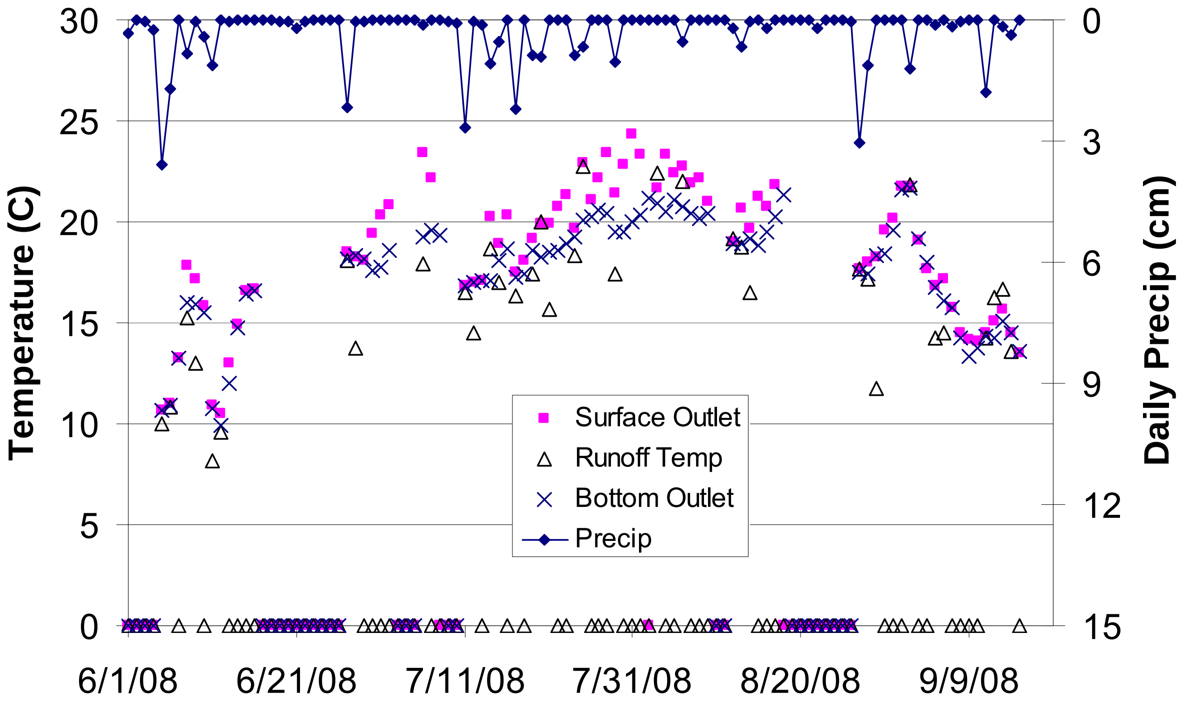


Figure 5.2. Daily inflow (untreated runoff) and outlet temperatures for ponds with surface and bottom outlets. Temperatures are only plotted on days with precipitation, plotted on the right axis.

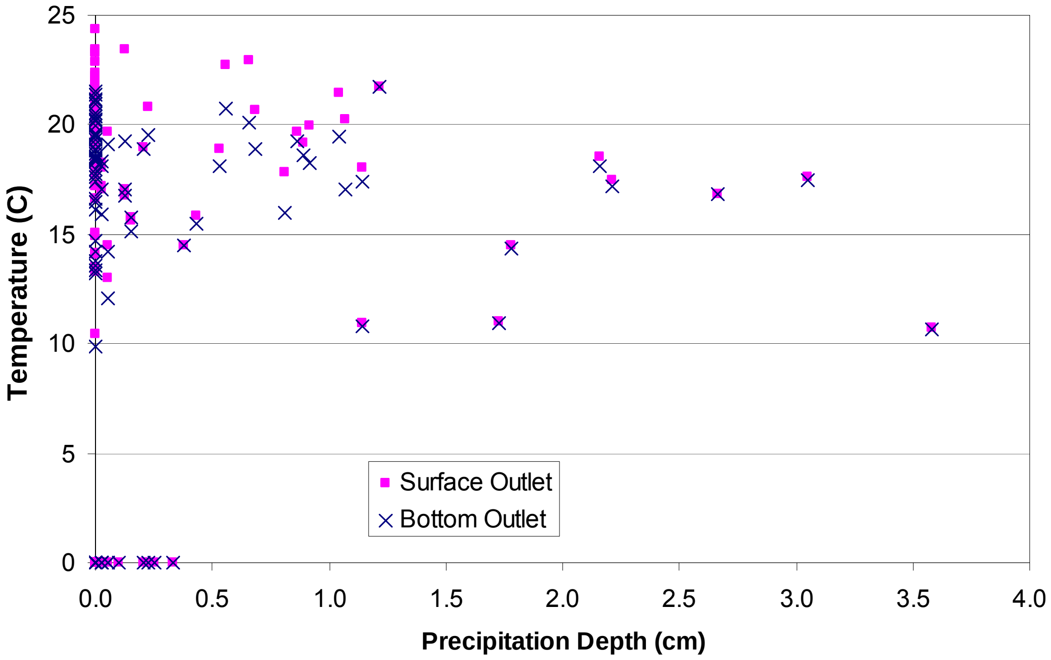


Figure 5.3. Daily pond outlet temperatures vs. precipitation depth for ponds with surface and bottom outlets, 2008.

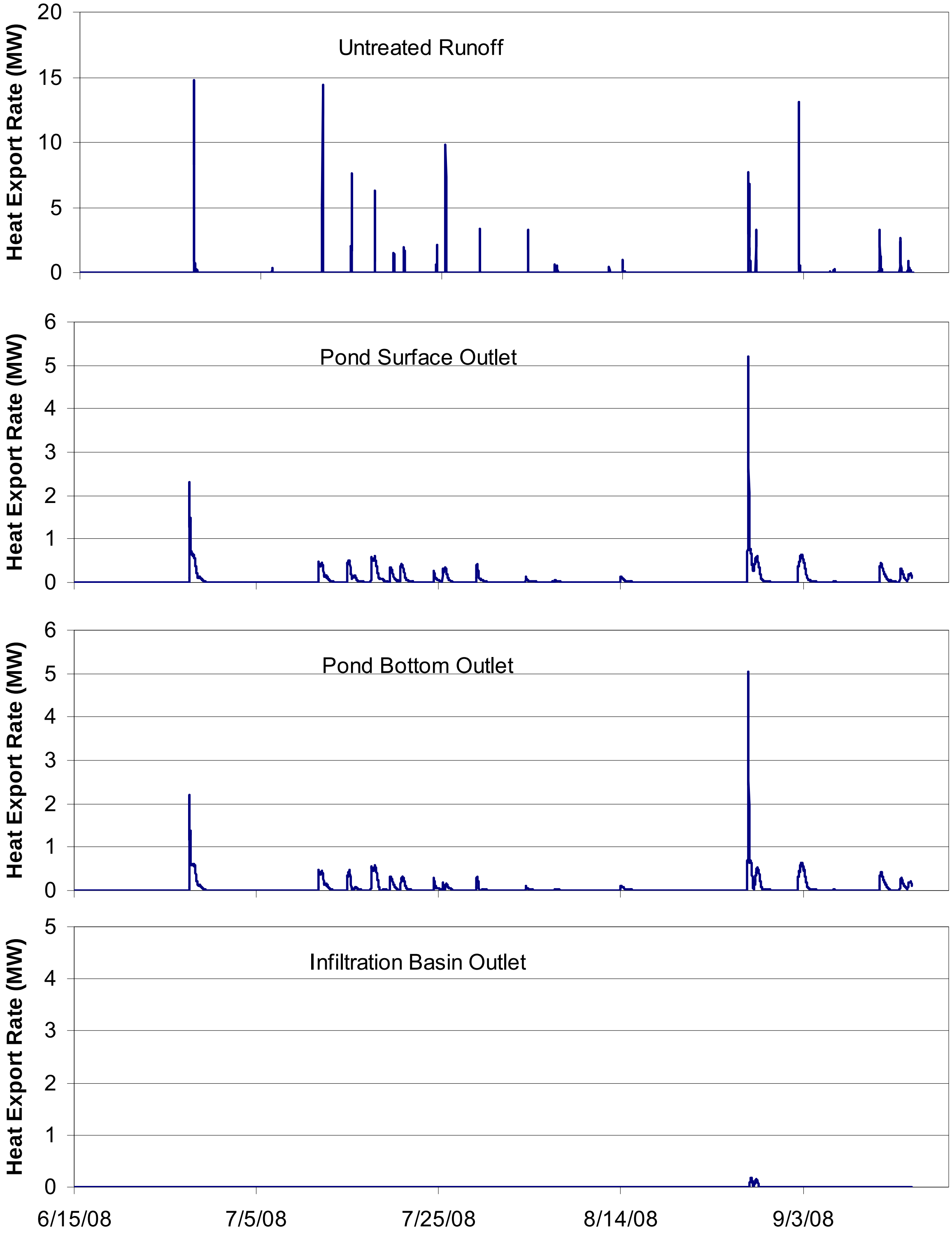


Figure 5.4. Heat export rate (MW = 10^6 Watts) at 15-minute resolution for untreated runoff and outflow from detention pond with surface or bottom outlet, and for the outflow from a infiltration basin with wet pond pre-treatment.

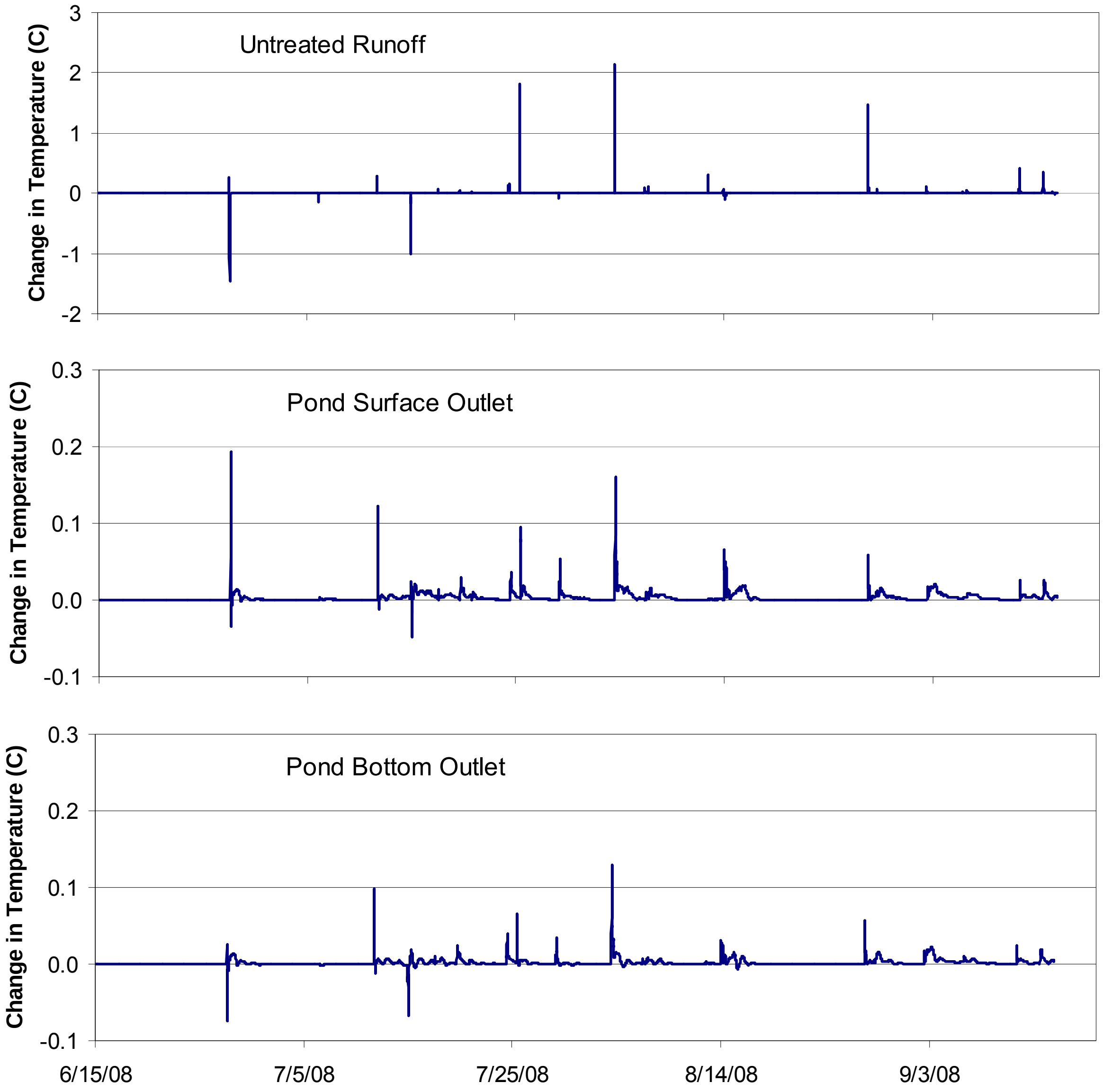


Figure 5.5. Local change in stream temperature at 15-minute resolution for untreated runoff and the outflow from detention ponds with surface and bottom outlets. Simulated runoff flows and temperatures mixed with observed temperatures and estimated flows at the Kohl's site.

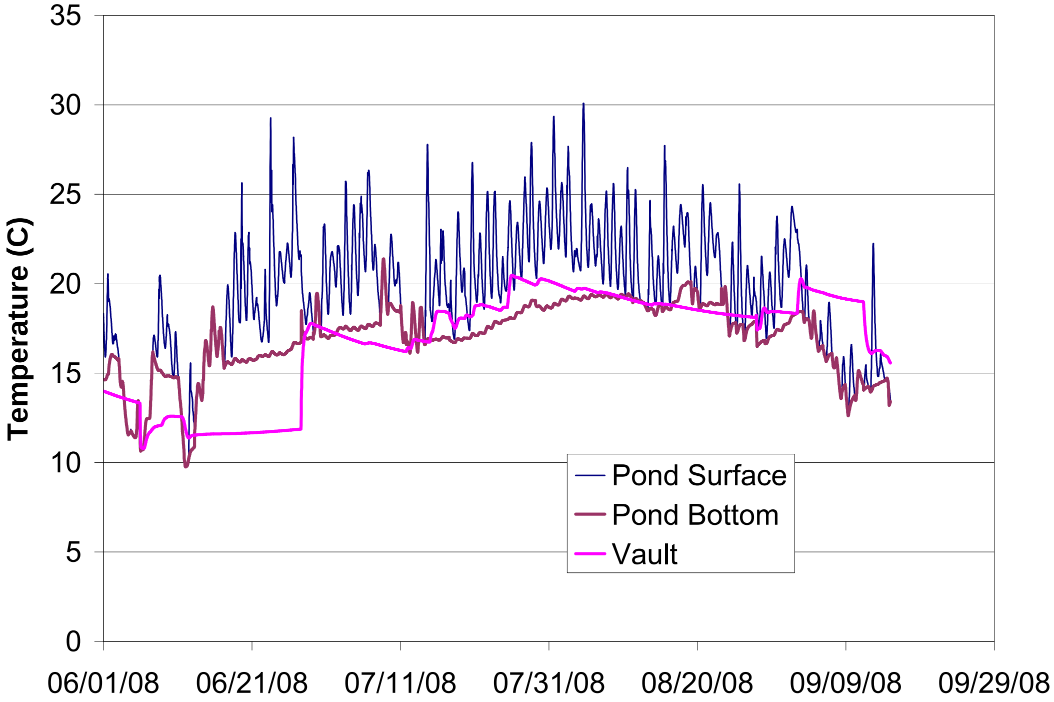


Figure 5.6. Simulated temperatures at the surface and the bottom of a wet detention pond and for standing water in a stormwater vault.

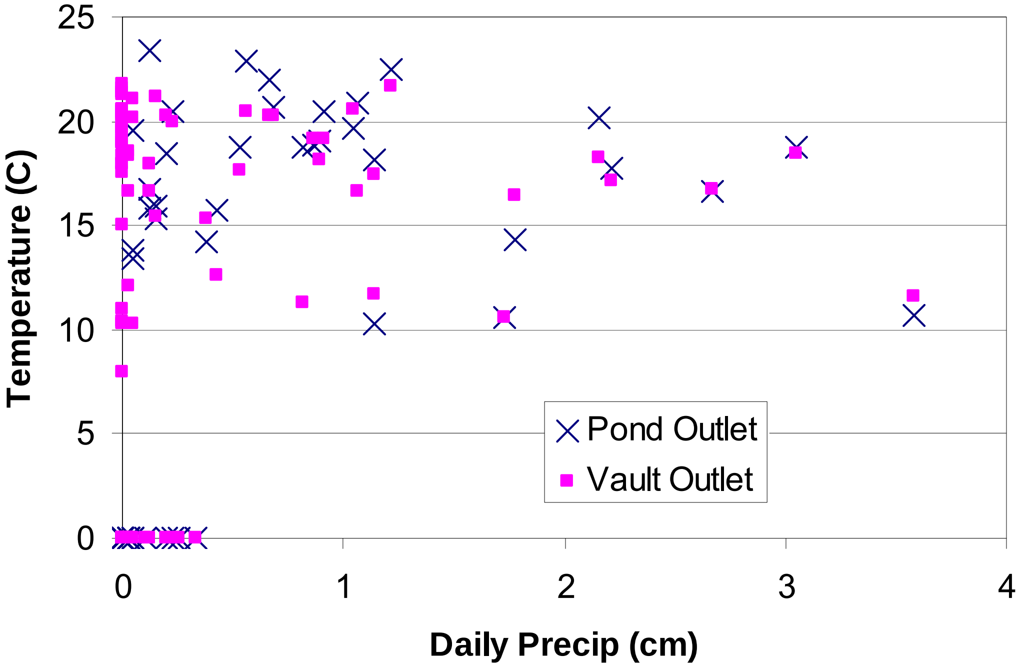


Figure 5.7. Simulated daily pond and stormwater vault outlet temperatures at the Gander Mountain facility vs. daily precipitation.

5.2 Stream temperature mitigation by increased riparian shading

Riparian shading by tree canopies or bushes or instream shading by emergent vegetation can be expected to reduce stream temperatures, mainly by blocking solar radiation from reaching the water surface. To investigate the potential stream temperature reduction by increased shading, the SNTEMP version 1 stream temperature model described in Section 3.2 was run for three riparian shading scenarios:

Scenario1: shading in upper part of watershed (upstream of Kohl's) increased to 0.7
Scenario 2: shading in lower part of watershed (downstream of Kohl's) increased to 0.75
Scenario 3: shading in upper and lower parts of watershed increased to 0.7 and 0.75, respectively.

The distributions of the shading coefficients for current shading and three potential shading scenarios are shown in Figure 5.8. In the upper part of the watershed, shading is largely supplied by tall wetland plants. The calibrated shading coefficients for reaches in Miller Creek in relatively unimpacted wetland areas, e.g. upstream of Arrowhead, was 0.7, and this value was chosen as a target for reaches in impacted wetland areas, e.g. upstream of Kohl's. In the lower part of the watershed (below Kohl's), shading is mainly by trees. The calibrated shading coefficient in relatively wooded reaches of Miller Creek was 0.75, and this value was chosen as a target for the lower part of the watershed. The biggest increases in shading for the potential future scenarios were in the impacted wetland above Kohl's (from 0.35 to 0.7) and the commercialized area between Kohl's and Miller Hill Mall (from 0.65 to 0.75).

The stream temperature simulation results for current shading and the three shading scenarios are shown in Figures 5.9 to 5.14. The plots in Figures 5.8 to 5.14 are from simulations for July and August 2008, which were close to normal for Duluth in air temperature and precipitation (Table 3.1). Figures 5.9 and 5.10 give the streamwise distributions of daily average and daily maximum temperatures, respectively, in July, while Figures 5.11 and 5.12 the same information for August 2008. Increasing the shading upstream of Kohl's (scenario 1) gives substantial reductions in daily maximum temperatures of up to 2 ºC. Reductions in maximum daily temperature persist for about 2 km downstream before the benefit of the shading increase is lost. Shading increases downstream of Kohl's (scenario 2) produce up to 1 ºC reduction in daily maximum stream temperatures. Since shading was not increased from Lake Superior College to 26th Ave., stream temperatures change relatively little in this reach. The mean changes in daily average and daily maximum stream temperatures are summarized in Table 5.4. The changes in atmospheric heat input to the Miller Creek for scenario 3 are given in Table 5.5.

The changes in daily maximum stream temperature are evident in stream temperature duration curves in Figures 5.13 and 5.14 for the Kohl's, Chambersburg, Firestone, and 26th Ave locations. The biggest shifts in the temperature duration curves (Kohl's, Firestone) are downstream of the biggest changes in shading.

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Table 5.4. Simulated average changes in the average and daily maximum stream temperatures for the three shading scenarios for the period from June 15 to September 15, 2008. All stations listed are points on the main stem of Miller Creek.

Station	Scenario 1		Scenario 2		Scenario 3	
	Δ Ave Temp (°C)	Δ Max Temp (°C)	Δ Ave Temp (°C)	Δ Max Temp (°C)	Δ Ave Temp (°C)	Δ Max Temp (°C)
Airport-Haines	0.00	0.00	0.00	0.00	0.00	0.00
Airpark Trib	-0.09	-0.25	0.00	0.00	-0.09	-0.25
Swan Lake	-0.19	-0.48	0.00	0.00	-0.19	-0.48
Wal-mart	-0.16	-0.37	0.00	0.00	-0.16	-0.37
Haines 53	-0.12	-0.11	0.00	0.00	-0.12	-0.11
Kohls Upstream	-0.41	-0.90	0.00	0.00	-0.41	-0.90
PCA Kohls	-0.43	-0.87	0.00	0.00	-0.43	-0.87
Firestone	-0.42	-0.39	-0.04	-0.32	-0.45	-0.71
Chambersburg DNR	-0.21	-0.21	-0.12	-0.37	-0.34	-0.58
LSC	-0.17	-0.12	-0.15	-0.11	-0.32	-0.23
LP10 SW	-0.13	-0.10	-0.12	-0.09	-0.25	-0.20
26th	-0.10	-0.07	-0.09	-0.07	-0.20	-0.14

Table 5.5. Simulated 2-week average atmospheric heat inputs (H_{atm}) to Miller Creek with current shading and for increased shading scenario 3.

Period		H_{atm} (GJ)	
Start	Stop	Current Conditions	Scenario 3
6/15/08	6/30/08	290.29	244.37
7/1/08	7/14/08	88.80	47.85
7/15/08	7/31/08	615.65	501.13
8/1/08	8/16/08	23.87	8.42
8/15/08	8/30/08	232.61	179.66
9/1/08	9/15/08	-448.15	-494.13
6/15/08	9/15/08	803.07	487.30

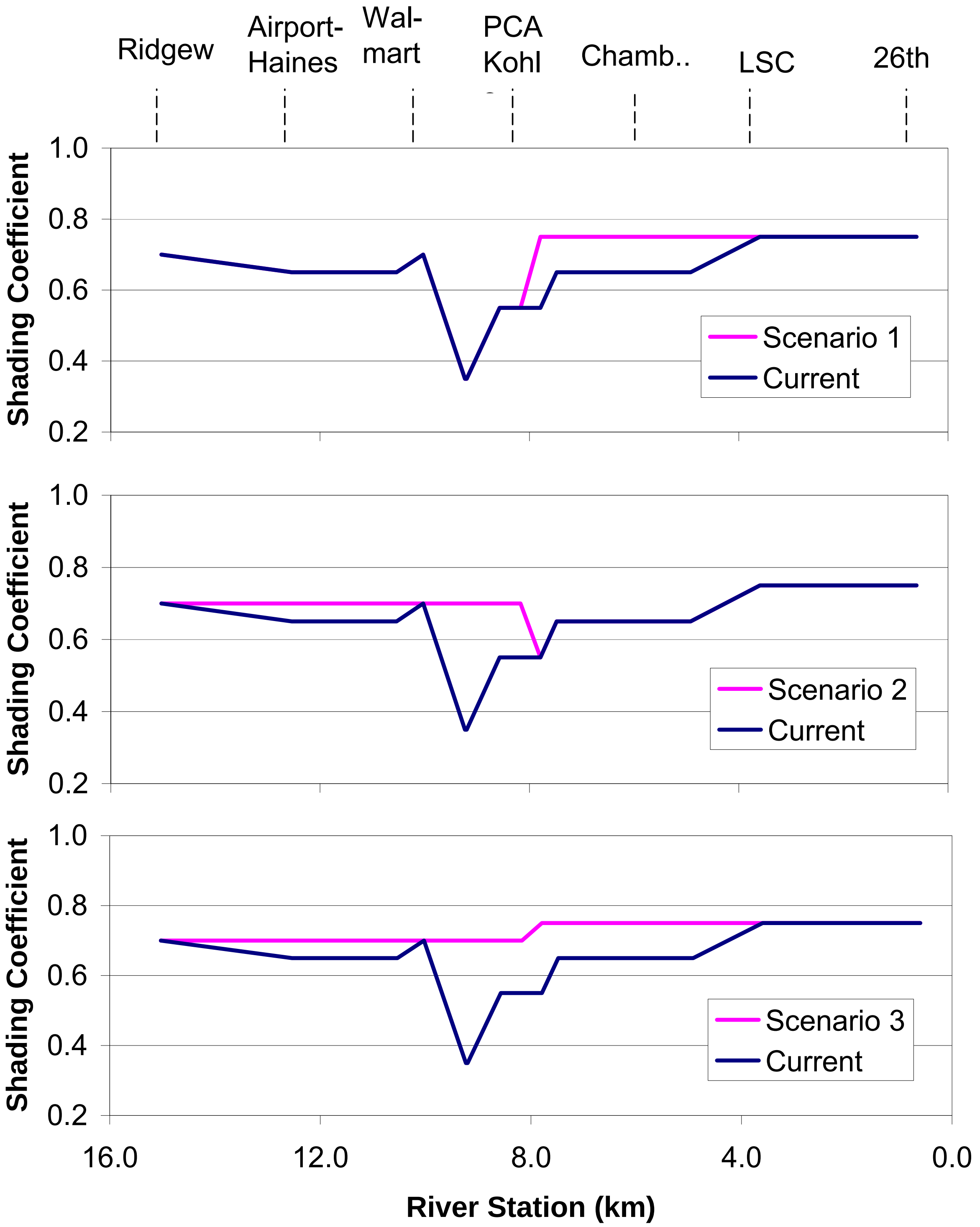

Figure 5.8. Distribution of the shading coefficient for current shading conditions and for three shading scenarios.

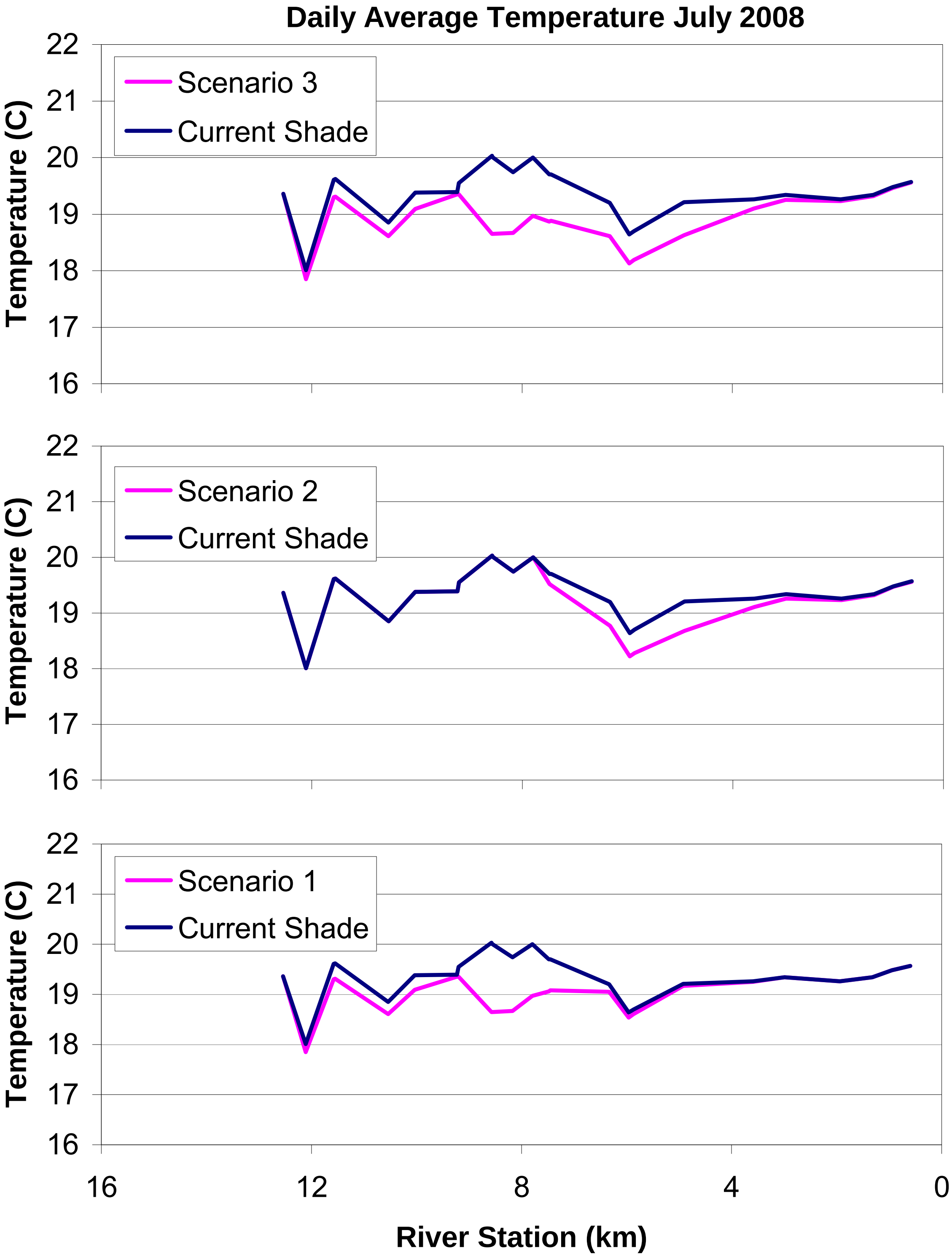

Figure 5.9. Streamwise distribution of daily average stream temperatures for July 2008, for current shading conditions and for three shading scenarios.

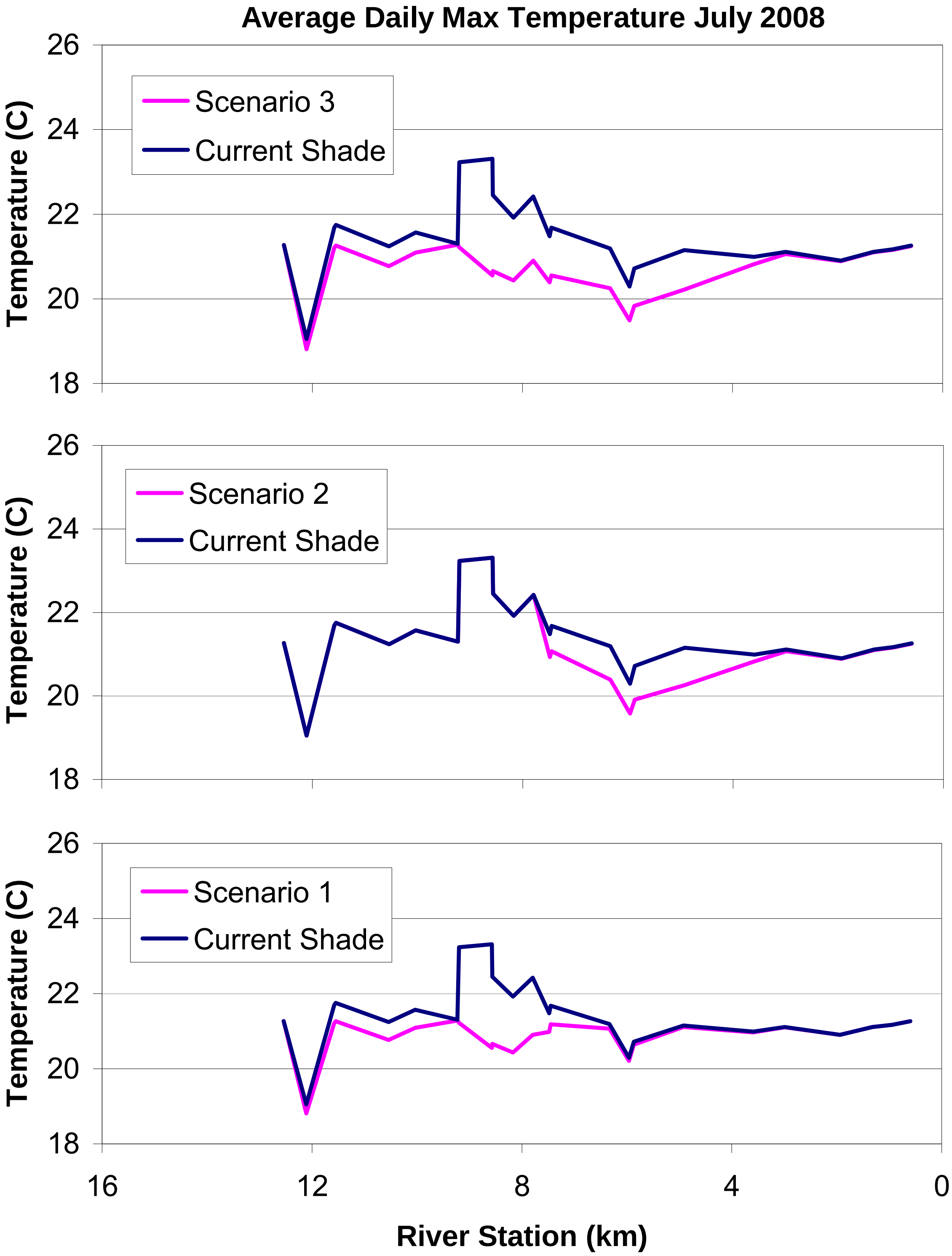

Figure 5.10. Streamwise distribution of average daily maximum stream temperatures for July 2008, for current shading conditions and for three shading scenarios.

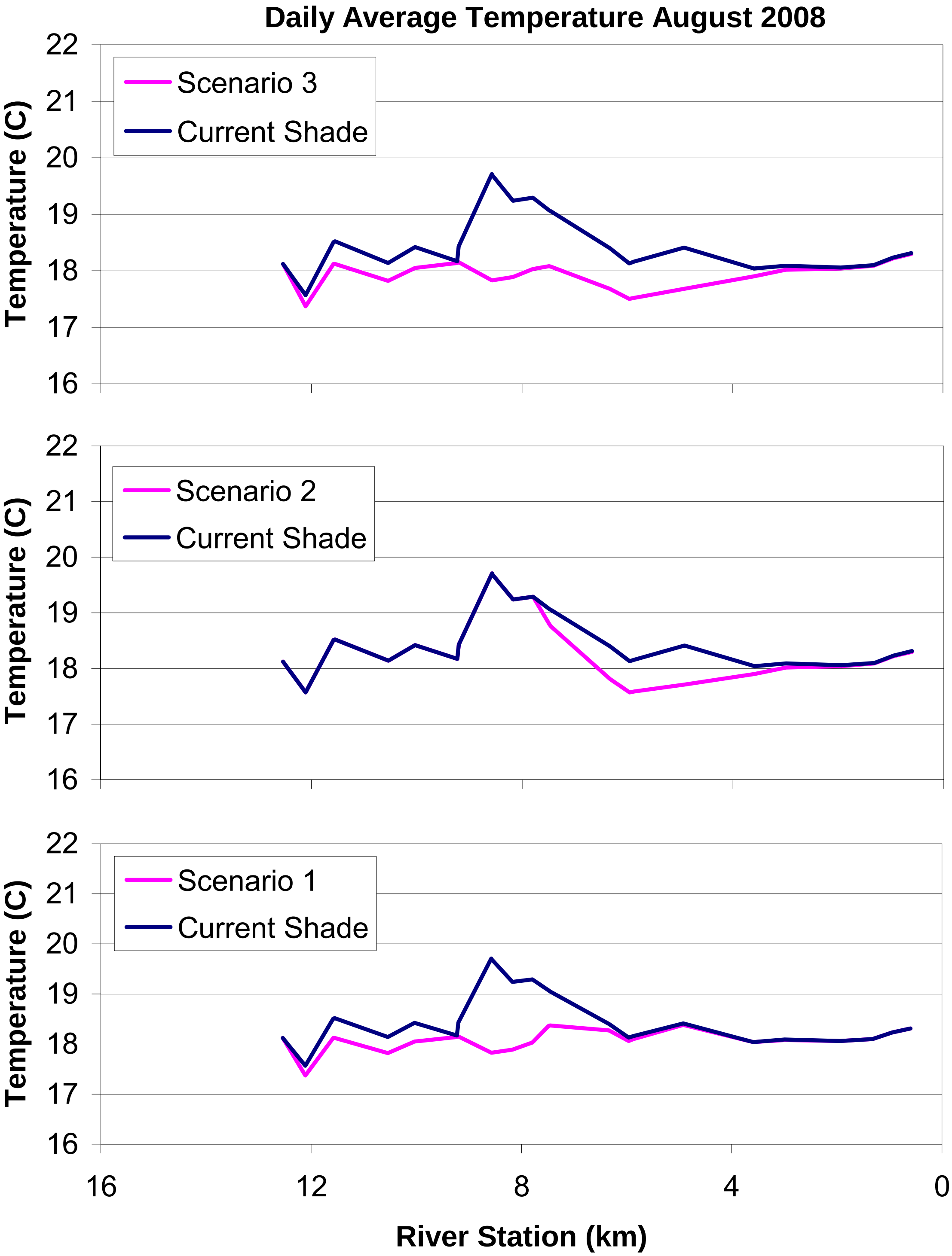

Figure 5.11. Streamwise distribution of daily average stream temperatures for August 2008, for current shading conditions and for three shading scenarios.

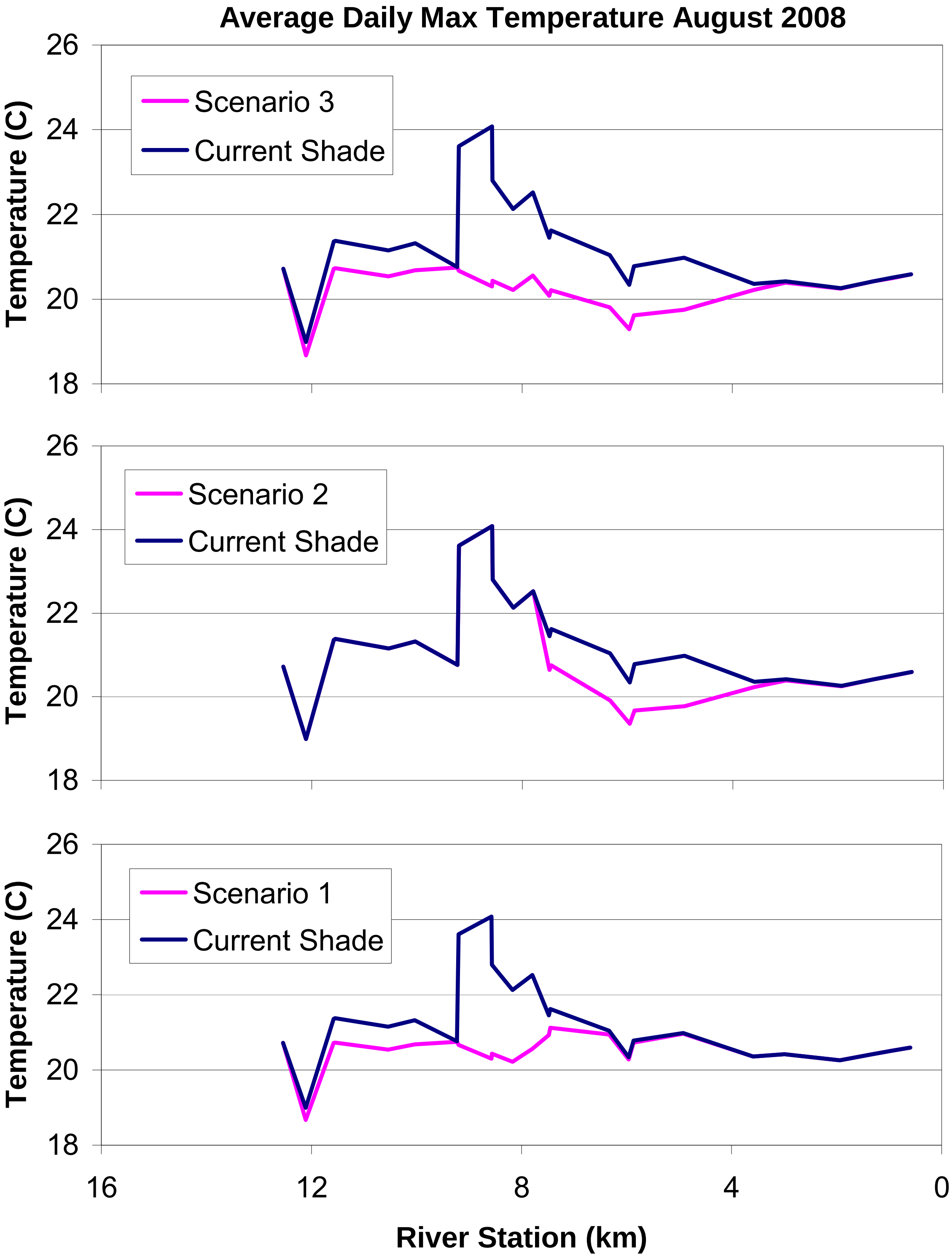

Figure 5.12. Streamwise distribution of average daily maximum stream temperatures for August 2008, for current shading conditions and for three shading scenarios.

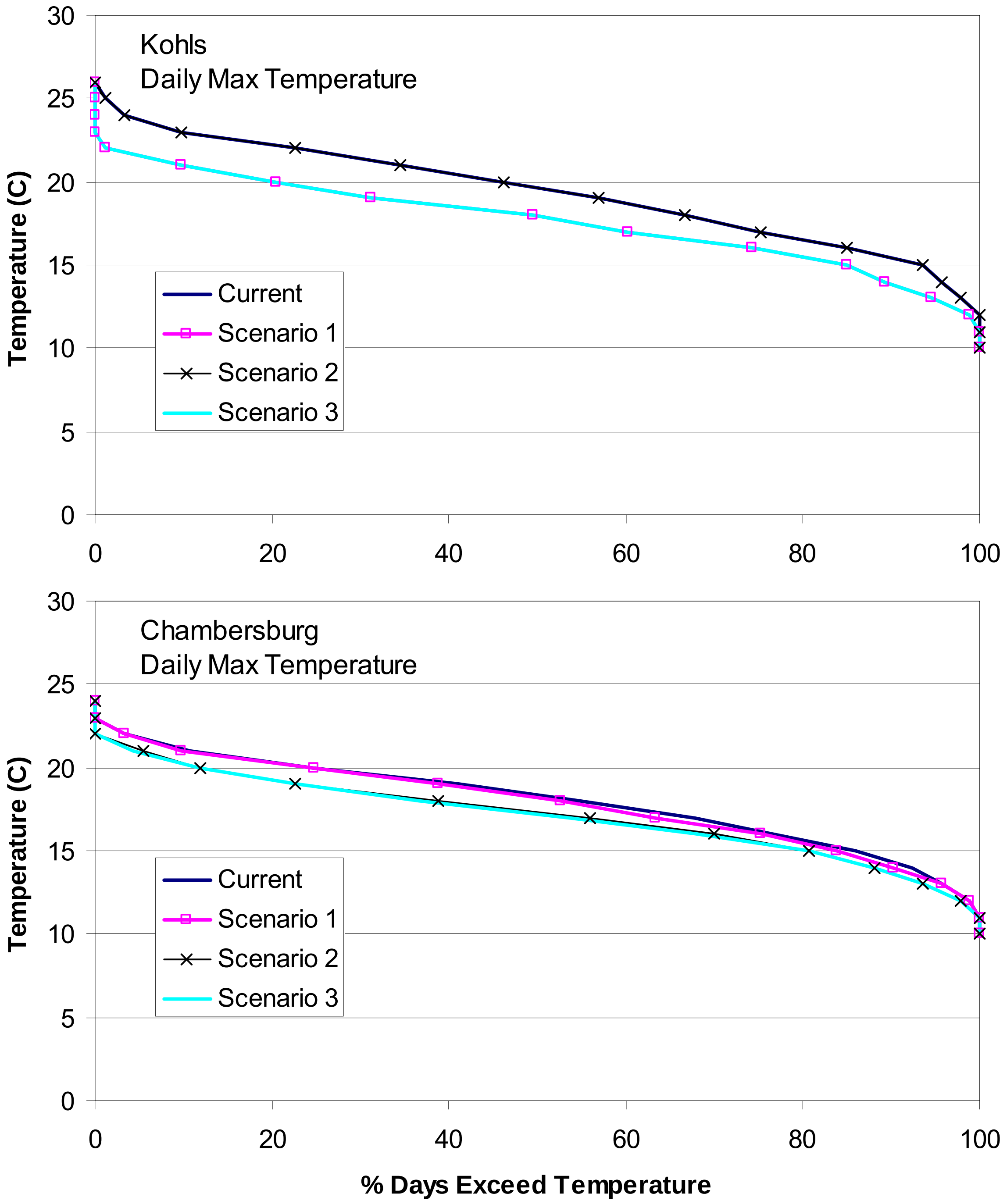

Figure 5.13. Stream temperature duration curves for July 2008 for current shading and three shading scenarios. Sites at Kohl's (upper panel) and Chambersburg (lower panel).

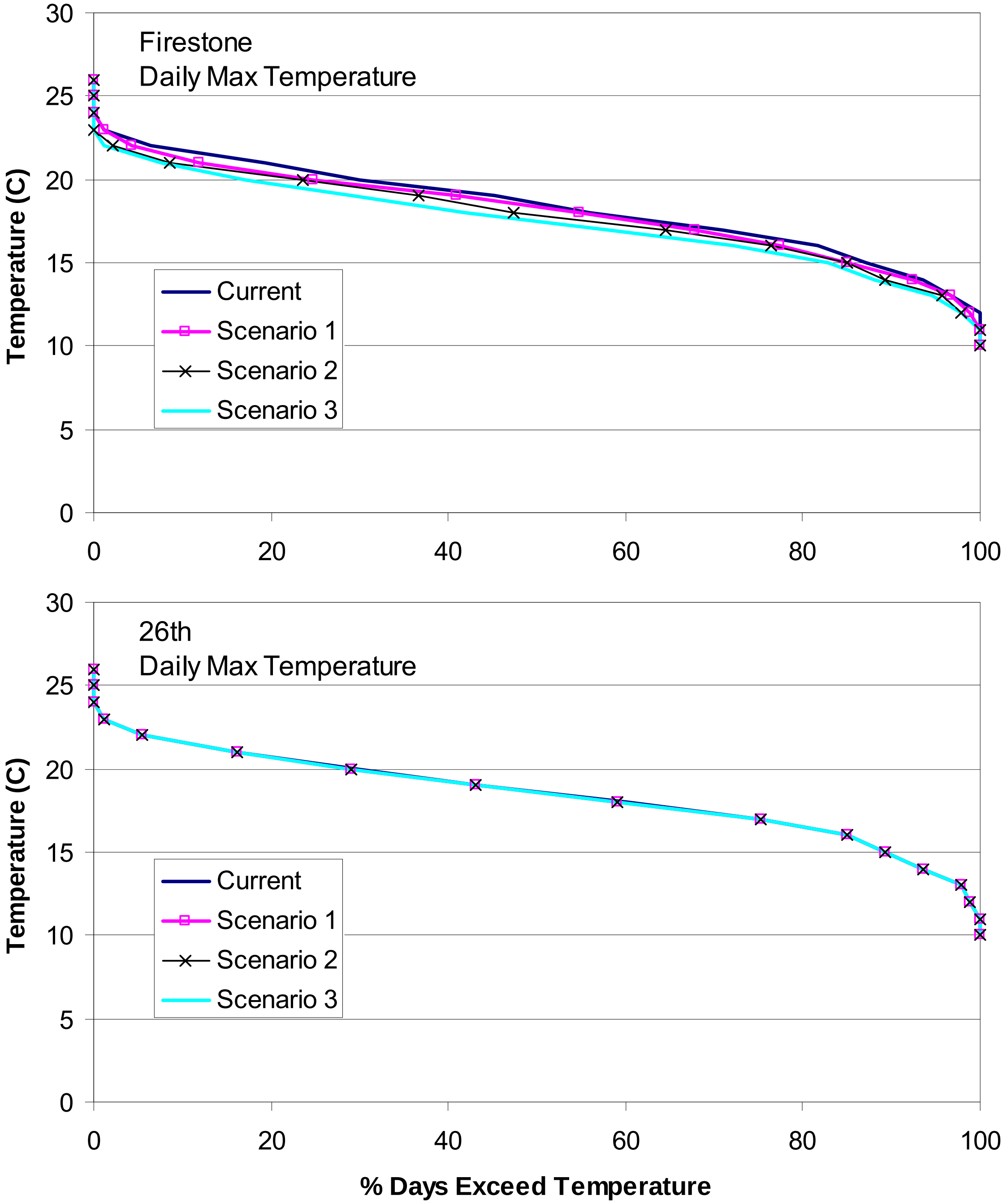

Figure 5.14. Stream temperature duration curves for July 2008 for current shading and three shading scenarios at Firestone (upper panel) and 26th Ave. (lower panel).

6. Conclusions

The results of this temperature and heat simulation study show that the temperature of Miller Creek is driven by atmospheric heat transfer during dry weather periods, by surface runoff during wet weather with substantial runoff, and by both mechanisms during small rainfall events. The increase in atmospheric heat transfer due to reduced shading, especially from the impacted wetland upstream of Kohl's down to Miller Hill Mall, causes maximum daily stream temperatures to increase by up to 1ºC. Temperature changes are most apparent in the stream reaches with low shading, but persist for several kilometers downstream into reaches with higher shading. Stream temperature and heat input reductions in Miller Creek that are attainable by increases in shading have been quantified for several cases, however, actual shading increases possible through channel and vegetation improvements assumed in this study may or may not be achievable. The accuracy of the stream temperature model and the calibrated shading coefficients is limited by 1) limited stream flow information in the upper part of the watershed and 2) limited information on channel geometry in all parts of the watershed.

Atmospheric (non-point source) heat inputs have been quantified, and can lead to high daily maximum temperatures during periods of low flow. Heat inputs due to surface runoff are more difficult to quantify, for the following reasons:
1) They are highly transient in nature.
2) There is still uncertainty on the surficial and subsurface flow paths of water in the receding limb of runoff events (when significant flow may come from stored water in wetland areas or interflow) although the SWMM developed for this study has given some insight on surface runoff routing and subsurface flow contributions.
3) The heat input to Miller Creek by stormwater runoff can be very high on days with high precipitation and runoff volumes, yet may cause relatively little change in stream temperature.
4) There is very little information on the unimpacted pristine condition of the Miller Creek watershed, so that developing a baseline for surface runoff before urban development is difficult.

Although it is difficult to compare heat loading from surface runoff to atmospheric heat loading in Miller Creek, it is, however, possible to estimate reductions in heat loading and stream temperature impact in Miller Creek from surface runoff. From such estimations by simulation it can be concluded that:
1) The reduction in peak flow rate in wet detention ponds leads to reductions in peak stream temperatures, even though integrated over time, wet ponds add heat energy to surface runoff. Compared to untreated runoff, wet pond effluent causes smaller stream temperature changes that have longer durations.
2) The use of bottom outlets in wet detention ponds gives some effluent temperature reduction for smaller rainfall events, e.g. < 1 cm. For larger events, detention ponds become well mixed, the runoff volume becomes a significant fraction of the stored volume, and the outlet structure has little or no impact on effluent temperatures.
3) Underground stormwater vaults (tanks) appear to give a similar benefit to wet ponds with bottom outlets. For small events, the stored water in the tank is often cooler than the runoff, and the vault effluent temperature is lower than the influent. For large events, the stored volume becomes small compared to the total runoff volume, and temperature reductions are minimal.

Further design studies of temperature mitigation by underground vaults of different configurations would be appropriate.
4) Infiltration gives a reduction in runoff volume reducing temperature impacts of runoff. Since infiltration practices in Miller Creek can be limited by low infiltration capacity, widespread implementation of infiltration practices may be difficult.

Stormwater mitigation practices that reduce peak runoff rate in Miller Creek and increase baseflow are of obvious benefit for reducing channel erosion and improving aquatic habitat. However, both the stream temperature models used in this study and previous studies of the relationship of stream temperature to stream flow suggest that increasing baseflow, by itself, will not necessarily lead to reductions in stream temperature.

The temperature of Miller Creek was found to be relatively sensitive to air temperature, i.e. a 1 ºC increase in air temperature led to a 0.6 ºC increase in stream temperature. This sensitivity is likely due to low groundwater inputs, which tend to buffer diurnal and seasonal changes in air temperature. This suggests that Miller Creek, and perhaps North Shore streams in general, may be particularly sensitive to climate change.

Acknowledgements

This study was conducted with support from the Minnesota Pollution Control Agency, St. Paul, Minnesota, with Bruce Wilson as the project officer. Nathan Schroeder of the South St. Louis SWCD provided the streamflow and stream temperature data used in this study, along with substantial technical assistance in interpreting the data. Tom Estabrooks of the Minnesota Pollution Control Agency Duluth office also provided data and other technical assistance for this project. The authors are grateful to these individuals and organizations for their assistance.

References

Dane County, Wisconsin Land and Water Resources Department, 2005. Excel Thermal Model (Temperature Urban Runoff Model (TURM)). Available at http://www.co.dane.wi.us/landconservation/thmodelpg.htm.

Erickson, T.O, W.R. Herb, and H.G. Stefan, 2009. Streamflow Modeling of Miller Creek, Duluth, Minnesota, St. Anthony Falls Laboratory, Project Report No. 536, October 2009, 61 pp.

Herb, William R. and Heinz G. Stefan, 2009a. Analysis of Stream Temperature Data from Miller Creek, Duluth, MN, St. Anthony Falls Laboratory, Project Report No. 529, 52 pp.

Herb, W.R., B. Janke, O. Mohseni and H.G. Stefan, 2009. MINUHET (Minnesota Urban Heat Export Tool): A software tool for the analysis of stream thermal loading by urban stormwater runoff, St. Anthony Falls Laboratory, Project Report No. 526, 44 pp.

Herb, William R. and Heinz G. Stefan, 2009b. Analysis of Flow Data from Miller Creek, Duluth, MN, St. Anthony Falls Laboratory, Project Report No. 522, 23 pp.

Herb, William R., 2008. Analysis of the effect of stormwater runoff volume regulations on thermal loading to the Vermillion River, St. Anthony Falls Laboratory, Project Report No. 520, 34 pp.

Herb, William R. and Heinz G. Stefan, 2008. A flow and temperature model for the Vermillion River, Part I: Model development and baseflow conditions, St. Anthony Falls Laboratory, Project Report No. 517, 32 pp.

Herb, W.R., O. Mohseni and H.G. Stefan, 2007. A Model for Mitigation of Surface Runoff Temperatures by a Wetland Basin and a Wetland Complex, St. Anthony Falls Laboratory, Project Report No. 496, 33 pp.

Iowa Department of Natural Resources, 2007. Water Quality Improvement Plan for McLoud Run, Linn County, Iowa. 87 pp.

Schomberg, J., Richards, C. and G. Host, 2000. *Miller Creek stormwater modeling*. Natural Resources Research Institute: Technical Report # NRRI/TR-2000/06, 85 pp.

State of New Mexico, 1999. Total Maximum Daily Loads (TMDL) for Little Muddy Creek and Tributary to Little Muddy Creek, Environment Department, Surface Water Quality Bureau.

U.S. Environmental Protection Agency, 2000. Navarro River Total Maximum Daily Loads for Temperature and Sediment, 40 pp. (http://www.epa.gov/owow/tmdl/examples/sediment/ca_navarro.pdf)

United States Environmental Protection Agency (USEPA), 2005. Storm Water Management Model. Ecosystems Research Division. Available at http://www.epa.gov/athens/wwqtsc/html/swmm.html. Accessed on November 21, 2009.

USGS, 2008. SNTEMP Stream Temperature Model. http://smig.usgs.gov/cgi-bin/SMIC/model_home_pages/model_home?selection=sntemp

Appendix I: Runoff temperature simulations by models of different complexity.

To increase modeling efficiency, we evaluated the use of simplified MINUHET models for sub-watersheds, where much of the detail of the drainage network is omitted, but total areas and typical runoff length scales are maintained. A detailed model for a 31.4 acre watershed with a Wal-mart facility in Hastings, MN was used as the baseline model with relatively complete presentation of roof and parking lot area and the drainage pipe network (Herb et al. 2008). The facility layout and the corresponding MINUHET schematic are given in Figure A1.1. A diagram of the simplified MINUHET model is given in Figure A1.2. Runoff simulations were run for each model for the period July 22 to September 1, 2008. The resulting simulations of runoff rate and temperature are given in Figure A1.3 for the simple and complex models. The RMSD (root-mean-square difference) of the flow and temperature simulations were 0.06 cfs and 0.25 ºC, respectively. Most importantly, the simulated heat loadings for the two models were very close (Figure A1.4). it was concluded that a simplified MINUHET model was viable.

Figure A1.1. Diagram of the 24 sub-watersheds used to represent the 31.4 acre Wal-mart facility (left) and parking lot, and the corresponding MINUHET schematic (right).

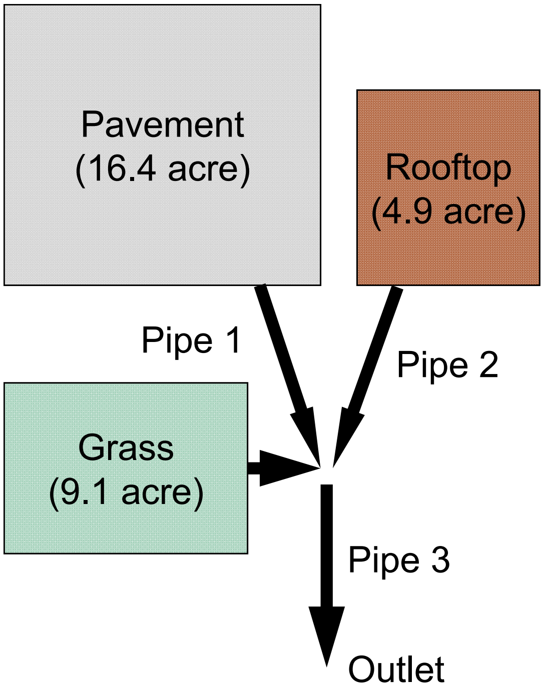

Figure A1.2. Schematic of the simplified MINUHET model for the Wal-mart facility.

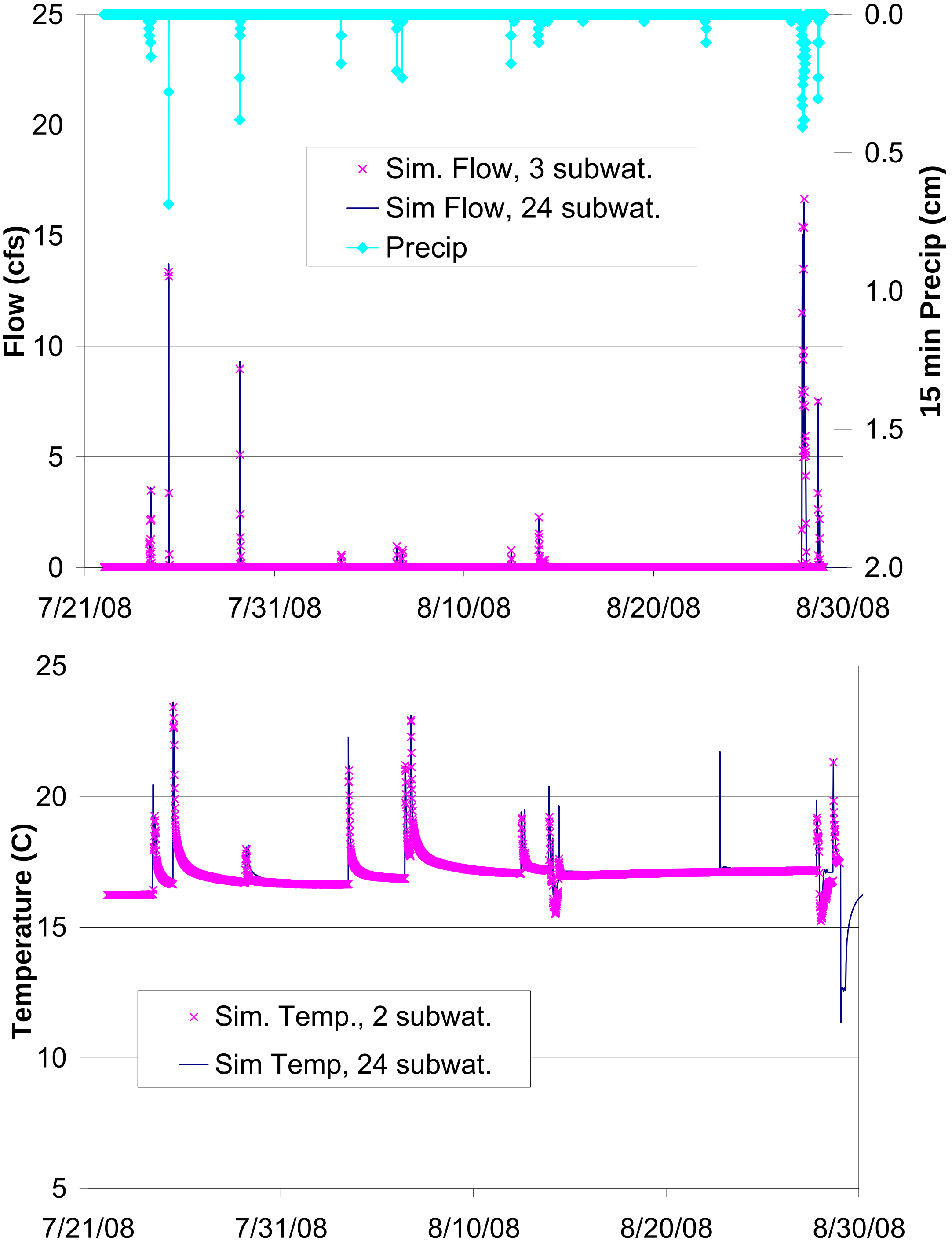

Figure A1.3. Times series of runoff rate (upper panel) and runoff temperature (lower panel) using the complete MINUHET model with 24 sub-watersheds and the simplified MINUHET model with 3 sub-watersheds.

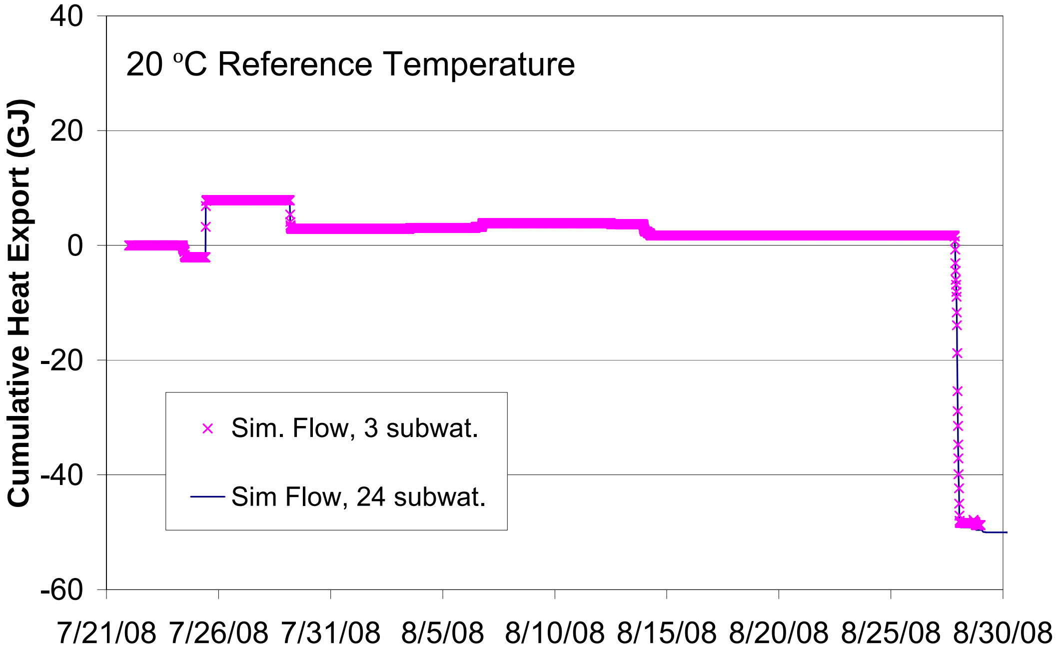

Figure A1.4. Cumulative heat export rate using the complete MINUHET model with 24 sub-watersheds and the simplified MINUHET model with 3 sub-watersheds.

Appendix II. Methods for stormwater heat input calculations

The rate of heat input to a stream from surface runoff (h_{ro}) depends on the rate of stormwater input (q_{ro}) and relative temperature of the stormwater (T_{ro}) and receiving stream (T_s).

$$h_{ro} = \rho c_p q_{ro} \left(T_{ro} - T_s\right) \qquad \text{(A2.1)}$$

Since stormwater inputs are transient events, the time scale of heat input calculations needs to be considered. The simplest approach is to pick a fixed value of T_s to, e.g., represent the temperature of an unimpacted stream. This approach does not take into account seasonal or diurnal changes in stream temperature, and is therefore better suited for analysis of single storm events.

A second approach is to use an observed or simulated daily average stream temperature for heat input calculations. Daily average stream temperatures can be obtained from relatively simple stream temperature models such as SNTEMP, so that it is easy to assess the impact of stormwater for different flow and shading scenarios, etc. This approach takes into account day-to-day and seasonal variations of stream temperature due to climate, and how each storm event changes stream temperature, but does not include diurnal variations of stream temperature.

A third approach is to use an instantaneous observed or simulated stream temperature, e.g. observed stream temperature at 15 minute intervals. This approach more accurately quantifies the heat input to a stream based on what time of day the runoff event occurs, etc. However, this requires either detailed stream temperature observations or simulations at 15 to 60 minute time intervals. This approach emphasizes heat inputs that cause changes in stream temperature from the ambient value, i.e. 16 ºC runoff entering 14 ºC stream has the same heat impact as 20 ºC runoff entering a 18 ºC stream. In contrast, using a fixed stream temperature (e.g. T_s = 20 ºC) emphasizes heat inputs that raise temperature above a threshold.

To compare heat input calculations using the three approaches (fixed, daily average, instantaneous) for stormwater heat input calculations, a test case was done. Simulated stormwater runoff rates and temperature for a commercial development for the period June 1 to September 15, 2008 were used as inputs (q_{ro} and T_{ro}). Heat inputs were calculated using Equation xx.1 for three cases:

1) Fixed stream temperature (20 ºC),
2) Daily average stream temperature from the Kohl's site
3) 15 minute observed stream temperatures from the Kohl's site.

Time series of the calculated heat input are shown in Figure A2.1. In mid-summer, heat inputs calculated for the three cases give similar results. In early summer and fall, heat input calculations using the fixed stream temperature (20 ºC) are large in magnitude and negative, because runoff temperatures during these periods tend to be much less than 20 ºC. Heat inputs calculated using daily average stream temperature and 15 minute stream temperature are similar, with both showing a mixture of positive and negative heat inputs over the season.

The cumulative heat input to the stream calculated for the three cases are shown in Figure A2.2, again highlighting the similarities of results for daily average and 15 minute stream temperature, in contrast to results using fixed stream temperature. To further compare the results obtained using daily average and 15 minute stream temperature, daily heat inputs calculated using these two methods are plotted against each other in Figure A2.3. The slope of the relationship is close to unity (0.96) and correlation is high (R^2=0.88). It can be concluded that for considering heat inputs over a period of several months, using daily average stream temperature is a reasonable approximation. To consider the details of the impact of a individual storm, it is preferable to use 15 minute or hourly stream temperature data for heat input calculations.

Based on the results of this test case, daily average stream temperature was used as the representative stream temperature for all subsequent stormwater heat input calculations. This is consistent with the non-point source, atmospheric heat input calculations given in Section 5, so that point source and non-point source heat inputs can be directly compared. This is also consistent with point source heat inflow calculations in previous temperature TMDLs (e.g. Tualatin sub-basin).

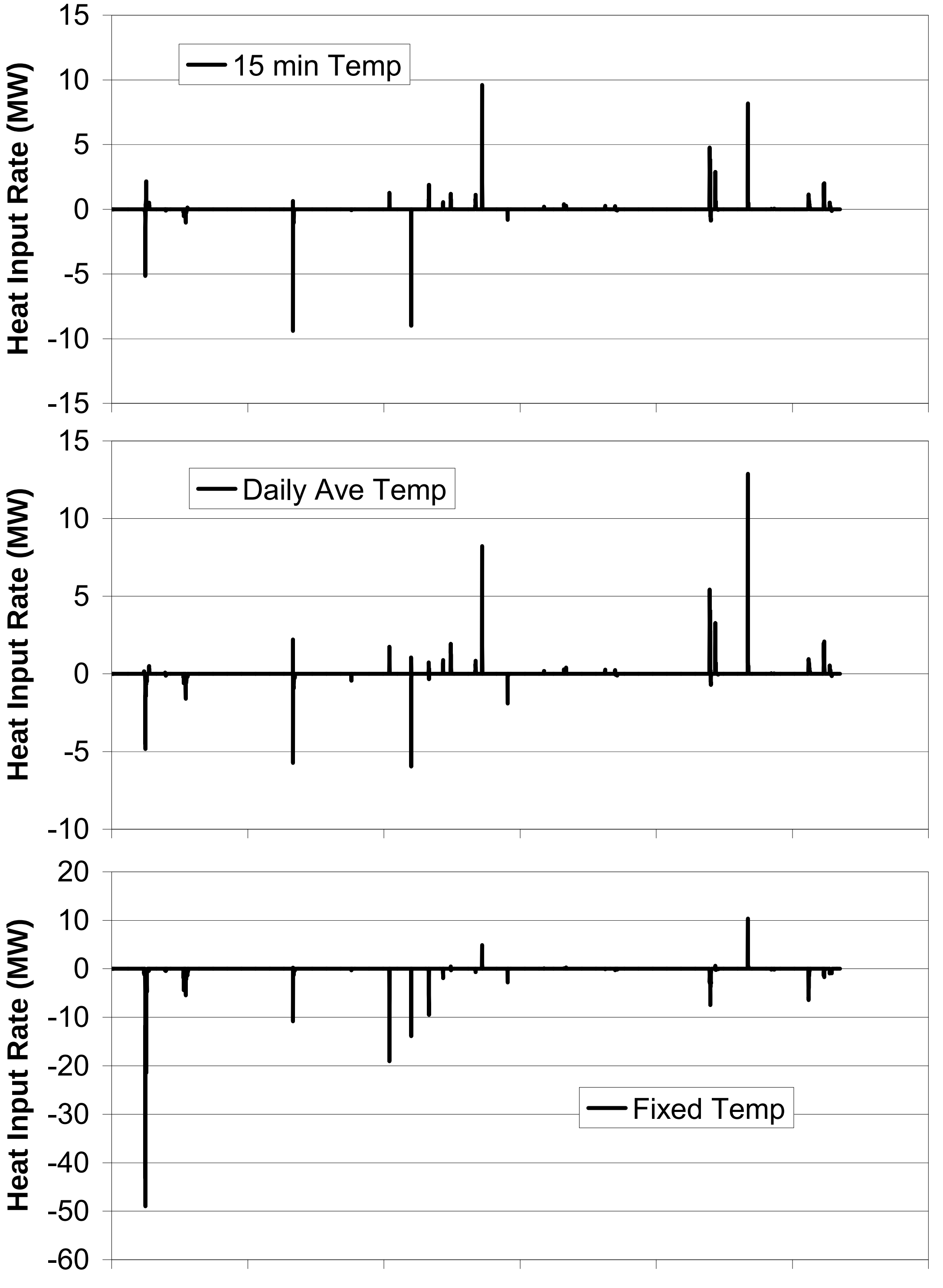

Figure A2.1. Simulated stormwater heat input time series to Miller Creek at Kohl's using three different stream temperatures: 1) fixed stream temperature = 20 ºC, 2) daily averaged stream temperature at Kohl's and 3) 15 minute observed stream temperature at Kohl's.

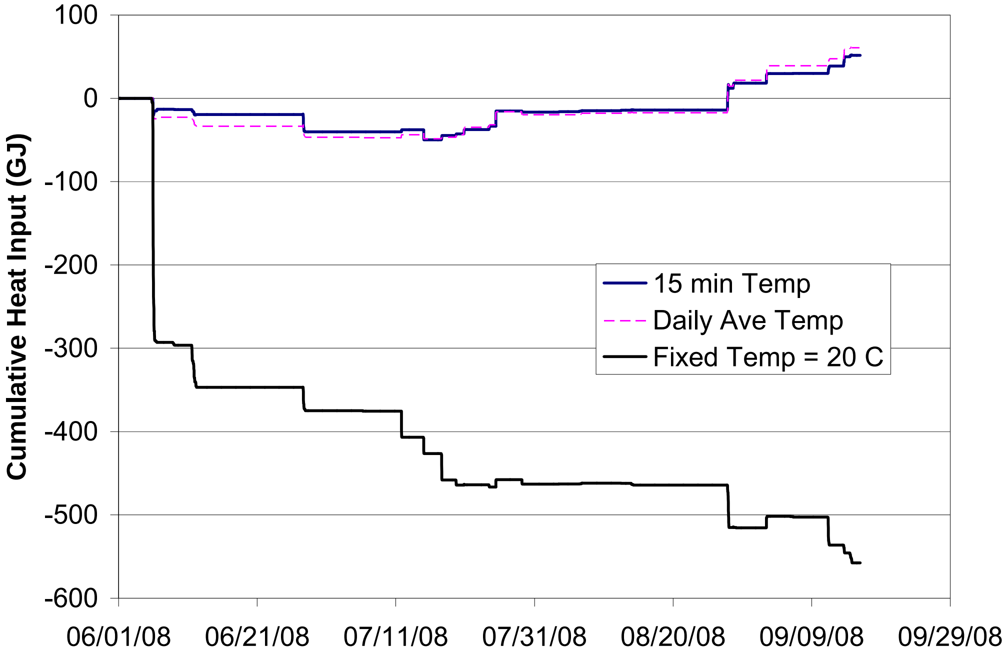

Figure A2.2. Simulated cumulative stormwater heat input to Miller Creek at Kohl's using three different reference temperatures: 1) fixed reference temperature = 18 ºC, 2) 15 minute observed stream temperature at Kohl's, and 3) daily averaged stream temperature.

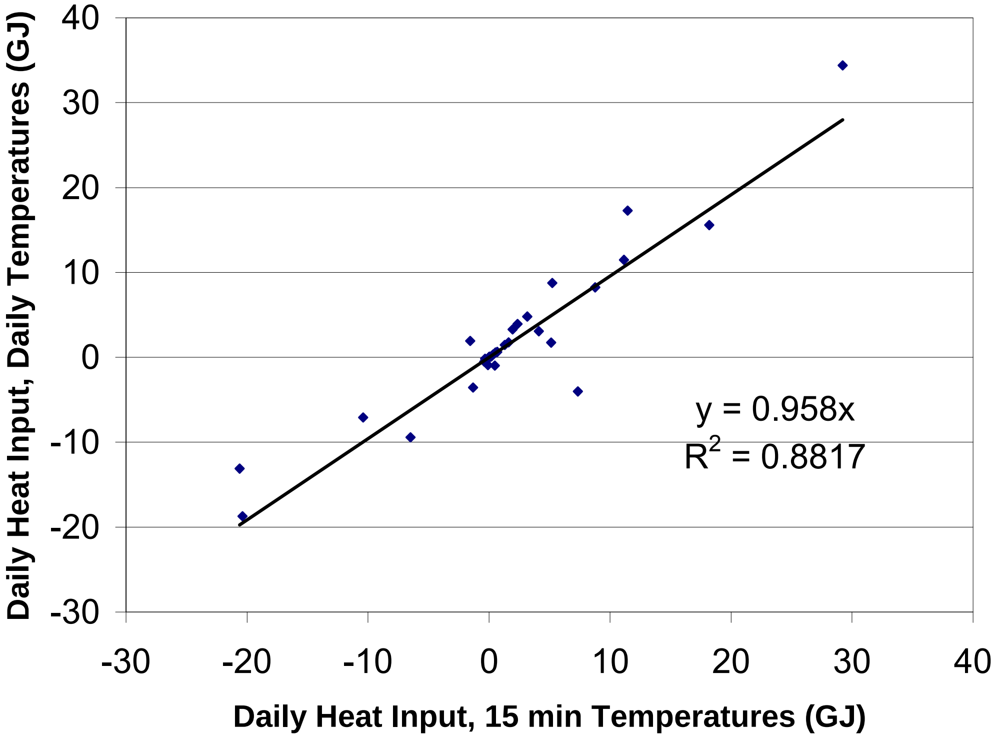

Figure A2.3. Simulated daily stormwater heat inputs to Miller Creek at Kohl's for 15 minute versus daily average stream temperature as reference temperature.

Appendix III. Stormwater 'Vault' Model

To simulate the effect of stormwater vaults on heat mitigation, a simple model was constructed in an Excel© spreadsheet. This model, or a similar model, will be implemented into MINUHET in the near future. The stormwater vault is treated like a well-mixed tank, with a specified total length and diameter. Inflow rates (Q_{in}) and temperatures (T_{in}) are a specified input. Outflow rates are calculated based on the current depth, the control depth, and the diameter of the outlet, which is assumed to be an orifice. For each time step (15 minutes in this study), the new tank level and outflow rate are calculated as follows:

$$\Delta V = (Q_{in} - Q_{out})\, \Delta t \tag{A3.1}$$

Outflow rates are calculated based on equations given in FHWA Urban Drainage Manual (1996). Equations A.2.2 and A.2.3 are used for partially and fully submerged orifice cases, respectively.

$$Q_{out} = C_{ws}\, A\, (2g\Delta h)^{1/2} \tag{A.3.2}$$
$$Q_{out} = C_o\, A_o\, (2g\, (\Delta h - D/2.))^{1/2} \tag{A.3.3}$$

where Δh is the head above the control level, g is the acceleration of gravity, A is the orifice flow, Ao is the total orifice area, and D is the orifice diameter. The orifice coefficients are taken to be C_o= 0.55 and C_{ws}=0.41 (FHWA 1996).

The tank is assumed to be well mixed. The temperature for each time step (T) is calculated based on the tank volume (V_o) and temperature (T_o) from the previous time step, the inflow rate and temperature, and a conductive heat transfer component based on the current tank temperature and an estimated soil temperature:

$$T \cdot V = T_o V_o + Q_{in}\, T_{in}\, \Delta t + \frac{K\, W_p \left(T_g - T\right)\Delta t}{\rho\, C_p} \tag{A.3.4}$$

where K is the heat transfer coefficient ($W/m^2/^oC$), T_g is the soil temperature, Δt is the time step, $\rho\ C_p$ are the density and specific heat of water, and W_p is the wetted perimeter in the tank. The conductive heat transfer term leads to an exponential decay of the water temperature towards soil temperature in the absence of inflow. K was calibrated to be about 4×10^{-6} $W/m^2/^oC$ to match the observed temperature decay rate at the Gander Mountain stormwater vault in Miller Creek (Figure A3.1). Input flows and temperatures for the vault were simulated using MINUHET. Runoff temperatures from the 8.6 acre pavement area and 1.5 acre roof of the facility were routed through a 0.18 acre, 1.5 m deep wet detention pond. From plans supplied by the South St. Louis SWCD, the tank diameter and total length were 3 m and 60 m, respectively, with a control level of 2.7 m, and a 30 cm diameter outlet. The vault model appears to reproduce the flow and temperature dynamics of the Gander Mountain vault (Figure A3.1), with the temperature simulation probably limted by the accuracy of simulated inflow temperatures.

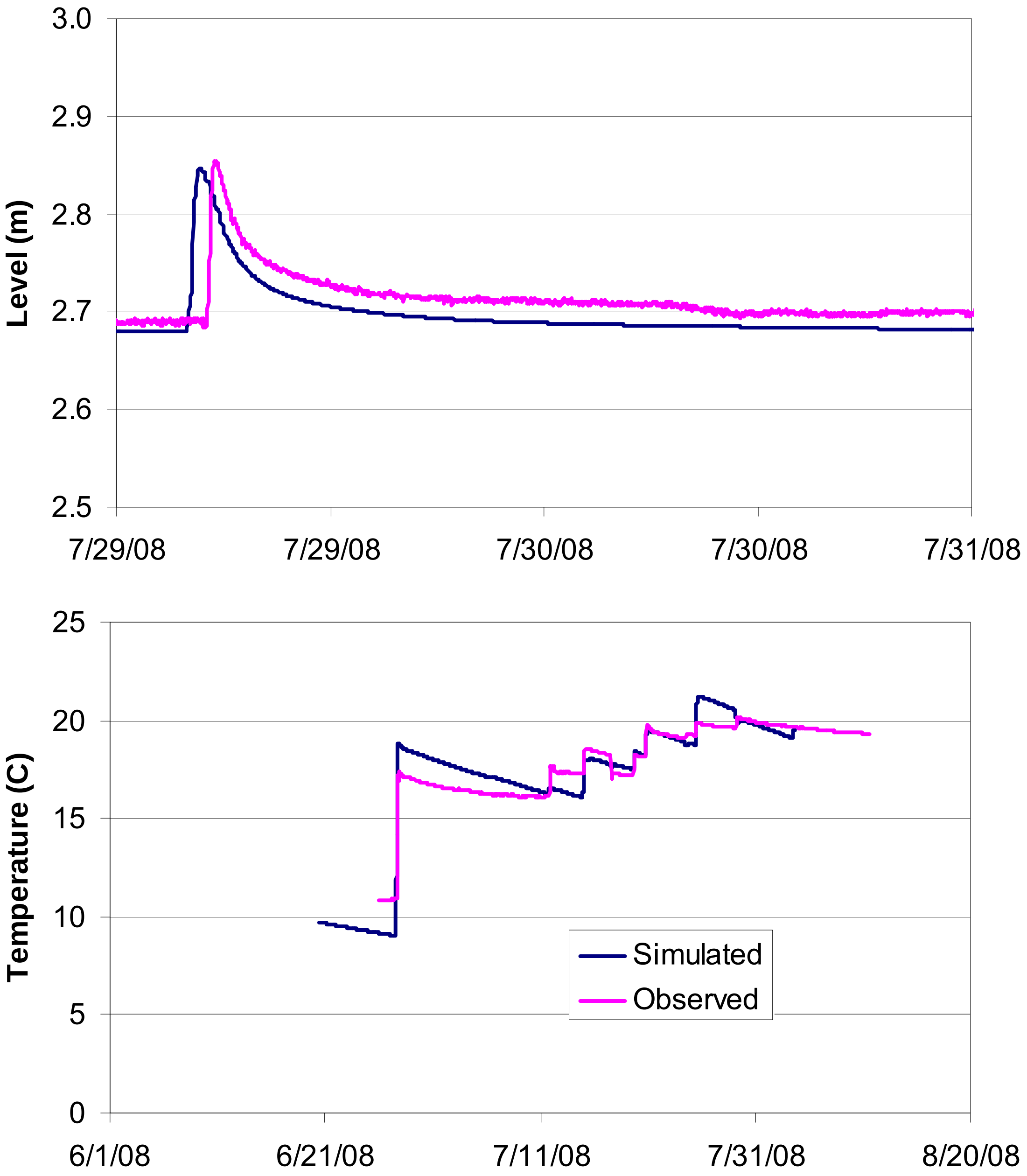

Figure A3.1. Simulated and observed water temperature (lower panel) and water level (upper panel) in a underground stormwater vault. Observations were made at in 2008 at the Gander Mountain facility.

Reference

Federal Highway Administration (FHWA) (1996), Urban Drainage Manual, HydraulicEngineering Circular No.22, FHWA-SA-96-078, Washington D.C.

Appendix IV. Listings of SNTEMP stream temperature models

The following listings give the DOS text files used as inputs to the SNTEMP model. Listings are included for the job control file, stream geometry file, hydrology file, and study file. The solid line separator marks the end of a text file. The climate and flwo inputs files are not listed due to their length. Electronic versions of all files are available by request. Details on the file formats may be found in Theurer et al. (1984).

References
Theurer, F.D., Voos, K.A. and W.J. Miller, 1984. Instream Water Temperature Model. Instream Flow Information Paper 16, U.S. Fish and Wildlife Service, FWS/OBS-84/15.

```
JOB CONTROL FILE: MILLER CREEK MAIN STEM Version 1

TFFFFFFFFFFFT"FFFFFF                          FFFFTFFFFFFFFFTTFFFFFFFFFF
     1.     0.     0.    93.    10.    11.    13.     5.     0.     0.
     0.     9.     0.     0.     0.     0.     0.     0.     3.     5.
     6.     0.     1.     0.     0.     1.     1.     1.    93.     2.
   0.00  0.0000    0.00  0.0000    1.20  0.0050    0.05  3.2800    0.00 93.0000
   0.00  0.0000    0.00  0.9000    0.00  0.0000    0.00  0.0000    0.00  0.0000
   0.00  0.0000    0.00  0.0000    0.00  0.0000    0.00  0.0000    0.00  0.0000
MCTME.DAT     MCMET.DAT     dummy        MCSTR.DAT      MCSTD.DAT
MCHDR.DAT     MCHYD.DAT     MCSHD.DAT
Main Stem          0.0    15.0
 STR. NAME #   2    0.0     0.0
 STR. NAME #   3    0.0     0.0
 STR. NAME #   4    0.0     0.0
 STR. NAME #   5    0.0     0.0
 STR. NAME #   6    0.0     0.0
 STR. NAME #   7    0.0     0.0
 STR. NAME #   8    0.0     0.0
 STR. NAME #   9    0.0     0.0
 STR. NAME #  10    0.0     0.0
```

```
  Stream Geometry File: Miller Creek Main Stem Version 1

Main Stem      S         15.03  Reach1
   0.81   423.8   0.220    1.22     0.0    0.70    0.70    15.0    1.65

Main Stem      C         12.54  Reach2
   0.81   416.6   0.031    1.83     0.0    0.65    0.65    15.0    1.65

Main Stem      C         11.58  Reach4
   0.81   411.9   0.050    1.83     0.0    0.65    0.65    15.0    1.65

Main Stem      C         10.03  Reach7
   0.81   409.9   0.060    2.44     0.0    0.70    0.70    15.0    1.65

Main Stem      C          9.23  Reach8
   0.81   407.0   0.200    2.44     0.0    0.35    0.35    15.0    1.65

Main Stem      C          8.57 Reach10
   0.81   405.5   0.200    2.44     0.0    0.55    0.55    15.0    1.65

Main Stem      C          7.79 Reach13
   0.81   401.1   0.164    2.13     0.0    0.65    0.65    15.0    1.65
```

```
Main Stem      C         4.92 Reach19
   0.81   390.0   0.020    2.90     0.0    0.75    0.75    15.0    1.65

Main Stem      C         3.59 Reach20
   0.81   338.7   0.040    2.90     0.0    0.75    0.75    15.0    1.65

Main Stem      C         1.32 Reach23
   0.81   262.8   0.032    3.05     0.0    0.75    0.75    15.0    1.65

Main Stem      E         0.60 Low End
   0.81   194.7
```

```
  Stream Hydrology File: Miller Creek Main Stem Version 1
Main Stem      S        15.03  Reach1
Main Stem      P        12.11  Reach3
Main Stem      Q         11.55  Reach5
Main Stem      Q         10.54  Reach6
Main Stem      Q          9.20 Reach10
Main Stem      Q          8.56 Reach11
Main Stem      P         8.17 Reach12
Main Stem      P         7.48 Reach14
Main Stem      Q          7.45 Reach15
Main Stem      Q          6.33 Reach16
Main Stem      P         5.96 Reach17
Main Stem      P         1.94 Reach22
Main Stem      E          0.60 Low End
```

```
  Stream Study File: Miller Creek Main Stem Version 1
Main Stem      S        15.03  Reach1
Main Stem      O          5.87 Reach18
Main Stem      O          2.99 Reach21
Main Stem      O          0.95 Reach24
Main Stem      E          0.60 Low End
```

JOB CONTROL FILE: MILLER CREEK MAIN STEM Version 2

```
TFFFFFFFFFFFT"FFFFFF                          FFFFTFFFFFFFFTTFFFFFFFFFF
    1.     0.     0.    93.    21.    24.    17.     2.     0.     0.
    0.    22.     0.     1.     0.     0.     0.     0.     0.    15.
    0.     0.     1.     0.     0.     1.     1.     1.    93.     2.
   0.00  0.0000   0.00  0.0000   1.20  0.0050   0.05  3.2800   0.00 93.0000
   0.00  0.0000   0.00  0.9000   0.00  0.0000   0.00  0.0000   0.00  0.0000
   0.00  0.0000   0.00  0.0000   0.00  0.0000   0.00  0.0000   0.00  0.0000
MCTME.DAT     MCMET.DAT     dummy        MCSTR.DAT      MCSTD.DAT
MCHDR.DAT     MCHYD.DAT     MCSHD.DAT
Main Stem          0.0    15.0
 STR. NAME #   2    0.0    0.0
 STR. NAME #   3    0.0    0.0
 STR. NAME #   4    0.0    0.0
 STR. NAME #   5    0.0    0.0
 STR. NAME #   6    0.0    0.0
 STR. NAME #   7    0.0    0.0
 STR. NAME #   8    0.0    0.0
 STR. NAME #   9    0.0    0.0
 STR. NAME #  10    0.0    0.0
```

Stream Geometry File: Miller Creek Main Stem Version 2

```
Main Stem      S        15.28  Reach1
   0.81   426.8   0.150   1.22    0.0   0.65   0.65   15.0   1.65

Main Stem      C        12.76  Reach2
   0.81   416.6   0.150   1.83    0.0   0.65   0.65   15.0   1.65

Main Stem      C        12.30  Reach3
   0.81   414.9   0.150   1.81    0.0   0.70   0.70   15.0   1.65

Main Stem      C        11.77  Reach4
   0.81   411.9   0.150   1.79    0.0   0.60   0.60   15.0   1.65

Main Stem      C        10.56  Reach5
   0.81   409.3   0.150   2.92    0.0   0.65   0.65   15.0   1.65

Main Stem      C        10.15  Reach6
   0.81   408.7   0.200   2.48    0.0   0.65   0.65   15.0   1.65

Main Stem      C         9.64  Reach7
   0.81   405.9   0.200   2.17    0.0   0.65   0.65   15.0   1.65
```

```
Main Stem       C          9.29  Reach8
   0.81   405.6   0.200   2.44     0.0    0.50    0.50    15.0    1.65

Main Stem       C          8.90  Reach9
   0.81   405.5   0.200   2.44     0.0    0.50    0.50    15.0    1.65

Main Stem       C          8.62 Reach10
   0.81   404.6   0.200   2.44     0.0    0.50    0.50    15.0    1.65

Main Stem       C          8.23 Reach11
   0.81   404.0   0.200   2.13     0.0    0.55    0.55    15.0    1.65

Main Stem       C          7.85 Reach12
   0.81   399.9   0.150   2.13     0.0    0.65    0.65    15.0    1.65

Main Stem       C          7.51 Reach13
   0.81   399.2   0.150   2.13     0.0    0.65    0.65    15.0    1.65

Main Stem       C          6.98 Reach14
   0.81   398.8   0.150   2.80     0.0    0.65    0.65    15.0    1.65

Main Stem       C          5.99 Reach15
   0.81   393.3   0.150   3.90     0.0    0.75    0.75    15.0    1.65

Main Stem       C          5.91 Reach16
   0.81   390.6   0.100   2.84     0.0    0.75    0.75    15.0    1.65

Main Stem       C          4.95 Reach17
   0.81   388.7   0.100   2.90     0.0    0.75    0.75    15.0    1.65

Main Stem       C          3.63 Reach18
   0.81   337.5   0.100   2.90     0.0    0.75    0.75    15.0    1.65

Main Stem       C          3.03 Reach19
   0.81   317.1   0.100   3.05     0.0    0.75    0.75    15.0    1.65

Main Stem       C          2.53 Reach20
   0.81   304.1   0.050   3.05     0.0    0.75    0.75    15.0    1.65

Main Stem       C          1.98 Reach21
   0.81   261.6   0.050   3.05     0.0    0.75    0.75    15.0    1.65

Main Stem       C          1.36 Reach22
   0.81   217.1   0.050   3.36     0.0    0.70    0.70    15.0    1.65
```

```
Main Stem     C        1.01 Reach23
   0.81   193.9   0.050    4.88     0.0    0.70    0.70    15.0    1.65

Main Stem     E        0.60 Low End
   0.81   188.1
```

```
  Stream Hydrology File: Miller Creek Main Stem Version 2.
Main Stem     S       15.28  Reach1
Main Stem     P       12.75  Reach2
Main Stem     P       12.30  Reach3
Main Stem     P       11.77  Reach4
Main Stem     P       10.56  Reach5
Main Stem     P        8.90  Reach9
Main Stem     P        8.23 Reach11
Main Stem     P        7.85 Reach12
Main Stem     P        7.51 Reach13
Main Stem     P        6.98 Reach14
Main Stem     P        5.91 Reach16
Main Stem     P        4.95 Reach17
Main Stem     P        3.03 Reach19
Main Stem     P        1.98 Reach21
Main Stem     P        1.36 Reach22
Main Stem     P        1.01 Reach23
Main Stem     E        0.60 Low End
```

```
  Stream Study File: Miller Creek Main Stem Version 2
Main Stem     S       15.28  Reach1
Main Stem     E        0.60 Low End
```