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

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Analysis of the effect of stormwater runoff volume regulations on thermal loading to the Vermillion River

by

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1. Introduction

Residential and commercial development dramatically alters the surface and groundwater hydrology of watersheds. Increasing areas of impervious surfaces can lead to higher peak stream flows and reduced baseflow, which both can lead to degradation of fish habitat. In addition, thermal pollution from surface runoff is increasing recognized as an additional mechanism for fish habitat degradation in coldwater stream systems. Stormwater best management practices (BMPs) such as infiltration ponds, rain gardens, and swales are often used to reduce stormwater surface runoff rates and volumes, and to increase infiltration and groundwater recharge. Wet detention ponds used to limit runoff flow rates and reduce sediment loads are not likely to reduce thermal loading, since there is no reliable mechanism for volume or temperature reduction. Infiltration practices that capture all of smaller storms and initial portion of larger storms are very likely to significantly reduce thermal loading, since the warmest surface runoff typically happens during low volume storms and the initial portions of larger storms.

To predict changes in thermal loading to streams due to land use changes, a simulation model of runoff temperature is currently being developed as part of a research project that SAFL is conducting for the Minnesota Pollution Control Agency (“Development and Implementation of a Tool to Predict and Assess the Impact of Stormwater Runoff on Trout Streams”). The current version of the tool, MINUHET (MINnesota Urban Heat Export Tool), has components for simulating runoff volume and temperature for mixed land use sub-divisions, routing of runoff flow and heat through both conventional storm sewer systems and pervious channels, and for simulating wet ponds and infiltration ponds. Thus, MINUHET has the capability to quantify the reduction in thermal loading due to the addition of infiltration practices.

This thermal loading study builds on a previous study by Barr Engineering Co., “VRWJPO Runoff Volume Standard Analysis: Methodology and Results” (Wilson and Barnes, 2008). In this study, stormwater runoff was modeled for a residential and commercial development for 1) traditional development practices with no runoff rate or volume control, 2) traditional development practices with rate control, 3) traditional development practices with rate and volume control, and 4) low impact development (LID) practices. Rate and volume control ponds were sized to meet VRWJPO standards:

- The peak runoff rate after development should not exceed the rate for pre-development conditions (agricultural) for the 1, 10 and 100 year, 24 SCS Type II storm events.
- The runoff volume after development should not exceed the pre-development conditions (agricultural) for the 2 year, 24 hour storm event. The infiltration basin used to achieve the volume standard must not retain standing water longer than 72 hours.

Cost estimates were made to implement the rate and volume controls for each development. Runoff rate and volume analyses were performed using XP-SWMM for 1, 2, 10, and 100 year, 24 hour rainfall events. In addition, continuous simulations were performed for a 50 year period (1952-2001), using 1 hour observed climate data from the Minneapolis/St. Paul International Airport. The study concluded that volume control (infiltration) ponds are a relatively small incremental cost over rate control only, and provide a cost-effective means to reduce runoff peak rate and achieve volume. The 50 year, continuous analysis indicated that the combination of rate and volume control ponds improved the runoff flow frequency and duration characteristics of both sites, even compared to pre-development conditions.

In the present study, the MINUHET tool was used to evaluate the change in total heat loading of surface runoff from the same residential and commercial developments considered in the Barr study. Heat loading analysis was performed for one residential and one commercial development using a 2 year, 24 hour storm for the same land use conditions used in the Barr study: 1) pre-development conditions, 2) developed conditions with no infiltration practices, and 3) developed conditions with infiltration practices.

The runoff simulation results obtained using MINUHET are compared to results for the same developments obtained using XP-SWMM, provided by Barr Engineering Co. The two simulation packages are found to give very similar results for runoff volume and peak flow rate for the different residential and commercial development cases. Runoff temperatures and heat export (flow x temperature) obtained using MINUHET are summarized and compared for the different cases. Infiltration basins as stand-alone units are found to reduce thermal loading, as expected. Wet detention ponds used for pre-treatment of runoff upstream of infiltration basins are found to substantially increase thermal loading and lower the effectiveness of the infiltration basins in reducing thermal loading.

In the present and previous thermal loading studies, the potential thermal impact of surface runoff is quantified using heat export, which quantifies the amount of heat that will be added to a receiving water body with a temperature T_{ref}. Flow and temperature data can be used to calculate a rate of heat export (h_{ro}) at any time (e.g. in Watts) and an integral, or total, heat export (g_{ro}) for an entire event (e.g., in Joules):

$$(1.1)\quad h_{ro} = (\rho C_p) q_{ro} (T_{ro} - T_{ref})$$

$$(1.2)\quad g_{ro} = \int h_{ro}\, dt = (\rho C_p) V_{ro} (\overline{T}_{ro} - T_{ref})$$

where q_{ro} and T_{ro} are the runoff flow rate (m^3/s) and temperature at a specific time during the storm event, $\overline{T}_{ro}$ is the volume-weighted, average runoff temperature, V_{ro} is the total runoff volume, and ρC_p is the product of water density and specific heat. From Equations 1.1 and 1.2, it is evident that runoff with temperature T_{ro} will have a higher heat export and thermal loading on a stream with a lower temperature, and that runoff entering a stream at the same temperature ($T_{ro}=T_{ref}$) has zero heat export (thermal loading). Therefore, heat export and thermal loading depend on both the runoff and receiving stream characteristics. In this study, heat export results are given for two different values of T_{ref} (18 ºC and 20 ºC), to represent two receiving stream temperatures.

2. Specification of a 2 year, 24 hour storm event for thermal loading analysis

For stormwater thermal loading analysis, the storm event used as input must include precipitation data and the associated climate parameters, including solar radiation, air temperature, dew point temperature or relative humidity, and wind speed.

A SCS Type-II precipitation distribution was used (USDA 1986), giving the rainfall distribution over 24 hours shown in Figure 2.1, with a total rainfall depth of 2.8 inches for the Twin Cities area. The 15 minute rainfall data have a maximum amount of 2.2 cm at the 12 hour midpoint of the storm (Figure 2.1).

Two observed climate data sets were used to help determine appropriate climate parameters for the 24 hour storm:

1) A 30 year climate data set (SAMSON) from the Minneapolis-St. Paul international airport (1961-1990)
2) A six year climate data set from the Minnesota Department of Transportation MnROAD facility in Albertville, MN (1998-2001, 2003-2005).

The dew point temperature sets the rainfall temperature in the thermal loading analysis, and thus is a key parameter in determining runoff temperature. For the purposes of this study, the goal was to select a relatively high, but realistic, dew point temperature, so that the 2 year design storm represents a high thermal loading storm. Analysis of dew point temperature versus total rainfall depth for both climate data sets suggest that high volume storms tend toward an upper limit of a 20 ºC dewpoint temperature for the Twin Cities metropolitan area (Figure 2.2). Both dew point temperature and air temperature were fixed at 20 ºC for the duration of the 24 hour storm event.

Solar radiation during the storm event was set based on the observed relationship between solar radiation and precipitation rate shown in Figure 2.3. The expected maximum solar radiation for each 15 minute interval of the specified day for the storm event (July 30) was multiplied by a factor computed from the exponential relationship in Figure 2.3 and the specified rainfall quantity (Figure 2.1). The resulting solar radiation reaches a maximum of 75 W/m^2 during daylight hours, but decreases during the heavier rainfall at mid-day (Figure 2.4). For reference, mid-day, cloudless solar radiation in July is about 1000 W/m^2.

A typical hourly wind distribution was calculated for the day of the storm event by finding the average hourly wind velocity for May – September using the 6 year MnROAD climate data set. The resulting wind velocity shown in Figure 2.4, with a maximum of 2.8 m/s at mid-day and an average of 1.9 m/s.

Observed climate data from the MnROAD site for July of 1999 were used to as climate conditions before and after the storm, which is specified to occur on July 30, 1999. These climate data include relatively warm, sunny climate before and after the storm, leading to relatively warm land surface and pond temperatures prior to the storm event. However, the precipitation time series (Figure 2.1) for the Type II, 24 storm gives ample time for land surface to cool down prior to the onset of high intensity rainfall at the midpoint of the storm.

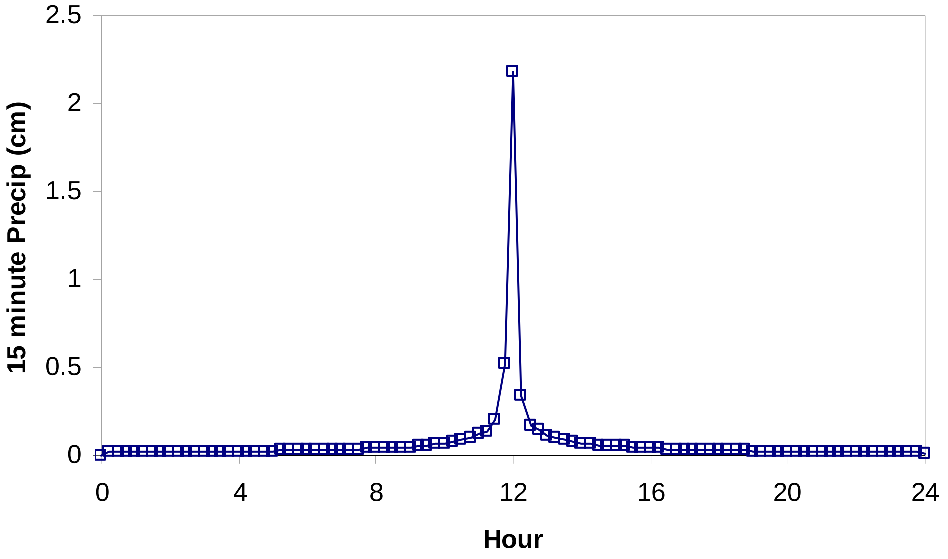

Figure 2.1. 15 minute precipitation data for the SCS Type II, 2 year, 24 hour rainfall event.

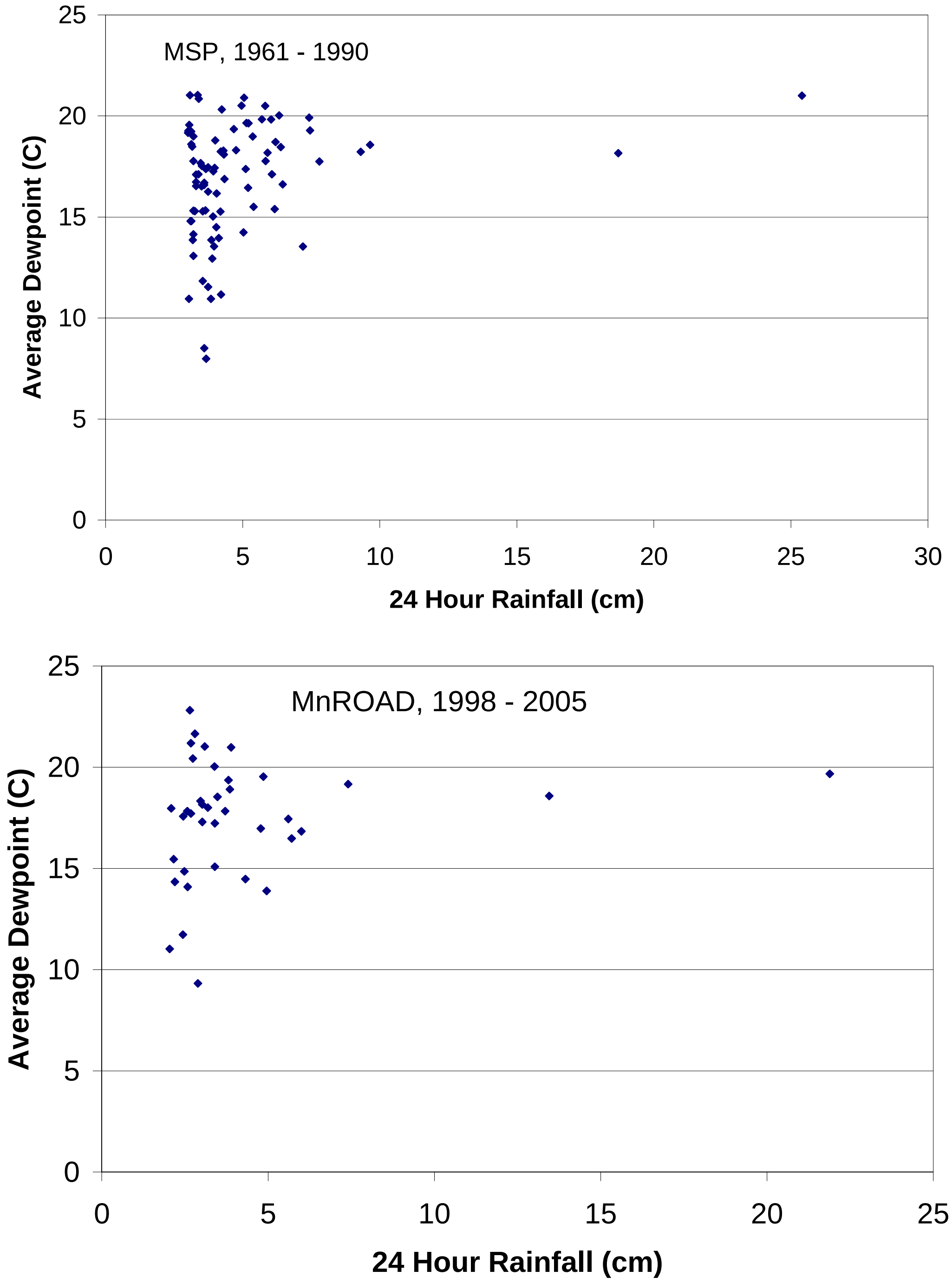

Figure 2.2. 24 hour average dewpoint temperature vs. 24 hour rainfall total for events with 3 cm or greater total precipitation, for observed climate data from the Minneapolis-St. Paul airport and the MnROAD facility in Albertville, MN.

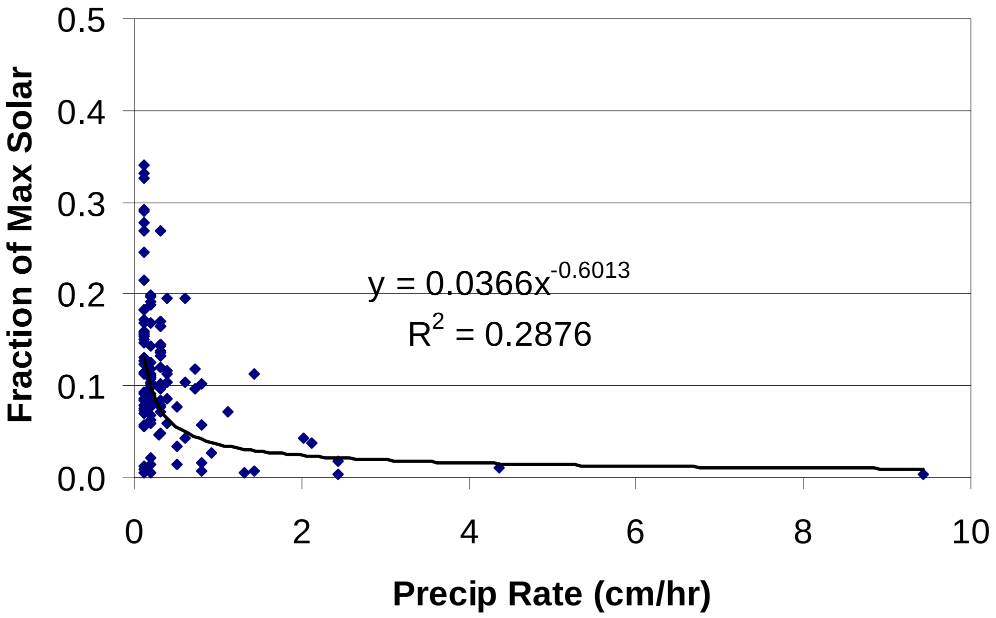

Figure 2.3. Observed fraction of maximum solar radiation versus precipitation rate for the six year MnROAD climate data set, May – September, 10 am – 4 pm only.

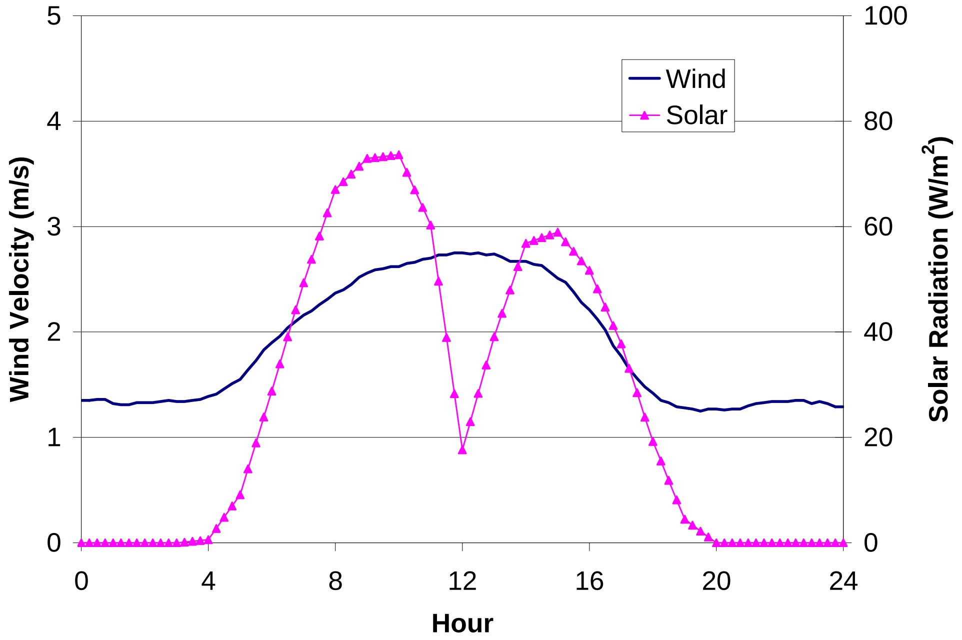

Figure 2.4. 15 minute solar radiation and wind velocity specified for the 2 year, 24 hour storm event.

3. Hydro-thermal runoff analysis of a residential development

3.1 Residential study site characteristics

The thermal loading of the 2 year, 24 hour storm event was calculated using the MINUHET model for a 12 acre residential watershed in Plymouth, MN. This watershed was previously used as a test case for the MINUHET model (Janke et al. 2007), because field data was available for stormwater runoff flow rate and temperature for several storms in 2005. For this study, the MINUHET model was used to evaluate the thermal loading of runoff from the 2 year, 24 hour storm for predevelopment conditions, developed conditions, and developed conditions with two different stormwater mitigation scenarios.

The 12 acre watershed in Plymouth was previously characterized in detail by the Three Rivers Park District as part of a phosphorus loading study. The watershed contains part of three separate residential developments. A schematic of the study site is shown in Figure 3.1. Table 3.1 summarizes the impervious areas in the watershed, as given by the Three Rivers Park District. A total of 5 subwatersheds were defined, draining to the catch basins shown in Figure 3.2. The characteristics of the five subwatersheds are summarized in Table 3.2. The watershed slopes were modified from the estimated actual values to match the value (4.3%) used by Barr Engineering in their runoff analysis using XP-SWMM. The undeveloped case was modeled using a single sub-watershed (12.4 acre), with row crop land use, a slope of 4.3%, a surface roughness coefficient of 0.21, and a characteristic runoff length of 150 m.

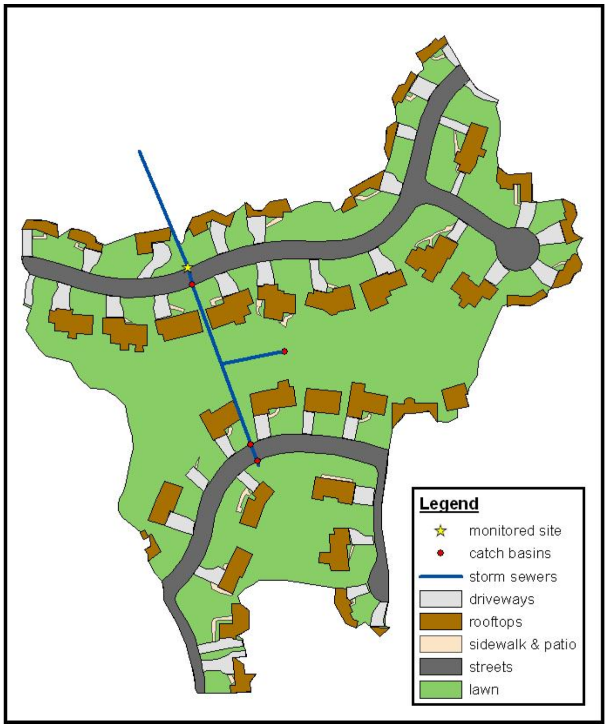

Figure 3.1. Schematic of residential study site in Plymouth, MN.

Table 3.1. Characterization of impervious areas within the Plymouth watershed. Data supplied by Three Rivers Park District.

Total Area (m^2)	Connected Imperv. (m^2)	% of Watershed	
50390	12021	23.9%	
Connected Impervioius Breakdown			
Driveways (m^2)	Sidewalk (m^2)	Roof (m^2)	Street (m^2)
4089	456	940	6536

Table 3.2. Sub-watershed parameters for the example Plymouth watershed

Sub-watershed	**SWS01**	**SWS02**	**SWS03**	**SWS04**	**SWS05**
Description	SW Corner	SE Corner	Greenspace	NE Corner	NW Corner
Connected Impervious					
Length (m)	63.3	43.5		26	62.6
Paved Area (m^2)	2155	1889		1677	5323
Conn. Roof (m^2)	197	226		155	318
Shading (%)	10	0		0	10
Wind Sheltering (%)	0	0		0	0
Slope	0.043	0.043		0.043	0.043
Pervious (Grass, Trees) + Disconnected Impervious					
Length (m)	36.2	27.9	23.2	23.2	42.2
Pervious Area (m^2)	5899	5881	5007	5537	8533
Disconn. Roof (m^2)	1445	1654	858	1135	2336
Shading (%)	20	50	80	20	50
Wind Sheltering (%)	0	0	0	0	0
Slope	0.043	0.043	0.043	0.043	0.043
Soil Type	B	B	B	B	B
Veg. Type	Grass	Grass	Grass	Grass	Grass
Veg. Density	0.9	0.9	0.9	0.9	0.9

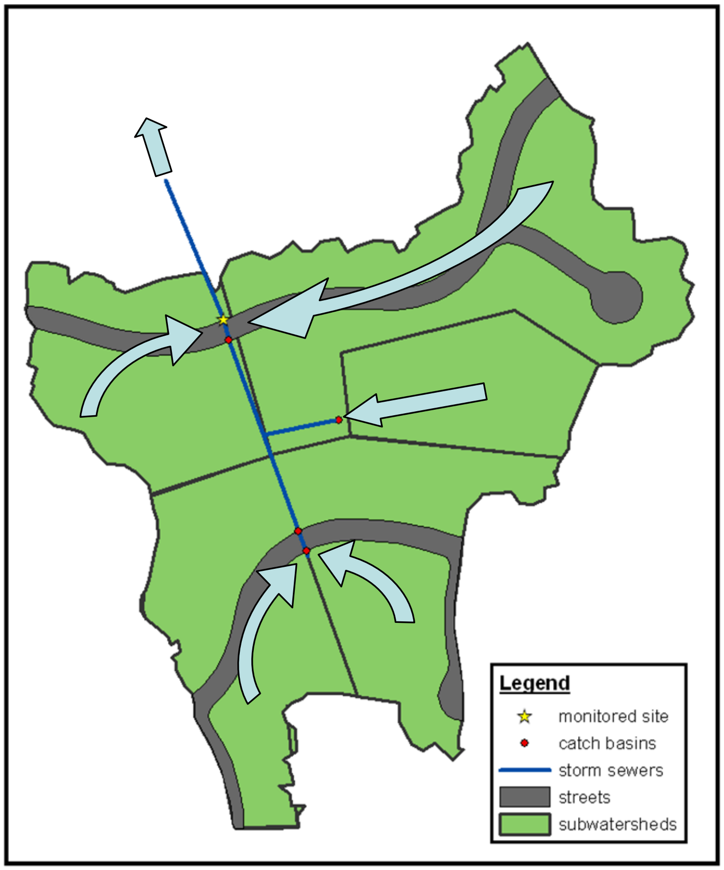

Figure 3.2. Sub-watershed delineation of the residential study site.

3.2 Thermal loading analysis of the residential site

Thermal loading analyses of the residential study site were performed for a total of five cases, using the 2 year, 24 hour storm as the loading storm in all cases:

1. Developed condition, no mitigation
2. Developed condition, rate control mitigation only
3. Developed condition, volume control mitigation only
4. Developed condition, rate and volume control mitigation
5. Undeveloped condition (Agricultural)

The mitigation ponds used for rate and volume control at the residential site are summarized in Table 3.3. The rate control pond is a wet detention pond, while the volume control pond is an infiltration pond. The ponds were designed to meet VRWJPO standards for stormwater runoff rate and volume limits by Barr Engineering.

MINUET simulations indicated that the storm sewer system specified in the development plans for the Plymouth watershed is inadequate to handle the 2 year, 24 hour event. To handle overload of the sewer system, small dry detention basins were added to the MINUHET model upstream of three of the pipe inlets, giving the ability to model ponding of the runoff. The resulting model configuration is shown in Figure 3.3, where the additional dry ponds are labeled dpnd01 to dpnd03.

MINUHET simulations results for runoff volume and maximum flow are compared to results obtained by Barr Engineering using XP-SWMM in Table 3.4. Runoff volumes differ by 1% to 14%, while peak flow rates differ by 4% to 40%.

For the 2 year, 24 storm event, average runoff temperatures for asphalt surfaces (22.1 ºC) were only moderately higher than pervious surfaces (20.6 ºC), because the highest intensity rainfall is preceded by almost 12 hours of wet weather (Figure 2.1). Results for the residential development outlet temperature, heat export rate, and total heat export are summarized in Table 3.5. Heat export results are given for two reference temperatures, 18 ºC and 20 ºC. Time series of the MINUHET simulation are given in Appendix I.

Table 3.3. Rate and volume control pond specifications for the residential watershed.

Pond	Type	Surface area, at overflow	Volume, at control depth	Volume, at overflow
Rate Control	Wet detention	0.25 acre (1012 m^2)	0.54 acre-ft (666 m^3)	0.77 acre-ft (950 m^3)
Volume Control	Infiltration basin	0.50 acre (2028 m^2)	n/a	0.45 acre-ft (558 m^3)

Table 3.4. Comparison of runoff volume and peak runoff rate obtained with MINUHET and XP-SWMM (Barr Engineering).

Case	Runoff Volume (acre-ft)		Peak Runoff Rate (cfs)	
	MINUHET	XP-SWMM	MINUHET	XP-SWMM
Undeveloped (Agricultural)	0.55	0.63	8.3	8.0
Developed, no mitigation	1.27	1.28	6.8	7.9
Developed, rate control only	1.31	1.24	6.2	5.8
Developed, rate and volume control	0.59	0.61	3.4	2.3

Table 3.5. Summary of runoff temperature and heat export values obtained with MINUHET for the residential site, using reference temperatures (T_{ref}) of 18 °C and 20 °C.

Case	Runoff Temp. (°C)		Max. Heat Export Rate (MW)		Total. Heat Export (GJ)	
	Ave.	Max.	T_{ref}=18 °C	T_{ref}=20 °C	T_{ref}=18 °C	T_{ref}=20 °C
Undeveloped (Agricultural)	21.7	22.3	3.3	1.3	10.4	4.7
Developed, no mitigation	21.2	22.6	2.9	1.4	21.2	8.0
Developed, rate control only	24.0	27.1	6.1	4.6	40.3	26.7
Developed, rate/volume control	23.6	25.6	2.7	1.9	17.2	11.0
Developed, volume control only	21.0	21.6	1.9	0.7	11.2	3.8

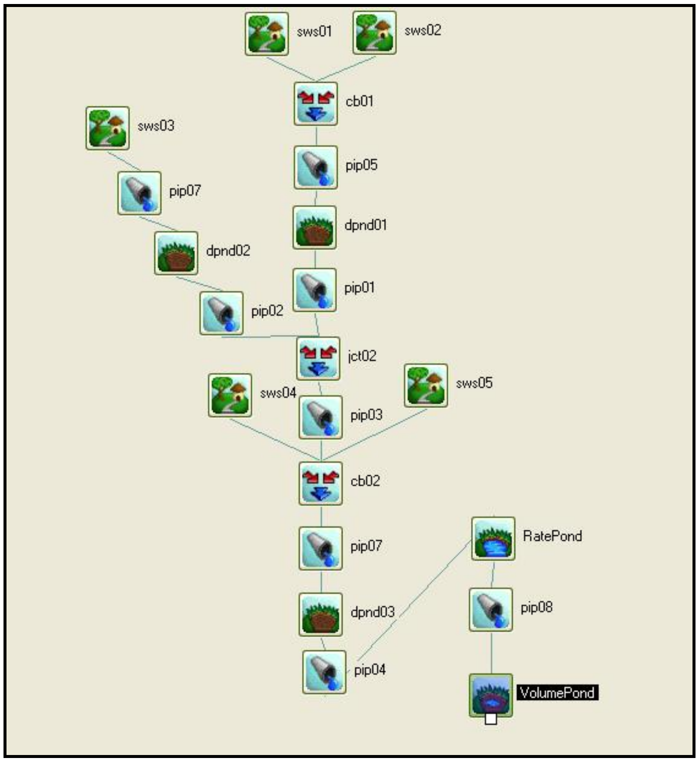

Figure 3.3. MINUHET layout for the Plymouth watershed, with runoff routed from top to bottom.

4. Hydro-thermal runoff analysis of a commercial development

4.1 Commercial study site characteristics

The 31.4 acre site in Hastings, MN is an existing Wal-Mart retail store, and includes 3.1 acres of road, 6.1 acres of rooftop, 13.1 acres of parking lot, and 9.1 acres of pervious area (Figure 4.1). A total of 24 sub-watersheds were defined for the hydrologic model, as shown in Figure 4.2. The sub-watershed areas are similar, but not identical to, the sub-watersheds used by Barr Engineering for their XP-SWMM model. The characteristics of the 24 sub-watersheds are summarized in Table 4.1. Per specifications by Barr Engineering, the slope and roughness (Manning's n) of al sub-watersheds were set to 4.2% and 0.2, respectively. The approximate location of the storm sewer network is also shown in Figure 4.2, with separate drainage networks for the parking lot and roof areas. A total of 24 separate piping elements were used to model the drainage network in MINUHET (Figure 4.3), which were sized according to building plans supplied by Barr. As with the residential site, the undeveloped case was modeled using a single sub-watershed, with row crop land use, a slope of 4.3%, a surface roughness of 0.21, and a characteristic runoff length of 250 m.

Table 4.1. Distribution of pavement, roof and pervious areas in the 24 sub-watersheds defined for the MINUHET model.

Sub-watershed	Connected Pavement (Acre)	Connected Roof (Acre)	Pervious (Acre)	Sub-watershed	Connected Pavement (Acre)	Connected Roof (Acre)	Pervious (Acre)
1	1.27	0.00	1.29	13	1.02	0.12	0.40
2	0.46	0.00	0.07	14	2.17	0.08	1.12
3	0.23	0.00	2.59	15	1.03	0.00	0.00
4	0.72	0.00	0.05	16	1.21	0.00	0.00
5	0.07	0.15	0.09	17	0.98	0.00	0.00
6	0.23	0.02	0.00	18	0.95	0.00	0.00
7	0.00	1.38	0.00	19	1.01	0.16	0.06
8	0.00	0.69	0.00	20	1.06	0.13	0.67
9	0.00	0.88	0.00	21	0.37	0.00	0.00
10	0.00	1.01	0.00	22	1.07	0.04	1.02
11	0.00	0.83	0.00	23	0.88	0.39	0.17
12	1.03	0.19	0.01	24	0.47	0.00	1.58

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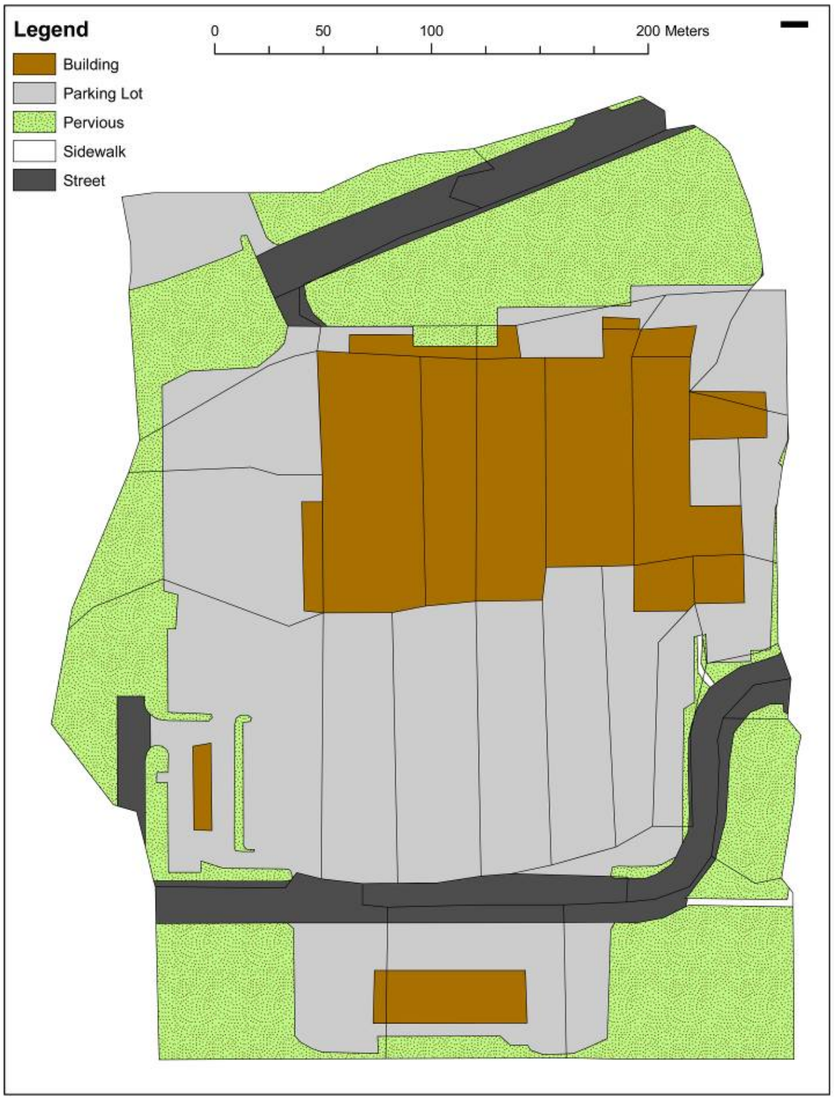

Figure 4.1. Land use map of the Wal-Mart in Hastings, MN, based on GIS data provided by Barr Engineering Co.

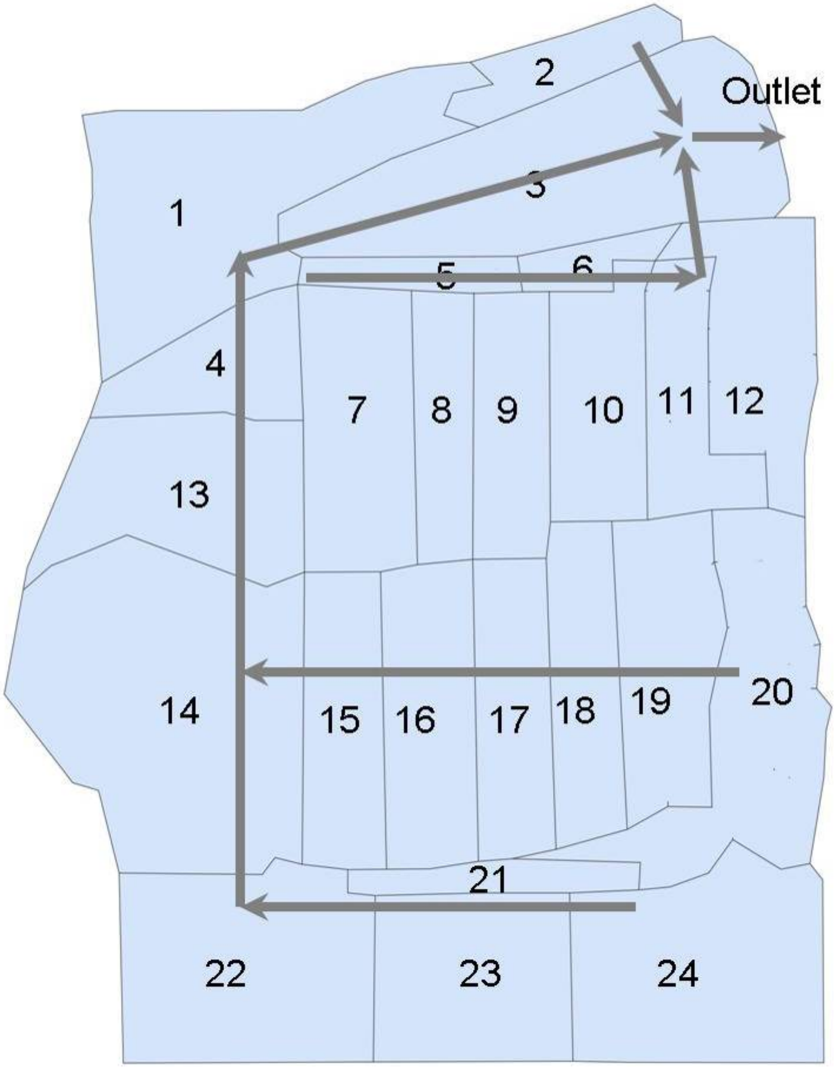

Figure 4.2. The subwatersheds (numbered polygons) and storm sewer drainage network (gray line) f the Wal-Mart site defined for the MINUHET model.

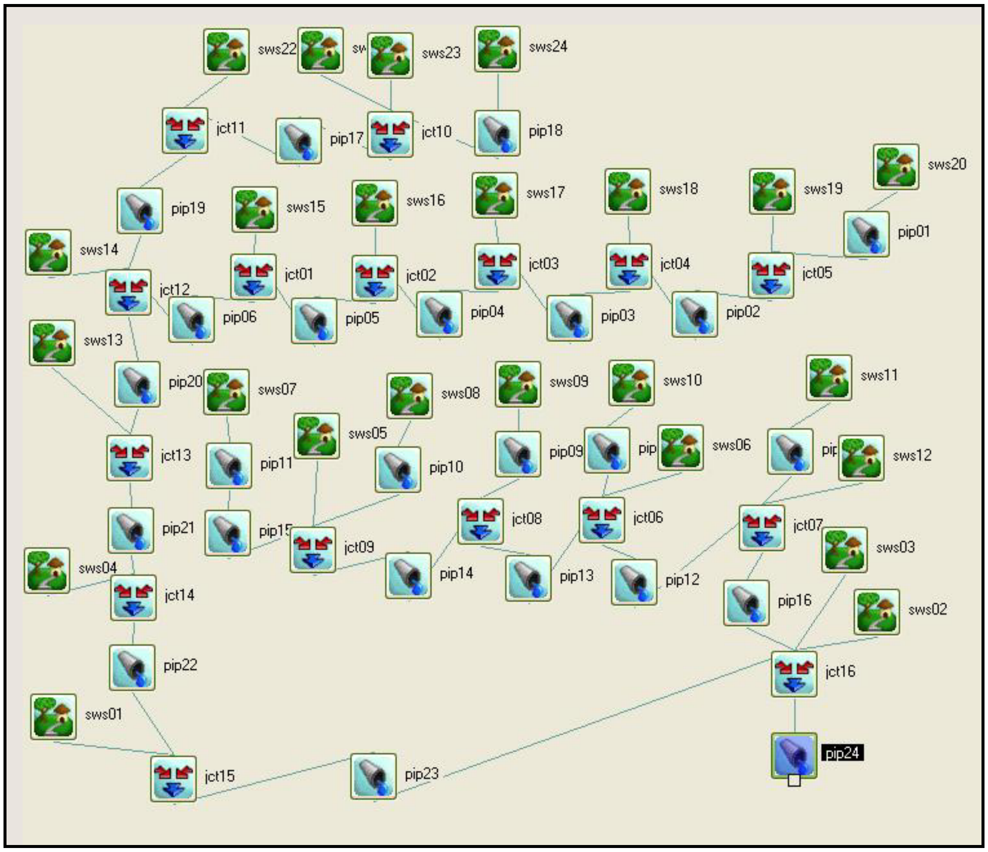

Figure 4.3. MINUHET schematic for the commercial site, with runoff proceeding towards the lower right corner (pip24).

4.2 Thermal loading analysis of the commercial site

Thermal loading analyses of the commercial study site were performed for a total of six cases, using the 2 year, 24 hour storm as the loading storm in all cases:

1. Undeveloped condition (Agricultural)
2. Developed condition, no mitigation
3. Developed condition, rate control mitigation only
4. Developed condition, volume control mitigation only
5. Developed condition, rate and volume control mitigation
6. Developed condition with LID practices

The mitigation ponds used for rate and volume control at the commercial site are summarized in Table 4.2. The rate control pond is a wet detention pond, while the volume control pond is an infiltration pond. The ponds were designed to meet VRWJPO standards for stormwater runoff rate and volume limits by Barr Engineering Co. For the undeveloped case, a single sub-watershed was used with a slope of 4.3%. The low impact development case (LID) was created by reducing pavement areas associated with streets by 15% and by inserting a rain garden to capture the first 0.5” of runoff from the parking lot areas, per Barr Engineering specs.

MINUHET simulations results for runoff volume and maximum flow are compared to results obtained by Barr Engineering using XP-SWMM in Table 4.3. Runoff volumes differ by 0 to 30%, while peak flow rate differ by 2% to 22%. Results for the commercial development outlet temperature, heat export rate, and total heat export are summarized in Table 4.4. Heat export results are given for two reference temperatures, 18 ºC and 20 ºC. Time series of the MINUHET simulation are given in Appendix I.

Table 4.2. Rate and volume control pond specifications for the commercial watershed.

Pond	Type	Surface area, at overflow	Volume, at control depth	Volume, at overflow
Rate control	Wet detention	0.84 acre ($3400\ m^2$)	1.96 acre-ft ($2424\ m^3$)	4.16 acre-ft ($5125\ m^3$)
Volume control, Standard	Infiltration basin	4.3 acre ($41506\ m^2$)	n/a	2.03 acre-ft ($2504\ m^3$)
Volume control, LID	Infiltration basin	3.7 acre ($37680\ m^2$)	n/a	1.76 acre-ft ($2170\ m^3$)
Parking lot runoff, LID	Rain Garden	0.69 acre ($2792\ m^2$)	n/a	0.34 acre-ft ($416\ m^3$)

Table 4.3. Comparison of runoff volume and peak runoff rate obtained with MINUHET and XP-SWMM (Barr Engineering) for the commercial development.

Case	Runoff Volume (acre-ft)		Peak Runoff Rate (cfs)	
	MINUHET	XP-SWMM	MINUHET	XP-SWMM
Undeveloped (Agricultural)	1.4	1.4	13.1	12.8
Developed, no mitigation	5.3	5.3	66.0	56.4
Developed, rate control only	5.2	3.8	13.4	10.7
Developed, rate and volume control	1.4	1.4	1.0	1.2
Developed, LID	1.2	1.2	0.7	1.1

Table 4.4. Summary of runoff temperature and heat export values obtained with MINUHET for the commercial site, using reference temperatures (T_{ref}) of 18 ºC and 20 ºC.

Case	Runoff Temp. (ºC)		Max. Heat Export Rate (MW)		Total. Heat Export (GJ)	
	Ave.	Max.	T_{ref}=18 ºC	T_{ref}=20 ºC	T_{ref}=18 ºC	T_{ref}=20 ºC
Undeveloped (Agricultural)	21.2	21.3	4.6	1.5	22.6	8.3
Developed, no mitigation	21.9	23.4	23.9	8.2	105.8	50.6
Developed, rate control only	24.1	28.2	13.6	10.4	164.2	110.2
Developed, rate/volume control	21.6	23.4	0.5	0.3	26.3	11.6
Developed, LID	21.6	22.9	0.4	0.2	21.8	9.7
Developed, volume control only	21.3	21.6	3.5	1.5	50.6	19.8

5. Discussion and Conclusions

The MINUHET model has been applied to a residential watershed and a commercial watershed to investigate the effect of runoff rate and volume standards on heat loading from the watersheds to receiving waters. The rate control structure, a wet detention pond, was also used as pre-treatment for the volume control structure, an infiltration pond. MINUHET gave similar results for runoff volume and peak runoff rate compared to results generated using XP-SWMM by Barr Engineering Co.

In the case of the residential watershed, the rate control pond was not required to markedly reduce the maximum runoff flow rate (Figure 5.1). Because the rate control pond is wet detention pond, it did increase the average and maximum runoff temperature, as the rainfall runoff entering the rate pond pushed warmed, standing water through the outlet structure. As a result, the rate control pond doubled the total heat export for the storm event over the unmitigated case, from 21.2 GJ to 40.3 GJ. The addition of the volume control pond did reduce the heat export via a reduction in runoff volume, but the resulting total heat export (17.2 GJ) was still higher than the undeveloped (Agriculture) case (10.4 GJ). The thermal mitigation benefit of the volume control pond was likely limited by its overflow volume (0.45 acre-ft), which is about 60% the volume of the rate pond (0.77 acre-ft). Using the volume control pond without the pre-treatment, rate control pond reduced the total heat export to a level (11.2 GJ) close to the undeveloped case (10.4 GJ).

For the case of the commercial development, the rate control pond design did markedly reduce the maximum runoff rate (Figure 5.1), but nonetheless substantially increased the total heat export over the unmitigated case, from 106 GJ to 164 GJ, due to a higher average outlet temperature (24.1 ºC verses 21.9 ºC). However, the combination of the rate and volume control ponds was quite effective at reducing total heat export (26.3 GJ), close to pre-development levels (22.6 GJ). The low impact development (LID) practices also effectively reduced heat export (21.8 GJ). The overall trends in runoff temperature and total heat export for the various residential and commercial cases are summarized in Figure 5.2.

The rate and volume control pond combination specified for the commercial site were more effective in reducing heat loading than the rate and volume control pond specified for the residential site (Figure 5.1). The major difference between the two sites is that the rate control pond for the residential site provided little reduction in rate, while the rate control pond for the commercial site provided about an 80% reduction in peak flow rate (Figure 5.1). The reduced rate of inflow to the volume control pond at the commercial site then led to more infiltration of the warmest, initial runoff, which led to a relatively low average outlet temperature for the commercial volume control pond (21.6 ºC) compared to the residential volume control pond (23.6 ºC). These results suggest that additional design considerations should be developed and employed for stormwater mitigation near temperature sensitive receiving water bodies.

The magnitude of thermal loading to a stream from surface runoff depends on both the runoff temperature (T_{ro}) and the temperature of the receiving water body (T_{ref}), as discussed in Section 2. As expected, maximum heat export rates and total heat export values were higher for T_{ref}=18 ºC compared to T_{ref}=20 ºC. However, the results given in Tables 3.5 and 4.4 indicate that relative increases and decreases in thermal loading for the different land use cases are very similar for the two values of T_{ref}.

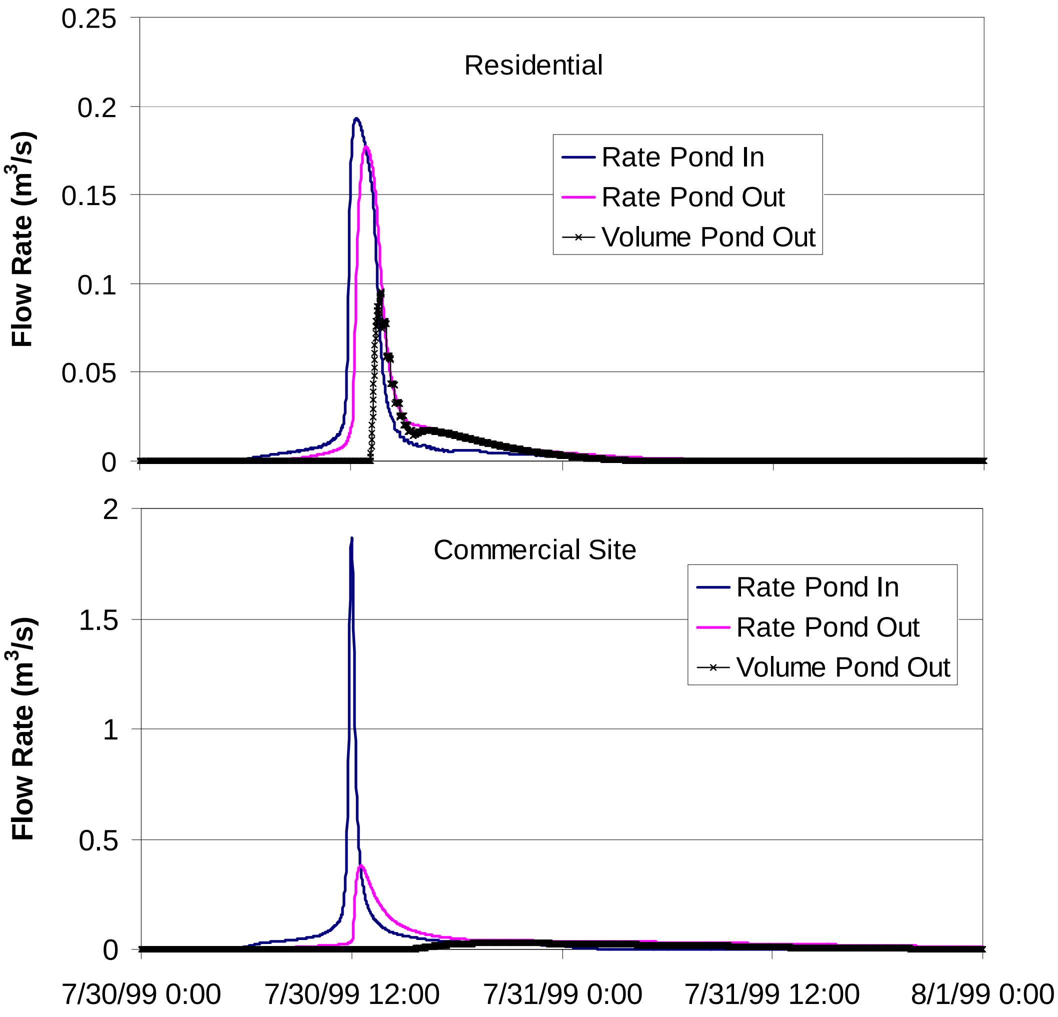

Figure 5.1. Simulated inflow and outflow rates of the rate control and volume control ponds specified for the residential and commercial sites.

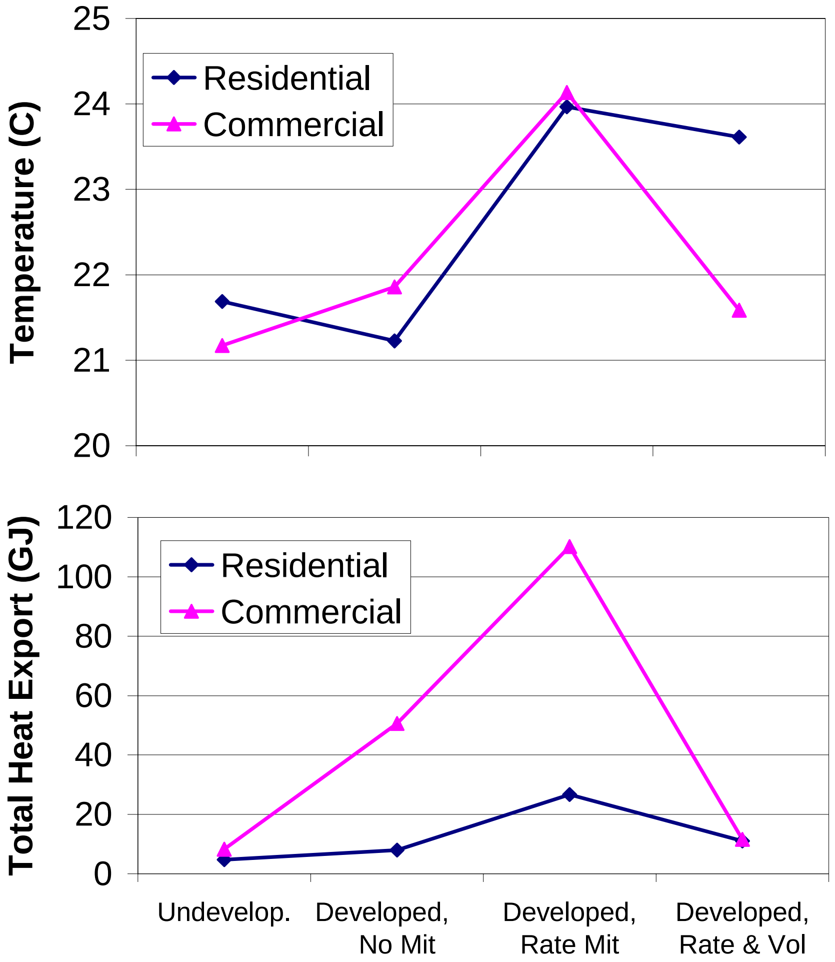

Figure 5.2. Simulated average runoff temperature (upper panel) total heat export (lower panel) from the residential and commercial sites for undeveloped, developed with no mitigation, developed with rate control pond, and developed with rate and volume control ponds. These data are also listed in Tables 3.5 and 4.4.

Acknowledgements

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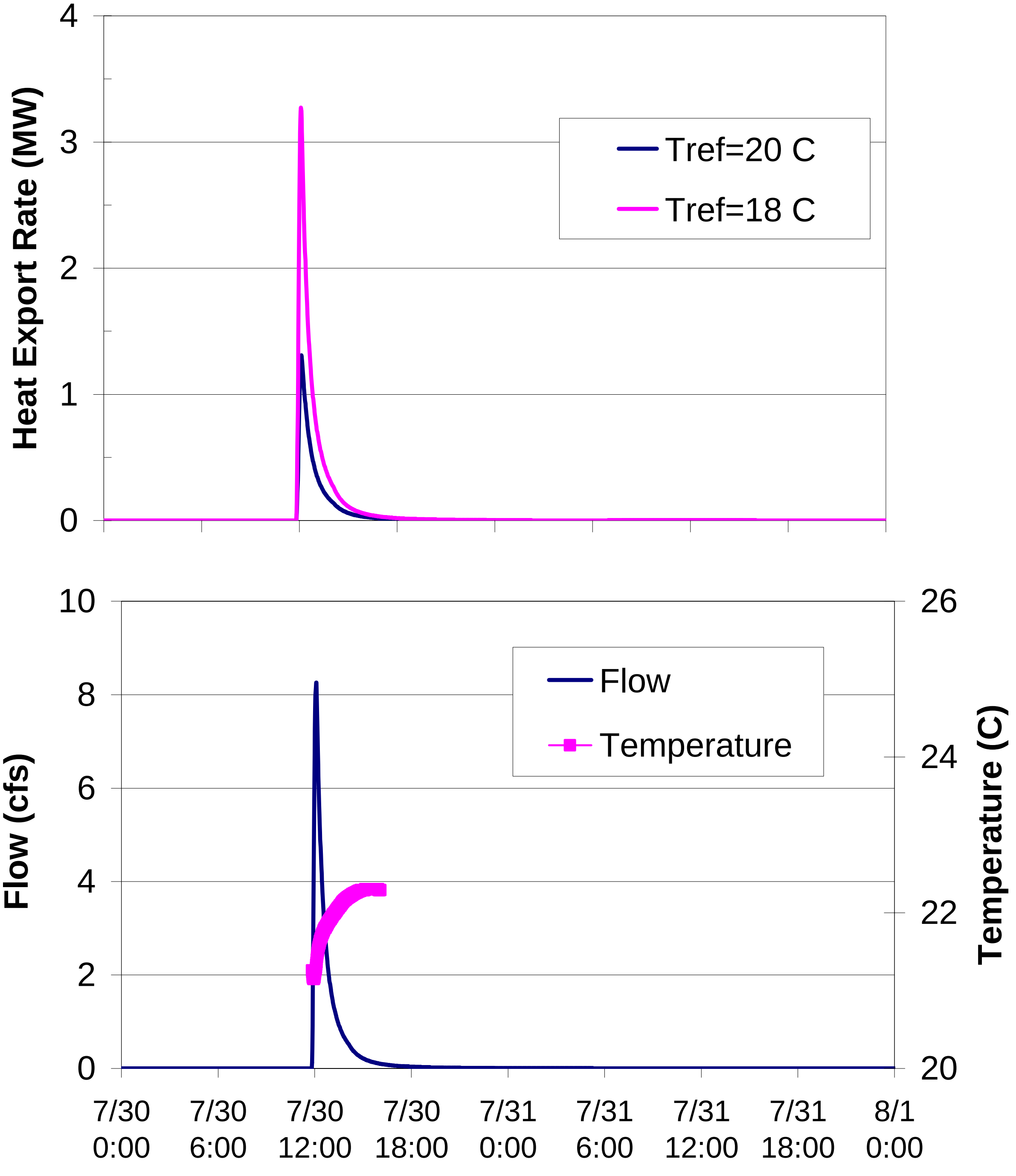
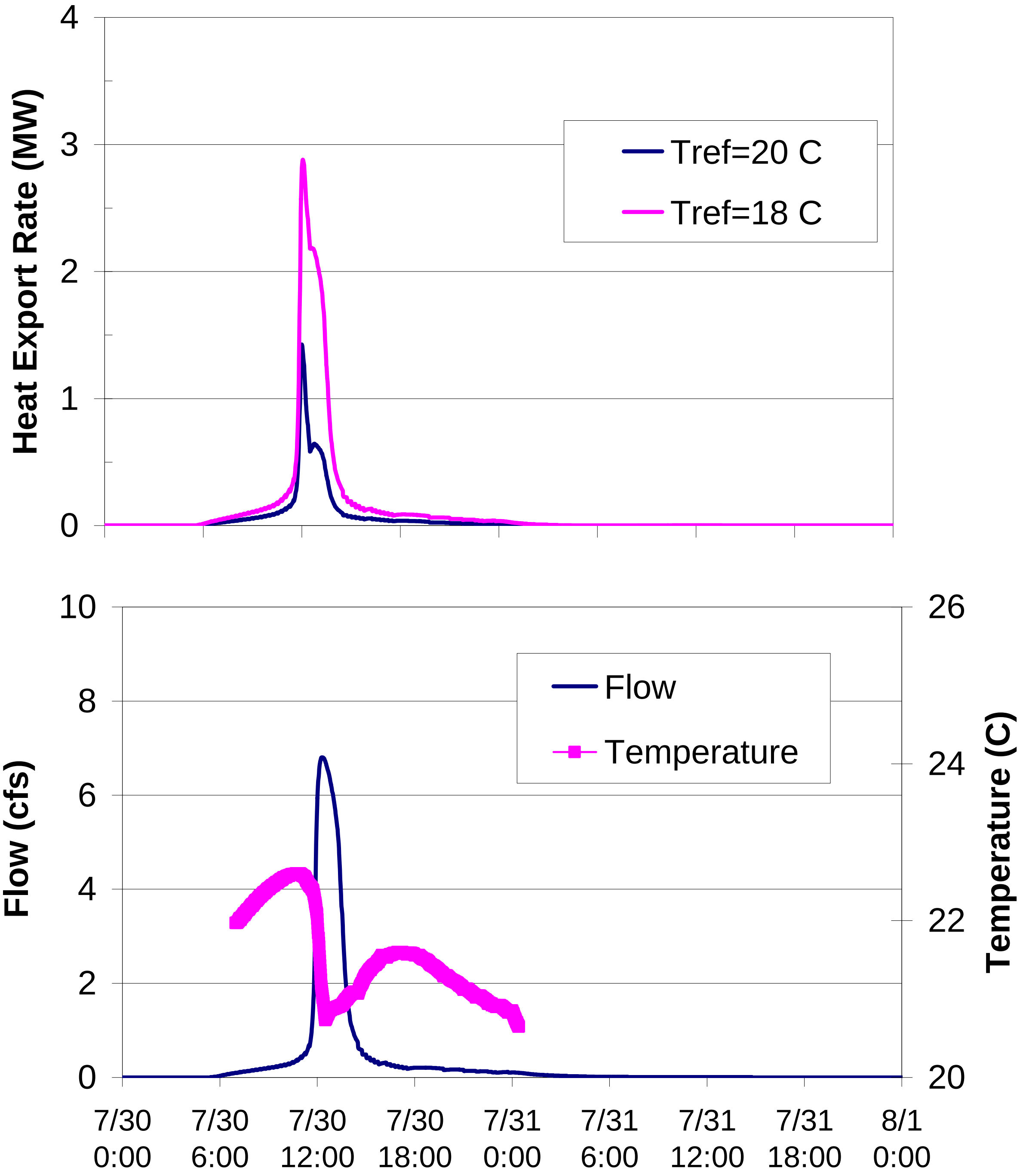
Appendix I. Simulated time series of flow rate, runoff temperature, and heat export

The following plots give time series of runoff flow rate, runoff temperature, and heat export rate at the downstream outlet of the residential and commercial developments for each study case. The simulated data were generated using MINUHET using the 2 year, 24 hour storm event, specified to begin on 12 am on July 30, 1999, with the peak precipitation rate at noon on July 30.

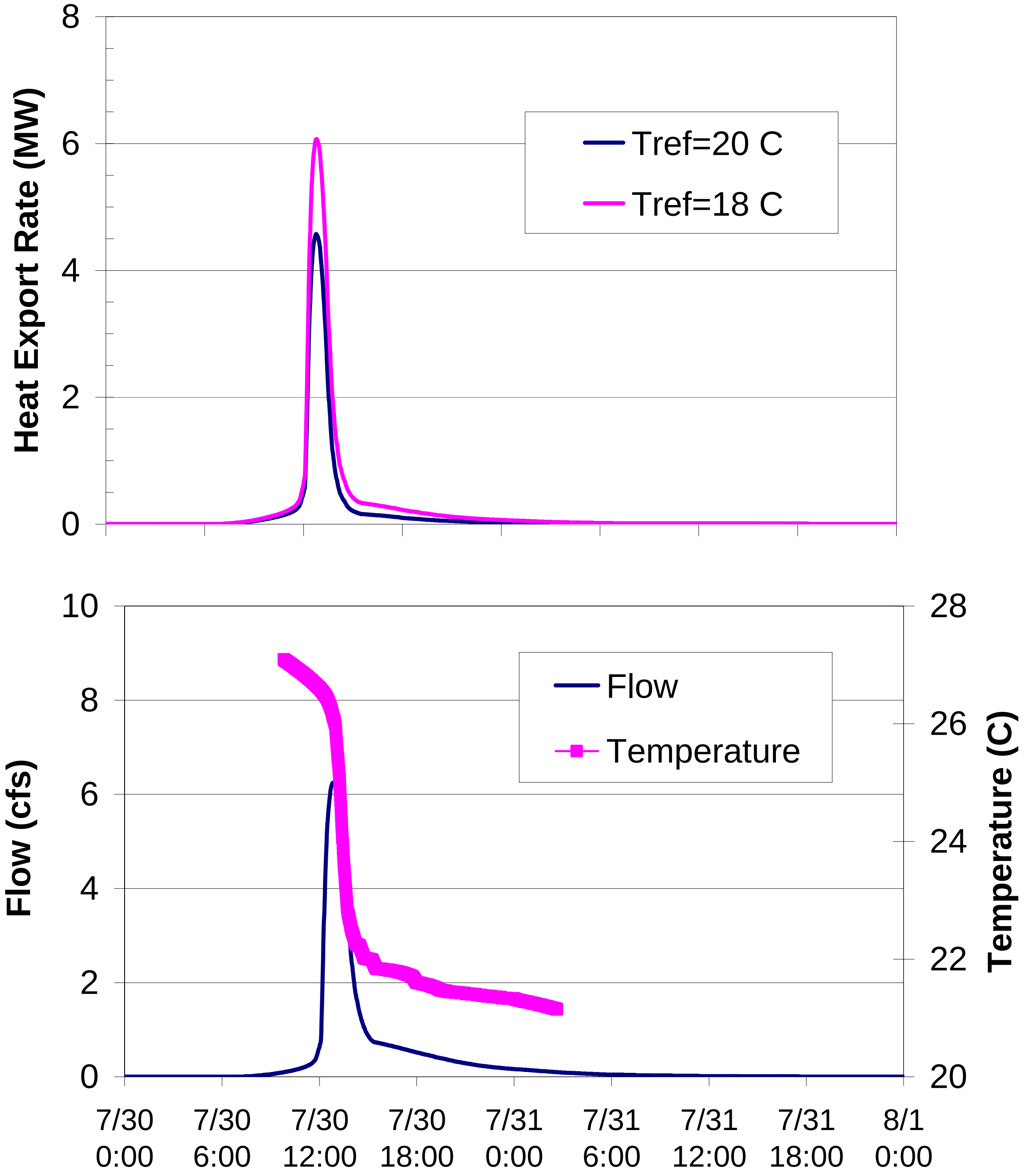
Residential Site, Undeveloped



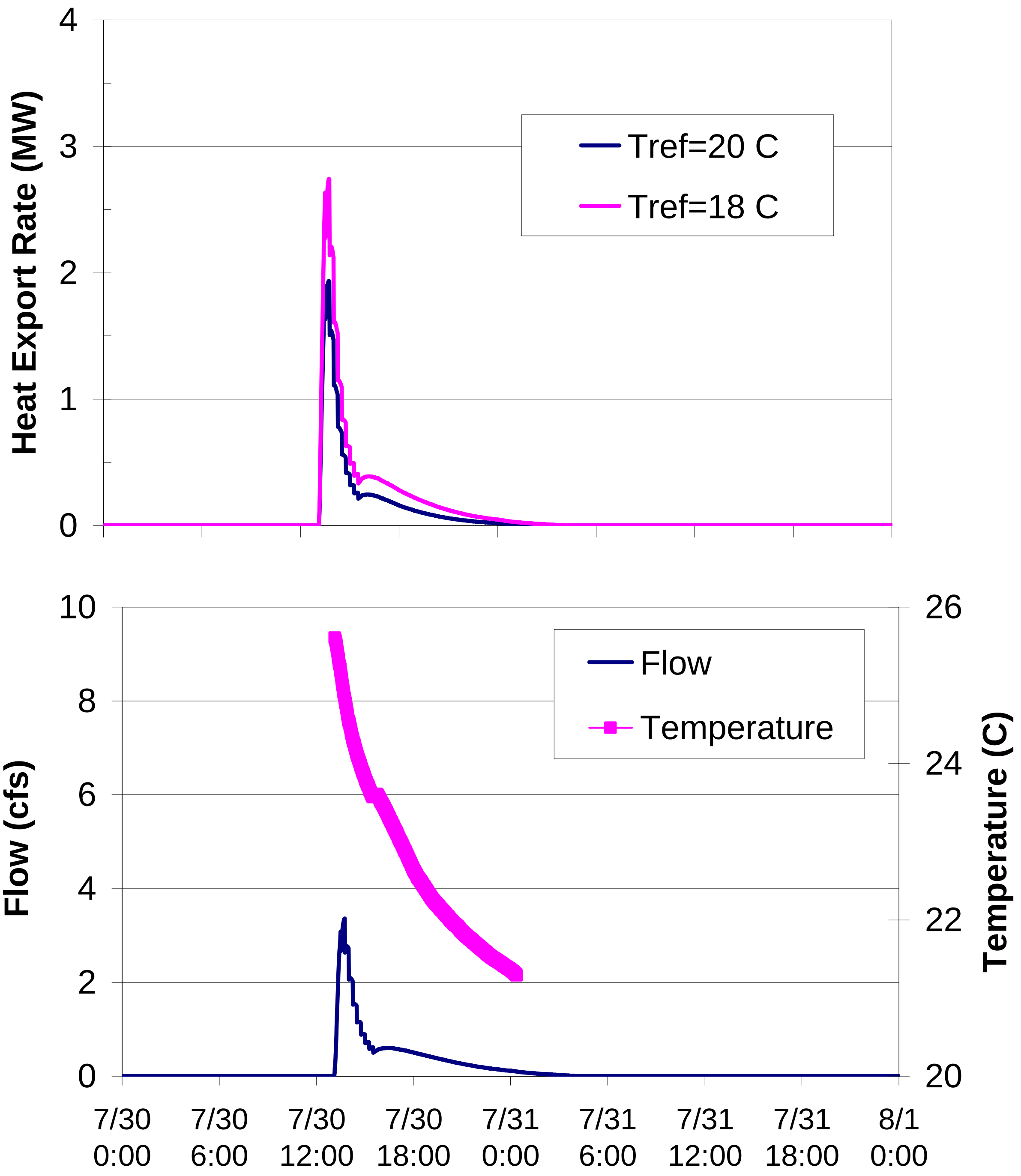
Residential Site, No Mitigation



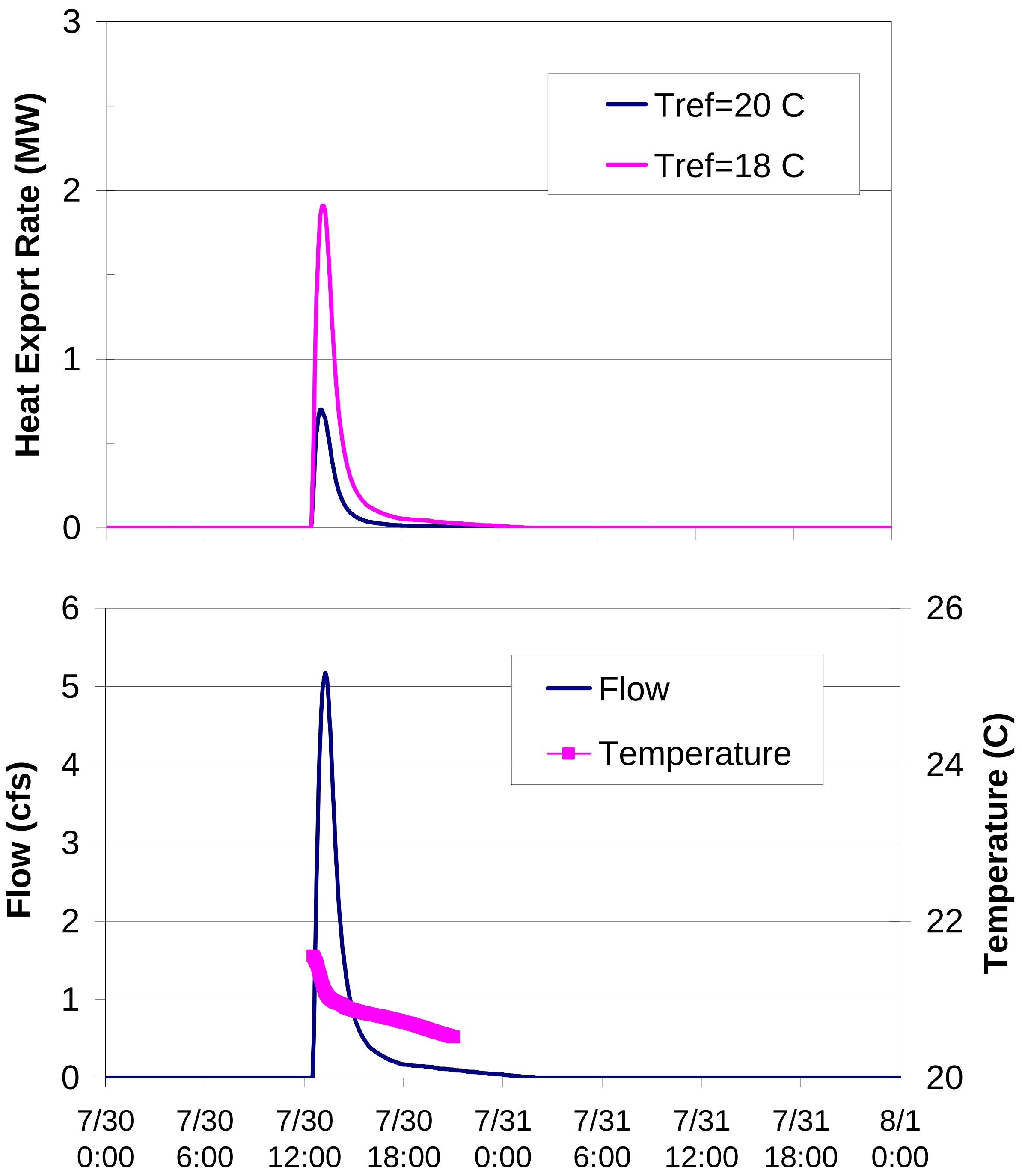
Residential Site, Rate Control Only



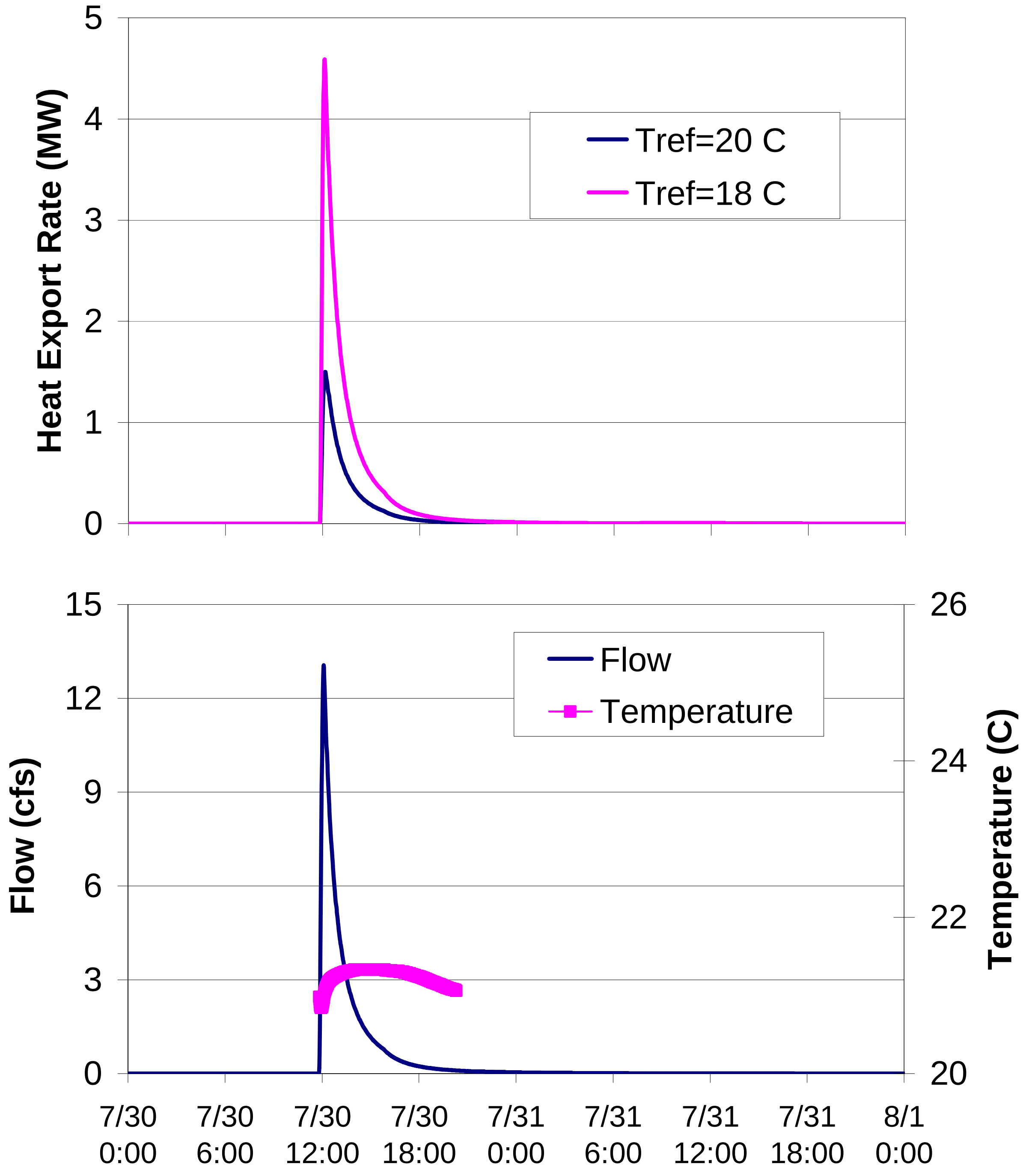
Residential Site, Rate and Volume Control



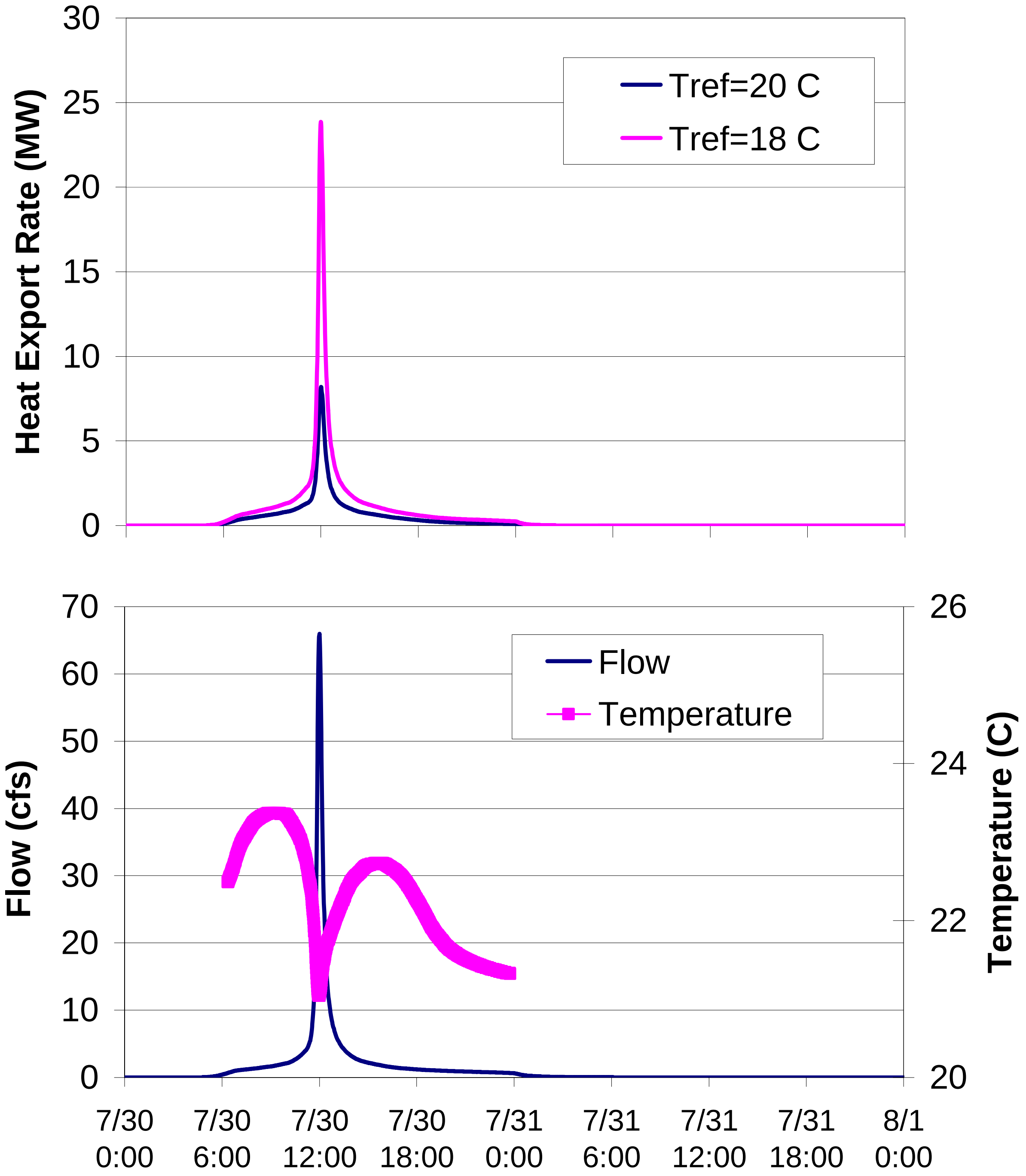
Residential Site, Volume Control Only



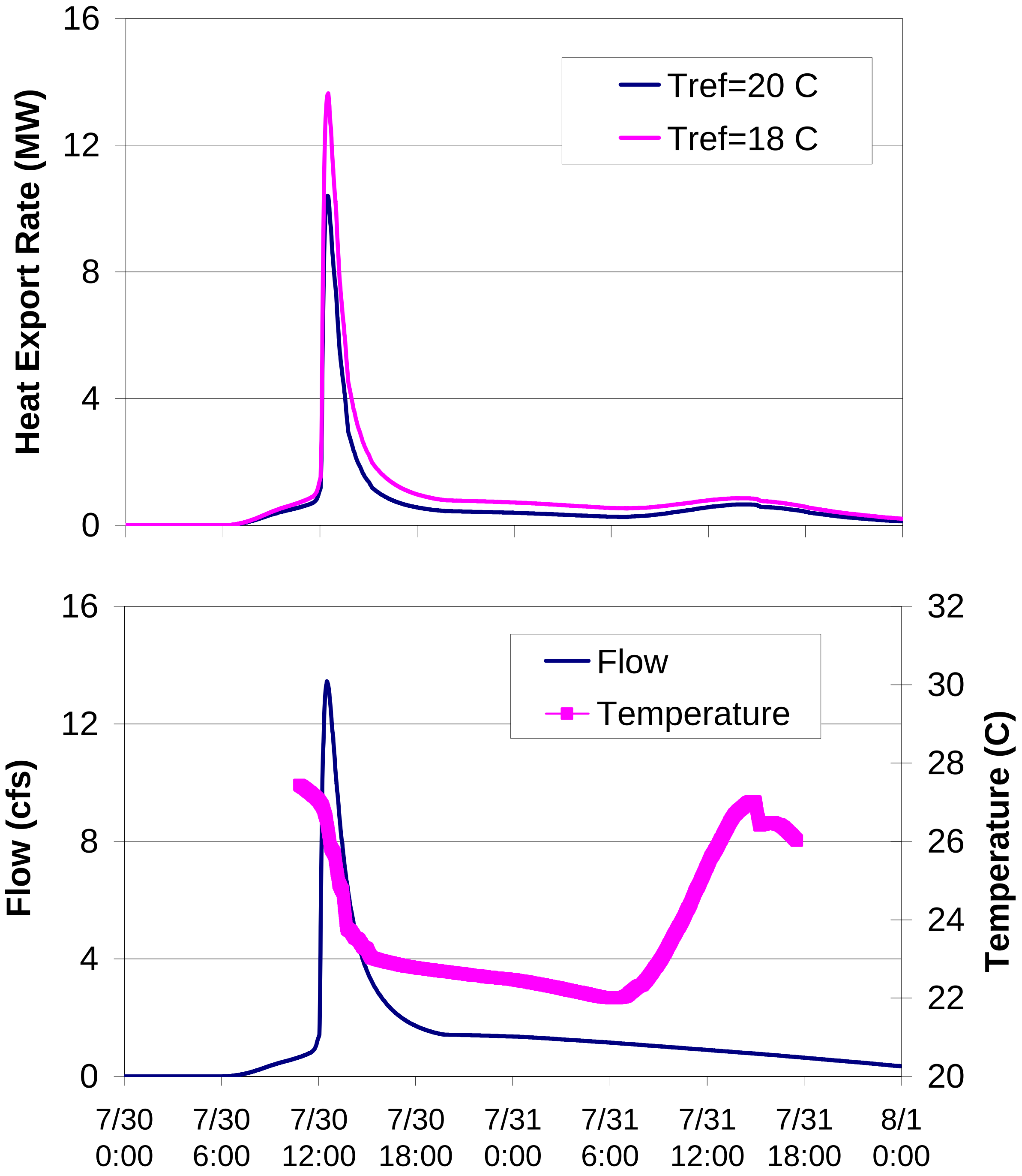
Commercial Site, Undeveloped



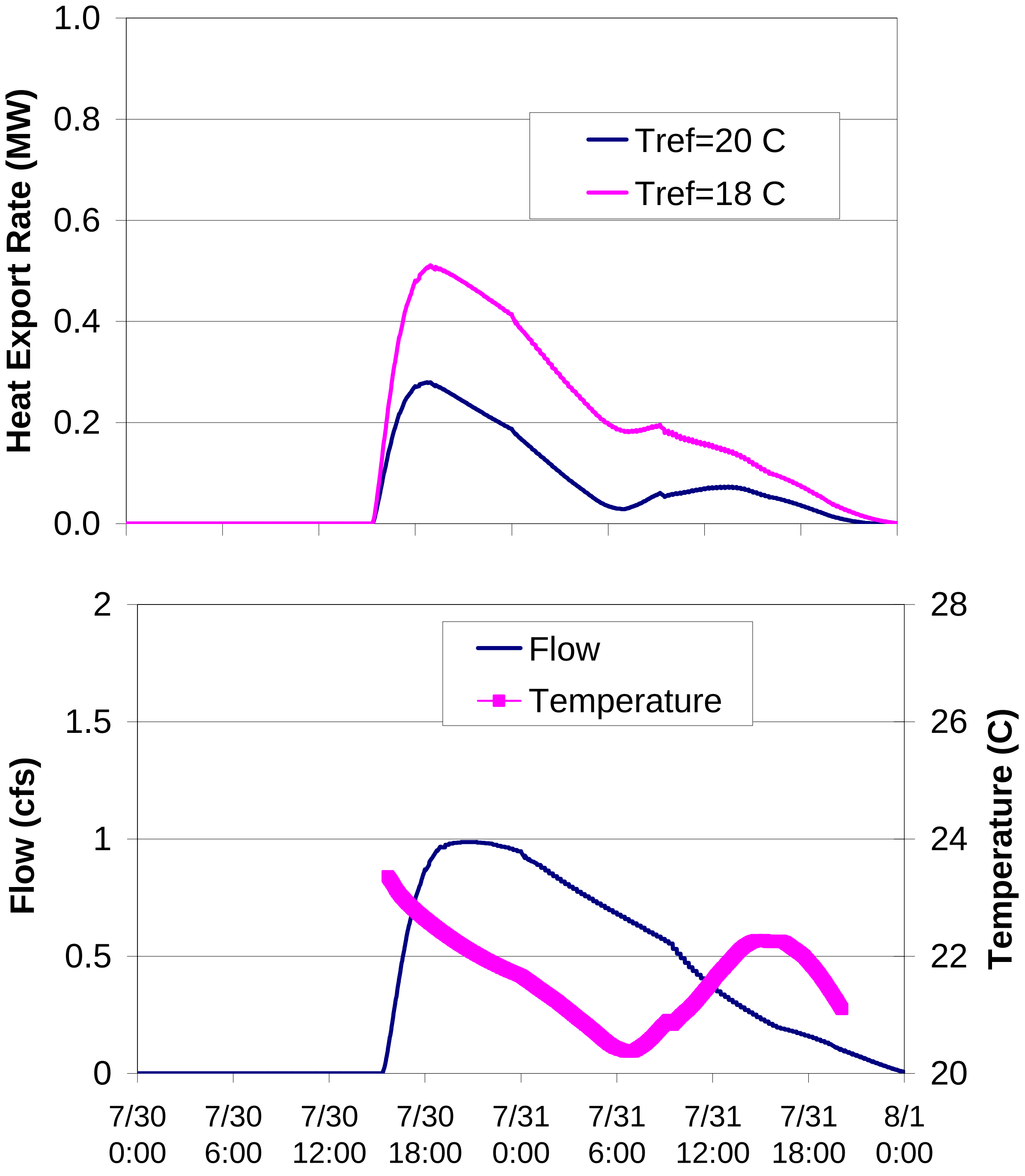
Commercial Site, No Mitigation



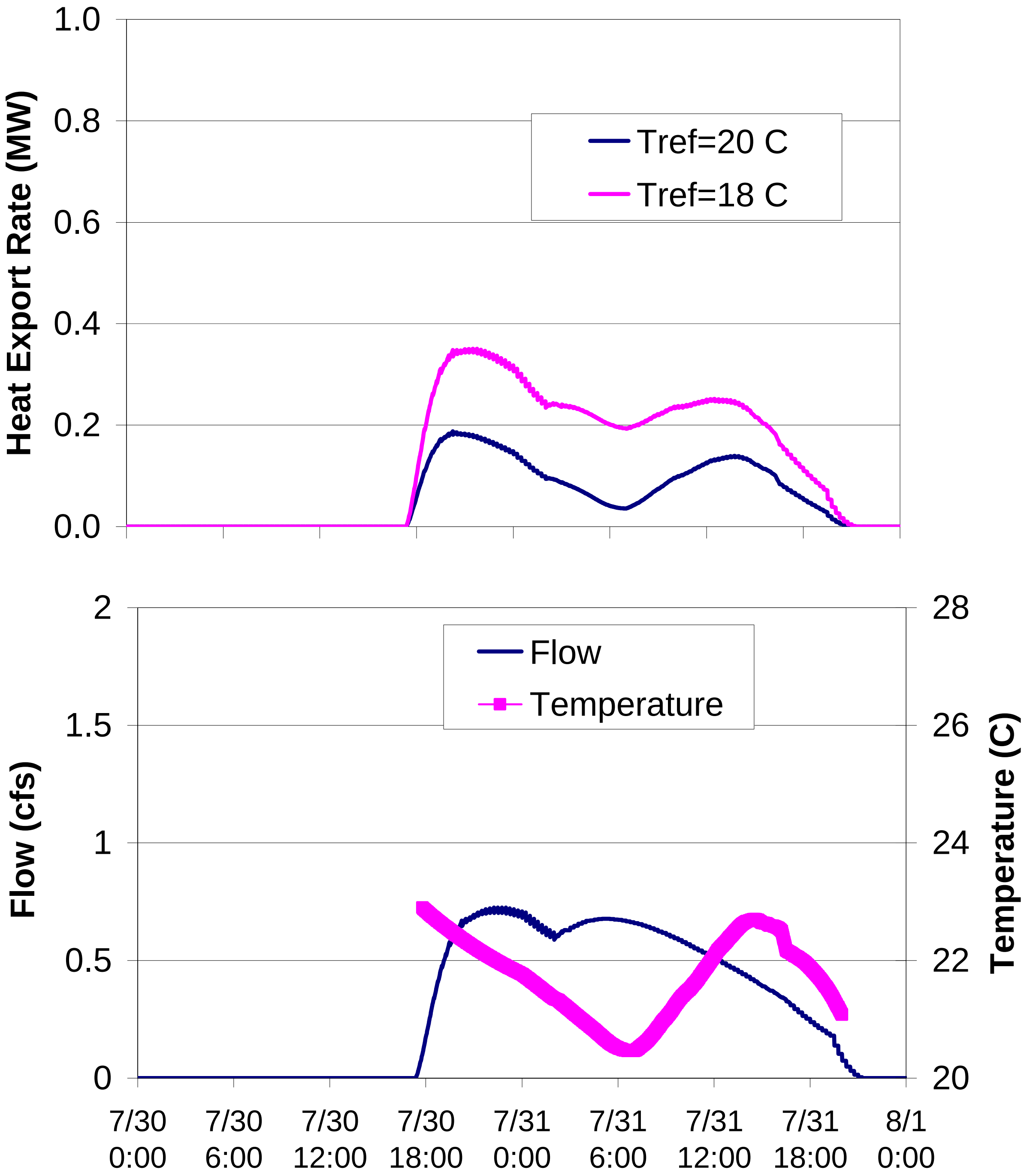
Commercial Site, Rate Control



Commercial Site, Rate and Volume Control



Commercial Site, LID Control



Commercial Site, Volume Control Only