ST. ANTHONY FALLS LABORATORY
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Estimation of Runoff Temperatures and Heat Export from Different Land and Water Surfaces

by

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ABSTRACT

This report describes work to analyze runoff temperatures and runoff heat export rates for a variety of terrestrial land covers and aquatic surfaces. Surface runoff temperatures and heat export have been simulated for ten terrestrial covers, an unshaded wet detention pond, a lake/reservoir, and a vegetated pond. A continuous simulation was run from April 1 to October 31, yielding a total of about 280 precipitation events for six years (1998-2000, 2003-2005). Six years of 15-minute climate data from the weather station at the MnROAD facility in Albertville, MN, were used as model input. In general, the variation in average runoff temperatures from terrestrial land covers and open water surfaces was moderate, from 24.9 °C for concrete to 21.5 °C for a forest. Pavements, commercial rooftops, bare soil, wet detention ponds, and lakes/reservoirs were all found to give runoff temperatures high enough to significantly impact stream temperature. Vegetated surfaces gave substantially lower runoff temperature and heat export than paved surfaces. Runoff temperatures from bare soils were consistently higher than from vegetated surfaces, but lower than from pavements. Residential roofs gave, on average, low runoff temperatures, due to very low thermal mass, while commercial roofs gave high runoff temperatures in some cases. Large water bodies (lakes and reservoirs) generally give very high runoff temperatures, but the quantity of runoff is highly dependent on the water level prior to the storm event. Analysis of a vegetated pond indicates that shading from emergent vegetation can reduce runoff temperature up to 6°C compared to an unshaded pond.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

Residential and commercial development dramatically alters a drainage system by landscaping, including changes in surface cover (pavements and buildings), and addition of new storm sewers and detention ponds. This produces short-term (single storm runoff) effects on stream temperatures, and long term (base flow) effects through changes in infiltration and ground water flow. The degradation of trout habitat by these short and long-term thermal effects is a particular concern of state agencies such as the Minnesota Pollution Control Agency and the Minnesota Department of Natural Resources. A current research project at SAFL therefore is to develop a simulation tool to enable prediction of the effects of residential and commercial developments on the temperature of nearby streams. A key component of this tool is a hydro-thermal model to simulate the temperature and flow rate of stormwater runoff. One and two-dimensional models have been developed that give continuous or event-based temperature and flow simulations for a variety of land uses, including pavement and vegetated land surfaces (Herb et al. 2006a, Herb et al. 2006d, Janke et al. 2006).

This report describes results for simulated runoff temperatures and heat export for a number of impervious and pervious surfaces and land uses. The available data on surface runoff from a variety of land uses do usually not include runoff temperature. Small data sets are described in thermal impact modeling studies, e.g. Van Buren et al. 2000 and thermal mitigation studies, e.g. Thompson and Vandermuss, 2004. Runoff temperature depends on many factors, including land use, the properties of the rainfall event, and the weather prior to the rainfall event. To compare runoff temperature for different land uses, it is necessary to apply the same rainfall event or events and measure the resulting runoff temperature. This dataset is difficult to obtain by field measurements, but is straight-forward to generate using computer simulations. The one-dimensional flow and heat transfer model developed at SAFL (Herb et al. 2006a, Herb et al. 2006d) was therefore used to simulate runoff temperature from different land covers using six years of recorded climate data as input.

2. METHODS OF ANALYSIS

Recorded weather data are the main input to the hydro-thermal analysis described in this report. Precipitation data are required to predict runoff hydrographs while air temperature, humidity, wind, and solar radiation data are required to predict land surface and runoff temperatures prior to and during precipitation events. Standard National Weather Service datasets give weather parameters at 1-hour intervals, which is too long to characterize the surface runoff and water temperature during a rainfall event. In this study we used six years of 15-minute climate data from the weather station at the MnROAD facility in Albertville, MN. Data for 1998 through 2005 were obtained from the Minnesota Department of Transportation (MnDOT). Data for 2001 and 2002 were discarded, because the precipitation data were erroneous.

The runoff temperature for each rainfall event in the 6-year MnROAD dataset was simulated using a one-dimensional (1-D) runoff/heat transfer model (hydro-thermal model), which is described in St. Anthony Falls Laboratory Project Reports No. 479 and 484 (Herb et al. 2006a, 2006d). The 1-D model gives time series of runoff temperature and surface runoff per unit width at, e.g. 15 minute time increments during runoff events, for a specified land use and runoff plot length. The surface and subsurface soil temperatures are also simulated during dry weather periods, to provide realistic initial conditions for each storm event. The model includes the effects of infiltration, soil evaporation, and vegetative shading and wind sheltering. For each year, a continuous simulation was run from April 1 to October 31, yielding a total of about 280 precipitation events for the six years (1998-2000, 2003-2005). Simulations were run for seven land covers: concrete, asphalt, short grass (lawn), tall grass (prairie), forest, crop (corn), and bare soil. Additional simulations were run using separate models for runoff from commercial and residential roofs and for runoff (discharge) from an unshaded wet pond, a lake or reservoir, and a wetland with emergent vegetation.

The runoff depth from pervious surfaces depends on the length of the flow path, since a longer flow path gives a longer residence time, and higher total infiltration for a given precipitation depth. This also influences runoff temperature, since the warmest runoff at the beginning of an event may be lost to infiltration. For the purpose of characterizing runoff temperature, the hydro-thermal runoff analyses were all run for a relatively short plot length of 10 meters, so that the effect of infiltration did not dominate the results. The exceptions are the analyses made for a wet stormwater pond.

To include runoff from rooftops, the hydro-thermal model was modified to replace the soil temperature model component with a simple thermal mass, to represent the thermal mass per unit area of the roof. The surface heat transfer module and the runoff module were unchanged from the standard hydro-thermal model formulations. The roof temperature model was calibrated for a horizontal commercial roof (asphalt/gravel) using 2006 temperature data from the St. Anthony Falls Laboratory (SAFL) roof, and for a sloping residential roof using 2005 data from a metro area house with an asphalt shingle roof. The roof temperature model is discussed in more detail in a report by Herb et al. (2006a).

In addition to land surfaces, including building roofs, the effect of several types of water bodies on runoff temperatures was also investigated. To characterize outflow temperatures from typical lakes and reservoirs, a modified version of the wet detention pond model was created based on previous lake temperature modeling (Riley and Stefan 1988, Hondzo and Stefan 1993). While the wet pond model uses a fixed value for the vertical turbulent diffusion coefficient, the lake model uses a coefficient that varies with lake area and with depth (Hondzo and Stefan 1993). The wet pond model was run at a one hour time step, while the lake model is run at a one day time step, using daily averaged weather parameters. This is done because deeper water bodies require longer time steps to appropriately balance the kinetic energy due to wind mixing with the potential energy of temperature stratification. As to be expected it was found that runoff from a single rainfall event and lake/reservoir thermal characteristics of outflow from a lake are largely uncoupled because of the large thermal inertia of lakes/reservoirs.

Simulation of runoff flow rate and temperature of an unshaded wet detention pond was accomplished using a previously developed pond model described by Herb et al. (2006b). The 1-D model simulated water temperature versus depth and time, typically at 15-minute to 1-hour time intervals. The model includes surface heat transfer with the atmosphere, light attenuation, sediment heat flux, and wind mixing. Outflow rate and temperature are calculated for each time step based on specified inflows and a specified outlet structure, e.g. a broad-crested weir. For the purpose of this study, the model was run using simulated inflow from a 24 acre asphalt parking lot to an actual 1.3 acre, 2.4 m deep wet pond in Woodbury, MN (Herb et al. 2006b). As with the terrestrial land uses, the runoff response of the wet pond was calculated for a database of approximately 280 storms from the MnROAD facility in Albertville, MN. The 20 rainfall events that gave extreme heat export and runoff temperatures in the analysis of different land surfaces (Table 2) were also applied to the pond model and the results are given in Table 4

In general, plant canopy shading and groundwater input may both have significant influence on the temperature of the standing water in a wetland, however, this study considered only the effect of emergent plant shading and wind sheltering. Simulation of the standing water and runoff temperature was performed using the previously described wet pond model (Herb et al. 2006b) with the addition of a plant canopy model. The plant canopy model used to simulate the reduction in water temperature due to emergent plants is the same model used to simulate the reduction in land surface temperature due to terrestrial plants, and is described in detail in Herb et al. (2006a). The model estimates the reduction in solar radiation and wind reaching the land/water surface, plant canopy temperature, and radiative heat transfer between the plant canopy and the underlying land/water surface.

Runoff temperature, by itself, is not a good predictor of thermal impact on a receiving stream. To quantify thermal impact, surface runoff flow rate or runoff depth (runoff volume) must also be considered. The computed surface runoff (q_{ro}, m^2/s) and runoff temperatures (T_{ro}, ^oC) at 15 minute intervals were used to calculate three other parameters: the total heat export (J/m^2) for each rainfall event, the average heat export rate, and the maximum heat export rate (W/m^2) during the rainfall event.

The export rate of heat (energy) per unit surface area (h_{ro} in W/m^2) was calculated for each time step as follows:

$$h_{ro} = (\rho C_p) q_{ro} (T_{ro} - T_{ref}) \tag{1}$$

where q_{ro} and T_{ro} are the surface runoff and runoff temperature at a specific time during the storm event, T_{ref} is a reference temperature. The reference temperature was chosen to be 20°C because coldwater streams can provide trout habitat up to approximately 20^oC. Thus, a positive heat export rate implies the runoff temperature is higher than 20^oC. The magnitude of heat export rate at a given time affects the corresponding increase in stream temperature.

The total heat export for each storm (g_{ro} in J/m^2 or kWh/m^2) is the time integral of the heat export rate (h_{ro}) over the duration of the storm (Equation 2). Precipitation events with gaps of up to 1 hour were treated as a single event. The magnitude of total heat export affects a stream temperature increase over some duration, and thus quantifies the integral thermal impact of a single precipitation event. Further information on heat export analysis is given by Herb et al. (2006c).

$$g_{ro} = \int h_{ro} \, dt \tag{2}$$

3. RESULTS: ALL-WEATHER (DRY AND WET) SURFACE TEMPERATURES

Surface temperatures for ten surface covers/land uses and continuous real weather parameter time series are given as weekly averaged values (Figure 1) and as mean monthly values (Table 1). These temperatures include both wet and dry weather periods. The seasonal variations are readily apparent. Since surface temperatures in July may be of most interest to thermal loading of trout streams, the rows of Table 1 are sorted by July temperature, from highest to lowest. The roof surfaces, although giving the highest peak temperatures, have lower average temperature than asphalt and concrete, because they cool off more at night. Asphalt and concrete surfaces give the highest average surface temperatures. Short grass, corn, soybeans and forest give very similar surface temperatures, about 10°C lower than pavement average temperature and 20°C lower than pavement average daily maximum temperature. Bare soil gives surface temperatures that lie between those for pavements and vegetated surfaces. Interestingly, the surface temperature of the wet stormwater pond is very similar to that of bare soil. The crop covers (corn or soybeans) give surface temperatures similar to bare soil earlier in the year, but are similar to the natural vegetative covers in mid-year, as the plant canopy develops. The small differences in temperature between the vegetative covers in mid-year are probably less than the uncertainty in the temperature simulations.

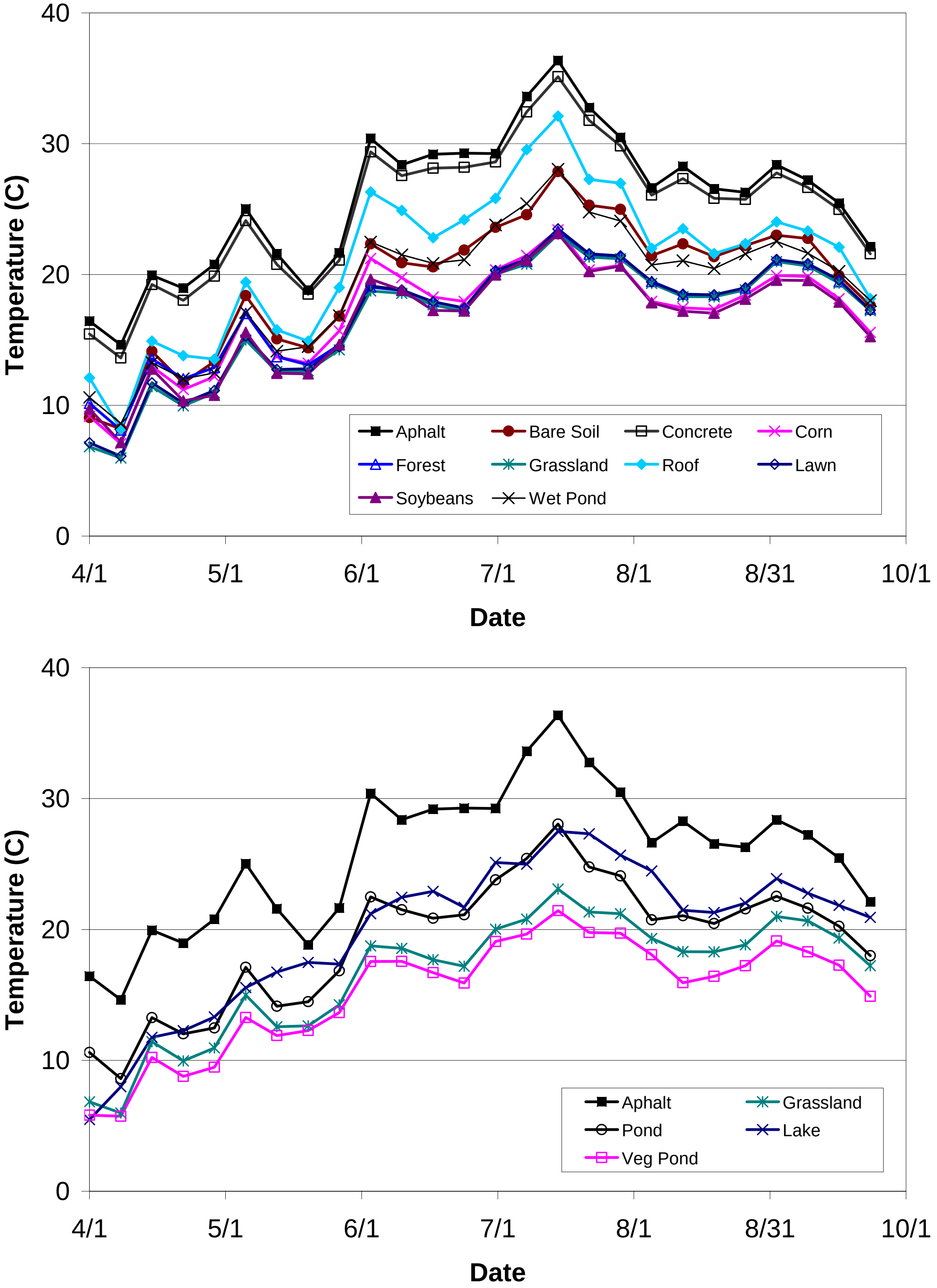

Figure 1. Simulated average weekly surface temperature for ten land uses calculated with hourly climate data from St. Paul (2004) as model input. The roof data shown are for a commercial roof; the residential data are very similar (Table 1).

Table 1. Simulated average surface temperature, average daily maximum surface temperature, and average daily minimum surface temperature by month for 2004 climate data from St. Paul.

Month	April	May	June	July	August	September
Average Surface Temp (°C)						
Asphalt	17.6	21.7	28.8	32.6	27.3	25.7
Concrete	16.8	21.0	27.8	31.7	26.7	24.8
Com. Roof	12.3	16.5	24.3	28.3	23.1	20.9
Res. Roof	12.5	16.7	23.6	27.1	21.8	20.3
Reservoir	9.6	16.2	21.8	26.1	22.8	19.4
Pond	11.2	15.1	21.2	25.2	21.4	18.9
Bare Soil	10.9	15.7	21.1	25.2	22.2	19.1
Sod	9.0	13.3	18.1	21.5	19.2	16.3
Forest	11.1	14.3	18.0	21.4	19.2	16.8
Grassland	8.8	13.1	17.8	21.2	19.0	16.0
Corn	10.2	14.5	19.0	21.2	18.2	16.7
Soybeans	10.1	13.2	18.0	20.9	18.0	16.1
Veg Pond	7.8	12.1	16.7	19.9	17.3	14.8
Average Daily Maximum Surface Temp (°C)						
Asphalt	35.5	37.4	46.9	50.8	44.7	43.2
Com. Roof	32.9	33.9	45.7	50.6	44.3	41.6
Res. Roof	34.9	36.2	46.0	50.5	43.9	42.5
Concrete	31.3	33.9	42.6	46.4	40.7	39.1
Bare Soil	20.5	23.7	29.9	34.3	31.8	28.2
Pond	15.9	19.3	25.9	29.9	26.4	23.5
Corn	17.2	20.4	24.1	24.3	20.7	21.4
Soybeans	16.6	16.8	21.5	23.8	20.3	19.8
Sod	11.3	15.2	20.1	23.7	21.2	18.4
Forest	17.3	17.3	19.9	23.4	21.0	19.8
Grassland	10.9	14.8	19.6	23.1	20.8	17.9
Veg Pond	9.1	13.4	18.3	21.7	18.9	16.4
Average Daily Minimum Surface Temp (°C)						
Pond	7.4	11.5	16.9	21.1	17.2	14.9
Concrete	6.5	11.9	16.9	21.0	17.3	14.8
Asphalt	5.6	11.1	16.0	20.0	16.3	13.9
Forest	5.9	11.4	16.0	19.3	17.2	14.0
Sod	6.7	11.2	15.7	19.2	17.0	14.0
Grassland	6.7	11.3	15.7	19.1	17.1	14.0
Veg Pond	6.8	11.0	15.4	18.5	16.1	13.6
Corn	4.5	9.3	14.4	18.1	15.4	12.4
Bare Soil	3.7	9.1	13.9	18.0	15.3	12.1
Soybeans	4.7	9.7	14.5	18.0	15.4	12.5
Com. Roof	-3.1	3.0	7.7	11.0	7.3	5.2
Res. Roof	-5.1	0.5	5.9	8.8	5.5	3.2

4. RESULTS: RUNOFF TEMPERATURES AND HEAT EXPORT FROM TERRESTRIAL SURFACES WITH DIFFERENT LAND USES

Simulated runoff temperatures and heat export parameters are given in Table 2 for nine land uses. Each table includes data for the twenty storm events that had the highest total heat export for runoff from asphalt. Each table therefore contains the same storm events in the same order. Twenty storm events are given in Table 3, giving the pond and lake/reservoir runoff events and the heat export and average runoff temperature for the asphalt parking lot draining to the pond for the same period of time.

Runoff from concrete, asphalt, and bare soil had similarly high runoff temperatures and heat export values; concrete had the highest average heat export. Although the average surface temperature of bare soil and concrete are lower than that of asphalt, the asphalt surface cooled more rapidly prior to rainfall events. Commercial roof surfaces also gave relatively high average heat export and runoff temperatures, but with greater storm to storm variation compared to pavement. An explanation for this behavior is that the commercial roof has higher average surface temperature and no infiltration, tending to increase heat export, but the roof cools more rapidly prior to storm events. The residential roof had the lowest overall runoff temperature and heat export values, because it has low thermal mass, and cools very quickly prior to and during a storm event.

As expected, the vegetated land surfaces (corn, lawn, tall grass, forest) had runoff temperatures and heat exports that are substantially lower than those for pavement. For mid-summer rainfall events, the vegetated land surfaces gave very similar results regardless of the type of vegetation. A difference between the vegetation types was apparent in early summer, e.g. during a June 20, 2005 rainfall event. Agricultural lands tend to give higher runoff temperatures and heat export values before the crop is fully developed. The runoff temperatures and heat export values per unit area given in this report may be considered to be on the high side, since a relatively short runoff length (10 m) was used for the analysis. Actual surface runoff rates and flow temperatures depend largely on the infiltration characteristics of the underlying soil.

It is worthwhile to point out differences in the rainfall events. The rainfall event with the highest heat export (June 24, 2003), was of very long duration (9.7 hrs) and had a very large amount of rainfall (21 cm) at a high dew point temperature (20.0^{o}C). The runoff temperatures for the paved surface and the vegetated land surface differed little for this rainfall event. In contrast, the rainfall event with the fourth highest ranking occurred on June 20, 2005, was of shorter duration (2 hrs), produced less total rainfall (3.8 cm) of lower temperature (18.3^{o}C) and had substantial solar radiation prior to the event. It produced more varied runoff temperature with land use. Climate data for these two rainfall events are shown in Figure 2, and Table 3 summarizes runoff temperatures for these two events for the nine land uses. The June 20 event gives much more variation in runoff temperature with land use (5.9^{o}C) compared to the June 24 event (2.1^{o}C).

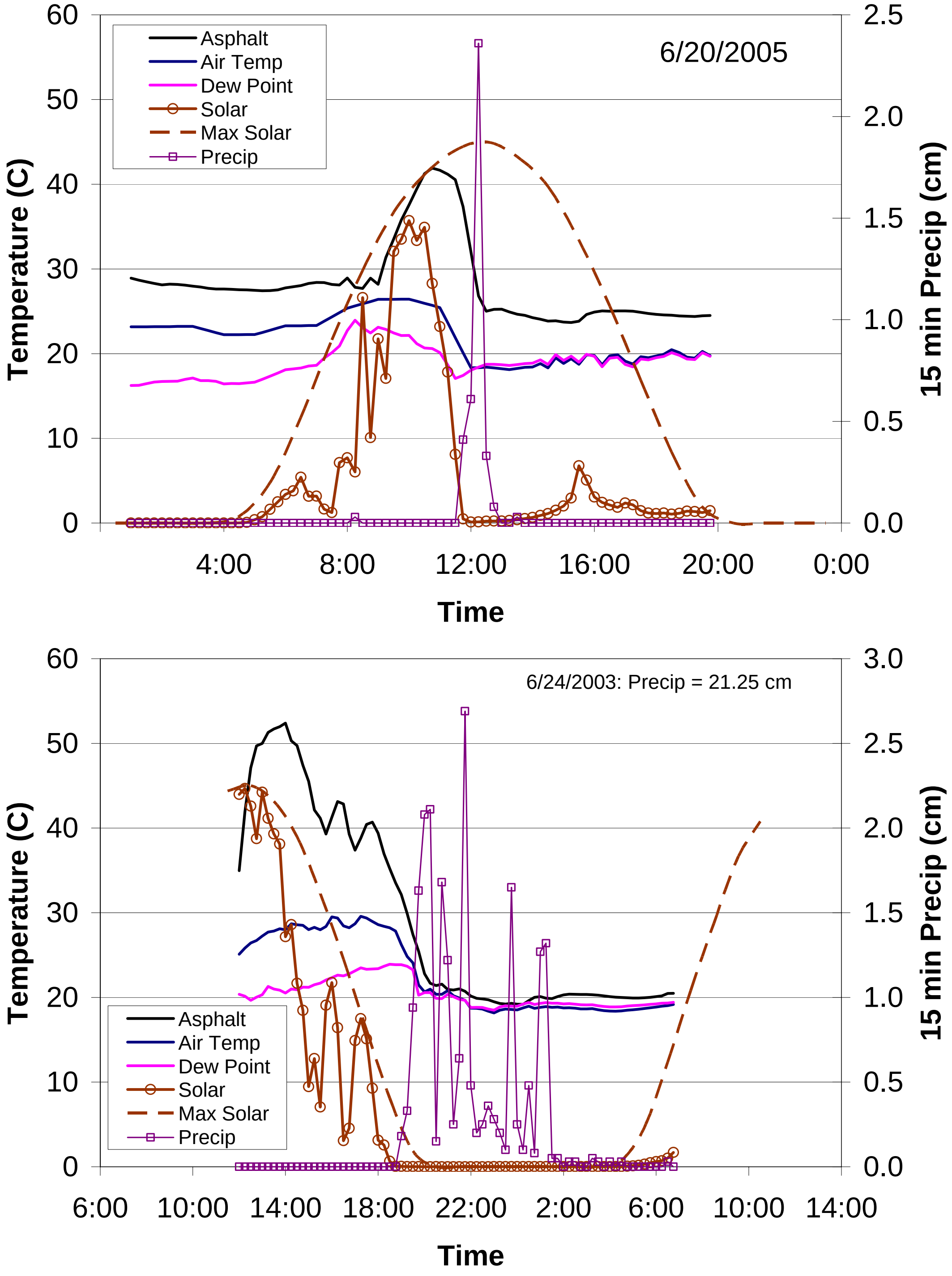

Figure 2. Climate data and asphalt temperatures for rainfall events on June 20, 2005 and June 24, 2003, from the MnROAD climate data base. Solar radiation is in W/m^2 per 15 min and can be read on the left scale.

Table 2. Ranking of the simulated top twenty heat export and runoff temperature events for nine types of land use. Rainfall events were taken from six years of climate data (1998-2000, 2003-3005) from the MnROAD site. Runoff data were simulated using the 1D hydro-thermal runoff model developed at SAFL.

Asphalt

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	862.16	24.56	232.27	9.75	21.22	21.06	20.01	20.97	29.66	1.02
83	2	7/25/99 21:29	499.43	61.66	241.60	2.25	3.18	3.14	21.64	23.79	24.61	1.25
265	3	8/16/05 16:30	431.89	239.94	432.20	0.50	1.12	1.09	16.63	29.41	30.07	1.02
256	4	6/20/05 11:30	429.83	59.70	204.30	2.00	3.82	3.77	18.29	22.72	31.78	0.41
85	5	7/30/99 15:45	371.21	29.46	188.73	3.50	2.06	1.96	20.65	24.52	30.91	1.01
24	6	7/14/98 19:59	355.90	18.83	277.78	5.25	5.61	5.57	18.41	21.52	28.90	2.00
34	7	9/19/98 15:45	327.98	121.48	328.73	0.75	1.47	1.42	16.40	25.50	35.29	1.27
77	8	6/22/99 15:14	300.34	15.17	199.43	5.50	1.46	1.26	20.02	25.66	29.20	0.52
215	9	8/25/04 16:44	291.96	29.49	290.55	2.75	2.96	2.94	18.88	22.37	26.09	1.14
255	10	6/13/05 17:15	255.91	40.62	155.38	1.75	0.53	0.47	19.95	32.97	35.10	0.25
254	11	6/11/05 12:29	254.14	40.34	95.98	1.75	1.03	1.00	23.87	26.04	27.62	0.40
262	12	7/23/05 9:00	246.43	34.23	143.96	2.00	1.92	1.90	19.11	23.09	25.13	0.67
276	13	9/21/05 17:30	246.25	22.80	268.19	3.00	5.65	5.63	17.90	21.04	25.14	1.24
13	14	6/18/98 13:15	235.50	65.42	112.60	1.00	1.17	1.14	20.14	24.93	27.99	0.55
175	15	7/31/03 15:45	232.38	36.89	153.23	1.75	0.77	0.69	18.41	28.01	32.27	0.55
209	16	7/28/04 18:29	229.89	25.54	171.34	2.50	1.69	1.58	19.86	23.46	24.60	0.89
170	17	7/14/03 12:29	226.17	41.88	101.33	1.50	2.09	2.05	20.01	22.62	26.49	1.17
17	18	6/26/98 16:30	217.30	80.48	111.84	0.75	0.74	0.69	20.22	27.51	32.46	0.44
259	19	6/27/05 16:44	189.10	23.35	70.93	2.25	1.98	1.95	18.92	22.31	26.21	0.65
16	20	6/25/98 0:00	182.55	33.80	157.54	1.50	1.80	1.79	20.55	22.43	23.66	1.03
		Average	319.32	52.28	196.90	2.60	3.11	3.06	19.49	24.54	28.66	3.57
		Standard Deviation	154.49	50.85	90.23	2.14	4.50	4.48	1.67	3.07	3.50	2.94

Bare Soil

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	969.22	27.61	228.39	9.75	21.22	18.07	20.01	21.28	28.00	1.66
83	2	7/25/99 21:29	464.65	57.36	233.02	2.25	3.18	2.41	21.64	24.59	25.13	1.08
265	3	8/16/05 16:30	359.26	199.59	360.63	0.50	1.12	0.89	16.63	29.63	29.91	0.87
256	4	6/20/05 11:30	379.84	52.76	181.60	2.00	3.82	3.25	18.29	22.78	28.76	2.43
85	5	7/30/99 15:45	271.53	21.55	216.02	3.50	2.06	1.12	20.65	25.78	31.23	0.85
24	6	7/14/98 19:59	528.28	27.95	375.90	5.25	5.61	3.56	18.41	23.54	29.65	1.83
34	7	9/19/98 15:45	322.65	119.50	313.44	0.75	1.47	1.20	16.40	26.39	32.54	1.11
77	8	6/22/99 15:14	191.18	9.66	111.38	5.50	1.46	0.86	20.02	25.27	27.00	0.38
215	9	8/25/04 16:44	207.86	21.00	202.54	2.75	2.96	2.02	18.88	22.45	24.95	0.97
255	10	6/13/05 17:15	88.21	14.00	51.62	1.75	0.53	0.21	19.95	30.20	30.41	0.12
254	11	6/11/05 12:29	91.90	14.59	53.96	1.75	1.03	0.46	23.87	24.78	25.97	0.27
262	12	7/23/05 9:00	257.71	35.79	141.91	2.00	1.92	1.39	19.11	24.42	25.89	0.91
276	13	9/21/05 17:30	148.74	13.77	161.13	3.00	5.65	4.53	17.90	20.78	23.55	1.08
13	14	6/18/98 13:15	138.13	38.37	83.65	1.00	1.17	0.71	20.14	24.64	26.09	0.42
175	15	7/31/03 15:45	120.78	19.17	104.70	1.75	0.77	0.45	18.41	26.40	28.38	0.41
209	16	7/28/04 18:29	175.53	19.50	126.05	2.50	1.69	1.17	19.86	23.57	24.12	0.73
170	17	7/14/03 12:29	155.36	28.77	94.87	1.50	2.09	1.50	20.01	22.47	24.91	1.00
17	18	6/26/98 16:30	98.67	36.55	78.42	0.75	0.74	0.37	20.22	26.42	29.58	0.31
259	19	6/27/05 16:44	83.01	10.25	38.82	2.25	1.98	1.17	18.92	21.69	23.30	0.49
16	20	6/25/98 0:00	137.00	25.37	110.70	1.50	1.80	1.24	20.55	22.64	23.06	0.86
		Average	259.48	39.66	163.44	2.60	3.11	2.33	19.49	24.49	27.12	3.57
		Standard Deviation	211.20	44.89	99.82	2.14	4.50	3.88	1.67	2.52	2.83	2.94

Commercial Roof (Asphalt/Gravel)

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	-195.85	-5.58	232.40	9.75	21.22	21.08	20.01	19.78	30.56	1.02
83	2	7/25/99 21:29	159.93	19.74	143.03	2.25	3.18	3.14	21.64	21.21	22.73	1.25
265	3	8/16/05 16:30	596.48	331.38	605.16	0.50	1.12	1.09	16.63	33.07	34.18	1.02
256	4	6/20/05 11:30	539.65	74.95	272.85	2.00	3.82	3.76	18.29	23.42	35.97	0.41
85	5	7/30/99 15:45	189.32	15.03	116.17	3.50	2.06	1.97	20.65	22.29	31.35	1.01
24	6	7/14/98 19:59	-170.01	-9.00	226.20	5.25	5.61	5.61	18.41	19.28	26.52	2.01
34	7	9/19/98 15:45	418.58	155.03	426.93	0.75	1.47	1.42	16.40	27.03	35.31	1.27
77	8	6/22/99 15:14	328.39	16.59	233.20	5.50	1.46	1.27	20.02	26.18	30.81	0.51
215	9	8/25/04 16:44	339.43	34.29	479.51	2.75	2.96	2.94	18.88	22.75	30.09	1.13
255	10	6/13/05 17:15	286.66	45.50	173.05	1.75	0.53	0.47	19.95	34.66	36.97	0.24
254	11	6/11/05 12:29	238.37	37.84	87.04	1.75	1.03	1.00	23.87	25.66	27.76	0.40
262	12	7/23/05 9:00	176.99	24.58	118.65	2.00	1.92	1.91	19.11	22.21	24.22	0.67
276	13	9/21/05 17:30	143.55	13.29	427.29	3.00	5.65	5.63	17.90	20.61	28.23	1.24
13	14	6/18/98 13:15	255.52	70.98	131.18	1.00	1.17	1.14	20.14	25.35	29.02	0.55
175	15	7/31/03 15:45	327.53	51.99	223.36	1.75	0.77	0.68	18.41	31.47	37.22	0.54
209	16	7/28/04 18:29	254.75	28.31	201.22	2.50	1.69	1.58	19.86	23.83	25.40	0.89
170	17	7/14/03 12:29	145.36	26.92	59.97	1.50	2.09	2.06	20.01	21.68	24.33	1.17
17	18	6/26/98 16:30	211.23	78.23	99.47	0.75	0.74	0.69	20.22	27.30	33.24	0.44
259	19	6/27/05 16:44	39.73	4.90	39.49	2.25	1.98	1.96	18.92	20.48	26.09	0.65
16	20	6/25/98 0:00	36.15	6.69	56.19	1.50	1.80	1.80	20.55	20.48	21.30	1.03
		Average	216.09	51.08	217.62	2.60	3.11	3.06	19.49	24.44	29.56	3.57
		Standard Deviation	196.96	75.81	155.46	2.14	4.50	4.49	1.67	4.44	4.83	2.94

Table 2. Continued

Concrete

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	1190.16	33.91	251.69	9.75	21.22	21.06	20.01	21.35	29.69	1.02
83	2	7/25/99 21:29	604.95	74.69	280.85	2.25	3.18	3.13	21.64	24.60	25.43	1.25
265	3	8/16/05 16:30	426.49	236.94	418.72	0.50	1.12	1.09	16.63	29.30	29.75	1.02
256	4	6/20/05 11:30	508.82	70.67	191.95	2.00	3.82	3.76	18.29	23.22	31.03	0.41
85	5	7/30/99 15:45	449.63	35.68	229.41	3.50	2.06	1.95	20.65	25.49	31.60	1.01
24	6	7/14/98 19:59	563.27	29.80	342.97	5.25	5.61	5.56	18.41	22.41	29.76	2.00
34	7	9/19/98 15:45	348.61	129.11	340.42	0.75	1.47	1.42	16.40	25.85	34.58	1.27
77	8	6/22/99 15:14	321.04	16.21	195.17	5.50	1.46	1.26	20.02	26.06	28.98	0.52
215	9	8/25/04 16:44	321.87	32.51	278.05	2.75	2.96	2.93	18.88	22.61	25.82	1.14
255	10	6/13/05 17:15	242.74	38.53	143.76	1.75	0.53	0.47	19.95	32.27	33.88	0.25
254	11	6/11/05 12:29	251.03	39.85	95.32	1.75	1.03	1.00	23.87	25.97	27.43	0.40
262	12	7/23/05 9:00	287.28	39.90	151.86	2.00	1.92	1.90	19.11	23.61	25.41	0.67
276	13	9/21/05 17:30	360.72	33.40	272.26	3.00	5.65	5.63	17.90	21.53	25.22	1.24
13	14	6/18/98 13:15	246.16	68.38	118.01	1.00	1.17	1.14	20.14	25.15	27.75	0.55
175	15	7/31/03 15:45	235.10	37.32	161.15	1.75	0.77	0.69	18.41	28.10	31.48	0.55
209	16	7/28/04 18:29	243.01	27.00	171.98	2.50	1.69	1.58	19.86	23.66	24.61	0.89
170	17	7/14/03 12:29	246.99	45.74	116.80	1.50	2.09	2.05	20.01	22.87	26.04	1.17
17	18	6/26/98 16:30	238.68	88.40	128.00	0.75	0.74	0.69	20.22	28.26	32.51	0.44
259	19	6/27/05 16:44	242.36	29.92	90.32	2.25	1.98	1.95	18.92	22.96	26.49	0.65
16	20	6/25/98 0:00	231.80	42.93	183.46	1.50	1.80	1.79	20.55	23.09	24.26	1.03
		Average	378.03	57.54	208.11	2.60	3.11	3.05	19.49	24.92	28.59	3.57
		Standard Deviation	223.91	49.74	91.20	2.14	4.50	4.48	1.67	2.83	3.19	2.94

Corn

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	614.12	17.50	178.00	9.75	21.22	18.08	20.01	20.81	25.82	1.66
83	2	7/25/99 21:29	338.86	41.84	176.46	2.25	3.18	2.41	21.64	23.35	23.88	1.08
265	3	8/16/05 16:30	75.84	42.13	79.25	0.50	1.12	0.89	16.63	22.03	22.18	0.87
256	4	6/20/05 11:30	123.02	17.09	52.23	2.00	3.82	3.26	18.29	20.90	24.46	0.28
85	5	7/30/99 15:45	176.47	14.01	140.26	3.50	2.06	1.12	20.65	23.75	27.39	0.85
24	6	7/14/98 19:59	270.26	14.30	220.03	5.25	5.61	3.57	18.41	21.80	26.23	1.83
34	7	9/19/98 15:45	122.72	45.45	122.46	0.75	1.47	1.20	16.40	22.43	25.93	1.11
77	8	6/22/99 15:14	117.51	5.93	68.38	5.50	1.46	0.87	20.02	23.23	24.27	0.38
215	9	8/25/04 16:44	25.38	2.56	70.60	2.75	2.96	2.02	18.88	20.30	21.72	0.97
255	10	6/13/05 17:15	55.17	8.76	32.28	1.75	0.53	0.21	19.95	26.27	26.41	0.12
254	11	6/11/05 12:29	62.64	9.94	37.37	1.75	1.03	0.46	23.87	23.24	23.87	0.27
262	12	7/23/05 9:00	105.74	14.69	59.97	2.00	1.92	1.39	19.11	21.81	22.76	0.52
276	13	9/21/05 17:30	-97.59	-9.04	-73.30	3.00	5.65	4.53	17.90	19.49	21.30	2.19
13	14	6/18/98 13:15	79.45	22.07	48.94	1.00	1.17	0.71	20.14	22.66	23.57	0.42
175	15	7/31/03 15:45	32.88	5.22	27.15	1.75	0.77	0.45	18.41	21.72	22.74	0.41
209	16	7/28/04 18:29	43.34	4.82	34.89	2.50	1.69	1.17	19.86	20.88	21.14	0.73
170	17	7/14/03 12:29	36.86	6.83	22.31	1.50	2.09	1.50	20.01	20.58	21.45	1.00
17	18	6/26/98 16:30	62.56	23.17	49.75	0.75	0.74	0.37	20.22	24.05	25.79	0.31
259	19	6/27/05 16:44	27.84	3.44	14.71	2.25	1.98	1.17	18.92	20.56	21.60	0.49
16	20	6/25/98 0:00	119.01	22.04	96.77	1.50	1.80	1.24	20.55	22.29	22.67	0.86
		Average	119.60	15.64	72.93	2.60	3.11	2.33	19.49	22.11	23.76	3.57
		Standard Deviation	148.25	14.20	67.48	2.14	4.50	3.88	1.67	1.59	1.96	2.94

Forest

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	469.17	13.37	144.44	9.75	21.22	18.05	20.01	20.62	24.14	1.62
83	2	7/25/99 21:29	368.44	45.49	179.73	2.25	3.18	2.33	21.64	23.76	24.39	0.97
265	3	8/16/05 16:30	50.45	28.03	50.56	0.50	1.12	0.87	16.63	21.38	21.56	0.77
256	4	6/20/05 11:30	15.80	2.19	24.49	2.00	3.82	3.24	18.29	20.12	22.30	0.52
85	5	7/30/99 15:45	205.24	16.29	150.99	3.50	2.06	1.11	20.65	24.41	27.96	0.77
24	6	7/14/98 19:59	267.59	14.16	191.51	5.25	5.61	3.54	18.41	21.80	26.02	1.68
34	7	9/19/98 15:45	92.20	34.15	87.58	0.75	1.47	1.17	16.40	21.88	25.32	1.00
77	8	6/22/99 15:14	62.74	3.17	34.28	5.50	1.46	0.84	20.02	21.77	22.34	0.54
215	9	8/25/04 16:44	7.72	0.78	46.78	2.75	2.96	1.96	18.88	20.09	21.28	0.87
255	10	6/13/05 17:15	17.15	2.72	10.32	1.75	0.53	0.19	19.95	22.12	22.13	0.12
254	11	6/11/05 12:29	20.90	3.32	13.55	1.75	1.03	0.43	23.87	21.15	21.42	0.26
262	12	7/23/05 9:00	113.42	15.75	60.49	2.00	1.92	1.38	19.11	21.96	22.96	0.89
276	13	9/21/05 17:30	-81.84	-7.58	-59.99	3.00	5.65	4.48	17.90	19.57	21.27	2.14
13	14	6/18/98 13:15	31.19	8.66	19.80	1.00	1.17	0.69	20.14	21.07	21.51	0.39
175	15	7/31/03 15:45	31.32	4.97	26.58	1.75	0.77	0.43	18.41	21.74	22.66	0.38
209	16	7/28/04 18:29	41.36	4.60	29.91	2.50	1.69	1.14	19.86	20.86	21.11	0.64
170	17	7/14/03 12:29	30.96	5.73	18.34	1.50	2.09	1.43	20.01	20.51	21.24	0.89
17	18	6/26/98 16:30	36.91	13.67	31.58	0.75	0.74	0.33	20.22	22.70	23.86	0.29
259	19	6/27/05 16:44	32.42	4.00	16.89	2.25	1.98	1.15	18.92	20.67	22.18	0.42
16	20	6/25/98 0:00	90.87	16.83	66.64	1.50	1.80	1.23	20.55	21.76	22.07	0.77
		Average	95.20	11.51	57.22	2.60	3.11	2.30	19.49	21.50	22.89	3.57
		Standard Deviation	133.62	12.55	63.64	2.14	4.50	3.88	1.67	1.19	1.86	2.94

Table 2. Continued

Residential Roof (Asphalt Shingle)

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	-651.22	-18.55	-169.97	9.75	21.22	21.09	20.01	19.26	25.07	1.79
83	2	7/25/99 21:29	24.86	3.07	60.33	2.25	3.18	3.15	21.64	20.19	21.15	1.25
265	3	8/16/05 16:30	41.94	23.30	57.79	0.50	1.12	1.10	16.63	20.91	21.34	1.03
256	4	6/20/05 11:30	-151.50	-21.04	-189.44	2.00	3.82	3.78	18.29	19.05	25.23	2.59
85	5	7/30/99 15:45	-47.02	-3.73	-13.27	3.50	2.06	1.99	20.65	19.44	23.46	1.02
24	6	7/14/98 19:59	-631.60	-33.42	-112.23	5.25	5.61	5.61	18.41	17.32	21.62	1.31
34	7	9/19/98 15:45	-28.17	-10.43	-29.00	0.75	1.47	1.43	16.40	19.53	29.88	0.31
77	8	6/22/99 15:14	44.30	2.24	73.35	5.50	1.46	1.29	20.02	20.82	23.31	0.53
215	9	8/25/04 16:44	-240.02	-24.24	-136.68	2.75	2.96	2.95	18.88	18.06	21.92	0.81
255	10	6/13/05 17:15	218.41	34.67	140.95	1.75	0.53	0.48	19.95	30.91	33.61	0.25
254	11	6/11/05 12:29	228.59	36.28	90.31	1.75	1.03	1.01	23.87	25.41	28.70	0.40
262	12	7/23/05 9:00	-2.41	-0.33	56.97	2.00	1.92	1.91	19.11	19.97	22.02	0.67
276	13	9/21/05 17:30	-648.88	-60.08	-268.47	3.00	5.65	5.65	17.90	17.26	20.55	2.33
13	14	6/18/98 13:15	88.90	24.69	47.03	1.00	1.17	1.15	20.14	21.84	24.14	0.55
175	15	7/31/03 15:45	63.21	10.03	48.85	1.75	0.77	0.70	18.41	22.14	25.92	0.20
209	16	7/28/04 18:29	31.67	3.52	52.07	2.50	1.69	1.59	19.86	20.47	21.39	0.89
170	17	7/14/03 12:29	68.08	12.61	29.30	1.50	2.09	2.06	20.01	20.79	25.58	0.12
17	18	6/26/98 16:30	28.58	10.58	18.03	0.75	0.74	0.71	20.22	20.96	24.44	0.10
259	19	6/27/05 16:44	-172.00	-21.23	-69.18	2.25	1.98	1.97	18.92	17.92	19.22	0.65
16	20	6/25/98 0:00	-39.55	-7.32	41.92	1.50	1.80	1.80	20.55	19.48	20.97	1.03
		Average	-88.69	-1.97	-13.57	2.60	3.11	3.07	19.49	20.59	23.98	3.57
		Standard Deviation	263.99	23.75	108.61	2.14	4.50	4.49	1.67	3.06	3.55	2.94

Short Grass (Lawn)

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	546.48	15.57	158.71	9.75	21.22	18.14	20.01	20.72	24.45	1.68
83	2	7/25/99 21:29	414.30	51.15	225.86	2.25	3.18	2.46	21.64	24.02	24.73	1.14
265	3	8/16/05 16:30	90.87	50.48	96.36	0.50	1.12	0.90	16.63	22.40	22.51	0.92
256	4	6/20/05 11:30	77.19	10.72	40.69	2.00	3.82	3.27	18.29	20.56	23.19	0.30
85	5	7/30/99 15:45	234.16	18.58	189.80	3.50	2.06	1.13	20.65	24.92	28.51	0.89
24	6	7/14/98 19:59	329.88	17.45	254.31	5.25	5.61	3.61	18.41	22.18	26.34	1.91
34	7	9/19/98 15:45	119.33	44.20	121.94	0.75	1.47	1.22	16.40	22.32	25.52	1.16
77	8	6/22/99 15:14	84.18	4.25	50.19	5.50	1.46	0.88	20.02	22.27	22.91	0.41
215	9	8/25/04 16:44	49.19	4.97	77.39	2.75	2.96	2.05	18.88	20.57	21.80	1.03
255	10	6/13/05 17:15	25.81	4.10	16.22	1.75	0.53	0.22	19.95	22.81	22.86	0.14
254	11	6/11/05 12:29	26.90	4.27	17.42	1.75	1.03	0.47	23.87	21.36	21.74	0.27
262	12	7/23/05 9:00	142.16	19.74	79.41	2.00	1.92	1.40	19.11	22.42	23.42	0.55
276	13	9/21/05 17:30	-28.57	-2.65	78.86	3.00	5.65	4.56	17.90	19.85	21.65	1.14
13	14	6/18/98 13:15	42.74	11.87	26.87	1.00	1.17	0.72	20.14	21.41	21.90	0.43
175	15	7/31/03 15:45	50.61	8.03	42.77	1.75	0.77	0.47	18.41	22.57	23.61	0.43
209	16	7/28/04 18:29	68.51	7.61	53.33	2.50	1.69	1.19	19.86	21.37	21.65	0.77
170	17	7/14/03 12:29	57.43	10.64	37.39	1.50	2.09	1.54	20.01	20.89	21.78	1.05
17	18	6/26/98 16:30	52.65	19.50	40.66	0.75	0.74	0.39	20.22	23.22	24.51	0.32
259	19	6/27/05 16:44	55.54	6.86	32.44	2.25	1.98	1.19	18.92	21.11	22.83	0.52
16	20	6/25/98 0:00	101.86	18.86	83.59	1.50	1.80	1.25	20.55	21.94	22.19	0.91
		Average	127.06	16.31	86.21	2.60	3.11	2.35	19.49	21.95	23.40	3.57
		Standard Deviation	145.10	15.28	69.64	2.14	4.50	3.89	1.67	1.24	1.82	2.94

Tall Grass (Prairie)

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	566.24	16.13	158.35	9.75	21.22	18.03	20.01	20.75	24.85	1.60
83	2	7/25/99 21:29	385.25	47.56	177.41	2.25	3.18	2.28	21.64	24.03	24.67	0.90
265	3	8/16/05 16:30	78.53	43.63	72.51	0.50	1.12	0.85	16.63	22.20	22.43	0.71
256	4	6/20/05 11:30	66.05	9.17	38.08	2.00	3.82	3.23	18.29	20.49	23.16	0.51
85	5	7/30/99 15:45	220.93	17.53	153.43	3.50	2.06	1.10	20.65	24.79	28.86	0.72
24	6	7/14/98 19:59	307.52	16.27	203.81	5.25	5.61	3.51	18.41	22.09	26.86	1.58
34	7	9/19/98 15:45	110.53	40.94	99.10	0.75	1.47	1.15	16.40	22.30	26.27	0.93
77	8	6/22/99 15:14	88.31	4.46	50.67	5.50	1.46	0.83	20.02	22.54	23.33	0.54
215	9	8/25/04 16:44	34.55	3.49	59.71	2.75	2.96	1.92	18.88	20.43	21.76	0.81
255	10	6/13/05 17:15	23.37	3.71	15.39	1.75	0.53	0.18	19.95	23.07	23.14	0.12
254	11	6/11/05 12:29	29.35	4.66	18.41	1.75	1.03	0.42	23.87	21.68	21.95	0.26
262	12	7/23/05 9:00	125.16	17.38	68.86	2.00	1.92	1.36	19.11	22.18	23.28	0.87
276	13	9/21/05 17:30	-34.10	-3.16	65.53	3.00	5.65	4.44	17.90	19.82	21.73	0.90
13	14	6/18/98 13:15	44.86	12.46	27.54	1.00	1.17	0.68	20.14	21.57	22.18	0.38
175	15	7/31/03 15:45	42.13	6.69	35.97	1.75	0.77	0.41	18.41	22.44	23.60	0.36
209	16	7/28/04 18:29	57.04	6.34	37.32	2.50	1.69	1.13	19.86	21.20	21.51	0.59
170	17	7/14/03 12:29	45.69	8.46	25.91	1.50	2.09	1.39	20.01	20.78	21.74	0.83
17	18	6/26/98 16:30	45.43	16.83	41.06	0.75	0.74	0.30	20.22	23.64	25.25	0.28
259	19	6/27/05 16:44	49.05	6.06	21.39	2.25	1.98	1.13	18.92	21.03	22.82	0.37
16	20	6/25/98 0:00	106.14	19.65	72.68	1.50	1.80	1.22	20.55	22.06	22.45	0.71
		Average	119.60	14.91	72.16	2.60	3.11	2.28	19.49	21.95	23.59	3.57
		Standard Deviation	145.31	13.97	56.81	2.14	4.50	3.88	1.67	1.27	1.98	2.94

Table 3. Ranking of heat export and runoff temperature from nine types of land use and three water bodies for two rainfall events: One of 2 hr duration,with warm surface prior to rainfall (June 20, 2005, 3.8 cm rainfall) and one of 9.7 hrs duration, with high dew point temperature (June 24, 2003, 21.2 cm rainfall). Temperature difference is (average runoff temp) – (average dew point temp).

Land Use	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Total Rainfall (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Temp Difference (C)
Reservoir	6/20/05 11:30			3.8	18.3	26.7	8.4
Commerical roof	6/20/05 11:30	539.7	74.95	3.8	18.3	23.4	5.1
Concrete	6/20/05 11:30	508.8	70.67	3.8	18.3	23.2	4.9
Pond	6/20/05 11:30	420.0	5.02	3.8	18.3	22.9	4.6
Bare soil	6/20/05 11:30	379.8	52.76	3.8	18.3	22.8	4.5
Asphalt	6/20/05 11:30	429.8	59.70	3.8	18.3	22.7	4.4
Corn	6/20/05 11:30	123.0	17.09	3.8	18.3	20.9	2.6
Lawn	6/20/05 11:30	77.2	10.72	3.8	18.3	20.6	2.3
Tall Grass	6/20/05 11:30	66.1	9.17	3.8	18.3	20.5	2.2
Forest	6/20/05 11:30	15.8	2.19	3.8	18.3	20.1	1.8
Residential Roof	6/20/05 11:30	-151.5	-21.04	3.8	18.3	19.0	0.8
Vegetated Pond	6/20/05 11:30	4.2	0.04	3.8	18.3	18.1	-0.2

Reservoir	6/24/03 18:45			21.2	20.0	25.3	5.3
Concrete	6/24/03 18:45	1190.2	33.9	21.2	20.0	21.4	1.3
Bare soil	6/24/03 18:45	969.2	27.6	21.2	20.0	21.3	1.3
Pond	6/24/03 18:45	1088.8	4.0	21.2	20.0	21.1	1.1
Asphalt	6/24/03 18:45	862.2	24.6	21.2	20.0	21.0	1.0
Corn	6/24/03 18:45	614.1	17.5	21.2	20.0	20.8	0.8
Tall Grass	6/24/03 18:45	566.2	16.1	21.2	20.0	20.8	0.7
Lawn	6/24/03 18:45	546.5	15.6	21.2	20.0	20.7	0.7
Forest	6/24/03 18:45	469.2	13.4	21.2	20.0	20.6	0.6
Commerical roof	6/24/03 18:45	-195.9	-5.6	21.2	20.0	19.8	-0.2
Vegetated Pond	6/24/03 18:45	-551.4	-14.6	21.2	20.0	19.4	-0.6
Residential Roof	6/24/03 18:45	-651.2	-18.6	21.2	20.0	19.3	-0.8

5. RESULTS: OUTFLOW TEMPERATURES AND HEAT EXPORT FROM LAKE OR RESERVOIR SURFACES

Lakes and reservoirs have temperature characteristics distinctly different from typical wet ponds, and are therefore treated separately in this study. While stormwater pond temperature may respond to climate at hourly time scales, lake temperature is largely determined by air temperature and solar radiation at daily to weekly time scales. Typically, stormwater inflow to a lake or reservoir has relatively little impact on the lake temperature, and the outflow temperature is decoupled from inflow temperature. Outflow temperature from a particular lake depends largely on the time of year rather than the characteristics of a storm. The outlet flow rate from a lake through a natural channel or a control structure also tends to have longer time constants compared to a wet pond, with lake level changes taking place over days or weeks. It can therefore be difficult to associate the runoff from a lake with a particular storm; the runoff may be due to the combined inflow volume of several storms.

To characterize outflow temperatures and flow rates for typical lakes and reservoirs, a modified version of the wet detention pond model was created based on previous lake temperature modeling (Riley and Stefan 1988, Hondzo and Stefan 1993). The lake model created for this study was verified on Medicine Lake, near Plymouth, MN, an 880 acre lake with an average depth of 16 feet (4.8m) and a maximum depth of 49 feet (14.7m). Several years of temperature profiles are available from the Lake Access project (www.lakeaccess.org), which were used to verify the simulated water temperatures. National Weather Service climate data from the Crystal airport was used to provide input to the lake model, along with solar radiation data from the MNROAD facility. Simulated and measured lake temperatures at 1 meter depth for the period June 1, 2003 to October 1, 2003 are given in Figure 3. The overall root mean square error (RMSE) of the simulated temperature is 0.9 °C. Simulating lake or reservoir temperature at a one day time step introduces some uncertainty to the surface (and runoff) temperature, e.g. the surface temperature in mid-afternoon is typically higher than daily average. Figure 4 gives the shorter term variation of lake temperature based on 6 hour measured temperature data from Medicine Lake. The diurnal variation of lake temperature is less than 1 °C, so the uncertainty in lake temperature due to a one day time step is also less than 1 °C.

The lake model was then used to simulate a reservoir with a single point inflow and with an outflow structure. The reservoir bathymetry was based on Orchard Lake, just north of Lakeville, MN, with an area of 243 acres and a maximum depth of 30 feet (9.1 m). Essentially, the model was used to simulate runoff from Orchard Lake with the addition of an outlet structure to create a reservoir. Stormwater inflow data (daily flow, temperature) was generated using the previously described runoff model, assuming a lake watershed area ten times the lake area (2430 acres), with 20% impervious area. Runoff was assumed to be completely from the impervious surface area. Precipitation and other climate data were taken from the MNROAD data set, to enable a direct comparison of runoff temperature to other land uses described previously.

Outflow was simulated assuming a 3m wide sharp-crested weir, so that outflow from the lake is supplied by surface water. The lake water level was calculated based on inflow, outflow, direct precipitation on the lake surface, and evaporation. The specified inflow rate and the corresponding simulated outflow rate for 2005 are given in Figure 5. Note that inflow events in July and August 2005 produced no outflow, due to a lowering of the lake level by evaporation. This implies that the lake, as specified, produces no heat export to receiving streams for some storm events, particularly in mid-summer. Simulated inflow and outflow temperatures for 2005 are given in Figure 6. Note that in many cases, the lake surface temperature is warmer than the stormwater inflow.

Temperature simulations were run with and without stormwater inflow, to quantify the effect of the inflow on lake/reservoir temperature. Figure 7 compares the seasonal variation of the lake/reservoir surface temperature for the two cases. For the lake as specified, the runoff volume entering the lake for a 1” storm is about 1.7% of the lake volume, compared to 17% for the stormwater pond analyzed earlier in this study. Monthly average surface temperatures for the lake/reservoir are given in Table 1, along with those for different land covers. The lake/reservoir temperatures are similar to those of the wet pond. The lake/reservoir temperatures are slightly higher than the pond temperatures during summer because there is relatively little cool inflow entering the lake/reservoir and relatively little warm water exiting via the surface outlet.

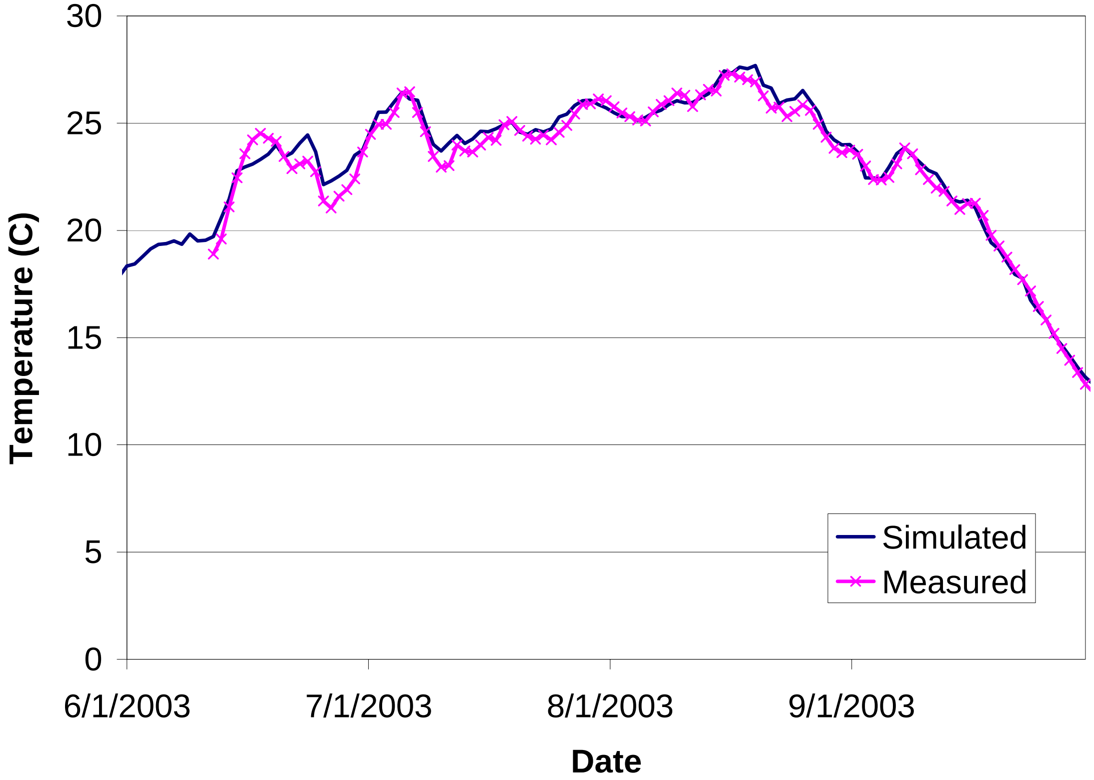

Figure 3. Simulated and measured daily average water temperature at 1m depth in Medicine Lake, June 1, 2003 to October 1, 2003.

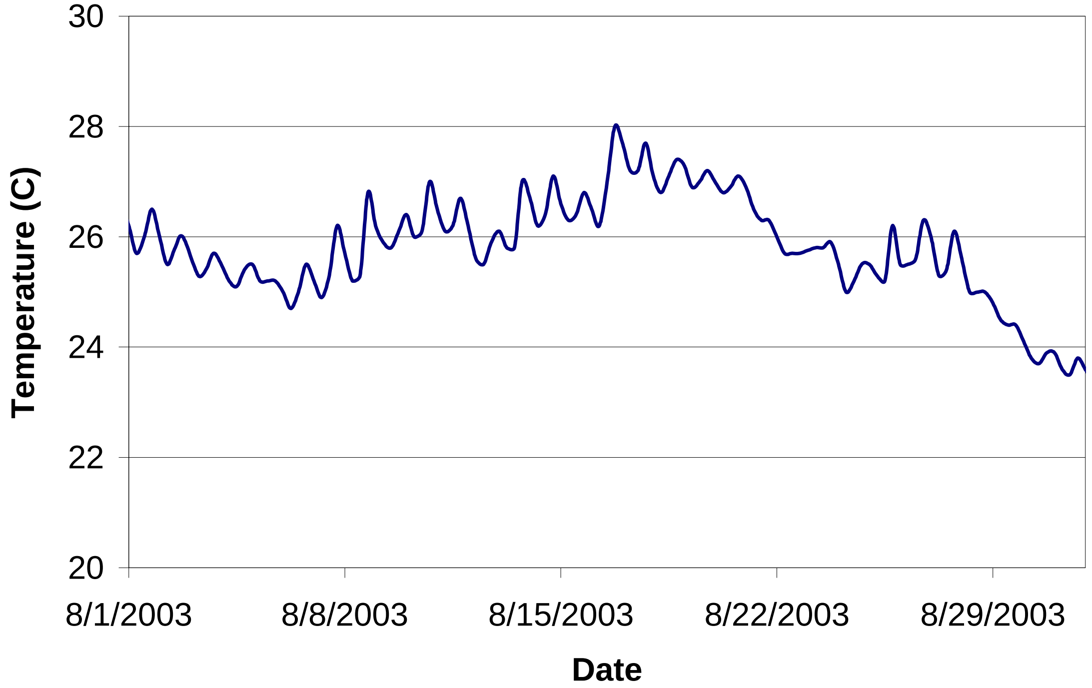

Figure 4. Measured 6-hour water temperature at 1m depth in Medicine Lake, August 1, 2003 to August 31, 2003.

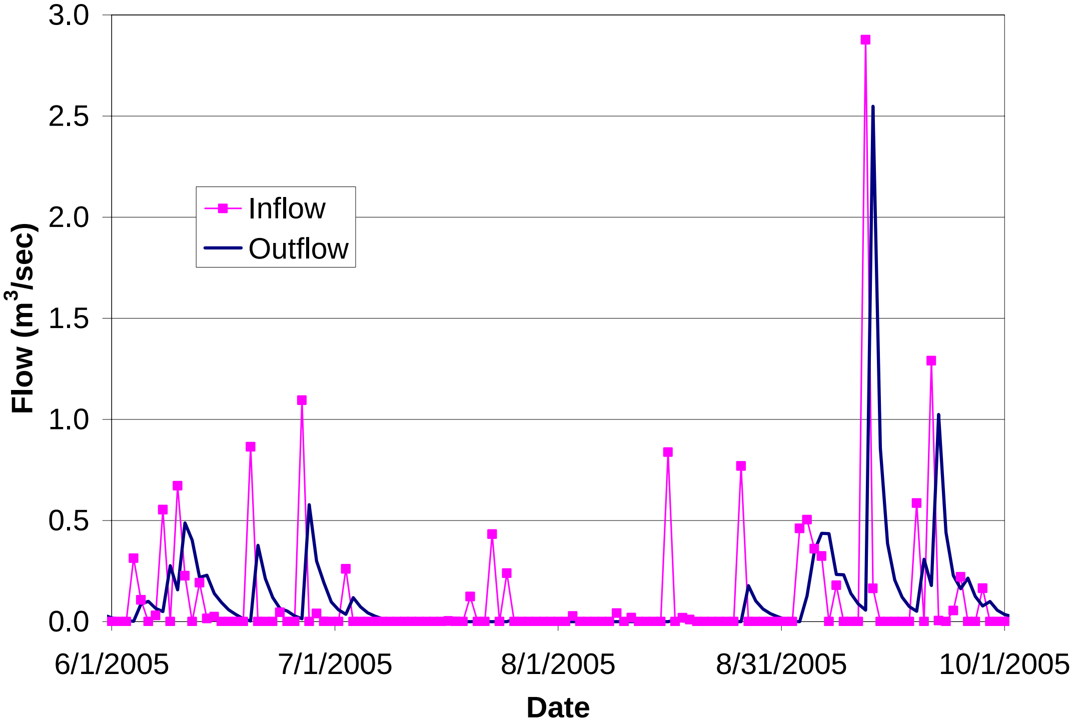

Figure 5. Simulated daily average inflow and outflow rate for Orchard Lake, June 1 to October 1, 2005.

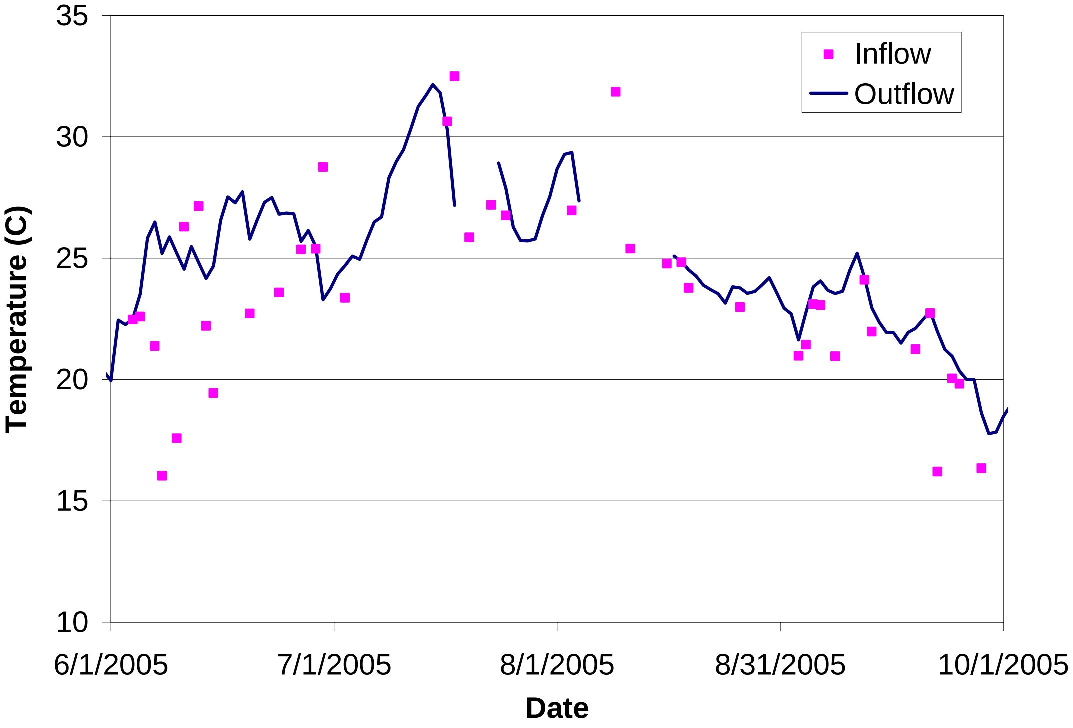

Figure 6. Simulated daily average inflow and outflow temperature for Orchard Lake, June 1 to October 1, 2005. Temperature values are plotted only for days with non-zero flow.

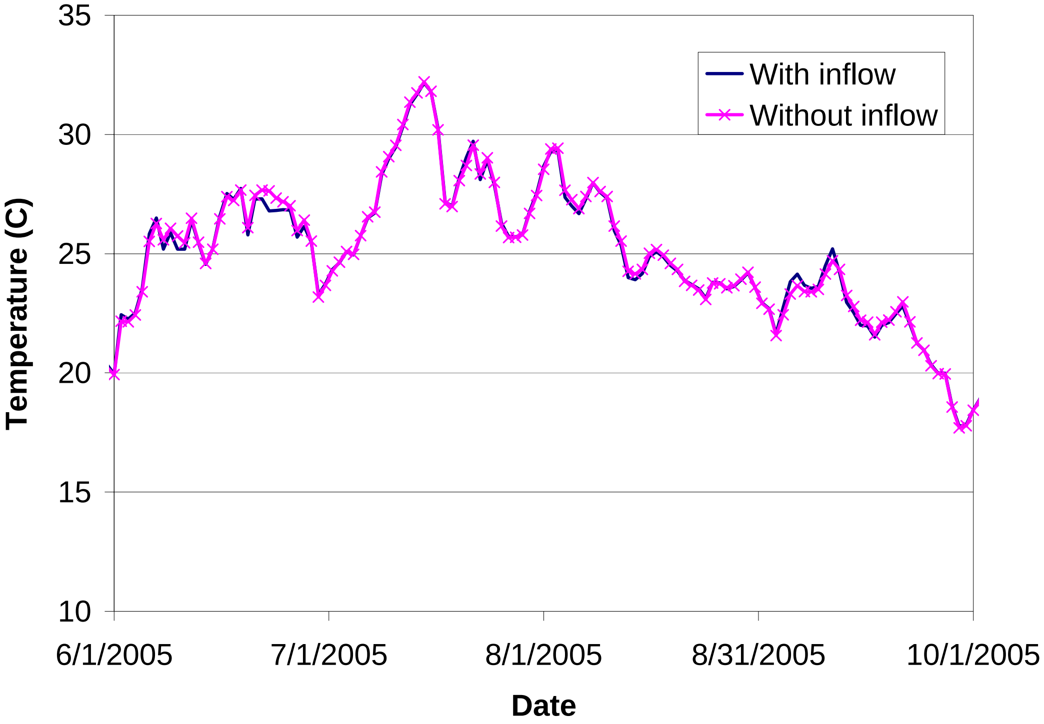

Figure 7. Simulated daily average lake surface temperature for Orchard Lake, June 1 to October 1, 2005, for cases with and without stormwater inflow.

As with the terrestrial land uses, the runoff response of the lake was calculated for a database of approximately 280 storms from the MnROAD facility in Albertville, MN. The 20 rainfall events that gave extreme heat export and runoff temperatures in the anlysis of different land surfaces (Table 2) were also applied to the lake model, and results are included in Table 4 in the next section. As was pointed out earlier, however, the coupling between rainfall events and lake outflow temperatures is very weak.

6. RESULTS: RUNOFF TEMPERATURES FROM PONDS WITH AND WITHOUT EMERGENT VEGETATION

Simulation of runoff flow rate and temperature of an unshaded wet detention pond was accomplished using a previously developed pond model described by Herb et al. (2006b For the purpose of this study, the model was run using simulated inflow from a 24 acre asphalt parking lot to an actual 1.3 acre, 2.4 m deep wet pond in Woodbury, MN (Herb et al. 2006b). As with the terrestrial land uses, the runoff response of the wet pond was calculated for a database of approximately 280 storms from the MnROAD facility in Albertville, MN. The 20 rainfall events that gave extreme heat export and runoff temperatures in the analysis of different land surfaces (Table 2) were also applied to the lake model, and results are given in Table 4

Table 4. Heat export and outflow temperatures from the surfaces of three water bodies (an unshaded wet detention pond, a pond with emergent vegetation, and a lake or reservoir). Rainfall events are the same as in Table 2 and were taken from six years of climate data (1998-2000, 2003-2005) from the MnROAD site.

Event Number	**Rank**	**Start Day/Time**	**Total Heat Export (KJ/m^2)**		**Average Heat Export Export Rate (W/m^2)**		**Duration (hours)**		**Total Rain (cm)**	**Average Dew Point Temp (C)**	**Average Runoff Temp (C)**		
			Wet Pond	Vegetated Pond	Wet Pond	Vegetated Pond	Wet Pond	Vegetated Pond			Wet Pond	Vegetated Pond	Reservoir
129	1	6/24/03 18:44	1088.80	-551.38	4.01	-2.53	75.50	60.50	22.13	19.92	21.12	19.40	25.3
67	2	7/25/99 21:29	773.94	193.53	10.24	1.49	21.00	36.00	3.39	21.80	24.08	22.10	30.2
134	3	8/16/05 16:30	391.63	-16.05	4.58	-0.12	23.75	37.00	3.81	20.32	23.06	19.83	24.1
167	4	6/20/05 11:30	419.96	4.19	5.02	0.04	23.25	32.00	3.89	21.15	22.52	20.04	26.7
69	5	7/30/99 15:44	423.08	56.91	7.02	0.36	16.75	44.50	2.09	20.65	24.35	20.99	29.8
160	6	7/14/98 19:59	1138.20	95.64	10.20	0.85	31.00	31.25	2.45	19.45	23.63	20.56	29.4
19	7	9/19/98 15:44	107.93	-96.86	2.22	-0.57	13.50	47.00	5.61	18.41	21.50	17.43	23.6
136	8	6/22/99 15:14	135.04	-28.45	2.03	-0.14	18.50	55.00	1.92	17.87	24.32	19.30	23.7
59	9	8/25/04 16:44	111.93	-57.73	1.50	-0.42	20.75	37.75	1.71	19.91	24.24	19.33	22.5
165	10	6/11/05 12:29	105.60	-24.80	1.75	-0.12	16.75	59.00	3.02	18.86	22.17	19.06	25.6
29	11	6/13/05 17:15	55.11	-38.44	0.68	-0.15	22.50	72.25	1.47	16.40	24.03	17.74	25.1
12	12	7/23/05 9:00	298.18	79.52	5.34	0.49	15.50	44.75	1.80	18.83	22.97	21.48	28.6
130	13	9/21/05 17:30	189.03	-226.37	1.72	-2.21	30.50	28.50	1.06	14.40	24.38	18.65	22.6
14	14	6/18/98 13:15	70.48	-64.67	1.19	-0.32	16.50	57.00	1.80	20.55	22.20	18.16	23.4
104	15	7/31/03 15:44	27.73	-9.26	0.30	-0.03	25.75	93.00	2.59	19.45	21.48	18.35	27.3
131	16	7/28/04 18:29	55.87	-50.21	0.80	-0.21	19.50	67.00	2.80	19.24	21.31	17.30	25.6
25	17	7/14/03 12:29	224.16	-25.91	3.04	-0.17	20.50	43.00	1.19	19.57	23.07	19.60	25.5
94	18	6/26/98 16:30	134.95	-11.85	2.05	-0.06	18.25	55.50	1.23	20.24	23.03	19.63	26.2
103	19	6/27/05 16:44	360.59	9.19	4.89	0.07	20.50	38.75	1.32	21.38	22.64	20.11	26.3
6	20	6/25/98 0:00	171.16	-12.58	3.22	-0.08	14.75	45.00	1.73	16.90	22.01	19.75	25.7
		Average	314.2	-38.8	3.59	-0.2		49.2	3.4	19.3	22.9	19.4	25.9
		Standard Deviation	327.1	146.0	2.89	0.9		16.0	4.6	1.8	1.1	1.3	2.3

In this study we also considered the effect of emergent plant shading and wind sheltering on pond outflow temperatures. Simulation of the standing water and runoff temperature was performed using the previously described wet pond model (Herb et al. 2006b) with the addition of a plant canopy model.

Simulated water temperatures for a pond with no vegetation, 50% vegetation, and 100% vegetation (full shading) are given in Figure 8. For the period shown, the average water surface temperature was 19.6, 16.1 and 14.2°C, and the average diurnal amplitude (daily maximum temperature - daily minimum temperature) was 2.7, 2.2, and 1.6 °C for 0, 50%, and 100% vegetation, respectively. Surface water temperature was found to be insensitive to variation in water depth, except for depths under 0.5 m. Varying the controlled water depth from 0.5 to 2.0 m produced less than 0.2°C change in average surface temperature

The vegetated pond model was calibrated using temperature data taken in a restored wetland system in Prior Lake, MN during the summer of 2006. An aerial photo of the wetland system is shown in Figure 9, and the monitoring points for surface and groundwater temperature have been added. A climate station exists at the wetland site; it records air and dew point temperature, wind speed and direction, precipitation, solar radiation, and pan evaporation at 30 minute increments. The 2006 climate data record and the water temperature and water level record from the stilling well at site S2 were obtained from Scott Walz, of the Shakopee Mdewakanton Sioux Community Land and Natural Resources Department.

Figure 10 is a plot of the water temperature, water level, and precipitation data taken at the wetland site in 2006. For the time record through July, the higher temperature at the unshaded pond (S1) and the lower temperature at wetland outlet (S2) are reasonable. As the water level increases due to a 7.7 cm rainfall event on August 1 and 2, the recorded surface temperature at site S2 changes character, displaying much reduced diurnal variation. After August 2, the measured S2 surface temperature resembles the stilling well temperature, which should represent the bottom pond temperature.

Point S1 measured surface water temperature at the outlet of a 0.57 hectare, unshaded wet pond. This temperature was also simulated using the standard wet pond model (Herb et al. 2006b), using climate data from the Flying Cloud airport. The simulated temperatures using a wind sheltering coefficient of 0.8 are in reasonable agreement with the measured values (Figure 11). The average diurnal temperature variation of the measured surface temperature is higher than the simulated one (3.6 °C versus 2.7 °C), and varying model coefficients for wind sheltering, water clarity, and water depth could not reproduce these higher diurnal variations.

Figure 12 gives the measured surface water temperature at point S2, i.e. at the outlet of the upper wetland basin. This wetland (WC-9) has an area of 1.7 hectares and a mean depth of 0.3 m. Average temperature and diurnal temperature variation are lower than those of the unshaded wet pond (S1). There is a distinct change in the character of the daily temperature fluctuations at the beginning of August, corresponding to the 7.7 cm of rainfall on August 1 and 2, and an increase in water level (Figure 10). Prior to this period, the surface water temperature is well represented by the pond model (Figure 12), with an RMSE of 1.3 °C. To best match the simulated and measured wetland surface temperature, the vegetation density was changed from 40% to 70%. After August 2,.the measured surface temperature at S2 more closely resembles the simulated pond bottom temperature simulated with the higher vegation density (not shown).

After model calibration to the Prior Lake wetland, the vegetated pond model was used to simulate outflow temperature and rate for the five year MNROAD climate data set used earlier in the astudy. The pond area was set at 1.7 hectares. The control structure was modeled to control the level to a depth of 0.5 m. The vegetated pond was given simulated inflow from a 24 acre parking lot, the same as used for the wet pond runoff simulations described in Section 4. Because the vegetated pond model is one-dimensional, it is not practical to model the reduction in lateral flow due to vegetation. As a result, the simulated outflow rate from the vegetated pond is controlled entirely by the outlet structure.

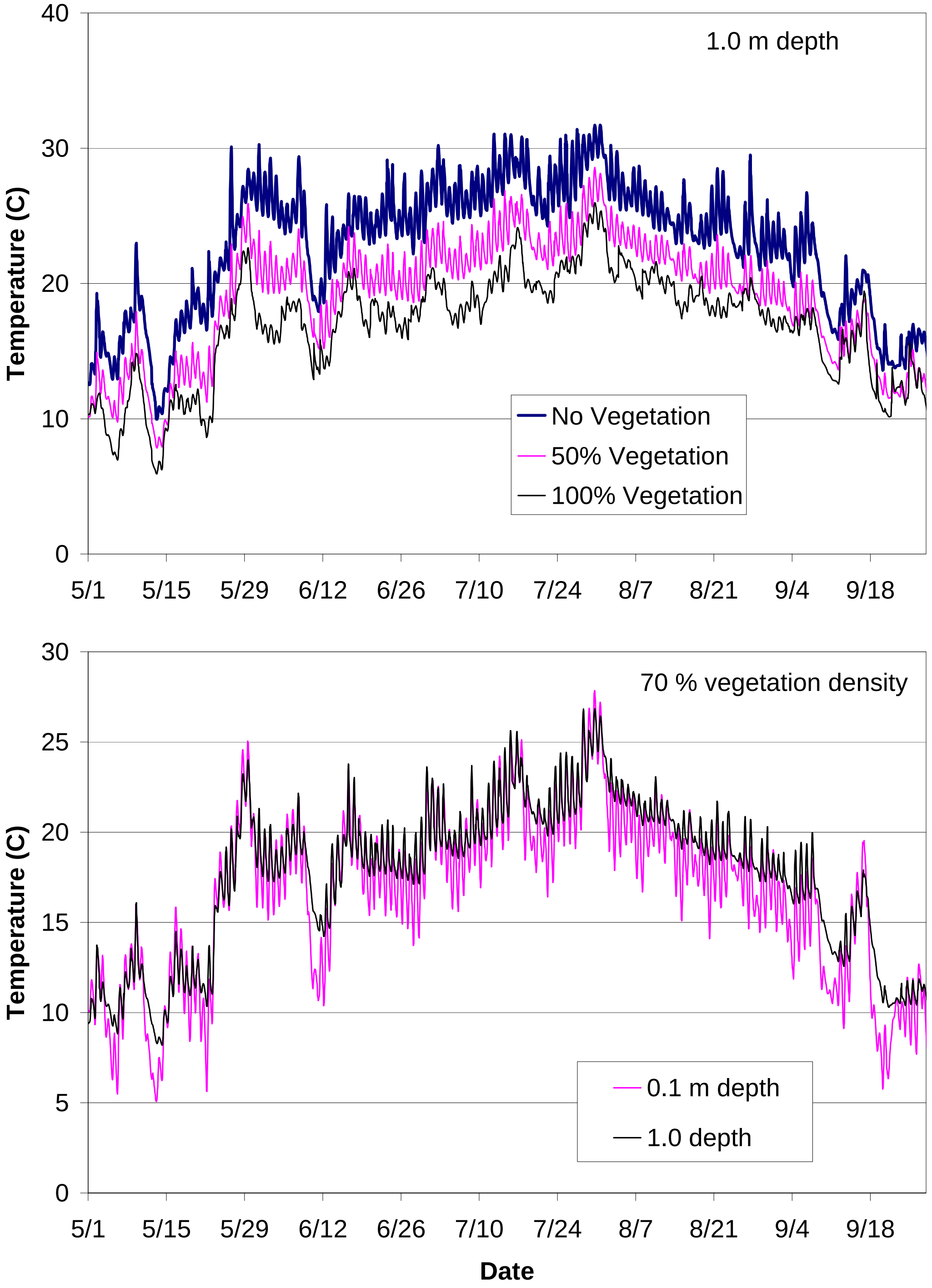

Figure 8. Simulated pond surface temperature versus time (May 1 to October 1, 2006) for three vegetation densities (upper panel), and for two water depths (lower panel).

Figure 9. Aerial photo of the Prior Lake wetland system with the surface water temperature (S1 – S3) and groundwater temperature (G1-G5) measurement stations. Groundwater and surface water flows from left to right.

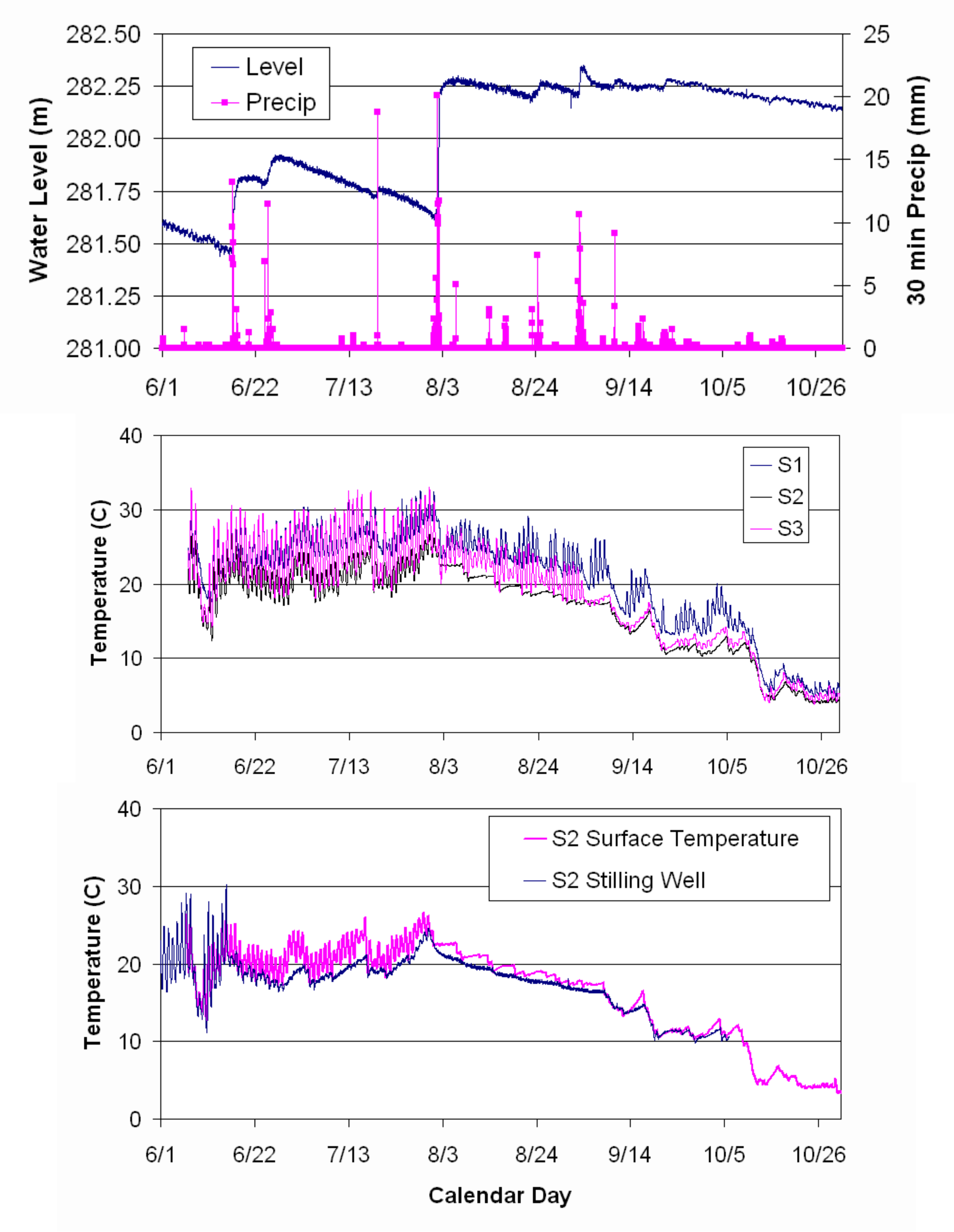

Figure 10. Measured precipitation and water level at site S2 (upper panel), measured water surface temperature (June 1 to October 30, 2006 and July 1 to July 30, 2006) at sites S1, S2, and S3 (middle panel), and surface and stilling well temperatures at site S2 (lower panel).

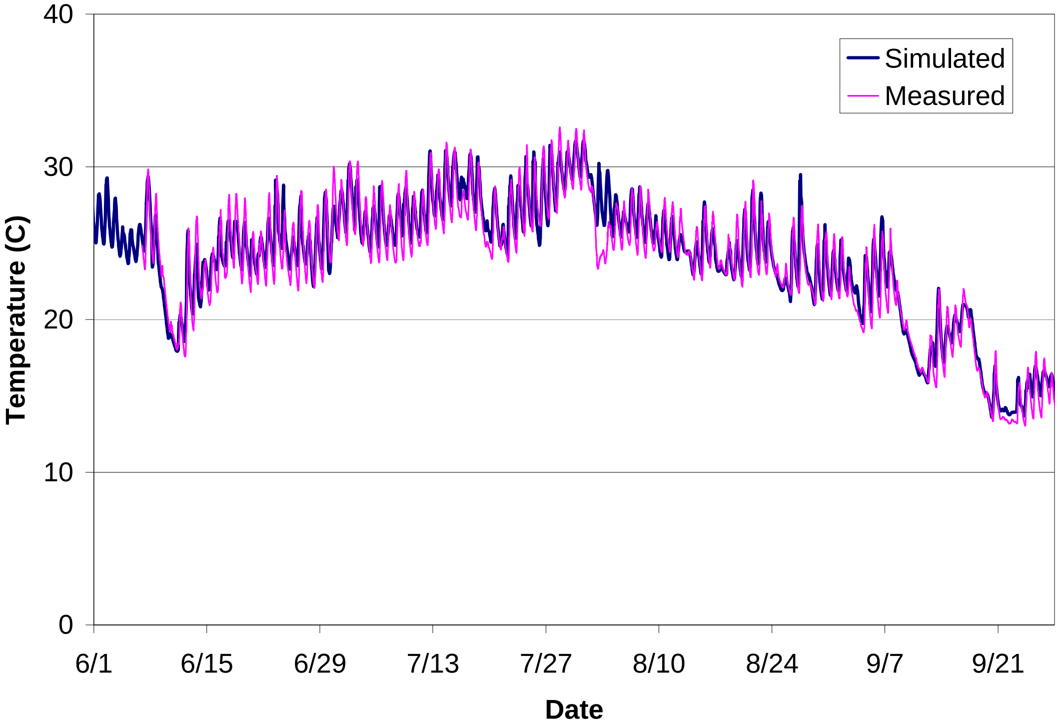

Figure 11. Simulated and measured pond surface temperature versus time (June 1 to October 1) for site S1, using no vegetation for the pond temperature simulation.

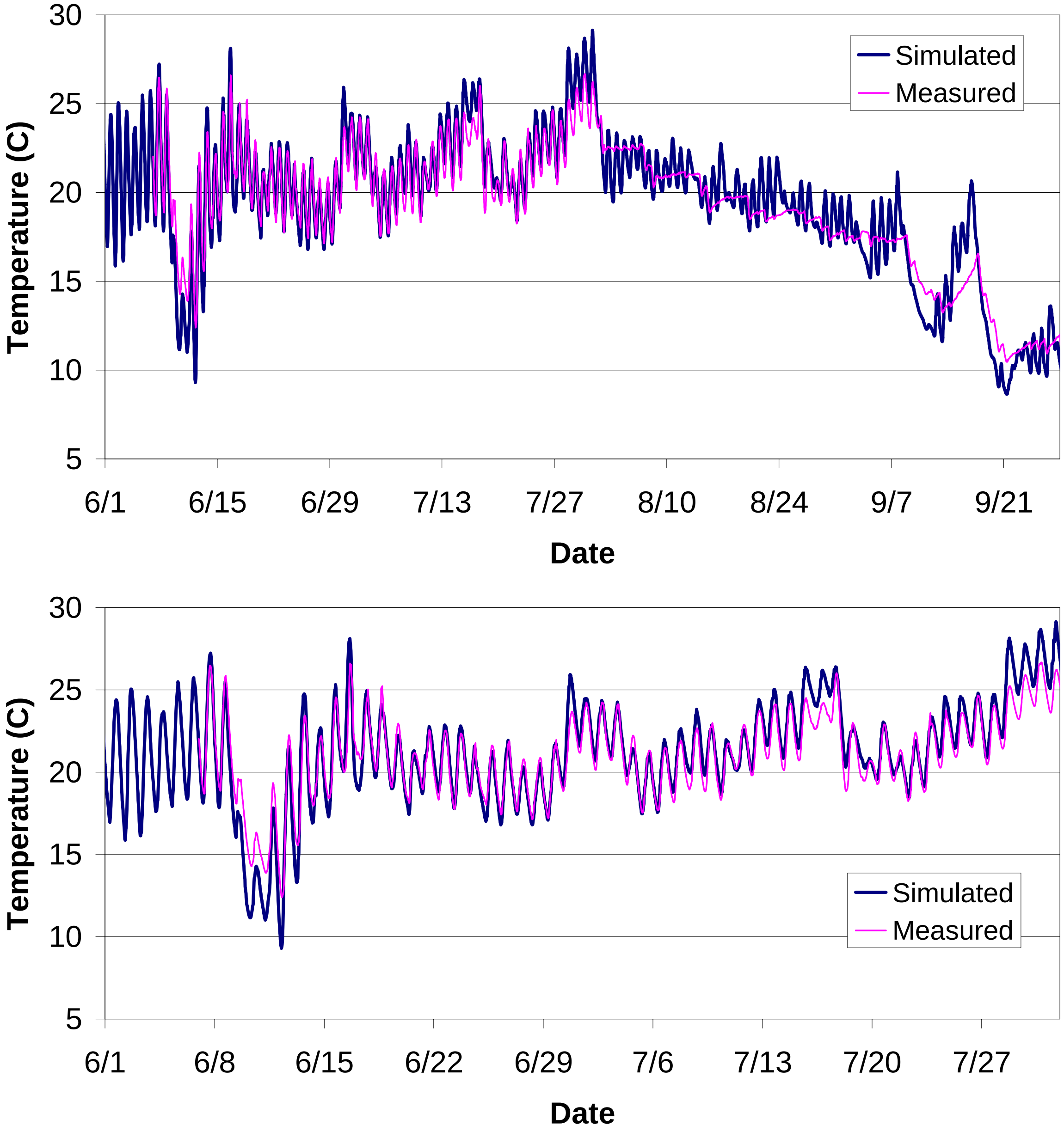

Figure 12. Simulated and measured pond surface temperature at wetland site S2 versus time (June 1 to October 1, upper panel, and June 1 to July 31, lower panel), using a vegetation density varying from 40% to 70% vegetation for the pond temperature simulation.

7. COMPARISON OF RUNOFF TEMPERATURES FROM DIFFERENT LAND USES TO OUTFLOW TEMPERATURES FROM DIFFERENT WATER BODIES

The runoff response of a lake, pond or a wetland to a single storm event can be difficult to compare to terrestrial land covers, since the time constant can be days or weeks for a lake or wetland compared to minutes or hours for a land surface. The outflow response from a lake, pond or wetland to a particular storm may be combined with the response to one or several previous storms. In addition, the one day time step used for the lake model analysis precludes detailed analysis of rainfall event or peak runoff temperature.

The outflow rate and temperature calculations for the wet detention pond, continued for each storm event until the runoff rate fell below 30% of the maximum value for that storm, often leading to runoff events of several days duration for a storm. To resolve the runoff response of a pond to each storm, the analysis of temperature and runoff for each storm event was run separately, i.e. subsequent precipitation events were suppressed. For example, analysis of a storm on July 15 would continue into July 16 and 17, as the pond runoff continued, but any storm occurring on July 16 or 17 would be ignored. This procedure was used for both the wet detention pond and the vegetated pond. In all cases, the pond was assumed to be at normal pool level prior to the storm, giving a worst case runoff volume.

Calculating the runoff response of a lake or reservoir poses additional challenges, because the model runs at a 1 day time step. Runoff temperature of a reservoir for a storm event was calculated as the average surface temperature for the day of the storm and the day after the storm (48 hours total), assuming that the lake/reservoir runoff from a storm lasts at least a day. Heat export and heat export rates were not calculated because of the lack of time resolution.

Table 4 gives heat export and runoff temperature data for outflow from a wet pond and a vegetated pond, for the same storm events listed in Table 2 for terrestrial surfaces. Average runoff temperatures are also given for a lake/reservoir. Outflow from the unshaded detention pond has, on average, a temperature (22.9°C) similar to that of runoff from asphalt (23.1°C in Table 2). The total heat export from the wet pond is also similar in magnitude to that from an asphalt pavement. The heat export rates from the pond are, however, an order of magnitude smaller than those for the runoff from asphalt pavement, indicating that a pond has can mitigate thermal impact in time but not in total heat released..

The average temperature and the average daily maximum temperature of outflow from the vegetated pond were lower than any land runoff temperatures (Figure 1, Table 1). For individual storm events (Table 3) outflow temperatures from vegetated ponds were also low, typically 3-5 °C less than for the unshaded pond runoff temperatures. This suggests that ponds with emergent vegetation that shades and shelters the water surface may be an effective mitigation measure for thermal pollution fron surface runoff. However, even the lowest simulated average runoff temperature did exceed 20 °C for several storms, suggesting that even the outflow from vegetated ponds holds a potential for thermal impact to a receiving stream.

Lake or reservoir outflow temperatures are substantially higher than those for the wet pond for many storms, with an average runoff temperature of 25.9 °C. This is primarily due to the higher thermal mass of the surface mixed layer of lakes or reservoirs. Cooler, cloudy weather cause only slow cooling of lake or reservoir surface temperature and outflow..

8. CONCLUSIONS

Surface runoff temperature and heat export have been simulated for ten land uses, an unshaded wet detention pond, a lake/reservoir, and a vegetated pond. Rainfall events producing the highest runoff temperature and heat export (thermal impact) are “cold front” storms with rapid onset of rainfall preceded by warm, sunny weather giving high surface temperatures. In general, the variation in average runoff temperature between land uses was not large (from 24.9 °C for concrete to 21.5 °C for a forest). However, this modest difference in runoff temperature translates into a large difference in thermal impact on cold-water streams. Average maximum runoff temperature varied more, from 28.7 °C for asphalt to 22.9 °C for a forest. Pavement, commercial rooftops, bare soil, wet detention ponds, and lakes/reservoirs were all found to give runoff temperatures high enough to significantly impact stream temperature. On average, concrete surfaces gave the highest runoff temperature of all land uses, but the results varied depending on the exact storm conditions. Vegetated surfaces gave substantially lower runoff temperature and heat export compared to pavement. Different vegetation types gave very similar runoff temperatures and heat export for mid-summer storms, but agricultural land use gave slightly higher runoff temperatures in May and June, due to a less developed plant canopy. Bare soil runoff temperatures were similar to those of pavement, but less runoff would be expected from bare soil due to infiltration. Residential roofs gave, on average, the lowest runoff temperature, due to very low thermal mass. However, residential rooftops can contribute increased heat energy to receiving streams for rainfall events with high dew point temperature. Large water bodies (lakes and reservoirs) generally give very high runoff temperatures, but the quantity of runoff is highly dependent on the water level prior to the storm event. Analysis of a vegetated pond indicates that shading from emergent vegetation reduces runoff temperature up to 6 °C compared to an unshaded pond.

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