UNIVERSITY OF MINNESOTA
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Stormwater Detention Pond Water Temperature Data Collection and Interpretation

by

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Abstract

This report summarizes a field study that was conducted for the MPCA to collect the data necessary to support the formulation and validation of a temperature simulation model for urban stormwater detention ponds. The urban stormwater detention pond simulation model is included in the MINUHET (MINnesota Urban HEat Transfer) model that computes (simulates) runoff temperatures for typical residential and commercial watersheds. The model simulates single rainfall events or continuous periods of several months. The simulated runoff temperatures and volumes are used to estimate the heat loading from urban surface runoff to coldwater streams. To support these simulations, weather data and urban runoff temperature data had to be collected to serve as model inputs and to validate model outputs.

In this report, a subset of the data collection effort is summarized. This report deals with stormwater detention ponds. The study was conducted in 2005 and 2006. Before a pond was chosen for detailed study, it was necessary to obtain an overview of typical stormwater detention ponds in an urban area. Eighteen stormwater detention ponds in Bloomington and Woodbury in the Twin Cities Metropolitan Area were documented, and are described in this report. Then a pond was selected for detailed instrumentation and data collection. That pond was on the former property of the State Farm Insurance Company Headquarters, near I94 and Radio Drive in Woodbury. The pond is a wet pond with an outflow structure and one major stormsewer inflow from two parking lots and the roof. Instrumentation was installed to measure and record weather data, temperature stratification data in the pond, surface inflow and outflow data, pavement temperature and pavement runoff temperature data.

In support of another study on the fate of road salt in the Twin Cities area, additional data were collected to document salinity profiles in urban stormwater detention ponds. These data are also presented in this report.

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1. INTRODUCTION

Stormwater detention ponds (SDPs) have become a standard feature in sub-urban development. When natural or agricultural areas are developed for residential, commercial or industrial use, permeable soil surfaces are paved or covered by buildings resulting in larger runoff volumes, higher peak runoff rates and shorter runoff times (times of concentration). The quality of the stormwater runoff is also changed by urban development. SDPs are usually designed to restore peak runoff, to extend the time of runoff, and to improve water quality, largely by sedimentation.

While the hydrology of SDPs is fairly well understood, many water quality effects are presently unquantifiable, under investigation, or unknown. The purpose of this data collection effort was to determine the impact that wet detention ponds have on runoff water temperature, particularly if the outflow drains into a cold, class A, trout stream. Consideration was given to various surrounding land uses/developments as they might affect the initial stormwater runoff temperature. A field survey of both man made and natural ponds was performed to identify candidate ponds. A man made pond was chosen and a field study was conducted to gather pond temperatures i.e. temperatures of the inflow, the outflow, and within the pond before, during and after rainfall events. The data was used to develop and to validate a model for predicting outflow temperature, and to offer recommendations for the reduction of stormwater pond outflow temperatures. In addition, less detailed field data were collected on a total of seventeen ponds in the metro area.

This research is important because at the periphery of the Minneapolis/St. Paul metropolitan area and in the city of Duluth are several cold water (trout) streams, including the Vermillion River in the Minneapolis/St. Paul metro area and Brown's Creek in the Stillwater area., that are threatened by urban development.

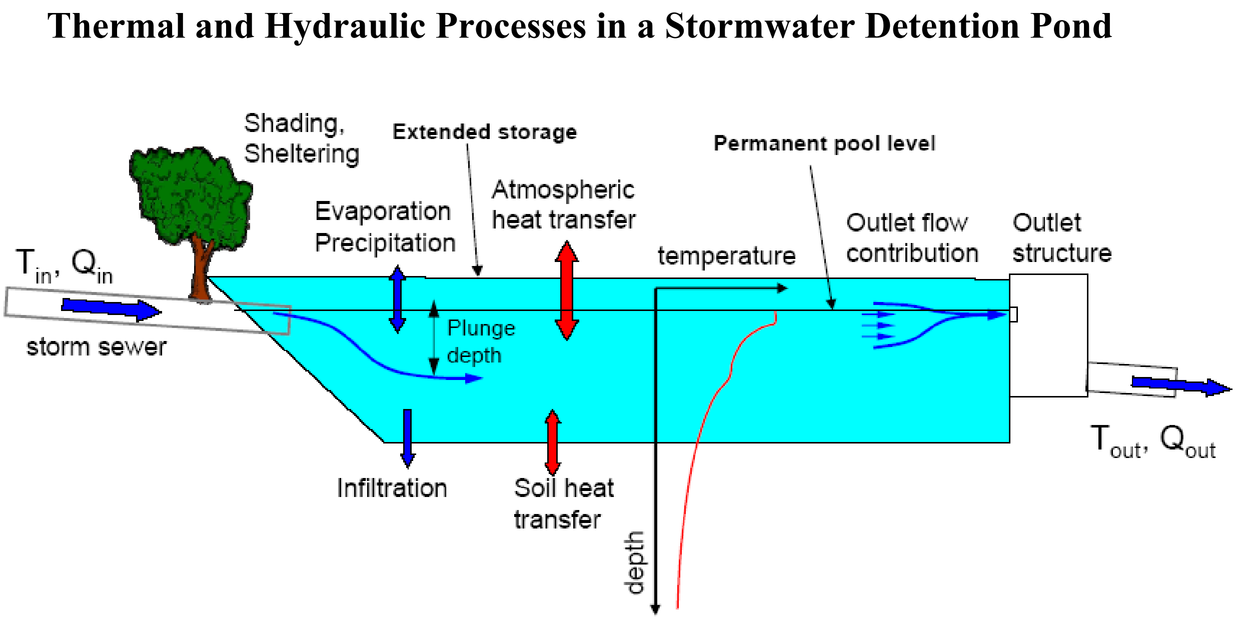
2. STORMWATER POND BASICS

The design and operation of SDPs is described in publications by many organizations including the American Society of Civil Engineers (ASCE), the U. S. Environmental Protection Agency (USEPA), the Minnesota Pollution Control Agency (MPCA), and the University of Minnesota Center for Transportation Studies (2002). A most relevant publication for wet detention ponds in the State of Minnesota is the Minnesota Stormwater Manual (2005). Its design guidelines encompass the USEPA regulations and the State of Minnesota Regulations. Additional restrictions or surface water handling or watershed requirements can be imposed by cities, watershed organizations, and other local government agencies.

The Minnesota Stormwater Manual (2005) describes a stormwater detention pond as “a constructed basin situated to receive local stormwater runoff and hold designated volumes of runoff for a specified period of time”, with the objectives being “to improve water quality through dynamic and quiescent settling of sediment particles and biological uptake, and to prevent downstream channel degradation or flood damage through storage and outflow rate reduction”.

This manual gives several distinct pond design variants, but due to the applicable regulations and variable climatic conditions throughout the state, only one design variant falls within the ‘Wet Sedimentation Basin’ category described in Part III.C.1 of the MPCA Construction General Permit. That variant, described as the “wet extended detention pond”, requires a combination of permanent pool storage, large enough to meet water quality needs, and sufficient extended storage above the permanent pool to provide rate control and additional water quality control, and to ensure adequate treatment during frozen conditions.

Storage in a stormwater pond can be either by a permanent pool or by extended detention. As the name implies, water in the permanent pool is meant to remain in the basin, allowing settling of particles in the stormwater and biological uptake to occur between storms, and protecting against sediment re-suspension. To maintain a permanent pool over a period of time, the pond must be designed with a sufficiently large drainage area. The Minnesota Stormwater Manual recommends a minimum of 25 acres. Extended detention storage refers to the volume above the permanent pool which is controlled by a primary outlet in the outlet structure, This primary outlet is sized so that runoff from larger storms can be captured and released over a period of time, keeping flow rates in check and allowing some settling to occur. Figure 2.1 shows a schematic diagram of a typical wet stormwater detention pond after a rain event. Notice that the water level shown is above what would be the permanent pool level based on the shown outlet.



Thermal and Hydraulic Processes in a Stormwater Detention Pond

Figure 2.1 Typical stormwater wet detention pond.

Many factors go into the general design of a SDP, including:

- Geometrical configuration and hydrologic performance, which require consideration of site limitations, surface area, shape, dead storage, water quality storage, maximum depth, additional storage for large events, number and size of stormsewer inlets, outlet structure design, specified yearly rainfall events and groundwater interaction.

- Drainage considerations, which include the watershed area, land use, slope, soil properties, and the stormsewer network.

- Water residence time, hydro-thermal considerations, which include shading by trees, emergent vegetation (reeds) or floating vegetation (duckweed), level of outlet and type of inflow and outflow structures.

- Aesthetic/ecological/maintenance considerations, which are important for the overall pond design. Wet ponds typically have a liner and retain water above a certain level; dry ponds fall/drain completely some time after a storm.

With regard to thermal pollution of coldwater streams by stormwater, the Minnesota Stormwater Manual (2005) states that the long detention or retention time associated with stormwater ponds can be problematic, and that coldwater fisheries sensitive to warming may make it inappropriate to use a wet pond due to potential for stream warming from pond outflows. If ponds are used, it is recommended that the 1-year, 24-hour storm be detained for no longer than 12 hours. If regulatory provisions allow, a smaller permanent pool with more extended detention storage or other treatment alternatives such as infiltration from a dry pond should be considered. Dry ponds, however, are highly susceptible to sediment re-suspension and often do not meet water quality performance criteria unless pre-treatment by a vegetated buffer, filter strip, or grass swale is used.

Other information for wet detention ponds from the Minnesota Stormwater Manual (2005) includes:

- A drainage area of 25 acres minimum is highly recommended to ensure a sufficient water input to maintain a permanent pool.
- The pond footprint area should be equal to approximately 1-3 percent of the drainage area.
- The site slope adjacent to the pond should be less then 25 percent and greater than 1 percent.
- The minimum head (elevation difference) recommended from inflow to outflow is 6-10 feet, but lower heads will work at small sites.
- The soils underlying the pond should be adequate to maintain a permanent pool.
- The permanent pool volume is required to equal 1800 cubic feet per acre of drainage.
- The required minimum and maximum pool depths are 3 feet and 10 feet respectively.

- A shallowly sloped (6%) access bench is recommended to extend 10 feet inward from the pond edge.

Also, consideration during the design process should be given to pre-treatment of stormwater inflow and outflow points, to reduce pond maintenance and erosion.

3. FIELD STUDY SITE SELECTION

3.1. Selection Criteria

For the selection of a representative stormwater detention pond (SDP) for this field study, land use was important. An SDP in an industrial or commercial development with high percentage of impervious area, or a residential area was most desirable. Other desirable pond attributes were:

- Ponds used in previous studies.
- Un-shaded pond surface.
- Only one inlet, instead of multiple inlets.
- Single outlet.
- Pond surface area of one to five acres.
- Continually flooded wet pond with open water area 3 feet to 10 feet deep.
- Not deteriorated or silted in pond.
- Drainage area easy to determine (no wetlands).

First considered, were ponds previously used for water quality studies by Drs. Bruce Wilson and John Nieber from the University of Minnesota. It was hoped that existing data would be useful for purposes of this thermal study. These ponds were located in the suburb of Bloomington, MN. This led to a search for other ponds in that suburb. Finally, 9 ponds in Bloomington and 9 ponds in Woodbury were considered.

3.2. Ponds Visited and Documented

The City of Bloomington's Wetland Protection and Management Plan lists all the ponds and wetlands in that city. From it, other pond locations and characteristics were obtained. For Woodbury ponds, the City of Woodbury Environmental Planner, Steve Kernick, gave selection guidance, and Sharon Doucette, the Environmental Resources Coordinator, gave GIS data for mapping and analysis. Table 3.1 lists the pond sites that were visited and documented. They are featured in Figures 4.1.1 to 5.9.5.

Table 3.1 Ponds visited and documented for possible temperature study.

Pond Name	**Location**	**Pond size (ac)**	**Est. shading (%)**	**No. of inlets**	**No. of outlets**	**Imperv. watershed area (%)**	**Watershed drainage area (ac)**
Smith Pond	Bloomington	8.2	2	5	1	44	not determined
Wright's Lake	Bloomington	4.5	2	2	1	44	Not determined
Highlands Court	Bloomington	1.6	3	4	1	not determined	not determined
Gideon	Bloomington	1.9	10	1	1	30	not determined
Curry Farms	Bloomington	0.3	25	1	1	not determined	not determined
Minnesota Bluffs	Bloomington	2.2	5	1	1	not determined	not determined
Mall of America	Bloomington	5.5	2	1	1	69	not determined
Overlook Manor	Bloomington	0.2	60	0	1	46	not determined
Canterbury Oaks	Bloomington	0.81	15	1	1	27	not determined
Upper Afton Road	Woodbury	~4	3	unsuitable	unsuitable	not determined	not determined
Woodwinds Health Campus	Woodbury	~1	3	unsuitable	unsuitable	not determined	not determined
Lake Road	Woodbury	~1	2	unsuitable	unsuitable	not determined	not determined
Windom Ponds	Woodbury	~.5	3	unsuitable	unsuitable	not determined	not determined
Pinehurst Road	Woodbury	~.8	3	unsuitable	unsuitable	not determined	not determined
Hudson Road	Woodbury	~1	3	unsuitable	unsuitable	not determined	not determined
Wedgewood	Woodbury	0.83	3	1	1	15	45.7
City Centre	Woodbury	0.75	5	2	1	47	27.9
State Farm	Woodbury	1.32	1	1	1	52	43.5
Average	------	**2 ac**	**8.3%**	**1.66**	**1**	**42%**	**39 ac**

A subjective shading scale of 0 -100% was used in which 0% indicates absolutely no shading over the whole pond (in comparison to pond size) during the entire day, and 100% indicates complete shading from sunlight reaching the pond surface over the whole pond for the entire day. Shading could be from any terrestrial object, such as buildings, trees, shrubs, tall grasses, emergent vegetation and reeds, higher surrounding topography, duckweed, or anything floating in the pond, and covering the time period of dawn to dusk. Bloomington pond sizes are from the individual descriptions in the **Bloomington Wetland Management and Protection Plan.** Also found there were "percent impervious" numbers for entire Bloomington drainage areas. Individual pond drainage areas were not given. For Woodbury ponds, the size was either estimated, or determined using the GIS data. Impervious watershed percent and drainage area were determined for three of the Woodbury ponds, using GIS data.

3.3. Average Pond Characteristics

On average, the 18 stormwater (wet) detention ponds documented and visited in Bloomington and Woodbury have a surface area of 2 acres; their average depths are not well documented, but are estimated to be on the order of 5 ft (1.5 m). They have on average 1.66 inlets and usually a single outlet. Most of the ponds, and especially the larger ones, do not have much shading by trees as a percentage of total surface area, while the smallest one is 60% (est.) shaded by trees. The average estimated shading percentage for all 18 ponds is 8.3%, but the median is only 3%. If the four highest percentages are excluded, the average is only 2.9%. Most of the ponds did not have significant shading.

Many of the stormwater ponds in Bloomington were natural water bodies before they were altered and used as urban stormwater ponds. Only 2 of the 9 Bloomington ponds investigated are completely manmade. The situation is similar in Woodbury. 42$^{\%}$ of the estimated or GIS determined drainage area (watershed) of 9 ponds total is impervious. The drainage areas were not known well enough to calculate an average, except for 3 Woodbury ponds.

The Bloomington Wetland Management and Protection Plan could be used to determine additional stormwater detention pond characteristics such as:

- Surrounding floral diversity.
- Surrounding wildlife habitat.
- Water quality protection.
- Shoreline protection.
- Groundwater interaction.
- Commercial and public uses.
- Flood/stormwater detention ability.
- Aesthetics and recreational uses

4. STORMWATER DETENTION PONDS IN BLOOMINGTON

Since two detention ponds in Bloomington were already being studied for water quality by University of Minnesota Professors John Nieber and Bruce Wilson, they were the first to be considered for this water temperature study. They are Wright's Lake and Smith Pond. These ponds, however, are quite large (4 - 8 acres) and are fed by complex and interconnected stormsewer lines. This geometry would introduce too many unknown variables into the heat transfer process analysis. Another seven ponds in Bloomington were therefore considered from among the detention ponds listed in the City of Bloomington's Wetland Protection and Management Plan of June 1997. That plan lists 313 wetlands and manmade ponds above the Minnesota River bluff line within the City of Bloomington, which is divided into 22 drainage areas covering approximately 39 square miles (Figure 4.1). Many of the wetlands in Bloomington are connected to the stormsewer system. Only ponds with no through-flow (not fed by an upstream pond) were candidates for further study.

The ponds considered are used primarily for stormwater detention, and for stormwater quality treatment. The Wetland Protection and Management plan characterizes and indexes each pond/wetland. The ponds considered for this study are mostly type 5 wetlands, which the Management Plan describes as being "inland open fresh water wetlands, including shallow ponds and reservoirs, with water less than six feet deep and fringed by a border of emergent vegetation". Some of these ponds have been chemically treated for algae and aquatic macrophyte control. Most chemical applications were of the chemical compounds diquat and copper sulfate. A smaller number of ponds had applications of glyphosate salts, endothal salts, 2-4D and surfactants. If a particular pond considered for this study had received treatment, it is identified in the individual description.

The following nine ponds in Bloomington were investigated as candidates for field study. Their locations are shown in Figure 4.1.

- Smith Pond
- Wright's Lake
- Highland Court Pond
- Gideon Pond
- Curry Farms Pond
- Minnesota Bluffs Pond
- Mall of America Pond
- Overlook Manor Pond
- Canterbury Oaks Pond

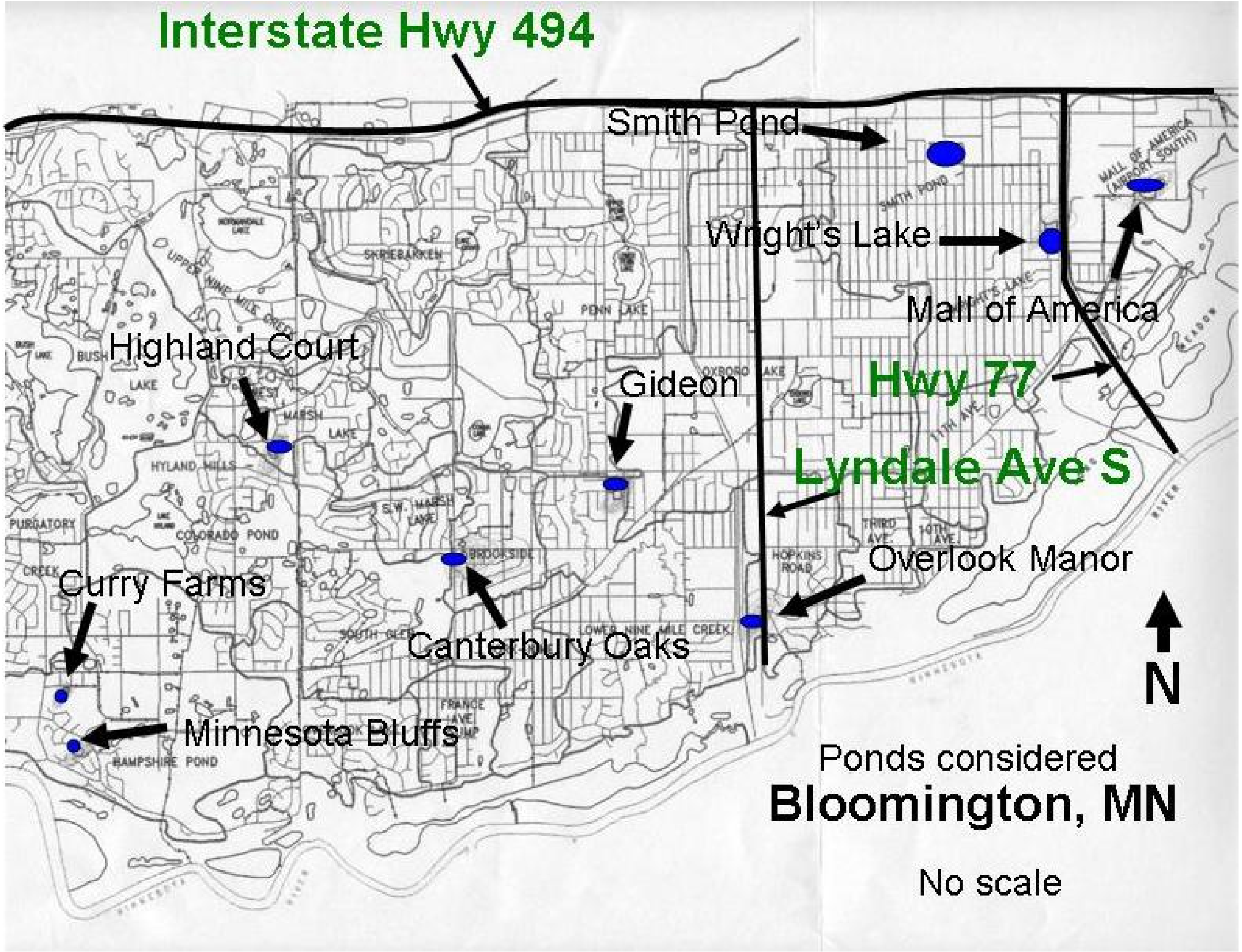
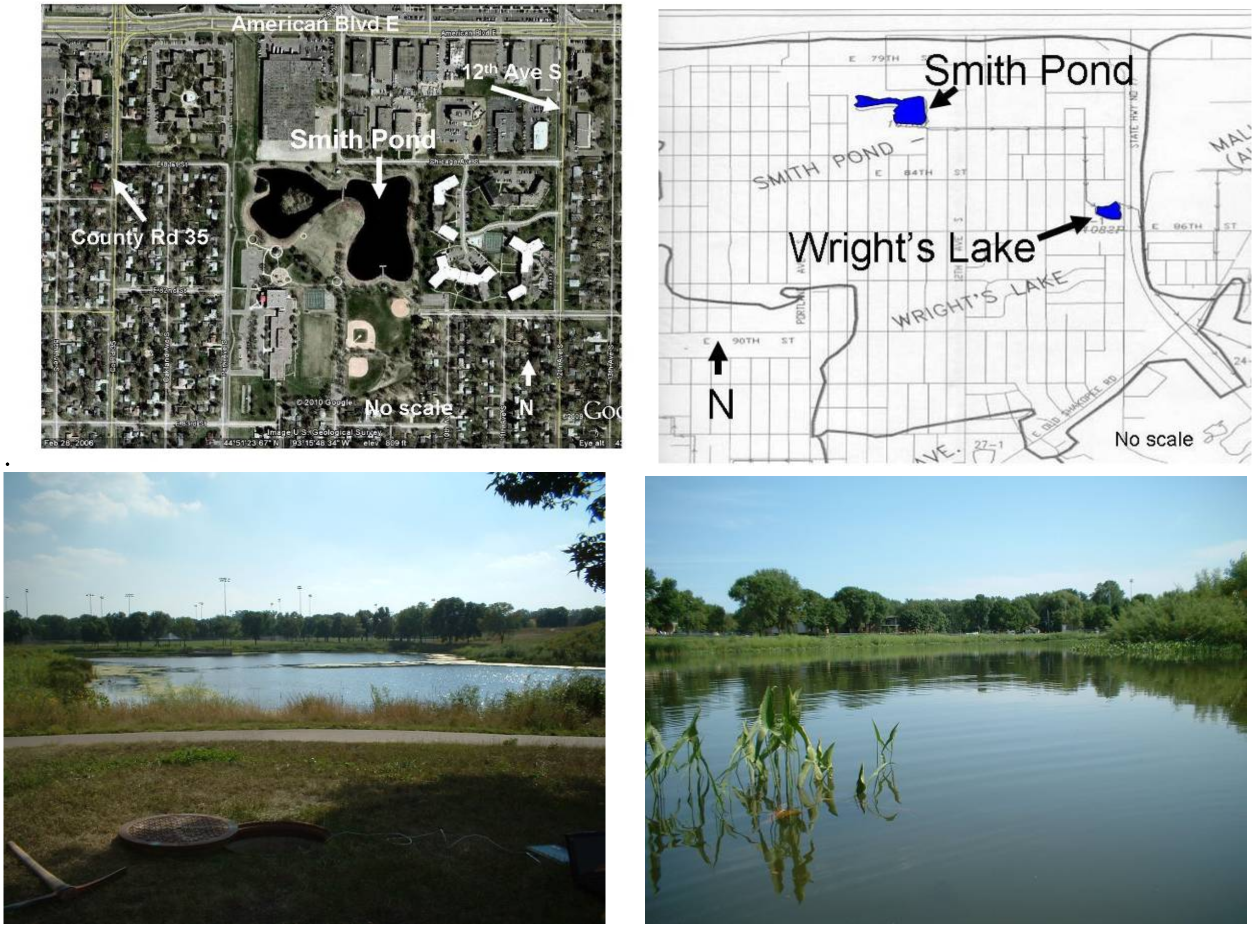


Figure 4.1 Bloomington Drainage Areas (Courtesy of City of Bloomington) with visited ponds identified by arrows and names.

4.1 Smith Pond

Smith Pond (Index # 03-01 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.1.1 – 4.1.4. It is located in the Smith Pond – Wright's Lake Drainage Area, more specifically in Smith Park, south of American Boulevard E. and west of 12th Ave S. It is a type 5 natural wetland with a surface area of 8.23 acres; it drains into Pond C, en route to the Minnesota River.

The Smith Pond – Wright's Lake Drainage Area drains 2265 acres into 2 natural wetlands, namely Smith Pond and Wright's Lake. Roughly 75 percent of the drainage area is covered by single and multiple family homes. The other 25 percent are covered by churches, schools, and industry. The drainage area is 44 percent impervious.

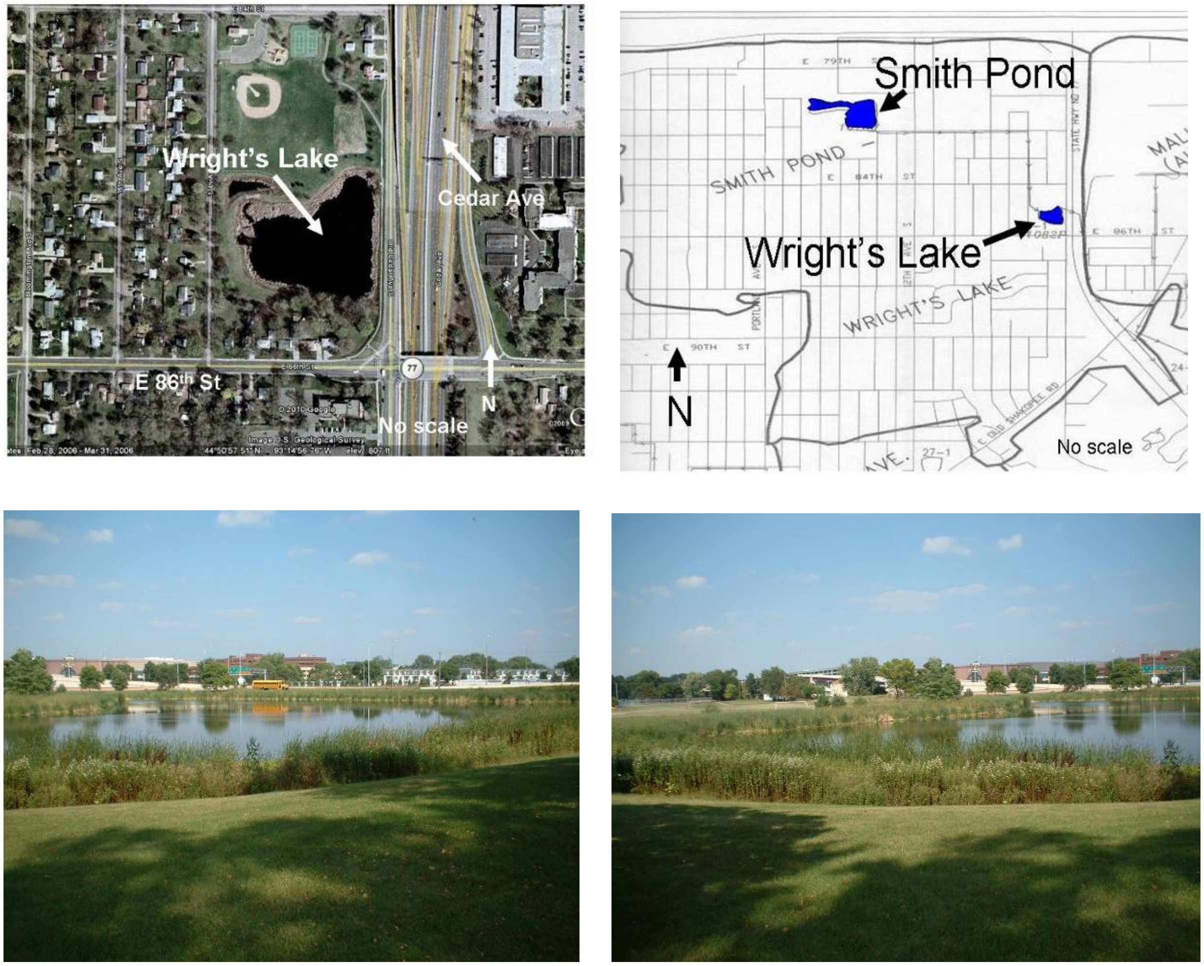


Figures 4.1.1 – 4.1.4 Smith Pond (Index # 03-01). Smith Pond – Wright's Lake Drainage Area.

Smith Pond is two larger water bodies connected by a short channel. It has several inlets, an island in the middle, and is more of a lake than a detention pond. It was deemed inappropriate for the field study because of its relatively large size and its many inlets. Smith Pond has been treated chemically by the City of Bloomington for algae and aquatic macrophyte control. This pond was revisited for salinity measurements, however, because of its' larger size.

4.2 Wright's Lake

Wright's Lake (Index # 04-01 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.2.1 – 4.2.4. It is also located in the Smith Pond – Wright's Lake Drainage Area. It is a type 5 natural wetland with a surface area of 4.55 acres that drains into Pond C and eventually into the Minnesota River.



Figures 4.2.1 – 4.2.4 Wright's Lake (Index #03-01). Wright's Lake Drainage Area.

Wright's Lake has a forebay, separated from the pond by rocks. The drainage map indicates that outflow from Smith Pond will enter Wright's Lake. It has one very large (~60") stormsewer pipe inlet, and one very large (~60") inlet from the direction of Smith Pond. It has one outlet weir. Shading by trees is minimal. This Lake is not a good study candidate because of its' size and the complexity of inflows.

4.3 Highland Court Pond

Highland Court Pond (Index # 66-03 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.3.1 – 4.3.4. It is a natural wetland located in the West Marsh Lake Drainage Area, more specifically it is located northwest of the intersection of Briar Rd and Hyland Courts Drive. This is a type 5 wetland with a surface area of 1.62 acres.

The West Marsh Lake Drainage Area drains 400 acres to Nine Mile Creek and eventually to the Minnesota River via 11 natural wetlands, including Hyland Courts Pond, and one manmade pond. Single family homes comprise 70 percent of the drainage area, with the other 30 percent being parks, wetlands, small commercial businesses, and churches or schools. The drainage area is 33 percent impervious.

Figures 4.3.1 – 4.3.4 Highland Court Pond (Index # 66-03). West Marsh Drainage Area.

Highland Court Pond has 3 water fountains, 4 inlets, and one outlet. It is slightly shaded along the perimeter. It is a very scenic pond but a poor candidate for study because of the water fountains and complex drainage area. Highland Court Pond is among the water bodies that the city has chemically treated for algae and aquatic macrophyte control.

4.4 Gideon Pond

Gideon Pond (Index # 32-01 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.4.1 – 4.4.4. It is located in the lower Nine Mile Creek Drainage Area. Specifically, it is located adjacent to and just south of the Creekside Community Center at the intersection of W 98th Street and Co Rd 32.

Figures 4.4.1 – 4.4.4 Gideon Pond (Index # 32-01). Lower Nine Mile Creek Drainage Area.

The lower Nine Mile Creek Drainage Area drains 1137 acres through 4 wetlands and 1 manmade pond, namely Gideon Pond, into Nine Mile Creek and eventually into the Minnesota River. About 75 percent of the area is residential with single and multiple family homes. The other 25 percent is comprised of city parks, Nine Mile Creek, and wetlands.

Gideon Pond is located on private property. It is totally fenced off and overgrown with trees. This pond appeared to be a semi-dry pond, with emergent vegetation throughout the entire pond area. The Wetland Protection Program lists it as 1.9 acres, however, it appeared shallow and to be only about 1/3 acre, and very muddy, due to a nearby construction site. It is a poor study candidate for those reasons.

4.5 Curry Farms Pond

Curry Farms Pond (Index # 72-04 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.5.1 – 4.5.4. It is located in the Hampshire Pond Drainage Area. Specifically, it is located just south of W109th Street, between Rhode Island Ave. S. and Quebec Ave. S. This is a manmade pond with a surface area of 0.30 acres.

Figures 4.5.1 – 4.5.4 Curry Farms Pond (Index #72-04). Hampshire Pond Drainage Area.

The Hampshire Pond Drainage Area drains 1307 acres to the Minnesota River through 10 natural wetlands and 8 manmade ponds, including Curry Farms Pond. Single family homes, apartments, townhomes, and the Minnesota Valley Golf Course comprise roughly 70 percent of the drainage area. The remaining 30 percent include Hyland Park and wetlands. This drainage area is 38 percent impervious.

Curry Farms Pond is a manmade elongated pond, tightly surrounded by condominiums. It has two water fountains and is slightly shaded by trees along the perimeter and cattails within the pond. It has a 24” diameter inlet and an 18” outlet. Curry Farms Pond is among the water bodies that the City of Bloomington has chemically treated for algae and aquatic macrophyte control. This pond was considered too small for a temperature study, was very shaded and had water fountains.

4.6 Minnesota Bluffs Pond

Minnesota Bluffs Pond (Index # 79-06 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.6.1 – 4.6.4. It is a natural wetland also located in the Hampshire Pond Drainage Area. This is a type 2 wetland, which the City of Bloomington also calls an inland fresh meadow. It is characterized as having soil that is without standing water during most of the growing season, but is saturated below the surface. This type of wetland provides waterfowl and wildlife habitat, water quality benefits and groundwater recharge. If flooded, it would have a surface area of 2.13 acres. Its primary use is as a detention pond. It is located just south of the intersection of Minnesota Bluffs Drive and Oregon Avenue S. There is a 60" concrete pipe inlet at the southwest end and an 18" overflow outlet on the north side.

Figures 4.6.1 – 4.6.4 Minnesota Bluffs Pond (Index #79-06). Hampshire Pond Drainage Area.

Minnesota Bluffs Pond is very overgrown with plants and is mostly a dry pond. Standing water is visible only near the inlet/outlet pipe. It is fairly shaded and has swamp type vegetation in the middle. This pond was also inappropriate for the field study.

4.7 Mall of America Pond

Mall of America Pond (Index # 02-01 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.7.1 – 4.7.4. It is located adjacent to and just southwest of the Mall of America Shopping Center and northeast of the intersection of County Road 1 and E. Old Shakopee Road. It is a manmade stormwater pond that drains directly into Pond “C”, Bass Ponds, or Long Meadow Lake, all of which are located below the bluff line and within the Minnesota Valley National Wildlife Refuge. These waters then flow into the Minnesota River. The Mall of America Pond is a semi-dry pond that is intermittently flooded by stormwater run-off. Vegetation varies according to the season and the amount of flooding. This type of wetland can benefit seasonal waterfowl and wildlife habitat, water quality protection, and groundwater recharge. The 30” pipe leading to the pond serves as both the inlet and outlet. It also has a significant amount of overland flow from paved areas. If filled, the pond would have a surface area of 4 acres.

Figures 4.7.1– 4.7.4 Mall of America Pond (Index # 02-01). Mall of America Drainage Area.

The Mall of America Drainage Area drains approximately 645 acres through 3 manmade ponds, including the Mall of America Pond. It is almost 100 percent developed, including the commercial Mall of America, single and multiple family homes and office/warehouse space. The drainage area is 69 percent impervious.

The Mall of America Pond has very little shading. These photos were taken a day after a 1.5 inch rainfall. The pond was 4/5 dry. The water present appeared to be 2-4 ft deep maximum and was estimated to be about 2 feet below the level of the inlet/outlet pipe. It was not considered for further study because it is a semi-dry pond.

4.8 Overlook Manor Pond

Overlook Manor Pond (Index # 41-01 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.8.1 – 4.8.4. It is located in the Hopkins Road Drainage Area and is the first of two inter-connected stormwater ponds in this drainage area. Overlook Manor Pond is a type 5 natural wetland with a surface area of 0.2 acres. It is located at the northwest corner of the intersection of Lyndale Avenue S. and W 106th Street. It has only overland inflow, and one 24” pipe outlet. It is very shaded and sheltered from the wind and was 100 percent algae covered in mid-late summer. This pond’s primary classification is as a detention pond, and the water quality is rated as highly impacted.

Figures 4.8.1 – 4.8.4 Overlook Manor Pond (Index # 41-01). Hopkins Road Drainage Area.

The Hopkins Road Drainage Area drains 411 acres via 1 manmade pond, namely Overlook Manor Pond, and 1 natural wetland, and is 90 percent residential, including single and multiple homes, and 10 percent city parks, retail commercial, and wetlands. The drainage area is 46 percent impervious.

Overlook Manor Pond sits in a depression between buildings and roads and is very sheltered from the wind. It was not chosen for further study because of its small size, extensive shading, algae cover and unknown bathymetry.

4.9 Canterbury Oaks Pond

Canterbury Oaks Pond (Index # 39-01 in the City of Bloomington Wetland Protection and Management Program) is shown in Figures 4.9.1 - 4.9.6. It is the first of three inter-connected stormwater ponds in the Brookside Drainage Area, which drains into Nine Mile Creek en route to the Minnesota River. Canterbury Oaks Pond is a type 5 natural wetland with a surface area of 0.81 acres. It is located just south-east of the intersection of France Ave S. and W 102nd St in Bloomington. The primary use classification is as a detention pond.

The Brookside drainage area drains 325 acres through 3 natural wetlands, including Canterbury Oaks Pond, and is characterized as 80 percent single family homes, apartments and townhouses, with the remaining 20 percent being wetlands and city parks. The drainage area is 27 percent impervious. The wetland quality for the Brookside Drainage Area is rated as highly to moderately impacted; human activities have significantly affected it.

Figures 4.9.1 – 4.9.2 Canterbury Oaks Pond (Index # 39-01). Brookside Drainage Area.

Figures 4.9.3 – 4.9.6 Canterbury Oaks Pond (Index # 39-01). Brookside Drainage Area.

Canterbury Oaks Pond appeared shallow and is fairly well shaded by mature trees around the perimeter. It was approx 30 percent covered with algae in mid-late summer. It has an 18” corrugated steel inlet pipe at the south end, and a 12” outlet at the north end. Canterbury Oaks pond has been chemically treated for algae and aquatic macrophyte control by the City of Bloomington. It was not chosen for this study because of the extensive shading, algae cover and unknown bathymetry. For the same reasons, however, Canterbury Oaks was revisited for salinity measurements, as variety was sought in the types of ponds selected for those measurements.

5. STORMWATER DETENTION PONDS IN WOODBURY

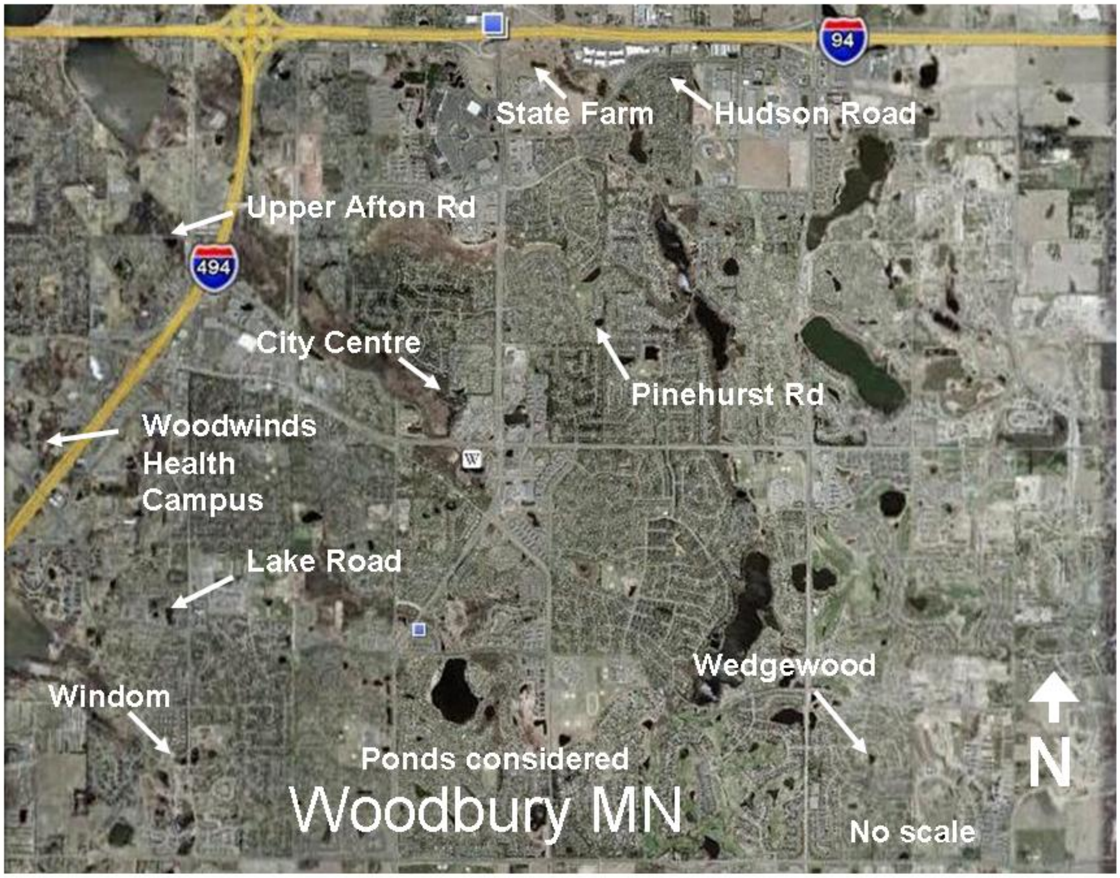


Figure 5.1 Woodbury ponds considered.

Nine ponds in Woodbury (Figure 5.1) were considered as potential sites for a field study. They are:

- Upper Afton Road Pond
- Woodwinds Health Campus Pond
- Lake Road Pond
- Windom Pond
- Pinehurst Road Pond
- Hudson Road Pond
- Wedgewood Pond
- City Centre Pond
- State Farm Pond

5.1 Upper Afton Road Pond

Upper Afton Road Pond, shown in Figures 5.1.1 and 5.1.2, is located just northwest of the I-494 and Valley Creek Road intersection. It was considered as a shaded study site. This pond was not chosen because it is adjacent to large low woodland, it is natural, and did not have watershed characteristics that could be easily related to urban residential or commercial development.

Figures 5.1.1 – 5.1.2 Upper Afton Road Pond.

5.2 Woodwinds Health Campus Pond

Woodwinds Health Campus Pond, shown in Figures 5.2.1 and 5.2.2, is located adjacent to the Woodwinds Health campus, just west of I-494 between Valley Creek Road and Lake Road. It is a manmade pond that drains directly into a marsh. This pond was not chosen for study because the outflow would have been difficult to gauge.

Figures 5.2.1 – 5.2.2 Woodwinds Health Campus Pond.

5.3 Lake Road and Woodlane Drive Pond

Lake Road Pond, shown in Figures 5.3.1 and 5.3.2, is located in a newer housing development northwest of the intersection of Lake Road and Woodland Drive. It is a natural pond surrounded by new homes. It has little shading and it is connected by a small channel to another pond. This connection makes it unsuitable as a field study site.

Figures 5.3.1 – 5.3.2 Lake Road Pond.

5.4 Windom Pond

Windom Pond, shown in Figures 5.4.1 and 5.4.2, is one of many located in the Windom Ponds development. It is a natural pond, with inflow from other ponds, making it unsuitable for a field study.

Figures 5.4.1 - 5.4.2 Windom Pond.

5.4 Pinehurst Road and Duckwood Trail Pond

Pinehurst Road Pond, shown in Figures 5.5.1 and 5.5.2, is a natural pond, nestled amongst newer homes. It appeared very shallow and had some algae cover in late October. Its' apparent shallow depth made it unsuitable for a field study.

Figures 5.5.1 – 5.5.2 Pinehurst Road Pond.

5.5 Hudson Road and Turnberry Alcove Pond

Hudson Road Pond, shown in Figures 5.6.1 and 5.6.2, is highly irregular in shape and has an island. It is perched on a hillside, behind newer homes. It has some shading, but its' shape makes it unsuitable as a field study site.

Figures 5.6.1 – 5.6.2 Hudson Road Pond.

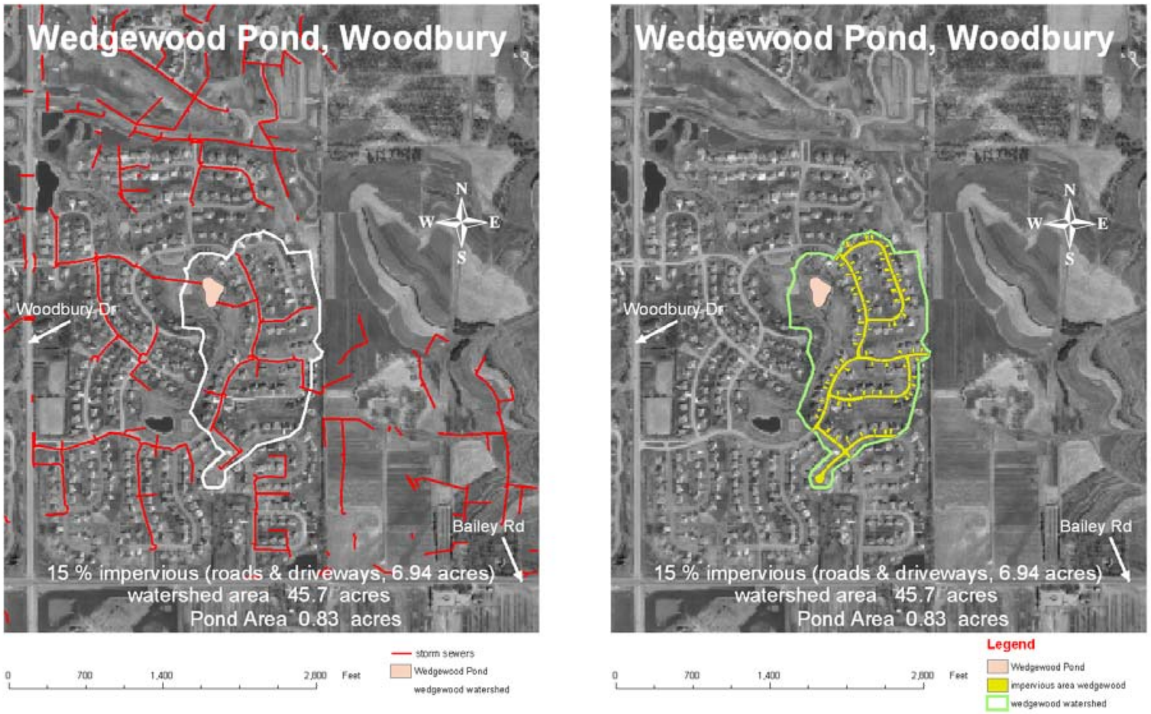
5.6 Wedgewood Park Pond

The Wedgewood Park Pond, shown in Figures 5.7.1 -5.7.6 and Figures 5.7.7 -5.7.8, is manmade and located 3.5 miles south of I-94, on Woodbury Drive, then east on Antrim Road. Its' surface area is 0.83 acres and it has only one piped inlet and one piped outlet. Its' drainage collection area of 45.7 acres is 15 percent impervious parking lots, roofs and sidewalks. It is on city property. Its' average depth is 1.3 meters, with 1.5 meters at deepest.

Figures 5.7.1 - 5.7.4 Wedgewood Park Pond.

Figures 5.7.5 - 5.7.6 Wedgewood Park Pond Details.

It was considered to be a good candidate for further field study because its watershed is solely residential. An analysis of the pond using GIS software combined with stormsewer line data obtained from the City of Woodbury is shown in figures 5.7.7 and 5.7.8. This pond was ultimately bypassed for study because of its rather shallow depth of about 1.3 meters. It was revisited later for salinity measurements though because of the openness and shallow depth.



Figures 5.7.7 - 5.7.8 GIS images of stormsewer (left) and drainage area (right) near Wedgewood Pond.

5.7 City Centre Drive Pond

The City Centre Drive Pond in Figures 5.8.1 – 5.8.6, is manmade and located north of City Centre Drive and west of Radio Drive. Its' surface area is 0.75 acres; it has two pipe inlets and one pipe outlet. Its drainage area of 27.9 acres is 47 percent impervious (parking lots, roofs and sidewalks). The pond is on city park property. Its depth is variable and ranges from less than a meter near the inlet to about 2 meters near the middle and back to about 1 meter near the outlet. There is significant shading by small trees along the perimeter.

Figures 5.8.1 -5.8.4 City Centre Drive Pond.

Figures 5.8.5-5.8.6 City Centre Drive Pond.

The drainage system is shown in Figures 5.8.7 - 5.8.8. This pond was not studied because of its irregular shape and somewhat shallow depths. It was revisited for salinity measurements because of its shading, and as an example of a pond fed by purely residential runoff.

Figures 5.8.7 - 5.8.8 GIS images of City Centre Drive Pond drainage area (left) and storm sewer system (right).

5.9 State Farm Pond - chosen for field study

The State Farm Pond, shown in Figures 5.9.1 - 5.9.3, is manmade and located southeast of the intersection of I-94 and Radio Drive. Its' surface area is 1.32 acres. It has only one pipe (stormsewer) inlet and one weir controlled outlet. Its drainage collection area of 43.5 acres is 52% impervious (parking lots, roofs and sidewalks). It is on private property and is almost completely un-shaded. The permanent pool depth is 2.4 meters.

Figure 5.9.1 State Farm Pond.

Figures 5.9.2 - 5.9.3 State Farm Pond.

Engineering data for the pond and stormsewer lines were made available by State Farm Insurance Company. The watershed was delineated using GIS software and is shown in Figure 5.9.4, and the bathymetry is shown in Figure 5.9.5. Salinity measurements were also taken in this pond.

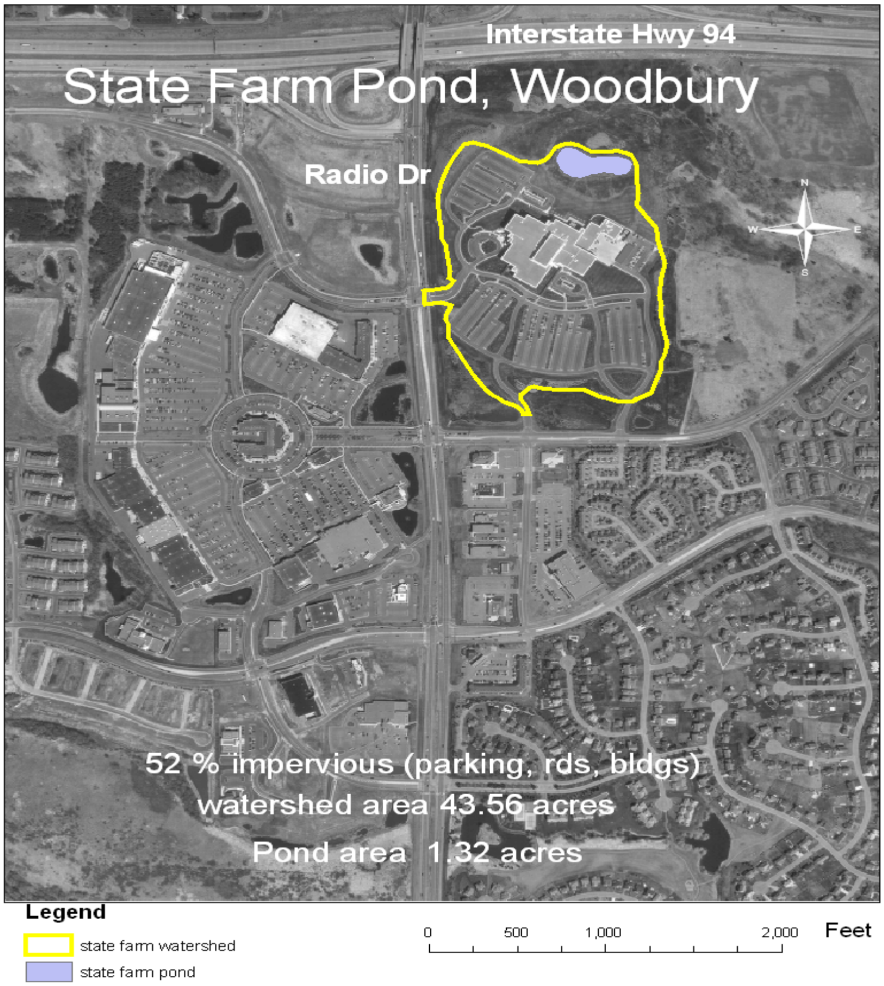


Figure 5.9.4 Drainage area (watershed) of the State Farm Pond.

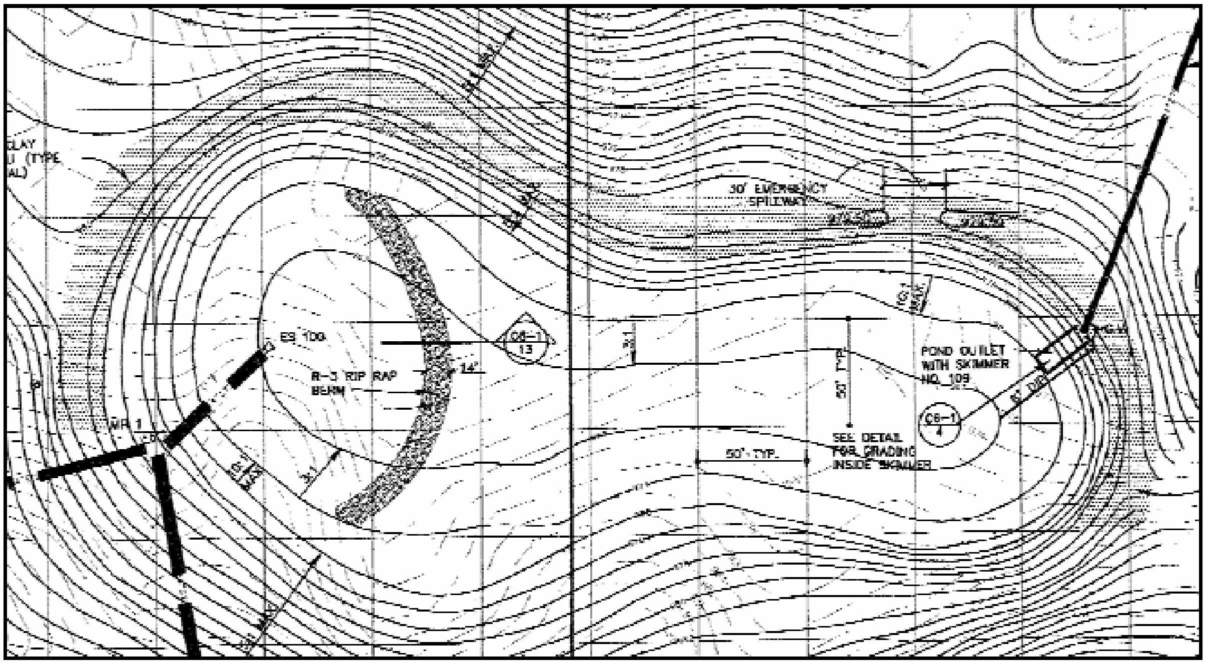


Figure 5.9.5 Bathymetry of the State Farm stormwater detention pond, courtesy of Ellerbe Becket, Inc. The contours are at 1 foot intervals. The stormsewer inlet structure is on the left (West), and the outlet structure is on the right (East).

6. DATA COLLECTION AT THE STATE FARM POND SITE

In support of the formulation and validation of a hydro-thermal stormwater detention pond model the following data had to be collected, i.e. recorded over time or assembled from nearby locations, or calculated:

(1) Weather data including rainfall, solar radiation, air temperature, relative humidity, dew point, wind speed, and temperature of rainfall.

(2) Runoff data including inflow rate and temperature of stormsewer discharges into the pond, pavement temperature and pavement runoff temperature, temperature and amount of surface runoff from overland flow into the pond, temperature and rate of outflow from the pond.

(3) Pond data including vertical temperature profiles, pond level, pond water transparency, and pond shading.

6.1. Available Weather Data

Weather data were available from the following sites in the Twin Cities area:

- MSP International Airport (National Weather Service, NOAA):
  rainfall, wind speed and direction, air temperature, dew point, relative humidity at 1 hour intervals
- SAFL (St. Anthony Falls Laboratory, University of Minnesota):
  solar radiation, air temperature, relative humidity, dew point, rainfall, wind speed and direction at 5 to 10 minute intervals
- St. Paul Campus Weather Station (Dept. of Soil, Water and Climate, University of Minnesota): solar radiation, air temperature, relative humidity, dew point, rainfall, wind speed and direction at 1 hour intervals

6.2. Instrumentation for Field Data Collection

Because the available weather stations listed under section 6.1 do not necessarily give data representative of the State Farm Pond (SFP) site, a weather station was erected in the middle of the pond.

The pond has a clay-liner to prevent water loss by infiltration. The pond has an outlet structure that stops the outflow from the pond when the maximum pond water depth has dropped to about 2.43m (permanent pool level). The surface area of the pond when it is not overflowing is about 5000 m^2 (1.2 acres). Surface water inflow is from the former State Farm Insurance Co. office complex which includes an upper and a lower asphalt parking lot shown in Figure 5.9.1 and 5.9.4.

The weather station installed for the field study was comprised of an anemometer, a wind direction vane, and a tipping bucket rain gauge. Below the water surface and not visible in the picture, is a thermistor chain consisting of 6 temperature sensors (thermistors) attached to the pole, and a pressure sensor to record pond water level. The chain was weighted with a 5 lb. lead weight and the bottom thermistor was secured immediately above the weight. The pond surface temperature came from a 7th thermistor attached to the underside of a floating body as shown in Figure 6.2.2. All instruments were connected to a Campbell Scientific data logger CR-10 that was attached to the pole above the water as shown in Figure 6.2.1. An example of the data can be seen later Figure 6.5.6.

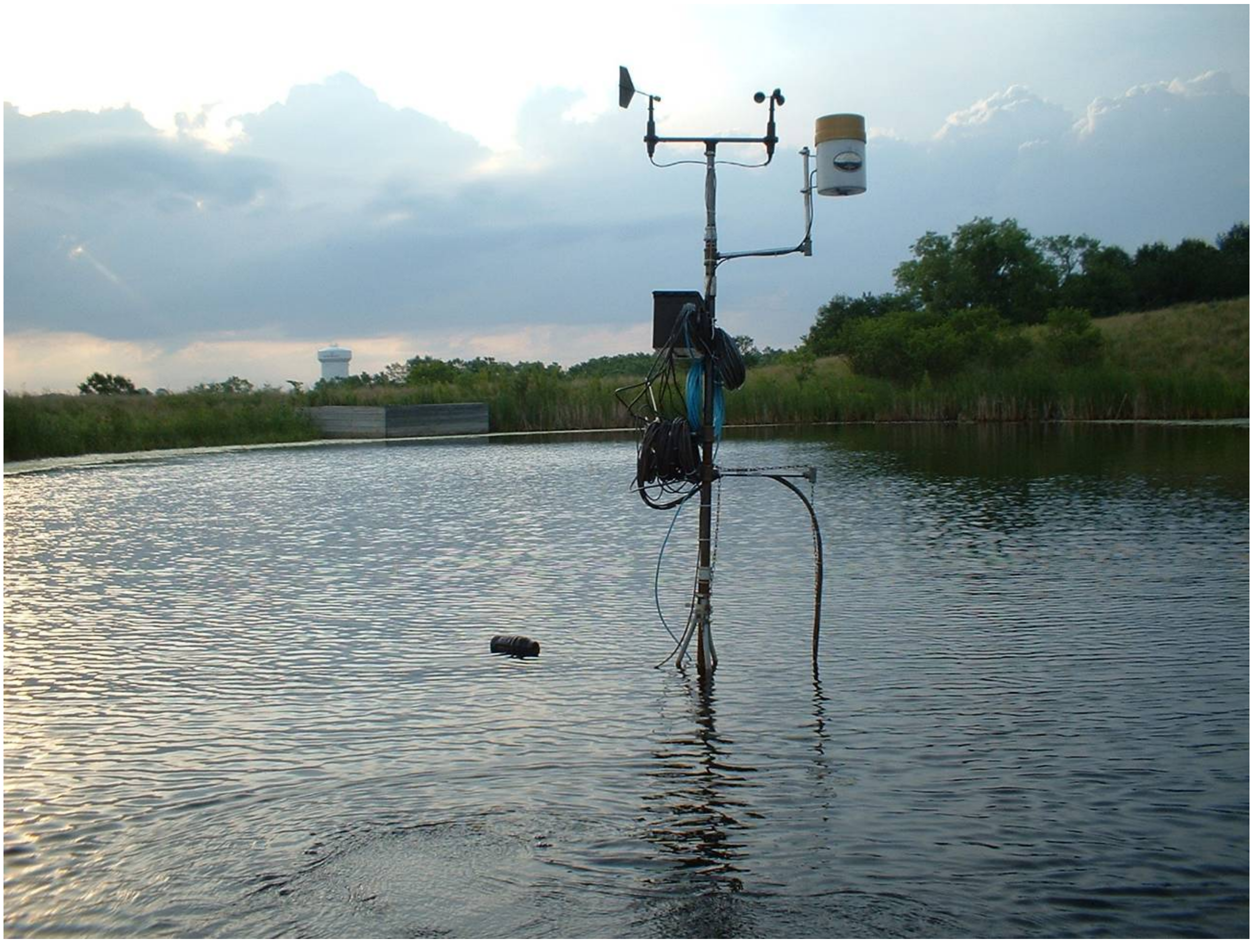


Figure 6.2.1 Weather station and Campbell Scientific data logger CR-10 set-up in the State Farm Pond.

Figure 6.2.2 Thermistor, attached to underside of floating body, recording surface temperature.

The weather parameters and the water temperatures in the pond were measured every minute and averages were recorded on the Campbell data logger every 10 minutes. Water temperatures were measured with YSI model 55032 thermistors with a time constant of about 10 seconds. Wind speed (m/s) was measured by an R.M. Young model 03001 anemometer and wind direction instrument. Water level was measured with an Instrumentation Northwest model 9805 pressure sensor. The instrumentation in the pond was operated from June 3 to August 25, 2005.

Already on site and 50 yards from the pond, was a functioning weather station shown in Figure 6.2.3. It was installed and used by the former KDWB Radio Station, and was subsequently used by State Farm to determine when lawn irrigation was needed. Air temperature data from this station were going to be used for this study but, as it turned out, the data was incomplete. Air temperature data from the St. Paul Campus weather station was used instead

Figure 6.2.3 On-site weather station at State Farm Headquarters.

Several Vemco Minilog and Onset Hobo temperature loggers were used to record water temperatures (°C) at 1 minute intervals at the pond inlet (Figures 6.2.4 - 6.2.5) and outlet structures (Figures 6.2.4 - 6.2.7), and at 1 minute initially, then 2 minute intervals at two stormwater catchments in the parking lots (Figures 6.2.8 - 6.2.9). Examples of the inlet and outlet temperature data are shown in Figures 6.5.13 and 6.5.15.

Figures 6.2.4 – 6.2.5 Manhole of single stormsewer draining into the pond at West end, where a Vemco temperature logger was placed.

Figures 6.2.6 – 6.2.7 Overflow weir (left panel) and circular 0.203m (8”) diameter outlet (right panel) at East end of pond where Vemco temperature logger was placed.

Figures 6.2.8 – 6.2.9 Vemco temperature loggers were attached to the underside of stormwater catchments in the parking lots.

An example of the runoff data can be seen in Figure 6.5.12.

Two additional temperature loggers were buried in the surface of the asphalt parking lot to record pavement temperature (°C) at 2 minute intervals initially, and then 5 minute intervals (Figures 6.2.10 - 6.2.13).

Figures 6.2.10 – 6.2.13 Vemco temperature loggers buried in upper and lower parking lot pavements.

After retrieving the data, it was realized that the Vemco loggers buried in the pavement had an upper recording limit of 36 °C. They were replaced with Onset Hobo miniloggers of similar size which yielded data at higher temperatures. An example of this data is shown in Figure 6.5.9.

Water transparency in the pond was measured manually using a Secchi disk. The Secchi depth (*d*) was recorded. From the measured Secchi depth (d) the radiation attenuation coefficient (*k*) in the pond water calculated using the relationship $k = 1.84/d$. Secchi data are listed in Table 6.5.1.

Solar radiation (W/m^2) and air temperature (°C) was obtained from the St. Paul Campus Weather Station. Figure 6.5.9 shows a comparison of solar radiation and air temperature as they relate to pavement temperature. Dew point temperature (°C) was also obtained from the St. Paul Campus Weather Station. Dew point data is plotted in Figure 6.7.22.

The data described in this section were used as input to a water temperature simulation model for stormwater detention ponds, as described in Appendix A, to validate the model for the State Farm pond.

6.3. Instrument Calibration

The pressure sensor was calibrated prior to installation. To do the calibration, the sensor was submersed in a bucket of water at incremental 1 inch depths. Readings were first taken for increasing depths from1 to 12 inches and then going back up. The two readings were averaged for each depth. The resulting regression line has very good correlation with an R^2 value of 0.9999 (Figure 6.3.1). It was both precise and accurate.

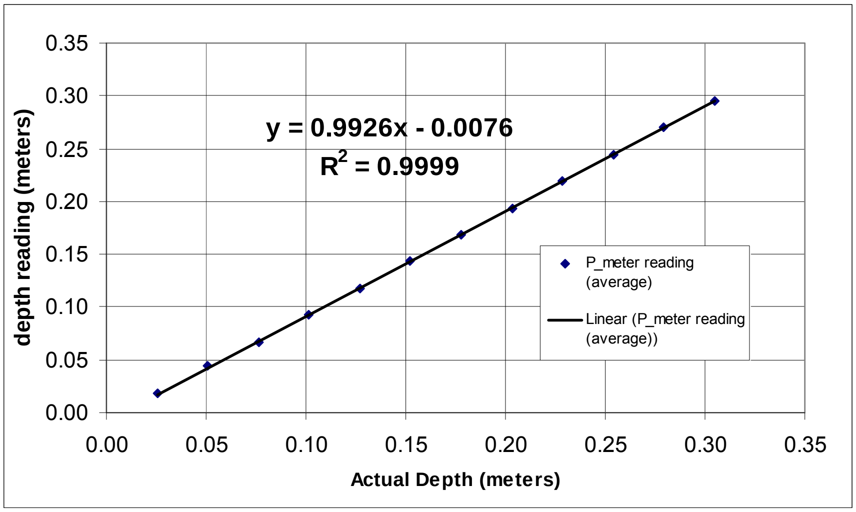


Figure 6.3.1 Pre-study calibration of Instrument Northwest model 9805 pressure sensor used to determine pond level.

The thermistors were calibrated prior to be placed in the pond. With data logger program offsets entered, they all recorded temperatures within 0.1 degree Celsius of actual temperature and of each other (Figure 6.3.2).

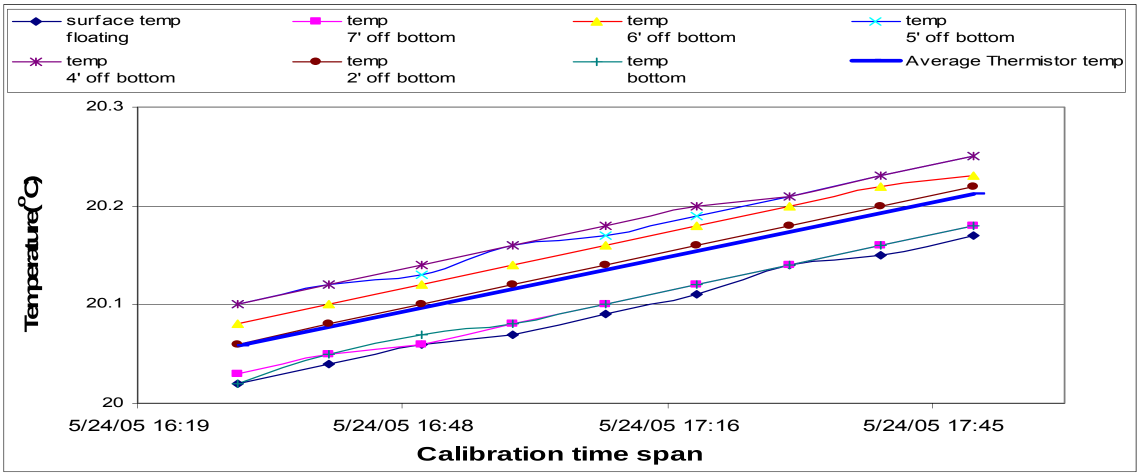


Figure 6.3.2 Pre-study thermistor calibration test results.

A post-study calibration of the thermistors was performed within a few days after they had been removed from the pond. Figure 6.3.3 shows that the bottom thermistor was far out of calibration, recording temperatures 3 - 4°C higher than actual. This error clearly showed up in plots of the raw data collected toward the end of the study, but was not clearly evident in plots of earlier data.

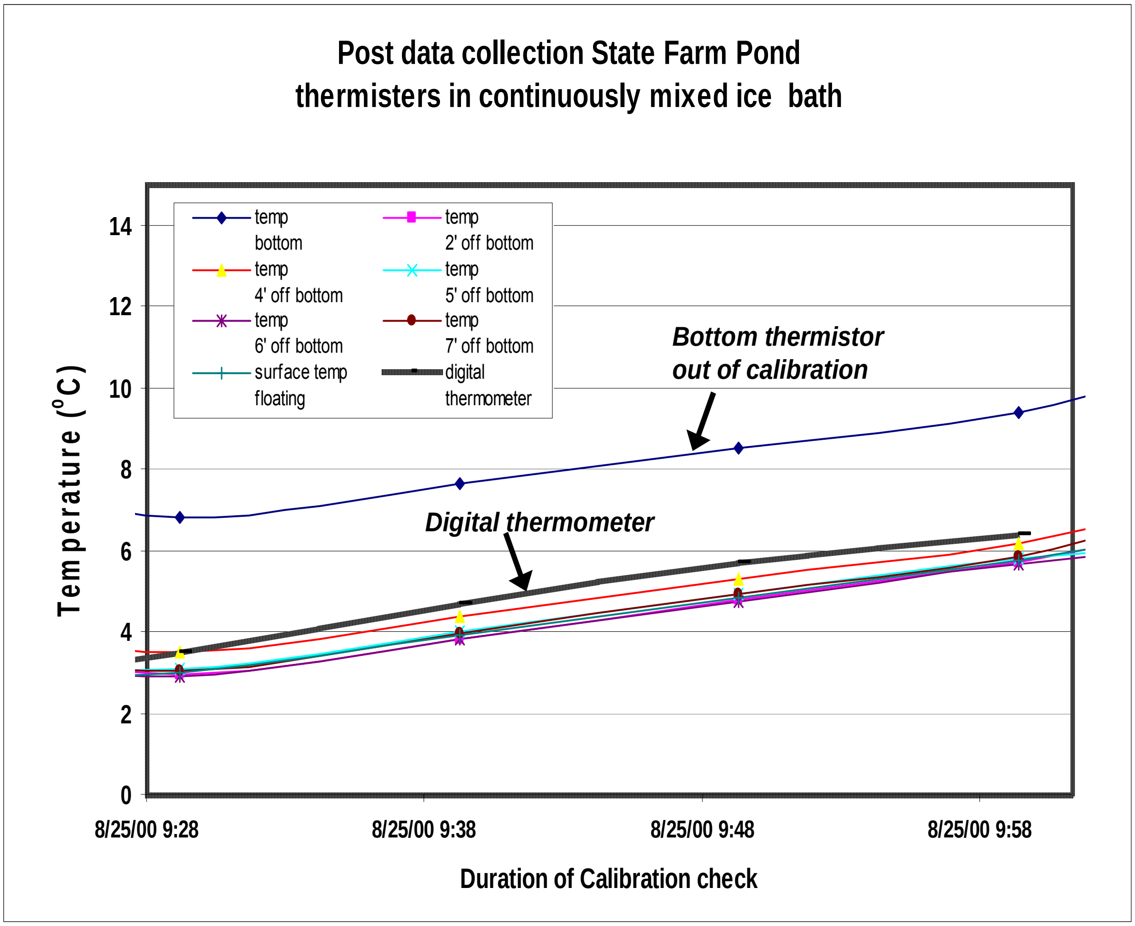
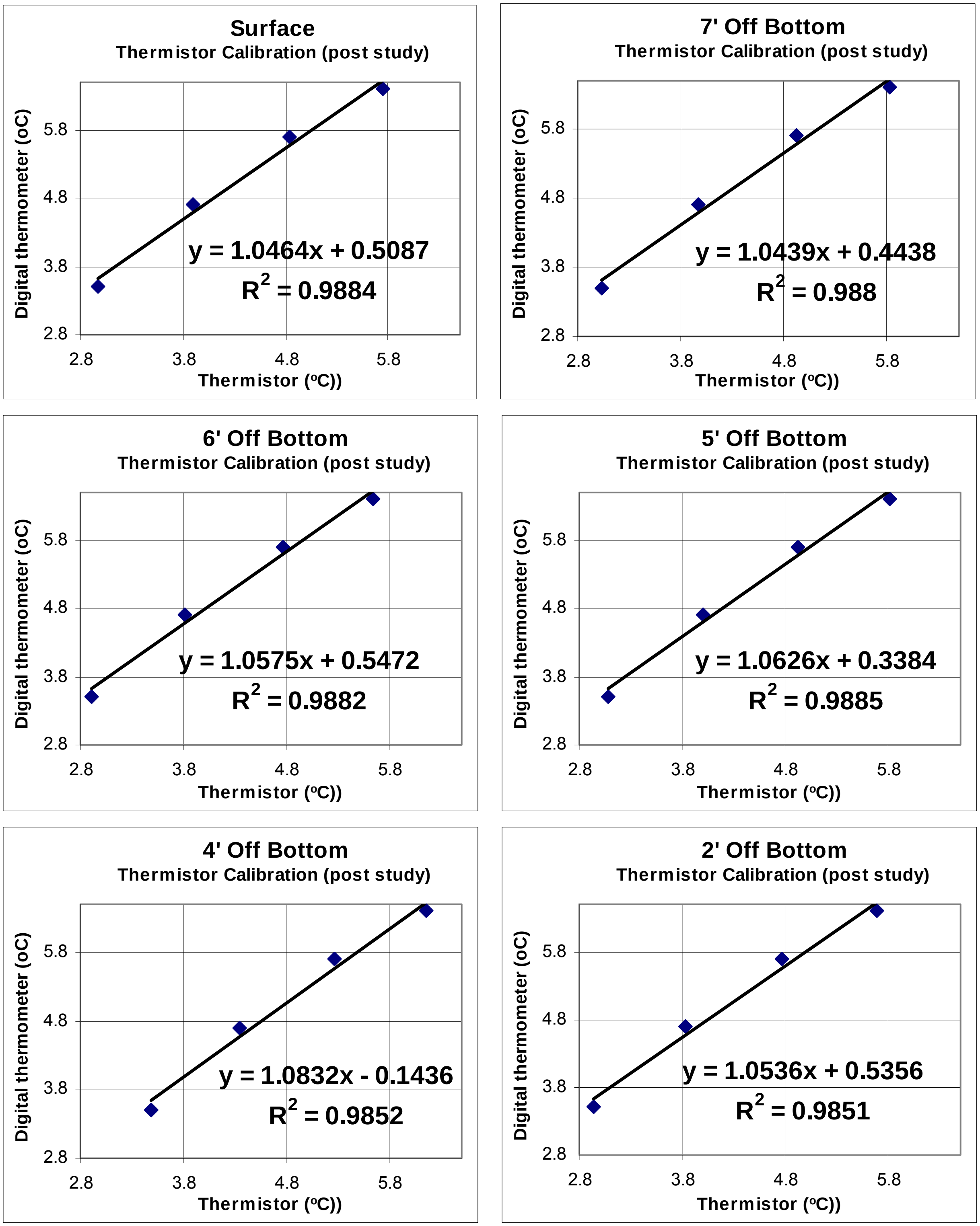


Figure 6.3.3 Post-study thermistor calibration.

Except for the bottom thermistor, all thermistors were fairly precise (Figures 6.3.4 through 6.3.9); the lowest R^2 value among them was 0.9851. They were slightly inaccurate, with recorded temperatures of one-half to three-quarters degree below the actual temperature. The bottom thermistor was also precise, with an $R^2 = 0.986$ but it was very inaccurate, recording temperatures of over 3 degrees Celsius above the actual temperature.

Since the bottom thermistor was in calibration at the start of the study but far out of calibration at the end of the study (Figure 6.3.10), the bottom temperatures were not used. It was uncertain when and how rapidly the thermistor went out of calibration, so all data from the bottom thermistor was suspect.



Surface
Thermistor Calibration (post study)

7' Off Bottom
Thermistor Calibration (post study)

6' Off Bottom
Thermistor Calibration (post study)

5' Off Bottom
Thermistor Calibration (post study)

4' Off Bottom
Thermistor Calibration (post study)

2' Off Bottom
Thermistor Calibration (post study)

Figures 6.3.4 – 6.3.9 Post-study regression calibration analysis for all but bottom thermistor.

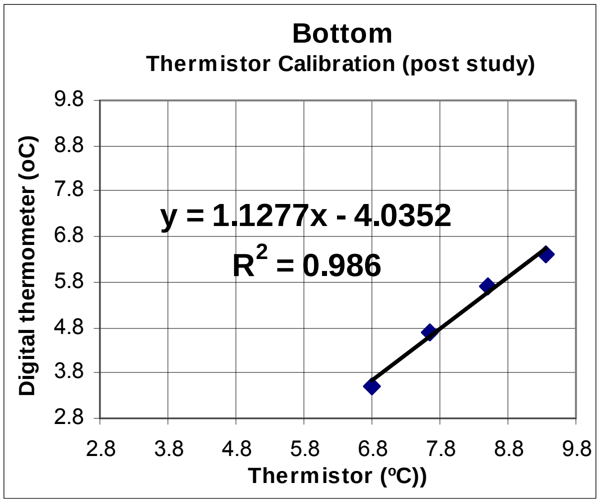


Figure 6.3.10 Post-study regression calibration analysis of bottom thermistor. Precise, but very inaccurate.

6.4. Pond Hydrology

The State Farm Pond has an outlet structure with an 8" (0.203m) diameter circular opening in a vertical wall for normal operation, and an emergency overflow weir positioned 61cm higher (Figure 6.2.6). Using pond level measurements, a relationship (Equation 6.1) between pond water elevation and outflow rate Q_{out} (m^3/s) was established (Herb et al. 2006).

$$Q_{out} = C_{port} A_{port} \sqrt{2g\Delta h} \, * \, \mathrm{Min}\left(1.0, \frac{3\Delta h}{2\mathrm{Dport}}\right) \tag{6.1}$$

In equation 6.1, C_{port} is the port discharge coefficient (nominally between 0.4 and 0.9 for a circular port in a thick wall, depending on inlet shape, pipe attachments and obstruction by debris). C_{port} was calibrated to have a value of 0.46. Other parameters in equation 6.1 are acceleration of gravity, g (m/s^2); Δh (m) is the difference in elevation between the pond water surface and the bottom of the port outlet pipe; D_{port} (m) is the port diameter = 0.203 m. The Min (minimum) function adjusts the outflow for cases when the pond water level drops below the top of the port, i.e. only a fraction of the port cross-section contributes to outflow. In that case, the outflow rate varies according to a weir equation and is proportional to $\Delta h^{3/2}$.

For an emergency overflow weir of width *B* at the crest, the model outflow rate Q_{out} as a function of the pond level *H* above the weir crest can be calculated from the Equation 6.2

$$Q_{out} = C_w \, B \, H^{3/2} \tag{6.2}$$

where C_w is the weir coefficient that is typically from 2.5 to 3.9, and can be determined from weir geometry (USBR 1987). During this study, the emergency overflow weir did not come into use.
The time history of the outflow rate was then calculated using the measured pond level and Equation 6.1.

A rate of storage change Q_{net} was calculated from the measured pond levels using Equation 6.3.

$$Q_{net} = A(h)\frac{dh}{dt} \tag{6.3}$$

where $A(h)$ is the pond surface area at level h, and dh/dt is the rate of change of pond level. The inflow rate Q_{in} was calculated (equation 6.4) as the sum of storage change and outflow:

$$Q_{in} = Q_{net} + Q_{out} \tag{6.4}$$

Since this pond is known to have a clay liner, seepage into or from ground water was not considered.

6.5. Examples of Field Data Collected

The field data collected at the State Farm Pond were used to formulate and validate a 1-D, unsteady water temperature stratification model for stormwater detention ponds (Herb et al., Project Report 479, SAFL, 2006). This model was also incorporated into the MINUHET model which simulates water temperatures of surface runoff from urban areas (Herb et al. 2009). Time series plots of data collected at the State Farm Pond in the summer of 2005 are presented in the report by Herb et al.. Examples of data collected will be given below.

6.5.1. Secchi depth transparency

Secchi depths measured in State Farm Pond in the summer of 2005 are given in Table 6.5.1 and shown in Figure 6.5.1.

Table 6.5.1 Secchi depths in State Farm Pond (maximum depth is 8 feet).

	State Farm Secchi depths
6/9/2005	4' 10"
6/16/2005	6' 00"
6/27/2005	7' 06"
7/8/2005	5' 09"
7/15/2005	5' 00" (estimated, was less clear than previous week)
7/28/2005	7' 02"
8/19/2005	8' 00" (could see Secchi disk on bottom of pond)
8/25/2005	7' 00"

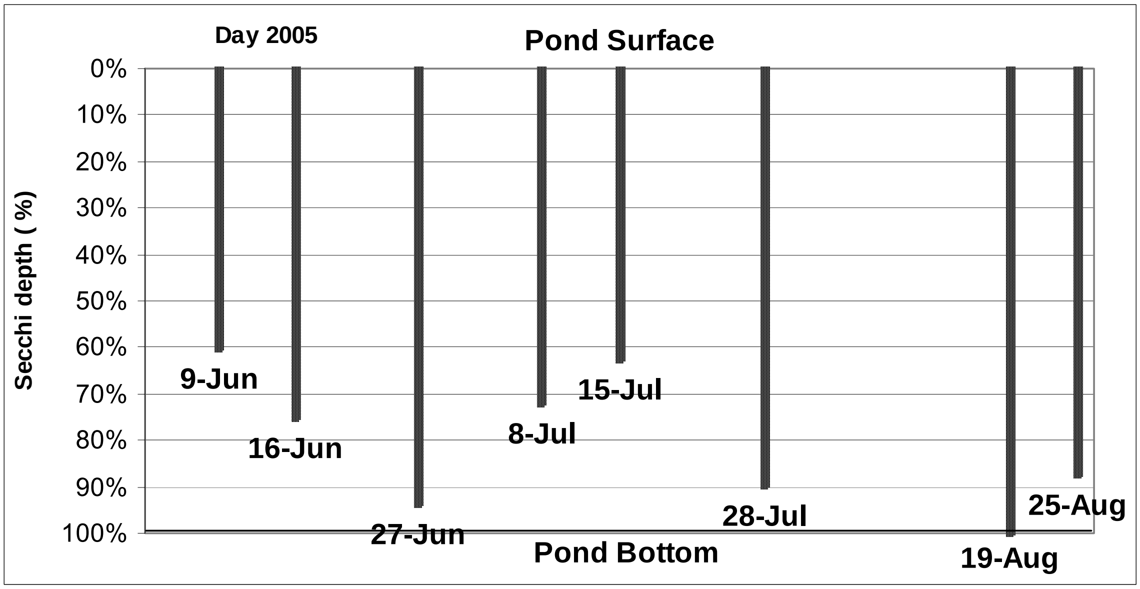


Figure 6.5.1 Secchi transparency in the State Farm Pond as a percentage of total depth.

A relationship is indicated in Figure 6.5.2, between Secchi depth and bottom temperature. A diurnal temperature fluctuation is recorded by the bottom thermistor when the transparency, i.e. Secchi depth, is 100 percent. On June 9 and 16, when Secchi depths were less than 100 percent, the diurnal temperature variation at the bottom of the pond was greatly reduced.

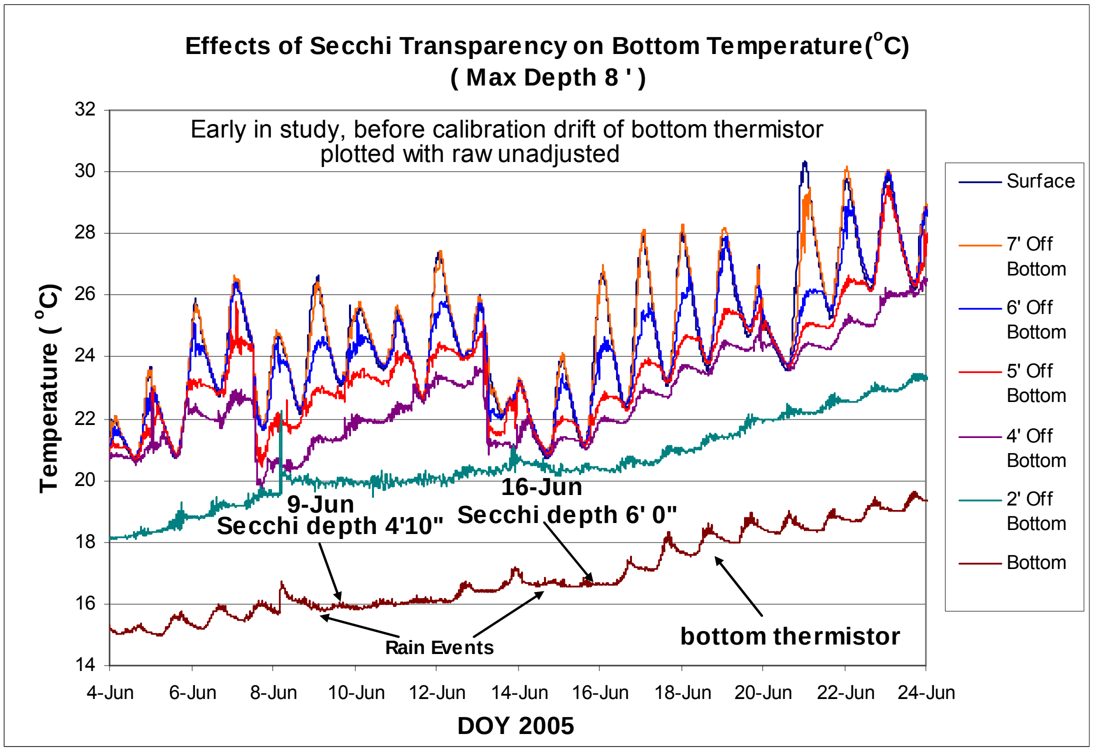


Figure 6.5.2 Water temperature raw data recorded at different depths of the State Farm Pond. Note the diurnal temperature changes near the pond bottom, and lack of bottom temperature changes when lesser Secchi depths were recorded following rain events.

6.5.2. Weather data and pond temperatures

The Campbell data logger recorded raw data from the sensors placed in the State Farm Pond in the following format.

```
115,143,1940,1.629,149.7,0,.298,19.62,19.62,19.62,19.57,19.61,19.63,19.59
115,143,1950,1.619,149.7,0,.298,19.62,19.61,19.62,19.56,19.61,19.63,19.59
115,143,2000,1.637,147.6,0,.298,19.62,19.61,19.62,19.57,19.6,19.63,19.59
115,143,2010,1.624,148.9,0,.298,19.62,19.61,19.62,19.57,19.6,19.63,19.59
115,143,2020,1.654,148.6,0,.298,19.62,19.62,19.63,19.58,19.61,19.64,19.59
```

The information presented in this sample of raw data is presented in Table 6.5.2 with headings. The sequence of information in the raw data is as follows: The first number (115) identifies the data logger. The second and third numbers (143,1940) give the day and time. The entries 4 to 6 (1.629,149.7,0) give weather data; and the last seven entries give the water temperature profile in the pond. It can be seen that the pond had no temperature stratification. The data in Table 6.5.2 are for a period of 40 minutes from 7:40 pm (1940) to 8:20 pm (2020) on day 143 (May 23, 2005).

Table 6.5.2 Information content of the raw data set.

Day of Year	Milit. time (hr)	Wind speed (m/s)	Wind direct. (deg North)	Rain (mm)	Depth (m)	Temp on bot (EC)	Temp 2' off bot (EC)	Temp 4' off bot (EC)	Temp 5' off bot (EC)	Temp 6' off bot (EC)	Temp 7' off bot (EC)	Surf temp (EC)
143	1940	1.629	149.7	0	0.298	19.62	19.62	19.62	19.57	19.61	19.63	19.59
143	1950	1.619	149.7	0	0.298	19.62	19.61	19.62	19.56	19.61	19.63	19.59
143	2000	1.637	147.6	0	0.298	19.62	19.61	19.62	19.57	19.60	19.63	19.59
143	2010	1.624	148.9	0	0.298	19.62	19.61	19.62	19.57	19.60	19.63	19.59
143	2020	1.654	148.6	0	0.298	19.62	19.62	19.63	19.58	19.61	19.64	19.59

A sample of the raw (un-calibrated) water temperatures recorded by the seven thermistors in the water column of the State Farm Pond at depths of 0, 2, 4, 5, 6, and 7 ft above the pond bottom, and at the water surface over a 4-day period from 2am on Aug 20, 2005 (calendar day 233.1) to noon on Aug 24, 2005 (calendar day 237.5) is plotted in Figure 6.5.3. Diurnal water temperature fluctuations of up to 3^{o}C due to solar irradiation during the daytime are readily apparent. The diurnal water temperature fluctuations are largest near the pond surface, and smallest at 2ft above the bottom of the pond. The thermistor at the pond bottom recorded no diurnal fluctuations. As explained earlier, the bottom thermistor went out of calibration during the data collection, and by the end of the study it registered 3-4°C high. That effect is clearly seen in figure 6.5.3. Over the 4-day period of record the water column cooled gradually by about on half a degree Celsius.

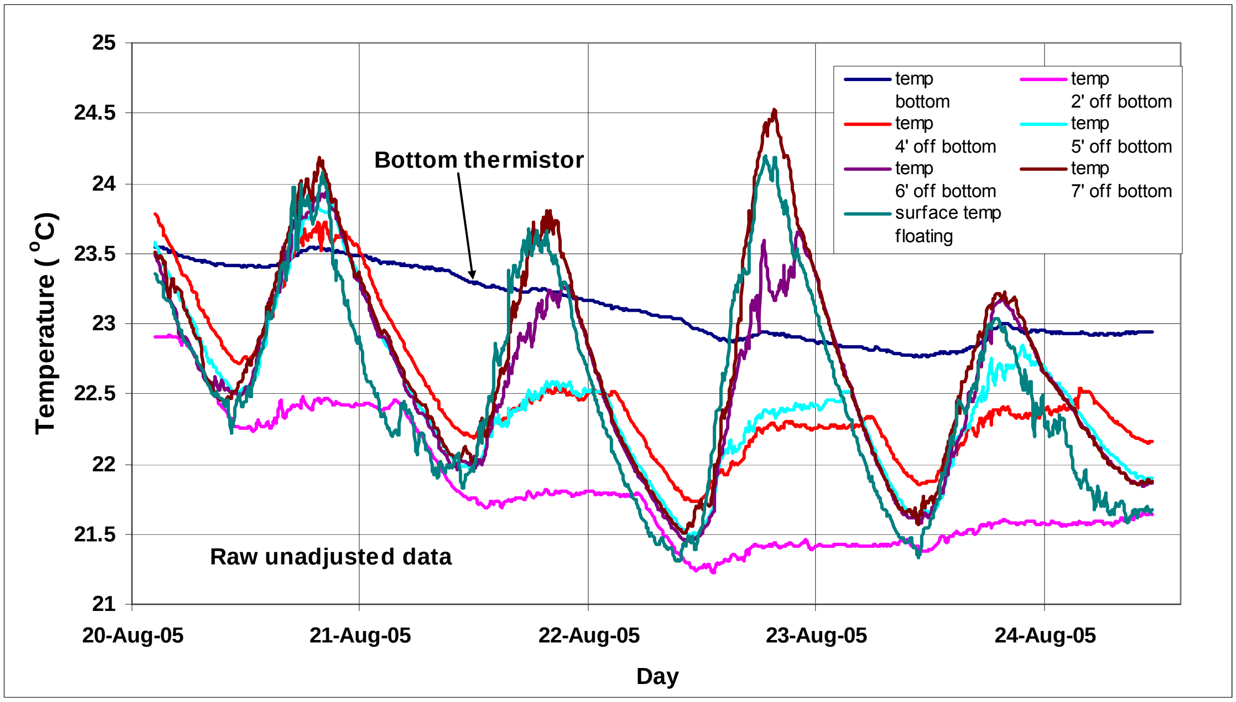


Figure 6.5.3 Example of diurnal water temperature fluctuations in the State Farm Pond over a 4-day period towards the end of the study using raw data; the bottom thermistor is apparently far out of calibration.

Details of the diurnal water temperature cycle in a stratified pond can also be seen in Figure 6.5.3. Overnight the pond cools at the water surface and mixes by natural convection from the water surface downwards. The overnight cooling and mixing is reflected in the convergence of the water temperatures recorded at different depths of the pond until the temperatures throughout the pond depth have become fairly uniform in the late night/early morning. Starting at dawn, and as the day progresses, the upper pond layers are warmed by solar radiation and the pond becomes distinctly temperature stratified with the warmest water temperatures occurring late afternoon near the pond surface. As the sun lowers in the sky (past 4 pm) and continuing throughout the night, the pond water temperatures drop at a somewhat linear rate until the pond again reaches a quasi-homogeneous temperature before the next dawn arrives.

Figure 6.5.4 gives the water temperatures for the same 4-day time period after applying post-study calibration error adjustments to the actual data,. Even with the data adjusted for thermistor errors, it appears that the bottom thermistors' data still should not be considered accurate.

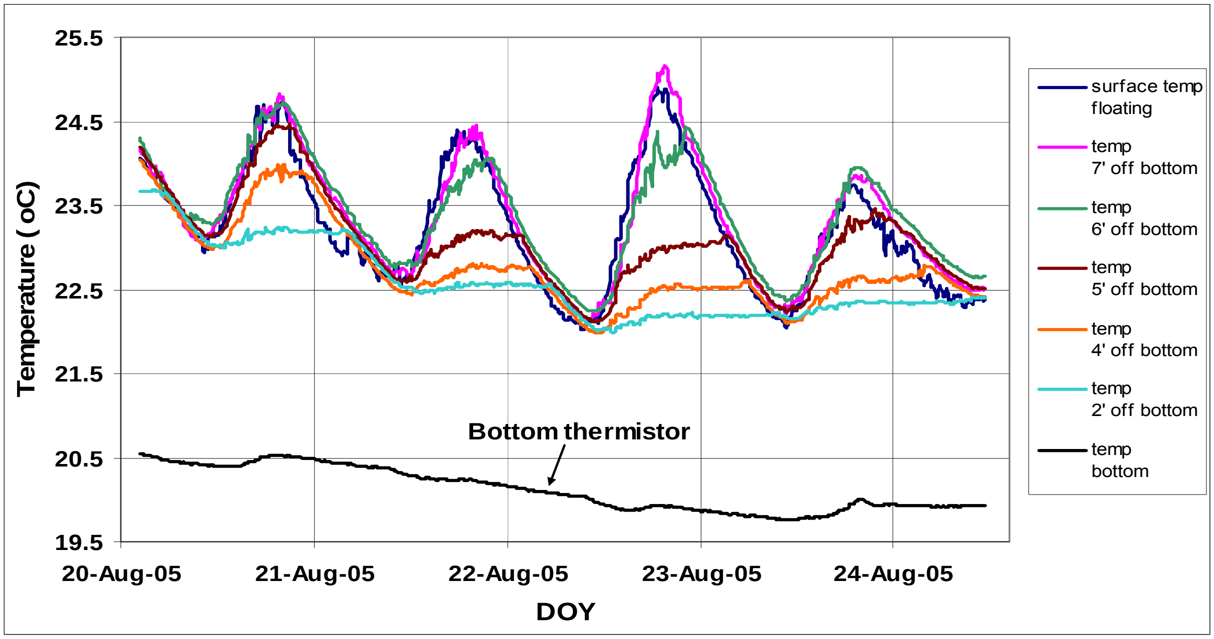


Figure 6.5.4 Example of daily water temperature fluctuations in the State Farm Pond over a 4-day period towards the end of the study with post- study calibration adjusted data.

Figure 6.5.4 clearly shows that the strongest thermal stratification of the pond occurs in the afternoon. An afternoon water temperature profile is shown in Figure 6.5.5. The surface layer is slightly cooler than the water at a depth of 1 foot. This is due to the heat loss that occurs at the water surface; to transport heat to the water surface from below, a lowered surface temperature is required. The water temperature stratification from 1 ft depth to 6 ft depth below the pond surface is the result of the daily solar radiation (heat) input. During the night following a sunny day, this heat input is lost back to the atmosphere by evaporative and convective cooling at the water surface, and as a result, this mid-afternoon water temperature stratification has typically disappeared by the next morning (dawn).

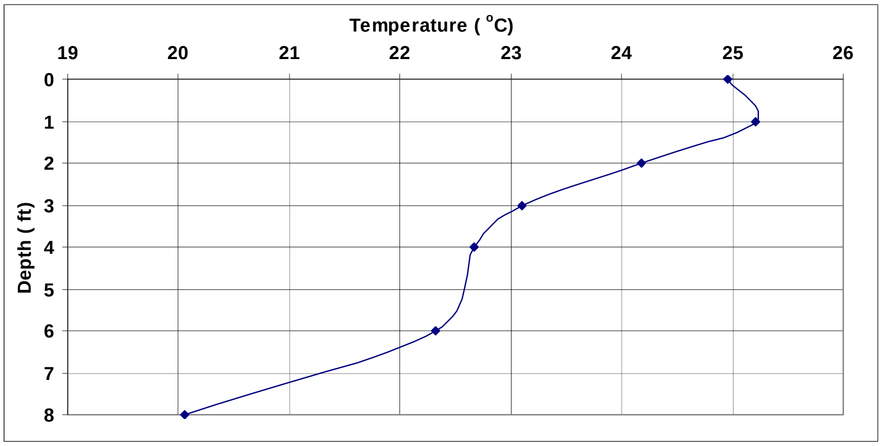


Figure 6.5.5 Water temperature stratification in the State Farm Pond on August 23, 2005 at 4:20 pm using calibrated data.

In contrast to data that were collected toward the end of the study and shown above, Figure 6.5.6 shows that early in the study, the bottom thermistor seems to be in calibration and the raw data plot seems to show what might be expected. The water temperature stratification profile is similar to prior studies of shallow water bodies (Gu and Stefan 1991, 1995, Gu et al. 1996).

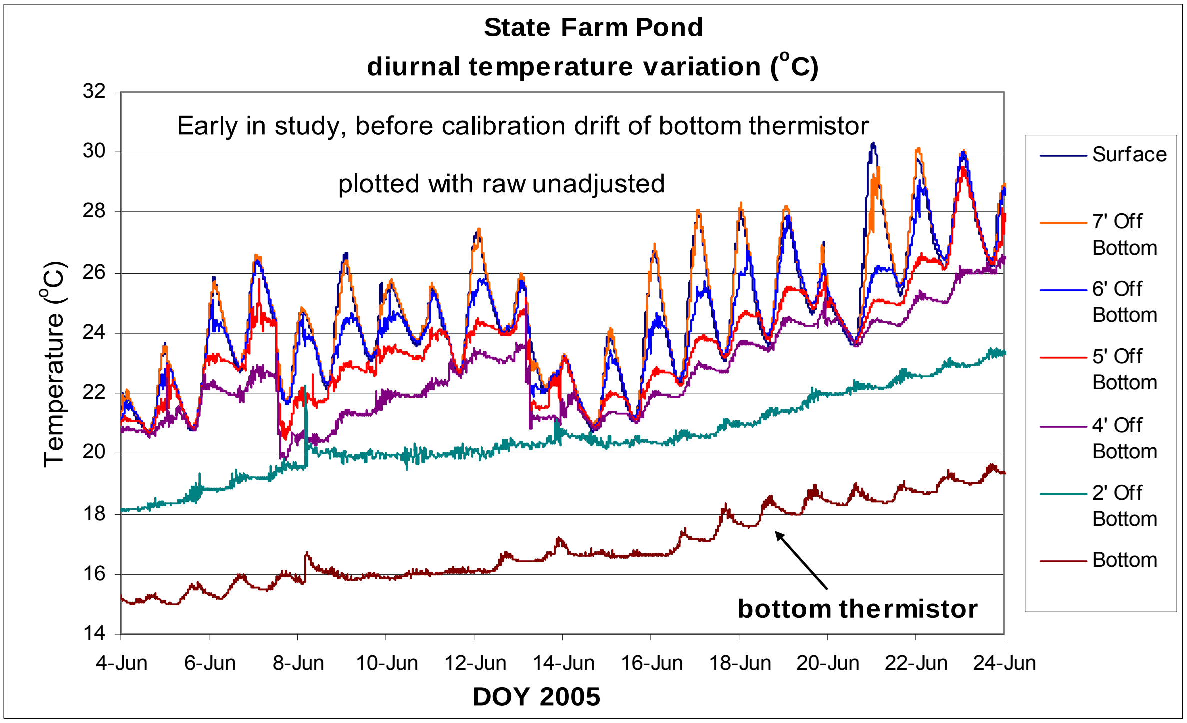


Figure 6.5.6 Water temperature (raw data) in the State Farm Pond over a 20-day period near the beginning of the study.

Water temperature profiles in State Farm Pond were recorded continuously for an entire summer period as shown above, with a gap in coverage from July 28 to August 4. In addition and for comparative purposes, the temperature profile was also measured with a YSI Model 63 handheld probe from a boat. A comparison of the water temperatures from the thermistor string and from the YSI handheld probe is shown in Figure 6.5.7. The profiles are similar but had a difference of about 1°C, possibly because the YSI probe had not been recalibrated since its' prior use for salinity studies ending in April 2005.

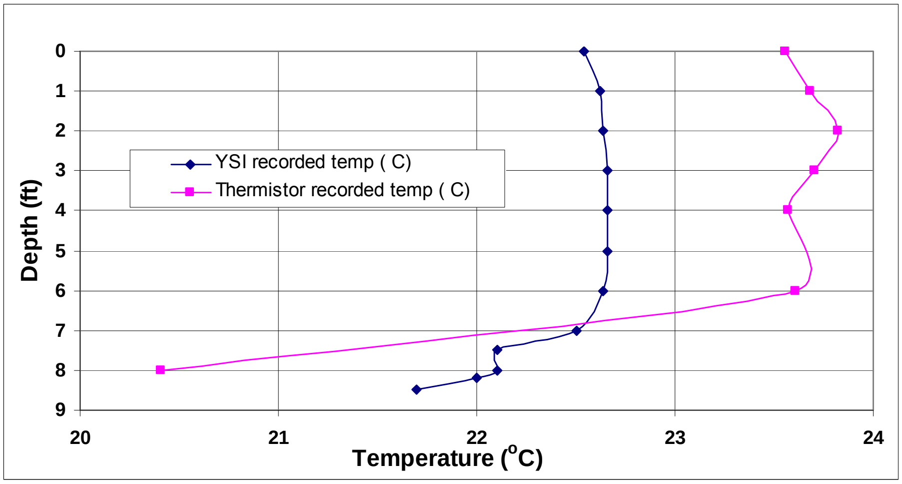


Figure 6.5.7 Comparison of thermistor temperature data (using data adjusted for post-study calibration) and average YSI handheld recorder data from five random samples taken at 8:00 a.m., August 19 2005 in the State Farm Pond.

6.5.3. Precipitation and pond levels

Changes in pond level for several rainfall events are shown in Figure 6.5.8. The normal drainage of the pond is through a 0.203m (8") circular port. The overflow weir is 0.61m above this port as seen in Figure 6.2.6, and allows for extended storage to control runoff volume. Considering just the July 25 rainfall event, the pond level reached 2.93m and was within 10cm of the overflow weir. It took 12 hours for the pond level to drop to 2.63m, the upper level of the outlet port, and 56 hours total for the pond level to drop to 2.44m, near the lower level of the outlet port. Note that on July 8th, the pond level dropped below the 2.43m lower level of the port (permanent pool level).

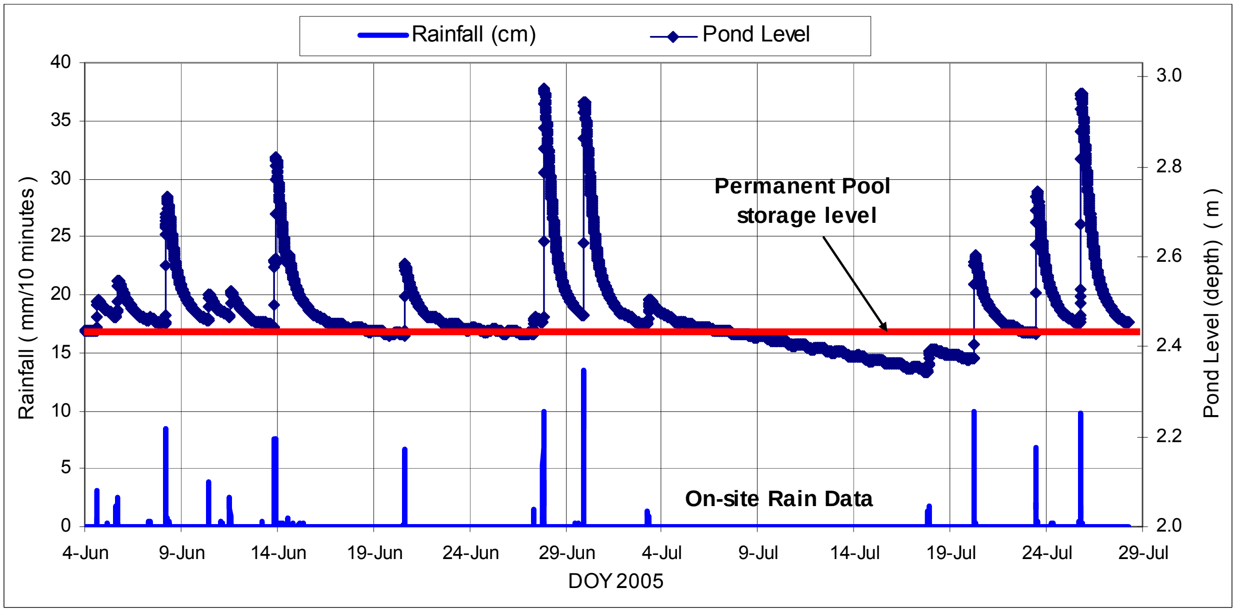


Figure 6.5.8 Changes in pond level with precipitation in June and July 2005.

6.5.4. Pavement temperatures and pavement runoff temperatures

Onset Hobo temperature loggers buried in the asphalt yielded data at all temperatures (Figure 6.5.9). Also shown with the pavement temperature data are on-site rainfall data and synoptic hourly air temperature data and solar radiation data recorded on the St. Paul Campus of the University of Minnesota.

The Woodbury pavement temperature record revealed that during the August 2005 period, a maximum pavement temperature of 53.7°C (128°F) occurred on August 5, at 3:03 pm, when the air temperature maximum recorded on the St. Paul Campus was 28.9°C (84.0°F) and the solar radiation maximum recorded on the St. Paul Campus was 904.1 W/m^2.

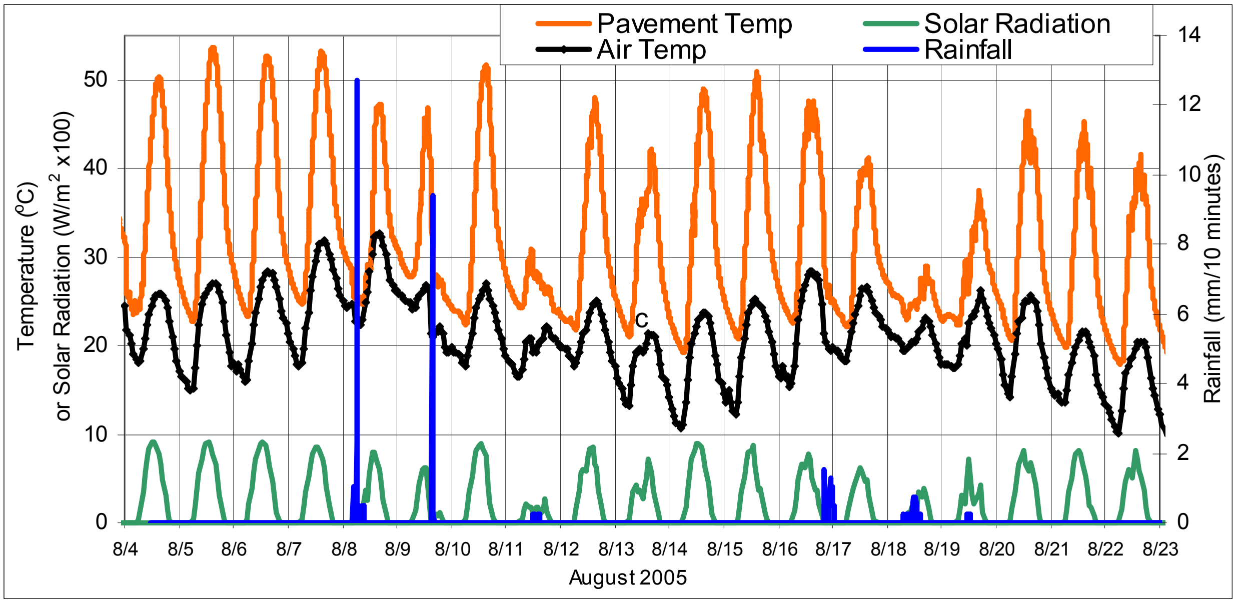


Figure 6.5.9 Pavement temperatures at the State Farm parking lot and synoptic rainfall and air temperature in St. Paul.

To gather runoff temperature data for paved surfaces, Vemco temperature loggers were wired tight to the underside of rainwater collection grates (Figures 6.2.8 and 6.2.9) in both the lower (closest to pond) and upper (furthest from pond) paved parking lots at the State Farm site. These grates are made of heavy cast steel and have significant mass which raises concerns about the accuracy of rainwater runoff temperature data for low volume runoff but, it is assumed that during heavier bursts of rain, these data should be more accurate and less influenced by the grate.

The next three plots display pavement temperature data and pavement runoff temperature data for the rain events on August 8 and 9. Although the runoff data plots continuously, it is only relevant during actual periods of rainfall. First, Figure 6.5.10 displays a wider time period encompassing both rainfalls. Then, Figures 6.5.11 and 6.5.12 display closely cropped individual events.

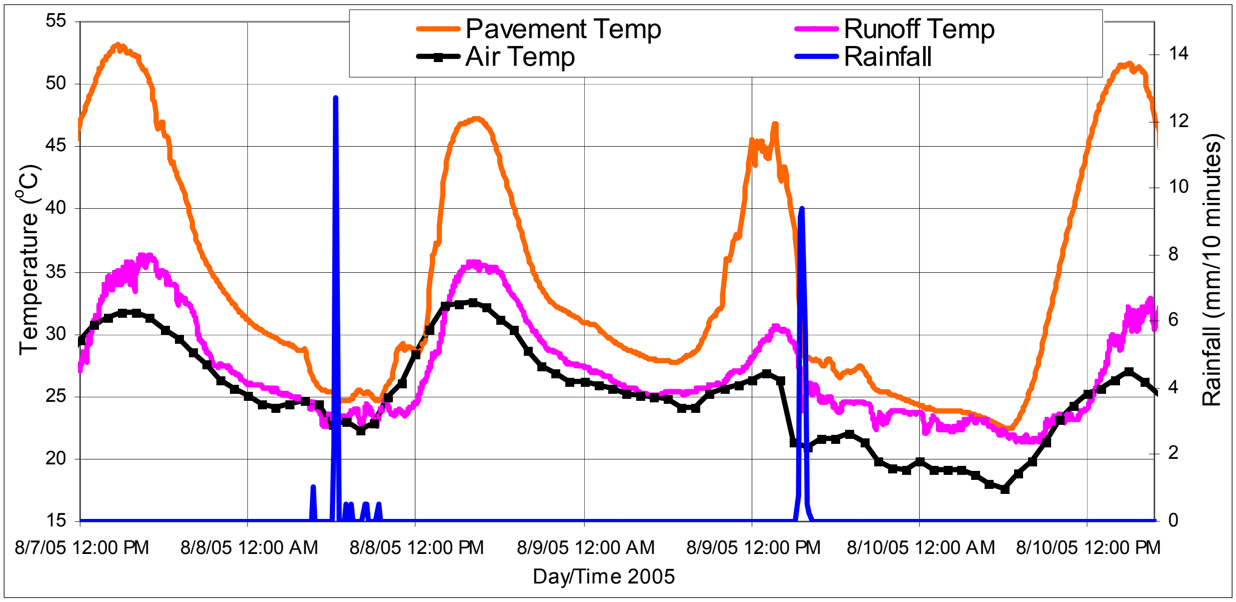


Figure 6.5.10 Rainwater runoff and pavement temperature data from the paved State Farm parking lot, with air temperature from the St. Paul Campus before, during, and after two rainfall events.

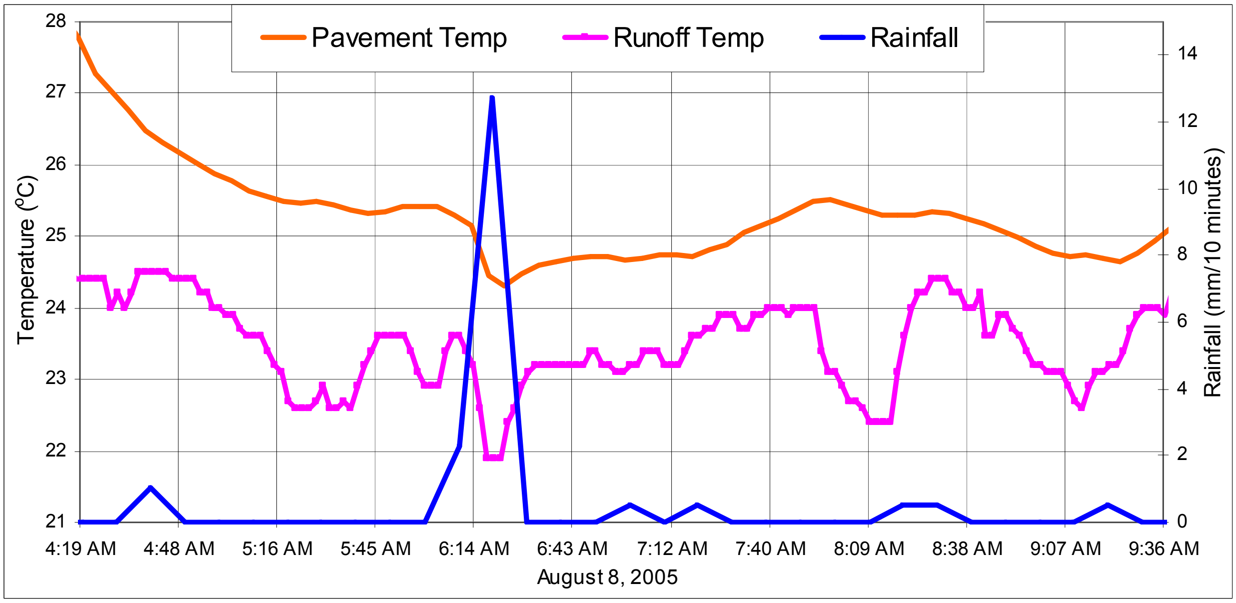


Figure 6.5.11 The August 8 rainfall event, showing rainwater runoff and pavement temperature data at high temporal resolution.

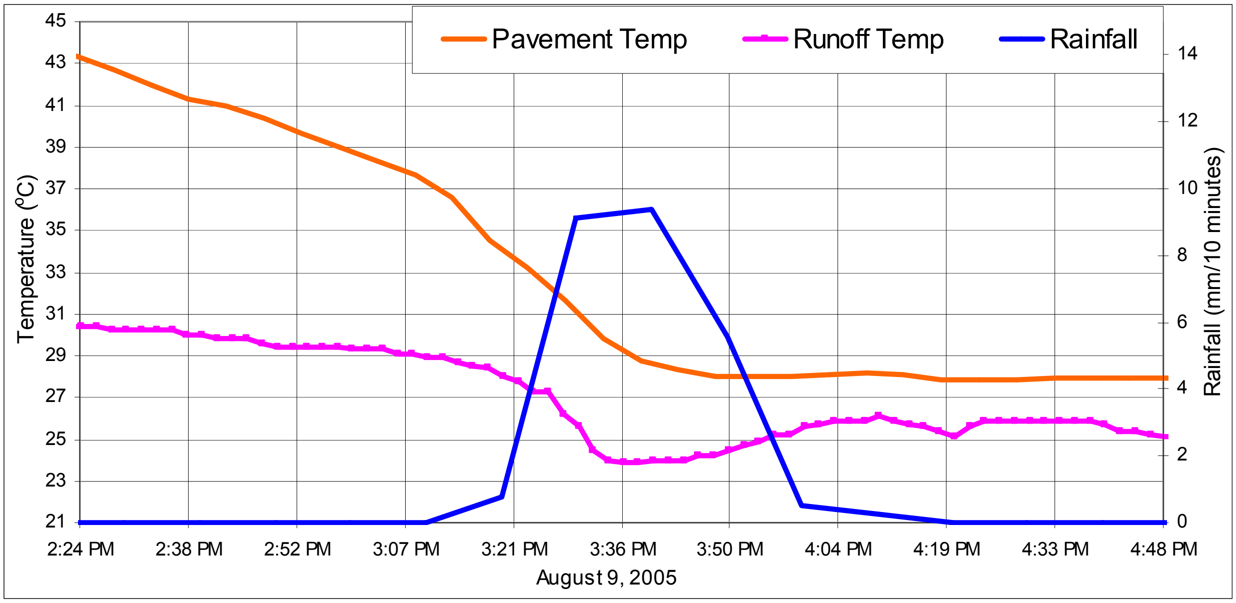


Figure 6.5.12 The August 9 rainfall event, showing rainwater runoff and pavement temperatures data at high temporal resolution.

For the August 8 rainfall, the runoff temperature during the largest burst of rain ranged from 23.7 to 21.9°C. For the August 9 rainfall, it ranged from 29 to 24ºC. The runoff temperature, for these two events, was lower than the corresponding pavement temperature by roughly 2.5 to 5°C.

6.5.5. Pond inflow temperatures and outflow temperatures

The inflow and outflow data recorded each minute by the Vemco Minilog data loggers, and covering a 50 day time period, are shown in Figure 6.5.13. The data show strong diurnal temperature fluctuations for both the inflow and outflow. Keep in mind though that there is very little actual inflow unless rain occurs. Figure 6.5.14 shows the pond level data to give a sense of the amount of inflow that occurred, based on rise in pond level, and periods of increased outflow after the rainfall as pond drawdown occurred. The out-flow water temperature is related and close to the pond surface temperature because the outlet is located near the pond surface (Herb, et. al. 2006). The inflow temperature is related to the rainfall temperature, the pavement temperature, and the water residence time in the stormsewer that carries the runoff from the parking lots to the pond.

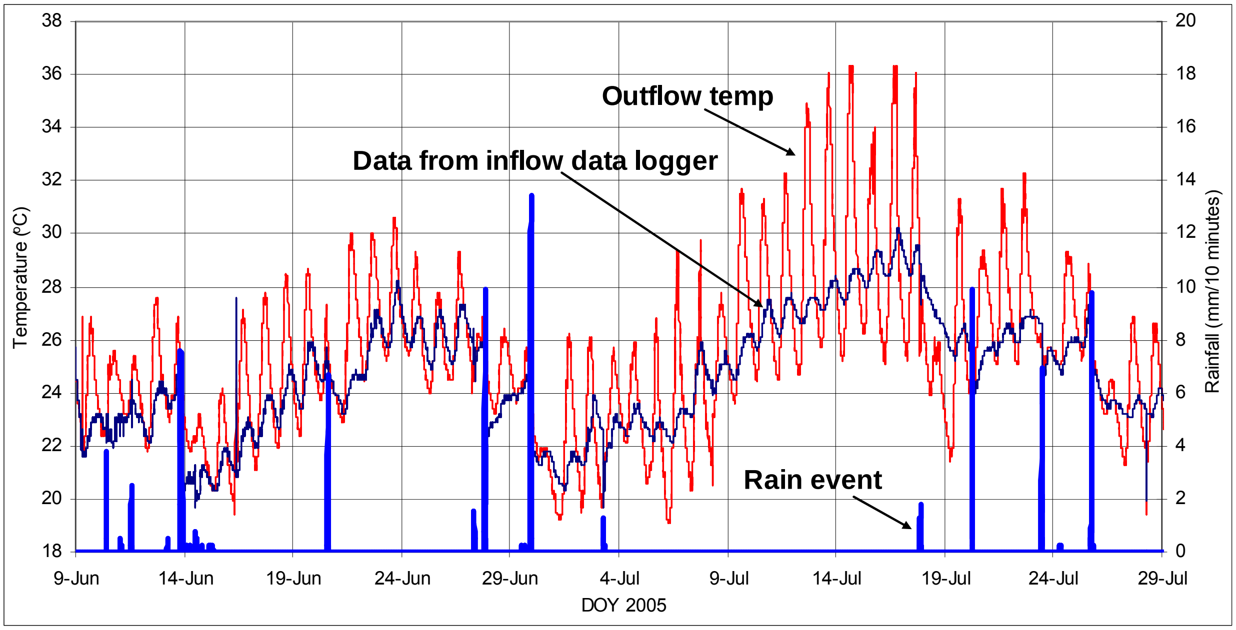


Figure 6.5.13 Inflow and outflow data for June and July 2005 from Vemco Minilog data loggers with rainfall recorded on-site by a tipping bucket rain gauge and the Campbell Scientific CR-10 data recorder.

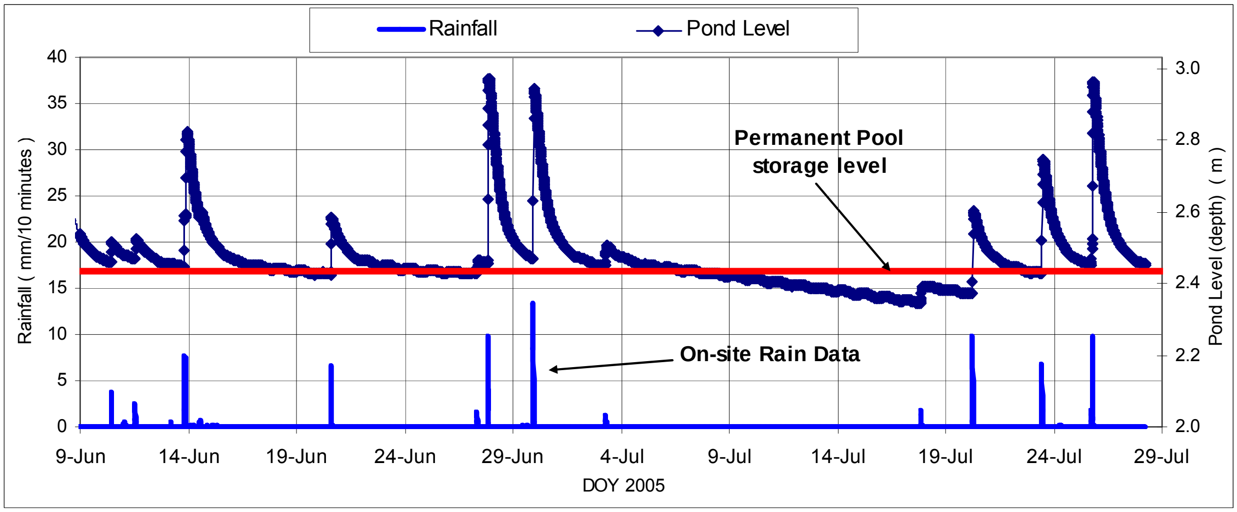


Figure 6.5.14 Pond level data for June and July 2005, showing increases in pond level with rainfall and periods of outflow as pond drawdown occurs after the rainfall.

The temperature sensor and data logger that recorded the inflow temperatures was in a manhole approximately 15 feet from the normal pond level shoreline. The water level in the manhole was the same as the pond level, but the pipe from the manhole to the pond, enters the pond at a level of 3’ to 4’ below the permanent pool level. Without rainfall, there is essentially no inflow to the pond. Thus, as the pond stratifies and with minimal or no runoff entering it, the water in the manhole structure is essentially the same as the pond water at the 3’ to 4’depth; the sensor in the manhole shows a diurnal temperature fluctuation that seems to correspond with the diurnal water temperature fluctuations at that depth within the pond.

In early July, there were no rainfall events, and the pond temperature steadily rose. On July 8, the pond level dropped below the outlet. With no outflow occurring, the temperature data logger was possibly recording air temperature until July 20, when another pond-filling rain event occurred.

Figure 6.5.15 shows the same data for the month of June 2005, with air temperature added. The pond surface temperature fluctuates daily up to six degrees Celsius while the air temperature fluctuates daily up to twelve degrees Celsius.

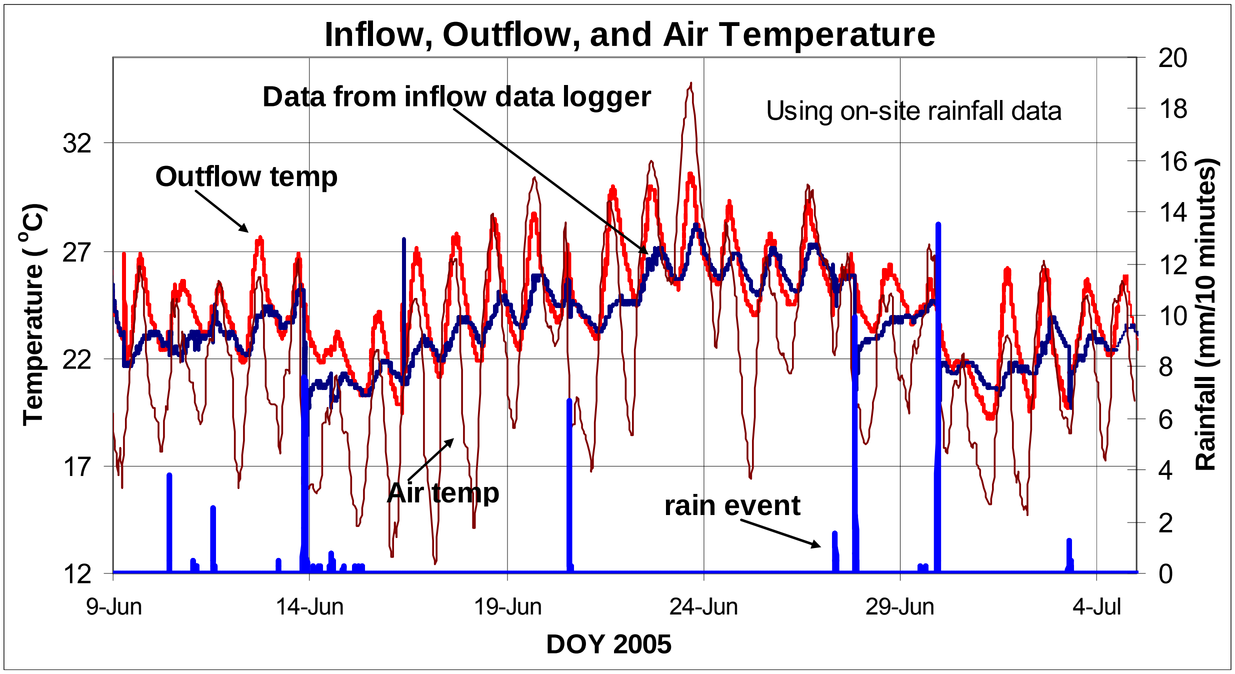


Figure 6.5.15 Inflow temperature, outflow temperature and air temperature for the State Farm Pond.

Data for rainfall events on June 27 and June 29, 2005, are shown in Figures 6.5.16 and 6.5.17. For the June 27 rainfall event, the pond inflow temperature quickly drops by approximately 5°C, while the outflow temperature drops slowly over several hours, never reaching the inflow temperature; the diurnal pattern of rising outflow temperatures during the day and falling outflow temperatures during the night is affected but not eliminated.

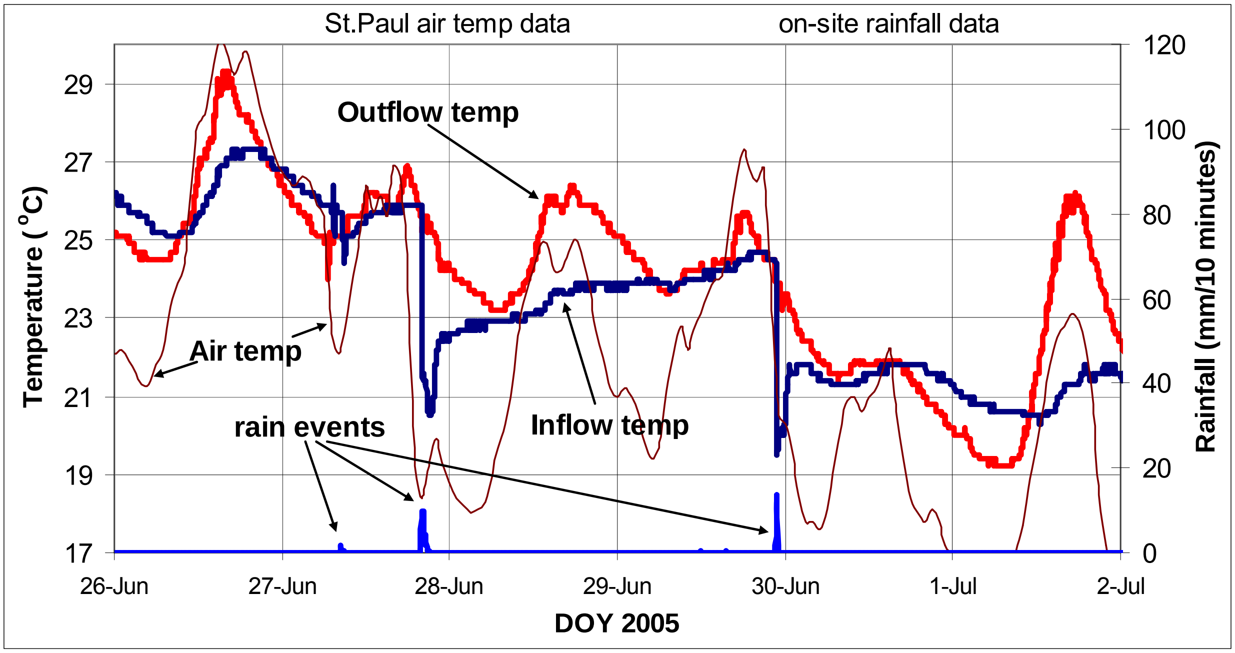


Figure 6.5.16 Inflow temperature, outflow temperature and air temperature over a 6-day period with three rain events.

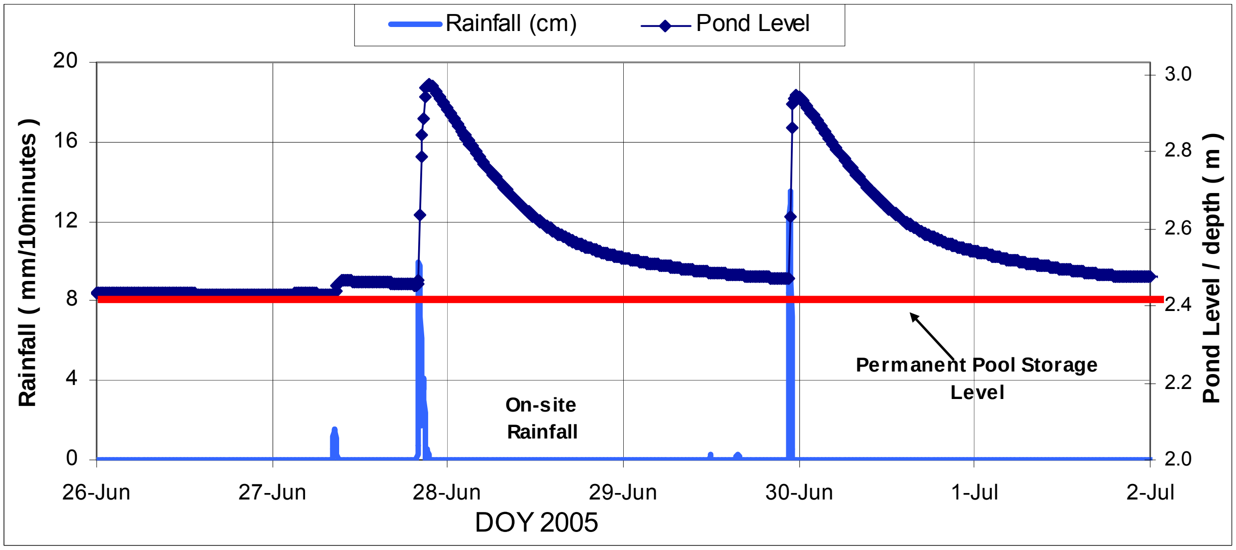


Figure 6.5.17 Pond level and rainfall for comparison with inflow and outflow temperatures.

A very detailed view of the June 27 rain event occurring around 8:00pm is shown in Figure 6.5.18. The recorded inflow temperature drops quickly from almost 26°C to about 21.5°C, until the next burst of rain drops it by another degree to around 20.5°C. The initial precipitous drop in the recorded inflow temperature over about 10 minutes is attributed to the colder rain (20.5°C) quickly absorbing the heat from the uppermost portion of the asphalt pavement and stormsewer walls as it makes its way to the pond inlet structure and mixes with the water in the structure. Note that there is no initial spike in the recorded inflow temperature to the pond. In other words, the heat contained in the uppermost pavement and stormsewer wall layers did nothing to raise the pond temperature: that heat input was balanced by the colder rain. So it appears that for this event the rain water runoff from heated pavement surfaces did not cause an increase in the temperature of the stormwater pond or the pond outflow. The runoff from the heated surfaces only lessened the potential cooling effect of the rainwater on the stormwater pond.

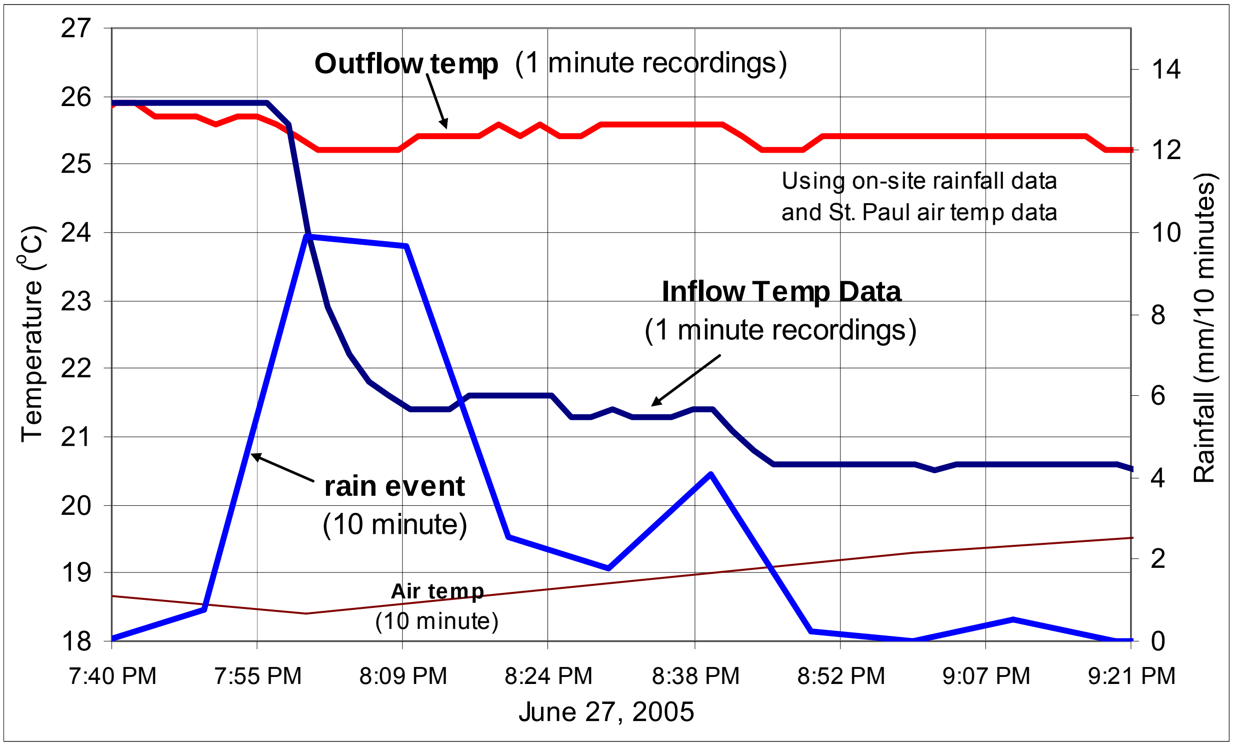


Figure 6.5.18 Detailed view of inflow and outflow data during rainfall event on June 27, 2005.

6.6. Additional off-site Data Collection – Rainfall Temperatures

It is often assumed that rainwater temperature is the same as dew point temperature, which is the temperature of the water saturated atmosphere through which the rain is falling. To test this assumption, a rainwater collection basin (Figures 6.6.1 – 6.6.2) was placed atop the roof of St. Anthony Falls Laboratory (SAFL) at the University of Minnesota. The apparatus consisted of a white styrofoam collection basin positioned so that collected water would run to a corner, where a thermistor was placed snuggly inside a drain hole. Weighted ropes lay across the top edges to hold it securely.

Figures 6.6.1 - 6.6.2 Rainfall temperature was measured by a thermistor placed in the drain hole of a styrofoam rainwater collector (left panel) on the roof of the St. Anthony Falls Laboratory (SAFL) at the University of Minnesota in Minneapolis (right panel).

Comparative dew point data was obtained from SAFL's own weather station, which is located within 100 meters of this device. The dew point temperature data is 10-minute averaged, whereas the rain temperature data was recorded at 1-minute intervals. Figures 6.6.3 through 6.6.6, show that for each of four separate rain events, the rainwater temperature is very close to the dew point temperature. During periods of heavier rainfall, the two data sets show better convergence. The rain temperature data is only relevant during periods of rainfall. The correlation between rainwater temperature and dew point may be a topic for further research, and require the collection of more exact data.

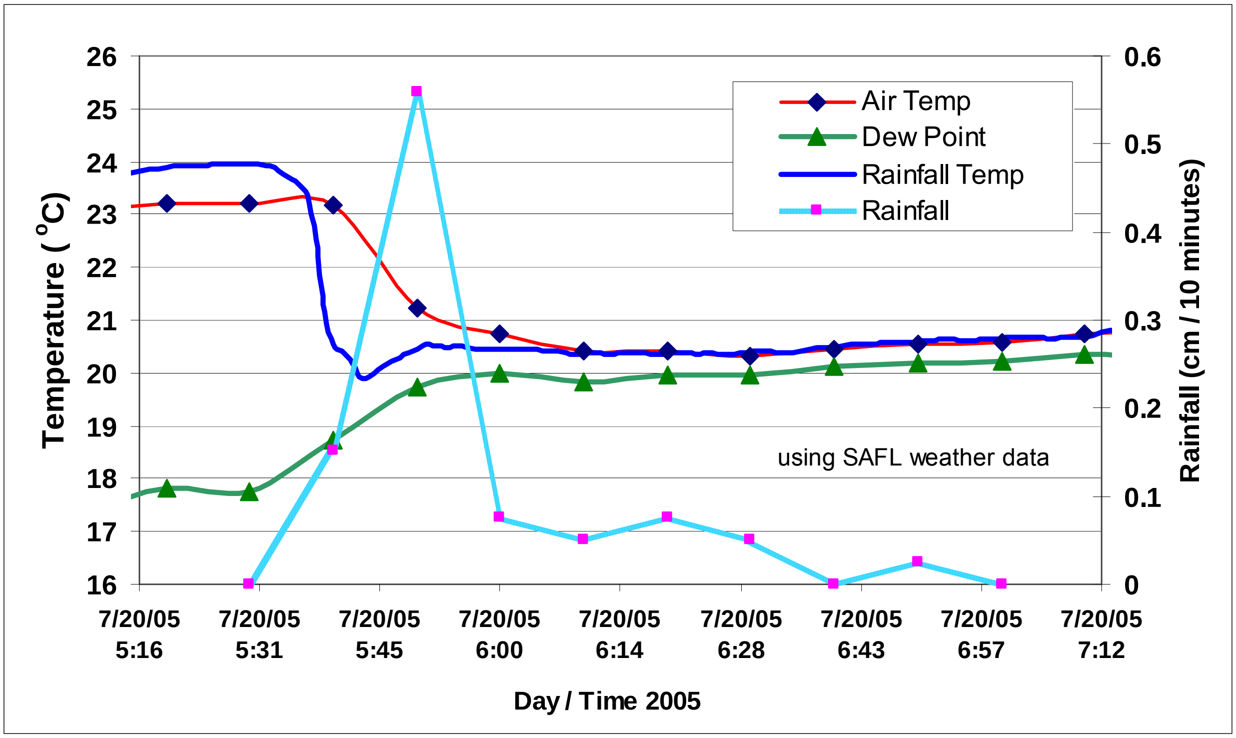


Figure 6.6.3 Comparison of dew point and rainwater temperatures on July 20, 2005.

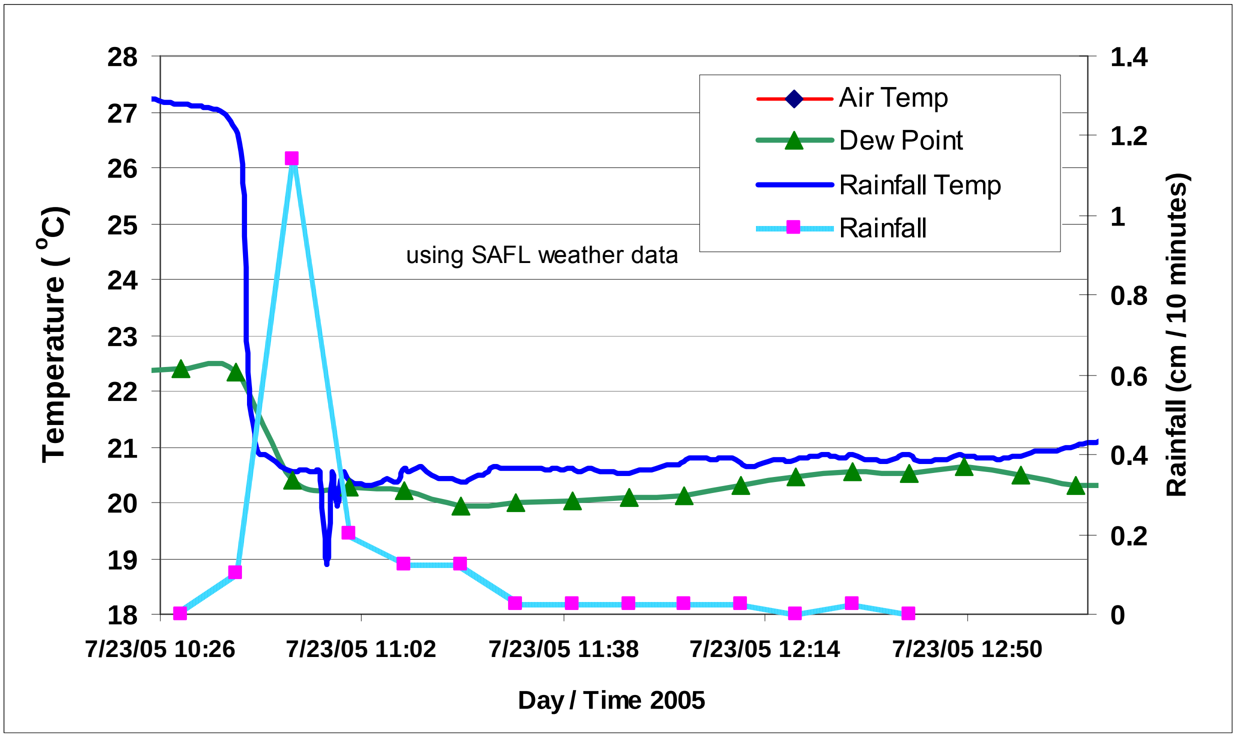


Figure 6.6.4 Comparison of dew point and rainwater temperatures on July 23, 2005.

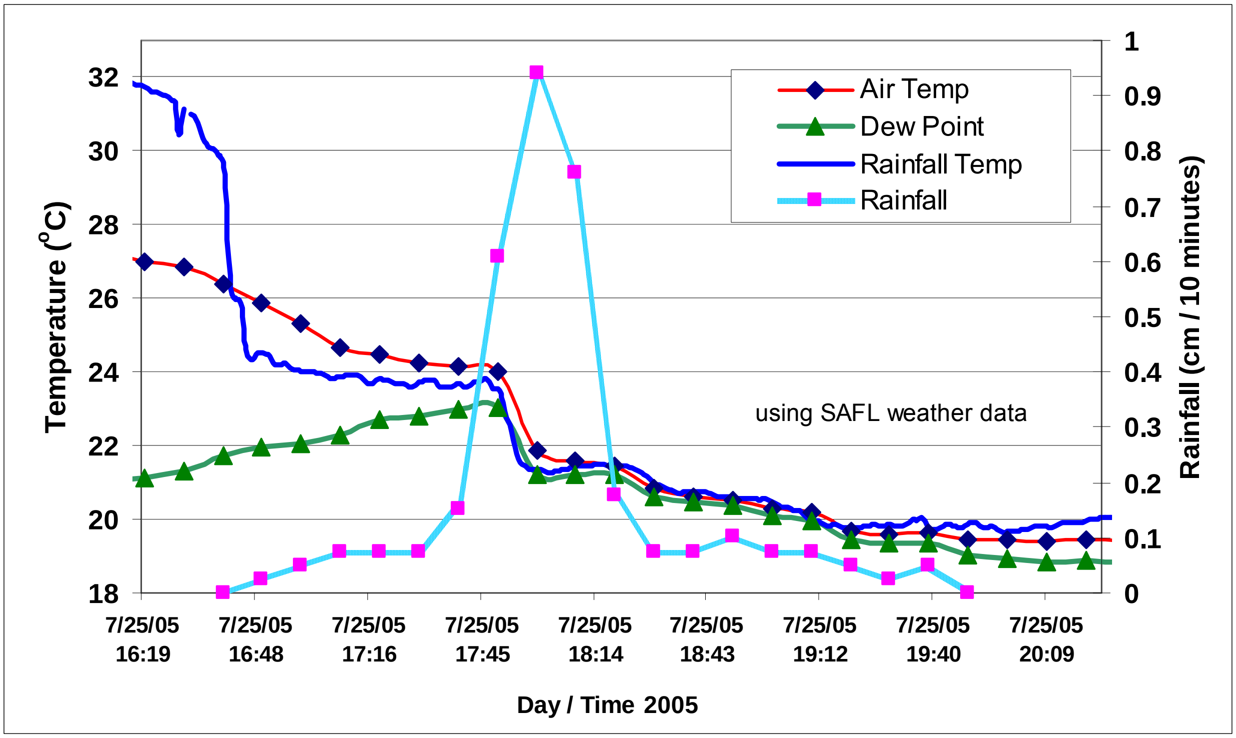


Figure 6.6.5 Comparison of dew point and rainwater temperatures on July 25, 2005.

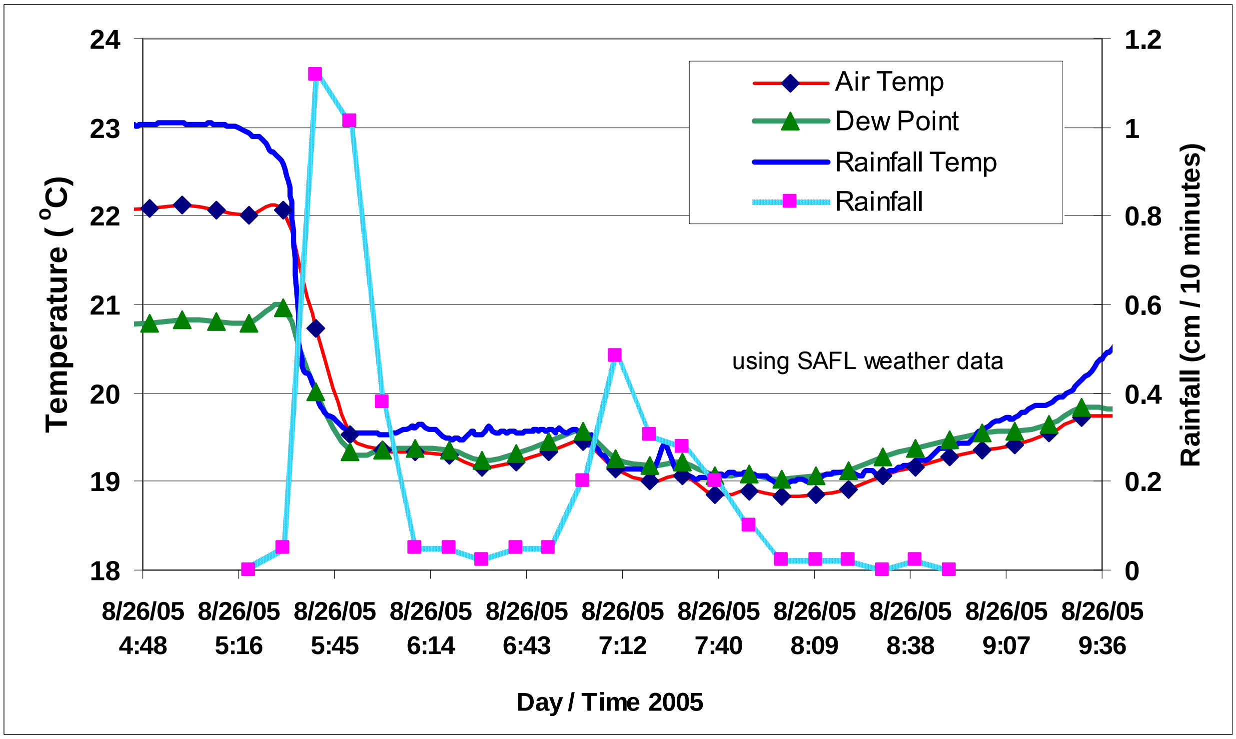


Figure 6.6.6 Comparison of dew point and rainwater temperatures on August 26, 2005.

Overall, the data gathered from this device during four separate rainfall events seems to uphold the assumption that rainwater temperature will be the same as dew point temperature.

6.7. Comprehensive View of Temperature Data for three Rain Events

Temperature data from recorders placed at several locations in and around the State Farm stormwater pond are plotted together here against a common time scale. Included in these plots are on-site data for rainfall, wind speed, upper parking lot pavement temperature, pavement runoff temperature, pond inflow temperature, outflow temperature, wind speed, and temperatures from various depths within the pond. Also included are air temperature, dew point temperature, and solar radiation data from the University of Minnesota St. Paul Campus weather station.

The next three plots, Figures 6.7.1 through 6.7.3, give a broad view of the time period from July 11 to July 28, 2005. During this period there were five rainfall events. These plots are included to show the daily temperature patterns preceding these storms. Of these five events, three had rain totals of 10 mm or more. Our analysis will focus on those three larger rainfall events occurring in the later half of July, a time period in which air temperatures on non-rain days commonly reached 30-34ºC (upper 80's ºF).

As a side note, the pavement temperatures in Figure 6.7.1 appear flat-topped because the Vemco Minilog temperature recorder buried in the pavement had a maximum temperature limit of 36ºC (that recording thermometer was later replaced with an Onset Hobo recorder with higher limits). Even though the upper range is missing, the data is still useful because as the plots show, the pavement had cooled enough before each rainfall event so that pavement temperatures were back within the limits of the recorder. Also, some of the measurements are relevant only during rainfall events. For example, the pavement runoff temperature data are relevant only during rainfall and shortly thereafter. Similarly, the inflow temperature data has relevance only when rainwater inflow is occurring (recall the placement of the recorder in the pond inlet structure which has a submerged pond inlet pipe; the fluctuating data seemed to correspond with the diurnal temperature pattern at a depth of about 1 meter during non-rain periods). Recall too that the permanent pool storage depth is 2.43 meters (8 ft).

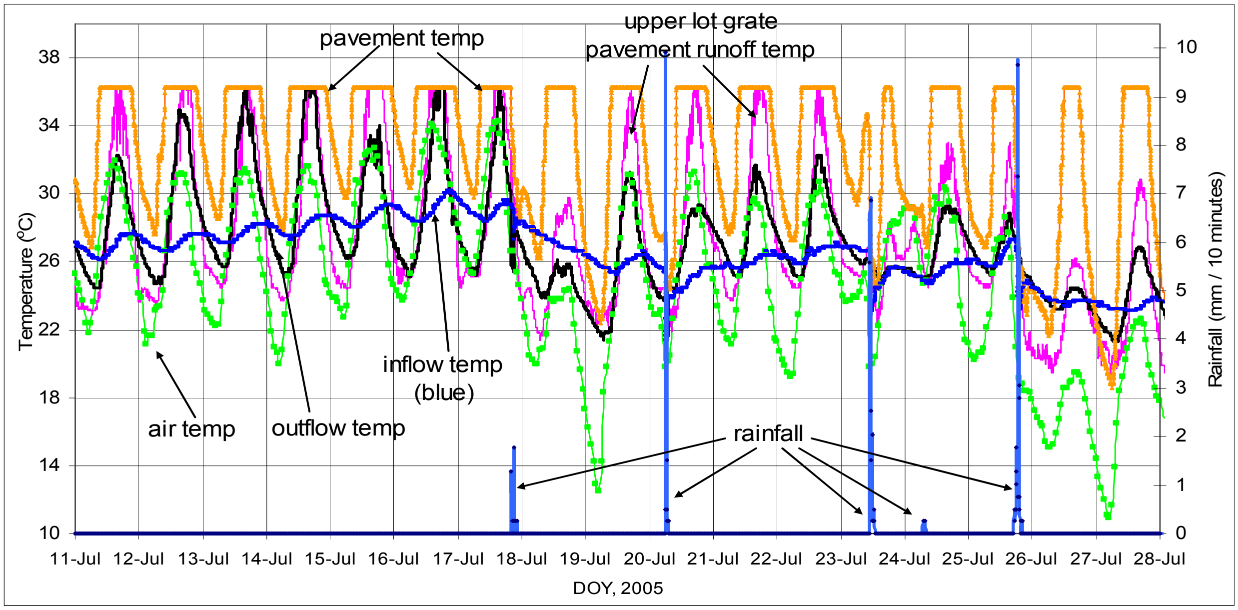


Figure 6.7.1 State Farm Pond temperature data for five rainfall events in mid-late July, 2005. (Note: pavement temperature recorder had an upper limit of 36º C)

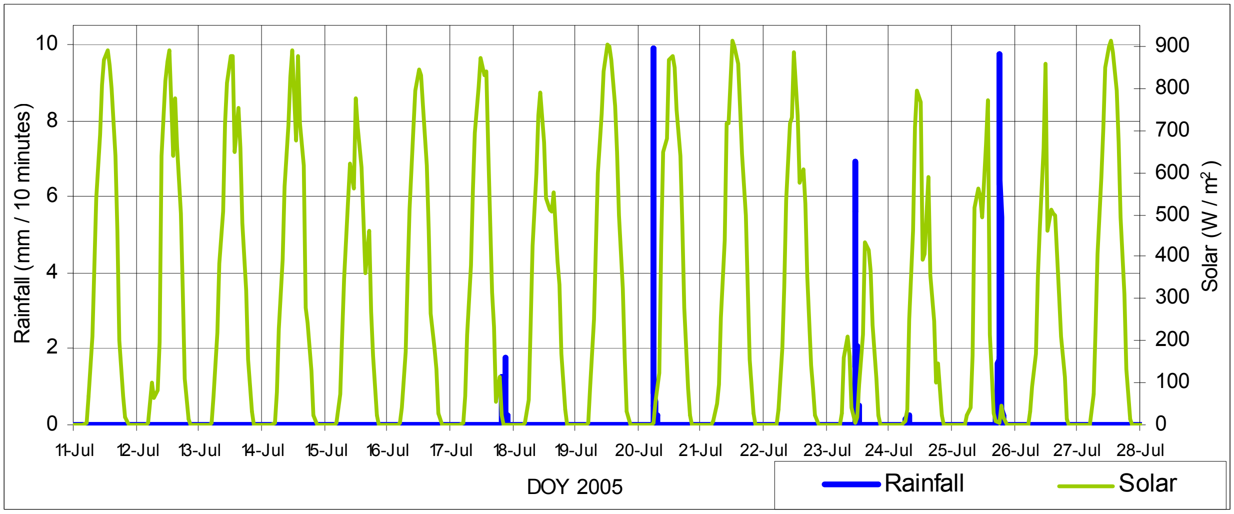


Figure 6.7.2 Solar radiation data for the same period as Figure 6.7.1 above. (Courtesy of University of Minnesota St. Paul Weather Station, St. Paul Campus)

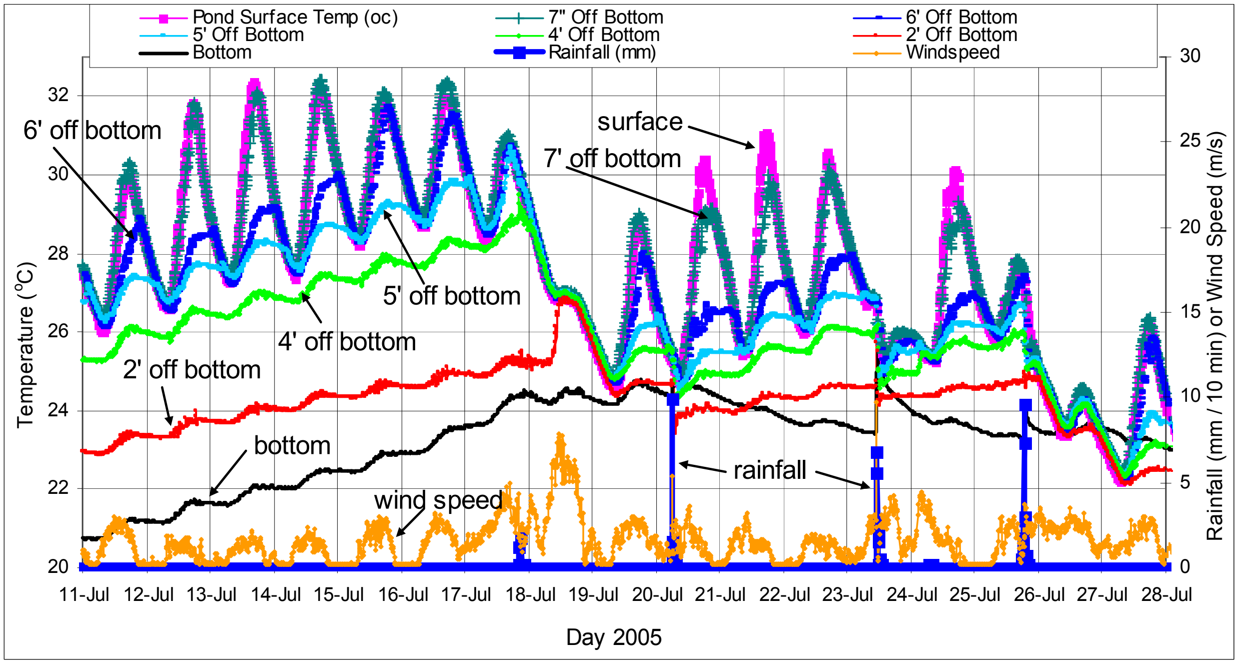


Figure 6.7.3 State Farm Pond temperature raw data for various depths, and wind speed for July 11–28, 2005.

For this comprehensive look at the data from the later half of July 2005, it is also important to note that leading up to the rain event on July 20,the pond level was below the outlet level, as shown in Figure 6.7.4. The pond level had dropped below the outlet level on July 8, and stayed below the outlet level until the rain event on July 20. A smaller rain event on July 17 was insufficient to raise the pond level to the outlet level. In total, the pond level was below the outlet for 11-12 days before the July 20 rainfall. An overall continued rise in pond temperatures, at all depths, occurred during this time and is shown in Figure 6.7.3. Note also in Figure 6.7.3 that before the July 20 rainfall, the surface temperature and the "7' off bottom" temperatures are almost identical, but after the rainfall, they differ during the day as the pond level has increased.

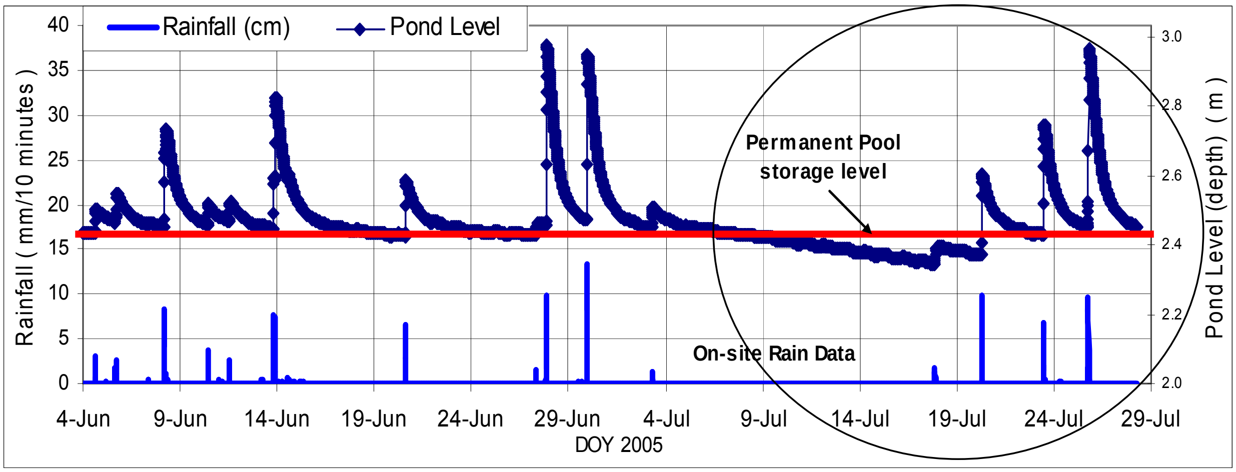


Figure 6.7.4 Recorded rain events and pond level of the State Farm wet detention pond in June and July, 2005, with the period for closer examination circled.

Pond surface temperature, outflow temperature, and air temperature during the July 11 - 28, 2005 time period, are shown in Figure 6.7.5. A few interesting features are as follows: First, leading up to July 17, the pond outflow data have higher peaks and lower valleys than the pond surface temperatures. In that period the pond surface level was below the outlet and there was no outflow from the pond. The outlet temperature sensor was partially out of the water, and may have been influenced by direct solar radiation and/or air temperature during the day and by air temperature at night. Second, there is a very close correlation of the surface temperature and outflow temperature after July 20, when the pond level is back to normal and outflow is occurring, which agrees with findings by Herb et al. (2006) for a pond with a surface outlet port. Note that during the daylight hours on July 20, after the rainfall and after the pond level had risen to 2.58m (which is within the 2.43m to 2.63m levels of the 0.20m circular outlet port) the outflow temperature peak was noticeably less than the surface temperature. This is not clearly evident for the July 23 and 25 events when the pond level surpassed 2.63m and outflow was from below the pond surface.

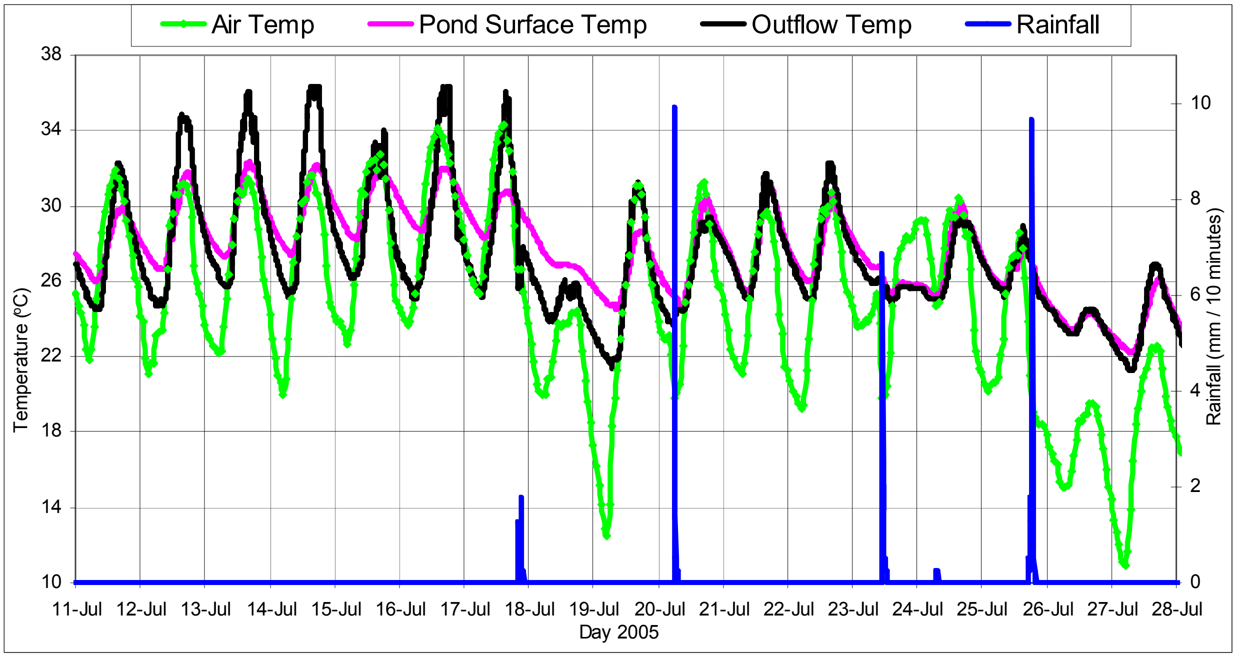


Figure 6.7.5 Comparison of State Farm Pond surface temperature and outflow temperature with air temperature from the University of MN St. Paul Campus for July 11 – 28, 2005.

Rainfall was measured every minute and averages were recorded on the Campbell data logger every 10 minutes. The depth of the rainfall, shown on the charts in this section, represents these 10-minute averages, but not the total amount of rain for the event. For each of the rainfall events that occurred in the second half of July, Table 6.7.1 gives the total rainfall amount and 10-minute averages.

Table 6.7.1 Rainfall data and totals for five events in late July, 2005; events for closer examination are circled.

State Farm on-site Rainfall Data

Date/Time	rainfall (mm)	Date/Time	rainfall (mm)	Date/Time	rainfall (mm)	Date/Time	rainfall (mm)	Date/Time	rainfall (mm)
7/17/05 20:10	1.27	7/20/05 6:00	0.508	7/23/05 11:00	5.588	7/24/05 6:50	0.254	7/25/05 17:10	0.508
7/17/05 20:20	0.254	7/20/05 6:10	9.91	7/23/05 11:10	6.858	7/24/05 7:00	0	7/25/05 17:20	0.508
7/17/05 20:30	0	7/20/05 6:20	1.524	7/23/05 11:20	2.54	7/24/05 7:10	0	7/25/05 17:30	0.254
7/17/05 20:40	0	7/20/05 6:30	0.508	7/23/05 11:30	1.524	7/24/05 7:20	0	7/25/05 17:40	0.508
7/17/05 20:50	0	7/20/05 6:40	0.508	7/23/05 11:40	2.032	7/24/05 7:30	0	7/25/05 17:50	1.27
7/17/05 21:00	0	7/20/05 6:50	0.254	7/23/05 11:50	0.254	7/24/05 7:40	0	7/25/05 18:00	1.778
7/17/05 21:10	1.778	7/20/05 7:00	0.254	7/23/05 12:00	0.254	7/24/05 7:50	0.254	7/25/05 18:10	1.016
7/17/05 21:20	0.254	7/20/05 7:10	0.254	7/23/05 12:10	0.254			7/25/05 18:20	0.762
7/17/05 21:30	0			7/23/05 12:20	0.508			7/25/05 18:30	7.37
7/17/05 21:40	0			7/23/05 12:30	0.254			7/25/05 18:40	9.65
7/17/05 21:50	0.254			7/23/05 12:40	0.254			7/25/05 18:50	3.048
7/17/05 22:00	0							7/25/05 19:00	2.794
7/17/05 22:10	0.254							7/25/05 19:10	0.762
								7/25/05 19:20	0.508
								7/25/05 19:30	0.254
								7/25/05 19:40	0
								7/25/05 19:50	0
								7/25/05 20:00	0.254
Total Rainfall (mm)	4.06		13.72		20.32		0.51		31.24
Maximum 10 minute Burst (mm)	1.78		9.91		6.86		0.25		9.65

The three rainfall events that occurred on July 20, 23 and 25, 2005, will be more closely examined,. For these events, the rain totals were consecutively larger, with the July 20 rainfall yielding 13.7 mm, the July 23 rainfall yielding 20.3 mm, and the July 25 rainfall yielding 31.24 mm. They also occur consecutively later in the day. The July 20 rainfall data run from 6:00 am to 7:10 am, the July 23 rainfall data from 11:00 am to 12:40 pm, and the July 25 rainfall data from 5:10 pm to 8:00 pm.

The next three figures show the same data in a slightly narrower time frame from July 19 through July 26. Figure 6.7.6 displays the daily solar radiation data around these rain events. It shows that on July 20 there was no solar heating of the pavement surfaces prior to the rainfall data starting at 6:00 am., but significant solar radiation afterwards. The July 23 event had some solar heating before the 11:00 am rainfall. The July 25 event had significant solar heating most of the day, i.e., before the 5:10 pm rainfall. Note that on July 25, solar radiation was recorded within the rainfall. A possible explanation is that solar radiation was recorded at the University of Minnesota St. Paul Campus, about 12 miles west of the State Farm study site, and thus may not be fully accurate for the study site, or there was broken cloud cover at the State Farm site during the rainfall event.

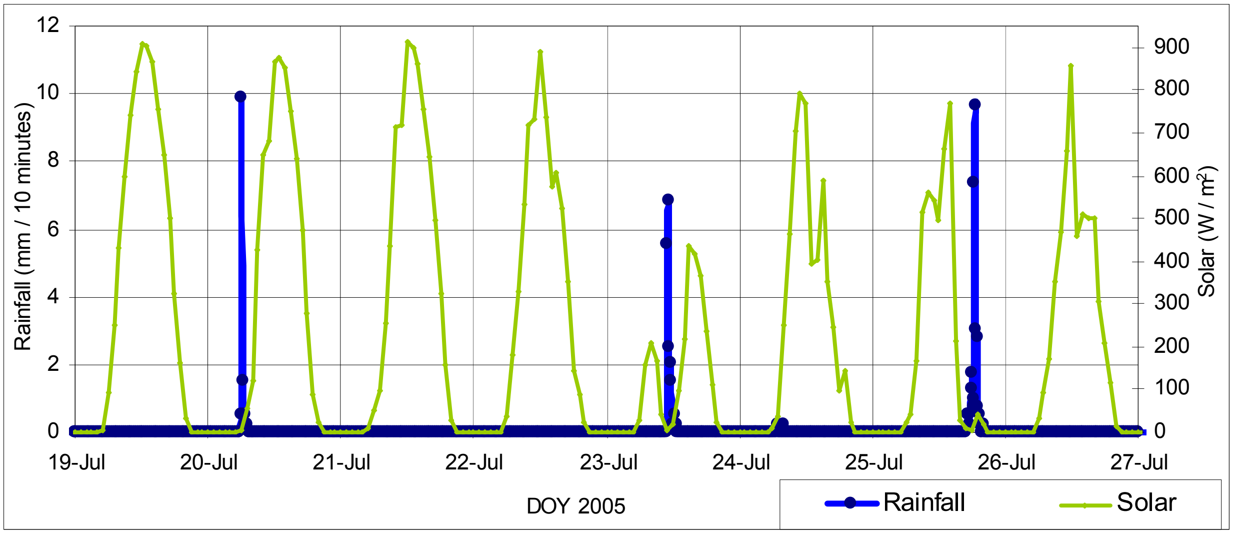


Figure 6.7.6 Solar radiation around the July 20, 23, and 25 rainfall events.

Figure 6.7.7 shows pavement and weather data, but no pond data. It is obvious that abrupt temperature changes occur at the time of the rainfall events, although not all details can be seen. It is clear though that the outflow temperature follows a diurnal pattern.

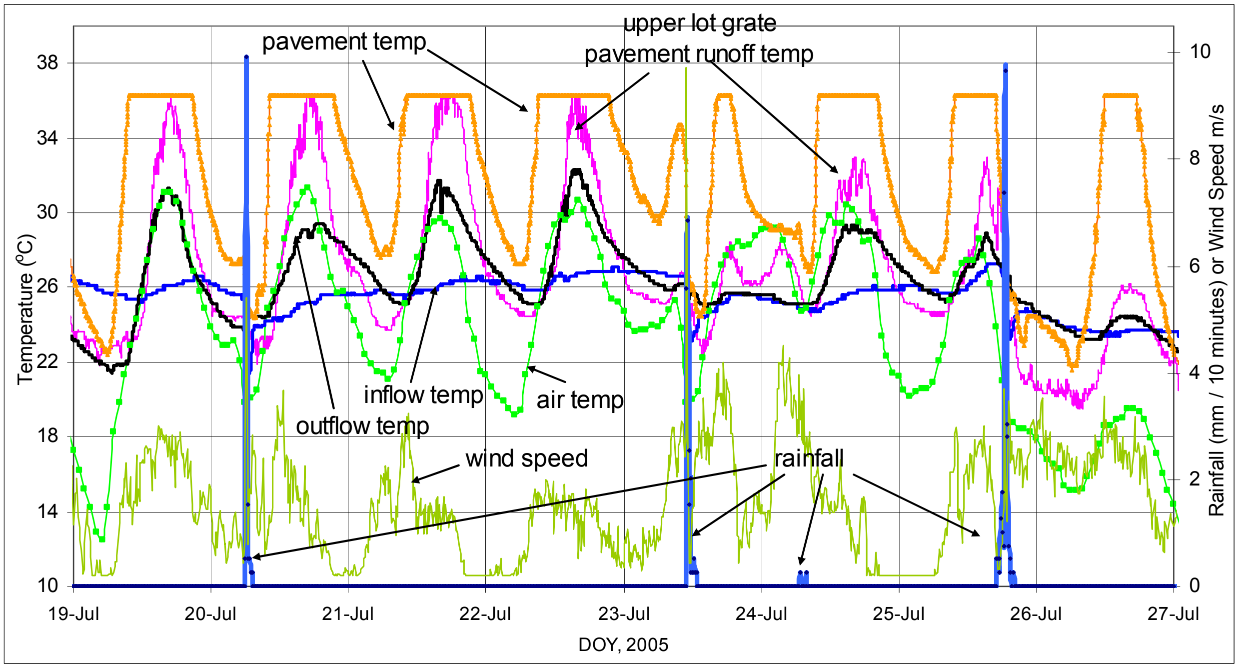


Figure 6.7.7 Weather and pavement data surrounding the July 20, 23, and 25 rainfall events.

A close view of pond layer temperatures is given in Figure 6.7.8. Note that on July 20 and 23 the rainfall events caused the recorded bottom temperature to be greater than the "2' off bottom" temperature for 6 to 24 hours after the event. This did not happen on July 25, which had the largest rain total of the three rainfall events. Even though the bottom sensor had drifted out of calibration by the end of data collection at the end of August 2005, before the July 20 rainfall, it's recorded temperatures were lower than those of the "2' off bottom" recorder, making it reasonable to think that it was still in calibration in July. It seems reasonable to expect a similar pattern in bottom temperature changes, unless there were major differences in the three rainfall events, - and there were. The July 25 rain event had the largest rain total, and the pond had not drained to a normal level since the July 23 rainfall, as can be seen in Figure 6.7.4. A third difference is that the maximum wind speed during the July 25 rainfall rose only slightly above 4 m/s, whereas the July 20 and July 23 rainfall events had wind speeds of over 5 m/s and 9 m/s respectively.

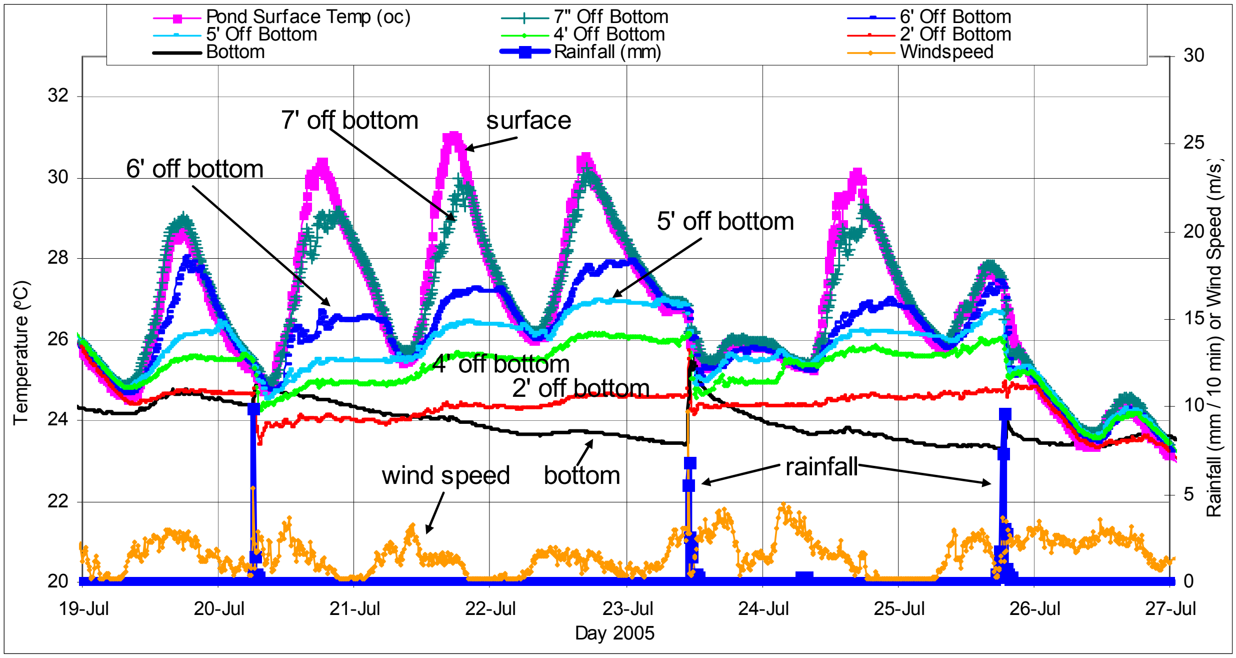


Figure 6.7.8 Pond layer temperatures (raw data) for the July 20, 23, and 25 rainfall events.

For details on the temperature changes that occurred during each of the three rain events, the reader is referred to sections 6.7.1 through 6.7.3 which give the data within the narrow time frame of each rainfall event.

6.7.1. July 20, 2005 rainfall event, 6 am, 13.7 mm

The July 20 rainfall event totaled 13.7 mm of rain, Figures 6.7.9 through 6.7.11 display all recorded data before, during, and immediately after this rainfall, as well as air temperature from the University of Minnesota St. Paul Campus.

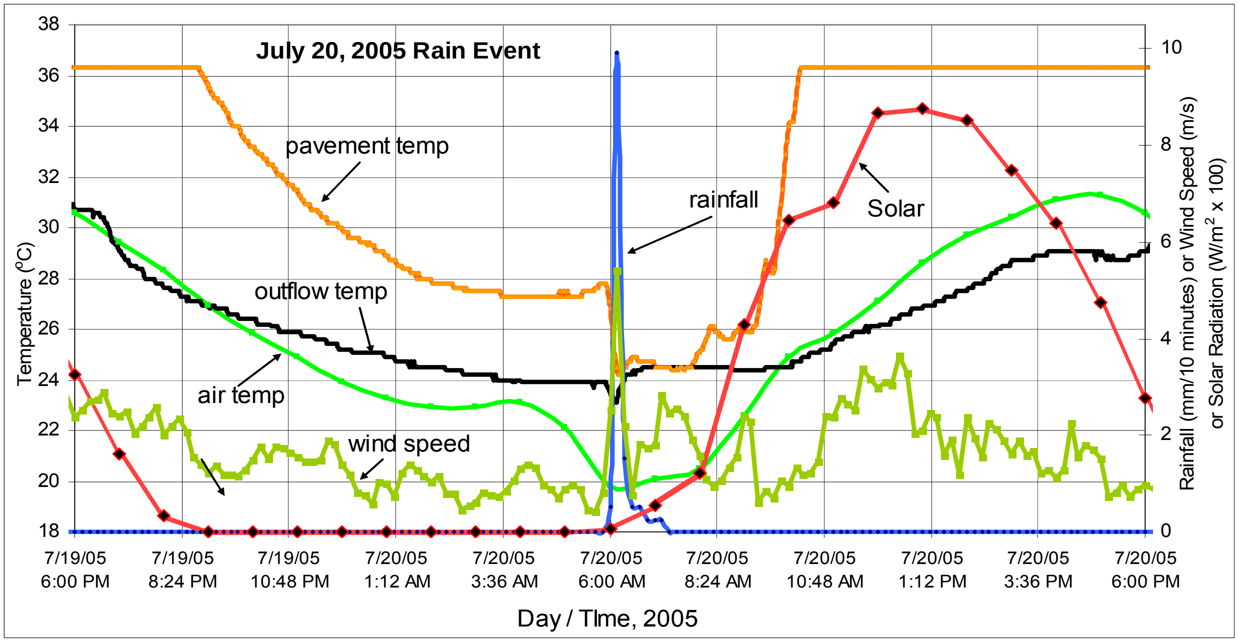


Figure 6.7.9 Temperature, wind speed and solar radiation plots for the 24 hour period surrounding the dawn rain event on July 20, 2005 at the State Farm Pond.

Before sunrise on July 20, the pavement temperature had dropped overnight to about 26.5°C, but had risen to about 27.5°C before the 6:00 am rainfall. Figure 6.7.10 shows that with the start of rainfall, the pavement temperature quickly dropped from about 27.5°C to just above 24°C during the largest burst of rain. It then rose slightly to near 25°C as the rain tapered, and by the end of the rain it dropped again to about 24.5°C.

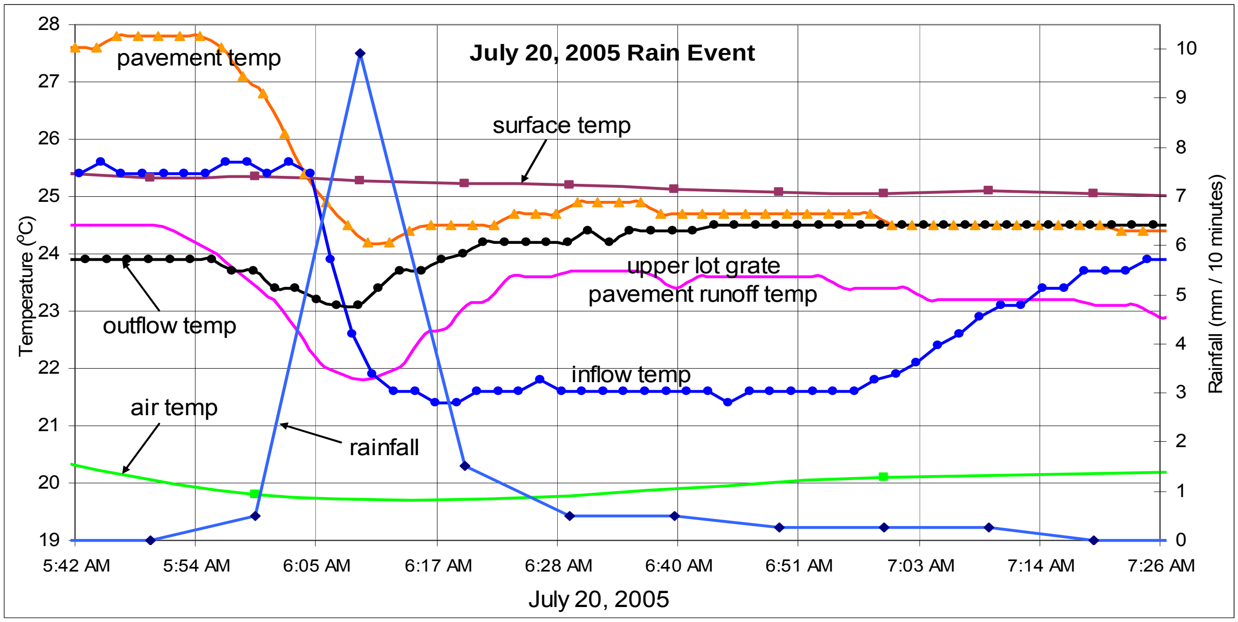


Figure 6.7.10 Temperatures for the July 20 rainfall event, including pavement runoff and pond inflow temperature, plotted at high temporal resolution.

The rainwater temperature at the parking lot grate (Figure 6.7.10) shows the pavement runoff temperature at just below 22°C during the heaviest burst, and then increasing to about 23.5°C within 15 minutes of the heaviest rain. In the following 40 minutes of lighter rain, runoff temperature gradually declines again to just above 23°C by the end of the rainfall. The pond inflow temperatures show a sudden drop from about 25.5 to 21.5°C with the onset of rain, and a lower temperature until near the end of the recorded rainfall; it rises to about 23.5°C by the end of the rainfall, perhaps from the pond back-mixing within the inflow structure. Note that there is a time offset of about 10 minutes between the upper grate pavement runoff temperature and the pond inlet temperature. This is due to the delay of the flow in the storm sewer system.

Analysis of the pond outflow temperature requires mentioning that the pond level was below the outlet before the rainfall started. The data indicate that the pond level reached the level of the outlet port at 6:20 am, 20 minutes after the first recorded rainfall data. The recorded outflow temperature data shows an irrelevant 24°C at the 6:00 am start of the rain, and then drops to around 23°C during the main rain burst (probably from direct rainfall contact), but then rises to around 24.5°C as the pond began draining through the port at 6:20 am.; outflow temperature remains there for the rest of the rainfall. The air temperature remained around 20°C during the rainfall.

Figure 6.7.11 gives a plot of water temperatures in the pond, as well as the wind speed for the 24 hour time period surrounding the July 20 rainfall event. Note that through the night and prior to the rainfall, the surface mixed layer of the pond gradually deepens until it reaches the depth of the "4' off bottom" recorder about 4 am.

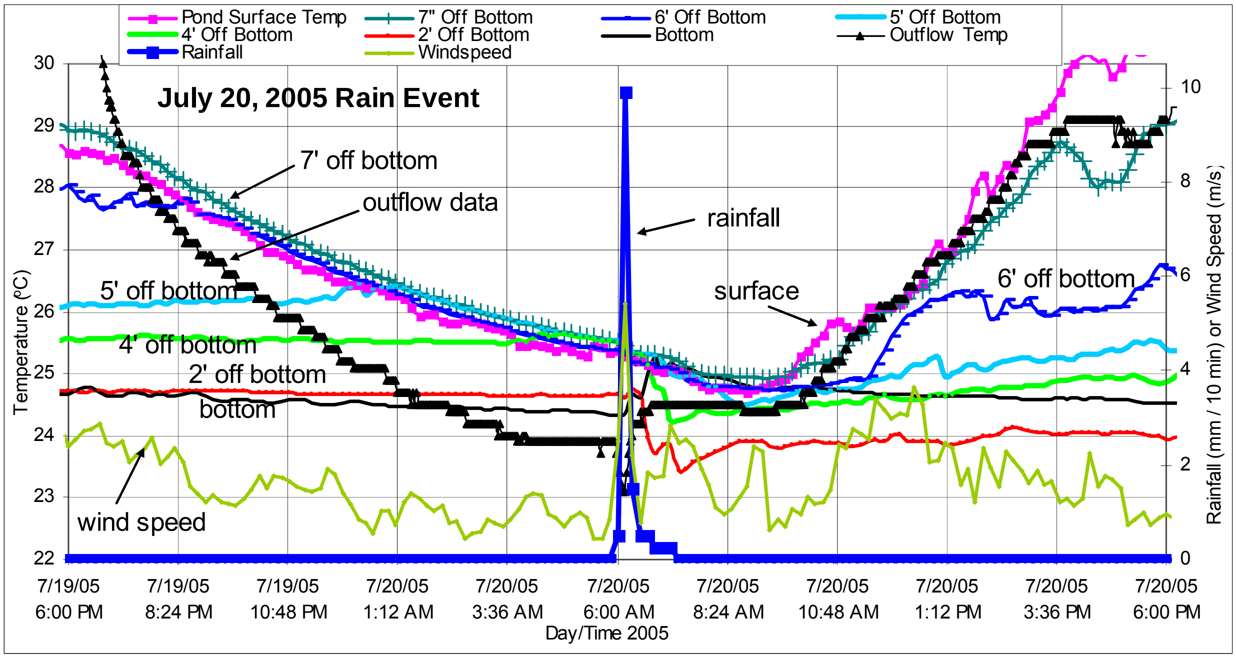


Figure 6.7.11 Pond temperatures, wind speeds and pond outflow temperatures for the 24 hour period surrounding the dawn rainfall event on July 20, 2005 at the State Farm Pond.

The data for the 24 hours surrounding the July 20 rainfall in Figure 6.7.11 show how the outflow temperature data greatly differ from the surface temperature data, especially before the rainfall. As mentioned earlier, this rainfall raised the pond level to 2.58m (which is within the range from 2.43m to 2.63m for the opening of the 0.20m diameter circular outlet pipe/port). Potential causes for the lower outflow temperatures could be plunging inflows and/or upwelling of colder waters, displacing some of the cooler pond water up towards the outlet, and creating a temporary lengthwise temperature gradient in the pond, from inlet to outlet. The most likely reason is that the outlet flow is withdrawn over a depth that extends deeper than the bottom of the outlet port/pipe. This type of selective withdrawal layer is well-known from surface outlets of large stratified reservoirs.

With the rainfall, there appear to be some abrupt temperature changes at the bottom and up to the “4’ from bottom” level. Wind speed spikes over 5 m/s occurred during the rainfall. The sensors above the “4’off bottom” level recorded a continued cooling progression in an uninterrupted fashion through the rainfall event. A view with high temporal resolution is given in Figure 6.7.12.

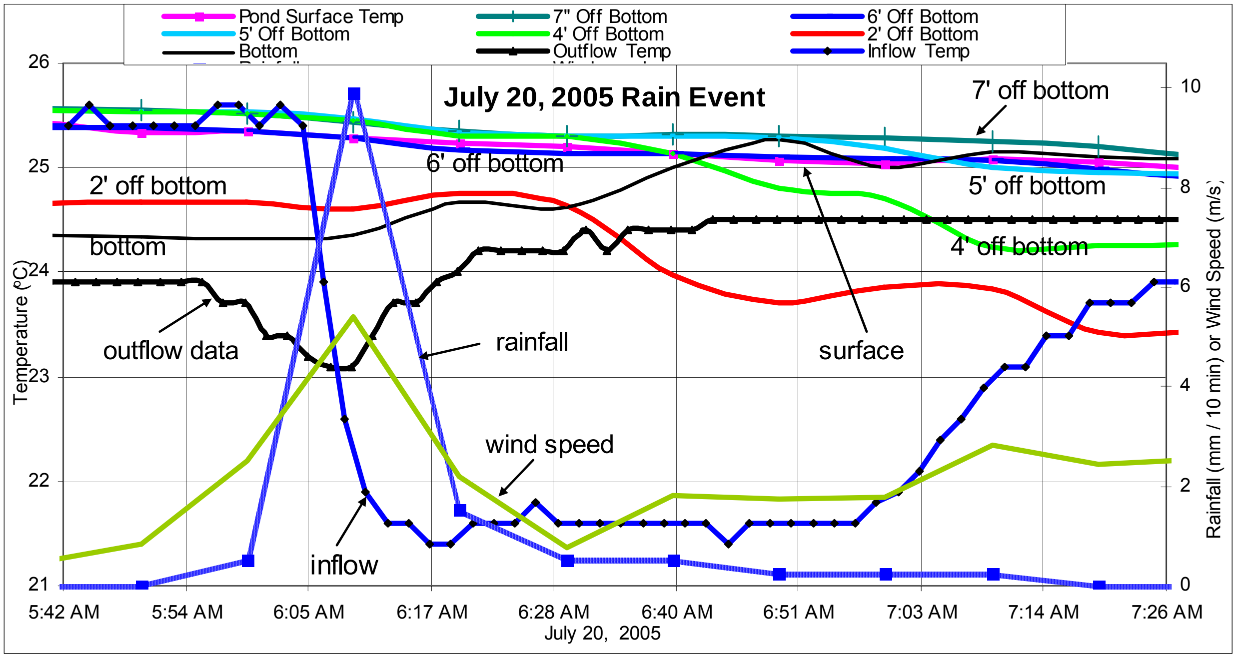


Figure 6.7.12 Pond temperatures during the July 20 rainfall event, inflow and outflow temperatures, as well as wind speeds plotted at high temporal resolution.

In Figure 6.7.12, the upper layers continue to be uniformly well mixed, but a few interesting things occur. The “4’ off bottom” and “2’ off bottom” recorded temperatures both drop after the rainfall event. This may be due to the runoff water, entering the pond through the submerged inlet pipe. There is a forebay in the pond which rises to a level of about “6’ off the bottom. Perhaps the colder water flowed over this forebay structure and then, being colder, immediately sank and mixed with the lower levels. Also in Figure 6.7.12, the outflow temperature drops initially, perhaps from the colder rain directly hitting the pond surface, but then rises as the pond begins to drain the relatively warmer water that it held, by the aforementioned selective withdrawal layer. That the bottom layer rises in temperature is rather intriguing, and may be explained by an inflow of some saline water, a residue of salty water from road salt applications in winter. Delayed (seasonal) releases of such water from the ground have been found in a study of small streams (Shingle Creek) in the Twin Cities, and the presence of saline water at the bottom of the State Farm Pond is documented in a later section of this report.

Earlier in section 6.6, rainfall temperature data was collected and compared with dew point temperature data, including for this July 20, 2005, rainfall event. It confirmed a widely held notion that the temperature of rainwater will be the same as dew point temperature during the time of the rain. With that in mind, Figure 6.7.13 gives a plot of dew point temperature data and inflow temperature data. The actual temperature of the rainwater inflow seems to have been approximately 21.6°C, based on the lower leveling of the inflow temperature plot. The average of the two "hourly averaged" dew point temperatures (and therefore rain water temperatures) recorded 12 miles west at the St. Paul Campus during this event is 20.6°C For comparison, dew point temperatures are also shown from the SAFL weather station which is 16 miles west. These dew point temperatures are considered applicable to the State Farm site because rainfall did occur at both St. Paul and SAFL at times very similar to the State Farm site. Assuming that the rainwater started out at 20.6°C and ended up being 21.6°C when it reached the pond, the water must have gained 1.0°C during the runoff process for this 6am, July 20, rainfall event.

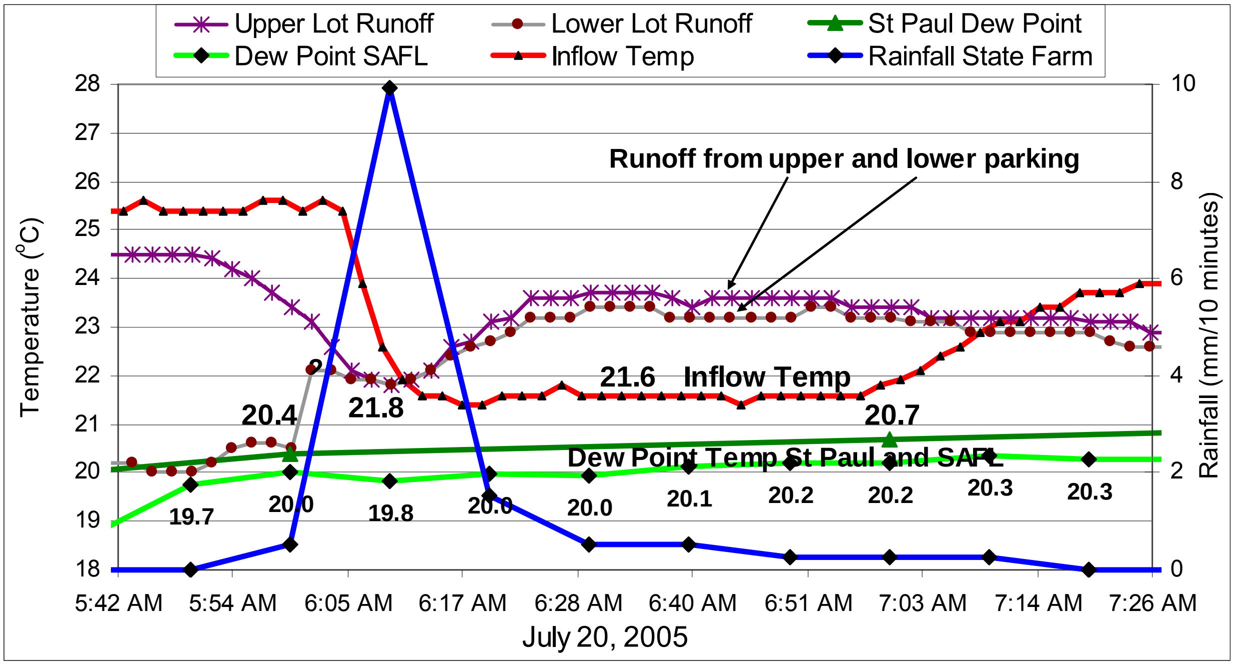


Figure 6.7.13 Comparison of dew point and inflow temperatures for the July 20 rainfall. A difference of approximately 1.0°C represents heat gained by the rain water during runoff.

Also shown in Figure 6.7.13 are parking lot runoff data from both the upper lot (furthest) and lower lot (closest). During the heaviest rainfall, the lowest recorded runoff temperature was 21.8°C. The lowest recorded inflow temperature of 21.4°C was recorded about 10 minutes afterwards. As the rainfall intensity, and therefore runoff volume, decreased, the runoff temperature increased, probably due to increased unit per volume heat extraction from the pavement due to lighter/slower runoff and continuing heat conduction, from below to the pavement surface. A slightly higher runoff temperature that occurs at a lower rate of runoff causes the inflow temperature to rise slightly to 21.6°C, where it remains fairly constant.

6.7.2. July 23, 2005 rainfall event, 11 am, 20.3 mm

The second rainfall event occurred on July 23, 2005. Beginning just before 11:00 am, it totaled 20.3 mm of rain. The 24 hour period surrounding it is shown in Figure 6.7.14. Unlike the July 20 rainfall, the pond level was at 2.42m prior to the rainfall, only very slightly below the permanent pool level. It rose above 2.43m (outlet, lower level) by 11:10 am, and reached a maximum level of 2.72m at 12:10 pm. With the top of the outlet port at the 2.63m level, this rainfall raised the pond level to 9 cm above the outlet port.

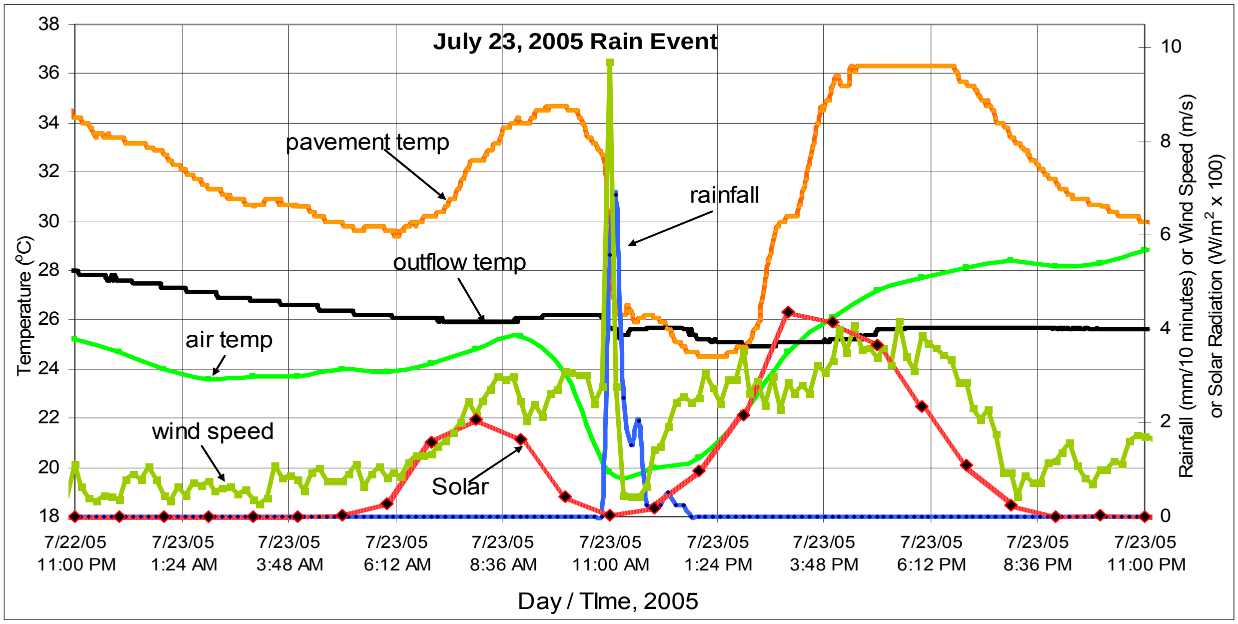


Figure 6.7.14 *Temperature, wind speed and solar radiation plot for the 24 hour period surrounding the mid-day rain event on July 23, 2005 at the State Farm Pond.*

Figure 6.7.14 shows that during the morning, before the July 23 rainfall, there was some solar heating of the parking lot; the pavement temperature warmed to approximately 35°C from the overnight pavement temperature of approximately 29°C. The pond outflow temperature dropped before, during and after the rain. There was a spike in wind speed to over 9 m/s during the rain. A view of the data at higher temporal resolution is given in Figure 6.7.15.

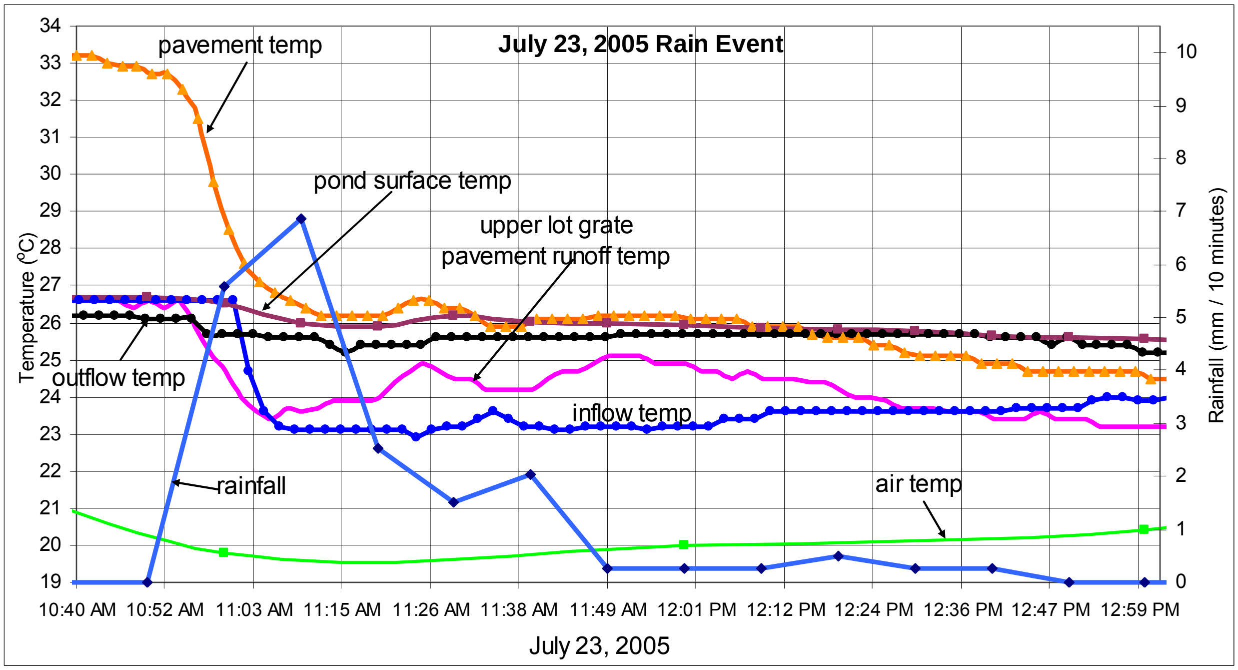


Figure 6.7.15 Temperatures during the July 23 rainfall event at the State Farm Pond, including pavement runoff temperature and inflow temperature, plotted at high temporal resolution.

In Figure 6.7.15, we see that this rainfall event lasted for about two hours, with most of the precipitation occurring within the first hour, and over half of the total rainfall occurring within the first half hour. After the onset of rainfall, the pavement temperature dropped by about 6°C, from roughly 33°C to 27°C, within 15 minutes. It then gradually dropped another ~2.5°C over the remainder of the rain event. A slight increase in pavement temperature just after the heaviest rainfall, is probably due to a lower rate of heat extraction from the pavement due to lighter runoff, while heat continues to be conducted from below to the pavement surface.

The run-off temperature is steadily dropping, reaching about 23.5°C after the first ~20 minutes of rainfall. With lessening of rainfall intensity during the first hour of rain, the runoff temperature rises, but during the lighter rainfall in the second hour, the runoff temperature slowly drops again and is recorded at approximately 23.5°C again at the end of the rain event.

It is noted that the pavement run-off temperature and pond inflow temperature both approach ~23.5°C after the first ~20 minutes, but then diverge, with the runoff temperature becoming 1 to 2°C warmer than the inflow temperature until about 1.5 hours into the storm, when the recorded temperatures converge again at slightly higher than 23.5°C. Perhaps this divergence is again due to more heat within the pavement reaching the pond surface during a period of lighter rain/runoff. The rate of heat transfer to the pavement surface is greater than the rate of heat carried away by the rainwater runoff, producing a rise in runoff temperature and a slight rise of pond inflow temperature.

The pond inflow temperature, in Figure 6.7.15, seems to equilibrate at just above 23°C within the first ~20 minutes of rainfall. It maintains this temperature until the later half of the rainfall event when the rate of rainfall is less than 1 mm per 10 minutes. The inflow temperature rises very slightly during the later lighter rainfall, possibly by feedback from the pond or by increased heat uptake during the runoff process.

Figure 6.7 16 shows temperatures for individual pond layers, inflow and outflow temperatures, and wind speeds for the 24 hour period surrounding the July 23 rainfall event.

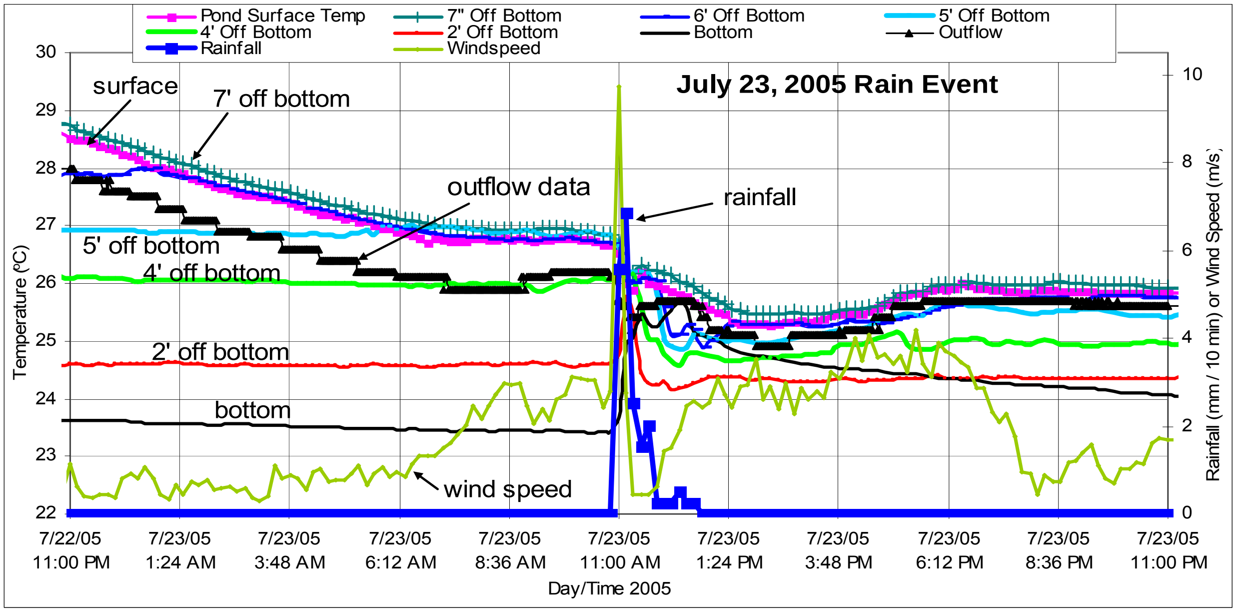


Figure 6.7.16 Pond temperatures (raw data), wind speeds and outflow temperatures for the 24 hour period surrounding the mid-day rain event on July 23, 2005 at the State Farm Pond,.

In Figure 6.7.16, we see again that the pond surface temperature was higher than the pond outflow temperature leading up to the rainfall, and also for about an hour afterwards. Outflow from the pond began by 11:10 am, with the pond level rising to 2.72m by 12:10 pm, surpassing the top of the outlet port by 9cm. The pond is better mixed after the rain within a tighter, and for the most part lower, temperature range. This is possibly the result of a spike in wind speed to over 9m/s during the rain. This spike is clearly seen in Figure 6.7.16 and Figure 6.7.17.

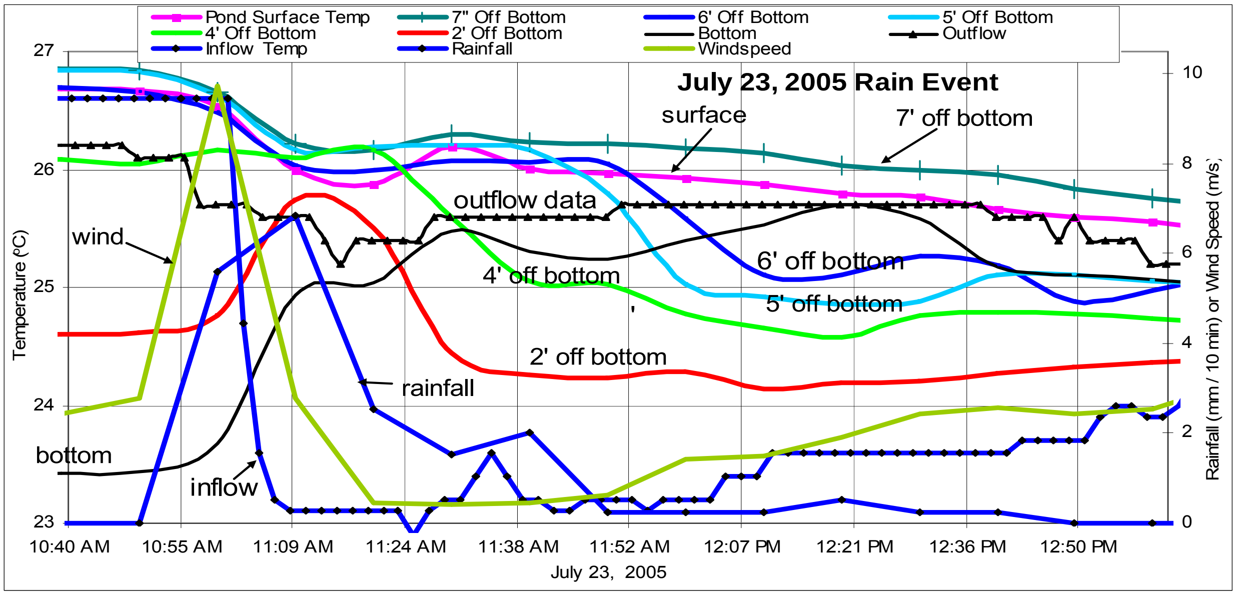


Figure 6.7.17 Pond temperatures (raw data), inflow and outflow temperatures, as well as wind speeds during the July 23 rainfall event, plotted at high temporal resolution.

Figure 6.7.17 shows that the bottom temperature rises to coincide with the upper layers, similar to the July 20 rainfall, while the “2’ off bottom” temperature rises but then quickly falls to a lower temperature than prior to the rainfall. The bottom sensor is in a saline layer. The “2’ off bottom” sensor may be showing a rise due to wind mixing or an internal wave followed by a drop due to cold water inflow sinking.

Figure 6.7.18 compares inflow temperature data with rainwater temperature data, which was verified in section 6.6 for the July 23 rainfall, to be equivalent to dew point temperature. The actual temperature of the rainwater inflow from this July 23 rainfall seems to have been approximately 23.1°C, based on the lower leveling of the inflow temperature plot shown in Figure 6.7.18. Assuming this rainwater temperature was 20.6°C (average of the two St. Paul dew point temperatures during this rainfall) and ended up being 23.1°C when it reached the pond, it must have gained 2.5°C during the runoff process. That is more than the July 20 rainfall, which may be explained by the fact that the July 23 rainfall event occurred in mid-day. Whereas the July 20 rainfall was an early morning event.

Parking lot runoff temperatures are also shown in Figure 6.7.18. The pattern is very similar to the July 20 rainfall.

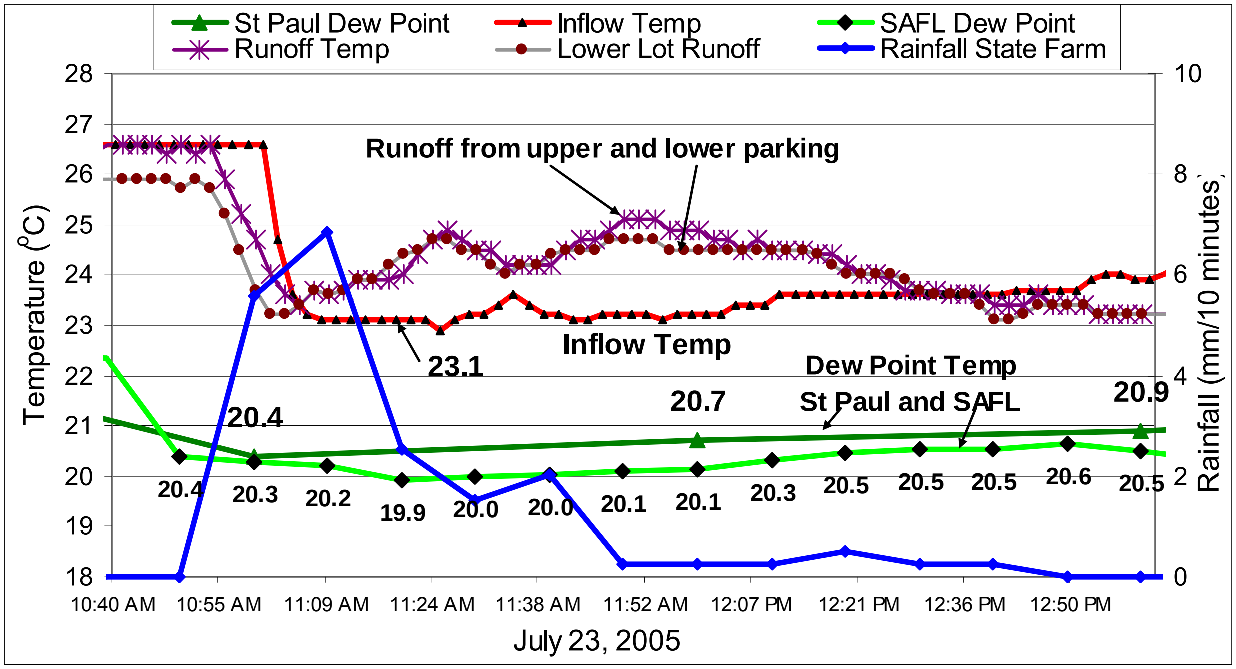


Figure 6.7.18 Comparison of dew point and inflow temperatures for the July 23 rainfall event shows a difference of approximately 2.5°C, which represents a heat gain by the rain water runoff.

6.7.3. July 25, 2005 rainfall event, 5 pm, 31.3 mm

The rain event on July 25, 2005 started at 5:00 pm and totaled 31.24 mm. The pond level was at 2.44m before the rainfall, and there was already a small out-flow. The pond surface reached the 2.93m level at 7:30 pm. Figure 6.7.19 shows the 24 hour period surrounding this rain. The main bursts of rain occurred around the middle of this rain period. Solar heating of the pavement occurred throughout the day before the rainfall. Pavement temperature had risen well above 36°C, however as the rain started, the pavement temperature had already dropped to below 36°C. The pond outflow temperature had risen during the day but started to decline by mid-afternoon, following a drop in solar radiation and air temperature, and continued to drop during and after the rainfall. This rainfall event did not have a large spike in wind speed whereas the first two events did.

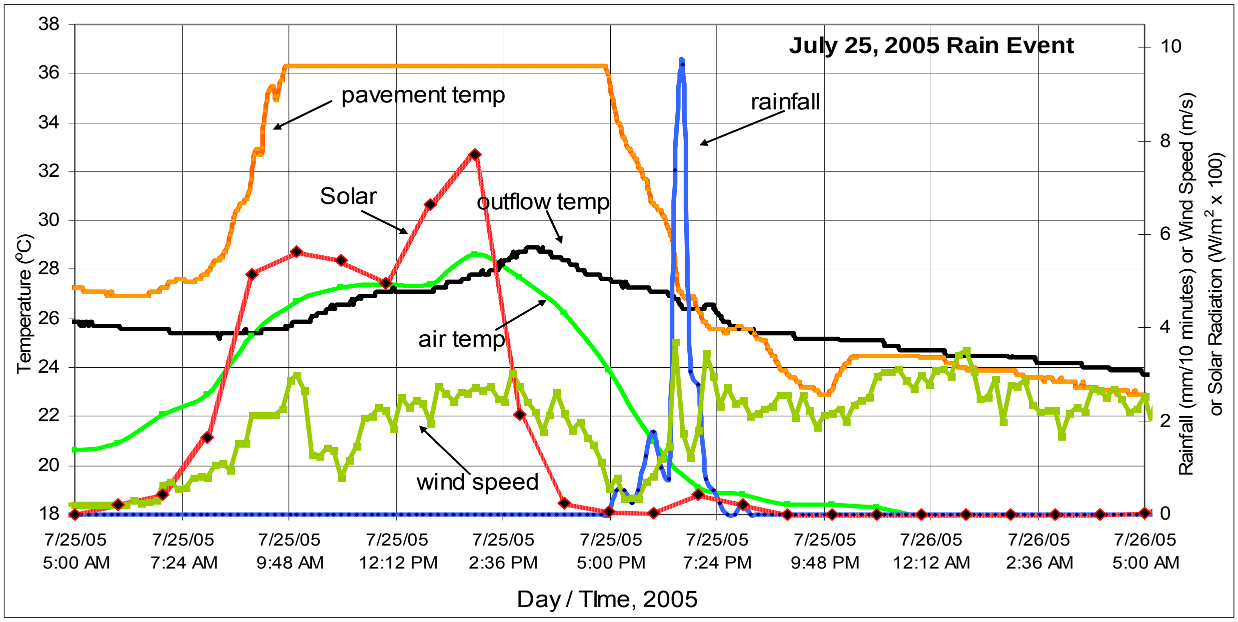


Figure 6.7.19 Temperature plot for the 24 hour period surrounding the late-day rainfall event on July 25, 2005 at the State Farm Pond.

For the time period of the actual rainfall, Figure 6.7.20 shows the pavement temperature dropping steadily during the early lighter rainfall, but more quickly with the heavier rain. The inflow temperature drops slightly with the early rain, but takes a big dive with the main burst of rain. The inflow temperature for this event dropped to roughly 24°C, after the main rain burst.

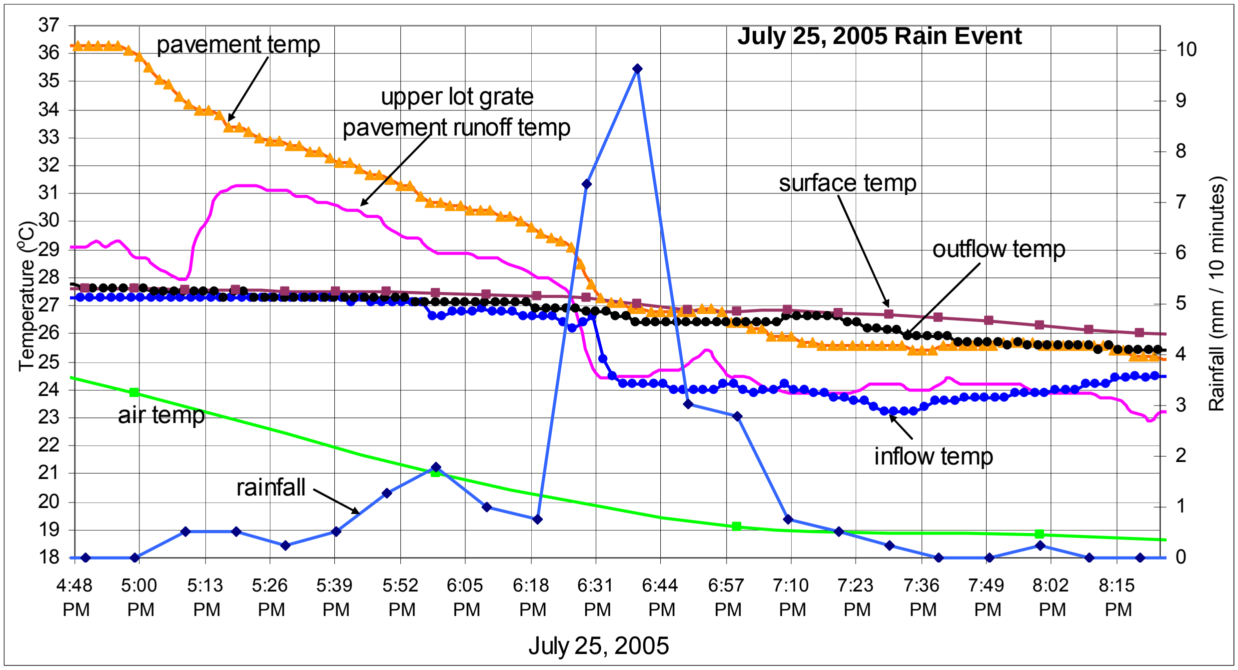


Figure 6.7.20 Temperatures during the July 25 rainfall event at the State Farm Pond, including pavement temperature, runoff temperature and inflow temperature, plotted at high resolution.

The pond outflow and surface temperatures are very similar. Figure 6.7.21 is a plot of the same data with higher temperature resolution. It shows that at the start of this rainfall, the outflow and pond surface temperatures were almost identical, but after the rainfall started, the outflow temperature dropped more quickly than the surface temperature, and continued to be recorded at a slightly lower reading throughout the rainfall. Again there is a slight bump in pavement runoff temperature after the main burst of rain.

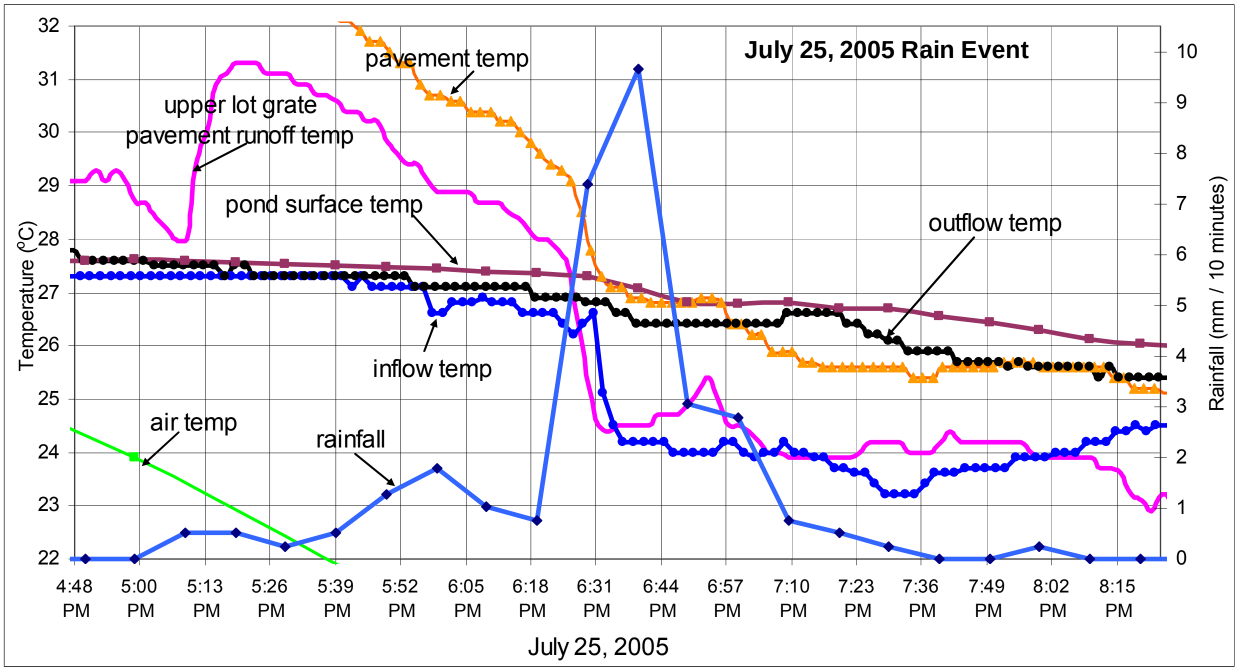


Figure 6.7.21 Data from Figure 6.7.20 plotted at a finer temperature scale for better differentiation within the 25 to 28 degree range.

Pond temperatures in individual layers and outflow temperatures for the 24 hour period surrounding the July 25 rainfall are shown in Figure 6.7.22. The pond became stratified during the day. The "bottom" and "2' off bottom" layers maintained their expected stratification during and after the rain. Lack of wind may have allowed this stratification to remain. The data from the bottom sensor appear reasonable, and imply that the calibration at this point of the study is still correct.

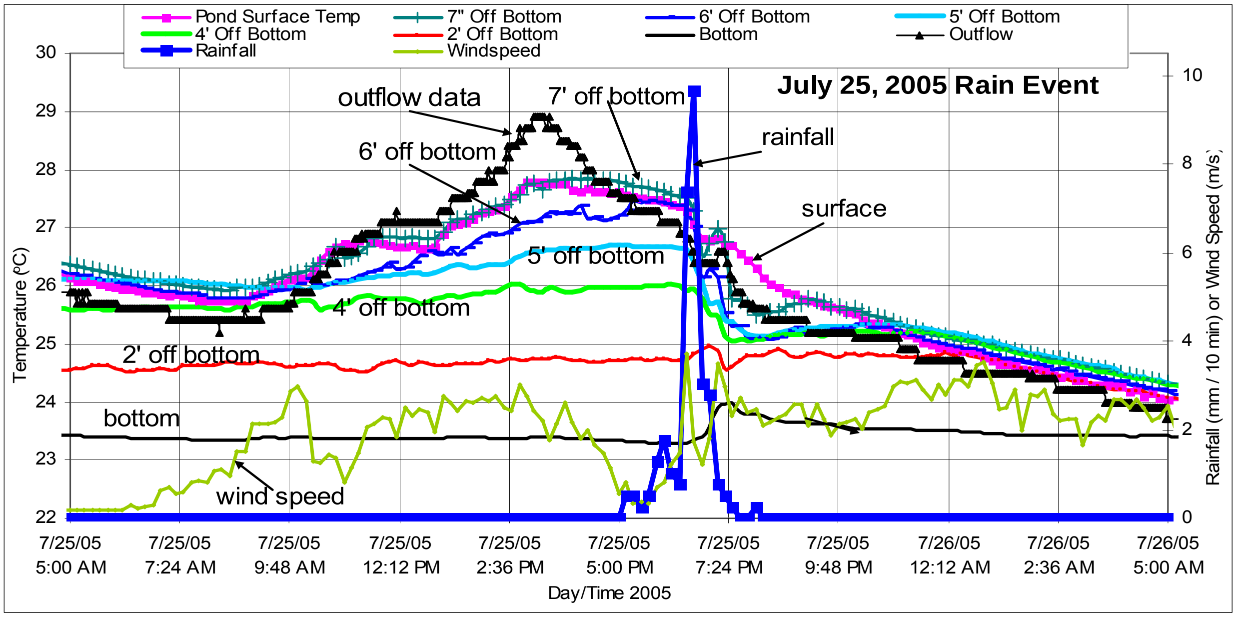


Figure 6.7.22 Pond temperatures (raw data), wind speeds and outflow temperatures for the 24 hour period surrounding the mid-day rainfall event on July 25, 2005 at the State Farm Pond,.

Figure 6.7.23 shows that until about 6:45pm, the outlet temperature was lower than the pond surface temperature, “7’ off bottom” and “6’ off bottom” temperature. This could again be due to plunging inflows and/or upwelling of colder waters, displacing some of the cooler pond water up towards the outlet, and creating a temporary lengthwise temperature gradient in the pond, from inlet to outlet, with the result being that the outlet flow is withdrawn over a depth that extends deeper than the bottom of the outlet port/pipe.

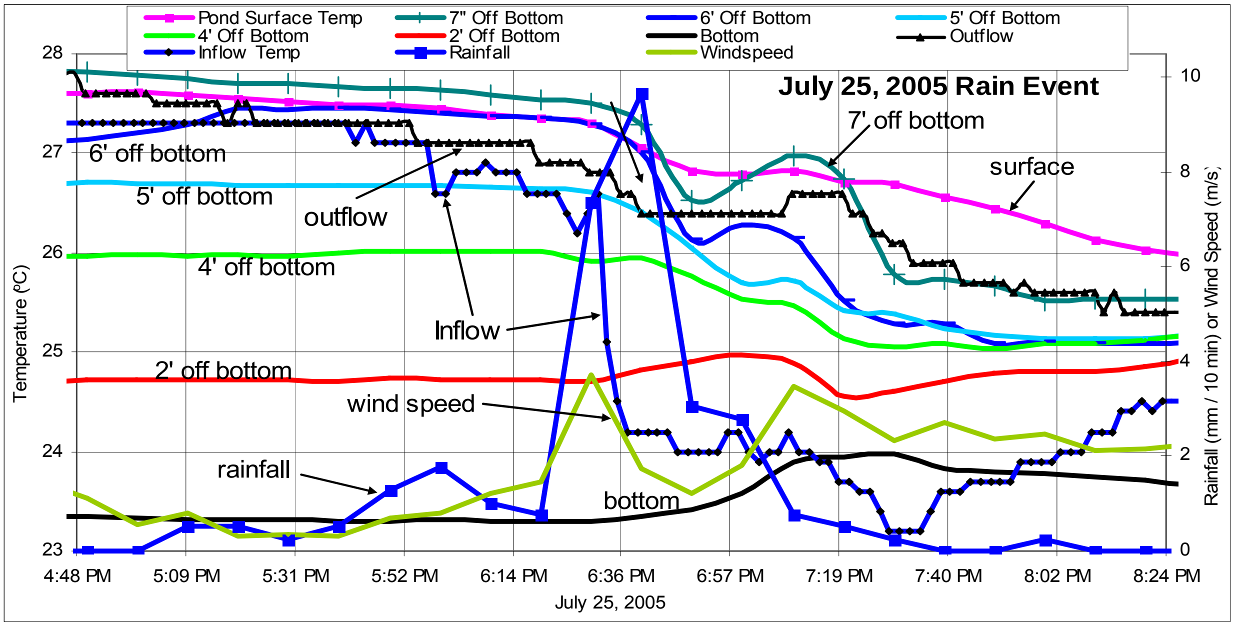


Figure 6.7.23 Pond temperature (raw data) during the July 25 rain event, inflow and outflow temperatures, as well as wind speeds plotted at high temporal resolution.

Pond level data indicate that at 6:40pm, the pond level surpassed the top of the outlet port. Figure 6.7.23 shows that by 7:25 pm, only the surface temperature was higher than the outflow temperature. This would be expected from a sub-surface outlet. Wind mixing may have caused the outflow temperature and "7' off bottom" temperature to become similar later in the rain, with the pond at its fullest. In general, the outflow temperature steadily dropped throughout this rain.

In Figure 6.7.24 dew point (rainwater) temperatures are compared to inflow temperatures for the July 25 rainfall event. The rainwater temperature for this July 25 rainfall was shown to be equivalent to dew point temperature in section 6.6. The dew point temperatures for this event are quite varied and downward trending. The inflow temperature data seem to reflect this as they also show a downward trend, with no easily discernable lower leveling inflow temperature. The lowest inflow temperature of 23.2°C,compared to the average of the later two St. Paul dew point temperatures, which were calculated to be 19.4°C, was warmer by 3.8°C. This 3.8°C represents the heat gained by the rainwater during the runoff process. This late afternoon rainfall runoff had the highest heat gain of the three rainfall events.

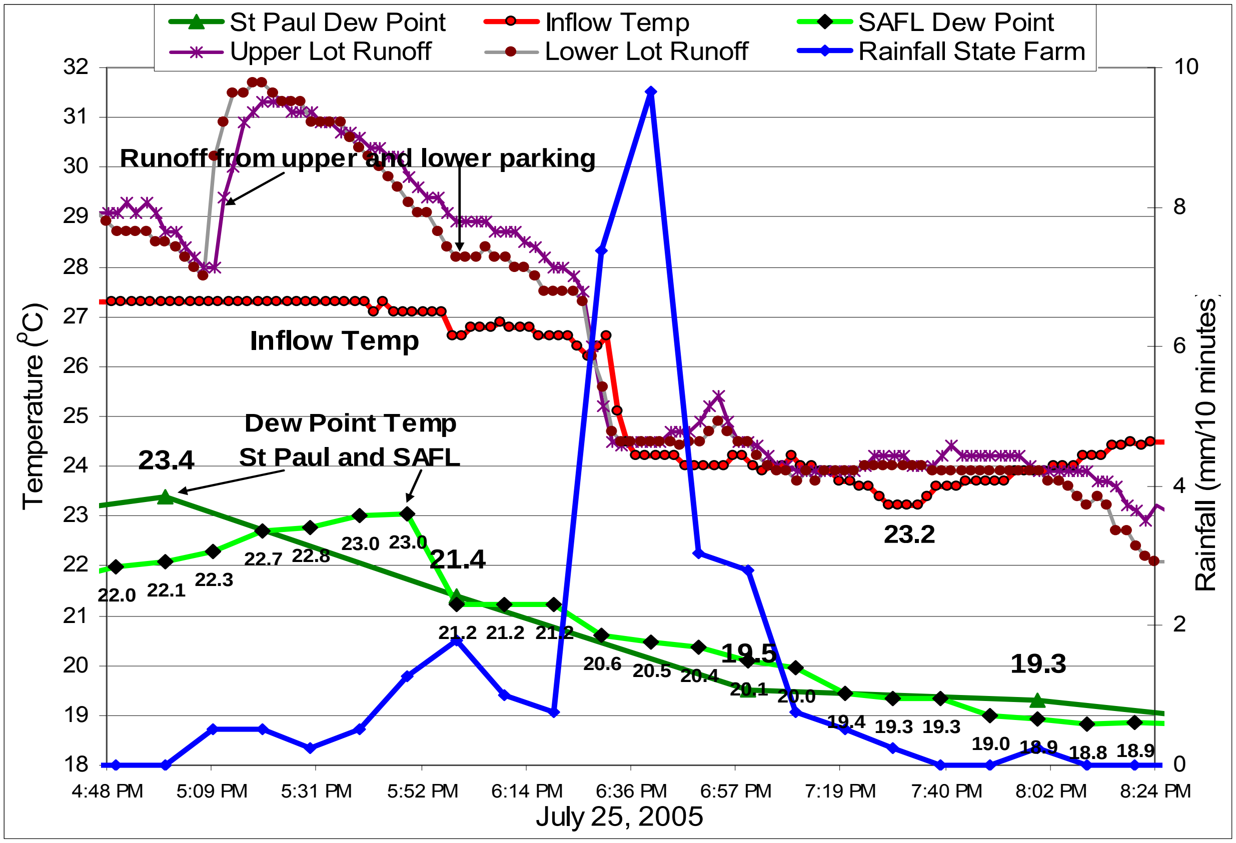


Figure 6.7.24 Comparison of dew point and inflow temperatures for the July 25 rainfall event showing a difference of approximately 3.8°C, which represents heat gained by the rain water during runoff.

Runoff temperature data from the upper and lower parking lots show a downward pattern, with no significant rise in temperature as seen in the previous two events, perhaps due to a larger volume and longer duration of rainfall.

6.8. Pond Outflow Temperature Analysis

The main purpose of this data collection effort at a stormwater detention pond was to help determine the impact that a wet detention pond might have on runoff water temperature from rainfall events, particularly if the runoff were to drain into a cold, class A, trout stream. For trout, stream temperatures below 20°C are best, and temperatures above 24°C are stressful if not deadly. In this section, we will examine the pond outflow temperature during the time periods following each of the observed rain events when the pond level was above the normal level and pond drawdown through the 8” outlet port was steady.

In the previous three sections giving a description of three rainfall events in late July, 2005 it could be seen that there is NO IMMEDIATE INCREASE in the pond outflow temperature as a result of rainfall/runoff, despite heat extraction from relatively large expanses of asphalt pavements and roof surface areas (52% impervious watershed) contributing to the runoff volume. The much cooler rain water was more than able to fully absorb any extra heat from the runoff surfaces before it entered the detention pond and, in almost all cases, brought cooler water to the pond than already existed in the pond. Only during the July 25 rainfall-runoff event were the lower layers, of water in the pond, cooler than the inflowing rain water. The outflow temperatures always decreased during rainfall and for a short time immediately after. The bulk of the runoff was stored in the pond and released gradually over the next few days. To truly understand the effect of stormwater detention ponds with controlled outlets on cold water receiving bodies, the outflow temperatures during the extended outflow time should be given consideration. Figure 6.8.1 shows each of the three rain events with boxes surrounding the outflow duration and the range of outflow temperatures.

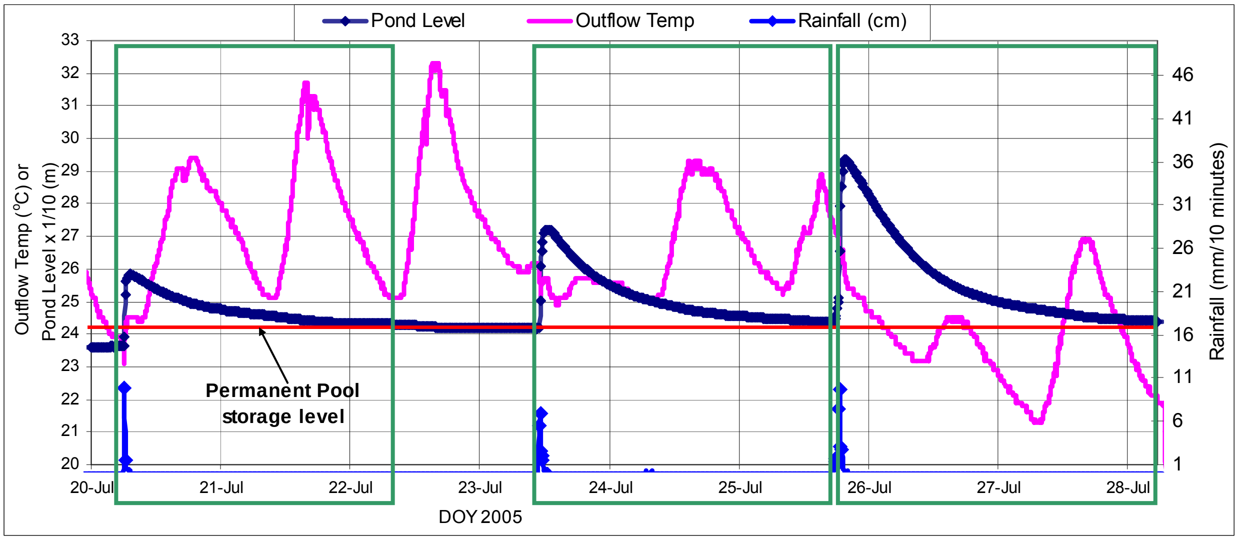


Figure 6.8.1 Pond outflow temperatures during pond drawdown following each of the rainfall events.

For the first and smallest rainfall event on July 20 (13.7 mm rainfall), continuous outflow occurred for just over 2 days following the rain. The outflow temperature dropped to around 23 °C during the rain, but for two days following the rain it ranged between 25°C and 32°C. This water would be very stressful if not lethal for trout, but the restricting outflow control structure allows for gradual release and therefore a high level of mixing with the colder receiving water body, resulting in a lesser but longer lasting rise in the receiving stream temperature.

For the second and medium size rain event on July 23 (20.3 mm rainfall), continuous outflow occurred for just over two days again. The outflow temperature dropped to just under 25°C during the rainfall, but in the two days following the rainfall it ranged between 25°C and just over 29°C, both stressful/lethal temperatures for trout.

For the third and largest rain event on July 25 (31.2 mm rainfall), continuous outflow occurred for about 2.5 days. The outflow temperature dropped from above 27°C at the start of the rainfall to around 26°C by the end of the rain, and it kept dropping throughout the night until mid-morning the next day. During the 2.5 days, the outflow temperature ranged between roughly 21.5°C and 27°C. Undiluted, this water would be stressful to trout.

Many factors affect the pond outflow temperature: the drainage area, wet pond storage volume and depth, the outflow structure design, the volume of rainwater inflow, the rainwater temperature itself, storage time, wind mixing and mixing by the inflow, groundwater inputs, air temperature, solar radiation, etc. For the State Farm pond, the epilimnion temperature preceding a rainfall seems to be the most important factor affecting the outflow temperature during and immediately after the rainfall. In the days following the rainfall, however, stratification quickly sets in or resumes, and the highly weather- affected surface and near surface water layers in the pond determine the outflow temperature.

Unless water from this stormwater pond is cooled on its way to a trout stream or mixed with colder water in a trout stream, trout will suffer because for each of the three summer rain events, the pond outflow was always above 21°C, and mostly above 24 °C, during normal drawdown in the days that followed a rainfall.

Figure 6.8.2 shows a plot of some weather data recorded at the University of Minnesota St. Paul Campus weather station in 2005. It shows the recorded hourly average dew point temperature (°C) during hours that also had recorded precipitation (cm/hr). Throughout this study it has been assumed that rain water temperature is the same as dew point temperature during the time of the rain, For the July 20 rainfall event, the recorded dew points were 19.3 and 20.4°C. For the July 23 rainfall event, the recorded dew points were 20.7, 20.4, and 20.6°C. For the July 25 rain event, the recorded dew points were 22.6, 23.4, 21.4, and 19.5°C. Figure 6.8.2 therefore implies that in the summer of 2005, the rainfall for many of the rain events was warmer than 20°C, i.e. rainfall had a temperature higher than the upper limit (20°C) for trout. Rainfall, by itself, can cause detrimental warming of a cold water (< 20°C) trout stream.

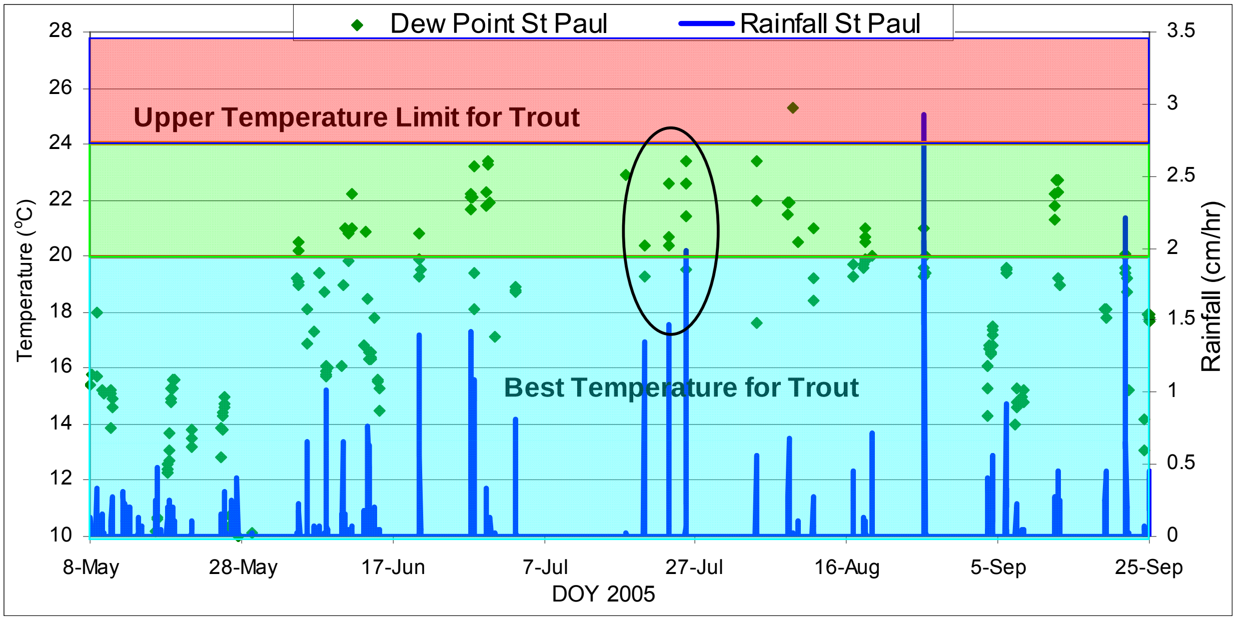


Figure 6.8.2 Hourly averaged dew point temperature during rainfall events in St. Paul in the summer of 2005, Dew point temperatures for the three rain events analyzed are within the circle.

For comparison with later years, Appendix F. contains plots similar to Figure 6.8.2, but for the years 2006 through 2009. Of these five summers total, 2005 appears to have the largest number of instances where the rainwater temperature was above 20°C.

In conclusion of this rainfall event analysis, the State Farm stormwater detention pond by itself could have a detrimental effect on a coldwater stream. Regardless of the temperature of the rainwater or the runoff, the surficial (epilimnion) water temperature of the pond will determine the outflow temperature. During the summer months, that temperature will be elevated compared to a cold stream.

7. SALINITY DATA COLLECTION IN STORMWATER DETENTION PONDS

Urban stormwater detention ponds collect surface runoff from city roads that are treated with road salt (NaCl) in the winter months to increase driving safety. The melt water of snow and ice on the city streets is therefore saline. In many natural environments there is no natural source of chloride, and Cl- concentrations in natural waters are no more then a few mg/L. This is the case for Minnesota, including the Twin Cities Metro Area (TCMA), where there are no significant natural sources of chloride (Wilson et al. 2006).

The one to one stoichiometry of sodium and chloride found in TCMA lakes suggests that NaCl is the source of both ions (Novotny et al. 2007). Water softening salt used in many households is an unlikely source of NaCl found in lakes, because domestic waste water is routed typically to a sanitary sewer and WWTP, and would not reach any lake.

Using data from 14 lakes in the Minnesota Pollution Control Agency (MPCA) Environmental Data Access, and their own water samples from 9 TCMA lakes, Novotny et al. (2007) had been able to establish a linear relationship between the concentration of chloride ions and specific conductance in lake water. To examine if the road salt can be detected in storm water detention ponds, measurements of specific conductivity, in units of micro Siemens per centimeter (µS/cm), and of water temperature degrees Celsius(ºC), were made in several ponds in the summer of 2005. Both parameters were measured at least once in July or August 2005 in stormwater detention ponds in Bloomington and Woodbury using a YSI Model 63 probe. The intent was to get a sampling of ponds with a variety of characteristics such as pond surface area, shading, depth, algae and duckweed, and even submerged vegetation.

Measurements were taken as a function of vertical distance in the water column, starting at the surface and then every foot until the pond bottom was reached. The surface temperature was obtained by holding the probe just beneath the surface. Salinity and temperature profiles were sampled at multiple locations in a pond; locations were chosen to get a representative average for that pond. Some of these stormwater ponds drain into Nine Mile Creek, which was classified as impaired water for high chloride levels in 2008 by the Minnesota Pollution Control Agency (MPCA).

The salinity data collected are of the same kind as described for lakes in SAFL Project Report No. 485, Seasonal Salinity Cycles in Eight Lakes of the Minneapolis/St. Paul Metropolitan Area, by Dan Murphy and Heinz Stefan, October 2006. Furthermore, the average results are converted to chloride concentrations (mg/L) using the relationship described in SAFL Project Report No. 505, Road Salt Effects on the Water Quality of Lakes in the Twin Cities Metropolitan Area, by Eric Novotny, Dan Murphy, and Heinz Stefan, December 2007.

7.1. Calculating Specific Conductance and Chloride Concentration

Specific conductance measures the electrical resistance of an aquatic solution and depends on ionic strength. Since the waters in the TCMA lakes have a high chloride and sodium content compared to other ions, e.g. Mg, Ca, specific conductance in these lakes will depend primarily on the concentrations of sodium (Na+) and chloride (Cl^-) ions.

Measured specific conductance (*SCm*), in units of micro Siemens per centimeter adjusted to 25°C, was calculated from measured field conductivity and temperature using equation (7.1).

$$SCm\ (\mu\text{S/cm @ }25^{o}\text{C}) = \frac{\text{Field Conductivity}}{1 + \text{TC}(\text{T} - 25)} \tag{7.1}$$

where TC is the temperature coefficient, T is the measured temperature in degrees Celsius (ºC), and Field Conductivity is the measured field conductivity in micro Siemens per centimeter (µS/cm). A temperature coefficient TC = 0.0191 was used to calculate SCm (YSI, Inc.1998).

The YSI Model 63 probe was calibrated for specific conductance twice by Murphy (Murphy and Stefan, 2006) during field data collection from February 18, 2004 through April 13, 2005, and was not recalibrated before collecting this data. Murphy's second calibration resulted in equation (7.2), which he applied to the data collected during the second half of his study (Murphy and Stefan, 2006).

$$\text{SC}\ (\mu\text{S/cm @ }25^{o}\text{C}) = 0.96(SCm) + 17.5 \tag{7.2}$$

Equation (7.2) was also applied to the data collected here.

The relationship between specific conductance (µS/cm @25°C) and chloride concentration (mg/L) for TCMA lakes developed by Novotny et al. (2007) is represented by equation 7.3.

$$\text{Chloride Conc. (mg/L)} = 0.2467 \times \text{Spec. Cond. } (\mu\text{S/cm@}25^{o}\text{C}) - 37.95 \tag{7.3}$$

Equation 7.3 was used here to calculate chloride concentrations in stormwater ponds.

7.2. Stormwater Ponds in which Salinity was measured

Seven stormwater ponds, listed in Table 7.2.1, were sampled for field conductivity and temperature. From those data, specific conductance (SC) (µS/cm@25°C) was calculated using equations 7.1 and 7.2. Each pond was sampled on one day during July or August of 2005. From one to six samples were taken across the pond on that day and averages were calculated.

Table 7.2.1 Summary of specific conductance and temperature measurements in seven stormwater detention ponds and corresponding chloride concentrations.

Pond	**Date of meas.**	**No. of profiles taken**	**Max. depth (m)**	**Avg. temp. (°C)**	**Est. Shading (%)**	**Specific Conductance (uS/cm@25oC) low**	**Specific Conductance (uS/cm@25oC) high**	**Specific Conductance (uS/cm@25oC) average**
Canterbury Oaks	7-6-05	1	6.5	20	15	124	492	303
Wedgewood	7-12-05	4	3.5	27	3	232	287	246
City Centre	7-14-05	5	4.2	29	5	188	166	134
Smith	8-10-05	5	18	19	2	127	1649	756
State Farm	8-19-05	5	8.5	22	1	195	346	231
Tamarack Village	8-24-05	5	9.5	22	2	273	441	300
Wood Duck Drive	8-24-05	5	7.5	20	2	172	249	190
Average		**4**	**8.2**	**22.7**	**4.2**	**187**	**519**	**353**
Chloride (mg/L)						**8**	**90**	**49**

The measurements listed in Table 7.2.1 show that the average low and average high SC (uS/cm@25^{o}C) were 187 and 519 respectively, with an overall average of 353. Converting these average SC readings to chloride concentration (mg/L) using equation 7.3 gives a low of 8 mg/L and a high of 90 mg/L, with an overall average of 49 m/L. The MN water quality standard for chronic chloride toxicity is 230 mg/L.

For comparison of these stormwater pond results with other water bodies, Table 7.2.1 lists the results from the Novotny et al.(2007) lake study and results of other studies. The average chloride concentration in the stormwater ponds tested (49 mg/L) is lower than the average in TCMA lakes studied (141 mg/L), but it is higher than pristine Wisconsin lake water (0.3 mg/L), the Minnesota and Mississippi River water (17.2 and 34 mg/L), Sea water has on the order of 19,400 mg/L of chloride,

Stormwater ponds have typically smaller volumes and shorter water residence times than lakes. They experience potentially more frequent flushing than lakes. Dissolved road salt enters stormwater ponds in late winter and early spring. Late summer measurements in ponds would therefore be expected to show a lower salinity than lakes.

Plots of temperature and specific conductance versus depth for the seven stormwater ponds sampled are given in Figures 7.2.1 to 7.2.7.

Table 7.4.1 Comparison of chloride concentrations (mg/L) in stormwater ponds to lakes and other waters (Novotny et al. 2007).

	Chloride concentration (mg/L) Low	Chloride concentration (mg/L) High	Chloride concentration (mg/L) Average
7 Stormwater ponds	8	90	49
14 TCMA lakes	80	615	141
Continental rain	---	---	0.2 - 2
Pristine Wisconsin lake	---	---	0.3
Minnesota type III lakes	---	---	4.3
North American Rivers	---	---	8
Mississippi River	---	---	17.2
Minnesota River	---	---	34.0
Sea water	---	---	19,400

7.2.1 Canterbury Oaks Pond – Bloomington

This pond is very shaded and covered with algae and duckweed. It is obviously a natural pond. There is a salinity stratification.

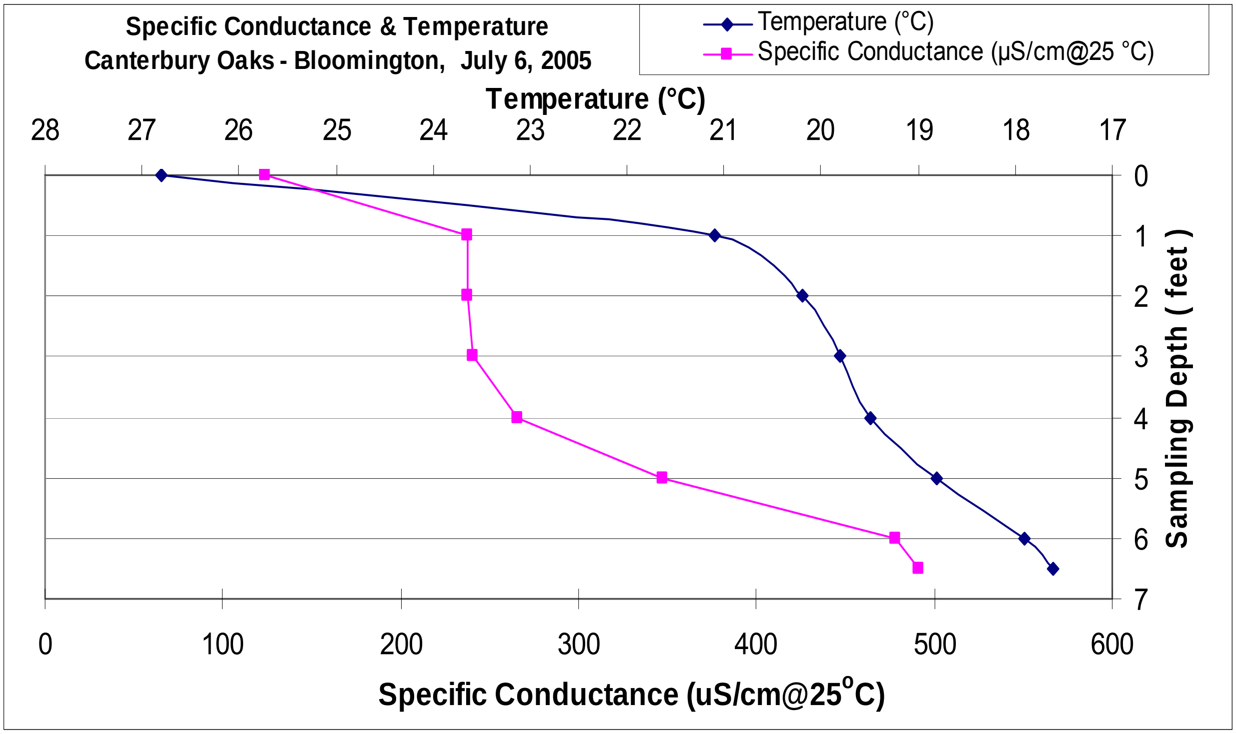


Figure 7.2.1 Canterbury Oaks Pond - Bloomington. Data collected on July 6, 2005. Field notes: 2:30 pm, very light winds, 50% cloud cover.

7.2.2 Wedgewood – Woodbury

This pond has some shading by trees but was included for salinity sampling because of its' relatively shallow depth of only 4 ft.

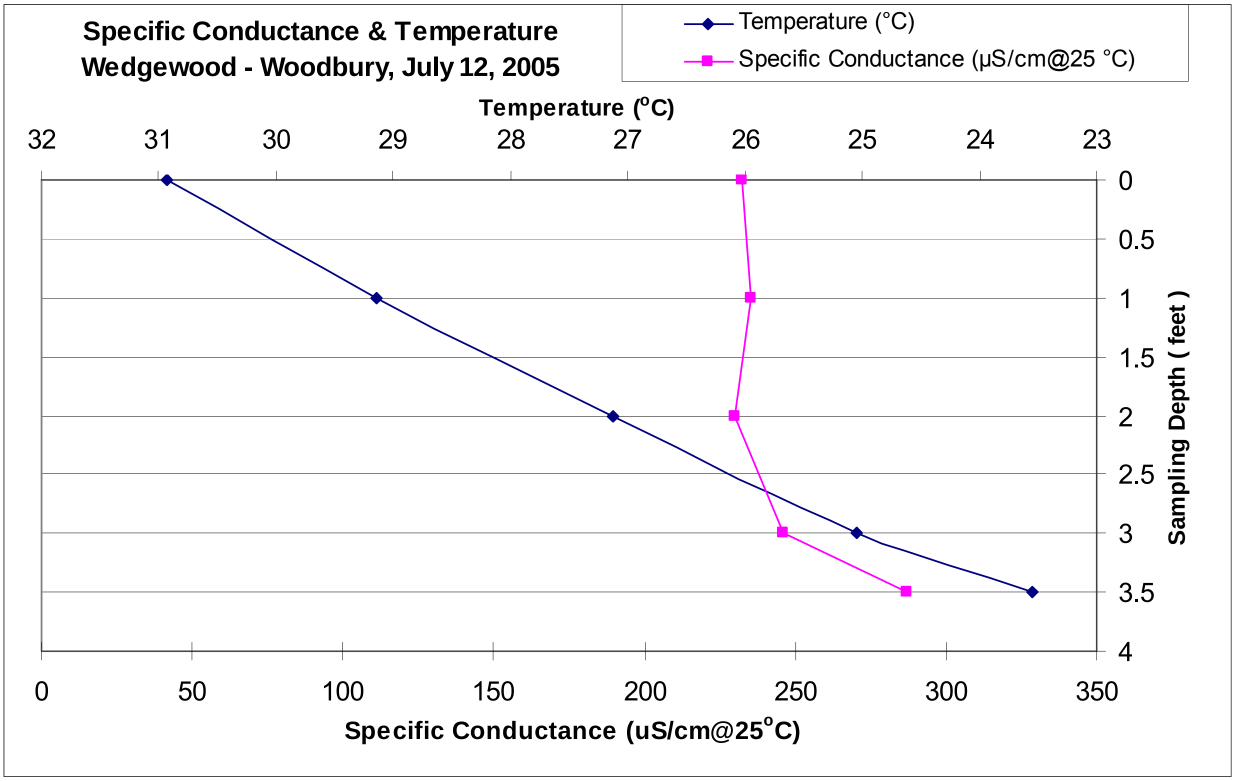


Figure 7.2.2 Wedgewood Pond - Woodbury. Data collected on July 12, 2005. Field notes: 1:20 pm, mostly sunny, winds est. 0 -5 mph, air temperature 80°F.

7.2.3 City Centre - Woodbury

This pond has trees surrounding it, especially on the south side. They are, however, far enough away so that they cannot provide shading from the mid-day sun. Coontail, a submerged vegetation, was present. The runoff entering this pond comes from a residential area. This pond had the lowest level of salinity among the ponds sampled.

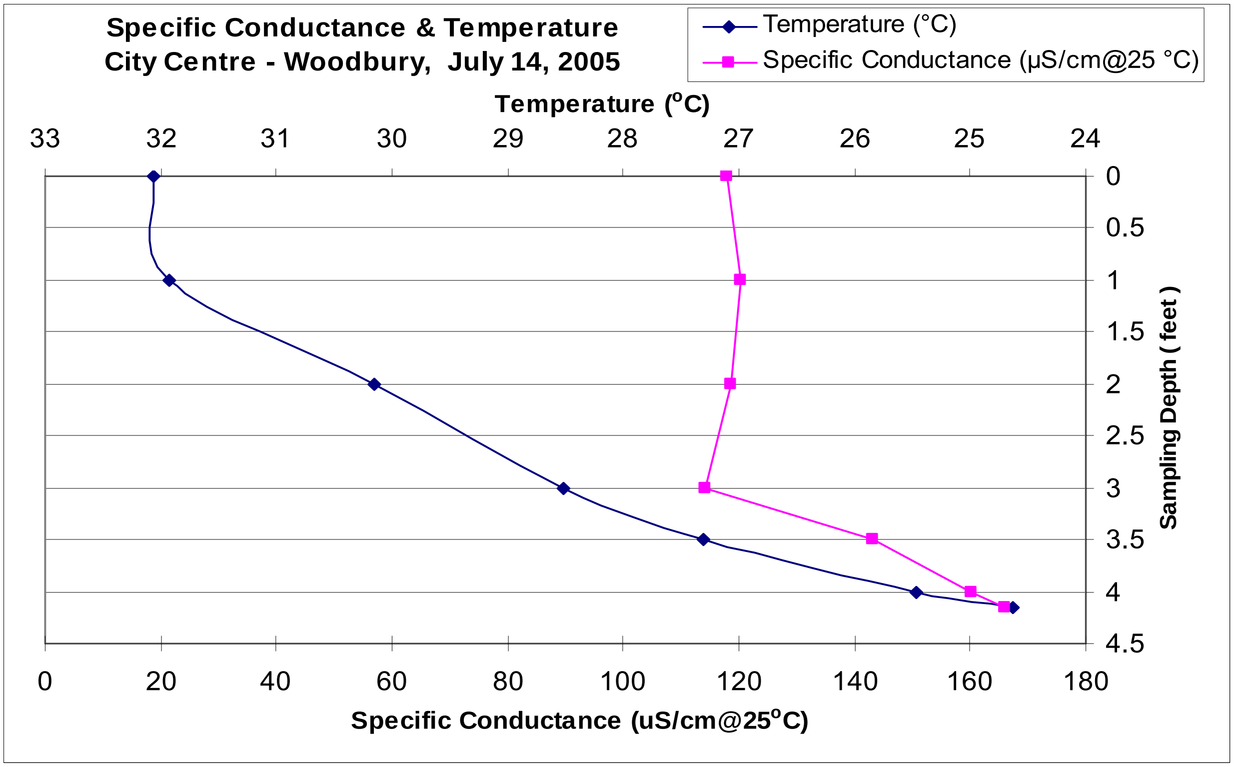


Figure 7.2.3 City Centre Pond - Woodbury. Data collected on July 14, 2005. Field notes: 2:10 pm, winds est. 5 -10 mph, mostly sunny, air temp 90°F, Coontail present at 2' depth and deeper.

7.2.4 Smith Pond – Bloomington

This pond is the deepest and largest (8.2 acres) of those sampled. It had the highest salinity concentrations, and its' salinity profile is similar to those found in lakes by Murphy and Stefan (2006).

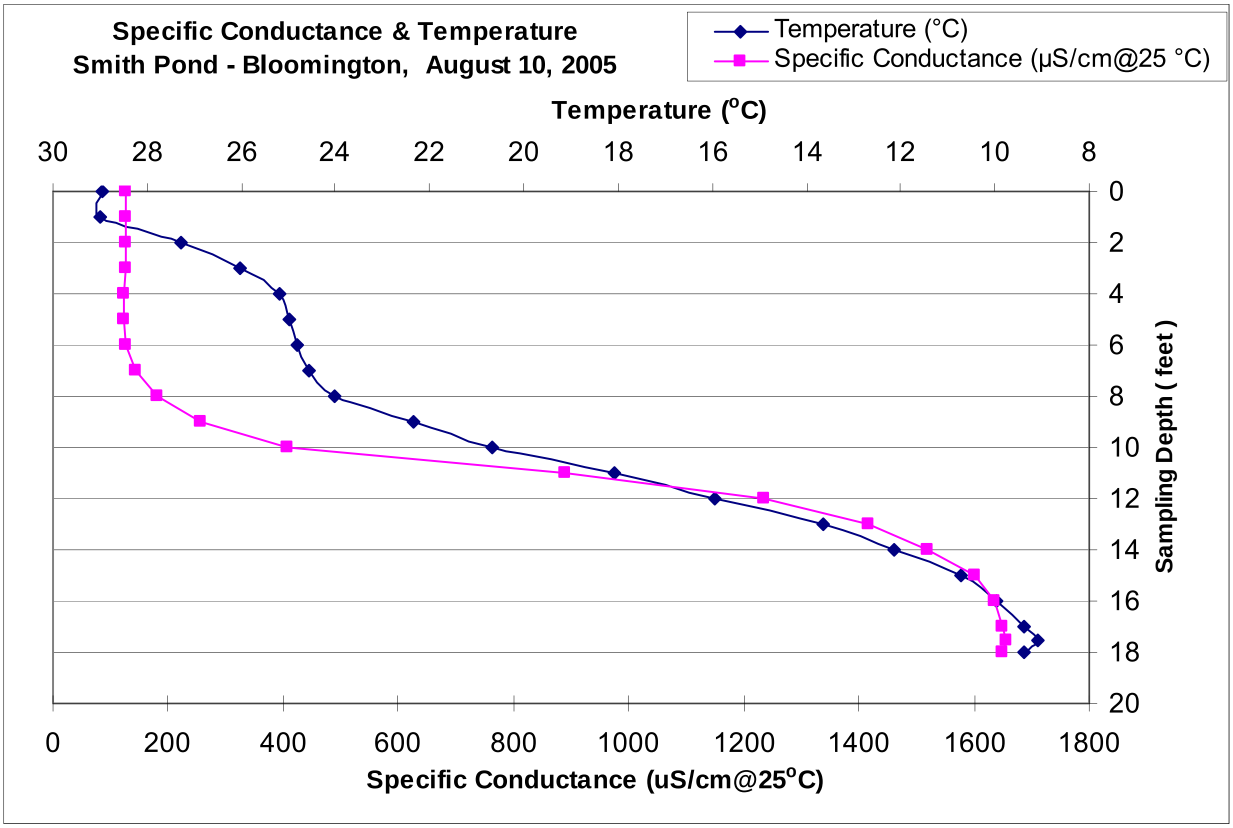


Figure 7.2.4 Smith Pond - Bloomington. Data collected on August 10, 2005. Field notes: 3:35 pm, light winds est. 0 -5 mph, partly cloudy, air temp 80°F. Smith Pond is more of a lake than a stormwater pond.

7.2.5 State Farm Pond – Woodbury

Salinity data was collected here to go along with the other data already being collected and to be used somewhat as a 'base pond' for comparison purposes. It showed a low level of overall salinity and a saline layer near the bottom.

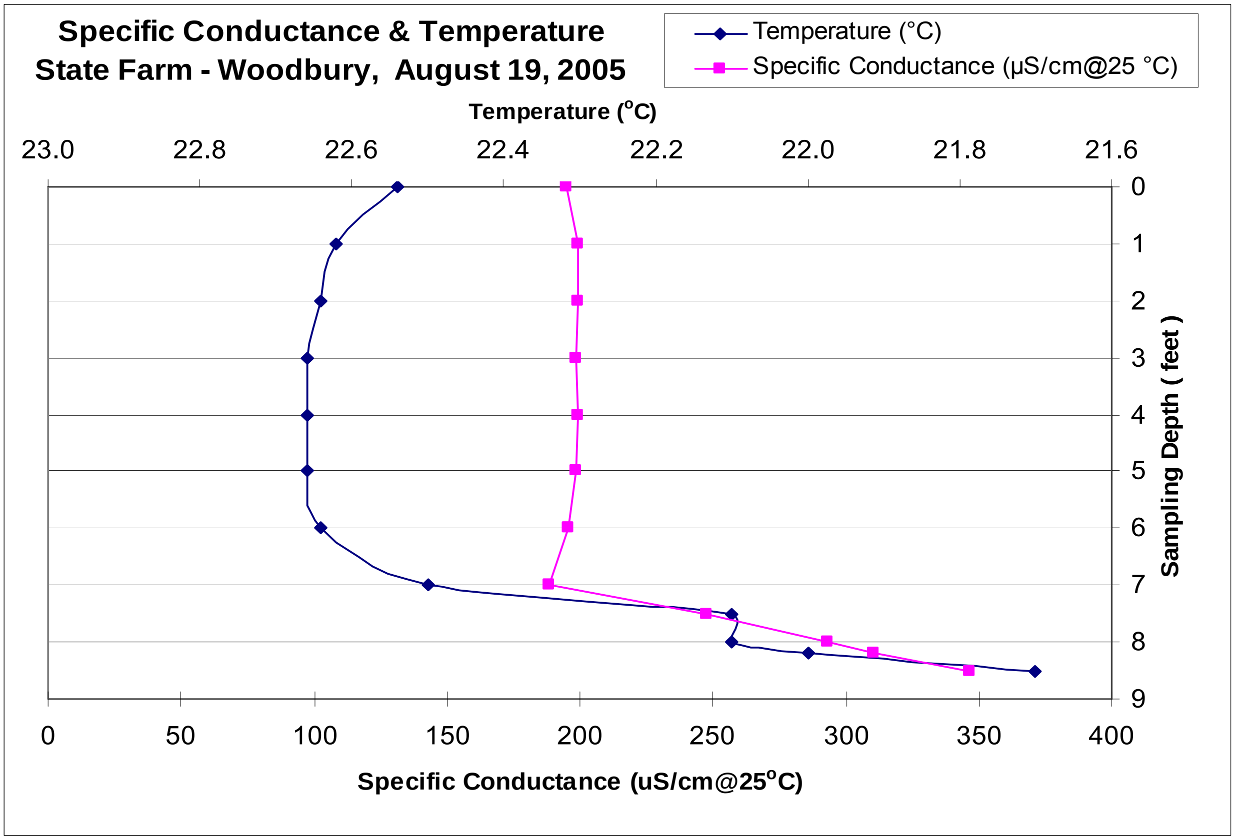


Figure 7.2.5 State Farm Pond –Woodbury. Data collected on August 19, 2005.
Field notes: 8:00 am

7.2.6 Tamarack Village – Woodbury

This pond is located directly behind a major shopping center with expansive asphalt parking areas. The data show salinity starting around 300 uS/cm in the upper water column. This is the highest upper level salinity concentration of all the ponds sampled.

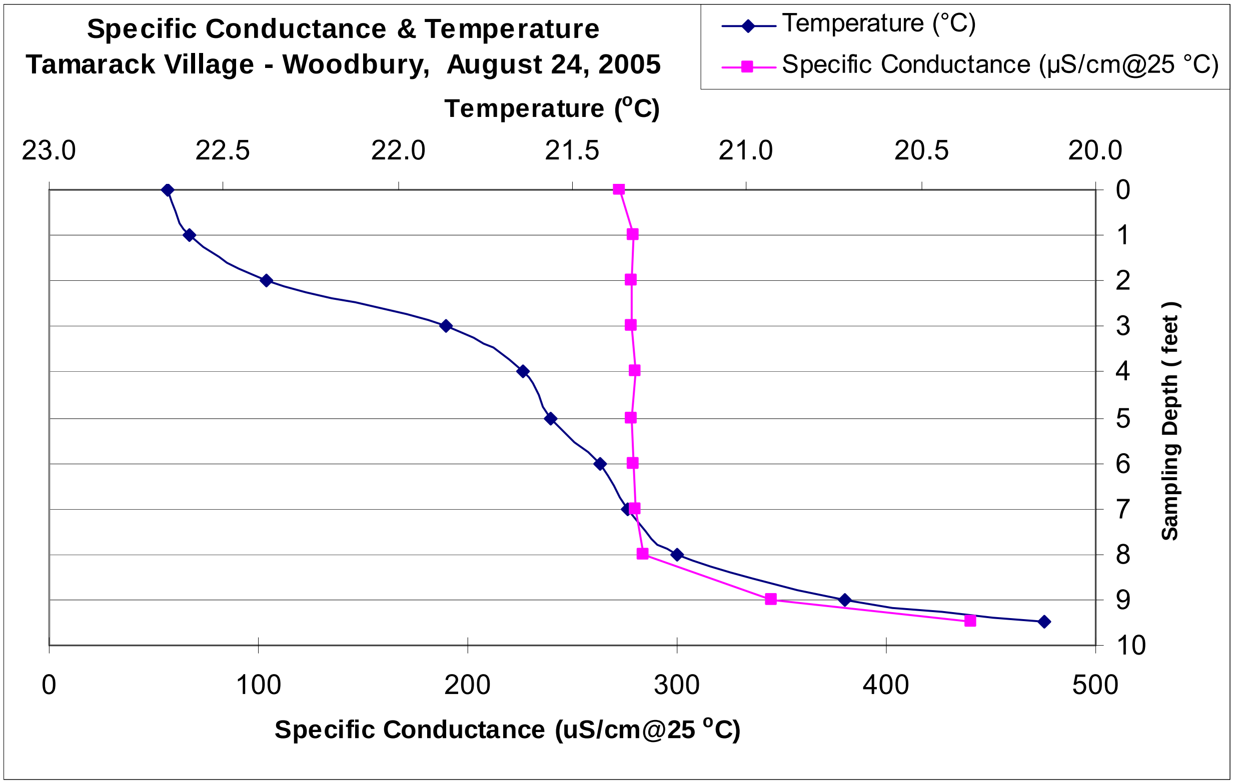


Figure 7.2.6 Tamarack Village Pond - Woodbury Data collected on August 24, 2005. Field notes: 2:30 pm, wind est. 5-10 mph, partly sunny but cloudy earlier, air temp 75°F. This large pond, estimated to be 2 acres in surface area, appears to drain into a natural wetland. Located behind the Tamarack Village Shopping Mall.

7.2.7 Wood Duck Drive - Woodbury

This pond is relatively small with a surface area, estimated to be 1/4 acre. Like Wedgewood Pond, it too collects only residential runoff. Salinity was evident, but the concentration was low.

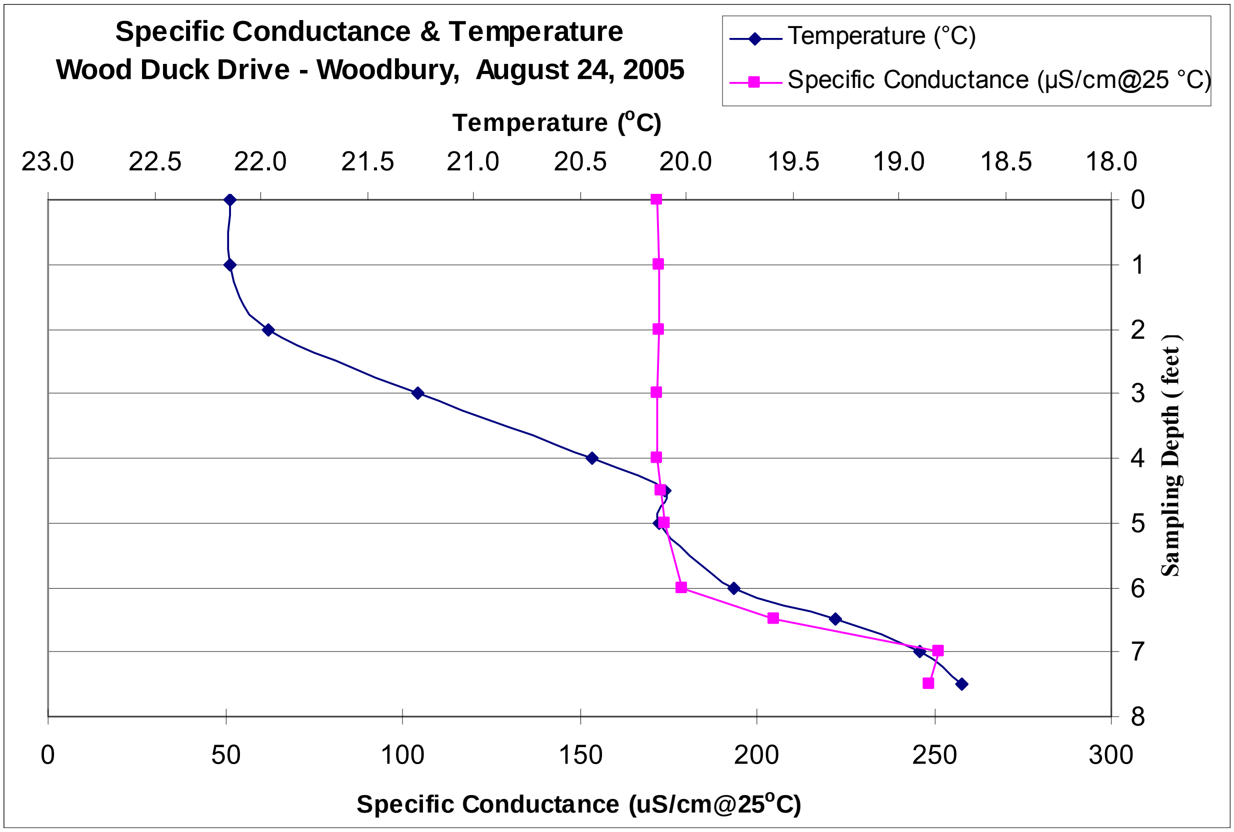


Figure 7.2.7 Wood Duck Drive Pond - Woodbury Data collected August 24, 2005.
Field notes: 3:40 pm, wind est.10 -15 mph, partly cloudy, air temp 80°F.
Pond size approximately 1/3 acre, bordered by houses and a road.
Located at the corner of Wood Duck Drive and Wood Duck Lane.

7.3. Comparison of Salinity Profiles in Ponds

Plotting the salinity profiles from all seven ponds on one graph shows a consistent pattern (Figure 7.3.1). The lowest SC (µS/cm@25°C) values were usually measured near the surface of the ponds. Specific conductance varied between 100 and 300 µS/cm@25°C near the surface of the ponds. At depths of 3 to 8 feet, chemoclines begin in the ponds. The highest specific conductance values, mostly between 300 and 500 µS/cm@25°C, were measured near the bottom of the ponds, indicating a higher salt content in the bottom waters. This is what would be expected in stormwater detention ponds which collect snowmelt water from roads on which road salt is applied. Because snowmelt water containing road salt is denser than fresh water, it sinks to the lowest levels in both lakes and ponds. Only one, Smith Pond, is deeper than 10 feet, and its specific conductance profile fits well with those of deeper small lakes. The saline layer in Smith Pond, between 10 and 18 ft depth, reaches specific conductance values of over 1,600 µS/cm@25°C.

It is interesting to note that the lover specific conductance values occurred in stormwater ponds that collected purely residential runoff, such as City Centre pond and Wood Duck Drive. The deepest, Smith Pond, also had very low specific conductance values in the upper water column. The highest upper water column salinity readings occurred in Tamarack Village pond, next to a shopping center, and also in the shallowest and most shaded site, Canterbury Oaks.

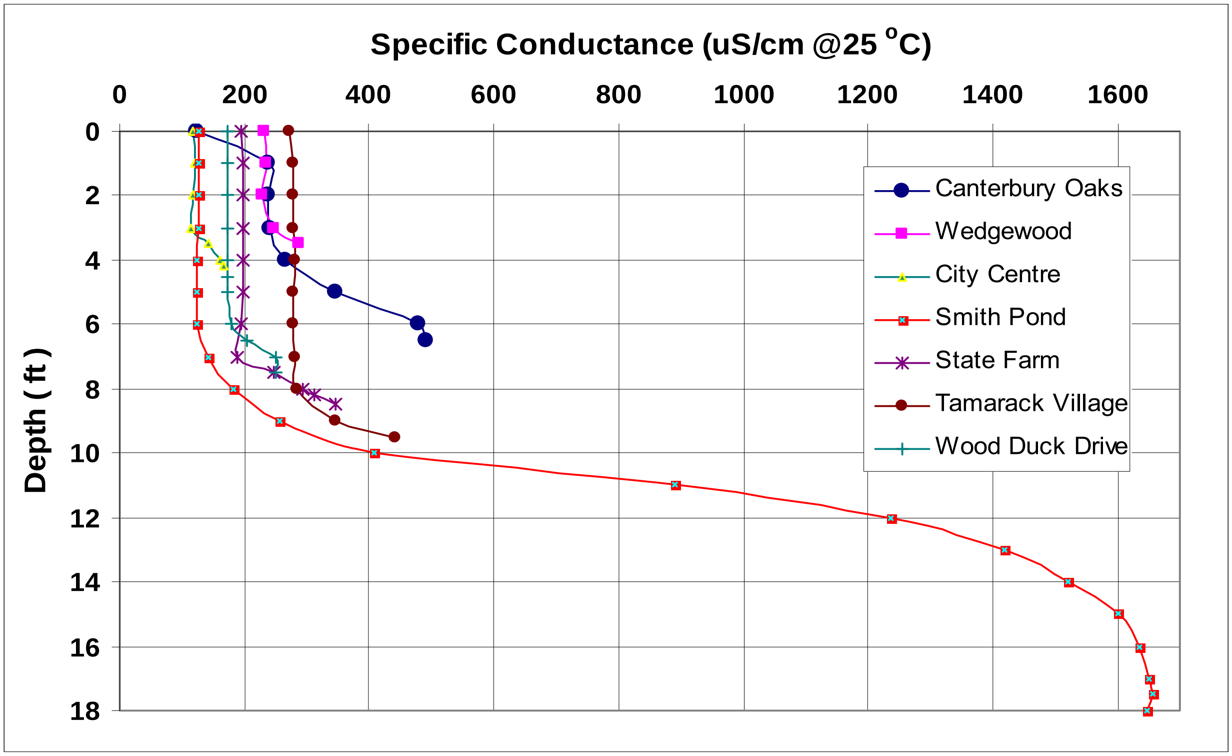


Figure 7.3.1 Salinity profile comparison of seven stormwater ponds.

A visual comparison of Figure 7.3.1 with salinity profiles from Twin Cities lakes (Murphy and Stefan 2006) shows strong similarities. Examples of lake salinity profiles are given in Figures 7.3.2. and 7.3.3. The TCMA lakes sampled have specific conductance levels between 500 and 700 uS/cm in the near-surface waters. Since the ponds have typically a shorter hydraulic residence time than lakes, the salinity in stormwater ponds can be expected to be lower in the summer than in lakes because of more frequent flushing, but a salinity increase from the water surface to the pond bottom, is similar to the salinity profiles in the lakes.

Because ponds have typically smaller surfaces areas and more wind sheltering, they may experience less wind mixing than lakes. In ponds, therefore, chemoclines can occur at shallower depths (Figure 7.3.1) than in lakes (Figure 7.3.3).

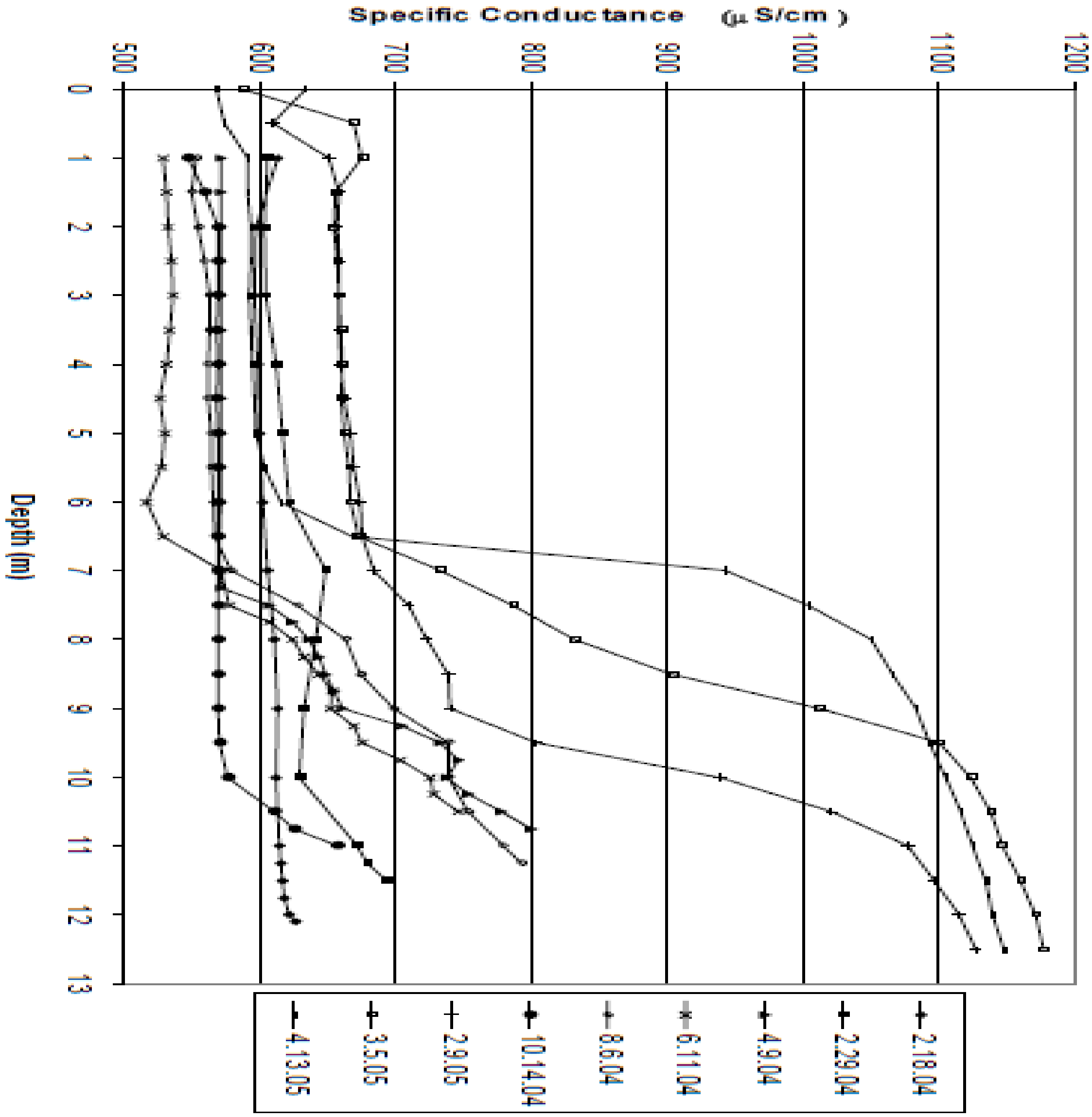


Figure 7.3.2 Specific conductance profiles in Medicine Lake , SW Bay, 2004-2005. (Murphy and Stefan 2006). (Note: plot is rotated for easier comparison.)

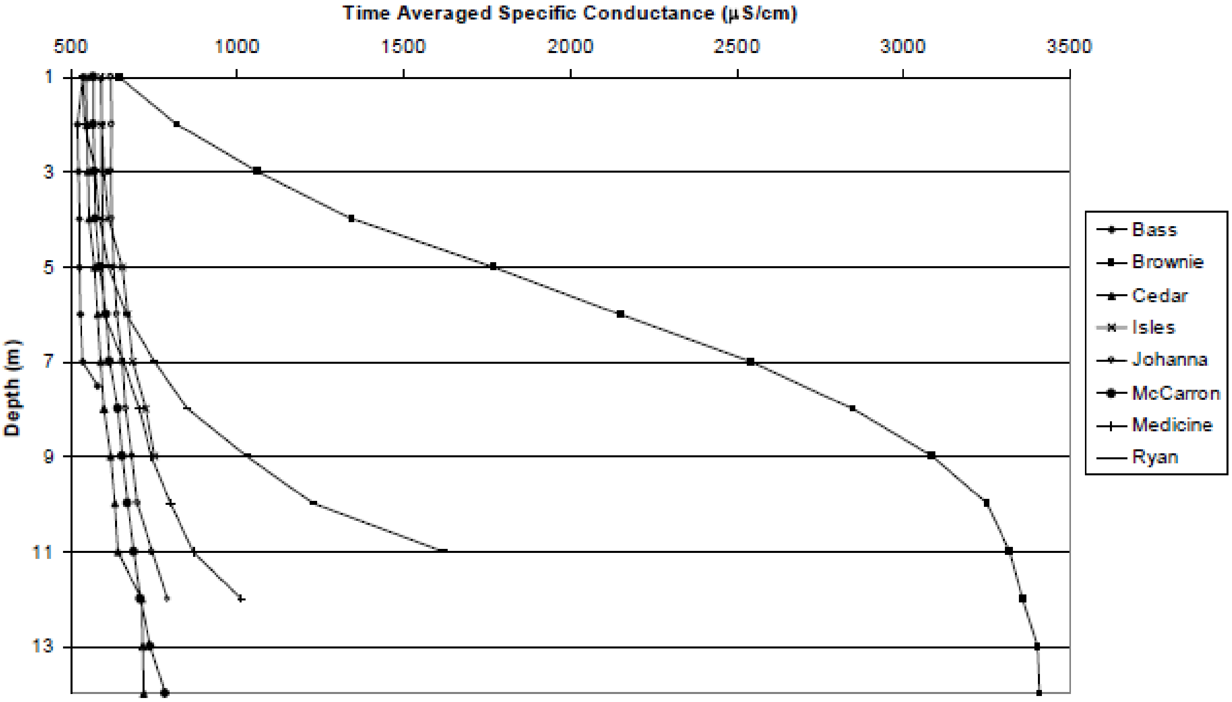


Figure 7.3.3 Average specific conductance profiles in eight TCMA lakes from Feb 15, 2004 to April 18, 2005. (Murphy and Stefan 2006).

7.4 Comparison of Surface Temperatures in Ponds

Surface water temperatures in shallow freshwater ponds are expected to by quite similar because of their strong dependence on heating and cooling through the water surface, and the low thermal inertia of the shallow water (as opposed to deep lakes). Instantaneous water temperatures measured in seven stormwater ponds are plotted on the continuous surface temperature record from the State Farm Pond in Figure 7.4.1. The individual data points were collected mostly during the mid-day period with the sun overhead. The single temperature points seem to fall on the continuous State Farm record, with no obvious effects from shading. The State Farm pond is estimated to be 1$^{\%}$ shaded, mostly by tall weeds and cat tails, whereas Canterbury Oaks pond was judged to be 15$^{\%}$ shaded from dawn to dusk by trees. and tall weeds. Table 7.4.2 summarizes the shading characteristics of the ponds.

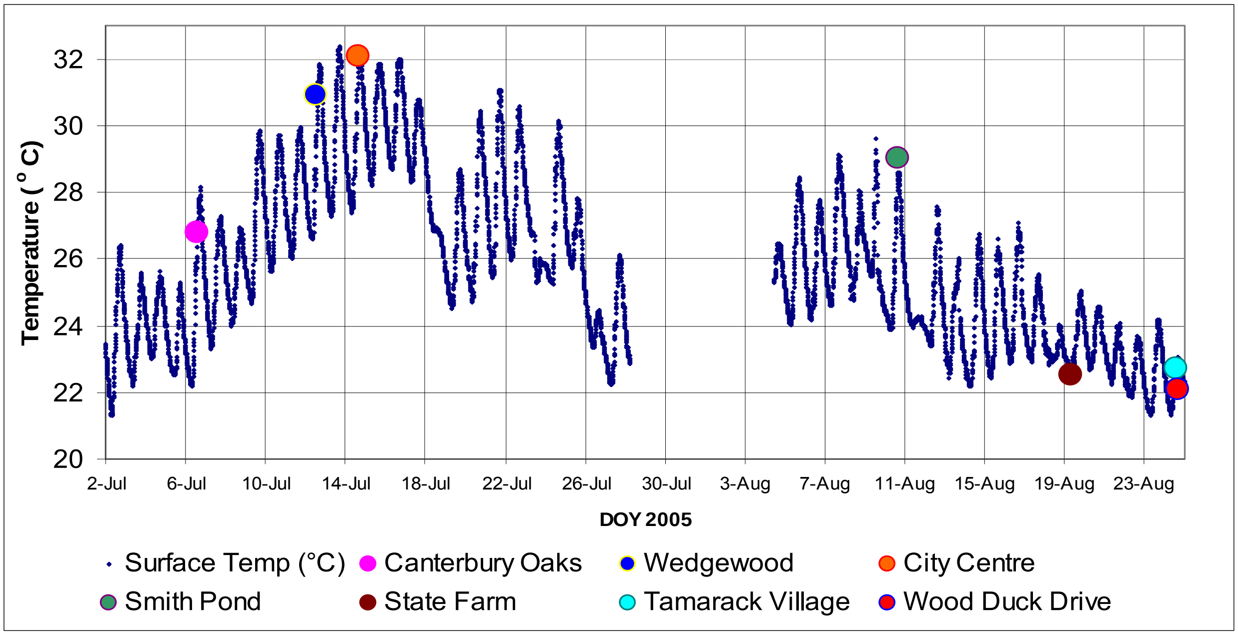


Figure 7.4.1 Comparison of samples of instantaneous daytime surface temperature measurements in six stormwater ponds (symbols) with the continuous surface temperature record from the State Farm Pond.

Table 7.4.2 Shading characteristics of stormwater ponds.

Pond Name	Estimated percent (%) of surface area shaded	Shading by
Canterbury Oaks	15	Trees and tall weeds
City Centre	5	Trees
Wood Duck Drive	2	Buildings and tall weeds
Wedgewood	3	Trees
Tamarack Village	2	Buildings and surrounding hilly topography
Smith	2	Trees and tall weeds
State Farm	1	Tall weeds and cattails

8. SUMMARY

Eighteen stormwater detention ponds in two major suburbs (Bloomington and Woodbury) of the Twin Cities Metropolitan Area (TCMA) were surveyed to find a site for the collection of field mostly pond water temperatures, runoff temperatures and weather. The data were needed for the formulation and validation of a hydrothermal stormwater pond model. The objective of the model is to simulate outflow rates, outflow water temperatures, and “heat export” from a stormwater pond. A site was found at the former State Farm Insurance Company headquarters in Woodbury. Instrumentation was installed and weather and hydrologic data were recorded in the summer of 2005. The data were used to formulate the hydrothermal stormwater pond model described in SAFL Report 479 (2006).
In addition, salinity profiles were measured in seven stormwater ponds to support a road salt study.

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This project was conducted with partial support from the Minnesota Pollution Control Agency, St. Paul, Minnesota. Bruce Wilson was the project officer. We thank the MPCA and Mr. Wilson for their support.

We also thank the following individuals for advice in selecting stormwater ponds:
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2) Steve Kernick, Environmental Planner for the City of Woodbury, provided guidance as well as specific information on pond areas, depths, inlets and outlets.
3) Sharon Doucette, Environmental Resources Coordinator for the City of Woodbury, provided GIS data for Woodbury.
4) Dr. Chris Ellis, University of Minnesota, Senior Research Associate, St Anthony Falls Laboratory, provided assistance with the data collection equipment set-up and programming.

We also thank State Farm Insurance Agency for allowing us to conduct a study of a pond on their premises.

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Appendix A.

Excerpts from SAFL Project Report No. 479.

Hydrothermal Simulation of a Stormwater Detention Pond or Infiltration Basin

by William R. Herb, Michael Weiss, Omid Mohseni and Heinz G. Stefan
September 2006, Minneapolis, Minnesota

Abstract

A numerical simulation model has been developed to simulate the hydraulic and heat transfer properties of a stormwater detention pond. The model is dynamic (unsteady) and based on basic principles of hydraulics and heat transfer. It is driven by hourly climate and weather data. To calibrate and validate the pond model field data were collected on a commercial site (State Farm Insurance Company) in Woodbury, Minnesota. The relationship between pond inflow and outflow rates to precipitation was effectively calibrated using continuously recorded pond level. Algorithms developed for surface heat transfer in lakes were found to be applicable to the pond with some modification. A significant diurnal thermal stratification was simulated and measured in the pond which had 2.4m depth. Temperature differences from top to bottom were as high as 13°C during daytime hours. The out-flowing water temperature was essentially equal to the pond surface temperature because the outlet was located near the pond surface. Outflow water temperatures were calculated with a RMSE of 1.4°C. Water clarity had little effect on the pond outflow temperatures but the pond bottom temperature was found to be highly sensitive to water clarity. For pond designs with outlet structures that take subsurface water, water clarity will introduce uncertainty to simulations of the pond temperature profile and the pond outlet temperature.

MODEL CALIBRATION AND VALIDATION

To calibrate and validate the pond model and its components, field data were collected, and the model was applied for the wet stormwater detention pond located at the State Farm office complex in Woodbury, Minnesota (Figures 5.1 and 5.2). The pond is un-shaded and has an outlet structure that withdraws surface water. A single inlet pipe drains the asphalt parking areas of the facility. Simulations were made for the period April 1 to September 30, 2005. Measured pond water temperatures and pond levels were available for verification for the period June 3 to August 25, with a gap from July 28 to August 4. Wind speed and direction and precipitation were also recorded at the station installed in the pond (Figure 5.2).

Figure 5.1. Aerial photograph of the State Farm office facility in Woodbury, MN. The stormwater detention pond is the dark elongated water body north of the building complex near the center of the photograph. I-94 and Radio Drive are north and west of the facility, respectively.

Figure 5.2 Ground level photograph of the State Farm stormwater detention pond, viewed from west to east, and close-up of the measurement station installed in the pond.

Appendix B.

Excerpts from SAFL Project Report No. 485.

Seasonal Salinity Cycles in Eight Lakes of the Minneapolis/St. Paul Metropolitan Area

by Dan Murphy and Heinz G. Stefan, October 2006, Minneapolis, Minnesota

Abstract

Substantial amounts of road salt are spread annually on highways, streets, sidewalks, and parking lots in the northern regions of the U.S. Road salt application is considered an economic necessity to keep roads free of ice for safe winter travel in northern climate zones. Commonly used road salts to deice roads are sodium chloride (NaCl) and calcium chloride (CaCl2). Because of a large difference in cost, NaCl is applied in much larger quantities. Snowmelt runoff containing dissolved road salt feeds many Twin Cities Metro Area lakes, but chloride levels in these lakes have not been studied explicitly. Little is known about the fate of NaCl entering these lakes.

Eight urban lakes in the Minneapolis/St.Paul metropolitan area were therefore studied for 14 months during two winters and the summer in between. Specific conductance profiles were measured at roughly bimonthly intervals in each of the eight lakes. Variations in specific conductance with season and with depth were found in each of the lakes. Specific conductance values varied from 400 to 1800 µS/cm in seven of the lakes and reached a maximum of 3500 µS/cm in the eighth lake which was meromictic. The largest specific conductance values were in late winter and at the bottom of the lakes, and the lowest in late summer near the surface of the lakes.

Chloride concentration was linearly related to specific conductance. Chloride concentration profiles were calculated from specific conductance, and integrated with depth to give the total chloride and the total NaCl content. There was clearly a seasonal pattern in all eight lakes, i.e. an accumulation of NaCl during the winter months and a decrease in total salt content during the summer. Chloride concentrations near the lake bottom in Brownie Lake and Ryan Lake exceeded the chronic MPCA chloride standard of 230 mg/L during the entire 14 months of the field study. Chloride concentrations exceeded the chronic standard near the lake bottom in McCarrons Lake during late spring in 2004 and Medicine Lake during late spring in 2005.

Density profiles were calculated from the temperature and conductance measurements. Density increases due to salinity were typically less than 0.0001kg/m3 and made only a weak contribution to the density stratification. The largest density increase due to salinity was calculated for the bottom of Brownie Lake (Δρ=0.00135kg/m3). The effect of vertical density gradients on the vertical dispersion coefficient was calculated with and without the effect of salinity. In all lakes the vertical diffusivity changed by less than a factor of 1.8. The vertical mixing coefficients are more strongly affected by temperature than by salinity.

The overall conclusion is that lakes are in the hydrologic pathway of roadway deicing salt. They act as a sink and provide temporary storage of dissolved salt in the winter months when road salt is applied, and they act as a source of salinity in the summer months. One of the eight lakes studied is a meromictic lake, i.e. it has a permanent salt water layer. It is still unknown under what conditions other lakes would act likewise.

Appendix C.

Specific conductivity and temperature data collected in stormwater ponds in Bloomington and Woodbury, Minnesota, in July and August 2005.

The actual data for temperature and field specific conductivity are presented here; calculated corresponding specific conductance (ΦS/cm@25 EC) and applied calibration corrections are also given. An asterisk indicates that no data was collected.

C.1 Canterbury Oaks Pond

Data collection date: July 6, 2005
Field notes: 2:30 pm, very light winds, 50% clouds.

Table C.1 Canterbury Oaks Pond salinity data.

	Specific conductance (µS/cm@25°C)calculated							**Temperature (°C)**							**Field conductivity (µS/cm)**					
Depth(ft)		sample							sample							sample				
	AVG	I	II	III	IV	V		**AVG**	I	II	III	IV	V		**AVG**	I	II	III	IV	V
0	*	124	*	*	*	*		*	26.8	*	*	*	*		*	115	*	*	*	*

1	*	237	*	*	*	*		*	21.1	*	*	*	*		*	212	*	*	*	*
2	*	237	*	*	*	*		*	20.2	*	*	*	*		*	208	*	*	*	*
3	*	240	*	*	*	*		*	19.8	*	*	*	*		*	209	*	*	*	*
4	*	265	*	*	*	*		*	19.5	*	*	*	*		*	231	*	*	*	*
5	*	347	*	*	*	*		*	18.8	*	*	*	*		*	303	*	*	*	*
6	*	478	*	*	*	*		*	17.9	*	*	*	*		*	415	*	*	*	*
6.5	*	492	*	*	*	*		*	17.6	*	*	*	*		*	424	*	*	*	*

C.2 Wedgewood Pond

Data collection date: July 12, 2005

Field notes: 1:20 pm, mostly sunny, winds est. 0-5 mph, air temp 80EF

Table C.2 Wedgewood Pond salinity data.

	Specific conductance (µS/cm@25°C)calculated							**Temperature (°C)**							**Field conductivity (µS/cm)**					
Depth(ft)		sample							sample							sample				
	AVG	I	II	III	IV	V		**AVG**	I	II	III	IV	V		**AVG**	I	II	III	IV	V
0	**232**	230	234	233	233	*		**30.9**	31.2	30.9	30.9	30.7	*		**249**	247	251	250	249	*
1	**235**	233	235	238	236	*		**29.2**	28.9	29.2	29.3	29.2	*		**245**	241	245	248	246	*
2	**230**	227	231	231	229	*		**27.1**	27.0	27.2	27.3	27.0	*		**230**	227	232	232	229	*
3	**246**	236	251	250	247	*		**25.1**	25.7	25.4	24.6	24.5	*		**238**	231	245	240	237	*
3.5	**287**	308	269	290	283	*		**23.6**	23.2	25.1	22.9	23.0	*		**273**	292	262	272	266	*

C.3 City Centre Pond

Data collection date: July 14, 2005

Field notes: 2:10 pm, winds est. 5 -10 mph, mostly sunny, air temp 90^{o}F, milfoil present at 2' depth and deeper.

Table C.3 City Centre Pond salinity data.

	Specific conductance (µS/cm@25°C) calculated							**Temperature (°C)**							**Field conductivity (µS/cm)**					
Depth(ft)		sample							sample							sample				
	AVG	I	II	III	IV	V		**AVG**	I	II	III	IV	V		**AVG**	I	II	III	IV	V
0	**118**	120	118	120	113	118		**32.1**	31.6	32.1	32.1	32.3	32.5		**119**	120	119	121	113	120
1	**120**	119	118	119	127	118		**32.0**	31.8	32.0	32.0	31.9	32.4		**121**	119	119	120	129	120
2	**118**	11	12	12	11	11		**30.2**	30.	30.	30.	30.	30.		**116**	11	11	11	11	11

		9	0	1	7	6			1	2	2	2	3			6	7	8	4	3
3	**115**	120	115	117	112	109		**28.3**	28.9	28.1	28.1	28.2	28.0		**108**	115	108	110	104	101
3.5	**143**	*	*	*	116	170		**27.3**	*	*	*	27.5	27.1		**137**	*	*	*	108	165
4	**160**	155	162	164	*	*		**25.5**	25.3	25.6	25.6	*	*		**150**	144	152	154	*	*
4.16	**166**	163	156	179	*	*		**24.6**	25.0	24.4	24.4	*	*		**154**	152	143	166	*	*

C.4 Smith Pond

Data collection date: August 10, 2005

Field notes: 3:35 pm, light winds est. 0 -5 mph, partly cloudy, air temp 80^{o}F

Smith Pond, with approx. 4 acres surface area, is seemingly more of a lake than a typical stormwater pond.

Table C.4 Smith Pond salinity data.

	Specific conductance (µS/cm@25°C) calculated							**Temperature (°C)**							**Field conductivity (µS/cm)**					
Depth(ft)		**sample**							**sample**							**sample**				
	AVG	I	II	III	IV	V		**AVG**	I	II	III	IV	V		**AVG**	I	II	III	IV	V
0	**127**	126	126	126	128	128		**29.0**	29.1	29.0	28.8	28.8	29.1		**122**	122	122	121	123	124
1	**127**	125	126	127	128	129		**29.0**	29.0	29.0	28.9	29.0	29.1		**123**	121	122	122	124	125
2	**126**	122	124	125	134	127		**27.3**	27.3	27.1	27.6	26.8	27.6		**118**	114	115	117	126	120
3	**127**	122	125	123	136	127		**26.0**	25.8	25.8	26.1	26.4	26.0		**116**	111	114	112	127	116
4	**125**	129	124	122	*	125		**25.2**	25.3	25.1	25.1	*	25.2		**112**	117	111	109	*	112
5	**124**	*	124	125	*	124		**25.0**	*	25.0	24.9	*	25.1		**111**	*	111	112	*	111
6	**125**	*	124	128	*	122		**24.8**	*	24.8	24.8	*	24.9		**112**	*	111	115	*	109
7	**143**	*	148	135	*	146		**24.6**	*	24.5	24.7	*	24.5		**130**	*	135	122	*	133
8	**181**	*	189	172	*	182		**24.0**	*	23.9	24.2	*	24.0		**167**	*	175	158	*	168
9	**257**	*	255	251	*	266		**22.4**	*	22.4	22.6	*	22.1		**237**	*	235	232	*	245
10	**407**	*	388	453	*	380		**20.7**	*	20.7	20.5	*	20.8		**372**	*	354	415	*	347
11	**890**	*	940	954	*	777		**18.1**	*	18.1	17.8	*	18.3		**788**	*	834	841	*	690
12	**1235**	*	1172	1250	*	1284		**15.9**	*	16.1	15.8	*	15.9		**1049**	*	998	1058	*	1090
13	**1418**	*	1439	1397	*	*		**13.7**	*	13.3	14.0	*	*		**1143**	*	1150	1135	*	*
14	**1519**	*	1518	1521	*	*		**12.2**	*	12.1	12.2	*	*		**1181**	*	1178	1183	*	*
15	**1601**	*	1601	1601	*	*		**10.7**	*	10.8	10.6	*	*		**1199**	*	1202	1196	*	*
16	**1635**	*	1636	1634	*	*		**10.0**	*	10.0	9.9	*	*		**1201**	*	1203	1198	*	*
17	**1651**	*	1652	1650	*	*		**9.4**	*	9.4	9.4	*	*		**1195**	*	1195	1194	*	*
17.5	**1655**	*	*	1655	*	*		**9.1**	*	*	9.1	*	*		**1188**	*	*	1188	*	*
18	**1649**	*	1649	*	*	*		**9.4**	*	9.4	*	*	*		**1193**	*	1193	*	*	*

C.5 State Farm Pond

Data collection date: August 19, 2005
Field notes: 8:00 am.

Table C.5 State Farm salinity data.

	Specific conductance (µS/cm@25°C) calculated							**Temperature (°C)**							**Field conductivity (µS/cm)**					
Depth(ft)		sample							sample							sample				
	AVG	I	II	III	IV	V		**AVG**	I	II	III	IV	V		**AVG**	I	II	III	IV	V
0	**195**	195	206	202	179	193		**22.5**	22.5	22.6	22.6	22.6	22.4		**176**	176	187	183	161	174
1	**199**	196	206	202	200	193		**22.6**	22.6	22.6	22.7	22.7	22.5		**181**	177	187	184	182	174
2	**199**	195	205	202	200	193		**22.6**	22.7	22.6	22.7	*22.7*	22.5		**181**	177	186	184	*182*	174
3	**199**	195	203	202	200	193		**22.7**	22.7	22.7	22.7	22.7	22.5		**180**	177	185	184	182	174
4	**199**	195	204	202	200	193		**22.7**	22.7	22.7	22.7	22.7	22.5		**181**	177	186	184	182	174
5	**199**	196	203	202	200	192		**22.7**	22.7	*22.7*	22.7	22.7	22.5		**180**	178	*185*	184	182	173
6	**195**	196	201	200	200	179		**22.6**	22.7	22.7	22.7	22.7	22.4		**177**	178	183	182	182	160
7	**188**	192	191	197	187	175		**22.5**	22.7	22.7	22.5	22.5	22.1		**170**	174	173	178	168	155
7.5	**247**	*	*	*	315	180		**22.1**	*	*	*	22.3	21.9		**227**	*	*	*	294	159
8	**293**	245	359	277	*	*		**22.1**	22.2	21.8	22.3	*	*		**271**	224	334	256	*	*
8.2	**311**	*	*	311	*	*		**22.0**	*	*	22.0	*	*		**288**	*	*	288	*	*
8.5	**346**	346	*	*	*	*		**21.7**	21.7	*	*	*	*		**321**	321	*	*	*	*

C.6 Tamarack Village Pond

Data collection date: August 24, 2005
Field notes: 2:30 pm, wind est. 5-10 mph, partly sunny but cloudy earlier, air temp 75^{o}F.
This large pond, with an estimated 2 acres surface area, appears to drain into a natural wetland.

Table C.6 Tamarack Village Pond salinity data.

	Specific conductance (µS/cm@25°C)calculated							**Temperature (°C)**							**Field conductivity (µS/cm)**					
Depth(ft)		sample							sample							sample				
	AVG	I	II	III	IV	V		**AVG**	I	II	III	IV	V		**AVG**	I	II	III	IV	V
0	**273**	273	249	280	279	281		**22.7**	22.6	22.5	22.6	22.8	22.8		**254**	254	230	261	**261**	263
1	**279**	27	27	28	28	28		**22.6**	22.	22.	22.	22.	22.		**260**	25	26	26	26	26

		6	9	0	0	0			6	6	6	8	4			7	0	1	2	0
2	**279**	276	279	280	279	280		**22.4**	22.4	22.5	22.5	22.5	22.0		**258**	256	259	260	259	258
3	**279**	277	278	279	280	280		**21.9**	21.9	22.0	21.9	21.9	21.6		**256**	254	256	256	257	256
4	**280**	281	278	280	279	281		**21.6**	21.6	21.8	21.7	21.6	21.5		**256**	257	255	256	255	256
5	**279**	278	279	278	278	280		**21.6**	21.5	*21.6*	21.6	21.6	*21.5*		**254**	253	*255*	254	254	*255*
6	**279**	277	281	279	279	279		**21.4**	21.4	21.5	21.4	21.4	21.4		**254**	252	256	254	254	254
7	**280**	280	280	279	280	280		**21.3**	21.3	21.4	21.4	21.3	21.3		**254**	254	255	254	254	254
8	**284**	285	287	285	284	281		**21.2**	21.2	21.2	21.2	21.2	21.2		**258**	258	260	258	257	255
9	**346**	322	339	396	371	301		**20.7**	20.9	20.8	20.5	20.5	20.9		**314**	292	308	360	337	272
9.5	**441**	479	385	492	407	*		**20.2**	20.1	20.2	20.1	20.2	*		**400**	436	348	448	369	*

C.7 Wood Duck Drive Pond (located at corner of Wood Duck Drive and Wood Duck Lane)
Data collection date: August 24, 2005
Field notes: 3:40 pm, wind est. 10-15 mph, partly cloudy, air temp 80^{o}F, pond surface area is approximately 1/3 acre, bordered by newer homes and Wood Duck Drive

Table C.7 Wood Duck Drive Pond salinity data.

	Specific conductance (µS/cm@25°C) calculated							**Temperature (°C)**							**Field conductivity (µS/cm)**					
Depth(ft)		sample							sample							sample				
	AVG	I	II	III	IV	V		**AVG**	I	II	III	IV	V		**AVG**	I	II	III	IV	V
0	**172**	170	173	173	172	172		**22.1**	22.3	22.2	22.0	22.1	22.1		**152**	151	153	153	152	152
1	**172**	171	173	173	172	173		**22.1**	22.2	22.2	22.1	22.1	22.1		**152**	151	153	153	152	153
2	**172**	171	173	173	172	174		**22**	22.1	22.2	22.0	21.9	21.6		**152**	151	153	153	151	152
3	**172**	171	173	173	171	172		**21.3**	20.9	21.8	21.1	21.3	21.2		**149**	147	152	150	149	149
4	**172**	171	172	172	172	172		**20.4**	20.4	20.4	20.4	20.5	20.5		**147**	146	147	147	147	147
4.5	**173**	*	*	*	*	173		**20.1**	*	*	*	*	20.1		**147**	*	*	*	*	147
5	**174**	173	173	175	174	*		**20.1**	20.1	20.2	20.1	20.1	*		**148**	147	147	149	148	*
6	**179**	177	178	182	180	*		**19.8**	19.7	19.8	19.8	19.8	*		**152**	149	151	154	152	*
6.5	**205**	186	203	225	*	*		**19.3**	19.4	19.4	19.1	*	*		**174**	157	173	192	*	*
7	**251**	*	*	*	251	*		**18.9**	*	*	*	18.9	*		**215**	*	*	*	215	*
7.5	**249**	*	*	*	249	*		**18.7**	*	*	*	18.7	*		**212**	*	*	*	212	*

Appendix D.

Excerpts from SAFL Project Report No. 505.

Road Salt Effects on the Water Quality of Lakes in the Twin Cities Metropolitan Area

By Eric Novotny, Dan Murphy and Heinz Stefan, December, 2007, Minneapolis, Minnesota

Abstract

Approximately 349,000 tons of road salts (NaCl) are applied annually for road de-icing in the Twin Cities Metropolitan Area (TCMA) of Minnesota. To determine if and how 13 lakes in the TCMA respond to seasonal applications of road salt, the ionic composition of lake water samples was analyzed, and specific conductance and temperature profiles in the lakes were measured over a 45-month period. The lakes were selected based on four criteria one of which was their proximity to roadways.

Natural lakes in Minnesota are dominated by calcium, sulfate and carbonate ions. Sodium and chloride are, however, the dominant ions in the TCMA lakes studied. The one to one stoichiometry of sodium and chloride in the lakes suggests that NaCl is the source of both ions. Concentrations of the two ions were linearly related to specific conductance.

Chloride concentrations in TCMA lakes have been increasing over several decades since the 1950 when road salt applications started to become popular. Long-term increasing trends in specific conductance in 39 lakes in the TCMA mimic amounts of rock salt purchases by the state of Minnesota. If current trends continue the chloride content of TCMA lake waters will continue to rise.

Chloride concentrations in TCMA lakes have a seasonal cycle; concentrations are highest during the winter and early spring months and lowest during the late summer and fall. This cycle matches road salt applications and snowmelt runoff in winter/spring, and flushing of lakes by rainfall runoff during the summer.

Concentrations in the lakes studied are highest at the bottom of the lake causing chemical stratification. This stratification can be strong enough to prevent complete vertical lake mixing (turnover) in the spring. In the lakes studied complete vertical lake mixing was only prevented in the spring, but not in the fall period, and varied from year to year.

There are no natural sources of NaCl in the geology of the TCMA. The salinity source for the TCMA lakes must therefore be man-made. The largest salt uses in the TCMA are for water softening and for road de-icing. Water softening backwash is typically disposed of in sanitary sewers and does not reach any lakes. Road salt, however, is a solute in snowmelt water which runs into lakes through stormsewers and small streams.

Chloride concentrations exceeded the chronic standard of 230 mg/L required for the protection of aquatic life at some point in time in 5 of the 13 lakes studied. These high concentrations were typically found during the winter and spring months and occurred in the deepest portion of the lakes.

Sodium and chloride ions penetrate into the lake sediment pore water by natural convection and diffusion. Lake sediment can therefore act as a sink or a source of sodium and chloride during stagnant and mixing periods, respectively. From the sediment pore water sodium and chloride may be conveyed into the groundwater, but this process was not investigated.

Taken together, these results clearly show a continued degradation of the water quality of urban lakes due to application of NaCl in the watersheds. No acute damage has been

observed, but the trend of increasing lake salinity is disturbing. Violation of existing water quality standards appears to occur in a few lakes occasionally. Road salt seems to be required for driving safety, but road salt application practices need to be implemented that also take into account the water quality trends in lakes, and in the groundwater.

Table 1: Lakes studied and sampling periods.

	Max Depth (m)	Lake Area (ha)	Watershed Area (ha)	Volume (m^3)	Percent Impervious (%)	Watershed District	Sampling Period (year/year)
Ryan	11.0	7.6	77	295,222	34	Shingle Creek	04/07
Gervais	12.5	94.7	1144	4,822,960	30	Ramsey Washington Metro	06/07
McCarron	17.4	27.6	549	2,150,795	24	Capitol Region	04/07
Johanna	13.1	86.2	1188	4,274,367	39	Rice Creek	04/05
Tanners	14.0	28.3	214	1,847,756	33	Ramsey Washington Metro	06/07
Medicine	14.9	358.6	4380	18,589,074	29	Basset Creek	04/05
Parkers	11.3	36.9	340	1,413,903	27	Basset Creek	06/07
Bass	9.4	70.4	1131	672,715	21	Shingle Creek	04/05
Sweeney	7.6	26.7	1512	951,751	37	Basset Creek	06/07
Cedar	15.5	68.4	537	4,432,514	28	Minnehaha Creek	04/07
Brownie	14.3	5.0	136	199,866	33	Minnehaha Creek	04/07
Bryant	13.7	65.2	901	3,245,083	24	Nine Mile Creek	06/07
Lake of the Isles	9.4	44.1	252	1,119,547	29	Minnehaha Creek	04/05

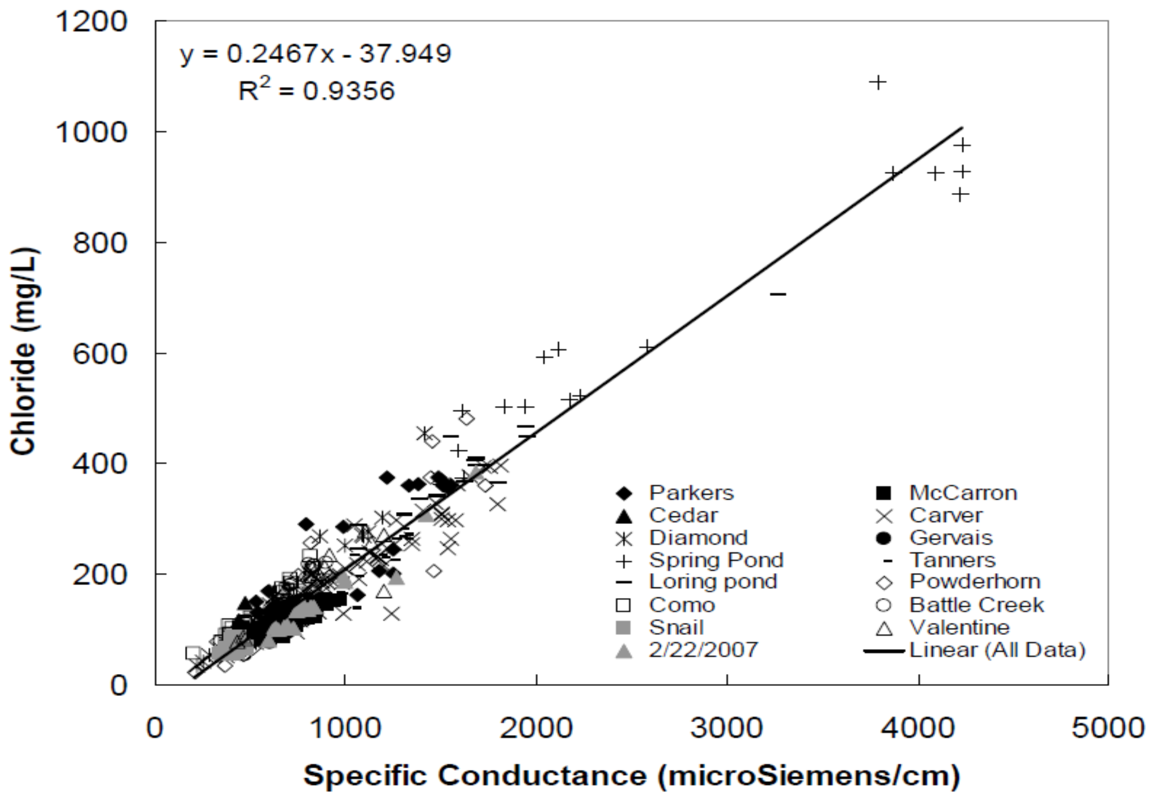

Figure 6. Relationship between specific conductance and chloride concentration in TCMA lakes. Data from 14 lakes in the MPCA Environmental Data Access (listed by names), and the authors' water samples from 9 TCMA lakes (2/22/2007).

Table 2. Ionic composition (mg/L) of 18 water samples taken on 2/22/2007 in 9 urban lakes of the TCMA, 1 m below the water surface and 1 m above the bottom of the lake.

Ion	Median all	Min all	Max all	Median top	Stdev top	Median bottom	Stdev Bottom
Cl-	140.85	79.48	614.80	132.00	38.32	186.00	160.87
Na+	80.85	48.82	366.90	73.14	21.05	104.80	99.40
SO_4^{2-}	13.80	1.72	56.73	13.50	17.09	15.68	17.37
NH_4+	0.91	0.26	36.22	0.79	1.18	1.98	11.56
K+	3.43	2.63	9.99	3.40	0.52	3.43	2.21
Mg++	16.82	4.69	37.58	16.73	9.40	17.57	8.77
Ca++	49.66	20.61	108.80	47.62	24.28	50.90	19.90
NO_3-	0.14	0.01	0.43	0.22	0.11	0.09	0.13

Table 3. Ionic composition (mg/L) of reference surface waters in North America.

	Continental Rain[a]	Pristine Wisconsin Lake[b]	Minnesota Type III lakes[d]	North American River waters[a]	Mississippi River (847.7)[c]	Minnesota River (39.4)[c]
Ca ++	0.2 - 4	12.6	29.3	21	50.3	103.1
Mg ++	0.05 - 0.5	3.3	15.5	5	17.1	47.1
Na +	0.2 - 1	1.6	5.5	9	11.6	31.6
K +	0.1 - 0.5	--	3.2	1.4	2.8	5.2
NH_4 +	0.1 - 0.5	--	--	--	--	--
SO_4^{2-}	1 - 3	--	13.5	20	17	161.8
Cl -	0.2 - 2	0.3	4.3	8	17.2	34.0
NO_3 -	0.4 - 1.3	--	--	1	0.8	5.6

a: from Wetzel (2001)
b: from Long Term Ecological Research (LTER) site (North Temperate Lakes (Crystal Lake) Region)
c: averages (2000-2007) from Metropolitan Council Database. Mile marker in ().
d: Averages from Type III lakes in Minnesota (Gorham Dean et al 1982).

Table 4. Correlation coefficient between specific conductance and seven different ion concentrations in TCMA lake water samples.

Ion	Correlation with SC	Median (moles/L)	Min (moles/L)	Max (moles/L)
Cl-	0.96	3.97	2.24	17.32
Na+	0.95	3.73	2.12	15.95
SO_4^{2-}	0.28	0.15	0.02	0.59
NH_4+	-0.02	0.06	0.01	2.01
K+	0.59	0.09	0.07	0.26
Mg++	0.27	0.69	0.19	1.55
Ca++	0.37	1.22	0.51	2.71

Appendix E.

Detailed composition of seawater at 3.5% salinity

Element	At.weight	ppm
Hydrogen H2O	1.00797	110,000
Oxygen H2O	15.9994	883,000
Sodium NaCl	22.9898	10,800
Chloride NaCl	35.453	19,400
Magnesium Mg	24.312	1,290
Sulfur S	32.064	904
Potassium K	39.102	392
Calcium Ca	40.08	411

Bromine Br	79.909	67.3

From: J. Floor Anthoni, “The Chemical Composition of Seawater”, (2000, 2006), *www.seafriends.org.nz/oceano/seawater.htm* (note ppm is equivalent to mg/L)

Appendix F.

Comparison of recorded dew point temperature (rainwater temperature) during rainfall events, for the summers of 2005 through 2009, showing instances when rainwater alone could have a negative impact on coldwater streams.

Figure F1 is duplicated from section 6.8.

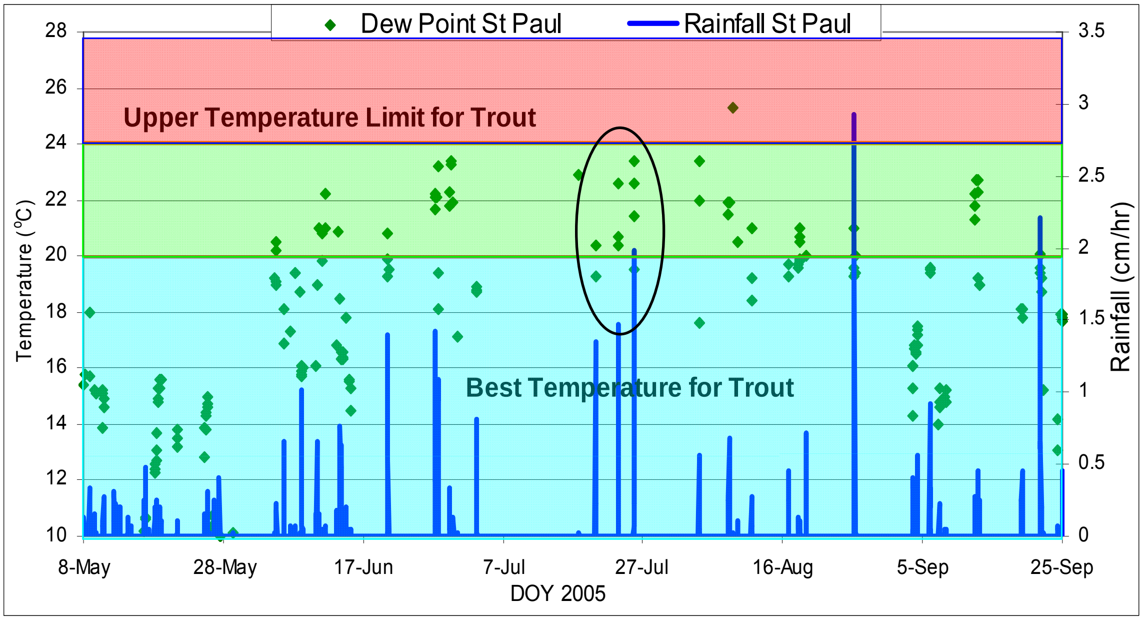

Figure F1. Hourly averaged dew point temperature (rainwater temperature), recorded during rainfall, at St. Paul, Minnesota, during the summer of 2005.

The following plots show hourly dew point temperature (rainwater temperature), during periods of rainfall at the Minneapolis - St. Paul Airport Weather Station, for the summers of 2006 through 2009. Comparing these plots to 2005 seems to confirm that 2005 was a relatively warm summer.

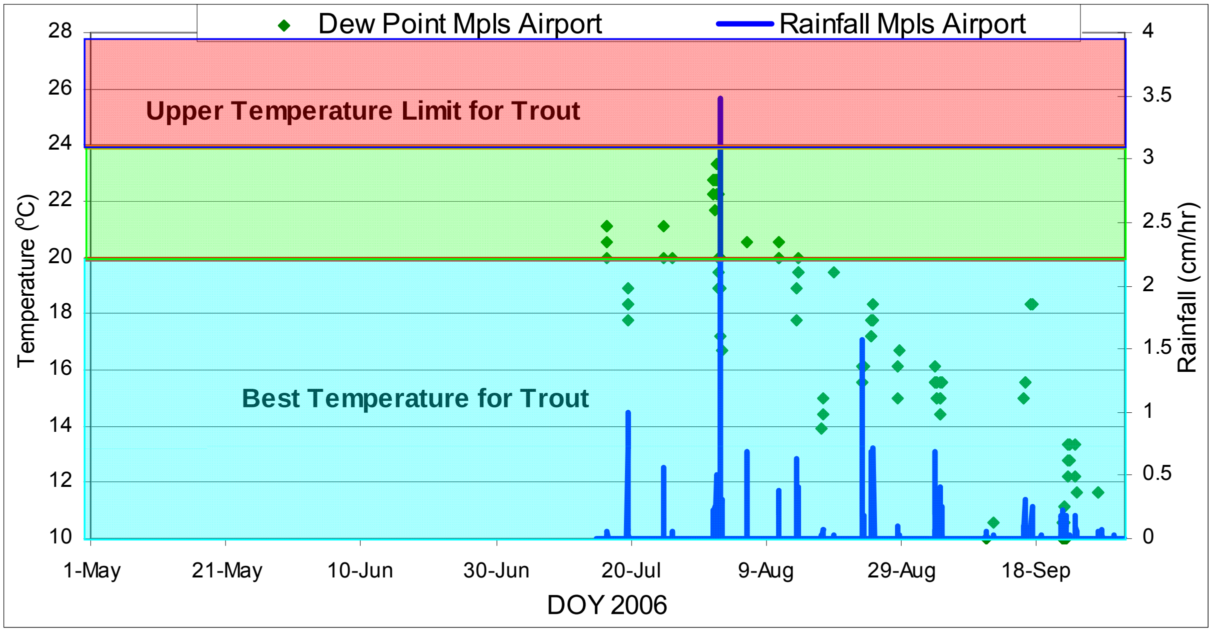

Figure F2. Hourly dew point temperature (rainwater temperature) recorded during rainfall, at the Minneapolis - St. Paul Airport Weather Station, for the summer of 2006. (Missing data prior to mid-July)

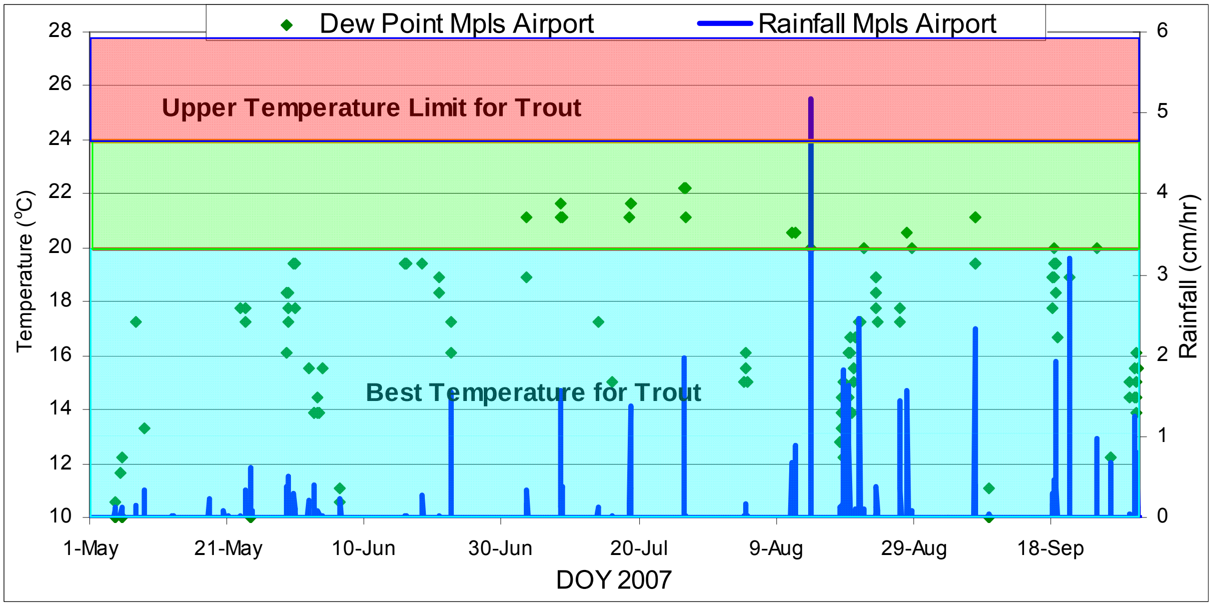

Figure F3. Hourly dew point temperature (rainwater temperature) recorded during rainfall, at the Minneapolis - St. Paul Airport Weather Station, for the summer of 2007.

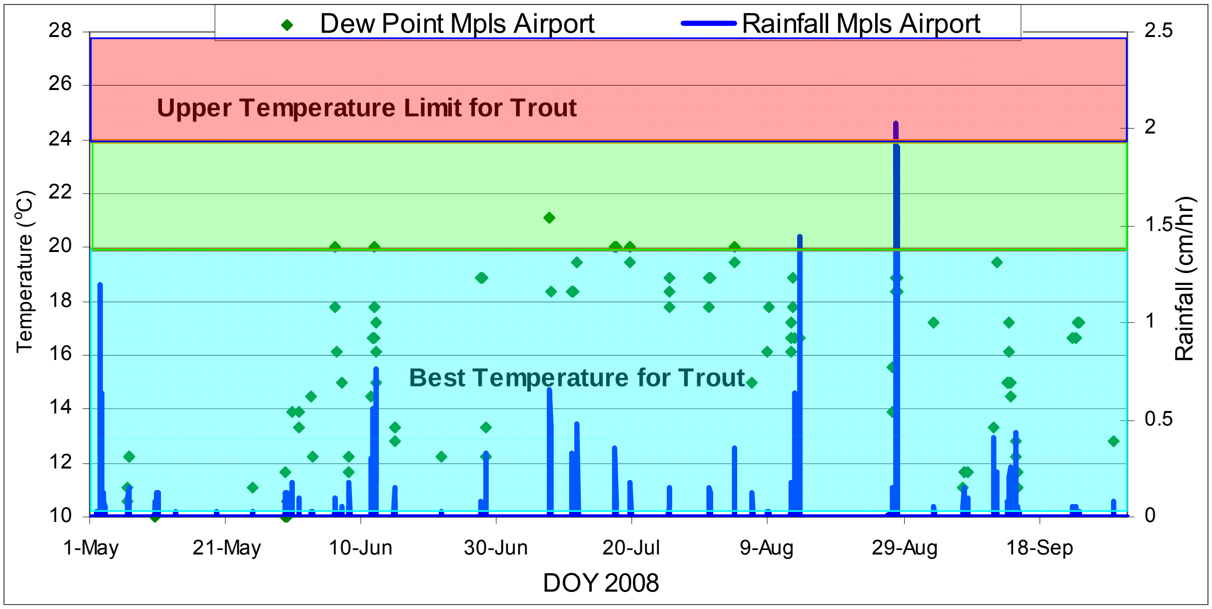

Figure F4. Hourly dew point temperature (rainwater temperature) recorded during rainfall, at the Minneapolis - St. Paul Airport Weather Station, for the summer of 2008.

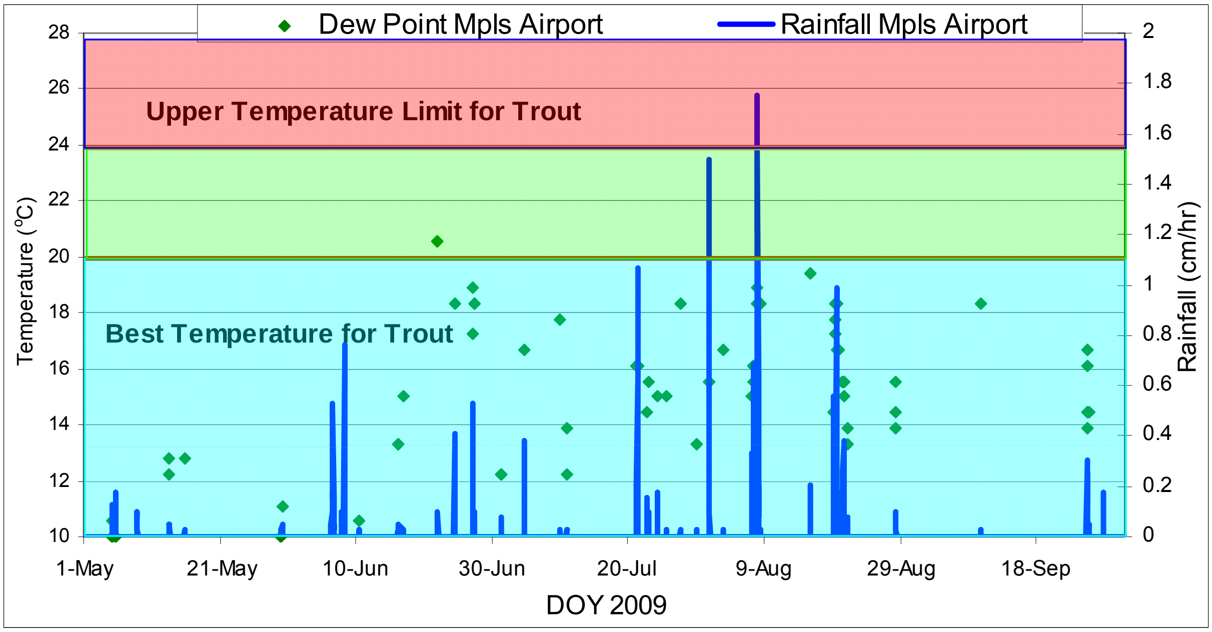

Figure F5. Hourly dew point temperature (rainwater temperature) recorded during rainfall, at the Minneapolis - St. Paul Airport Weather Station, for the summer of 2009.