# PREDICTING THE IMPACT OF URBAN DEVELOPMENT ON STREAM TEMPERATURE USING A THERMAL URBAN RUNOFF MODEL (TURM)

A. Roa-Espinosa[1], T.B. Wilson[2], J.M. Norman[2], and Kenneth Johnson[3]
[1]Dane County Land Conservation Department, Fen Oak Resource Center, 1 Fen Oak Court, Madison, WI 53718. Biological Systems Engineering, University of Wisconsin, Madison, 460 Henry Mall, Madison, WI 53706
[2]Department of Soil Science, University of Wisconsin-Madison, 1925 Linden Drive, Madison, WI 53706
[3]Wisconsin Department of Natural Resources

## Abstract

In this paper, we present a Thermal Urban Runoff Model (TURM) developed by the Dane County Land Conservation Department and the University of Wisconsin-Madison to predict the effect of urban development on runoff thermal regime. The model can predict the temperature increase of runoff from impervious surface by calculating the heat transfer between runoff and the heated impervious surfaces that commonly exist in urban areas. The model mainly assumes a complete mixing of runoff water to predict the heat transfer and the thermal gradient within the impervious media in contact with the runoff flow. Runoff temperature measurements indicate that the hot paved surfaces receiving rainfall initially produce energy released by evaporation, but high temperature runoff is quickly generated by the gradual increase in rainfall intensity. TURM can also predict the temperature reduction after the runoff passes through rock-filled channels; open vegetated swales, infiltrating surfaces; conduits and rock-filled chambers that can be used to cool the first flush of heated storm water runoff. Data collected during summertime storms indicate that determination of the air and rainfall temperatures is critical in predicting the runoff temperature.

TURM was used to evaluate the heating of runoff water during summertime and its impact characteristics at two urban subdivisions in Dane County, Wisconsin with different proportions of imperviousness. The percentage of imperviousness and rainfall depth defined the changes in runoff rate, volume and the timing of runoff. The model predictions for the temperature increase in runoff agree very well with site-specific measurements.

This study is an attempt to fill the knowledge gap that currently exists in determining the thermal impact of urban runoff on coldwater systems. The justification of this research effort is to provide a useful tool to urban planners, fishery managers, biologists, and the engineering community in Wisconsin to better manage impact of large urban development. TURM is still at the early stages of development and additional work is required to make the model applicable to wide array of practical situations.

Keywords: urban imperviousness, runoff: cold water stream, heat transfer, and thermal impact.

## 1. Introduction

The increase in temperature of stream waters has historically received little attention. However, recent studies have suggested that the expanding urbanization has a strong thermal impact on small streams, and as a result, water temperature is now being considered as a part of the permitting process for urban development throughout Wisconsin. Stream water temperature is a limiting factor for cold-water fisheries and is the “narrowest door” in the water system, as all biological activity depends on temperature. Over time, the cumulative impact of hundreds of individual development sites will slowly increase water temperature, affecting the habitat for every stream biota.

Temperature is a characteristic of water quality and is very important in chemical and biochemical processes, particularly those involving biochemical activity. Higher stream temperatures result in lower dissolved oxygen (DO) concentrations and may cause biological oxygen demand (BOD) to increase. Temperature increases in streams can also result in changes in the behavior of fish and macro invertebrates (aquatic insects). Stenothermal fish are very sensitive to temperature changes, with a physiological optimum temperature of <20 º C, while temperatures above 26 º C are considered lethal. Brown Trout (<u>Salmo</u> <u>trutta</u>), for example, have an optimum temperature range of 7 to 17 º C and become stressed at temperatures above 19 º C. Macro invertebrates, such as Stoneflies (Plecoptera sp) and Caddis flies (Trichptera sp), have a maximum temperature of 17 º C and are important not only because they are the primary food source for trout, but because they are indicators of the overall health of the ecosystem. As a result, cold-water streams are apparently the most ecologically sound at temperatures between 7 and 17 º C (Lyons and Wang, 1996, Simonson, 1996)

Urban runoff heating is recognized as the biggest threat to cold-water streams. The permanent warming of streams is often due to the increase in imperviousness and the heating of runoff water in contact with warm surfaces. The runoff is heated as it passes over the impervious surfaces with large heat storage due to solar radiation. In Dane County, Wisconsin, measured runoff temperatures from urban impervious areas have been as high as 29 $^0$C. Excessive heated runoff can substantially and permanently harm runoff receiving cold-water streams. Widely elevated water temperatures can impair the health of aquatic organisms and are responsible for habitat degradation in the headwaters of cold-water streams in urban areas. It is also warmed by the displacement of stored runoff heated by summer conditions that are in line with the storm water conveyance systems, such as wet detention basins.

Increased area under impervious surface in urban areas is a major source of thermal heating in cold climates and can threaten the health of cold-water ecosystems. Impervious areas absorb energy from the sun, which causes them to become warmer. As water runs over these areas, it absorbs some of that heat energy and is warmed, causing thermal pollution in lakes, rivers, and streams. Impervious areas also compound the problem by reducing infiltration, which in turn increases the volume of runoff that is created, leading to higher permanent stream temperatures in the summer months. By mitigating runoff and water temperature impacts, the stream community will benefit not only from temperature reduction, but also from a decline in the amount of sediment, nutrients, and pollution that reaches receiving waters.

The issues of urban runoff thermal impacts require the use of detailed models of the urban surface-water-atmosphere system. Modeling the heat transfer from warm surfaces to runoff water provides a means of assessing the contributions of various factors to the overall rise in water temperature. Some of these factors that may significantly affect the water temperature are solar radiation, air temperature, relative humidity, wind speed, the temperature and amount of rainfall or runoff, and the temperature and amount of ground water entering the river or stream.

The objective of this analysis is to develop a reliable urban rainfall-runoff model that includes a thermal component for impervious areas. The justification of the Thermal Urban Runoff Model (TURM) is to enable communities with cold-water streams to better manage development and minimize thermal impacts to streams. The focus of this paper is therefore on three specific objectives: (1) to provide evidence of the thermal impact of urban imperviousness, (2) to validate the performance of TURM, and (3) to evaluate the effectiveness of using a rock crib as a temperature moderating device.

## 2. Methods

### *2.1. Field measurements*

Data were collected at several sites from May 28th to September 30th, 2000 (Figure 1). Stream discharge data was collected in the Token Creek subwatershed at 6 locations, temperature data at 11 locations, and rainfall data at 6 locations. The University of Wisconsin Geology Department collected stream flow and temperature data at two locations. A weather station located at Shonas Heights recorded the following measurements: wind speed with cup anemometer, solar radiation with a silicon cell pyranometer, rain and air temperature with thermocouple wires, relative humidity with a humidity probe, and rainfall with a tipping bucket rain gauge. The flow and rainfall data was collected every 5 minutes and the temperature every 15 minutes. The data was summarized for seven rainfall events in four-hour intervals. Interflow and groundwater discharge, as a base flow, is an important source of cool water for streams. The average base flow temperatures measured in the study area ranged from approximately 9 to 10 ° C and remained nearly constant during the entire summer season. The exact study area is described in Table 1 below.

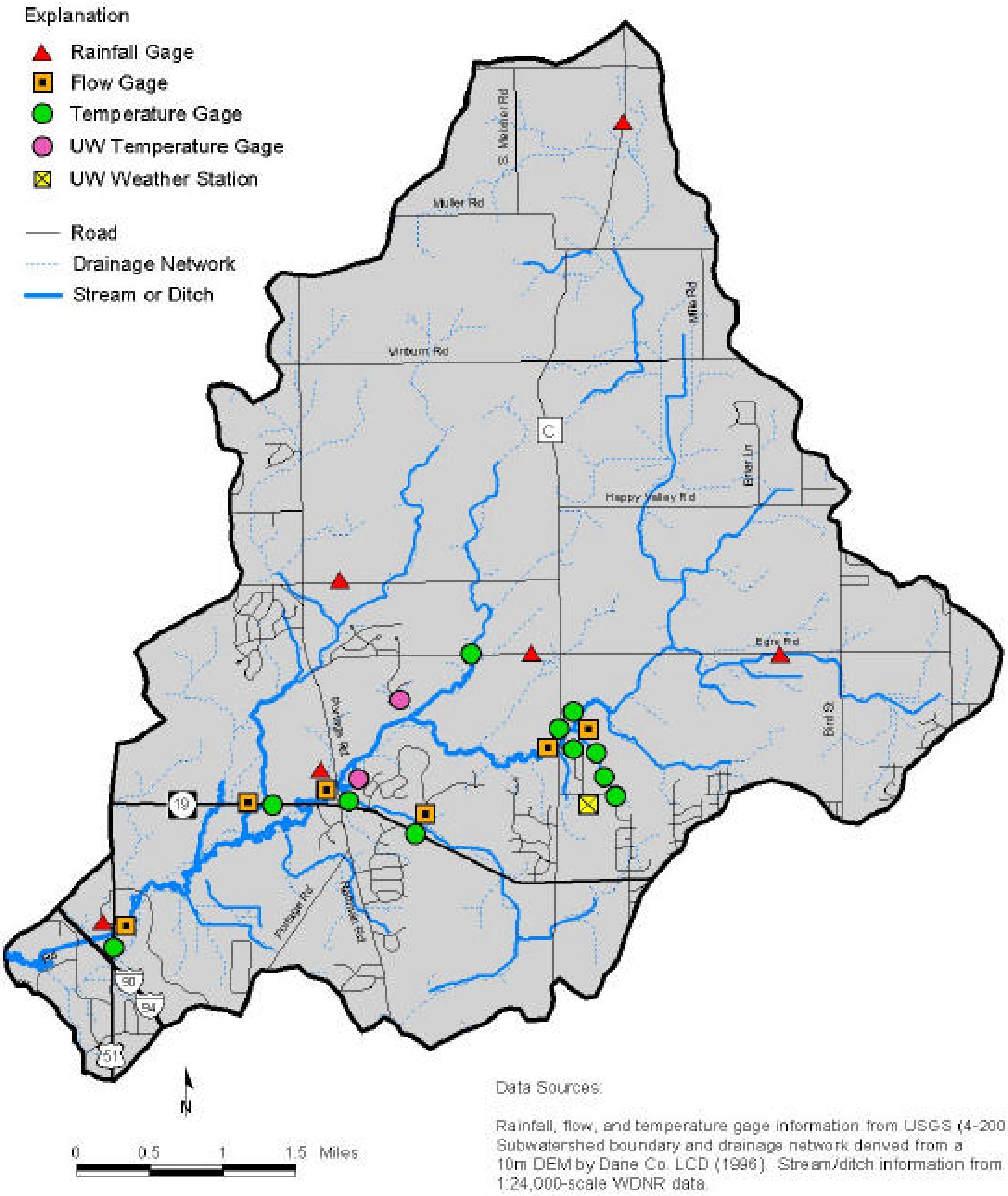
Token Creek Subwatershed illustrated in Figure 1 and 2 was selected to study the impact that imperviousness has on stream temperatures. This subwatershed extends west from Sun Prairie to Cherokee Marsh, and north to the Dane County line, and contains naturally occurring springs as well as urban, agricultural, and naturally vegetated areas, encompassing an area of 22.2 square miles (14,212 acres). The storm water in this subwatershed is discharged to streams or stream segments that are classified as either existing or proposed cold water communities by the Wisconsin Department of Natural Resources and thus are more susceptible to thermal impacts than other streams. Token Creek is a major contributor of fresh water to Lake Mendota, with a base flow of about 22.21 cubic feet per second (cfs) during July 2000 (data collected by the USGS); contributing 93% of all stream flow the lake receives (A Water Resources Study, U.W, 1997).

Table 1. Site descriptions and measurements.

| Site | Description | Measurement |
|---|---|---|
| Culver Springs | Naturally spring-fed area | Base flow |
| St Albert Pond | Urban area with 20% imperviousness | Runoff temperature |
| Shonas Upstream Pond | Urban area with 20% imperviousness | Runoff temperature |
| Shonas East Subdivision (Figure 3) | Urban development | Runoff temperature |
| Shonas West Subdivision (Figure 3) | Urban area with 35% imperviousness | Runoff temperature |
| Rock Crib (Figure 3) | Rock chamber of 255 $m^3$ | Base flow/Runoff temperature |
| Token Branch | Urban drainage area | Base flow/Runoff temperature |
| Stonehaven | Natural grass area | Runoff temperature |
| Highway C | Confluence of streams | Base flow/runoff temperature |
| Highway 51 | Confluence of streams | Base flow/runoff temperature |

The thermal impact on Token Creek was measured over 7 rainfall events that occurred between June 1st and August 5th 2000. Table 2 and Figure 4 present the summary of runoff temperatures for the study area in 4-hour increments (0, 4, 8, 12, 16, 20). Table 2 and Figure 4 show that the runoff temperature from this area is consistently above the threshold for many cold-water species. Other impervious areas, such as Shonas Upstream Pond, Shonas East, and Shonas West, also had temperatures that were consistently above the threshold, but showed a period between the hours of 4 and 8 when the temperatures were lower and suitable for cold-water species. The total thermal impact on the Token Creek sub watershed is clear when the temperatures observed at Culver Springs (~10º C) are compared with those observed at Highway C. Highway C has temperatures that are approximately 7 to 8º C higher than those at Culver Springs (Table 2). The cooling effect that Culver Springs has on Token Creek can be seen at Highway 51, where the temperatures measured remained within the optimum temperature for trout

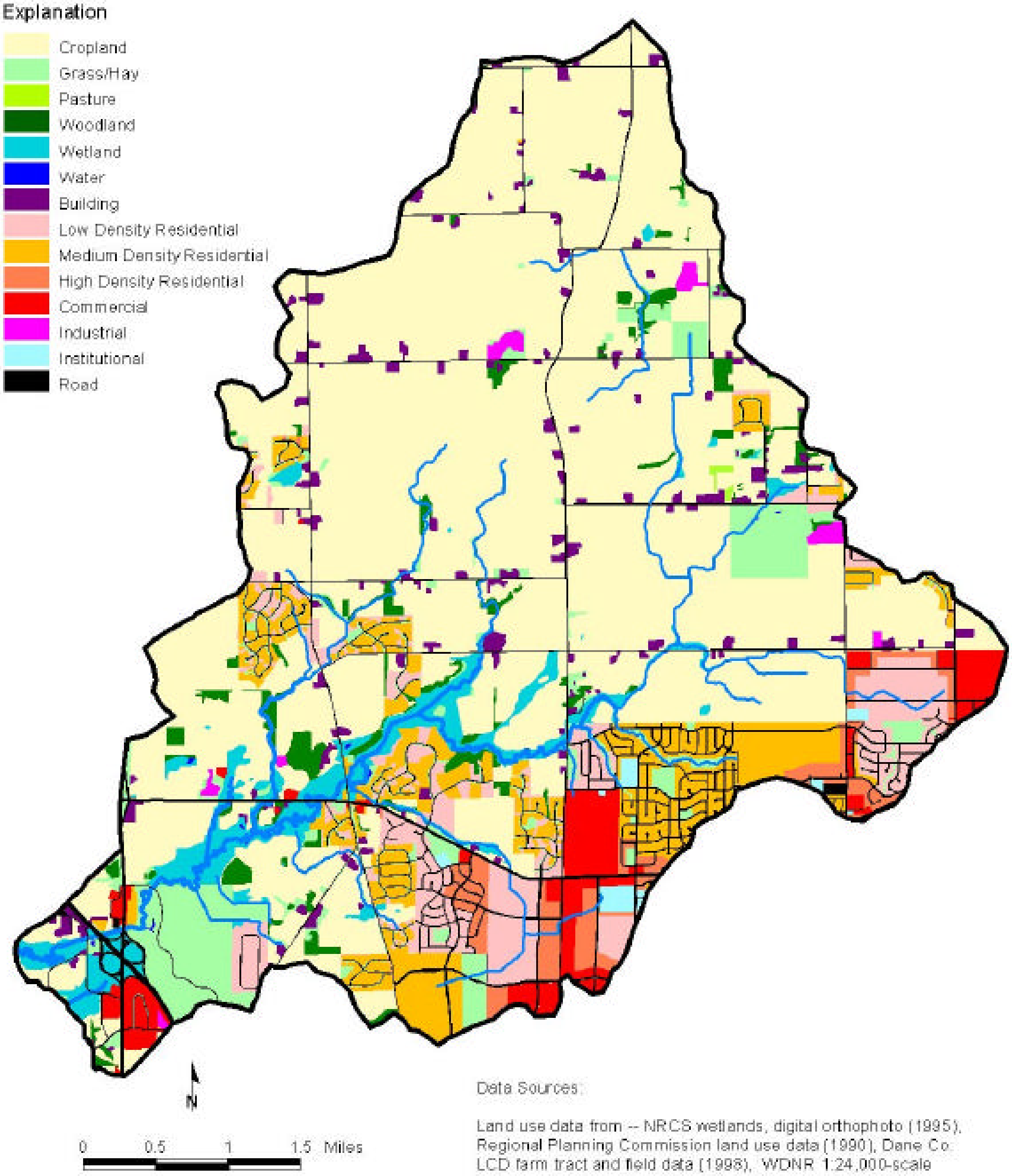
Figure 1. Data Collection Locations in the Token Creek Subwatershed



Data Sources:

Rainfall, flow, and temperature gage information from USGS (4-2000).
Subwatershed boundary and drainage network derived from a
10m DEM by Dane Co. LCD (1996). Stream/ditch information from
1:24,000-scale WDNR data.

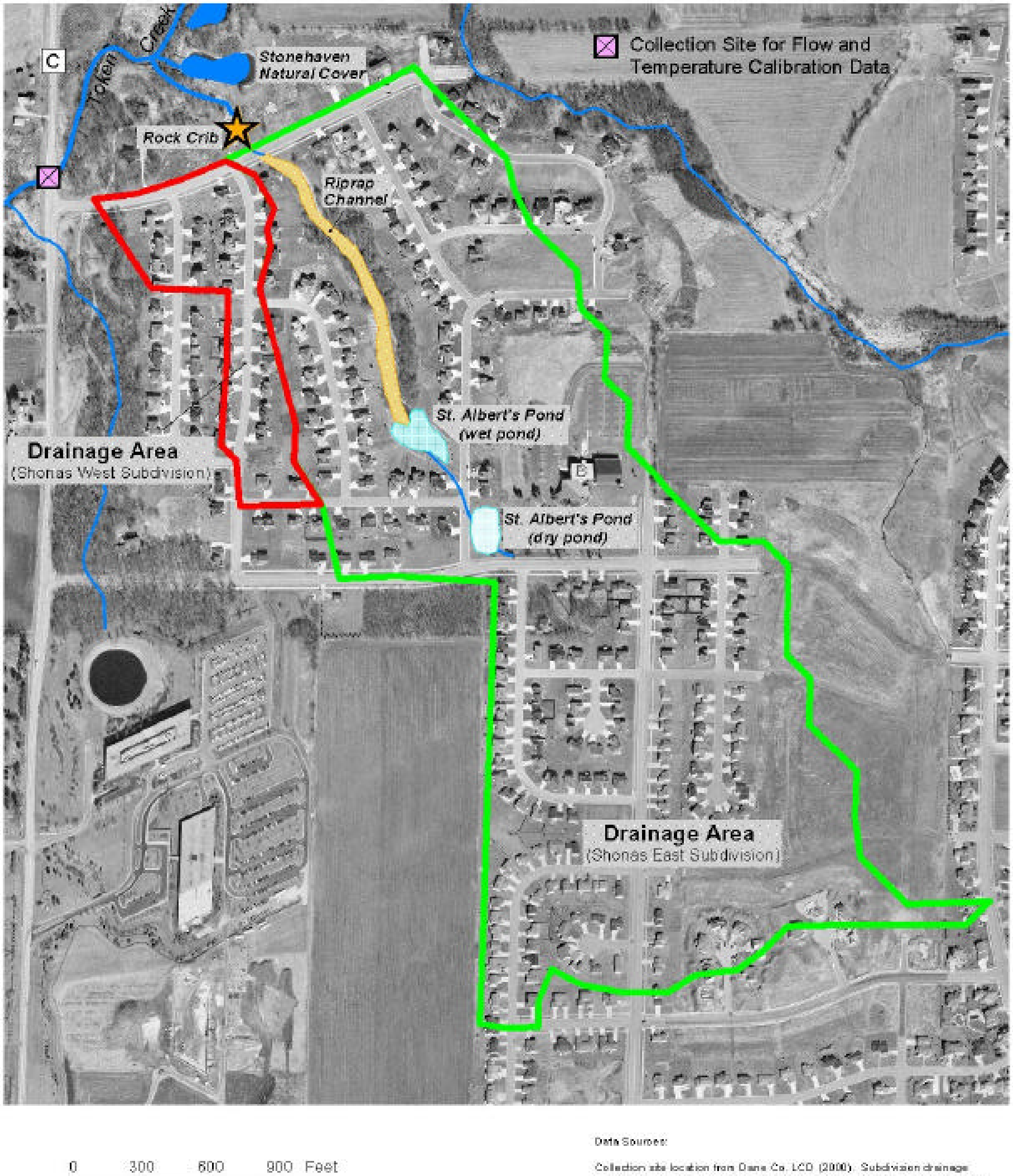
Figure 2. Land Use in the Token Creek Subwatershed



Data Sources:

Land use data from -- NRCS wetlands, digital orthophoto (1995), Regional Planning Commission land use data (1990), Dane Co. LCD farm tract and field data (1998), WDNR 1:24,000-scale hydrography data, City of Sun Prairie land use data (2000) and field verification (2000).

Figure 3. Detail of the TURM Model Testing Site



Data Sources:

Collection site location from Dane Co. LCD (2000). Subdivision drainage area boundaries from Vierbicher Associates data. Stream/ditch information from 1:24,000-scale WDNR data. Digital orthophoto taken March/April 2000.

### *2.2. TURM model in brief*

To estimate the thermal impacts of the study, TURM was used for urban sewer sheds. This model accounts for the fact that stormwater not only absorbs heat from impervious surfaces, but that it also cools these surfaces, reducing the ability of the impervious surface to heat runoff from additional rainfall. Other model considerations include: the amount and temperature of impervious surfaces, the ambient air temperature, the gain or loss of heat from the passage of water through swales, detention basins, and streams, the gain or loss of heat due to tree canopy, the heat loss due to evaporation, heat loss due to heat exchange in rock cribs, and the time and duration of storm events. In addition, the model accounts for the time difference between the runoff from impervious surfaces ($TC_{imperv}$) and from vegetated areas ($TC_{veget}$). However, TURM does not account for the inherited variability of rainfall due to changes in intensity and the type of storm, as the model assumes that the rainfall is uniform over the entire duration of the event.

The specific theoretical developments of TURM are listed as follows:

1) The convective transfer coefficient from Raney and Mihara (1974) was inappropriate for use in TURM, and under-estimated the heat lost to the air. The equation from Ryan and Harleman (1973) seems more appropriate.
2) Equations were developed to estimate the temperature of pavement on a clear day, before rain falls. This simple model formulation for estimating the difference between the surface pavement temperature and air temperature produces reasonable results when compared with field measurements.
3) The inclusion of air and rainfall temperature as inputs into the model indicates that wet bulb temperature during the rainfall period is a reasonable approximation of raindrop temperatures.
4) A routine was developed in the model to account for the cooling effect of dry and water fill rock crib.

## 3. Measurements

The thermal analysis data from TURM indicates that storm-water runoff from Token Creek subwatershed’s impervious areas can increase the temperature of the stream. Furthermore, depending on the time of day that the rainfall event occurred, the impact of runoff on the receiving waters can cause the stream temperature to reach lethal levels (Figure 4).

The model results are based solely on the data obtained between June 1st and August 15th, although the model is capable of producing year-round results. These months were chosen because, historically, they produce the largest amount of rainfall and the highest temperatures of the year. Runoff volumes for urban areas were calculated using the rainfall data collected by the University of Wisconsin’s Soil Science Weather Station, the Wisconsin Department of Natural Resources, and the United States Geological Survey. The runoff was measured as a continuous stream flow in cubic feet-per-second at six gauging stations, (Figure 1), while the flow rate at the outfall of each sewershed was determined by the ratio of rainfall depth to the individual land use (curve numbers).

Table 2. Runoff Temperature Summary (June 1st –August 15th, 2000)

| Site | Time (In 4 Hour Intervals) | | | | | |
|---|---|---|---|---|---|---|
| Time | 0 | 4 | 8 | 12 | 16 | 20 |
| St Albert Pond | 19.51 | 18.34 | 18.11 | 18.95 | 20.91 | 21.58 |
| Shonas Upstream Pond | 17.84 | 16.66 | 17.08 | 18.75 | 20.70 | 20.81 |
| Shonas East Subdivision | 18.43 | 17.82 | 17.79 | 18.12 | 18.49 | 19.48 |
| Shonas West Subdivision | 18.25 | 17.39 | 17.16 | 17.82 | 18.67 | 19.40 |
| Token Branch Up | 16.60 | 15.80 | 15.24 | 15.53 | 16.16 | 17.85 |
| After Rock Crib | 17.45 | 16.09 | 15.38 | 15.52 | 16.50 | 17.30 |
| Stonehaven Grassed Area | 15.06 | 14.80 | 15.22 | 16.30 | 16.62 | 17.91 |
| Highway C | 17.45 | 16.76 | 16.26 | 16.73 | 17.62 | 19.18 |
| Culver Springs | 10.02 | 9.89 | 9.89 | 9.93 | 10.07 | 10.18 |
| Highway 51 | 17.12 | 16.44 | 15.49 | 15.12 | 16.15 | 17.57 |
| Rainfall (inches) | 0.88 | 2.40 | 0.22 | 1.94 | 2.49 | 2.67 |

The data presented in tables 2 through 5 and displayed in Figures 4 through 10 represents a summary of the field data collected by the USGS and WDNR Fisheries Department during June, July, and August 2000.

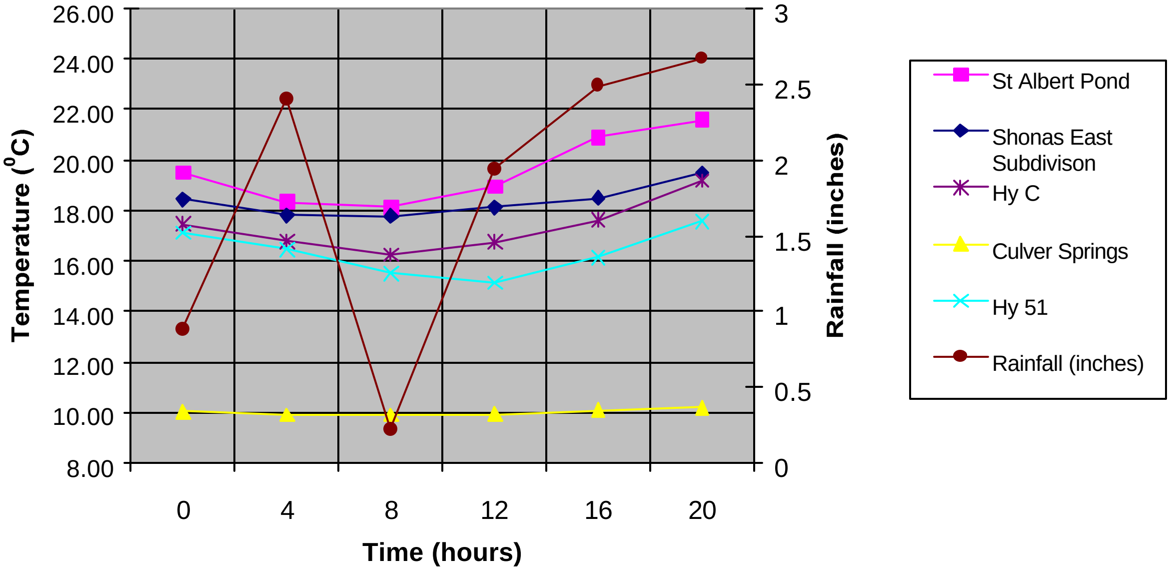


**Figure 4. Average Summer Runoff Temperature (June 1st to August 15th, 2001)**

### *3.1. Measurements of June 4, 2000*

The 0.37 inches of rain fell in the early morning hours of June 4th. During this event, a temperature difference of approximately 3° C was observed between the non-urban (Stonehaven, Token Branch Up) and urban areas at the onset of the rain. The urban areas measured, on average, 6° C higher than Culver Springs, or twice the temperature increase measured at the non-urban areas. Because this rainfall occurred in the early morning hours, the impervious areas had not yet been warmed by the sun, resulting in a lower than average high water temperature for urban areas. The high temperatures for the urban and non-urban areas for this event were very similar, separated by ~2° C.

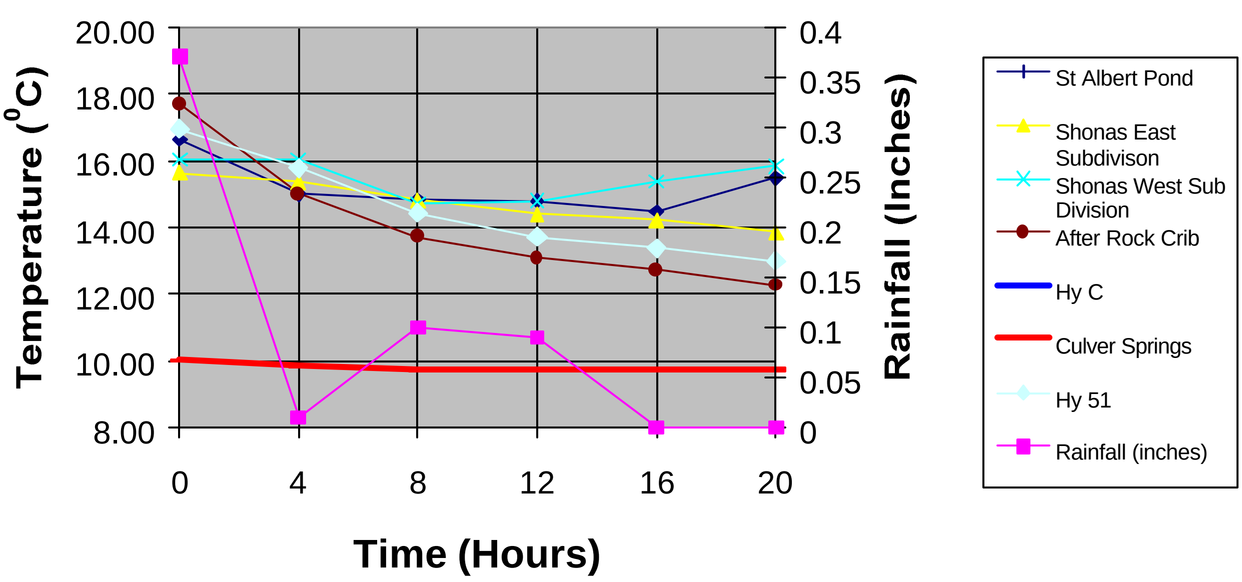
The rain began at hour 4 and ended at hour 16 with 0.1 inches of rain. The runoff temperatures for the entire study area declined throughout the storm event and were compared to the air temperature, rainfall temperature, and the solar radiation data (measured at the weather station). The resulting temperatures were the lowest recorded during the entire study period (Table 3 and Figure 5). This data relates that thermal impact is closely related to the weather conditions and the time of day when the rainfall event occurred.

The thermal impact of the runoff from the Shonas urban area on the crib was minimal, measuring only 2.5° C. This is significant because the temperature of the runoff after the crib represents the temperature of the ground water during and after the rainfall event (Figure 5). Due to the low intensity and long duration of this storm event, the runoff from the Shonas urban areas did not overwhelm the heat exchange capacity of the rock or the cooling effect of the water in the rock crib. Thus, the temperature of the runoff after crib was within 1° C of the temperature of the stream at Highway 51 (table 3).

Table 3. Temperature and rainfall data summary for June 04, 2000

| Site | Time (Hour) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Date | 0 | 4 | 8 | 12 | 16 | 20 |
| Shonas St. Albert | 04-Jun | 16.63 | 15.00 | 14.84 | 14.80 | 14.47 | 15.48 |
| Shonas Upstream Pond | 04-Jun | 16.53 | 15.36 | 14.22 | 14.02 | 14.34 | 15.04 |
| Shonas East Subdivision | 04-Jun | 15.64 | 15.36 | 14.82 | 14.39 | 14.22 | 13.85 |
| Shonas West Subdivision | 04-Jun | 16.03 | 16.02 | 14.68 | 14.79 | 15.37 | 15.83 |
| Token Branch Up | 04-Jun | 16.08 | 14.77 | 13.78 | 13.18 | 13.01 | 12.98 |
| After Rock Crib | 04-Jun | 17.69 | 15.00 | 13.72 | 13.08 | 12.72 | 12.26 |
| Stonehaven | 04-Jun | 13.79 | 13.43 | 13.31 | 13.09 | 12.89 | 13.30 |
| Highway C | 04-Jun | | | | | | |
| Culver Springs | 04-Jun | 10.01 | 9.83 | 9.73 | 9.73 | 9.76 | 9.73 |
| Highway 51 | 04-Jun | 16.94 | 15.77 | 14.43 | 13.71 | 13.38 | 13.00 |
| Rainfall (Inches) | 04-Jun | 0.37 | 0.01 | 0.1 | 0.09 | 0 | 0 |

**Figure 5. Temperature and Rainfall Summary for 6-04-00**



### *3.2. Measurements of July 10, 2000*

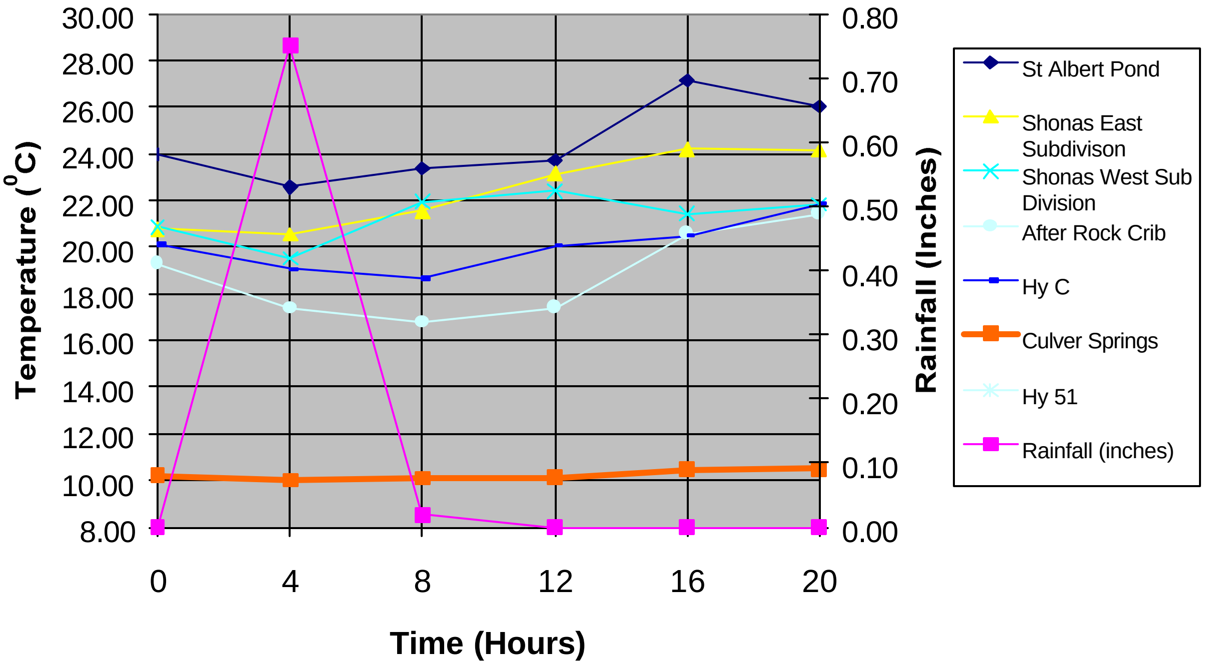
Table 4 and Figure 6 show the results of a 0.77-inch rainfall, which was preceded by 0.20 inches of rain on July 9th between the hours of 10 and 12. The rain on the 10th began at hour 0 and ended at hour 8, during a period of time when the sun shines only briefly, meaning that most of the increase in runoff temperature is due to the stored heat in impervious surfaces.

The temperatures at St. Albert Pond, which collects drainage from an urbanized area, ranged from 22.59º C to 27.15º C, with an average temperature of 24.47º C. These temperatures were the highest that were recorded at any location during the course of this study and represent near lethal to lethal temperatures for many cold-water species; including fish such as the Brown and Brook Trout. In contrast, the temperatures recorded at Culver Springs reached a high of only 10.51º C, 12-17 º C lower than the temperatures recorded at St. Albert Pond.

Table 4. Temperature and Rainfall Data Summary for July 10, 2000

| Site | Time (Hour) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Date | 0 | 4 | 8 | 12 | 16 | 20 | |
| Shonas St. Albert | 10-Jul | 23.98 | 22.59 | 23.36 | 23.72 | 27.15 | 26.03 | |
| Shonas Upstream Pond | 10-Jul | 21.87 | 20.04 | 21.84 | 22.35 | 24.99 | 24.43 | |
| Shonas East Subdivision | 10-Jul | 20.76 | 20.55 | 21.55 | 23.14 | 24.19 | 24.13 | |
| Shonas West Subdivision | 10-Jul | 20.86 | 19.53 | 21.96 | 22.39 | 21.42 | 21.83 | |
| Token Branch Up | 10-Jul | 20.08 | 18.96 | 18.48 | 19.78 | 20.29 | 21.93 | |
| After Rock Crib | 10-Jul | 19.28 | 17.39 | 16.79 | 17.42 | 20.56 | 21.41 | |
| Stonehaven | 10-Jul | 16.75 | 16.05 | 19.18 | 22.09 | 22.22 | 21.28 | |
| Highway C | 10-Jul | 20.14 | 19.07 | 18.66 | 20.06 | 20.48 | 21.88 | |
| Culver Springs | 10-Jul | 19.25 | 18.86 | 17.16 | 15.79 | 18.08 | 20.33 | |
| Highway 51 | 10-Jul | 10.22 | 10.02 | 10.11 | 10.13 | 10.48 | 10.51 | |
| Rainfall (Inches) | 10-Jul | 0 | 0.75 | 0.02 | 0 | 0 | 0 | 0 |

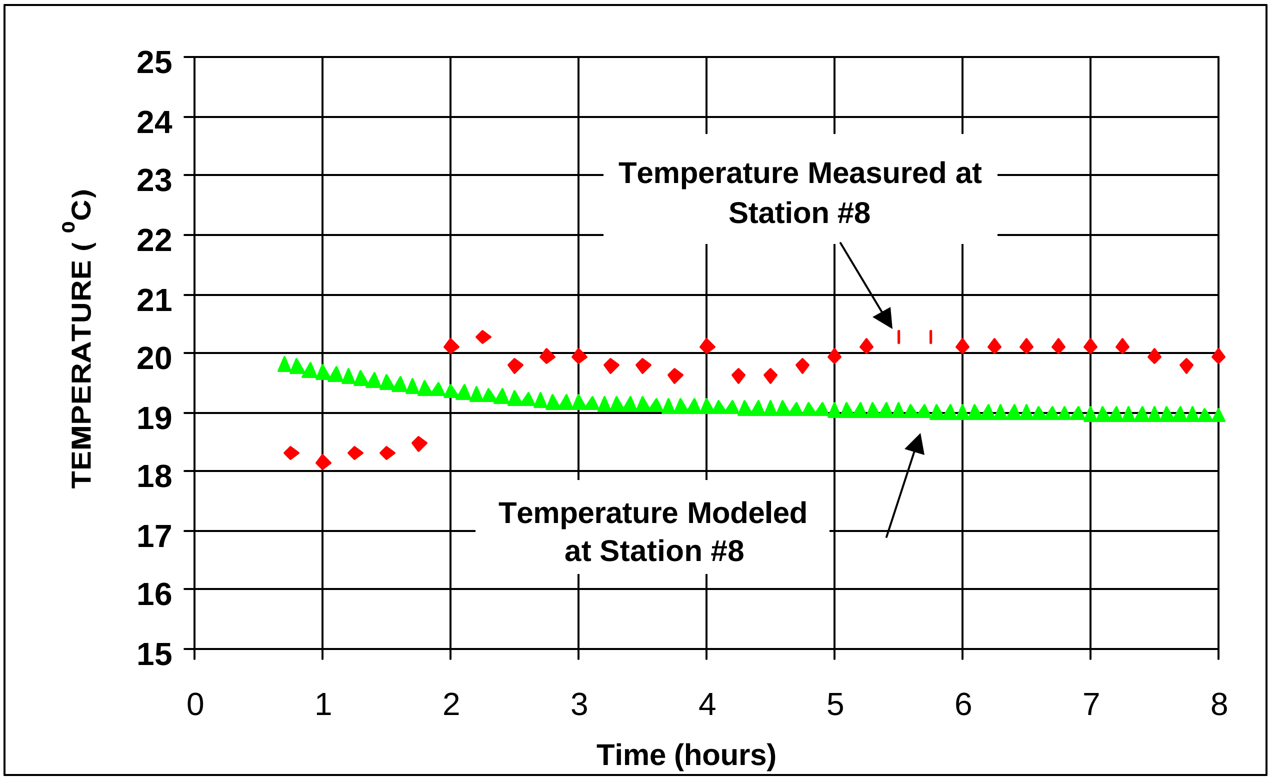
Figure 6. Temperature and Rainfall Summary for 7-10-00



### *3.3. Comparison of model results with measurements at St. Albert Shonas*

Figure 7 presents the average temperature of runoff that drained into St. Albert's dry detention pond. The measured temperature averaged 19.54° C, 0.42° C greater than the modeled temperature, 19.12° C. The model, represented in Figure 7, over-predicts the initial runoff temperature by ~2° C because the model assumes that runoff is produced immediately after the rainfall event starts. However, some rainfall evaporates when it meets the pavement, while some is stored in the micro-depressions present in pavement and other impervious surfaces. Because of this assumption, this immediate runoff has the highest modeled temperature for the event. At mid-day (between hours 12 and 16), pavement temperatures in urban areas are often considerably higher than air temperatures, and TURM requires an initial temperature before an estimate of runoff temperature can be made. To correct this problem, maximum air temperature, minimum air temperature, and mean wind speed at midday hours were used to solve for the temperature difference. The approach for this simple set of equations is to solve for the temperature difference between the black top surface and the air at hour 17, when the conduction flux into the pavement is zero, and also at hour 5 when surface heat conduction equals zero.

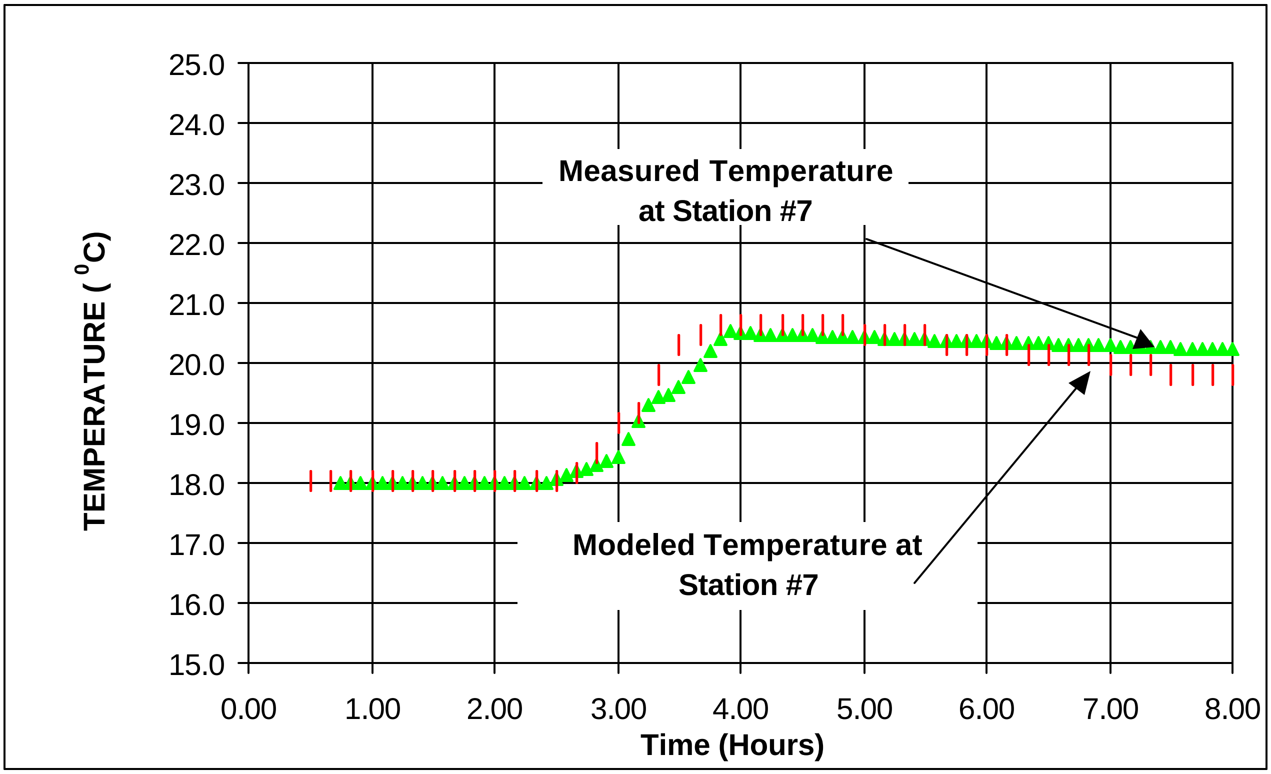
**Figure 7. Measured and predicted runoff temperatures at St Albert Shonas**



***Shonas Pond***: The temperatures predicted for the St. Albert Shonas areas were assumed to be the initial temperature of the runoff when it was delivered to the pond. The average runoff temperature over the duration of the rainfall and the duration of the effective runoff was measured at 20.27º C, while the model predicted a temperature of 20.76º C, a difference of 0.5º C. However, the actual runoff temperature was influenced by the storage water in the pond, which was assumed to be equal to the air temperature prior to the rain, which may account for some of the difference in the results.

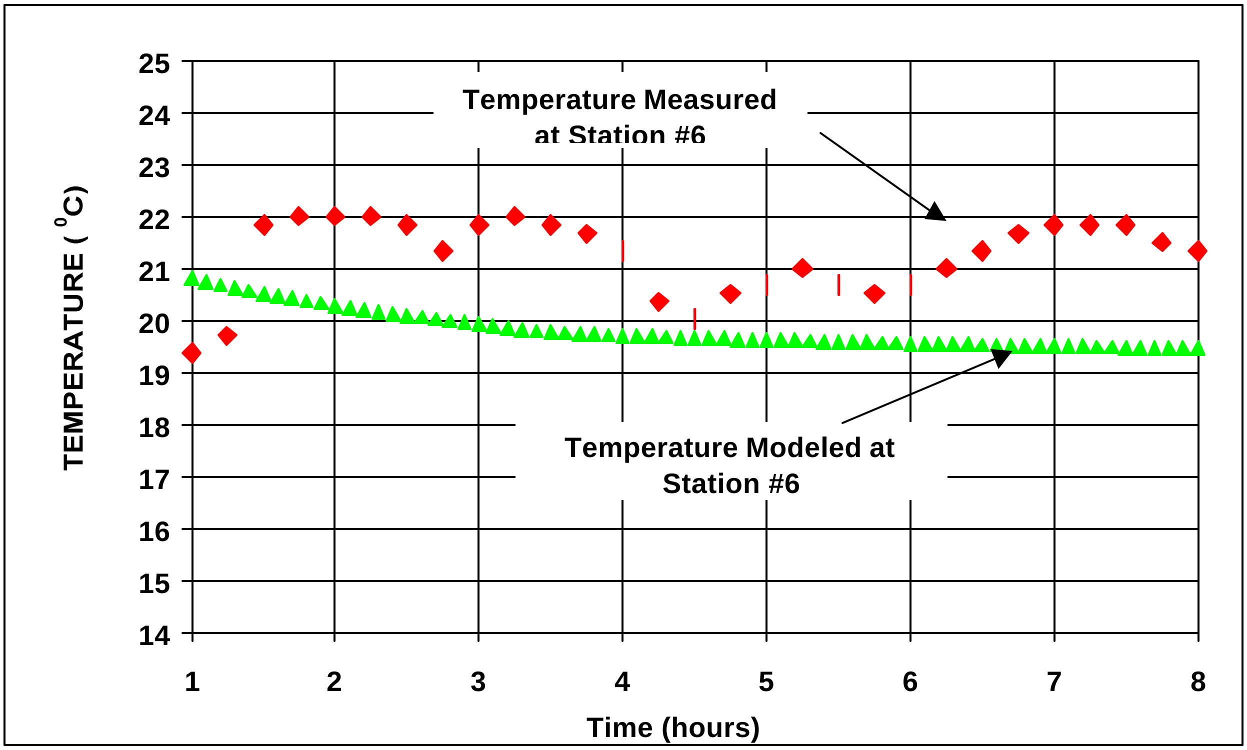
***Shonas East***: The runoff from Shonas East is delivered to the rock crib by a rock-lined channel. The rock-lined channel's time of concentration is related to the voids of the channel bottom, the interception by the rock, and the roughness coefficient of the rocks that impede the free flow of the runoff. These characteristics reduce the inherited variability of the rainfall, stabilizing the time of concentration and allowing the model to more accurately predict the temperature of the runoff. The rock temperature was assumed to be the same as the air temperature when the rain began to fall, while the initial temperature of the runoff was assumed to be the same temperature of the pond. The temperatures changed according to the relationship developed in Figure 8. The heat exchange in the rock channel was modeled to occur initially at air temperature (before the rain fell) and the heated runoff from the impervious areas and was calculated utilizing the model for dry rock basins. The predicted runoff temperature (19.25º C), proved to be very close (within 0.27º C) to the field data (19.52º C).

**Figure 8. Measured and predicted runoff temperatures at Shonas East**



***Shonas West***: The runoff was delivered to the rock crib directly by a 24-inch concrete pipe. The temperature of the runoff from Shonas West (12 acres and 40% impervious) was modeled as a direct heat transfer from the impervious areas to the runoff. Figure 9 presents the average runoff temperatures from the impervious areas that drain to the outfall at Shonas West. The average, calculated over 12 hours, was measured at 21.25° C and modeled at 19.82° C, for a difference of 1.4° C over the entire runoff event. The model, represented in Figure 9, shows that the model over-predicted the initial runoff temperature by 1.5 ° C. As previously discussed, the model assumes immediate runoff and does not allow for the delays that occur in the field. TURM also does not account for the inherited variability of the rainfall due to changes in intensity and the type of storm; rather, it assumes a uniform rainfall over the entire duration. This relationship is shown in Figure 9.

**Figure 9. Measured and predicted runoff temperatures at Shonas West**



In a study conducted by Steve Greb of the WDNR in 1996, measurements were made of the runoff flow and temperature, and pavement temperature from a parking lot in the City of Madison, Wisconsin. The weather conditions during this study showed 0.43 mm of rain, wind speed of 3.3 m/s, air temperature of 26° C, relative humidity of 92%, as well as the temperature of the pavement and roof tops (40° C and 50° C). The rainfall lasted 39 minutes. The results from the study proved to be very encouraging. The measured runoff outflow temperature averaged 29.3° C. Using the TURM, the predicted the temperature of the runoff was 29.4° C, indicating a difference between measured and predicted temperatures of only 1° C.

### 3.4. *Runoff Thermal Regime Best Management Practice (BMP)*

The thermal impact of the impervious areas on stream temperature for the St. Albert events was moderated by rock crib and by the base flow from Culver Springs, resulting in little change in stream temperature. Overall, after the rainfall event began, the temperatures predicted by TURM remained within 1º C of the actual measured temperatures for this event (Figures 7 to 10).

The rock crib was monitored for flow and temperature at the two inlets that drain into the crib, as well as 50 feet below the crib. The crib was built with the assumption that water that runs off impervious areas could be cooled by passing it through an underground rock chamber. From initial calculations, if the crib is empty, the conduction of heat from the rock limits heat transfer to the water, rather than the convective transfer coefficient of the moving water. As a result, the problem is one of transient heat conduction from spheres. If the space between the rocks is filled with water, the heat exchange in the crib is one of mixing, displacement, and the convective transfer coefficient of the moving water. Unfortunately, no analytical solution to this transient heat conduction is available, so a numerical solution was used.

The 255 $m^3$ rock crib received runoff from Shonas East (140 acres) and Shonas West (12 Acres). The runoff flowed through paving blocks (25% porous) on the surface to an opening filled with pea gravel, where the runoff was filtered into the rock crib, which is filled with ground water and stone. The temperature of the rock in the crib was assumed to be the same as the ground water temperature (15º C). The runoff (initially 30º C, enters and filters into the ground at the moment of the rain, with the temperature of the runoff (measured at each time step) changing according to the relationship developed in Figure 10. As previously discussed, the temperature of rain and the air are closely related, and the runoff temperature depends on the heat exchange with the stone in the riprap channel. The model has two heat exchange processes: the initial exchange between the heated runoff and the stone, followed by the heat exchange caused by the mixing of ground water with the runoff. The effectiveness of the rock crib depends on the ratio of the volume of runoff and the volume of the rock crib, as well as the volume of water stored in the crib prior to the rainfall event. In this case, the crib was filled to capacity (9,000 $ft^3$), resulting in an effective thermal treatment for the 140 acres of urban development it drained. The field data shows that the rock crib mitigates the thermal impact caused by impervious areas until the initial volume of the crib has been completely replaced by the runoff. After the volume has been replaced, the rock crib no longer provides a thermal reduction for stormwater.

**Figure 10. Measured and Predicted Runoff Temperatures at the Rock Crib**

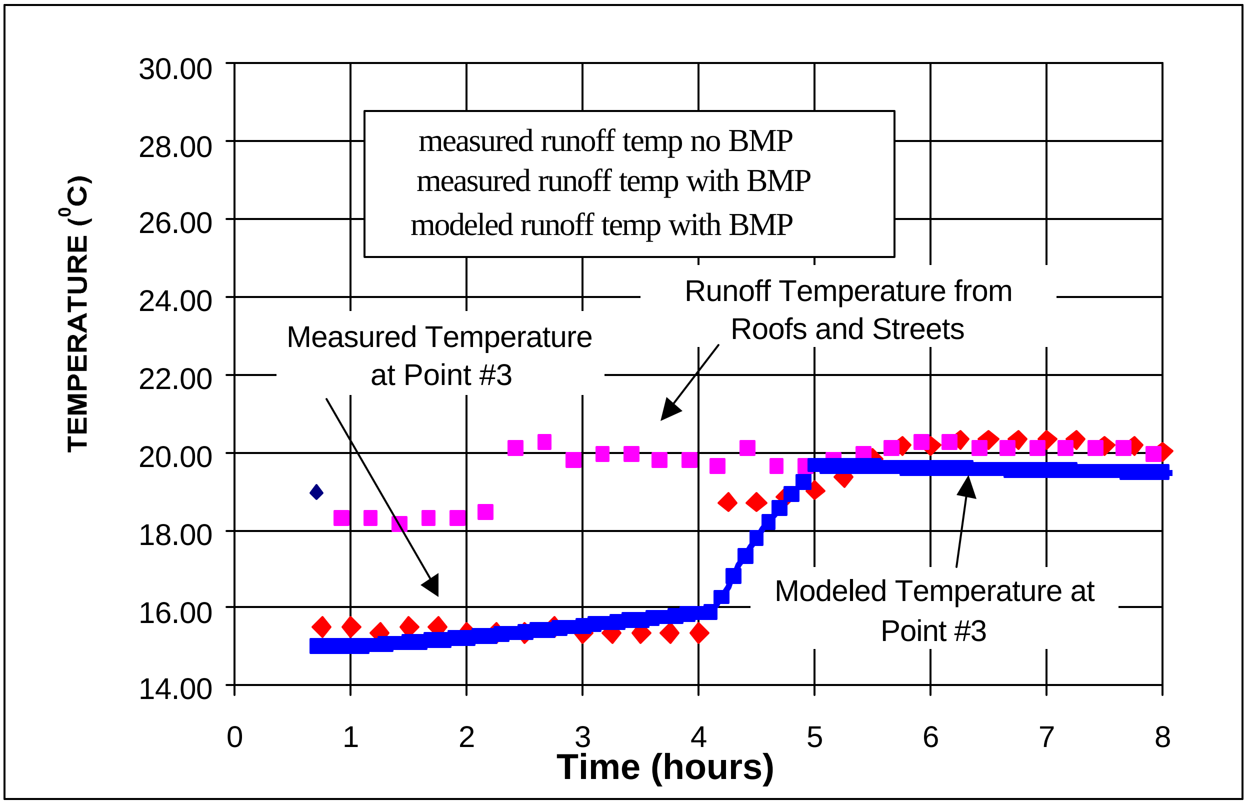


Table 5 shows a summary of the measured temperatures (recorded every 15 minutes) and the modeled temperatures (predicted every 5 minutes). The thermal impact was modeled for a 14-hour period because runoff and heat exchange continue after the rain has stopped. When runoff is directly discharged into an outfall from an impervious surface, the model does not account for the variability in rainfall intensity changes. However, when the runoff is delivered to a BMP, such as a pond, grassed channel, or rock crib, the variability of the attenuation factor is reduced because BMPs temporarily store runoff before releasing it at a preset rate to a receiving streams.

## Table 5. Measured vs. Modeled Runoff Temperatures at Selected Sites (15-Minute Intervals)

| Time of Rainfall Event | Measured Temperature Albert Shonas (Station #8) (º C) | Calculated Temperature at St. Albert Shonas (Station #8) (º C) | Measured Temperature at Shonas East (Station #7) (º C) | Calculated Temperature at Shonas East (Station #7) (º C) | Measured Temperature at Shonas West (Station #6) (º C) | Calculated Temperature at Shonas West (Station #6) (º C) | Measured Temperature at Rock Crib Shonas (Station #3) (º C) | Calculated Temperature at Rock Crib Shonas (Station #3) (º C) |
|---|---|---|---|---|---|---|---|---|
| 12:00 | 18.32 | 19.61 | 18.02 | 18.00 | 19.55 | 21.05 | 15.35 | 15.50 |
| 12:15 | 18.16 | 19.54 | 18.02 | 18.00 | 19.38 | 20.88 | 15.51 | 15.50 |
| 12:30 | 18.32 | 19.48 | 18.02 | 18.00 | 19.71 | 20.68 | 15.51 | 15.50 |
| 12:45 | 18.32 | 19.42 | 18.02 | 18.00 | 21.84 | 20.57 | 15.35 | 15.50 |
| 13:00 | 18.48 | 19.37 | 18.02 | 18.00 | 22.01 | 20.42 | 15.35 | 15.50 |
| 13:15 | 20.12 | 19.32 | 18.02 | 18.00 | 22.01 | 20.34 | 15.35 | 15.50 |
| 13:30 | 20.28 | 19.27 | 18.02 | 18.06 | 22.01 | 20.25 | 15.51 | 15.50 |
| 13:45 | 19.79 | 19.23 | 18.02 | 18.25 | 21.84 | 20.14 | 15.35 | 15.60 |
| 14:00 | 19.95 | 19.19 | 18.02 | 18.42 | 21.34 | 20.03 | 15.35 | 15.70 |
| 14:15 | 19.95 | 19.17 | 18.02 | 19.03 | 21.84 | 19.96 | 15.35 | 15.80 |
| 14:30 | 19.79 | 19.16 | 18.02 | 19.48 | 22.01 | 19.86 | 15.35 | 15.90 |
| 14:45 | 19.79 | 19.14 | 18.02 | 19.76 | 21.84 | 19.80 | 15.35 | 17.33 |
| 15:00 | 19.63 | 19.13 | 18.02 | 20.41 | 21.67 | 19.75 | 18.71 | 18.59 |
| 15:15 | 20.12 | 19.12 | 18.18 | 20.49 | 21.34 | 19.72 | 18.71 | 19.67 |
| 15:30 | 19.63 | 19.10 | 18.51 | 20.48 | 20.36 | 19.71 | 18.87 | 19.66 |
| 15:45 | 19.63 | 19.09 | 18.99 | 20.47 | 20.03 | 19.69 | 19.03 | 19.66 |
| 16:00 | 19.79 | 19.08 | 19.16 | 20.45 | 20.52 | 19.66 | 19.36 | 19.65 |
| 16:15 | 19.95 | 19.07 | 19.81 | 20.43 | 20.68 | 19.64 | 19.84 | 19.64 |
| 16:30 | 20.12 | 19.06 | 20.29 | 20.42 | 21.01 | 19.61 | 20.17 | 19.63 |
| 16:45 | 20.28 | 19.05 | 20.46 | 20.41 | 20.68 | 19.60 | 20.17 | 19.63 |
| 17:00 | 20.28 | 19.05 | 20.62 | 20.39 | 20.52 | 19.58 | 20.33 | 19.62 |
| 17:15 | 20.12 | 19.04 | 20.62 | 20.38 | 20.68 | 19.57 | 20.33 | 19.61 |
| 17:30 | 20.12 | 19.03 | 20.62 | 20.36 | 21.01 | 19.55 | 20.33 | 19.60 |
| 17:45 | 20.12 | 19.02 | 20.62 | 20.35 | 21.34 | 19.54 | 20.33 | 19.60 |
| 18:00 | 20.12 | 19.02 | 20.62 | 20.33 | 21.67 | 19.52 | 20.33 | 19.59 |
| 18:15 | 20.12 | 19.01 | 20.62 | 20.32 | 21.84 | 19.52 | 20.17 | 19.59 |
| 18:30 | 20.12 | 19.00 | 20.62 | 20.30 | 21.84 | 19.50 | 20.17 | 19.58 |
| 18:45 | 19.95 | 19.00 | 20.46 | 20.29 | 21.84 | 19.49 | 20.01 | 19.57 |
| 19:00 | 19.79 | 18.99 | 20.46 | 20.27 | 21.51 | 19.48 | 20.01 | 19.57 |
| 19:15 | 19.95 | 18.99 | 20.46 | 20.32 | 21.34 | 19.52 | 20.01 | 19.56 |
| 19:30 | 19.79 | 18.98 | 20.46 | 20.26 | 21.51 | 19.47 | 19.84 | 19.56 |
| 19:45 | 19.95 | 18.98 | 20.29 | 20.25 | 21.67 | 19.46 | 19.84 | 19.55 |
| 20:00 | 20.12 | 18.97 | 20.29 | 20.25 | 21.67 | 19.46 | 19.68 | 19.55 |
| **Average** | **19.54** | **19.12** | **19.41** | **19.70** | **21.25** | **19.82** | **18.40** | **18.33** |
| **Standard Deviation** | **0.90** | | **0.73** | | **1.90** | | **.57** | |

Figure 11. Daily Measured Temperature in Token Creek (June 2000)

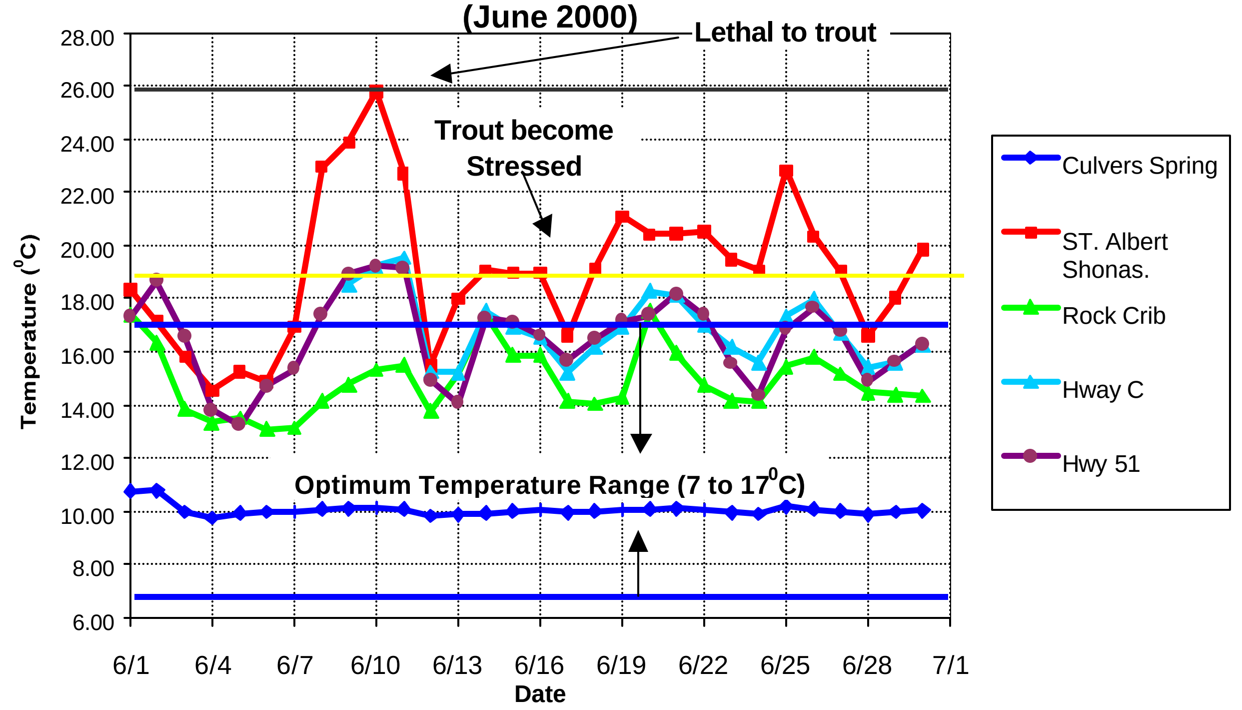
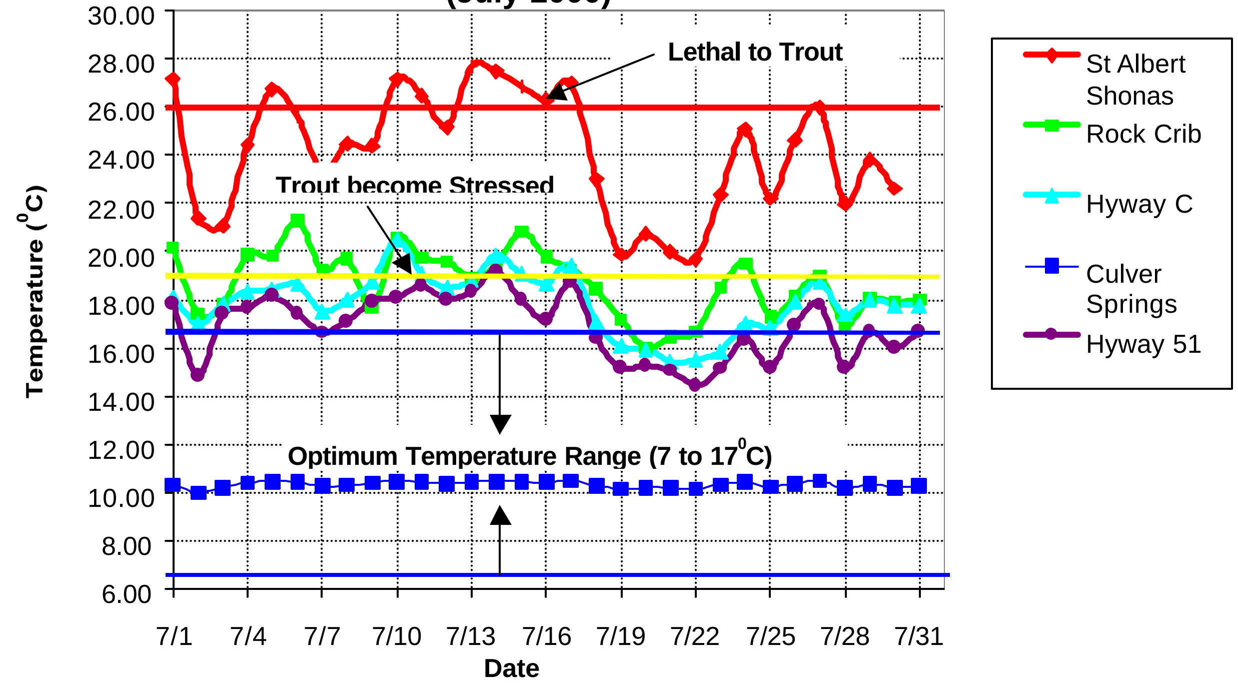


Figure 12. Daily Measured Temperature in Token Creek (July 2000)



## 4. Conclusions

In this study, we have clearly illustrated that the existing urban development in the Token Creek subwatershed causes an increase in runoff temperatures. Further, the increases recorded at Highway 51 suggest that these increases cause a permanent rise in stream temperature.

The daily temperatures of Token Creek are presented in Figures 11 and 12 for the months of June and July. During June, the temperature of Token Creek did not increase above the lethal limit (26° C, but did rise above 19° C at several points, including St. Albert Pond and St. Albert Shonas, as well as at the major points of confluence in Token Creek Subwatershed (Highway C and Highway 51). The runoff temperatures at the outfall of St. Albert Pond were directly impacted by the heat exchange between the black top and the rainfall. The temperatures recorded during June continued to rise after each rainfall, reaching levels above the threshold for trout (19° C), while temperatures recorded during July often reached the lethal threshold (26° C). The cumulative temperature increase caused by new developments will have a profoundly negative impact on the sensitive cold-water community in Token Creek if provisions to reduce the thermal impact are not implemented. In order to predict the conduction of heat to the runoff, TURM takes into account two factors:

1) Time of concentration. In the present model, the runoff from impervious areas is delivered instantaneously to the conveyance system. However, due to micro-depressions and evaporation, peak runoff flow does not begin instantaneously.
2) A correction in the convective transfer coefficient, resulting in less heat being lost to the air. The result is that the pavement heats rainwater up more and during longer periods, which is the case for runoff in impervious surfaces in urban settings.

TURM was validated successfully, predicting temperatures within 1° C of the actual temperatures recorded. The standard deviation was less than one, and significant at the 1% level for all sites when the field data was compared having the same mean ($\mu_1=\mu_2$). When used for estimating the difference between pavement and air temperatures, TURM produces reasonable results compared to the field data collected by USGS (pavement temperatures during this research were from 10 to 20° C above air temperature at midday). The results indicate that rain and air temperature are very closely related, a unique finding as little, if any, data has been published previously on the subject. Due to this correlation, it is possible to have an analytical solution based on the atmospheric variables that were incorporated into TURM.

Thermal impact analysis accounts for the impact that impervious areas have on stream temperatures. These impervious areas are generally associated with urban development and are a major source of thermal pollution in cold climates, not only because they remove water's ability to infiltrate into the soil, increasing the quantity of runoff, but because they store heat. As rainfall passes over impervious areas such as rooftops, roadways, and parking lots, it absorbs a portion of the energy stored in the surface. Cumulatively, the rise in runoff temperature causes an increase in the temperature of the stream, degrading the habitat and the diversity of the stream. To reduce the thermal impacts on streams, effective Storm Water Best Management Practices should be used. Some examples of BMPs include: rain gardens, rock catchment basins, swales, deep tilling, constructed wetlands, reforestation, and buffer strips

The model for the rock crib indicates that cooling can be obtained from rock storage for a limited time and that the cooling depends on the size of the crib. Because TURM is based on an analytical solution, we can extend the model to other temperature reduction devices, such as detention ponds, dry ponds, deep rock trenches, drain tiles filled with pea gravel, grassed swales, and green areas. These practices and many others can be utilized to reduce runoff temperatures; however, any device selected should be integrated as part of a storm water management plan.

As a result of this study, it is clear that municipalities and developers alike should implement a system of BMPs to reduce the impact that impervious areas have on lakes, rivers, streams, and wetlands. Rock cribs, which are a relatively new thermal reduction device developed by the Dane County Land Conservation Department, proved to be very successful at reducing runoff temperatures during this study. In addition, they are a practical, attractive option for new developments and can be used to augment existing thermal reduction systems. The use of BMPs is critical to reduce the thermal impacts caused by urban areas and imperviousness and to ensure the future diversity and health of aquatic ecosystems.

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