APPENDIX C: THERMAL IMPACT EDUCATIONAL MATERIAL[1]

UNDERSTANDING THERMAL IMPACT

INTRODUCTION:

Dane County is home to a number of streams that are identified by the Wisconsin Department of Natural Resources (WDNR) as Cold Water Communities. These streams are "capable of supporting cold water fish and other aquatic life, or serving as a spawning area for cold water fish species" (Wisconsin Administrative Code NR 102.04(3)(a). In an attempt to protect these streams from temperature increases, a thermal control section was included in the newly adopted countywide Erosion Control and Stormwater Management Ordinance. The ordinance requires stormwater management plans to include thermal control practices for all sites that drain to a Cold Water Community. For more information on the ordinance, see the Dane County Lakes and Watershed Commission's Erosion Control and Stormwater Management (http://www.co.dane.wi.us/commissions/lakes/stormwater.shtml) page.

URBANIZATION AND STREAM TEMPERATURE:

When water falls on the land surface, it can run off (travel over the land surface), infiltrate (enter the soil), or evaporate back into the atmosphere. Runoff water eventually reaches lakes or streams. Infiltrating water can either be taken up for use by plants and returned to the atmosphere (evapotranspiration) or continue to travel through the soil toward the groundwater. A portion of the groundwater moves toward streams and feeds them from below, maintaining their flow even during dry periods. This is known as baseflow.

Urbanization tends to replace porous surfaces with impervious surfaces. Surfaces such as grass or other vegetation allow some of the water that falls on them to infiltrate into the soil. Impervious surfaces (such as pavement or roofs) prevent infiltration, thus forcing the water that falls on them to run off. Therefore, as development increases, infiltration tends to decrease and runoff tends to increase.

The addition of impervious surfaces can increase stream temperature for two reasons. First, impervious surfaces absorb solar radiation, which raises their temperature. When a storm event occurs, some of this heat is transferred to the water that falls on these surfaces. This heated water becomes runoff and eventually flows into streams, raising their temperature. Second, impervious surfaces reduce infiltration, which decreases baseflow. Baseflow tends to have a cooling effect on stream temperature because

[1] This material is intended to be available both as web pages and as a downloadable document from the Dane County Land Conservation Department website.

groundwater is usually maintained at a relatively constant temperature, despite fluctuations in surface temperatures. As baseflow decreases, this cooling effect decreases as well. Therefore, as more impervious surfaces are created, stream temperatures increase due to the combined effect of increasing warmer runoff and decreasing cooler baseflow.

IMPLEMENTING THE ORDINANCE:

Since the Erosion Control and Stormwater Management Ordinance requires thermal control practices for development projects (which involve the cumulative addition of at least 20,000 ft^2 of impervious surfaces) on all sites that drain to a Cold Water Community, the first step in implementing the ordinance was to identify the portions of Dane County that fall into this category (thermally sensitive areas). A web-based locator tool was developed to allow interested parties to determine if a parcel of interest is within a thermally sensitive area. This tool is available at http://www.co.dane.wi.us/landconservation/cws/index3.html.

Once it is determined that a particular parcel is within a thermally sensitive area and will therefore require thermal control practices if developed, the next step is to choose management practices that would mitigate the thermal impact of a proposed development project. A Thermal Urban Runoff Model (TURM) for Dane County has been developed by the University of Wisconsin-Madison and the Dane County Land Conservation Department to assist developers in this process. The model predicts the impact of proposed development projects on stream temperatures. It uses weather parameters (such as air temperature, solar radiation, wind speed, rainfall temperature, rainfall intensity and relative humidity) along with development parameters (such as parcel area and percentage imperviousness) to predict runoff temperature from both pervious and impervious surfaces. These values are combined with pre-storm stream temperature and stream baseflow to predict the stream temperature resulting from a storm event. TURM has been tested in a field study in the Token Creek Watershed of Dane County, Wisconsin. Results have shown only small differences between measured and modeled stream temperatures, thus indicating that it is a reasonable model to use to predict stream temperature changes created by proposed development projects during storm events in Dane County.

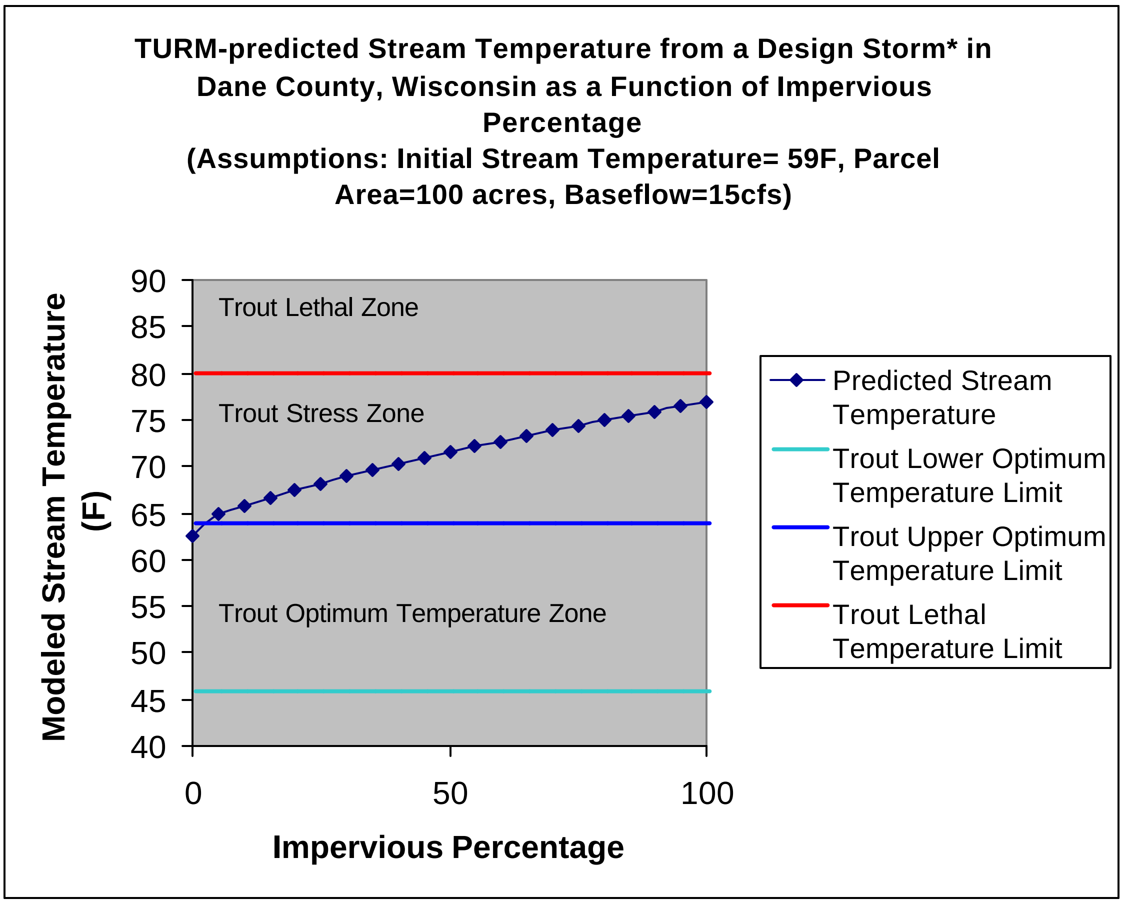
IMPORTANT VARIABLES AFFECTING STREAM TEMPERATURE:

A number of sample model runs were done to demonstrate how several variables interact to generate the stream temperatures predicted by the model. (See the assumptions section below for more information on the assumptions made in these model runs.)

Three of the important variables that determine stream temperature as a result of a storm event* are the impervious percentage of the parcel, the parcel area and the baseflow of the stream where the parcel drains.

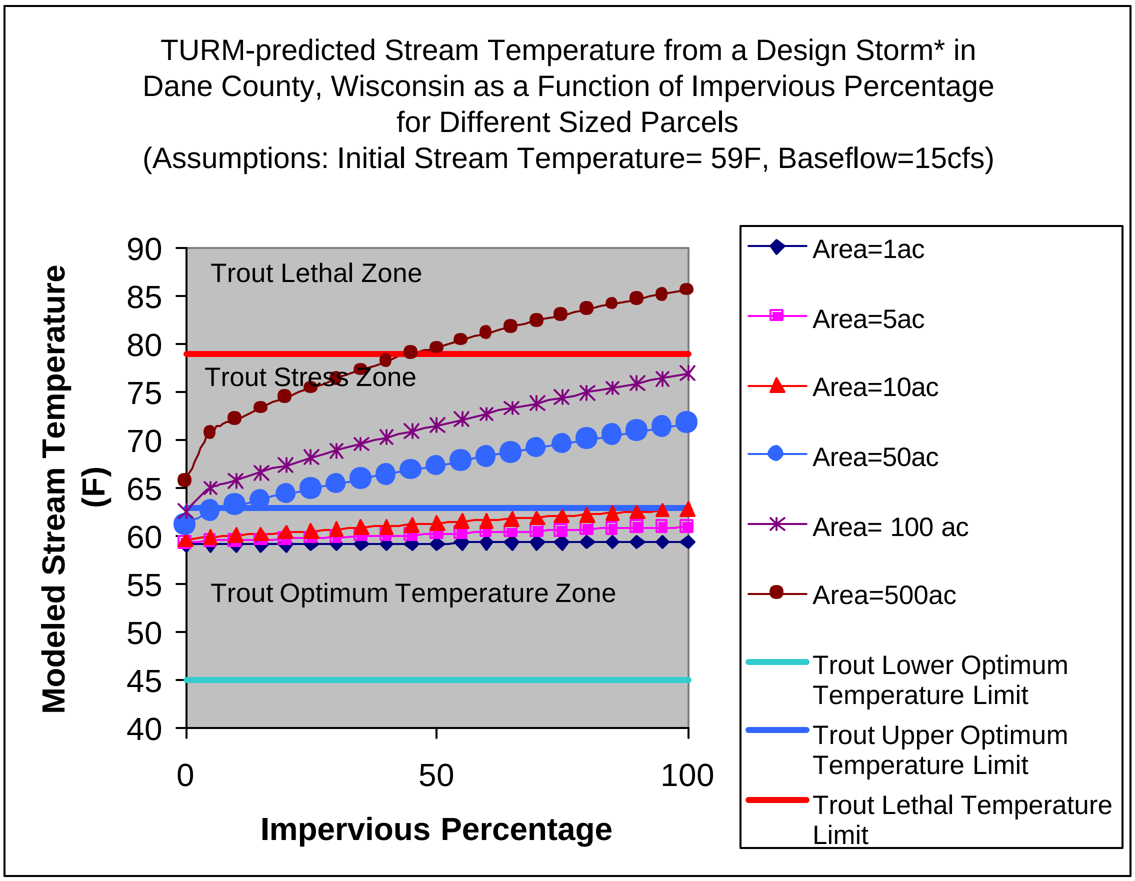
1. Impervious Percentage

For any given parcel, TURM shows that as the percentage of impervious surfaces increases, stream temperature increases as well. The graph below shows this trend for an example parcel area and baseflow.



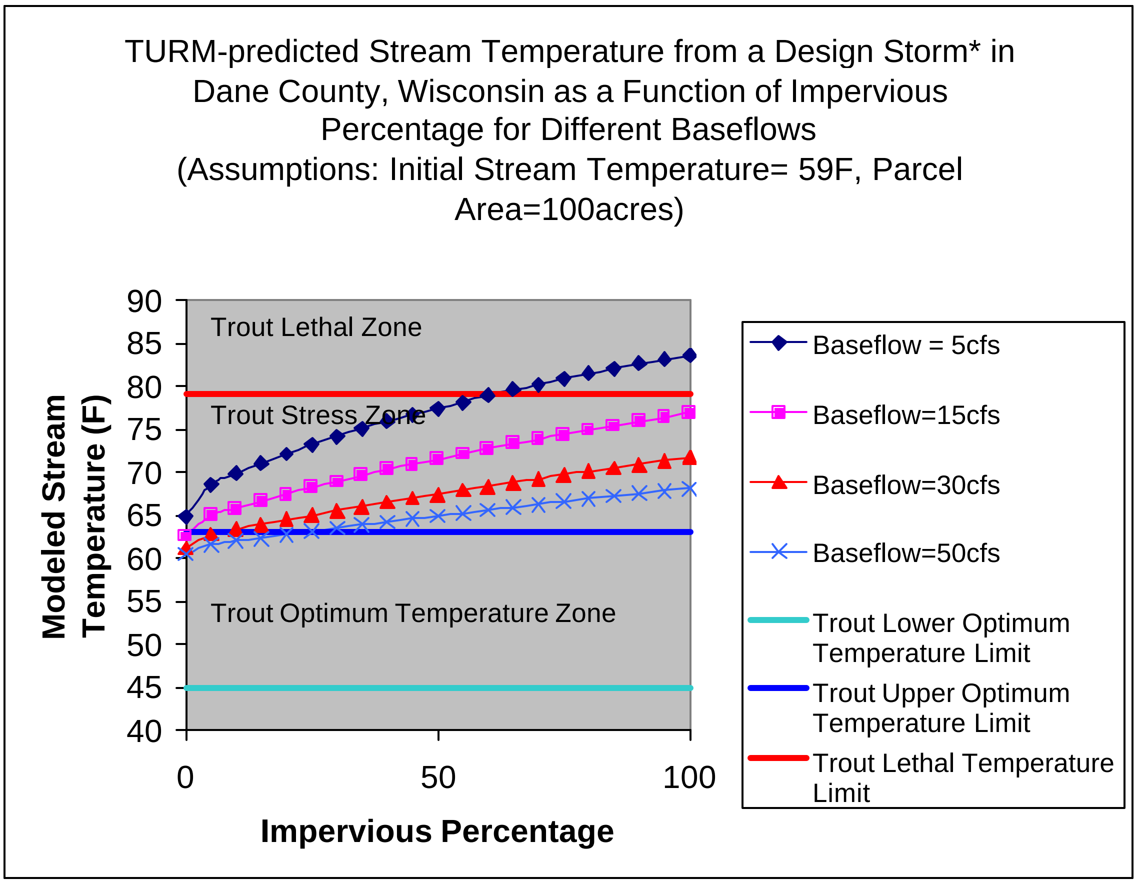
2. Parcel Area

Impervious percentage refers to the area of impervious surfaces of a parcel relative to the parcel's total area. For example, a 1-acre parcel with a 10% impervious percentage only contains 0.1 acres of impervious surfaces, while a 100-acre parcel with the same impervious percentage contains 10 acres of impervious surfaces. Therefore, the 100-acre parcel will contribute more heated runoff to the same stream, thus causing a much greater increase in stream temperature. The graph below shows the combined effects of parcel area and impervious percentage on stream temperature.



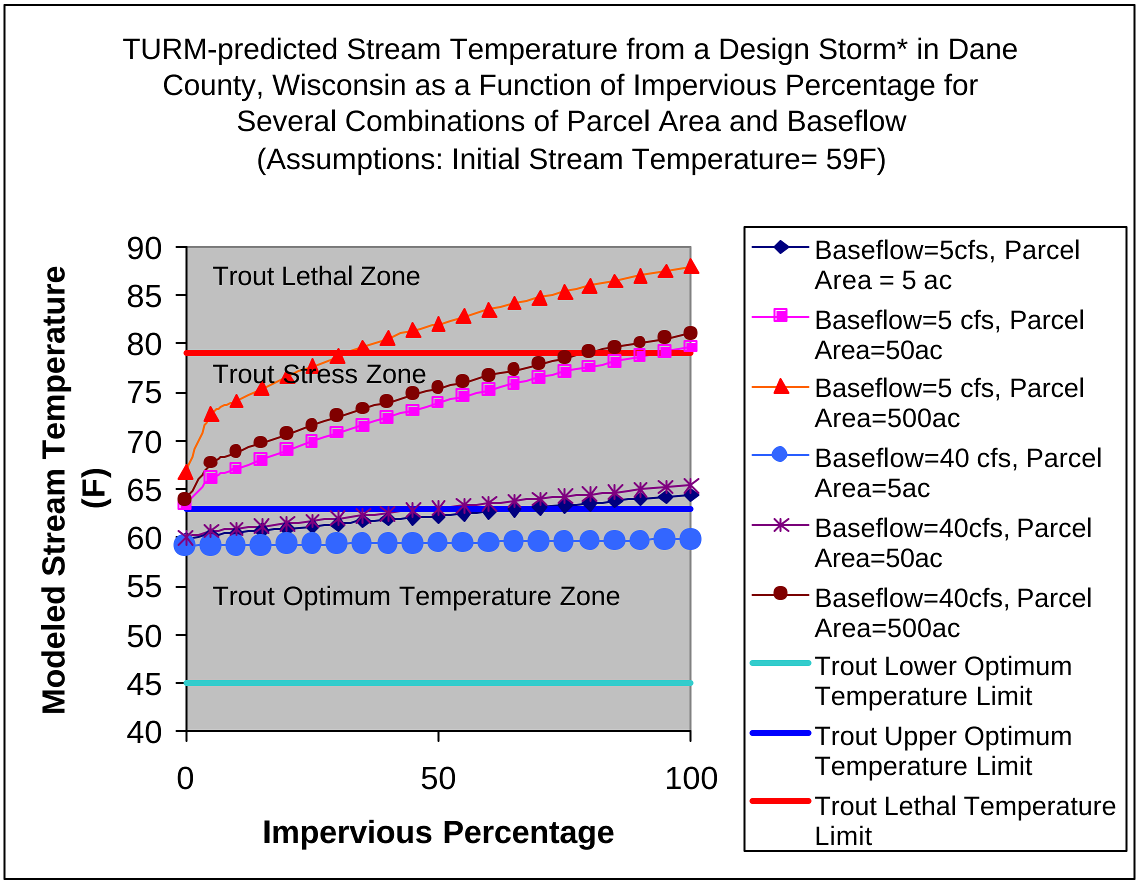
3. Baseflow

Baseflow is the flow rate (volume of water per unit time) of groundwater feeding a stream. During dry periods in the summer, baseflow can be assumed to be the major component of total stream flow rate. Small baseflows are found on small streams and tributaries, while large baseflows may be found on large streams. Stream temperature resulting from a storm event is affected by initial stream temperature and runoff temperature. At a given volume of heated runoff (determined from the parcel area and the percentage imperviousness) there is a greater stream temperature increase in a stream with a small baseflow than a stream with a large baseflow. This is because the runoff volume is a greater proportion of the stream volume in a small stream than a large stream. The graph below shows this trend for four different baseflows that are representative of the baseflow range of cold water streams in Dane County. Baseflows are given in cubic feet per second (cfs).



COMBINING ALL THREE VARIABLES:

The graph below shows the relative trends of how stream temperature varies with impervious percentage for different combinations of parcel areas and baseflows. For small parcels and large baseflows, there is little thermal impact to the stream, regardless of the impervious percentage. On the other hand, large parcels that drain into a stream with a small baseflow cause a significant stream temperature increase, even at relatively low impervious percentages. Other combinations of baseflow and parcel area result in stream temperature impacts in between these two extremes.



HOW CAN THERMAL IMPACT BE REDUCED?

The model runs used to create the graphs above represent the predicted thermal impact of those development scenarios if heated runoff has little opportunity to cool before entering a stream. The combinations of impervious percentage, parcel area and baseflow do not necessarily have the impact shown above if temperature reduction practices are used to reduce the thermal impacts of development. The two basic principles behind thermal reduction practices are to slow down heated runoff on its way to the stream (to give it time to cool through evaporation and contact with cooler surfaces) and to increase infiltration of heated runoff (to reduce the volume of heated water that reaches the stream). Some commonly used temperature reduction practices include building rock cribs, thermal swales and retention ponds. These practices have been incorporated into TURM to enable it to predict the thermal impact of a proposed development plan after they are installed. For more information about these practices, see the Erosion Control and Stormwater Management Manual. To obtain a copy of the manual, refer to http://www.co.dane.wi.us/commissions/lakes/stormwatermanual.htm.

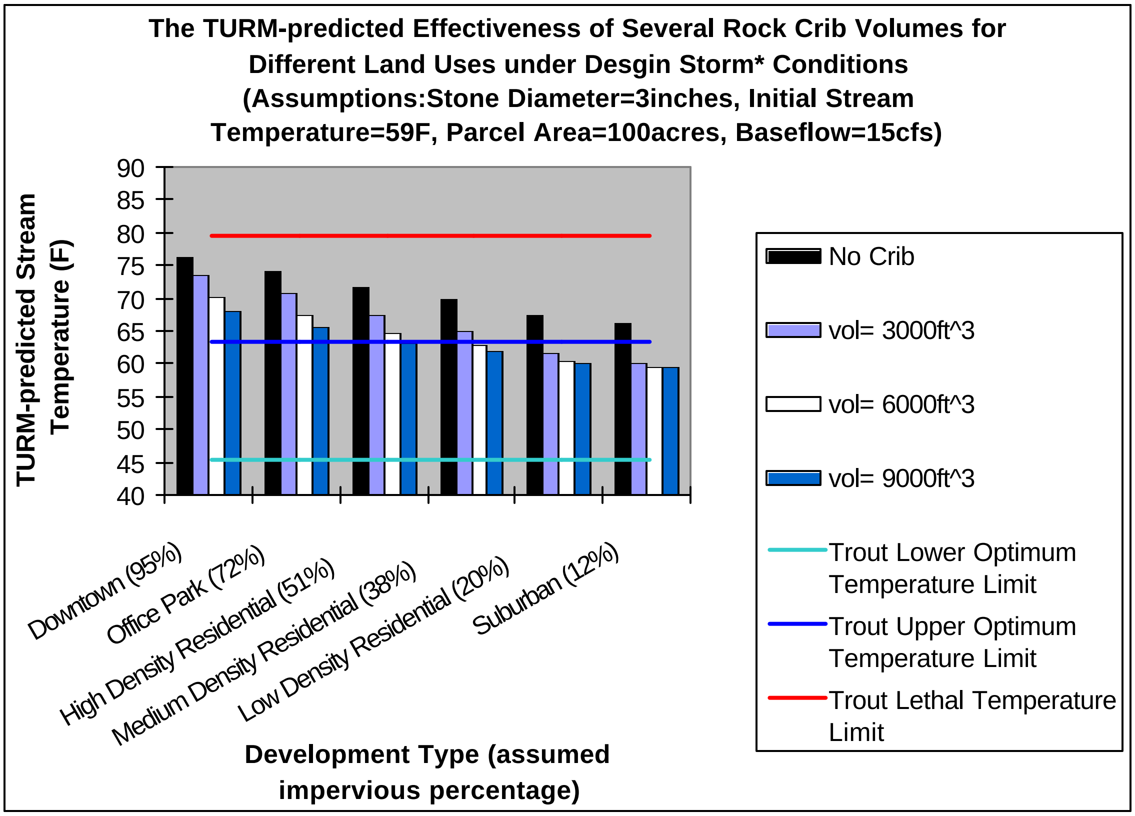
1. The Effect of Rock Cribs

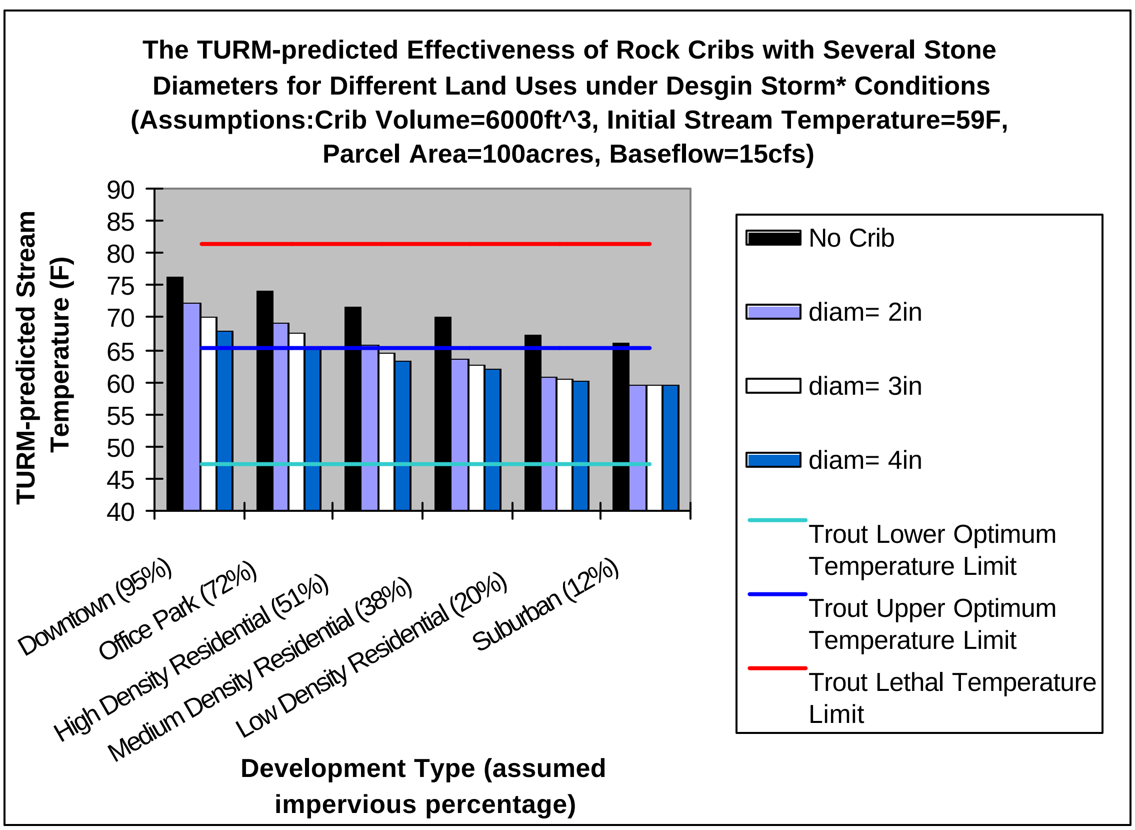
A rock crib is a bed of rocks that receives runoff from a developed area. The purpose of such a structure is to cool heated runoff during its journey to a cold water stream, thereby reducing its thermal impact. This cooling occurs because of heat exchange between hotter water and cooler rocks.

The following graphs show the TURM-predicted temperature reduction that can be achieved by rock cribs under different land uses. The assumed impervious percentages for each land use were based on measured values from the TURM validation study. It is important to note that these graphs are only meant to demonstrate the effectiveness of rock cribs at reducing runoff temperatures. They should not be used to determine an appropriate rock crib design for a particular development project.

The first graph indicates that larger rock cribs are generally more effective for reducing the thermal impact of developed areas. As hot water moves through a crib, it is cooled by the rocks, but it also raises the rocks' temperature, making them less able to reduce the temperature of additional heated water. Therefore, a larger rock crib (with more cool rocks) generally offers a greater capacity for heat exchange between water and rocks, making it more effective for reducing runoff temperatures. The increasing effectiveness of larger rock cribs is most evident for high-density land uses. These areas produce the highest runoff temperatures, so increasing the rock crib volume is very effective for increasing heat exchange between water and rocks. Because low-density land uses produce lower runoff temperatures, a relatively small rock crib is able to achieve the maximum heat exchange between water and rocks and further increases in rock crib size will produce little additional stream temperature reductions.

The second graph indicates that larger stone diameters within a crib of a given volume increase the crib's ability reduce runoff temperature. Stones with larger diameters are warmed more slowly by the runoff passing through them, so they are more able to reduce the temperature of additional runoff. Increasing stone diameter is most effective for reducing runoff temperatures in high-density developments. Again, this is because the temperature difference between runoff and rocks in such areas is relatively large, so increasing stone diameter is more able to increase heat exchange between the two.


The TURM-predicted Effectiveness of Several Rock Crib Volumes for Different Land Uses under Desgin Storm* Conditions (Assumptions:Stone Diameter=3inches, Initial Stream Temperature=59F, Parcel Area=100acres, Baseflow=15cfs)
TURM-predicted Stream Temperature (F)
90
85
80
75
70
65
60
55
50
45
40
Downtown (95%)
Office Park (72%)
High Density Residential (51%)
Medium Density Residential (38%)
Low Density Residential (20%)
Suburban (12%)
Development Type (assumed impervious percentage)
No Crib
vol= 3000ft^3
vol= 6000ft^3
vol= 9000ft^3
Trout Lower Optimum Temperature Limit
Trout Upper Optimum Temperature Limit
Trout Lethal Temperature Limit

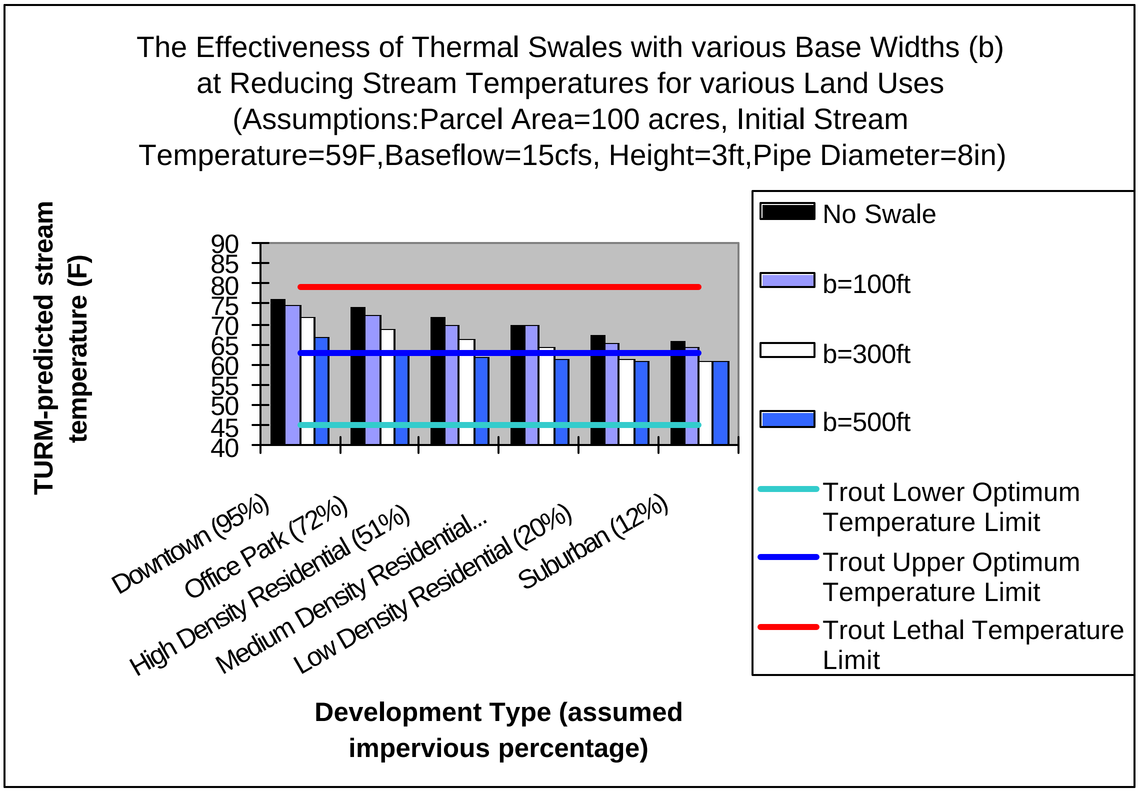

The TURM-predicted Effectiveness of Rock Cribs with Several Stone Diameters for Different Land Uses under Desgin Storm* Conditions (Assumptions:Crib Volume=6000ft^3, Initial Stream Temperature=59F, Parcel Area=100acres, Baseflow=15cfs)
TURM-predicted Stream Temperature (F)
90
85
80
75
70
65
60
55
50
45
40
Downtown (95%)
Office Park (72%)
High Density Residential (51%)
Medium Density Residential (38%)
Low Density Residential (20%)
Suburban (12%)
Development Type (assumed impervious percentage)
No Crib
diam= 2in
diam= 3in
diam= 4in
Trout Lower Optimum Temperature Limit
Trout Upper Optimum Temperature Limit
Trout Lethal Temperature Limit

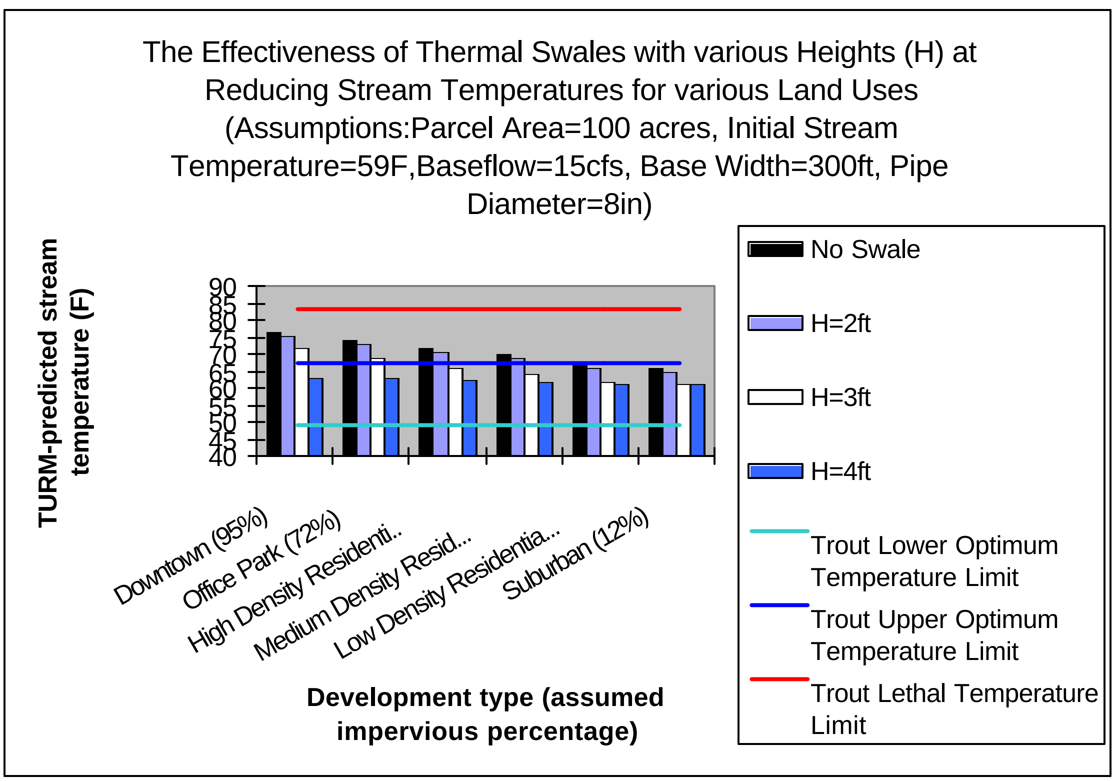
2. The Effect of Thermal Swales

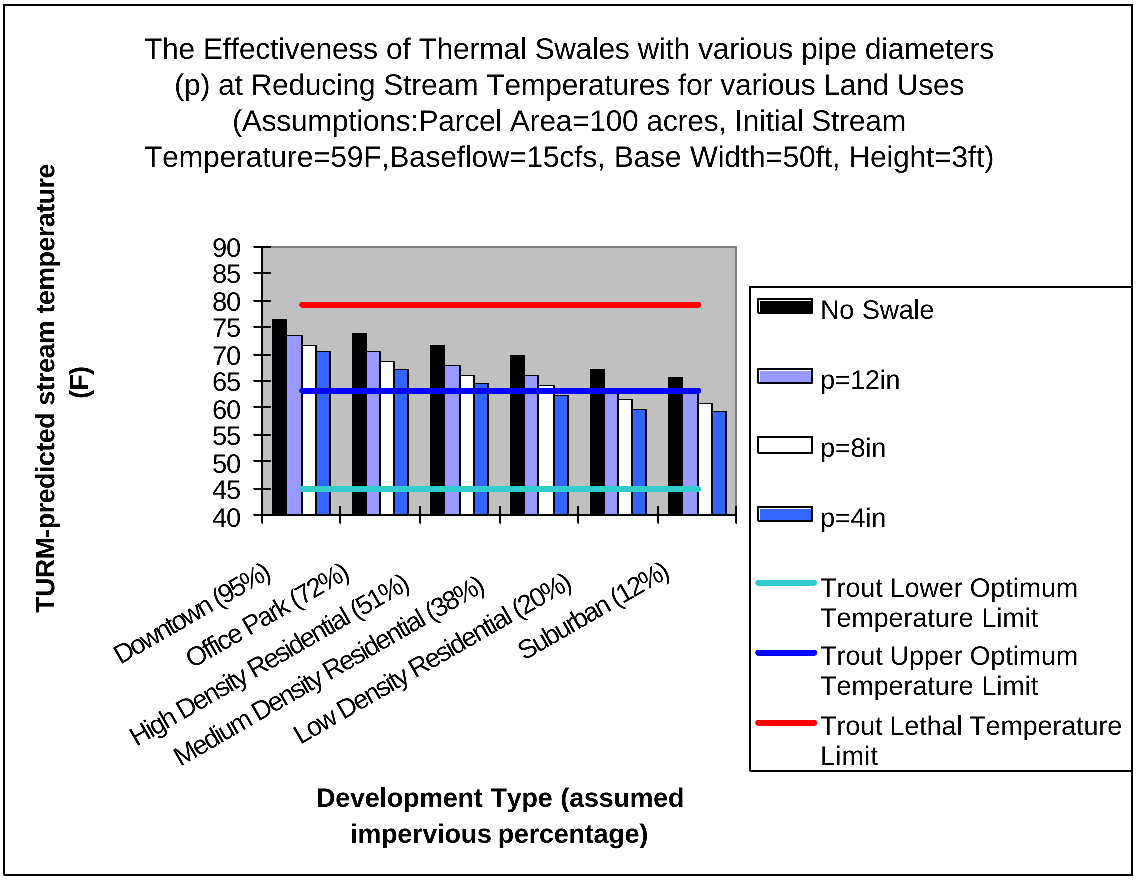
A thermal swale is a vegetated trench that receives runoff from a developed area. A gentle slope along the bottom of the swale directs runoff toward an outlet pipe, which is at the bottom of one end of the swale. A swale allows for some cooling of heated runoff water through evaporation and some reduction in heated runoff volume through infiltration, both of which contribute to its ability to reduce the thermal impact of runoff from a developed area to a cold water stream. However, the most important reason why a swale can be an effective structure to reduce thermal impact is that it can reduce the rate of delivery of heated runoff to a stream. If heated runoff is added slowly enough to a cold water stream, it does not raise the stream's temperature significantly because the runoff flow is insignificant relative to the total stream flow.

The first two graphs below demonstrate how different swale base widths and depths affect the TURM-predicted stream temperature resulting from a storm event for several land uses. Like a rock crib, a swale must be sufficiently sized in order to be effective. If the volume of runoff from a parcel exceeds the volume of the swale, the swale will overflow and the heated runoff will be delivered to the cold water stream at a rate uncontrolled by the swale outlet. If a swale's volume is smaller than the runoff volume, then increasing the swale volume (either by increasing base width or depth) will make the swale more effective since it will be able to control the delivery rate of a larger portion of the runoff volume to the cold water stream. This effect is seen on the first two graphs for the land uses with higher impervious percentages (those with greater runoff volumes). However, if a swale's volume is already sufficient to hold all of the runoff from a parcel, then increasing its volume further leads to relatively small increases in effectiveness (due to slight increases in cooling by evaporation and infiltration in larger swales). The first two graphs also show that increasing a swale's volume beyond a certain size has little impact on stream temperature in the lower impervious percentage land uses (low density residential and suburban).

The third graph below shows that swale with smaller outlet pipe diameters are more effective for minimizing the stream temperature increases caused by heated runoff from developed areas. Smaller outlet pipes allow heated runoff to be introduced into a stream more slowly, making less able to increase the stream's temperature. This trend is apparent for all land uses.


The Effectiveness of Thermal Swales with various Base Widths (b) at Reducing Stream Temperatures for various Land Uses (Assumptions:Parcel Area=100 acres, Initial Stream Temperature=59F,Baseflow=15cfs, Height=3ft,Pipe Diameter=8in)
TURM-predicted stream temperature (F)
90
85
80
75
70
65
60
55
50
45
40
Downtown (95%)
Office Park (72%)
High Density Residential (51%)
Medium Density Residential...
Low Density Residential (20%)
Suburban (12%)
Development Type (assumed impervious percentage)
No Swale
b=100ft
b=300ft
b=500ft
Trout Lower Optimum Temperature Limit
Trout Upper Optimum Temperature Limit
Trout Lethal Temperature Limit


The Effectiveness of Thermal Swales with various Heights (H) at Reducing Stream Temperatures for various Land Uses (Assumptions:Parcel Area=100 acres, Initial Stream Temperature=59F,Baseflow=15cfs, Base Width=300ft, Pipe Diameter=8in)
TURM-predicted stream temperature (F)
90
85
80
75
70
65
60
55
50
45
40
Downtown (95%)
Office Park (72%)
High Density Residenti..
Medium Density Resid...
Low Density Residentia...
Suburban (12%)
Development type (assumed impervious percentage)
No Swale
H=2ft
H=3ft
H=4ft
Trout Lower Optimum Temperature Limit
Trout Upper Optimum Temperature Limit
Trout Lethal Temperature Limit



THERMAL IMPACT AT THE WATERSHED SCALE

Although the thermal control section of the ordinance focuses on controlling thermal impact contributed by individual parcels, the cumulative thermal impact of development within a cold water watershed is also important. (A cold water watershed refers to the area of land that drains to the most downstream point of a cold water stream.) For example, TURM may predict little thermal impact for a relatively small parcel whose runoff enters a moderate-sized cold water stream, even at moderate levels of imperviousness. However, if many small parcels within a cold water watershed are developed in this manner, the TURM prediction for a parcel's thermal impact will not be an accurate prediction of the total thermal impact of development on that cold water stream. Therefore, stormwater management plan reviewers will find it necessary to run TURM for an entire cold water watershed (instead of for an individual parcel) in order to assess the overall thermal impact of additional development in that watershed.

ASSUMPTIONS:

1. Weather:

The weather parameters were selected to simulate a typical late-afternoon summer thunderstorm in Dane County, Wisconsin. TURM is very sensitive to many of these parameters, therefore it is not appropriate to use these model runs to make assumptions about the thermal impacts of development in areas outside of Dane County where different weather parameters may be more appropriate. The values used for the following weather parameters are listed below:

Maximum Solar Radiation: 970 W/m^2
Maximum Air Temperature: 78 F
Minimum Air Temperature: 58.6 F
Relative Humidity prior to the storm: 50%
Wind Speed: 2.9 ft/s
*Depth of Rainfall: 1.2 inch
*Duration of Rainfall: 4.5 hours
*Hour of the Start of Rainfall: 2:00 pm
*Solar Radiation during the storm: 160 W/m^2
*Rainfall Temperature: 67.5 F

2. Time of Concentration:

The time of concentration is defined as the time it takes for all parts of a parcel to be contributing runoff to a point of interest in a channel. There are three different runoff patterns that water goes through as it travels from the upland parts of a parcel to the point of interest. Runoff starts as sheet flow, which refers to water that is uniformly traveling over the whole land surface as a “sheet”. Sheet flow then gives way to shallow concentrated flow, which happens when water starts to become more concentrated on the land surface. Eventually, shallow concentrated flow turns into open channel flow as runoff water moves downstream and concentrates in man-made or natural channels. The time of concentration is the sum of the time it takes runoff to travel in each of these patterns.

Slightly different assumptions about time of concentration were used for residential and commercial areas. The residential time of concentration parameters were used for land uses with less than 50% imperviousness and the commercial time of concentration parameters were uses for land uses with at least 50% imperviousness. The following table demonstrates how time of concentration was calculated for this material:

Residential Fixed T of C parameters:

Flow Type	Length (ft)	Slope	Surface	Velocity (ft/sec)	TT (hr)
Sheet	75	3.00%	dense grass	n/a	0.169
SC	varies, see below	3.00%	unpaved	2.79(from slope)	varies, see below
Channel	200	1.00%	n/a	1.5	0.337

Parcel Area (ac)	Assumed SC Flow Length (~square root of parcel area)	SC Flow Travel Time (hr)	TC (hr)
1	200	0.02	0.226
5	400	0.04	0.246
10	600	0.06	0.265
50	1400	0.139	0.345
100	2000	0.199	0.405
500	4600	0.457	0.663

Commercial Fixed T of C parameters:

Flow Type	Length (ft)	Slope	Surface	Velocity (ft/sec)	TT (hr)
Sheet	varies, see below	1.00%	smooth surface	n/a	varies, see below

Parcel Area (ac)	Assumed SC Flow Length (~square root of parcel area)	Sheet Flow Travel Time (hr)	TC (hr)
1	200	0.049	0.049
5	400	0.085	0.085
10	600	0.117	0.117
50	1400	0.231	0.231
100	2000	0.307	0.307
500	4600	0.599	0.599

SC= shallow concentrated
TT=travel time
TC=time of concentration

Disclaimer: This material was created as an educational tool to help users understand the relative thermal impacts of developed parcels of different sizes and different impervious percentages, whose runoff enters streams with different baseflows in Dane County, Wisconsin. It should not be used as a predictive tool to design a stormwater management plan to comply with the new Dane County Stormwater Ordinance because not all of the assumptions made for these model runs are necessarily appropriate for every parcel in Dane County.

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