Kinnickinnic River at River Falls, Wisconsin
Thermal Study

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St. Paul District
St. Paul, Minnesota

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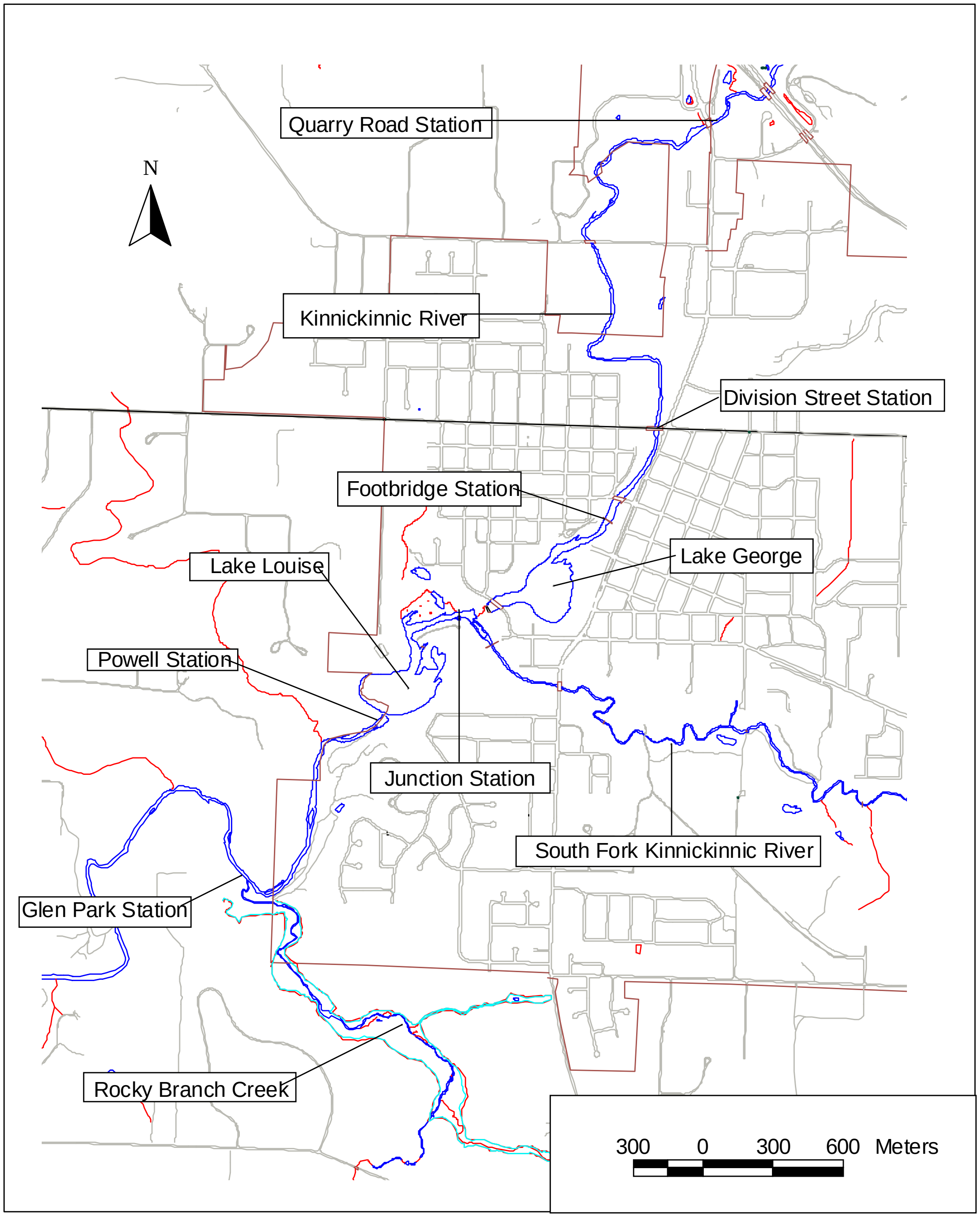
1.0 INTRODUCTION

The purpose of this study was to construct a Kinnickinnic River CE-QUAL-W2 thermal model that would help evaluate the efficacy of different storm runoff management plans currently being developed to manage a cold-water fishery downstream of River Falls, Wisconsin.

The Kinnickinnic River, a premier trout stream known for dense populations of brown trout, is an at-risk resource from the effects of a rapidly growing community (Johnson, 1995). Located in west-central Wisconsin, the City of River Falls (population 12,000) saw a 20 percent population increase in the 1990's. The city's population is projected to grow to 16,500 by the year 2010 (Johnson and Lamberson, 2003). As the community grows and creates more impervious land cover, the Kinnickinnic River would most likely be subjected to increased storm runoff flows and elevated temperatures.

In 1996 and 1997, the Wisconsin Department of Natural Resources (DNR) monitored stream temperatures upstream and downstream of downtown River Falls (Figure 1.1). During that time, flashes of increased stream temperatures downstream of the city's storm sewer effluents were observed during summer storm events. The magnitude of these temperature spikes was pronounced and usually ranged between 2 and 4 degrees C.

Figure 1.1 - Stream monitoring stations- Kinnickinnic River flowing through two impoundments and downtown River Falls



In Figure 1.2, stream temperatures at different points along the Kinnickinnic River are shown for two particular 1997 storms. Both figures depict a stream temperature spike that appeared below Quarry Road, became diminished at Junction Station, and then reappeared below Lake Powell.

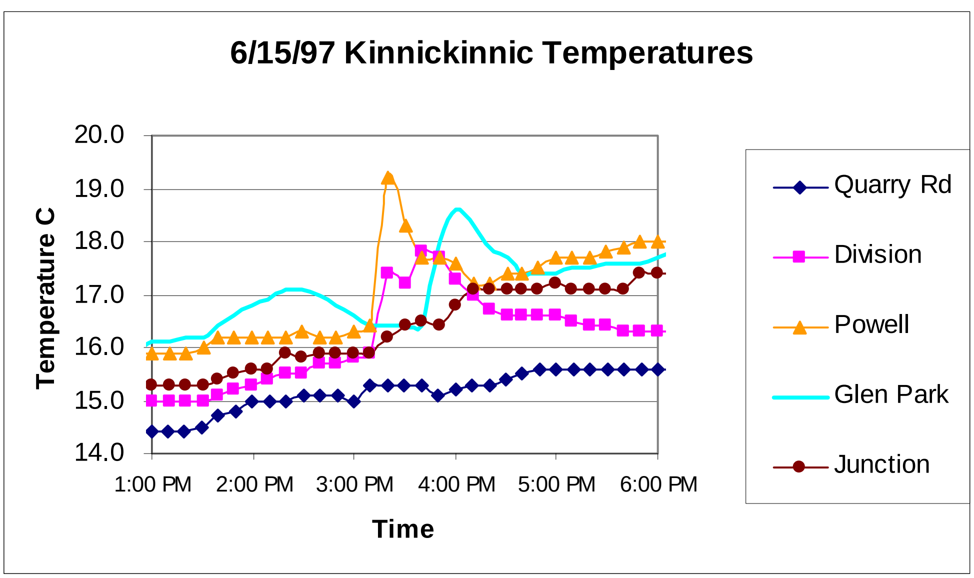
The temperature spikes seen between Quarry Road and Lake George were probably due to storm sewers discharging heated runoff from impervious areas into the river.

The temperature regime seen at Junction Station was primarily an outcome of mixing outflows from Junction Dam and the South Fork Kinnickinnic (Figure 1.3). During the 6/15/97 and 7/1/97 storm sewer runoff periods, the temperatures observed at Junction Station were cooler than the temperatures observed above Lake George at Division Station and at the South Fork Kinnickinnic Station. The dam's discharge at Lake George effectively dampened the temperature spike seen above the reservoir and overwhelmed with much larger flows the warmer temperatures contributed by the South Fork Kinnickinnic at Junction Station.

After the storm runoffs flowed through Powell Dam, a temperature spike reappeared at Powell station and at Glen Park for both storm events. Again, the spikes were probably caused by storm sewer discharges into Lake Louise and into the Kinnickinnic River below Powell Dam. The reason that the maximum temperatures seen at Glen Park were less than the maximum temperatures seen at Powell Station was probably due to the relatively cold-water discharge from Rocky Branch into the Kinnickinnic River immediately upstream from Glen Park.

Figure 1.2 - Stream temperatures observed during a) 6/15/97 and b) 7/1/97 at different river stations along the Kinnickinnic River

a)



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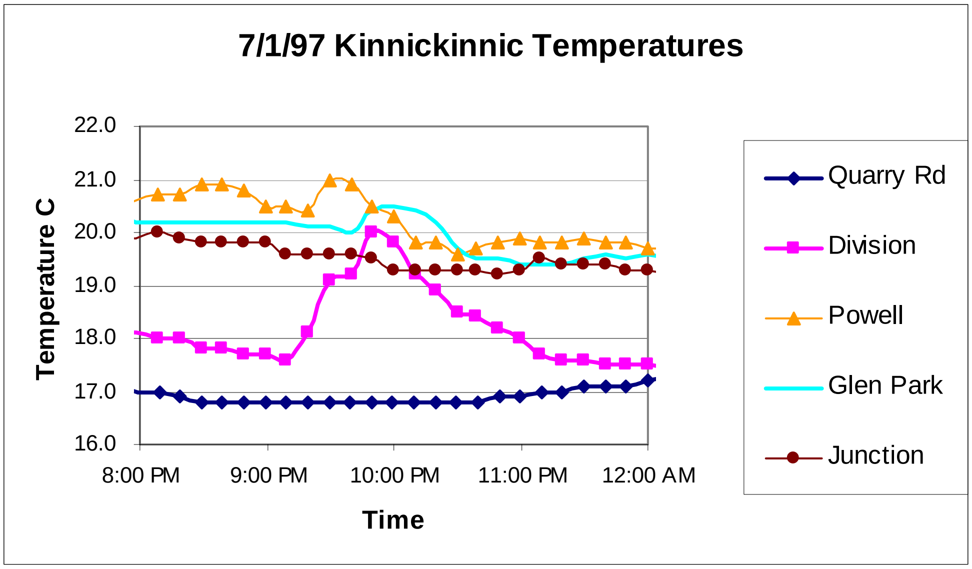
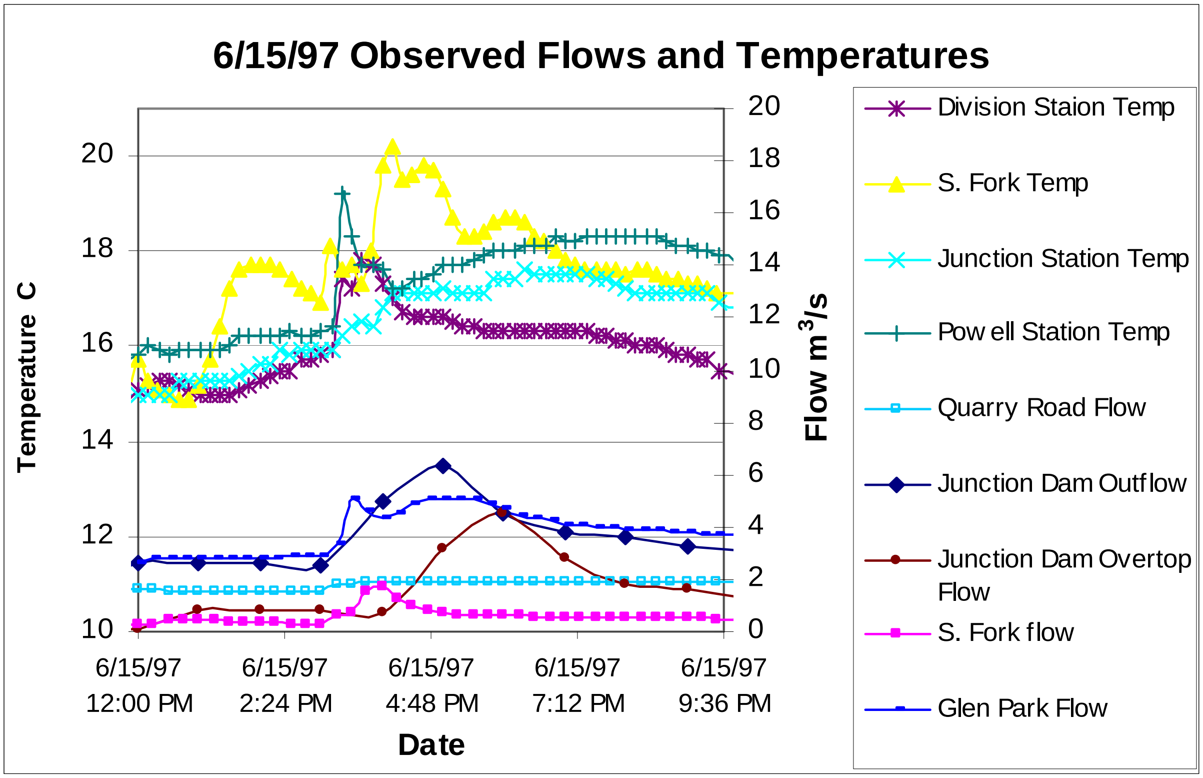


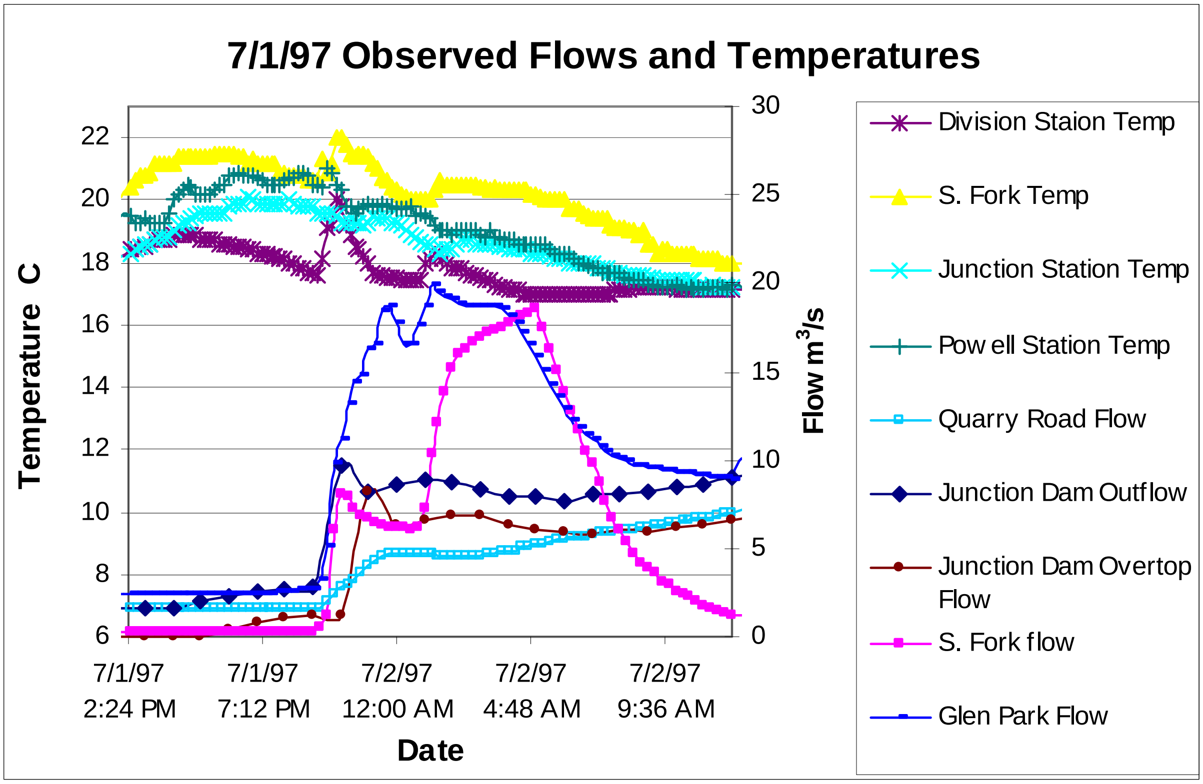
Supported by earlier studies that documented elevated stream temperatures after storm events (Johnson, 1995), a need to address the effects of the city's storm sewer system downstream developed. Utilizing data from these two 1997 rain events and a dry period in August 1997, a CE-QUAL-W2 model was created to simulate the June 15, 1997, and July 1, 1997, storm sewer runoff conditions and the 1997 summer base flow condition. The intended use for the model was to assist water resource managers in evaluating how different storm runoff management plans will alter the temperature and flow regimes observed during these three specific time periods.

Figure 1.3 - Stream temperatures and flows observed during a) 6/15/97 and b) 7/1/97 storms at different river stations along the Kinnickinnic River and South Fork Kinnickinnic River

a)



b)

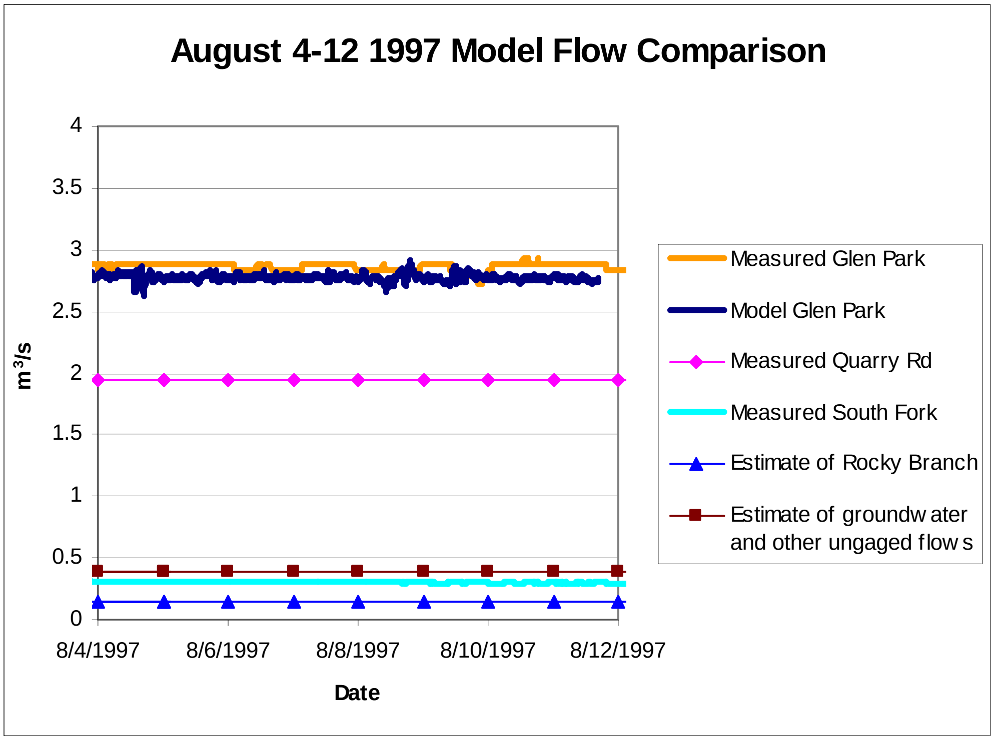


2.0 STUDY AREA

The Kinnickinnic River flows approximately 22 miles from its headwaters in southeastern St. Croix County, Wisconsin, to its confluence with the St. Croix River. On average, it is about 40 feet wide and 2 feet deep. Inside the study area between Quarry Road and Glen Park (Figure 1.1), the Kinnickinnic River runs through two hydroelectric dams that impound Lake George and Lake Louise. Lake George is a relatively shallow reservoir with depths less than 4 feet, except in the old river channel (~ 4 to 8 feet) and immediately upstream of the dam (~ 8 to 20 feet). Lake Louise is of similar shape, but does not have the severe drop-off upstream of its dam as in Lake George. The reported surface area and storage of Lake George at normal pool elevation (865.5 feet) are 16.5 acres and 155 acre-feet, respectively. The reported surface area and storage of Lake Louise at normal pool elevation (821.8 feet) are 19.3 acres and 64 acre-feet, respectively (Ayers, April 1988).

The major tributary entering the Kinnickinnic River is the South Fork Kinnickinnic. The South Fork Kinnickinnic enters just below Lake George and contributes around 5 to 10 percent of the Kinnickinnic River's flows. Just upstream of Glen Park, a smaller tributary, called Rocky Branch, enters the Kinnickinnic River with minimal flows but discharges significantly cooler temperatures. For the 1997 base flow condition (Figure 2.1), the Kinnickinnic River recorded flows averaging around 68.5 cubic feet per second (cfs) at Quarry Road and 100.5 cfs at Glen Park. The South Fork Kinnickinnic averaged about 10.5 cfs and Rocky Branch was estimated at about 3.5 cfs. To balance the flows observed at Glen Park, 14 cfs were distributed into the model. These ungaged flows were assumed to be a combination of groundwater and small drainages that enter the Kinnickinnic River between Quarry Road and Glen Park. The temperatures of these flows were estimated to be a constant 11 degrees C. In Lake Louise, a wastewater treatment plant's effluent was represented in the model with fairly constant flows of 1.4 cfs at 20.5 degrees C.

Figure 2.1 - Stream base flows observed between August 4 and 12, 1997, at different river stations along the Kinnickinnic River and the base flow model flows at Glen Park



3.0 MODEL METHODOLOGY

3.1 Model Description

CE-QUAL-W2 version 3.1 is a two-dimensional (longitudinally/vertical), hydrodynamic and water quality model suitable for relatively long and narrow water bodies that exhibit vertical and longitudinal gradients. The original model was developed by Edinger and Buchak (1975) and was known as LARM (Laterally Averaged Reservoir Model). Since then, the model has been continually updated by the U.S. Army Corps of Engineers Waterways Experiment Station and was renamed CE-QUAL-W2. At its present version 3.1, the model has been shown to be successful in accurately modeling lakes, reservoirs, estuaries, and rivers (Cole and Wells, 2002).

3.2 Model Inputs

In order to run CE-QUAL-W2 on the Kinnickinnic River, several input data sets were needed. The available data supplied for the study were from the summer of 1996 and 1997. Because of the lack of tributary data from 1996, model runs were completed using only 1997 data. Inputs to the model included bathymetry data, meteorological data, time-varying in-stream water temperatures and flows, hourly dam releases, and time-varying storm sewer temperatures and flows (generated by a separate thermal model).

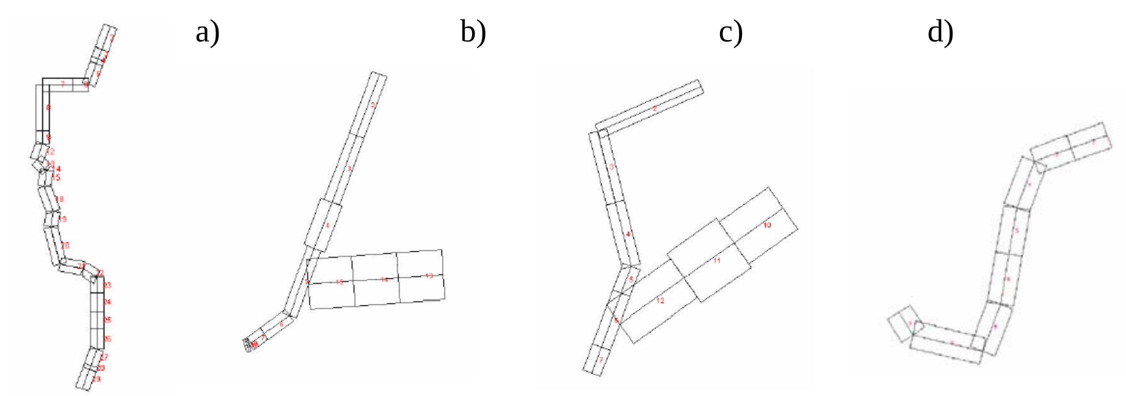
Bathymetry:

For this study, stream temperatures were simulated by splitting the study area into four water bodies:

1) Upper Kinnickinnic (Quarry Road to Lake George)
2) Lake George
3) Lake Louise
4) Lower Kinnickinnic (Lake Louise to Glen Park)

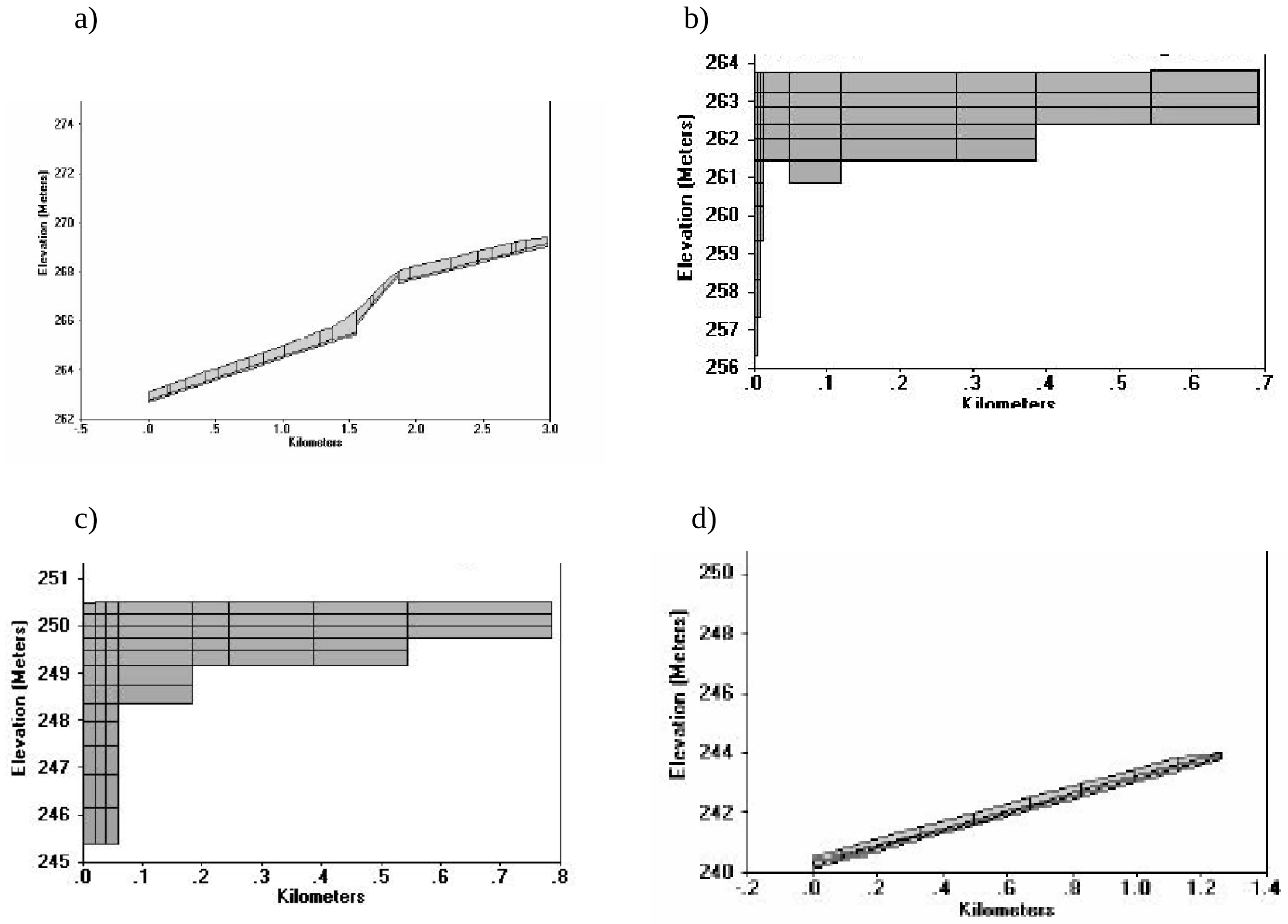
Each water body was divided longitudinally into a number of segments ranging from 5 meters at Junction Dam (Lake George) to over 250 meters along the upper and lower reaches of the river (Figure 3.1). The bathymetry for the river sections was estimated from HEC-2 data files originally developed from cross sections used in the city's flood insurance study (FIS report, 2002). The reservoirs' bathymetries were estimated from several different sources, including cross section surveys, a topographic map of Lake George completed as a school project, and volume and surface area data furnished by the River Falls Municipal Utility. Because of CE-QUAL-W2's assumption of laterally averaged segments, Lake George and Lake Louise were depicted in the model as having side branches. This modification was done to account for flows being heavily influenced by the old river channel and appearing to short-circuit the shallower areas of the reservoirs.

Figure 3.1 - Water body segments: a) Upper Kinnickinnic b) Lake George c) Lake Louise and d) Lower Kinnickinnic



Vertically, the water bodies were divided into 14 layers ranging from 0.1 meter to 1.0 meter (Figure 3.2).

Figure 3.2 - Side view of the four water bodies: a) Upper Kinnickinnic, b) Lake George, c) Lake Louise, and d) Lower Kinnickinnic



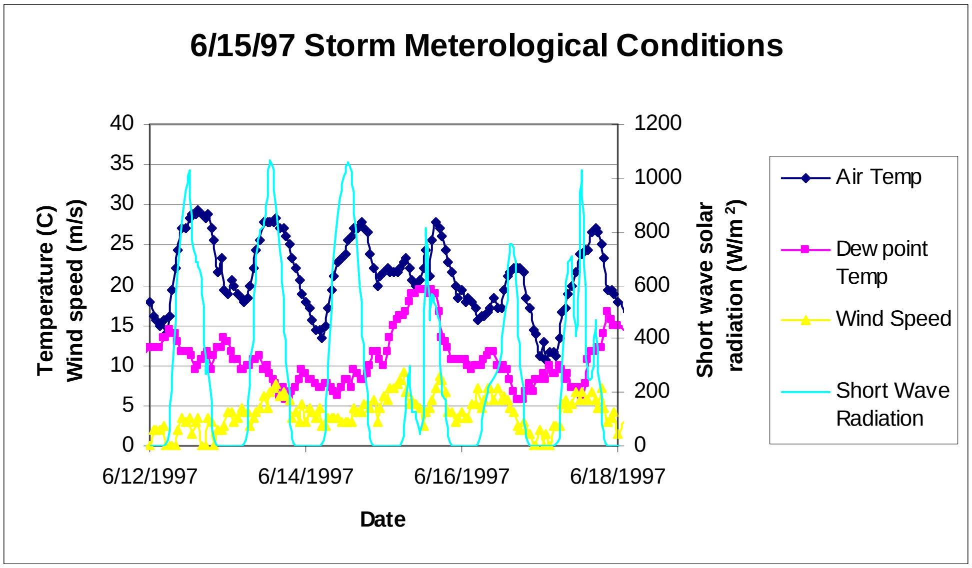
River bottom slopes for the Upper Kinnickinnic and the Lower Kinnickinnic were estimated from water surface levels generated by a HEC-2, 100 cfs steady-state simulation. The Upper Kinnickinnic part of the model grid was divided into three branches with differing slopes. The Lower Kinnickinnic was represented by a single branch and slope. The bottom slopes of the two impoundments were zero.

Meteorological Data:

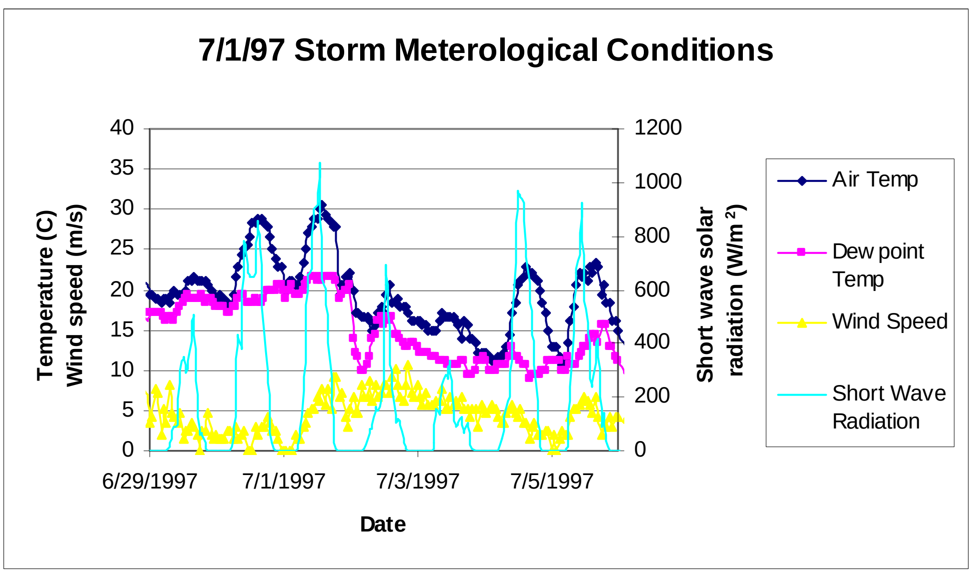
Types of meteorological data required were air temperature, dew point, wind speed, wind direction, and cloud cover. As an added and more accurate method to measure surface heat exchange, incident short-wave solar radiation was also included from a local source. All other meteorological data were taken from the Minneapolis-St. Paul International Airport, except for cloud cover, which was taken from the Eau Claire, Wisconsin, Airport (Figure 3.3 a-c).

Figure 3.3 - Meteorological Data during the (a) June 15, 1997 storm, (b) July 1, 1997 storm and (c) August 1997 base flow

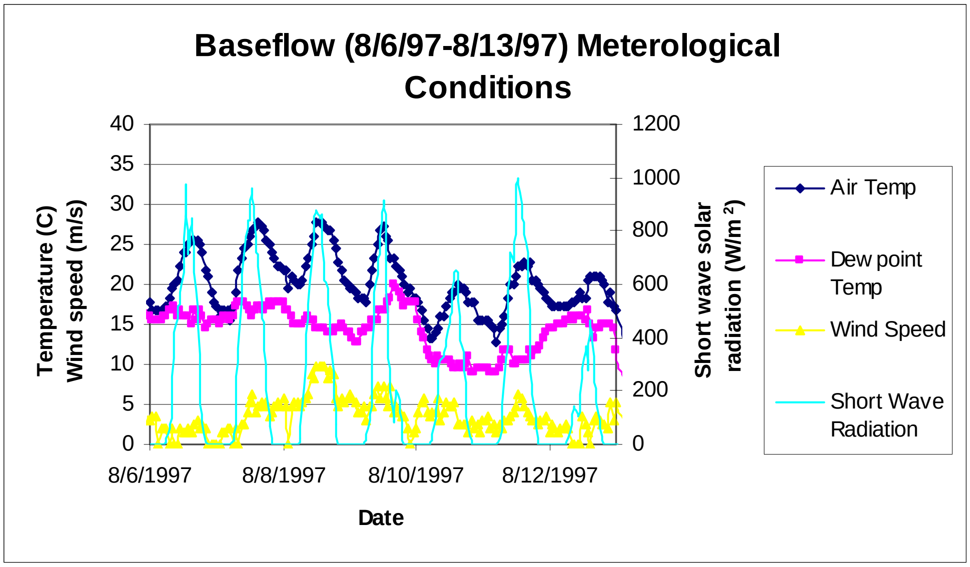
a)



b)



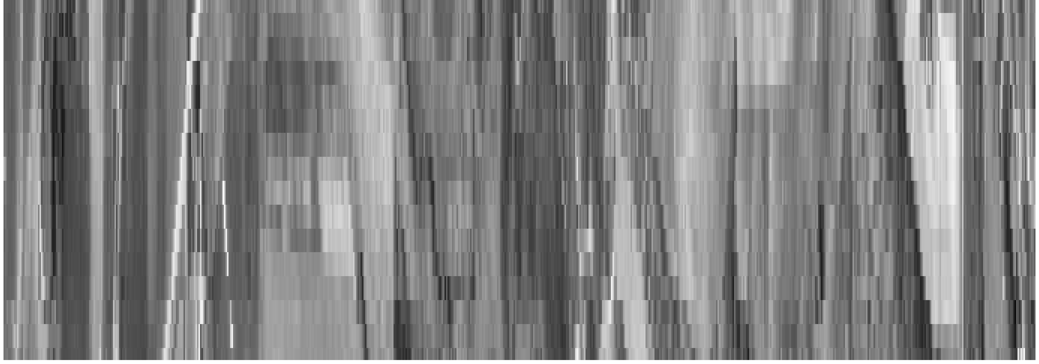
c)

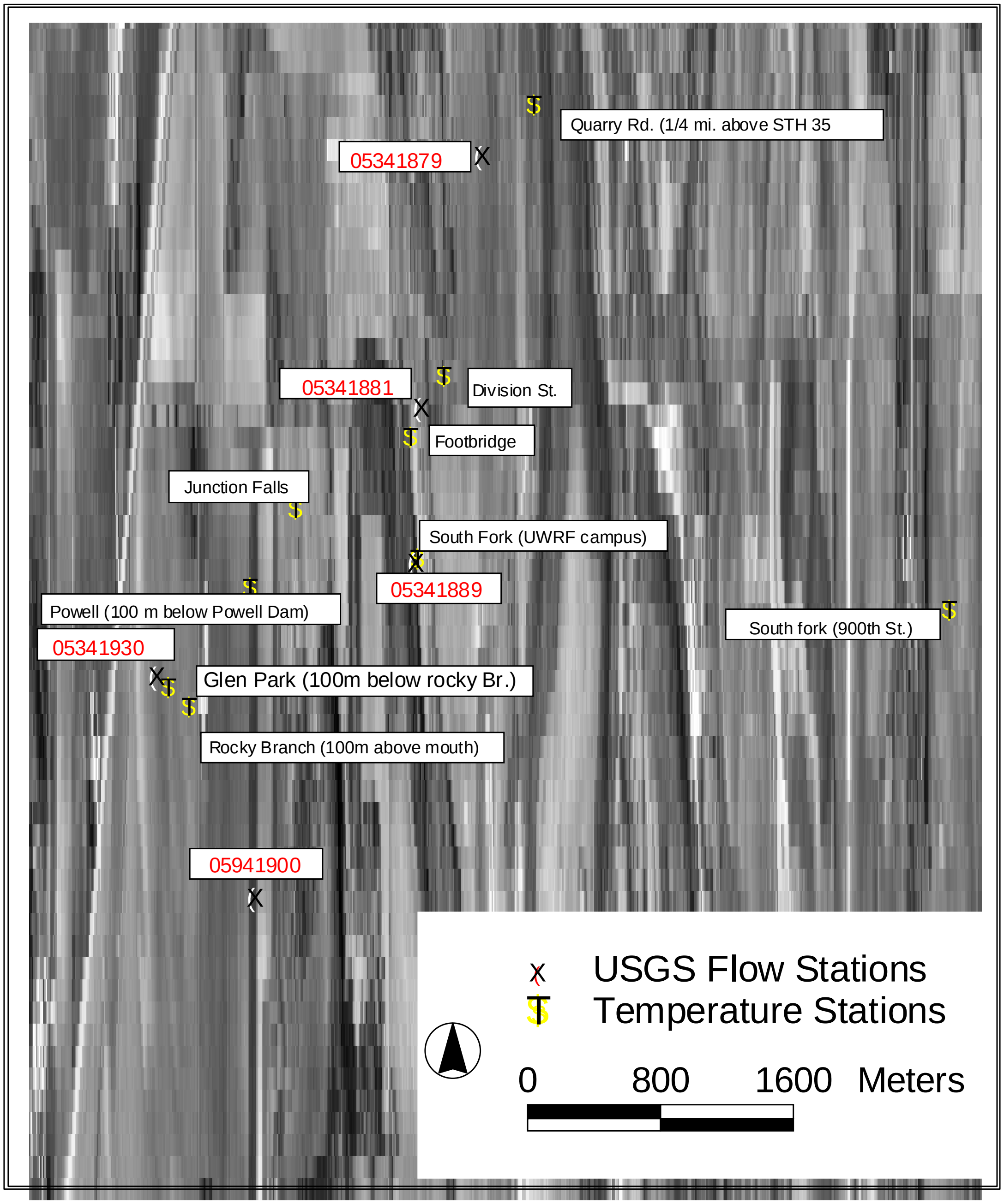


In-stream Water Temperatures and Flows:

At the upper boundary of the model, where storm sewers are largely absent and urbanization of River Falls is not as dramatic as downstream, flow measurements were taken at U.S. Geological Survey (USGS) station #05341870 at 15-minute intervals. Approximately ¼ mile upstream of the USGS station, stream temperatures were recorded with thermisters logging at 10-minute intervals (Figure 3.4).

Model development required the use of time-varying tributary temperature and flow inputs from the South Fork Kinnickinnic, Rocky Branch, and sources not accounted for in the system's water budget (groundwater, overland flow, precipitation, etc.). The South Fork temperature and flow data were collected from the University of Wisconsin-River Falls campus every 10 to 15 minutes. The Rocky Branch temperature data were collected every 10 minutes from just upstream of the creek's confluence with the Kinnickinnic River. Rocky Branch flow data were not available for 1997, but 1996 flow data collected about 50 times during the summer showed an average flow of 0.14 m^3/s (5 cfs). Estimates for the Rocky Branch June 15th and July 1st storm flows were roughly based on the shapes of the corresponding South Fork hydrographs and then were refined through calibration. The Rocky Branch base flow was estimated at 0.1 m^3/s. The River Falls Wastewater Treatment Facility and the Wisconsin DNR collected daily flow and temperature data from the wastewater treatment plant effluent, respectively. To balance the flows the model generated at Glen Park with observed data, 0.396 m^3/s at 11 degrees C were distributed along the study reach (Figure 2.1). These unaccounted flows were probably composed mostly of groundwater.





Quarry Rd. (1/4 mi. above STH 35
05341879
05341881
Division St.
Footbridge
Junction Falls
South Fork (UWRF campus)
05341889
Powell (100 m below Powell Dam)
South fork (900th St.)
05341930
Glen Park (100m below rocky Br.)
Rocky Branch (100m above mouth)
05941900
USGS Flow Stations
Temperature Stations
0 800 1600 Meters

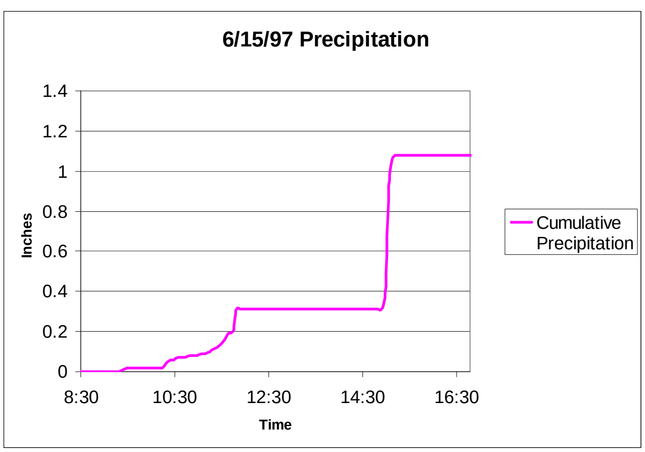
The dam at Lake George is called Junction Dam and the dam at Lake Louise is called Powell Dam. Both dams supply hydropower to the City of River Falls and discharge via a penstock and a weir. The regulation of the dams is structured to simulate the "run of the river," thus trying to maintain a pool elevation equal to the top of the weirs. The penstock discharges and pool elevations are recorded hourly by the municipal utility, and the penstock gate is modified accordingly. The water temperatures discharging from the dam can vary significantly depending on the amount of surface water that is flowing over the dam's weir, the flow through the penstock and the temperature profile at the dam. During storm events, the majority of the water is inevitably released from over the weir. For model inputs, the penstock discharges and the weir discharge/stage parameters were entered for each dam.

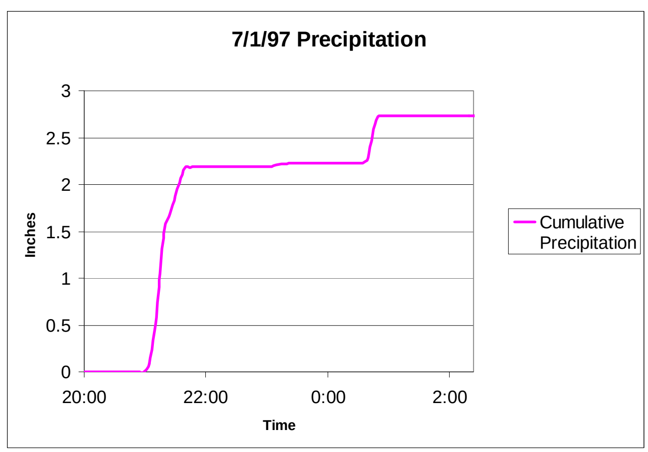
Storm sewer temperatures and flows:

Time-varying flow and temperature measurements from the city's storm sewers were needed as model inputs to accurately simulate the stream temperatures during and after storm events. In lieu of field data, the Wisconsin DNR was able to provide modeled data for two storms. The 6/15/97 storm and the 7/1/97 storm (Fig. 3.5) were selected based on the availability of meteorological, stream flow and stream temperature data.

The two storm's precipitation data (Figure 3.5) were measured by a rain gage located at the City Hall. The June 15th storm occurred during the day with two major downpours totaling over one inch of precipitation. The storm's modeled runoff data was generated from only the second downpour. The precipitation from the July 1st storm was over 2.5 inches and also consisted of two downpours. The storm's first downpour shortly after 9 pm was used to generate the modeled runoff data.

Figure 3.5 - Cumulative rainfall amounts for the June 15 and July 1, 1997, storm events





The Thermal Urban Runoff Model (TURM) (Dane County, WI, 2003) was used to generate the two storm's runoff data. This simple spreadsheet model utilizes net energy flux equations at the impervious surfaces of urban areas to account for the heat transferred to runoff. The runoff temperature is determined as a function of the physical characteristics of the impervious areas, the weather, and the heat transfer between the moving film of runoff and the heated impervious surfaces that commonly exist in urban areas. Key variables affecting the runoff temperature prediction are slope, length and makeup of impervious surfaces, wind speed, air temperature, humidity, solar radiation before and during rain, rainfall intensity, rainfall temperature, fraction of impervious area, and time of concentration associated with pervious areas.

The River Falls urban basin was broken into subwatersheds and basin attributes such as percent imperviousness and curve number were calculated for each subwatershed. This information was provided by the City of River Falls city engineer's office. Meteorological data was supplied by either WDNR, local school weather station or nearby NOAA weather stations. The runoff water volumes and time series were concurrently calculated with the runoff temperatures within the TURM model. The runoff hydrology is driven by the 5-minute rainfall data, thus the runoff time series is also calculated as a 5-minute time step. The TURM model utilizes a rough approximation method, assuming that the total runoff volume is equal to 90 percent of the impervious area times the rainfall depth during the given measurement time interval. Because the model has no routing capabilities (i.e. rainfall falling on a surface is discharged at the end of the time step), a smoothing function was applied to the output data to more closely simulate urban runoff hydrographs. The form of the equation used was:

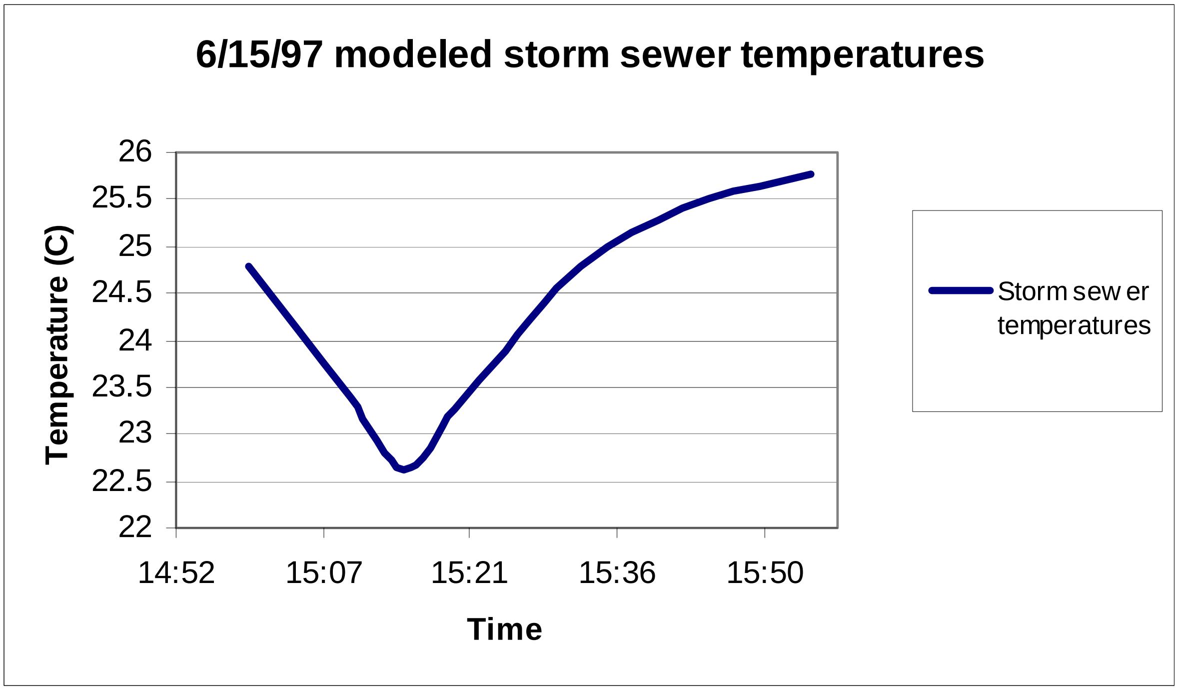
$Q_t = (Q_{t-2} * \alpha) + (R_t * (1 - \alpha))$

Where Q=Flow at time step t, α= alpha, smoothing coefficient, R=Rainfall flow (depth*surface area/5 min).

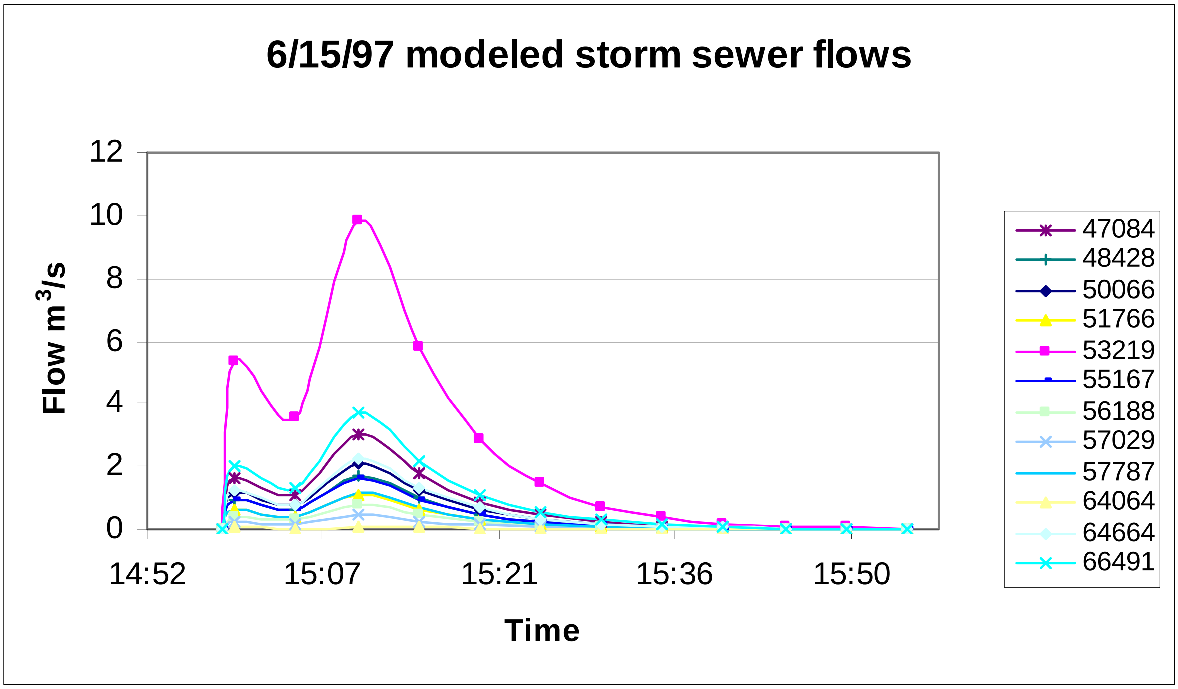
The resulting flows and water temperatures were imputed into the CE-QUAL-W2 model as tributaries. The number of storm sewer pipes discharging to the river was reduced for modeling purposes by combining sewer sheds into 12 discharges to the river (Fig. 3.6). Temperatures for each storm, due to model limitations, were identical for all sewersheds.

Figure 3.6 - a) June 15th modeled storm sewer temperatures, b) June 15th modeled storm sewer flows, c) July 1st modeled storm sewer temperatures, and d) July 1st modeled storm sewer flows

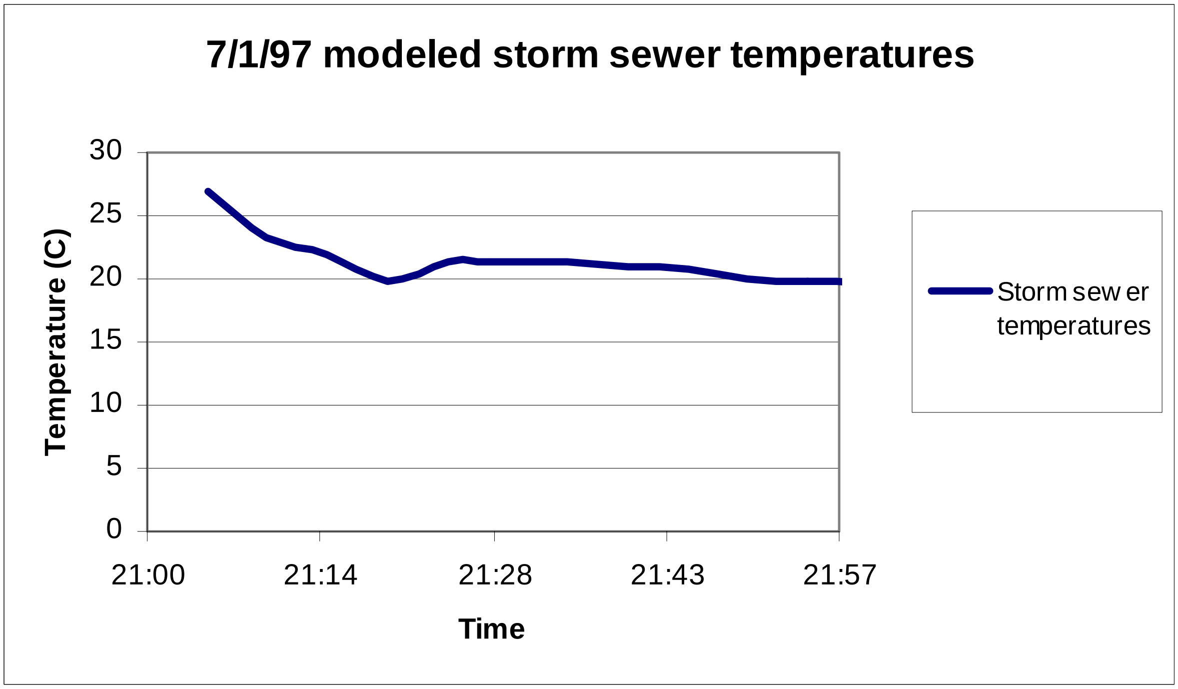
a)



b)



c)


7/1/97 modeled storm sewer temperatures
Temperature (C)
30
25
20
15
10
5
0
21:00
21:14
21:28
21:43
21:57
Time
Storm sewer temperatures

d)

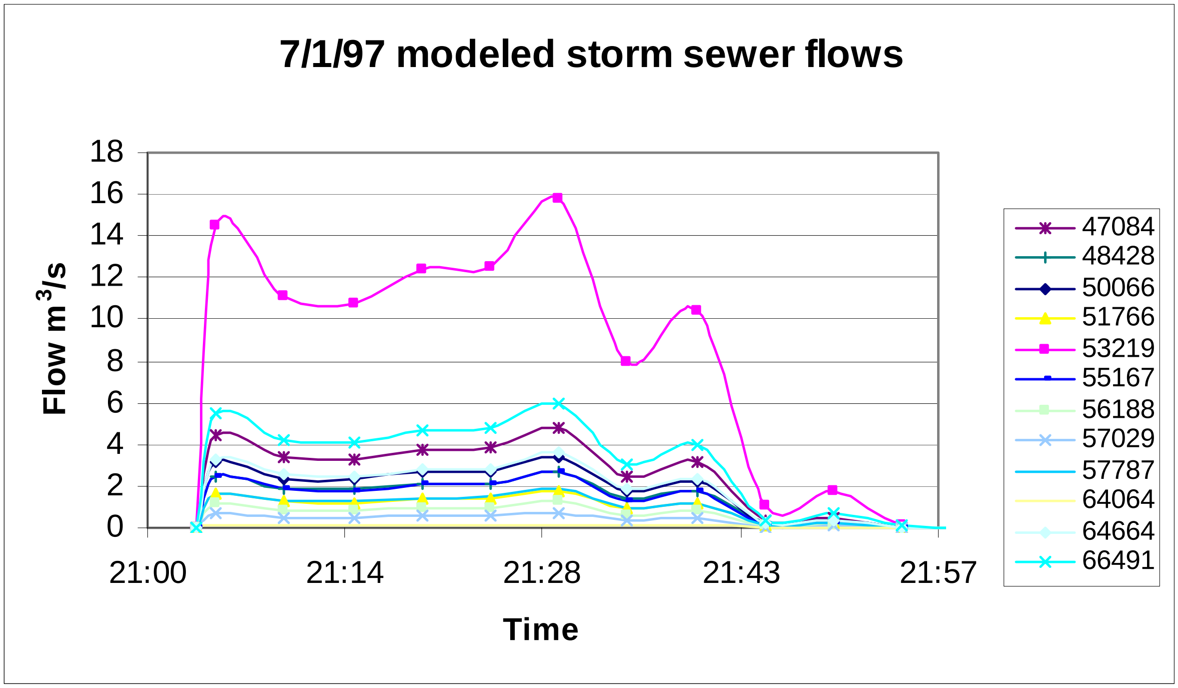
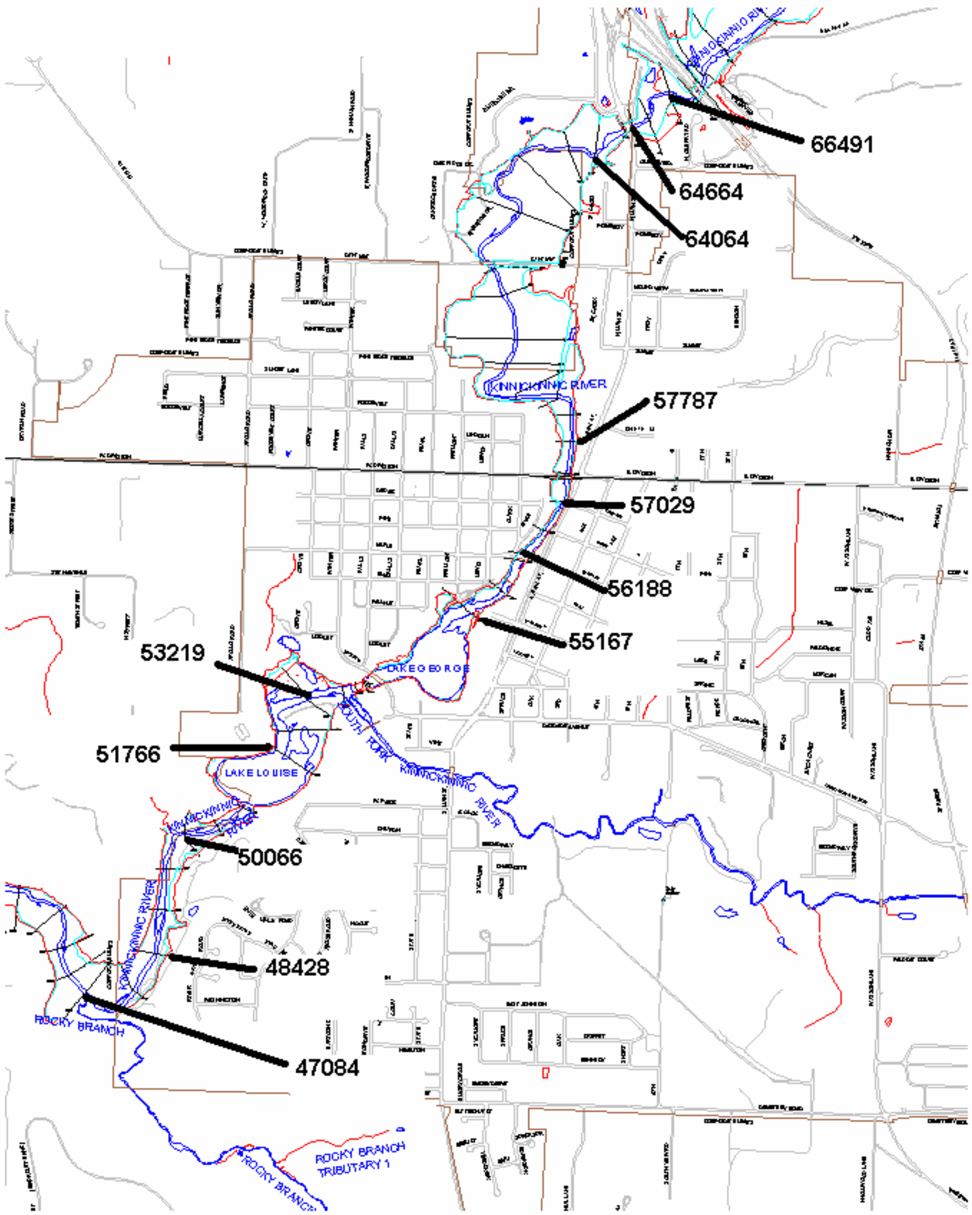

7/1/97 modeled storm sewer flows
Flow m³/s
18
16
14
12
10
8
6
4
2
0
21:00
21:14
21:28
21:43
21:57
Time
47084
48428
50066
51766
53219
55167
56188
57029
57787
64064
64664
66491

Figure 3.6 - Modeled storm sewer discharges to the Kinnickinnic River inputted as tributaries in CE-QUAL-W2



3.3 Model Calibration

Calibration Statistics:

Field data from 1997 were used to calibrate the model's August 4-12 base flow and storm conditions. Three types of error statistics were used to describe the model's performance. Mean Error (ME) was defined as the sum of all the deviations across time at a station divided by the number of deviation measurements. Mean Error was used in the calibration process to give an indication if the model's overall temperature was too warm or cold. Calibration parameters that have a global warming effect like shading or extinction coefficients were used to reduce the mean error. Absolute Mean Error (AME) was defined as the sum of the absolute values for each deviation divided by the number of deviations. Absolute Mean Error gives an average error value for the time period. AME is not affected by the canceling out of negative and positive deviations. Therefore, AME does not show bias, but gives a better indication of an average predictive error than ME. Root Mean Square (RMS) was defined as the root of the sum of squares of the deviations across time for each station. RMS is a more stringent test for replicating observations than AME or ME, since it emphasizes the error of individual predictions, not the average error of all the deviations. RMS is a good statistic to judge the model's ability to replicate the system's diurnal variations.

Calibration Parameters:

Temperature calibration in CE-QUAL-W2 version 3.1 is limited by the accuracy of the input data and the model calculations. Under ideal conditions, few parameters need to be adjusted after input data are taken from the field. Assuming the bathymetry data, meteorological data, shading data, bottom roughness (Manning's n), flow and water temperature data, and parameters that control solar radiation attenuation are correct, the model should come close to predicting observed data without changing the model's default settings (Cole and Wells, 2002). However, in this study, the shading parameter, the light extinction parameters (EXH2O and BETA), the flows and temperatures of the ungaged inflows, the wind sheltering coefficient (WSC) and the fraction of solar radiation reflected by the sediments back into the water column (TSEDF) were not explicitly measured and had to be adjusted during the calibration process. Table 3.1 lists the calibrated values used for the CE-QUAL-W2 model.

Table 3.1- Calibrated values for the Kinnickinnic River W2 model

Coefficient	Upper Kinni	Lake George	Lake Louise	Lower Kinni
WSC	0.25	0.50	0.50	0.25
TSEDF	1.0	0.5	0.5	1.0
Shading	0.50	0.95	0.95	0.75
EXH20	0.45	0.45	0.45	0.45
BETA	0.45	0.45	0.45	0.45
Ungaged Flow (CMS)	0.2	0.066	0.066	0.066
Ungaged Temp (C)	11	11	11	11

Base Flow:

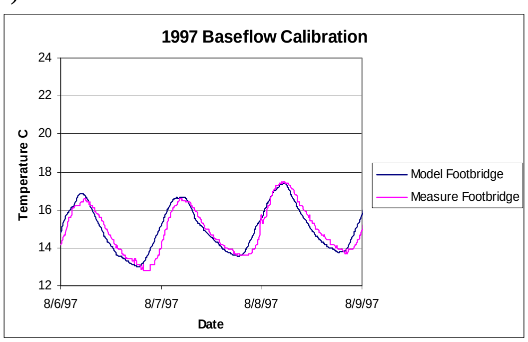
Calibration of the model was evaluated with temperature measurements at four river stations: Foot Bridge, Junction Falls, Below Powell Dam, and Glen Park (Figure 1.1). Using the parameter settings listed in table 3.1, the CE-QUAL-W2 model was calibrated to the August base flow condition to generally accepted standards of less than 1°C AME/RMS error. Table 3.2 shows a statistical summary of the CE-QUAL-W2 model and average travel times at four temperature stations during the August 7 to 11, 1997, time period, and Figure 3.7 graphically compares CE-QUAL-W2 temperatures to field temperatures.

Table 3.2 - Error statistics for the August 7 to 11, 1997 calibration, °C

Station	AME, °C	ME, °C	RMS, °C	Count	Ave. Travel Time (Hrs)
FootBridge	0.38	0.02	0.46	505	1.99
Junction Falls	0.41	0.05	0.48	505	10.72
Below Powell	0.35	-0.15	0.42	505	5.43
Glen Park	0.39	-0.22	0.49	505	0.64

Figure 3.7 - CE-QUAL-W2 and observed temperature data at four stations: a) Footbridge, b) Junction Falls, c) Below Powell Dam, and 4) Glen Park.

a)



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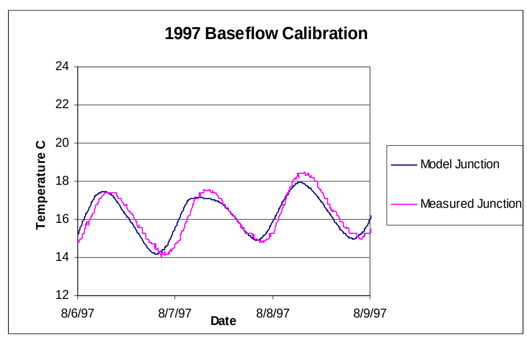

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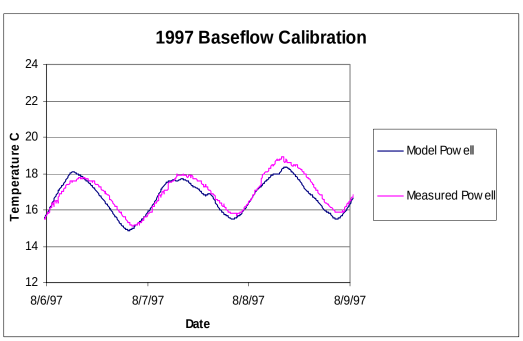
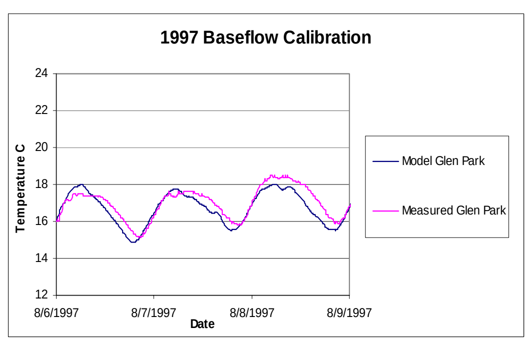


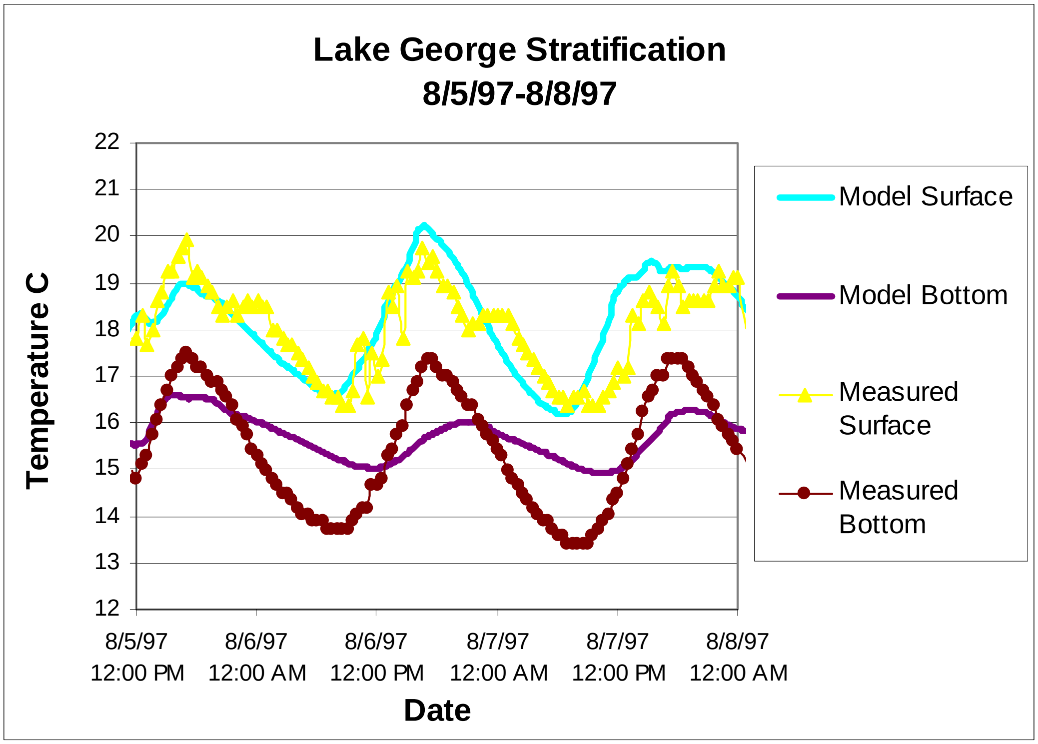
d)



Lake George Stratification:

A further test to see if the model was reproducing field data was to compare model generated temperatures at different depths with August 1997 field data (Figure 3.8). The exact location and bottom elevation of the field data were not documented, but it was assumed that the simulated temperatures taken at the surface and 1.5 meters in the middle of the model's side channel were suitable for comparison. The modeled data showed a stratification of the water column in Lake George that was similar to the observed data, except that the model's bottom temperatures lacked the observed diurnal fluctuations. This difference may be due to the artificial segmentation of the model into a side channel and a main stem, which largely excludes the side channel from the temperature regime of the upstream river water. Nonetheless, the data suggests that the model is reproducing the thermal and hydrodynamics of the system reasonably well.

Figure 3.8 - Modeled and observed data from the surface and bottom of Lake George



Storm Events:

After the model was calibrated to the base flow condition, the model was run for the June 15 and July 1, 1997, storm events with the same parameters. Because observed storm sewer runoff data were not available, storm sewer flow and thermal data derived by TURM were inputted into CE-QUAL-W2 (Figure 3.5). The CE-QUAL-W2 model simulations generated with storm sewer inputs did show an increase in Glen Park discharge flows at the right time periods, but the flows were larger than observed. To correct the flow discrepancies, storm sewer flow inputs were multiplied by 3/5 (Figures 3.9 and 3.10). Statistics comparing flows for the two storms and the August base flow at Glen Park are shown in Table 3.3. After the storm flows compared well between CE-QUAL-W2 output and the measured data, TURM storm sewer temperature data were calibrated for downstream water temperatures. CE-QUAL-W2 outputs demonstrated that 90% of the TURM generated flow temperatures were needed to reproduce observed stream temperatures at each monitoring station.

Figure 3.9 - Comparison of model and observed discharge flows during June 15th with and without storm sewer inputs

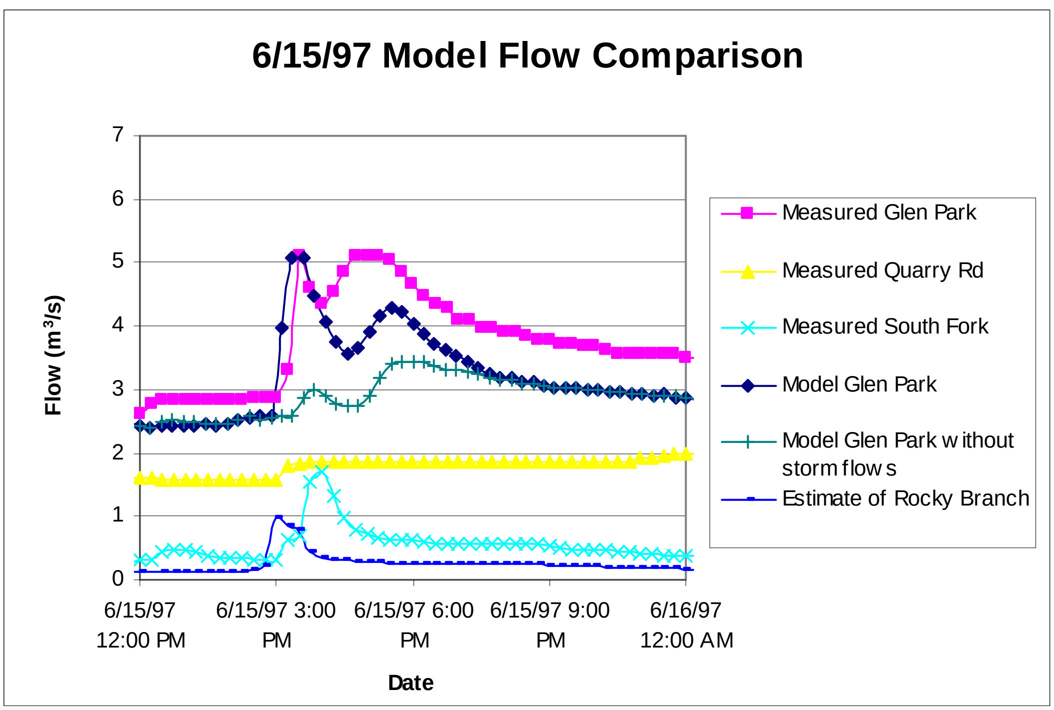


Figure 3.10 - Comparison of model and observed discharge flows during July 1st with and without storm sewer inputs

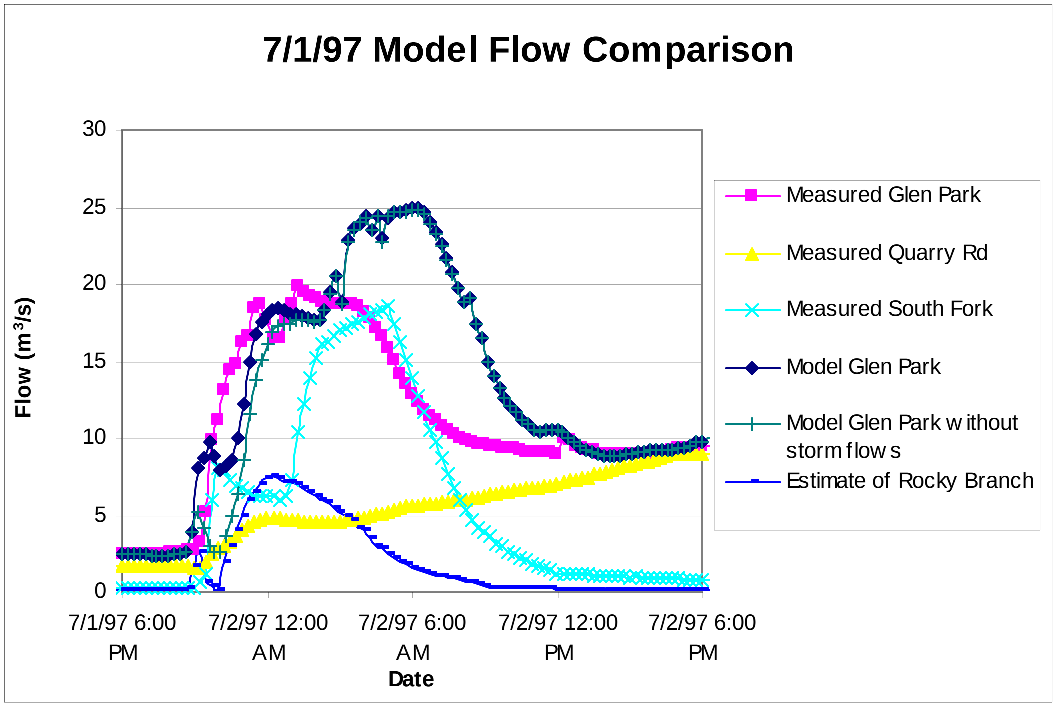


Table 3.3 - Statistical comparison of observed Glen Park flow with CE-QUAL-W2 Glen Park flows for the August base flow and the two storms

Calibration Run	Time Period	AME, m^3/s	ME, m^3/s	RMS, m^3/s	Count
Base Flow	8/3/97 7:15 8/11/1997 16:45	0.09	-0.09	0.09	807
6/15/97 Storm	6/15/97 17:15 6/16/97 5:30	0.66	-0.66	0.66	50
7/1/97 Storm	7/1/97 12:00 7/3/97 11:45	1.79	1.09	3.48	192

On Figures 3.11 and 3.12, temperatures at the four river stations predicted by CE-QUAL-W2 using 90 percent of the computed storm sewer temperatures and their corresponding modified flows are shown along with the observed data for the June 15th and July 1st storms.

Figure 3.11 - CE-QUAL-W2 storm temperatures generated with 90% of computed storm sewer temperatures and observed temperatures at four river stations for June 15th storm event

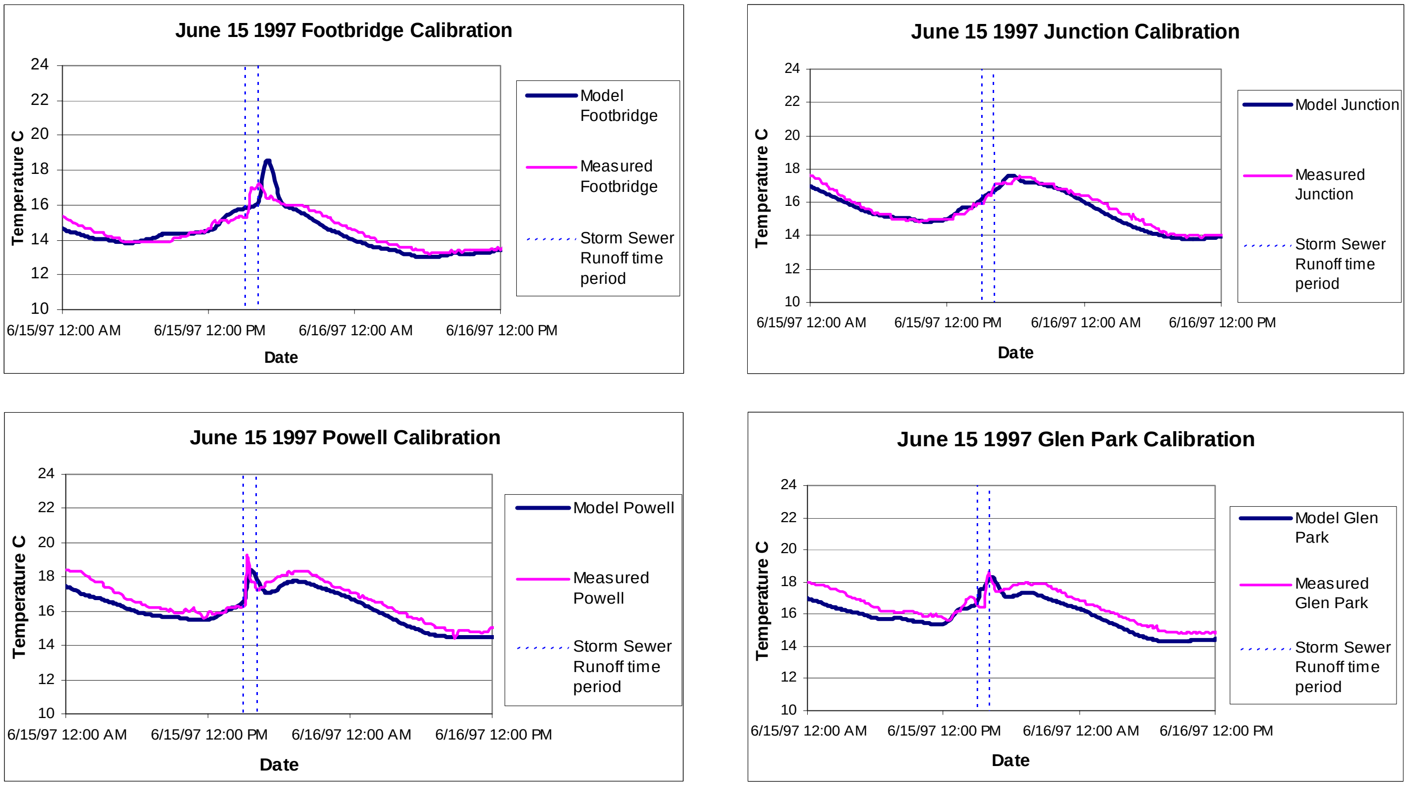
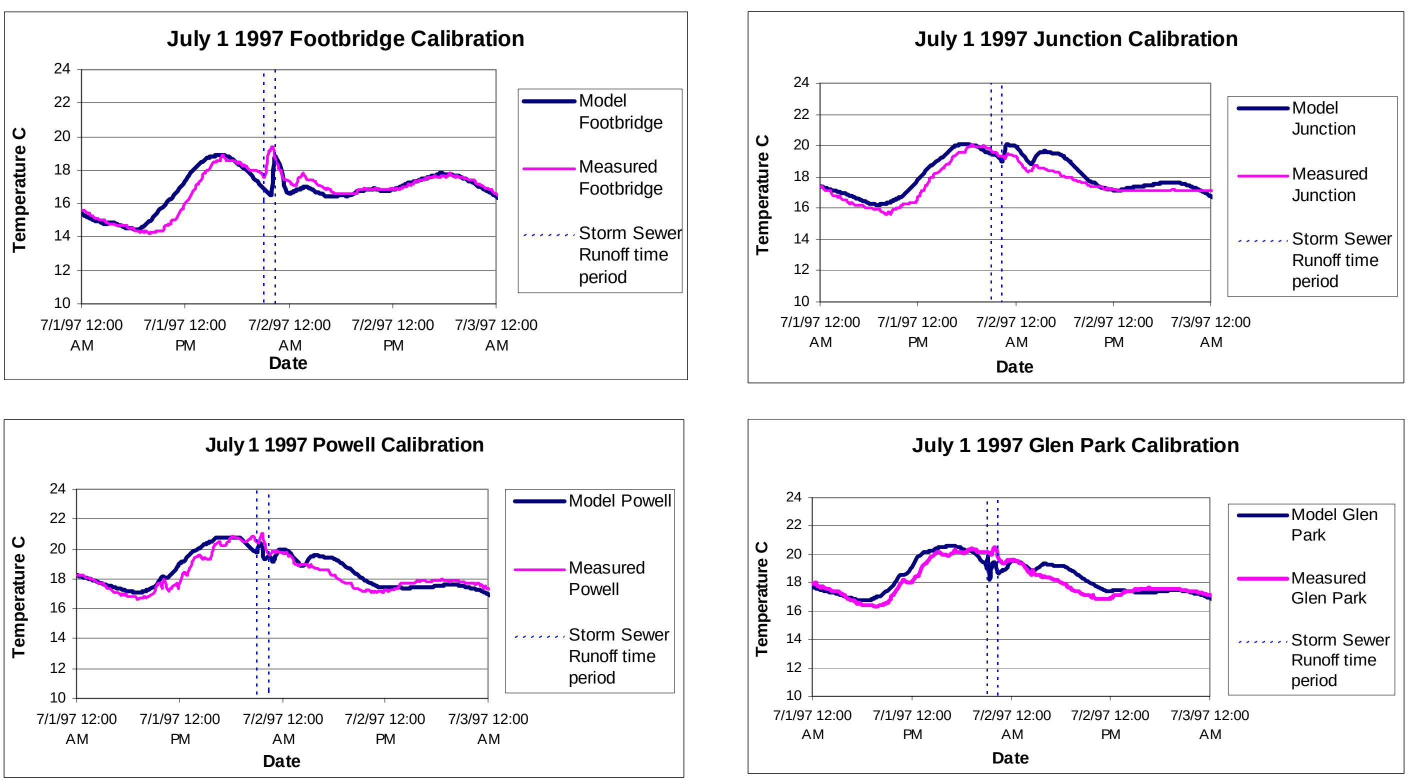


Figure 3.12 - CE-QUAL-W2 storm temperatures generated with 90% of computed storm sewer temperatures and observed temperatures at four river stations for July 1st storm event



4.0 MODEL SENSITIVITY

Determination of the model's sensitivity to different parameters was achieved by first running the model under August 6-10 base flow conditions shown in Table 4.1. By changing one parameter at a time, the model's sensitivity was detailed for wind sheltering (WSC), shading (SHD), solar radiation reflection from the sediment (TSEDF), light extinction coefficients (EXH2O and BETA), and distributed tributary temperatures (Tables 4.1 through 4.5 and Figures 4.1 through 4.5).

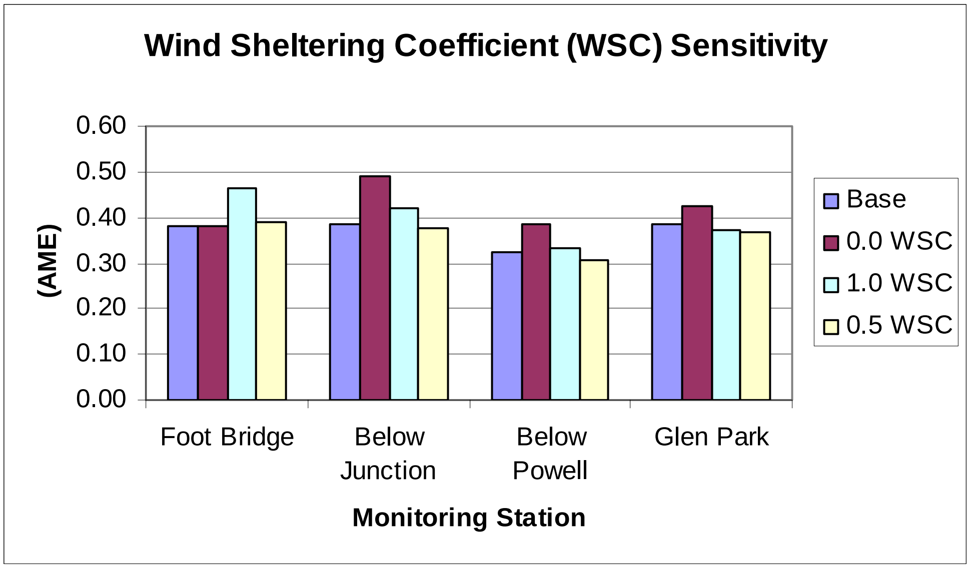
Wind Sheltering Coefficient (WSC):

The Kinnickinnic model is somewhat sensitive to the wind-sheltering coefficient (WSC). The WSC can be adjusted between 0 and typically 1.0; values around 0.5 are used for protected water bodies, and values near 1.0 are used for large open water bodies. This coefficient corrects the wind from the measuring station to a point over the water surface and in some cases can be higher than 1. Because Lake George and Lake Louise are fairly open, but are small and situated in a river valley, a value of 0.50 was used. For the highly protected river sections, a value of 0.25 was used.

Table 4.1- Statistical summary of Wind Sheltering Coefficient (WSC) sensitivity

Scenario	Station	WSC	AME. °C	ME, °C	RMS, °C	Count
base flow	Foot Bridge	0.25	0.38	0.03	0.47	505
	Below Junction	0.50	0.38	-0.03	0.45	505
	Below Powell	0.50	0.32	-0.22	0.38	505
	Glen Park	0.25	0.38	-0.28	0.47	505
1.0 WSC	Foot Bridge	1	0.46	0.24	0.62	505
	Below Junction	1	0.42	0.20	0.53	505
	Below Powell	1	0.33	-0.01	0.39	505
	Glen Park	1	0.37	-0.09	0.45	505
0.5 WSC	Foot Bridge	0.5	0.39	0.08	0.49	505
	Below Junction	0.5	0.38	0.00	0.45	505
	Below Powell	0.5	0.31	-0.19	0.36	505
	Glen Park	0.5	0.37	-0.26	0.45	505
0.0 WSC	Foot Bridge	0	0.38	0.02	0.46	505
	Below Junction	0	0.49	-0.06	0.57	505
	Below Powell	0	0.39	-0.18	0.46	505
	Glen Park	0	0.42	-0.25	0.53	505

Figure 4.1 - Absolute Mean Error (AME) for different Wind Sheltering Coefficients



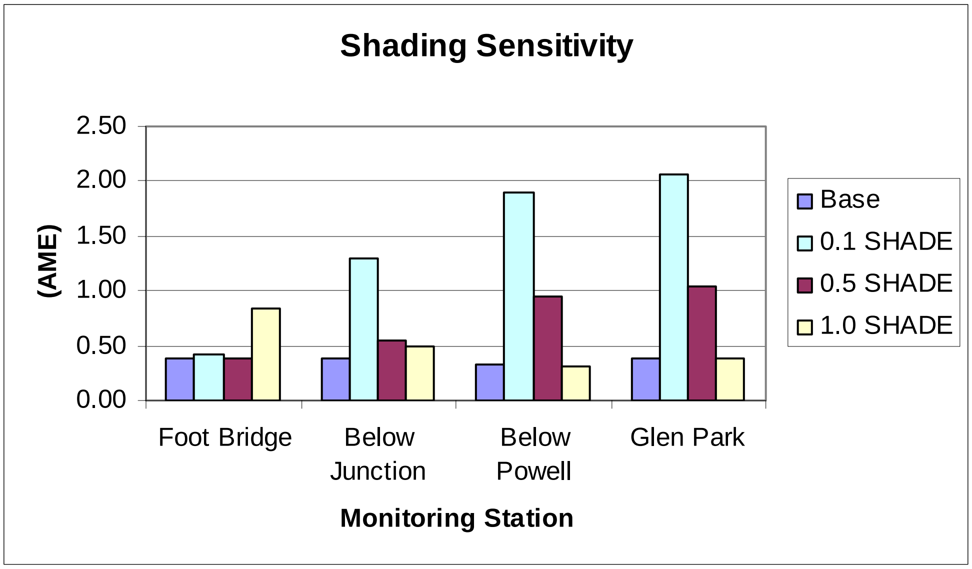
Shading:

Table 4.2 and Figure 4.2 demonstrate that the shading parameter strongly influences the CE-QUAL-W2 thermal calculations. It was apparent that the river sections were shaded from solar radiation more than the reservoirs and that the warming effect of the reservoirs dominates under base flow conditions.

Table 4.2 - Statistical summary of Shading (SHD) sensitivity

Scenario	Station	SHADE	AME. °C	ME, °C	RMS, °C	Count
base flow	Foot Bridge	0.5	0.38	0.03	0.47	505
	Below Junction	0.95	0.38	-0.03	0.45	505
	Below Powell	0.95	0.32	-0.22	0.38	505
	Glen Park	0.75	0.38	-0.28	0.47	505
1.0 SHD	Foot Bridge	1	0.83	0.55	1.12	505
	Below Junction	1	0.49	0.40	0.63	505
	Below Powell	1	0.31	0.20	0.40	505
	Glen Park	1	0.39	0.19	0.48	505
0.5 SHD	Foot Bridge	0.5	0.38	0.03	0.47	505
	Below Junction	0.5	0.54	-0.52	0.62	505
	Below Powell	0.5	0.95	-0.95	0.99	505
	Glen Park	0.5	1.05	-1.05	1.08	505
0.1 SHD	Foot Bridge	0.1	0.42	-0.39	0.50	505
	Below Junction	0.1	1.29	-1.29	1.39	505
	Below Powell	0.1	1.90	-1.90	1.98	505
	Glen Park	0.1	2.06	-2.06	2.14	505

Figure 4.2 - Absolute Mean Error (AME) for different Shading values



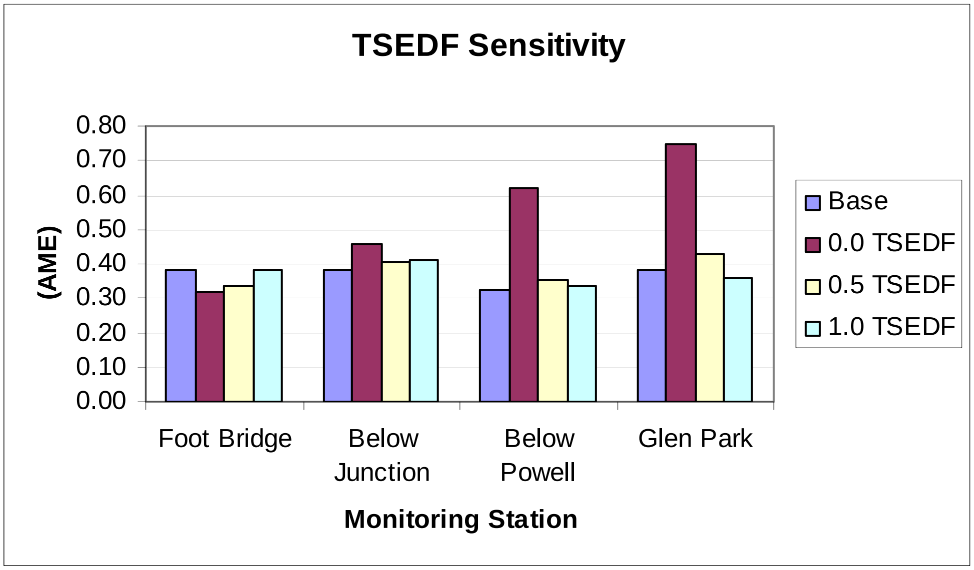
TSEDF:

TSEDF is a coefficient that regulates how much solar radiation is re-radiated as heat after it hits the channel bottom. A value of 1 means 100 percent of the incident short wave solar radiation is re-radiated as heat back into the water column. For the Kinnickinnic thermal model, the TSEDF seems more relevant in the reservoirs (where there is less shading) than in the river segments.

Table 4.3 - Statistical summary of TSEDF

Scenario	Station	TSEDF	AME. °C	ME, °C	RMS, °C	Count
base flow	Foot Bridge	1	0.38	0.03	0.47	505
	Below Junction	0.5	0.38	-0.03	0.45	505
	Below Powell	0.5	0.32	-0.22	0.38	505
	Glen Park	1	0.38	-0.28	0.47	505
1.0 TSEDF	Foot Bridge	1	0.38	0.03	0.47	505
	Below Junction	1	0.41	0.12	0.51	505
	Below Powell	1	0.34	0.08	0.41	505
	Glen Park	1	0.36	-0.01	0.44	505
0.5 TSEDF	Foot Bridge	0.5	0.34	-0.05	0.40	505
	Below Junction	0.5	0.40	-0.09	0.47	505
	Below Powell	0.5	0.35	-0.27	0.42	505
	Glen Park	0.5	0.43	-0.38	0.51	505
0.0 TSEDF	Foot Bridge	0	0.32	-0.13	0.37	505
	Below Junction	0	0.46	-0.30	0.53	505
	Below Powell	0	0.62	-0.62	0.68	505
	Glen Park	0	0.75	-0.75	0.80	505

Figure 4.3 - Absolute Mean Error (AME) for different TSEDF values



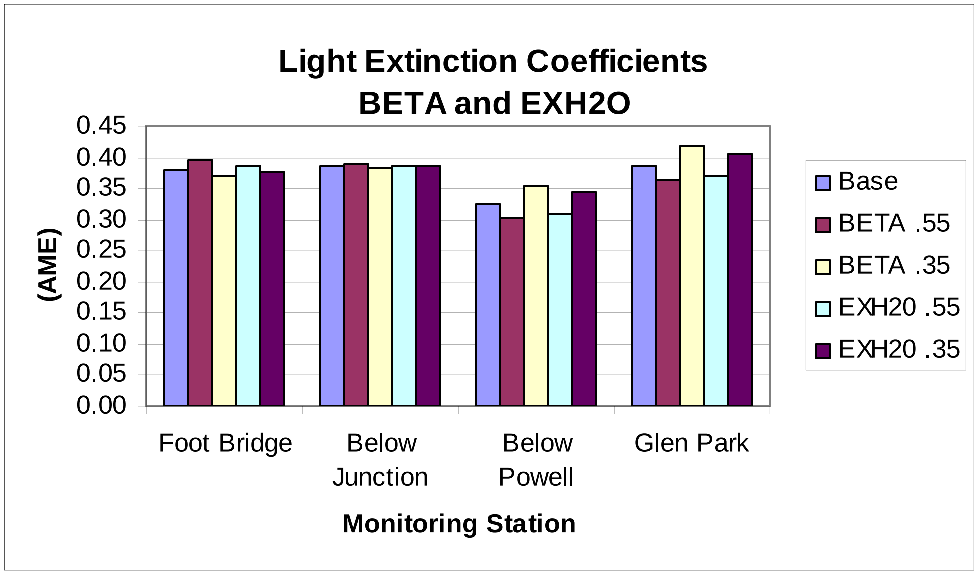
Light Extinction Coefficients:

Both parameters EXH20 and BETA were used for calculating the light extinction through the water column. For this study, light extinction data were not available; therefore, values of 0.45 for EXH20 and 0.45 for BETA were selected on the basis of a sensitivity analysis. To check the sensitivity of the model to these two parameters, 0.35 and 0.55 were run separately for EXH20 and BETA. The model reacted only slightly to the change in the values, but the change may not be so trivial in the deeper sections of the reservoirs where light is limited and stratification occurs.

Table 4.4 - Statistical summaries of Light Extinction Coefficients EXH20 and BETA

Scenario	Station	EXH20/BETA	AME. °C	ME, °C	RMS, °C	Count
base flow	Foot Bridge	0.45/0.45	0.38	0.03	0.47	505
	Below Junction	0.45/0.45	0.38	-0.03	0.45	505
	Below Powell	0.45/0.45	0.32	-0.22	0.38	505
	Glen Park	0.45/0.45	0.38	-0.28	0.47	505
0.55 EXH2O	Foot Bridge	0.55/0.45	0.38	0.04	0.47	505
	Below Junction	0.55/0.45	0.39	0.01	0.46	505
	Below Powell	0.55/0.45	0.31	-0.17	0.37	505
	Glen Park	0.55/0.45	0.37	-0.23	0.45	505
0.35 EXH2O	Foot Bridge	0.35/0.45	0.38	0.03	0.46	505
	Below Junction	0.35/0.45	0.39	-0.07	0.45	505
	Below Powell	0.35/0.45	0.34	-0.27	0.41	505
	Glen Park	0.35/0.45	0.41	-0.33	0.49	505
0.55 BETA	Foot Bridge	0.45/0.55	0.39	0.06	0.49	505
	Below Junction	0.45/0.55	0.39	0.03	0.47	505
	Below Powell	0.45/0.55	0.30	-0.14	0.36	505
	Glen Park	0.45/0.55	0.36	-0.20	0.44	505
0.35 BETA	Foot Bridge	0.45/0.35	0.37	0.01	0.45	505
	Below Junction	0.45/0.35	0.38	-0.08	0.44	505
	Below Powell	0.45/0.35	0.35	-0.29	0.42	505
	Glen Park	0.45/0.35	0.42	-0.36	0.50	505

Figure 4.4 - Absolute Mean Error (AME) for Light Extinction Coefficients EXH20 and BETA



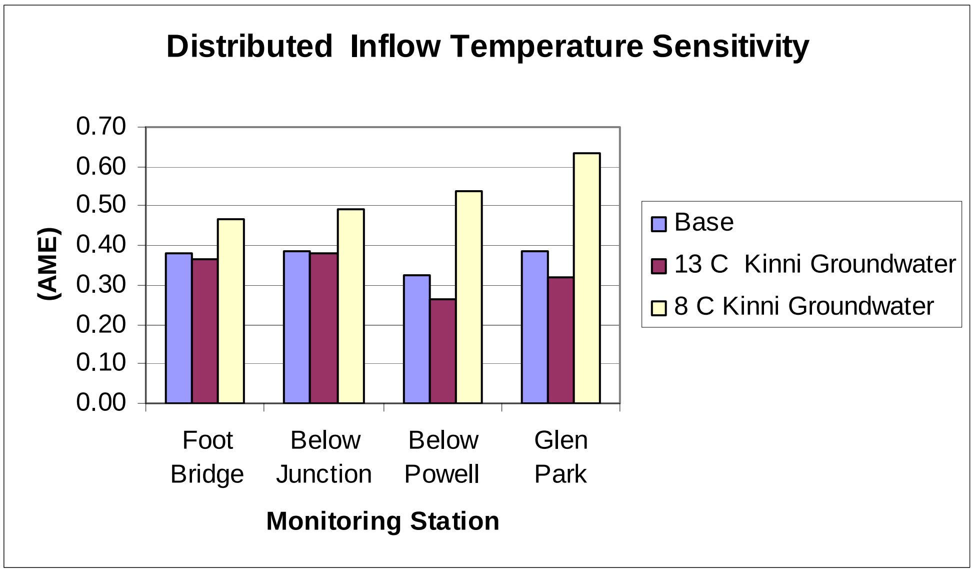
Kinnickinnic Distributed Tributary Temperatures:

Groundwater and other ungaged flows entering the study reach were added in order to maintain observed flows throughout the system. The temperatures of these flows were estimated by performing a sensitivity analysis.

Table 4.5 - Statistical summary of sensitivity of the model to constant distributed tributary temperatures at 8 ºC and 13 ºC and Quarry Road temperatures

Scenario	Station	Dist. Temp C	AME. °C	ME, °C	RMS, °C	Count
base flow	Foot Bridge	11.00	0.38	0.03	0.47	505
	Below Junction	11.00	0.38	-0.03	0.45	505
	Below Powell	11.00	0.32	-0.22	0.38	505
	Glen Park	11.00	0.38	-0.28	0.47	505
8 C	Foot Bridge	8.00	0.47	-0.23	0.52	505
	Below Junction	8.00	0.49	-0.32	0.56	505
	Below Powell	8.00	0.54	-0.52	0.61	505
	Glen Park	8.00	0.63	-0.62	0.73	505
13 C	Foot Bridge	13.00	0.36	0.21	0.51	505
	Below Junction	13.00	0.38	0.16	0.48	505
	Below Powell	13.00	0.26	-0.01	0.32	505
	Glen Park	13.00	0.32	-0.05	0.38	505

Figure 4.5 - Absolute Mean Error (AME, °C) for different distributed temperature data sets

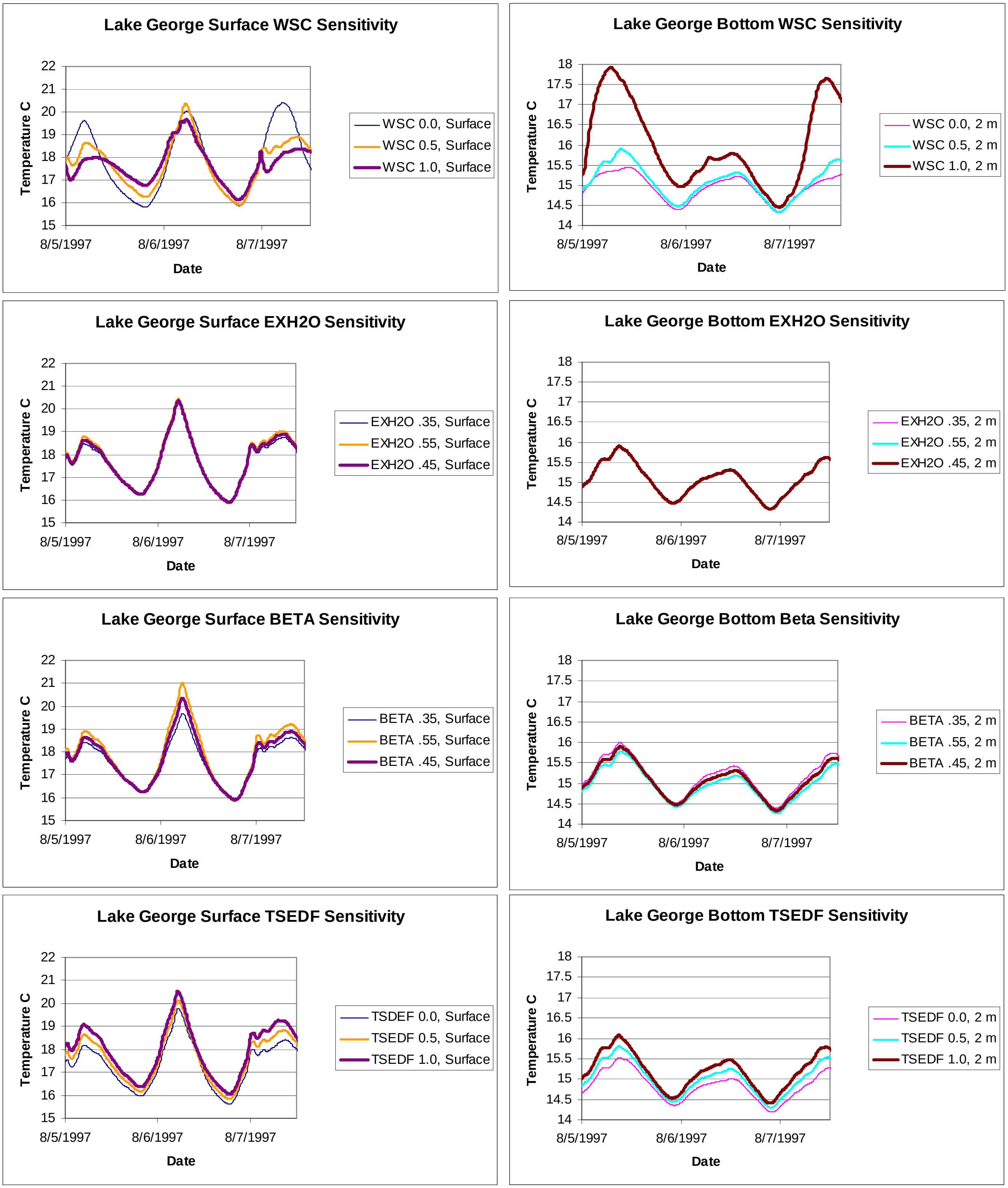


The results of the sensitivity analysis demonstrated that the distributed flow at 13 degrees C produced the lowest AME values. However, distributed flow temperatures of 11 degrees C were used for the model in order to better reproduce stream temperatures during storms and to reflect that the actual temperatures of the groundwater are probably below 10 degrees C.

Lake George Stratification Sensitivity:

Stratification dynamics in the two reservoirs were important for the model to reproduce to correctly generate dam discharge temperatures. To check the model's stratification sensitivity, the response of Lake George's surface and bottom temperatures to changes in WSC, TSEDF and light extinction coefficients EXH2O and BETA were documented. The wind-sheltering coefficient (WSC) had the most effect on Lake George's surface and bottom temperatures. As Lake George was increasingly exposed to wind, the stability of the reservoir's stratification dramatically decreased. Least visible, changes in EXH2O showed very little difference in the reservoir's surface and bottom temperatures. The other parameters, BETA and TSEDF, were moderately sensitive to changes. Increasing TSEDF had a global effect of increasing the bottom and surface temperatures, whereas, increasing BETA only increased the temperatures at the surface and the bottom during the diurnal temperature peaks (Figure 4.6).

Figure 4.6 – Modeled Lake George surface and bottom temperatures sensitivity to WSC, EXH2O,BETA, and TSEDF.



5.0 DISCUSSION AND RECOMMENDATIONS FOR FURTHER WORK

The predictive ability of this Kinnickinnic CE-QUAL-W2 thermal model was limited to evaluation of the thermal and hydrologic response of different storm water runoff management plans using three specific time periods: the June 15, 1997, storm; the July 1, 1997, storm; and the August 6-10 base flow. Of the three, the base flow model was probably the most reliable. The base flow's primary advantage was that the model did not require storm sewer inputs which were based on several questionable assumptions: 1) uniform rainfall over the basin; 2) simplified runoff routing; and 3) lack of pervious contributions. Also, the base flow model used estimated Rocky Branch flows that were fairly small, steady, and predictable from past data. The Rocky Branch estimated flows used for the two storm models, however, were based on calibration runs, and the tributary's inputs greatly influenced the flows and temperatures seen at Glen Park. In the following sections, other important factors that affected the model's reliability are discussed as suggestions for further work.

Detailed Bathymetry of the Reservoirs:

Lake George, in particular, is an instrumental feature in the model's grid that controls the temperatures downstream. Without a detailed bathymetry and elevation/storage data, it was difficult to simulate the complex hydrodynamics and water temperatures that occurred in the reservoir. Also, an old wooden dam, approximately 30 feet upstream of the current withdrawal structure, was poorly mapped and needs detailing. Any BMPs that involve reconfiguring the reservoir should be based on more reliable bathymetry data.

Storm Sewer Flow and Temperature Field Data:

There is always uncertainty with data derived from models. With this study's focus on the Kinnickinnic River's thermal reaction to storm sewer runoff, field data from the storm sewers would have been preferred over computed data. However, monitoring storm sewers, stream stations, and meteorological conditions for an additional summer were not a part of this study's scope of work.

Tracer Simulation:

To be assured that the model had correct hydrodynamics, a tracer study would have been useful. Besides temperature comparisons at different points along the river, it was difficult to verify that the model had similar transport times and flow patterns. If observed tracer data were available, travel times and hydrodynamics of the system would have been better known.

Shading Data:

Crude estimates of the amount of canopy and shade could be improved by including data that allows CE-QUAL-W2 to utilize its dynamic shading computations. For this study, static coefficients were used to describe the amount of shading on each segment. If for each bank of the river, vegetative type data, topographic data, and leaf growth and leaf fall data for deciduous trees were included, a more accurate dynamic shading coefficient could have been used.

Light Extinction Coefficients:

To estimate the light extinction parameters (GAMMA and BETA), average Secchi depth (Z_s) can be used in the following equations: $\gamma = 1.11Z_s^{-0.73}$, $\beta = 0.27 \ln(\gamma) + 0.61$ (Cole and Buchak, 1995). Without Secchi depths and without modeling water quality and algae in CE-QUAL-W2, these parameters were left at 0.45. During the two rain events, dynamic values for GAMMA and BETA could have been measured to better represent changes in stream turbidity.

Missing Flows:

A large factor in achieving reliable results from the CE-QUAL-W2 model was the inputting of accurate time-varying data for the distributed tributaries. As an estimate of these unaccounted flows, which were assumed to be composed mostly of groundwater, a simple water budget calculation using the hourly or daily upstream flows and downstream flows was made. The temperatures were estimated at a constant 11 degrees C. Without a doubt, a better understanding of these inputs would have improved the model.

Rainfall Data:

For the two storms modeled, rain gage data collected at the City Hall were used in the generation of their corresponding storm sewer inputs. Using one rain gage and assuming a constant rainfall over the entire basin may be a source of significant error for each storm sewer's flow estimation. It is quite likely that these two summer storms were not uniform in rainfall distribution, thus causing individual storm sewers represented in the model to have inaccurate timings and flows. The Kinnickinnic CE-QUAL-W2 model would provide more reliable results during storm events if more rain gages were available in the basin.

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