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Application of a Runoff Temperature Model (MINUHET) to a Residential Development in Plymouth, MN

by

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Abstract

The MINUHET (MINnesota Urban Heat Export Tool) model is a simulation tool used to route heat and storm water through a sub-watershed for a rainfall event or events of interest. The model includes components for developed land uses, undeveloped or vegetated land uses, pervious and impervious open channels, storm sewer systems, and storm water ponds. As a case study, the model has been applied to a 12.5 acre housing development in Plymouth, MN. The process of identifying necessary data is outlined, as well as a general strategy for organizing the input data and setting up the model for this particular watershed. A catch basin at the outlet of the development was instrumented for flow and temperature, and data were collected at the site from August 25, 2005 to October 1, 2005. The model was run for three rainfall events, and a comparison was made between observed and simulated flow rate and flow temperature at the development outlet. Overall, the model performed well. The RMSE for flow was 42.0 L/s, 10.4 L/s, and 14.3 L/s for the three events respectively, and the corresponding RMSE in storm water runoff temperature was 1.6 ˚C, 1.2 ˚C, and 1.9 ˚C. Observed and simulated volume-averaged mean runoff temperature differed by less than 1.5 ºC for all three events. Total volume of runoff was predicted with reasonable accuracy by the model, especially for the first two events. Heat export, which is a measure of the heat content of the runoff above a certain reference temperature (in this case 16.0 ˚C), was accurately predicted for the second and third events. The model was found to be highly sensitive to saturated hydraulic conductivity and rainfall temperature (dew point temperature): volume of runoff from the pervious areas varied considerably with changes in hydraulic conductivity, and runoff temperature often tended toward dew point temperature, especially in the absence of large atmospheric or ground heat fluxes (e.g., late at night or early in the morning). This suggests that special care should be taken in selection of soil properties, and that all climate data should be collected as near to the study site as possible to improve the accuracy of runoff temperature estimation.

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1. INTRODUCTION

The purpose of this report is to present an application of the heat and storm water routing model, MINUHET, to a study site in Plymouth, MN. MINUHET is a simulation tool, complete with user interface, which integrates previously developed modeling components, including models for overland runoff on a variety of developed and vegetated surfaces [1,2], both vegetated and impervious open channels, storm sewer systems, and storm water detention ponds [3]. A data set has been assembled for the purpose of the case study, and this report presents the comparison of the simulated and measured runoff flow rates and temperatures. Unfortunately, the data set is limited in terms of length of record and accuracy, and routing of overland runoff at the study site may not be known in great detail. Nevertheless, an attempt was made to correlate the simulation results with the measured flow and temperature values, and surprisingly good agreement between the two was achieved in spite of being unable to calibrate model inputs. This report is intended to present the details of the study site and data set, as well as the methodology employed in setting up the model. In the future it will be necessary to find alternate study sites and additional data to test the model.

2. MODEL BACKGROUND

The MINUHET (MINnesota Urban Heat Export Tool) model is a simulation tool used to route heat and storm water through a sub-watershed for a rainfall event or events of interest. The model includes components for developed land uses, undeveloped or vegetated land uses, pervious and impervious open channels, storm sewer systems, and storm water ponds. Each individual model component is treated in one dimension (vertical), and takes into account atmospheric heat fluxes at the surface where appropriate. Surface heat fluxes include solar radiation, longwave radiation, sensible heat, and evapotranspiration. A vegetation model capable of handling a variety of vegetation types is also included [4]. For more detail concerning development of the model components, see [1,2,3,4].

To link multiple elements, MINUHET takes a lumped approach. The model first determines routing and heat flux in each sub-watershed element beginning at the upstream end of the system, using climate data and a rainfall hyetograph as input. The model then feeds the flow and temperature from one element into the next element downstream (e.g., from a developed sub-watershed to a storm sewer system), using the same climate data and hyetograph as before to determine storm water flow and temperature at the outlet of the downstream element. In this way heat flow and storm water flow are routed through the system, and flow and temperature can essentially be predicted at any location in the system. However, it is primarily the flow and temperature at the outlet of the entire system that will be of interest to most users.

Although the model could be run entirely from the command line once all input files have been generated, a graphical user interface (GUI) was developed for the model to ensure user-friendliness, make it easier to operate, and provide visualization of the system layout

and simulation results. Under guidance from the project group, the GUI was developed by Minnetonka Audio Software, Inc. A user's manual for MINUHET, including use of the GUI input and output systems, is currently being developed.

3. STUDY SITE

The study site is located in a residential area of Plymouth, MN, a city in the Minneapolis/St. Paul metropolitan area. The development consists of 39 houses on roughly 12.5 acres of land, 24% of which is connected impervious area. Construction began on the development more than 20 years ago; the area has more mature trees and vegetation than would be typically found in a new development.

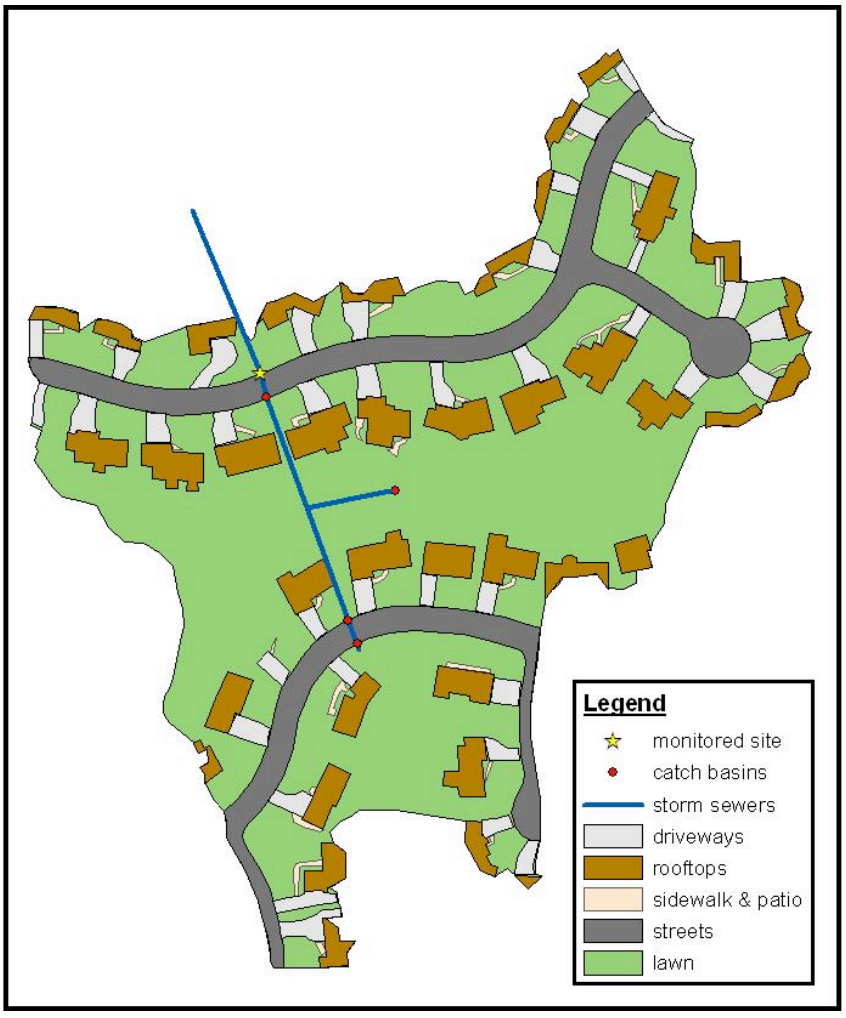

Figure 3.1. Schematic of study site, residential development in Plymouth, MN.

The relatively simple storm sewer system and the small catchment area made the site attractive for application of the model. Considerable GIS data exists for the watershed; a delineation of the drainage area and highly detailed land use data was provided by the

Three Rivers Park District. Storm sewer plans as well as elevation contour maps for both pre-development and post-development conditions for the three housing developments comprising the drainage area were provided by the city of Plymouth. A schematic of the study site is shown in Figure 3.1.

4. DATA COLLECTION

A catch basin at the study site was instrumented by the Three Rivers Park District during summer 2005 to record flow rate and collect storm water samples as part of a project investigating water quality (see Figure 1). A thermistor for measuring flow temperature was added to the system in late summer to provide data for the current model. An ISCO sampler placed in the catch basin was used to measure flow depth in the pipe at one-minute intervals, which was converted to flow velocity and volumetric flow rate using a rating curve. Storm water temperature was recorded at one-minute intervals using a HOBO temperature logger. Combined temperature and flow data were collected from July 9 to October 1, 2005.

Solar radiation and precipitation data were recorded at one-minute intervals at the Three Rivers Park District headquarters, approximately a half mile from the study site. This data was recorded as part of a related project, and was collected from August 24 to October 1, 2005. Additional climate data were needed, including air temperature, relative humidity, and wind speed. These data had to be taken from an airport in Crystal, MN, which is located roughly five miles northeast of the study site. This data was only available at hourly intervals, a much coarser resolution than the data collected at the study site.

5. PREPARING WATERSHED DATA FOR INPUT TO THE MODEL

Even after acquiring the necessary watershed information (drainage area delineation, topography, land use, and storm sewer routing), processing the data for input to MINUHET required a significant amount of effort. A general strategy for this process is as follows:

1) Determine all points within the watershed to which overland runoff would drain in a rainfall event, e.g., catch basins, channels, or ponds.
2) Divide the watershed into sub-watersheds, with no more than two or three sub-watersheds draining into each drainage point as determined in Step 1.
3) Select a characteristic length and slope for each sub-watershed. Generally, the length is the travel distance of a parcel of water from the farthest point in the sub-watershed to the outlet, and the characteristic slope is the average slope along this path.
4) Determine the area of pervious, connected impervious, and disconnected impervious surface in each sub-watershed. Rooftop area is partitioned into disconnected and connected area. The definition of each type is described in more detail below (see Figure 5.1).

5) Determine the amount of shading in each sub-watershed, which is the approximate percentage of incoming solar radiation that is prevented by trees and other vegetation from reaching the ground surface.
6) Additional parameters must be chosen for both the pervious and impervious surface areas within each sub-watershed (see Tables 5.1 and 5.2). Soil type follows the USDA hydrologic soil group classification [5], with moisture selected from one of three levels.
7) To start the routing between drainage points, sub-watersheds are assumed to have an outlet to a routing element, which includes storm sewers and open channels. Sub-watersheds and routing elements can both have an outlet to a storm water pond, which in turn can have an outlet to a storm sewer or channel. Multiple routing elements can be joined together at junctions.
8) Properties of routing elements need to be specified, including length, slope, roughness, and (if applicable) soil type and moisture. Pond parameters are more numerous, and require knowledge of the pond's design (see Table 5.3).

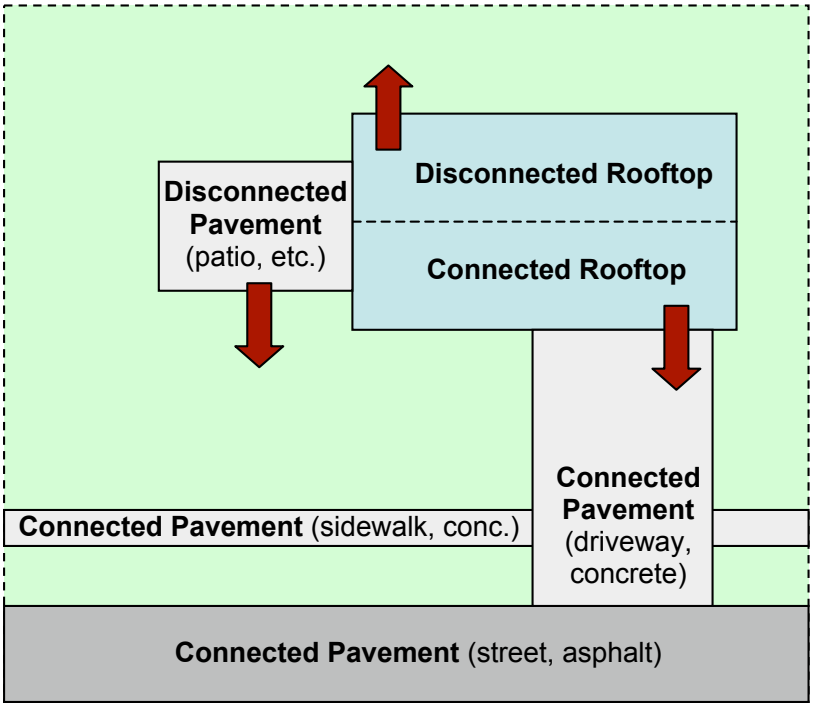

Figure 5.1. Schematic of typical residential housing lot and designation of connected/disconnected impervious surfaces, including rooftop areas.

Table 5.1. Sub-watershed parameter values: Connected impervious surfaces.

Parameter	**Units**	**Allowed Values**
Pavement Area	square meter	10.0 – 100000.0
Length	meter	2.0 – 1000.0
Slope	meter/meter	0.001-0.2
Sheltering	percent	0 – 100%
Shading	percent	0 – 100%
Land Use	none	AS (asphalt) CO (concrete) CR (commercial roof) RR (residential roof)
Additional Contributing Area [1]	square meter	1.0 – 10000.0

1. The additional contributing area for the connected impervious land use is e.g. equal to the connected rooftop area.

Table 5.2. Sub-watershed parameter values: Pervious surface area.

Parameter	**Units**	**Allowed Values**
Area	square meter	10.0 – 100000.0
Length	meter	2.0 – 1000.0
Slope	meter/meter	0.001-0.1
Sheltering	percent	0 – 100%
Shading	percent	0 – 100%
Soil Type	none	A,B,C,D
Soil Moisture	none	DRY NOR (normal) WET
Vegetation Density	percent	0 - 100
Pervious Land Use	none	AG (row crop) BS (bare soil) FR (forest) SG (short grass) TG (tall grass)
Additional Contributing Area [2]	square meter	1.0 – 10000.0

2. The additional contributing area for the pervious land use is equal to the sum of the disconnected rooftop area and the disconnected pavement area.

Table 5.3. Storm water detention pond parameters.

Parameter	**Units**	**Allowed Values**
n (number of specified bathymetric points)	none	2 - 20
Bathymetry	meter (elevation), square meters (area)	Elevation = 0 - 2000 Area = 0 – 40,000
Infiltration Rate	cm per day	0 - 100
Secchi Depth	meters	0.1 - 10
Sheltering	percent	0 – 100%
Shading	percent	0 – 100%
Initial Elevation	meters	0 - 2000
Reference Elevation	meters	0 - 2000
Number of Inflows	none	1 - 5
Inflow Elevation	meters	0 - 1000
Outflow Elevation	meters	0 - 1000
Outflow Control Elevation	meters	0 - 1000
Outflow Type	none	OR = orifice, PI = pipe, WS = sharp crested weir, WB = broad crested weir
Outflow Diameter or Width	meters	0 - 10

For the Plymouth study site, a total of three drainage points were identified: 2 sets of street catch basins, and a single drain/catch basin located in the greenspace behind the houses (Figure 3.1). Two sub-watersheds were assumed to drain into each street catch basin, and a single sub-watershed comprised of the greenspace was assumed to drain into the remaining catch basin, for a total of five sub-watersheds (Figure 5.2).

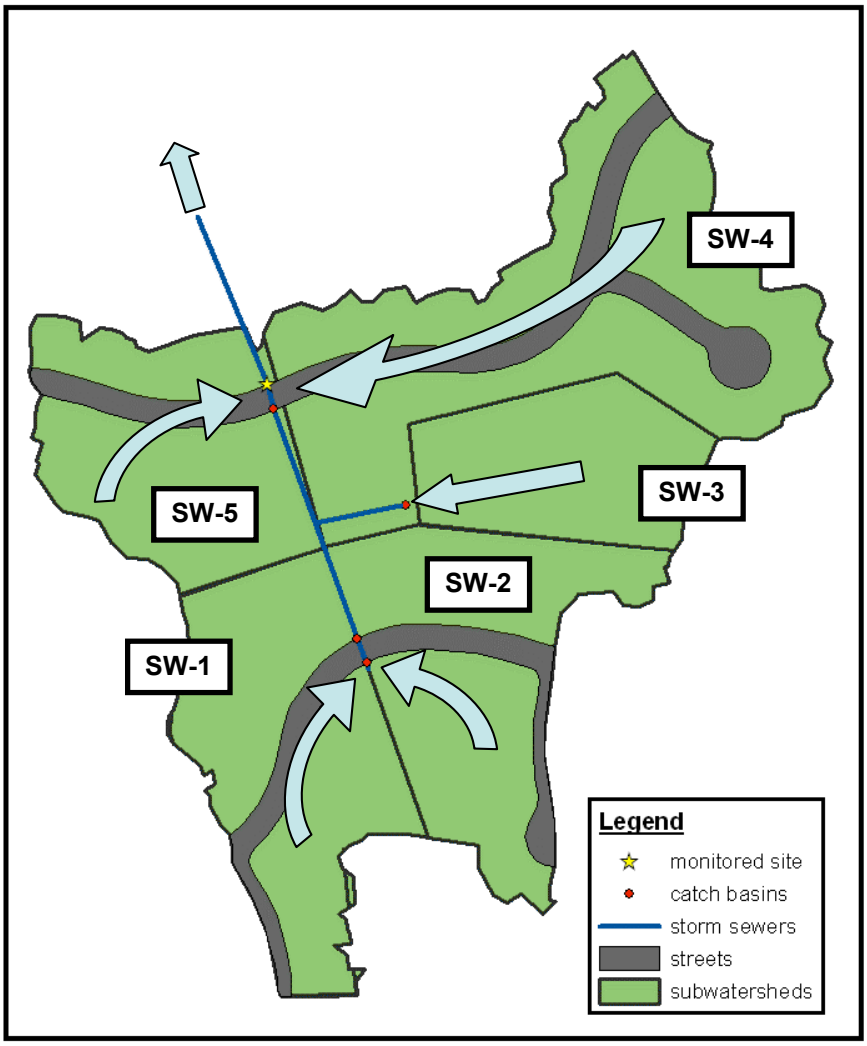

Figure 5.2. Division of study site into sub-watersheds. Direction of overland runoff is also shown.

Within each sub-watershed, parameters had to be defined for both the pervious and impervious surfaces it contained (see Steps 3-6 above). Length for impervious surface was defined by the longest distance a parcel of water could travel along a road to a catch basin. The change in elevation over this distance was the slope, and was determined from contour maps. In sub-watershed 1 (labeled 'SW-1' in Figure 5.2), the length was 63.3m, with a slope of 0.0162. Length for the pervious surfaces was determined in a similar fashion as the largest distance a parcel of water could travel over pervious surface alone, whether or not the eventual outlet was to the road or directly to a catch basin. Slope was defined by change in elevation over this distance. In the case of SW-1, the length and slope were 36.2m and 0.0256, respectively. Lengths and slopes for each sub-watershed are given in Appendix A.

The next step was to determine the area of the surface types in each sub-watershed. In this Plymouth watershed the land use was residential throughout, and the partitioning shown in Figure 5.1 was used. Rooftop area is divided into connected area (that which

drains to a driveway or street) and disconnected area (that which drains to the lawn). Paved areas are similarly divided: connected area consists of sidewalks and driveways that drain to the street, and disconnected area includes patios and walkways that drain to the lawn. Disconnected area is added to the pervious surface category; it produces an extra volume of water that is assumed to contribute little or no heating. Disconnected rooftop area is added to the pervious surface category in the same way, contributing additional water but no heat. Connected pavement contributes both heat and a volume of water. While the process of dividing the areas may seem complicated, it was easily implemented using the available GIS data. In SW-1, for example, impervious area consisted of 2155 m^2 of connected pavement and 197 m^2 connected rooftop area. The pervious portion consisted of 5899 m^2 pervious area and 1445 m^2 disconnected rooftop area. Partitioning of the other sub-watersheds is shown in Appendix A.

Another parameter required by MINUHET is shading, which is the fraction of solar radiation blocked by tree cover. Aerial photography was used to estimate shading percentage to the nearest 10%. In this particular development, the presence of mature trees meant that a fair amount of shading was present, with some trees large enough to overhang roads and houses. Assigned shading values are shown in Appendix A. Vegetation density, which is a parameter used to characterize longwave radiation exchange at the ground surface, also had to be specified for the pervious surfaces. To simplify this input, it was assumed that vegetation density would be around 90%, which is typical of a fully-developed canopy in midsummer, and is independent of vegetation type.

For each sub-watershed, additional surface and subsurface parameters had to be specified. For the land use on previous surfaces, choices include agriculture, bare soil (for areas under construction), forest, short grass, or tall grass (prairie). In a housing development the typical land use will be for short grass. Soil thermal and hydrologic properties are built into the model for choices of soil type and soil moisture; in this development a loam soil (Type B) was present, with moderate moisture content. Soil hydraulic properties were taken from [6]. For the impervious surface, land use is specified as either concrete or asphalt. Given that roads tend to dominate the percentage of impervious surface in this neighborhood, asphalt was the chosen land use for the impervious surfaces. Thermal properties of asphalt and the chosen soil type are given in Appendix A.

For Step 7, the connectivity of the various sub-watershed areas was determined with the help of the storm sewer layout (Figure 5.2). Sub-watersheds 1 and 2, for example, feed into a set of catch basins, which are then routed via storm sewer pipe to a junction that includes storm-water inflow from sub-watershed 3, and so on. A routing schematic showing all sub-watershed and routing elements is shown in Figure 5.3.

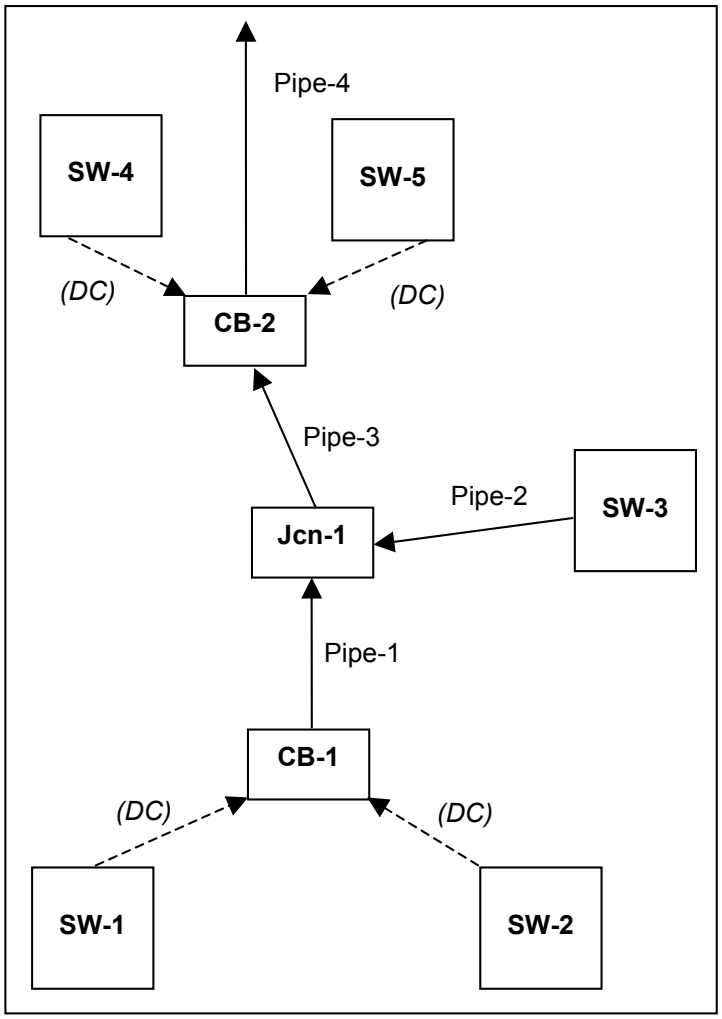

Figure 5.3. Schematic showing connectivity of sub-watersheds and routing elements. 'DC' stands for 'direct connection,' and is used when no routing element is used for that particular connection. 'CB' refers to a catch basin, 'Jcn' refers to a junction, and 'SW' refers to a sub-watershed.

Finally, parameters for the various routing elements had to be specified. In this particular system, the only routing elements for which parameters were needed were the storm sewer pipes; a 'junction' is not a physical structure, but is an element used to join multiple elements together within the routing model. If open channels or a detention pond were present in the development, parameters would be required to describe these elements. For a pipe, necessary parameters include length, diameter, Mannings n, and slope. These data were found in the grading plans for the development, provided by the city of Plymouth. Pipe-1, for example, had a length of 51.7m, a diameter of 0.305m (12in.), a roughness of 0.012 (a typical value for reinforced concrete pipe), and a slope of 0.048. Parameters values for the other pipes are given in Appendix A.

6. CLIMATE DATA AND SELECTION OF STORM EVENTS

MINUHET requires climate data as an input, including solar radiation, air temperature, relative humidity, wind speed, and precipitation. This information is required both for running the model for chosen rainfall events, and for initialization. MINUHET can be run for multiple events, requiring a single input file for each event. Each input file includes weather data for the rainfall event, as well as 'dry' weather data for three days prior to the event. The three-day data are used to properly initialize the model, by running it continuously for those three days to set up subsurface temperatures.

The input data can be on any time scale, but hourly or less is recommended since the model will run on the time scale specified in the climate input file. For this study, precipitation and solar radiation were recorded at 2-minute intervals, while the remainder of the climate data (which came from a local airport) was on hourly intervals. From this data set, an input file utilizing a 15-minute time step was created; linear interpolation was used for the airport data, averaging was used for the solar radiation, and precipitation was summed by 15-minute increments.

Given the relatively short runoff data record at the study site, few rainfall events (storms) were sufficiently well documented to test the model. Three events were eventually selected to test the model under different rainfall scenarios. Characteristics of the selected storms are summarized in Table 6.1. The first storm selected was the largest event on record, with a total rainfall depth of 5.0cm over a duration of 3.5 hours in the early morning of 8/24/05. The second storm, which occurred during the afternoon and evening of 9/3/05, was an intermittent event and occurred over a span of roughly six hours. The third storm occurred on 9/12/05, and was a small, cloudburst-type event that occurred just before midnight. Rainfall temperature for the events was assumed to be equal to the observed dew point temperature.

Table 6.1. Summary of selected rainfall (storm) events.

Date	Duration (hr)	Begin	End	Depth (mm)	Mean i (mm/h)
8/26/2005	3:22	5:00	8:22	50.04	14.86
9/3/2005	5:46	13:48	19:34	23.37	4.05
9/12/2005	0:26	22:32	22:58	17.27	1.22

7. SIMULATION RESULTS

With the necessary climate data and the watershed parameters described above, MINUHET was run for the three selected rainfall events. Features of the simulated storm water flow and temperature at the development's outlet are described in this section, and a comparison is made between MINUHET's output and the recorded runoff flow and temperature data.

7.1. Flow rate and flow temperature

Figure 7.1 shows a plot of simulated versus observed flow rate and temperature at the development outlet for the **first rainfall event (8/26/2005).** Precipitation and dew point temperature are also shown. In general, the model appears to under-predict the outflow temperature, with a volume-averaged runoff temperature of 19.1 ºC (versus 20.5 ºC observed). The RMSE in runoff temperature was 1.6 ºC. An important feature of the plot is that the outflow temperature appears to be very strongly correlated with dew point temperature, which is assumed to be a good approximation of rainfall temperature. In particular, the correlation is strong during the beginning of the event, when there is a large flow; in this case there is likely enough flow that any heat absorbed from the pavement (which will be small at this time of day) is lost in the large volume of water and does not impact its temperature significantly. The sensitivity of the model to rainfall temperature will be discussed in a later section.

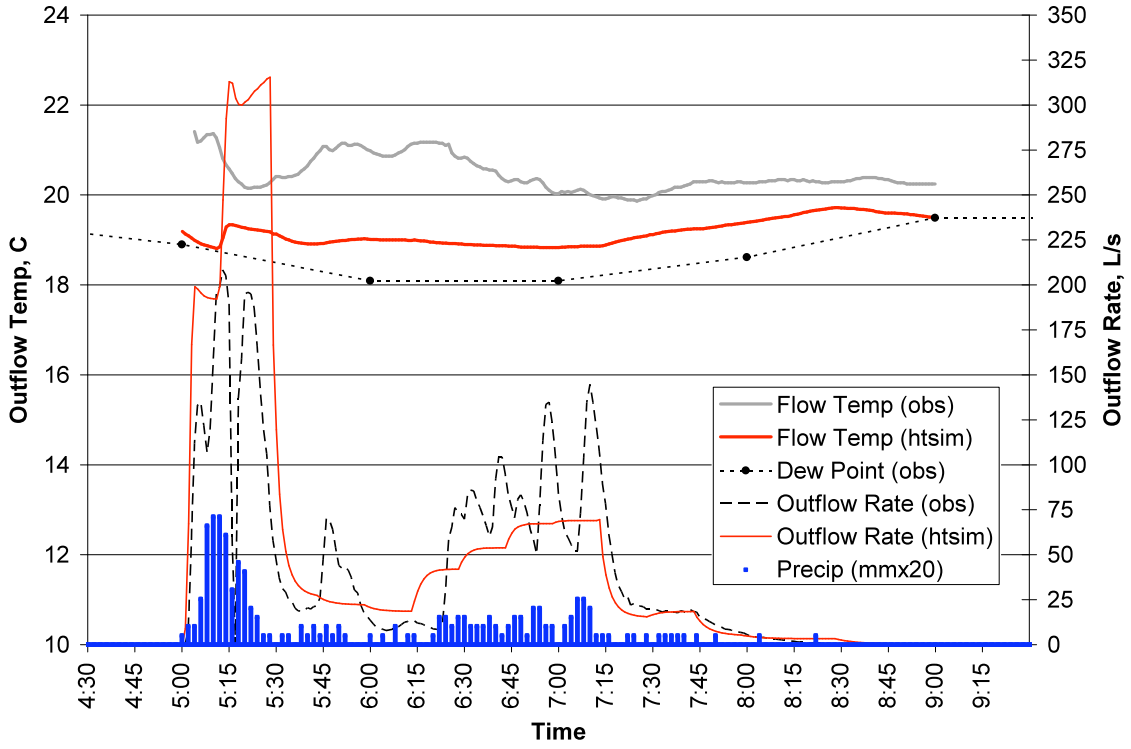

Figure 7.1. Simulated and observed flow rate and flow temperature at the development outlet, for Event #1 (8/26/2005).

In addition, the observed and simulated hydrographs show fair agreement (RMSE = 42 L/s). It should be noted that the simulation does not capture the peaks in outflow because the climate data input file uses 15-minute intervals, while the flow data is measured on one-minute intervals and is thus able to capture these spikes. It is also possible that abrupt changes in flow rate are related to obstructions or debris in the storm sewers. The total volume of flow for the event are 616 m^3 and 753 m^3 for the observed and simulated flow, respectively. It was found that the simulated volume is especially sensitive to saturated hydraulic conductivity of the soil, which is known to be a crucial parameter in any

infiltration modeling. It is encouraging that the model was able to predict the second pulse of runoff from the rainfall event (starting around 6:15am). Given the rainfall distribution, this second pulse is likely a combination of 'fresh' runoff from the impervious surfaces and delayed runoff from the pervious surfaces, or runoff that occurs because a portion of the first pulse of precipitation infiltrated and saturated the soil.

The **second rainfall event (9/03/2005)** had a more even distribution of rainfall and was not as intense as the first event. A plot of simulated and observed flow rate and temperature, as well as precipitation and dew point temperature is shown in Figure 7.2. The simulated and observed outflow temperatures were close (RMSE of 1.2 ºC), with the simulation again slightly under-predicting runoff temperature (mean simulated runoff temperature of 17.5 ºC, versus 18.1 ºC observed). Because the rainfall was not as intense as in the first event, and the initial pavement temperature was warmer (the rain occurred later in the day), the initial runoff temperature was well above the rainfall temperature. However, towards the end of the event as most of the available heat had been extracted from the ground, runoff temperature tended strongly towards dew point temperature, again indicating a strong dependence on this parameter.

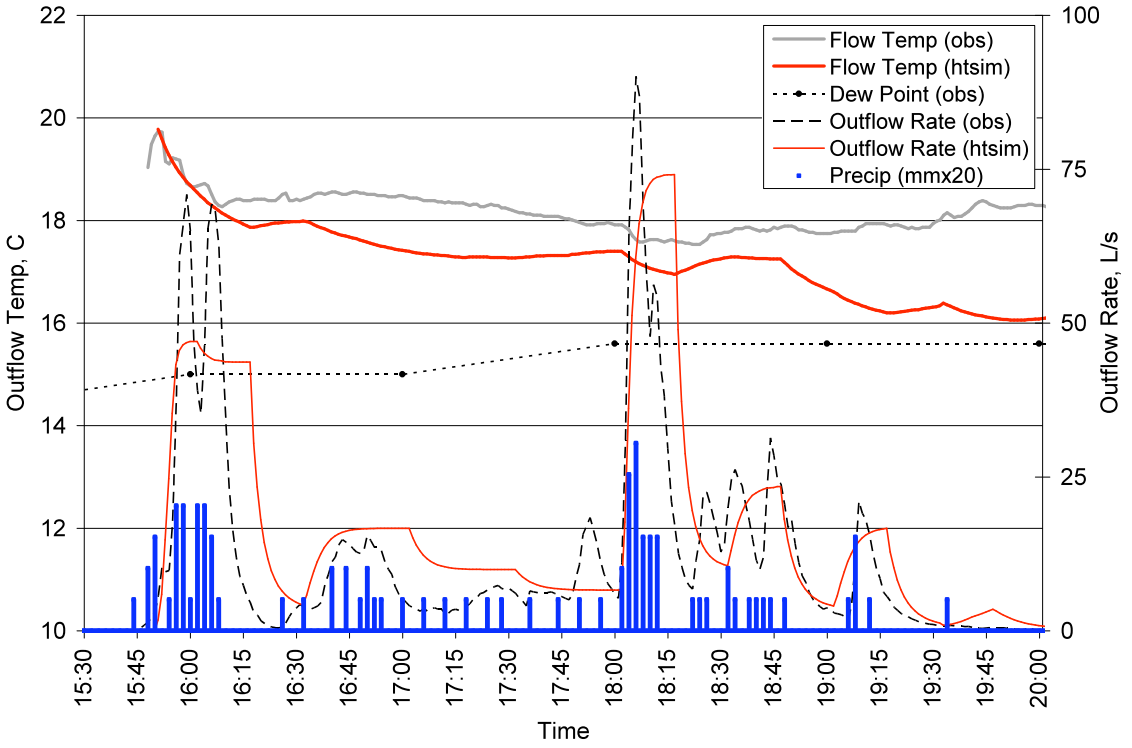

Figure 7.2. Simulated and observed flow rate and flow temperature at the development outlet, for Event #2 (9/03/2005).

The simulated and observed flows showed similar hydrographs (RMSE = 10.4 L/s). Total runoff volume was 197 m^3 observed versus 254 m^3 simulated. All watershed input parameters were unchanged from the simulation for Event #1.

The same plot for the **third rainfall event (9/12/2005)** is shown in Figure 7.3. This day was characterized by a series of brief, low-intensity showers throughout the day, with a more intense cloudburst late in the evening. Flow and temperature had RMSE values of 14.3 L/s and 1.9 ºC for flow and temperature, respectively. Volume-averaged mean runoff temperature was again fairly close (20.7 ºC simulated versus 21.7 ºC observed). Runoff temperature was closer for the low-intensity mid-day rainfall than for the late evening event; in the evening, simulated temperature tended towards the dew point temperature while the measurements remained higher. This behavior seems to contradict the observation that little heat could be extracted from the paved surfaces, given the lack of solar radiation during the cloudy day. The result illustrates again the dependence of the model on rainfall temperature, and the importance of a representative dew point temperature. It is likely that some error is introduced into the model by using a dew point temperature measured 5 miles away; local dew point temperature (rainfall temperature) could be higher. A summary of all flow and temperature results for the three storms can be found in Table 7.1.

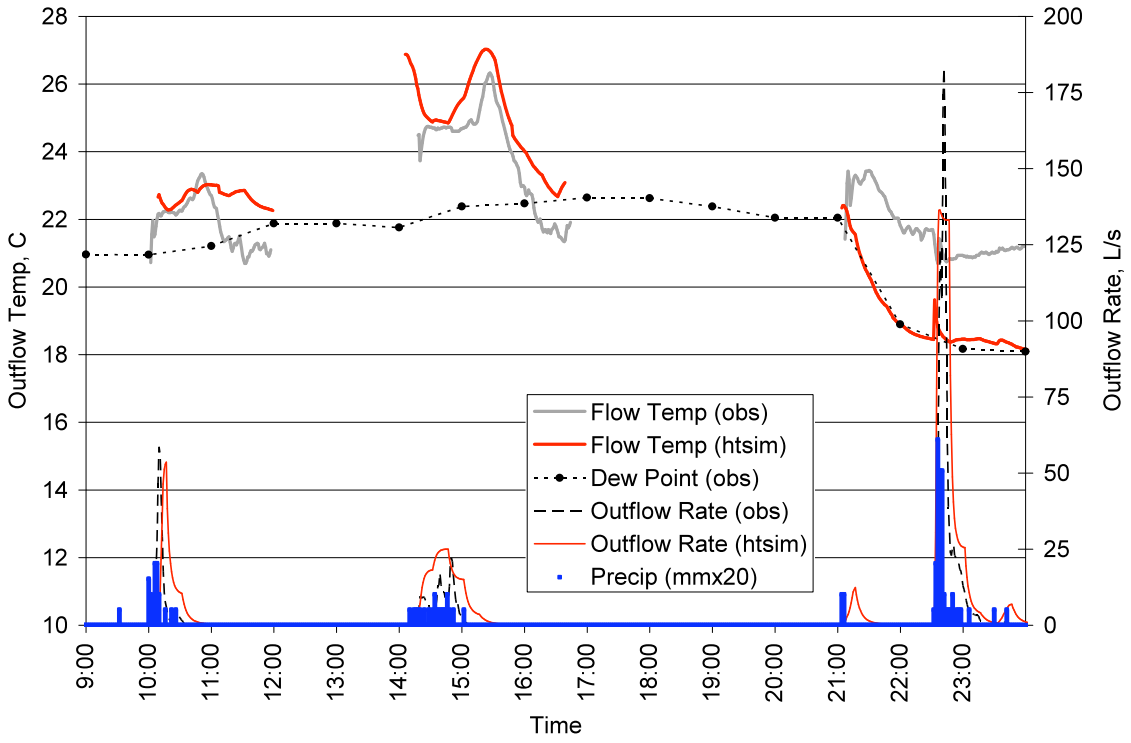

Figure 7.3. Simulated and observed flow rate and flow temperature at the development outlet, for Event #3 (9/12/2005).

Table 7.1. Summary of runoff flow rate and runoff temperature characteristics for three rainfall events at the study site. Note that mean runoff temperature is volume-weighted.

	RMSE, Runoff Flow Rate (L/s)	RMSE, Runoff Temperature (ºC)	Mean Runoff Temperature (ºC)	
			Observed	Simulated
Event 1	42	1.6	20.5	19.1
Event 2	10.4	1.2	18.1	17.5
Event 3	14.3	1.9	21.7	20.7

7.2. Heat export and total volume

Given that the ultimate application of the model will be to assess thermal impact of a development on a trout stream, runoff temperature or flow by itself are not completely useful. A more appropriate measure of potential thermal impact is the heat export from the development, which is a measure of the heat content of the runoff as a function of both temperature and flow. Heat export for some time interval, Δt, is defined as follows:

$$H_{\exp} = \rho_w C_{p,w} \cdot Q_{ro} \cdot \left(T_{ro} - T_{ref}\right) \cdot \Delta t \qquad (1)$$

where H_{exp} is in Joules, Q_{ro} is the volumetric flow rate at the outlet, T_{ro} is the outlet runoff temperature, and T_{ref} is some reference temperature. Total heat export from the rainfall event is the sum of the heat export for every time interval of the event. The reference temperature, T_{ref}, can be chosen such that the heat export represents the heating load above some significant value of temperature, e.g., a temperature above which trout experience thermal stress (20 ºC). In the case of the simulations presented here, the runoff temperature is often less than 20 ºC, resulting in a negative heat export. An arbitrary reference temperature of 16 ºC is therefore used to ensure that heat export remains positive in all cases.

For the three events, total event heat export and volume of flow were calculated (Table 7.2.) For Event #1, simulated total runoff volume is about 22% higher than the observed runoff volume, yet the heat export is under-predicted by 17%. This discrepancy in heat export can be traced to the under-prediction of runoff temperature, which is in turn related to an observed dew point temperature (rainfall temperature) that is likely lower than the actual dew point temperature at the site. For Event #2, the predicted runoff volume and event heat export were close to the observed values, likely the result of the event occurring during the middle hours of the day when heat content of the pavement would be at its maximum. As long as heat is available for extraction, the tendency of the runoff temperature to approach rainfall temperature appears to be reduced. For Event #3, considerable difference (given the small amount of rainfall) between simulated and observed heat export exists. This is the result of a large discrepancy between observed and simulated flow volume, and a significant under-prediction of runoff temperature during the most intense portion of the rainfall event (late evening). Results may be improved by increasing the amount of infiltration in the pervious areas (by increasing the saturated hydraulic conductivity), but such an exercise was not performed here.

Table 7.2. Observed versus simulated total event heat export and runoff volume for three rainfall events.

	Total Runoff Volume (m3)		Total Event Heat Export (MJ)	
	Observed	Simulated	Observed	Simulated
Event 1	616	753	11562	9644
Event 2	199	254	1765	1575
Event 3	144	251	3436	4919

7.3 Sensitivity of results

Overall, the results indicate a strong dependence of the model upon selection of dew point temperature and saturated hydraulic conductivity. To illustrate sensitivity of the model to dew point temperature, the simulation was re-run for Event #1 with a dew point temperature raised by an average of 0.7 ºC. In the model the dew point temperature is calculated from relative humidity and air temperature; the increase in dew point temperature by 0.7 ºC corresponds to an increase in air temperature of 1.5 ºC. The results are shown in Figure 7.4.

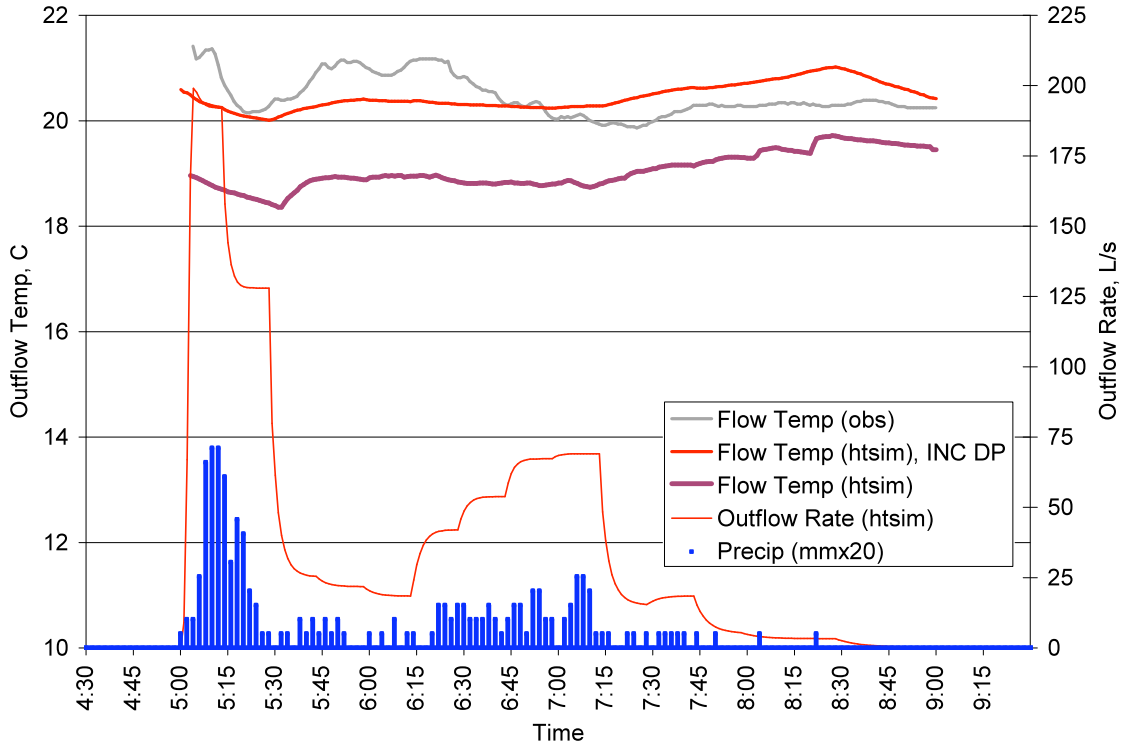

Figure 7.4. Simulated versus observed runoff temperature for Event #1 (8/26/2005), for a mean increase in dew point temperature of 0.7 ºC.

For the 0.7 ºC increase in dew point temperature, the simulated runoff temperature increased by 1.1 ºC. This illustrates the extent to which the model result is sensitive to the

dew point (rainfall) temperature. For the elevated dew point temperature the RMSE in runoff temperature improved to 0.45 ºC, while the simulated heat export was 10,287 MJ – about 11% different from the observed heat export. This result suggests that the model accuracy depends on the availability and careful selection of input data, and in particular the dew point temperature. In the case of the current field site, dew point temperature was taken from an airport located 5 miles away. Given that humidity / dew point temperature can vary considerably spatially, especially during locally heavy rainfall events (such as Event #1), it will be important in future applications of the model to measure all climate parameters as close to the study site as possible.

8. SUMMARY

The MINUHET (Heat Transport Simulation) model is a simulation tool used to route heat and storm water through a sub-watershed for a rainfall event or events of interest. The model includes components for developed land uses, undeveloped or vegetated land uses, pervious and impervious open channels, storm sewer systems, and storm water ponds. As a case study, the model has been applied to a small housing development in Plymouth, MN. This development is relatively mature (approximately 25 years old), and the 12.5-acre drainage area has roughly 24% connected impervious area. The process of identifying necessary model input data is outlined, and a general strategy for organizing the input data and setting up the model for this particular watershed is illustrated.

A catch basin at the outlet of the development had been instrumented by the Three Rivers Park District as part of a water quality monitoring project, and from this study a small data set including storm water flow rate and temperature was acquired. Solar radiation and precipitation data were collected at a nearby site. The remainder of the climate data come from the Crystal, MN airport, located 5 miles away. Flow rate and temperature data were collected at the development from August 25, 2005 to October 1, 2005.

From this data set, three rainfall events were selected for application to the model. These events occurred on August 26, September 3, and September 9, with rainfall totals of 5.0 cm, 2.3 cm, and 1.7 cm, respectively. The model was run for each event and a comparison was made between observed and simulated flow rate and flow temperature at the development outlet. The default hydrologic and thermal properties were used (i.e., no calibration). The RMSE for flow was 23.0 L/s, 10.4 L/s, and 14.3 L/s for the three events respectively, with corresponding RMSE in flow temperature of 1.6 ˚C, 1.2 ˚C, and 1.9 ˚C. Total volume of flow was predicted with reasonable accuracy by the model, especially for the first two events. Heat export, which is the measure of the heat content of the runoff above a certain reference temperature (in this case 16.0 ˚C), was also predicted.

Two significant issues related to model sensitivity should be noted. First, the total volume of runoff was strongly related to the value of saturated hydraulic conductivity. This is due to the fact that hydraulic conductivity controls the amount of infiltration occurring in pervious areas of the watershed, which make up roughly 75% of the surface area at this site. The range of the parameter spans nearly two orders of magnitude for common soil

types, and is known to be both difficult to specify and crucial to the accuracy of any hydrologic modeling. Second, the model results are very sensitive to dew point temperature, which is assumed to be equal to rainfall temperature. Especially when the heat content of the pavement and soil was minimal (if the rainfall event occurred early in the morning, for example), predicted runoff temperature tended to approach the rainfall temperature. Thus it is critical to be able to accurately measure dew point temperature or relative humidity as close to the site as possible. Given that the dew point temperature data came from a location five miles from the study site, it is possible that a difference between simulation results and measurements can in large portion be attributed to spatial variation in dew point temperature, which is especially an issue for high-intensity events (such as Event #1). When Event #1 was re-simulated with a dew point temperature artificially elevated by 0.7 ˚C, the RMSE of flow temperature was improved to 0.45 ˚C and the difference in heat export was reduced from 40% to 11%. This suggests that the accuracy of simulations can be improved by careful selection of input data, especially in regards to dew point temperature and saturated hydraulic conductivity.

In the future, it will be necessary to apply the model to a more complicated housing development. The site used for this case study did not include any BMPs or storm water conveyances other than storm sewer pipes. Ideally, all necessary climate data will be collected at or near the site at high resolution. A more detailed sensitivity analysis on input parameters needs to be conducted in the future.

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A delineation of the drainage area and highly detailed land use data were provided by the Three Rivers Park District. Storm sewer plans as well as elevation contour maps for both pre-development and post-development conditions for the three housing developments comprising the drainage area were provided by the city of Plymouth.

The watershed in Plymouth, MN, was instrumented by the Three Rivers Park District. The rainfall, runoff and water temperature data used in this study were made available by James Johnson. We are grateful to James Johnson, the Three Rivers Park District and the City of Plymouth for their cooperation.

The weather data were collected by William Herb.

The graphical user interface was developed under sub-contract by Minnetonka Audio Software, Inc., Minnetonka, MN.

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APPENDIX A: SUMMARY OF INPUT DATA FOR THE STUDY SITE

A.1. Sub-watershed Inputs

Sub-watershed-1		**Sub-watershed-2**	
Description	SW Corner	*Description*	SE Corner
Land Use	Residential	*Land Use*	Residential
Impervious A		Impervious A	
Description	SW Corner of Dev.	*Description*	SE Corner of Dev
Land Use	Roads, Driveways, Sidewalks	*Land Use*	Roads, Driveways, Sidewalks
Length (m)	63.3	*Length (m)*	43.5
Paved Area (m2)	2155	*Paved Area (m2)*	1889
Conn. Roof (m2)	197	*Conn. Roof (m2)*	226
Shading (%)	10	*Shading (%)*	0
Wind Sheltering (%)	0	*Wind Sheltering (%)*	0
Slope	0.0162	*Slope*	0.0128
Pervious		Pervious	
Description	SW Corner of Dev.	*Description*	SE Corner of Dev
Land Use	Grass, Trees	*Land Use*	Grass, Trees
Length (m)	36.2	*Length (m)*	27.9
Pervious Area (m2)	5899	*Pervious Area (m2)*	5881
Disconn. Roof (m2)	1445	*Disconn. Roof (m2)*	1654
Shading (%)	20	*Shading (%)*	50
Wind Sheltering (%)	0	*Wind Sheltering (%)*	?
Slope	0.0256	*Slope*	0.0167
Soil Type	B	*Soil Type*	B
Soil Moisture	normal	*Soil Moisture*	normal
Veg. Density	0.9	*Veg. Density*	0.9

Sub-watershed-3	
Description	Greenspace (E)
Land Use	Residential
Impervious A	
Description	Greenspace
Land Use	Roads, Driveways, Sidewalks
Length (m)	n/a
Paved Area (m2)	n/a
Conn. Roof (m2)	n/a
Shading (%)	n/a
Wind Sheltering (%)	n/a
Slope	n/a
Pervious	
Description	Greenspace
Land Use	Grass, Trees
Length (m)	23.2
Pervious Area (m2)	5007
Disconn. Roof (m2)	858
Shading (%)	80
Wind Sheltering (%)	0
Slope	0.064
Soil Type	B
Soil Moisture	normal
Veg. Density	0.9

Sub-watershed-4	
Description	NE Corner
Land Use	Residential
Impervious A	
Description	NE Corner of Dev.
Land Use	Roads, Driveways, Sidewalks
Length (m)	26
Paved Area (m2)	1677
Conn. Roof (m2)	155
Shading (%)	0
Wind Sheltering (%)	0
Slope	0.026
Pervious	
Description	NE Corner of Dev.
Land Use	Grass, Trees
Length (m)	23.2
Pervious Area (m2)	5537
Disconn. Roof (m2)	1135
Shading (%)	20
Wind Sheltering (%)	0
Slope	0.04
Soil Type	B
Soil Moisture	normal
Veg. Density	0.9

Sub-watershed-5	
Description	NW Corner
Land Use	Residential
Impervious A	
Description	NW Corner
Land Use	Roads, Driveways, Sidewalks
Length (m)	62.6
Paved Area (m2)	5323
Conn. Roof (m2)	318
Shading (%)	10
Wind Sheltering (%)	0
Slope	0.026
Pervious	
Description	NW Corner
Land Use	Grass, Trees
Length (m)	42.2
Pervious Area (m2)	8533
Disconn. Roof (m2)	2336
Shading (%)	50
Wind Sheltering (%)	0
Slope	0.0441
Soil Type	B
Soil Moisture	normal
Veg. Density	0.9

A.2. Routing Element (Storm Sewer Pipe) Inputs

Pipe-1	
Description	Connects CB-1 to Jcn-1
Type	RCP
Length (m)	51.7
Diameter (m)	0.305
Manning's n	0.012
Slope	0.048

Pipe-2	
Description	Connects greenspace drain (SW-3) to Jcn-1
Type	RCP
Length (m)	24.2
Diameter (m)	0.305
Manning's n	0.012
Slope	0.0045

Pipe-3	
Description	Connects Jcn-1 to CB-2
Type	RCP
Length (m)	52.3
Diameter (m)	0.457
Manning's n	0.012
Slope	0.0092

Pipe-4	
Description	Connects CB-2 to Outlet
Type	RCP
Length (m)	64.6
Diameter (m)	0.381
Manning's n	0.012
Slope	0.075

A.3. Thermal and Hydrologic Properties

Note: These property values are default values in the model and do not need to be specified individually by the user; they are listed here as a reference.

Thermal Properties	
Soil (generic)	
Thermal Diffusivity (m/s^2):	1.00E-06
Heat Capacity (J/kg*K):	2.00E+06
Asphalt	
Thermal Diffusivity (m/s^2):	1.00E+06
Heat Capacity (J/kg*K):	2.00E+06

Hydrologic Properties	
Loam soil type	
Porosity:	0.463
Field Capacity:	0.27
Wilting Point:	0.117
Sat. Hydraulic Cond. (m/s):	3.67E-06
Bubbling Pressure (m):	0.112

APPENDIX B: COMPARISON OF SIMULATION RESULTS TO UNDEVELOPED VERSION OF STUDY WATERSHED

B.1. Background and Application

One of the primary applications of the model will be to assess the impact of land use change on the runoff flow rate and temperature from a particular watershed. In order to complete such a task, a comparison is needed of the simulation results from both a developed and undeveloped version of the site of interest. In most applications, the model will be applied to a proposed development and to the existing, undeveloped site. In this particular case study, the development has been in place for roughly 20 years, so the model is being used to estimate the impact the development has had on surface runoff.

Application of the model to pre-development conditions for this particular watershed was relatively simple since pre-development land use and topographical data were readily available. Given that the significant earth-moving associated with development tends to alter drainage patterns of a watershed, the approach to modeling a site of interest had to be modified, however. In order to accurately compare total volumes of flow between the two conditions, it was important that the drainage area remain the same. Another issue to address was the direction of runoff; in the developed condition, all surface runoff drains to a single point through a storm sewer conveyance system, but this will not necessarily be the case for the undeveloped condition. It was determined that the pre-development contours should be imposed on the existing (developed) drainage area, and the runoff from the undeveloped parcels combined to give a total runoff from the drainage area. The direction of runoff in this case was deemed less important than knowing the quantity of runoff.

For the undeveloped version of the study site, the first step was to determine where drainage delineations should be made, based on the pre-development elevation contours (see Figure B.1.) Given the absence of a storm sewer system, the partitioning of the watershed was considerably simpler, resulting in only two sub-watersheds. The largest of these, SW-1, had an area of 41,846 $m^2$and drained to the northwest, while the other, SW-2, had an area of 8501 m^2 and drained to the southwest. A significant difference between the pre- and post-development scenarios is that the land slope was considerably higher for the pre-development conditions, at roughly 12% for each subwatershed. Shading was estimated at 25% for the entire watershed. According to historical land use data, the area was formerly agricultural, so the simulation was run for a row crop land use. Normal soil moisture condition was assumed, and a soil map (SSURGO) revealed that the area was dominated by loamy soils (Type B). A summary of input parameters for each subwatershed can be found in Table B.1.

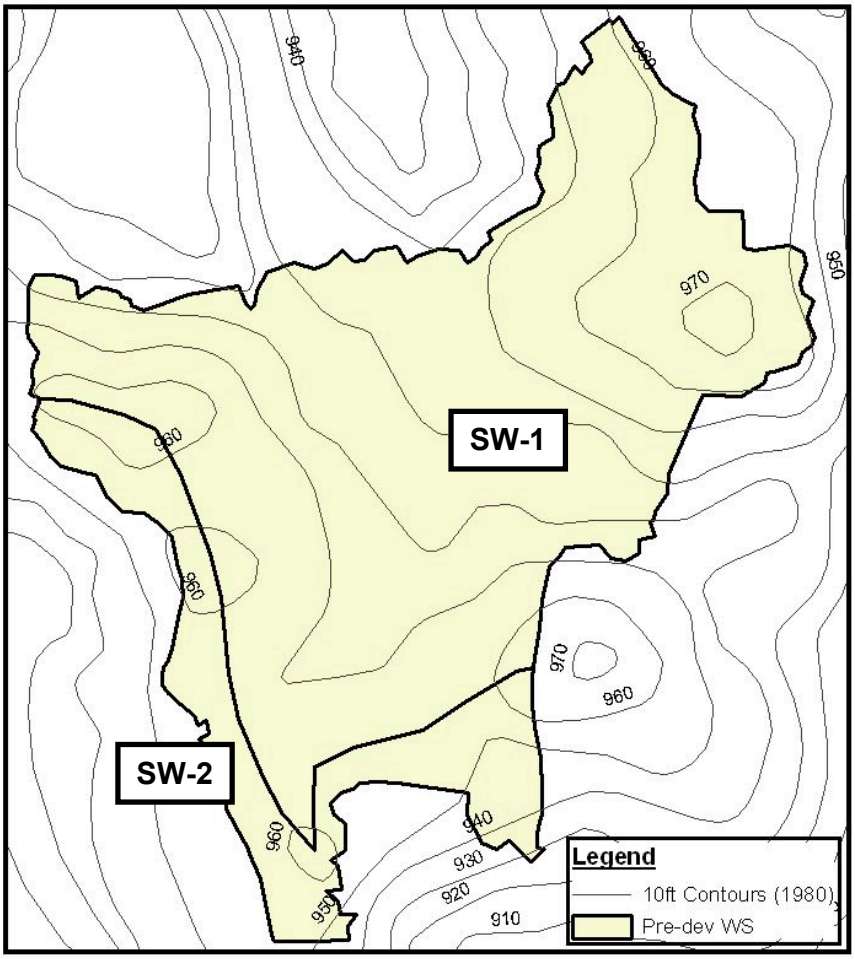

Figure B.1. Pre-developed conditions for Plymouth, MN study site, showing partitioning of watershed into sub-watersheds. Contours shown are from 1980.

Table B.1. Summary of input parameters for pre-development condition of the watershed.

Subwatershed-1	
Description	SW Corner
Land Use	Residential
Pervious	
Description	Main
Land Use	Row Crop
Length (m)	190
Pervious Area (m2)	41846
Disconn. Roof (m2)	0
Shading (%)	25
Wind Sheltering (%)	0
Slope	0.12
Soil Type	B
Soil Moisture	normal
Veg. Density	0.9

Subwatershed-2	
Description	SE Corner
Land Use	Residential
Pervious	
Description	SW Corner
Land Use	Row Crop
Length (m)	23
Pervious Area (m2)	8501
Disconn. Roof (m2)	0
Shading (%)	25
Wind Sheltering (%)	0
Slope	0.12
Soil Type	B
Soil Moisture	normal
Veg. Density	0.9

B.2. Results

Comparisons between the developed (existing) and pre-developed conditions were made in terms of total volume of flow and heat export for the three design storms used for the existing development (see Section 6). Interestingly, only the first rainfall event produced any runoff from the pre-developed watershed; for the latter two events the rainfall intensity was not high enough to produce runoff. While this behavior limits the comparisons that can be made between the developed and undeveloped conditions, it is not unreasonable that low-intensity rainfall events of very small total depth (such as Event #2 and Event #3) could be completely infiltrated. The logical conclusion is that presence of impervious surface in the developed watershed allows runoff to occur during events that previously would have been completely infiltrated; for certain combinations of antecedent conditions and rainfall intensity, this may not be an insignificant phenomenon. Further comparisons between the two conditions are made for Event #1 only.

Figure B.2 shows a time series of runoff flow rate and runoff temperature for the two conditions. Nor surprisingly, there is a greater flow rate and duration of runoff from the developed version of the site than from the undeveloped version, and the runoff temperature is slightly higher for the developed case, as well. In terms of total volume, the development contributed roughly 750% more runoff to the system than did the undeveloped site for the event; 753 m^3 versus 99 m^3. The corresponding change in heat export was slightly larger. The total event heat export for the developed case was 9648 MJ, which is roughly nine times the total event heat export for the undeveloped case (1016 MJ). It should be noted that a reference temperature of 16 ºC was used to calculate heat export, and that while the difference between the two conditions seems large, it is entirely dependent upon selection of a reference temperature. In other words, the percent difference can be changed by simply selecting a different reference temperature (though the absolute difference remains the same); thus percent difference is not a very useful method for comparison. Perhaps of more use is the volume-weighted mean runoff temperature, which does not require a reference temperature. For the developed scenario, the mean runoff temperature was 19.1 ºC, while for the undeveloped case it was 18.4 ºC. A summary of volume, heat export, and mean runoff temperature calculations for both scenarios and for all three rainfall events is shown in Table B.2. As this simple exercise illustrates, the tendency of development to increase surface runoff flow rate and runoff temperature is unmistakable, though it is important to note that in this particular case there are no storm water BMP's included.

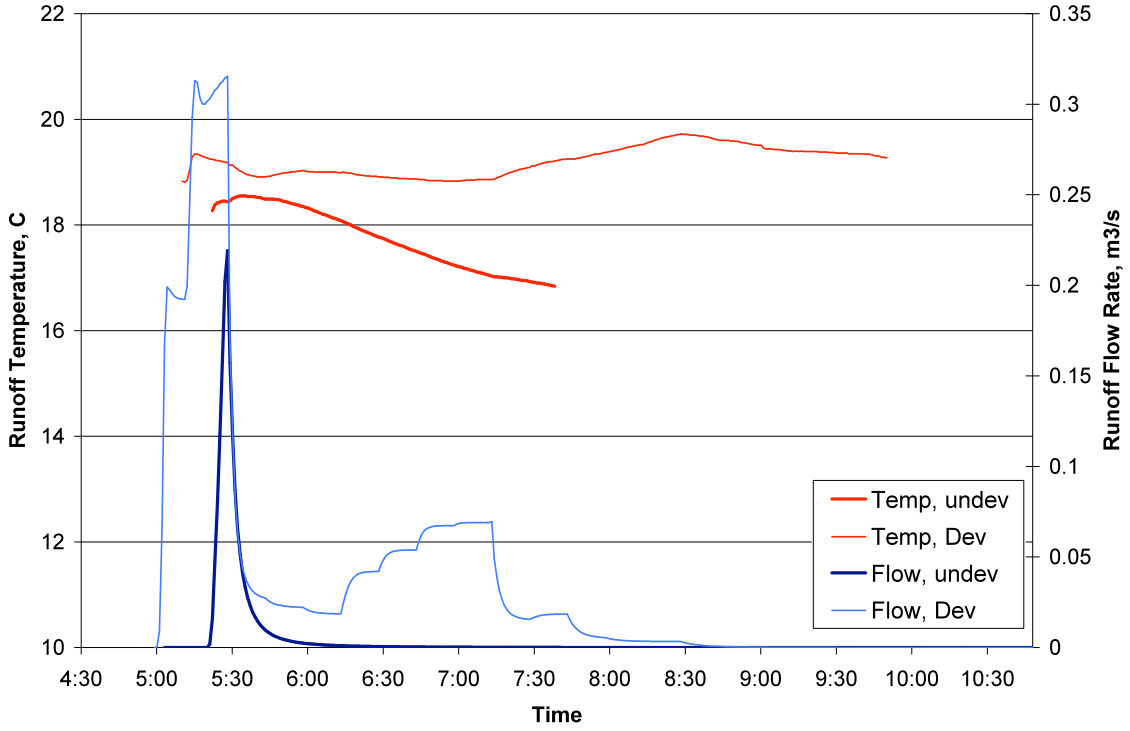

Figure B.2. Time series of runoff flow rate and temperature for both pre-developed and developed conditions at the study site, for Event #1 (8/26/2005).

Table B.2. Summary of output parameters for developed and undeveloped scenarios at Plymouth, MN study site, for three selected storm events. Heat export is calculated with a reference temperature of 16.0 ºC and mean runoff temperature is a flow-weighted average.

	Total Discharge Volume (m^3)		**Total Event Heat Export (MJ)**		**Mean Runoff Temp (ºC)**	
	Developed	*Undeveloped*	*Developed*	*Undeveloped*	*Developed*	*Undeveloped*
Event #1	753	99	9648	1016	19.1	18.4
Event #2	254	0.0	1575	0.0	17.5	n/a
Event #3	284	0.0	5486	0.0	20.6	n/a

APPENDIX C: SENSITIVITY OF MODEL TO SOIL HYDROLOGIC PROPERTIES

C.1. Soil Hydrologic Properties

When applying the model to the study watershed, and in particular to the pre-developed version of the site, it became apparent that certain hydrologic properties of the soil could greatly influence the amount of runoff from pervious areas. Therefore selection of soil type and associated soil properties is not a trivial matter. The model requires specification of five parameters, which are used in determining infiltration. These parameters include:

Saturated Hydraulic Conductivity: a measure of the ability of a saturated soil to transmit water, usually given in units of length per time,

Field Capacity: the moisture content of a soil corresponding to a matrix potential (pressure) of 1/3 bars, determined from a moisture-release curve,

Wilting Point: the moisture content of a soil corresponding to a matrix potential (pressure) of 15 bars, determined from a moisture-release curve,

Porosity: the fraction of a soil that is occupied by pores, which also represents its maximum water content,

Soil Suction: a measure of the soil suction forces, or the pressure required to remove water from the largest pores of a saturated soil, specified in units of pressure. Soil suction is generally a function of soil composition, porosity, and moisture content.

Considerable research has been conducted previously to determine these properties, among others, for soil types as a function of soil texture class [6,7]. A summary of these soil properties is given in Table C.1. Given that identification of soil texture class can be potentially difficult, the model only requires specification of the hydrologic soil group (A/B/C/D). Soil properties were specified as a function of hydrologic soil group by averaging the mean values for each texture class within the soil group. These values are summarized in Table C.2.

Table C.1. Soil hydrologic properties by soil texture class, from Rawls et al. [6]. HSG is the hydrologic soil group the soil belongs to, as per USGS TR-55 classification. Numbers in italics represent the range spanning the 25th to 75th percentile of values.

Texture Class	HSG	Porosity	Suction Head *cm*	Field Capacity	Wilting Point	Sat Hyd Cond *cm/h*
Sand	A	0.437 *.347-.5*	7.26 *1.36-38.74*	0.091 *0.018-0.164*	0.033 *0.007-0.059*	21
Loamy Sand	A	0.437 *0.368-0.506*	8.69 *1.80-41.85*	0.125 *0.060-0.190*	0.055 *0.019-0.091*	6.11
Sandy Loam	A	0.453 *0.351-0.555*	14.66 *3.45-62.24*	0.207 *0.126-0.288*	0.095 *0.031-0.159*	2.59
Loam	B	0.463 *0.375-0.551*	11.15 *1.63-76.40*	0.27 *0.195-0.345*	0.117 *0.069-0.165*	1.32
Silt Loam	B	0.501 *0.420-0.582*	20.76 *3.58-120.4*	0.33 *0.258-0.402*	0.133 *0.078-0.188*	0.68
Sandy Clay Loam	C	0.398 *0.332-0.464*	28.08 *5.57-141.5*	0.255 *0.186-0.324*	0.148 *0.085-0.211*	0.43
Clay Loam	D	0.464 *0.409-0.519*	25.89 *5.80-115.7*	0.318 *0.250-0.386*	0.197 *0.115-0.279*	0.23
Silty Clay Loam	D	0.471 *0.418-0.524*	32.56 *6.638-158.7*	0.366 *0.304-0.428*	0.208 *0.138-0.278*	0.15
Sandy Clay	D	0.43 *0.370-0.490*	29.17 *4.96-171.6*	0.339 *0.245-0.433*	0.239 *0.162-0.316*	0.12
Silty Clay	D	0.479 *0.425-0.533*	34.19 *7.04-166.2*	0.387 *0.332-0.442*	0.25 *0.193-0.307*	0.09
Clay	D	0.475 *0.427-0.523*	37.3 *7.43-187.2*	0.396 *0.326-0.466*	0.272 *0.208-0.336*	0.06

Table C.2. Soil hydrologic properties as a function of soil hydrologic group (HSG).

HSG	Porosity	Suction Head *cm*	Field Capacity	Wilting Point	Sat Hyd Cond *cm/h*
A	0.442	10.2	0.141	0.061	9.90
B	0.482	16.0	0.300	0.125	1.00
C	0.398	28.1	0.255	0.148	0.43
D	0.464	31.8	0.361	0.233	0.13

C.2. Sensitivity Study

Sensitivity of the model to changes in hydrologic soil properties was investigated by observing changes in runoff volume and event heat export for small changes in soil properties. Given that these properties affect infiltration, the pre-development version of the study site was used in order to maximize the amount of pervious area. A constant-

intensity rainfall event (2 inches over a one-hour duration) was used, and assumed to begin at the same time as Event #1 (5:00am, 8/26/2005). Soil at the study site is known to be loam, so base property values were selected accordingly. Modified properties were found by increasing base values by 10% of the range from the mean to the 75th percentile value. However, no range had been given by Rawls et al. [6] for the saturated hydraulic conductivity values. In a later report, Rawls et al. [7] specified a range for saturated hydraulic conductivity for each soil texture class, as well as mean values of porosity, field capacity, and wilting point, which were similar to those specified in Table C.1. The base and modified properties as used in the sensitivity analysis are shown in Table C.3. It should be noted that surface depression storage, which in this case also includes an estimation of interception by vegetation, is included in the sensitivity analysis even though it is not necessarily a function of soil type. It is included because the parameter can have a significant effect on the amount and timing of surface runoff.

Table C.3. Base and modified values of selected soil and surface hydrologic parameters.

Parameter	Base Value	Modified Value
Depression Storage [m]:	0.007	0.0077
Sat. Hydr. Cond. [m/s]:	1.08E-06	1.76E-06
Porosity:	0.463	0.4718
Field Capacity:	0.27	0.2775
Wilting Point:	0.117	0.1218
Soil Suction Head [m]:	0.112	0.1772

Each parameter was varied independently and the resulting volume and event heat export was compared against that of a base simulation in which none of the parameters had been modified. The simulation results are shown in Table C.4.

Table C.4. Change in total volume and heat export of storm water runoff from test watershed for an increase in the given parameter, for a 1-hour, 2-inch constant-intensity rainfall event.

Parameter	Percent Difference		Absolute Difference	
	Volume	*Heat Export*	*Volume (m^3)*	*Heat Export (MJ)*
Depression Storage [m]:	-2.2	-2.2	-36	-533
Sat. Hydr. Cond. [m/s]:	-13.4	-13.5	-216	-3209
Porosity:	-0.7	-0.7	-11	-162
Field Capacity:	0.6	0.6	9	134
Wilting Point:	0.0	0.0	0	0
Soil Suction Head [m]:	-7.3	-7.3	-117	-1744

Not surprisingly, saturated hydraulic conductivity appears to be the most sensitive soil property; it can vary by more than two orders of magnitude over the whole range of soil texture classes. Model output also tends to be sensitive to selection of soil suction head as well, which is logical given that the parameter varies by nearly 200 cm over the range of texture classes, and is a function of soil composition (texture), porosity, and moisture

content. The effect of surface depression storage is also not negligible, and considerable variation exists in published values of estimated surface depression storage and vegetative interception, so this parameter must also be specified with care [8,9,10]. Wilting point had no effect on volume of runoff since the parameter is only used to determine the minimum moisture content of the soil, which is a condition that will not be reached during periods of heavy infiltration (such as during a rainfall event).