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MINUHET
(Minnesota Urban Heat Export Tool)

USER MANUAL

by

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1. Introduction

1.1 Model Concept

MINUHET (Minnesota Urban Heat Export Tool) is a tool used to simulate the flow of stormwater surface runoff and its associated heat content through a small watershed for a rainfall event or events of interest. The main output of MINUHET is a time series of flow rate and temperature at the outlet of the watershed, to enable prediction of thermal impact on receiving streams. MINUHET is event-based, i.e. it is designed primarily to simulate a single storm event. The MINUHET tool includes a database of observed and/or synthetic storm events that have the potential to produce high thermal loading in receiving streams.

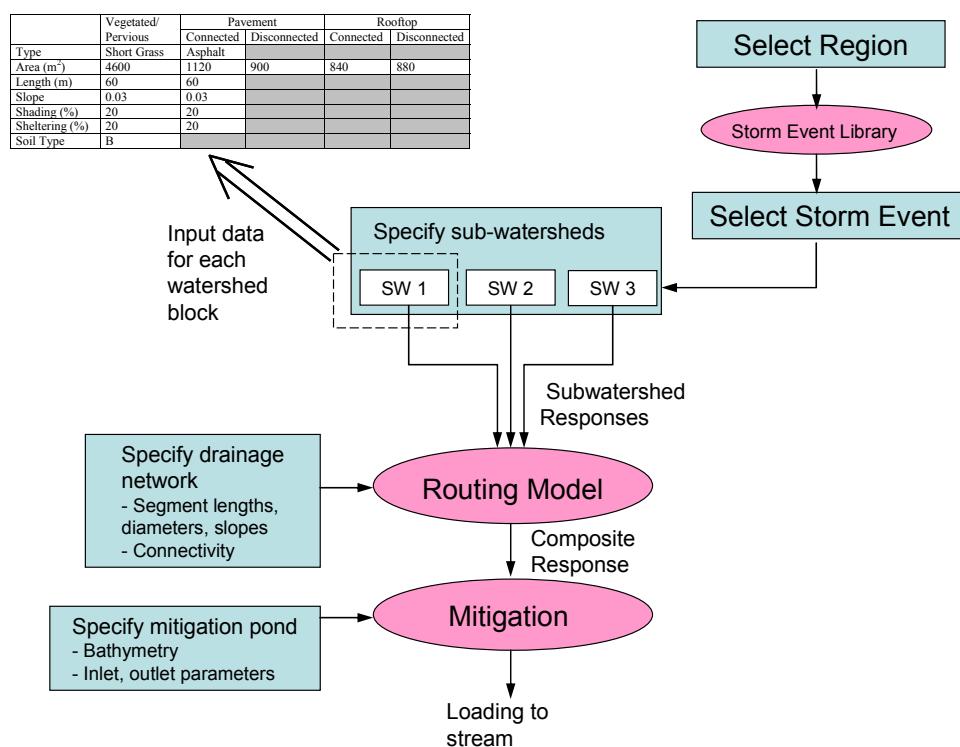


Figure 1.1. Schematic diagram of the process of assembling and running an MINUHET model.

The overall process of assembling and running a model within MINUHET is depicted in Figure 1.1. MINUHET requires the input of basic descriptions of sub-watersheds (pervious and impervious areas, slopes, etc.), drainage network elements (lengths, diameters, slopes, etc.) and ponds (bathymetry, output structures, etc.). The connectivity of the individual components is established by constructing a drainage schematic of the watershed. MINUHET is not capable of directly importing spatial information from, e.g., GIS shape files, but GIS software is helpful for preparing the needed parameters for the model components. The drainage network can include mitigation ponds, including wet ponds, dry ponds, infiltration pods, underground tanks and rock

cribs, and rain gardens. Storm events to apply to the model are selected based on one of seven climate regions within Minnesota.

A common application of MINUHET may be to compare the thermal loading of stormwater runoff from an area of land before and after development, to quantify possible increases in thermal loading due to development. As a result, MINUHET includes components for developed and undeveloped land parcels (sub-watersheds), pervious and impervious open channels, storm sewer systems, and stormwater ponds.

1.2 Model Structure

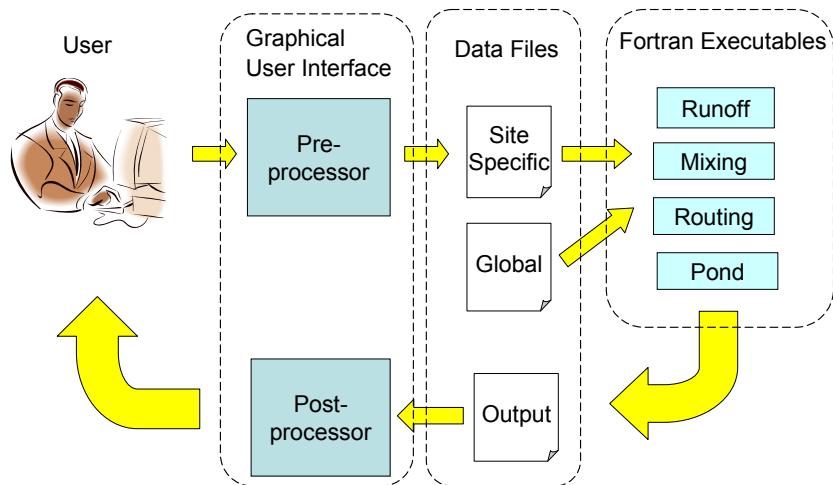


Figure 1.2. The structure of MINUHET

MINUHET is a self-contained software tool that includes several model component executables and a graphical user interface (Figure 1.2). There are three main sub-programs that perform the runoff and heat transfer calculations: the runoff model, the routing model, and the pond model. The sub-programs are written and compiled in FORTRAN 90. Although the model components could be run using MSDOS commands, a graphical user interface (GUI) was developed for the model to make it easier to design the model, enter the required watershed parameters, and to provide visualization of the system layout and simulation results. Under guidance SAFL, the GUI was developed by Minnetonka Audio Software, Inc., based on the Microsoft .NET framework.

Each of the three main FORTRAN model components must calculate a balance for the surface runoff flow rate (Q) and for the heat flux (H) contained in the surface runoff, as shown schematically in Figure 1.3. By definition, sub-watersheds receive precipitation but not surface inflow ($Q_{in}=0$). Drainage network components and stormwater ponds may add or subtract flow and heat content, depending on the particular watershed and storm event.

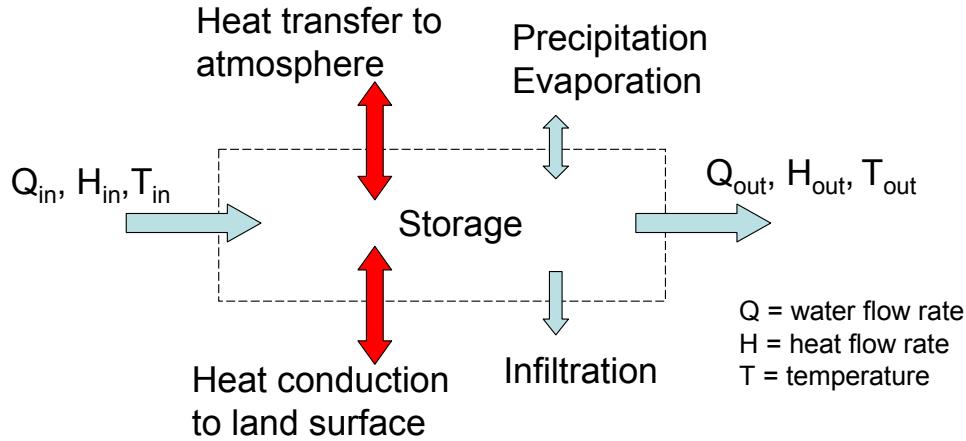


Figure 1.3. Schematic diagram for the balance of runoff flow and heat flux for each sub-watershed, drainage network, and pond component.

The MINUHET sub-watershed model has two major components: 1) a land surface temperature model, 2) a surface runoff model. The land surface temperature model is based on a surface heat transfer model that calculates the radiation, convection, and evaporation components based on specified climate. A one-dimensional finite difference model is then used to calculate the vertical conduction of heat through the soil column and the soil temperature profile to a depth of three meters. The MINUHET storm files include at least several days of antecedent climate conditions prior to the rainfall event, so that realistic surface temperatures and soil temperature profiles are calculated as the rainfall event begins. During a rainfall event, the surface temperature model calculates the heat transfer between the surface runoff and the land surface, such that the surface runoff and the land surface reach the same temperature. Details of the surface temperature model are given in Section 5.3.1 and in SAFL Project Report #536 (Herb et al. 2009).

The surface runoff model was created to simulate runoff from relatively small impervious areas, e.g. a parking lot, at high time resolution, for steady or unsteady rainfall events. The runoff model uses an analytic formulation to simulate the time history of flow rate and temperature at the outlet of an area with uniform slope. The analytic model is based on Manning's equation, and closely matches the results of a kinematic wave model. The runoff model is described in more detail in Section 5.3.1 and in SAFL Project Reports #484 and 536 (Herb et al. 2006d and Herb et al. 2009). The surface runoff model also calculates a mean runoff depth for the area, which is used by the land surface temperature model to calculate runoff temperature. The sub-watershed model also includes a soil moisture model, so that infiltration can be handled for runoff from pervious surfaces.

The hydro-thermal routing model uses a kinematic wave algorithm to simulate the flow of water and heat through a drainage network. In its current configuration, the routing model does not include atmospheric heat transfer for the routing elements, so that it is not appropriate to simulate

long open channel drainage networks. The routing model does not include junction losses, so that MINUHET should not be used as a tool for designing stormwater handling systems. There are three types of routing elements available for simulation of a drainage network: circular storm sewer pipes, impervious open channels (e.g. concrete open channels) with trapezoidal cross section, and pervious open channels with trapezoidal cross section. Infiltration and heat transfer to the channel/pipe wall, and atmospheric heat transfer are included where appropriate.

The MINUHET pond model can be used to simulate wet detention ponds, infiltration ponds and rain gardens, and dry ponds. The pond model is based on previous 1-D models for lakes (Ford and Stefan 1980, Hondzo and Stefan 1993) and wastewater detention ponds (Gu and Stefan 1995). Given the inflow rates and temperatures of the storm sewers discharging to a pond, the hydrology of the inflows, and the design of any outlet structure, the model projects the rate and temperature of the outflow from the pond. The pond vertical temperature profile is calculated for each time step based on atmospheric heat transfer, heat conduction through the pond bottom, and the flow rate and temperature of inflows. Atmospheric heat transfer includes solar and long wave radiation components, atmospheric convection, and evaporation. Pond level is calculated based on inflow and outflow rates, infiltration, direct precipitation, and evaporation. Further details on the MINUHET pond model may be found in Section 5.4.1 and SAFL Project Report #479 and 536 (Herb et al 2006b).

1.3 Changes from MINUHET version 1.x to version 2.x

A number of changes have been made to both the FORTRAN executable programs and the user interface from MINUHET version 1 to version 2. **While the user operation and input parameters are similar, the version 1 model files (*.minu) are not compatible with version 2.** The following list summarizes the important changes and improvements made to MINUHET in version 2.x:

Main Window:

- The main window now has separate icons for wet pods, infiltration ponds, and dry ponds.
- There is a new option in the Tools -> Options drop down menu to specify the reference temperature for heat export calculations
- Additional parameter checking has been added with associated error messages for missing parameter specification, etc.

Simulation Run Browser

- In addition to flow rate and temperature, the user can now plot heat export rate.
- The graphing window now includes a table of storm-averaged and storm-total quantities, including total runoff volume, average runoff temperature, and total heat export.

- View -> Graph has been added to the drop-down menu, which enables users to specify which quantities are displayed in the graphing window.
- View -> Summary Table has been added, to enable a summary of the results of a simulation to be copied to an spreadsheet or saved as a file.

Runoff model

- The second impervious area specification has been eliminated in version 2. Each subwatershed now contains one impervious area, one pervious area, and one rain garden specification.
- The soil moisture model has been improved to handle continuous simulations of several months.

Routing Elements

- The global routing parameters (depth, soil type, soil moisture) have been eliminated and incorporated into the parameter specifications for the individual elements.
- Atmospheric heat transfer has been added to the open channel elements
- The ability to introduce a groundwater inflow has been added to the pervious open channel elements

Pond Model

- Improvements have been made to the pond model to better handle, e.g., infiltration ponds with zero initial depth.
- The Reference Elevation (bottom elevation) parameter has been eliminated. The bottom elevation is now taken as lowest elevation in the specified bathymetry.
- The ability to specify a rating curve for the pond outlet has been added

Underground tank and rock crib models

- A model for an underground stormwater tank (vault) has been added
- A model for an underground, rock filled trench has been added

Postprocessor

- The ability to optionally plot precipitation data has been added
- Summary statistics are recalculated for the displayed time period as the zoom feature is used

2. Installing MINUHET

Hardware and Software Requirements

MINUHET is currently available for Windows® based computers only. Apple and Unix systems are not supported. MINUHET requires 10 Mb of hard-drive space for installation and Windows

2000 or Windows XP. Microsoft .NET version 2.0 or better should be installed. A computer with at a Pentium III processor or better and at least 512 mB of memory is recommended.

To install MINUHET, insert the installation CD and run the **installMINUET.msi** installation program. By default, a SAFL/MINUHET sub-directory in Program Files will be created.

3. Using the MINUHET Main Window

Chapters 3, 4 and 5 describe the MINUHET tool in detail and the general methods for using the tool to simulate runoff flow and temperature from a watershed.

3.1 Starting MINUHET

By default, installing MINUHET creates a desktop icon and a link to the program in the Windows start menu; either may be used to start MINUHET. When MINUHET is started, the main window appears (Figure 3.1). The main window includes:

- 1) The **Workspace** on the left. This area is used to create the schematic layout of the watershed.
- 2) The **Toolbar** contains a set of element icons on the far left. By dragging elements from the Toolbar, the user adds sub-watersheds, routing elements, and ponds to the schematic layout.
- 3) The **Element Properties** area on the right. When an element is selected, a set of user-defined properties appears in this area.
- 4) The drop-down menu items at the top
- 5) The **Regional Storm Selection** menu just below the drop down menu. These controls are used to select the climate region for the study, based on the county, and a design storm or storms to apply to the watershed.

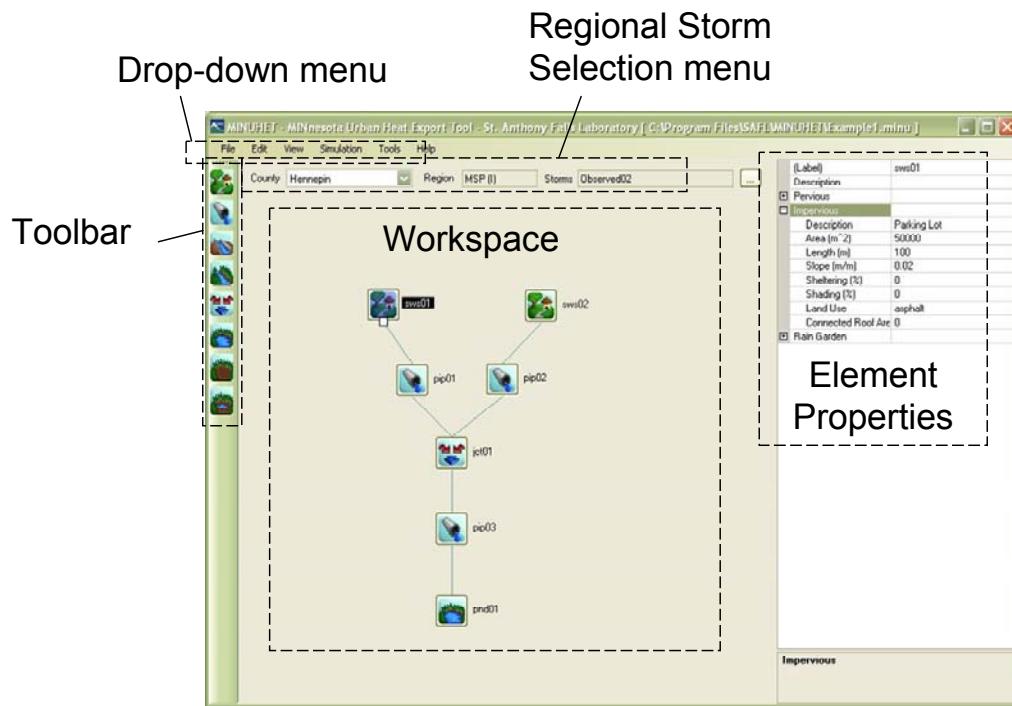


Figure 3.1. MINUHET main window.

3.2 MINUHET Project File Management

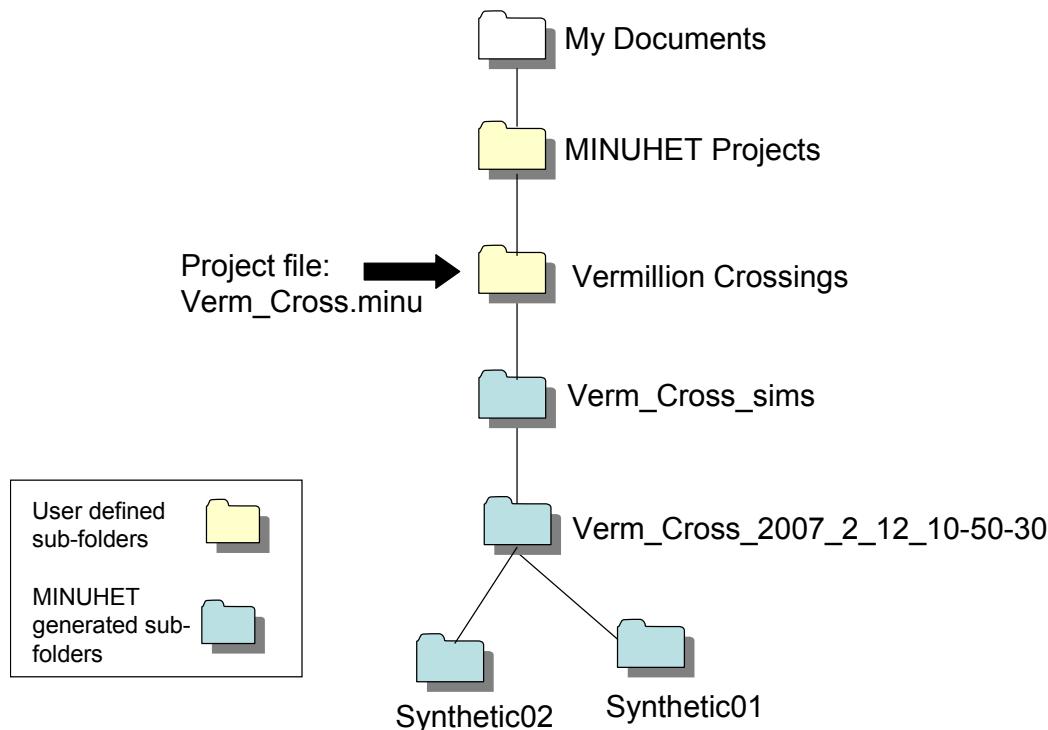
For each project (model), MINUHET creates a case file that contains all of the user input information for the watershed. This file is stored in the directory selected by the user when the model is saved for the first time. For example, a folder called *MINUHET Projects* can be created in *My Documents*, with a sub-folder for each new MINUHET project (Figure 3.2). Each time a simulation is run, MINUHET automatically creates sub-folders that contain the simulation results files. In general, the user does not need to directory access these folders, since the simulation results are accessed via the MINUHET post-processor. Several versions of the same model or multiple models can be saved in the same folder, as long as each model and model version is given a distinct project name. Once a model schematic has been created, the case file is updated each time the user saves (File → Save) and each time a simulation is run.

Creating a new model from an existing model.

A new model schematic can be created based on an existing model, as follows:

1. Using the File→ Open to open an existing MINUHET project file (file.minu).
2. Use File→ Save As menu command to create a new file with a new name and/or and directory.

3. Edit the schematic in the MINUHET main window.



File 3.2. Example of a file structure for a MINUHET project. The user has set up a *MINUHET Projects* folder to store all MINUHET models, and a sub-folder, *Vermillion Crossings*, for a specific project. The user saved the MINUHET project file, *Verm_Cross.minu*, in the *Vermillion Crossings* folder. When the user runs the model, MINUHET creates the *Verm_Cross_sims* folder with two levels of sub-directories to store input and output files for each simulation run. In this example, one simulation has been performed with two storms (*Synthetic01* and *Synthetic02*).

3.3 Choosing a system of units

A MINUHET model can be set up using either SI units (length in meters, area in square meters, flow in cubic meters per second) or US units (length in feet, area in acres, flow in cubic feet per second). The system of units is specified using the Tools → Options command from the drop-down menu (Figure 3.1). A new project will be in metric units, by default. In its present configuration, the units option changes the units of the input parameters only – the output flows and temperatures are always in [m^3/s] and [$^{\circ}C$], respectively. The units option can be changed at any time, but it is suggested that the units should be selected at the beginning of the model construction process.

4. Creating a MINUHET watershed schematic

The process of building a schematic layout includes three main steps:

- 1) Adding sub-watershed, routing, and pond elements to the layout
- 2) Defining the parameter values for each element
- 3) Connecting the elements together to define the flow paths of stormwater

The MINUHET schematic layout process is quite flexible, so that the above steps can be performed in different orders, as the user chooses. The example process given below provides the details for one approach to building a layout.

4.1 Using the MINUHET Menu Tools in the Main Window

- To drag a new element into the layout, click the left mouse button on the desired element icon, and drag the element to the desired position in the layout while holding the left mouse button down. Any existing element in the layout can be re-positioned by selecting it with the left mouse button and dragging it to a new position while holding the left mouse button down.
- To set the parameter values for an element, select the element with the left mouse button. A menu of parameter values will appear in the element properties area of the window (Figure 3.1). Each parameter appears in a table, with the parameter name on the left and an editable value on the right. As the parameter value in the right field of the table is selected, additional information on the parameter appears at the bottom of the element parameter area, and a numerical value can be entered. Some parameters are grouped, e.g. for the pervious and impervious areas of a sub-watershed. To edit the parameters in the group, click on the  symbol to the left of the parameter group name to expand the table.
- Each element is given a default name as it is created. The name of each element can be edited, if desired, by editing the label field at the top of the element parameter table.
- To connect two elements together, select the element. Then select the small box on the underside of the upstream element with the left mouse button and drag the mouse pointer while holding the button down. Drag the mouse pointer over the downstream element and release the button. A line will be automatically drawn between the two elements to indicate a successful connection.
- If a layout has multiple sub-watersheds, ponds, or routing elements that are similar, the cloning command (Edit → Clone Element) can be used to create copies of an element after the parameter values have been set. The parameter values of the new copy can be edited to make any minor changes required.

4.2 Procedure for Creating a MINUHET Schematic

The following procedure outlines one possible general procedure for creating an MINUHET layout. As the layout is created, it should be saved at regular intervals (File → Save).

1. Place the sub-watersheds into the layout by dragging the sub-watershed icons into the layout. Set the parameter values for each sub-watershed as it is inserted in the layout. Each subwatershed must have, at a minimum, at least one impervious or pervious area with non-zero area, slope and roughness values.
2. Layout the drainage network by dragging pipe, open channel, and junction elements into the layout area.
3. Set the slope, diameter, and roughness of each pipe and channel element. Note that junctions have no parameter values to set.
4. Connect the drainage network elements together with the sub-watersheds
5. Add the detention ponds to the layout, if required, and set the parameters for the pond.
6. Connect the detention pond(s) to the drainage network.
7. Set the inflow level parameter for each inflow pipe to the pond elements by selecting the pipe.

General rules for drainage network layouts:

- By definition, sub-watersheds are sources of runoff only; they cannot receive runoff from other sub-watersheds.
- The relative position of the elements in the layout is not important for the MINUHET analysis. Flow directions are established by the connectivity of the sub-watersheds to the routing elements, and flow distances are determined by the length parameter of the pipe and open channel elements.
- Sub-watersheds may be connected to a pipe, an open channel, or directly to a junction. A sub-watershed may also be analyzed as an independent entity, i.e. a MINUHET layout may be composed of a single sub-watershed only.
- Pipes and open channels have only one inflow and one outflow.
- Junctions can have up to five inflows from pipes, open channels, or sub-watersheds, but have only one outflow.
- Ponds can both receive inflow and produce outflow. Ponds can have up to five inflows from pipes or open channels, but have only one outlet to a pipe or channel. A pond need not have a pipe or channel connected to its outlet, if it is the most downstream element – MINUHET will still calculate the outlet flow rate and temperature.
- A MINUHET layout may have multiple, independent watersheds. For example, an undeveloped area of land on a hill may drain stormwater in two directions. The two watersheds may be created as two separate MINUHET models or combined into a single MINUHET layout, with two, separate calculated outflows for each storm analysis.
- The most downstream element (outlet) of a MINUHET layout can be a pipe, open channel, or pond. The outlet may not be junction element.

5. The MINUHET Model Components

5.1 Required information for creating a MINUHET model

For developed watersheds, it is straightforward to plan the MINUHET schematic based on the planned storm sewer system and the development plans, if they are available. It may be helpful to set up a spreadsheet containing a list of the sub-watersheds along with the area, slope, and length parameters of each.

- 1) Determine the sub-watersheds and the drainage network for the system.
 - For developed watersheds, the sub-watersheds are usually based on the catch basins, e.g. each sub-watershed is defined as the area of land draining to a catch basin. This information may be readily available from the storm sewer design itself.
 - For undeveloped watersheds, the network of tributaries that drain the watershed must be determined from topographic maps, digital elevation maps, or other resources. Sub-watersheds can then be defined on each side of the tributaries, with an assumed outlet point from the sub-watershed to the tributary at the midpoint of the downstream end of the sub-watershed.
- 2) Determine the area of each of the five land uses for each sub-watershed: Connected pavement, disconnected pavement, pervious, connected rooftop, and disconnected rooftop.
- 3) Determine the characteristic length and slope of connected pavement and pervious areas. The characteristic length is based on the longest flow path for the major features.

5.2 The Sub-watershed Model

5.2.1 The MINUHET surface runoff flow and temperature solver

Land surface temperature model

The land surface temperature model is based on a surface heat transfer model that calculates the radiation, convection, and evaporation components based on specified climate (Figure 2.1). A one-dimensional finite-difference model is then used to calculate the vertical conduction of heat through the soil column and the soil temperature profile to a depth of one meter. The MINUHET storm files include at least several days of antecedent climate conditions prior to the rainfall event, so that realistic surface temperatures and soil temperature profiles are calculated as the rainfall event begins. Details of the surface temperature model are given in SAFL Technical Report #478 (Herb et al. 2006a). A new feature of MINUHET version 2 is that the soil thermal properties (diffusivity, specific heat) are adjusted based on water content, using the relationships diffusivity and specific heat to volume fraction air given in Ochsner et al. (2001).

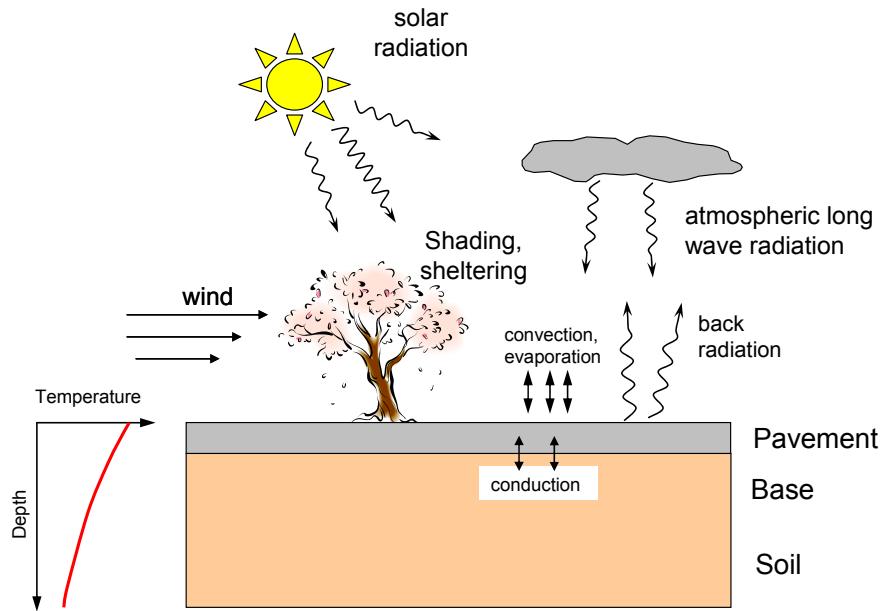


Figure 5.1. Processes included in the MINUHET surface temperature model.

Surface runoff model

The surface runoff model was created for MINUHET to simulate runoff from relatively small impervious areas, e.g. a parking lot, at high time resolution, for steady or unsteady rainfall events. The runoff model uses an analytic formulation to simulate the time history of flow rate and temperature at the outlet of an area with uniform slope (Figure 5.2). The runoff model is based on Manning's equations, a commonly used empirical equation relating flow rate and depth to slope and roughness for open-channel and surface runoff flows (Mays 2001).

$$(5.1) \quad q = \frac{S^{1/2} y^{2/3}}{n}$$

where q is the flow rate per unit width, S is slope, y is the flow depth, and n is Manning's roughness coefficient. The total length of the runoff area (L) is divided into a length, L_e , that has fully developed (equilibrium) runoff flow and the developing flow length ($L-L_e$), where the runoff thickness is assumed constant. The length of the equilibrium flow region varies as a function of time based on previously developed expressions for the time to equilibrium (t_e) (Mays, 2001).

$$(5.2) \quad t_e = \frac{n L_e}{S^{1/2} y^{2/3}}$$

Based on the defined geometry, the total runoff volume per unit width (v) is given by:

$$(5.3) \quad v = \frac{5}{8} h L_c + y(L - L_e) = y\left(L - \frac{3}{8}L_e\right)$$

Based on conservation of mass, the rate of change of the total runoff volume can be expressed as:

$$(5.4) \quad \frac{\partial v(t)}{\partial t} = iL - q(t)$$

where i is the precipitation rate. The MINUHET runoff model uses these basic equations to calculate the runoff rate and average runoff thickness as a function of time. Because Manning's equation is non-linear, finite-difference formulations are used. The MINUHET runoff model is described in more detail in SAFL Project Report #494 (Herb et al. 2006d).

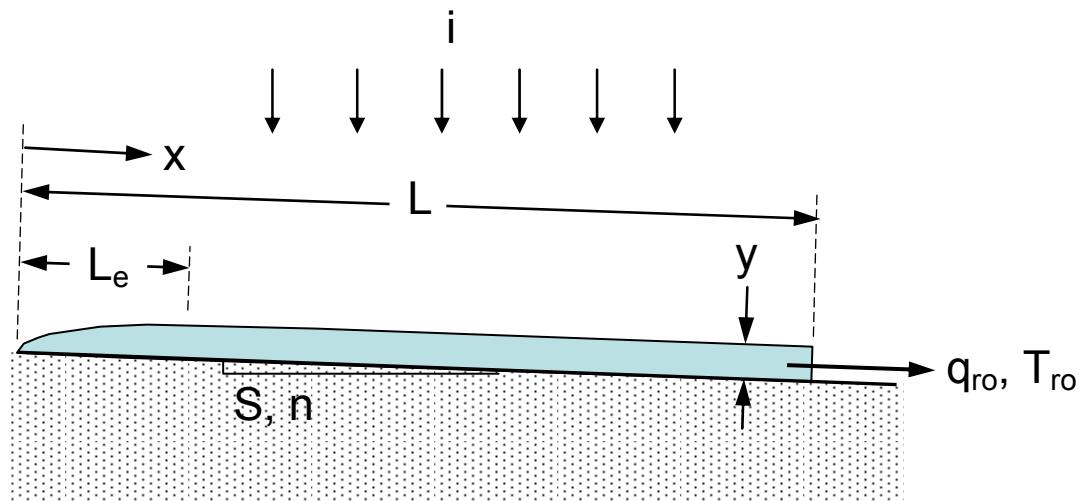


Figure 5.2. Schematic diagram of the parameters used in the MINUHET runoff model.

Runoff heat transfer

A basic description of the runoff model is given here. Further details can be found in Herb et al. (2009). An important component of the runoff model is the algorithm to calculate the heat transfer from the runoff to the land surface, as this has a major influence on the runoff temperature. The heat transfer model assumes that the surface runoff, assumed to be initially at dew point temperature, and pavement surface must equilibrate to the same temperature over the time step (Δt), as shown in Figure 5.3. To achieve this equilibrium, a convective heat flux Q_{ro} can be calculated, which draws heat out of a thin layer of pavement at the surface with thickness δ . The size of δ can be estimated from the thermal properties of the pavement and the time step, based on analytic solutions for heat conduction into an infinite slab subject to a change in surface temperature (Eckert and Drake, 1972).

$$(5.5) \quad \delta = \sqrt{4\alpha\Delta t}$$

where α is the thermal diffusivity and Δt is the time step. An equation for the heat balance for the water film layer and the pavement may then be written as:

$$(5.6) \quad Q_{ro} = y(\rho c_p)_w(T_s - T_{ro}) = -\frac{\delta}{2}(\rho c_p)_p(T_s - T_{so})$$

where $(\rho c_p)_p$ and $(\rho c_p)_w$ are (density · specific heat) for the pavement and water, and the factor $(\delta/2)$ takes into account that the temperature change in the pavement decreases with depth, whereas the temperature change in the water film is assumed to be uniform across the thickness y . If the dew point temperature and the initial surface temperature are known, Equation 5.6 can be solved for T_s .

$$(5.7) \quad T_s = \frac{T_{ro} + \beta T_{so}}{1 + \beta}, \text{ where } \beta = \frac{\delta(\rho c_p)_p}{2y(\rho c_p)_w}$$

Using Equation 5.7, the heat flux from the pavement to the runoff may be calculated for each time step based on the total precipitation in each time step, and is simply added to the atmospheric heat flux components.

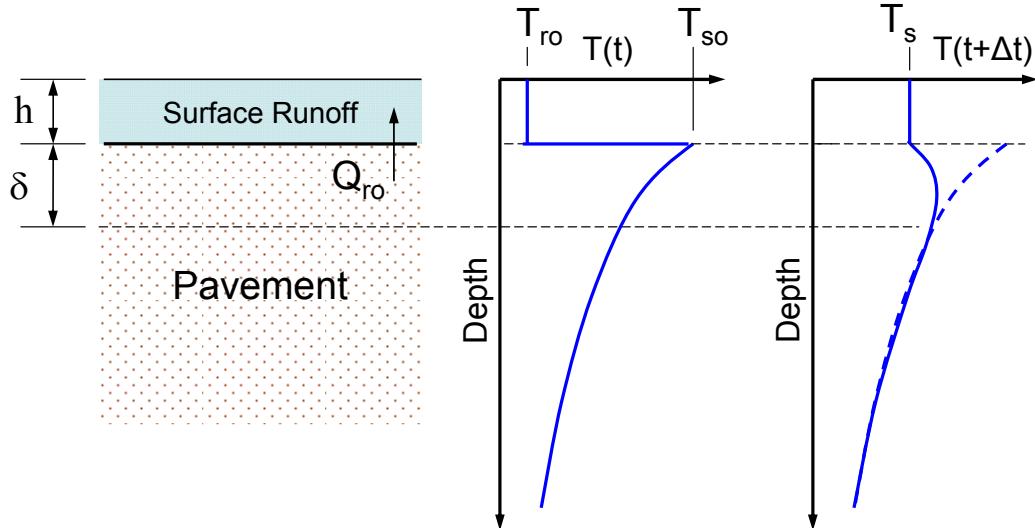


Figure 5.3. Schematic of the formulation for heat transfer between surface runoff and the underlying pavement. Example temperature profiles show the temperatures in the pavement prior to a rainfall event ($T(t)$) and after a rainfall event ($T(t+\Delta t)$), where the initial surface temperature (T_{so}) has equilibrated with the initial runoff temperature (T_{ro}) to yield the new surface and runoff temperature (T_s).

Infiltration model

MINUHET calculates soil infiltration for each time step during a runoff event using the Green-Ampt algorithm (Mays 2001). The Green-Ampt model is based on an estimate for the propagation of a wetting front through the soil column during a runoff event. The rate of infiltration (f) depends on soil properties (saturated hydraulic conductivity (K), capillary soil suction (ψ)), the initial soil moisture content, and the cumulative depth of the wetting front (F) during the event. During each runoff event, an incremental the depth of infiltration is calculated based on Equation 5.8:

$$(5.8) \quad f = K \left(\frac{\psi \Delta \theta + F}{F} \right)$$

where $\Delta \theta$ is the difference between the soil moisture content and the saturated moisture content. The solution to Equation 5.8 is obtained using a linearized solution form given by Li et al. (1976). The use of the Green-Ampt model implies that the volume of runoff from pervious areas will depend on the chosen soil type and initial soil moisture content.

5.2.2 The sub-watershed parameters

A subwatershed represents an area of land that drains to a catch basin (in sewered watersheds) or a tributary (in unsewered/undeveloped watersheds). Since the runoff from each sub-watershed is modeled as sheet-flow, the length of a subwatershed should be limited to about 100 meters (330 ft). In the MINUHET model structure, sub-watersheds are *sources* of stormwater runoff, so that flow is always routed out of a sub-watershed.

The sub-watershed parameters are lumped into three major groups: Impervious, Pervious, and Rain Garden. By default, the areas associated with each of these groups are set to zero. Thus, the parameters for a particular group are used only if a non-zero area is specified for that group.

The pavement area parameter gives the total area of connected pavement, including streets, driveways, and parking lots. The Length parameter is based on the longest flow path for the major features (Figure 5.4). The type parameter should be set to Asphalt or Concrete, based on the dominant pavement material for the impervious area being modeled. The Shading parameter is used to estimate the level of solar shading from trees, buildings, and topography. The additional area parameter is used to take into account roof areas draining onto the connected pavement. In general, the additional area should not exceed 30% of the pavement area, since the treatment of runoff from the additional area is highly simplified. Large connected roof areas, particularly commercial roofs, should be treated as a separate sub-watershed, as described in Section 5.3.4.

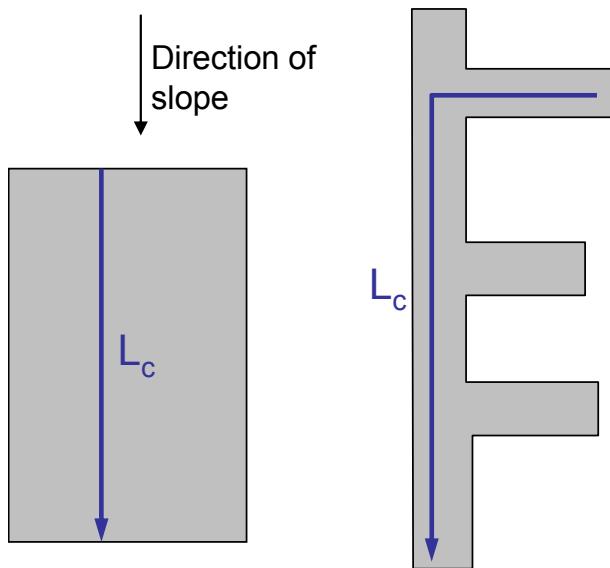


Figure 5.4. Examples of the characteristic flow length for regular and irregular connected pavement areas.

Table 5.1. Subwatershed Parameter Values: Impervious

Parameter	Description	Allowed Values
Description	An optional label or description of the area	
Area	Area of connected streets, driveways, parking surfaces.	10 – 100000 (m ²)
Length	The maximum runoff travel distance.	2 – 1000 (m)
Slope	Average slope of the pavement area	0.001-0.2 (m/m)
Shading	Level of solar shading	0 – 100%
Sheltering	Level of wind sheltering	0 – 100%
Land Use	The dominant type of impervious surface	asphalt, concrete, commercial roof, residential roof
Connected Roof Area	Connected roof area draining to connected pavement	1.– 10000 (m ²)

The parameters for a pervious area within a sub-watershed are summarized in Table 5.2. The area, length, slope, shading, and sheltering parameters are defined in a similar manner to those of the impervious areas. For pervious areas, the additional area parameter represents the area of rooftop and pavement draining into the pervious area. The specified soil type has relatively little effect on surface and runoff temperature, but may significantly affect the **quantity** of runoff from the pervious area.

Table 5.2. Subwatershed Parameter Values: Pervious surface

Parameter	Description	Allowed Values
Description	An optional label or description of the area	
Area	Total pervious area	10 – 100000 (m ²)
Length	The maximum runoff travel distance.	2.0 – 1000.0 (m)
Slope	Average slope the pervious area	0.001-0.2
Sheltering	Level of wind sheltering	0 – 100%
Shading	Level of solar shading	0 – 100%
Soil Type	Soil type	A,B,C,D
Soil Moisture	Soil moisture level prior to the storm event	DRY, NOR (normal), WET
Vegetation Density	The density of the vegetation canopy. Dense lawn = 100% Row Crops = 60-100% Forest = 60-100% Prairie/Tall Grass = 95%	0 – 100%
Land Use	The dominant or representative land use for the pervious area	row crop, bare soil, forest, short grass, tall grass
Disconnected Area	Disconnected roof and pavement area draining to pervious area	1 – 10000 (m ²)

Table 5.3. Hydraulic and thermal soil parameters corresponding to USDA soil types A-D.

USDA Soil Type	A	B	C	D
Saturated Thermal Diffusivity (m ² /s)	8.5E-07	8.5E-07	8.5E-07	8.5E-07
Saturated Specific Heat (J/m ³ /°C)	3.0	3.0	3.0	3.0
Maximum water content (water volume fraction)	0.442	0.462	0.398	0.464
Field Capacity (water volume fraction)	0.141	0.30	0.255	0.361
Wilting Point (water volume fraction)	0.061	0.125	0.148	0.233
Saturated Hydraulic conductivity (m/s)	2.75E-05	2.98E-06	1.19E-06	3.61E-07
Soil Suction (m)	0.10	0.16	0.28	0.32
Brooks/Corey Exponent	2.3	4.65	4.0	6.64

5.2.3 Setting the Sub-watershed Parameters for a Residential Development

For residential developments, it is typically not practical to define separate sub-watersheds for each area of pavement, rooftop, and pervious area. As a result, the MINUHET tool incorporates features to lump multiple houses into a single subwatershed. Each sub-watershed may contain a combination of pervious and impervious surface areas: up to five areas of different land use can be specified (Figure 6.1):

- (1) The total area of connected pavement, e.g. driveways, streets, and parking areas
- (2) The total area of disconnected pavement, e.g. pavement drained into pervious areas.
- (3) The total surface area of the rooftop drained into connected pavement, e.g. driveways
- (4) The total surface area of the rooftop drained into pervious areas (lawns, other vegetation)
- (5) The total area of the pervious land

No attempt is made to represent the detailed shapes and location of each area within the subwatershed. The connected pavement area and the impervious area are represented as an area and a characteristic length.

Thermo-hydrographs (water flow and temperature time series) are simulated using the runoff model for each subwatershed, based on the selected storm event and the subwatershed characteristics. For each subwatershed, two separate thermo-hydrographs will be calculated for the connected impervious area and for the pervious area. The two thermo-hydrographs will then be combined (mixed) to give a single flow and temperature for each subwatershed using a simple mixing FORTRAN executable (Figure 5.6).

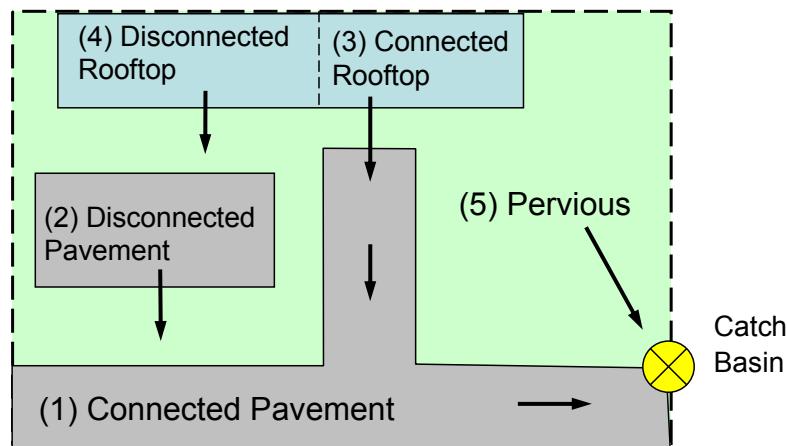


Figure 5.5. Schematic of developed sub-watershed, showing the five land use types and their hydraulic connectivity. For each sub-watershed, one (upper diagram) or two (lower diagram) areas of connected pavement may be defined.

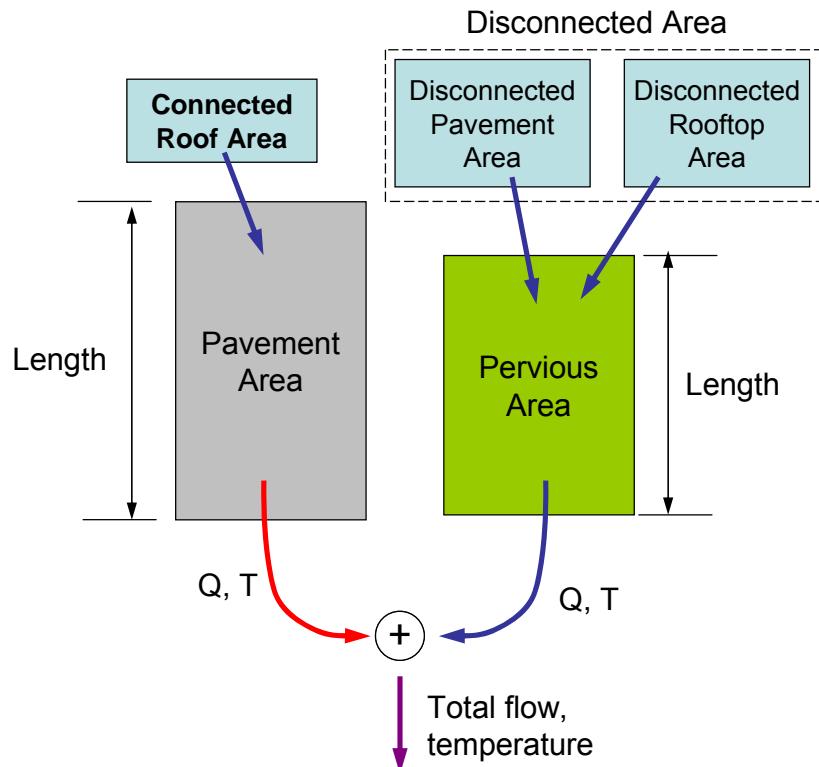


Figure 5.6. Flow chart of the simplified model for each sub-watershed.

For sewered developments, it is typically a good strategy to define one sub-watershed for each catch-basin. However, if a catch-basin receives flow from two or more directions with distinct length scales, multiple sub-watersheds can be defined. The outputs of the sub-watersheds should then be connected with a junction element to feed the combined flow into a single sewer pipe, as shown in Figure 5.7.

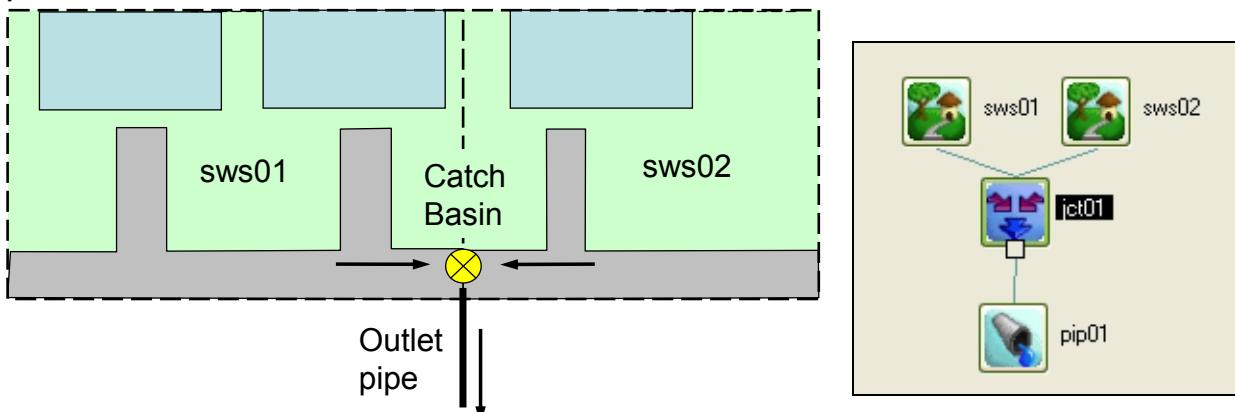


Figure 5.7. Schematic of a catch basin receiving flow from two sub-watersheds (sws01 and sws02) and the corresponding MINUHET layout to handle this case, using two sub-watershed elements and a junction to model the combined flow to the outlet pipe.

Vegetation Effects

The effect of vegetation on surface runoff and heat transfer can be included at several different levels in the MINUHET model:

- 1) A vegetation type is specified for each pervious area within a sub-watershed. The hydro-thermal runoff model then includes the effect vegetation on the surface temperature prior to the storm, the runoff temperature during the storm, and the surface roughness for runoff rate calculations.
- 2) For both pervious and impervious areas with a sub-watershed, a shading coefficient may be specified. This coefficient (0 – 100%) represents the amount of solar shading from intermittent tree cover, e.g. boulevard and other landscaping trees, buildings, and topography (hills). Setting a non-zero shading coefficient reduces the amount of solar radiation that reaches the land surface. Setting the coefficient equal to 100% implied complete shading, i.e. no solar radiation reaches the land surface.
- 3) For both pervious and impervious areas with a sub-watershed, a sheltering coefficient may be specified. This coefficient (0 – 100%) represents the amount of wind sheltering from intermittent tree cover, e.g. boulevard and other landscaping trees. Setting a non-zero shading coefficient reduces the wind velocity used in surface heat transfer model. Setting the coefficient equal to 100% implied complete sheltering, i.e. there is no wind at the land surface.

It is quite possible for the pervious area of a sub-watershed to have both 1) a vegetated land use, e.g. short grass, and 2) some level of additional sheltering and shading from tree cover. However, adding tree cover to a pervious land use will have relatively little effect on runoff quantity and temperature. Adding tree shading to an area of pavement may significantly reduce the surface temperature prior to the onset of rainfall, and thus may reduce runoff temperature.

Determining % Shading

Shading can be estimated via site visits or aerial photographs. The % shaded land area should be determined for the period of time approximately 2 to 4 hours prior to the onset of rainfall, e.g. mid-day shading if the design storm occurs in the afternoon. Typically, tree shading is more significant for narrow pavement features (streets, sidewalks) and less significant for wide areas such as parking lots.

5.2.4 Setting the Sub-watershed Parameters for a Commercial Development

Sub-watersheds with commercial buildings may require a different strategy compared to residential developments. It may be appropriate to define separate sub-watersheds for the building roof and parking lot, since these areas often have their own sewerage in large commercial buildings. If the building roof is defined as separate sub-watershed, then the primary impervious surface area is set to type commercial roof. A large parking lot for a commercial building may require several sub-watersheds, which may be defined based on the locations of the

catch basins. An example of a MINUHET model for a commercial building is given in Figure 5.8.

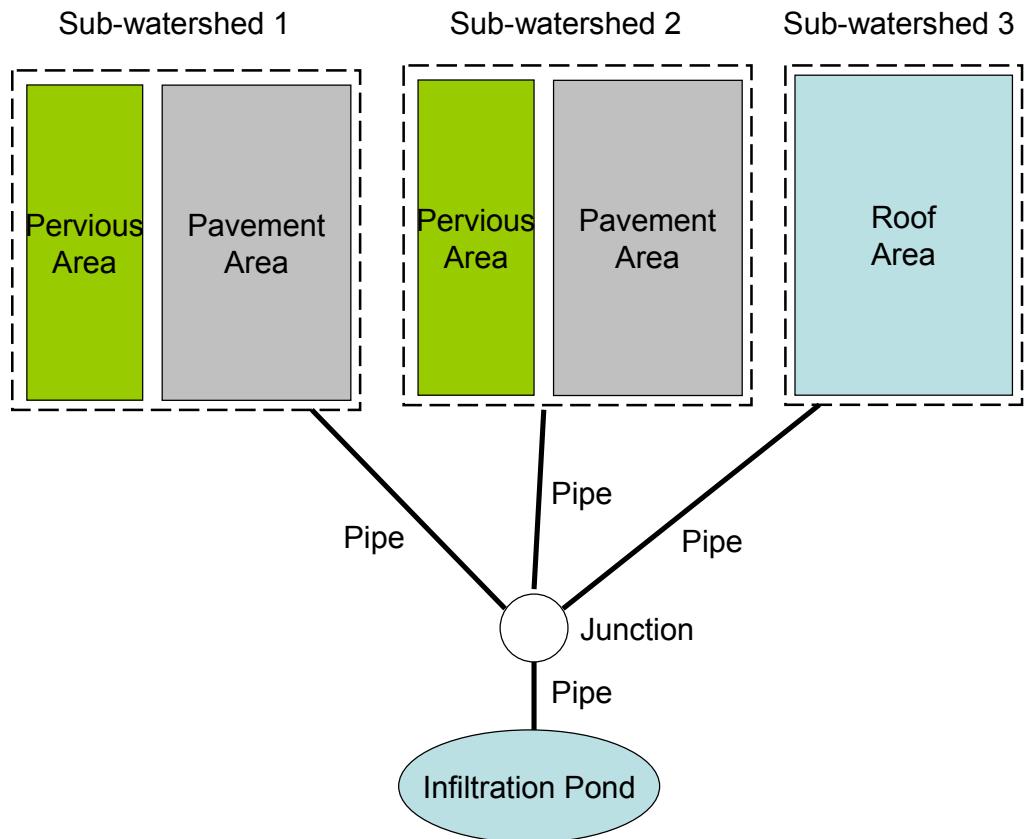


Figure 5.8. Schematic showing the components of a model for a commercial building and parking lot.

5.3 The Routing Network

5.3.1 The MINUHET routing network flow and temperature solver

A basic description of flow and heat routing solver is given here. Further details can be found in Herb et al. (2009). The basic problem of the routing solver is to solve for the flow rates and temperatures at each node in the drainage network , based on the flow inputs from the sub-watersheds (Figure 5.9). The flow rate through the drainage network is calculated first, using Manning's Equation and a non-linear kinematic wave formulation (Chow 1976). The equation of continuity at any point in the flow is:

$$(5.9) \quad \frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_l$$

where Q is the flow rate, x is the streamwise coordinate, A is the cross-sectional area of the flow, t is time, and q_l is a specified lateral inflow rate per unit length. Equation 5.9 has 2 unknowns, flow and area, however, flow can be related to area through Manning's equation:

$$(5.10) \quad Q = \frac{S^{1/2}}{n} \frac{A^{5/3}}{P^{2/3}}$$

where S is slope, n is Manning's roughness coefficient, and P is the wetted perimeter of the flow cross-section. Combining Equations 5.9 and 5.10 produces a single, non-linear equation for flow.

$$(5.11) \quad \frac{\partial Q}{\partial x} + \alpha \beta Q^{\beta-1} \frac{\partial Q}{\partial t} = q_l$$

where $\alpha = \sqrt{S}/n$ and b is a constant that depends on the geometry of the flow conduit. Equation 5.11 is solved for each pipe or channel section using finite-difference formulations given in Chow (1976).

The flow solver assumes no backwatering effects, i.e. the pipes do not reach full capacity. For open channels, the trapezoidal cross section has no inherent depth limit.

After the flow solution is completed, the temperature at each flow node in the network is calculated, beginning with the known inflow temperatures from the sub-watersheds. For each pipe or open channel, the downstream temperature is calculated using the Equation 5.12 based on a heat balance (Figure 5.10):

$$(5.12) \quad \frac{\partial}{\partial t} (V \cdot T) = Q_{in} T_{in} - Q_{out} T_{out} + h_a B L + H_w A_w (T_w - T)$$

where T is temperature, V is the water volume in the pipe segment, H_w is the wall heat flux, A_w is the wetted area in the pipe, T_w is the temperature of the pipe wall, h_a is the atmospheric heat transfer rate (W/m^2), B is the top width of the flow, L is the reach length. The wall heat transfer is calculated using the same method that is used to calculate surface runoff - land surface heat exchange (Section 5.2.1). An increasing thermal boundary layer thickness in the pipe wall and soil is estimated as a function of time, starting at the onset of a flow event. As a result, wall heat transfer is highest at the start of the flow event.

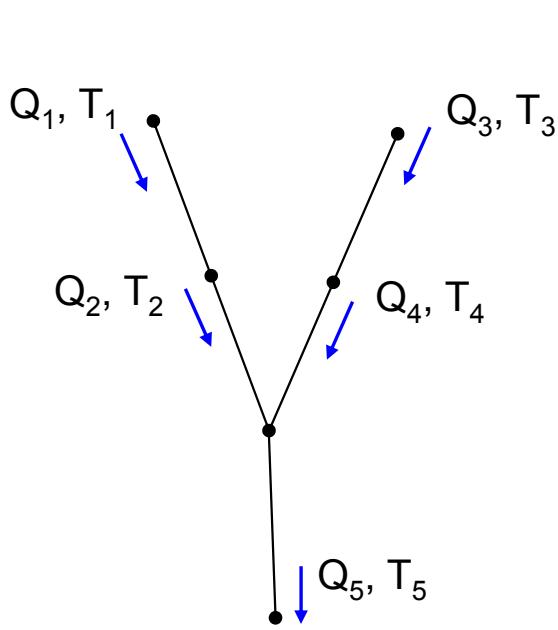


Figure 5.9. Schematic of a simple drainage network with two inflows from sub-watersheds.

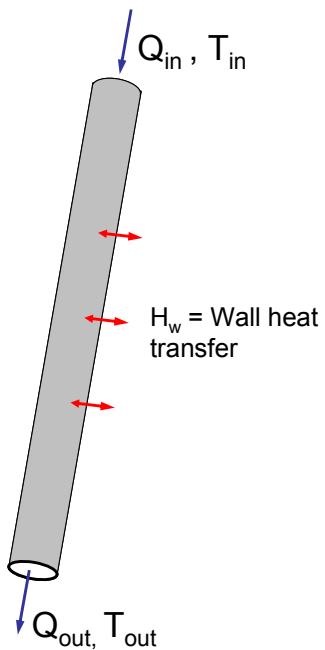


Figure 5.10. Schematic of the heat balance on a single pipe segment.

5.3.2 MINUHET Routing Elements

MINUHET has several routing elements to specify a natural or man-made drainage network and routes stormwater runoff from sub-watersheds. MINUHET uses a kinematic wave algorithm to simulate the flow of water and heat through the drainage network. In its current configuration, MINUHET does not include atmospheric heat transfer for the routing elements, so that it is not appropriate to simulate long open channel drainage networks. The routing model does not include junction losses, so that MINUHET should not be used as a tool for designing stormwater handling systems. The routing model can handle up to 256 routing elements. There are four types of routing elements available for simulation of a drainage network:

1. Pipes: Circular storm sewer pipes. No infiltration is included in the flow calculation, but heat transfer from the stormwater to the pipe wall is included in the temperature calculations. A mean depth of the pipes beneath the land surface is specified a global parameter for the routing model. This depth is used to estimate an initial pipe wall temperature.

Pipe elements may also be used to simulate culverts, but effects such as entrance losses and back-watering are not considered. For culverts with substantial upstream or downstream pooling, the pond model element with a pipe outlet may be more appropriate.

2. Impervious open channels: Concrete open channels with trapezoidal cross section. No infiltration is included in the flow calculation.
3. Pervious open channels: Vegetated or bare soil open channels with trapezoidal cross section. Infiltration is included, at a rate based on the specified soil type. Swales can be modeled using the pervious open channel elements. Pervious open channels can include specification of a distributed groundwater inflow.
4. Junction Elements: Junction elements are used to represent any point where two or more flows are combined, including pipe junctions, catch basins, and channel junctions. A junction element may have up to five inputs from pipes and/or sub-watersheds, but has only 1 output. As a result, flow splitting is not currently implemented in MINUHET.

5.3.3 Setting the parameters for routing elements

Routing elements are used in MINUHET to create the stormwater drainage network. The drainage network may consist of storm sewer pipes, pervious channels (tributaries, gullies, swales, and ditches), impervious open channels (e.g. concrete-lined channels), or some combination of these elements. The connectivity of the routing elements and the flow direction through the routing elements are completely determined from the schematic layout, therefore the main task described here is to set the lengths, slopes, roughness, and cross-section geometry of the routing elements.

All routing elements require a length-wise slope, where the element is assumed to slope downward in the direction of flow. The slope should always be specified as a positive number. Specification of a zero or negative slope will result in a solution error.

Pipe Elements: For MINUHET pipe elements, the length, inside diameter, length-wise slope (vertical/horizontal), the Manning's roughness, and the depth of the pipe invert beneath the land surface are specified. Guideline values for setting Manning's roughness are given in Table 5.4 for common pipe materials.

Open Channel Elements: Open channel elements are assumed to be impervious, i.e. no infiltration of runoff is calculated. As with pipe elements, the length, length-wise slope (vertical/horizontal), and Manning's roughness are specified. The cross-section of open channels is constant over the length of each element, and is specified with the width and side-slope parameters (Figure 5.11).

Pervious Open Channel Elements: MINUHET pervious open channel elements have the same geometric specifications as open channel elements, but include additional features to model infiltration through the channel bottom: the soil type (USDA A,B,C,D), and the initial soil moisture content (Dry, Normal, or Wet). As with the sub-watershed model, the infiltration rate

is calculated using the Green-Ampt equation (Equation 5.8). A distributed groundwater inflow rate and temperature can be specified.

Junction Elements: As implemented in MINUHET, junction elements act simply to combine inflows, with no energy loss mechanisms or storage. As a result, junction elements have no parameters to specify except for an optional description.

Table 5.4 Manning's roughness coefficient (n) for open channel flow. All values are taken from Mays (2001).

Material	n
Asphalt	0.01-0.015
Bare soil	0.02-0.023
Grass, Bermuda	0.045-0.25
Grass, bluegrass sod	0.03-0.10
Concrete	0.01-0.013
Corrugated metal	0.022-0.037
Gravel	0.012-0.030
Grouted riprap	0.028-0.040
Stone masonry	0.03-0.042

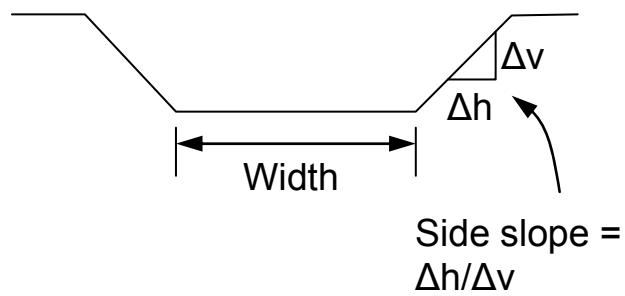


Figure 5.11. Cross-sectional parameters for MINUHET open channel elements.

5.4 The MINUHET Pond Model

5.4.1 Pond model description

The MINUHET pond model can be used to simulate wet detention ponds, infiltration ponds and rain gardens, and dry ponds. The purpose of the pond model is to simulate the pond response (outflow rate and temperature) to stormwater inflow events. The outflow rate and temperature depend on both the initial condition of the pond prior to the event (stage, temperature) and the characteristics of the inflow event. The processes considered in the MINUHET pond model are illustrated in Figure 5.12.

The pond model is based on previous 1-D models for lakes (Ford and Stefan 1980, Hondzo and Stefan 1993) and wastewater detention ponds (Gu and Stefan 1995). The model divides a detention pond into a system of horizontal water layers, and simulates the time-variable water temperature as well as in- and outflow rates for each layer. Given the geometry of all storm sewers discharging to a pond, the hydrology of the inflows, and the design of any outlet structure, the model projects the rate and temperature of the outflow from the pond. The pond vertical temperature profile is calculated for each time step based on atmospheric heat transfer, heat conduction through the pond bottom, and the flow rate and temperature of inflows.

Atmospheric heat transfer includes solar and long wave radiation components, atmospheric convection, and evaporation. Pond level is calculated based on inflow and outflow rates, infiltration, direct precipitation, and evaporation. Inflow calculations include a simple jet entrainment model and a model that determines the depth to which the inflow plunges. Pond outflow calculations include an estimate of the range of depth from which water is drawn to the outlet, to better estimate the outlet temperature. Each pond may be connected to up to five inflows from pipes or open channels. A number of outflow types may be specified for each pond element. Further details on the MINUHET pond model may be found in SAFL Project Report #479 (Herb et al 2006b).

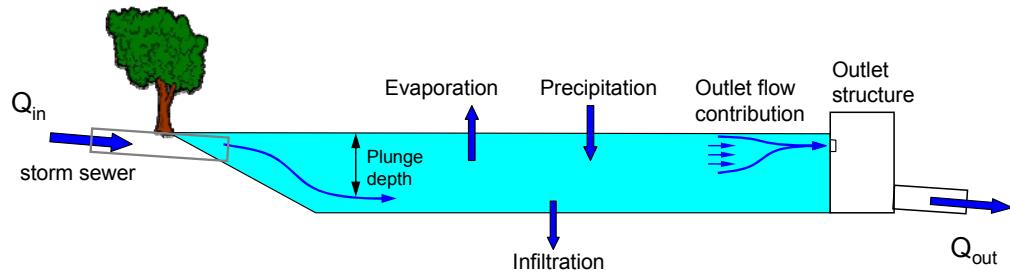
5.4.2 Setting the pond parameters

The bathymetry of the pond is specified by clicking on the Collection field next to the Bathymetry label, and then clicking on the [...] icon, which opens a pop-up table. Click on the “Add” button to add each pair of (Elevation, Area) data points. Click on “Ok” when all the bathymetry data have been entered. The (Elevation, Area) pairs will be listed on the left side of the pop-up window, but the values are not updated until the table is closed and re-opened.

The Secchi depth determines the mean water clarity for the pond. The main effect of varying Secchi depth is to change the degree of temperature stratification prior to the storm event.

For ponds, the infiltration rate at the pond bottom is set directly using the infiltration rate parameter, rather than specifying a soil type. The initial elevation parameter is important to specify, because it determines the degree of storage available at the start of the storm event. The reference elevation is the elevation of the pond bottom.

Pond Model Hydraulic Processes



Pond Model Thermal Processes

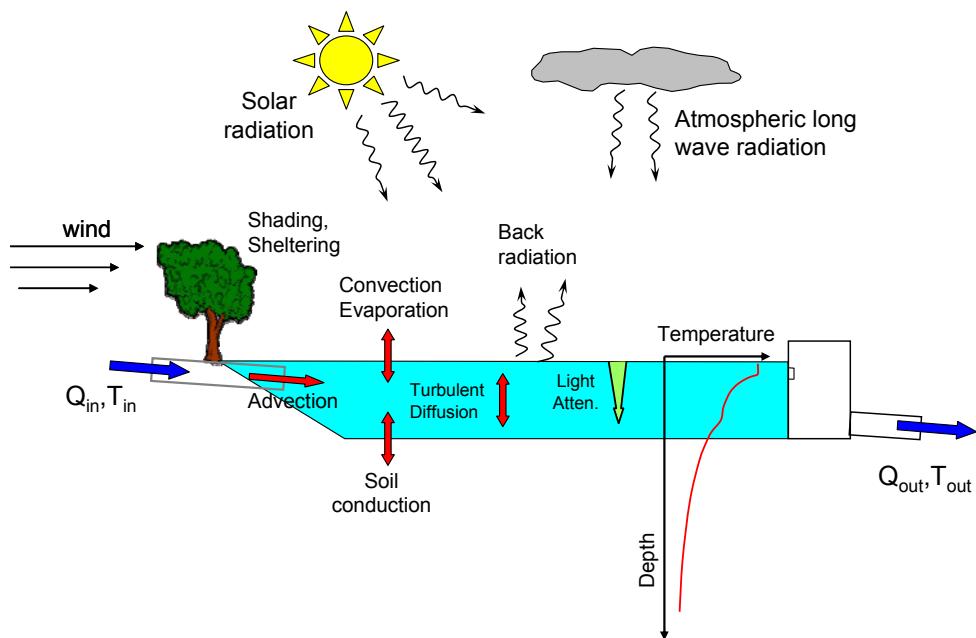


Figure 5.12. Schematic of the pond model hydraulic (top) and thermal (bottom) processes.

Modeling a Wet Detention Pond

To use the MINUHET pond model to simulate a wet detention pond, the infiltration rate parameter is typically set to a low value (e.g. 1 cm/day or less), and the vegetation density parameter is typically set to a low number (0 - 10 %). The initial pond elevation may be set, e.g., to be equal to the outlet elevation, so that any stormwater inflow will produce an outflow from the pond. Setting a lower initial pond elevation will give the wet pond some storage capacity, and reduce thermal loading from the pond outlet. The pond model parameters are summarized in Figure 5.13 and Table 5.5. Shading can be estimated via site visits or aerial photographs, and should be estimated as the average % surface area that is shaded, on average, for the period 9 am

and 5 pm. Emergent vegetation surrounding the edge of a pond, e.g. in the shallow safety bench area, is expected to have little effect on the temperature of water in the deep area of a pond.

Modeling an Infiltration Basin, Rain Garden, or a Dry Detention Pond

To use the MINUHET pond model to simulate an infiltration pond, the infiltration rate parameter is typically set to a higher value (e.g. 10 - 100 cm/day), and the vegetation density parameter is typically set to a high number (70 -90 %), assuming that healthy vegetation exists in the pond. The initial pond elevation may be set to be zero for an infiltration pond, dry detention pond, or a rain garden. If the rain garden contains an engineered soil layer with significant volume, the pore volume of the engineered soil should be included in the bathymetry of the pond model. The infiltration rate parameter should be set based on the soil beneath the engineered soil layer. For storms of moderate length, this infiltration rate will likely have minimal effect on flow volume and temperature from the outlet of the pond.

Specifying the outlet structures for a pond

Six types of outlet structures can be specified for each pond. Up to two outlet types may be specified for each pond, e.g. an orifice discharge to establish normal stage plus a broad-crested weir for overflow. If a pipe or open channel element is connected to downstream of the pond element, the total pond outflow is routed to the single pipe or channel element, i.e. it is not possible to rout the flow from two different pond outlet structures to separate pipe elements. Table 5.6 gives the six pond outlet types that may be specified and the associated parameters for each type.

or each outlet structure, the control elevation and the withdrawal elevation can be separately specified. A pipe outlet may be specified in a normal configuration, with the pipe sloping away from the pond outlet (inflow elevation > outflow elevation), or as a submerged outlet pipe (inflow elevation < outflow elevation), as shown in Figure 5.14. Similarly, an orifice outlet in a box outlet structure can be specified in a standard configuration, where the surface water is taken (withdrawal elevation=control elevation), or with a submerged withdrawal (control elevation < withdrawal elevation), as illustrated in Figure 5.15. Weirs are typically specified with withdrawal elevation = control elevation. Parameters for a v-notch weir are illustrated in Figures 5.16.

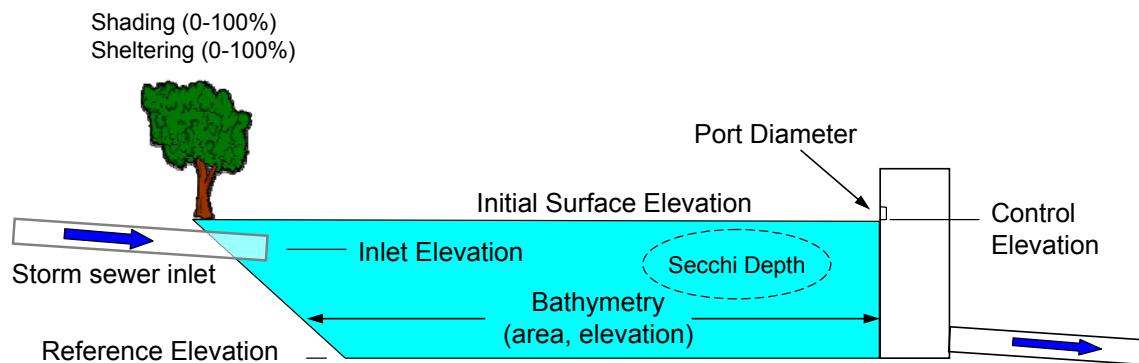
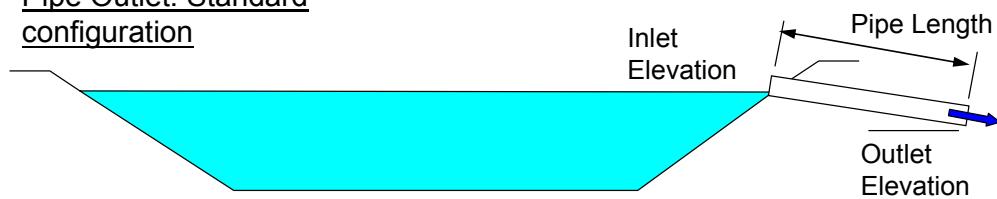


Figure 5.13. Typical input parameters for a wet detention pond, including bathymetry, and the elevations of the outlet structures.

Pipe Outlet: Standard configuration



Pipe Outlet: Submersed intake configuration

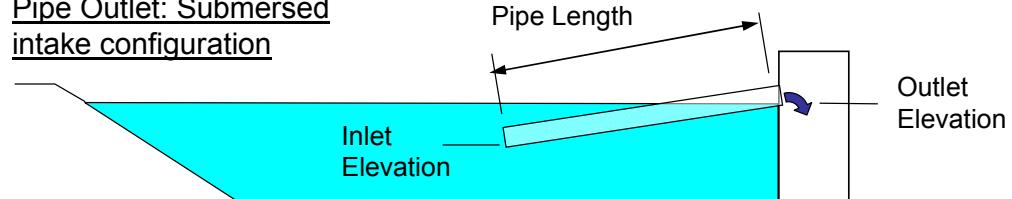


Figure 5.14. Schematic diagram of a wet pond with a pipe outlet in a standard configuration (top) and a submersed intake configuration (bottom).

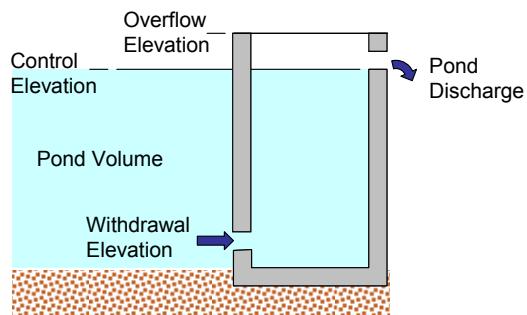
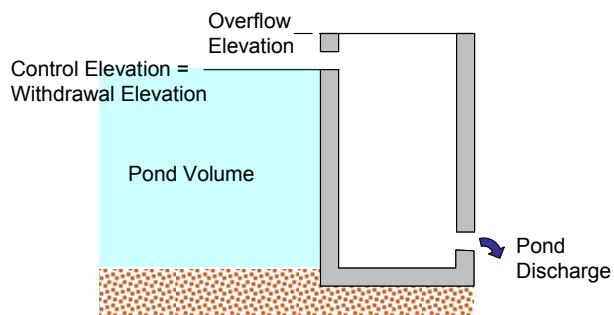


Figure 5.15. Schematic diagram of a wet pond with a box outlet structure in a standard configuration (top) and a submersed intake configuration (bottom).

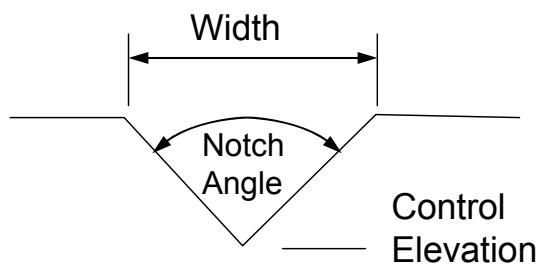


Figure 5.16. Parameter specifications for a v-notch weir outlet structure.

Table 5.5. Pond Parameters

Parameter	Description	Allowed Values
Description	An optional description of the pond	
Bathymetry	meter (elevation), square meters (area)	Elevation = 0 -2000 Area = 0 – 40,000
Infiltration Rate	cm per day	0 - 100
Initial Elevation	meters	0 - 2000
Secchi Depth	meters	0.1 - 10
Shading	percent	0 – 100%
Sheltering	percent	0 – 100%
Vegetation Density	The average coverage of emergent vegetation.	0 – 100%
Outflow1	see Table 5.6	
Outflow2		

Table 5.6. Pond outflow (outlet) structure types and associated user-specified parameters

Outlet Type	Parameters (units)
Sharp-crested weir	Length (m): Total weir linear length Control Elevation (m) Withdrawal Elevation (m)
Broad-crested weir	Length (m): Total weir linear length Control Elevation (m) Withdrawal Elevation (m)
V-notch Weir	Notch Angle (degrees): See Figure 5.16 Width (m): See Figure 5.16 Control Elevation (m) Withdrawal Elevation (m)
Pipe	Diameter (m): Pipe inside diameter Length (m) Roughness (Dimensionless Manning's roughness) Inflow Elevation (m) Outflow Elevation (m)
Orifice	Diameter (m) Control Elevation (m) Withdrawal Elevation (m)
User-specified stage-discharge relationship	Table of Elevation (m), Discharge (m^3/sec) data Withdrawal Elevation (m)

5.5 Modeling Rain Gardens

Rain gardens can be handled in MINUHET at two levels.

- 1) Small rain gardens that are internal to a sub-watershed can be specified within each subwatershed element. Adding a rain garden volume to a sub-watershed effectively increases the amount of surface storage in the pervious area, so that more rainfall is stored prior to the onset of runoff. These small rain gardens are assumed to affect runoff quantity, but not runoff temperature.
- 2) Larger rain gardens that are external to a sub-watershed can be included using the pond model. The rain garden storage volume is set using the pond bathymetry, an infiltration rate is specified for the underlying soil, and the initial water depth can be specified to be zero, assuming the rain garden is designed properly.

For both cases, the rain garden volume is calculated as the above ground storage volume plus the pore volume of the engineered soil layer (Figure 5.17). For case 1, the total rain garden storage volume (V_{tot}) is input directly in the sub-watershed attributes. The infiltration rate of the underlying native soil is set automatically in MINUHET, based on the soil type selected for the pervious area. For case 2, the storage volume of the engineered soil can be included in the pond bathymetry definition, if it adds significantly to the above ground storage volume. Since the

effect of the engineered soil is included in the pond bathymetry, the infiltration rate should be set to be a suitable value for the underlying native soil.

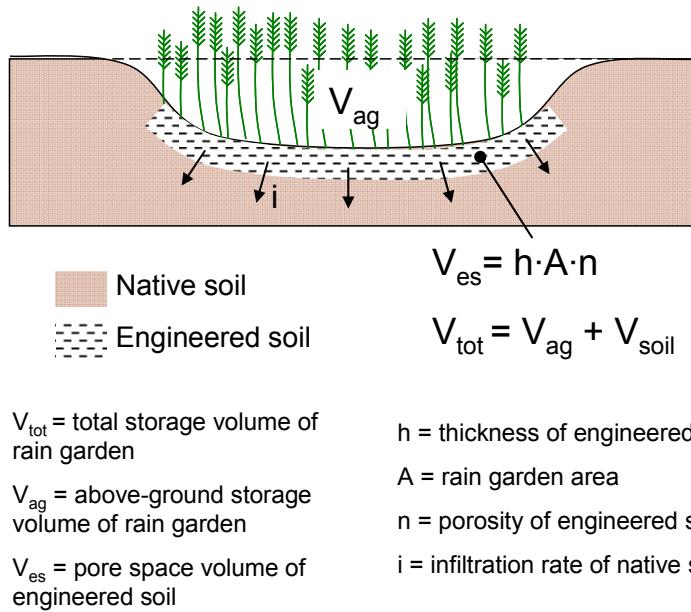


Figure 5.17 Schematic showing the components of total storage volume in a rain garden.

6. Modeling Undeveloped Watersheds

Stormwater runoff from undeveloped land parcels can be modeled using MINUHET. The most challenging task in modeling undeveloped watersheds is determining the drainage network. Ideally, the size of the sub-watersheds and the drainage network of open channel tributaries are chosen in the model so that the sub-watersheds are dominated by sheet flow runoff processes, while the channel elements represent the places where the runoff becomes channelized. The current version of MINUHET does not consider distributed lateral inflow to channels, therefore the channel nodes should be placed at representative locations relative to the sub-watershed areas.

Figure 6.1 gives an example of an undeveloped land parcel with the sub-watersheds and tributaries delineated.

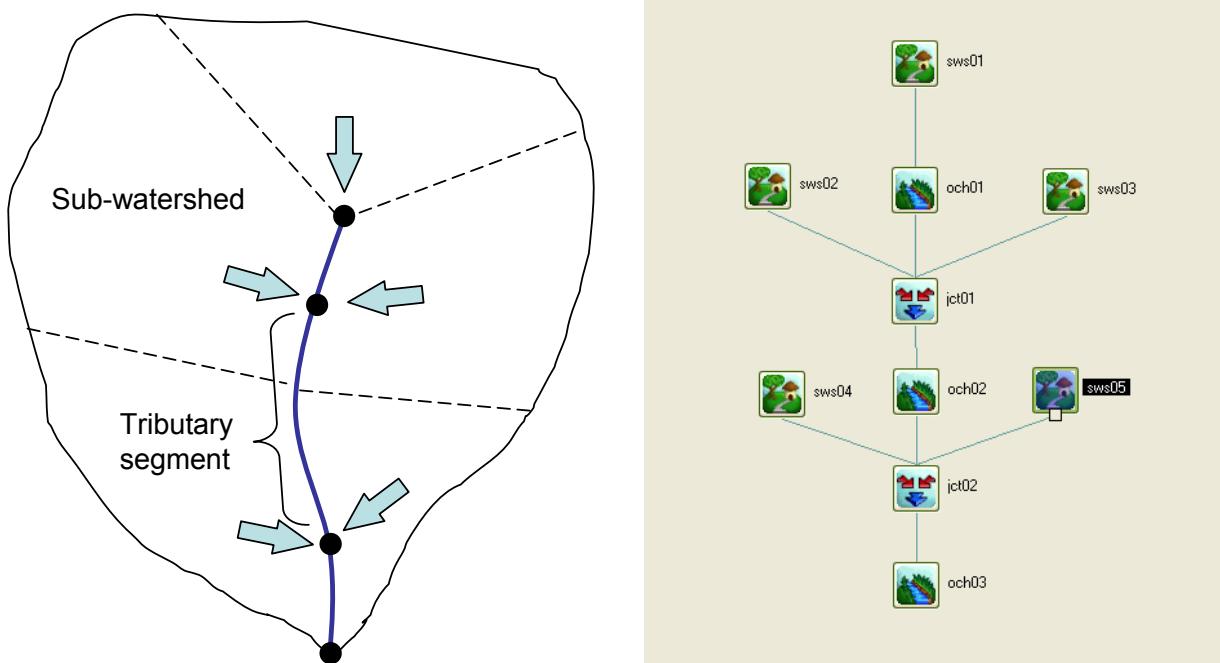


Figure 6.1. Typical sub-watershed boundaries and inflow points to a tributary in a small, undeveloped watershed (left panel) and the corresponding MINUHET schematic using five sub-watersheds and three open-channel elements.

7. Running a MINUHET simulation

7.1 Selecting a storm event

The climate database in MINUHET includes both continuous climate data for different regions of Minnesota (Figure 7.1) and a number of individual storm events. The storm selection process moves from left to right in the Region/Storm Selection menu (Figure 7.2):

1. The user selects a county from the in the Region/Storm Selection menu.
 2. Based on the selected county, MINUHET determines the appropriate climate region, which is displayed, but not editable, in the *Region/Storm Selection* menu.
 3. At least one year of continuous climate data and a number of individual storms are then available for selection. The user chooses a storm or climate data set by clicking on the icon on the far right of the *Region/Storm Selection* menu. A small window pops-up, with checkboxes next to the list of available storms and continuous climate data.
 4. A default start and stop time are display, which can be edited. This feature is primarily to allow the user tp select a range of climate data in the continuous climate files. It is suggested that the start/stop times not be changed by the for the individual storm events.

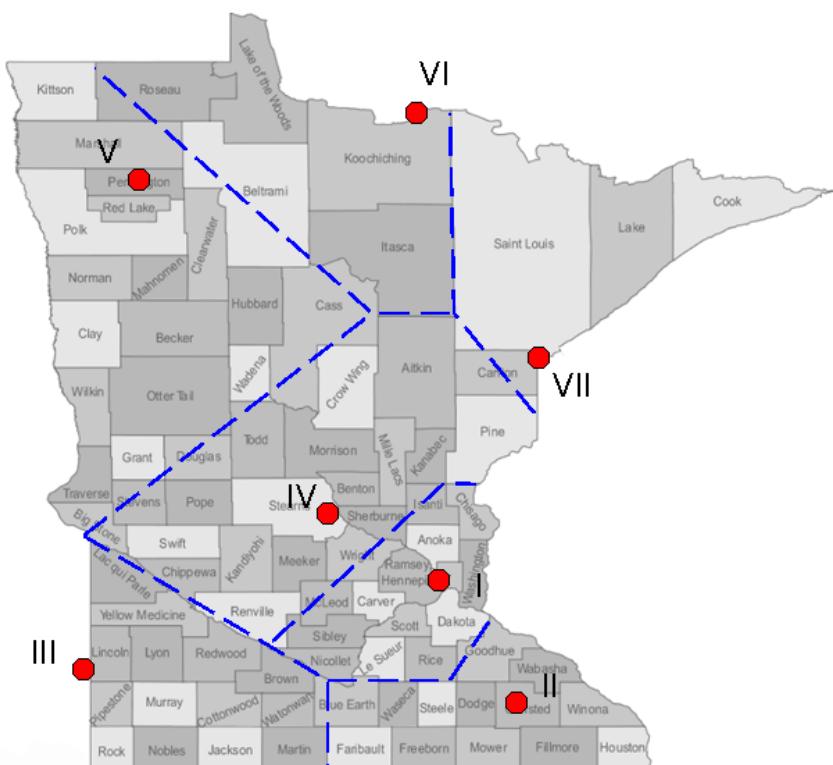


Figure 7.1. Map of Minnesota and the seven climate regions used in the simulation tool



Figure 7.2. Region/Storm Selection menu in the pre-processor.



Figure 7.3. Storm selection pop-up window.

The current design storm set includes two observed design storms and three synthetic design storms, as summarized in Table 7.1. The observed storms (Observed01 = June 20, 2005 and Observed02 =August 16, 2005) are taken from 15 minute climate data set from the MnROAD facility in Albertville, MN, and are shown in Figure 7.4. Both storms have the potential to produce high thermal impact, i.e. the combination of runoff temperature and runoff volume.

Synthetic storms 1 and 2 are both 1 hour duration events. The climate data prior to and after the actual storm are taken from the MnROAD climate data set for period July 20 – August 2, 1999, which included a rainfall event at 16:00 hours on July 30. With the rainfall fixed at 1 hour, the precipitation quantity and dew point temperature during the storm were adjusted to produce storms of 1 and 10 year return period for total heat export (Table 7.1), with the resulting hyetographs shown in Figure 7.5.

Synthetic storm 3 is a 2 year recurrence, 24 hour duration storm event. The precipitation is distributed over 24 hours according to the SCS Type II distribution (Figure 7.6). Solar radiation during the storm event is based on the observed relationship between solar radiation and precipitation rate. More details on this storm event can be found in Herb (2008).

Continuous climate data sets are also included for the seven climate regions. These data are all observed climate data for either 2005 or 2008, from various sources, as summarized in Table 7.2. Wherever possible, data were obtained that included observed solar radiation, because solar

radiation is crucial in determining runoff temperatures. Several data sets use simulated solar radiation, obtained from the National Renewable Energy Lab (NREL).

Antecedent Conditions

All individual storm events include one week of antecedent climate. At the start of a MINUHET analysis, surface temperature, soil temperatures, and pond temperatures are estimated based on the time of year. Running the model for several days prior to the storm of interest allows the various estimated temperatures to adjust to more accurate values for the particular soil types, moisture conditions, etc. in each model. Figure 7.7 gives the antecedent climate data used for the synthetic storms, currently data from the MnROAD facility in Albertville, MN, July 24 – July 30, 1999. Figures 7.8 and 7.9 give the antecedent climate for the observed storms on 6/20/2005 and 8/16/2005.

Table 7.1. Summary of observed design storms and synthetic design storms.

Name	Return Period ¹	Date	Start Time	Duration (hours)	Average Dew Point (°C)	Total Precip (cm)
Observed01	3.2	6/20/05	11:30	2.3	18.3	3.8
Observed02	3.7	8/16/05	16:30	4.0	16.6	1.1
Synthetic01	1	7/30/99	16:00	1.0	17.0	1.5
Synthetic02	10	7/30/99	16:00	1.0	18.5	7.5
Synthetic03	2	7/30/99	00:00	24.0	20.0	7.1

1. The return period listed is based on total heat export from an asphalt surface (see SAFL Project Report #483, Herb et al. 2007). For the synthetic storms, the precipitation depth also corresponds to the return period for the Minneapolis/St. Paul region.

Table 7.2. Continuous climate data sets. All data sets from June 15 to September 15.

Climate Region	Year	Climate Station Site	Time Resolution	Solar Data
I	2005	U of M St. Paul Campus ¹	1 hour	Observed
II	2005	Rochester, MN Airport ²	1 hour	Modeled
III	2008	Aurora, SD ³	1 hour	Observed
IV	2008	Albertville, MN (MnROAD facility) ⁴	1 min	Observed
V	2008	Mavie, MN ⁵	1 hour	Observed
VI	2005	International Falls, MN airport ²	1 hour	Modeled
VII	2008	Duluth, MN ⁶	15 min	Observed

1. Data were obtained from Dr. David Ruschy at the St. Paul Climatology Office.

<http://climate.umn.edu/doc/observatory.htm>

2. Observed climate data and modeled solar radiation from the NREL web site:

http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/

3. Data obtained from the South Dakota State University:

http://climate.sdstate.edu/climate_site/archive_data.htm

4. Data supplied by MnDOT

5. Data obtained from the North Dakota Agricultural Weather Netowrk:

<http://ndawn.ndsu.nodak.edu/>

6. Precipitation, air temperature, and relative humidity data from a weather station in the Miller Creek watershed, supplied by the South St. Louis Soil and Water Conservation District. Wind data obtained from the Duluth International Airport. Observed solar radiation data from Lincoln School, in the Miller Creel watershed, supplied by the Minnesota Pollution Control Agency.

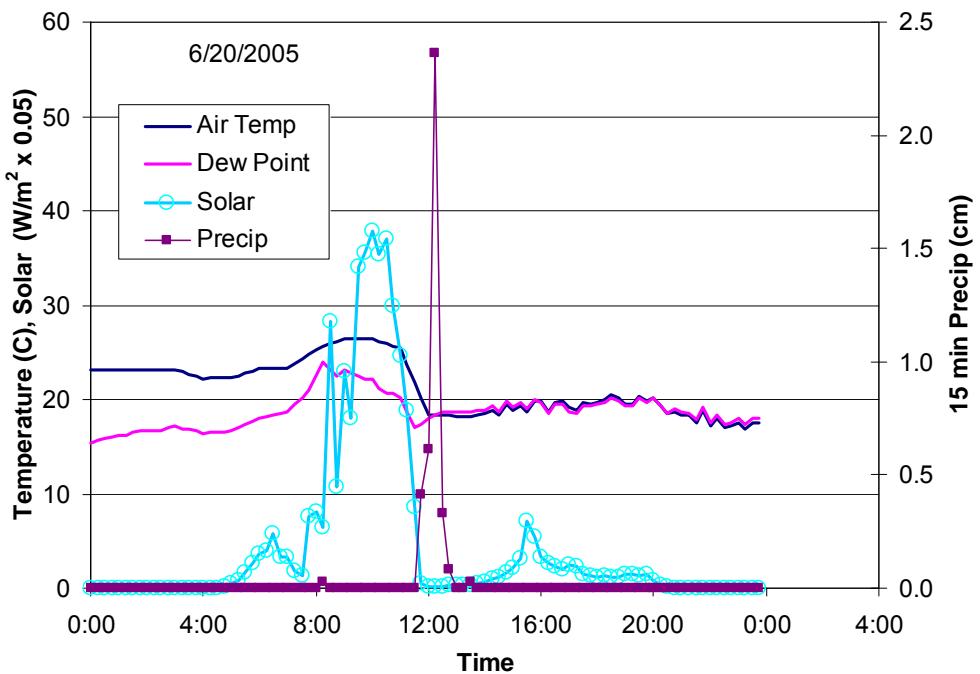
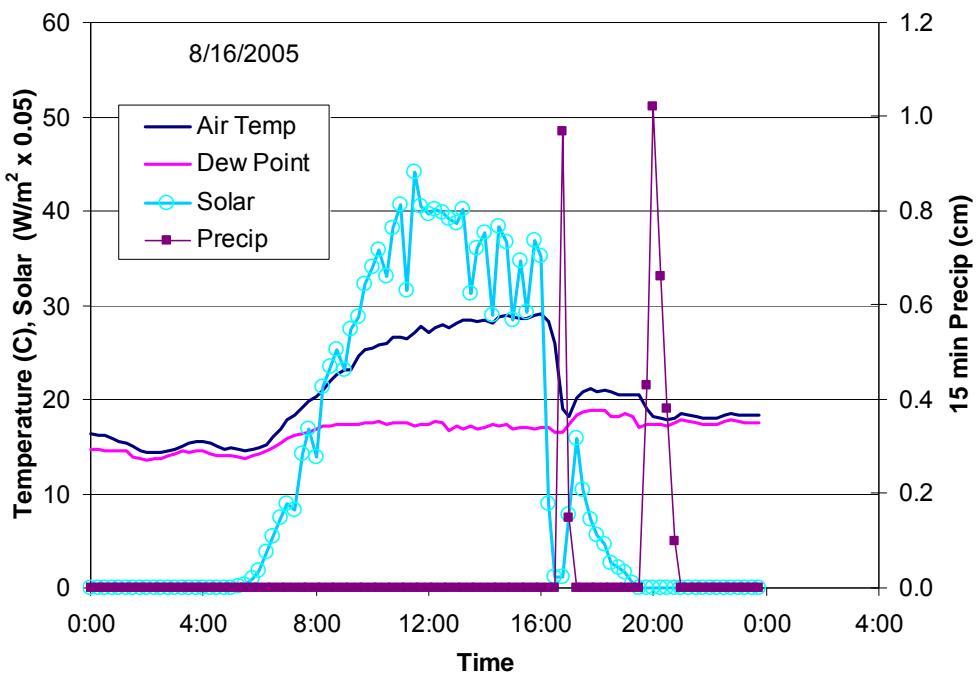


Figure 7.4. Detailed 15 minute climate data (Air and dew point temperature, solar radiation, and precipitation) for the two observed storm events (6/20/05 and 8/16/05) included with MINUHET.

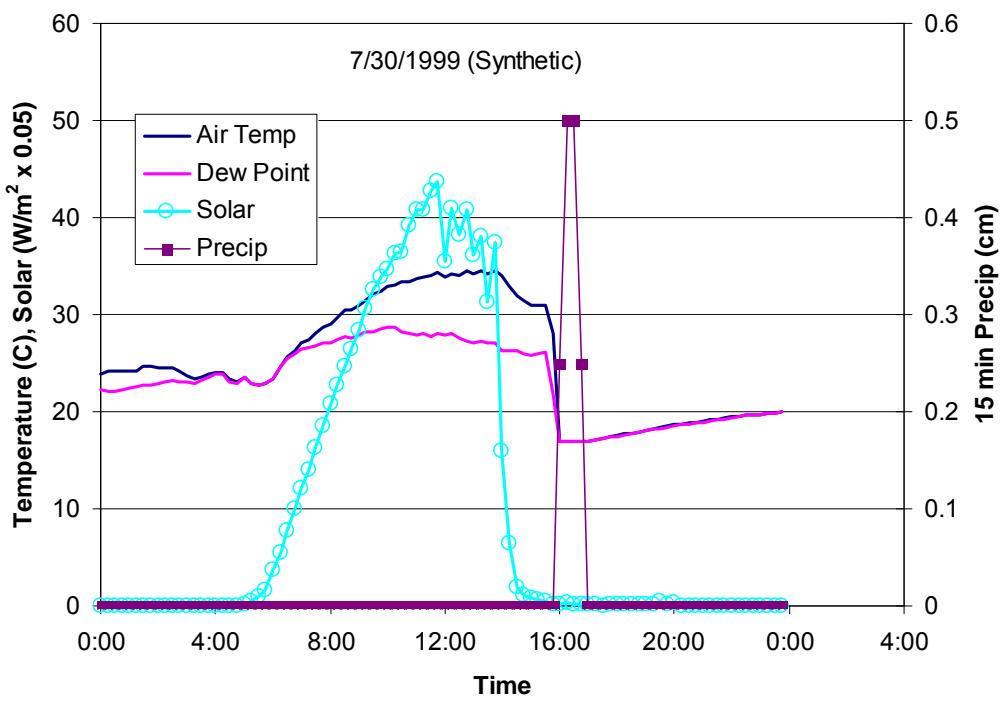
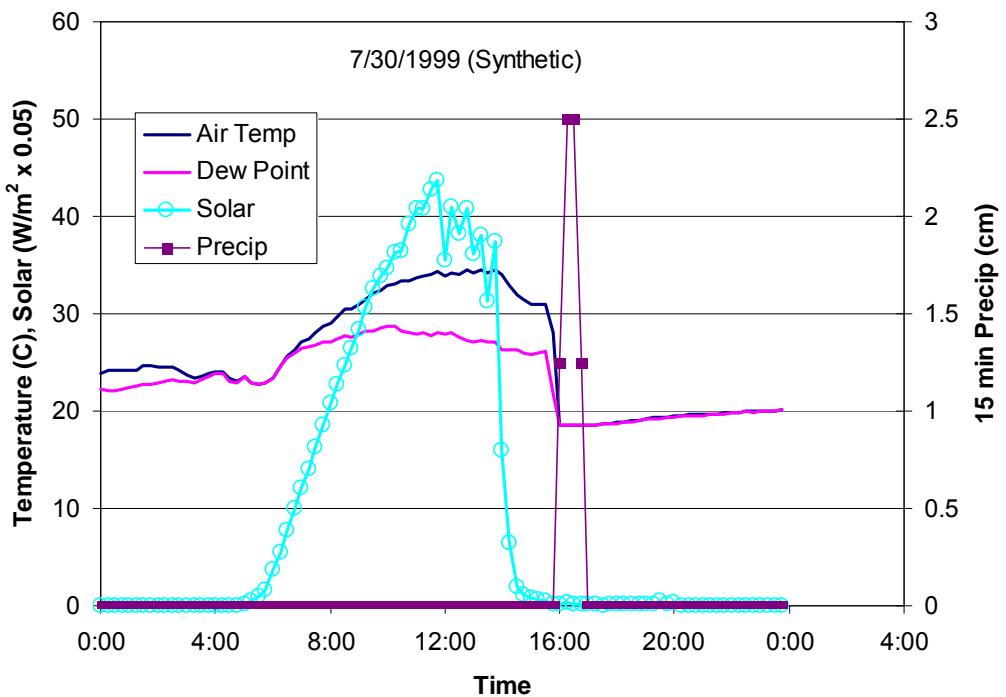


Figure 7.5. Detailed 15 minute climate data (Air and dew point temperature, solar radiation, and precipitation) for the one year (lower panel) ten year (upper panel) synthetic storm events included with MINUHET.

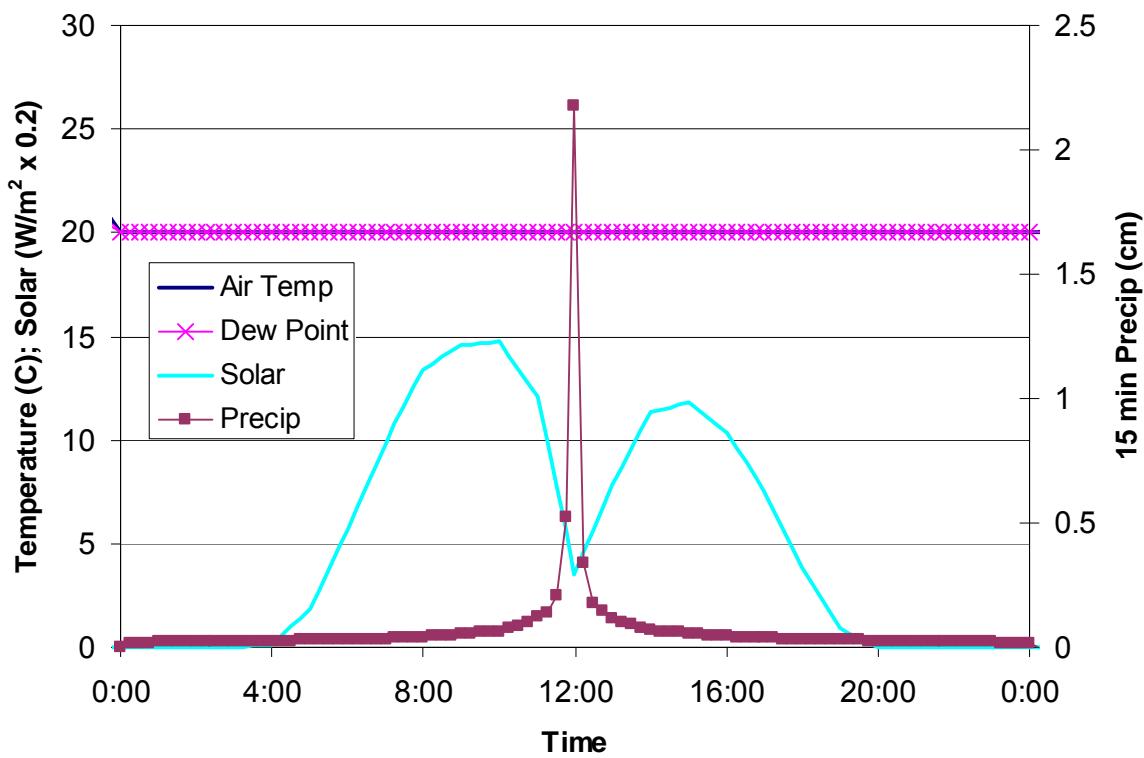


Figure 7.6. Detailed 15 minute climate data (Air and dew point temperature, solar radiation, and precipitation) for the 2 year 24 hour synthetic storm events included with MINUHET. Air temperature = dew point temperature = 20 °C for this storm.

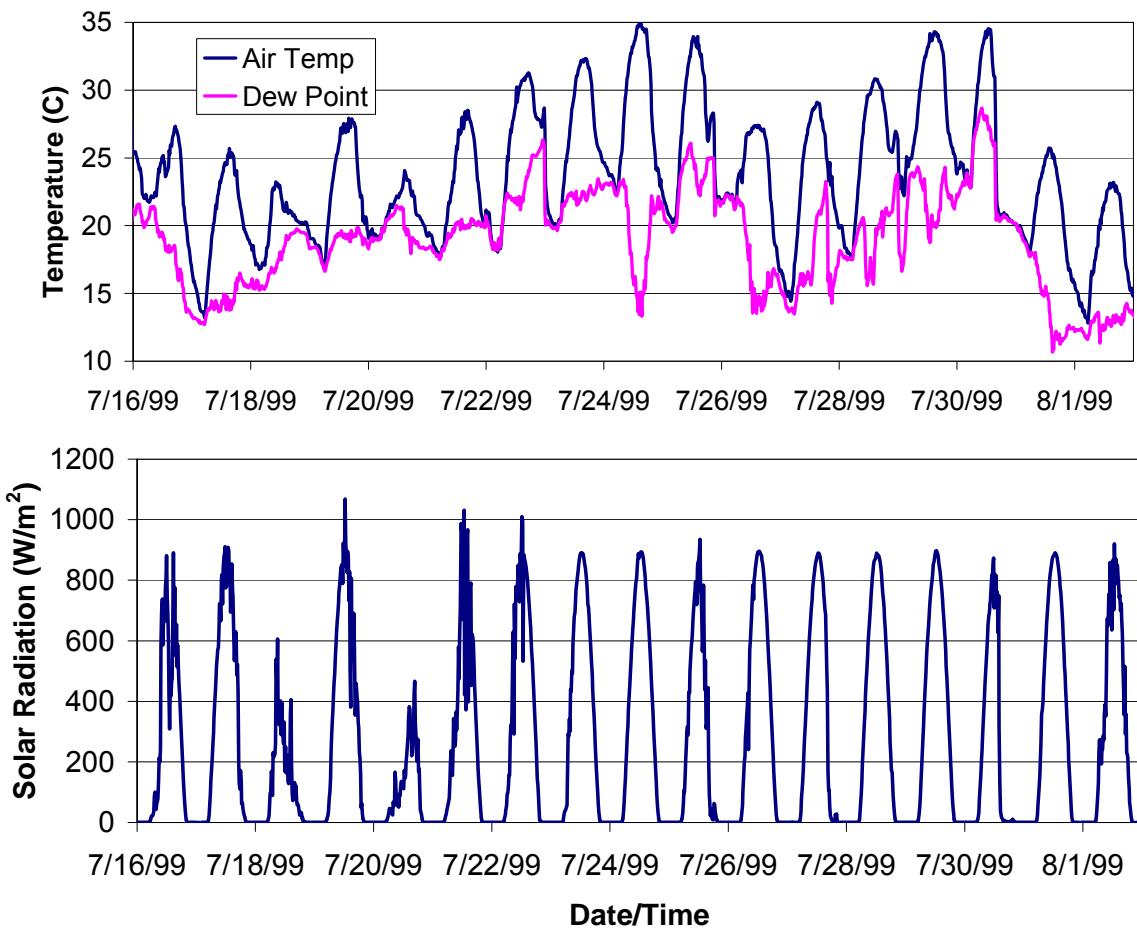


Figure 7.7 Observed air temperature, dew point temperature, and solar radiation for July 19 to August 2, 1999 at the MnROAD facility in Albertville, MN. The data are used for the antecedent climate data for the synthetic storm events.

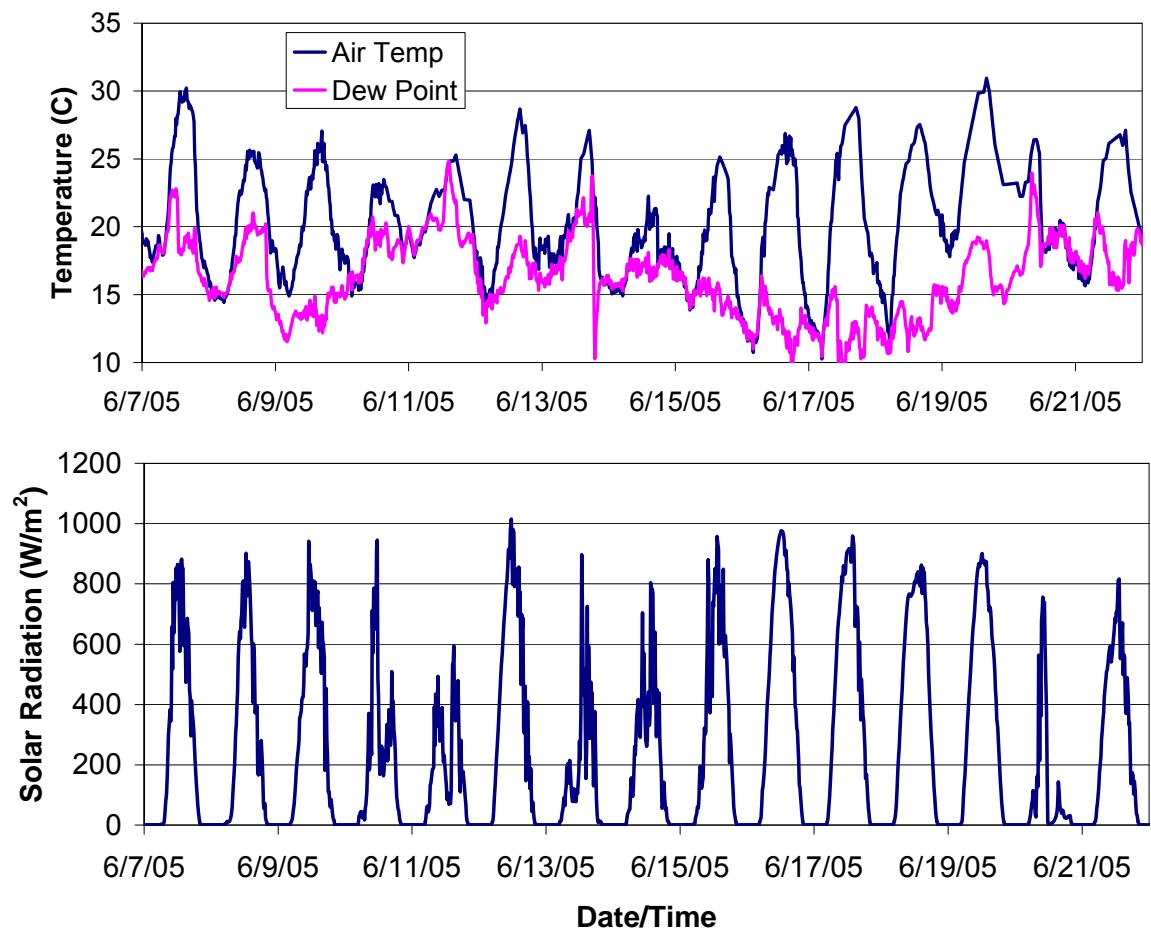


Figure 7.8 Observed air temperature, dew point temperature, and solar radiation for June 7 to June 22, 2005 at the MnROAD facility in Albertville, MN.

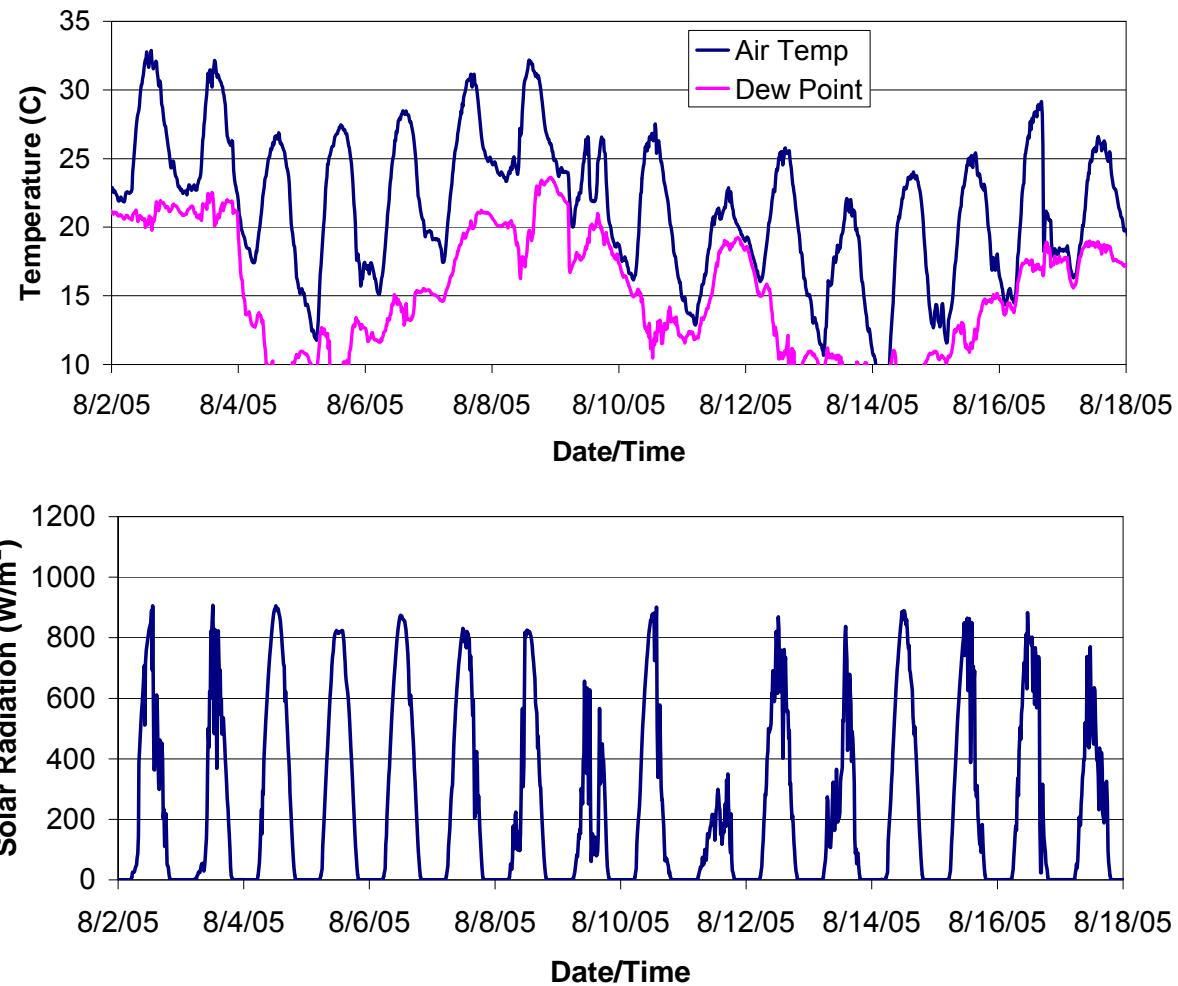


Figure 7.9. Observed air temperature, dew point temperature, and solar radiation for August 2 to August 18, 2005 at the MnROAD facility in Albertville, MN.

7.2 Running a Simulation

With the schematic layout completed and a storm event is selected, an MINUHET hydro-thermal runoff simulation may be initiated by selecting Simulation → Run from the drop-down menu at the top of the MINUHET window. If the simulation is successful, the ***Simulation Run Browser*** window will appear, described in the Chapter 8. If the simulation is not successful, a message window will appear with information about the run error, described in the troubleshooting section (Chapter 10).

Note: By default, the project file is saved prior to each simulation, so that any recent edits to the model schematic and element properties are updated.

8. Viewing the results: The MINUHET Simulation Run Browser

The MINUHET Simulation Run Browser (SRB) performs all the post-processing functions for the system, allowing the user to view the simulation results and export the results to word processing files, spreadsheets, etc. The SRB is opened automatically when a simulation is run, but may also be accessed at any time from the MINUHET main window by selecting Tools → Simulation Run Browser from the drop-down menu. Once opened, the SRB can be used to view the current or previous simulation results for the current model.

The components of the MINUHET SRB are illustrated in Figure 8.1. Areas of the SRB window include the Simulation History, the Schematic, the Element Properties Area, and the Graphing window. The SRB also has a small drop-down menu at the top of window.

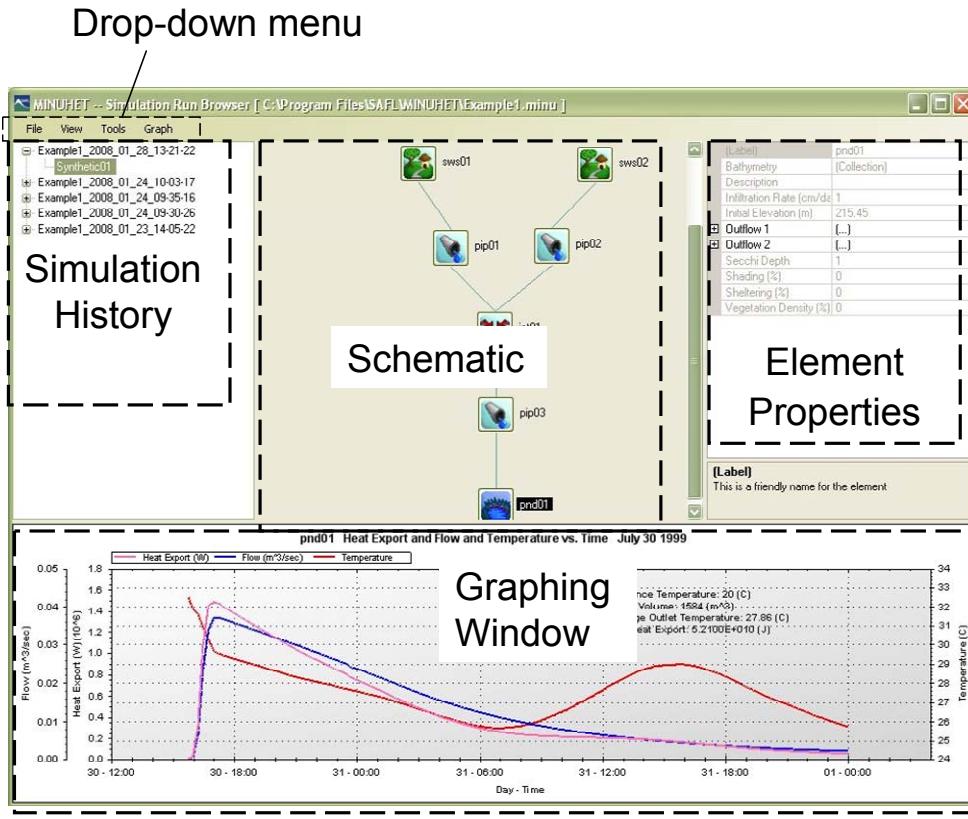


Figure 8.1. The MINUHET Simulation Run Browser (SRB).

The **Simulation History** gives a selectable, chronological list of all the simulations that have been run for current model. Each simulation run may include one or more storm events. Selecting a simulation run and a storm event from the history makes the simulation results for that storm available for display in the SRB. The simulation runs are named with the model name, followed by the date and time that the simulation was run. The **Schematic** window displays the model schematic. When a simulation run and storm are selected, the simulation results are displayed for the farthest downstream point of the system. Simulation results may be displayed for other points in the system by selecting elements in the schematic. Flow rate and flow temperature may be displayed for the outlet of any sub-watershed, pipe, open-channel, or pond. For example, selecting a pipe element in the schematic causes the flow rate and temperature at the outlet of that pipe to be displayed in the Graphing window. As an element is selected, its properties are displayed, but not editable, in the Element Properties Area. If the schematic is too large to be displayed in the Schematic window, a scroll bar will appear that can be used to move around to different areas of the schematic.

Note that if the model schematic was modified between subsequent simulation runs, the SRB automatically loads in the correct version of the model schematic for display along with the simulation results for the selected simulation.

The **Graphing Window** displays the time history of flow rate and flow temperature for the chosen point in the model.

- If a sub-watershed is selected, average surface temperature is plotted when flow is zero, and runoff temperature is plotted when flow is non-zero.
- If a pipe or channel is selected, the pipe wall temperature is plotted when the flow rate is zero.
- If a pond is selected, the pond water surface temperature is plotted when the outflow rate is zero.

The Graphing Window includes several useful functions that are accessed with the left and right mouse buttons. The user can zoom-in one the graph by clicking and dragging the left mouse button. Clicking the right mouse button within the graph enables the following functions:

- Copy: copies the graph to the clipboard. The graph image can then be pasted in other documents (MS Word™, MS Powerpoint™, etc.). This function may also be accessed using the Graph → Copy to Clipboard function in the drop-down menu.
- Save Image As: saves an image file of the graph to a user-defined file name/location, in Png, Gif, Jpeg, Tiff, or Bmp format.
- Page Setup: Used to set the printing page parameters
- Print: Print the graph
- Show Point Values: Enabling this feature cause the numerical values of flow, temperature and time to be displayed in a small box as the mouse is moved over the graph.
- Un-zoom: Go back one zoom step
- Undo All Zoom/Pan: Undo all zoom steps
- Set Scale to Default: Similar to Undo All Zoom/Pan, but resets the vertical scales to even increments of flow/temperature.

The graphing window includes summary data on the right side: average runoff temperature, total runoff volume, total heat export, and total precipitation. These data are calculated for the data that are displayed in the graphing window, and are therefore updated if the zoom feature is used.

The SRB drop-down menu has several useful commands:

File → Export Graph Data: This function is used to export the time, flow rate, and flow temperature data to a comma-delimited (.csv) file that is easily loaded into MS Excel™, for example. The csv data file will include the full time series for the selected element in the schematic.

File → Export Case File: This function can be used to export the Case File (see Section 3) for the selected simulation run. This function can be used in conjunction with the Simulation History to extract an older version of the current model and create a new model.

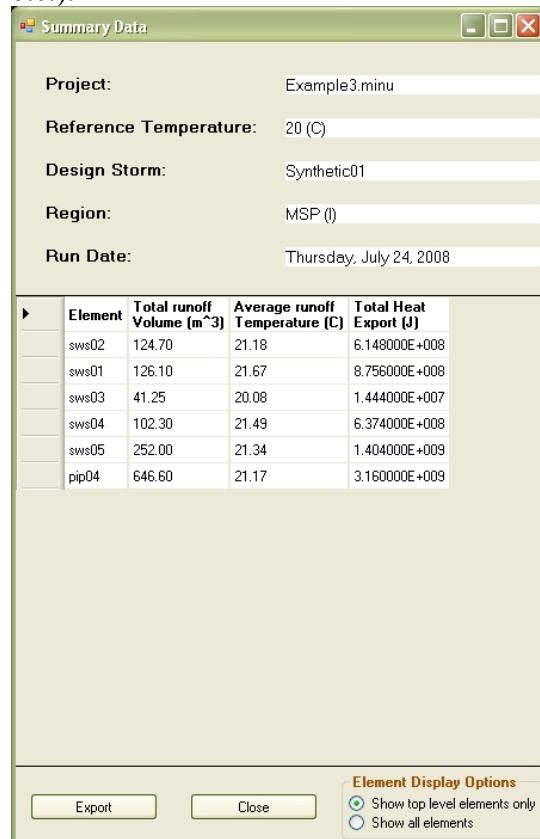
File → Close: Used to close the Simulation Run Browser

View→ Summary Table: Used to open the Summary Table (Figure 8.2), which gives a table of top level results (average runoff temperature, total heat export, total runoff volume) for elements of the model. The table entries can be copied and pasted to a spreadsheet, or the entire table can be saved as a comma-separated-variable file using the export button.

View→ Properties: Used to open and close the Element Properties window
View→ History: Used to open and close the Simulation History window

Closing the Simulation and/or Element Properties window frees up more of the SRB window space for the Schematic and Graphing windows. The relative size of the various windows can by changed by selecting and dragging the border regions of the windows.

Graph → Copy to Clipboard: Used to copy a bitmap image of the currently displayed graph to the clipboard. The image can then be pasted in other documents (MS Word™, MS Powerpoint™, etc.).



The screenshot shows the 'Summary Data' window with the following details:

- Project:** Example3.mnw
- Reference Temperature:** 20 (C)
- Design Storm:** Synthetic01
- Region:** MSP (I)
- Run Date:** Thursday, July 24, 2008

	Element	Total runoff Volume (m ³)	Average runoff Temperature (C)	Total Heat Export (J)
sws02	124.70	21.18	6.148000E+008	
sws01	126.10	21.67	8.756000E+008	
sws03	41.25	20.08	1.444000E+007	
sws04	102.30	21.49	6.374000E+008	
sws05	252.00	21.34	1.404000E+009	
pip04	646.60	21.17	3.160000E+009	

At the bottom right of the window, there is an 'Element Display Options' section with two radio buttons:

- Show top level elements only
- Show all elements

Buttons at the bottom left include 'Export' and 'Close'.

Figure 8.2. The Summary Table, which can be used to save a summary of the results for a simulation, or copy the results into a spreadsheet.

9. Example MINUHET schematic construction for a residential watershed

The following section describes an example of the application of MINUHET to a 12.5 acre land parcel with residential development. 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 (Table 9.1).

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.

Although there is not a direct interface between MINUHET and GIS packages, GIS is a useful tool for characterizing a land parcel to determine the required input data for MINUHET. In the case of the Plymouth 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. A GIS map of the study site is given in Figure 9.1, showing the houses, streets, driveways, and pervious areas. Based on this information, the sub-watershed input data for MINUHET was assembled, as given in Table 9.2. The storm sewer map was used to create Table 9.3, which summarizes the four sewer pipe sections, as illustrated in Figure 9.1. Further details on the application of MINUHET to this watershed are given in SAFL Project Report #497 (Janke et al. 2007).

The flow routing schematic for this watershed is shown in Figure 9.3. In this case, the two pairs of catch-basins located across the street from each other were combined, resulting in two catch basins (CB) and 1 junction for the model. Figure 9.4 gives the implementation of the flow routing schematic into MINUHET, where the elements have been arranged so that the flow goes from top to bottom. The MINUHET schematic could also be arranged as in Figure 9.2, since the flow direction is not dependent on the spatial position of the elements in the schematic.

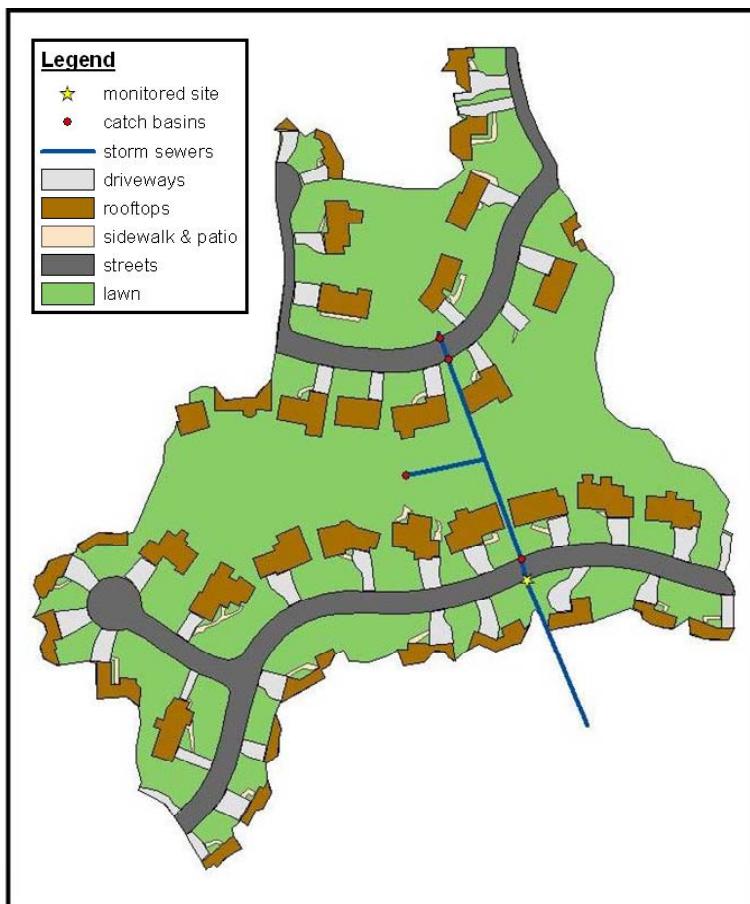


Figure 9.1. Schematic of study site, residential development in Plymouth, MN.

Table 9.1. Characterization of impervious areas within the Plymouth watershed

Total Area (m ²)	Street (m ²)	Roofs (m ²)	Connected Roof (m ²)	Driveways (m ²)	Sidewalk (m ²)	Connected Impervious (m ²)	% of Watershed
50390	6536	8078	940	4089	456	12021	23.9%

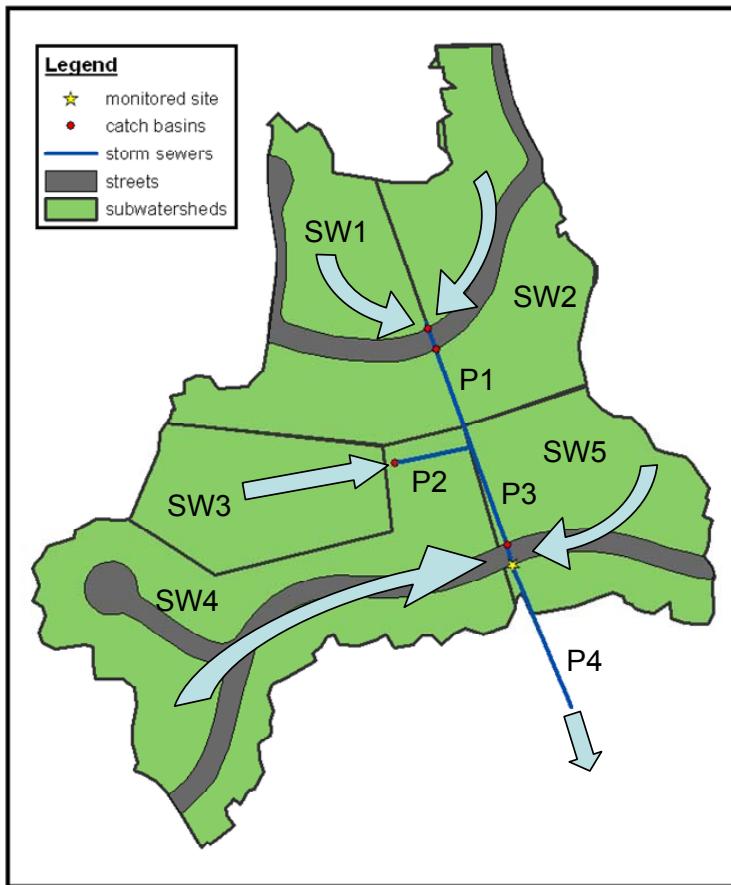


Figure 9.2. Division of study site into sub-watersheds SW1-SW5. Direction of overland runoff is also shown.

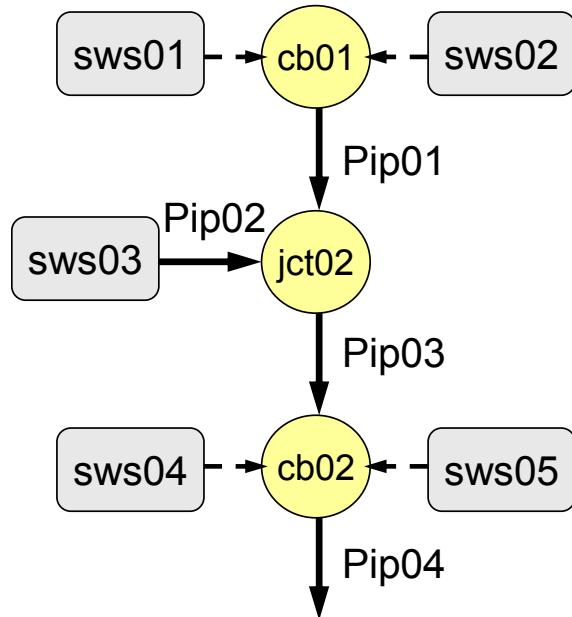


Figure 9.3. Flow routing schematic for the Plymouth watershed.

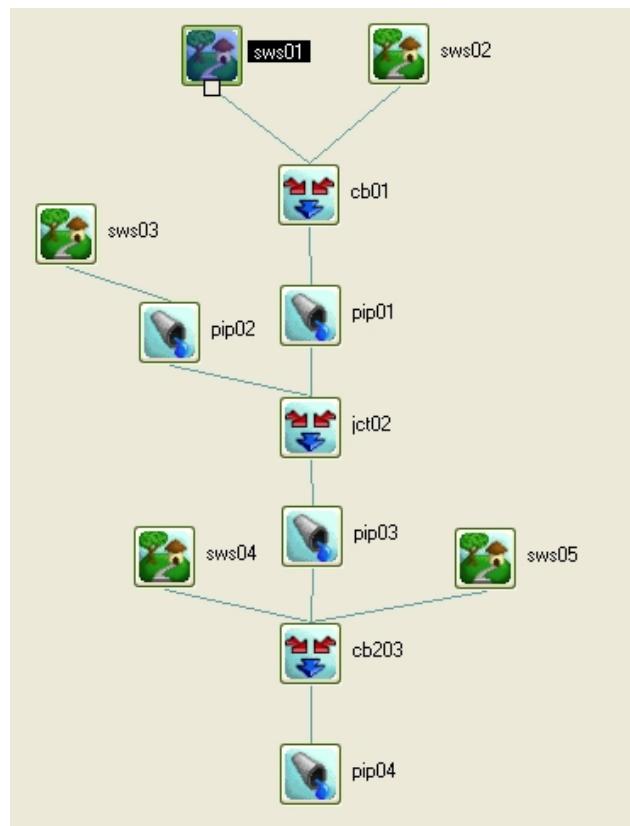


Figure 9.4. Flow routing schematic implemented in MINUHET

Table 9.2. Sub-watershed parameters for the example Plymouth watershed

Sub-watershed	SWS01	SWS02	SWS03	SWS04	SWS05
<i>Description</i>	SW Corner	SE Corner	Greenspace	NE Corner	NW Corner
Connected Impervious					
Length (m)	63.3	43.5		26	62.6
Paved Area (m ²)	2155	1889		1677	5323
Conn. Roof (m ²)	197	226		155	318
Shading (%)	10	0		0	10
Wind Sheltering (%)	0	0		0	0
Slope	0.0162	0.0128		0.026	0.026
Pervious (Grass, Trees) + Disconnected Impervious					
Length (m)	36.2	27.9	23.2	23.2	42.2
Pervious Area (m ²)	5899	5881	5007	5537	8533
Disconn. Roof (m ²)	1445	1654	858	1135	2336
Shading (%)	20	50	80	20	50
Wind Sheltering (%)	0	?	0	0	0
Slope	0.0256	0.0167	0.064	0.04	0.0441
Soil Type	B Short Grass	B Short Grass	B Short Grass	B Short Grass	B Short Grass
Veg. Type					
Veg. Density	0.9	0.9	0.9	0.9	0.9

Table 9.3. Storm sewer parameters for example Plymouth watershed

Pipe	P1	P2	P3	P4
Length (m)	51.7	24.2	52.3	64.6
Diameter (m)	0.305	0.305	0.457	0.381
Roughness	0.012	0.012	0.012	0.012
Slope (m/m)	0.048	0.0045	0.0092	0.075
Depth (m)	2.5	2.5	2.5	2.5

10. Error messages and troubleshooting

The MINUHET tool is designed to give reliable simulation results for reasonable watershed specifications. MINUHET has error checking and reporting on several levels. The graphical user interface (GUI) does some simple checks and reports warnings and errors with a pop-up window.

- During the schematic building process, MINUHET will not allow “illegal” connections, e.g. connecting two sub-watersheds together without a junction element, or connecting a sub-watershed or a junction directly to a pond inflow.
- If a schematic contains multiple, disconnected drainage networks, MINUHET gives a warning as a simulation is attempted. The simulation may proceed if desired, giving a separate multiple flow/temperature solution for each system.

The FORTRAN executables report problems on reading input files, bad sub-watershed parameters (e.g. Area=0), and solution convergence problems to a test file (error.txt), which is then automatically displayed by the GUI in a pop-up window.

All sub-watershed elements must have at least one positive area (Impervious or Pervious) with positive, length, and slope. Attempting to run a simulation with ill-specified subwatershed elements will result in an error message.

All routing elements (pipes and open-channels) must have positive length, diameter or width, slope, and roughness specified. If the calculated inflow rates from the sub-watersheds exceed the capacity of the storm sewer system (pipe elements), a flow solution convergence error may result and the simulation is stopped. The user can then modify the sewer system, e.g. increase the pipe diameters, or run a lower intensity storm event.

Generally, MINUHET should not report file reading problems, since all input files are either permanently stored or created in the correct format by the GUI. File read errors are then likely to be the result of accidentally deleting, moving, or modifying the permanent data files (global.dat, storm data files) in the MINUHET/Toolspace directory.

List of References

- Chow, V.T. (1964). *Handbook of Applied Hydrology*. McGraw-Hill Inc., New York, NY.
- Eckert, E.R.G., and R.M. Drake (1972), *Analysis of Heat and Mass Transfer*, McGraw-Hill.
- Ford,D.E. and H.G.Stefan (1980). Thermal prediction using integral energy model. *J. Hydraulics Division ASCE* 106(1): 39 -55.
- Gu, R. and H.G. Stefan (1995). Stratification dynamics in wastewater stabilization pond. *Water Research* 29(8): 1909 – 1923.
- Herb, W.R, B. Janke, O. Mohseni and H.G. Stefan (2006a). All-Weather Ground Surface Temperature Simulation. Project Report No. 478, St. Anthony Falls Laboratory, University of Minnesota, September 2006, 57pp.
- Herb, W.R, M. Weiss, O. Mohseni and H.G. Stefan (2006b). Hydrothermal Simulation of a Stormwater Detention Pond or Infiltration Basin. Project Report No. 479, St. Anthony Falls Laboratory, University of Minnesota, September 2006, 35pp.
- Herb, W.R, B. Janke, O. Mohseni and H.G. Stefan (2006c). Heat Export and Runoff Temperature Analysis for Rainfall Event Selection: Simulation for a paved surface and analysis of historical events . Project Report No. 483, St. Anthony Falls Laboratory, University of Minnesota, September 2006.
- Herb, W.R, B. Janke, O. Mohseni and H.G. Stefan (2006d). Analytic Model for Runoff and Runoff Temperature from a Paved Surface. Project Report No 484, St. Anthony Falls Laboratory, University of Minnesota.
- Herb, W.R., 2008. Analysis of the effect of stormwater runoff volume regulations on thermal loading to the Vermillion River, St. Anthony Falls Laboratory Report 520, 34 pp.
- Herb, W.R, B. Janke, O. Mohseni and H.G. Stefan (2009). MINUHET (Minnesota Urban Heat Export Tool): A software tool for the analysis of stream thermal loading by urban stormwater runoff. Project Report No 526, St. Anthony Falls Laboratory, University of Minnesota.
- Hondzo, M. and H. G. Stefan (1993). Lake Water Temperature Simulation Model, Jour. of Hydraulic Engineering, ASCE, 119(11), 1251-1273.
- Janke, B., W.R. Herb, O. Mohseni and H.G. Stefan, (2006). A Quasi 2-D Model for Runoff Temperature from a Paved Surface. Project Report No 477, St. Anthony Falls Laboratory, University of Minnesota, 76pp.

Janke, B., W.R. Herb, O. Mohseni and H.G. Stefan, (2007). Application of a Runoff Temperature Model (MINUHET) to a Residential Development in Plymouth, MN. Project Report No 497, St. Anthony Falls Laboratory, University of Minnesota, 34pp.

Li, R. M., Stevens, M. A., and Simons, D. B. (1976). "Solutions to Green-Ampt infiltration equation." J. Irrig. and Drain. Div., ASCE, **102**(2), 239–248.

Mays, L.W. (2001). *Water Resources Engineering*, First Ed., John Wiley and Sons, New York.

Ochsner, T.E., Horton, R., and Ren, T. 2001. A new perspective on soil thermal properties. Soil Sci. Soc. Am. J., 65: 1641-1647.

Riley, M. and H. G. Stefan, 1988. MINLAKE: A Dynamic Lake Water Quality Simulation Model, Ecological Modeling, Vol. 43, 155-182.

Appendix 1: Files formats used by MINUHET

Storm file format

The following page gives a sample storm file used by MINUHET. The example file is much shorter than the typical 2 week duration, to better illustrate the file structure.

The first seven lines are comment lines that are not used by MINUHET.

The WRUN parameter set (FORTRAN namelist) contains three parameters: WSTART and WSTOP are the start and stop times, in days, for the given climate data. ASTART is the runoff analysis start time, usually just prior the storm event of interest. Both WSTART and WSTOP are in days, referenced to January 1, 1900 (Excel time format). TSTEP is the time step, in minutes, of the climate data.

WDATA is parameter set (namelist), containing WDAT, the (NWD x 6) array containing the climate data, with comma separation. Column 1 is Air Temperature ($^{\circ}\text{C}$), column 2 is Relative Humidity (%), column 3 is Solar Radiation (W/m^2), column 4 is Wind Speed (m/s), column 5 is Precipitation Depth (cm), and column 6 is Cloud Cover fraction (0=clear, 1= full cloud cover). The climate data array may optionally end with a “/” delimiter, as shown.

The example file format given below is truncated to fit it on 1 page. The example uses comma delimited format; tab delimited file formats are also acceptable.

```
! MINUHET synthetic design storm file
! Contains site run time parameters and weather data
! WSTART=start date/time for weather data in Excel format
! ASTART=start date/time for runoff analysis in Excel format
! TSTEP = weather time step (minutes), NWD = number of weather time steps,
! WDAT=weather data (air temp (C), RH (%), Solar (W/m^2, Wind (m/s),
! Precipitation (cm), Cloud Cover Fraction (0=clear, 1= full cloud cover)
```

```
&WRUN
WSTART=36365.00000
WSTOP=36373.00000
TSTEP=15.0/
```

```
&WDATA
WDAT =
18.9, 85.4, 0.0, 0.32, 0.00, 0.2
18.8, 85.5, 0.0, 0.37, 0.00, 0.2
18.9, 86.2, 0.0, 0.34, 0.00, 0.2
18.8, 87.3, 0.1, 0.54, 0.00, 0.2
18.6, 87.7, 0.2, 0.70, 0.00, 0.2
19.1, 86.5, 0.1, 1.21, 0.00, 0.2
19.1, 86.8, 0.1, 0.93, 0.00, 0.2
18.9, 88.8, 0.1, 1.31, 0.00, 0.2
18.9, 88.6, 0.1, 1.17, 0.00, 0.2
18.5, 90.9, 0.1, 1.01, 0.00, 0.2
18.1, 92.6, 0.0, 0.71, 0.00, 0.2
17.7, 94.0, 0.0, 0.60, 0.00, 0.2
17.8, 94.8, 0.0, 0.38, 0.00, 0.2
17.7, 95.3, 0.0, 0.29, 0.00, 0.2
17.4, 96.1, 0.0, 0.58, 0.00, 0.2
17.7, 96.2, 0.0, 0.70, 0.00, 0.2
17.9, 95.7, 0.3, 0.76, 0.00, 0.2
18.2, 95.3, 0.4, 0.69, 0.00, 0.2
18.4, 94.8, 0.4, 0.62, 0.00, 0.2
18.6, 94.4, 0.5, 0.55, 0.00, 0.2
18.6, 94.2, 0.6, 0.20, 0.00, 0.2
18.5, 95.3, 1.0, 0.48, 0.00, 0.2
18.7, 95.3, 0.5, 0.28, 0.00, 1.0
19.4, 95.4, 1.4, 3.81, 0.03, 1.0
19.1, 97.4, 2.8, 2.18, 0.03, 1.0
18.5, 98.6, 3.0, 0.97, 0.00, 1.0/
```