WATER TEMPERATURE TRANSACTION TOOL (W3T): TECHNICAL AND USER'S GUIDE (V1.0)

A Report for

National Fish and Wildlife Foundation (NFWF)

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Executive Summary

The Water Temperature Transaction Tool (W3T) is an easy-to-use, interactive model for quickly evaluating stream temperatures under a variety of scenarios. The tool allows users to define a simple river reach and change basic characteristics, such as surrounding shade, cross-section form, channel slope, and tributaries and diversions, to evaluate potential benefits of flow transactions as they relate to river temperature. In defining the river reach, tributaries and diversions may be placed anywhere along the reach length and can be moved, removed, or added to develop different scenarios for comparison. Users may interactively specify reach length, inflow, tributary flow, and diversion amount. Water temperature can be assigned within W3T from a list of records and assigned to each inflow. Unique shade scenarios can be developed within W3T and assigned to individual sections of a reach.

To evaluate potential management decisions and compare scenarios, a set of summary tables and graphs are included. These summaries include tables of input parameters and results and graphs of inflow versus outflow temperatures, longitudinal daily minimum, mean and maximum temperatures, and solar radiation resulting from scenario assumptions. W3T includes the ability to save a baseline scenario for comparisons. Outflow temperatures and solar radiation under baseline conditions may be graphically compared to results from current scenario conditions. Solar reductions (compared to theoretical maximum as well as versus a "pre" and "post" condition) are also reported (consistent with Shade-a-lator reporting). In addition, heat leaving the reach (kcal/day) is calculated and compared to baseline.

A companion document, "An Example Application of W3T: Rudio Creek," is available to provide guidance in identifying data needs, collecting data, and running the W3T model.

Water Temperature Transaction Tool (W3T): Technical and User's Guide (V1.0)

1. Background

W3T was developed for the National Fish and Wildlife Foundation (NFWF) as part of the Conservation Innovation Grant (CIG) exploring flow transactions and their potential effect on habitat and water quality. Ideally, such a tool should be capable of calculating stream water temperature for shaded and un-shaded reaches for a variety of flow conditions. Flows may affect temperature in several ways: increasing flow volume can moderate daily maximum water temperatures, reduce daily range (maximum minus minimum), and reduce travel time (and thus exposure time of waters to meteorological conditions) through a reach. If added flows are colder than in-stream waters, the benefits can lead to locally cool conditions or longer, cool water river reaches/habitats. Finally, woody riparian vegetation shading can notably reduce incoming solar radiation, thus directly reducing energy input to the stream. (Topographic shade can also lead to reductions in solar energy, but this is a largely uncontrollable factor.) Thus, a water temperature tool to quantitatively assess flow transaction would necessarily require a flow component (including volume and velocity information), a heat budget to assess energy transfer across the air-water interface (and ground-water interface, i.e., bed conduction), and a representation of vegetation (and topographic) shading. Further, the tool should calculate daily minimum, mean, and maximum water temperature for use in various biological metrics. Finally, such a tool would need to be transparent and uncomplicated, require modest data inputs, and calculate results quickly. These assumptions result in a tradeoff between simplicity and uncertainty; however, the approach outlined herein aims to strike a balance that provides sufficient accuracy to support a flow transaction program (wherein assessment of temperature impacts are quantified to identify benefits associated with such a transaction) and minimize data needs and computational time.

W3T is based on a steady flow approach (e.g., based on the Manning equation) requiring basic stream parameters (velocity, depth, cross sectional area, and surface area). Subsequently, this information is used to model water temperature based on energy transfer to and from the water across the air-water interface and accounts for transport of heat energy in the downstream direction. The current model for heat budget is consistent with Heat Source (v 7) and includes simulation of topographic and riparian shade. Other heat budget formulations from other water quality models may be included in future as user-selected options to provide flexibility and transferability among different regions or regulatory areas.

The maximum size and complexity of the river and canopy are limited only by ease-of-use. Currently, the model is limited to 11 subreaches with a combined maximum number of 10 tributaries and diversions (e.g. 3 tributaries and 7 diversions, 5 tributaries and 5 diversions, etc.). Each subreach may have its own hydrodynamic characteristics and 4 zones of riparian vegetation. While energy transfer across the ground-water interface can have a moderating effect on water temperatures. While time constraints did not allow for this process to be modeled in the current version of W3T, this process is planned in forthcoming versions of the model. Maximum simulation time is seven days.

2.   Technical Development

The Water Temperature Transaction Tool (W3T) uses river and landscape characteristics to estimate hourly solar radiation and overall heat loss or gain, and from these estimations it calculates temperature changes in a river reach. The reach is described by reach length and width, bed roughness, and topographical and vegetation features such as surrounding zones of vegetation that provide shade and inhibit solar radiation. Meteorological data are included to describe the local environmental conditions affecting heat transfer at the air-water interface. A schematic of the modeling framework is shown in Figure 1.

The user specifies inflow rates and water temperatures. As water travels downstream from the top to the bottom of the reach, the model estimates incoming solar radiation and atmospheric heat exchange. Summing short wave (direct solar), longwave, evaporative, and conductive heat fluxes, the model calculates a net change in temperature in short computational segments. Along the reach, tributary inflows with distinct temperature signals mix with river water, and diversions from the stream are represented. Parcels of water are tracked and temperatures at each inflow and outflow location are reported for every hour of a simulation.

To capture varying meteorology and tributary inputs, and to accommodate varying vegetation structure, a reach is subdivided into subreaches and computational segments. A reach, defining the entire length of stream to be simulated, is divided by the user into subreaches that are described by hydrodynamic and/or vegetation characteristics. Each subreach is homogeneous along its length and characterized by consistent channel geometry, vegetation structure, and flow. Within the model, these subreaches are further subdivided into equal computational segments so that meteorological conditions are interpolated at intervals no longer than 15 minutes. For example, a subreach with a travel time of 17 minutes is subdivided into two computational sections of 8 ½ minutes each, and a subreach with a travel time of 10 minutes is not subdivided at all. Meteorological conditions are established at the beginning of each computational section by interpolation of reported hourly data. The resulting meteorological conditions are used to estimate average heat flux over the length of each computational segment, and this estimated heat gain or loss is used to compute a change in water temperature. An example of a simulated reach subdivided by a tributary and a diversion into three subreaches is shown in Figure 4.

DATA **FLOW MODULE** **TEMPERATURE MODULE**

Channel Info.

Flow Data → Calculate Flow Characteristics

Water Temp.

Meteorology

Riparian Vegetation → Solar Reduction (Shade-a-lator) → Heat Budget → Fate and Transport

OUTPUT
— Flow
— Temperature
— Solar Reduction
— Other
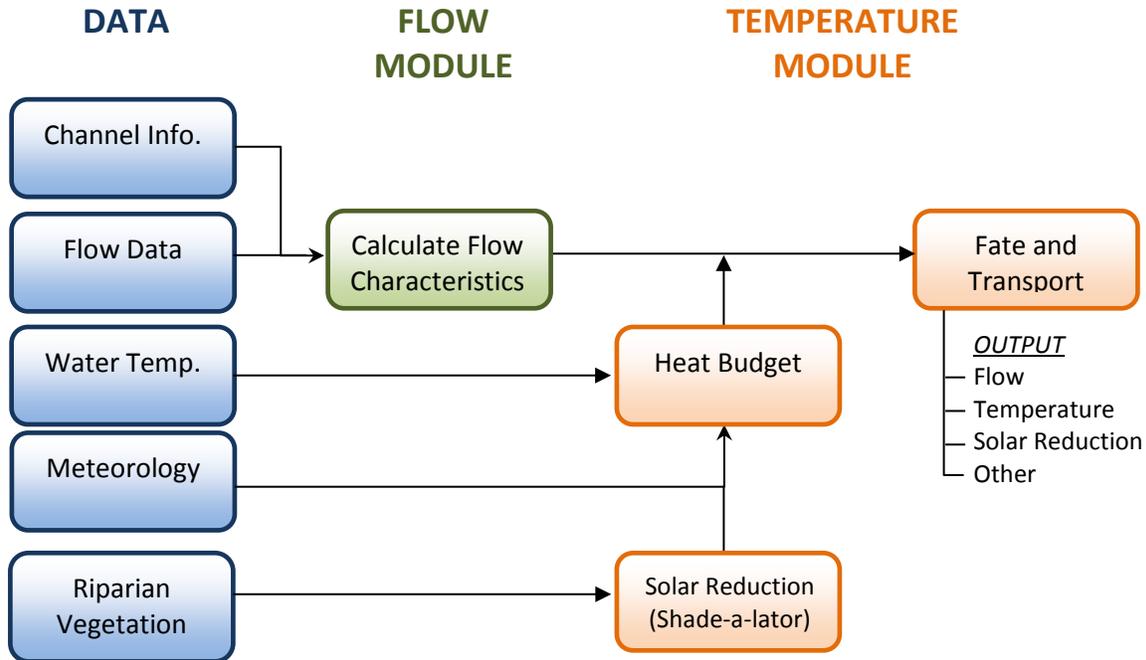
Figure 1. W3T schematic of data and flow and temperature modules.

The W3T simulates a minimum of a 24-hour period, even if travel time through the reach is less than a day. This is achieved by calculating an outflow temperature for each hour in a day (or longer if the specified simulation period is greater than a day). For each hour of the simulation, the model reads inflow water temperature for a parcel of water entering the reach and computes changes to that temperature as the parcel moves through the reach. The water temperature at the end of the reach is a function of initial water temperature, reach configuration (flow, tributaries and diversions), shade, and meteorological conditions. In this manner, the model can produce a full diurnal signal of hourly water temperatures in the study area, providing resource managers with daily maximum, mean, and minimum temperatures, which may be useful in assessing potential transactions in light of ecologically meaningful metrics. Maximum simulation time is seven days.

W3T resides in an Excel workbook with various worksheets used to collect and store model data and results. The model depends upon user-supplied input data that includes:

- Flow data (inflows and outflows and location of tributaries and diversions)
- Channel information (reach length, bottom width, side slope, bed roughness, and bed slope)
- Inflow water temperatures
- Meteorology (e.g., air temperature, cloudiness, wind speed, relative humidity, and wet bulb temperature, atmospheric pressure)
- Riparian vegetation for each subreach (height and density of vegetation in each of the 4 vegetation zones in 7 directions: NE, E, SE, S, SW, W, and NW. The model assumes that the sun is never due north.). This description of vegetation comes from

Shade-a-lator and, when available, these parameters may be taken directly from Shade-a-lator input files.

A summary of data required to run W3T is given in Table 1.

Table 1. W3T data types and their scope

Data type	Specific datasets	Units	Scope
Meteorological	Air temperature Cloudiness Wind Relative humidity Wet bulb temperature Evaporative coefficients[1]	^{o}C percent as a fraction m/s percent as a fraction ^{o}C unitless	Entire reach
Channel geometry	Bottom width Side slope, avg. of both banks Channel slope Manning roughness, n[1]	ft ft/ft ft/ft no units	Each subreach
Topographic shade	Elevation angle	degrees	Entire reach
Riparian vegetation (general)	Width of riparian zones Height of emergent vegetation Density of emergent vegetation	m m percent as a fraction	Entire reach
Riparian vegetation (by subreach)	Overhang	m	Each subreach in each direction
Riparian vegetation (by zone)[2]	Height Density Elevation at ground	m percent as a fraction m	Each zone in each direction
Water temperatures	Inflow water temperatures Instream water temperatures[1]	^{o}C ^{o}C	Specific to each inflow or location
Flows	Inflow rates Diversion rates Instream flow rates[1]	cfs cfs cfs	Specific to each inflow, diversion or location

(1) Typically used for model calibration and/or verification

(2) Specified for each band, or zone, of vegetation away from stream in each compass direction

3. Quick-Start Guide to Running the Model

To run the model, a reach must be fully described with tributaries and diversions characterized, all relevant parameters given values and boundary conditions defined. Relevant parameters include both global reach and subreach-specific parameters describing hydrodynamic qualities and riparian vegetation. Steps to set up and run the model, which need not be taken in any particular order, include:

1. Set global parameters.

2. Set subreach-specific parameters.

3. Define shade scenarios.

4. Describe inflow water temperature records.

5. Describe meteorology.

6. Configure reach.

7. Run model.

8. Save baseline.

9. Repeat steps 1 through 7 for alternatives.

To run the model, eleven specific worksheets must be present in the workbook. These required worksheets are identified in Table 2.

4. User's Guide

W3T resides in an Excel workbook with various worksheets used to collect and store model data and results. The following sections provide basic information and instructions on using W3T.

The W3T workbook contains four different types of worksheets to provide model parameters and boundary conditions, run the model, and display results. The types of worksheets and the names of the associated worksheets are listed in Table 2.

Table 2. W3T worksheet types, names and descriptions

Worksheet Type	Name	Description
Model Interface[1]	*River*	*Reach schematic, temperature graphs, reach summary information*
Input[1]	*Parameters*	*Global parameters for heat calculations*
	Reach	*Reach-defining parameters (channel geometry and vegetation structure for each subreach)*
	Shade_input	*Vegetation structures for different scenarios*
	Met	*Hourly meteorological data*
	Inflow_Tw	*Hourly water temperatures*
Output[1]	*Summary*	*Information describing current reach and results*
	Solar_Summary	*Hourly solar radiation above and below vegetation for each subreach*
	Results_# [2]	*Hourly inflow and outflow temperatures and heat fluxes for subreach "#"*
	Solar_Results_# [2]	*Hourly results from Shade-a-lator logic for subreach "#"*
	Baseline	*"Summary" sheet for the Baseline simulation*
General Information	*Notes*	*Misc notes including conversions and constants*
	Versions	*A list of model version releases*

[1] All sheets of this type are required.

[2] Represents a set of sheets. "Results_1" and "Solar_Results_1" sheets are required. Other sheets are created by the model, up to total number of reaches.

Each of these worksheet types and the information layout are discussed below. Worksheets contain reference values and calculated values as well as input data. In general within any

worksheet, only values in blue font should be changed by the user. Values in shaded worksheet cells are for reference only.

4.1. Model Interface (River Worksheet)

The *River* worksheet provides an interface to easily change reach configuration, set simulation date, and to run the model. The interface includes an interactive schematic of the reach, a table for specifying inflow and outflow configuration (i.e., name, temperature record, flow and location), tables and graphs to view results, and buttons to run the model (Figure 2).
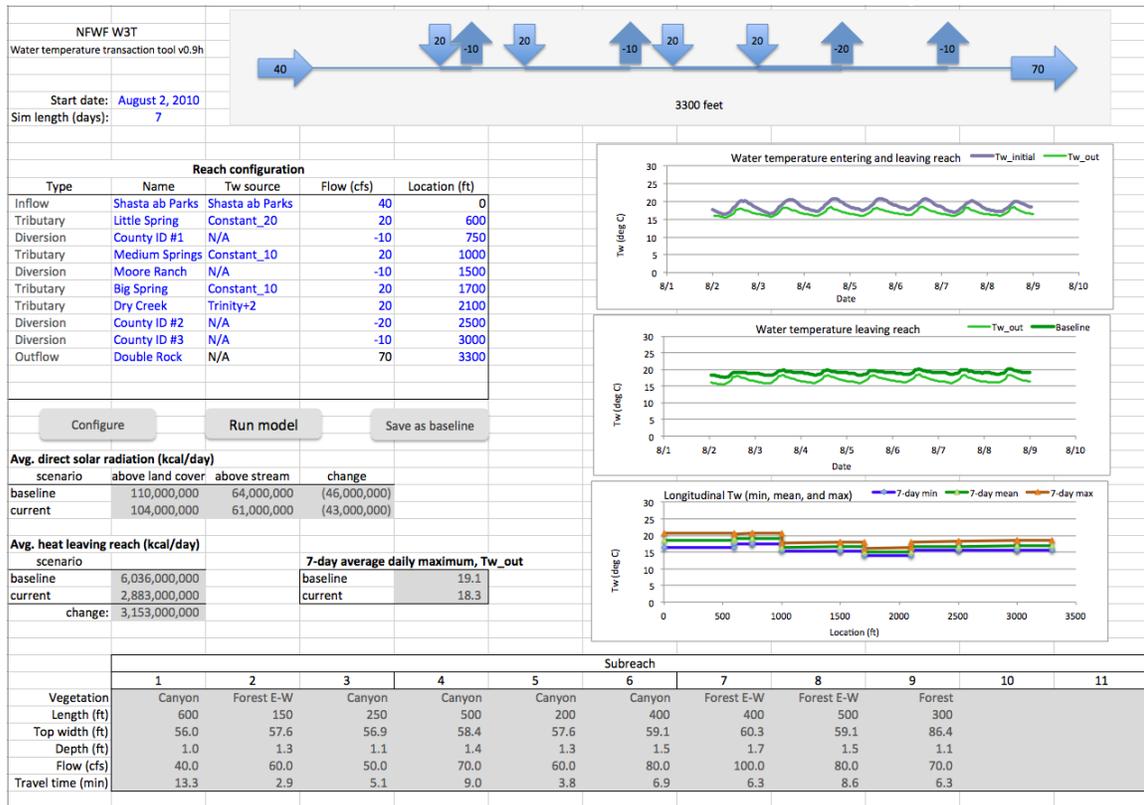
Figure 2. The *River* worksheet.

4.1.1. Reach Configuration

A reach is configured in the "Reach Configuration" table (Figure 3). In this table, a user sets up the river reach by entry (i.e., row). Tributaries and diversions may be removed or added to the simulation (maximum combined total of ten), but entries must be listed contiguously with no empty rows. The order in which inflow, outflow, tributaries, and diversions are listed does not matter. The model will re-order the entries from upstream to downstream and the entry farthest downstream will become the outflow. The model will assign an entry "Type" based on location and flow (e.g., an entry with a positive flow in the middle of the reach will be assigned as a "Tributary" type, while a negative flow in the middle of the reach will be assigned as a "Diversion" type).

Entries in the "Reach Configuration" table have four attributes: name, water temperature source, flow, and location. "Name" is provided for the user to identify the entry and is not used by the model. "Tw source" provides the name of the hourly water temperature record

associated with the entry. This name must match one of the headers on the *Inflow_Tw* worksheet. "Flow" describes the flow associated with an inflow or diversion and is constant throughout the simulation. Diversion flows are defined by negative values. "Location" describes the position of a tributary or outflow downstream relative to the inflow (upstream-most location). The model designates the entry with the most downstream location as the outflow, and any water temperature associated with that entry is discarded. Reach length and outflow location are equivalent. Configuring the reach need not be the last step, but if parameters and input data (even default values) are not specified for each subreach, error warning messages will be generated to identify missing information.

The reach schematic is a visual representation of the Reach Configuration table (Figure 4). This schematic, located directly above the Reach Configuration table, depicts inflows and outflows as arrows located on a line representing the reach. Tributaries and diversions are placed on the reach according to their specified locations. In Figure 4, the river reach is defined by an inflow, an outflow, four tributaries, and four diversions. The inflows and outflows delineate nine "subreaches."

Once tributaries and diversions have been specified, the user may choose to change reach attributes using the graphical interface built into the schematic. Single-clicking any of schematic arrows will allow the user to change attributes for the selected the inflow or outflow. A drop-down menu provides convenient access to a list of available water temperature sources. Also, by selecting the text box showing reach length at the bottom center of the schematic, the user can change reach length (i.e., the location of the outflow). Making any changes through the graphical interface will cause the reach configuration table to be updated and the schematic to redraw to the new specifications

Reach configuration				
Type	Name	Tw source	Flow (cfs)	Location (ft)
Inflow	Shasta ab Parks	Shasta ab Parks	40	0
Tributary	Little Spring	Constant_20	20	600
Diversion	County ID #1	N/A	-10	750
Tributary	Medium Springs	Constant_10	20	1000
Diversion	Moore Ranch	N/A	-10	1500
Tributary	Big Spring	Constant_10	20	1700
Tributary	Dry Creek	Trinity+2	20	2100
Diversion	County ID #2	N/A	-20	2500
Diversion	County ID #3	N/A	-10	3000
Outflow	Double Rock	N/A	70	3300

Figure 3. Example "Reach configuration" table.
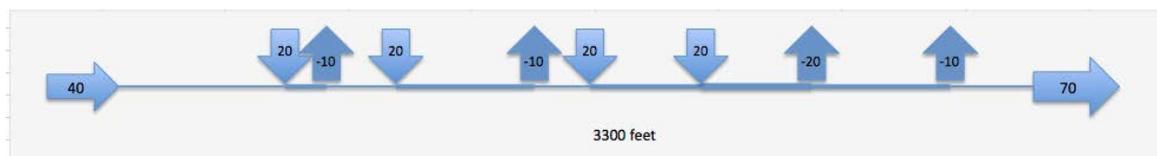
Figure 4. Example reach schematic. This schematic shows a 3300-foot long reach subdivided by four tributary inflows and four diversions into nine subreaches.

4.1.2. Graphs and Tables

Graphs and tables on the *River* worksheet present simulation results and provide immediate feedback to the user. Graphs include:

- Inflow and outflow water temperature,
- Outflow water temperatures from current and baseline simulations, and
- Longitudinal hourly, minimum, mean and maximum water temperatures along the reach over the simulation period.

An example graph, showing outflow temperatures under currently simulated and baseline scenarios, is presented in Figure 5. This graph comes from an example application of W3T to a flow transaction.
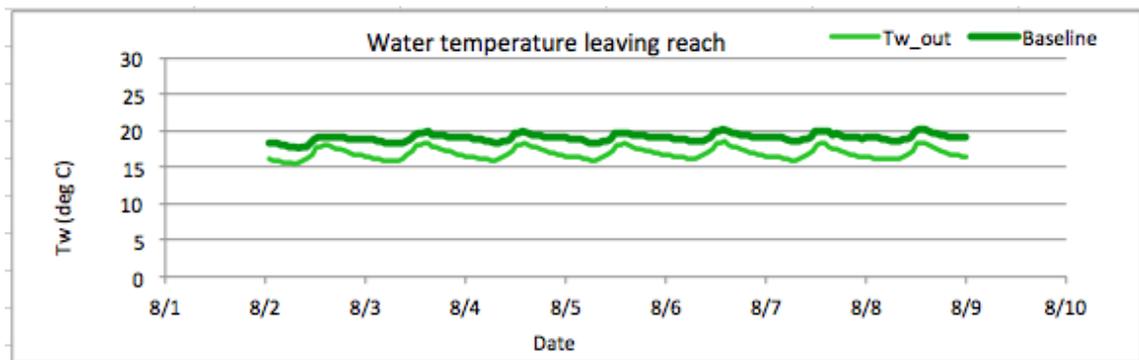
Figure 5. Water temperature leaving reach from example analysis.

Tables on the *River* interface worksheet display:

- Direct solar radiation above land cover and at water surface for baseline and current simulations (kcal/day),
- Total heat leaving the reach under current and baseline simulations (kcal/day),
- Average maximum daily temperature at bottom of reach (Tw_out) over length of simulation, and
- General reach characteristics (length, top width, depth, flow, travel time, and type of riparian shade) assigned under the current simulation.

4.1.3. Buttons

Three buttons on the *River* interface worksheet control macros that redraw a reach configuration, run the model, and save baseline results. The buttons and their functions are listed in Table 3.

Table 3. Buttons and button functions.

Button Name	Function
"Configure"	Places inflows and outflows in order, calculates outflow and redraws the reach schematic
"Run Model"	Configures the reach (using the "Configure" routines), runs shade and heat budget simulations, and outputs results
"Save as baseline"	Saves the current simulation as the baseline for comparison purposes

After tributaries, diversions, flows, locations and temperature sources have been specified in the reach configuration table, the reach schematic will be updated when the "Configure" button is clicked. This button causes the entries from upstream to downstream to be re-ordered, calculates outflow, and redraws the reach schematic to reflect the new reach configuration. This button does not run either the shade or heat budget calculations and may be used to simply arrange the physical layout of the reach before simulation.

Once the reach is configured, and input parameters and data are specified for the simulation period, press the "Run Model" button to estimate water temperatures along the reach for the simulation period. The model will read in reach data and boundary conditions (i.e., inflow temperatures, meteorology and riparian vegetation), simulate shade and the heat budget, and print out results.

To save the current simulation as a baseline simulation, press the "Save as baseline" button. This button runs a macro that copies all the data on the simulation *Summary* sheet to the *Baseline* sheet. Data on the baseline sheet are automatically linked to comparison charts and tables on the *River* and *Solar_Summary* sheets.

4.2. Input Data

The W3T workbook contains five worksheets with input data describing global reach, meteorological, topographical shade, riparian shade, and hydrodynamic characteristics of the reach. These worksheets and their contents are listed in Table 4. Guidance in collecting and estimating input data values may be found in a companion documents (Holmes *et al*. 2013, Basdekas and Deas 2013, Watercourse 2013).

Table 4. Input worksheets and contents.

Worksheet name	Contents
Parameters	Global parameters describing attributes applied to the entire reach including evaporation coefficients and topographic angles.
Reach	Reach-specific hydrodynamic parameters and shade.
Shade_input	Riparian vegetation scenarios used in specifying shade.
Inflow_Tw	Hourly records of water temperature. Any of these records may be associated with any inflow.
Met	Hourly meteorological record for the reach.

4.2.1. *Parameters* Worksheet

The global parameters describe conditions that are applied to the entire reach. These parameters are set in the *Parameters* worksheet and describe location on earth (time zone, longitude, latitude, elevation), topography (the angles subtended by topographic features in the west, south, and east directions), vegetation characteristics (width of the vegetation zones that define riparian shade, and height and density of emergent vegetation), and atmospheric variables (e.g., air pressure and evaporative coefficients) (Figure 6). A list of data required on the *Parameters* worksheet includes:

- Time
    - Time zone (limited to "East," "Central," "Mountain" or "Pacific")
- Sediments (currently not used by model)
    - Particle size (mm)
    - Embeddedness (%)
- Topo
    - Longitude
    - Latitude
    - Elevation (meters). Average elevation of stream.
    - Angles subtended by topography in the west, south, and east directions (degrees above horizontal)
- Vegetation
    - Width of the vegetation zones (meters)
    - Height of emergent vegetation (meters)
    - Density of emergent vegetation (%)
- Miscellaneous
    - Atmospheric pressure (mbar)
    - Evaporative coefficients "a" and "b".

Particle size and embeddedness are used in modeling heat interactions between the water and the bed. Streambed interactions can produce a significant moderating influence on water temperatures, noticeably dampening fluctuations in some river systems. Although planned for implementation in future versions, bed interaction is not currently modeled in this initial version of W3T. Atmospheric pressure is necessary for some formulations of the heat budget. In W3T, site elevation can be used to calculate atmospheric pressure, but it also is not used in the current calculation method. Note that the evaporative coefficients "a" and "b" control wind-driven evaporation rate and are often used to calibrate a water temperature model (Brown and Barnwell, 1987).

	A	B	C	D	E	F	G	H
1	Time							
2	theTimeZone	Pacific		("East," "Central," "Mountain" or "Pacific")				
3	Morphology							
4	Width	not used	m	widths assigned in "Reach" worksheet				
5	theParticleSize	62.5	mm	see Notes	(not currently used)			
6	theEmbeddedness	0		see Notes	(not currently used)			
7	Topo	from Ttools						
8	theLongitude	-122.8						
9	theLatitude	41.4						
10	theElevation	870	m					
11	theTopo_W	7.3	deg	angle subtended by topographic features to the west				
12	theTopo_S	2.9	deg	angle subtended by topographic features to the south				
13	theTopo_E	7.4	deg	angle subtenedd by topographic features to the east				
14	Vegetation							
15	VegZone width	15	m	width of the riparian vegetation zones defined in shade input file				
16	Emergent vegetation height	0	m	INACTIVE				
17	Emergent vegetation density	0	%	INACTIVE				
18								
19	Atmospheric variables							
20	Pressure_WC:	921.22	mbar	air pressure specified for Watercourse Pond model only (inactive)				
21	Evaporation coefficient, a	1.72E-09						
22	Evaporation coefficient, b	1.53E-09						

Figure 6. *Parameters* **worksheet.**

4.2.2. *Reach* Worksheet

Parameters that describe subreach hydrodynamic qualities are assigned in the *Reach* worksheet along with the type of riparian shade that is associated with each subreach (Figure 7). This page contains a mix of variables: some specified by the user, some calculated for use by the model, and some written by the model during execution. All variables that may be specified by the user are grouped at the top of the worksheet and, in keeping with the protocols of this workbook, are displayed in blue color. A list of these required data includes:

- Bottom width (ft),
- Side slope,
- Channel slope,
- Manning roughness, and
- Vegetation (shade scenario; as defined on "Shade_input" worksheet)[1].

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[1] Shade scenario is a text tag (e.g., "No shade" or "Forest" or "Residential") that matches one of the shade scenario tables specified on the *Shade_input* worksheet.

		Subreach												
1		1	2	3	4	5	6	7	8	9	10	11	Total	
2	Reach Parameters													
3	Bottom Width at start (ft)	50	50	50	50	50	50	50	50	80	---	---		
4	Side Slope, SS (H:V = SS:1)	3	3	3	3	3	3	3	3	3	---	---		
5	Channel Slope, S (no units)	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	---	---		
6	Manning Roughness, n	0.0380	0.0380	0.0380	0.0380	0.0380	0.0380	0.0380	0.0380	0.0380	---	---		
7	Riparian vegetation	Canyon	Forest E-W	Canyon	Canyon	Canyon	Canyon	Forest E-W	Forest E-W	Forest	---	---		
8														
9	Length (ft)	600	150	250	500	200	400	400	500	300	---	---		
10	Q_in (cfs)	40	60	50	70	60	80	100	80	70	---	---		
11														
12														
13	Wetted Perimeter, P at start (ft)	56.3	58.1	57.2	58.8	58.1	59.6	60.9	59.6	86.7	---	---		
14	Top Width (ft)	56.0	57.6	56.9	58.4	57.6	59.1	60.3	59.1	86.4	---	---		
15	Cross-sectional Area (ft^2)	53.2	68.6	61.2	75.7	68.6	82.4	95.0	82.4	88.4	---	---		
16	Hydraulic Radius, Rh = A/P at start(ft)	0.9	1.2	1.1	1.3	1.2	1.4	1.6	1.4	1.0	---	---		
17														
18	Depth (ft)	1.0	1.3	1.1	1.4	1.3	1.5	1.7	1.5	1.1	---	---		
19														
20	Velocity (ft/s)	0.8	0.9	0.8	0.9	0.9	1.0	1.1	1.0	0.8	---	---		
21	Q_manning (cfs)	40.0	60.0	50.0	70.0	60.0	80.0	100.0	80.0	70.0	---	---		
22														
23	Travel Time (sec)	797	172	306	541	229	412	380	515	379	---	---	3,730	sec
24	Travel Time (min)	13.3	2.9	5.1	9.0	3.8	6.9	6.3	8.6	6.3	---	---	62.2	min
25	Travel Time (hour)	0.2	0.0	0.1	0.2	0.1	0.1	0.1	0.1	0.1	---	---	1.0	hour
26	Travel Time (day)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	---	---	0.0	day
27														
28														
29	Length travelled (ft)	600	150	250	500	200	400	400	500	300	---	---	3,300	feet
30														
31	Reach surface area (ft2)	33,611	8,647	14,217	29,189	11,530	23,626	24,134	29,532	25,912	---	---	200,399	ft2
32														
33	Computational setup													
34	Computational sections	1	1	1	1	1	1	1	1	1	---	---		
35	Computational interval (min)	13	3	5	9	4	7	6	9	6	---	---		
36														
37		Note: cell values in green are protected.												

Figure 7. *Reach* **worksheet.**

4.2.3. *Shade_input* Worksheet

Defining shade scenarios is the most complicated step in setting up a representative model. Shade scenarios describe riparian vegetation surrounding any given subreach based on radial zones and directions (Figure 8). All vegetation zones have the same width, specified on the *Parameters* worksheet ("VegZone" width in Figure 6). In the model, each subreach may be assigned its own shade scenario and any number of shade scenarios may be defined on the *Shade_input* worksheet.

Figure 8. *Shade_input* **worksheet.**

The scenarios are described from the perspective of a single representative location (or, "node") on the subreach. Each shade scenario is defined by a table listing height, density and elevation of riparian vegetation in each of four zones radiating away from the stream in seven directional lines (NE, E, SE, S, SW, W, and NW). The model assumes that the sun is never in the due north direction. The path of the river is assumed to be straight along each subreach

and, in the direction of river flow both upstream and downstream, "open water" should be assigned. Depending upon the alignment of the stream, this opening in riparian vegetation can allow a significant amount of solar radiation to reach the water surface.

The shade scenario table is tied to the land cover characteristics table and schematic. Values for elevation are entered directly into the shade scenario table (blue font). Values for height, and density are established indirectly from the specified "type" (vegetation code) for each direction and zone. An example shade scenario table is shown in Figure 9. This shade scenario is named "Forest," which is one of the Vegetation types listed on the *Reach* worksheet (Figure 7).

Type codes are not entered directly into the shade scenario table. Instead, to provide a visual reference when defining land cover, they are read from a schematic view of the vegetation structure (Figure 11). A lookup table, depicted in Figure 10 (land cover characteristics), provides values for height and density given the landscape type code. Up to ten codes may be added to the current list to describe site-specific land cover.

To help visualize riparian vegetation, a schematic is provided below each shade scenario table. The schematic contains a land cover characteristic code for each zone in each direction. Each zone (1 through 4) is distinguished by color. In Figure 11a, the direction and zone numbers (e.g., W1) were placed in lieu of the land cover characteristic code for visual purposes only. For example, all of zone 1 is light green and closest to the center "node". When developing a shade scenario, the user must specify a land cover characteristic code in the land cover schematic. Land cover codes in the scenario table are linked to corresponding locations on the schematic. Through use of the lookup table, the codes establish height and density of riparian vegetation surrounding any subreach. An example land cover schematic is shown in Figure 11.

As an example of establishing vegetation height and density, suppose that land cover between 30 and 45 meters away from the stream in the NW direction is best described as "small mixed conifers." Because zone widths are 15 meters, this area defines Zone 3 (light purple in Figure 11). "Small mixed conifers" have a land cover code of "501." To designate land cover for this area, set the worksheet cell corresponding to Zone 3 in the NW direction in the schematic to "501." (These would be the cell labeled NW3 in Figure 11a.) Once set, this code automatically appears in the shade scenario table at the appropriate location under "Type" and produces a corresponding height of 15 meters and a density of 60 percent (based on the information in the land cover characteristic table).

A scenario is defined by its name as listed directly above the "Direction" header in the upper left corner of a scenario table. When processing a subreach, the model looks along the first row of the *Shade_input* worksheet for the name of the shade scenario specified for that subreach. Finding that name it reads the height, density and elevation for each zone in each direction from the table below it. The model also reads the length of riparian overhang in each direction from a small table below the main table.

Additional shade scenarios may be developed by the user. This is most easily done by copying the columns containing an existing scenario table and schematic and pasting this

information to the right of the last existing scenario. Changing the name of the scenario and the vegetation codes in the schematic creates a new scenario. No two scenarios should be given the same name.

Note: In constructing a new shade scenario it is only important to configure the input table correctly. The name must be in the top row of the worksheet, and height, density, elevation, and overhang must be listed in the same position relative to the name as shown in existing examples. The lookup table and the schematic are provided for ease-of-use and clarity, but the user could specify the land cover characteristic code directly in the shade scenario table (deleting the links to the land cover schematic).

Forest Direction	Zone	Type*	Height (m)	Density	Elevation (m)
NE	1	100	30	1	869
NE	2	500	25	0.6	869
NE	3	501	15	0.6	869
NE	4	550	25	0.3	869
E	1	100	30	1	869
E	2	500	25	0.6	869
E	3	501	15	0.6	869
E	4	550	25	0.3	869
SE	1	100	30	1	869
SE	2	500	25	0.6	869
SE	3	501	15	0.6	869
SE	4	550	25	0.3	869
S	1	301	0	0	869
S	2	301	0	0	871
S	3	301	0	0	871
S	4	301	0	0	872
SW	1	100	30	1	870
SW	2	500	25	0.6	871
SW	3	501	15	0.6	872
SW	4	550	25	0.3	872
W	1	100	30	1	870
W	2	500	25	0.6	870
W	3	501	15	0.6	871
W	4	550	25	0.3	871
NW	1	100	30	1	869
NW	2	500	25	0.6	869
NW	3	501	15	0.6	869
NW	4	550	25	0.3	869

Figure 9. Example shade scenario table.

Land Cover Characteristics			
Code	Height (m)	Density (%)	Land Cover Name (optional)
301	0	0	Water
302	0.5	0.75	Pasture/Cultivated Field/lawn
304	0	0	Barren - Rock/Gravel Bar
305	1	1	Barren Embankment
309	0	0	Barren - Soil
400	0	0	Road
500	25	0.6	L. Mixed Conifer/Deciduous
501	15	0.6	S. Mixed Conifer/Deciduous
550	25	0.3	L. Mixed Conifer/Deciduous
551	15	0.3	S. Mixed Conifer/Deciduous
555	25	0.1	L. Mixed Conifer/Deciduous
600	15	0.75	Large Deciduous
601	5	0.75	Small Deciduous
650	15	0.3	Large Deciduous
651	5	0.3	Small Deciduous
700	30	0.6	Large Conifer
701	20	0.6	Small Conifer
750	30	0.3	Large Conifer
751	20	0.3	Small Conifer
800	2	0.75	Small Bushes
801	2	0.75	Wetland Shrubs
850	2	0.25	Upland Shrubs
901	0.5	0.75	Upland Grasses
3011	0	0	Active Channel
3248	10	1	Residential Development
100	30	1	User_1

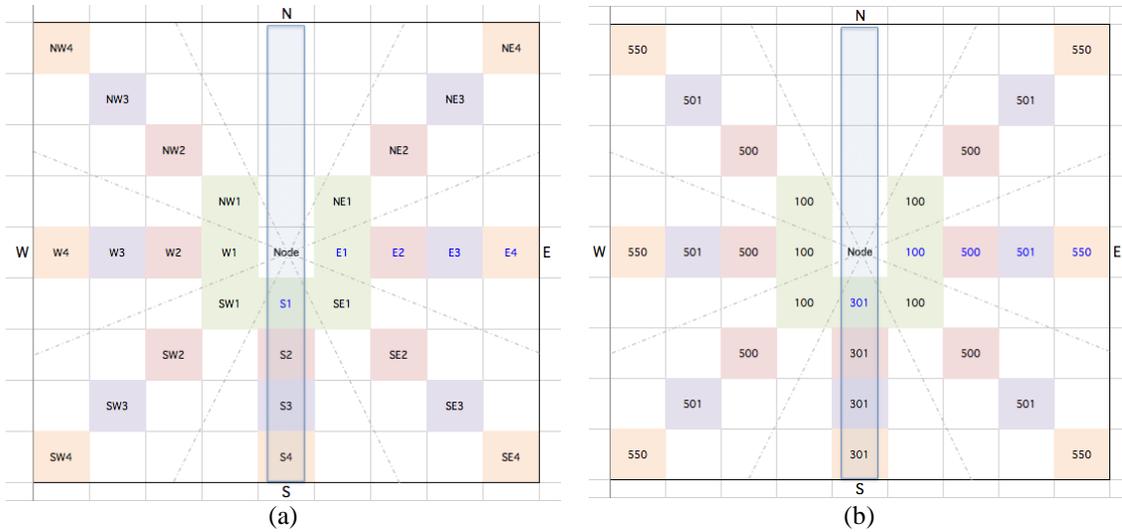**Figure 10. Example land cover characteristics table for shade scenarios.**

Figure 11. Land cover schematic showing a reach node for a N-S oriented stream and adjacent vegetation zones with (a) direction and zone code and (b) vegetation type and shade characteristic (land cover characteristics) codes.

4.2.4. *Inflow_Tw* Worksheet

The *Inflow Tw* worksheet contains water temperature records to be assigned to inflow. Each record is a time series of temperatures. The first column of the sheet lists date and time. Adjacent columns lists unique water temperature records with an identifying name in the first row (Figure 12). The name is used to assign a water temperature record to each inflow or tributary on the *Reach* worksheet.

As an example, consider the reach configuration in Figure 3. Inflow at the top of the reach is assigned the "Shasta ab Parks" water temperature time series. When run, the model will search the *Inflow_Tw* worksheet to find a time series with the "Shasta ab Parks" identifier (column C, Figure 12). Once it has found the matching identifier, it will associate the corresponding temperature record with the inflow.

	A	B	C	D	E	F	G
1	Date-time	Trinity@Hoopa	Shasta ab Parks	Trinity+2	Trinity+5	Constant_20	Constant_10
2	1/1/2010 0:00	6.56	6.611	8.56	11.56	20	10
3	1/1/2010 1:00	6.61	6.636	8.61	11.61	20	10
4	1/1/2010 2:00	6.61	6.763	8.61	11.61	20	10
5	1/1/2010 3:00	6.67	6.839	8.67	11.67	20	10
6	1/1/2010 4:00	6.67	6.914	8.67	11.67	20	10
7	1/1/2010 5:00	6.72	6.914	8.72	11.72	20	10
8	1/1/2010 6:00	6.72	6.965	8.72	11.72	20	10

Figure 12. *Inflow_Tw* worksheet.

There can be additional (unused) water temperature records on the *Inflow_Tw* worksheet, but every identifier used in the reach configuration table (*Reach* worksheet) must correspond to a time series on the *Inflow_Tw* worksheet. There can be up to fifteen temperature records listed in the worksheet and there can be no empty columns between "Date-time" and records that will be used in simulation.

4.2.5. *Met* Worksheet

There is only one meteorological record for the reach and that record is set up on the *Met* worksheet in a range of contiguous columns, similar in this respect to inflow water temperatures (Figure 13). In the first column of the meteorological record is a list of dates and times. The record must span the period of time simulated and the record must contain one entry for each of these variables for each hour of simulation. Adjacent columns contain data used in calculating shade and heat exchange. The following meteorological data is required by the model (in the order specified):

- Air temperature (degC),
- Water temperature (degC)
- Cloudiness (fraction),
- Wind speed (m/s),
- Relative humidity (%),
- Solar radiation (W/m^2), and
- Wet bulb temperature (degC).

	A	B	C	D	E	F	G	H
1	Date-time	Tair (oC)	Tw	Cloudiness	Wind (m/s)	RH (%)	Solar (W/m2)	Twet (oC)
2	1/1/2010 0:00	10.56	6.56	0.30	6.26	0.87	0.00	9.44
3	1/1/2010 1:00	10.56	6.61	0.30	4.02	0.90	0.00	9.70
4	1/1/2010 2:00	10.56	6.61	0.30	4.47	0.89	0.00	9.62
5	1/1/2010 3:00	9.44	6.67	0.30	0.89	0.97	0.00	9.19
6	1/1/2010 4:00	10.00	6.67	0.30	4.92	0.96	0.00	9.66
7	1/1/2010 5:00	10.00	6.72	0.30	6.26	0.92	0.00	9.33
8	1/1/2010 6:00	10.00	6.78	0.30	1.34	0.96	0.00	9.66
9	1/1/2010 7:00	10.56	6.83	0.30	4.47	0.94	0.00	10.05

Figure 13. *Met* **worksheet.**

Note: The simulation doesn't end until after the last parcel of water travels through the reach. Meteorological data must be supplied through the end of simulation as calculated by:
end_time (hours) = start_time + simulation length + reach_travel_time.

4.3. Output

The W3T model writes heat budget and solar radiation summary results for the reach, and detailed results for each subreach. As a result, there will be multiple *Results_#* and *Solar_Results_#* worksheets (where "#" refers to the subreach number).

4.3.1. *Summary* Worksheet

The *Summary* worksheet contains all of the data describing reach parameters and configuration along with all results used in comparison charts and tables. These data are organized in four sections:

- Reach description,
- Reach inflow and outflow water temperature,

- Solar radiation, and
- Subreach inflow and outflow water temperature.

The first columns of the worksheet are copied from the *Reach* interface worksheet and describe reach configuration and calculated characteristics such as top width, depth of flow, and travel time. A second section of the worksheet lists time and water temperature in and out of the reach along with calculated heat flux of water leaving the reach. A third section lists solar radiation above land and above stream for each reach. A final section lists inflow and outflow water temperature for each subreach and calculates minimum, mean and maximum values over the first 24-hour period. These data are used in graphically describing water temperature longitudinally along the reach.

4.3.2. *Solar_Summary* Worksheet

The *Solar_Summary* worksheet compiles solar radiation for each subreach at two locations along its path from the sun to the stream water surface as depicted in Figure A-1. Following Shade-a-lator terminology, the locations are defined as "Above Land Cover" and "Above Stream" and represent, respectively, solar radiation just above all land cover and solar radiation just above the stream after riparian vegetation, bank shade, and emergent vegetation have been accounted for. Values are compiled for each hour of the simulation for each subreach and provide an indication of the effectiveness of shade features by graphically showing the reduction in solar radiation due to shading. For comparison, "Above Stream" solar radiation from baseline conditions is also listed for each subreach. Small graphs above the data provide a comparison of "Above Land Cover," "Above Stream," and baseline "Above Land Cover" solar radiation for each reach over a day's time. An example graph is shown in Figure 14.
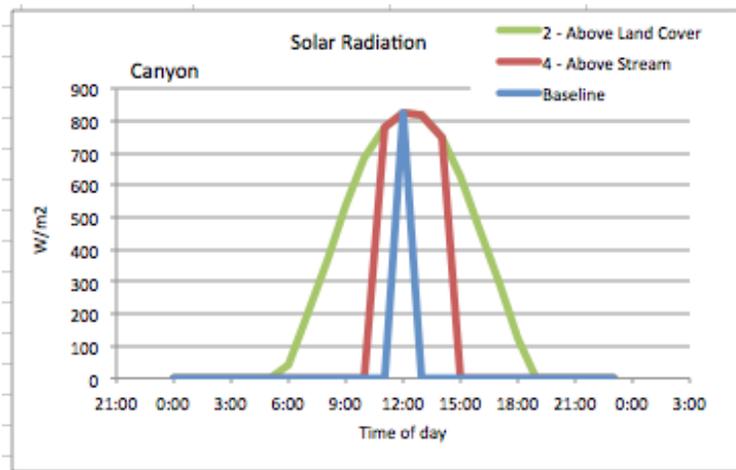

Figure 14. **Example graph showing solar energy summary for a subreach.**

4.3.3. *Results_#* Worksheets

The *Results_#* sheets contain time and water temperature into and out of the subreach, and average heat flux terms (solar, longwave, evaporative, and conductive radiation) for each time step of the simulation. There is one worksheet for each subreach.

4.3.4. *Solar_Results_#* Worksheets

The *Solar_Results_#* sheets contain the results of shade modeling for each time step of simulation and include time, sun direction and altitude, estimated "view to sky," and both direct and diffuse solar radiation at each of seven steps along light's path from the atmosphere to its reflection from the reach bed. There is one worksheet for each subreach.

4.3.5. *Baseline* Worksheet

The W3T maintains a *Baseline* worksheet that holds all the data of a *Summary* worksheet. This *Baseline* worksheet is a copy of the *Summary* worksheet and is updated with summary information for the current run when you press the "Save as Baseline" button on the *Reach* worksheet. Data from this worksheet are used in comparison graphs and tables.

4.4. General Information

Currently, there are two informational sheets in the W3T workbook: *Notes* and *Versions*. The *Notes* worksheet contains unit conversions, constant values, and miscellaneous information on parameter selection. The *Versions* worksheet provides a history of model versions and release dates.

5. Next Steps

W3T is envisioned as an evolving tool and should undergo continued development as new information becomes available. New features and elements currently under consideration include:

- Distributed inflow representing groundwater or surface water along the length of a sub-reach,

- Tabulated cross section data to replace the basic trapezoidal channel form with actual channel morphology, and

- Incorporate bed conduction into the heat budget of the stream.

These, as well as other attributes, can be incorporated in future versions of the model.

6. Citations

Basdekas, P, and M.L. Deas. 2013. *Example application of W3T to Prickly Pear Creek flow transaction to assess potential water temperature implications*. Memorandum prepared for R. Holmes. September 19. 17 pp.

Boyd, M., and Kasper, B. 2003. *Analytical methods for dynamic open channel heat and mass transfer: Methodology for heat source model Version 7.0*.

Brown, L.C. and Barnwell, T.O. 1987. *The Enhanced Stream Water Quality Model QUAL2E and QUAL2E UNCAS: Documentation and Users Manual*. Environmental Research Laboratory, Environmental Protection Agency, Athens, GA Report EPA/600/3-87/007.

Holmes, S.R., Willis, A.D., Nichols, A.L., Jeffres, C.A. Deas, M.L., Purkey, A. 2013. *Water Transaction Monitoring Protocols: Gathering information to assess the effects of instream flow transactions*. Prepared for the National Fish and Wildlife Foundation. July, 2013. 55 pp.

Martin, J.L. and S.C. McCutcheon. 1999. *Hydrodynamics and Transport for Water Quality Modeling*. Lewis Publishers. New York. 794 pp.

Watercourse Engineering, Inc. (Watercourse). 2013. *An Example Application of W3T: Rudio Creek*. September 19. 22 pp.

Appendices

Appendix A. Model Formulation

The W3T currently consists of a flow module and a temperature module. Other water quality modules are envisioned for future development. The flow module calculates flow characteristics such as depth, cross-sectional area, velocity, and travel time. The temperature module is comprised of units estimating solar radiation and heat budget. The solar radiation unit calculates direct solar radiation based on solar flux routines in Oregon DEQ's Heat Source Model version 7. This is the latest version for which documentation and code were available. Heat budget calculations are based on standard formulations for calculating longwave, evaporative, and conductive heat flux. Currently, the W3T uses the heat budget as implemented in Heat Source. A heat budget option similar to the QUAL2E heat budget is also available, but is not implemented in the model. The HeatSource and QUAL2E heat budgets have both been run in W3T and have been found to yield similar results.

A.1. Flow Module

Flow characteristics in W3T are calculated assuming steady flow using the Manning's Equation substituted into the continuity equation. This formula describes flow, Q, as a function of channel hydraulic radius and slope:

$$Q = \frac{C_0}{n} A_c R^{2/3} S_e^{1/2} \qquad (\text{L}^3/\text{T})$$

where,

        C_0 = a constant depending upon units
        n = Manning's roughness coefficient
        R = channel's hydraulic radius = A_c/P
        A_c = channel's cross-sectional area = f(depth, width)
        P = wetted perimeter = f(depth, width)
        S_e = channel slope

Flow, Q, is determined for each subreach by mass balance as the sum of instream flow, Q_s, and net tributary flow, where net tributary flow is the difference between tributary flow, Q_t, and diversion flow, Q_d, at the upstream boundary.

$$Q = Q_s + (Q_t - Q_d) \qquad (\text{L}^3/\text{T})$$

Given flow, Manning's equation and values for Manning's roughness coefficient, bottom width and side slope, W3T determines flow depth for each subreach by iteration using Microsoft Excel's Goal Seek feature. Channel flow characteristics such as top width, cross-sectional area, velocity and travel time result from the determination of depth.

A.2. Temperature Module

The temperature module of W3T establishes incident solar radiation, performs a heat budget, and calculates resultant changes in water temperature. Solar radiation incident on

a stream's surface is a function of atmospheric solar radiation and shade features such as topography and vegetation. Solar radiation is calculated using methods and algorithms from Heat Source 7.

Shade features such as topography and riparian vegetation attenuate or block solar radiation depending upon their height and density. Using the methods and algorithms of Heat Source and Shade-a-lator, W3T calculates solar radiation at four levels above the stream and estimates the heat penetrating the stream surface. At each calculation step, W3T determines the location of the sun and calculates the following fluxes:

1. Solar Radiation Heat above Topographic Features.

2. Solar Radiation Heat below Topographic Features.

3. Solar Radiation Heat below Land Cover.

4. Solar Radiation Heat above Stream Surface.

5. Solar Radiation Heat Penetrating the Stream Surface.

A schematic showing the location of these calculations is given in Figure A-1. Details of these calculations are given in the Heat Source Model Version 7.0 manual (Boyd and Casper, 2003).
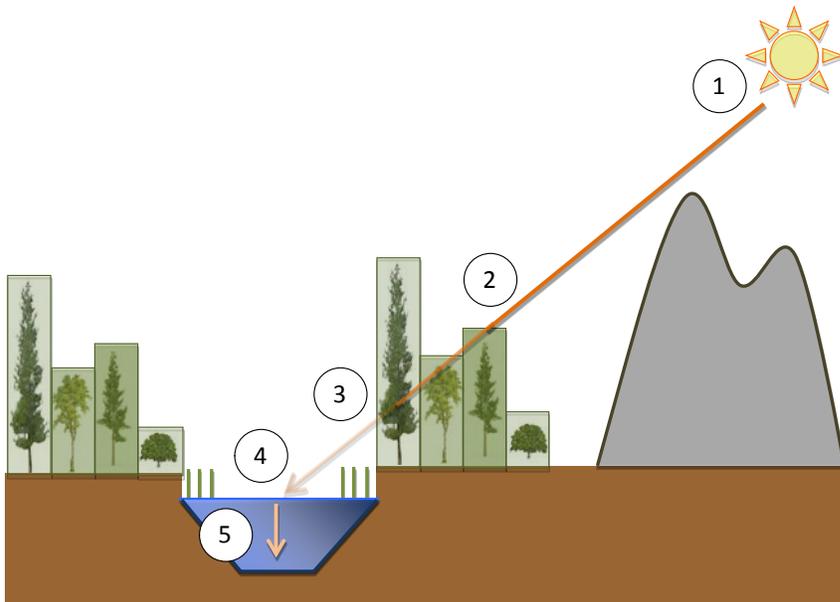

Figure A-1. Shade calculation schematic.

Direct solar radiation that penetrates the stream surface is used in W3T heat budget calculations. In addition to solar (shortwave) radiation, a heat balance includes terms describing heat exchange with the atmosphere. The net rate of thermal energy exchange at the air-water interface can be represented as the sum of heat fluxes, as given by Martin and McCutcheon (1999):

$$H_{net} = H_{sn} + H_{at} - (H_{ws} + H_h + H_e) \qquad (E/L^2T)$$

where:

H_{net} = net heat flux

H_{sn} = net short wave (solar) radiation flux,

H_{at} = net atmospheric longwave radiation flux,

H_{ws} = net water surface longwave radiation flux,

H_h = sensible (conductive) heat flux, and

H_e = evaporative (latent) heat flux.

W3T is capable of using sets of equations from either Heat Source or QUAL2E to estimate these heat fluxes. Both sets are similar and produce similar results. Currently, the W3T uses equations from Heat Source.

W3T calculates water temperature in Lagrangian space. That is, the model follows parcels of water as they travel through the reach, calculating change in water temperature over a discreet time. Because spatial temperature gradients are generally slight in the stream systems that W3T is designed to analyze, diffusion is neglected. In Lagrangian space with diffusion neglected, the change in temperature for any parcel of water over a discreet time is a function of net heat flux, H_{net}, surface area, A_s, and volume, V, and is given by:

$$\frac{\Delta T_w}{\Delta t} = S = \frac{H_{net} A_s}{C_p \rho V} \qquad (\theta/T)$$

where:

T_w	:	water temperature (θ)
Δt	:	computational time step (T)
S	:	heat sources and sinks (θ/T)
H_{net}	:	net heat flux (E/L^2)
A_s	:	area of water body surface (L^2)
C_p	:	specific heat of water at 15°C (4185.5 Jkg^{-1}°C^{-1} where 1 J = 1 W-s)
ρ	:	calculated density of water (M/L^3)
V	:	volume of water body (L^3)

At the top of each subreach, initial water temperature, T_i, is determined from conservation of energy:

$$T_i = (Q_{up} \cdot T_{up} + Q_{trib} \cdot T_{trib})/Q_T$$

where:

Q_{up} :   flow just above subreach (L^3/T)

T_{up} :   water temperature just above subreach (θ)

Q_{trib} :   net tributary inflow (L^3/T)

T_{trib} :   tributary water temperature (θ)

Q_T : $= Q_{up} + Q_{trib}$; total flow at top of subreach (L^3/T)