Specification for Thermal Loading Estimator

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Contents

[Context 1](#_Toc52032206)

[Stream flow and stream temperature 2](#_Toc52032207)

[Water parcels 2](#_Toc52032208)

[Daily water mass and energy balance 3](#_Toc52032209)

[Estimating the rate of flow in a stream reach 4](#_Toc52032210)

[Water temperature from thermal energy 5](#_Toc52032211)

[Initial conditions for Flow: the IC file 5](#_Toc52032212)

[Boundary conditions for stream water temperature 5](#_Toc52032213)

[Thermal stratification in reservoirs is not represented 6](#_Toc52032214)

[Thermal loading 6](#_Toc52032215)

[Data Requirements 7](#_Toc52032216)

[A new GIS data layer for stream segments 7](#_Toc52032217)

[Attibutes of the new stream segment layer 8](#_Toc52032218)

[USGS data 8](#_Toc52032219)

[Insolation 9](#_Toc52032220)

[Longwave Radiation 10](#_Toc52032221)

[Evaporation and Precipitation 10](#_Toc52032222)

[Performance Testing 11](#_Toc52032223)

[References 11](#_Toc52032224)

# Context

This document is a deliverable for the McKenzie wetlands research project. The project itself is funded by the U.S. Environmental Protection Agency through a grant to the Lane Council of Governments (LCOG) in Eugene, Oregon. LCOG contracted some of the work to Land Craft Design and Consultation LLC. This document is a product of Oregon Freshwater Simulations, a subcontractor to Land Craft.

This document is called for in the “Scope of Work & Schedule” appendix to the contract between Oregon Freshwater and Land Craft. The requirement is Deliverable (1) in Task 1:

“This deliverable consists of model specifications, including input dataset specifications, output data, and any necessary data configuration, for two module components to incorporate into the CW3M Modeling Framework:

1. A thermal loading estimator for waterbodies and wetlands. Model performance specification is to match Oregon DEQ HeatSource/Shade-a-lator model output for identical data inputs describing a lower reach of the McKenzie River.
2. ...”

CW3M refers to the Community Willamette Whole Watershed Model. CW3M will be used in this project to simulate the McKenzie River basin; the McKenzie is a tributary of the Willamette River, with its headwaters in the Cascade Mountains east of Eugene. Simulations using actual weather data for the decade of the 2010s will be used to calibrate the model and assess its skill, and simulations using future climate data from general circulation models will be run for the period from the present through 2060.

The source code and data for CW3M are held in a Subversion repository on GitHub, and, due to the 100MB file size limitation on GitHub, in a Box account belonging to Oregon Freshwater for a few of the largest files. Most of the source code changes and additions necessary to implement the thermal loading estimator affect the Flow Visual Studios (VS) project within the CW3M VS solution. The “Stream flow and stream temperature” section below is adapted from version 41 of the CW3MdigitalHandbook.docx file in the repository at trunk\DataCW3M\CW3MdigitalHandbook. Some of the language of that section is descriptive rather than prescriptive, but at the time it was first added to the Digital Handbook document, it was aspirational; at that time the WaterParcel class was not yet operational in CW3M. The WaterParcel class has now been fleshed out and made operational as part of Freshwater’s work on the McKenzie wetlands project.

# Stream flow and stream temperature

## Water parcels

Water flows continuously. Digital computers use discrete quantities to represent, approximately, the continuous elements and properties of the real world. CW3M accounts for the water on a landscape as “parcels”, represented in the C++ code as objects of the class WaterParcel. The properties of a water parcel, represented in C++ as members of the WaterParcel class, are

volume, expressed in units of cubic meters

thermal energy, expressed in units of kilojoules, relative to 0 for liquid water at 0 deg C

The volume property is used as a surrogate for mass, at a constant density of 998.2 kg per cubic meter. This approximation reflects the fact that observational data for water in streams and water bodies is always in units of volume, and the convenient reality that the density of liquid water is relatively constant over the range of conditions encountered in natural environments. In the future, the WaterParcel class could be extended to include other properties, such as sediment load and dissolved pollutants.

In CW3M, spatial units have water parcels associated with them. Each subreach in the stream network has a parcel of water in it, whose properties change from one daily timestep to the next. The total volume of a reach is the sum of the subreach volumes, and the total thermal energy is the sum of the subreach thermal energies. Landscape polygons (“IDUs”) and bodies of water also have associated water parcels. While reaches may be of any length, subreaches are never longer than a parameterized value (*subnode\_length* in <streams> in Flow\_McKenzie.xml), currently set at 1000 meters. Reaches of length less than *subnode\_length* consist of a single subreach. Reaches longer than *subnode\_length* are divided into the smallest number of equal-length subreaches such that the subreaches are no longer than *subnode\_length*.

## Daily water mass and energy balance

Thermal energy algorithms will be added to CW3M as part of the McKenzie wetlands study. Inspiration and technical information for the thermal energy code is from the 204-page manual for Heat Source Model Version 7.0, prepared by Matthew Boyd and Brian Kasper in 2003 and 2007 for the Oregon Department of Environmental Quality (Boyd & Kasper 2003).

CW3M estimates the properties of water parcels at a daily timestep. The basic equation for daily subreach volume is straightforward

Vt = Vt-1 + Vup + Vlateral - Vdown - Vevap + Vprcp

where (all quantities in m3)

Vt = volume in day t

Vt-1 = volume in the previous day

Vup = volume flowing in from upstream

Vlateral = volume entering (+) or leaving (-) the subreach through the stream banks or streambed, or from withdrawals for irrigation or municipal use, or discharges from municipal points of central discharge

Vdown = volume flowing out to downstream

Vevap = volume lost to evaporation

Vprcp = volume gained from precipitation falling on the water surface

The equation for subreach thermal energy has additional terms

Et = Et-1 + Eup + Elateral – Edown + ESW – ELW - Eevap + Eprcp

where (all quantities in kJ)

Et = thermal energy in day t

Et-1 = thermal energy in the previous day

Eup = thermal energy in the water flowing in from upstream

Elateral = thermal energy entering or leaving in water from stream banks, withdrawals for irrigation or municipal use, groundwater exchange, etc.

Edown = thermal energy leaving in water flowing out of the reach

ESW = incoming shortwave solar radiation

ELW = outgoing longwave radiation

Eevap = energy carried away from the reach through evaporation

Eprcp = energy entering via precipitation

There are corresponding equations with somewhat different terms for landscape polygons and bodies of water. The equations attempt to account for first order effects; they neglect effects which are usually (but not always) of lesser magnitude: the conversion of mechanical energy to thermal energy, convective heat exchange with the air and the streambed, and so on.

Thermal energy density (i.e. temperature) affects the rate of evaporation and the outgoing longwave radiation. As a result, the mass and energy balance calculations are interrelated; the estimate of thermal energy is made in the same subroutine which calculates the flow in the reach, so that the flow to downstream can be corrected for the loss of water to the atmosphere by evaporation. Precipitation on the surface of the stream also affects volume and thermal energy. The amount of evaporation lost and the amount of precipitation received are proportional to the surface area of the stream reach or water body.

Note in connection with evaporation from stream reaches that the model tiles the land surface with IDU polygons, and treats the stream network as a set of lines with no area of their own. Water bodies – reservoirs and lakes – are represented in the IDU layer. This makes it difficult to track precipitation which falls on stream reaches, because that precipitation has already been accounted for in the amount simulated as falling on the IDUs that the reach traverses. In effect, Vprcp is included in Vlateral. Eprcp contributes to Elateral, but an error is introduced inasmuch as the thermal energy of precipitation falling directly on the stream water surface is more closely correlated to the temperature of the air than to the temperature of the soil.

## Estimating the rate of flow in a stream reach

CW3M uses a kinematic wave algorithm to estimate the average daily flow rate in each subreach and reach. Each reach is represented as an ordered set of equal length subreaches. As described previously, the maximum subreach length is specified in the Flow XML file. The kinematic wave algorithm is used to estimate the average daily outflow from each subreach. The daily flow rate for the reach is taken as the average daily flow rate of the most downstream subreach of the reach.

The daily outflow from a subreach is a function of the length and average slope, the amount of water in the reach, yesterday’s outflow, today’s inflow from upstream, and today’s inflow from the seepage into the stream from the banks of the stream (a.k.a. lateral flow). The subreach slope, the parameters *n* and *wd\_ratio*, and yesterday’s outflow are used to calculate the width and depth of the channel, with the assumption that the channel is rectangular and that its width-to-depth ratio is parameterized, with a default value of 10. The parameter, *wd\_ratio*, is an optional field in the <streams> block of the Flow XML file. Addition of the WIDTH\_BASE and BANK\_HT\_L/R attributes in a new stream segment data layer to facilitate estimation of surface areas, discussed later, may allow for a more sophisticated estimate of the channel shape and size as a function of flow rate.

The kinematic wave algorithm itself is parameterized with a value for *n* = 0.3. As implemented, the algorithm makes the rate of flow out of a subreach more immediately responsive to the inflow from upstream than to the lateral flow. In the original WW2100 implementation, this characteristic led to unrealistic accumulation of water in headwater reaches, since by definition there is no inflow from upstream into the upstream end of a headwater reach. A workaround was later adopted to compensate for this malfunction, in the form of logic which treats any volume in a subreach in excess of the sum of the current day’s actual inflow from upstream and the current day’s lateral flow as if it were part of the current day’s inflow from upstream.

## Water temperature from thermal energy

The amount of thermal energy in the water in a reach or reservoir, referenced to zero energy for liquid water at the freezing point of water, is estimated and tracked within CW3M’s Flow model. The average temperature of the water in a reach can then be calculated for output purposes from the thermal energy per unit volume

temperature = thermal energy / (volume \* water density \* specific heat of water)

where

temperature = average temperature of the water in the reach (degC)

thermal energy = the thermal energy of the water in the reach, rel. to the freezing pt. (kJ)

volume = volume of water (m3)

water density = 998.2 kg/m3

specific heat of water = 4.187 kJ/(kg degC)

## Initial conditions for Flow: the IC file

The Flow model has the ability to read initial values for the water in the stream network from an IC file. The name and location of the IC file are specified in the *initial\_conditions* field of the <flow\_model> block of the Flow XML file. The Flow XML file itself is specified in the ENVX file. When the IC file is not specified or cannot be accessed, Flow initializes with nominal water amounts and flows; customarily, a 10-year simulation from that point is used for spinup. On completion of every simulation run, CW3M saves a new IC file with the values from the end of the run, to the user’s Documents folder. The name of the newly saved file is suffixed with “.ic<year>” (e.g. “.ic2006”), where “year” is the calendar year following the final year of the simulation run. The IC files will be extended to include thermal energies.

## Boundary conditions for stream water temperature

Water enters stream reaches from upstream, from lateral flow, and from precipitation falling on the surface of the stream water. As of 9/10/20, two symbols are used in the source code to parameterize the temperature of water entering the streams:

#define DEFAULT\_SOIL\_H2O\_TEMP\_DEGC 5.

#define DEFAULT\_REACH\_H2O\_TEMP\_DEGC 10.

The soil temperature parameter value is used for water entering through the stream banks in the HBV submodel. The reach water temperature is used when initializing flow data in the absence of an IC file and, currently as of 9/24/20, for the discharge from reservoirs.

Further elaboration of water temperature boundary conditions is necessary. Water returns to stream reaches from municipal water systems at points of central discharge, but there are no points of central discharge on the McKenzie at present. Municipal discharge water is typically warmer than stream water, and its temperature may vary seasonally. The temperature of the water reaching the streams via the stream banks also varies seasonally (e.g. cold streams in spring from snow melt). A 2019 article by Leach and Moore in Water Resources Research provides some clues and further references for improving the representation of the temperature of water entering via the stream banks.

## Thermal stratification in reservoirs is not represented

For the purpose of simulating water temperature, reservoirs will be represented as water bodies characterized by a single uniform temperature. Discharges will be at that temperature. This is a necessary but unfortunate oversimplification, because in reality temperature is a function of depth during the summer, and the Army Corps of Engineers can manage downstream water temperatures to some extent by choosing how much water to release from outlets at different depths. This approach to modeling the reservoir water temperature is necessary due to the lack of adequately simple algorithms for simulating thermal stratification and lack of algorithms for simulating USACE’s daily operating decisions about how much water to release from outlets at different depths.

## Thermal loading

A thermal loading algorithm will be implemented in CW3M as part of the McKenzie wetlands study. To the extent that it is practical, we will replicate the methods used in the Shade-a-lator model, part of the Heat Source model.

For CW3M, the relevant output of Shade-a-lator is the thermal load in kcal/day of insolation on specific stream segments (1 kcal = 4.184 kJ). Shade-a-lator calculates the kcal/day figure for each “node” along a stream; nodes are typically 25 meters apart. A single node is characterized by elevation, aspect, stream width, right and left bank vegetation height and density, and topographic shading.

CW3M divides streams up into reaches from the National Hydrography Dataset (NHD), and subdivides the reaches into subreaches. Within a reach, CW3M’s subreaches are of equal length and no longer than 1000 meters. NHD’s reaches are represented by a series of points; conceptually, the stream flows from point to point. Importantly, the points are not equally spaced and are not collinear. Some reaches are curved, and are represented by relatively many closely-spaced points. Other reaches are straighter, and are represented by fewer points spaced farther apart.

CW3M represents the McKenzie system with 1,047 reaches of average length 1,781 meters. The longest reach is 9,010 meters; the shortest is just 6 meters. The Reach\_McKenzie.shp file which stores the points which define the reaches is 6,361,228 bytes long, an average of 6,076 bytes per reach. Even if each point required as many as 100 bytes of storage, that would be an average of 61 points per reach and a total of 63 thousand points, representing more than 60 thousand straight stream segments averaging about 30 meters in length. Double precision floating point numbers require 8 bytes of storage, so 3 coordinates, if stored as double precision floating point numbers, would require only 24 bytes. So it is likely that each point takes up much less than 100 bytes, and that hence there are many more than 63 thousand points altogether, with an average distance between them of much less than 30 meters.

Short, straight stream segments correspond to the nodes used in Shade-a-lator, as they can be characterized by single values for elevation, aspect, stream width, and vegetation characteristics. Elevation and aspect can be calculated from the 3D coordinates of the points themselves. Other values, e.g. vegetation characteristics, are available from the IDUs within which the stream segments are situated. Since there are only 16,883 IDUs, the values derived from the IDUs would necessarily apply, on average, to about 4 contiguous stream segments. On sharply curved reaches with closely spaced points, the same IDU-derived values would apply to many such contiguous segments.

# Data Requirements

## A new GIS data layer for stream segments

In order to reproduce the Shade-a-lator results as much as is practical, the CW3M thermal loading code will require a new GIS data layer, similar to the reach layer but more detailed spatially. Since the terms “subreach” and “subnode” have already been used in the CW3M code base to refer to the equal length pieces of each reach used in the flow calculations, we’ll call this new layer the “stream segment” layer. Its characteristics are:

* segments are subdivisions of reaches
* segments are straight and defined by just 2 points, the endpoints, which are themselves points from the reach of which the segment is a part
* segments are not less than 25 meters in length, except when the reach itself is less than 25 m long
* segment attributes include midpoint elevation, aspect, slope, and topographic shading, all derived from the reach file and digital elevation map
* each of the two stream banks for each segment is associated with an IDU, which may be the same IDU for both banks; since segments may cross more than one IDU, a rule will have to be devised to pick the IDU most characteristic of the stream bank, when there is more than one
* additional segment attributes are derived from the IDUs which the segment traverses, and include vegetation type, height, and density or some other characterization of vegetative shading
* additional attributes may be necessary to satisfy the data requirements of the Shade-a-lator algorithms (e.g. to calculate bank shading), for example channel width under baseflow conditions and bank heights

The stream segment layer will consist of simple straight line segments, generally at least 25 meters in length, defined by points already present in the reach layer. Reaches will decompose into one or more contiguous segments. Segments would be in a many-to-one relationship with reaches. Segments would be the unit of computation for the “Shade-a-lator” thermal loading calculations.

Some of the data needed for the thermal loading calculations will be constant and can be precalculated offline, for example topographic shading characteristics. Other data may change seasonally (vegetation density) or interannually (tree height). Insolation is also dependent on the season and the weather. Accordingly, the thermal loading calculation will be added to the daily calculation of stream flow for each reach.

## Attibutes of the new stream segment layer

Unless otherwise noted, the attribute values are constants which can be calculated offline ahead of time and loaded into the initial state of the data layer. “Left” and “right” are as looking downstream.

ABSORB\_FRC – daily average fraction of shortwave radiation incident on the water surface which is absorbed by the water, calculated daily

ASPECT – aspect category as in Shade-a-lator, an integer from 1 to 7 inclusive

BANK\_HT\_L and BANK\_HT\_R – left and right bank heights, meters

COMID – comid of the reach to which the segment belongs

ELEV\_MIDPT – elevation of the midpoint of the segment, in meters above sea level

EVAP\_RATE – evaporation rate, mm H2O/day, calculated daily

IDU\_LEFT and IDU\_RIGHT – IDU\_ID attribute of the IDUs which characterize the banks of the segment. Vegetation type, height, and density will be inferred from attributes of the IDUs.

LENGTH – segment length in meters

RAD\_LW\_NET – daily average net longwave radiation from the water back to the atmosphere, W/m2, calculated daily

RAD\_SW – daily average unshaded shortwave radiation, W/m2, from climate data

SHADE\_FRAC – fraction of daily shortwave radiation which does not reach the water surface due to topographic shading, vegetative shading, and bank shading, calculated daily

SLOPE\_DEG – slope in degrees from horizontal, comparable to the IDU SLOPE\_DEG attribute

SURF\_AREA – water surface area, m2, calculated daily

T\_SHADE\_E, T\_SHADE\_S, and T\_SHADE\_W – topographic shade angles to the east, south, and west

WIDTH\_BASE – channel width, meters, under baseflow conditions

## USGS data

The USGS operates a number of stream gages in the McKenzie River basin. Flow and temperature data from these gages from 2000 through 2019 will be useful for calibrating CW3M for the McKenzie and for assessing its skill at reproducing observations when running hindcasts. The list of USGS sites below was generated by browsing the waterdata.usgs.gov/nwis/ website on 9/25/20. Data from a number of the gages in this list has been used in earlier projects to calibrate and assess the skill of the Willamette basin model. Numbers beginning with 14 are USGS site numbers; numbers beginning with 2377 are the COMIDs of associated stream reaches. Actual applicability of the data from these sites will depend on the dates for which the data is available.

flow temp 14158500 23773373 MCKENZIE RIVER AT OUTLET OF CLEAR LAKE, OR

flow temp 14158790 23773393 SMITH RIVER ABV SMITH R RESV NR BELKNAP SPRNGS

flow temp 14158798 ????????? SMITH RIVER ABV TRAIL BRDG RESV NR BELKNAP SPRINGS

flow temp 14158850 23773359 MCKENZIE R BLW TRAIL BR DAM NR BELKNAP SPRINGS

flow temp 14159110 ????????? MCKENZIE RIVER ABOVE SOUTH FORK, NEAR RAINBOW, OR

flow temp 14159200 23773037 SO FK MCKENZIE RIVER ABV COUGAR LAKE NR RAINBOW

ac-ft 14159400 ????????? COUGAR LAKE NEAR RAINBOW, OR

flow temp 14159500 23773009 SOUTH FORK MCKENZIE RIVER NEAR RAINBOW

gage ht. 14159410 ????????? COUGAR DAM TAILWATER NEAR RAINBOW, OR

flow temp 14161100 ????????? BLUE RIVER BELOW TIDBITS CREEK, NR BLUE RIVER, OR

flow temp 14161500 23773411 LOOKOUT CREEK NEAR BLUE RIVER

ac-ft 14162100 ????????? BLUE RIVER LAKE NEAR BLUE RIVER, OR

flow temp 14162200 23773405 BLUE RIVER AT BLUE RIVER

flow temp 14162500 23772909 MCKENZIE RIVER NEAR VIDA

flow temp 14163150 ????????? MCKENZIE RIVER BLW LEABURG DAM, NR LEABURG, OR

flow temp 14163900 ????????? MCKENZIE RIVER NEAR WALTERVILLE

flow temp 14164550 ????????? CAMP CRK AT CAMP CRK RD BRIDGE, NR SPRINGFIELD, OR

flow temp 14164700 23774369 CEDAR CREEK AT SPRINGFIELD

flow temp 14164900 23772751 MCKENZIE RIVER ABV HAYDEN BR, AT SPRINGFIELD, OR

flow 14165000 23773513 MOHAWK RIVER NEAR SPRINGFIELD

In order for CW3M to ingest the observation data, it has to be in a certain format. Each file can contain daily data for only a single variable (i.e. flow in cfs or temperature in degC, but not both in the same file) for every day between two dates (e. g. 1/1/2000 through 12/31/2019). Intervals other than 1/1/2000-12/31/2019 are acceptable, but only the portion starting in 2000 or later will be useful for this project.

Data files should be in CSV format, i.e. “comma-separated values” text data. If the first line starts with a semi-colon, it is treated as a comment. The first line should be used to identify the data and its provenance. The second line is interpreted as column names. The first column is called “day\_index”. The second column name identifies the type of data, e.g. “Q\_cfs”. The third, fourth, and fifth column names are “year”, “month”, and “day”. Starting with the third line, each line has 5 numbers, delimited by commas, and represents the value of the variable on a single day. The calendar date for that day is held in the third, fourth, and fifth columns. The value is in the second column. The first column holds the number of days since January 1, 1900; the day\_index for 1/1/1900 is 0, the day\_index for 1/2/1900 is 1, and so on. The data should appear in order of increasing date, and there shouldn’t be any missing dates. Data files for USGS gage data in this format are in the CW3M repository at trunk/DataCW3M/Observations/includingLeapDays.

An optional but desirable sixth column in the CSV data files could contain a data quality indicator, for distinguishing between measured values and values estimated in order to fill gaps in the measurement record.

# Insolation

More sunlight reaches the stream surface on sunny days than on cloudy or rainy days. The climate data files include a daily shortwave radiation number in W/m2. Algorithms from Shade-a-lator will be used to adjust the daily shortwave estimate from the climate data to take into account shading and convert it to a term in kJ for the amount of thermal energy added to the water in the stream segment each day by sunlight.

ESW = RAD\_SW \* (1 – SHADE\_FRAC) \* ABSORB\_FRC

where

SHADE\_FRAC is calculated using the methods in Sections 2.2.1 through 2.2.6 of Section 2.2 “Solar Radiation” in the Boyd and Kasper HeatSource documentation (pages 29-45, equations 2-2 through 2-46).

ABSORB\_FRC is the net fraction of the shortwave radiation energy reaching the water surface which is absorbed as thermal energy by the water, calculated by the methods in Sections 2.2.7 and 2.2.8 in the Boyd & Kasper documentation (pages 46-50, equations 2-47 through 2-72).

# Longwave Radiation

Streams and water bodies radiate energy back to the atmosphere day and night as longwave radiation. The amount of energy lost depends on stream temperature and stream depth and width. Streams also receive energy as longwave radiation from the sky, terrain, and vegetation above the water surface. Section 2.2 “Longwave (Thermal) Radiation” on page 51 of the Boyd & Kasper HeatSource documentation has equations which we will use for calculating the net longwave radiation into the stream in W/m2, as a function of air temperature, water temperature, humidity, cloudiness, and atmospheric emissivity. Cloudiness and atmospheric emissivity will be estimated from the daily weather stream and other data, by some method which remains to be determined.

ELW = RAD\_LW\_NET \* SURF\_AREA \* 86,400 seconds/day \* 0.001 kJ/W-sec

# Evaporation and Precipitation

Streams and water bodies lose both water and energy through evaporation. Evaporative losses depend on the weather and on the surface water temperature. The “Combination Method (Penman)” from page 61 of the Boyd & Kasper HeatSource documentation will be used to calculate the daily evaporation rate.

Vevap = SURF\_AREA \* EVAP\_RATE

Eevap = Vevap \* (L + TEMP\_H2O \* 998.2 kg/m3 \* 4.187 kJ/(kg degC))

where

L = latent heat of vaporization, a function of temperature

Water volume losses due to evaporation on dry days are offset by gains on days with precipitation. While those losses and gains in volume may be small relative to the total volume of water, Boyd & Kasper assert that “the evaporative heat flux across the air-water interface is generally the most significant factor in dissipation of stream heat” (p. 59 in Boyd & Kasper). The natural units for both precipitation and evaporation are measures of depth, rather than volume. For the purpose of calculations related to conservation of mass, the precip and evap depths are multiplied by the area of the relevant surface. The thermal energy of precip falling on the stream segment or water body will be calculated using the air temperature from the climate data file. Snow will enter the stream at a negative thermal energy reflecting the energy required for the phase change from solid to liquid at the melting point. Use of the air temperature as a surrogate for the temperature of the precipitation itself is an approximation, as is evident from the fact that hail and snow sometimes fall on days above freezing. Our climate datasets do not specify whether precipitation is in the form of rain or snow; CW3M, like other models, infers the phase of the precip from the air temperature.

Vprcp = SURF\_AREA \* PRECIP

Eprcp = Vprcp \* TEMP\_AIR \* 998.2 kg/m3 \* 4.187 kJ/(kg degC)

# Performance Testing

The scope of work requires comparison of CW3M thermal loading output data to output data from Shade-a-lator. Generating the appropriate CW3M output for the comparison is part of this specification. Generating the corresponding input datasets for Shade-a-lator, and running Shade-a-lator, requires expertise which is outside of Oregon Freshwater’s skill set.

The principal CW3M output for the comparison will be the reach water temperature attribute, TEMP\_H2O in the Reach layer. A number of attributes in the new stream segment layer may also contribute to comparisons with Shade-a-lator, for example EVAP\_RATE, RAD\_LW\_NET, RAD\_SW, and SURF\_AREA.

# References

Boyd M and Kasper B (2003). Analytical methods for dynamic open channel heat and mass transfer: Methodology for heat source model Version 7.0. <https://www.oregon.gov/deq/FilterDocs/heatsourcemanual.pdf>

Leach JA and Moore RD (2019). Empirical stream thermal sensitivities may underestimate stream temperature response to climate warming. Water Resources Research, 55. <https://doi.org/10.1029/2018WR024236>