Technical Support Document

Lower Columbia-Sandy River Subbasin Temperature TMDL - DRAFT

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State of Oregon
DEQ Department of Environmental Quality

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1. Introduction

1.1. Document purpose and organization

This document provides comprehensive supporting information on technical analyses completed for the Total Maximum Daily Load (TMDL) and Water Quality Management Plan (WQMP) for addressing temperature impairments in the waters of the Lower Columbia-Sandy River Subbasin. This technical support document (TSD) provides explanation of TMDL concepts and analysis and support for conclusions and requirements included in the Lower Columbia-Sandy River Subbasin TMDL and WQMP, which are proposed for adoption by Oregon's Environmental Quality Commission, by reference, into rule [add OAR 340-042-0090(xx) post adoption].

This TSD is organized into sections with titles matching the TMDL elements required by OAR 340-042-0040(4) in the Lower Columbia-Sandy River Subbasin TMDL for temperature. This organization is intended to facilitate readers' access to information needed for TMDL element-specific determinations.

1.2. Overview of TMDL elements

According to OAR 340-042-0030 Definitions (15): "Total Maximum Daily Load" means a written quantitative plan and analysis for attaining and maintaining water quality standards and includes the elements described in OAR 340-042-0040. Determinations on each element are presented in the Lower Columbia-Sandy River Subbasin TMDL for temperature. Technical and policy information supporting those determinations are presented in this TSD at the section headings that correspond to the TMDL elements for which complex analysis was undertaken.

In plain language, a TMDL is a water quality budget plan to ensure that a receiving water body can attain water quality standards that protect its beneficial uses. This budget calculates and assigns maximum allowable pollutant loads for discharges from point (end-of-pipe) and non-point (diffuse/landscape) sources, in consideration of natural background levels and determinations of a margin of safety and reserve capacity.

A margin of safety (MOS) accounts for the uncertainty in predicting pollutant reduction effectiveness at meeting water quality standards, and can be expressed either explicitly (as a portion of the allocations) or implicitly (by incorporating conservative assumptions in the analyses).

Reserve capacity (RC) sets aside a portion of the loading capacity for future pollutant discharges that may result from growth and new or expanded sources.

A key TMDL analysis element is determining the pollutant amount that a waterbody can receive and still meet the applicable water quality standard; this is referred to as the “loading capacity” (LC) of a waterbody. Because the LC must not be exceeded by pollutant loads from all existing sources plus the MOS and RC, it can be considered the maximum load. Hence, the LC is often referred to as the TMDL.

Another key analysis element is allocating portions of the LC (TMDL) to known sources. “Allocations” are quantified maximum pollutant loads distributed among nonpoint, point, and background sources that assure water quality standards will be met. “Load allocations” (LA) are LC portions allocated to: 1) non-point sources such as urban, agriculture, rural residential or forestry activities; and 2) natural background sources such as soils or wildlife. “Wasteload allocations” (WLA) are LC portions allocated to point sources of pollution, such as permitted discharges from sewage treatment plants, industrial facilities, and/or stormwater systems. As noted above, allocations can also be reserved for future uses, termed “reserve capacity” (RC).

This general TMDL concept is represented by the following equation:

TMDL = ∑Wasteload Allocations + ∑Load Allocations + Reserve Capacity + Margin of Safety

Together, these elements establish the maximum allowed pollutant loads necessary to meet applicable water quality standards for impaired pollutants and protect beneficial uses in a given waterbody.

2. Location

Per Oregon Administrative Rule 340-042-0040(a), this element describes the geographic area for which the TMDL is developed. The Lower Columbia-Sandy River Subbasin is located on the west slopes of the Cascade Range of northwestern Oregon, east of the Portland metropolitan area. This Lower Columbia-Sandy River Subbasin TMDL covers the freshwater perennial and intermittent streams in Oregon within the Lower Columbia-Sandy River Subbasin (Hydrologic Unit Code 8, 17080001).

2.1. Climate

The Lower Columbia-Sandy River Subbasin is characterized by a temperate maritime climate with mild temperatures and a relatively high level of precipitation. According to PRISM normals of annual conditions over the past 30 years (1991-2020), average annual precipitation generally varies with elevation and from west to east, ranging from 1,148 mm (45”) near Troutdale to 3,917 mm (154”) near the North Fork Bull Run River (Figure 2.1). Most precipitation occurs from November-January. Preciptation is lower in July-August. Average annual maximum air temperatures in the Lower Columbia-Sandy River Subbasin range from 1.3°C (34°F) at Mt. Hood to about 17°C (63°F) at Troutdale (Figure 2.2). Generally, July and August are the hottest months of the year (average air temperature: 24°C (75.2°F)) (PRISM Climate Group, 2022).

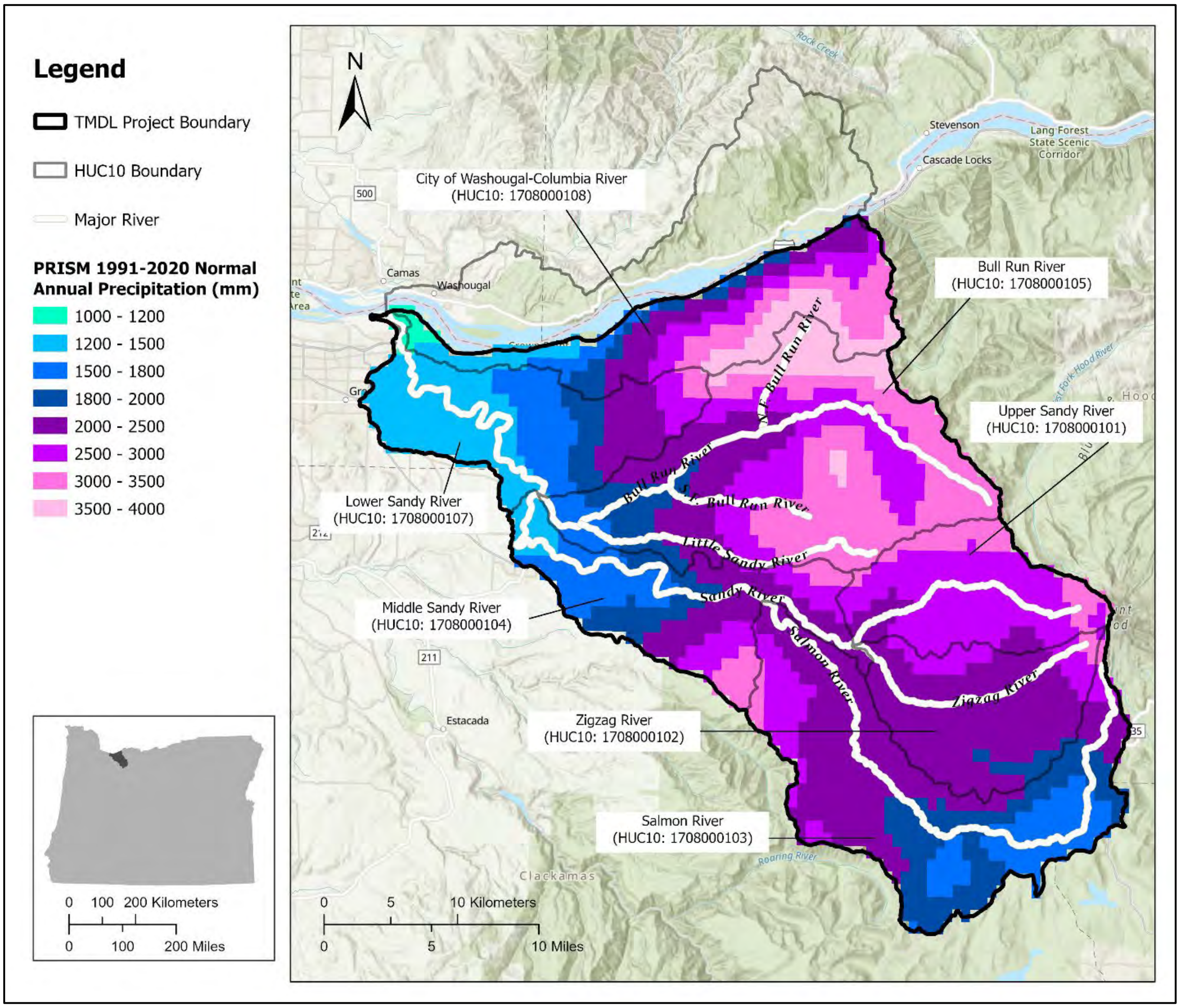

Figure 2.1 PRISM 1991-2020 Normal Annual Precipitation in the Lower Columbia-Sandy River Subbasin (Data Source: PRISM Climate Group, 2022).

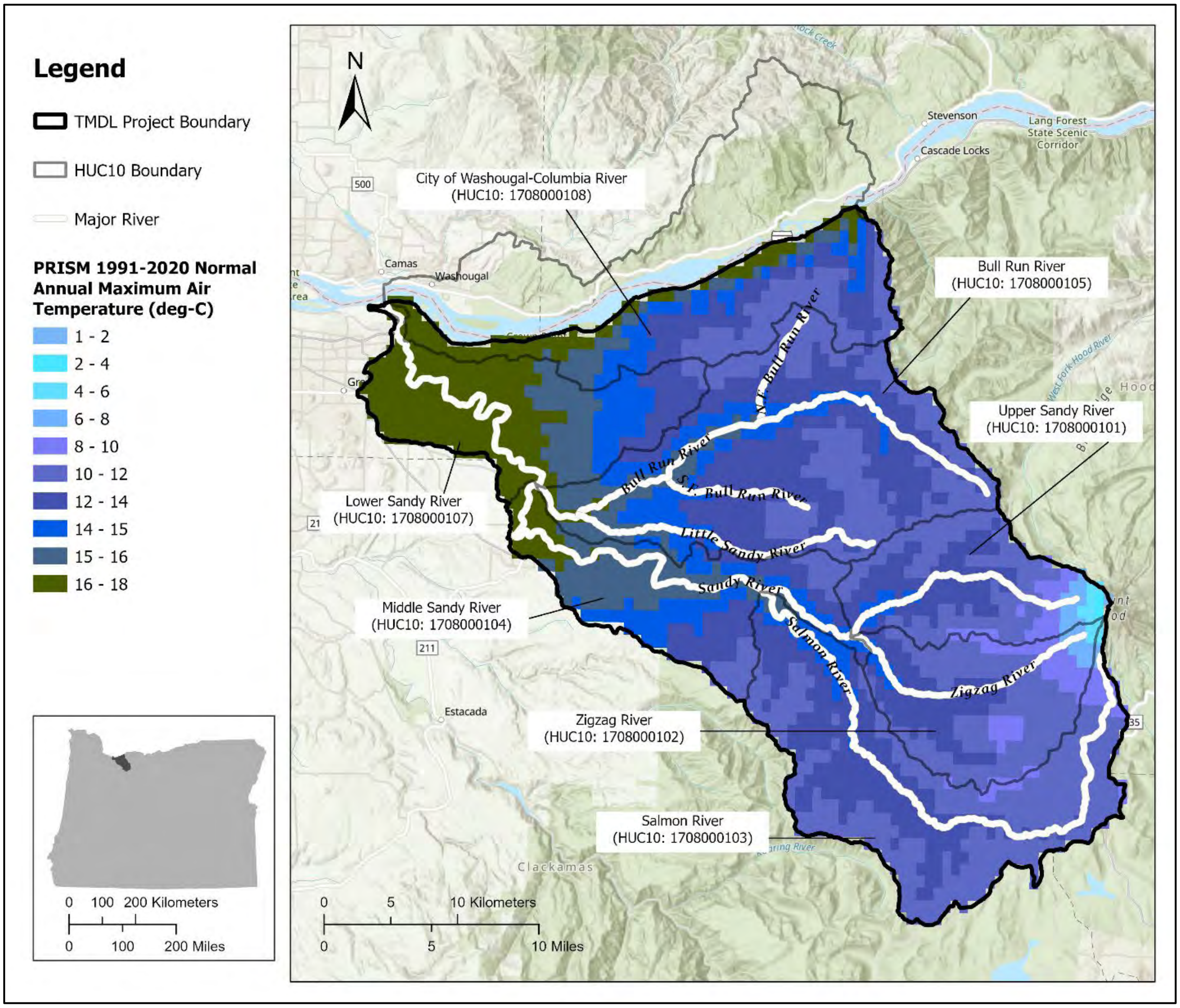

Figure 2.2 PRISM 1991-2020 Nomal Annual Maximum Air Temperature in the Lower Columbia-Sandy River Subbasin (Data Source: PRISM Climate Group, 2022).

2.2. Hydrology

[discuss dams/reservoirs, water withdrawals, etc.]

The Lower Columbia-Sandy River Subbasin drains approximately 1,315 km^2 (508 mi^2) in northwestern Oregon (Figure 2.3). The Sandy River originates from glaciers on the western slopes of Mt. Hood (approx. elevation (above mean sea level (MSL): 157.5 m (6,200’)) and extends 90 km (56 mi) before flowing into the Columbia River near Troutdale, OR. The Sandy River is the only major glacial river draining the western Cascades in Oregon. Glacially-derived fine particulate matter known as “glacial flour” gives the Sandy River its distinctive milky-grey color in summer. Major Sandy River tributaries include the Bull Run River, Little Sandy River, Salmon River, and Zigzag River. The Little Sandy River is the largest tributary to the lower Bull Run River.

The City of Portland Bull Run Dams and Reservoirs:

The City of Portland's drinking water supply project comprises Reservoir & Dam 1, Reservoir & Dam 2, and a dam structure on Bull Run Lake. Dam 1 is a concrete gravity arch dam that was completed in 1929, which created Reservoir 1 with a max. water capacity of 10 billion gallons. Dam 1 has a selective withdrawal structure that allows water withdrawal at different reservoir depths, thus giving some control over discharge temperatures. Reservoir 1’s surface elevation varies between 295-319 m (970-1,045’) above MSL.

Dam 2, located downstream of Dam 1, is an earthfill dam project completed in 1962 with a max. water capacity of 6.8 billion gallons. In 2014, a selective withdrawal structure was completed for Dam 2. The City attempts to maximize Reservoir 2 storage volumes throughout the year (including summer). Reservoir 2’s surface elevation varies between 256-262 m (840-860’) above MSL.

The project has a Federal Energy Regulatory Commission license to produce electricity (FERC License No. 2821, currently valid until 2029). Water is routed through powerhouses before returning to the Bull Run River; any overflow is routed over spillways during winter storms.

Bull Run Lake, a natural lake above the Bull Run River headwaters, was formed from a landslide before European settlement. Although the lake and river have no surface water connection, groundwater seepage contributes significantly to Bull Run River flows. The U.S. Forest Service (USFS) issues a special use permit to the City of Portland to withdraw water from the lake for municipal supplies. The permit restricts withdrawals to ensure adequate water is available to support the local ecosystem. Thus, lake water is only used during dry years. A 10’ dam structure was installed to increase the lake surface elevation and storage capacity.

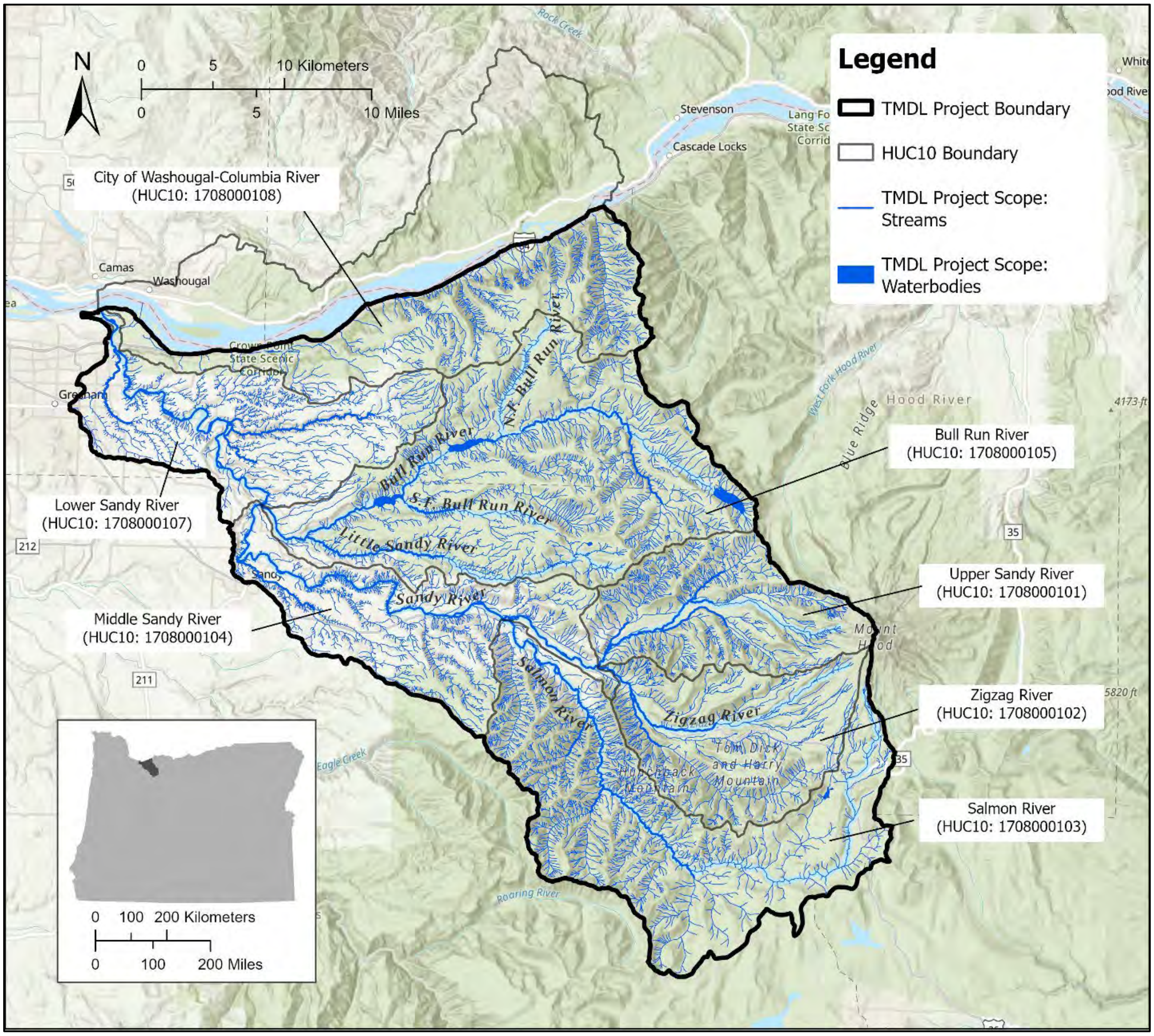

Figure 2.3 Waterbodies in the Lower Columbia-Sandy Subbasin temperature TMDL project area.

2.3. Land Use

[describe land use info and present any NLDC maps/tables not used in the TMDL Rpt]
The Lower Columbia-Sandy River Subbasin is characterized by a variety of land uses, including forested lands, agriculture, and urban development, which are summarized in Table 2.1 and Figure 2.4 based on the 2019 National Land Cover Database (Dewitz and USGS, 2021). Most of the land area (approx. 86%) is forested. Timber harvesting and related activities (e.g., road construction) were the primary land uses in forested areas in the 19th-20th Centuries, but were dramatically reduced after Northwest Forest Plan implementation in 1994 (SRBWG, 2007). Agricultural land uses (e.g., grazing, hay production, and berry farming) occur primarily in the

subbasin’s lower regions. Urban development is concentrated along the lower Sandy River, including the cities of Gresham, Sandy, and Troutdale.

Table 2.1 Land use summary in the Lower Columbia-Sandy River Subbasin based on the 2019 National Land Cover Database.

2019 NLCD Land Cover	Acres	Percent of Total Area
Evergreen Forest	284581.3	78.1
Herbaceous	14412.1	4.0
Mixed Forest	13642.8	3.7
Hay/Pasture	12424.7	3.4
Shrub/Scrub	11637.9	3.2
Developed, Open Space	7145.1	2.0
Developed, Low Intensity	3579.4	1.0
Barren Land	3490.3	1.0
Woody Wetlands	3166.9	0.9
Developed, Medium Intensity	3016.3	0.8
Open Water	2540.2	0.7
Emergent Herbaceous Wetlands	1769.4	0.5
Perennial Snow/Ice	1279.9	0.4
Developed, High Intensity	677.9	0.2
Deciduous Forest	579.1	0.2
Cultivated Crops	218.6	0.1

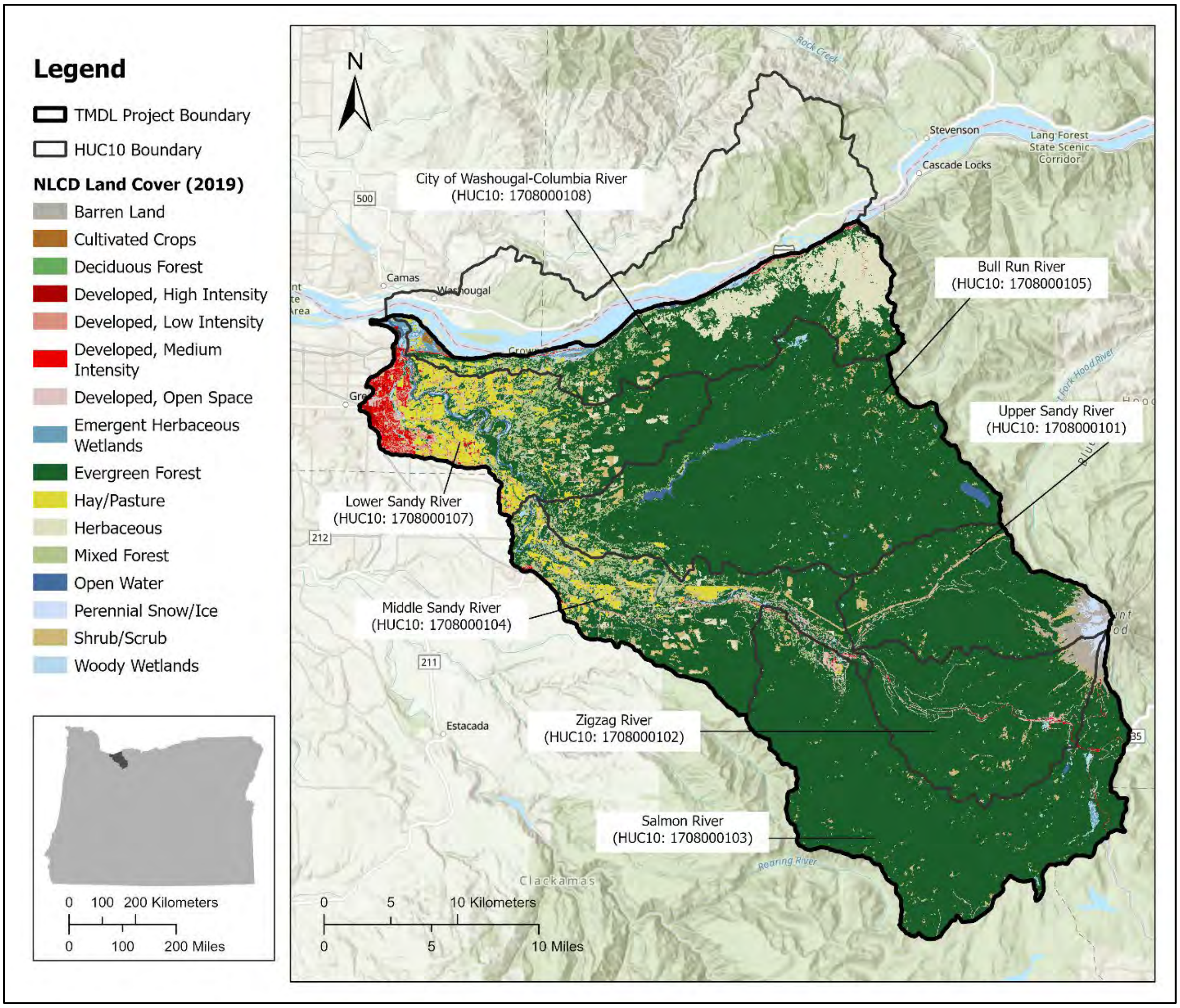

Figure 2.4 Land cover in the Lower Columbia-Sandy Subbasin temperature TMDL project area. *(Note: Shrub/Scrub and Herbaceous land uses can be areas where forest clearcuts have occurred and would be classified as forest after regrowth.)*

2.4. Land Ownership and Jurisdiction

[provide any supporting info/maps/figures not provided in TMDL Rpt]

The Lower Columbia-Sandy River Subbasin is within Multnomah and Clackamas counties. Approximately 70% of the basin consists of Mt. Hood National Forest, which is owned and managed by the USFS, 22% is privately owned, and 4% is owned and managed by the Bureau of Land Management (BLM). The remainder is owned by state, local or regional governments (SRBWG, 2007). The Lower Columbia-Sandy River Subbasin land ownership and jurisdiction, also referred to as the designated management agency (DMA), are shown in Figure 2.5 and Appendix XXX Table XX.

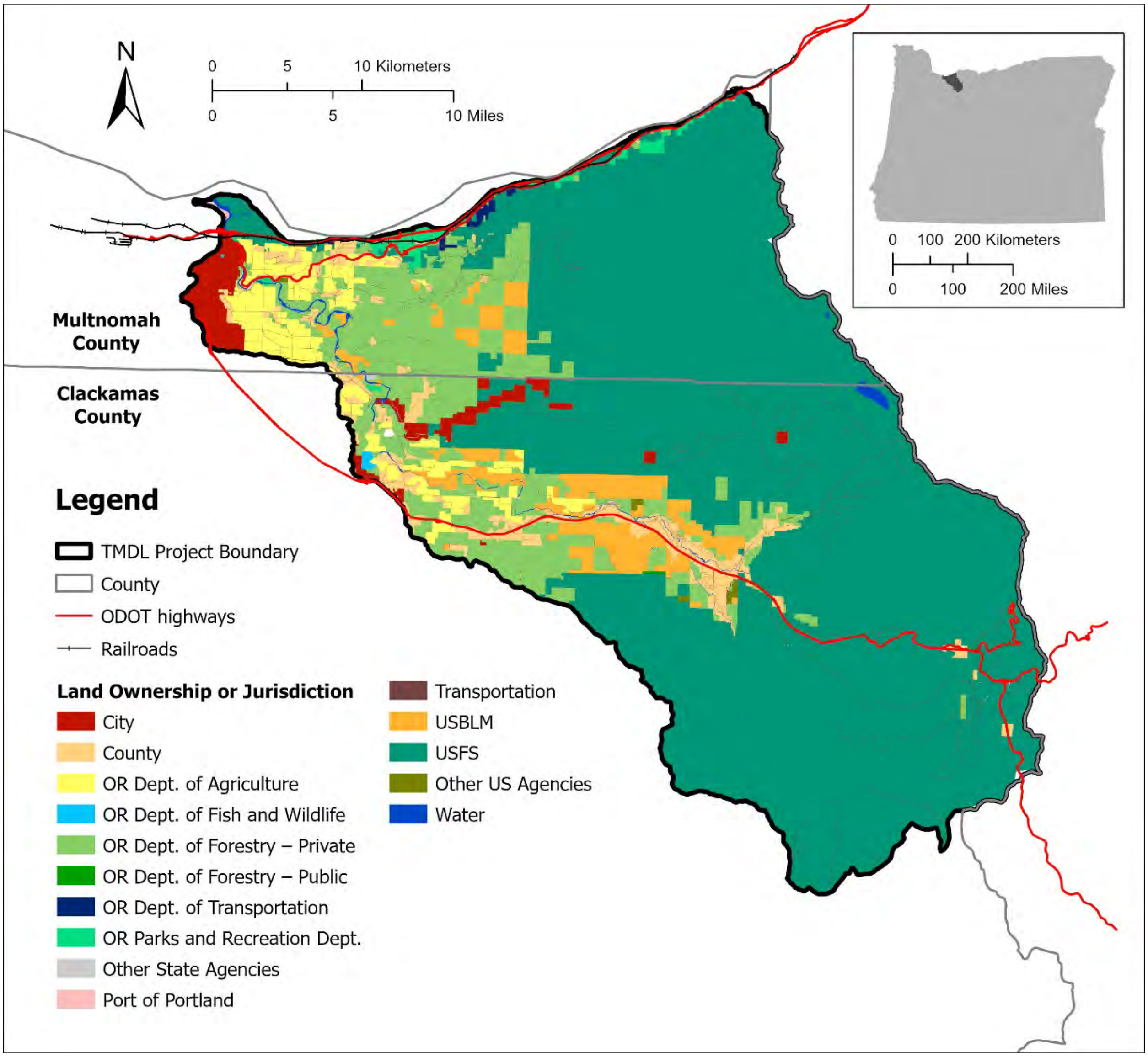

Figure 2.5 Designated management agencies (DMAs) in the Lower Columbia-Sandy Subbasin temperature TMDL project area.

3. Temperature water quality standards and beneficial uses

[provide any analysis or supporting information regarding IR deviations, explanation of standard application, beneficial use info, etc.]

Temperature water quality standards are set to protect the most sensitive beneficial uses for fish and aquatic life. Lower Columbia-Sandy River Subbasin temperature water quality standards are based on the rolling seven-day average daily maximum (7DADM) and include the following numeric criteria:

- Salmon and steelhead spawning: 13.0°C (55.4°F) (OAR 340-041-0028(4)(a))
- Core cold water habitat: 16.0°C (60.8°F) (OAR 340-041-0028(4)(b))
- Salmon and trout rearing and migration: 18.0°C (64.4°F) (OAR 340-041-0028(4)(c))

The locations and periods of criteria applicability are determined from designated fish use maps in OAR 340-041-0286 Figure 286A and Figure 286B. For Lower Columbia-Sandy River Subbasin rivers and streams, Figure 3.1 shows various designated fish uses and applicable criteria, while Figure 3.2 specifically shows salmon and steelhead spawning use designation, based on the National Hydrography Dataset (NHD).

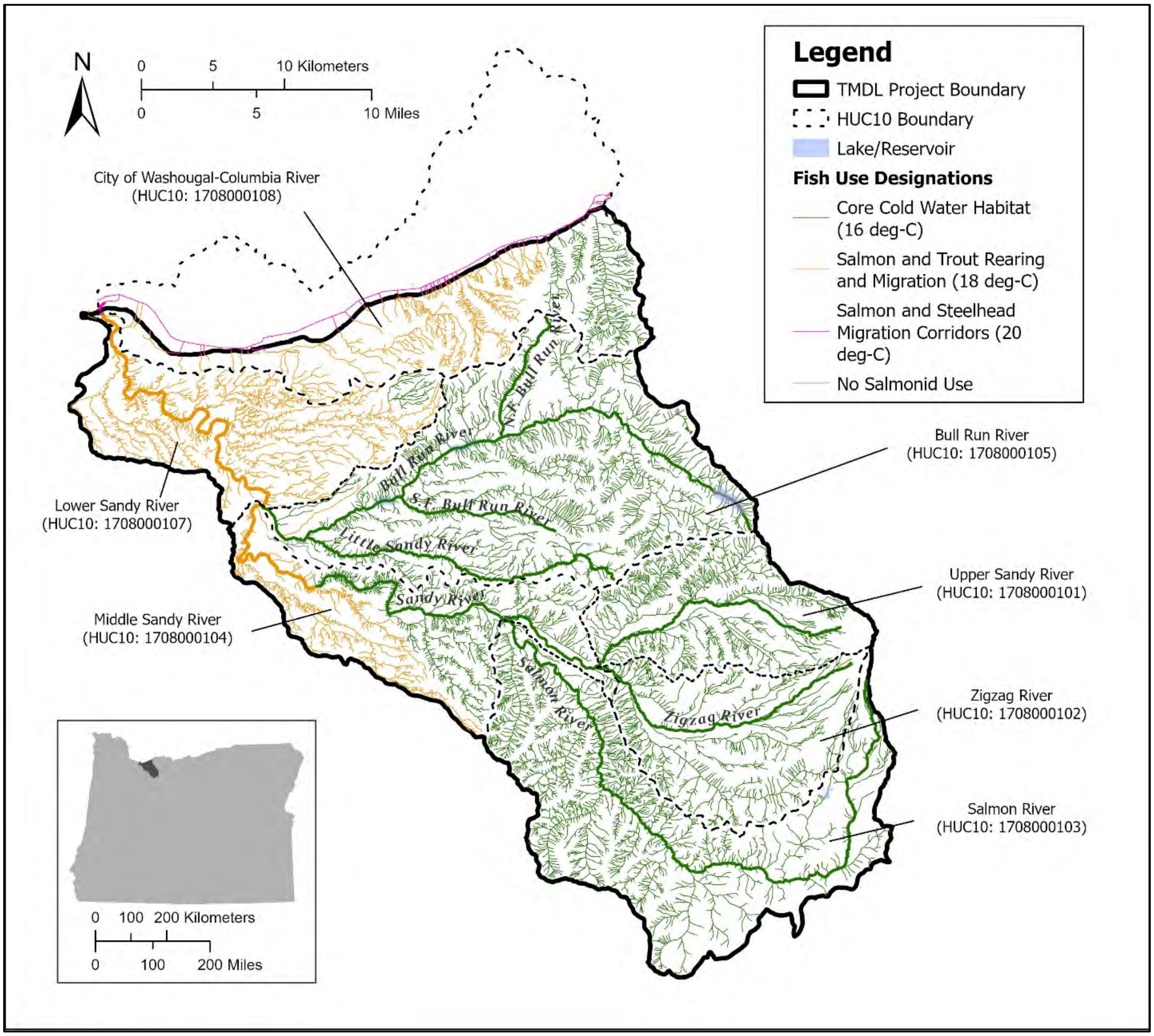

Figure 3.1 Fish use designations in the Lower Columbia-Sandy River Subbasin.

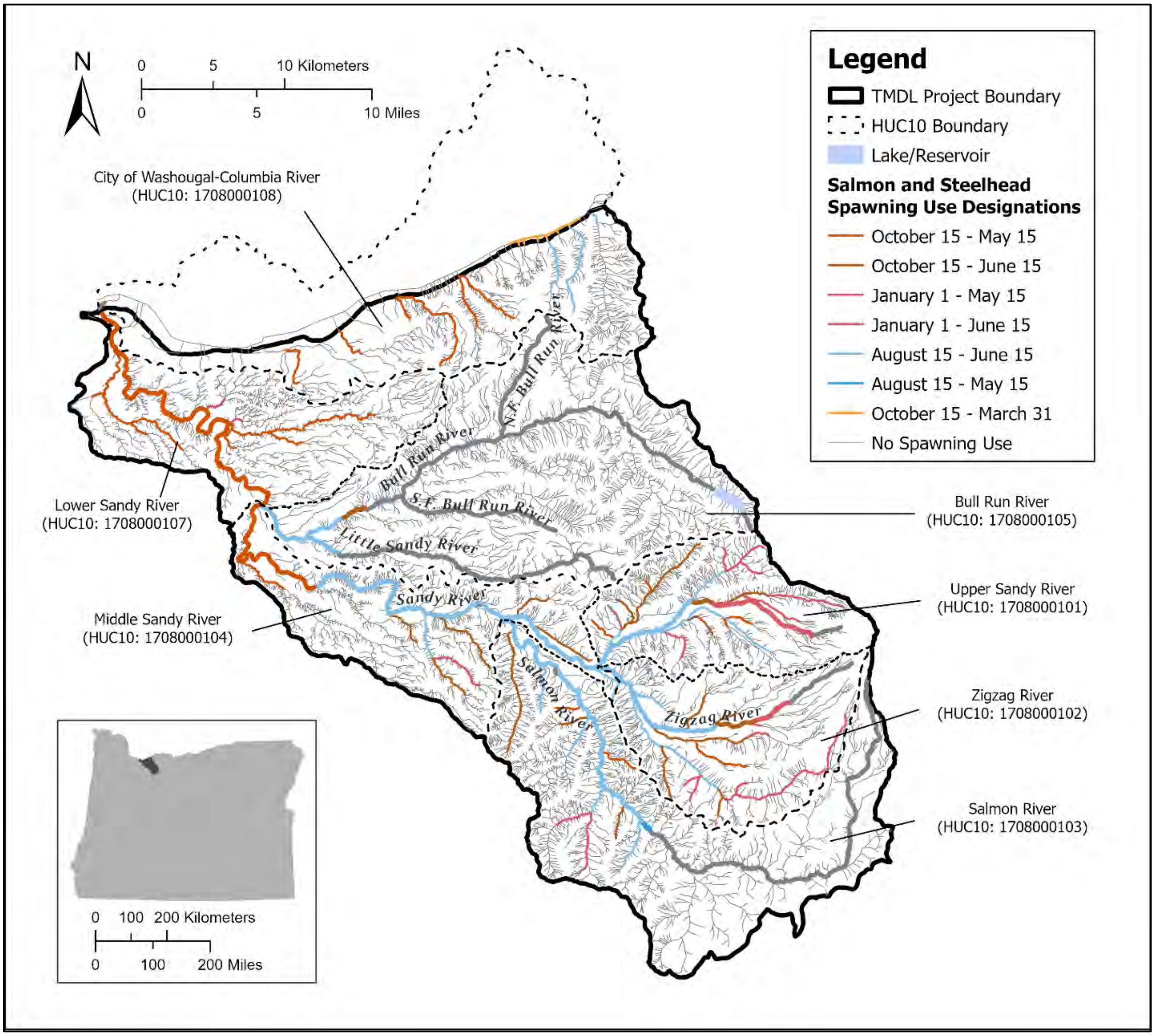

Figure 3.2 Salmon & steelhead spawning use designations in the Lower Columbia-Sandy River Subbasin.

The temperature standard authorizes insignificant anthropogenic heat additions in waters that exceed applicable temperature criteria as follows: following a temperature TMDL or other cumulative effects analysis, the Human Use Allowance (HUA) will restrict all NPDES point sources and nonpoint sources to a cumulative increase of ≥0.3°C (OAR 340-041-0028(12)(b)).

4. Water quality data evaluation and analyses

A critical TMDL element is water quality data evaluation and analysis to the extent that existing data allow. To understand the water quality impairment, quantify the loading capacity, and assess the ability of various possible scenarios to achieve the TMDL and applicable water quality standards, the analysis requires a predictive component. Certain models provide a means to evaluate potential stream warming sources and, to the extent existing data allow, their current and potential pollutant loads. Heat Source and CE-QUAL-W2 models were used in this effort and are described in model appendices.

4.1. Analysis overview

The modeling framework needs for this project included the abilities to predict/evaluate hourly:

1. Stream temperatures spanning months at ≤500m longitudinal resolution.
2. Solar radiation fluxes and daily effective shade at ≤100m longitudinal resolution.
3. Stream temperature responses due to changes in:
    a. Streamside vegetation,
    b. Water withdrawals and upstream tributaries' stream flow,
    c. Channel morphology in the upstream catchment,
    d. Effluent temperature and flow discharge from NPDES permitted facilities.

To function properly, water quality models have specific input and calibration data requirements. Data collected for this TMDL analysis are summarized in Figure 4.1 and Table 4.1 and described more fully in Appendix B. All data are available upon request. Figure 4.1 also provides an overview of the analyses completed for this TMDL, which are described in the remaining sections of this TSD.

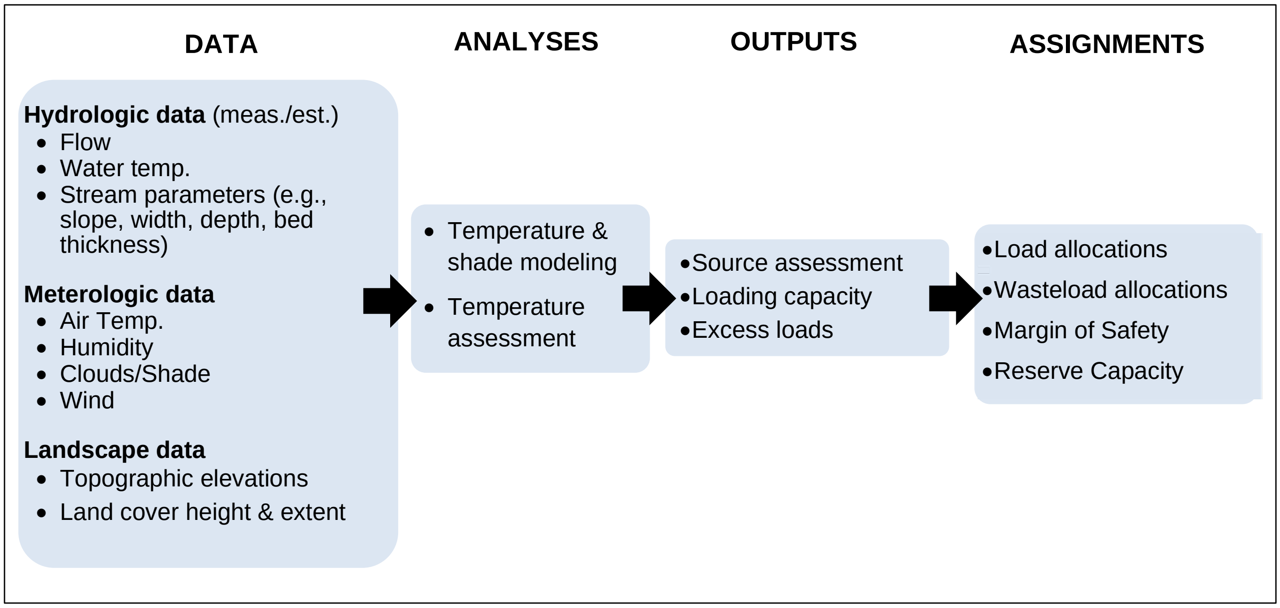

Figure 4.1 Lower Columbia-Sandy River Subbasin temperature analysis overview.

4.2. Data overview

As illustrated in Figure 4.1, data for numerous hydrologic, meteoroligic, and landscape/ geographic parameters within the spatial and temporal boundaries of the TMDL are required to conduct effective analysis for TMDL development. Section 2 of Appendix B to this document describes these parameters, their applications in this TMDL development, and provides information on the specific datasets and sources utilized for this effort. For the Bull Run River, a CE-QUAK-W2 model previously developed by the City of Portland and used for this TMDL. For the Sandy River and Salmon River, the following procedures were applied. All data are available upon request.

Table 4.1 Data types used in Lower Columbia-Sandy River Subbasin Temperature TMDL modeling.

Data Source Type	Dataset Types	Data Sources
Field-acquired	• Continuous stream temperature • Stream flow rate: continuous & instantaneous • Point source discharge temperatures & flows	DEQ Ambient Water Quality Monitoring System (AWQMS); USGS National Water Information System (NWIS); DEQ data solicitation responses; Portland Water Bureau; 2016 NPDES Discharge Monitoring Reports
GIS and/or remotely sensed	• 3-ft Digital Elevation Model (DEM) • Light Detection and Ranging (LiDAR) • Aerial imagery: Digital Orthophoto Quads (DOQs) • Thermal Infrared Radiometry (TIR) temperature data	Oregon Department of Geology and Mineral Industries (DOGAMI); Oregon LiDAR Consortium (OLC); Portland State University (PSU); Watershed Sciences, Inc.

Derived from above data types via: (a) quantitative methods or (b) proxy substitution (for certain tributary flows & temps.)	• Stream position, channel width, channel bottom width, elevation, gradient • Topographic shade angles • Land cover mapping • Tributary flows & temperatures	DEMs, LiDAR, DOQs (for stream morphology, land cover, topography, & geography); USGS Streamstats, historical data, proxy site data, estimated (constant) data (for tributary flows & temperatures if direct 2016 monitoring data were unavailable)

4.2.1. The 7Q10 low-flow statistic

The “7Q10” is a summary low-flow statistic equal to the lowest seven-day average flow that occurs once every ten years (on average). For the Sandy Subbasin temperature TMDL, estimated 7Q10s used to calculate numeric loading capacities and allocations. DEQ calculated annual 7Q10s for temperature-impaired streams in the Sandy Subbasin (Table 4.2), and for the receiving waterbodies that have NPDES permitted discharges with a waste load allocation (Table 4.3).

The 7Q10 estimates were based on the following approaches:

1) If sufficient daily mean flow data from USGS or OWRD gaging stations were available for a given waterbody, 7Q10 estimates were calculated using these data. Available flow data were retrieved for up to a 30-year period (October 1, 1992 to September 31, 2022). DEQ relied on quality control protocols implemented by USGS and OWRD. Only data with a result status of “Approved” (USGS) or “Published” (OWRD) were included in 7Q10 calculations. 7Q10s were calculated by the method of EPA’s DFLOW program (Rossman, 1990), which computes extreme design flows using the log-Pearson Type III probability distribution. A minimum of 10 years of flow data were used with some exceptions. For ungaged locations, if there were sufficient gage data from confluent streams, 7Q10 were estimated from (a) the sum of mean daily flows (for upstream gages), or (b) the difference of mean daily flows (for downstream gages), prior to application of the DFLOW procedure.

2) If insufficient daily mean flow data from USGS and OWRD stream flow gaging stations were available, the web-based tool StreamStats (USGS) was used to estimate 7Q10s. Details of StreamStats are described below.

3) 7Q10s calculated and reported elsewhere (e.g. consultant studies, water quality permits, TMDLs) may have been used. In such cases, DEQ relied on the source’s data quality.

4) For tidally-influenced streams, DEQ reviewed each situation and made 7Q10 estimates based on the best available data from the relevant gaging stations. Methods are described for each case.

StreamStats version 4 is a web-based geographic information system (GIS) application developed by the USGS (https://streamstats.usgs.gov/ss/). StreamStats has a map-based interface that allows the user to determine drainage area delineations, basin characteristics, and estimates of stream flow statistics for user-selected locations along available streams. The program also provides users with access to stream monitoring data by selecting USGS data-collection stations in the map application and providing access to flow statistics and other information for the stations. StreamStats provides estimates of various stream flow statistics for user-selected sites by solving site-specific regression equations. The regression equations were developed through a process, known as regionalization, which involves use of regression analysis to relate stream flow statistics computed for a group of selected stream gages (usually within a state) to basin characteristics measured for the stream gages. Basin characteristics are used to obtain estimates of the stream flow statistics for ungaged sites.

StreamStats regression equations for Oregon were developed by Cooper (2005) and Risley et al. (2008). These equations were based on basin characteristics and flow statistics (e.g., historical percentile flow-exceedance values and annual and monthly 7Q10). Flow statistics were computed at 466 gaging stations across Oregon and proximal out-of-states areas. This study area was divided into 10 regions based on ecological, topographic, geologic, hydrologic, and climatic criteria. StreamStats includes 910 annual and monthly regression equations to estimate 7Q10s for ungaged stream sites in the 10 aforementioned regions. These equations were developed for unregulated streams (without major dams, constructed reservoirs, catchment development, or significant diversions/withdrawals). If the equations are applied to ungaged streams subject to such influeneces, the resultant estimates may require adjustment to approximate actual flows.

The StreamStats user selects a stream location of interest and the program estimates the associated drainage area and summary flow statistics. For this TMDL, DEQ's procedure specified that selected stream locations should be the most downstream location on each stream for which DEQ required flow estimates; the exception was if DEQ required 7Q10 estimates for NPDES-permitted point source receiving waters, in which case the selected stream location was immediately upstream of the point source outfall. StreamStats also estimates basin characteristics for the selected catchment, including drainage area, mean annual precipitation, mean slope, and climactic characteristics (Cooper, 2005; Risley et al., 2008). If estimates are outside suggested parameter ranges, the warning message "extrapolated with uncertainty" appears in the StreamStats report.

Table 4.2 The 7Q10 low-flow estimates for modeled temperature-impaired rivers in the Lower Columbia-Sandy Subbasin.

Assessment Unit Name	Assessment Unit ID	Estimated 7Q10 (cfs)	Flow Estimation Method	Flow Estimation Latitude/Longitude	Gage Period
Bull Run River	OR_SR_1708000105_11_103611	4.1	USGS: 14140000	45.437, -122.180	1992-10-01 ~ 2022-04-28
Little Sandy River	OR_SR_1708000105_11_103609	10.5	USGS: 14141500	45.415, -122.171	1992-10-01 ~ 2022-08-03
Salmon River	OR_SR_1708000103_02_103606	174	StreamStats	45.376, -122.030	
Sandy River	OR_SR_1708000101_02_103595	14.3	StreamStats	45.390, -121.863	
Sandy River	OR_SR_1708000101_02_103599	50.3	StreamStats	45.349, -121.944	
Sandy River	OR_SR_1708000104_02_103608	215.9	USGS: 14137000	45.400, -122.137	1992-10-01 ~ 2021-11-18

Assessment Unit Name	Assessment Unit ID	Estimated 7Q10 (cfs)	Flow Estimation Method	Flow Estimation Latitude/Longitude	Gage Period
Sandy River	OR_SR_1708000107_02_103616	271.9	USGS: 14142500	45.449, -122.245	1992-10-01 ~ 2022-05-16
Zigzag River	OR_SR_1708000102_02_103600	48.2	StreamStats	45.348, -121.945	

Table 4.3 The 7Q10 low-flow estimates for NPDES permitted discharges receiving a numeric waste load allocation in this TMDL.

Facility Name (Facility Number)	Stream	Estimated 7Q10 (cfs)	Flow Estimation Method	Flow Estimation Latitude/Longitude	Gage Period
City of Troutdale WPCF (89941)	Sandy River	278.4	USGS/OWRD: 14142500 + 14142800	45.449, -122.245	1999-10-01 ~ 2022-09-30
Government Camp STP (34136)	Camp Creek	5.7	Sandy River Basin TMDL (DEQ, 2005)		
Sandy WWTP (78615)	Sandy River	215.9	USGS: 14137000	45.3996, -122.1373	1992-10-01 ~ 2021-11-18
ODFW Sandy River Fish Hatchery (64550)	Cedar Creek	4.89	StreamStats	45.405, -122.253	
Hoodland STP (WES) (39750)	Sandy River	80.3	StreamStats	45.354, -121.973	

4.3. Model setup and application overview

As described in the model report appendicies, DEQ and parnters setup and calibrated models for the Sandy River, Salmon River, Bull Run River, Little Sandy River, and Zigzag River. The models were adjusted iteratively until acceptable goodness-of-fit was achieved relative to the observed current conditions, The models were setup and calibrated agains conditions in 2001 or 2016. These results are provided in the appendices and were used in tandem with applicable water quality standard data to predict (7DADM) standard exceedances and derive the loading capacities, excess loads, and allocations presented in the TMDL report. To predict the effects of various changes in riparian conditions and other and management scenarios, the model parameters were adjusted and the results evaluted. The results of these model scenarios were then evaluated to determine if those management strategies would result in attainment of water quality standards.

5. Source assessment and load contributions

A key component of TMDL development is a complete, comprehensive source assessment for the relevant water quality pollutant(s). This includes identification of all relevant point and nonpoint sources to the impaired waterbody, characterization/quantification of their pollutant load contributions, determination of seasonal variation, and delineation of periods when applicable temperature criteria are exceeded at various locations, to the extent that existing data allow. The TMDL report and its Appendices describe the significant thermal pollutant sources identified within the Sandy Subbasin temperature TMDL area and subwatersheds, and the data sources that DEQ accessed for TMDL modeling.

[Addtional source assessment summary from model reports coming soon.]

6. Allocation approach

Figure 6.1 provides three separate conceptual representations of the total load to a temperature-impaired water. The left (completely orange) block shows the total load, with the bisecting lines representing the load that would meet the biologically-based numeric criteria and the temperature standard. The middle block represents the portions of the total load contributed by the different source categories (point, nonpoint, and background).

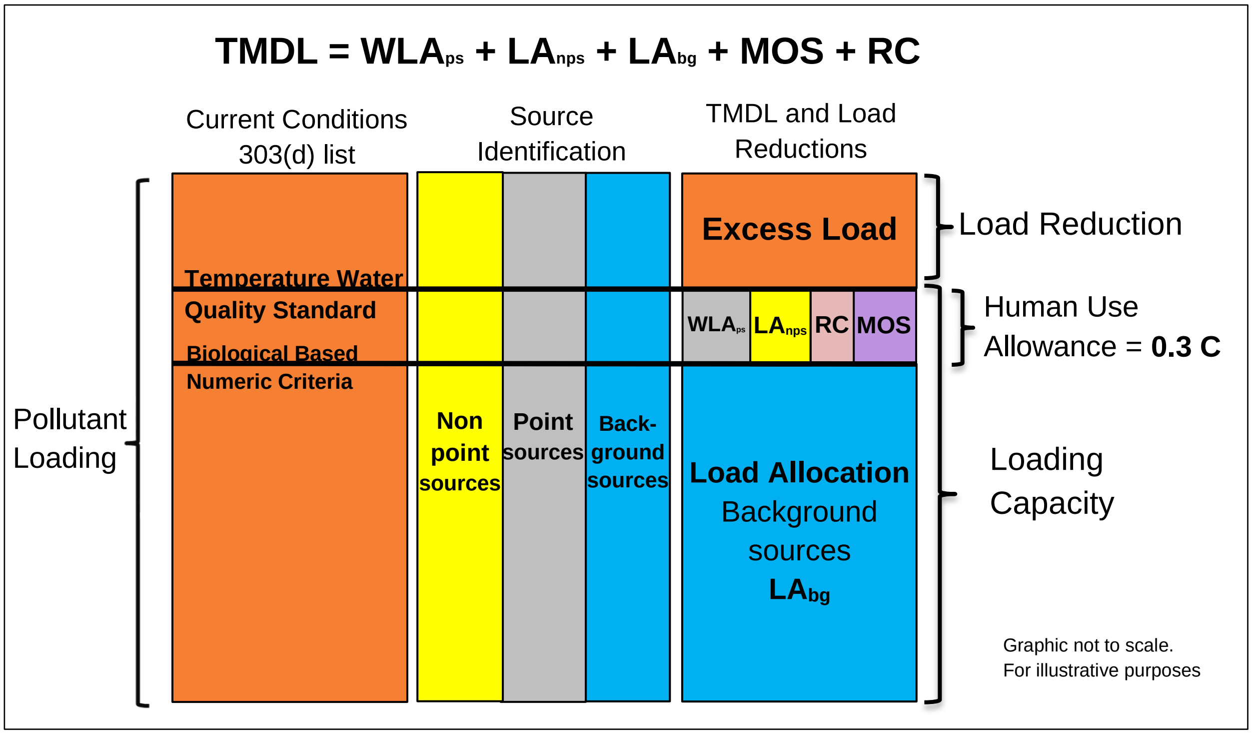

Figure 6.1 Conceptual representation and breakdown of total pollutant loading to a temperature-impaired waterbody.

Wasteload allocations (shown as WLA) are the portion of the TMDL loading capacity allocated to point sources and load allocations (shown as LA) are the portion distributed to nonpoint sources. OAR 340-042-0040(6) identifies the factors that DEQ or EQC may consider when distributing wasteload and load allocations. The factors include:

a) Contributions from sources;
b) Costs of implementing measures;
c) Ease of implementation;
d) Timelines for attainment of water quality standards;
e) Environmental impacts of allocations;
f) Unintended consequences;
g) Reasonable assurances of implementation.
h) Any other relevant factor.

Oregon's temperature standard provides a framework for how the loading capacity is distributed between human sources of warming and background sources. The human use allowance at OAR 340-041-0028(12)(b)(B) identifies the portion of the loading capacity reserved for human uses. The rule requires wasteload and load allocations restrict all NPDES point sources and nonpoint sources to a cumulative increase of no greater than 0.3 degrees Celsius (0.5 Fahrenheit) above the applicable criteria after complete mixing in the water body, and at the point of maximum impact. DEQ allocated a thermal load equivalent to 0.3 degrees to human sources and the remainder of the loading capacity to background sources.
When distributing the thermal loads associated with a 0.3 degrees Celsius increase, DEQ considered the magnitude of the thermal load contributed from known sources, ease of implementing the allocations, the environmental impact of those contributions including where the impact occurs and how the source contribution impacts cumulative warming.

For point sources discharging to the Sandy River, DEQ allocated a portion of the human use allowance that was equally distributed among the point sources and consistent with their current thermal loads. Through analysis of available effluent discharge data and modeling DEQ determined that a point of discharge increase less than 0.07 degrees Celsius would require thermal reduction below current operations and put those facilities in immediate violation. A thermal load equal to a 0.07 degree Celsius human use allowance at the point of discharge limits the cumulative increase at the point of maximum impact, located near Troutdale, to be no more than 0.13 degrees Celsius. For these reasons, the NPDES sources discharging to the Sandy River were allocated a wasteload allocation equal to a 0.07 degree increase.

On Cedar Creek, DEQ allocated the entire 0.3 degrees Celsius to ODFW Sandy River fish hatchery. This decision was based upon the limited extent of riparian restoration needed upstream, and the complexity and associated cost required for ODFW to achieve the allocation. Available effluent discharge data indicated the facility will be in immediate violation even with an allocation of the entire 0.3 degrees Celsius human use allowance.

DEQ evaluated land use activities upstream of the ODFW fish hatchery to assess potential sources of warming. Immediately upstream of ODFW facility for approximately 2 miles the land uses adjacent to the stream are primarily rural residential. Based on aerial imagery analysis there are some locations within this reach that appear to lack sufficient riparian vegetation. Upstream for another 2 miles the land use is a mix of forestry and agriculture. The riparian area looks to be relatively intact or in a state of regrowth with limited restoration potential. The land uses return to rural residential paralleling highway 26. Upstream of highway 26 the USFS manages the majority of land.

Clackamas County manages the streamside vegetation requirements in rural residential areas. Clackamas County ordinances already require a buffer width between 50 feet and 150 feet depending on site conditions. On the Salmon River, DEQ determined the required buffer widths (110 feet) are within two percentage points of attaining the shade targets. Assuming these requirements are enforced and areas lacking shade are addressed, DEQ determined these rural residential areas will have limited potential for stream warming. On USFS's land the current management of streamside vegetation does not lead to thermal increases in the majority of cases. The exception being intermittent streams on USFS lands (see WQMP Section 5.2.4).

On the Bull Run River, DEQ allocated the entire 0.30 degrees Celsius to the City of Portland for operation and management of the Bull Run dams and reservoirs. The entire human use allowance was allocated because there do not appear to be any other significant sources of warming to the Bull Run River, with the exception of a handful of private forestland properties near the mouth of the Bull Run River. If these properties were to ever be harvested under current forest practices act there could be a decrease in shade and increase in temperatures.

The remainder of the watershed is owned by the City of Portland or USFS. DEQ determined that the City of Portland and USFS's current management of streamside vegetation in the Bull Run does not lead to thermal increases in the majority of cases. The exception being intermittent streams on USFS lands (see WQMP Section 5.2.4). On City of Portland owned lands adjacent to the Lower Bull Run River, the city maintains a 200 foot no cut buffer from the river's average high water level (City of Portland, 2008).

On Camp Creek, DEQ allocated 0.20 degrees Celsius to Government Camp STP. Through analysis of available effluent discharge data from the year 2020, it was determined that a point of discharge wasteload allocation equal to a 0.20 degrees Celsius increase would not result in thermal load reductions. This allocation is consistent with the allocation DEQ provided in the 2005 Sandy Basin TMDL (DEQ, 2005). Anlaysis conducted for this TMDLs showed that increases less than 0.17 degrees Celsius during low river flows could require thermal load reduction below current operations and put the facility in immediate violation.
DEQ allocated 0.05 degrees Celsius to diversions and water withdrawal activities in the subbasin.

Modeling on the Sandy River shows that existing transportation corridors, existing buildings and existing utility infrastructure increase stream seven day average daily maximum (7DADM) stream temperature about 0.02 degrees Celsius, except near the mouth where the increase is larger. Solar loading, in general caused by anthropogenic removal of streamside vegetation, increases 7DADM stream temperature between 0.5 and 1 degrees Celsius. Temperature increases from existing transportation corridors, existing buildings and existing utility infrastructure may be more complex and costly to address compared to solar loading from areas where there is simply a lack streamside vegetation. For this reason, DEQ allocated a 0.02 degrees Celsius increase on various streams from solar loading from existing transportation corridors, existing buildings and existing utility infrastructure were . For all other anthropogenic sources of solar loading and other nonpoint sources not identified above, DEQ allocated a zero increase. DEQ set aside any remainder of the human use allowance for reserve capacity.

6.1. Loading capacity

As described in the TMDL report, the pollutant load that a waterbody can receive and still meet water quality standards is called the loading capacity (LC). For temperature, thermal loading capacity is calculated using **Equation 1**.

Equation 1 $LC = (T_C + \mathrm{HUA}) \cdot Q_R \cdot C_F$

where,

$LC =$ Loading Capacity (kcal/day).

$T_C =$ The applicable river temperature criterion (°C).

$\mathrm{HUA} =$ The 0.3°C human use allowance allocated to point sources, nonpoint sources, margin of safety, or reserve capacity.

$Q_R =$ The daily mean river flow rate (cfs).
When river flow is <= 7Q10, Q_R = 7Q10. When river flow > 7Q10, Q_R is equal to the daily mean river flow.

$C_F =$ Conversion factor using flow in cubic feet per second (cfs): 2,446,665

$$\frac{1\ m^3}{35.31\ ft^3} \cdot \frac{1000\ kg}{1\ m^3} \cdot \frac{86400\ sec}{1\ day} \cdot \frac{1\ kcal}{1\ kg\ \cdot 1℃} = 2{,}446{,}665$$

The TMDL report Table 8.1 presents minimum LCs for certain assessment units with an NPDES discharge or that were modeled for the TMDL analysis. Minimum LCs are calculated based on the 7Q10 low flow.

Oregon's temperature standard provides a framework for how the loading capacity is distributed between human sources of warming and background sources. The human use allowance at OAR 340-041-0028(12)(b)(B) identifies the portion of the loading capacity reserved for human uses. The rule requires wasteload and load allocations restrict all NPDES point sources and nonpoint sources to a cumulative increase of no greater than 0.3 degrees Celsius (0.5 Fahrenheit) above the applicable criteria after complete mixing in the water body, and at the point of maximum impact. DEQ allocated a thermal load equivalent to 0.3 degrees to human sources and the remainder of the loading capacity to background sources.

When distributing the thermal loads associated with a 0.3 degrees Celsius increase, DEQ considered the magnitude of the thermal load contributed from known sources, the environmental impact of those contributions including the location where the impact occurs and how the contribution impacts cumulative warming, and ease of implementing the allocations.

Wasteload allocations are the portion of the TMDL loading capacity allocated to point sources and load allocations are the portion distributed to nonpoint sources. OAR 340-042-0040(6) identifies the factors that DEQ or EQC may consider when distributing wasteload and load allocations. The factors include:

a) Contributions from sources,
b) Costs of implementing measures,
c) Ease of implementation,
d) Timelines for attainment of water quality standards,
e) Environmental impacts of allocations,
f) Unintended consequences,
g) Reasonable assurances of implementation, and
h) Any other relevant factor.

6.2. Point pource waste load allocations (WLAs)

6.2.1. Wasteload allocation equation

The following equation was used to calculate the thermal waste load allocations.

Equation 2 $$WLA = (\Delta T) \cdot (Q_E + Q_R) \cdot C_F$$

where,

$WLA =$ Waste load allocation (kilocalories/day).

$\Delta T =$ The maximum temperature increase (°C) above the applicable temperature criterion using 100% of river flow not to be exceeded by each individual source from all outfalls combined.

$Q_E =$ The daily mean effluent flow (cfs).
When effluent flow is in million gallons per day (MGD) convert to cfs:

$$\frac{1{,}000{,}000\ gallons}{1\ day} \cdot \frac{0.13368 ft^3}{1\ \text{gallon}} \cdot \frac{1\ day}{86{,}400\ sec} = 1.5472\ ft^3/sec$$

$Q_R =$ The daily mean river flow rate, upstream (cfs).
When flow is <= 7Q10, Q_R = 7Q10. When flow is > 7Q10, Q_R equals the daily mean river flow, upstream.

$C_F =$ Conversion factor using flow in cubic feet per second (cfs): 2,446,665

$$\frac{1\ m^3}{35.31\ ft^3} \cdot \frac{1000\ kg}{1\ m^3} \cdot \frac{86400\ sec}{1\ day} \cdot \frac{1\ kcal}{1\ kg\ \cdot 1℃} = 2{,}446{,}665$$

6.2.2. WLA permit compliance equation.

When evaluating current discharge, DEQ used Equation 3 to determine compliance with the waste load allocation (WLA).

Equation 3

$$ETL = (T_E - T_C) \cdot Q_E \cdot C_F$$

where,

$ETL =$ The daily excess thermal load (kilocalories/day) used to evaluate compliance with the waste load allocation (WLA) from Equation 1.

$T_{C,i} =$ The point of discharge applicable river temperature criterion (ºC) (T_c); or when the minimum duties provision at OAR 340-041-0028(12)(a) applies $T_{C,i}$ = the 7DADM measured at the facility intake (T_i). Use Equation 7 to determine if the minimum duties provision applies.

$T_E =$ The daily maximum effluent temperature (ºC)

$Q_E =$ The daily mean effluent flow (cfs or MGD)

$C_F =$ Conversion factor for flow in cubic feet per second (cfs): 2,446,665

$$\frac{1\,m^3}{35.31\,ft^3} \cdot \frac{1000\,kg}{1\,m^3} \cdot \frac{86400\,sec}{1\,day} \cdot \frac{1\,kcal}{1\,kg\ \cdot 1℃} = 2{,}446{,}665$$

Conversion factor for flow in millions of gallons per day (MGD): 3,785,411

$$\frac{1\,m^3}{264.17\,gal} \cdot \frac{1000\,kg}{1\,m^3} \cdot \frac{1000000\,gal}{1\,million\,gal} \cdot \frac{1\,kcal}{1\,kg\ \cdot 1℃} = 3{,}785{,}441$$

6.2.3. Calculating current change in temperature

The following equation is used to determine compliance with the allowed ΔT allocated in the TMDL

Equation 4

$$\Delta T_{Current} = \left(\frac{Q_E}{Q_E + Q_R}\right) \cdot (T_E - T_C)$$

where,

$\Delta T_{Current} =$ The current river temperature increase (ºC) above the applicable river temperature criterion using 100% of river flow.

$Q_E =$ The daily mean effluent flow (cfs).
When effluent flow is in million gallons per day (MGD) covert to cfs:

$$\frac{1\ \text{million}\ gallons}{1\ day} \cdot \frac{1.5472\,ft^3}{1\ \text{million gallons}} = 1.5472$$

$Q_R =$ The daily mean river flow rate, upstream (cfs).
When river flow is <= 7Q10, Q_R = 7Q10. When river flow > 7Q10, Q_R is equal to the daily mean river flow, upstream.

$T_E =$ The daily maximum effluent temperature (ºC)

$T_C =$ The point of discharge applicable river temperature criterion (ºC). When the minimum duties provision at OAR 340-041-0028(12)(a) applies TC = the 7DADM measured at the facility intake.

6.2.4. Calculating TMDL allocation river temperature

Equation 4 was to determine the ambient river temperature downstream of a point of discharge based on the allowed ∆T or waste load allocation in the TMDL. The equation assumes 100% mixing between river and effluent discharge. The equation was used to assess ODFW's Sandy River Fish Hatchary impact on Cedar Creek and for devlopment of the Cedar Creek triburary input temperaures for the Sandy River wasteload allocation model scenerio (See Tetra Tech Model Scnerio Appendix C).

$$T_{R\_WLA} = Q_R \cdot \frac{\left(T_{R\_up} - T_C\right)}{(Q_E + Q_R)} + (T_C + \Delta T)$$ **Equation 4a** (using ∆T)

$$T_{R\_WLA} = T_{R\_up} + \frac{Q_E}{(Q_E + Q_R)} \cdot \left(\left(\frac{WLA}{(Q_R \cdot C_F)} + T_C\right) - T_{R\_up}\right)$$ **Equation 4b** (using WLA)

$$T_{R\_WLA} = T_{R\_up} + \left(\frac{Q_E}{Q_E + Q_R}\right) \cdot \left(T_{E\_WLA} - T_C\right)$$ **Equation 4c** (using effluent temp)

where,

$T_{R\_WLA} =$ Ambient river temperature (°C) downstream of the point of discharge assuming 100% mix.

$\Delta T =$ The maximum temperature increase (°C) above the applicable river temperature criterion using 100% of river flow not to be exceeded by each individual source from all outfalls combined. When the minimum duties provision at OAR 340-041-0028(12)(a) applies, ΔT = 0.0.

$WLA =$ Waste load allocation (kilocalories/day) from Equation 1.

$Q_E =$ The daily mean effluent flow (cfs).
When effluent flow is in million gallons per day (MGD) covert to cfs:

$$\frac{1 \text{ million } gallons}{1\ day} \cdot \frac{1.5472\ ft^3}{1 \text{ million gallons}} = 1.5472$$

$Q_R =$ The daily mean river flow rate, upstream (cfs).
When river flow is <= 7Q10, Q_R = 7Q10. When river flow > 7Q10, Q_R is equal to the daily mean river flow, upstream.

$T_{E\_WLA} =$ Daily maximum effluent temperature (°C) allowed under the waste load allocation from Equation 5a or Equation 5b.
When T_{E_WLA} is > 32 deg-C, T_{E_WLA} = 32 deg-C as required by the thermal plume limitations in OAR 340-041-0053(2)(d)(B).

$T_C =$ The point of discharge applicable river temperature criterion (°C). When the minimum duties provision at OAR 340-041-0028(12)(a) applies T_C = the 7DADM measured at the facility intake.

$T_{R\_up} =$ Ambient river temperature upstream of the point of discharge (°C).

6.2.5. Calculating acceptable effluent temperatures

The daily maximum effluent temperatures (°C) acceptable under the allowed ∆T and the waste load allocation (WLA).

$$T_{E\_WLA} = \frac{(Q_E + Q_R) \cdot (T_C + \Delta T) - (Q_R \cdot T_C)}{Q_E}$$ **Equation 5a** (using ∆T)

$$T_{E\_WLA} = \frac{(WLA)}{Q_E \cdot C_F} + T_C$$ **Equation 6b** (using WLA)

where,

$T_{E\_WLA} =$ Daily maximum effluent temperature (ºC) allowed under the waste load allocation. When T_{E_WLA} is > 32 deg-C, T_{E_WLA} = 32 deg-C as required by the thermal plume limitations in OAR 340-041-0053(2)(d)(B).

$WLA =$ Waste load allocation (kilocalories/day) from Equation 1.

$\Delta T =$ The maximum temperature increase (ºC) above the applicable river temperature criterion using 100% of river flow not to be exceeded by each individual source from all outfalls combined. When the minimum duties provision at OAR 340-041-0028(12)(a) applies, ΔT = 0.0.

$Q_E =$ The daily mean effluent flow (cfs). When effluent flow is in million gallons per day (MGD) covert to cfs:

$$\frac{1 \text{ million } gallons}{1\ day} \cdot \frac{1.5472\ ft^3}{1 \text{ million gallons}} = 1.5472$$

$Q_R =$ The daily mean river flow rate, upstream (cfs). When river flow is <= 7Q10, Q_R = 7Q10. When river flow > 7Q10, Q_R is equal to the daily mean river flow, upstream.

$T_{C,i} =$ The point of discharge applicable river temperature criterion (ºC) (T_c); or when the minimum duties provision at OAR 340-041-0028(12)(a) applies $T_{C,i}$ = the 7DADM measured at the facility intake (T_i).

$C_F =$ Conversion factor for flow in cubic feet per second (cfs): 2,446,665

$$\frac{1\ m^3}{35.31\ ft^3} \cdot \frac{1000\ kg}{1\ m^3} \cdot \frac{86400\ sec}{1\ day} \cdot \frac{1\ kcal}{1\ kg\ \cdot 1℃} = 2{,}446{,}665$$

6.2.6. Calculating acceptable effluent flows

The daily mean effluent flow (cfs) acceptable under the allowed ΔT and the waste load allocation (WLA).

$$Q_{E\_WLA} = \frac{(Q_R \cdot T_C) - ((T_C + \Delta T) * Q_R)}{T_C + \Delta T - T_E}$$

Equation 6a (using ΔT)

$$Q_{E\_WLA} = \frac{(WLA)}{(T_E - T_C) * C_F}$$

Equation 6b (using WLA)

where,

$Q_{E\_WLA} =$ Daily mean effluent flow (cfs) allowed under the waste load allocation.

$WLA =$ Waste load allocation (kilocalories/day) from Equation 1.

$\Delta T =$ The maximum temperature increase (ºC) above the applicable river temperature criterion using 100% of river flow not to be exceeded by each individual source from all outfalls combined. When the minimum duties provision at OAR 340-041-0028(12)(a) applies, ΔT = 0.0.

$T_E =$ The daily maximum effluent temperature (ºC).

$Q_R =$ The daily mean river flow rate, upstream (cfs). When river flow is <= 7Q10, Q_R = 7Q10. When river flow > 7Q10, Q_R is equal to the daily mean river flow, upstream.

$T_{C,i} =$ The point of discharge applicable river temperature criterion (ºC) (T_c); or when the minimum duties provision at OAR 340-041-0028(12)(a) applies $T_{C,i}$ = the 7DADM measured at the facility intake (T_i).

$C_F =$ Conversion factor for flow in cubic feet per second (cfs): 2,446,665

$$\frac{1\ m^3}{35.31\ ft^3} \cdot \frac{1000\ kg}{1\ m^3} \cdot \frac{86400\ sec}{1\ day} \cdot \frac{1\ kcal}{1\ kg\ \cdot 1℃} = 2{,}446{,}665$$

6.2.7. Determination of when minimum duties applies

DEQ may apply the minimum duties provision at OAR 340-041-0028(12)(a) if a facility operation meets acceptable operation and design requirements in regard to flow pass through. Generally, the facility must be operated as a “flow through” facility where intake water moves through the facility and is not processed.

In the Lower Columbia-Sandy, DEQ determined that ODFW’s Sandy River Fish hatchery is the only facility that operates as a flow through facility. When implementing the waste load locationon, the

The minimum duties provision applies on days when $T_{E\_WLA} < T_i$.

When the minimum duties provision at OAR 340-041-0028(12)(a) applies, $\Delta T = 0.0$.

where,

$T_{E\_WLA} =$ Daily maximum effluent temperature (ºC) allowed under the waste load allocation as calculated using Equation 5a or Equation 5b.

$T_i =$ The daily maximum influent temperature (ºC) measured at the facility intake.

7. Water quality management plan support

[add any needed supporting info for elements of the WQMP – i.e timelines for meeting standards, shade gap/shade curves use and specifics, priority areas, flow considerations…]

8. Acknowledgements

9. References

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Appendix A:
Lower Columbia-Sandy Subbasin Model Report - DRAFT

March 2023

State of Oregon
Department of Environmental Quality

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1. Overview

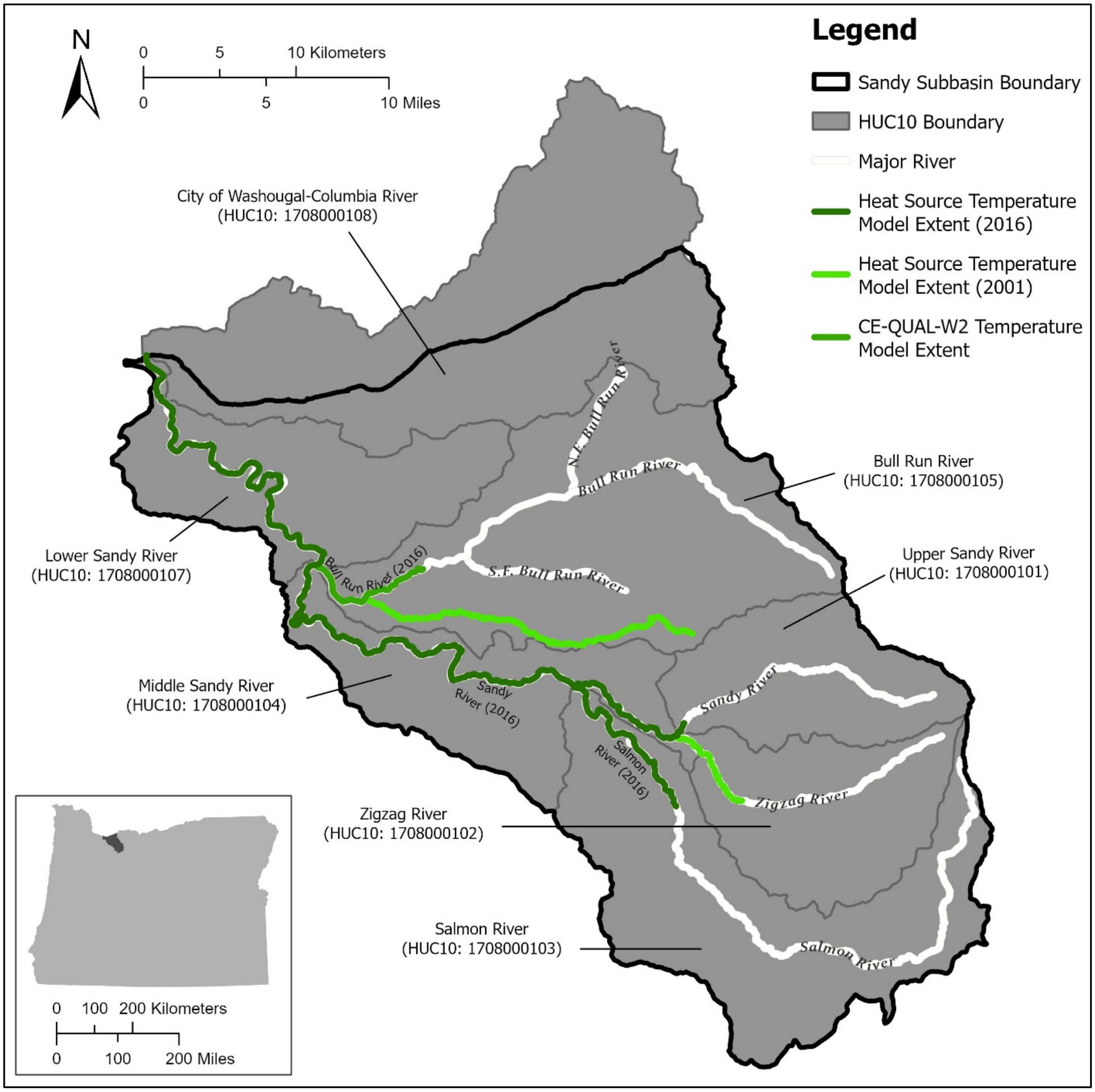

Figure 1. Overview of TMDL project area with stream temperature model extents.

This document - Appendix A to the Technical Support Document (TDS) for the Lower Columbia-Sandy Subbasin (17080001) temperature TMDL replacement project - summarizes the numerical modeling and analytic methods applicable to the TMDL. This includes subbasin-wide and Salmon River-specific descriptions of data and data sources; current conditions model setup and calibration; alternative scenario models and results comparisons; and model sensitivity analysis. Updated analyses were completed for the Sandy River, Salmon River, and Bull Run River subbasins. TSD Appendices B and C provide model-specific details for the

Sandy River and Bull Run River, respectively. For the Little Sandy River and Zigzag River subbasins, the analysis from the 2005 TMDL was retained and summarized herein.

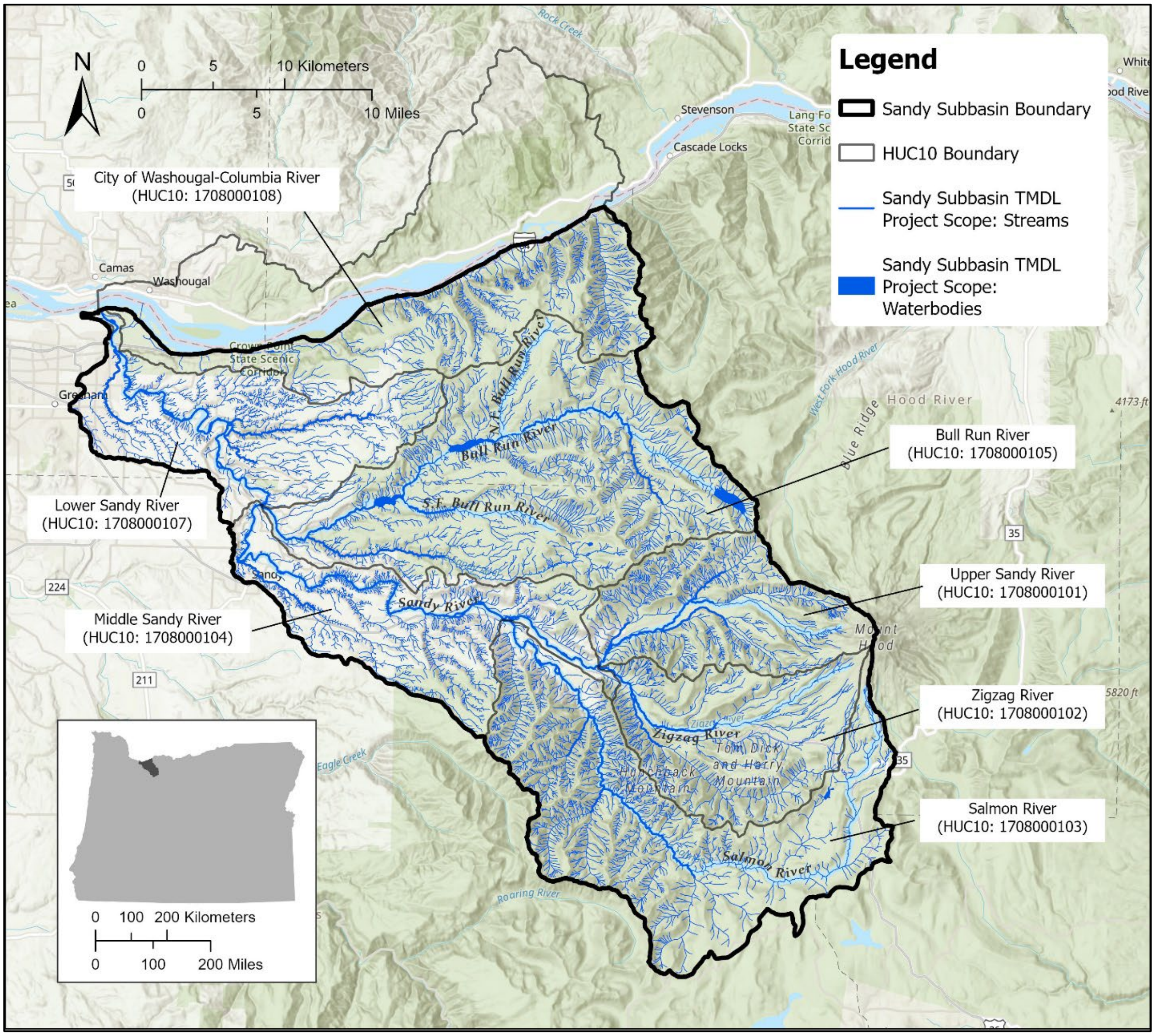

Figure 2. Scope of surface waters within the temperature TMDL project area.

2. Acquired Data

Section 2 describes the field-collected (2.1), remotely acquired (2.2), and derived (2.3) data that were available and applied to support this TMDL modeling effort.

2.1 Field Data

2.1.1 Continuous stream temperature

Continuous stream temperature data were retrieved from DEQ's Ambient Water Quality Monitoring System (AWQMS), USGS's National Water Information System (NWIS), or were obtained during the data solicitation for DEQ's Temperature TMDL Replacement Project. Temperature data retrieved from DEQ's AWQMS database were coded with a Data Quality Level (DQL) of A, B or E, and a result status of "Final" or "Provisional" as outlined in DEQ's Data Quality Matrix for Field Parameters (DEQ, 2013). For TMDL development, only temperature results with a DQL of A or B were used without further review (DEQ, 2021). Data of unknown quality were used per professional judgment following specific quality assessment and control review. Stream temperature datasets are available from DEQ by request.

Available continuous stream temperature monitoring site data are listed in the respective model setup sections. These data were used:

- To evaluate if the waterbody achieves temperature water quality standards,
- As model inputs for tributary inflows and/or the upstream boundary condition,
- To assess model performance and goodness-of-fit by comparing observed to predicted stream temperature data.

2.1.2 Stream flow rate – continuous and instantaneous measurements

Continuous and instantaneous stream flow rate data were collected by various entities at several sites (Figure 3, Table 1) during the 2016 Sandy Subbasin model period. These measurements supported DEQ estimations of flow mass balances, tributary inputs, and other parameters required for the temperature models.

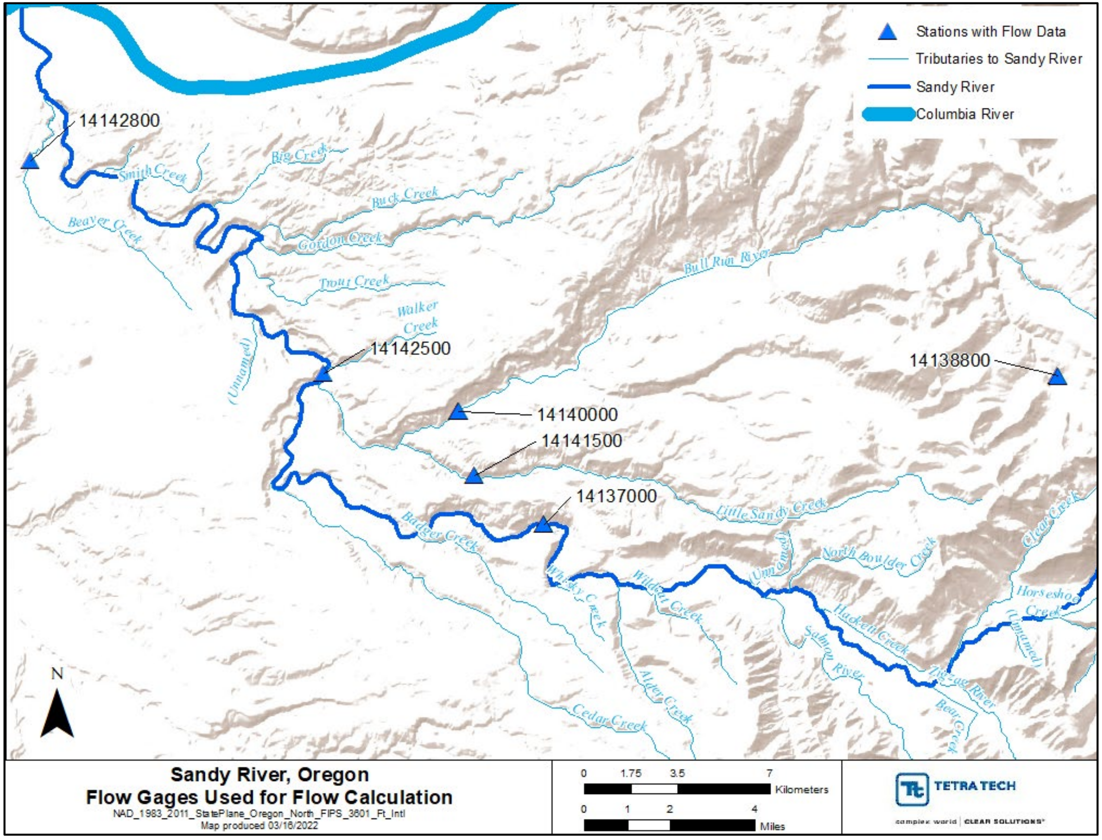

Figure 3. Stream flow rate measurement sites.

Table 1. Continuous flow rate measurement sites for Sandy Subbasin model development.

Subbasin	Station ID	Station Name	Latitude	Longitude	Data Source
Bull Run	PWB_BR_DNSTM_PP	Bull Run Dam 2 outflow	45.4444	-122.159	PWB
Bull Run	14138850	Bull Run R. near Multnomah Falls	45.4983	-122.011	USGS
Bull Run	14139800	S. Fork Bull Run R.	45.4447	-122.108	USGS
Bull Run	14138900	North Fork Bull Run R.	45.4944	-122.035	USGS
Bull Run	14138870	Fir Creek	45.4803	-122.025	USGS
Bull Run	14141500	Little Sandy R.	45.4154	-122.171	USGS
Bull Run	14140000	Bull Run R. Near Bull Run	45.4373	-122.18	USGS
Bull Run	HDWTI025	Lamprey Barrier (primary)	45.4489	-122.155	PWB
Sandy	14142800	Beaver Cr.	45.51929	-122.389	USGS
Sandy	14137000	Sandy R. Near Marmot	45.4000	-122.1373	USGS
Sandy	14142500	Sandy R. Below Bull Run R., Near Bull Run	45.4490	-122.2451	USGS

2.1.3 Point Source discharges

Table 2 identifies NPDES permittees currently covered by an individual permit or registered under the general GEN03 (industrial wastewater-fish hatcheries). These permittees are required to submit annual Discharge Monitoring Reports (DMR). DEQ used DMRs and other permittee-submitted information including monitoring data (when applicable) to characterize relevant point source discharges for the TMDL modeling effort.

Table 2. Instantaneous NPDES discharge measurements for Sandy Subbasin model development.

Subbasin	WQ File Number	NPDES permittee	Latitude	Longitude	Data Source
Sandy	39750	WES (Hoodland STP)	45.3464	-121.969	2016 Discharge Monitoring Report
Sandy	89941	City Of Troutdale Water Pollution Control Facility	45.5535	-122.387	2016 Discharge Monitoring Report
Sandy	34136	Government Camp STP	45.3023	-121.776	Response to Data Solicitation
Sandy	64550	ODFW Sandy R. Fish Hatchery	45.4070	-122.254	Response to Data Solicitation
Sandy	78615	Sandy WWTP	45.4064	-122.320	Response to Data Solicitation

2.2 GIS and Remotely Sensed Data

This TMDL modeling effort entailed inclusion of various GIS and remotely acquired data types as described in Table 3 and the remainder of Section 2.2.

Table 3. Remotely-acquired data used for Sandy Subbasin model development.

Spatial Data Type	Applications
Digital elevation models (DEM), 3-ft	Measure stream elevation and gradient, topography, and shade
Light detection and ranging (LiDAR)	Map, measure, and/or derive ground and surface feature elevations, stream depths, bathymetry, and vegetation heights; develop DEMs
Aerial imagery – digital orthophoto quads	Map/digitize vegetation, stream channels, development, and infrastructure
Thermal infrared radiometry (TIR) stream temperature data	Measure/confirm surface temperatures; develop longitudinal temperature profiles; identify significant thermal features (e.g., springs)

2.2.1 3-ft Digital Elevation Model (DEM)

A digital elevation model (DEM) comprises digital information that provides a uniform matrix of terrain elevation values. It provides basic quantitative data for deriving terrain and stream elevations, stream slope, and topographic information. A 3-ft DEM contains a land surface elevation value for each 3-ft square (i.e., 3-ft resolution). DEMs for this TMDL were produced by DEQ, the DEQ consultant (TetraTech), and the City of Portland from LiDAR data acquired through the Oregon Department of Geology and Mineral Industries (DOGAMI) and Portland State University (PSU).

2.2.2 Light Detection and Ranging (LiDAR)

Light detection and ranging (LiDAR) is a remote sensing method that uses light pulses to calculate ground and surface feature elevations to a high degree of accuracy and resolution. LiDAR data are used to develop high-resolution digital surface models (DSM) and DEMs that can be used to derive canopy height and other parameters. DOGAMI oversees the Oregon LiDAR Consortium (OLC), which develops cooperative agreements for LiDAR collection and provides a LiDAR data download portal [1]. For the updated analysis, LIDAR data collected in 2015, 2014, 2012, 2011, and 2009 were used to characterize vegetation height, ground elevations, and stream depth and bathymetry.

2.2.3 Aerial Imagery – Digital Orthophoto Quads (DOQs)

A digital orthophoto quad (DOQ) is a digital image of an aerial photograph from which displacements caused by the camera angle and terrain have been removed. DOQs are projected in map coordinates, thus combining photographic image characteristics with map geometric qualities. For the updated analysis, DEQ obtained color DOQs representing 2018-collected imagery and data from the DOGAMI portal[1]. For the original TMDL analysis (DEQ 2005), DOQs collected in 1997 and 2000 were used.
These were used to:

- Map/digitize stream features such as position, channel edges, and wetted channel edges,
- Map/digitize near-stream vegetation, and
- Map/digitize instream structures such as dams, gages, and unmapped diversions/withdrawals.

2.2.4 Thermal Infrared Radiometry (TIR) temperature data

Thermal infrared radiometry (TIR) stream temperature data were used to:

- Develop continuous spatial temperature data sets,
- Calculate longitudinal heating profiles/gradients,
- Visually observe complex distributions of stream temperatures at a large landscape scale,
- Map/identify significant thermal features,
- Develop flow mass balances,
- Validate simulated stream temperatures.

A powerful use of TIR-derived stream temperature data is the direct observation of spatial temperature patterns and thermal gradients. In a longitudinal stream temperature profile, thermally significant areas can be identified and directly ascribed to specific sources (e.g., water withdrawal, tributary confluence, vegetation patterns). Areas where stream and subsurface water mix (e.g., hyporheic and spring inflows) are typically apparent in TIR data. TIR-represented thermal changes are quantifiable as specific stream temperature changes, or gradients that reflect a temperature change over a specific distance. TIR data can be viewed as GIS point coverages or TIR imagery.

TIR imagery measures the surface temperature of waterbodies or objects captured in the TIR image (i.e., ground, vegetation, and stream). TIR data were acquired via a helicopter-mounted sensor that collected digital data directly to an on-board computer at a rate that ensured the imagery maintained a continuous image overlap of ≥40% with a resolution of <0.5m/pixel (Watershed Sciences, 2001). The TIR detected and recorded emitted radiation levels at 8-12 µm wavelengths (long-wave) as a digital image across the sensor's full 12-bit dynamic range. Each image pixel contained a measured value that was converted directly to a temperature value. A visible video sensor captured the same field-of-view as the TIR sensor, with GPS time and coordinates encoded on the imagery. In-stream temperature data loggers were installed throughout the survey in each subbasin to verify the TIR-measured radiant temperatures.

Data collection was timed to capture maximum daily stream temperatures, which typically occur between 1400h-1800h. The helicopter was flown longitudinally over the stream channel center with the sensors in a vertical (or near-vertical) position. Generally, flight altitude was maintained so the stream channel comprised ~20-40% of the image frame, with ~300m minimum flight altitude maintained for safety and maneuverability. If a stream split into two channels that could not be contained in a single field of view, the survey was completed on the larger of the two channels. The TIR survey reports contain detailed flight information, results discussions, sample imagery, and longitudinal temperature profiles. TIR datasets are available upon request from DEQ.

DEQ utilized TIR data collected in 2001 in the Sandy Subbasin (Table 5). Longitudinal river temperatures were sampled with TIR in separate flights for each stream. Temperature data sampled from the TIR imagery revealed that spatial patterns varied due to localized stream heating, tributary mixing, and groundwater influences. Thermal stratification was identified in TIR imagery and by comparison with the instream temperature loggers. For example, TIR imagery may reveal a sudden cooling at a riffle or downstream of a structure where water was relatively stagnant or deep just upstream of a dam.

Table 4. TIR survey extents and collection dates in the Sandy Subbasin.

Stream	Survey Extent	Survey Date	Time	Survey Distance (mi)	Survey Distance (km)
Bull Run R.	Mouth to Bull Run Lake	2001-08-08	13:54-14:36	23.42	37.69
Little Sandy R.	Mouth to headwaters	2001-08-08	14:44-14:59	15.05	24.22
Salmon R.	Mouth to headwaters	2001-08-08	15:11-16:24	32.36	52.08
Sandy R.	Mouth to headwaters	2001-08-09	14:02-14:31	53.33	85.83
S. Fork Bull Run R.	Mouth to headwaters	2001-08-09	14:38-15:50	6.31	10.15
S. Fork Salmon R.	Mouth to headwaters	2001-08-09	14:58-15:08	5.18	8.34
Zigzag R.	Mouth to headwaters	2001-08-09	15:57-16:19	12.38	19.92

2.3 Derived Data

For model setup, several spatial datasets were derived from landscape-scale GIS data. Sampling density was user-defined and typically matched GIS data resolution and accuracy. As detailed in 2.3.1-2.3.7, the derived parameters used in stream temperature analyses were:

Figure 4. Examples of digitized channel (blue segment) and stream nodes (green dots).

- Stream position and morphology, e.g., aspect, gradient, width
- Land cover classification and designated management agency (DMA)
- Maximum topographic shade angles, i.e., East, South, West
- Vegetation type, height, and canopy density

2.3.1 Stream Position and Channel Width

Stream position and active channel width were estimated and applied at 50m increments via the following steps:

1. Stream right and left banks (relative to downstream) were digitized at a 1:2,000 or smaller map scale from a combination of USDA National Agricultural Imagery Program (NAIP) aerial imagery and hillshade data derived from LiDAR data. Digitized streambanks corresponded to the active channel width, i.e., width between shade-producing riparian vegetation and/or the low-flow channel edge.

2. The stream center flowline was digitized at a 1:2,000 or smaller map scale by following the volume-estimated center of the active channel.

3. The stream center flowline was segmented into 50m reaches, each separated by a node, using the Python TTools scripts [2]. These nodes (e.g., in Figure 4) defined the discrete modeling locations and flow path.

2.3.2 Channel Bottom Width

2.3.2.1 Heat Source 8: Sandy River and Salmon River Models

The Heat Source model assumed a trapezoidal channel shape and required channel bottom width inputs (b_2) (Figure 5) that were estimated with Equation 1. For Equation 1, the active channel width (b_1) was the digitized channel width (Sec 2.3.1). Mean depth (D) was calculated as b_1/(width:depth) (measured or estimated) at each node. Channel angle (z) and the width-to-depth ratios (width:depth) are estimated model calibration parameters.

Equation 1

$$b_2 = b_1 - 2 \cdot z \cdot \mathrm{D}$$

where,

$b_2 =$ Bottom width (m)

$b_1 =$ Active channel width (m)

$\mathrm{D} =$ Mean active channel depth (m). Estimated as b_1/(width:depth).

$z =$ Channel angle (unitless), defined as the horizontal distance change per unit vertical distance change of the channel side slope.

2.3.3 Stream Elevation and Gradient

For the Sandy and Salmon Rivers, stream elevation and gradient were derived for each stream node from the 3-ft LiDAR data (DOGAMI, PSU). Stream gradients were calculated as the inter-node elevation change divided by the inter-node distance (50m).

For the Bull Run River, stream elevation and gradient data were derived from an existing PSU model with no adjustments except for some cases in which segment lengths were adjusted slightly to align the segments in the GIS layer, which had a nominal effect on stream gradient.

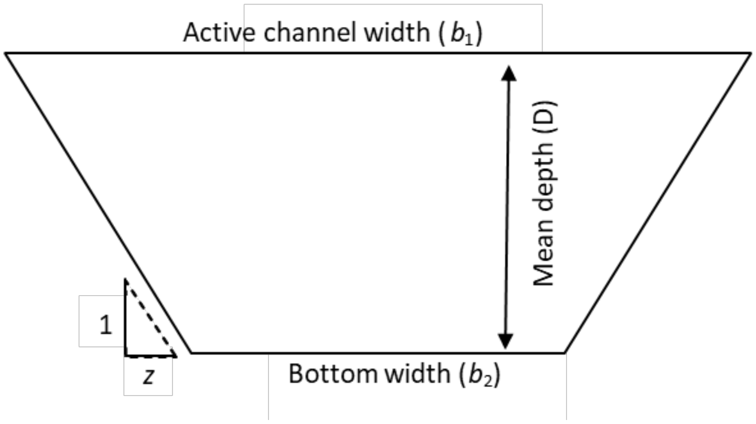

Figure 5. Conceptual diagram of trapezoidal channel and terms used in Equation A1.

2.3.4 Topographic Shade Angles

A topographic shade angle represents the vertical angle from a node along a flat horizon to the highest (visible) topographic feature in each direction. When the sun's angle ≤ topographic shade angle, the referenced topographic feature casts a shadow over the referenced stream node. Topographic shade angles were used to derive effective shade information for the current conditions model and various modeled scenarios.

For the Salmon and Sandy Rivers, topographic shade angles were calculated for three directions (W, S, E) using Equation A2 with the TTools python script [1]. Elevations were sampled from the 3-ft LiDAR bare earth data (DOGAMI, PSU). For each stream node and direction, the derived topographic shade angle was the maximum value calculated (Equation A2) among all raster cells typically within 10km of the node in that direction.

For the Bull Run River, topographic shade angle was calculated using Equation 2 using sampled geometry statistics from ArcMap and solving for maximum angles of effect in R. Elevations were sampled from (Sciences, 2014). The maximum topographic shade angle in each direction for each stream node was the maximum value calculated (Equation A2) among all raster cells typically within 10km in 18 directions (20° vectors).

Equation 2

$$\theta_T = \tan^{-1}\left(\frac{Z_T - Z_S}{d}\right)$$

where,

$\theta_T =$ The topographic shade angle (°)
$Z_T =$ The elevation (m) at the topographic feature.
$Z_S =$ The elevation (m) at the stream node.
$d =$ Horizontal distance (m) from stream node to topographic feature.

Because there is a direct and quantifiable relationship between effective shade and thermal flux, OAR 340-042-0030(14) and OAR 340-042-0040(5)(b) allow the use of effective shade as a surrogate measure target for thermal loading targets. One benefit of this surrogate measure use is that it is simpler and therefore more feasible for many practitioners to assess effective shade than thermal loading in their management areas.

2.3.5 Land Cover Mapping

DEQ and contractor staff developed and mapped land cover type and above-ground elevation data for all 3-ft square areas within 300 ft of the channel edges as follows:

1. Staff manually digitized GIS polygons and polylines via visual analysis of DOQs and aerial images at a 1:5,000 map scale or less. Each polygon was bounded to include a single land cover type.
2. A categorical land cover type (number) and density was assigned to each polygon. Land cover types (Table 6) included various vegetation groups (e.g., conifers, hardwoods, shrubs, grasses, barren), development types (e.g., industrial/commercial, residential, roads, bridges, dams), and surface waters.
3. Land cover heights were calculated for each 3-ft cell from LiDAR data analysis.
4. Staff generated a series of six-digit codes to represent each combination of land use type/density (digits 1-3) and height (digits 4-6) present in the near-stream area (i.e., within 300' of channel edges).

5. In the updated analysis, for each node, TTools was used to sample the six-digit code of each (3-ft) cell every 8m in a 120m radius in seven directions: NE, E, SE, S, SW, W, and NW. This sampling rate resulted in 3360 land cover measurements per stream km. In the original TMDL analysis, TTools sampled every ~4.6m from the stream node perpendicular to both stream banks up to ~36.5m from the channel edge for a total of 948 land cover measurements per stream km. These data served as land cover inputs for Heat Source models.

Table 5. Land cover codes used in land cover mapping.

Code	Description	Height (m)	Density (%)	Overhang (m)
300	Pastures/Cultivated Field	from LiDAR	75	0.0
301	Water – Non-Active Channel	from LIDAR	0	0.0
302	Water - Active Channel Bottom	from LIDAR	0	0.0
305	Barren - Embankment	from LIDAR	0	0.0
308	Barren - Clearcut	from LIDAR	75	0.0
309	Barren - Soil	from LIDAR	0	0.0
348	Development - Residential	from LIDAR	100	0.0
349	Development - Industrial/Commercial	from LIDAR	100	0.0
352	Dam/Weir	from LIDAR	0	0.0
355	Canal	from LIDAR	0	0.0
400	Barren - Road	from LIDAR	0	0.0
401	Barren - Forest Road	from LIDAR	0	0.0
500	Mixed Conifer/Hardwood - High Dense	from LIDAR	60	0.0
550	Mixed Conifer/Hardwood - Medium Dense	from LIDAR	30	0.0
555	Mixed Conifer/Hardwood - Low Dense	from LIDAR	10	0.0
600	Hardwood - High Dense	from LIDAR	75	0.0
650	Hardwood - Low Dense	from LIDAR	30	0.0
700	Conifer - High Dense	from LIDAR	60	0.0
750	Conifer - Low Dense	from LIDAR	30	0.0
800	Upland Shrubs - High Dense	from LIDAR	75	0.0
850	Upland Shrubs - Low Dense	from LIDAR	25	0.0
900	Grasses - Upland	from LIDAR	75	0.0
950	Grasses - Wetland	from LIDAR	75	0.0

2.3.6 Derived Tributary Stream Flow

When flow data were unavailable for a given tributary to a modeled stream for the model period, streamflow was estimated based on historical data for the stream or model period data from proxy monitoring sites. For small tributary inputs, a constant flow was often ascribed if detailed proxy or historical data were unavailable. Otherwise, flows were estimated using StreamStats v4 [3], which applies the flow-percentile-percentile-flow (QPPQ) method to derive time-series data for target unmonitored locations from proxy (monitored) locations based on their relative characteristics and the proxy streamflow data [4,5]. Staff identified suitable proxy stations for StreamStats parameterization based on between-location similarities of location, stream aspect, land cover, and watershed size. Proxy information for locations represented by derived flow data is provided in Section 3 for each stream model's "Flow Inputs" subsection.

2.3.7 Derived Tributary Temperatures

For each modeled stream's tributaries, if 2016 model period temperature data were unavailable, estimated values were applied based on direct substitution of contemporaneous data from proxy locations; linear regression of the target tributary's 2001 data against a proxy location's 2001 and 2016 data; TIR data (input as constant temperature), or calibrated Heat Source model results for the tributary. Proxy information for all such locations is provided in Section 3 for each stream model's "Temperature Inputs" subsection.

3. Model setup, calibration, and results

3.1 Background and general set-up methods:

3.1.1 General background, purpose, objectives

Stream temperature TMDLs are generally scaled to a subbasin or basin scale since water temperatures
are influenced by cumulative effects of upstream and local sources. Accordingly, this TMDL considers all surface waters that affect the temperatures of 303(d) listed waterbodies (e.g., the Sandy River) in the subbasin. To address listings in this TMDL, the analysis considers all upstream waters of the state and applies TMDL allocations through the entire stream network. This technical support document (TSD) reports on new models developed (with 2016 data) for this TMDL (i.e., for the Bull Run River, Salmon River, and Sandy River). Results from pre-existing models (developed with 2001 data) are described in the TMDL Quality Assurance Project Plan (QAPP).

An important purpose of this modeling is to provide quantitative stream heat source assessments that differentiate various background and anthropogenic source contributions. Another is to determine seasonal variation and delineate periods when applicable temperature criteria are exceeded at various locations. Ultimately, this modeling establishes the loading capacity (LC) that specifies the amount of heat that relevant waterbodies can receive and still meet water quality standards. This also allows us to quantitatively assess the effects that various modifications to watershed parameters would have on the flow and water temperature regimes overall and for critical periods and in-stream locations. Modeling these *potential* conditions is referred to as "scenario modeling" and is discussed in Section 4.

Anthropogenic nonpoint and NPDES permitted point sources may not heat a waterbody more than 0.3 °C above the applicable criterion, cumulatively at the point of maximum impact (POMI). Modeling determines the portion of the human use allowance (HUA) allocated to each source in the TMDL. These are translated into numeric or narrative wasteload allocations (WLAs) for each NPDES permittee.

For this TMDL, general modeling requirements include the ability to evaluate and/or predict hourly:

1) Solar radiation flux and daily effective shade at ≤100m longitudinal resolution.
2) Stream temperatures over several months at ≤500m longitudinal resolution.
3) Stream temperature responses to upstream in-catchment changes to:
    a. Streamside vegetation/shade.
    b. Water withdrawals and tributary flows.

c. Channel morphology.
d. NPDES permitted facilities' effluent temperatures and flows.

3.1.2 General model inputs and parameters

3.1.2.1 CE-QUAL-W2 version 4

The Bull Run River was modeled by the City of Portland Water Bureau using the CE-QUAL-W2 v4.2 2-dimensional hydrodynamic and water quality model . The model was updated from a prior version developed by Portland State University. Documentation for the model, set-up, and input and calibration parameters is described in the Bull Run River Model Report (PWB, 2022).

3.1.2.2 Heat Source version 8

The main input parameter types for Heat Source 8 include water and thermal fluxes, meteorology, stream morphology, vegetation, and more general geographic, geologic, and spatiotemporal parameters and boundaries. These acquisition and development of the corresponding datasets are described in Section 2. Stream-specific procedures and characteristics are discussed for the Salmon River in Section 3.2, the Sandy River in TetraTech's modeling report section, and the Bull Run River in the Portland Water Bureau's modeling report section.

Model calibration was conducted when basic model setup was complete. The basic approach to calibration was to compare actual available field data for water and temperature in the modeled stream (i.e., calibration data) to the model results for the same parameters and locations as existing calibration data. Calibration data and model results are compared using goodness-of-fit procedures in the R statistical software environment and visually to assess model precision, accuracy, and identify specific results (e.g., certain times or stream locations) where model accuracy should be improved.

To improve model fitness, different model iterations reflecting variations of specific DEQ-identified model parameters were completed. Model output was reassessed as above, and the most optimal model was selected as the final calibrated model based on the aforementioned goodness-of-fit and other model output assessments. Stream-specific calibrations are discussed in the following sections. Calibration parameters included meteorological (wind speed, air temperature, cloudiness), hydrogeomorphological (tributary temperatures, withdrawal rates, channel gradient, channel width, channel angle z, Manning's roughness coefficient, hyporheic zone thickness and exchange rates, porosity, sediment thermal conductivity and bed thickness).

Heat Source 8 models the effective shade parameter. Because Heat Source 8 modeling can determine thermal loading under current conditions and various scenarios, which includes quantification of the TMDL for the modeled area, and because effective shade is accepted as a surrogate measure for thermal loading, this modeling also allows determination of effective shade targets (that will effectively meet the Temperature TMDL). The effective shade achieved under current conditions and various potential conditions (model scenarios) can thus be compared to effective shade targets to determine (i) if a given area meets its shade target (i.e., meets the TMDL requirement), and (ii) the amount of any "shade gap" between the modeled condition and the target.

3.2 Salmon River

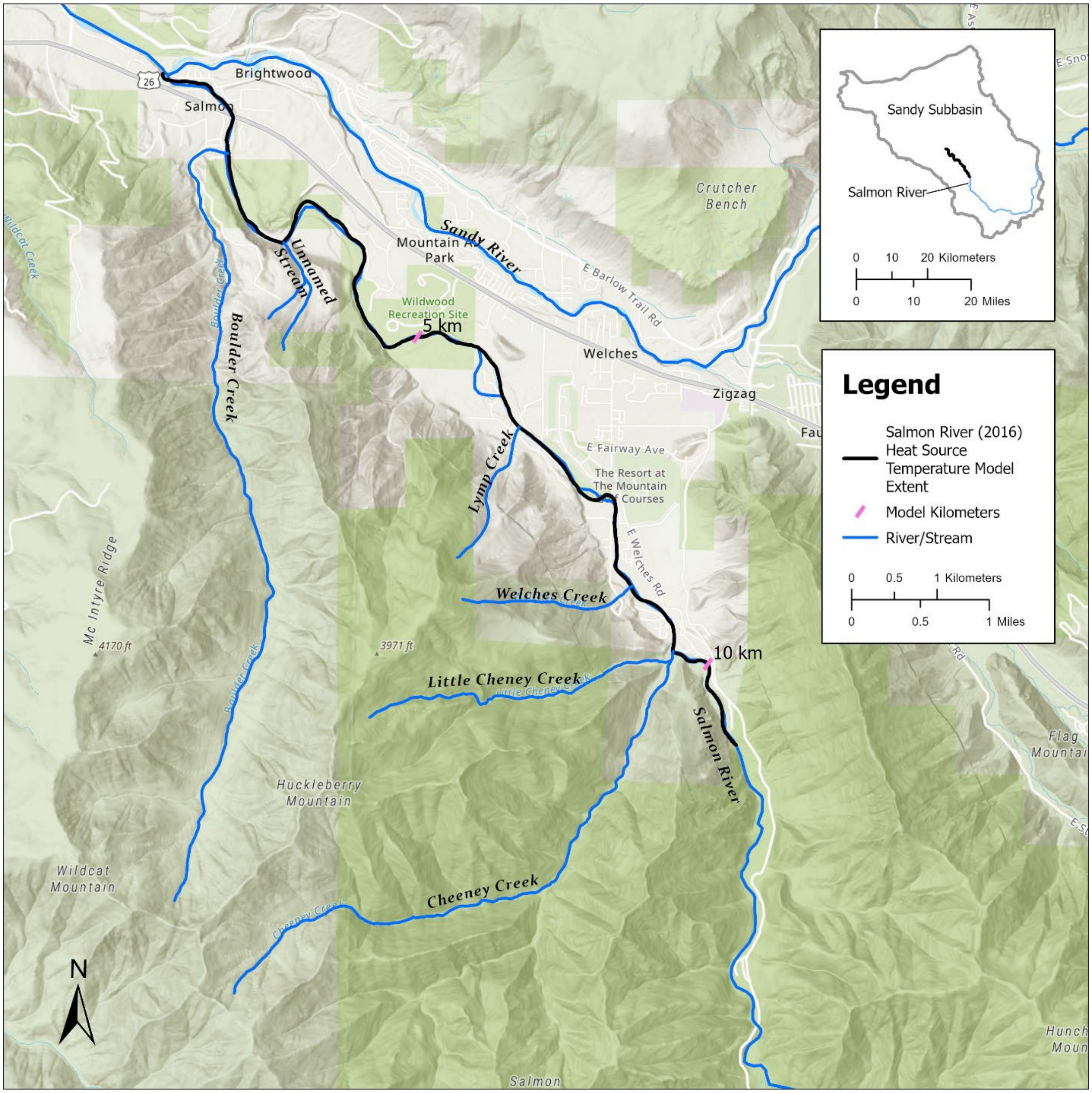

Figure 6. Salmon River model extent

Table 6. Salmon R. model meteorological, water temperature, and flow inputs.

Station ID	Station	Model location (km)	Lat/Long	Input Type	Parameters	Data Source
10009634	Portland Troutdale Airport	13.0	45.5511/-122.409	Meteorological	Air temp., relative humidity, wind speed	MesoWest
EW6654	Rhododendron	13.0	45.3463/-121.951	Meteorological	Cloudiness	NCDC
MHNF-077	Salmon R. at Forest Boundary_LTWT	13.0	45.3072, -121.944	Boundary condition	Flow	Derived: proxy ORWD 14134000 (USGS StreamStats)

MHNF-077	Salmon R. at Forest Boundary_LTWT	13.0	45.3072, -121.944	Boundary condition	Water temp.	USFS
MHNF-048	LinneyCr_LTWT		45.2189, -121.859	Proxy for other tributaries	Water temp.	USFS;
26411-ORDEQ	Boulder Cr. at mouth	1.5	45.3687, -122.023	Tributary	Water temp., flow	Derived by linear regression (temp), USGS StreamStats (flow)
26413-ORDEQ	Cheeney Cr.	11.45	45.31662, -121.954	Tributary	Water temp., flow	Proxy: MHNF-048
	Lymp Cr.	7.85	45.33931, -121.977	Tributary	Water temp., flow	Proxy: MHNF-048
	Spring Brook (LB) from TIR image sfsa0215	6.05	45.3493, -121.991	Tributary	Water temp., flow	TIR-derived constant (15.9°C)
	Spring in TIR image sfsa0199 (LB) (TIR)	5.60	45.3481, -121.996	Tributary	Water temp., flow	TIR-derived constant (13.3°C)
	Unnamed Stream (LB)	2.85		Tributary	Water temp., flow	Derived.

Water temperatures in the Salmon River were modeled with Heat Source 8.0.8 by Oregon DEQ as described below.

3.2.1 Spatial and temporal extent

The model extent is the Salmon River from the mouth to the USFS boundary at monitoring site MHNF-077. The model extent is shown in Figure 6. The model period is July 15, 2016 to September 05, 2016.

3.2.2 Spatial and temporal resolution

The model input spatial resolution (dx) is 50 meters. Outputs are generated every 50 meters. The model time step (dt) is 1 minute and outputs are generated every hour.

3.2.3 Meteorological inputs

Meteorological data (i.e., cloudiness, air temperature, and relative humidity) from Portland Troutdale Airport (10009634) were used for the Salmon River model extent and period (Figures 7-9, Table 7). Although wind speed data were available, wind speed was used as a model calibration parameter given the distance from the data source to the Salmon River calibration locations. Cloud cover data were also modified during calibration under the same rationale.

3.2.4 Temperature inputs

Stream temperatures for seven in-stream locations were input for the model period, including the upstream model boundary and six tributaries (Figure 10, Table 7). Only the upstream boundary location had direct temperature monitoring data available. Temperatures for the tributaries were ascribed based on a constant TIR-derived temperature (Salmon 6.05, Salmon 5.6, and Salmon 2.85), surrogate location data (Salmon 11.45 and Salmon 7.85), or linear regression of 2001 data vs. 2001 and 2006 data from a nearby station (Salmon 1.5).

3.2.5 Flow inputs

Streamflows for seven locations were input for the model period (Figure 20, Table 6). For six locations, streamflow data were derived using Streamstats v4 [1] as described in Section 2.3.6 with the Streamstats-identified reference locations. At the seventh location (a spring at Salmon River km 5.6), a previously estimated constant value (0.0284 cms) was applied. Note: for each in-stream location, there was a direct drainage area and discharge associated with the between-location streambank length (Figure 12). These were included in the model with parameters of flow rate calculated by relative drainage area and water temperature corresponding to the nearest upstream tributary location.

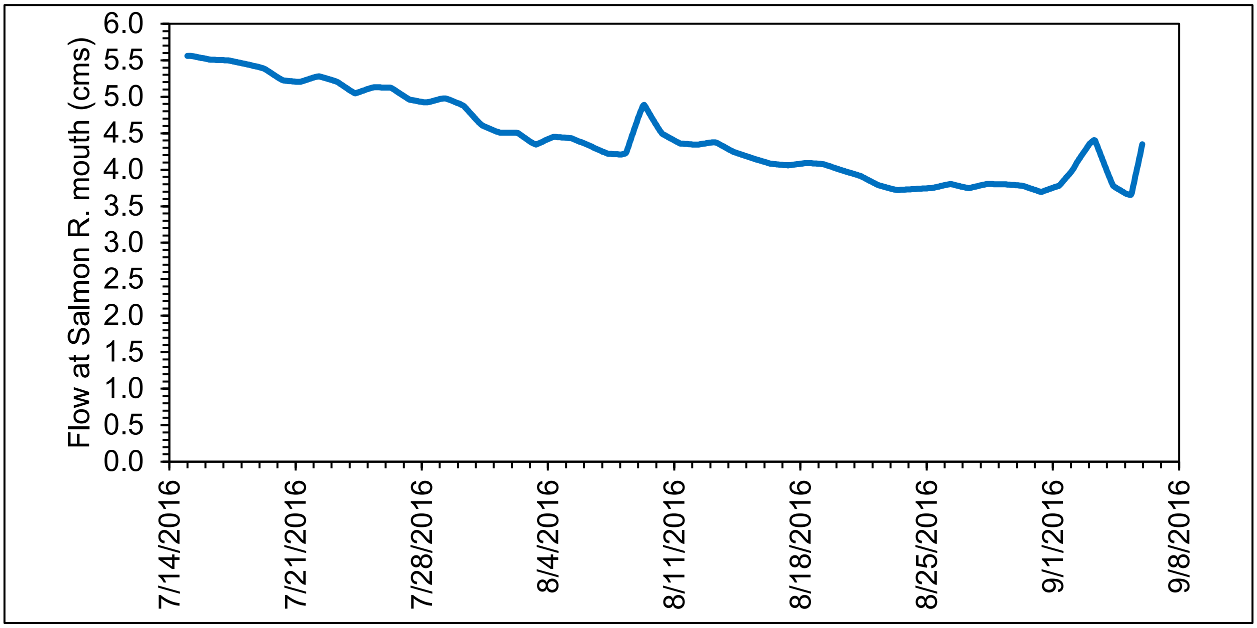

Figure 7. Streamflow at Salmon R. mouth.

3.2.6 Point source inputs

There were no active point source inputs on the Salmon River from the model period to present day.

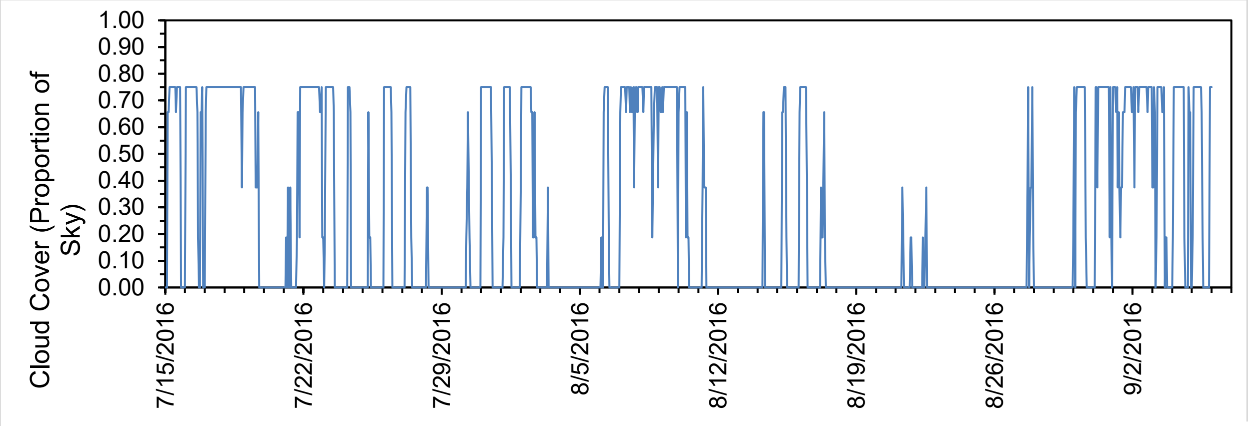

Figure 10. Model setup cloudiness.

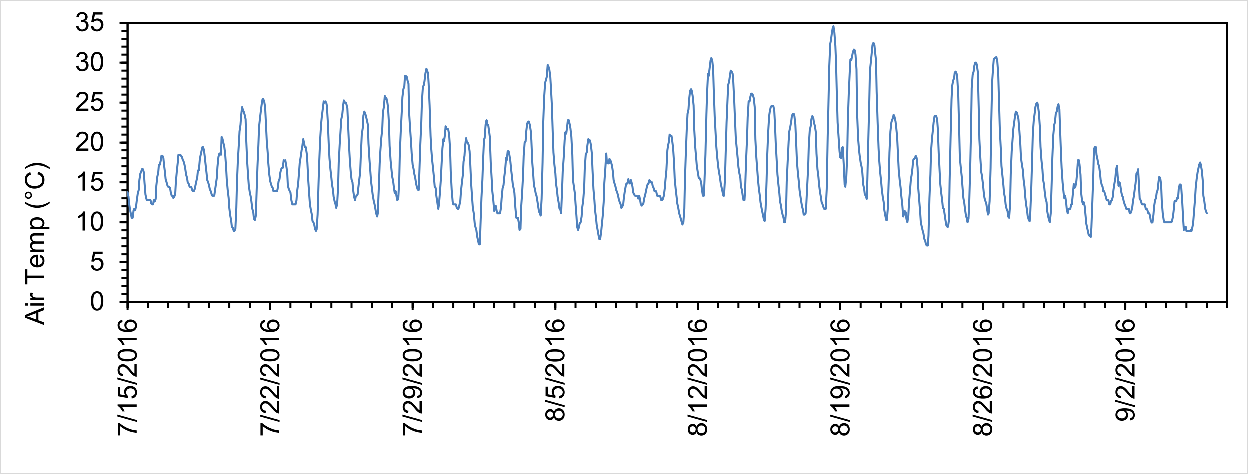

Figure 10. Model setup air temperature.

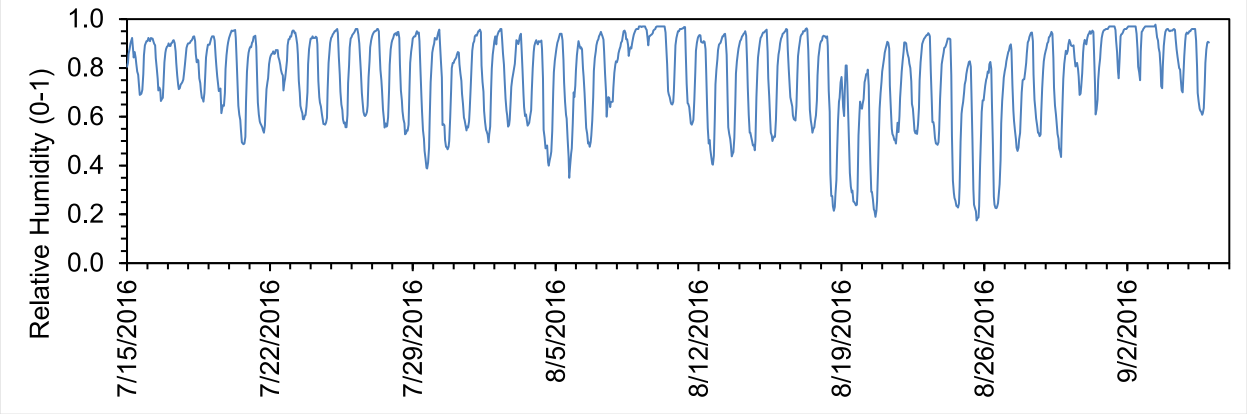

Figure 10. Model setup relative humidity.

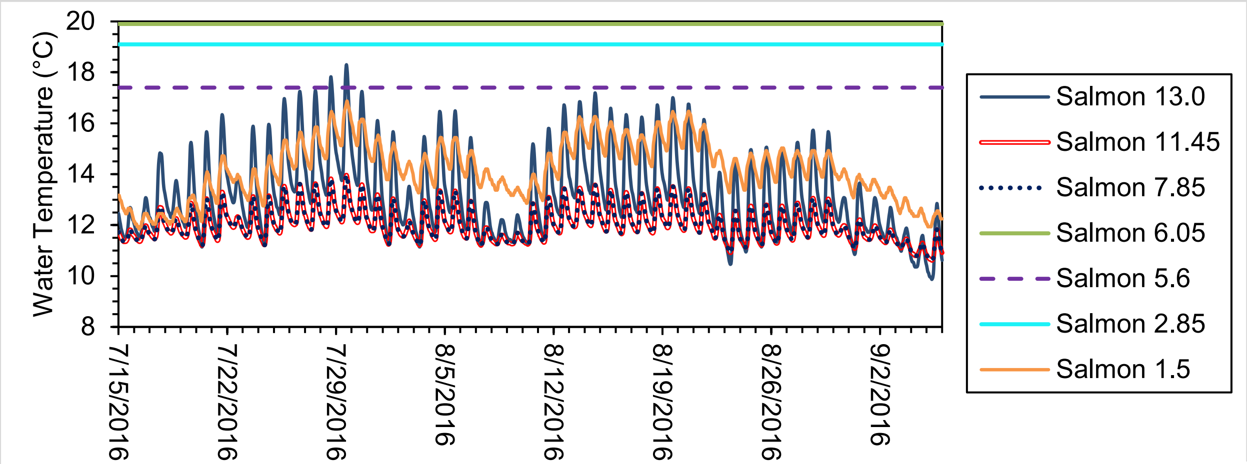

Figure 11. Model setup tributary and boundary condition temperatures.

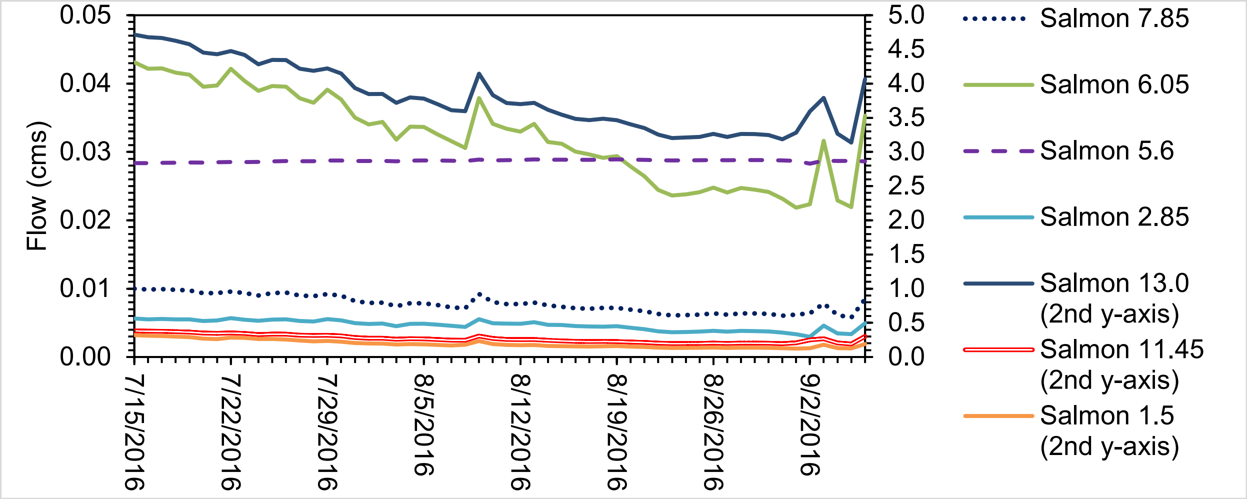

Figure 13. Model setup tributary and boundary condition flow rates.

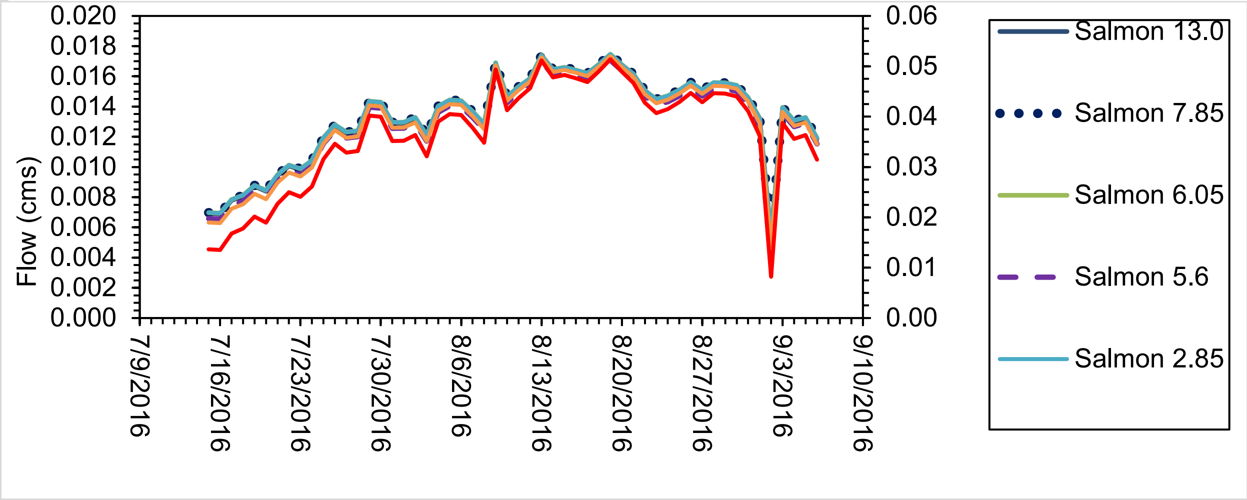

Figure 13. Model setup for between-tributary direct drainage area flow rates.

3.2.7 Landcover and topographic shade inputs

Topography and land cover data were derived as described in 2.3.4-2.3.5. Figures 13-14 present these results for the Salmon River.

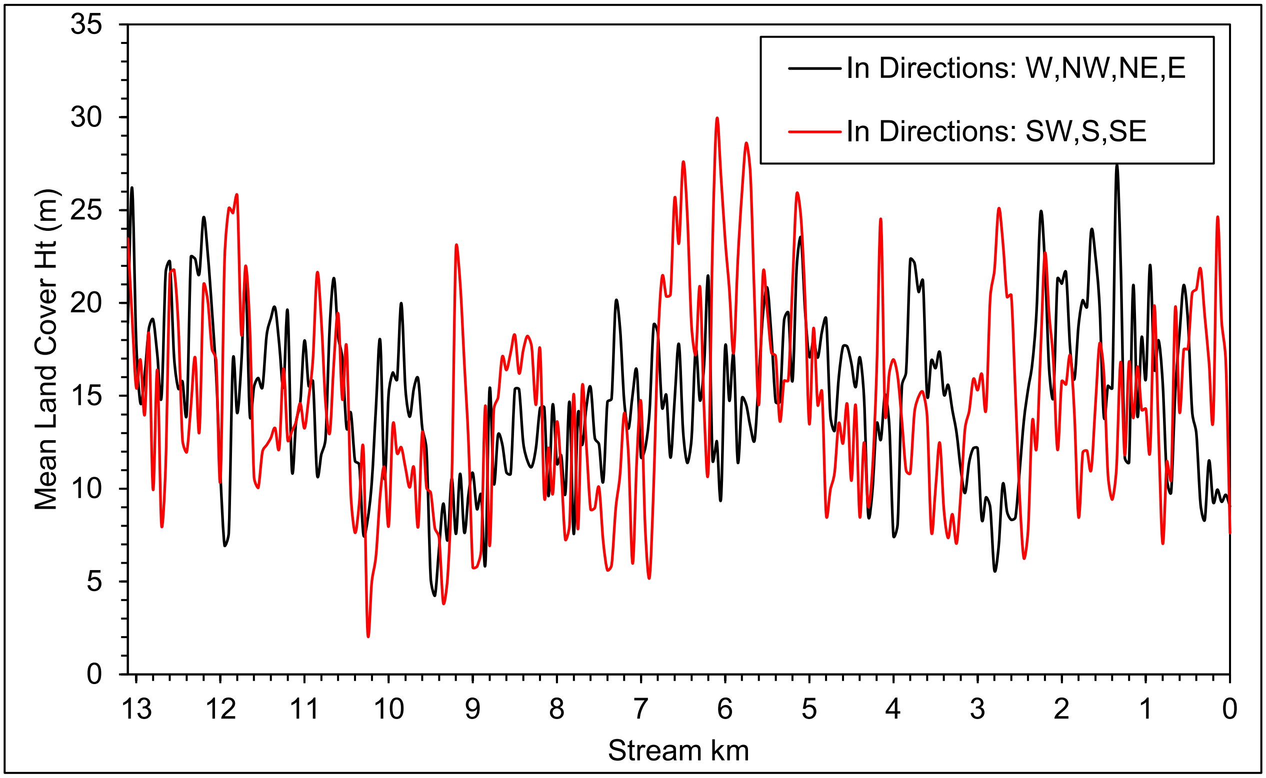

Figure 15. Model setup landcover height (m).

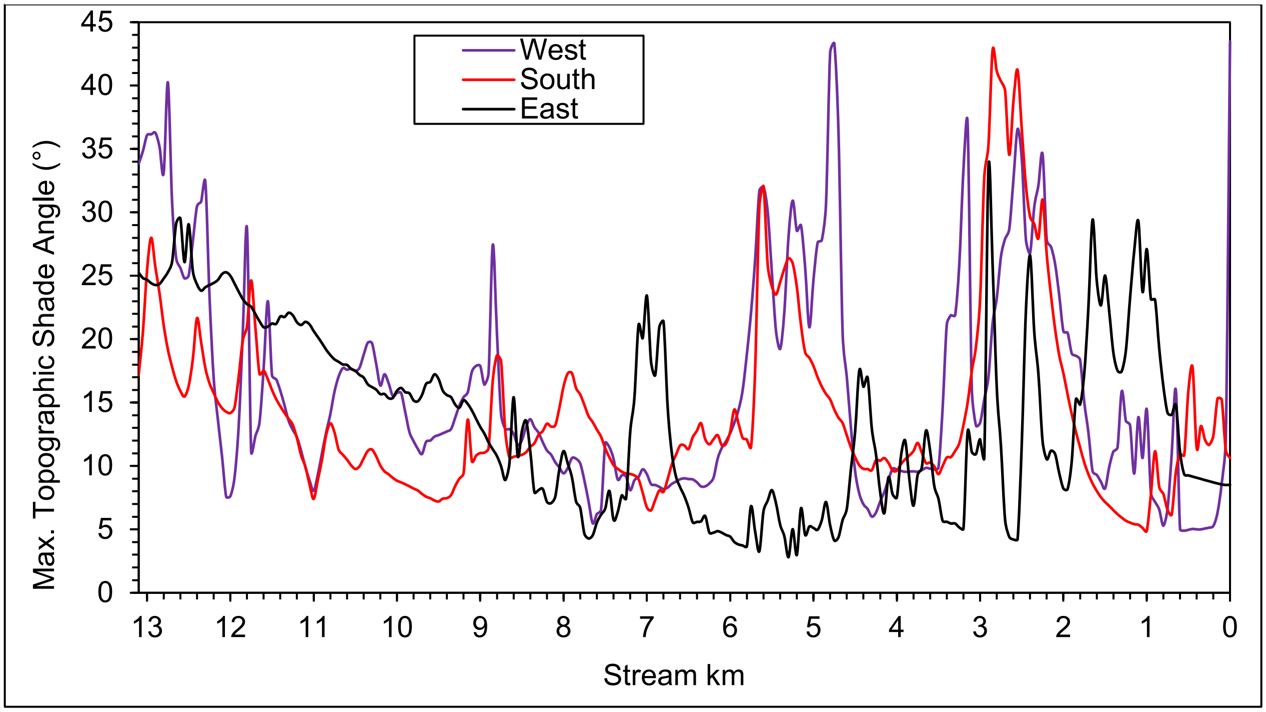

Figure 15. Model setup topographic shade angles.

3.2.8 Channel setup

Channel morphology model input data were derived as described in sections 2.3.2-2.3.3. Figures 15-16 present these results for the Salmon River.

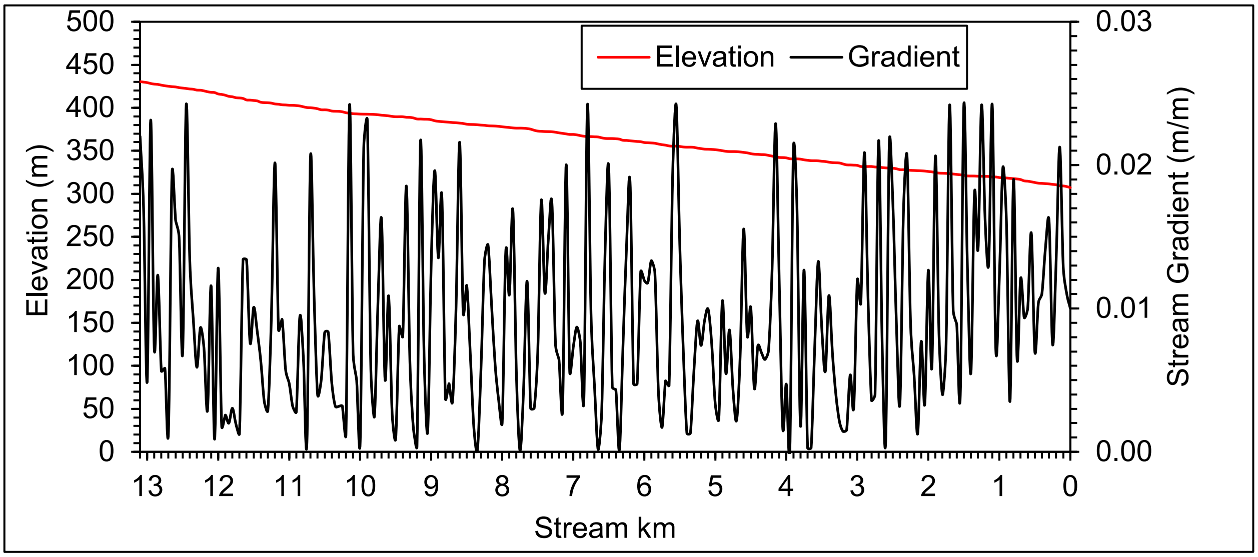

Figure 17. Model setup stream channel elevation (m) and gradient.

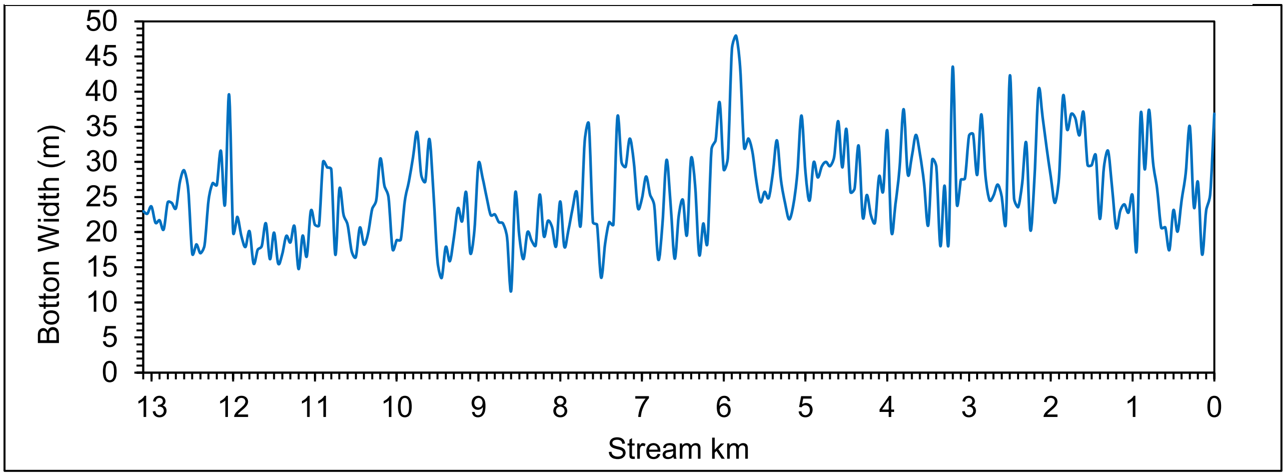

Figure 17. Model setup bottom width (m).

3.2.9 Other model parameters

Table 8 lists additional hydrologic, benthic, and meteorologic parameters included in Salmon River Heat Source modeling. These values were determined based on ranges identified through literature review. Several of these parameters (e.g., Manning's n, Channel angle, hyporheic zone thickness) were used as calibration parameters for CCC model calibration.

Table 7. Model values for non-spatially varying parameters.

Parameter name (units)	Value
Wind function coefficient a	1.51×10^{-9}

Wind function coefficient b	1.60 x 10^{-9}
Channel angle	1.4
Sediment thermal conductivity (W/(m*°C))	1.67
Sediment thermal diffusivity (cm^2/sec)	0.0070
Manning's roughness coefficient (n)	0.205
Sediment hyporheic zone thickness (m)	0.200
Hyporheic exchange (%)	0.015
Porosity	0.35

3.2.10 Salmon River model calibration and results

3.2.10.1 Temperature calibration

Observed stream temperature data for two locations were available to calibrate the 2016 Salmon River model (MHNF-078, Salmon_0.5, Table 1). Modeled and observed data were compared for these locations during the model period (Figure 17). Calibration fitness for the daily maximum temperature and hourly temperature parameters at the two locations was assessed with goodness-of-fit statistics, i.e., the Nash-Sutcliffe efficiency coefficient (NSE), the mean absolute error (MAE), and the root mean square error (RMSE) (Table 8). Target goodness-of-fit values were NSE >0.8, MAE <0.5, and RMSE <1.5.

Table 8. Salmon R. water temp. calibration sites.

Station ID	Station Description	Model location (km)	Lat.	Long.	Source
MHNF-078	Salmon R. trap WT site	3.25	45.3623	-122.011	USFS
Salmon_0.5	Salmon R. above Sandy Brightwood Bridge	0.50	45.3730	-122.021	PSU

When necessary to improve model fitness, adjustments to parameters, i.e., tributary and corresponding direct drainage area water temperatures, Manning's n, cloudiness, wind speed, and stream morphology were tested. Testing was done by making incremental model setup parameter adjustments, rerunning the adjusted model, and selecting the optimal model among all model runs based on the goodness-of-fit statistics. The final calibrated current conditions (CCC) model reflected adjustments to all Manning's n (0.205), cloud cover (coefficient of 0.75 applied to proxy data), and wind speed (all values set to zero) inputs. Stream gradient values were adjusted for 11 of the 263 nodes, including eight extreme high (adjusted to 0.242 based on the maximum values of the non-adjusted nodes) and three extreme low calculated values (adjusted to 0.0001 based on the minimum values of the non-adjusted nodes). For water temperatures, if a given location's values were adjusted, all time-series temperature data for that location were adjusted by a single constant value. Specifically, temperature adjustments comprised the following values for the following tributary locations and corresponding direct drainage areas: Salmon 11.45 km by +3.3°C, Salmon 7.85 km by +3.3°C, Salmon 6.05 km by +4.0°C, and Salmon 5.6km by +4.1°C. No other parameters were adjusted for model calibration.

Table 9. Goodness-of-fit results for observed vs. modeled stream temp.

Monitoring Location ID	Constituent	ME	MAE	RMSE	NSE	n

MHNF-078 & Salmon_0.5	7DADM Temperature	-0.28	0.41	0.53	N/A	106
MHNF-078	7DADM Temperature	-0.53	0.54	0.67	N/A	53
Salmon_0.5	7DADM Temperature	-0.02	0.28	0.32	N/A	53
MHNF-078 & Salmon_0.5	Daily Maximum Temperature	-0.28	0.61	0.75	N/A	106
MHNF-078	Daily Maximum Temperature	-0.51	0.8	0.92	N/A	53
Salmon_0.5	Daily Maximum Temperature	-0.05	0.43	0.53	N/A	53
MHNF-078 & Salmon_0.5	Hourly Temperature	0.02	0.41	0.53	0.93	2544
MHNF-078	Hourly Temperature	-0.04	0.42	0.55	0.93	1272
Salmon_0.5	Hourly Temperature	0.09	0.40	0.51	0.93	1272

The final CCC model met the target goodness-of-fit criteria (Table 8) and showed the best goodness-of-fit among tested model iterations.

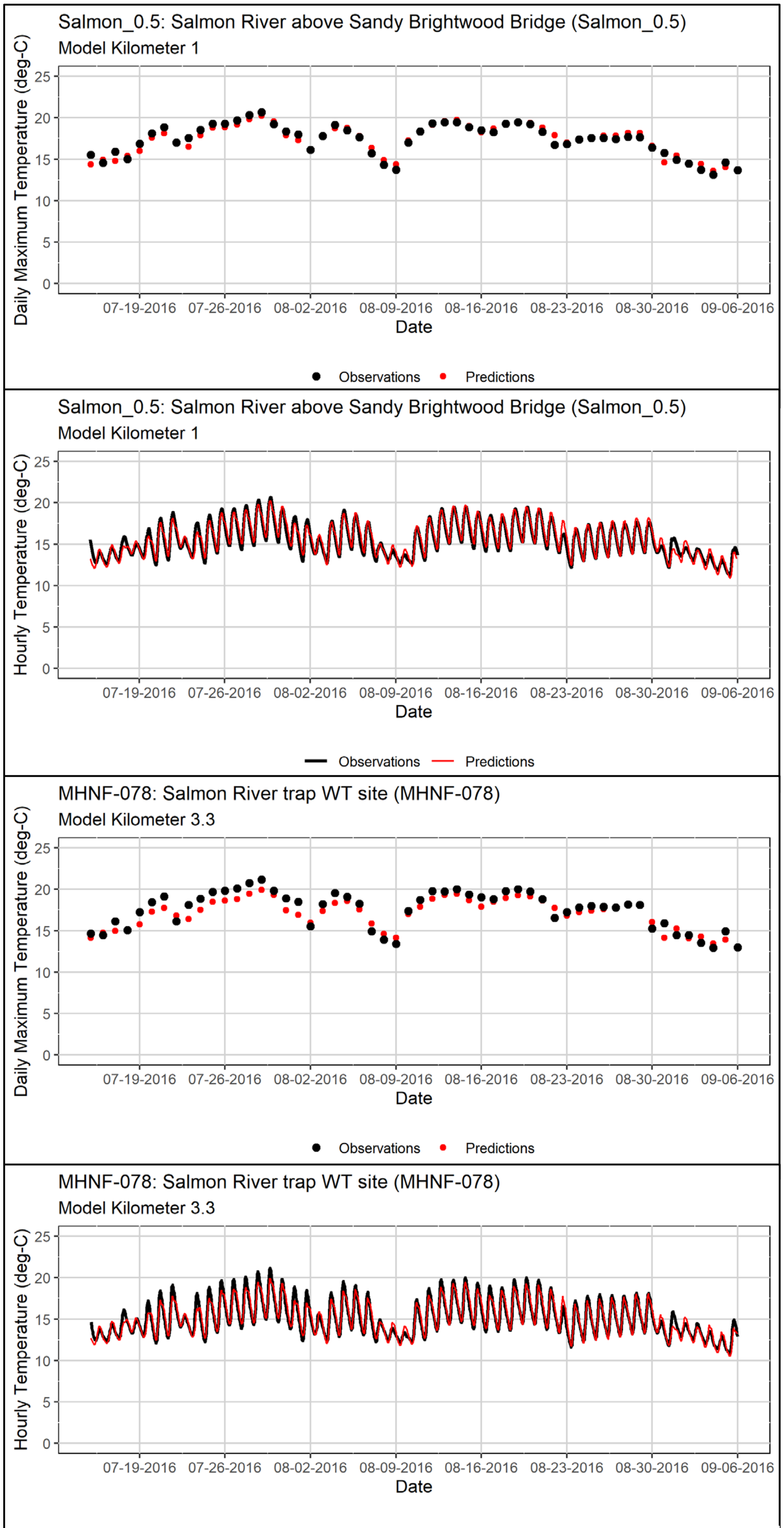

Figure 18. Modeled vs. observed hourly & daily max. temp., two Salmon R. locations.

3.2.10.2 Results – Effective shade

Effective shade for the Salmon River was modeled for July 29th, 2016, with Heat Source 8. Heat Source 8 applies information on coordinates, meteorology, stream morphology, surrounding topography, and existing and potential restored near-stream vegetation to estimate effective shade (%) for each modeled stream node (Figure A35). As discussed in section 3.1, effective shade is an accepted surrogate measure for thermal loading in Oregon. Thus, the effective shade results from the CCC model are compared to target effective shade values that will meet the TMDL and to effective shade estimated under various potential conditions (model scenarios, discussed in Section 4).

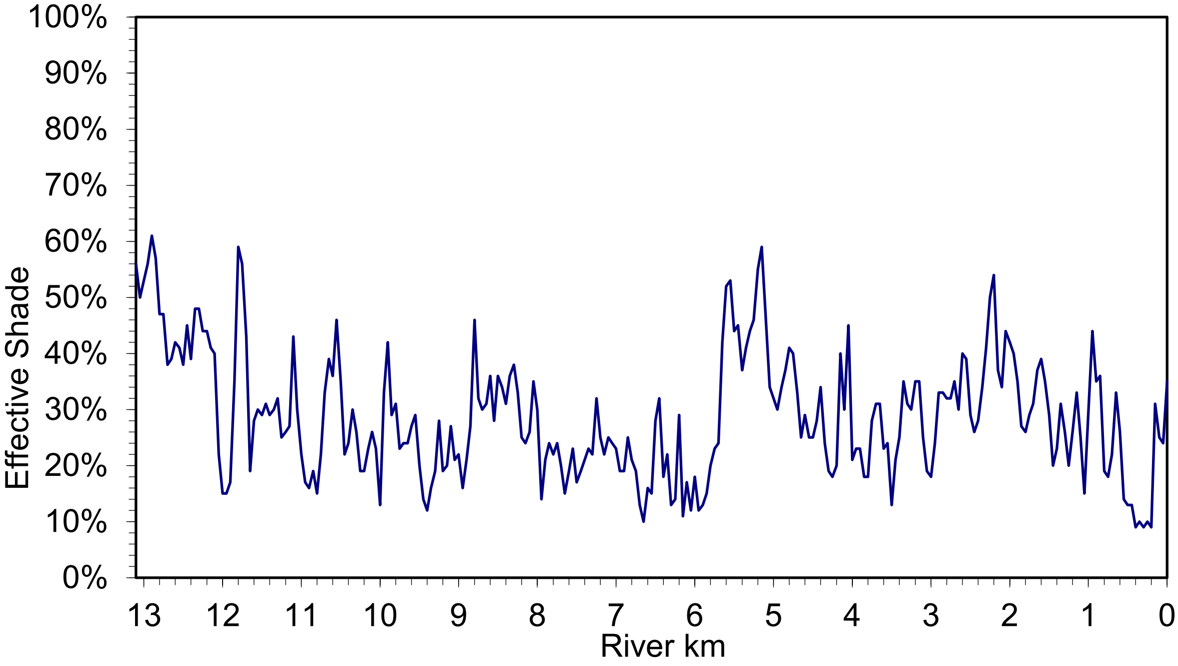

Figure 19. Salmon R. modeled mean effective shade, 7/29/2016.

3.2.10.3 Results - Stream temperature

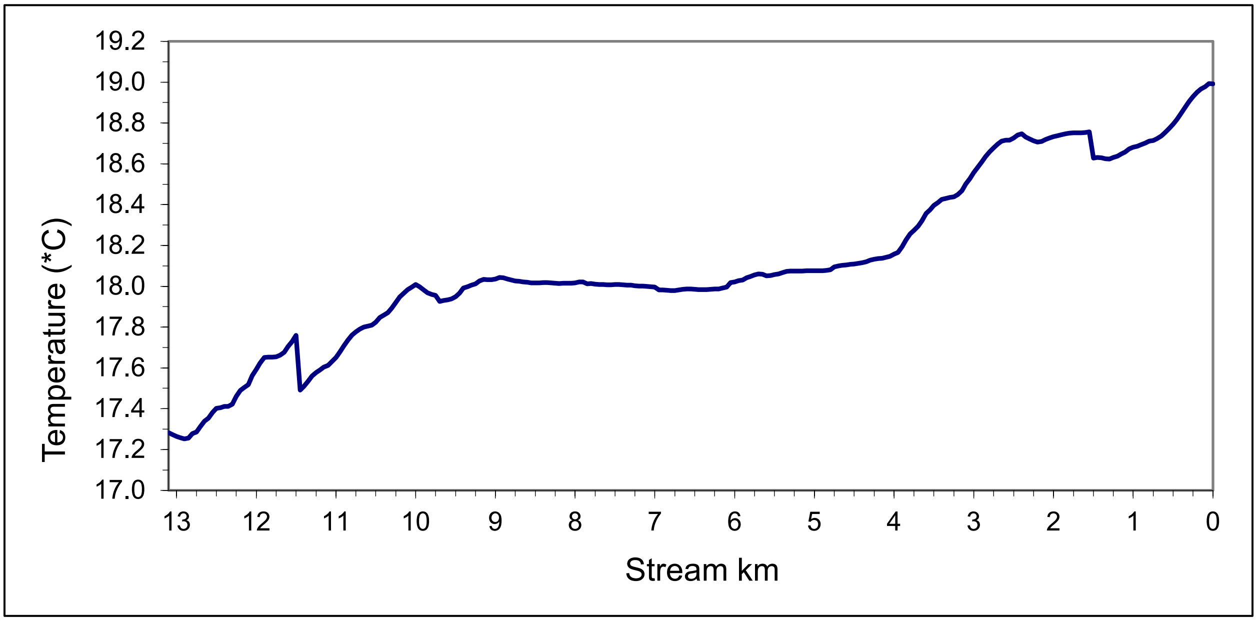

Figure 20. Longitudinal max. 7DADMs during model period.

3.3 Little Sandy River

The Little Sandy River model is a temperature model developed by DEQ using Heat Source 6.5.1.

3.3.1 Spatial and temporal extent

The model domain extent is the Little Sandy River from the mouth upstream to USNF Road 14 (approx. 17.1 km, Figure 19). The model period is a single day: August 09, 2001.

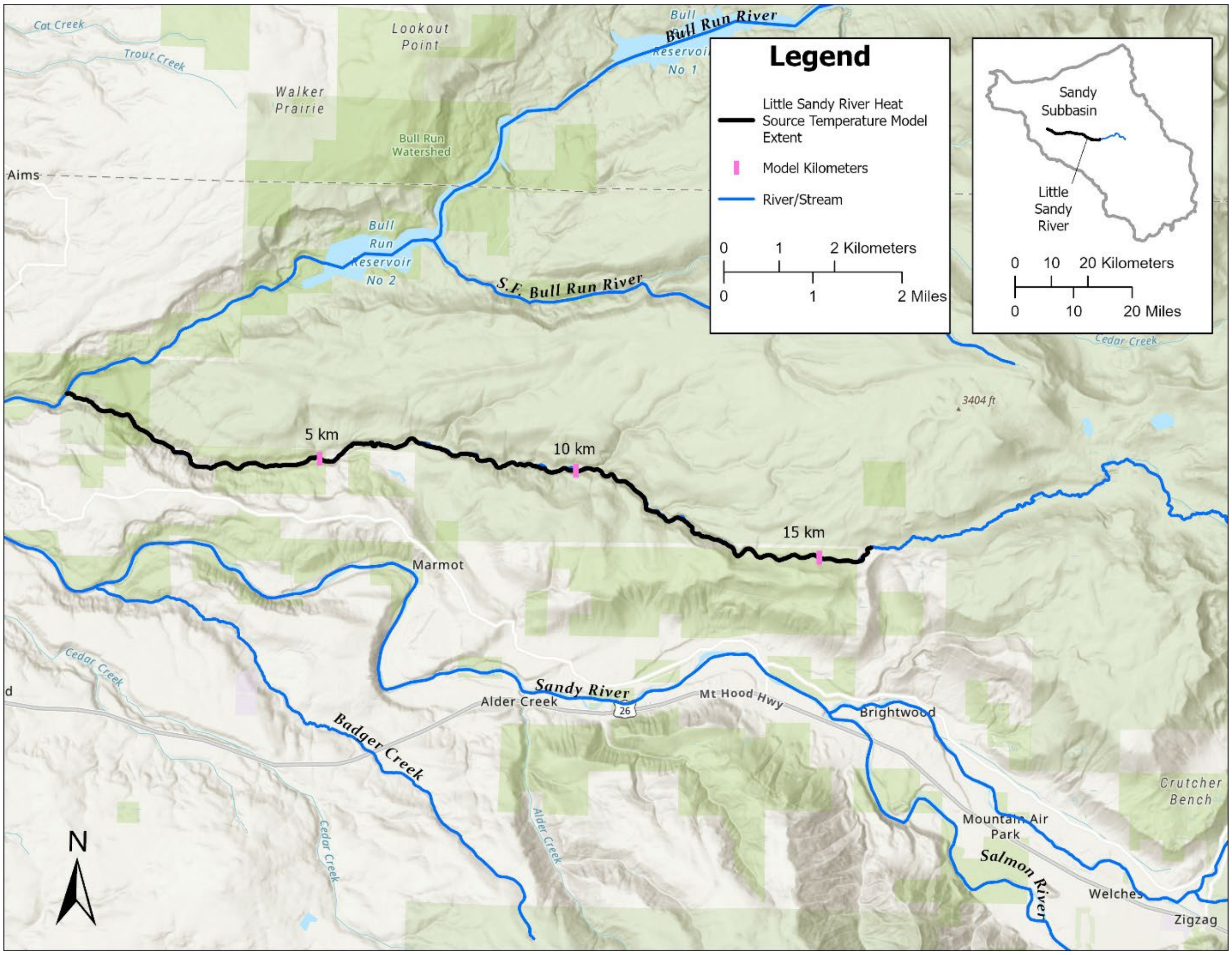

Figure 21. L. Sandy R. model extent.

3.3.2 Spatial and temporal resolution

The model input spatial resolution (*dx*) is 30 m. Outputs are generated every 100 m. The model time step (*dt*) is 1 minute and outputs are generated every hour.

3.3.3 Meteorological, water temperature, and flow inputs

Table 11 summarizes the model meteorological, water temperature, and flow inputs and data sources.

Model meteorology inputs include hourly air temperature, relative humidity, and wind speed. A dry adiabatic lapse rate adjustment was applied to air temperature data to account for elevation differences between the measurement and model input locations. Wind speeds were adjusted with a wind-sheltering coefficient to account for wind speed differences between monitored and modeled locations.

Table 10. L. Sandy R. model meteorological, water temperature, and flow inputs.

Station ID	Model Locations (m)	Input Type	Parameter	Data Source
14140000	0, 14112, 17130	Meteorological	Air temp.,relative humidity, wind speed	USGS
Little Sandy at USNF Road 14 (26391-ORDEQ)	0	Boundary condition	Water temp.	DEQ
Groundwater accretion	15758, 16368	Tributary	Flow	Derived flow constant
Marmot inflow	14326	Tributary	Flow	Derived flow constant
Unnamed site	4724	Tributary	Flow	Derived flow constant
Spring	4206	Tributary	Flow	Derived flow constant
Spring	4084	Tributary	Flow	Derived flow constant
Spring	1554	Tributary	Flow	Derived flow constant
Groundwater accretion	16368	Tributary	Water temp.	Constant (13.0 °C)
Groundwater accretion	15758	Tributary	Water temp.	Constant (13.0 °C)
Marmot inflow	14326	Tributary	Water temp.	26408-ORDEQ (proxy)
Unnamed site	4724	Tributary	Water temp.	26407-ORDEQ on 8/9/2001 (proxy)
Spring	4206	Tributary	Water temp.	Constant (12.0 °C)
Spring	4084	Tributary	Water temp.	TIR-derived constant (7.2 °C)
Spring	1554	Tributary	Water temp.	TIR-derived constant (7.5 °C)

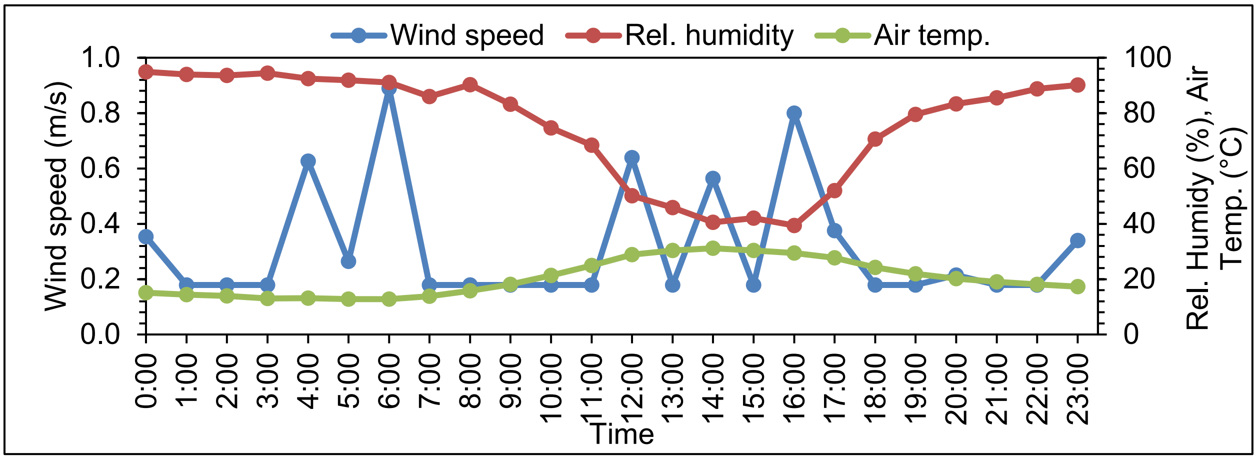

Figure 24. Temporally variable L. Sandy R. model meteorological inputs (8/9/2001).

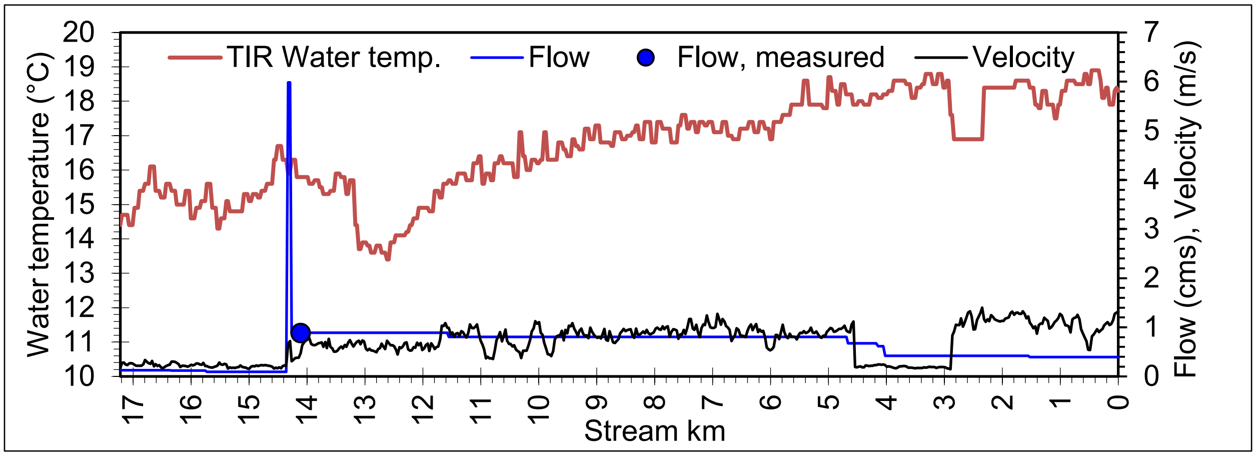

Figure 24. L. Sandy R. model longitudinal hydrologic and water temp. inputs.

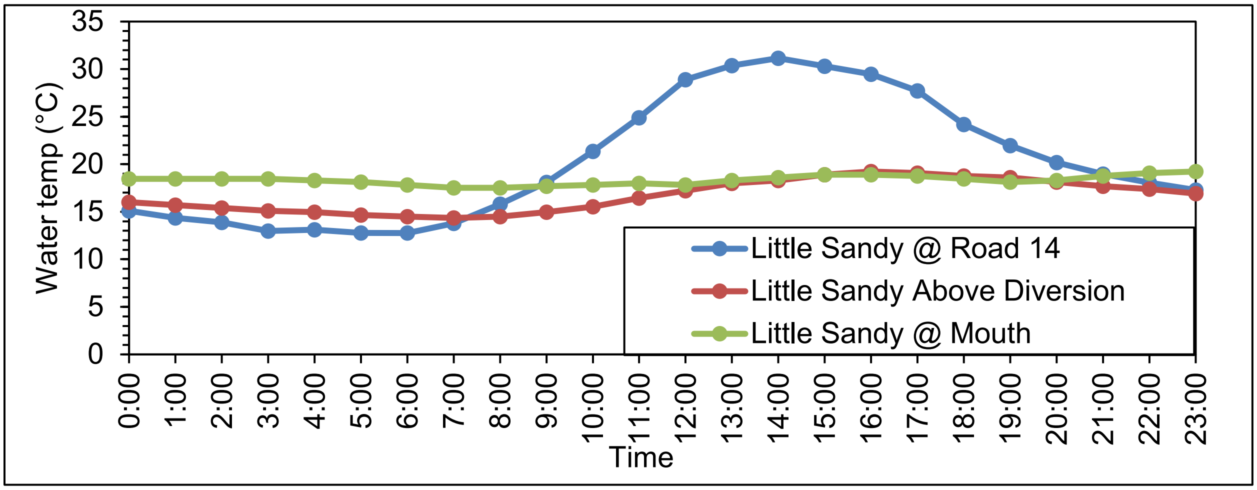

Figure 24. L. Sandy R. model node water temp. inputs.

3.3.4 Point source inputs

There are no permitted NPDES point sources along the Little Sandy River model extent.

3.3.5 Landcover and topographic shade inputs

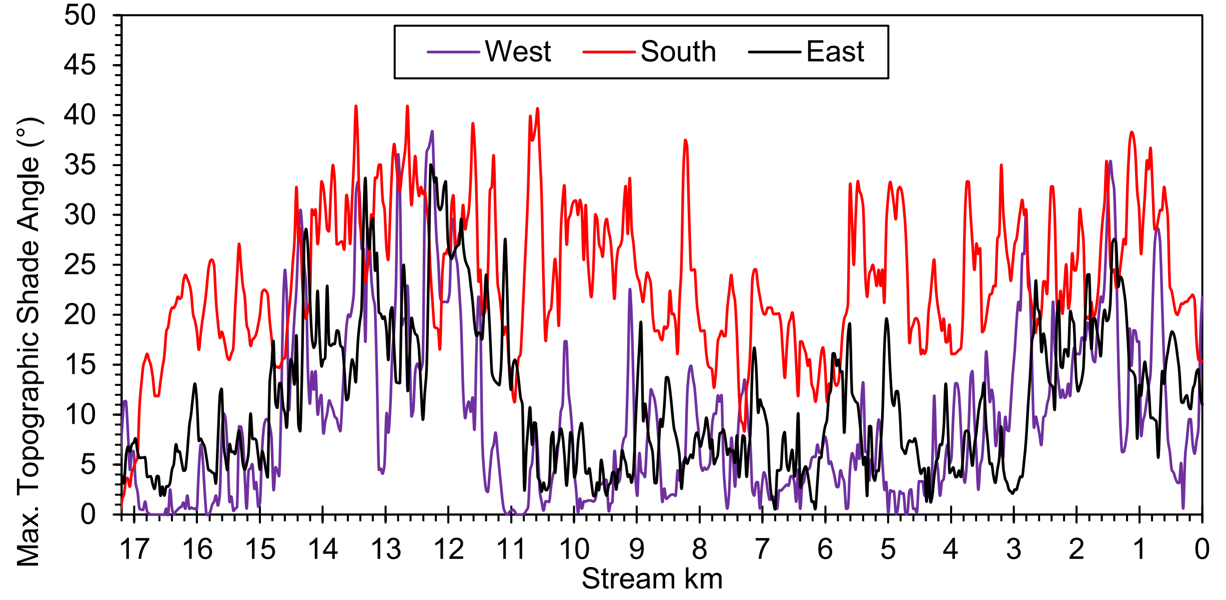

Figure 26. L. Sandy R. model max. topographic shade angle inputs.

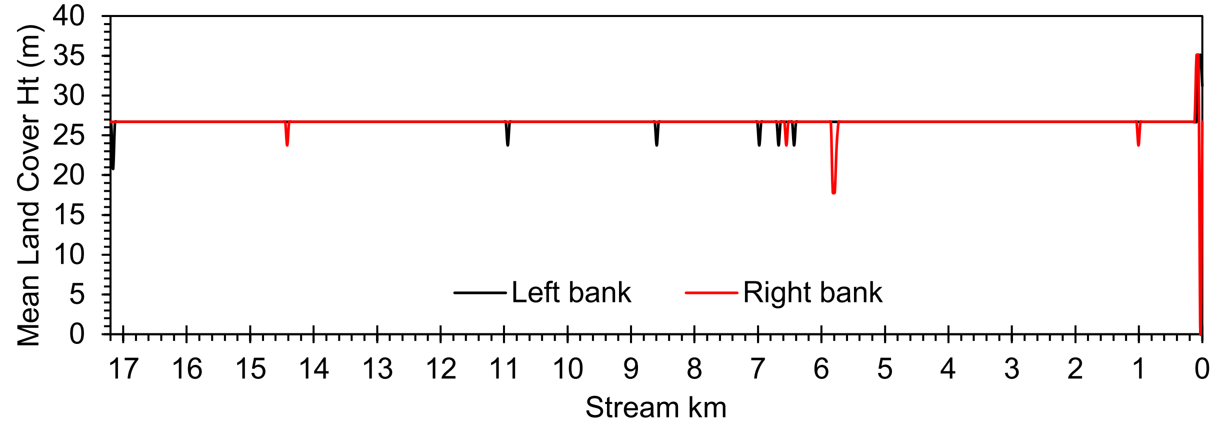

Figure 26. L. Sandy R. model setup landcover height (m).

3.3.6 Channel setup

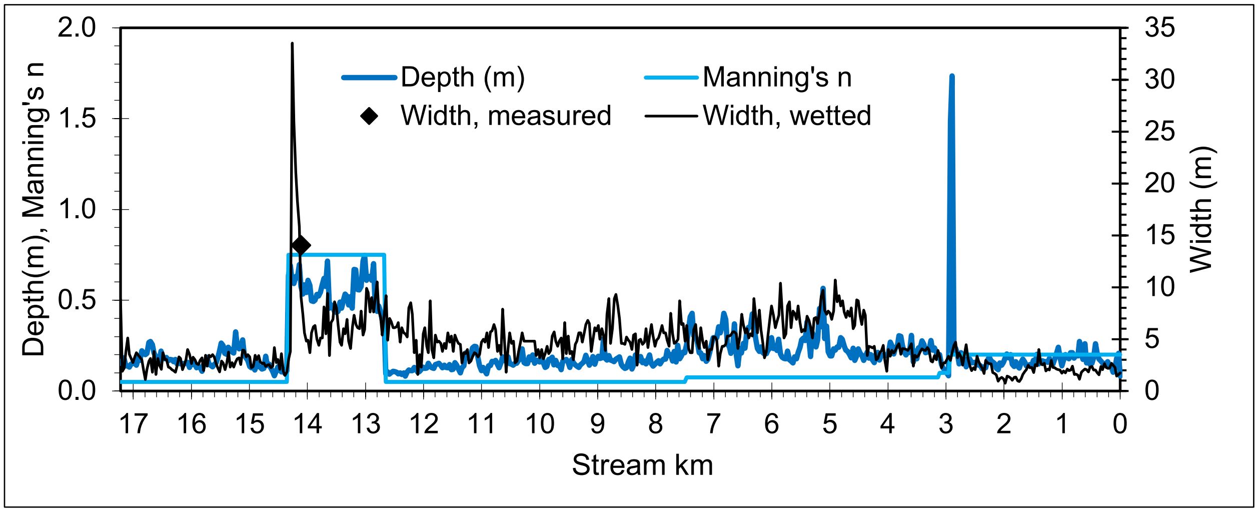

Figure 28. L. Sandy R. model channel dimension and friction (Manning's n) inputs.

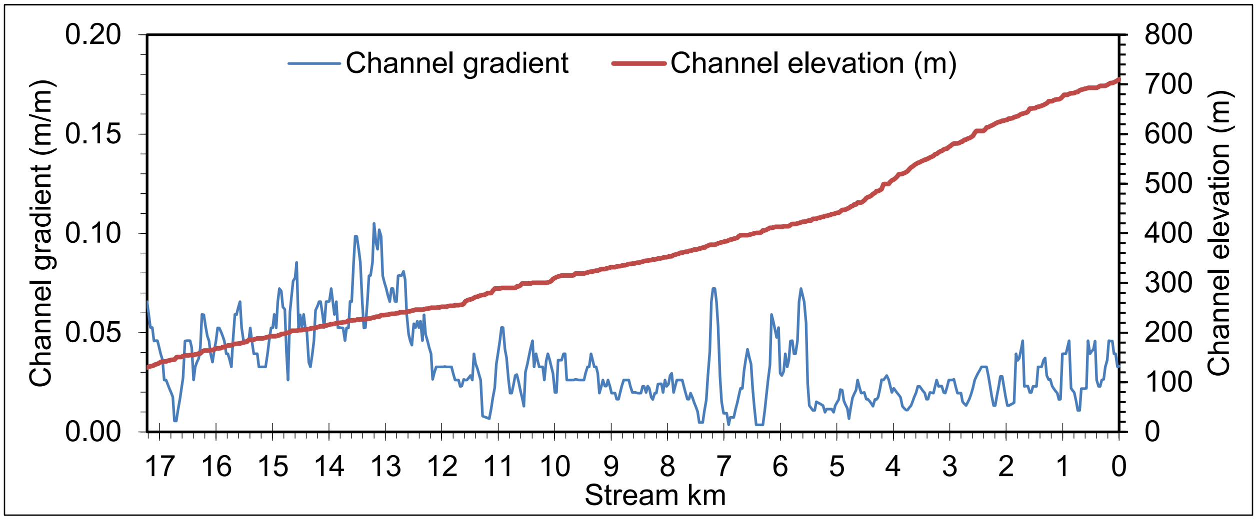

Figure 27. Little Sandy R. model channel gradient and elevation inputs.

3.3.7 Other model parameters

Table 11. Other L. Sandy R. model parameters.

Parameter name (units)	Value
Bedrock (%)	0
Riparian zone width (m)	4.57
Channel incision (m)	0.0

3.3.8 Model calibration

Observed stream temperature data for two sites were available to calibrate the 2001 Little Sandy River model (Table 12). Additionally, TIR water temperature data were available for the model extent (Watershed Sciences, 2001). Table 13 provides effective shade calibration data.

Table 12. Water temp. data available for 2001 L. Sandy R. model calibration.

Station ID	Station	Stream km	Latitude/Longitude	Data source
26389-ORDEQ	Little Sandy R. at mouth	0	45.4261/-122.207	City of Portland
26390-ORDEQ	Little Sandy R. above Diversion	3.1	45.4153/-122.171	DEQ
Model extent	Model extent	Model extent		Watershed Sci. (2001) (TIR)

Table 13. Effective shade data available for L. Sandy R. 2001 model.

Station ID	Station	Stream km	Latitude/Longitude	Effective shade (%)	Data source
26389-ORDEQ	L. Sandy at mouth	0	45.4261/-122.207	100	City of Portland
26390-ORDEQ	L. Sandy above Diversion	3.1	45.4153/-122.171	56	DEQ
26391-ORDEQ	L. Sandy at USNF Rd 14	17.2	45.4037/-122.172	69	DEQ

3.3.9 Model results – effective shade and longitudinal temperature

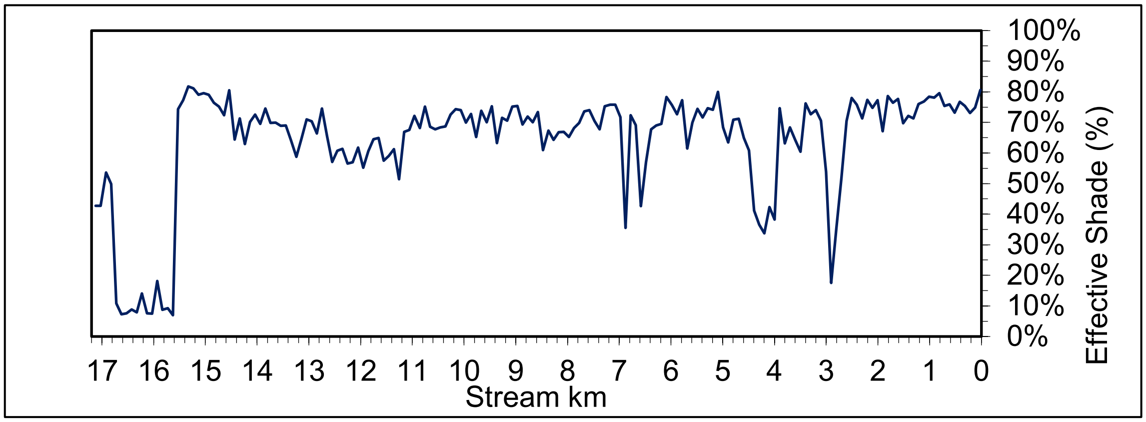

Figure 30. L. Sandy R. effective shade, calibrated model

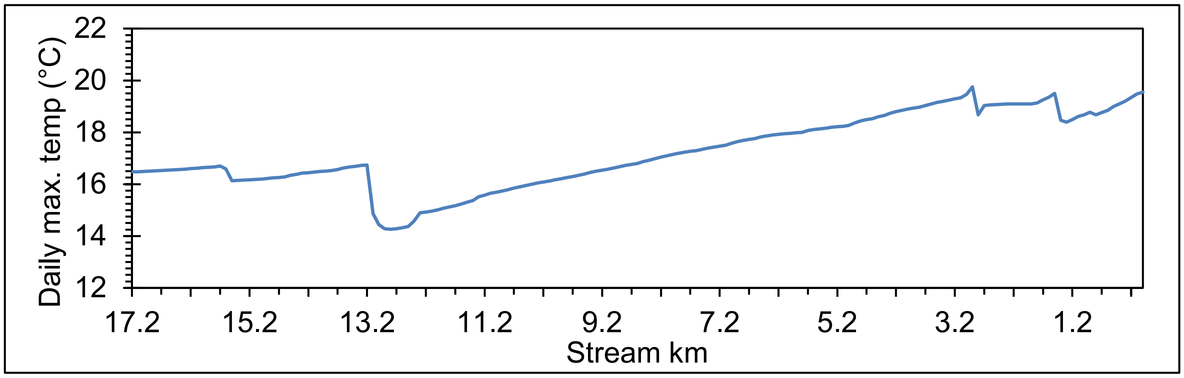

Figure 30. L. Sandy R. longitudinal daily max. temp. profile

3.4 Zigzag River

The Zigzag River model is a temperature model developed by DEQ using Heat Source 6.5.1.

3.4.1 Spatial and temporal extent

The model domain extent is the Little Sandy River from the mouth to just upstream of Camp Creek at Highway 26. The model extent is shown in Figure 20. The model period is a single day: August 09, 2001.

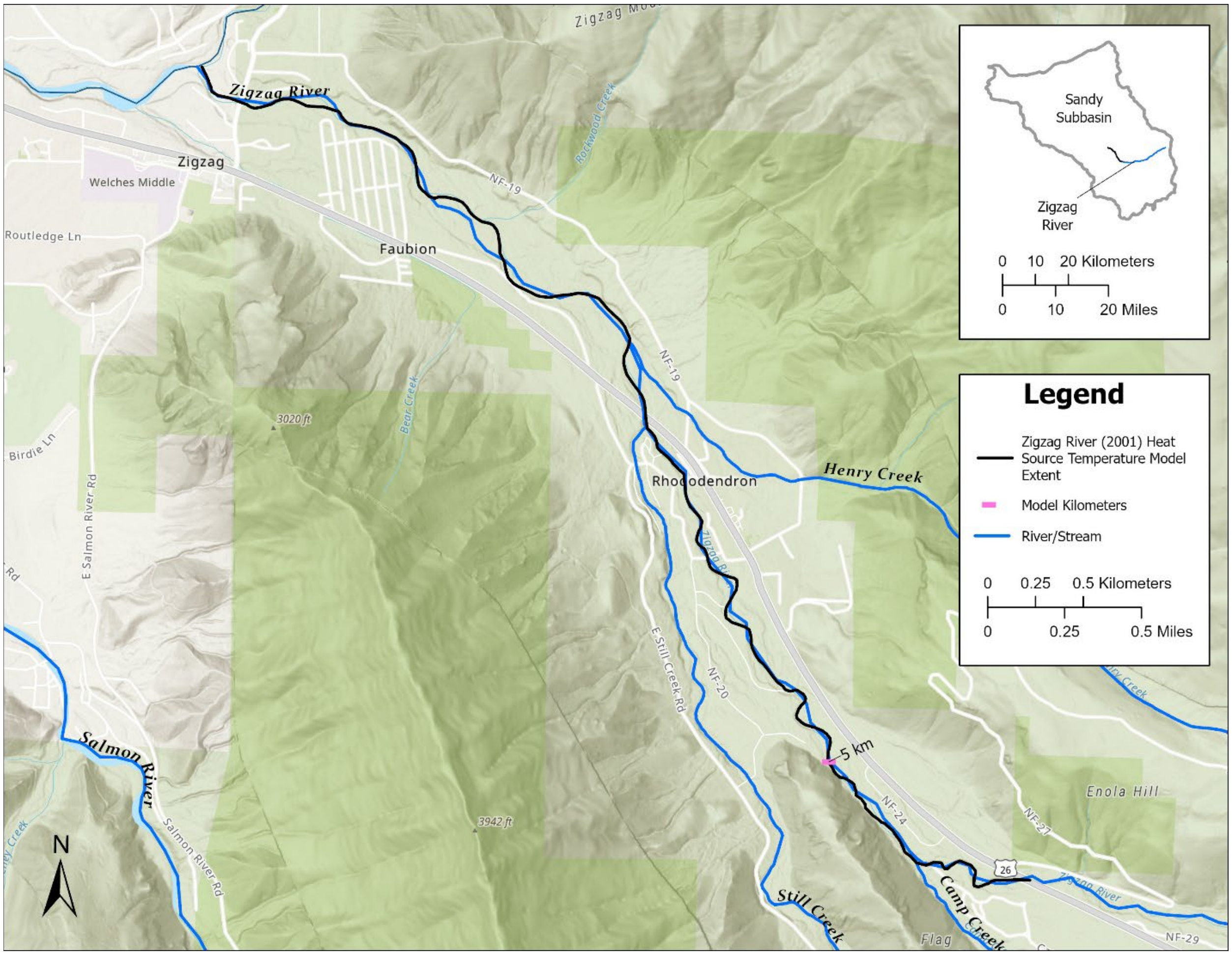

Figure 31. 2001 Zigzag R. model extent.

3.4.2 Spatial and temporal resolution

The model input spatial resolution (*dx*) is 30 m. Outputs are generated every 100 m. The model time step (*dt*) is 1 minute and outputs are generated every hour.

3.4.3 Meteorological, water temperature, and flow inputs

Table 14 summarizes the model meteorological, water temperature, and flow inputs and data sources.

Table 14. Zigzag R. model meteorological and water temp. data sources.

Station ID	Model Locations (m)	Input Type	Parameter	Data Source
14140000	0, 3475, 7010	Meteorological	Air temp., relative humidity, wind speed	USGS
Zigzag above Camp Cr./Hwy 26	0	Boundary condition	Water temp.	26420-ORDEQ
Spring	6187	Tributary	Water temp.	TIR-derived constant (13.7 °C)
Unnamed tributary	5944	Tributary	Water temp.	TIR-derived constant (17.4 °C)
Spring	5883	Tributary	Water temp.	TIR-derived constant (13.1 °C)
Spring	5548	Tributary	Water temp.	TIR-derived constant (11.7 °C)
Henry/No Name	4389	Tributary	Water temp.	TIR-derived constant (12.9 °C)
Still Creek	3871	Tributary	Water temp.	26417-ORDEQ
Camp Creek	792	Tributary	Water Temp.	26419-ORDEQ

Model meteorology inputs include hourly air temperature, relative humidity, and wind speed. A dry adiabatic lapse rate adjustment was applied to air temperature data to account for elevation differences between the measurement and model input locations. Wind speeds were adjusted with a wind-sheltering coefficient to account for wind speed differences between monitored and modeled locations.

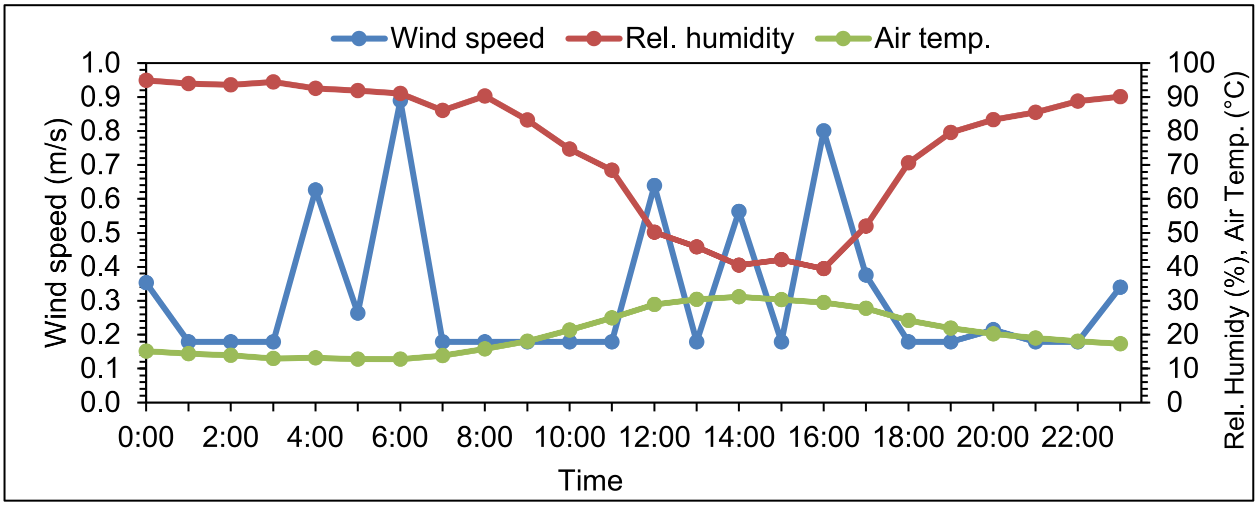

Figure 33. Zigzag R. model meteorological inputs (8/9/2001).

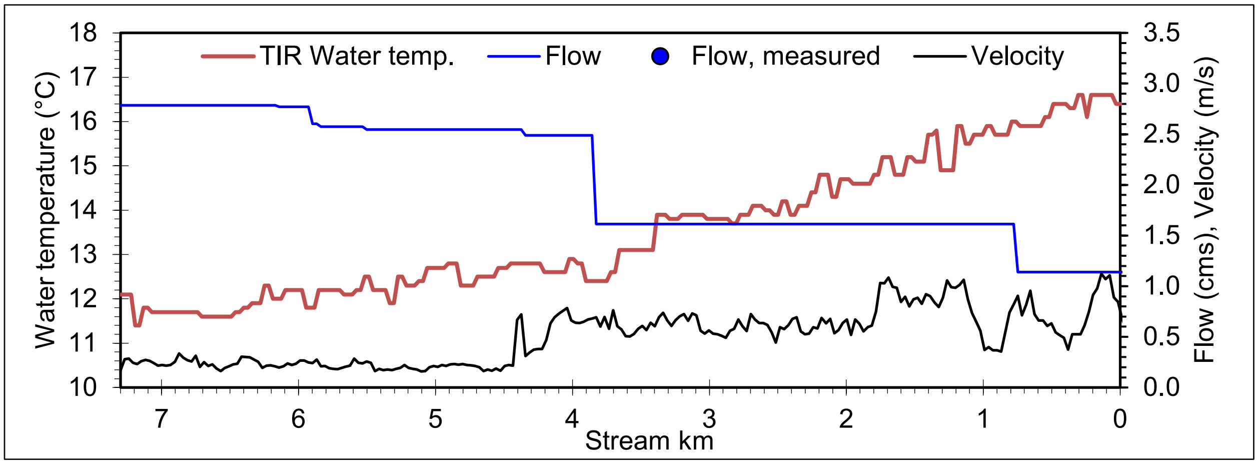

Figure 33. Zigzag R. model longitudinal hydrologic and water temp. inputs.

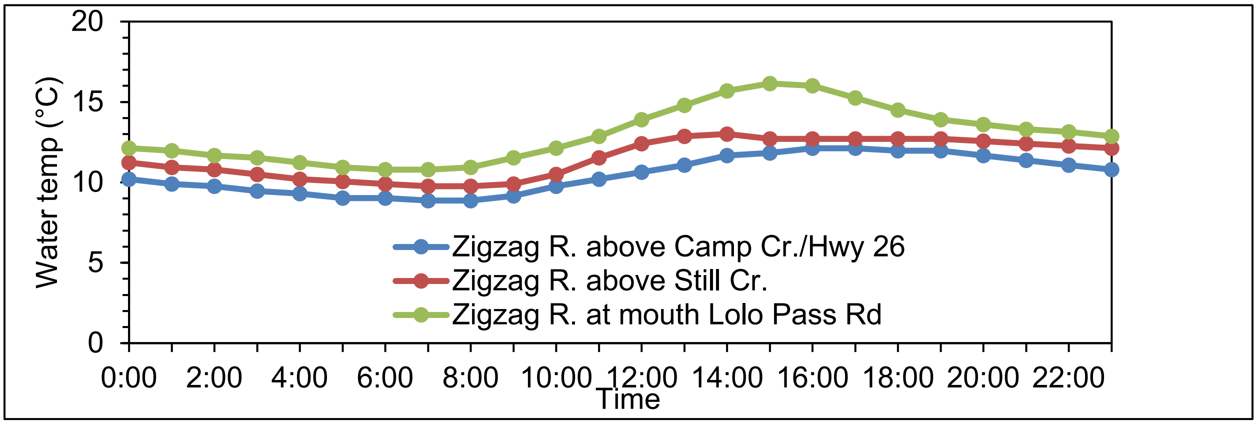

Figure 34. Zigzag R. model node water temp. inputs.

3.4.4 Point source inputs

There are no permitted NPDES point sources along the Little Sandy River model extent.

3.4.5 Landcover and topographic shade inputs

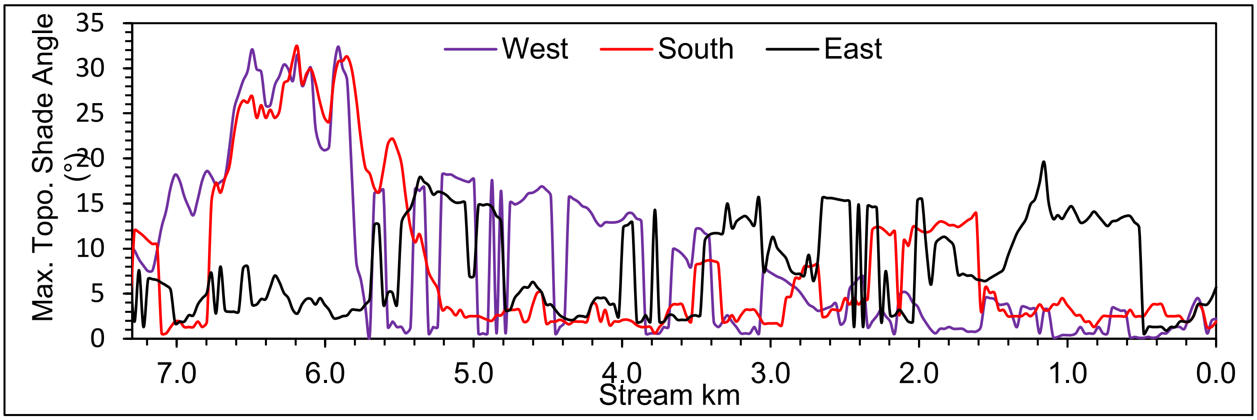

Figure 36. Zigzag R. model max. topographic shade angle inputs.

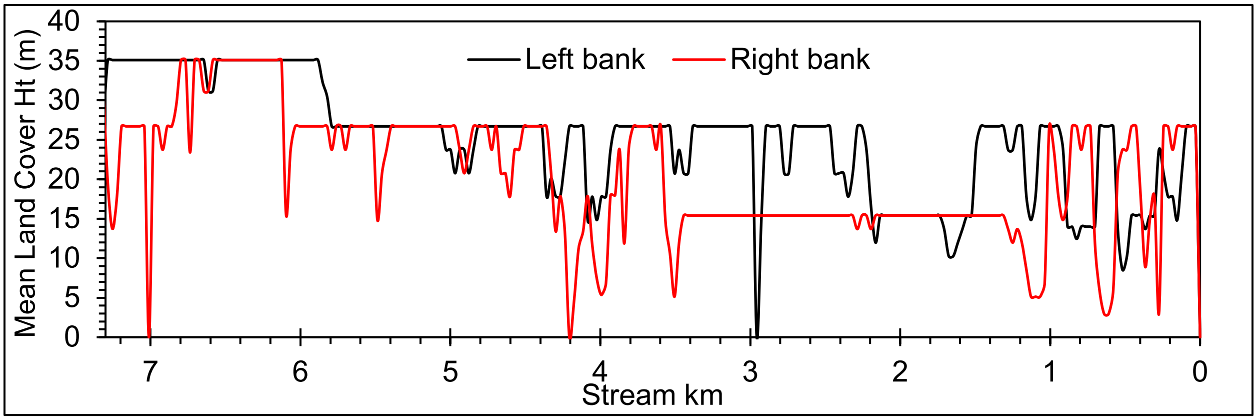

Figure 36. Zigzag R. model setup landcover height (m).

3.4.6 Channel setup

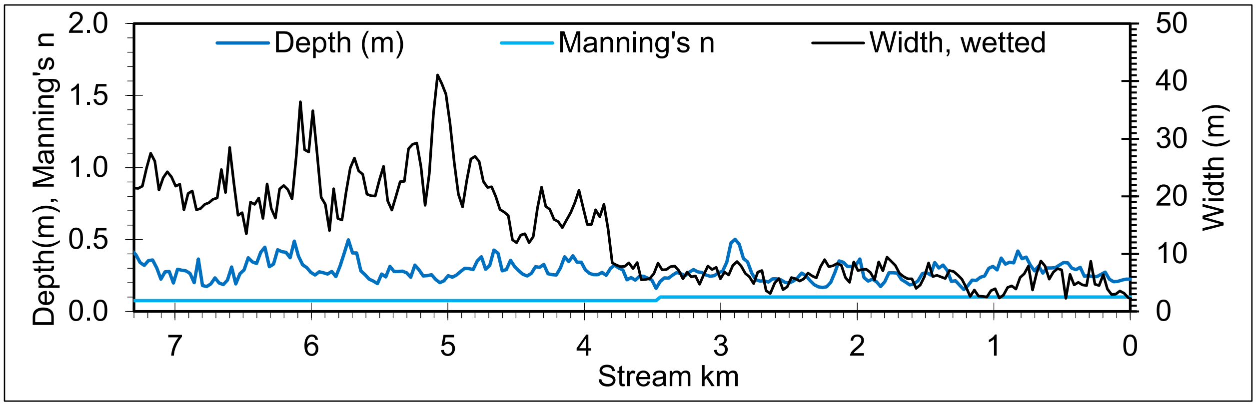

Figure 38. Zigzag R. model channel dimension and friction (Manning's n) inputs.

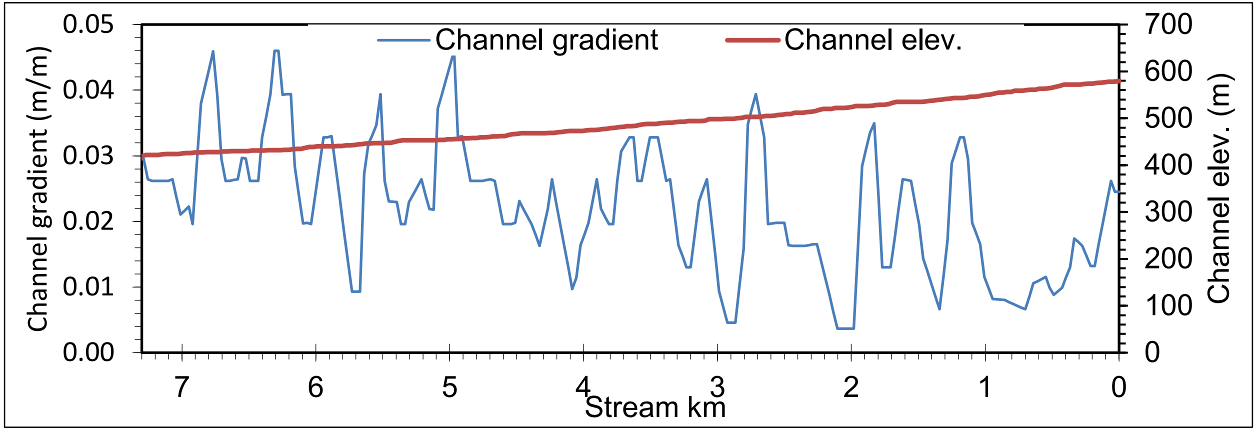

Figure 38. Zigzag R. model channel gradient and elevation inputs.

3.4.7 Other model parameters

Table 15. Other Zigzag R. model parameters.

Parameter name (units)	Value
Bedrock (%)	50
Riparian zone width (m)	4.57
Channel incision (m)	0.0

3.4.8 Model calibration

Observed stream temperature data for two sites were available to calibrate the 2001 Zigzag River model (Table 15). Additionally, TIR water temperature data were available for the model extent (Watershed Sciences, 2001). Table 16 provides effective shade calibration information.

Table 16. Water temp. data available for 2001 Zigzag R. model calibration.

Station ID	Station	Model location (m)	Data source
26416-ORDEQ	Zigzag R. at mouth Lolo Pass Rd.	7010	DEQ

26418-ORDEQ	Zigzag R. above Still Cr.	3475	DEQ
Model extent	Model extent	Model extent	Watershed Sciences (2001) (TIR)

Table 17. Effective shade data available for 2001 Zigzag R. model calibration.

Station ID	Station	Latitude/Longitude	Effective shade (%)	Data source
26416-ORDEQ	Zigzag R. at mouth Lolo Pass Rd.	45.3471, -121.942	19	DEQ
26418-ORDEQ	Zigzag R. above Still Cr.	45.3297, -121.912	72	DEQ
26420-ORDEQ	Zigzag R. above Camp Cr. Hwy 26	45.311, -121.89	95-100	DEQ

3.4.9 Model results – effective shade and longitudinal temperature

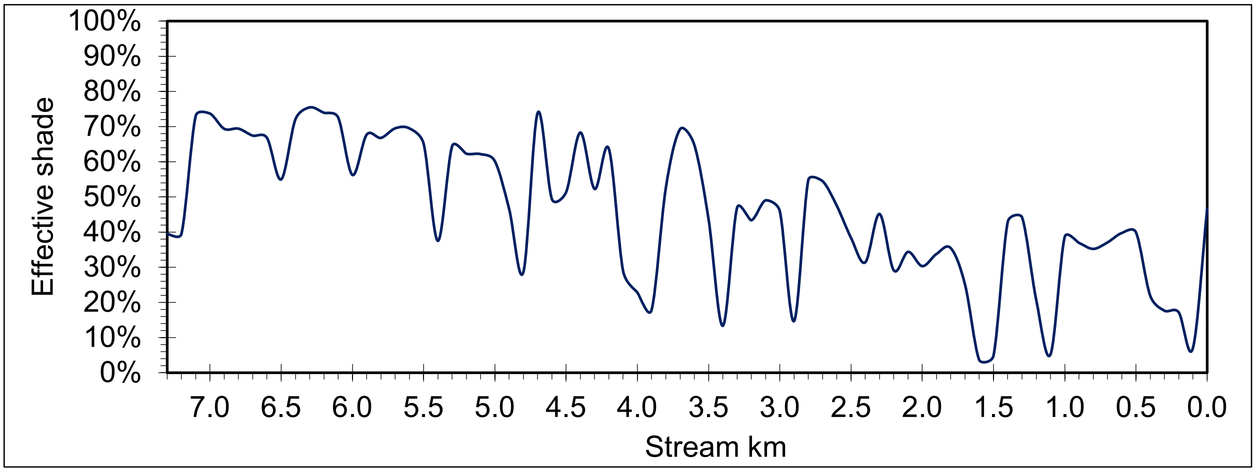

Figure 39. Zigzag R. longitudinal effective shade profile.

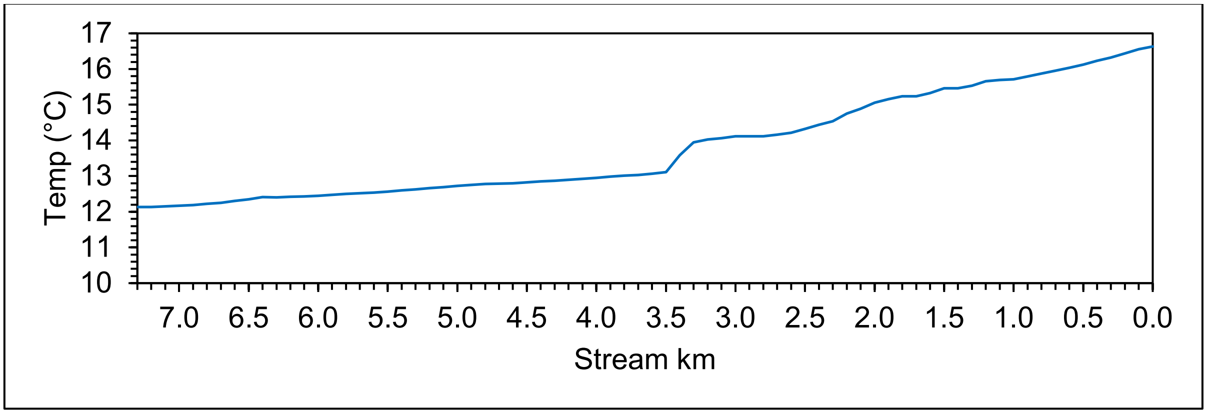

Figure 40. Zigzag R. modeled longitudinal daily max temp., Aug 9, 2001.

4. Model scenarios

4.1 Scenario background and descriptions

DEQ and supporting organizations developed models that reflect various possible scenarios (i.e., sets of conditions) to understand the potential in-stream water temperature effects of variation in, e.g., anthropogenic water withdrawals and discharges, vegetation shading and removal, presence of dams, and other anthropogenic or natural conditions in the TMDL area. This allowed DEQ to quantify the actual or potential effects of these scenario variables on instream temperatures in the modelled streams. Each scenario reflected specific potential management action(s) and/or natural processes in a model river. Scenario models and current conditions model outputs were compared to determine the effects of specific variables on instream temperatures. Table 18 outlines the various Sandy Subbasin scenarios and methods; Section 4.2 describes additional details and results as applicable.

For stream temperature modeling, the point of maximum impact (POMI) is the longitudinal stream location and date associated with the greatest in-stream 7DADM temperature difference between the current conditions model output and a given scenario's model output. Typically, the maximum allowable anthropogenic 7DADM instream temperature change (i.e., HUA) is 0.3°C above the applicable criteria at the POMI, cumulatively for all point and nonpoint sources. To summarize differences between current conditions and a hypothetical scenario model (e.g., fully restored riparian vegetation), the temperature change at the POMI is expressed in terms of the UCL95s of both the 7DADM and the daily maximum temperature.

Table 18. Sandy Subbasin simulated scenarios descriptive summary.

Scenario #	Scenario	ID	Equivalent to CCC except:
2	Future Point Source[1]	FPS	With new planned point source (City of Sandy WWTP) as modified tributary input
3	No Point Sources[1]	NoPS	No NPDES-permitted point source discharges
4	TMDL Wasteload Allocations[1]	WLA	NPDES-permitted point source discharges reflect proposed WLAs
5	Restored Veg. A	RV_A	Fully restored veg. in all human-affected areas
	Restored Veg. B	RV_B	Fully restored veg. in all human-affected areas except existing infrastructure (i.e., bldgs, roads, utility corridors)
6	No Dams[2]	ND	**Bull Run R.**: ND model represents stream morphology w/o Bull Run River Dams #1 & #2 ; **Sandy R.:** Bull Run R. tributary inputs reflect Bull Run R. ND model outputs.
7	Restored Flow	RQ	Boundary & tributary flows reflect median natural monthly flows (i.e., no anthropogenic riparian veg. changes or water withdrawals)
8	Water Withdrawals[2]	WW	Same as RQ but accounts for consumptive human withdrawals of: (A) 9.7%; (B) 2%
9	Background	BG	Equivalent to combined Restored Veg. A & No Dams scenarios.
10	Protected Veg. A1[3]	PV_A1	Protected areas (w/binding mgmt. plans) have fully restored riparian vegegation[3]; unprotected areas have no veg.
	Protected Veg. A2[4]	PV_A2	Protected areas (w/binding mgmt. plans) have fully restored riparian veg.[4]; unprotected areas have no veg.; certain protected areas have extended stream buffer width
	Protected Veg. B1[3]	PV_B1	Protected areas (w/binding mgmt. plans) have fully restored riparian vegegation[3]; unprotected areas have CCC veg.

	Protected Veg. B2[4]	PV_B2	Protected areas (w/binding mgmt. plans) have fully restored riparian veg.[4]; unprotected areas have CCC veg.; certain protected areas have extended stream buffer width
11	Topography	Topo	All veg. heights & densities are set to 0 (zero)
12	Tributary Temps.	TT	For any tributaries with applicable temp. standard exceedances in the model period, their entire temp. dataset is reduced by the max. exceedance.

[1] Scenario only applies to the Sandy River Mainstem model.

[2] Scenario does not apply to Salmon River.

[3] Federal DMAs have 300' protected stream buffer; protected Clackamas County and ODF-Private DMAs area have 100' protected stream buffer.

[4] Federal DMAs have 300' protected stream buffer; protected Clackamas County and ODF-Private DMAs area have 110' protected stream buffer.

Table 19. Explanation of scenario comparisons.

Scenario 1	Scenario 2	Question/topic addressed RE: modeled stream temperatures, shade, and/or flows[3]
FPS	CCC	Effect of proposed City of Sandy WWTP discharge.[1]
ND	CCC	Effect of existing dams & reservoirs.[2]
NoPS	CCC	Effect of NPDES-permitted point sources.[1]
BG	CCC	Effect of anthropogenic riparian veg. alteration & dams.
Topo	CCC	Effect of current shading under human control.
TT	CCC	Effect of tributary temperature standard exceedances.
WLA	CCC	Effect of achieving HUAs.[1]
WLA	NoPS	Effect of achieving HUAs vs. no permitted point sources.[1]
RQ	WW	Effect of anthropogenic riparian veg. alteration & water withdrawals; max. withdrawal rates that still attain the (9.7% withdrawal) overall HUA & (2.0% withdrawal) HUA portion allocated to permitted withdrawals.
RV_A	CCC	Effect of current anthropogenic riparian veg. alteration.
RV_A	RV_B	Effect of unrestored vs. restored veg. in infrastructure zones
RV_A	PV_A1; PV_A2	Will existing protection measures attain shade surrogate & HUA targets if unprotected veg. remains as CCC; Effects of various TMDL shade target iterations (PV_A1, PV_A2) vs. fully restored veg. in protected & unprotected areas (RV_A).
RV_A	PV_B1; PV_B2	Will existing protection measures attain shade surrogate & HUA targets if unprotected veg is removed; Effects of various TMDL shade target iterations (PV_B1, PV_B2) vs. fully restored veg. in protected & unprotected areas (RV_A).
CCC	PV_A1; PV_A2	Will current regulatory protection fulfillment by DMAs attain this TMDL's effective shade targets if unprotected area veg is removed
CCC	PV_B1; PV_B2	Will current regulatory protection fulfillment by DMAs attain this TMDL's effective shade targets if unprotected area veg remains as CCC
PV_A1	PV_B1	Effect of removal of unprotected areas' shade veg.[4]
PV_A2	PV_B2	Effect of removal of unprotected areas' shade veg. (with expanded buffer zone for some DMAs)[5]
PV_A1	PV_A2	Effect of 110' protected buffers (PV_A2) for DMAs with 100' protected buffers under PV_A1 (Clackamas Cty, ODF-Private Forestry)[4]
PV_B1	PV_B2	Effect of 110' protected buffers (PV_B2) for DMAs with 100' protected buffers under PV_B1 (Clackamas Cty, ODF-Private Forestry)[5]

[1] Comparison only applies to the Sandy River Mainstem model.

[2] Scenario does not apply to Salmon River.

[3] When scenarios have multiple versions or comparisons, these are further described in relevant scenario-specific section(s) of this report.

[3] Federal DMAs have 300' protected stream buffer; protected Clackamas County and ODF-Private DMAs area have 100' protected stream buffer.

[4] Federal DMAs have 300' protected stream buffer; protected Clackamas County and ODF-Private DMAs area have 110' protected stream buffer.

Table 20. DMA buffer widths used in protected vegetation scenarios modeling

DMA	Buffer width (ft)
Clackamas Cty.	100[1]; 110[2]
ODF - Private	
US BLM	300
USFS	
ODOT	0

4.2 Scenario results

For Salmon River modeled current conditions and each modeled scenario, Table 19 provides: UCL95s of the 7DADM and the daily maximum temperature at the mouth; and the maximum temperature differences between current conditions and each scenario at the mouth and POMI. Section 4.2.1 summarizes the results of each applicable scenario (certain scenarios were inapplicable to certain streams). Appendices B and C provide Sandy River and Bull Run River results, respectively.

4.2.1 Salmon River

Scenarios that were inapplicable to the Salmon were: restored stream flow, no point sources, TMDL wasteload allocations, and no dams. This is because there were insignificant permitted withdrawals, no permitted discharges, and no dams present on the Salmon River.

Table 21. Salmon R. scenarios & comparisons: temperature results.

Scenario	Value Type	Location	Model km	7DADM		Model km	Daily Max. Temp.	
				Date	WT (°C)		Date	WT (°C)
Current Cond. (CCC)	**Salmon CCC**	Mouth	0	07/31/2016	18.99	0	07/29/2016	20.01
Restored Vegetation (RV_A)	Salmon RV_A	Mouth	0	07/30/2016	18.55	0	07/29/2016	19.55
	RV_A vs. CCC	Mouth	0	08/29/2016	0.68	0	08/30/2016	0.80
	RV_A vs. CCC	POMI	6.10	08/29/2016	1.14		08/23/2016	1.19
Restored Vegetation, Modified (RV_B)	**Salmon RV_B**	Mouth	0	07/30/2016	18.62	0	07/29/2016	19.61
	RV_B vs. RV_A	Mouth	0	07/30/2016	0.07	0	08/03/2016	0.07
	RV_B vs. RV_A	POMI	0.40	07/29/2016	0.07		08/18/2016	0.08
Protected Vegetation version A1 (PV A1)	**Salmon PV A1**	Mouth	0	07/30/2016	18.72	0	07/29/2016	19.72
	PV A1 vs. CCC	Mouth	0	08/30/2016	0.49	0	08/30/2016	0.61
	PV A1 vs. CCC	POMI	6.30	08/25/2016	0.91		08/23/2016	0.95
	RV_A vs. PV A1	Mouth	0	08/29/2016	0.20	0	08/17/2016	0.20
	RV_A vs. PV A1	POMI	5.95	08/29/2016	0.29		08/27/2016	0.30
Protected Vegetation version A2 (PV A2)	**Salmon PV A2**	Mouth	0	07/30/2016	18.63	0	07/29/2016	19.63
	PV A2 vs. CCC	Mouth	0	08/30/2016	0.61	0	08/30/2016	0.73
	PV A2 vs. CCC	POMI	6.10	08/29/2016	1.08		08/23/2016	1.13
	RV_A vs. PV A2	Mouth	0	07/21/2016	0.13	0	07/17/2016	0.27
	RV_A vs. PV A2	POMI	0.10	07/21/2016	0.14		07/17/2016	0.27
Protected Vegetation version B1 (PV B1)	**Salmon PV B1**	Mouth	0	07/30/2016	18.68	0	07/29/2016	19.67
	PV B1 vs. CCC	Mouth	0	08/29/2016	0.56	0	08/30/2016	0.64
	PV B1 vs. CCC	POMI	6.55	08/26/2016	0.95	6.50	08/21/2016	0.99
	RV_A vs. PV B1	Mouth	0	07/30/2016	0.13	0	08/30/2016	0.16
	RV_A vs. PV B1	POMI	6	08/28/2016	0.25	6	08/27/2016	0.27
Protected Vegetation version B2 (PV B2)	**Salmon PVB2**	Mouth	0	07/30/2016	18.62	0	07/29/2016	19.61
	PV B2 vs. CCC	Mouth	0	08/30/2016	0.64	0	08/30/2016	0.74
	PV B2 vs. CCC	POMI	6.1	08/29/2016	1.1	6.1	08/23/2016	1.14
	RV_A vs. PV B2	Mouth	0	07/21/2016	0.14	0	07/17/2016	0.27
	RV_A vs. PV B2	POMI	0.25	07/21/2016	0.14	0.2	07/17/2016	0.27

Topography	**Salmon Topo**	Mouth	0	08/19/2016	20.02	0	07/29/2016	20.91
	CCC vs. Topo	Mouth	0	08/29/2016	1.4	0	08/28/2016	1.47
	CCC vs. Topo	POMI	0.85	08/29/2016	1.53		08/28/2016	1.59
Tributary Temperatures (TT)	**Salmon TT**	Mouth	0	07/31/2016	18.75	0	07/29/2016	19.77
	TT vs. CCC	Mouth	0	07/22/2016	0.25	0	08/09/2016	0.25
	TT vs. CCC	POMI	12.75	07/23/2016	0.31		7/15/2016	0.30
Natural Flow	**Natural Flow**	Mouth	0	08/18/2016	20.22	0	08/14/2016	20.97
	Natural Flow vs. CCC	Mouth	0	08/16/2016	1.44	0	08/04/2016	1.68
	Natural Flow vs. CCC	POMI	0.15	08/16/2016	1.45		08/04/2016	1.69

4.2.1.1 Restored vegetation

The POMI refers to the stream node (km) with the greatest in-stream temperature change under a given condition. For the Salmon River restored vegetation scenario, the POMI was at river km 6.05 and corresponds to a median 7DADM change of 1.14°C. At the river mouth, the maximum 7DADM during the model period under current conditions was 18.99°C on 2016-07-31 and under restored vegetation conditions was 18.55°C on 2016-07-30. At the mouth, the greatest daily maximum temperature under current conditions was 20.01°C on 2016-07-29 and under restored vegetation conditions was 19.55°C on 2016-07-30.

Table 22. Shade scenario comparisons: CCC vs. Restored Vegetation A.

Extent	Shade (%): CCC	Shade (%): RV_A	Shade Gap (%)	Stream km Assessed	Stream km (%) Shade Gap			
					0-15%	**16-25%**	**26-50%**	**51-100%**
Study Area	28	41	13	13.1	8.4	3.4	1.3	0
Clackamas Cty.	26	39	13	6.8	4	2	0.7	0
ODF - Private	30	47	17	1.2	0.6	0.4	0.2	0
ODOT	10	49	39	0	0	0	0	0
US BLM	29	38	9	4.3	3.3	0.9	0.1	0
USFS	44	59	15	0.7	0.5	0	0.2	0

Table 23. Shade scenario comparisons: Restored Vegetation A vs. Restored Vegetation B.

Extent	Shade (%): RV_A	Shade (%): RV_B	Shade Gap (%)	Stream km Assessed	Stream km (%) Shade Gap			
					0-15%	**16-25%**	**26-50%**	**51-100%**
Study Area	41	40	1	13.1	13.1	0	0	0
Clackamas Cty.	39	38	1	6.8	6.8	0	0	0
ODF - Private	47	47	0	1.2	1.2	0	0	0
ODOT	49	10	39	0	0	0	0	0
US BLM	38	38	0	4.3	4.3	0	0	0
USFS	59	59	0	0.7	0.7	0	0	0

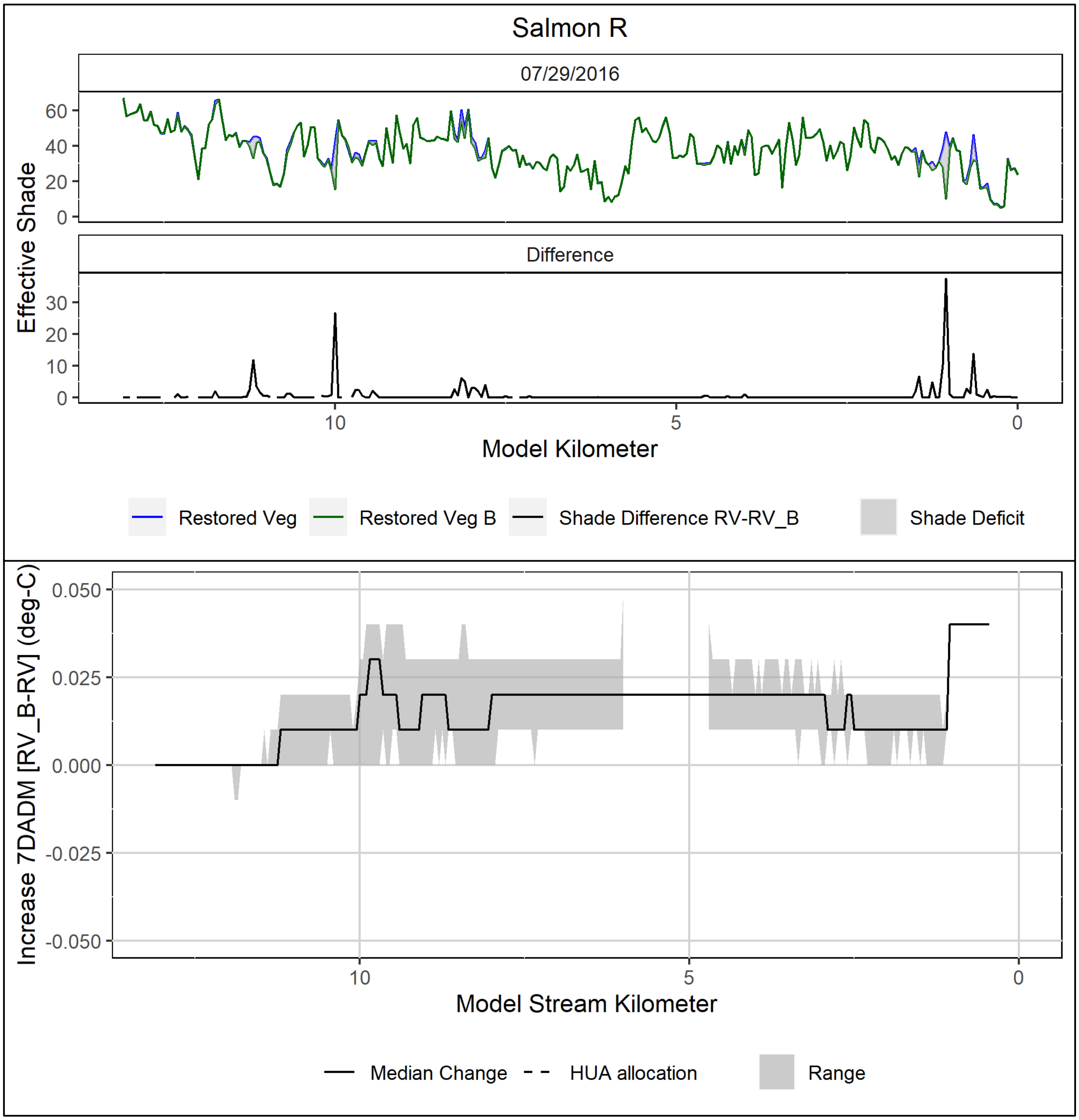

Figure 41. Scenario Model Results: Restored Veg. A vs. Restored Veg, B.

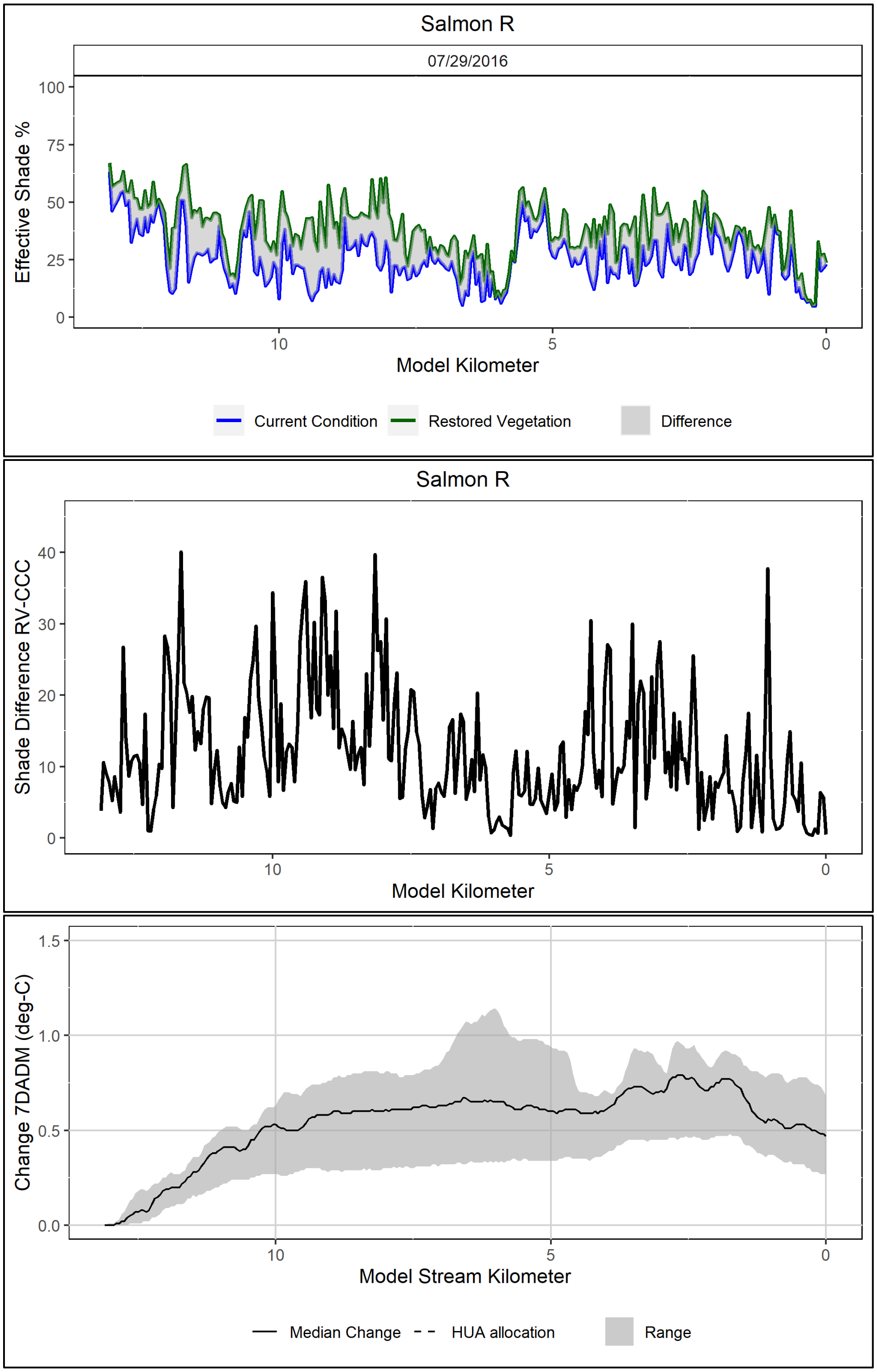

Figure 42. Scenario Model Results: Restored Vegetation A vs. CCC.

4.2.1.2 Protected vegetation

	Shade Results (%) by Scenario		Shade Gap (%)	Stream km Assessed	Stream km shade gap (%)			
					0-15%	16-25%	26-50%	51-100%
Extent	**CCC**	**PV_A1**						
Study Area	28	38	10	13.1	9.8	2.6	0.8	0
Clackamas Cty.	26	35	9	6.8	5.2	1.4	0.2	0
ODF - Private	30	45	15	1.2	0.7	0.4	0.2	0
ODOT	10	10	0	0	0	0	0	0
US BLM	29	38	9	4.3	3.5	0.8	0.1	0
USFS	44	58	14	0.7	0.5	0	0.2	0
Extent	**CCC**	**PV_A2**						
Study Area	28	40	12	13.1	8.9	3.1	1.1	0
Clackamas Cty.	26	38	12	6.8	4.4	1.8	0.6	0
ODF - Private	30	46	16	1.2	0.6	0.4	0.2	0
ODOT	10	10	0	0	0	0	0	0
US BLM	29	38	9	4.3	3.4	0.9	0.1	0
USFS	44	58	14	0.7	0.5	0	0.2	0
Extent	**CCC**	**PV_B1**						
Study Area	28	39	11	13.1	9.6	2.7	0.8	0
Clackamas Cty.	26	36	10	6.8	5	1.5	0.2	0
ODF - Private	30	45	15	1.2	0.7	0.3	0.2	0
ODOT	10	10	0	0	0	0	0	0
US BLM	29	38	9	4.3	3.5	0.8	0.1	0
USFS	44	58	14	0.7	0.5	0	0.2	0
Extent	**CCC**	**PV_B2**						
Study Area	28	40	12	13.1	8.9	3.1	1.1	0
Clackamas Cty.	26	38	12	6.8	4.4	1.8	0.6	0
ODF - Private	30	46	16	1.2	0.6	0.4	0.2	0
ODOT	10	10	0	0	0	0	0	0
US BLM	29	38	9	4.3	3.4	0.9	0.1	0
USFS	44	58	14	0.7	0.5	0	0.2	0
Extent	**PV_A1**	**RV_A**						
Study Area	38	41	3	13.1	12.7	0.3	0.1	0
Clackamas Cty.	35	39	4	6.8	6.3	0.3	0.1	0
ODF - Private	45	47	2	1.2	1.2	0	0	0
ODOT	10	49	39	0	0	0	0	0
US BLM	38	38	0	4.3	4.3	0	0	0
USFS	58	59	1	0.7	0.7	0	0	0
Extent	**PV_A2**	**RV_A**						
Study Area	40	41	1	13.1	13	0.1	0	0
Clackamas Cty.	38	39	1	6.8	6.7	0.1	0	0
ODF - Private	46	47	1	1.2	1.2	0	0	0
ODOT	10	49	39	0	0	0	0	0
US BLM	38	38	0	4.3	4.3	0	0	0
USFS	58	59	1	0.7	0.7	0	0	0
Extent	**PV_B1**	**RV_A**						
Study Area	39	41	2	13.1	12.8	0.1	0.1	0
Clackamas Cty.	36	39	3	6.8	6.5	0.1	0.1	0
ODF - Private	45	47	2	1.2	1.2	0	0	0
ODOT	10	49	39	0	0	0	0	0
US BLM	38	38	0	4.3	4.3	0	0	0

USFS	58	59	1	0.7	0.7	0	0	0
Extent	**PV_B2**	**RV_A**						
Study Area	40	41	1	13.1	13	0	0	0
Clackamas Cty.	38	39	1	6.8	6.7	0	0	0
ODF - Private	46	47	1	1.2	1.2	0	0	0
ODOT	10	49	39	0	0	0	0	0
US BLM	38	38	0	4.3	4.3	0	0	0
USFS	58	59	1	0.7	0.7	0	0	0

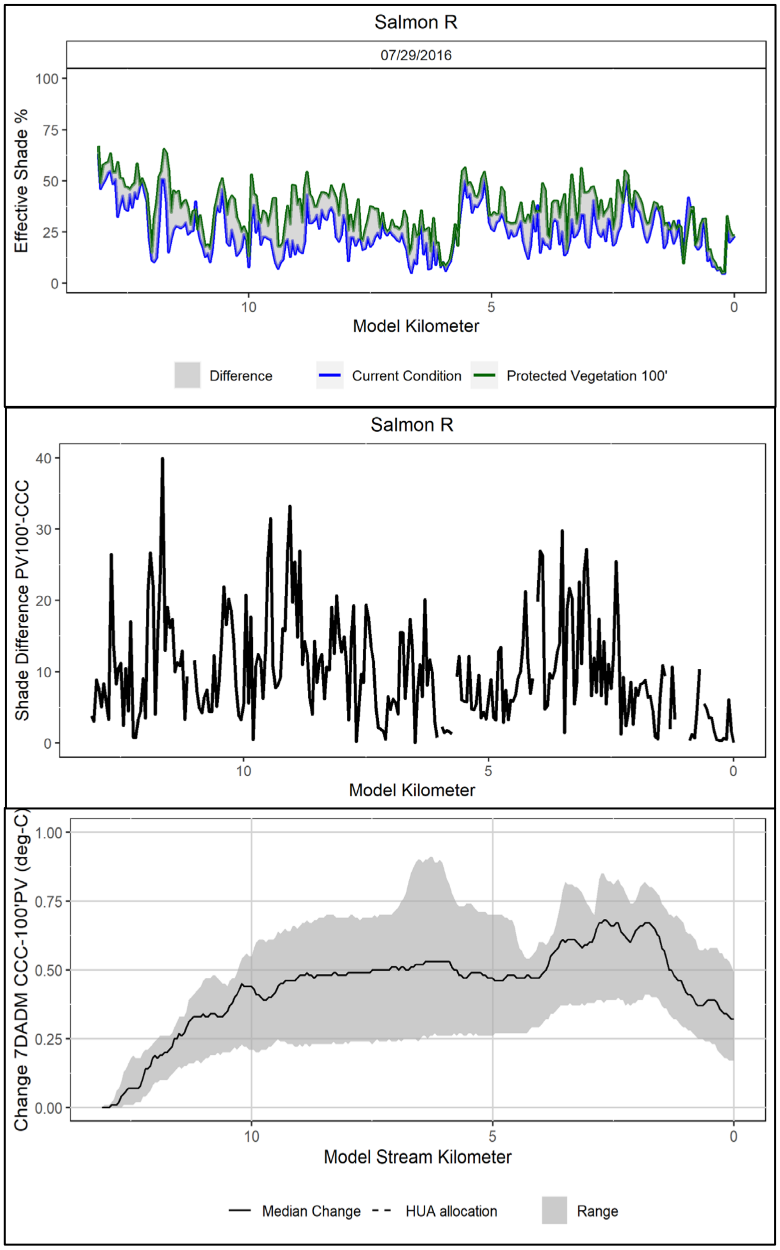

Figure 43. Scenario Results: Protected Vegetation A1 vs. CCC.

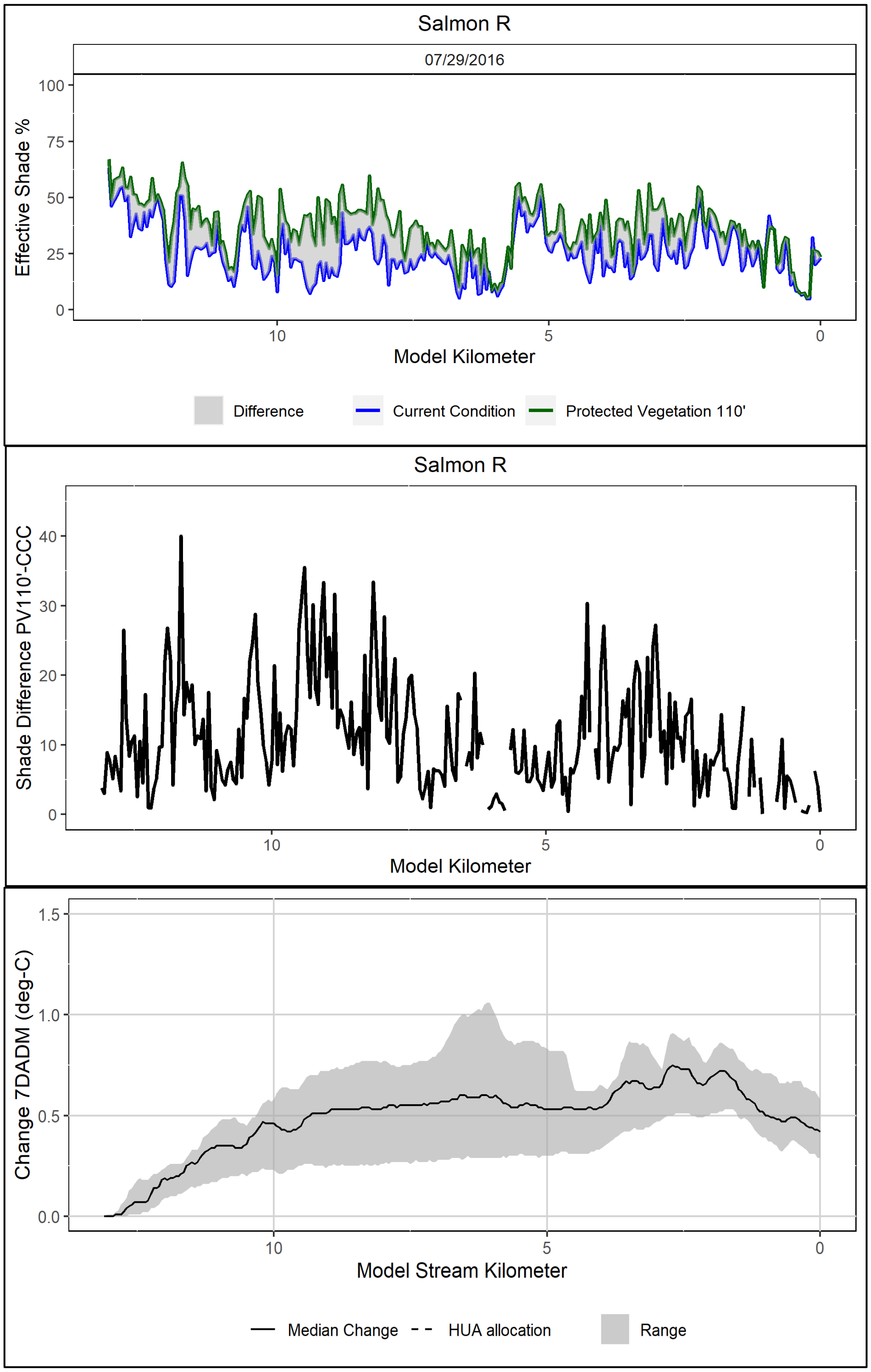

Figure 44. Scenario Results: Protected Vegetation A2 vs. CCC.

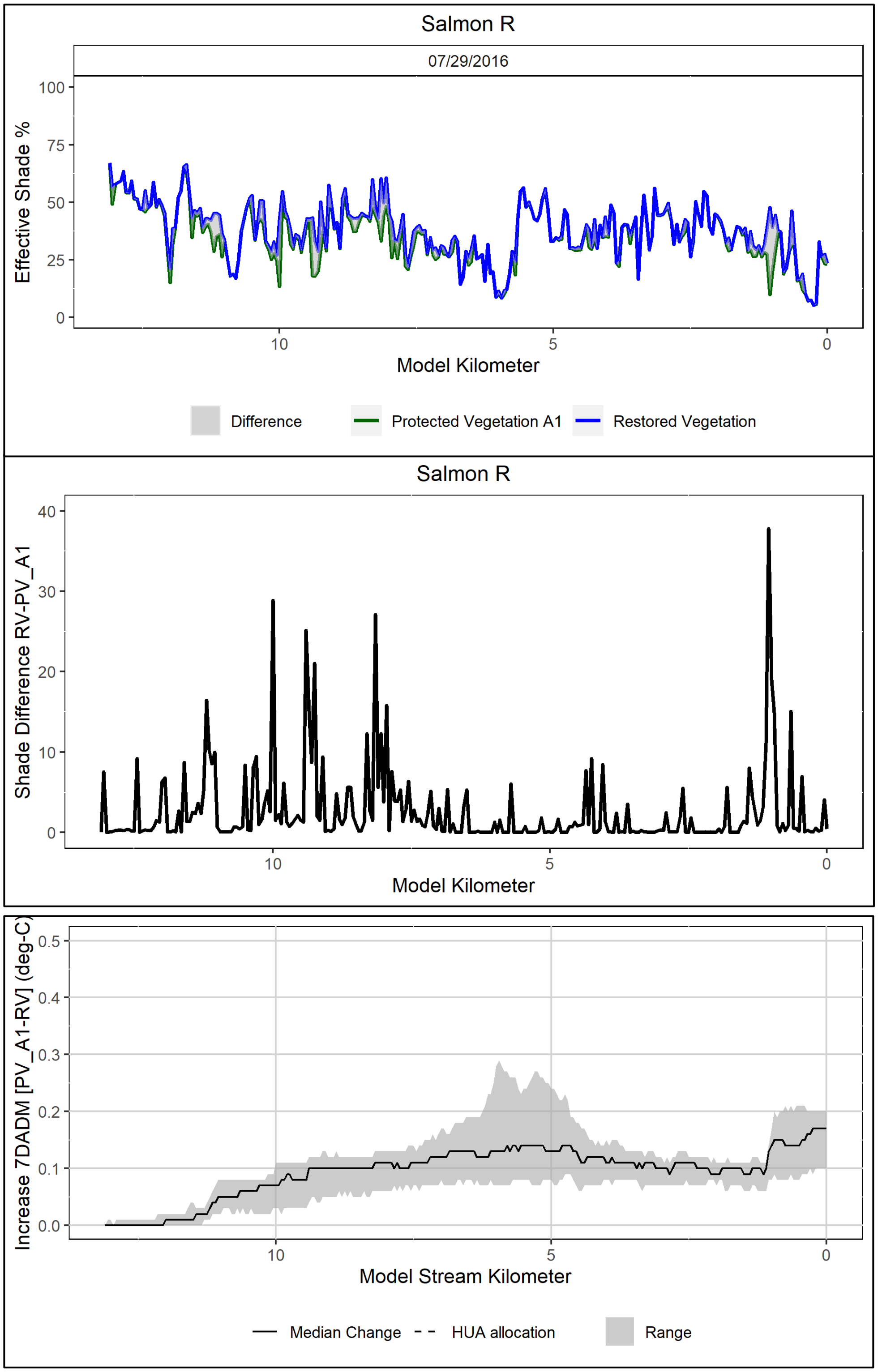

Figure 45. Scenario Results: Protected Vegetation A1 vs. Restored Vegetation A.

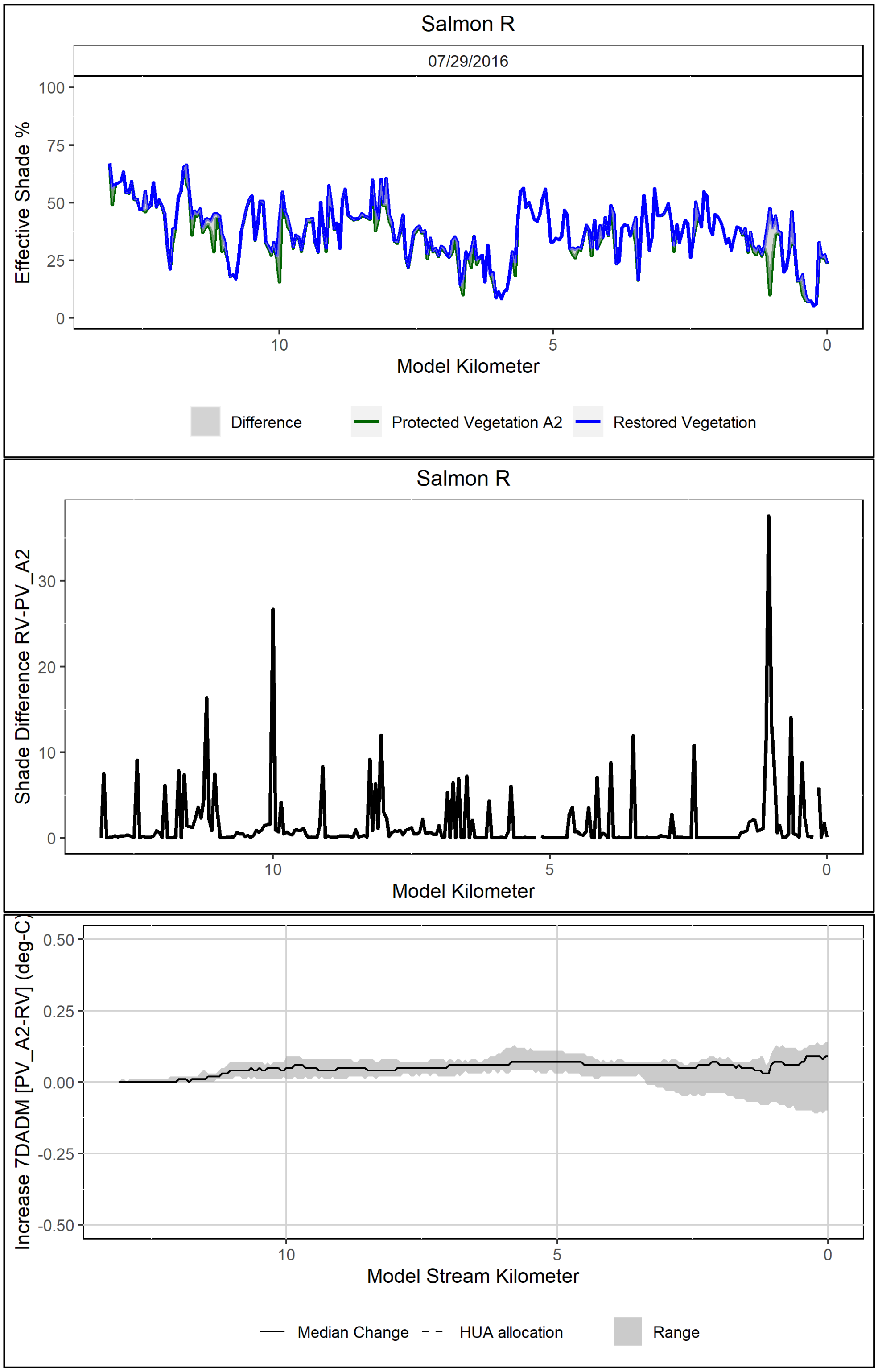

Figure 46. Scenario Results: Protected Vegetation A2 vs. Restored Vegetation A.

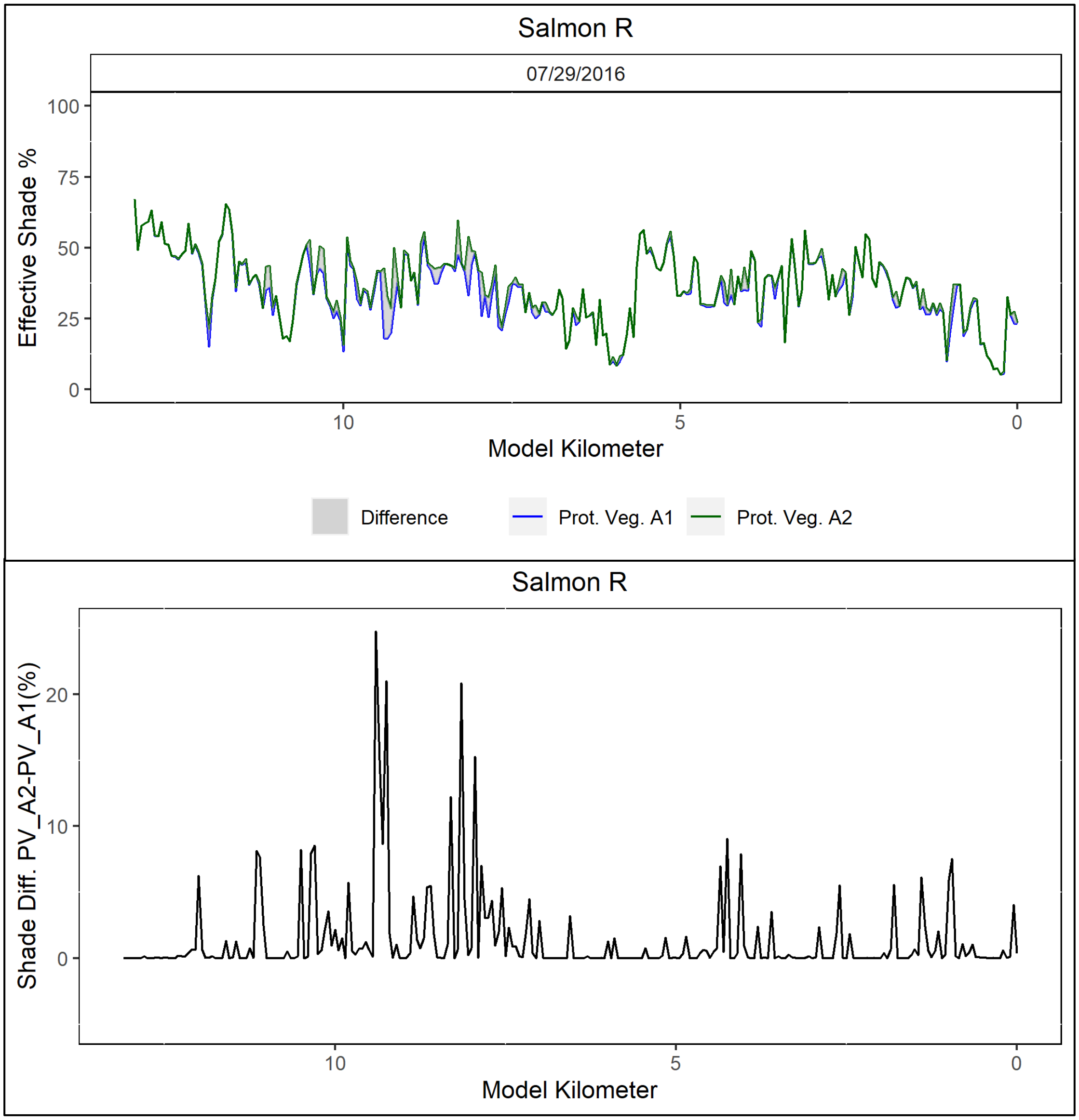

Figure 47. Scenario Results: Protected Vegetation A1 vs. Protected Vegetation A2.

4.2.1.3 Topography

Extent	Shade (%): Topo	Shade (%): CCC	Shade Gap (%)	Stream km Assessed	Stream km: 0-15% Shade Gap	Stream km: 16-25% Shade Gap	Stream km: 26-50% Shade Gap	Stream km: 51-100% Shade Gap
Study Area	8	28	20	13.1	4.3	4.9	3.9	0
Clackamas Cty.	7	26	19	6.8	2.5	2.7	1.6	0
ODF - Private	8	30	22	1.2	0.4	0.4	0.4	0

ODOT	9	10	1	0	0	0	0	0
US BLM	8	29	21	4.3	1.2	1.8	1.4	0
USFS	16	44	28	0.7	0.1	0	0.5	0

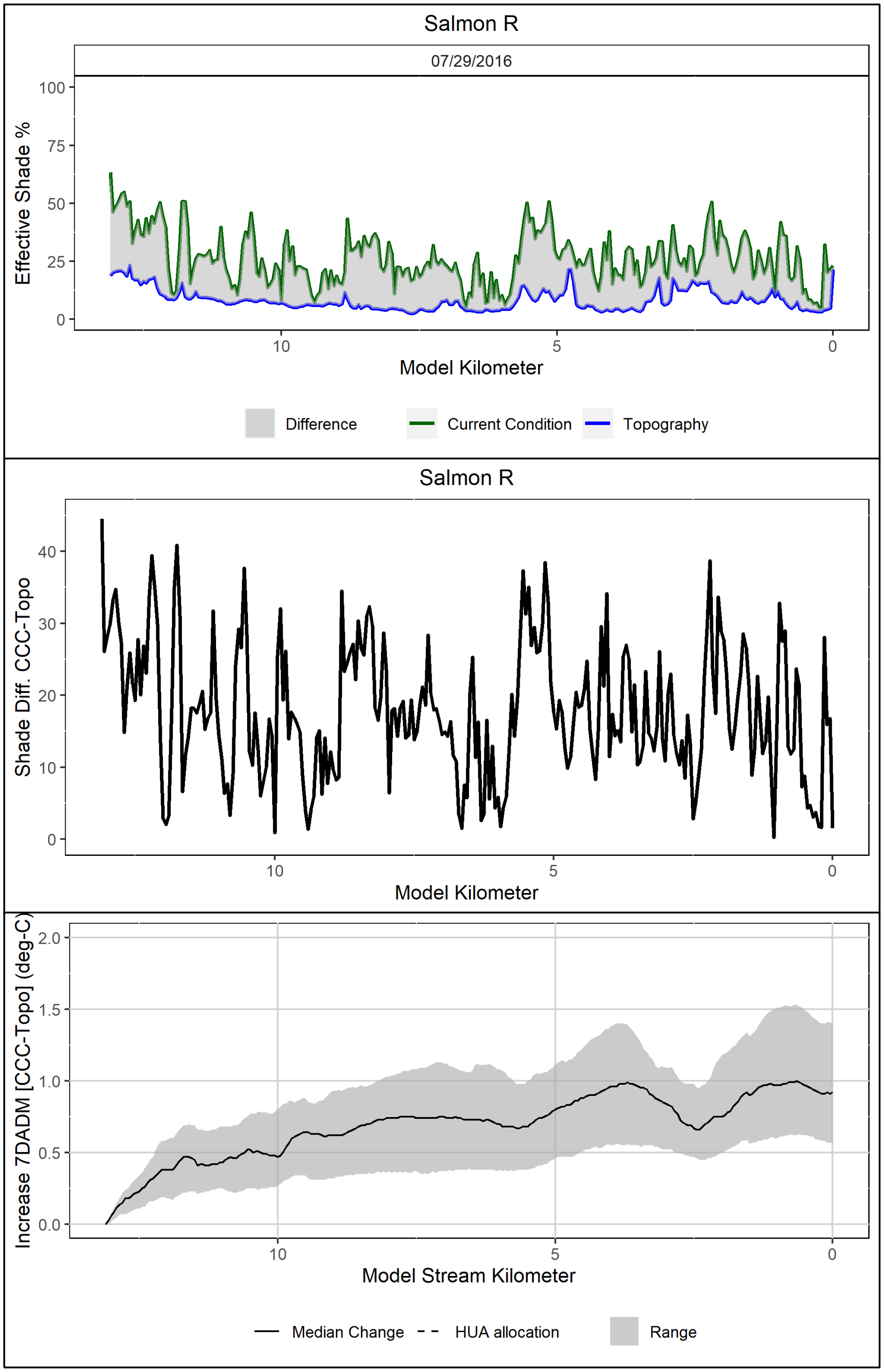

Figure 48. Scenario Results: Topography vs. CCC.

4.2.1.4 Tributary temperatures

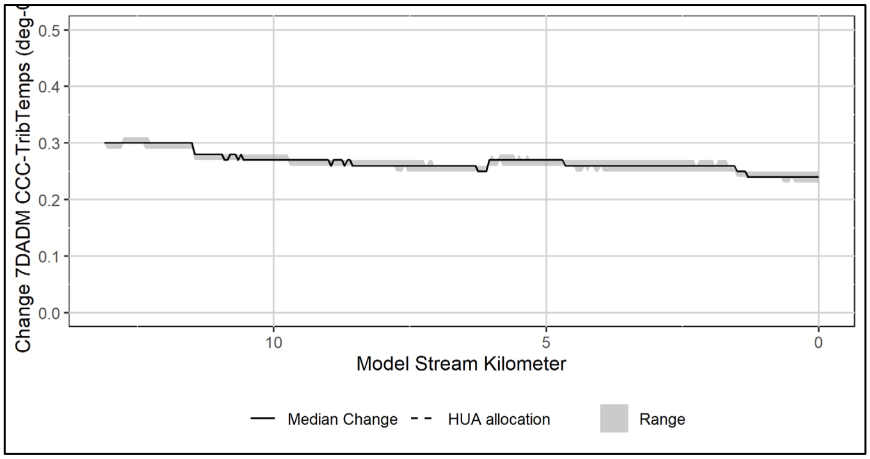

Figure 49. Scenario Results: Tributary Temperatures vs. CCC.

4.2.1.5 Natural Flow

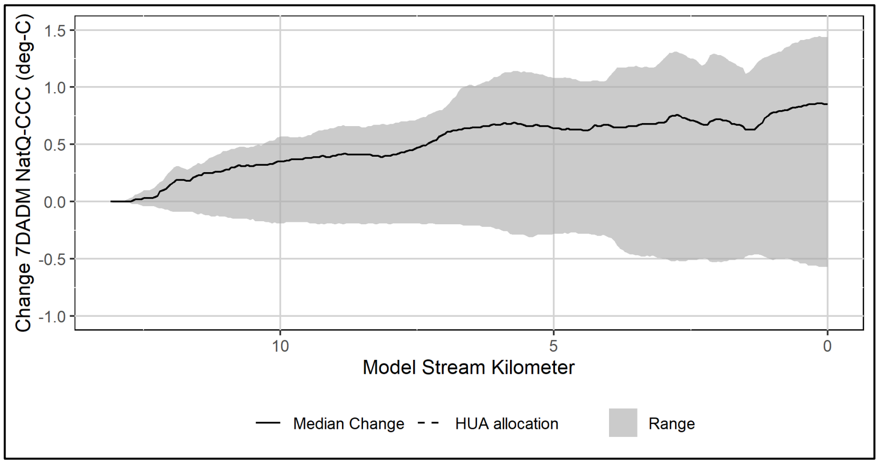

Figure 51. Scenario Results: Natural Flow vs. CCC.

4.2.1.6 Background

For the Salmon River, the background scenario conditions are equal to the restored vegetation (RV_A) conditions and the results are identical to those presented in Section 4.2.1.1.

5. References

DEQ (Oregon Department of Environmental Quality). 2013. “Data validation criteria for water quality parameters measured in the field. DEQ04-LAB-0003-QAG Version 5.0.”

DEQ (Oregon Department of Environmental Quality). 2021. “Quality Assurance Project Plan, Monitoring and assessment for Total Maximum Daily Loads”. DEQ21-LAB-0013-QAPP Version 1.0.

Automatic citation updates are disabled. To see the bibliography, click Refresh in the Zotero tab.

Appendix B:

Sandy River Temperature Model Configuration and Calibration Report - Final

100-WTR-T94501.3
June 21, 2022

PRESENTED TO

US Environmental Protection Agency, Region 10

and

Oregon Department of Environmental Quality

PRESENTED BY

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1.0 INTRODUCTION

Tetra Tech is assisting the Oregon Department of Environmental Quality (ODEQ) and USEPA Region 10 with technical and modeling activities to support the development of TMDLs for spawning temperature impairments in the Sandy River (Figure 1-1) These TMDLs are part of a group of 15 Oregon temperature TMDLs that cumulatively address over 700 temperature impaired segments, all of which are being replaced pursuant to a court order and judgement issued October 4, 2019. The TMDLs must be replaced over an eight-year period.

The Sandy River is in northwestern Oregon and flows through Clackamas and Multnomah Counties. The Sandy River originates from glaciers on the western slopes of Mt. Hood at an approximate elevation of 6200 feet above sea level and travels 56 miles before flowing into the Columbia River near the City of Troutdale (ODEQ, 2005). Major tributaries to the Sandy River include the Zigzag, Salmon, and Bull Run Rivers (Figure 1-1). This report describes the technical approach being used to develop the Sandy River model, summarizes available data, and serves as documentation of the model configuration and calibration for the Sandy River mainstem,

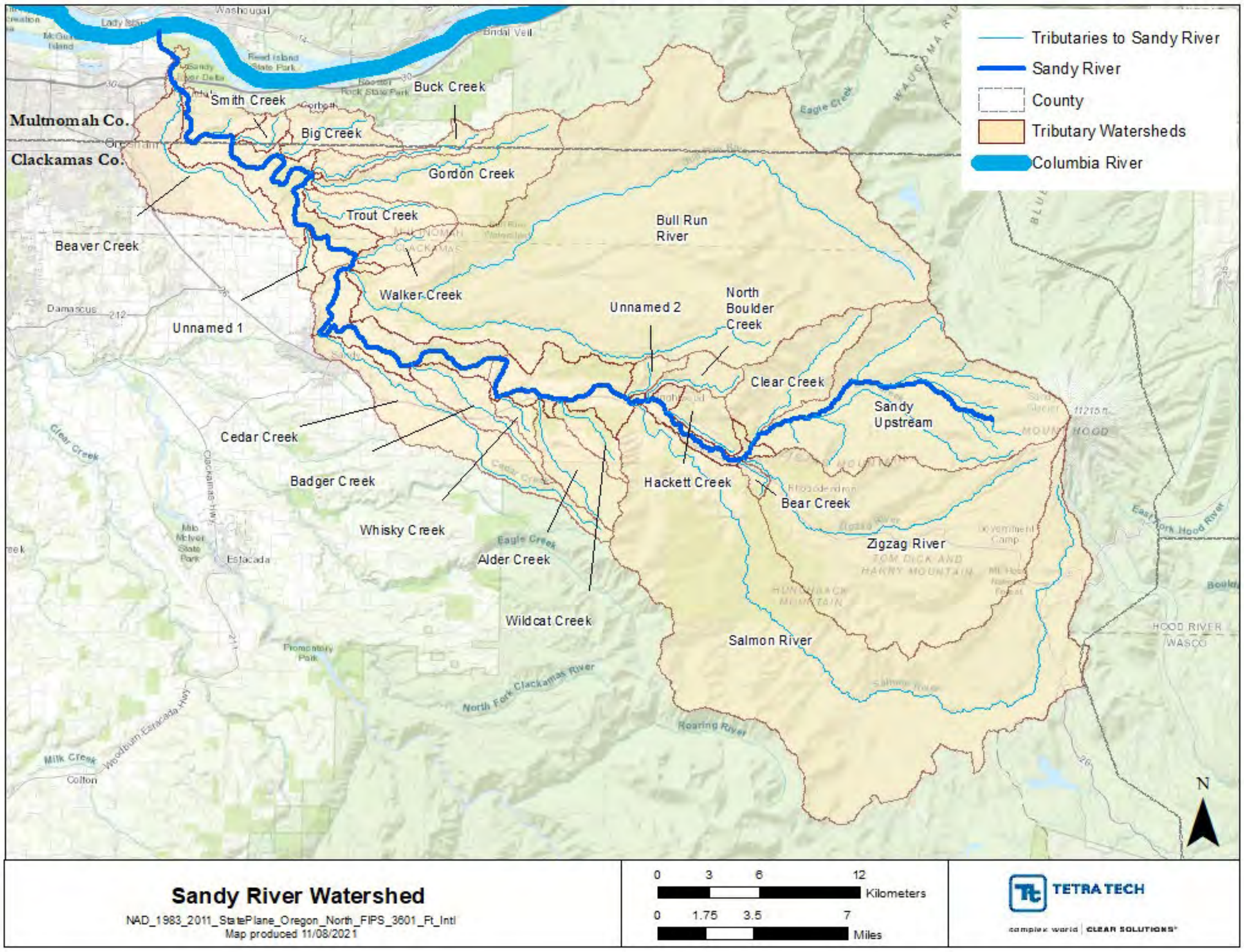


Figure 1-1 Sandy River Watershed

2.0 TECHNICAL APPROACH

Due to the number of TMDLs to be replaced and the mandated schedule, EPA and ODEQ agreed that the approach to completing these TMDLs will rely on previously completed technical work as much as possible. In general, there will be no new modeling or new data collection unless essential for source characterization or development of allocations. Updates to the model or technical analysis will only be made to characterize major new sources (e.g., new NPDES source), or when a significant change to a source or condition has occurred compared to the previous TMDL (e.g., removal of a dam, discontinued discharge by an NPDES source). Additionally, EPA and ODEQ agreed that model updates may be needed to improve characterization of the restored landscape condition and estimates of background temperatures. Details of the technical approach are documented in the Sandy River TMDL QAPP (DEQ 2021).

The replacement TMDLs will retain the estimates of thermal loading/warming from existing sources or source categories if the sources existed at the time the original TMDL was developed. Existing TMDL surrogate measures such as shade curves or channel morphology targets will be retained and used in the replacement TMDLs.

For the 2005 Sandy River Basin TMDL (DEQ, 2005) a computer model - Heat Source version 6.5.1 (HS6) was used to simulate the 2001 stream temperatures. The Heat Source model includes multiple modules that simulate open channel hydraulics and flow routing, heat exchange processes occurring in the stream, effective shade (topographic and vegetation) and predicts stream temperature (Boyd and Kasper, 2003). The modeling time-period for the HS6 model was a single day and was developed for simulating conditions during August 8, 2001.

The HS6 model was developed before the removal of the Marmot Dam, which occurred during 2008/2009. Within the impoundment and approximately 2 kilometers downstream of the dam, monitoring studies show changes to channel morphology have occurred (Major et al 2012) due to the large amount of sediment transported downstream after dam removal. Further, the model also included withdrawals to Little Sandy occurring from the Sandy River, which no longer exist.

As a result of these significant changes to the system relative to conditions present under the original TMDL, a new Heat Source Model version 8.0.8 (HS8) has been developed for the Sandy River to characterize the current hydrology and channel morphology conditions post Marmot Dam removal and to support TMDL replacement in this watershed. In addition, the model also includes NPDES point sources inputs to the Sandy, which were included in the TMDL but were not modeled previously using the HS6 model. The Heat Source version 8 model is discussed in the following section.

2.1 HEAT SOURCE MODEL VERSION 8

The model parameters for HS8 are similar to HS6. HS 8 provides several improvements over version 6. Some of the notable examples are given below. Detailed differences between the Heat Source and version 8 are documented in the Sandy River TMDL QAPP (DEQ 2021).

- The major difference is that the model code is now written in Python 2.5 and C rather than Visual Basic (DEQ 2008) with Excel used as the interface;
- HS8 can simulate an unlimited number of days, compared to a single day simulation.
- Star pattern landcover input with variable landcover height, density, and ground elevation inputs;
- allows for variable flow rate time series on the boundary conditions and tributary inputs;
- requires input of latitude, longitude and aspect for each node of the model;
- uses Manning's equation exclusively to calculate channel hydraulics;
- includes cloudiness (as a percentage of clear sky) as a meteorological input—Heat Source version 6 assumes clear sky conditions;
- allows specifically for groundwater (accretion) and diversion inputs to the model;
- specifies additional morphology data such as bottom width, bed sediment parameters and channel gradient;
- specifies bed conduction inputs such as hyporheic exchange parameters; and

- allows for the use of LiDAR data to be used for vegetation density and overhang.

3.0 MODEL CONFIGURATION

3.1 GIS DATA

Multiple GIS data sets were used in the development of the HS8 model, which requires specification of channel morphology and land cover data—data intensive inputs. The GIS datasets included existing stream and landcover shapefiles, high resolution LiDAR, orthophotos, bare earth hill shade, and aerial imagery data. The data were used for digitizing stream centerline and banks, and for digitizing landcover data or for sampling/deriving stream morphology data such as channel alignment, widths, slope, elevation, topographic shading, and vegetation heights. Table 3-1 lists the spatial datasets and provides a brief description of how the datasets were used in the development of the HS8 model. Due to changes in the stream channel shape and alignment, stream centerlines along with left and right banks were re-digitized using the more detailed aerial imagery and LiDAR data, as the previously digitized stream shapefiles were not representative of the existing system at several locations. The digitized landcover classification from the 2005 modeling effort was used as a reference to digitize the landcover and create a new layer using the more recent high resolution aerial imagery and LiDAR data.

Table 3-1. Data used in developing inputs for the Heat Source Model

Spatial data	Source	Application	Remarks
Streams (2001)	DEQ	Stream centerline and alignment, left bank and right bank	
Bare Earth (DSM) Oregon Department of Geology and Mineral Industries (DOGAMI)[1]	DEQ	DEM bare land surface data used to estimate topographic shading angles and elevation	3 x 3-ft LiDAR data
Bare Earth Hillshade	DEQ	Delineation of stream centerline and stream banks	ArcGIS layer file
Vegetation (DHM) Oregon Department of Geology and Mineral Industries (DOGAMI)[1]	DEQ	Canopy height data derived	3 x 3-ft LiDAR data
National Agriculture Imagery Program (NAIP) ortho photos, and	NAIP, 2016	Support land cover digitization and delineation of stream centerline and stream banks	2016
Oregon Statewide Imagery Program (OSIP)	OSIP, 2018	Primary DOQ used for land cover digitization and delineation of stream centerline and stream banks	2018 one-foot resolution color Digital Orthophoto Quadrangles (DOQ).

Spatial data	Source	Application	Remarks
Digitized land cover classification (2001)	DEQ	Used as a guide for interpreting vegetation codes while digitizing the vegetation for current Heat Source	2001 land cover classification shapefile
Building Footprint	Metro 2021	Used to get building footprints	Oregon Regional Land Information System (RLIS) building footprint shapefile

[1] Datasets used from various collection years were: OLC 2009 covering years 2007-2009; OLC Sandy River 2011, OR LIDAR project; OLC WASCO 2014 and 2015 LiDAR project Several pre-processing steps were required to be completed before sampling the geospatial datasets for providing input to the Heat Source Model. These steps are discussed in the following sections.

3.2 MODEL TIME PERIOD AND EXTENT

The model was developed for the period from July 15, 2016 to September 05, 2016. This period corresponded to the period when hourly water temperature data were collected by Portland State University at five locations along the Sandy River, as listed in the QAPP. (DEQ, 2021). Further, the period of record of water temperature data collected also covered the critical summer and spawning period. Hourly stream temperature data were also collected at several major tributaries such as Bull Run, Salmon River, and Zig Zag and minor tributaries, which were used for model boundary configuration.

The extent of the model domain is the Sandy River from the mouth at the Columbia River to just upstream of Clear Creek. The upstream extent was defined based on the availability of stream temperature data that could be used to define the upstream boundary on the Sandy. The Sandy River stream channel was digitized using a combination of LiDAR digital terrain model data, 2016 National Agriculture Imagery Program (NAIP) ortho photos, and Oregon Statewide Imagery Program (OSIP) 2018 one-foot resolution color Digital Orthophoto Quadrangles (DOQ). The extent of the Sandy River Heat Source model is shown below (Figure 3-1).

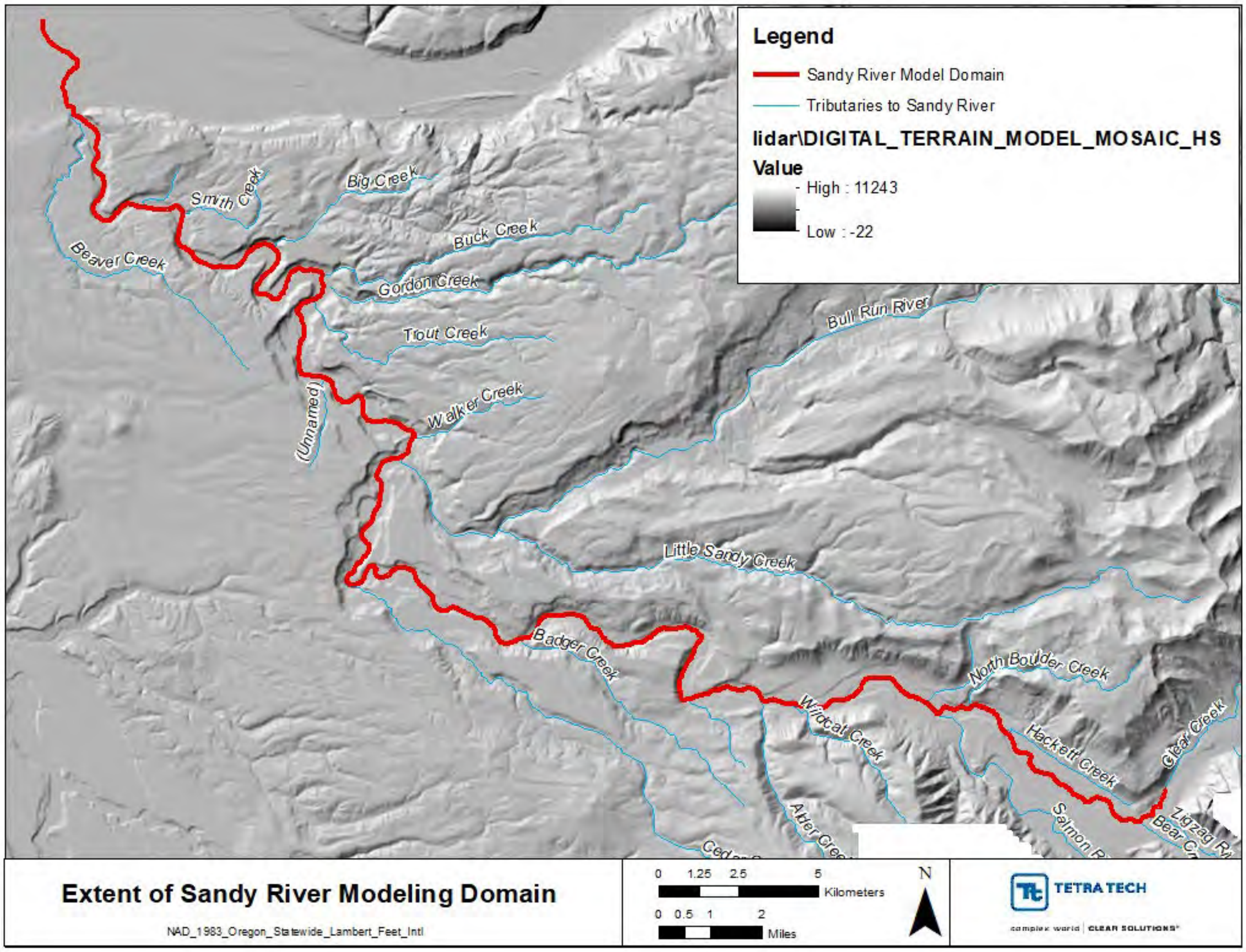


Figure 3-1. Extent of Sandy River modeling domain

3.3 DIGITIZATION OF STREAM CENTERLINE AND STREAM BANKS

Stream reaches were digitized using a combination of DOQs (OSIP, 2018) and high resolution OR bare earth hill-shade layer provided by DEQ. The digitization was performed at a scale finer than 1:1000. In cases where the stream was braided, the dominant channel was chosen. Stream left and right banks were digitized to follow the wetted perimeter where discernable or according to active channel boundaries. In some cases where the stream bank lines were concealed in the imagery, the best estimate of likely active channel bank lines was digitized. In these cases, the high-resolution bare earth hill-shade allows for viewing the channel widths. NAIP 2016 imagery, along with stream channel centerlines and stream banks from the 2005 TMDL were also used as necessary for reference purposes to aid in the digitization process. Figure 3-2 shows an example of the stream bank digitization. Stream segment distances along the centerline and stream widths were measured using TTools at every 50 meters. All river kilometer designations were calculated using this more recent high resolution stream delineation and revised modeling extent, therefore, they may not match historical river kilometer designations.

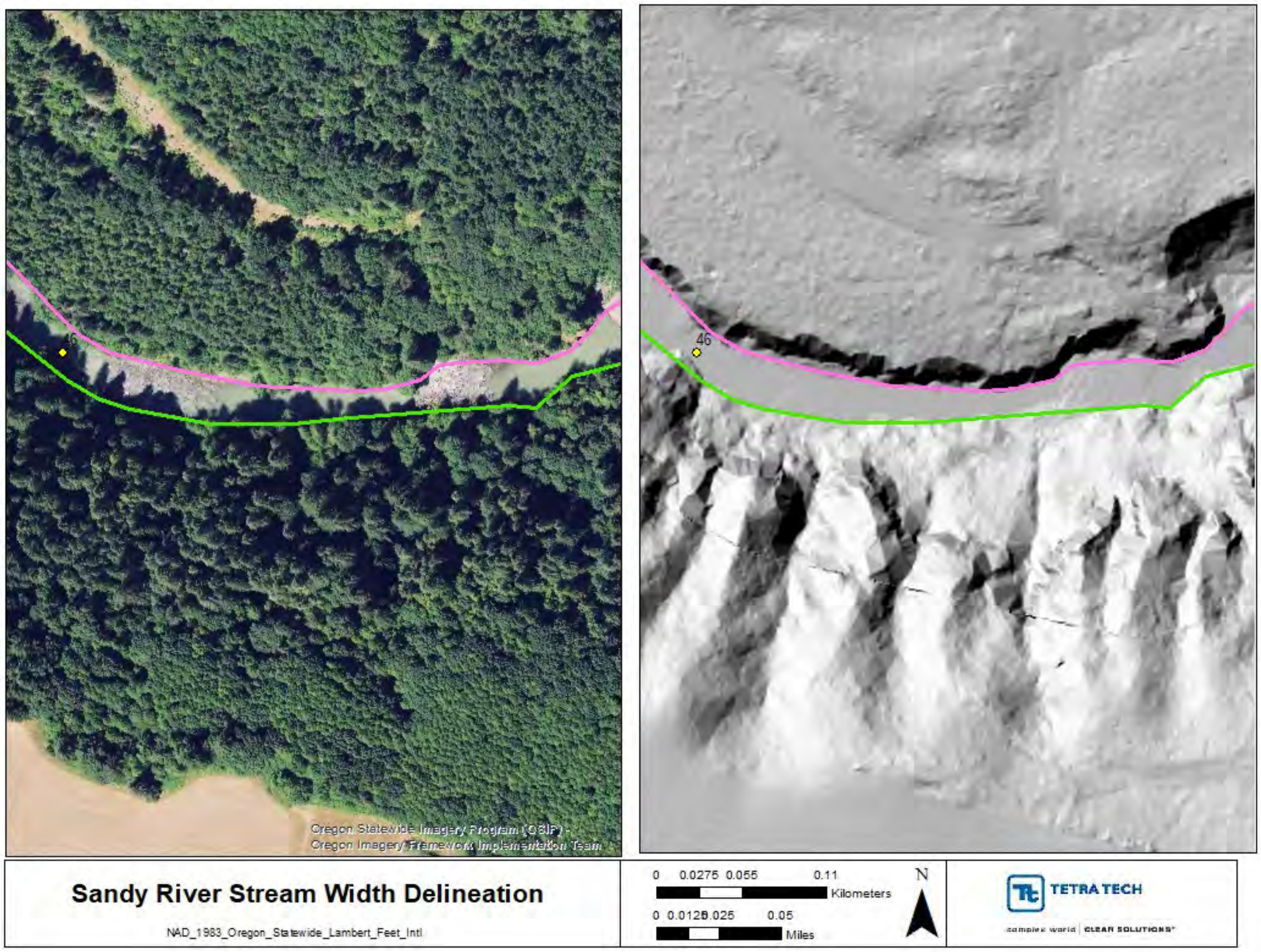


Figure 3-2 Digitization of stream bank edges

3.4 LANDCOVER PROCESSING

The majority land use along the Sandy River is forest accounting for about 81 percent of the near-stream area (DEQ 2021). A landcover raster was created using a combination of digitized landcover and vegetation height data derived from LiDAR. A unique landcover code consisting of landcover type and height was created. Development of the vegetation raster is discussed further in the following sections.

3.4.1 Landcover Mapping

The stream was buffered 100-meters from each bank and the resulting buffer was divided into polygons based on the various land cover type. The land cover was digitized using the OSIP 2018 DOQ imagery layer into polygons to map the various species and land cover types (e.g., Hardwood/Conifer/Roads, developed residential/industrial/commercial). The building footprints for the developed categories were derived using the RLIS building footprint shapefile (Metro, 2021), which contains regional building footprint data from local jurisdictions, or created and compiled by Watershed Sciences from regional Lidar data with average building heights. The building footprints were included using a union of the shapefile into the 100-meter buffer corridor within GIS. Finally, the digitized vegetation was assigned landcover type codes for different landuse types. The original TMDL (DEQ 2005) landcover digitization was used as a guide during the digitization process to guide the digitization and characterization of the vegetation species and landcover code assignment. Landcover codes used in the mapping were provided by DEQ and are similar to those used in the 2005 TMDL.

Note that there are multiple heights associated with each land cover code. The final landcover codes used in the calibrated model are a concatenation of two codes: landcover type and landcover height as determined from LiDAR. An example landcover code is shown below where the current condition land cover type (600 - Hardwood - High Dense) and the current height (20 meters) is concatenated as landcover code 600020.

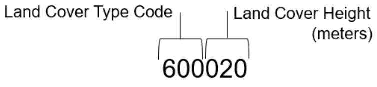


Table 3-2 shows the codes used in the assignment. It was also assumed that there is no in-stream vegetation and no overhanging vegetation.

Table 3-2. Landcover code assignment

Landcover Type Code	Description	Height (m)	Density (%)	Overhang (m)
300	Pastures/Cultivated Field	height from LiDAR	75%	0.0
301	Water - Non Active Channel	height from LiDAR	0%	0.0
302	Water - Active Channel Bottom	height from LiDAR	0%	0.0
305	Barren – Embankment	height from LiDAR	0%	0.0
308	Barren – Clearcut	height from LiDAR	75%	0.0
309	Barren – Soil	height from LiDAR	0%	0.0
348	Development - Residential	height from LiDAR	100%	0.0
349	Development - Industrial/Commercial	height from LiDAR	100%	0.0
352	Dam/Weir	height from LiDAR	100%	0.0
355	Canal	height from LiDAR	0%	0.0
400	Barren – Road	height from LiDAR	0%	0.0
401	Barren - Forest Road	height from LiDAR	0%	0.0
500	Mixed Conifer/Hardwood - High Dense	height from LiDAR	60%	0.0
550	Mixed Conifer/Hardwood - Medium Dense	height from LiDAR	30%	0.0
555	Mixed Conifer/Hardwood - Low Dense	height from LiDAR	10%	0.0
600	Hardwood - High Dense	height from LiDAR	75%	0.0
650	Hardwood - Low Dense	height from LiDAR	30%	0.0
700	Conifer - High Dense	height from LiDAR	60%	0.0
750	Conifer - Low Dense	height from LiDAR	30%	0.0
800	Upland Shrubs - High Dense	height from LiDAR	75%	0.0
850	Upland Shrubs - Low Dense	height from LiDAR	25%	0.0
900	Grasses – Upland	height from LiDAR	75%	0.0
950	Grasses – Wetland	height from LiDAR	75%	0.0

Figure 3-3 shows an example of the near stream landcover digitization. Note that the Developed Residential and Industrial/Commercial landcover were derived using the RLIS building footprint dataset discussed previously.

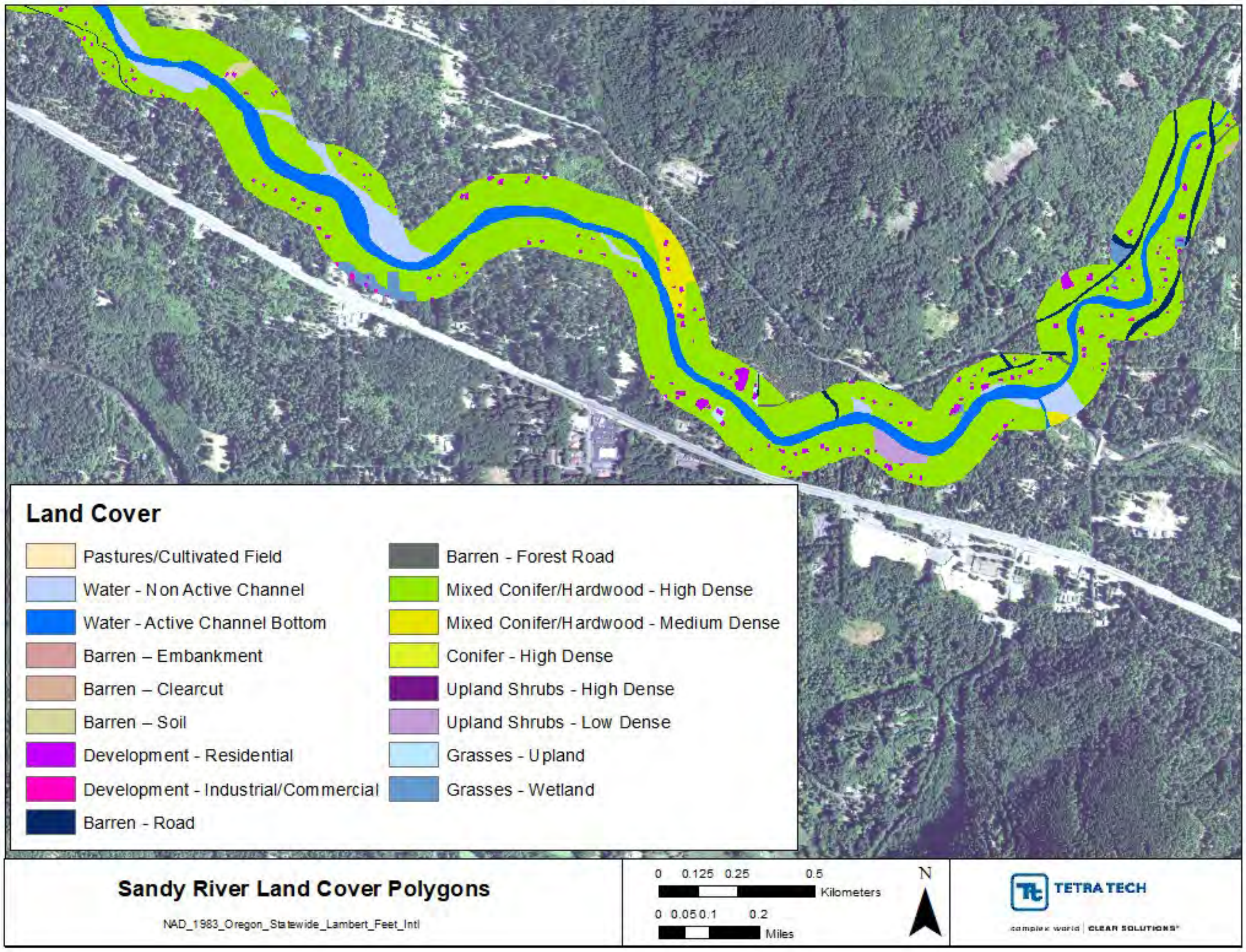


Figure 3-3 Digitized near stream land cover polygons

3.4.2 Vegetation Height

DEQ provided the processed vegetation height raster layer. Tree height information was derived from 3-foot resolution LiDAR data from 2017. The LiDAR first and last returns are processed to generate two data sets: a Digital Ground Model (DGM) representing the first return and a Digital Surface Model (DSM) representing the last return. These two grids were subtracted from each other to generate a Digital Height Model (DHM), which represents the height of features, such as trees, on the ground. The vegetation height raster was further processed to remove any nodata values and clipped along the stream corridor buffer area.

3.4.3 Vegetation Raster

A vegetation raster layer was finally created using the digitized land cover and vegetation height layer. The land cover shapefile was first converted to a raster layer. The resulting raster was combined with the vegetation height raster layer using raster addition in ArcGIS to create a new raster layer with a unique code as follows: [veg_raster_code x 1000 + vegetation height]. The resulting value was then converted to an integer composite raster code to reduce the numerous codes generated due to float values. For example, the code for a particular pixel 500033 would represent Mixed Conifer/Hardwood – High density with a height of 33 feet. A total of 1,025 unique land cover codes were created. The resulting processed vegetation raster layer was used in the vegetation sampling step (5) of TTools discussed below.

3.5 HEAT SOURCE MODEL INPUT CREATION USING AUTOMATED GIS SAMPLING

DEQs TTools utility was used to create channel related inputs to the heat source model. TTools samples geospatial data and allows assembling of high-resolution data inputs for use in the heat source model. The utility program comprises a set of automated GIS sampling tools used to create an input database that feeds directly into HS8. TTools includes five steps for sampling/extracting data at user defined intervals along the stream, which are outlined below:

Step 1 of TTools established channel centerline sampling points every 50 meters beginning at the upstream end of the delineated channel centerline and the stream length between each node. Each point was then populated with the point latitude/longitude and aspect. Figure 3-4 shows the stream sampling points every 50-meters, along with points every 1 kilometer for reference. Sandy River generally flows in a north-westerly directly. Aspect is used to calculate the solar flux on the stream surface based on its orientation. Figure 3-5 shows the calculated channel aspect.

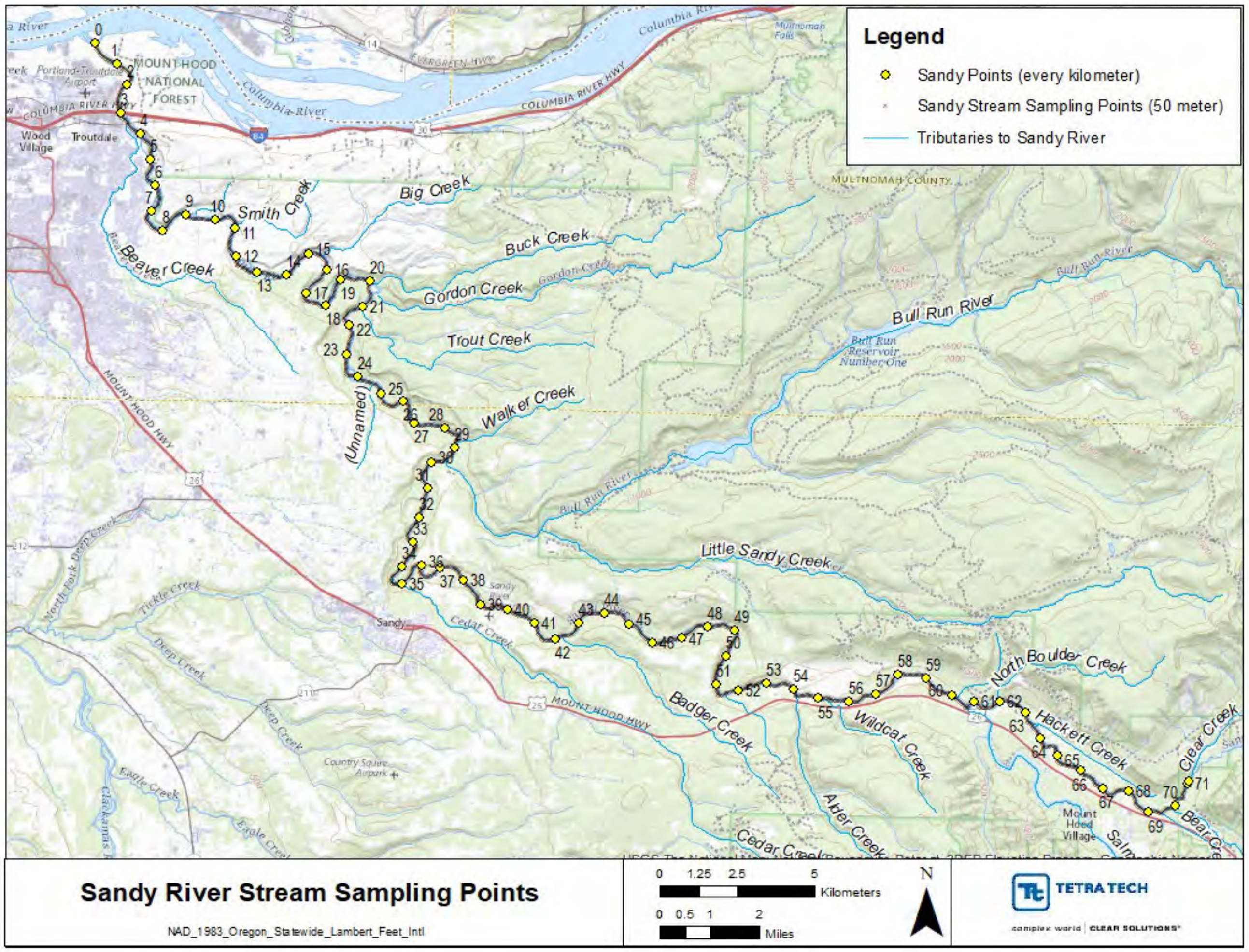


Figure 3-4 Sandy River Stream Sampling Points

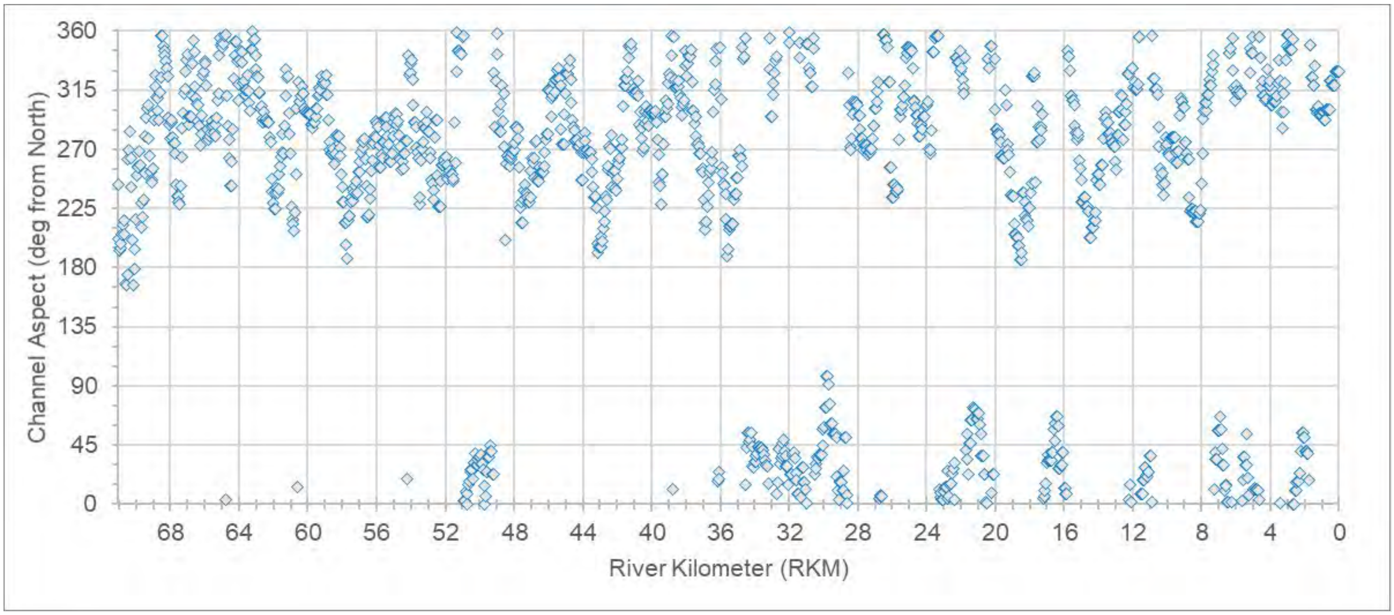


Figure 3-5 Sandy River calculated channel aspect

Step 2 calculated the channel width using the distance between the delineated left and right banks established with a line orthogonal to the aspect of each channel centerline point. Figure 3-6 shows the calculated channel widths for Sandy River. The channel widths ranged from 13.2 meters to 279.9 meters, with a mean of 55.6 and median of 47.6 meters.

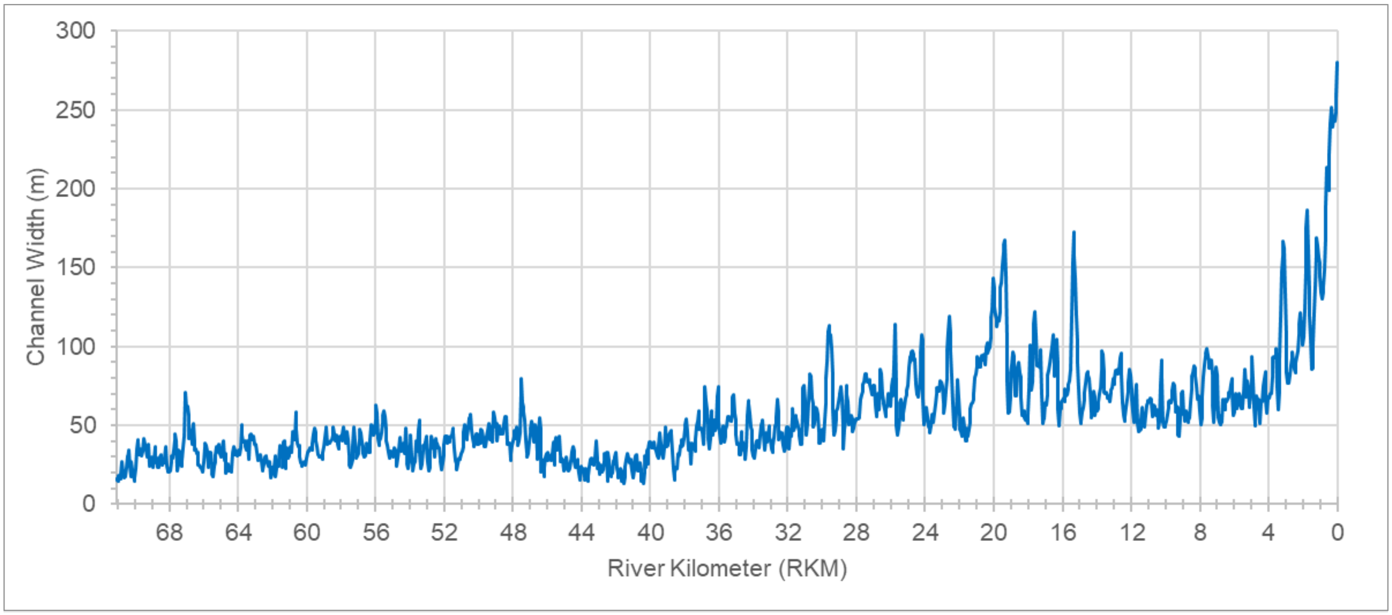


Figure 3-6 Sandy River calculated width

The stream channel within Heat Source is represented as a trapezoidal cross-section. Unlike previous versions where the bank full width is an input into the model, the version 8 model requires input of the channel bottom width. A separate macro that utilizes the methodology from Heat Source Model version 7 was provided by DEQ, which was used to calculate the channel bottom width using the estimated bank full width from TTools, a width to depth ratio (W:D=8) and channel angle (z=1). The channel bottom widths were further refined during calibration. The final channel bottom widths used in the model ranged from 7.5 meters to 198 meters, with a mean of 36.4 and median of 28.5 meters.

Step 3 sampled channel elevation at each point from the bare earth LiDAR DEM (3 ft x 3 ft) from the cell containing the point (nine cell setting for minimum elevation setting). Figure 3-7 shows the computed stream channel elevation and gradient. As can be seen over the 71.08 RKM stretch, the channel changes from a high gradient cobble-boulder stream to a low-gradient channel at the downstream (around 0.0006 m/m gradient and 4 meter elevation) before its confluence with the Columbia River. Below the Marmot dam, which is located at approximately 48.4 RKM, the channel flows through a high gradient gorge area (Sandy River Gorge), which is characterized by a narrower channel width up to around RKM 40 after which it gets broader and then starts to decrease in gradient.

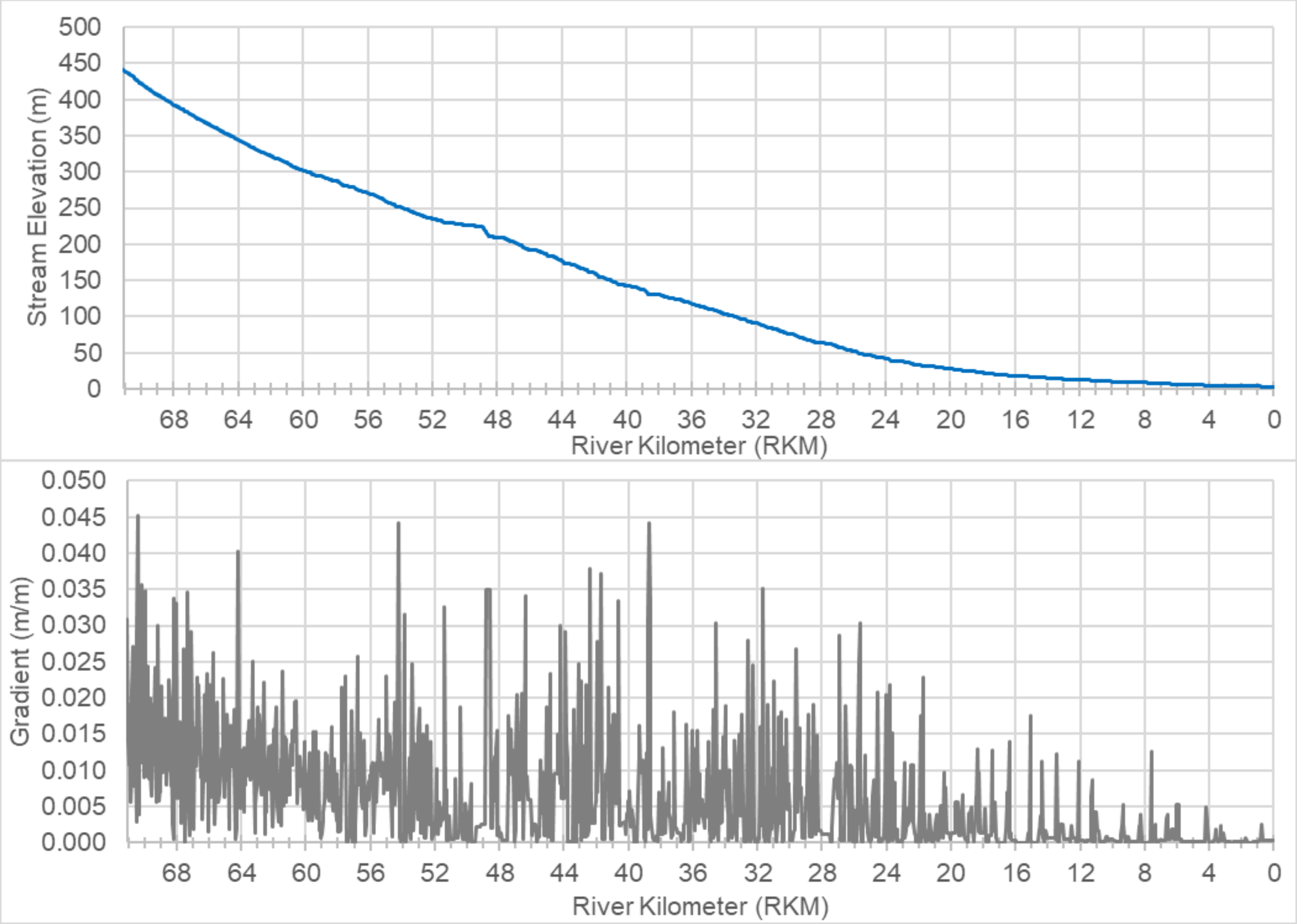


Figure 3-7 Sandy River Elevation and Gradient

Step 4 from the bare earth LiDAR DEM (3 ft x 3 ft) sampled topographic shade angles to the east, west, and south of each point in a 10-km search radius. Figure 3-8 shows the topographic shading angles for the Sandy River. The Sandy River flows generally in a westerly direction to the north, the lowest topographic angles are generally produced to the West, with the highest topographic angles produced were in the vicinity of the Sandy Rivercanyons to the south e.g. RKM 48 to 40.

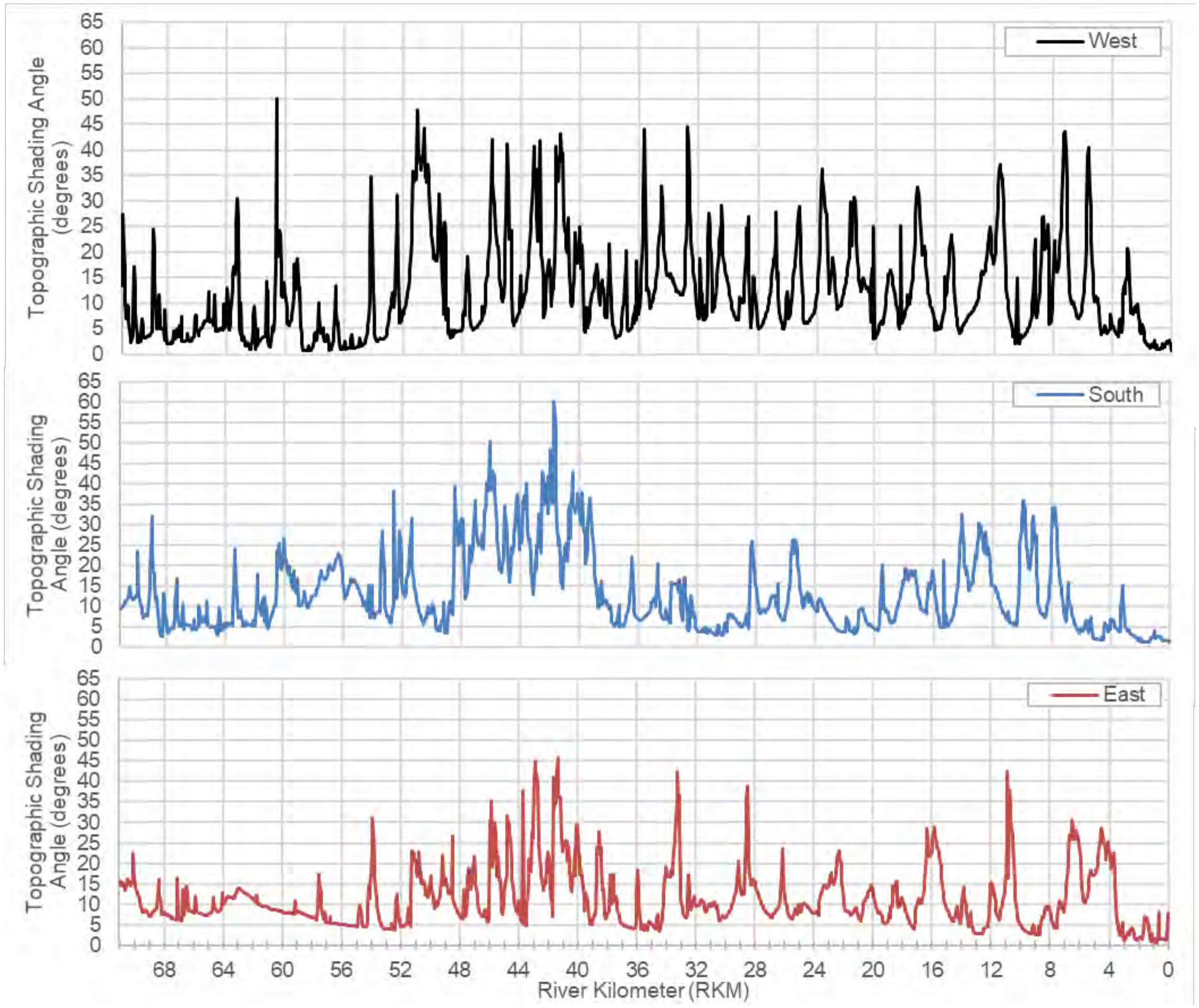


Figure 3-8 Sandy River Topographic Shading Angles

Step 5 sampled landcover from the 3-ft resolution vegetation raster layer at each 50-meter node using a dense radial sampling pattern. Five transverse vegetation samples were taken in each of the seven cardinal directions, with the distance between samples taken as 8 meters. The vegetation raster layer creation is discussed previously under the vegetation raster processing section.

3.6 FLOW DATA

Flow data were available in the Sandy River watershed at limited locations. Specifically, flow data during the 2016 modeling period were available for Bull Run and Beaver Creek tributaries, no flow data were available for any of the remaining (19) tributary inputs specified in the Heat Source Model. In addition, no flow data were available to configure the head water – upstream boundary condition. Two flow gages were available along the Sandy that were used for flow calibration purposes. Table 3-3 shows an inventory of the available flow data available and notes how they were used. Note that the sum of the flows from the Little Sandy River and Bull Run River gages comprise of the total input going into Sandy.

Table 3-3. Inventory of available flow data in the Sandy River watershed used in the Heat Source Model development

Station ID	Latitude/ Longitude	Source	Type
Little Sandy River (14141500)	45.4153977/ -122.171475	USGS	Boundary condition
Bull Run River (14140000)	45.4373/ -122.179656	USGS	Boundary condition
Beaver Creek (14142800)	45.5192866/ -122.388979	USGS	Boundary condition
Blazed Alder Creek (14138800)	- 45.4526183/ -121.891468	USGS	Used to derive flow boundary condition
Sandy River Near Marmot (14137000)	45.3995642/ -122.137307	USGS	Used to derive flow boundary condition & calibration
Sandy River Below Bull Run River, Near Bull Run (14142500)	45.4490094/- 122.2450885	USGS	Used to derive flow boundary condition & Calibration

3.6.1 Flow Estimation

Due to the lack of flow data for most of the system, stream flows had to be estimated to configure the model at certain locations. Three USGS flow gages with continuous daily data during the model period were evaluated to be used as the source flow data for derived model flow inputs (Figure 3-9): Beaver Creek (14142800), Blazed Alder Creek (14138800) and Sandy River near Marmot (14137000). Note that Beaver Creek and Blazed Alder Creek were also chosen since they had good long-term flow records. Beaver Creek is a tributary to Sandy River and the Blazed Alder Creek is a headwater tributary to Bull Run (unmanaged).

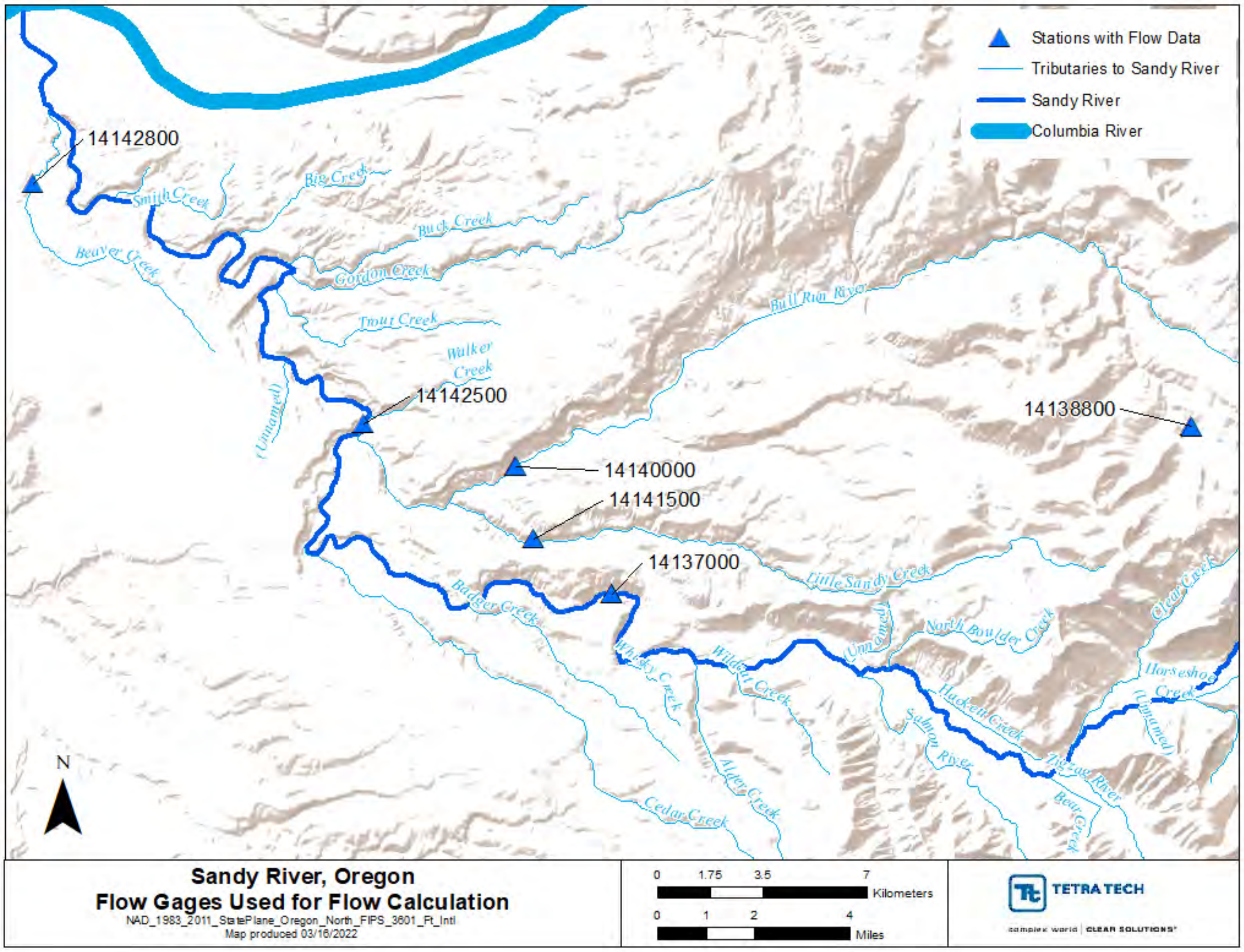
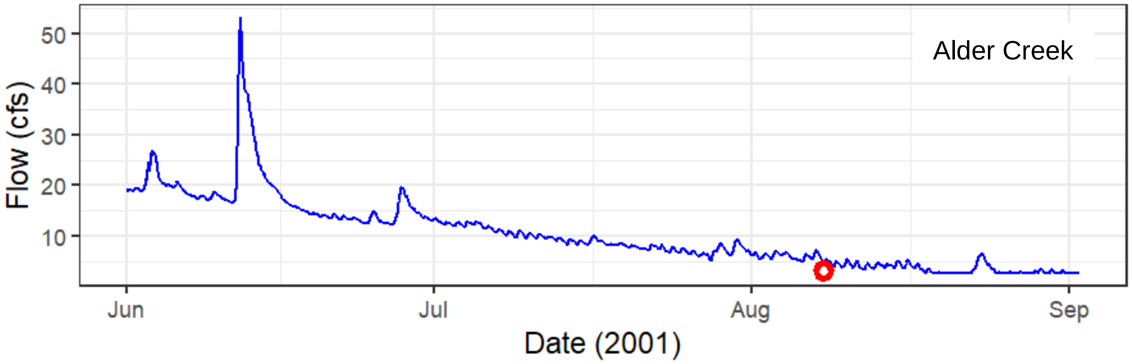


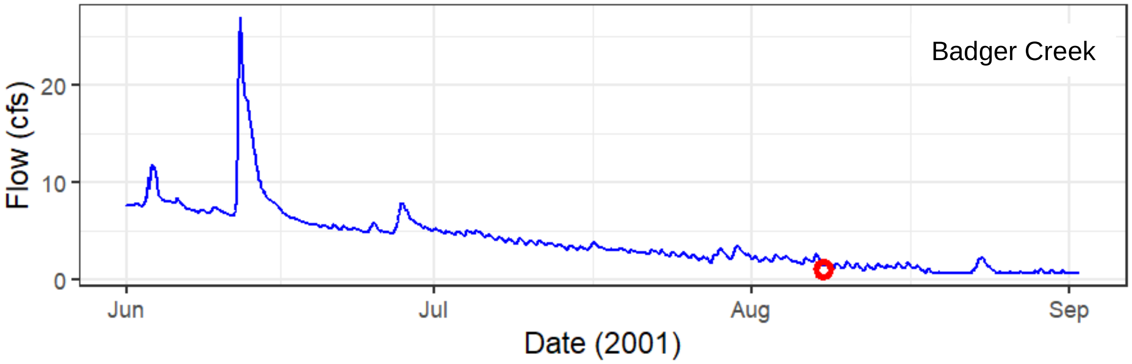
Figure 3-9 Flow gages used for flow calculations

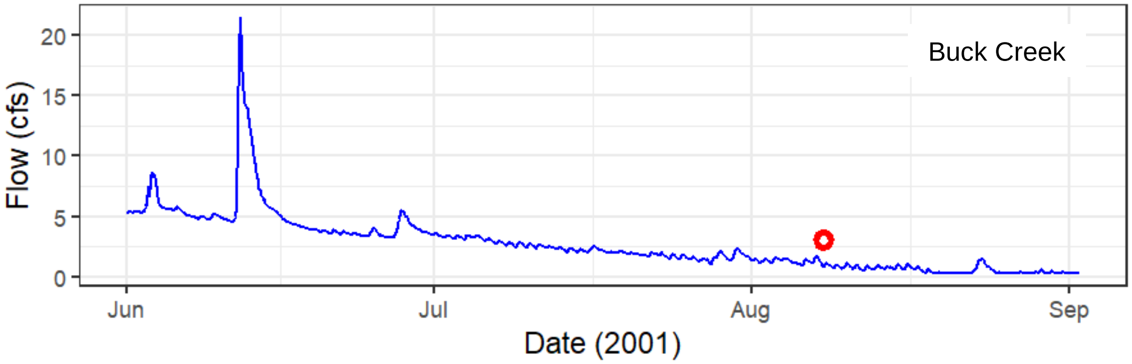
The Beaver Creek gage was not used to derive flows for other tributaries due to a large area of adjacent urban land cover, while the other tributaries were predominantly undeveloped. Two methods of generating derived flow input time series were tested for each ungaged model input:

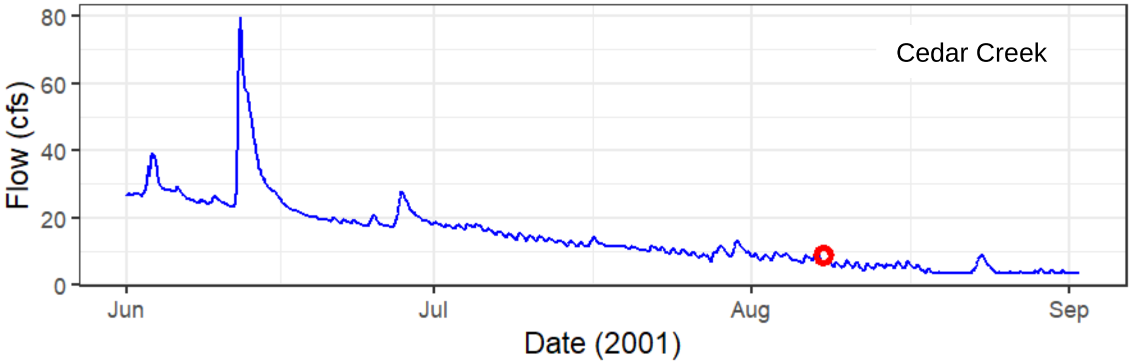
1. Applying flow duration information retrieved from Stream Stats (Risley et al 2008) to the source gage flows (the “Stream Stats method”), based on the methods discussed in Lorenz & Ziegeweid (2016), Gazoorian (2015), and Stuckey (2016).
2. Applying the ratio of drainage areas directly to the source gage flows (the “area ratio method”).

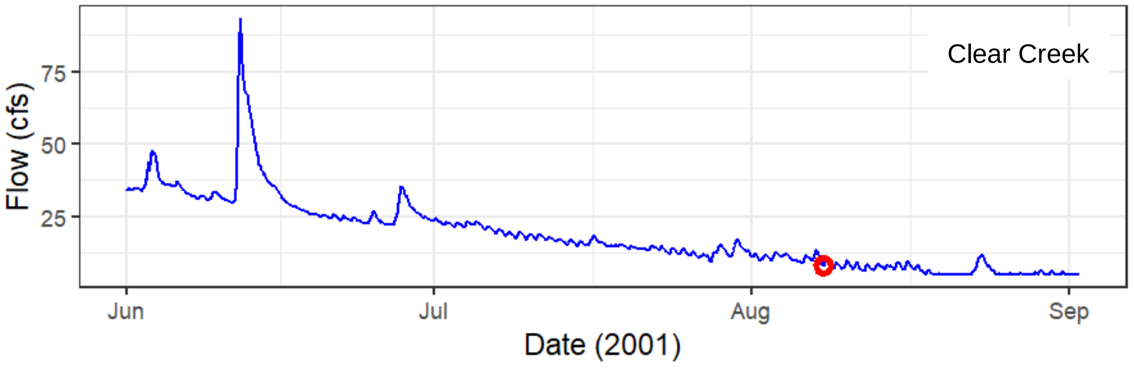
Each method was applied to both the Sandy River and Blazed Alder Creek gage timeseries, for a total of four different timeseries options tested for each input. First, measurements of flow used in the 2001 version of the Sandy River HS6 model were compared with the estimated flow timeseries for June-September 2001. Results from the Stream Stats method with the Sandy River at Marmot gage as the source station showed the best agreement overall with the 2001 flow observations (Figure 3-10). Table 3-4 further shows the observed vs estimated flows on August 8, 2001. Therefore, the Stream Stats method was selected as the preferred method to derive the input flow timeseries for the ungagged streams.

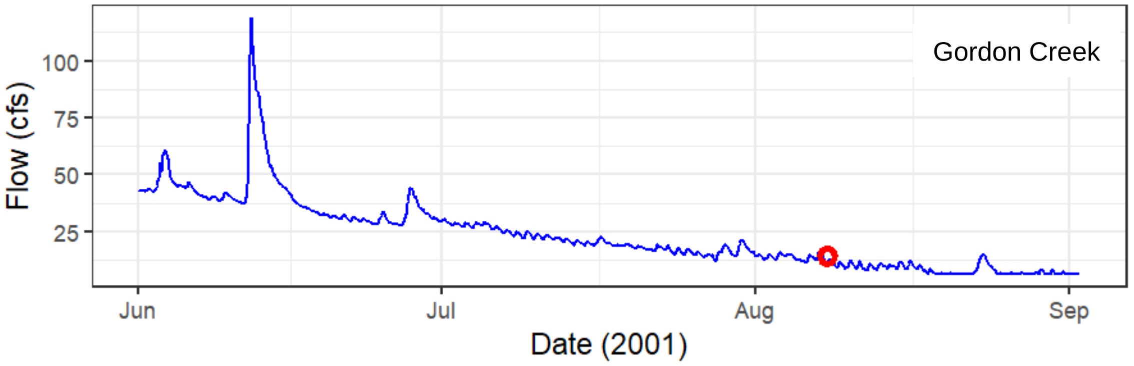

Alder Creek
Flow (cfs)
50
40
30
20
10
Jun
Jul
Aug
Sep
Date (2001)

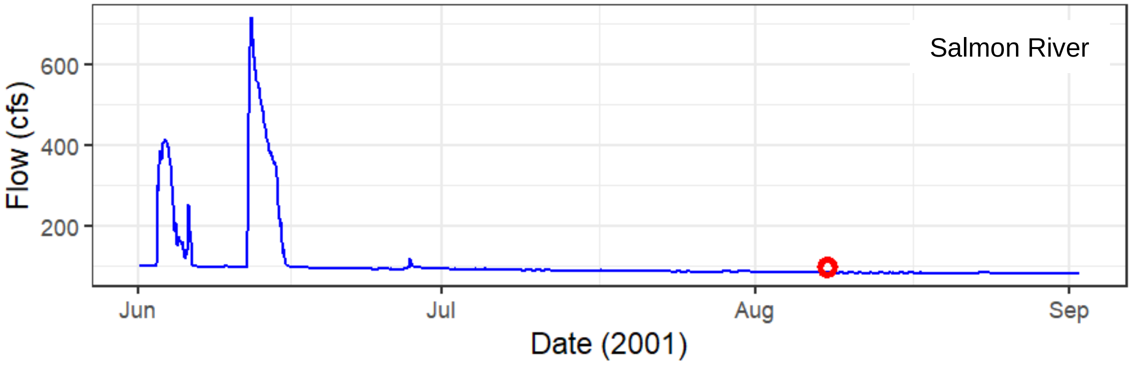

Badger Creek
Flow (cfs)
20
10
0
Jun
Jul
Aug
Sep
Date (2001)

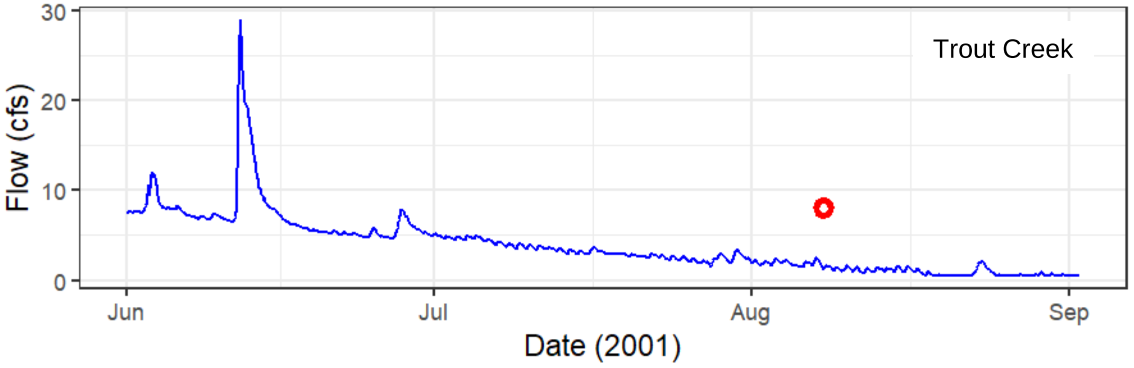

Buck Creek
Flow (cfs)
20
15
10
5
0
Jun
Jul
Aug
Sep
Date (2001)


Cedar Creek
Flow (cfs)
80
60
40
20
0
Jun
Jul
Aug
Sep
Date (2001)


Clear Creek
Flow (cfs)
75
50
25
Jun
Jul
Aug
Sep
Date (2001)


Gordon Creek
Flow (cfs)
100
75
50
25
Jun
Jul
Aug
Sep
Date (2001)


Salmon River
Flow (cfs)
600
400
200
Jun
Jul
Aug
Sep
Date (2001)


Trout Creek
Flow (cfs)
30
20
10
0
Jun
Jul
Aug
Sep
Date (2001)

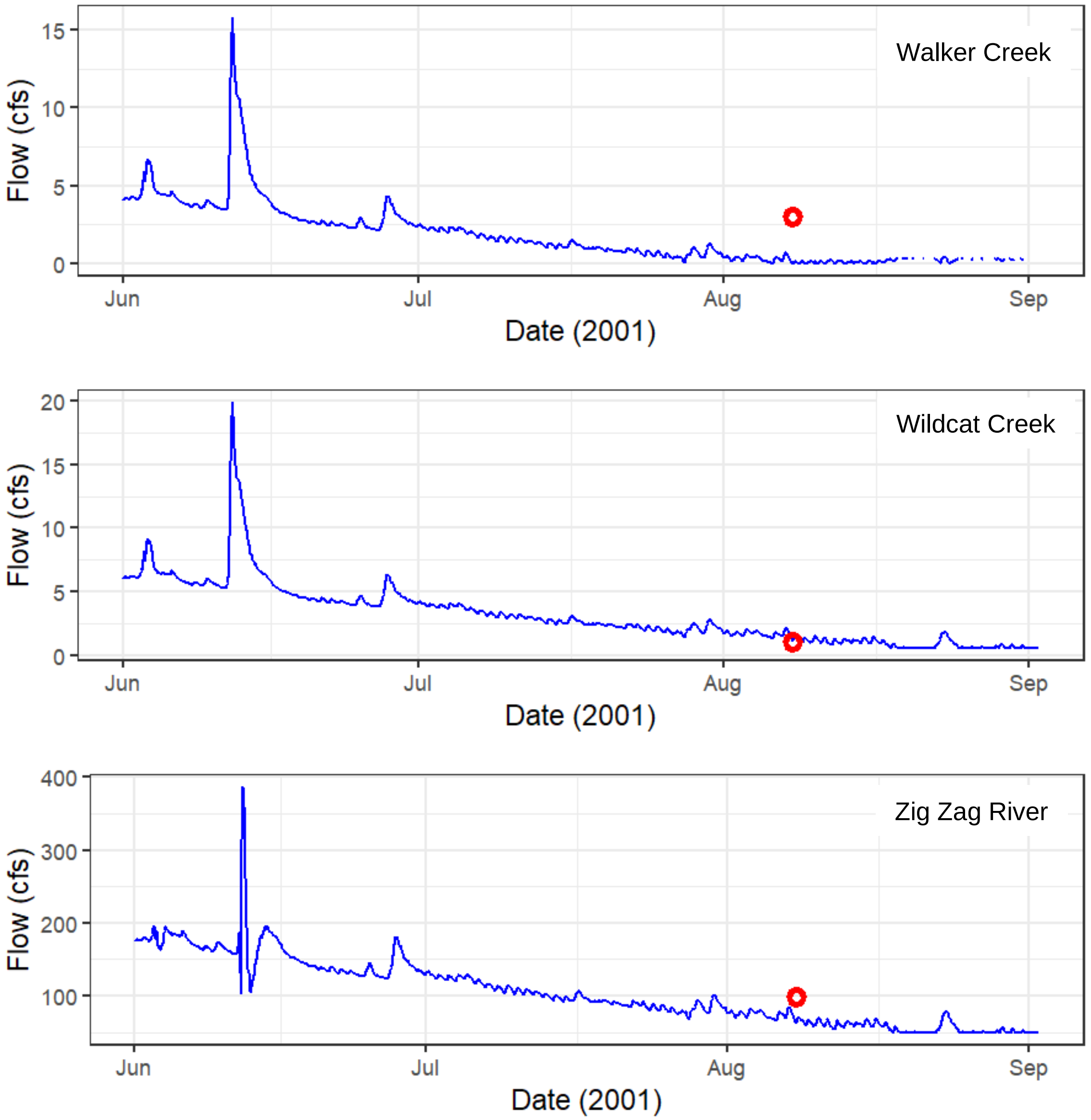


Figure 3-10 Estimated Summer 2001 flows (blue) with observed flow used in 2001 model (red).

Table 3-4. Observed and Estimated flows on August 8, 2001

Name	Observed Flow (cfs)	Estimated Flow (cfs)
Alder Creek	3.2	4.8
Badger Creek	1.0	1.5
Bear Creek	8.0	0.2
Buck Creek	3.0	1.0
Cedar Creek	9.0	6.5
Clear Creek	8.0	8.8
Gordon Creek	14.0	11.1
Salmon River	96.1	83.4

Name	Observed Flow (cfs)	Estimated Flow (cfs)
Trout Creek	8.0	1.4
Walker Creek	3.0	0.1
Wildcat Creek	1.0	1.3
Zigzag River	98.4	65.7

For the 2016 model period, the timeseries produced with the Stream Stats method using either the Sandy River at Marmot or Blazed Alder Creek gage were very similar, with the Sandy River at Marmot derived timeseries providing a finer resolution of flow values. The 2016 timeseries derived from the Sandy River at Marmot flows also had a greater flow rate resulting from the storm in the second week of August, compared to those using the Blazed Alder Creek gage as a source station. Mean daily flow rates were calculated for each timeseries, which were then smoothed by linear interpolation of hourly flow rates from the mean daily flows.

3.6.2 Flow Balance

The estimated flows were derived based on reference gages and are subject to estimation errors due to flow estimation methodologies used, which can introduce flow estimation errors in each of the nineteen tributaries that were derived. A flow balance calculation was conducted to ensure that the modeled input flows all summed to equal the observed flows at the two Sandy River gages. The 2016 model input flows were estimated using the Stream Stats method, with the Sandy River gage near Marmot as the source station, and then adjusted to match the flow balance.

First the flow balance between the Marmot gage (14137000) and the Sandy River below Bull Run River (14142500) was evaluated. Flows from Little Sandy River (14141500) and Bull Run River (14140000) were summed, and the area ratio method was used to account for additional drainage area between the Bull Run confluence with Little Sandy and Sandy River. Raw estimated flows from Badger and Cedar Creeks were added to the observed flows from the Marmot gage, and the area-scaled sum of the Bull Run and Little Sandy Rivers. The sum of these flows closely matched the observed flows at the Sandy River gage below Bull Run (Figure 3-11), providing confirmation of the input flows across this portion of the model, as well as the flow observations at the Marmot gage. Any minor differences between the gage 14142500 and the summed flows (as seen in Figure 3-11) were then distributed among the model flow input timeseries (Bull Run, Badger, and Cedar), weighted by drainage area, to match the gage 14142500.

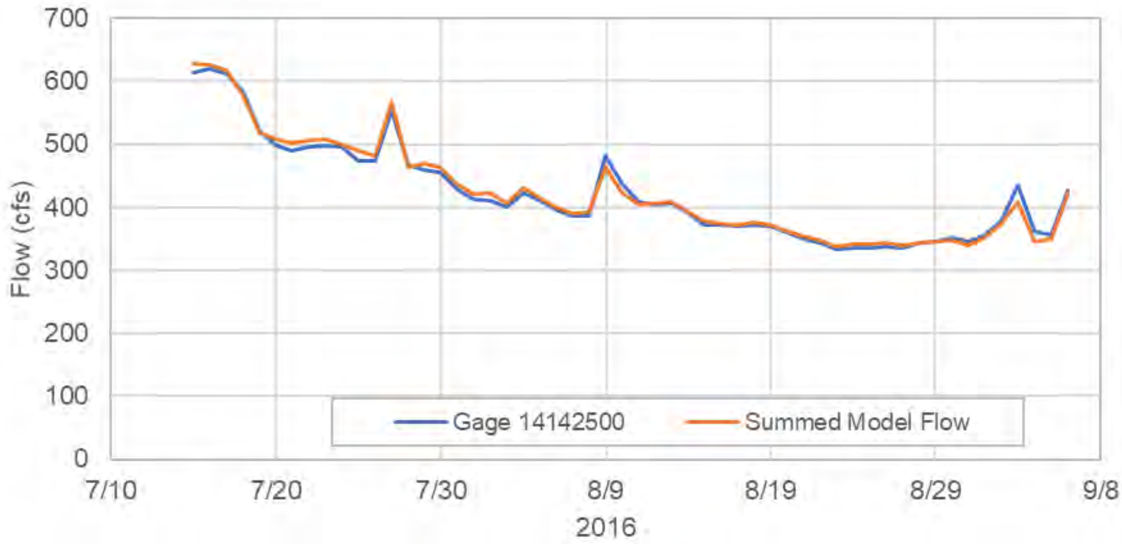


Figure 3-11 Estimated Comparison of summed model flows with observed flows below Sandy River confluence with Bull Run

A flow balance was then conducted for the model inputs upstream of the Marmot gage. The sum of the raw, unadjusted tributary flow estimates of all tributaries upstream of Marmot, including at the upstream model boundary on Sandy River were notably lower than the observed Marmot gage flows (Figure 3-12).

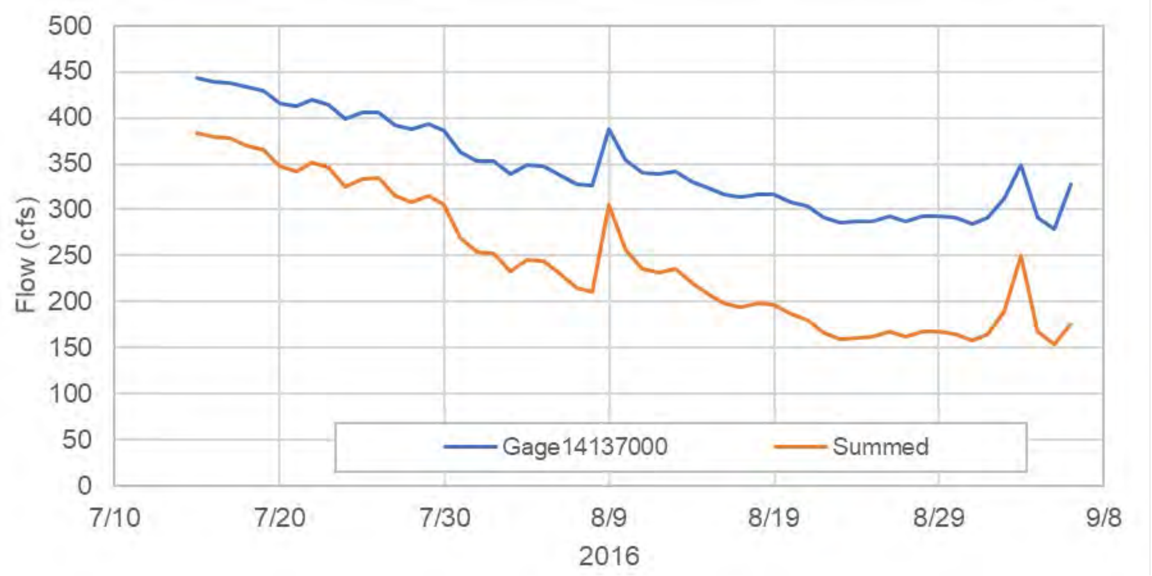


Figure 3-12 Comparison of raw unadjusted estimated tributary flows and headwater upstream of Marmot gage with Marmot gage

Further examination of flow records and estimates was performed to identify the origin of the flow deficits. It was hypothesized that the flows not accounted for may be due to groundwater or surface water inputs not being adequately represented by the Stream Stats estimation method for these upstream tributaries. Further comparison of historical flow records at the now inactive Salmon River headwater gage (14134000) with flows estimated with the Stream Stats method showed a similar deficit (Figure 3-13).

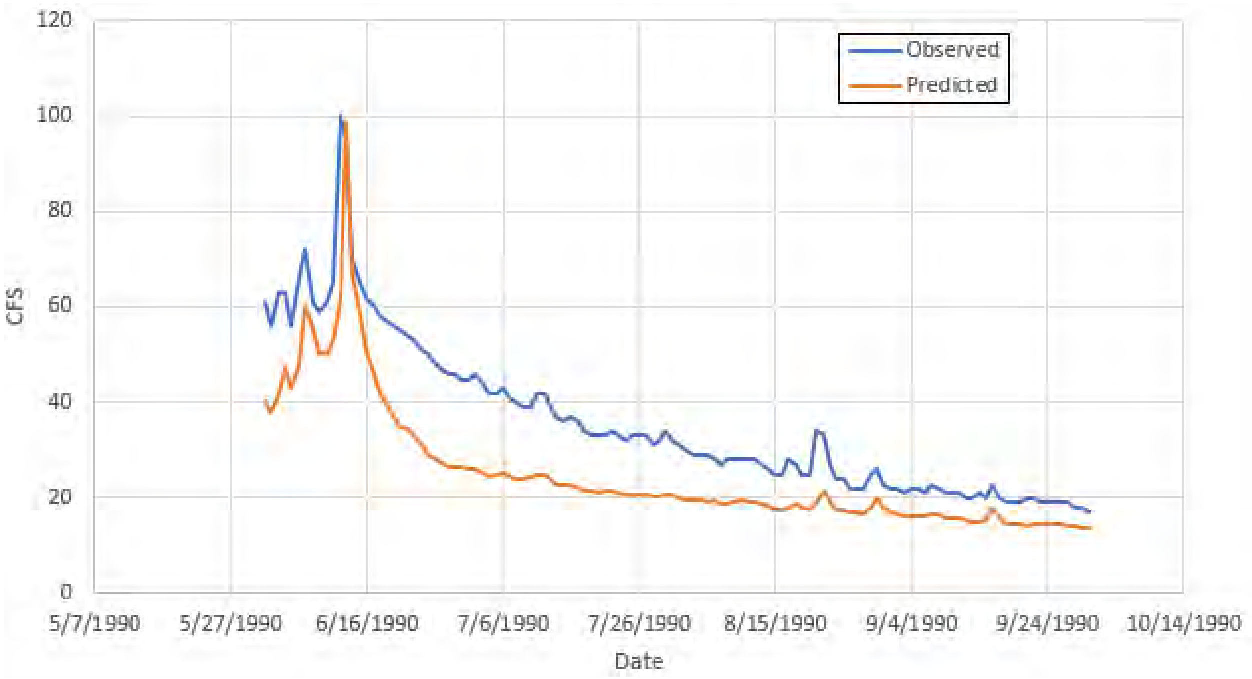
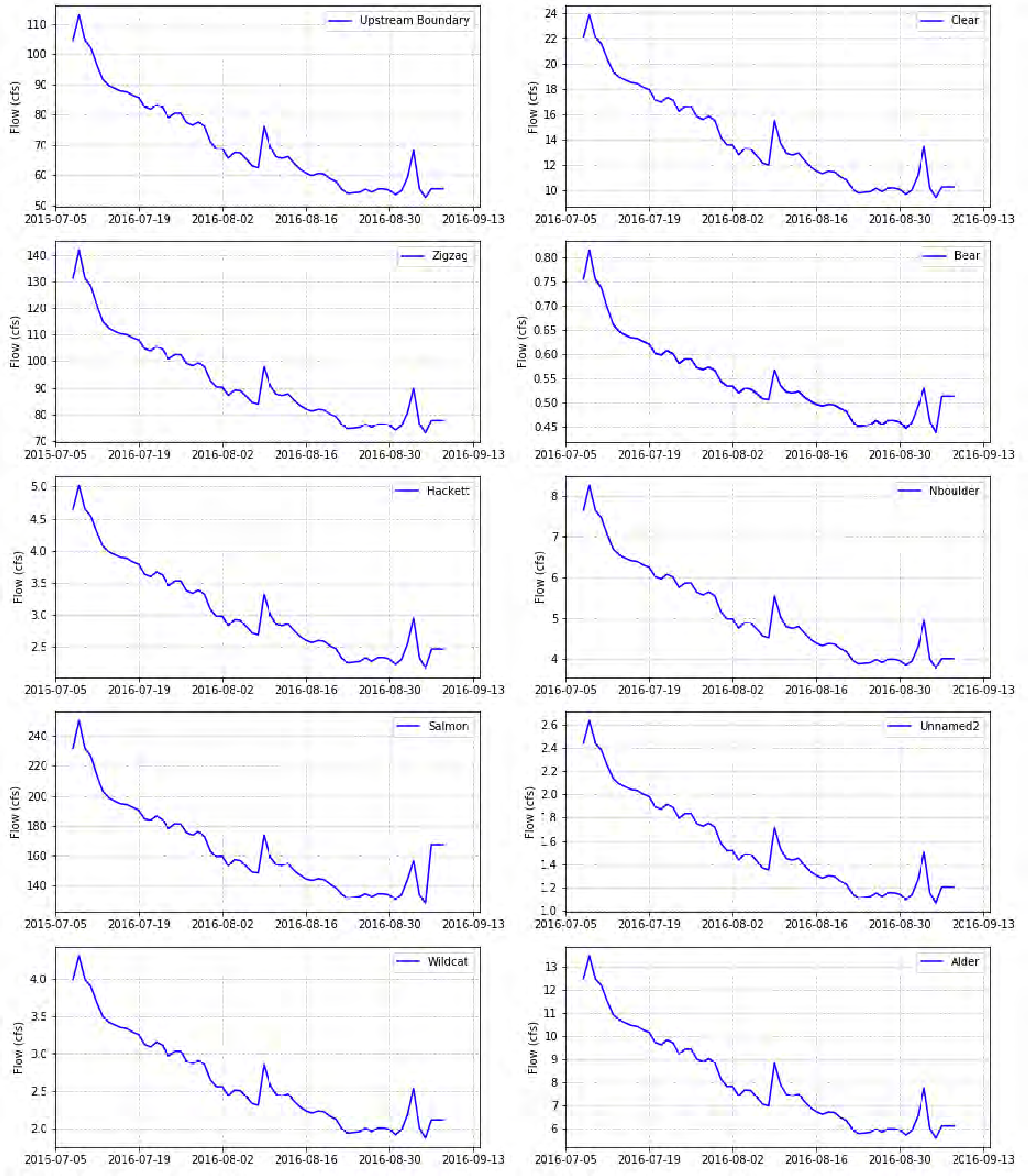
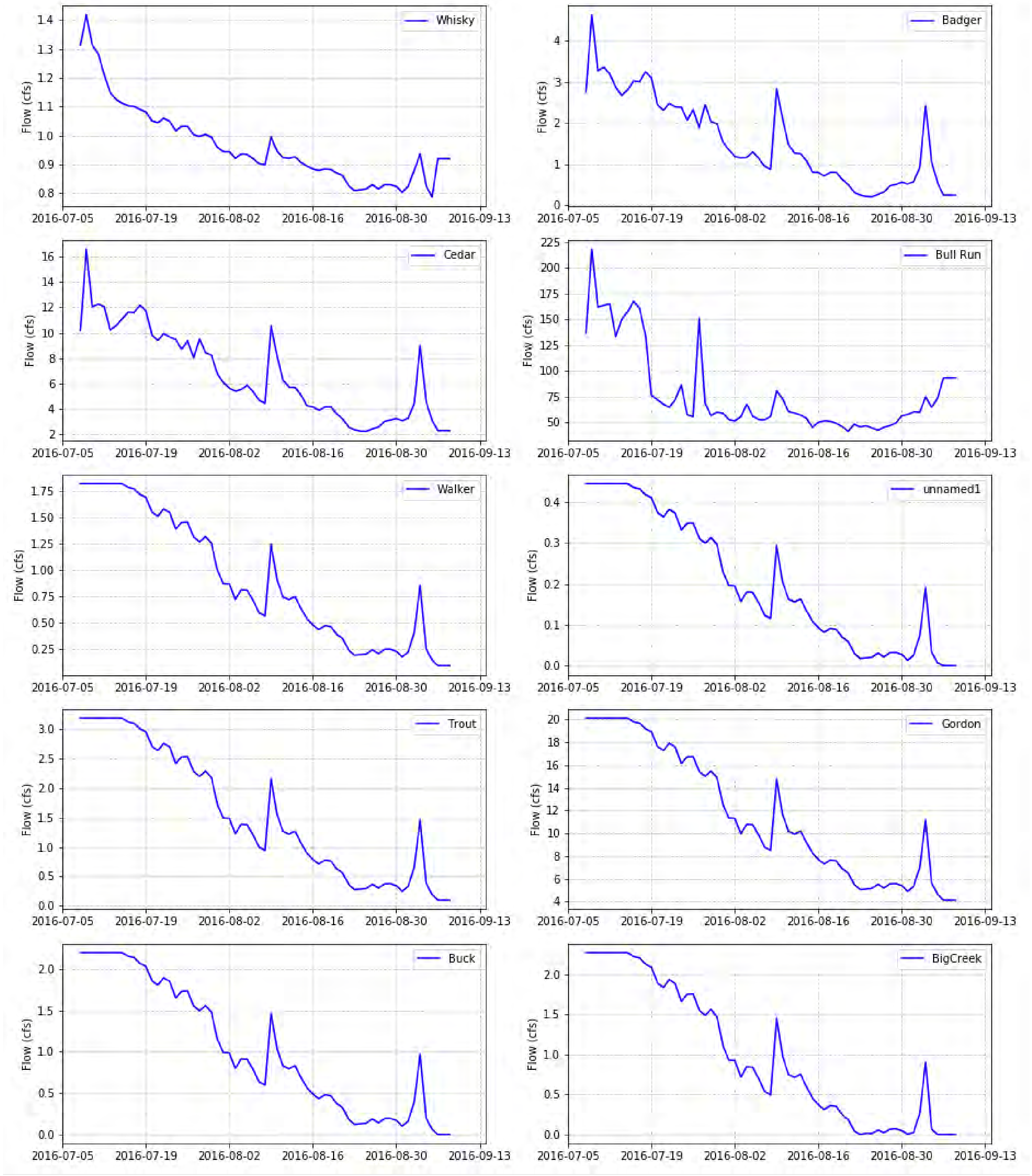


Figure 3-13 Comparison of historical flow record at Salmon River headwater gage (14134000)

Due to the underestimation represented by the Stream Stats method for the upstream areas, and evidence that the deficit is attributable to not just the Sandy mainstem, but the other upstream tributaries, the inputs upstream of the Sandy River at Marmot gage were adjusted. The difference between the summed estimated tributary flows and the observed flow at the Marmot gage was calculated. Because it is not possible to determine whether the difference is due to surface or groundwater contributions, this difference was then distributed among the model flow input timeseries for the upstream tributaries and upstream model boundary, weighted by drainage area. As a result of this adjustment, the model flows upstream of the Marmot gage all sum to equal the observed flows at the Marmot gage. No further adjustments were made for flow inputs downstream of the Marmot gage, due to the consistent flow balance calculation and lack of additional downstream flow gages on the Sandy mainstem. The resulting flow timeseries for model tributaries are presented in Figure 3-14


Upstream Boundary
Flow (cfs)
110
100
90
80
70
60
50
Clear
Flow (cfs)
24
22
20
18
16
14
12
10
Zigzag
Flow (cfs)
140
130
120
110
100
90
80
70
Bear
Flow (cfs)
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
Hackett
Flow (cfs)
5.0
4.5
4.0
3.5
3.0
2.5
Nboulder
Flow (cfs)
8
7
6
5
4
Salmon
Flow (cfs)
240
220
200
180
160
140
Unnamed2
Flow (cfs)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
Wildcat
Flow (cfs)
4.0
3.5
3.0
2.5
2.0
Alder
Flow (cfs)
13
12
11
10
9
8
7
6
2016-07-05
2016-07-19
2016-08-02
2016-08-16
2016-08-30
2016-09-13


Whisky
Flow (cfs)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
Badger
4
3
2
1
0
Cedar
16
14
12
10
8
6
4
2
Bull Run
225
200
175
150
125
100
75
50
Walker
1.75
1.50
1.25
1.00
0.75
0.50
0.25
unnamed1
0.4
0.3
0.2
0.1
0.0
Trout
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Gordon
20
18
16
14
12
10
8
6
4
Buck
2.0
1.5
1.0
0.5
0.0
BigCreek
2.0
1.5
1.0
0.5
0.0
2016-07-05
2016-07-19
2016-08-02
2016-08-16
2016-08-30
2016-09-13

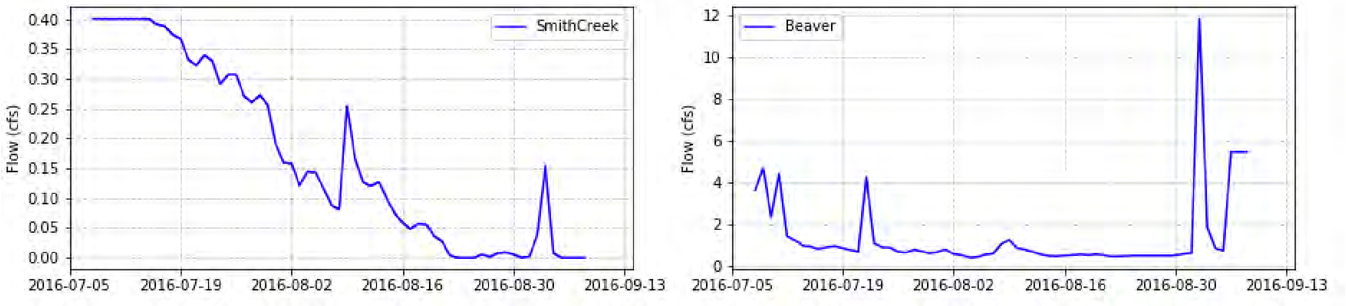


Figure 3-14 Estimated flow timeseries for 2016 (u/s to d/s)

3.7 WATER TEMPERATURE BOUNDARY CONDITION

Observed hourly water temperature time series data were available from various agencies to support this modeling effort. Data were available from Portland State University, East Multnomah Soil and Water Conservation District, City of Portland Water Bureau, and the US Forest Service - Mt. Hood National Forest region. Figure 3-15 shows the locations of the various stream temperature monitoring locations that were used as boundary conditions to configure the model or for calibration. Table 3-5 provides an inventory of the water temperature data used in the model development and shows that nine stations were available for configuring the model tributary boundary conditions, and five stations were used for model calibration along the Sandy River. Although water temperature data were only available for nine out of the 22 tributaries, the data covered the major tributaries going into the Sandy River e.g., Zig Zag, Salmon, and Bull Run. Figure 3-16 shows the observed stream temperature time series data for the July through September during 2016.

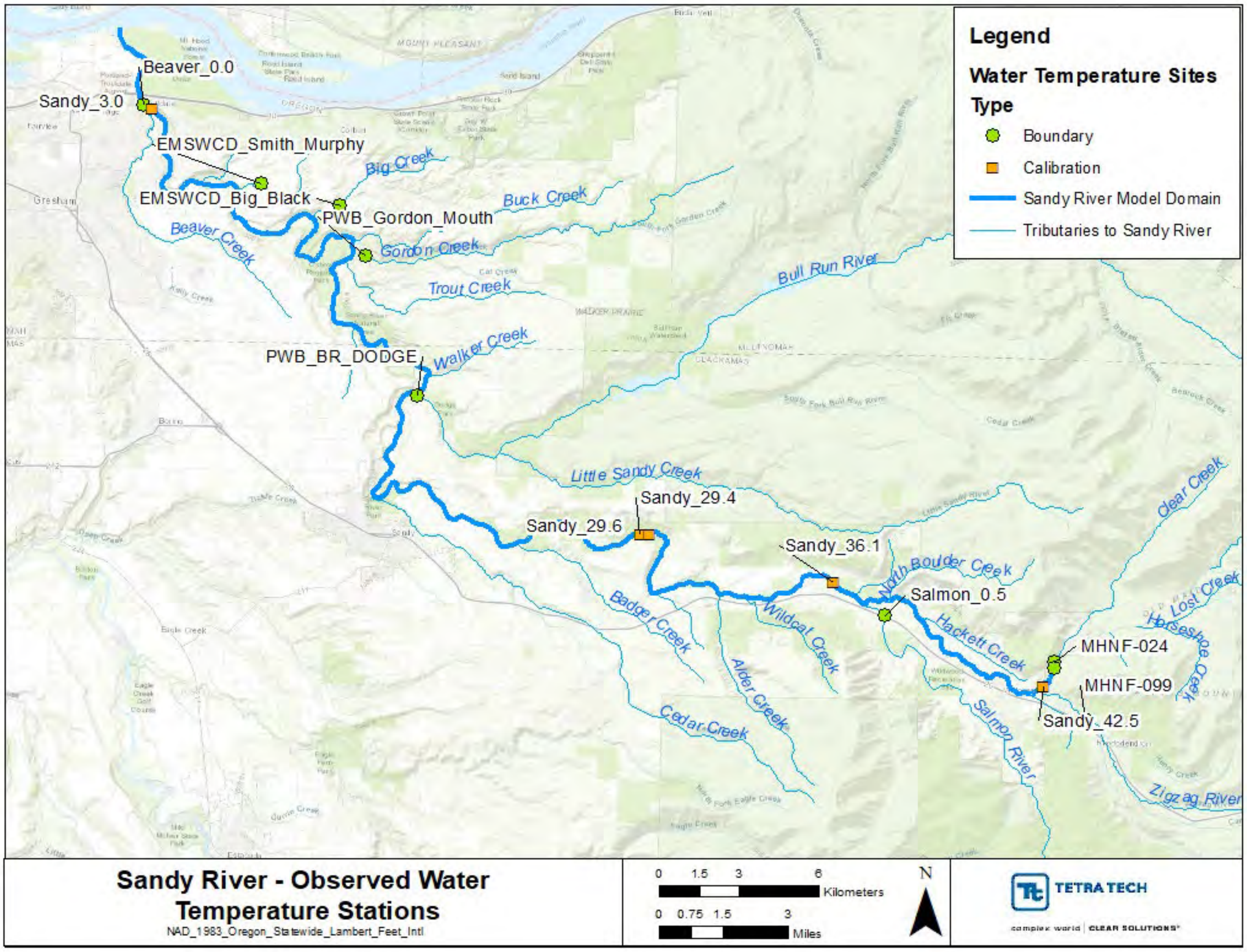


Figure 3-15 Sandy River observed steam water temperature locations

Table 3-5. Inventory of available water temperature data locations used to configure the Sandy River model

Station ID	Station Description	Model RKM	Latitude/ Longitude	Source	Type
Beaver_0.0	Beaver Creek at Mouth	3.55	45.54098 / -122.383	Portland State University	Boundary
EMSWCD_Smith_Murphy	Smith Creek downstream of Christensen Rd.	10.85	45.51536/ -122.326	East Multnomah Soil and Water Conservation District	Boundary
EMSWCD_Big_Black	Big Creek @ Hurlburt Rd.	15.45	45.50836/ -122.287	East Multnomah Soil and Water Conservation District	Boundary

Station ID	Station Description	Model RKM	Latitude/ Longitude	Source	Type
PWB_Gordon_Mouth	Gorden Creek approximately 600 feet upstream of Gordon Creek Rd bridge	20.45	45.4915/ -122.274	City of Portland Water Bureau	Boundary
PWB_BR_DODGE	Bull Run River approximately 500 feet upstream of Sandy River confluence (contributions from Bull Run & Little Sandy)	29.45	45.44442/ -122.248	City of Portland Water Bureau	Boundary
Salmon_0.5	Salmon River above Sandy Brightwood Bridge	60.7	45.37302/ -122.021	Portland State University	Boundary
MHNF-099	ZigZag R at Forest Boundary_LTWT	69.85	45.33883/ -121.923	US Forest Service - Mt. Hood National Forest	Boundary
MHNF-024	Clear Creek trap HOBO temperature site	70.8	45.35806/ -121.938	US Forest Service - Mt. Hood National Forest	Boundary
No Station ID [CedarCrk_usHatchery]	Cedar Creek 10 feet upstream of Sandy River Fish Hatchery Outfall	34.75	45.4039/ -122.2507	Oregon Department of Fish and Wildlife	Boundary
MHNF-080	Sandy R at Forest Boundary_LTWT	71.08	45.35631/ -121.938	US Forest Service - Mt. Hood National Forest	u/s Boundary
Sandy_3.0	Sandy River Above Beaver Creek	3.8	45.53983825/ -122.3790211	Portland State University	Calibration
Sandy_29.4	Sandy River below Marmot Dam	47.90	45.39884548/ -122.1392906	Portland State University	Calibration
Sandy_29.6	Sandy River at Marmot Dam Site	48.30	45.39902629/ -122.1347308	Portland State University	Calibration
Sandy_36.1	Sandy River at Barlow Trail bridge below Salmon River	59.15	45.3839383/ -122.0459735	Portland State University	Calibration
Sandy_42.5	Sandy River upstream of Zigzag River	70.10	45.3497407/ -121.9436897	Portland State University	Calibration

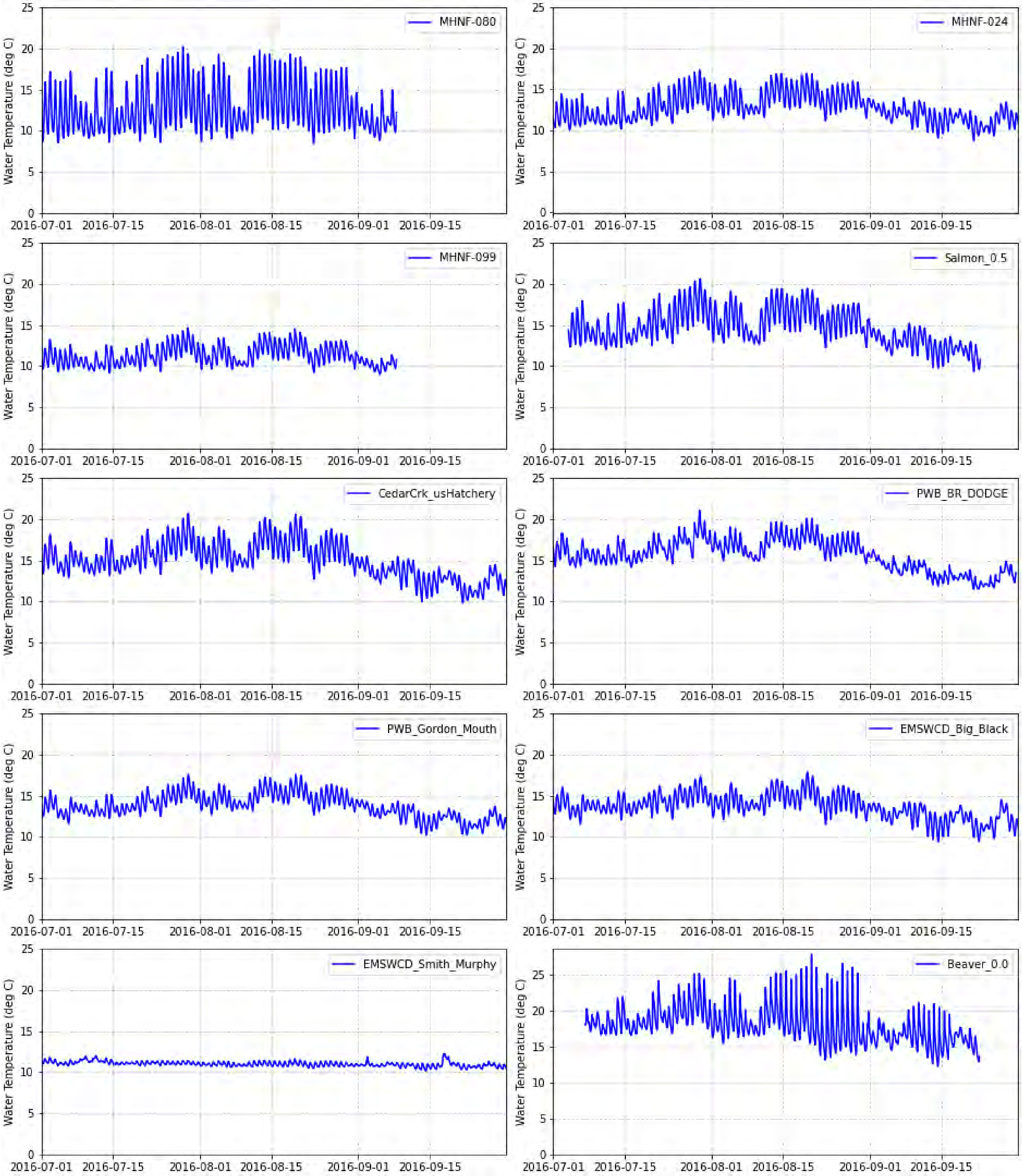


Figure 3-16. **Observed hourly water temperature of tributaries feeding into Sandy River**

As already noted, observed hourly stream temperature data were available for nine of the 22 tributaries. Stream water temperatures for the remaining tributaries were derived using either a linear regression approach or using a direct surrogate from a neighboring or nearby tributary watershed. Alder Creek andBadger Creek were derived based on regression using the limited observed air and water temperature data from August 8, 2001, available from the 2005 TMDL (DEQ, 2005). Figure 3-17 shows the regression at the three locations.

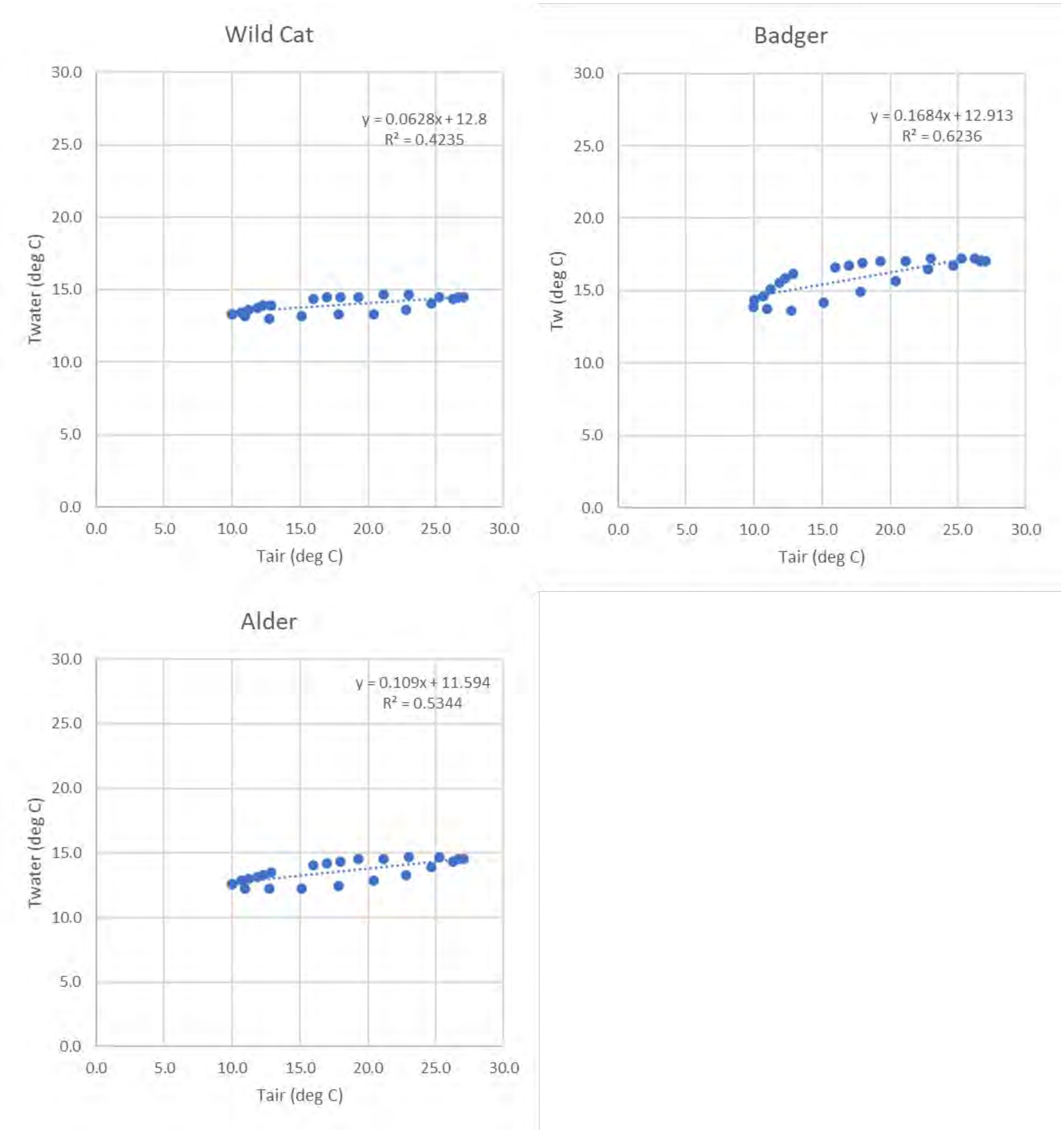


Figure 3-17 Regression between air and water temperature at Wild Cat, Badger, and Alder Creeks (August 8, 2001)

The regression equations developed for Badger andAlder were then used to derive hourly stream temperature for 2016 using observed air temperature from the Meso West station Sandy DW4118. The relationship developed for Wild Cat was not used as the r^2 value waslow (a r^2 value of <0.4 was not considered for this study).. Wild Cat was assigned the same stream temperatures derived for Alder.

Cedar Creek water temperature boundary to Sandy was derived by constructing a mass balance using the data provided by the Oregon Department of Fish and Wildlife (ODFW) for the Sandy River Hatchery which discharges to Cedar Creek. The Sandy River Hatchery is located close to the Cedar Creek Mouth before its confluence with Sandy River. The ODFW data comprised of observed flow and water temperature from the Fish Hatchery (Figure 3-18), and Cedar Creek ambient temperature collected 10 feet upstream of the Hatchery outfall (Figure 3-16). In addition, estimated flows for Cedar Creek as discussed in the flow estimation section were also used (Figure 3-14).

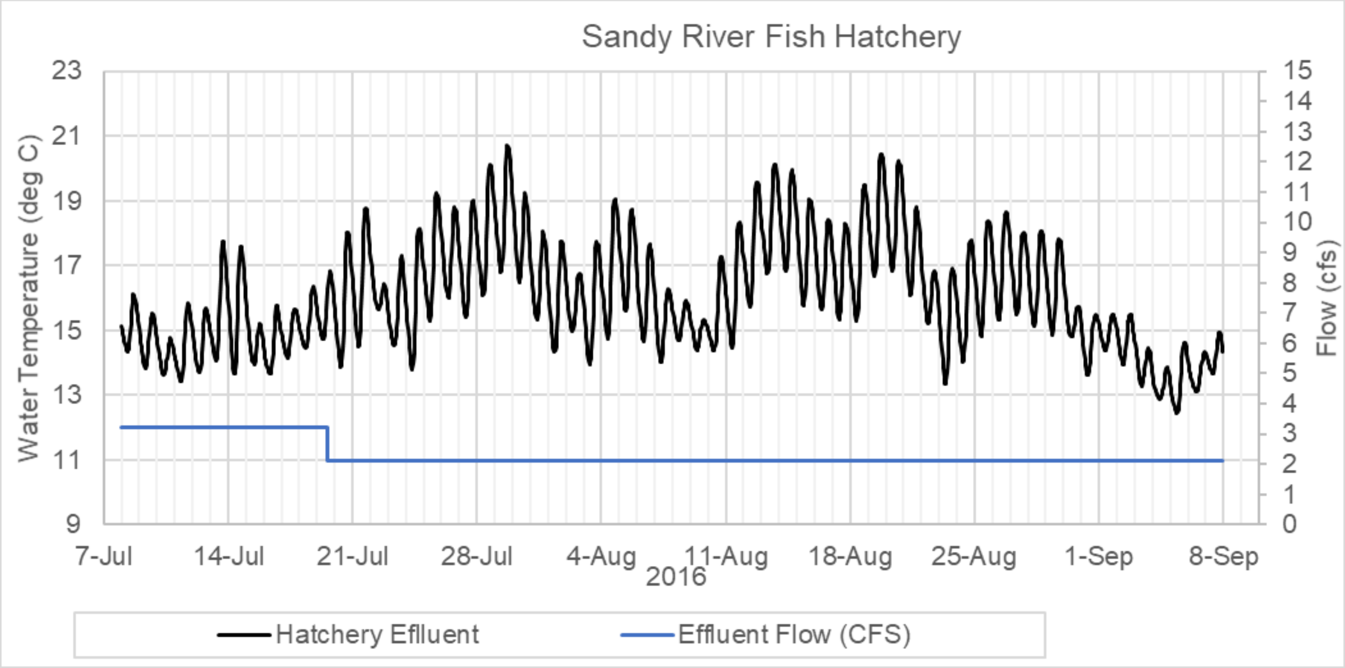


Figure 3-18 Sandy River Fish Hatchery – Hourly flow and water temperature data

The mass balance was constructed as follows to calculate the water temperature downstream of the Hatchery:

$$T = \frac{Q_r \cdot T_r + Q_e \cdot T_e}{Q_r + Q_e}$$

Where:
Q_r = Cedar Creek flow (cfs)
T_r = Cedar Creek temperature (deg C)
Q_e = Hatchery effluent flow (cfs)
T_e = Hatchery effluent water temperature (deg C)
T = calculated Cedar Creek water temperature (deg C) downstream of the Hatchery

Figure 3-19 shows the estimated stream temperatures for Cedar, Badger, and Alder Creeks

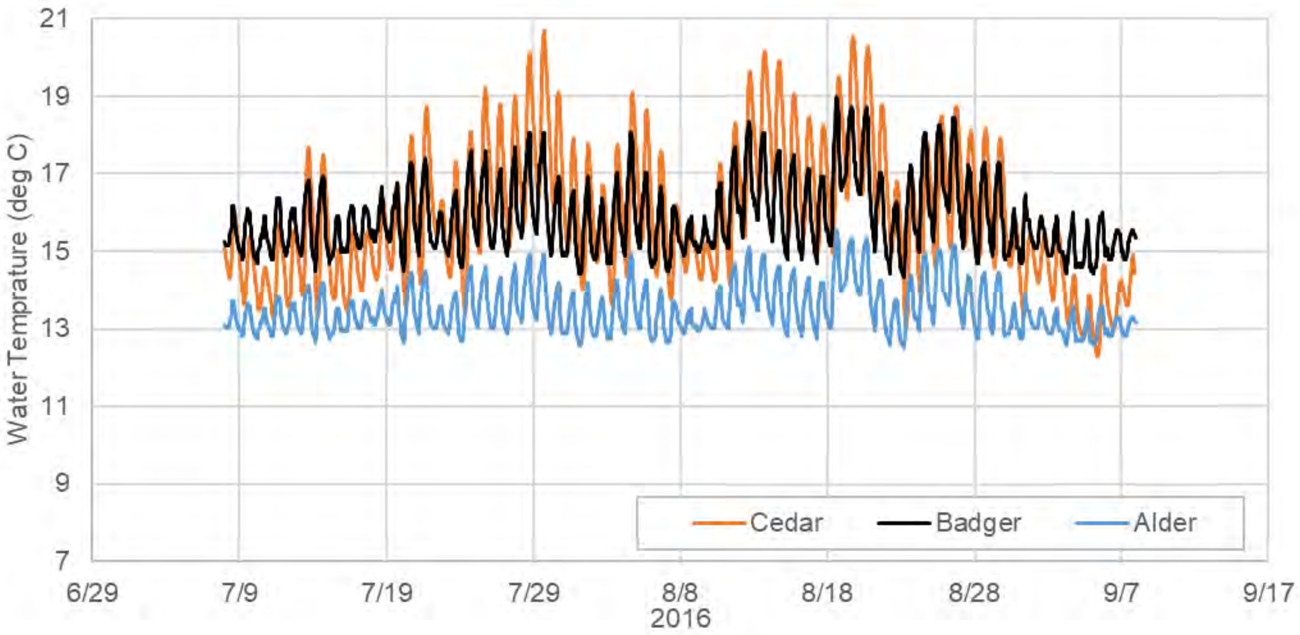


Figure 3-19 Estimated stream temperature for Cedar, Badger, and Alder Creeks

The remaining creeks were assigned a direct surrogate based on proximity to the creek. Table 3-6 shows the model stream temperature input assignments used to construct the model for each of the tributaries.

Table 3-6. Stream boundary condition and tributary input assignments

Model Location Name	Model Location (RKM)	Data Source	Notes
u/s boundary	71.08	Observed data	MHNF-080
Clear	70.80	Observed data	MHNF-024
Zigzag	69.85	Observed data	MHNF-099
Bear	69.50	2005 TMDL	Derived - Constant temperature input of 12.0 deg C. (same as DEQ 2005)
Hackett	63.35	Same as Bear	Derived - direct surrogate
Nboulder	61.85	Same as Bear	Derived - direct surrogate
Salmon	60.70	Observed data	Salmon_0.5
Unnamed2	60.20	Same as Bear	Derived - direct surrogate
Wildcat	55.20	Same as Alder	Derived - direct surrogate
Alder	54.30	2005 TMDL	Estimated based on regression of Ta and Tw data from DEQ 2005 model
Whisky	51.55	Same as Badger	Derived - direct surrogate
Badger	42.25	2005 TMDL	Estimated based on regression of Ta and Tw data from DEQ 2005 model
Cedar	34.75	2005 TMDL	Estimated based on regression of Ta and Tw data from DEQ 2005 model
Bull Run	29.45	Observed data	PWB_BR_DODGE
Walker	28.75	Same as Cedar	Derived - direct surrogate

Model Location Name	Model Location (RKM)	Data Source	Notes
unnamed1	24.55	Same as Cedar	Derived - direct surrogate
Trout	21.00	Same as Gordon	Derived - direct surrogate
Gordon	20.45	Observed data	PWB_Gordon_Mouth
Buck	20.10	Same as Gordan	Derived - direct surrogate
BigCreek	15.45	Observed data	EMSWCD_Big_Black
SmithCreek	10.85	Observed data	EMSWCD_Smith_Murphy
Beaver	3.55	Observed data	Beaver_0.0

3.8 POINT SOURCE DISCHARGES

There are two active point sources that discharge to the Sandy River – the City of Troutdale Water Pollution Control Facility (WPCF) and the Hoodland Sewage Treatment Plant (STP). Table 3-7 provides information related to each of the point sources. Figure 3-20 shows the spatial location of the point sources along Sandy River.

Table 3-7. Summary of individual NPDES permitted discharges to the Sandy River

Facility Number (EPA Number)	Facility Name	Latitude/Longitude	Permit Type and Description	Sandy River Model RKM
39750 (OR0031020)	WES (Hoodland STP)	45.3464/-121.969	NPDES-DOM-Da: Sewage - less than 1 MGD	67.4
89941 (OR0020524)	City of Troutdale Water Pollution Control Facility	45.5535/-122.387	NPDES-DOM-C2a: Sewage - 1 MGD or more but less than 2 MGD	2.15

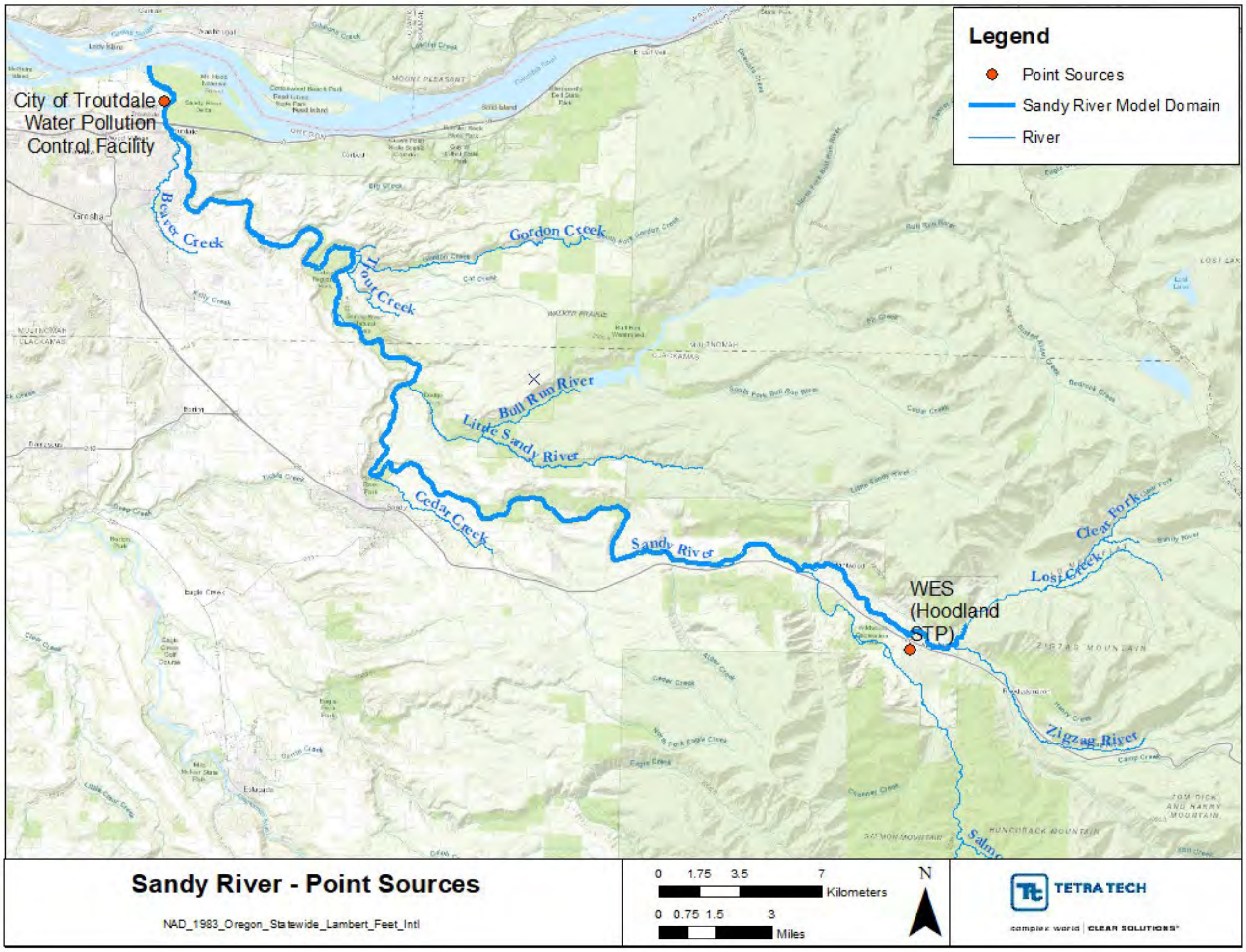


Figure 3-20 Sandy River Point Source Locations

The Hoodland STP discharges treated municipal wastewater from communities along the HWY 26 corridor into the Sandy River near Welches (DEQ, 2005). The outfall is located on Sandy River near model RKM 67.4, upstream from the confluence of the Salmon River and downstream from the confluence of the Zigzag River (Figure 3-20). Daily flow and water temperature from monthly DMR data were provided by Hoodland STP. Note that water temperature provided was daily maximum water temperature. Typically, hourly water temperature timeseries are desired but since hourly data were not available, the daily maximum was used as it was the best information available. The daily data were compiled along with appropriate unit conversion, and then linearly interpolated to create hourly time series of flow and water temperature for specification into the model. Figure 3-21 shows the flow and water temperature data specified in the model for the Hoodland STP.

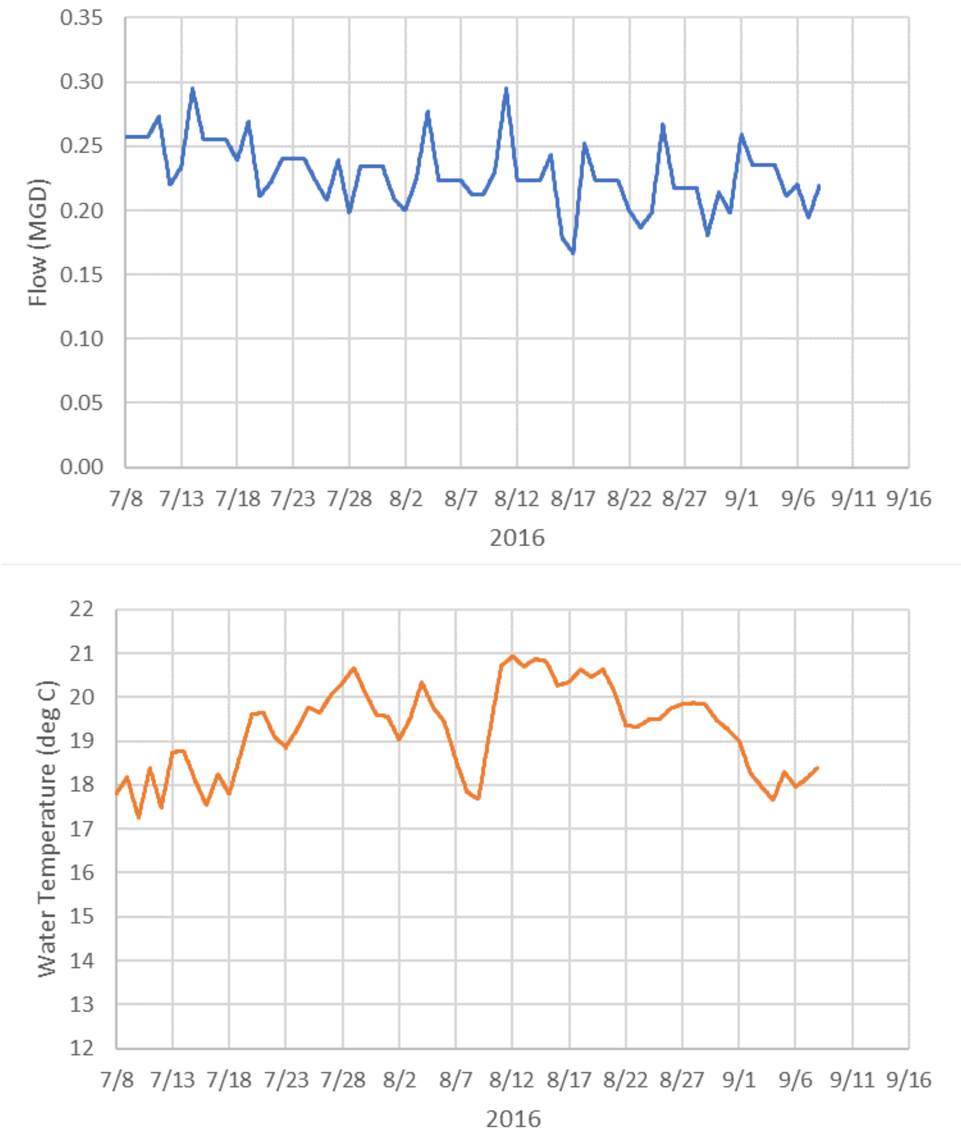


Figure 3-21 Hoodland STP - hourly flow and water temperature used in the model

The City of Troutdale Water Pollution Control Facility discharges treated municipal wastewater from the Troutdale area into Sandy near model RKM 2.15 (Figure 3-20). Monthly DMRs containing daily flow data in pdf format and hourly water temperature in digital format were provided by City of Troutdale Water Pollution Control Facility. These data were compiled and then processed after appropriate unit conversion to create hourly time series of flow and water temperature for specification in the model. Figure 3-22 shows the flow and water temperature data specified in the model for the Troutdale point source.

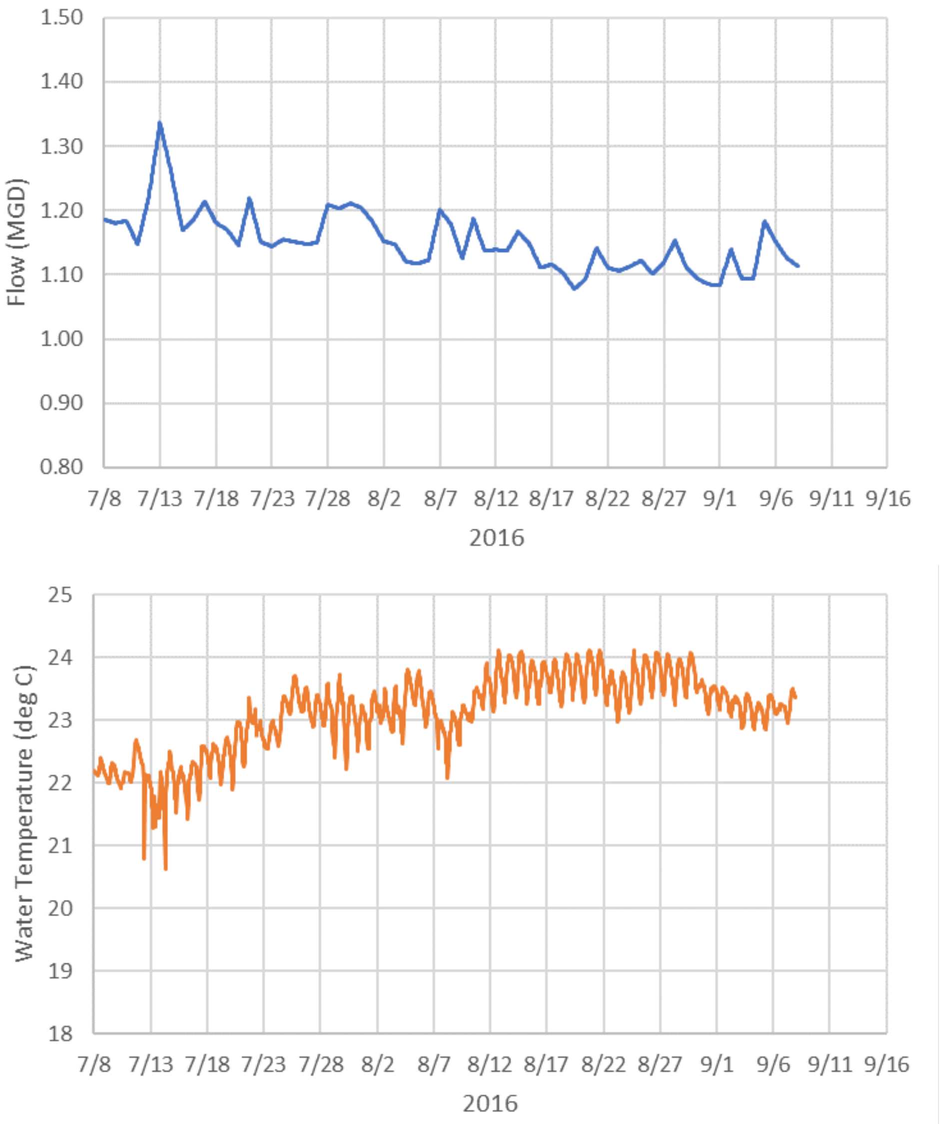


Figure 3-22 City of Troutdale - hourly flow and water temperature used in the model

3.9 METEOROLOGICAL DATA

Meteorological data needed for the HS8 model include air temperature, relative humidity, cloudiness, and wind speed. Available data from the National Oceanic and Atmospheric Association (NOAA)'s National Climatic Data Center (NCDC), and University of Utah MesoWest database were queried. The meteorological data obtained from the NCDC includes the Local Climatological Dataset (LCD) (NOAA, 2005), which includes hourly quality controlled meteorological data from airports. The Automatic Position Reporting System WX NET/Citizen Weather Observer Program (APRSWXNET/CWOP) aggregated stations served via the MesoWest were specifically queried for station in the nearby vicinity of the model domain. Table 3-8 lists available meteorological data from these sources along the Sandy River model subdomain with relevant data for the required time period.

Table 3-8. Inventory of available Meteorological Station Data in the Sandy River

Station ID	Station Name	Latitude/ Longitude	Elevation (m)	Frequency	Available Met Data	Source
24242	Portland Troutdale Airport	45.5511/-122.4089	8.8	Hourly	Air Temperature, Wind Speed, Sky Conditions, Relative Humidity	NCDC-LCD
D9403	DW9403 Corbett	45.504/-122.27	218.0	15-minute	Air Temperature, Wind Speed, Relative Humidity	MesoWest, APRSWXNET/CWOP
D4118	DW4118 Sandy	45.3915/-122.108	381.1	15-minute	Air Temperature, Wind Speed, Relative Humidity	MesoWest, APRSWXNET/CWOP
E6654	EW6654 Rhododendron	45.3463/-121.951	430.2	15-minute	Air Temperature, Wind Speed, Relative Humidity	MesoWest, APRSWXNET/CWOP

Station elevations vary widely from east to west along the Sandy River, ranging from 12 ft at the downstream end where the Sandy meets the Columbia River to 4000 ft at western slopes of Mt. Hood near the headwaters of Sandy. Weather stations along the modeled Sandy River mainstem were identified such that this spatially varying elevation change can be accounted for using the observed meteorological data (Table 3-8 and Figure 3-23).

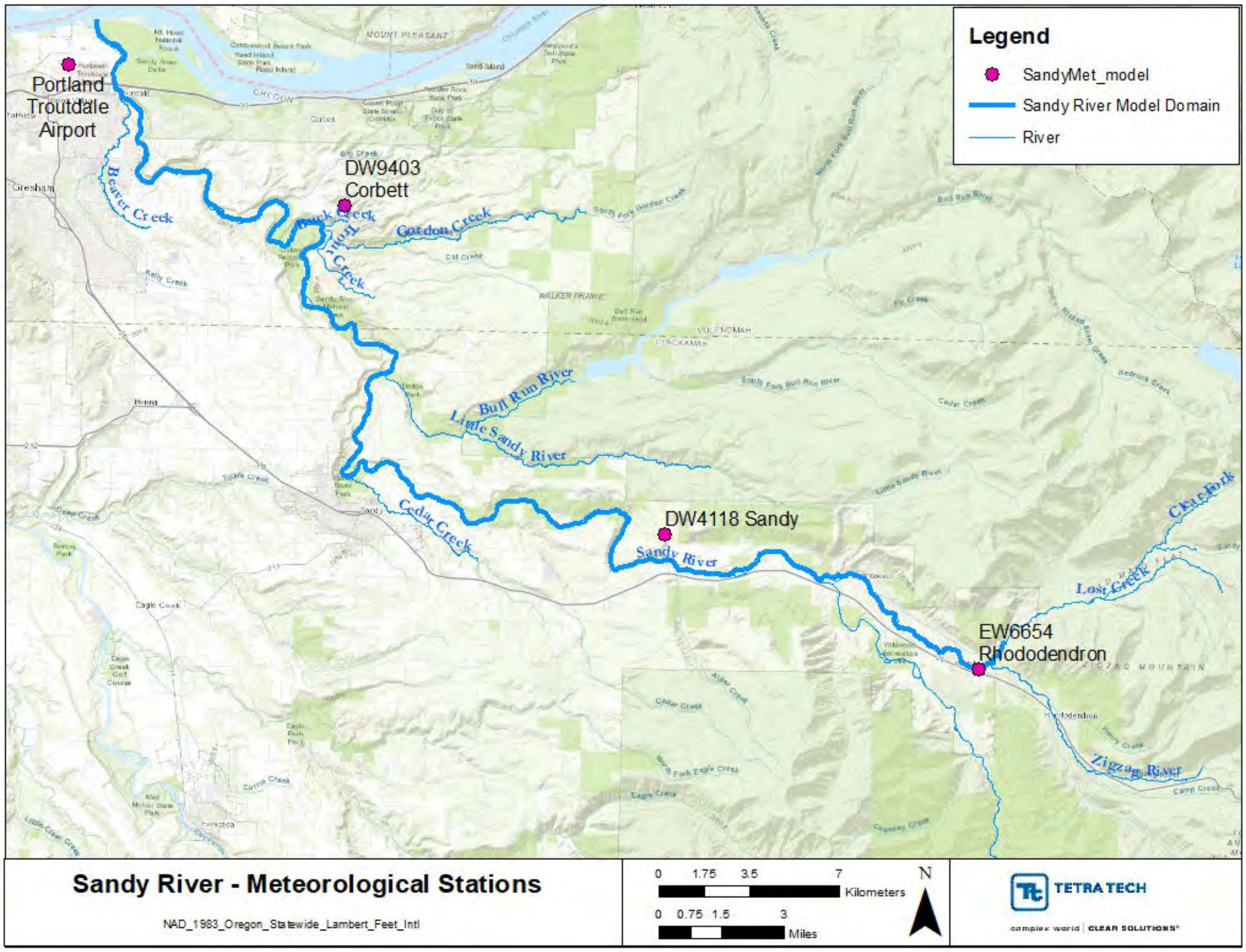


Figure 3-23 Sandy River Meteorological Stations

As expected, the air temperatures increase from the headwater areas to the mouth due to changing elevation (Figure 3-24). Mean monthly air temperatures of the daily maximum were highest during the month of August, followed by July, and then September. Average maximum temperatures in August ranged from 24.41 deg C at Rhododendron, to 26.02 deg C at Sandy, to 29.28 deg C at Troutdale. In September the average maximum temperature ranged from 18.45 deg C at Rhododendron, to 19.50 deg C at Sandy, to 23.02 deg C at Troutdale (Figure 3-25).

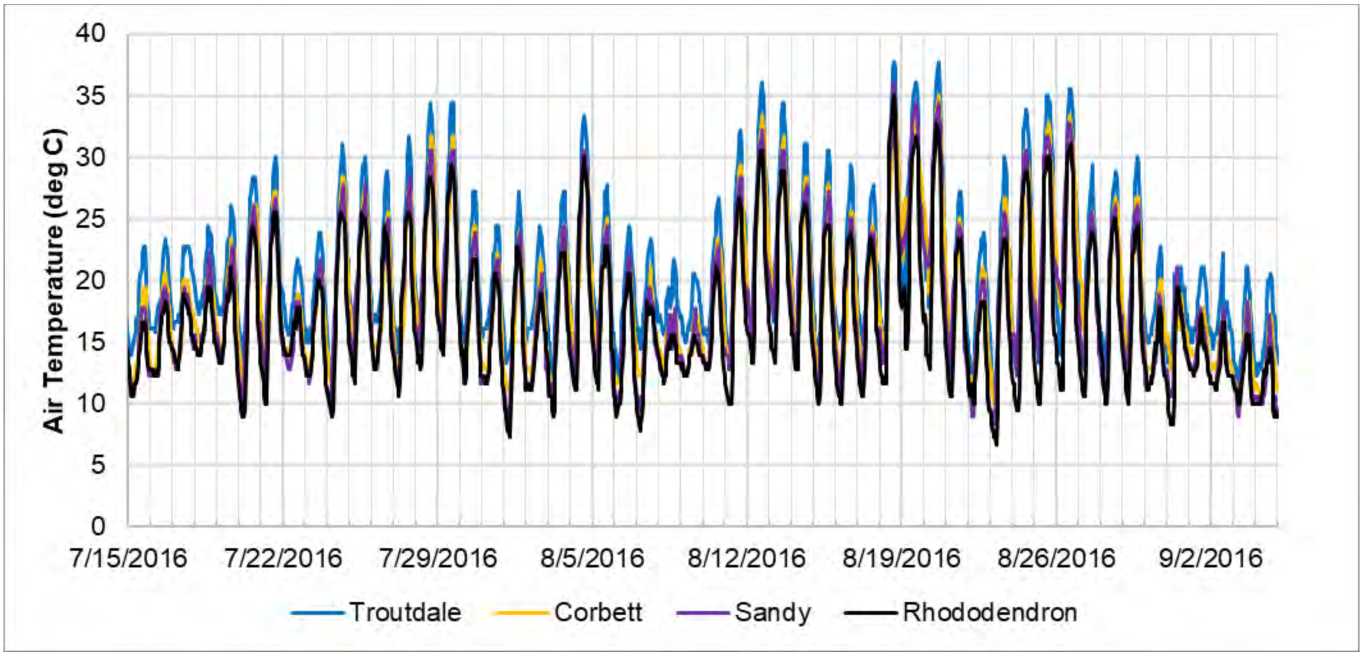


Figure 3-24 Observed hourly air temperature

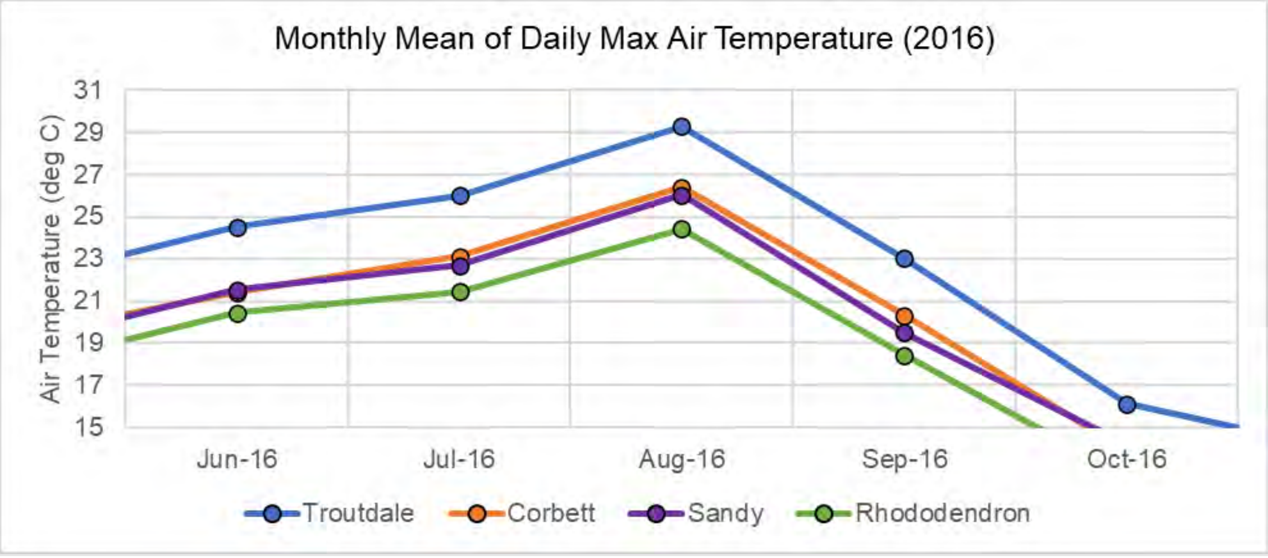


Figure 3-25 Monthly Mean of the daily maximum air temperature

Hourly relative humidity, wind speed, and cloud cover data are also required inputs for the Heat Source Model. Relative humidity and wind speed data were available at all the locations of interest; however, cloud cover data were only available at the Troutdale Airport NCDC station. The Troutdale station provided descriptive sky cover information, which was converted to tenths from 0 to 1 for input in the Heat Source Model. The wind speed data served by MesoWest indicated that the minimum wind speed recording threshold was sparse and was typically measured at 0.45 m/sec increments. The data are dominated by the value of zero which seems to be associated with wind speeds below the reading threshold (or possibly calms in wind but is unknown). The wind speed data at the Rhododendron station was found to be the sparsest with numerous zeros. There were no data flags associated with the wind speed data from MesoWest. The NCDC wind speed measurements at Troutdale on the other hand have a higher resolution and show more variability, with some wind gust reported at high values close to 12 m/sec.

In general, data were available at all stations for the modeling period with minimal missing data. In cases where data were missing for a few hours such as that observed at the Rhododendron station, the data were filled using linear interpolation. Figure 3-26, Figure 3-27, Figure 3-28, and Figure 3-29 show the meteorological input specified in the Heat Source Model at the Rhododendron, Sandy, Corbett, and Troutdale Airport respectively.

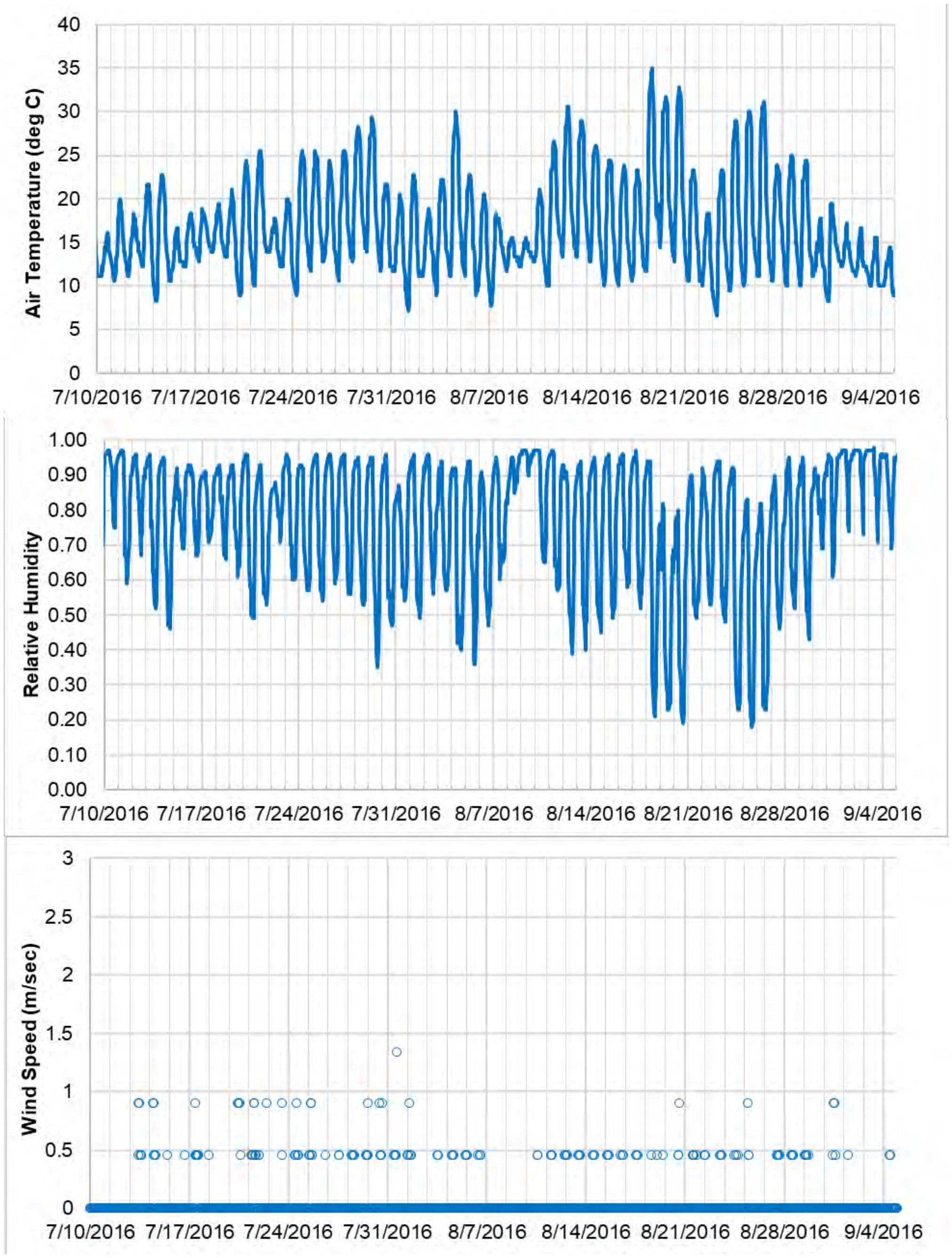


Figure 3-26 Hourly Air Temperature, Relative Humidity and Wind Speed at Rhododendron

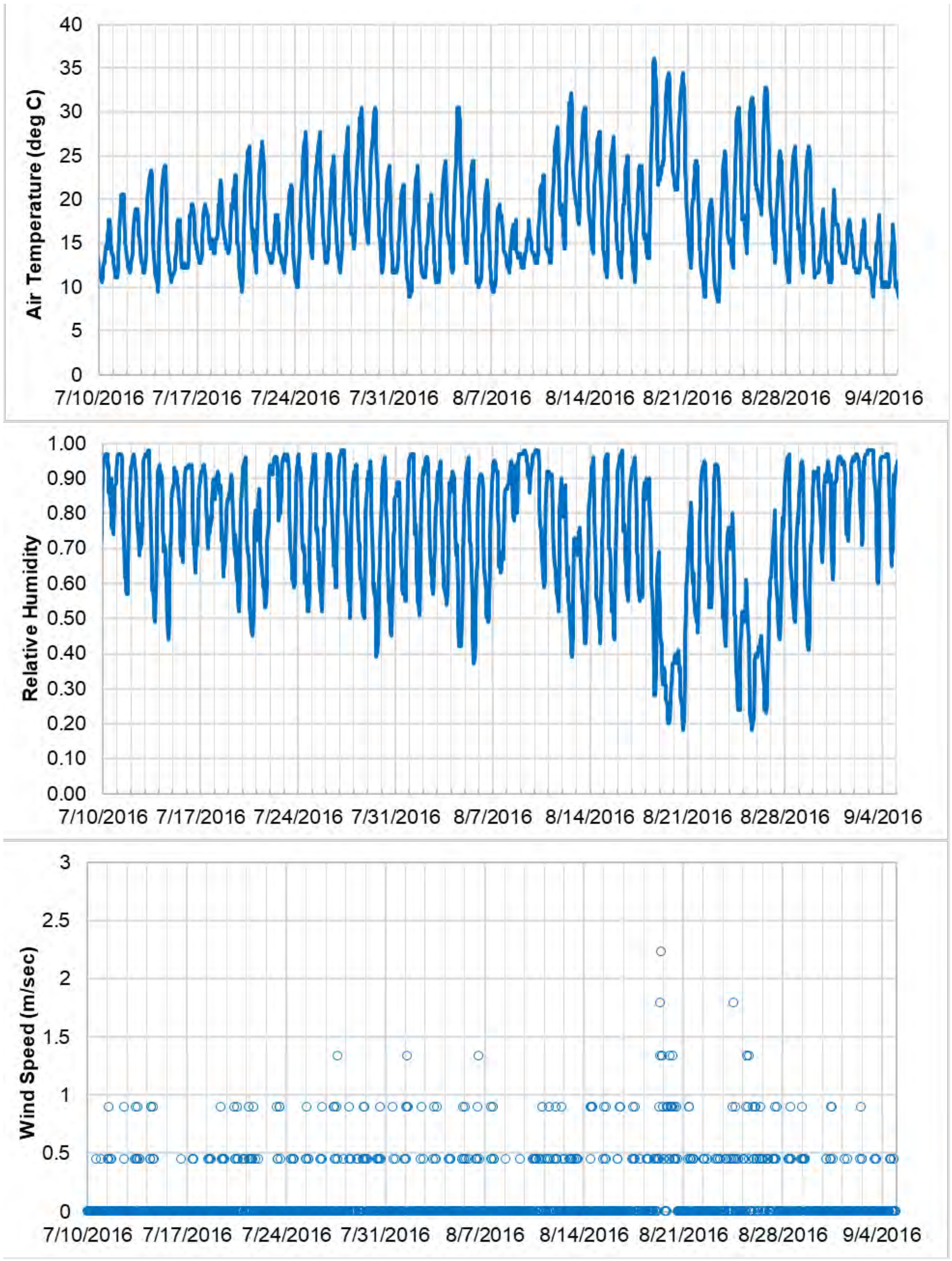


Figure 3-27 Hourly Air Temperature, Relative Humidity and Wind Speed at Sandy

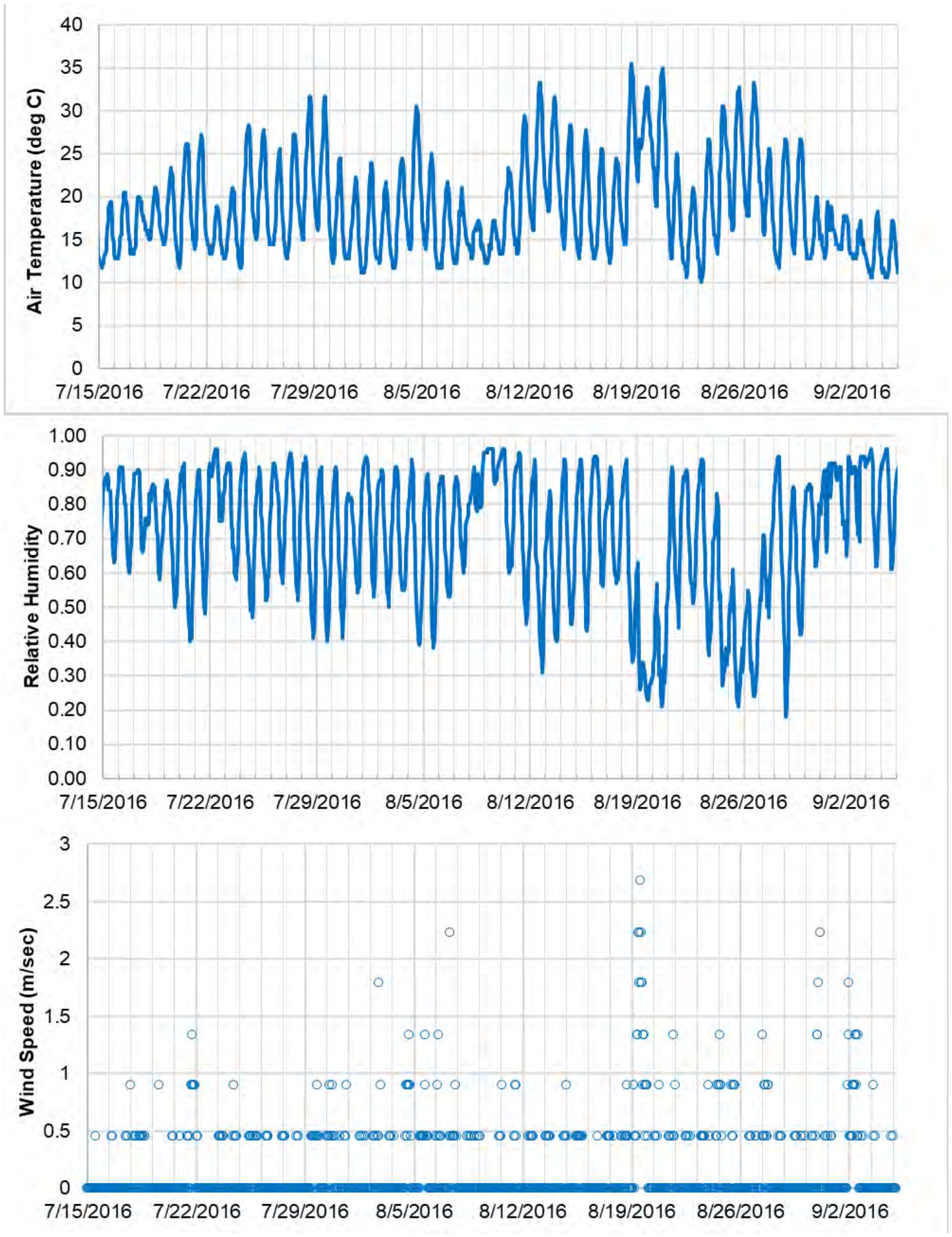


Figure 3-28 Hourly Air Temperature, Relative Humidity and Wind Speed at Corbett

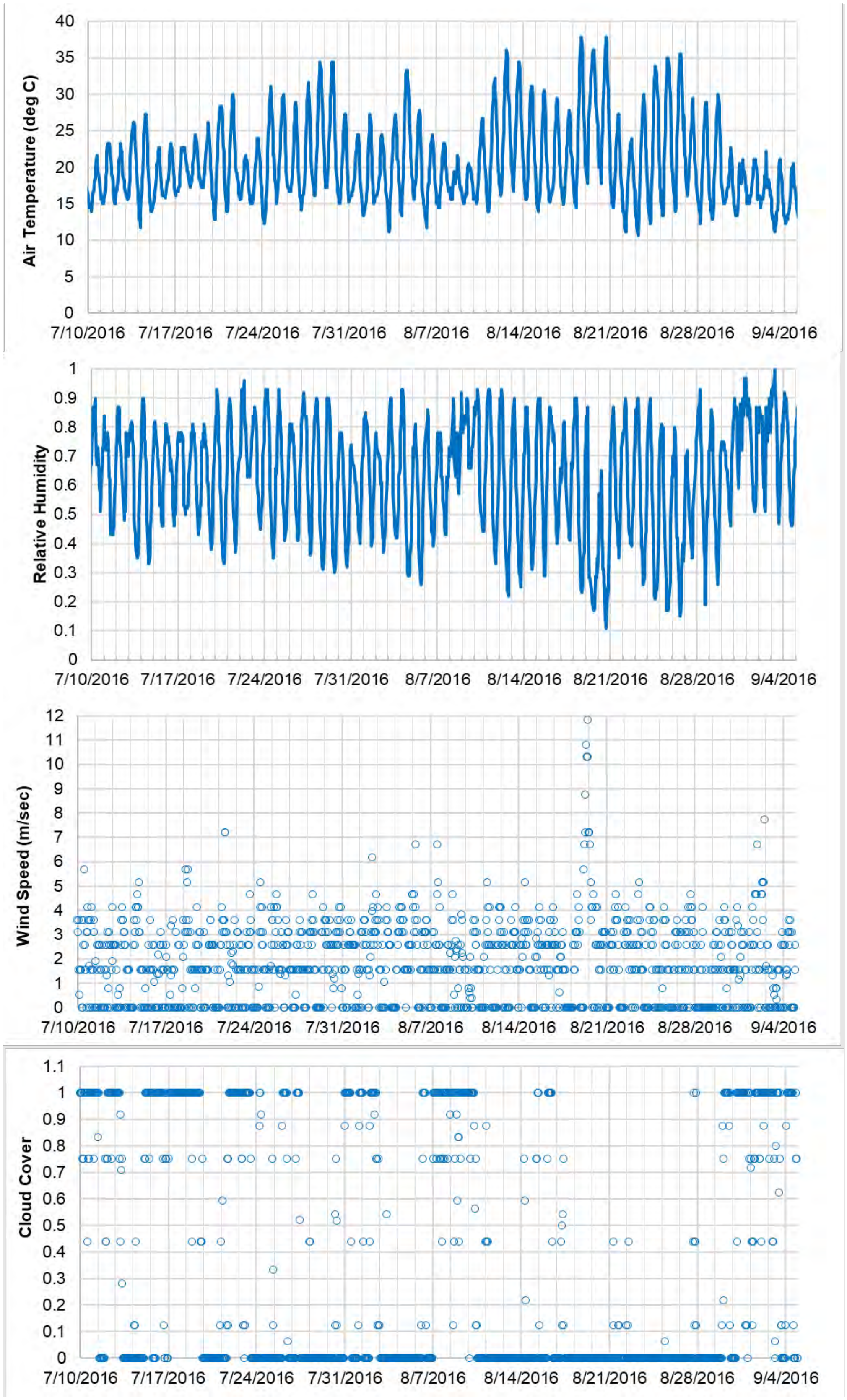


Figure 3-29 Hourly Air Temperature, Relative Humidity and Wind Speed at Troutdale Airport

4.0 MODEL CALIBRATION

The Sandy River Heat Source model was simulated for the time period from July 15, 2016, to September 9, 2016, over the 71-kilometer study area from just upstream of Clear Creek to the mouth of the Columbia River. The model incorporated spatially varying hourly meteorology, 21 hourly flow and stream temperature inputs (including the upstream boundary, and major tributaries such as Zig Zag, Salmon and Bull Run), and two NPDES point sources that discharge into the system.

The model was then calibrated against observed data. Model calibration refers to the comparison of observed data to modeled values. Table 4-1 shows the sites used in the Sandy River Heat Source model flow, water temperature and effective shade calibration. There were no effective shade measurements available for calibration during 2016. Observed effective shade measurements collected at three locations along the Sandy River in August 2001 were used to roughly compare with the predicted 2016 shade results. Refer to Figure 3-9 and Figure 3-15 for the location of the flow and stream temperature calibration stations.

Table 4-1. Calibration sites used in the Sandy River Heat Source Model Calibration

Station ID	Description	Latitude/ Longitude	Model RKM	Data Type	Source
Hourly Flow					
14137000	Sandy River Near Marmot	45.3995642/ -122.137307	48.05	Hourly Flow	USGS
14142500	Sandy River Below Bull Run River, Near Bull Run	45.4490094/ -122.245089	29.1	Hourly Flow	USGS
Hourly Water Temperature					
Sandy_3.0	Sandy River Above Beaver Creek	45.53983825/ -122.379021	3.8	Hourly Water Temperature	Portland State University
Sandy_29.4	Sandy River below Marmot Dam	45.39884548/ -122.139291	47.90	Hourly Water Temperature	Portland State University
Sandy_29.6	Sandy River at Marmot Dam Site	45.39902629/ -122.134731	48.30	Hourly Water Temperature	Portland State University
Sandy_36.1	Sandy River at Barlow Trail bridge below Salmon River	45.3839383/ -122.045974	59.15	Hourly Water Temperature	Portland State University
Sandy_42.5	Sandy River upstream of Zigzag River	45.3497407/ -121.94369	70.10	Hourly Water Temperature	Portland State University
Effective Shade Measurements					
10676	Sandy above Salmon near Brightwood	45.3786/ -122.013	62.4	August 2001(Observed effective shade:0%)	DEQ

Station ID	**Description**	**Latitude/ Longitude**	**Model RKM**	**Data Type**	**Source**
26422	Sandy above Clear Creek at Lolo Pass Rd.	45.3565/ -121.938	70.95	August 2001 (Observed effective shade:61%)	DEQ
No Station ID	Sandy River at Troutdale STP	45.4982/ -122.01	3.8	August 2001 (Observed effective shade:11%)	DEQ

The model was run at a time step of 0.3 minutes and outputs were generated hourly, every 50 meters. The modeled stream flows were calibrated first, followed by stream temperature. Channel morphology related inputs were identified for calibration purposes since channel hydraulics are important for predicting the flow and stream temperatures. Channel hydraulics govern the surface area of water that could be exposed to solar radiation, the residence time for exposure, and the degree of light penetration into the water column. Heat Source is a one-dimensional model, and the channel configuration is represented in a trapezoidal shape.

Parameters that directly influence channel hydraulics such as channel elevation, Manning's n, and channel bottom width were identified for calibration. Channel elevations were left unadjusted since they were derived from high resolution bare earth LiDAR. Manning's n value in the channel, which represents channel roughness and other flow factors, and estimated channel bottom widths were adjusted for calibration. Manning's n was initially set to the default 0.3 to prevent model instability due to dewatering of the channel. Through model calibration, this value was reduced to be within typical literature values (< 0.1). A Manning's n value of 0.068 was finally arrived at through iterative adjustment. During calibration it was found that the model diurnal range was being overpredicted compared to the observed data. To reduce the diurnal range, and better correspond with the observed data, the estimated model bottom widths were further scaled by spatially reducing the bottom widths. The initial bottom widths arrived at were scaled by 10-percent from RKM 71 to RKM 50 and 20-percent from RKM 50 to RKM 25 This resulted in making the channel less shallow and increasing the depth, thereby helping in better predicting the diurnal range. The bottom widths for the last 25 RKM up to the streams confluence with the Columbia River were left unchanged as the channel is quite wide in the downstream reach and reducing the bottom widths in this region did not help in the temperature calibration of the most downstream station. Figure 4-1 shows the starting and final bottom width arrived at during calibration.

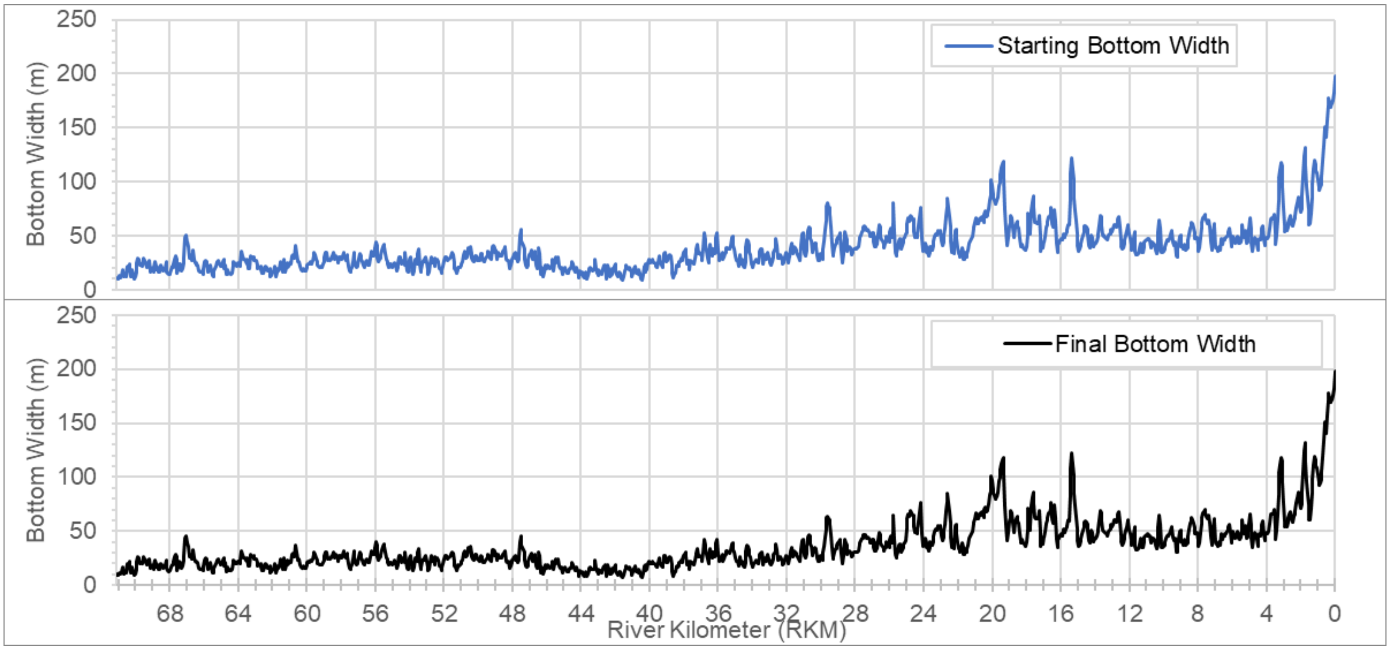


Figure 4-1 Sandy River starting and final bottom width

The sediment heat exchange parameters, i.e., sediment thermal conductivity and diffusivity, and wind coefficients were left unchanged at their default values. Table 4-2 below shows some of the parameters and constants used in the Heat Source model, their values, and their literature reference if applicable are presented.

Table 4-2. Parameters and constants used in Heat Source, value range shows minimum and maximum values measured over the study area

Constant	**Value**	**Reference**
Channel bottom width [m]	7.5 to 198	Estimated.
Sediment thermal diffusivity [cm2/sec]	0.0064	Default (Pelletier et al. 2006 as noted in the model)
Thermal conductivity of sediment [W/m/deg C)]	1.57	Default (Pelletier et al. 2006 as noted in the model)
Manning's n	0.068	Estimated. (Chow, 1959, Jarrett, 1985 suggest a range of 0.035 to 0.070)
Wind Function Coefficient a	1.505E-09	Default (Boyd and Kasper, 2003)
Wind Function Coefficient b	1.600E-09	Default (Boyd and Kasper, 2003)

A combination of visual and computed error statistics was used to assess the model calibration. The goodness of fit for the Heat Source model was summarized using the mean error (ME), average absolute mean error (MAE), root mean square error (RMSE), and the Nash-Sutcliffe efficiency coefficient (NS) as a measure of the deviation of model-predicted shade values from the measured values. Detailed explanation on each of the statistics can be found in the QAPP for this project (DEQ 2021). These model performance measures were calculated as follows:

$$ME = \frac{1}{n}\sum(P - O)$$

$$MAE = \frac{1}{n}\sum|P - O|$$

$$RMSE = \sqrt{\frac{1}{n}\sum(P - O)^2}$$

$$NS = 1 - \frac{\sum(P - O)^2}{\sum(O - \bar{O})^2}$$

where

P = model predicted values

O = observed values

$\bar{O}$ = the mean of observed values

n = number of samples

4.1 FLOW BALANCE

Hourly flow values at the two flow stations along Sandy River (Table 4-1) were compared against each other. Figure 4-2 and Figure 4-3 compares the simulated and measured flow volumes at the gages for the simulation time-period. The simulated daily flow values were nearly identical to the gage flow data because those gages were used as a reference starting point for the stream flow balance calculations. Refer to section 3.6.1 for more details on the flow balance comparisons. Table 4-3 shows the flow calibration statistics.

Table 4-3. Flow calibration statistics

Flow cms (cfs)	Sandy River Near Marmot (USGS 14137000)	Sandy River Below Bull Run River, Near Bull Run (USGS 14142500)
MES	0.02 (0.8)	0.04 (1.29)
MAE	0.06 (2.17)	0.14 (4.78)
RMSE	0.09 (3.3)	0.21 (7.51)
NS	0.99	0.98

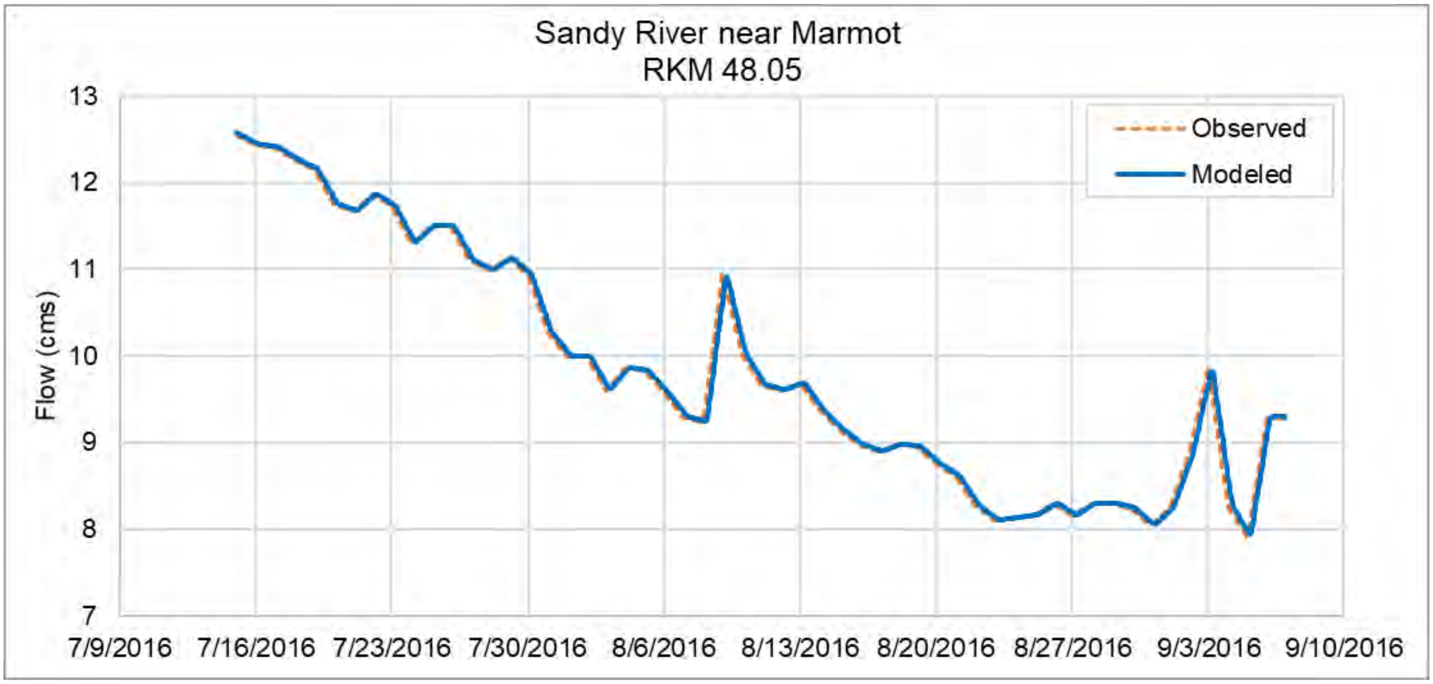


Figure 4-2 Sandy River Near Marmot (USGS 14137000)

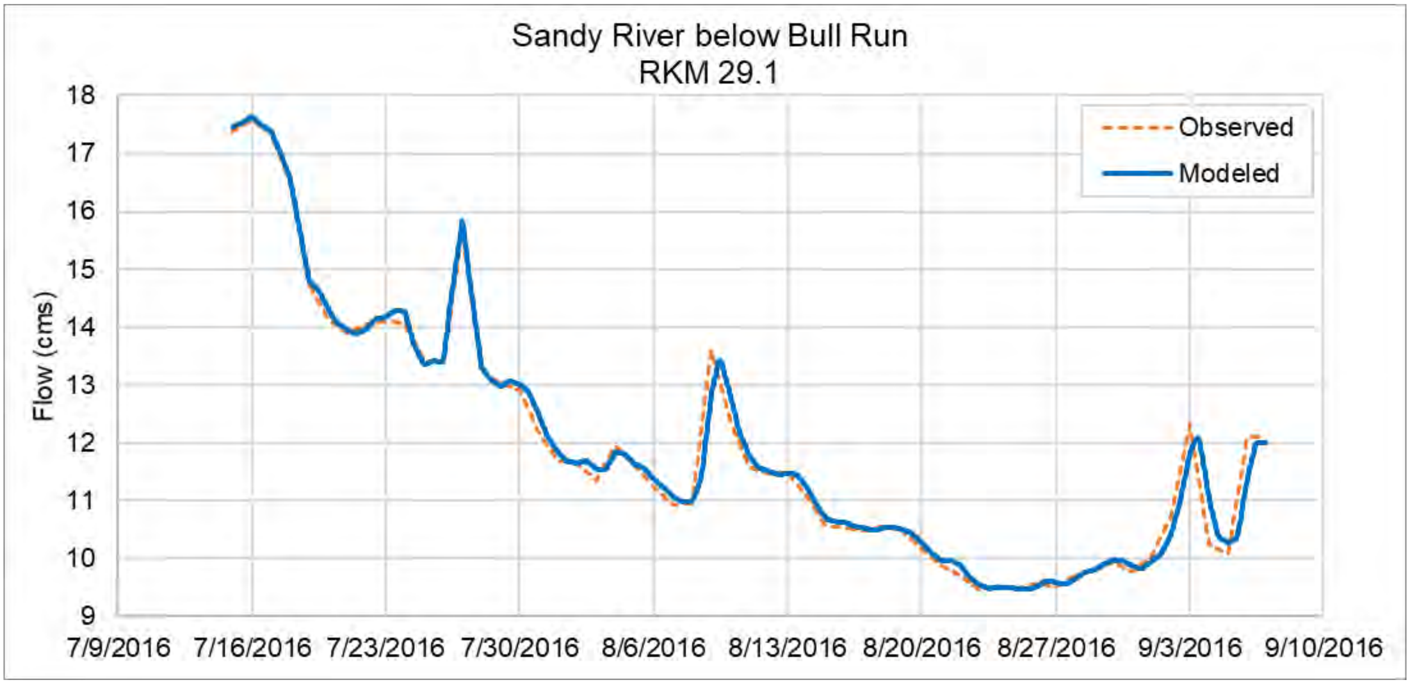


Figure 4-3 Sandy River Below Bull Run River, Near Bull Run (USGS 14142500)

4.2 EFFECTIVE SHADE

Effective shade is the percent of potential daily solar radiation flux that is blocked by vegetation and topography. No shade measurements were made during the 2016 time-period. There were three locations along the Sandy River where shade measurements were made in August 2001, using the solar pathfinder (Table 4-4). Observed effective shade data from three locations were overlaid with the daily predicted shade for 2016.

Tetra Tech reviewed the vegetation conditions at effective shade measurement sites and compared the vegetation conditions from aerial photos in 2000 to vegetation conditions observed in 2016. Based on aerial photo analysis, the vegetation conditions do not appear to have changed significantly and using effective shade measured in 2001 as a rough guide for model calibration purposes was appropriate.

Table 4-4. Effective shade data collected along the Sandy River on August 8, 2001 and model prediction August 2016

Site ID	Site Name	Latitude	Longitude	Shade Month	Shade Year	Result (%)	Model Prediction (%)
10676-ORDEQ	Sandy above Salmon near Brightwood	45.3786	-122.013	August	2001	0	10
26422-ORDEQ	Sandy above Clear Creek at Lolo Pass Rd.	45.3565	-122.938	August	2001	61	58
No Station ID	Sandy River at Troutdale STP	45.4982	-122.01	August	2001	11	8.6

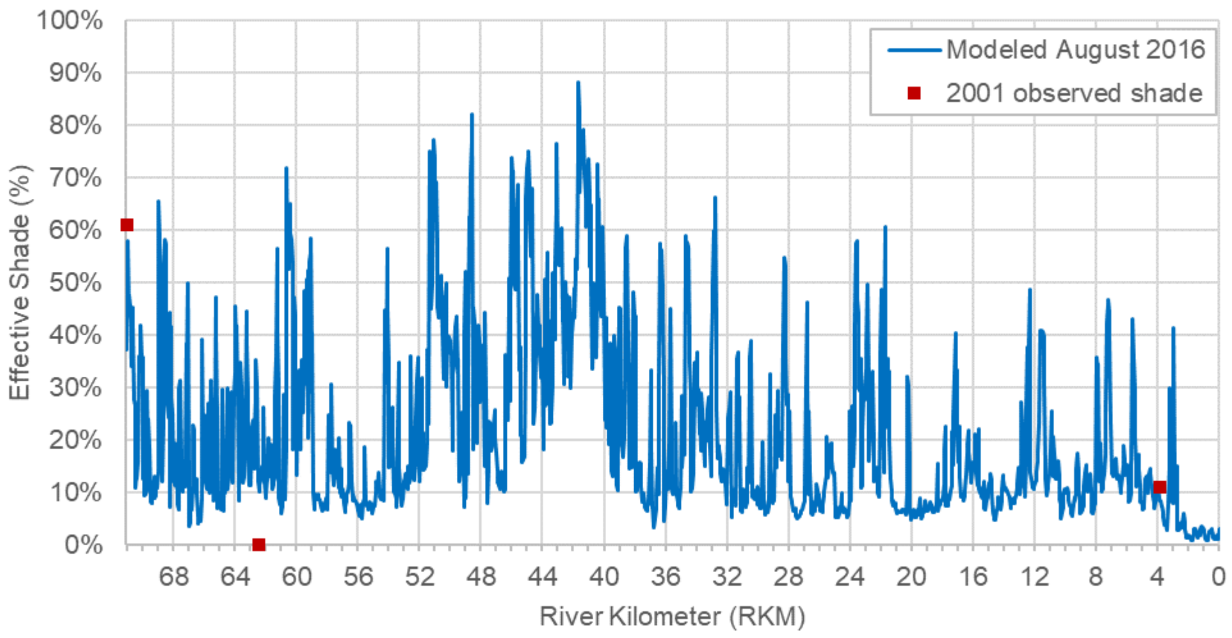


Figure 4-4 Sandy River modeled shade August 8 (2001 observed and 2016 modeled)

Note that the Sandy above Salmon near Brightwood station recorded an effective shade observed value of 0 percent. Aerial photo imagery shows vegetation in the immediate surrounding area of this station, with some shade expected in this area. Figure 4-5 shows the location of the station. Based on consultation with DEQ it was determined that this is most likely a transcription error and should not be considered for calibration purposes.

Figure 4-5 Location of the Sandy River near Brightwood shade measurement station (model RKM 62.4)

Figure 4-6 shows the spatially varying daily average shade for a non-cloudy day in the simulation period. A review of the cloud cover data for the modeling period showed that there were only two days in the entire simulation period (August 18, and 19) when the entire day was clear. An additional day in July was also identified that was not cloudy during July 25 (most of the day was cloudy except for 3-hrs). Daily average shade results for these two days in July and August are presented Figure 4-6. The purpose of this shade plot is to show the longitudinal variability along the Sandy River.

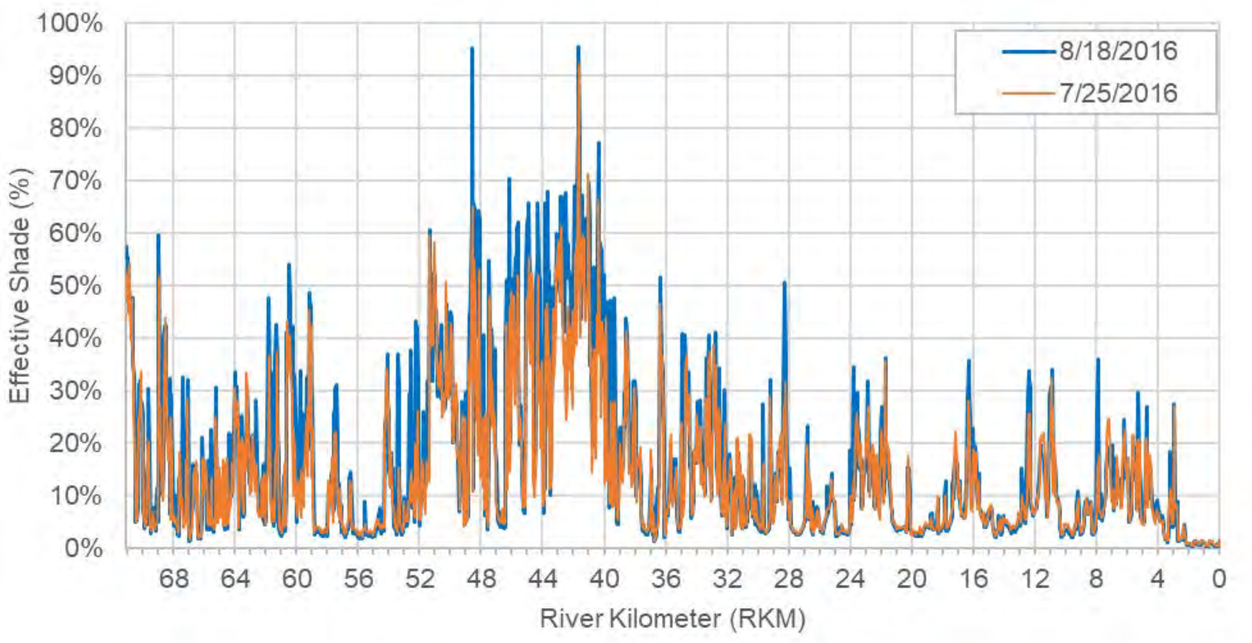


Figure 4-6 Predicted shade during the 2016 model simulation period for a non-cloudy day

4.3 TEMPERATURE CALIBRATION

Hourly temperature observations were compared at each of the stream temperature calibration monitoring stations shown in Figure 3-15 and listed in Table 4-1. The model is able to capture the hourly diurnal pattern and daily maximums well at the two upstream stations - Sandy River upstream of Zig Zag (Figure 4-7) and at the Barlow Trail Bridge below Salmon locations (Figure 4-8). Figure 4-9 and Figure 4-10 show the comparisons at the two Marmot stations located upstream and downstream of the location where the Marmot dam existed. At the two Marmot station locations, the model showed some underprediction during the two high flow events during early August and early September. Overall, all four stations capture the daily maximum fairly well, especially during the low flow periods. The calculated error statistics show a MAE and RMSE of less than 1 deg C. The NS efficiency at all four stations was greater than 0.9 for the hourly and daily maximum (except for the hourly results at Sandy below Marmot dam which had a NS of >0.75). Table 4-5 show the model calibration statistics for each of the calibration locations.

Figure 4-11 shows the stream temperature comparison at the most downstream calibration location on Sandy located just above Beaver Creek (RKM 3.8). The model is unable to capture the observed hourly temperatures at this location as well as upstream locations. The MAE was close to 1 deg C and the RMSE is 1.25 deg C. On further investigation in consultation with DEQ/EPA it was found that the hourly temperature pattern at this station to be quite different from the other stations located upstream and that the station location was in the portion of Sandy River which is tidally influenced by the Columbia River. DEQ was able to confirm that the station location is tidally influenced, and that the extent of the tidal influence is approximately 1 ¼ river miles above I84 which covers the station. This was further confirmed using the head of the tide information which was near East Columbia River Highway that is available from the DEQ mapper ([WR Map Tool (state.or.us)]()). Heat Source is a one-dimensional model, and does not model the tidal influence, which is the most likely reason that the model is unable to capture the observed temperature patterns at this station. Due to this station being tidally influenced, no further adjustments were made to the model for this station and the remaining four stations in the non-tidal portion were used to primarily judge the overall performance of the model.

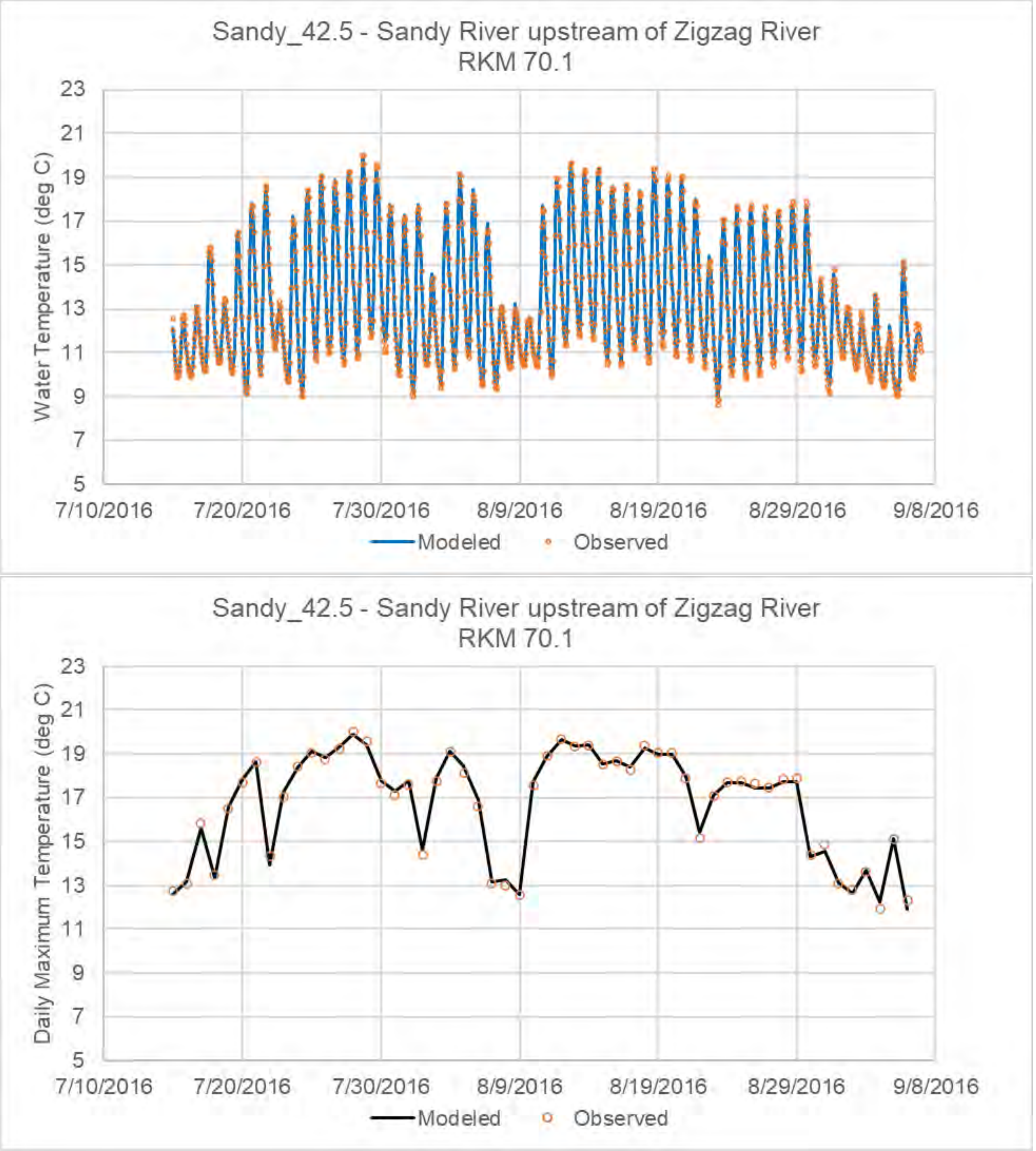


Figure 4-7 Observed versus Modeled Water Temperature - Sandy River upstream of Zig Zag River

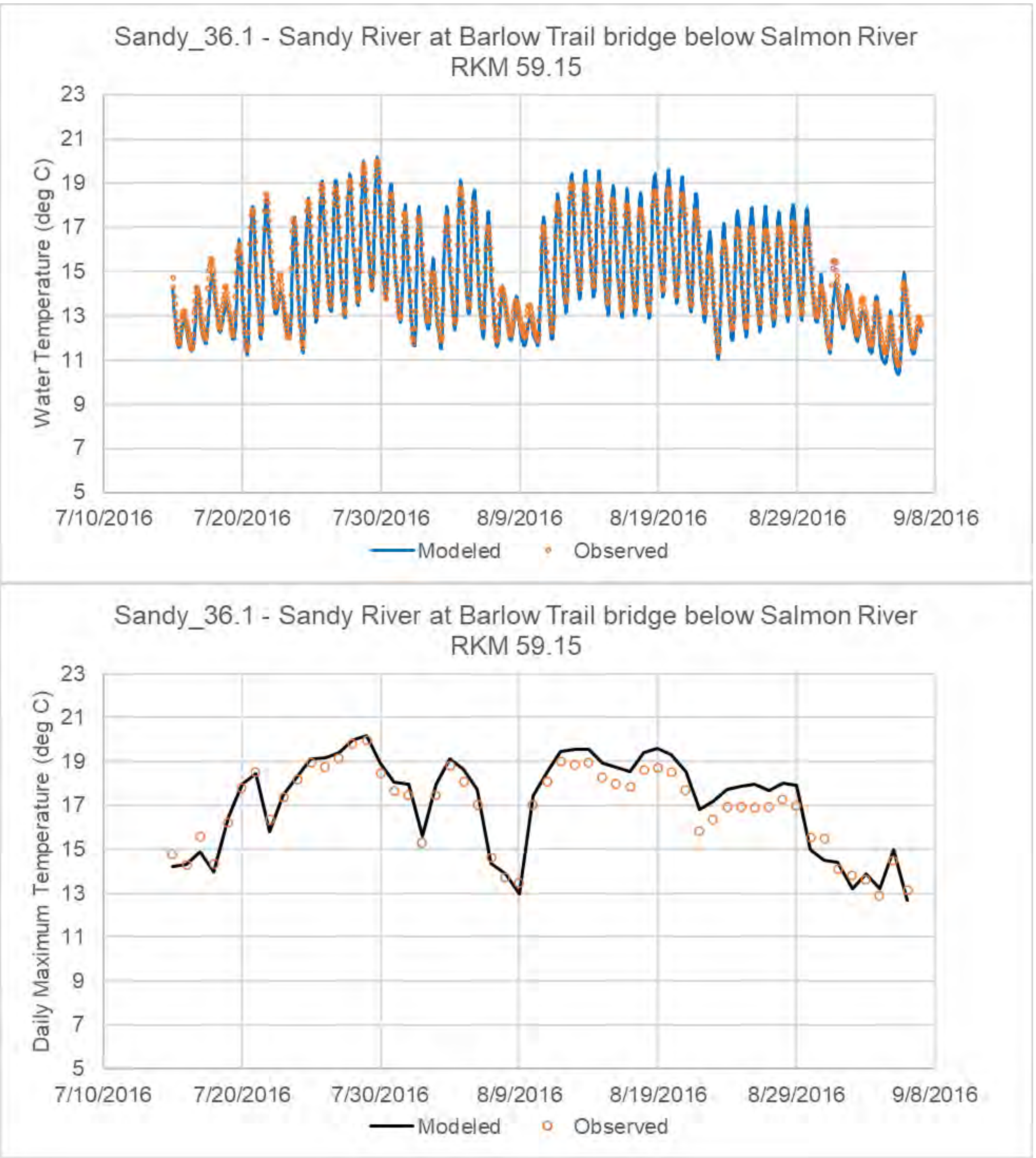


Figure 4-8 Observed versus Modeled Water Temperature - Sandy River at Barlow Trail bridge below Salmon River

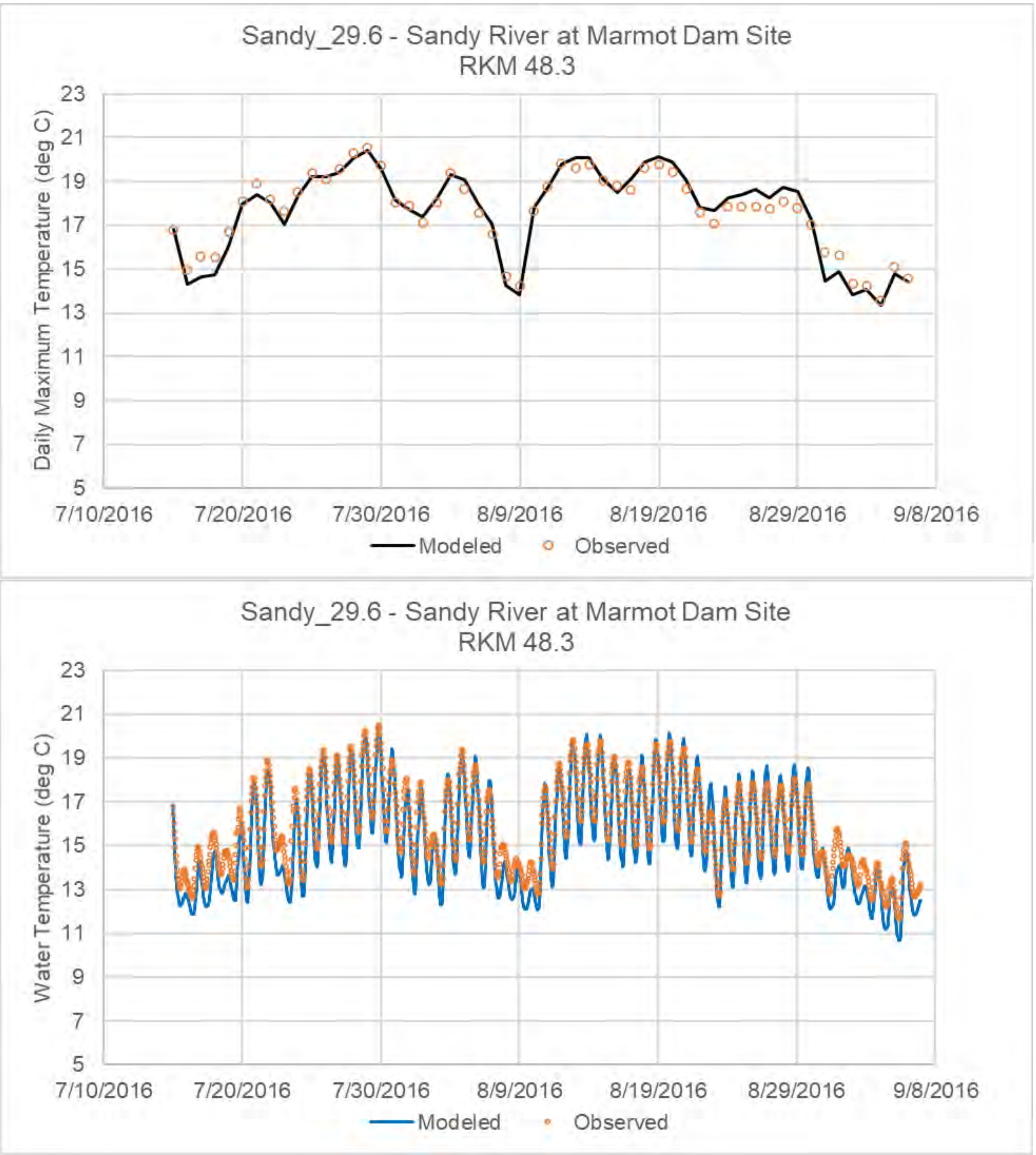


Figure 4-9 Observed versus Modeled Water Temperature - Sandy River at Marmot Dam Site

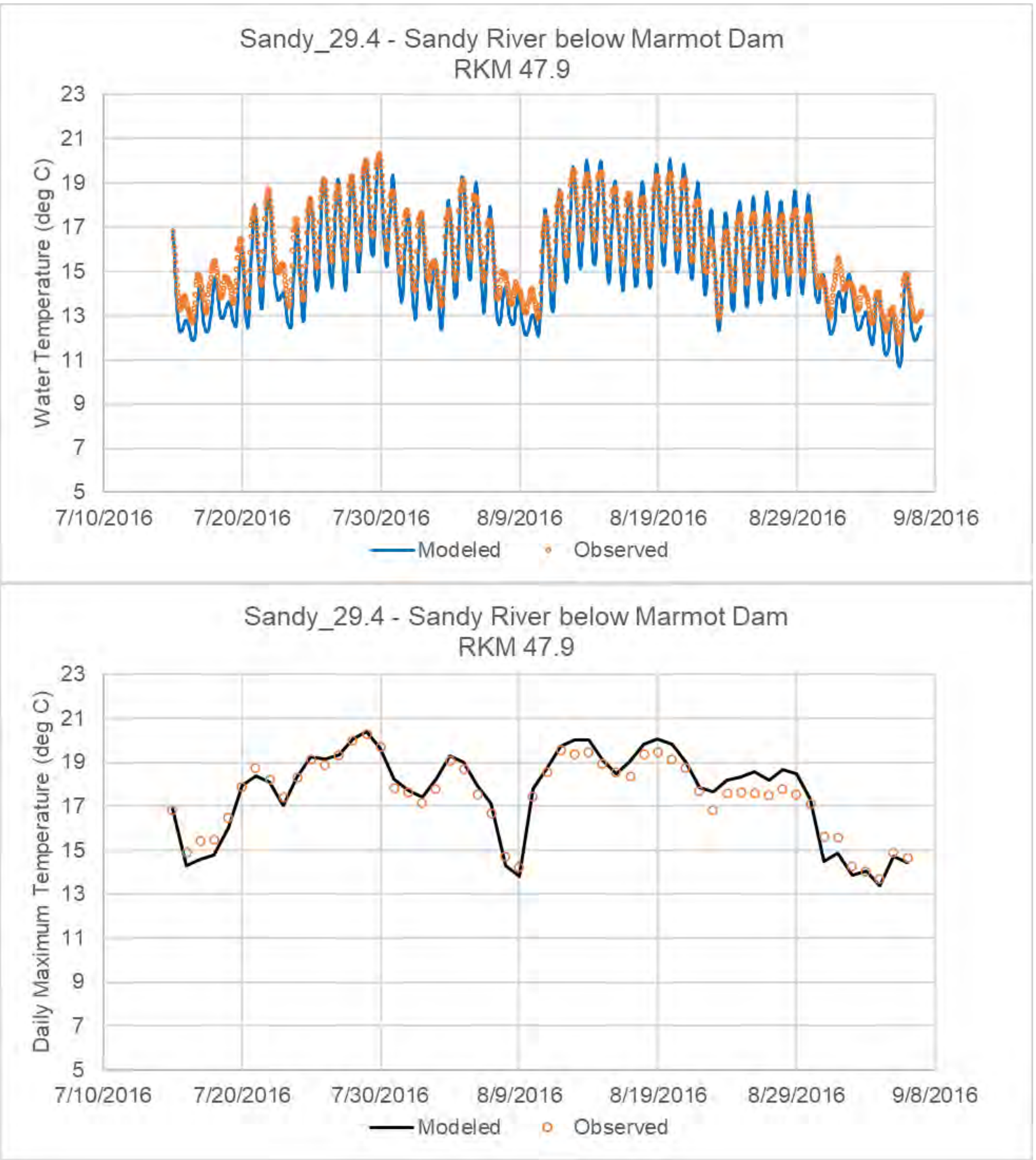


Figure 4-10 Observed versus Modeled Water Temperature - Sandy River below Marmot Dam

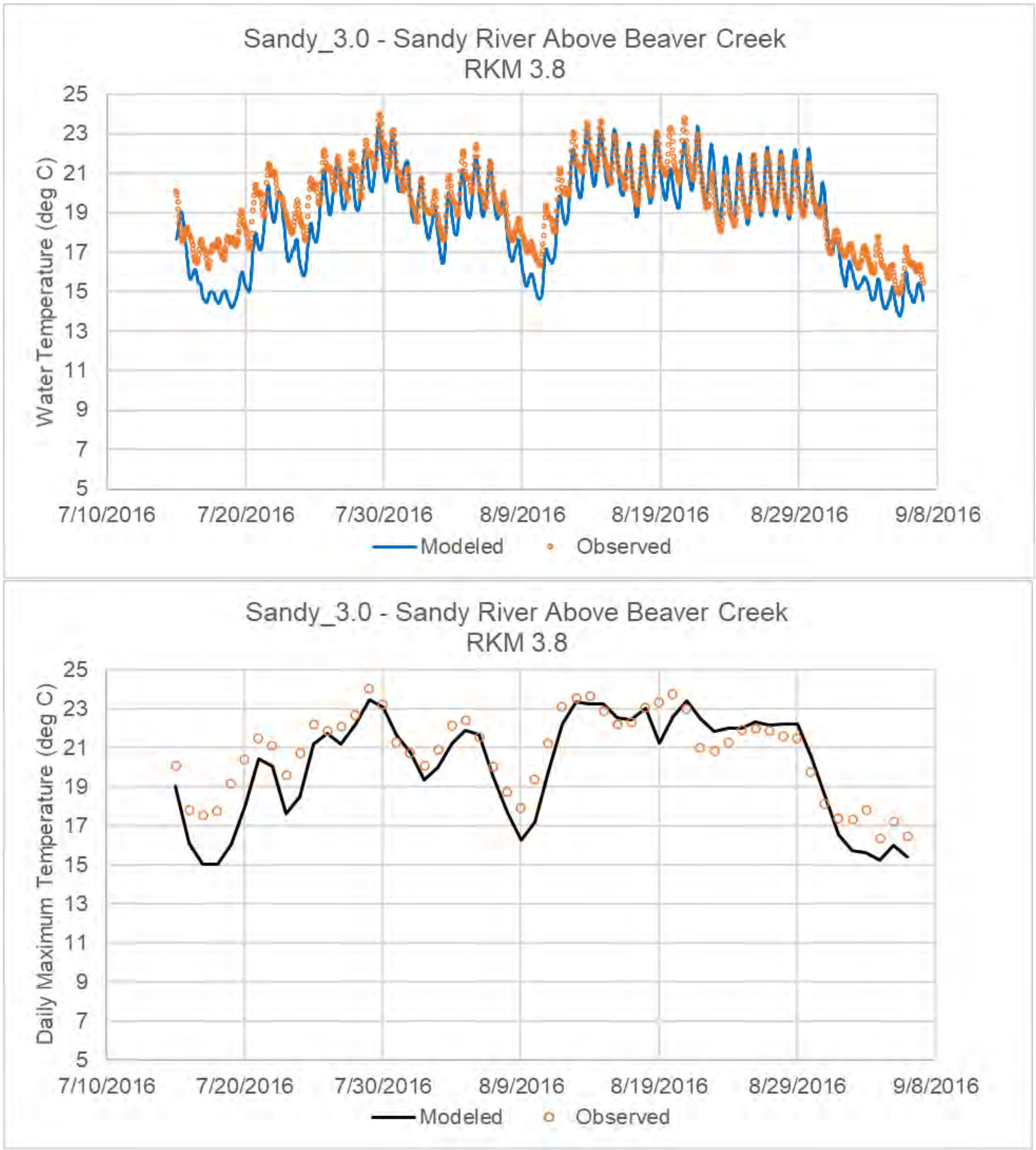


Figure 4-11 Observed versus Modeled Water Temperature - Sandy River above Beaver Creek

Table 4-5. Hourly and Daily Maximum Stream Temperature calibration statistics for Sandy River (July 15 to September 9, 2016)

Statistic	**Sandy_42.5 - Sandy River upstream of Zigzag River**	**Sandy_36.1 - Sandy River at Barlow Trail bridge below Salmon River**	**Sandy_29.6 - Sandy River at Marmot Dam Site**	**Sandy_29.4 - Sandy River below Marmot Dam**	**Sandy_3.0 - Sandy River Above Beaver Creek[a]**
Hourly Temperature Statistics					
ME	0.04	-0.26	-0.60	-0.62	-0.79
MAE	0.30	0.44	0.69	0.76	1.04
RMSE	0.36	0.51	0.82	0.89	1.29
NS	0.98	0.94	0.823	0.78	0.56
Daily Maximum Temperature Statistics					
ME	0.01	0.31	-0.01	0.13	-0.69
MAE	0.13	0.52	0.37	0.40	0.99
RMSE	0.16	0.58	0.45	0.49	1.24
NS	0.99	0.90	0.93	0.92	0.64

a: Note that this station exceeds the calibration statistics criteria of <=1 deg C, due to tidal influence which cannot be simulated using Heat Source (refer to text under the Temperature Calibration section). This station was not used to evaluate the overall performance of the model.

5.0 SUMMARY

A Heat Source version 8 shade and water temperature model was developed for the Sandy River to support TMDL development for spawning temperature impairment in river. The extent of the modeling domain was from the mouth of the Columbia River to just upstream of Clear Creek. The model was developed for the critical summer and spawning period during 2016 when data are available for model development. The model used high resolution LiDAR and Orthophotos for configuring the morphology, and vegetation data for simulating shade and temperature within the Heat Source model. Observed meteorological data from four stations along the Sandy River were used to account for the differences in elevation from headwaters to the mouth of the drainage. The model used DMR data from two active point sources that discharge to the Sandy River – City of Troutdale WPCF and the Hoodland STP. Flow data required for configuring the flow boundaries for all model tributaries were not available and were estimated using an observed reference flow gage near Marmot using the StreamStats flow estimation method. Model water temperature data boundaries were configured using observed hourly stream temperature data that was available for nine of the 22 tributaries. Stream water temperature for the remaining tributaries were derived using either a linear regression approach or using a direct surrogate from a neighboring or nearby tributary watershed.

The model was calibrated using hourly water temperature at four separate locations along the Sandy River mainstem. Overall, the diurnal temperature patterns and daily maximum, especially during the low flow periods were captured at each of the four station locations. The model showed some underprediction during the two high flow events during early August and early September at the two Marmot station locations. In general, the calculated MAE and RMSE were less than 1 deg C at each of the calibration station locations. The calibration station locations in 2001 were different from those in 2016, except for the Marmot location. The calibration MAE at Marmot during 2016 (Table 4-5) were similar to those reported at the Marmot gage in the previous 2001 model (0.67 deg C). In addition, in the current study there is a station below Salmon which had an MAE of 0.44 deg C, whereas in 2001 the station was above Salmon and had a MAE of 0.67 deg C. Note that the 2001 statistics were based on those computed over a 24- hour period during August 8, 2001, whereas the 2016 statistics were computed using hourly data over the period from July 15 to September 9, 2016. The NS efficiency at all four stations in the 2016 study were greater than 0.9 for the hourly and daily maximum (except for the hourly results at Sandy below Marmot dam which had a NS of >0.75). There was also a fifth water temperature observation at the downstream of Sandy River just above Beaver Creek. This station was not considered for evaluating the calibration, as it was determined to be tidally influenced by the Columbia River. This station had an AME of daily maximums of 0.99 deg C and RMSE of 1.24 deg C.

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Appendix C

Sandy River Model Scenario Report

To:	Ryan Michie, David Fairbairn, Ben Cope, Peter Leinenbach, Jayshika Ramrakha
From:	Aileen Molloy, Sen Bai, Mustafa Faizullabhoy
Date:	December 9, 2022
Subject:	Sandy River Scenarios

This document discusses the development and results of the various model scenarios used to support the Sandy River Temperature TMDL. The Sandy River Heat Source Temperature model (Tetra Tech, 2022) was used for scenarios simulation. The extent of the model domain for the Sandy River was from the mouth at the Columbia River to just upstream of Clear Creek, covering a stretch of 71.08 river kilometers (RKM). The model was configured and calibrated for the period from July 15, 2016, to September 05, 2016. This period covered the critical summer and spawning periods. The following scenarios were evaluated using this model:

i. Baseline conditions scenario
ii. Future proposed point source scenario
iii. No point sources scenario
iv. TMDL waste load allocation (WLA) scenario
v. Restored vegetation scenario
vi. No dams scenario
vii. Restored stream flow scenario
viii. Water withdrawal scenario
ix. Background condition scenario

Model scenario interpretation in terms of calculation metrics that applied to all scenarios is discussed first, followed by a description of each scenario and the corresponding results.

1.0 MODEL SCENARIO INTERPRETATION

This section discusses the calculation metrics that were used when evaluating the scenarios.

1.1 SIGNIFICANT DIGITS AND ROUNDING

The TMDL analysis, interpretation of the model results, and all scenarios account for significant digits and rounding. For evaluation of the attainment of the human use allowance (HUA), Oregon Department of Environmental Quality (DEQ) tracks values to the hundredths. Because DEQ is providing some of the HUA allocations out to the hundredths, attainment must be tracked in a similar manner. DEQ has a permit related internal management directive (IMD) on rounding and significant digits (DEQ 2013). The TMDL analysis follows the rounding procedures outlined in this IMD. The significant figures IMD says that for “calculated values” (which includes model results), if the digit being dropped is a “5,” it is rounded up. For example, for water withdrawals DEQ is proposing a 0.05 °C HUA allocation. If the model shows warming equal to 0.054 °C it gets rounded down to 0.05 °C and the result is attainment. If the model shows warming equal to 0.055 °C, it gets rounded up to 0.06 °C, and the result is non-attainment.

1.2 CALCULATING THE 7-DAY AVERAGE MAXIMUM TEMPERATURE

For each scenario the 7-day average maximum (7DADM) temperature was calculated using the hourly model output. The 7DADM was calculated using the procedure outlined in DEQ's Temperature IMD (DEQ, 2008). As outlined in the document the 7DADM temperature is calculated by first calculating the daily maximum for each day, followed by calculating a rolling average of the daily maximums, the result for which lands on the 7th day.

1.3 COMPARING TEMPERATURE BETWEEN TWO SCENARIOS

When comparing the hourly results from two model scenarios to determine the temperature changes, the following steps were taken:

1. Calculate the 7DADM temperatures for scenario 1 at every model output for every day during the model period.
2. Calculate the 7DADM temperatures for scenario 2 at every model output for every day during the model period.
3. For allocation scenarios the HUA is based on an increase above the applicable criteria, so for determining the maximum change in temperature, the days when the 7DADM river temperatures do not exceed the applicable biologically based numeric criteria (BBNC) were excluded. This step was necessary to ensure that we only consider the maximum change in temperatures when the river exceeds the BBNC criteria for analysis. Note that the BBNC varied spatially and temporally.
4. Compute the difference between the 7DADM temperatures of scenario 1 and scenario 2 only for days that exceed the BBNC.
5. Round the differences to the hundredths, based on the adopted rounding procedure discussed in Section 1.1.

1.4 BIOLOGICALLY BASED NUMERIC CRITERIA

The applicable temperature criteria for the Sandy River are outlined below:

- Salmon and Steelhead Spawning: 13.0 °C August 15 – September 5 (OAR 340-041-0028(4)(a))
- Core Cold Water Habitat: 16.0 °C, July 15 – August 14 (OAR 340-041-0028(4)(b))
- Salmon and Trout Rearing and Migration: 18.0 °C July 15 – September 5 (OAR 340-041-0028(4)(c))

The BBNC vary spatially and temporally and are evaluated based on the 7DADM. Figure 1-1 below shows the variation of the BBNC along the Sandy River Heat Source Model domain. The Sandy River stream sampling points and the location of the applicable numeric criteria are shown in Figure 1-2.

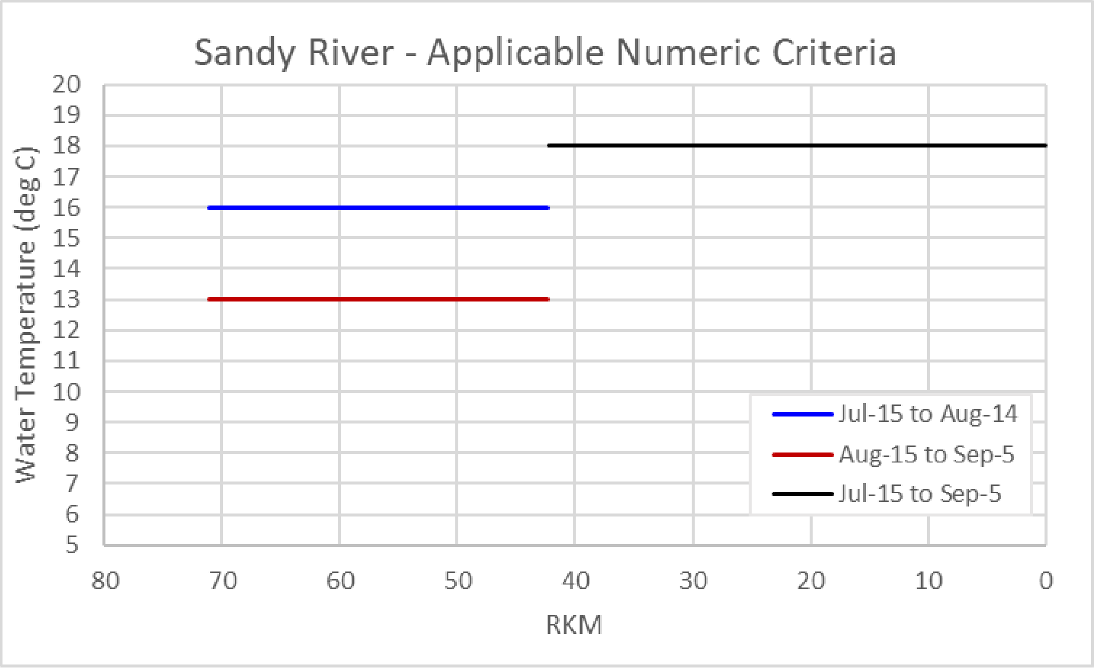

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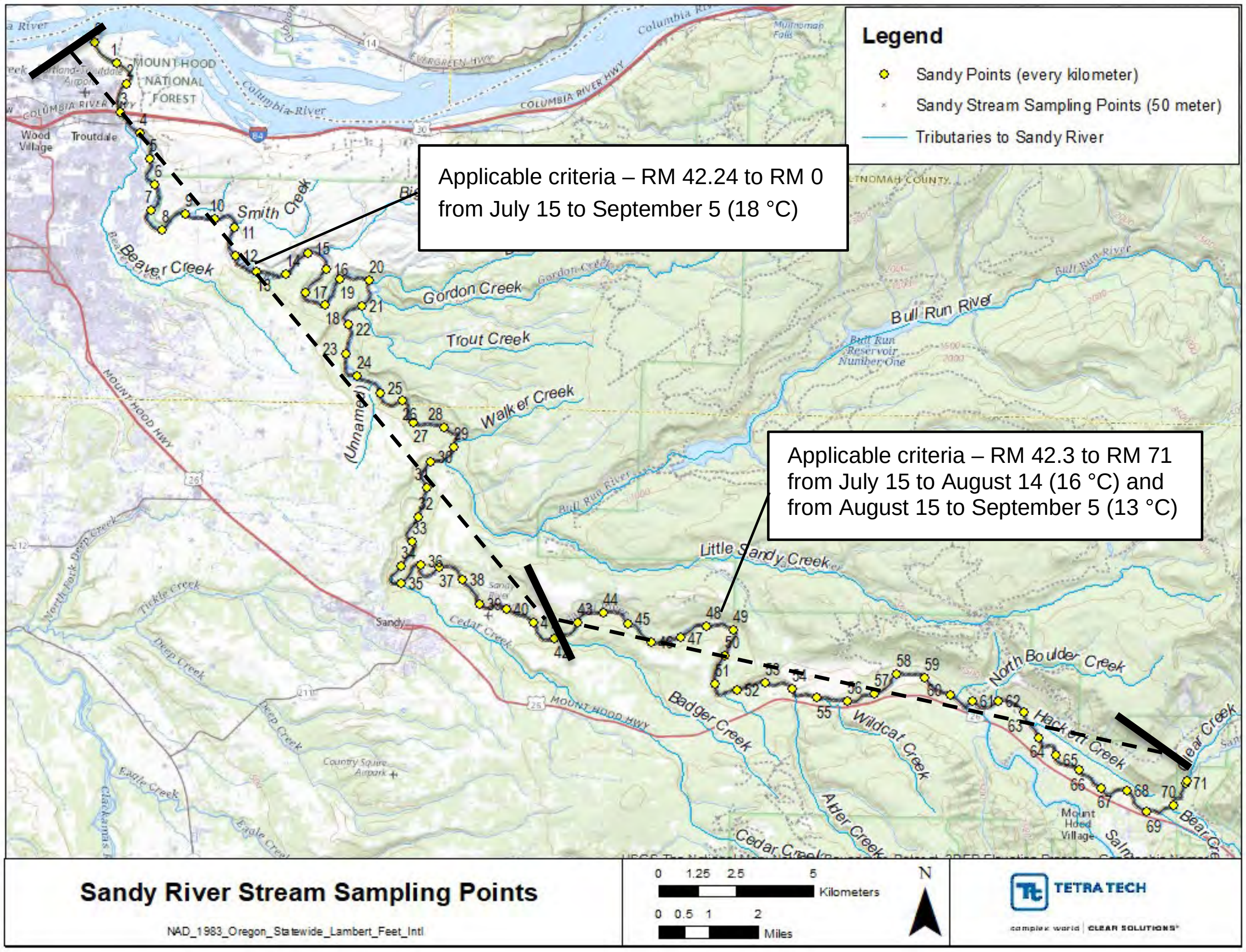
Figure 1-1. Applicable BBNC along the Sandy River modeling domain.



Applicable criteria – RM 42.24 to RM 0 from July 15 to September 5 (18 °C)

Applicable criteria – RM 42.3 to RM 71 from July 15 to August 14 (16 °C) and from August 15 to September 5 (13 °C)

Figure 1-2 Sandy River Stream Sampling Points.

2.0 BASELINE CONDITIONS SCENARIO

This scenario is the based on the 2016 current condition calibration (CCC), with the model boundaries and existing point sources for the period from July 15, 2016 to September 05, 2016. The only difference is that the flow and temperature inputs from Salmon River and Bull Run in the CCC were replaced with the calibrated existing condition Salmon River Heat Source (HS) model developed by DEQ and the existing condition Bull Run W2 model developed by the City of Portland (Figure 2-1 and Figure 2-2). For the Bull Run W2 model, the water temperature was extracted from the last active segment in the model (segment 99). The flow was extracted from segment 98 since the last active segment does not output the corresponding flow. These flow and temperature adjustments were completed to maintain a consistent baseline for comparison with scenarios that reflected changes made to the Salmon and Bull Run model (e.g., for the restored vegetation and no dams scenarios).

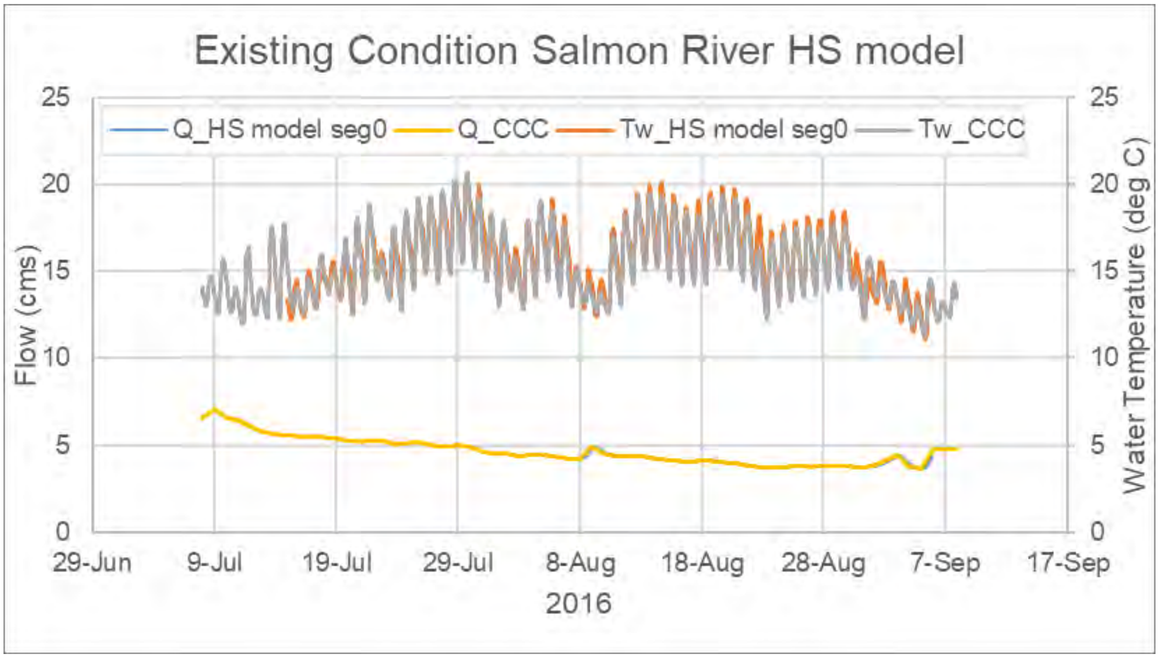


Figure 2-1. Salmon River HS model existing condition output at segment 0 and Salmon River measured flows and temperatures (used as inputs in CCC Sandy River model) for flow (Q) and water temperature (Tw).

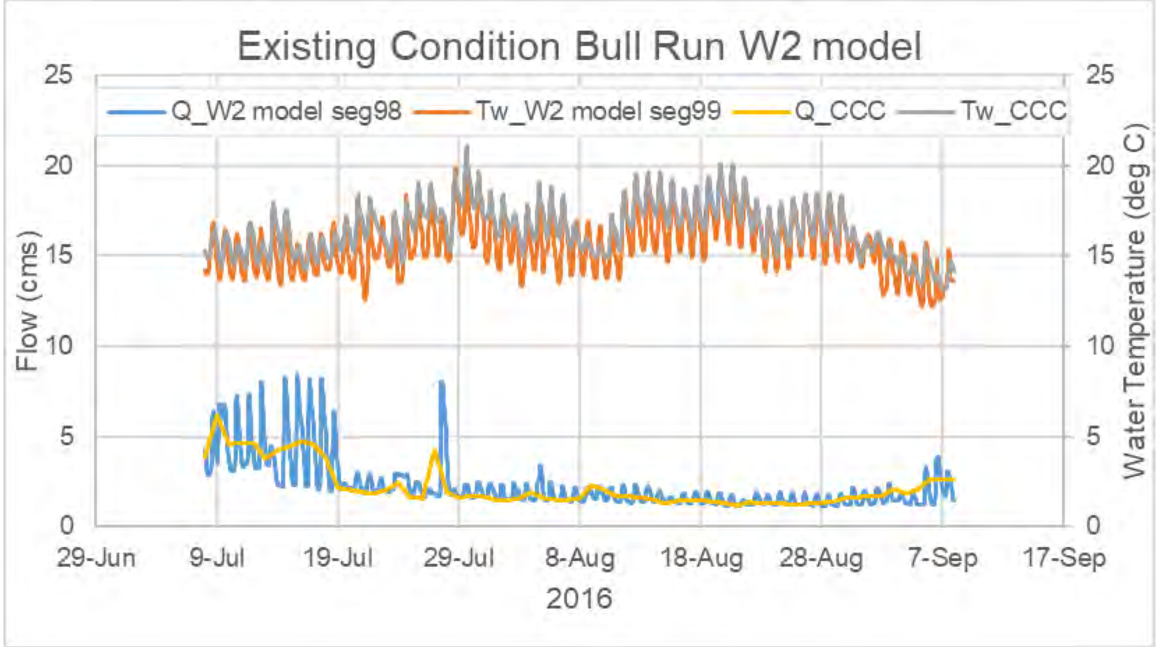


Figure 2-2. Bull Run W2 model existing condition output at segments 98 & 99 and Bull Run measured flows and temperatures (inputs used in CCC Sandy River model).

Daily maximum values were calculated from the hourly time series output from the model at each segment and then the 7DADM was calculated by averaging the daily maximum instream water temperatures for 7 consecutive days as a rolling average. The modeled maximum, minimum, and mean 7DADM at each segment for the entire modeling period (July – Sept) are presented in Figure 2-3.

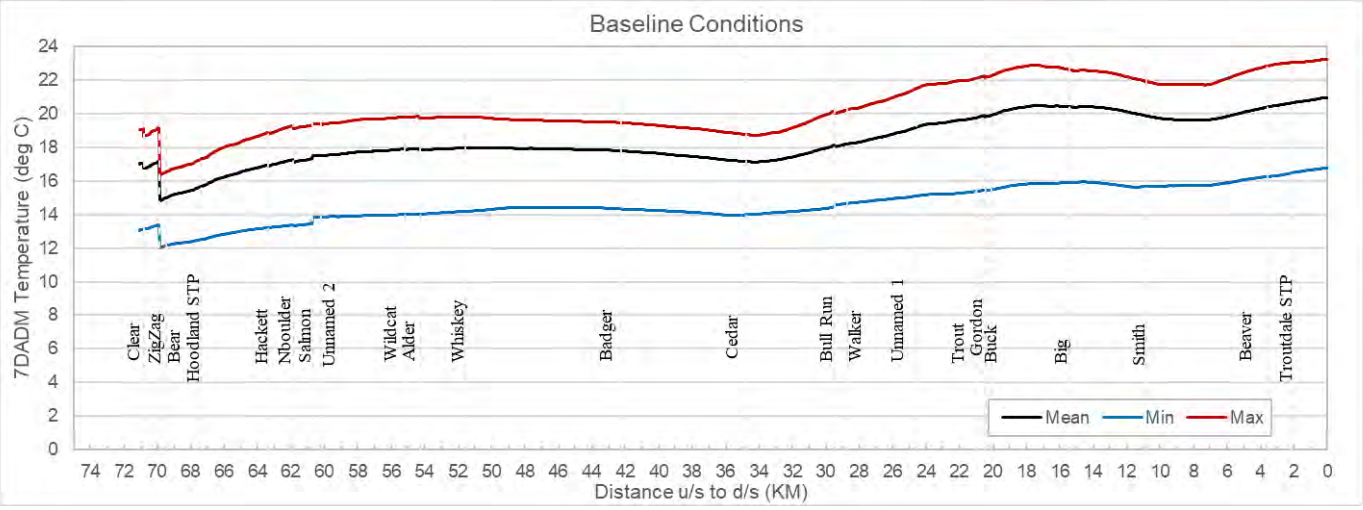


Figure 2-3. Baseline conditions Min/Max/Mean 7DADM water temperatures (upstream [u/s] to downstream [d/s] in kilometers [KM]).

The longitudinal 7DADM temperature profile shows the variation in temperature from upstream to downstream as it is influenced by the various point sources and tributaries along the system. Near the upstream boundary the longitudinal temperature profile shows a sharp drop in the maximum 7DADM from 19.18 °C to 16.34 °C where ZigZag River comes in. This is because the water temperatures in the ZigZag River are colder than the Sandy River. Further downstream from ZigZag the temperatures steadily increase until the Salmon River feeds into the Sandy River. The Salmon River water temperatures are much warmer than ZigZag River and are close to that of the Sandy River temperatures, leading to minimal impact being seen in the water temperatures. After which, the water temperatures remain similar until after Cedar Creek feeds into the Sandy River. From there the temperatures in the Sandy River continue to steadily increase after the Bull Run confluence and reach a maximum 7DADM of 22.90 °C at RKM 17.5 downstream of where Buck Creek enters the Sandy River, then the 7DADM water temperature fluctuates ±1 °C until the confluence with the Columbia River.

3.0 FUTURE PROPOSED POINT SOURCE SCENARIO

This scenario is the based on the baseline conditions scenario except that the proposed City of Sandy WWTP discharge was added into the model. The proposed outfall is located just downstream of Ten Eyck Road at RKM 38.5 (Figure 3-1).

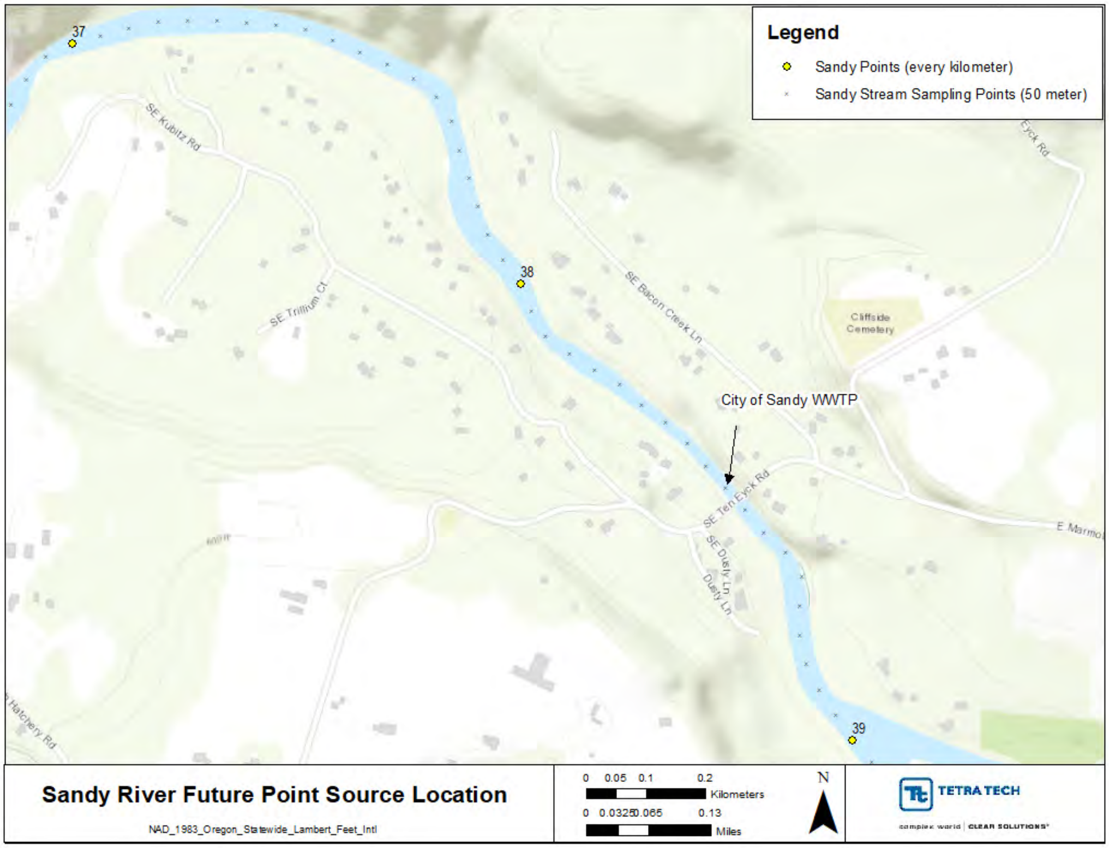


Figure 3-1. Location of proposed future City of Sandy WWTP point source.

Estimated effluent flow and temperature were provided to DEQ by the City of Sandy. Proposed flows from the years 2026 and 2040 were available. Based on direction from Oregon DEQ, the effluent temperatures provided corresponded to the year 2040 flows. The effluent flow and temperatures in the model were set to the 2040 values as shown in Table 1 below.

Table 1. Estimated City of Sandy WWTP effluent flow and temperature.

Month	Flow (MGD)		Effluent Temp (°C)
	2026	2040	
January	0.96	1.14	14.3
February	0.89	1.07	14.0
March	0.98	1.16	14.7
April	0.87	1.15	15.5
May	0.80	1.04	17.6
June	0.71	0.88	18.7
July	0.61	0.70	20.0
August	0.57	0.66	20.6

	Flow (MGD)		Effluent Temp (°C)
Month	2026	2040	
September	0.59	0.68	20.2
October	0.87	1.05	19.4
November	1.05	1.45	17.4
December	1	1.3	15.5

Figure 3-2 shows the longitudinal profiles of the modeled minimum, maximum, and mean 7DADM water temperature along the Sandy River with the location of the proposed City of Sandy WWTP point source location.

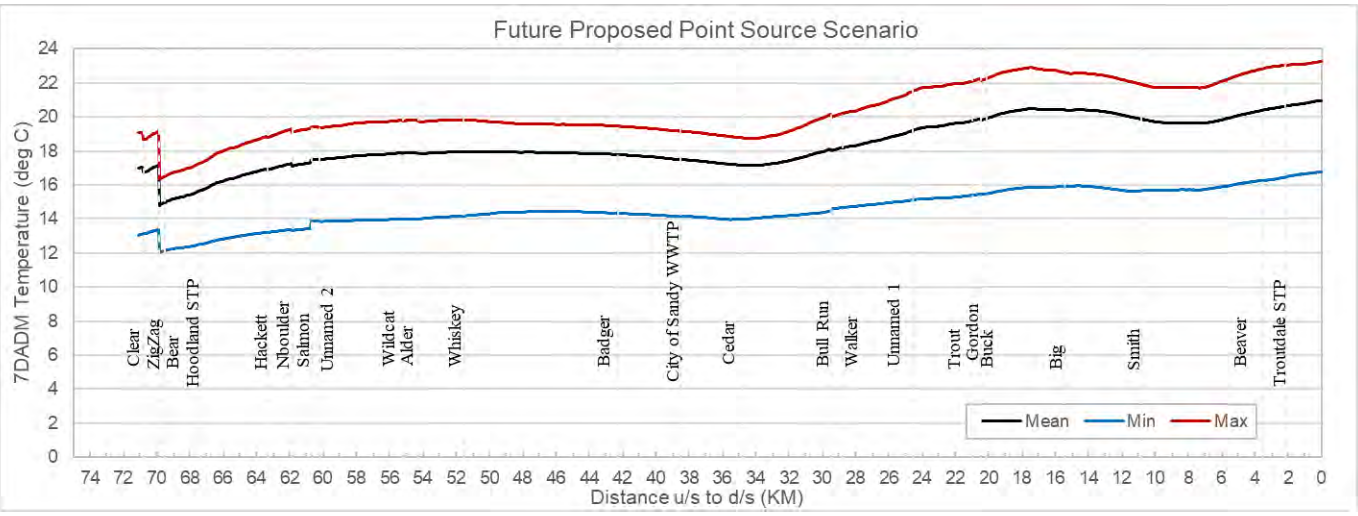


Figure 3-2. Future proposed point source - Min/Max/Mean 7DADM water temperatures.

At each node, the maximum 7DADM change due to the proposed point source was calculated as the maximum among the time-series of differences between the 7DADM results of this scenario and the baseline conditions scenario. Figure 3-3 shows the proposed point source's impact at its discharge location and downstream. The maximum 7DADM temperature change predicted at the proposed point source discharge location was 0.022°C.

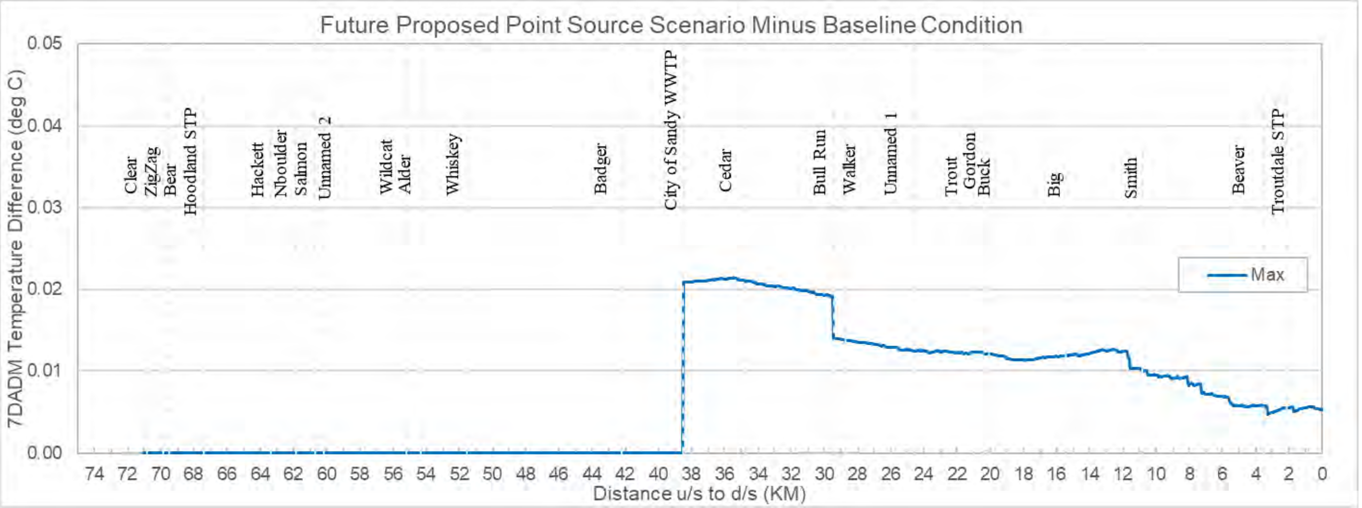


Figure 3-3 Impact of proposed City of Sandy WWTP point source - maximum 7DADM difference over model period.

4.0 NO POINT SOURCES SCENARIO

This scenario is identical to the baseline conditions model except that all point source discharges are removed. Cedar Creek tributary temperatures were updated to remove the Oregon Department of Fish and Wildlife (ODFW) Sandy River Fish Hatchery. Specifically, temperatures measured upstream of the hatchery outfall were used as Cedar Creek tributary temperatures (Figure 4-1), identified as “ambient temperatures” in data provided by ODFW.

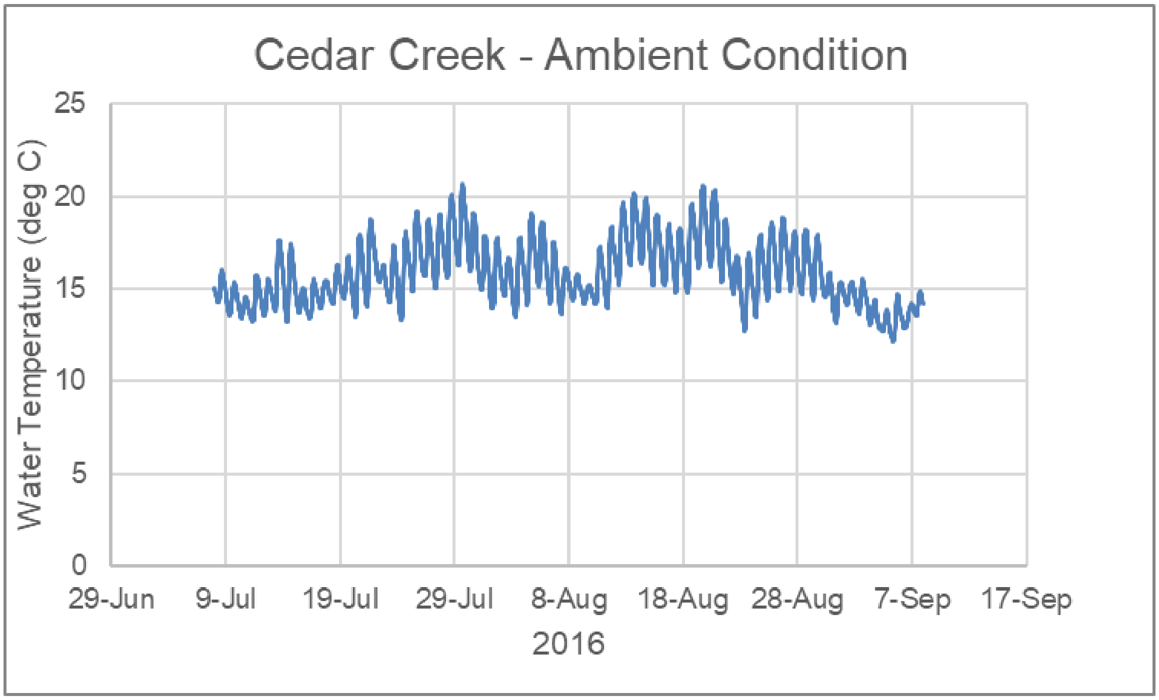


Figure 4-1. Cedar Creek 10 feet upstream of Sandy River Fish Hatchery Outfall.

The maximum 7DADM change (warming) from permitted NPDES point sources was determined by computing the difference in 7DADM temperature between the baseline conditions and the no point sources model scenarios. Figure 4-2 shows the impact of the point sources at their discharge locations and downstream. The maximum impact at the Troutdale STP location was 0.029 °C. Note that these differences are only calculated when the no point sources scenario temperature exceeds the BBNC.

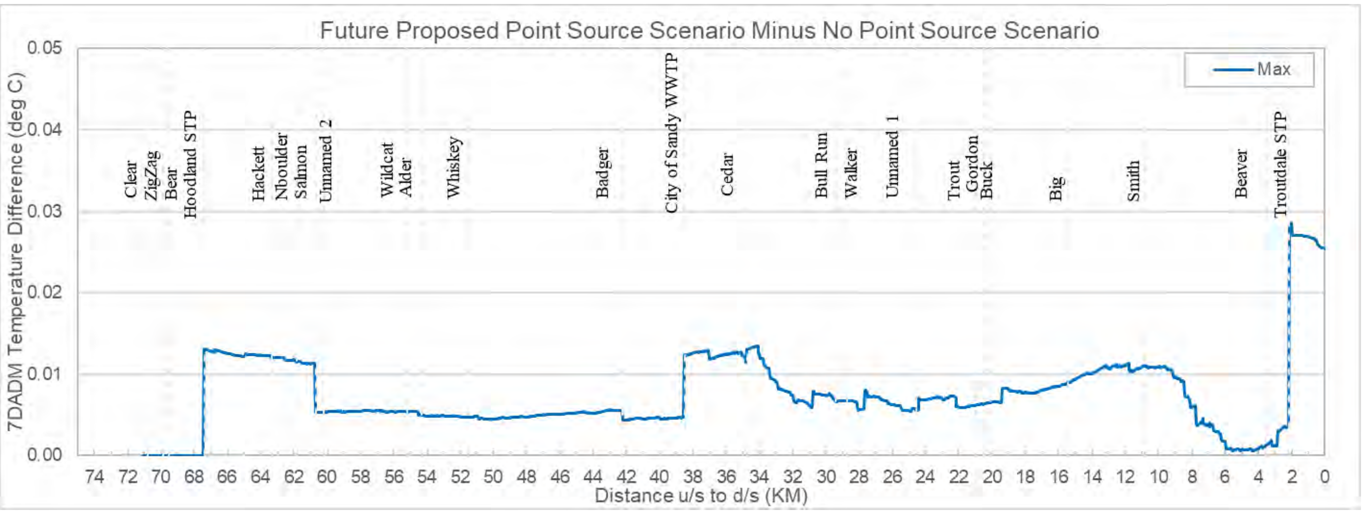


Figure 4-2. Scenario showing maximum estimated warming due to point sources (including future proposed point source) - maximum 7DADM difference.

5.0 TMDL WASTE LOAD ALLOCATION SCENARIO

This scenario is identical to the baseline conditions scenario except that the point source discharges reflect the proposed TMDL WLAs. Based on DEQ guidance, the TMDL WLA scenario aimed to achieve a cumulative WLA impact in the Sandy River at Troutdale of ≥0.2 °C and if possible, the point of discharge (POD) HUA should be defined to minimize immediate noncompliance issues, be consistent across permittees, and be similar to the 2005 TMDL. For the first scenario iteration, ΔT was set to 0.10 °C for Hoodland, Sandy WWTP, and Troutdale, but through iterations it was determined that the POD HUA should be reduced. The POD HUAs for Hoodland, Sandy WWTP, and Troutdale were eventually set to 0.07 °C. The point source effluent temperatures were adjusted by DEQ based on relevant equations presented by DEQ in the Technical Support Document to calculate acceptable point source effluent temperatures, and then provided to Tetra Tech. The Sandy River Fish Hatchery located close to the Cedar Creek mouth before its confluence with Sandy River was also given an allocation. In the model scenario, the river temperatures for Cedar Creek downstream of the POD of the ODFW Hatchery were increased by the HUA value of 0.3 °C assigned to the Hatchery. This incorporated the impact of the hatchery allocation in the Sandy River model simulation.

Specifically, Technical Support Document equation 5a, which calculated acceptable effluent temperatures for the various point sources, and equation 4a, which calculated TMDL allocation Cedar River temperatures considering impacts from the ODFW Hatchery, were used to calculate the WLA boundaries.

The effluent flows for all point sources were based on average dry weather facility design flow. The effluent temperatures were calculated to produce a change in temperature consistent with the allocation; however, on days when the calculated effluent temperatures were greater than 32 °C, the temperatures were capped at 32 °C per DEQ's mixing zone rules. The WLA temperature boundaries for Hoodland, Sandy WWTP, Troutdale, and Cedar Creek due to Sandy Hatchery were calculated by DEQ, provided to Tetra Tech. Figure 5-1 shows the flow and back-calculated temperatures for the point source dischargers that meet the 0.07 °C HUA at each POD in the TMDL WLA scenario. Figure 5-2 shows the flow and calculated temperatures for boundary inputs from Cedar Creek that account for the allowed ODFW Hatchery effluent allocation for the TMDL WLA scenario.

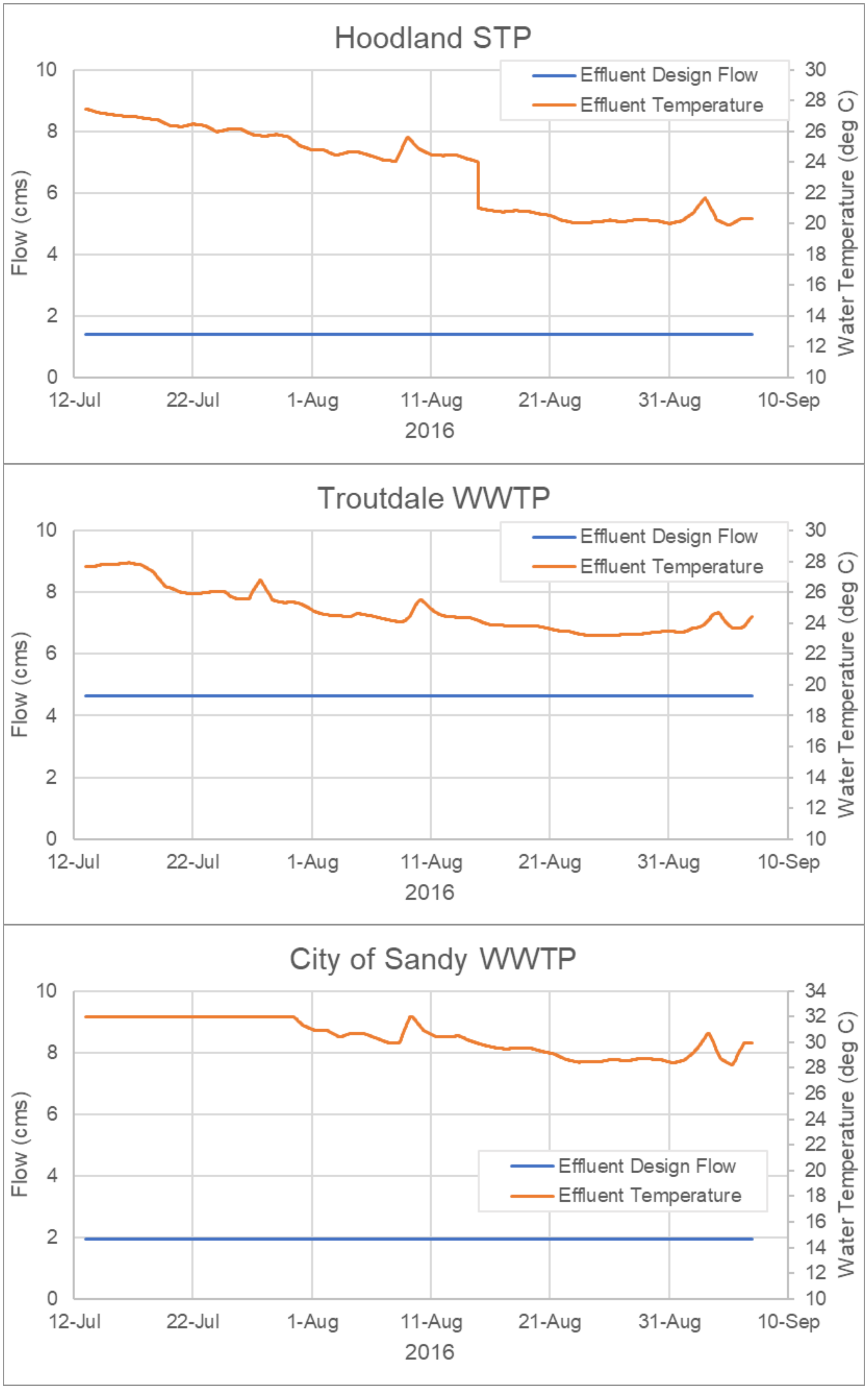


Figure 5-1. Hoodland, Troutdale, and City of Sandy WLA scenario flows and temperatures.

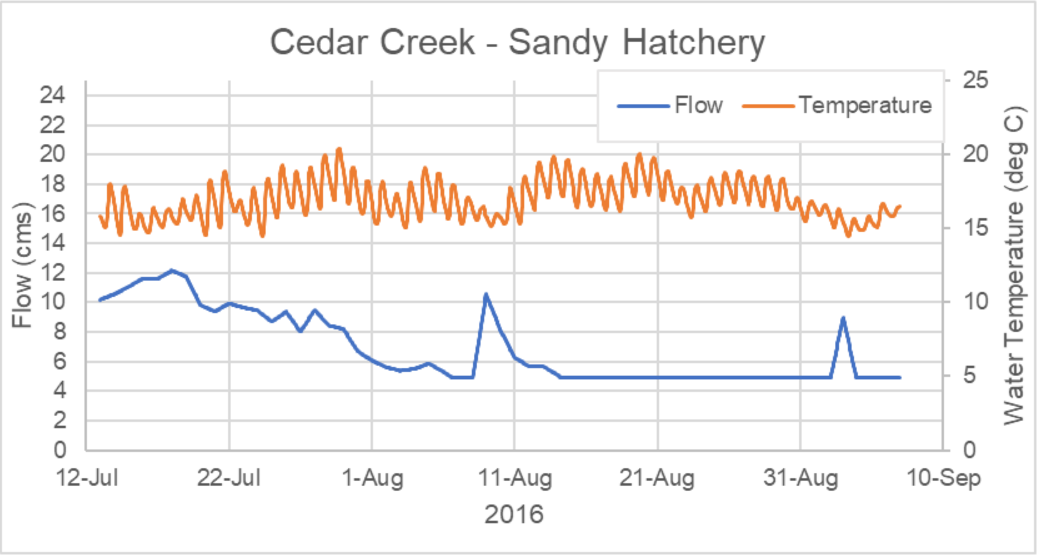


Figure 5-2. Cedar Creek WLA scenario flow and temperature.

At each node, the maximum 7DADM stream warming from permitted NPDES point sources set at the TMDL WLA was calculated as the maximum among the time-series of differences between the 7DADM results of this scenario and the no point sources scenario (Figure 5-3). Note that the 7DADM difference is calculated only when the no point sources model scenario temperature exceeds the BBNC. This scenario has a cumulative warming impact in the Sandy River at Troutdale of 0.13 °C.

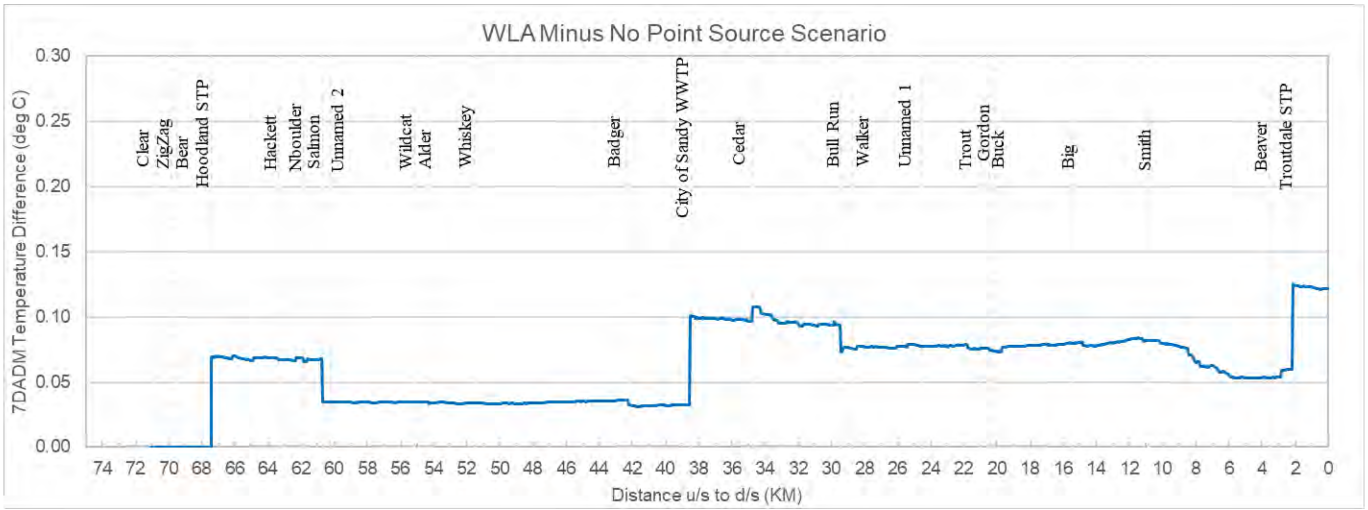
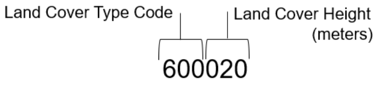


Figure 5-3. Impact due the NPDES point source temperatures set at TMDL - maximum 7DADM difference.

6.0 RESTORED VEGETATION SCENARIO

This scenario reflects fully restored streamside vegetation in areas along the model extent that are characterized as currently having reduced streamside vegetation due to anthropogenic disturbance. Current condition landcover used in the model is a 6-digit concatenation of two 3-digit codes: landcover type and landcover height (m) as determined from LiDAR. An example landcover code is shown below, where the current condition land cover type (600 - Hardwood - High Dense) and the current height (020) are concatenated as landcover code 600020.



The Heat Source model uses the landcover type code to lookup the restored vegetation type, height, cover, and overhang values. Table 2 shows the lookup values provided by DEQ. In the restored vegetation scenario model, the greater of the two vegetation heights (i.e., current LiDAR and restoration heights) (Table 2) was used.

Table 2. Landcover and associated codes, restored vegetation type, height, cover, and overhang values.

Land Cover Type Code	Current Landcover Description	Restored Vegetation Description	Restoration Height (m)	Canopy Cover	Overhang (m)
300	Pastures/Cultivated Field	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
301	Water - Non Active Channel	Water - Non Active Channel	0.0	0%	0.0
302	Water - Active Channel Bottom	Water - Active Channel Bottom	0.0	0%	0.0
305	Barren - Embankment	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
308	Barren - Clearcut	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
309	Barren - Soil	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
348	Development - Residential	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
349	Development - Industrial/Commercial	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
352	Dam/Weir	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
355	Canal	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
400	Barren - Road	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
401	Barren - Forest Road	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
500	Mixed Conifer/Hardwood - High Dense	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
550	Mixed Conifer/Hardwood - Medium Dense	Mixed Conifer/Hardwood - Medium Dense	26.7	30%	0.0
555	Mixed Conifer/Hardwood - Low Dense	Mixed Conifer/Hardwood - Low Dense	26.7	10%	0.0
600	Hardwood - High Dense	Hardwood - High Dense	20.1	75%	0.0
650	Hardwood - Low Dense	Hardwood - Low Dense	20.1	30%	0.0
700	Conifer - High Dense	Conifer - High Dense	35.1	60%	0.0
750	Conifer - Low Dense	Conifer - Low Dense	35.1	30%	0.0
800	Upland shrubs - High Dense	Upland shrubs - High Dense	1.8	75%	0.0
850	Upland Shrubs - Low Dense	Upland Shrubs - Low Dense	1.8	25%	0.0
900	Grasses - upland	Mixed Conifer/Hardwood - High Dense	26.7	60%	0.0
950	Grasses - wetland	Grasses - wetland	1.6	75%	0.0

In addition to the restored vegetation data calculated along the Sandy River model extent, this Sandy River scenario included updated tributary inputs based on the restored vegetation scenario results for the Salmon River (Heat Source, Figure 6-1) and Bull Run River (W2, Figure 6-2) models provided by DEQ and the City of Portland, respectively.

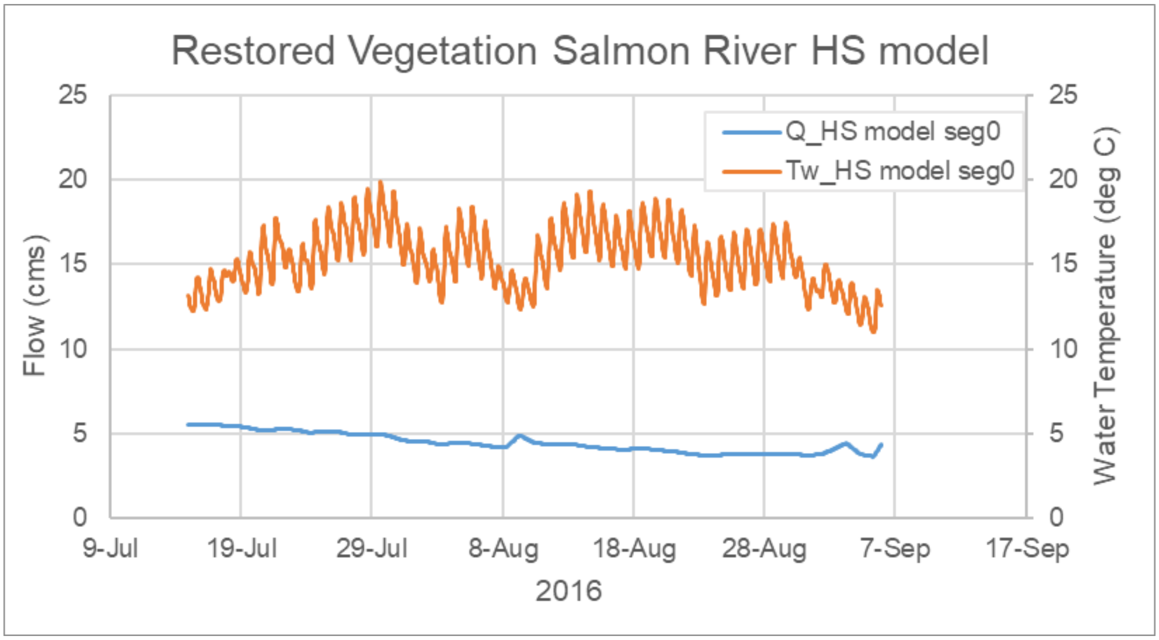


Figure 6-1. Salmon River restored vegetation scenario output.

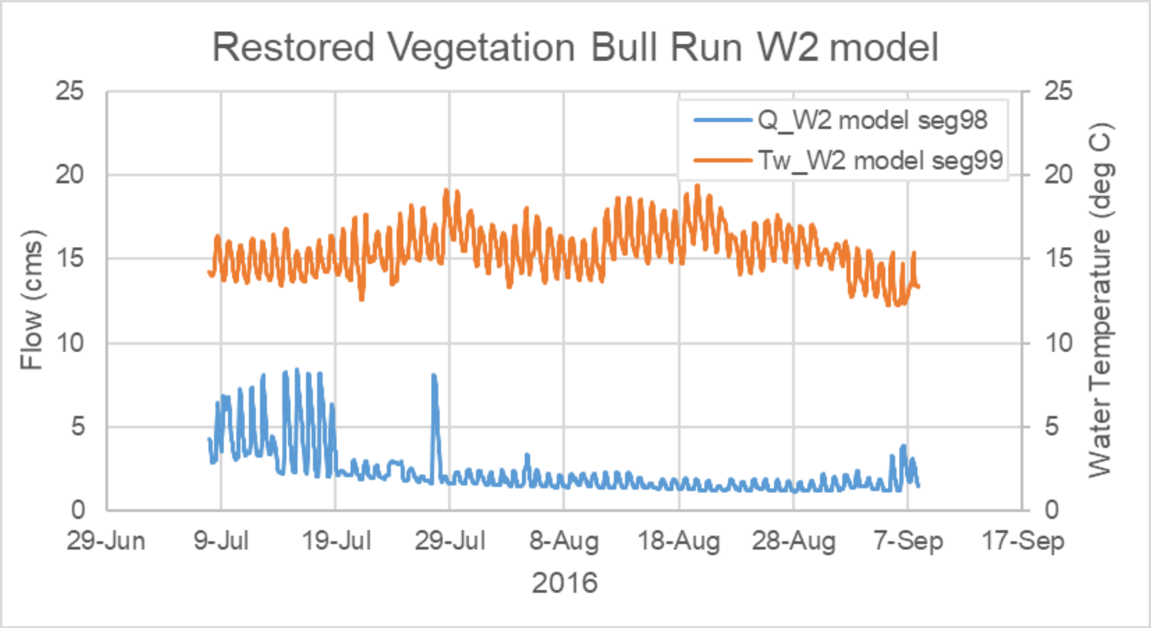


Figure 6-2. Bull Run River restored vegetation scenario output.

At each node, the maximum 7DADM warming from anthropogenic vegetation reduction was calculated as the maximum of the time-series of differences in 7DADM temperature between this scenario and the future proposed point source scenario (Figure 6-3). Note that the 7DADM difference was calculated only when the restored vegetation scenario temperature exceeded the BBNC.

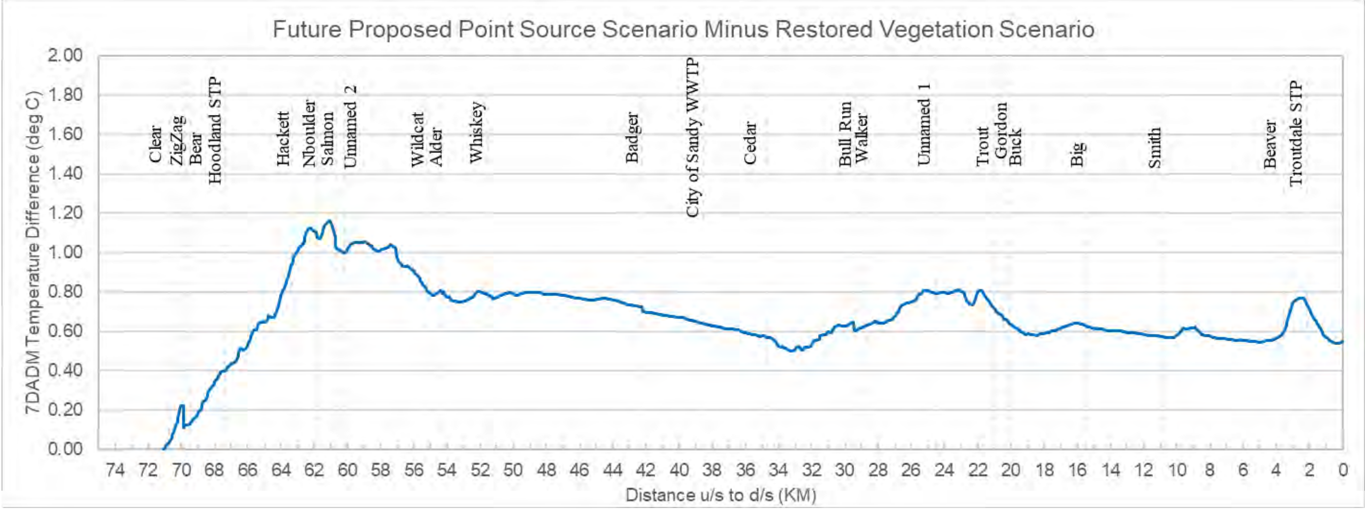


Figure 6-3. Warming impact due to anthropogenic vegetation reduction - maximum 7DADM difference.

The resulting impact on effective shade was also calculated. For a non-cloudy day in the simulation period, the shade deficit was the difference between daily shade results from the baseline and restored vegetation conditions at each node. The cloud cover data for the modeling period included only two completely cloudless days (August 18 and 19). A third “mostly clear” day (July 25) was cloudless for 21h. Figure 6-4 presents the differences in daily average shade results between the two scenarios for July 25 and August 18. The within-day spatial variability along the model extent indicates a greater shade deficit upstream versus downstream.

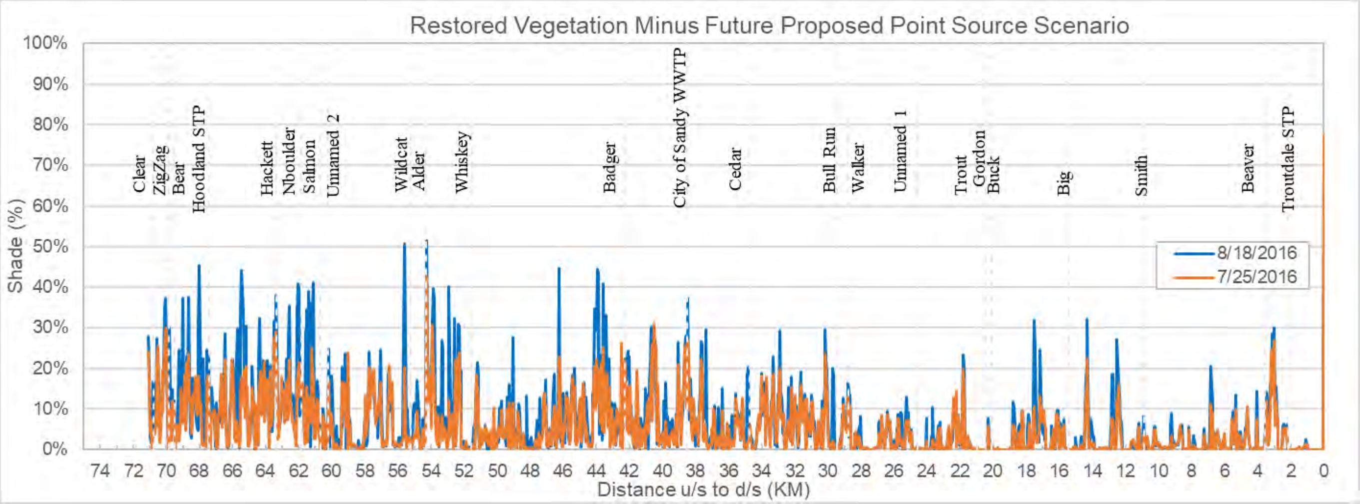


Figure 6-4. Difference in effective shade between the Sandy River future proposed point source and restored vegetation scenarios.

7.0 NO DAMS SCENARIO

The no dams scenario estimates the Sandy River stream temperatures without the Bull Run Dam and Reservoirs Number One and Number Two. This scenario is built upon the future proposed point source scenario; the only changes made to the Sandy River model under this scenario were setting the Bull Run River tributary input to the Bull Run River W-2 no dam scenario temperature and flow outputs provided by the City of Portland (Figure 7-1).

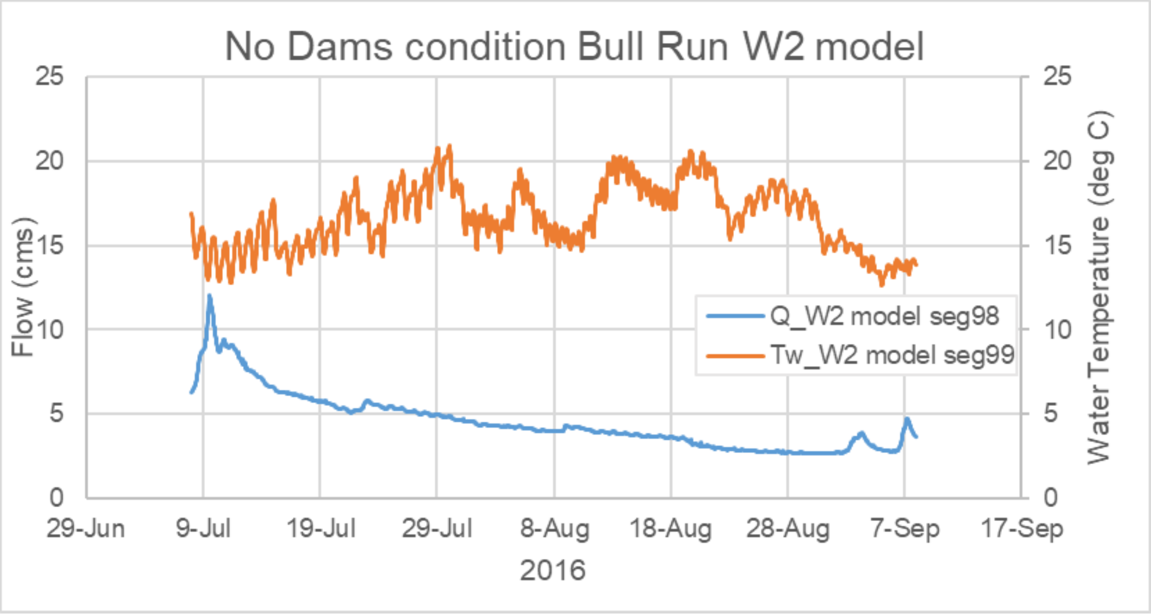


Figure 7-1. No dams condition Bull Run W2 model output (downstream boundary).

For each Sandy River node throughout the model period, a time-series of 7DADM temperature changes due to dam operation was calculated as the difference in 7DADM temperature between the future proposed point source and the no dams scenarios. Figure 7-2 shows the modeled minimum, maximum and mean 7DADM differences (impacts) at each model node. Note that the difference is calculated only when the no dams scenario temperature exceeds the BBNC.

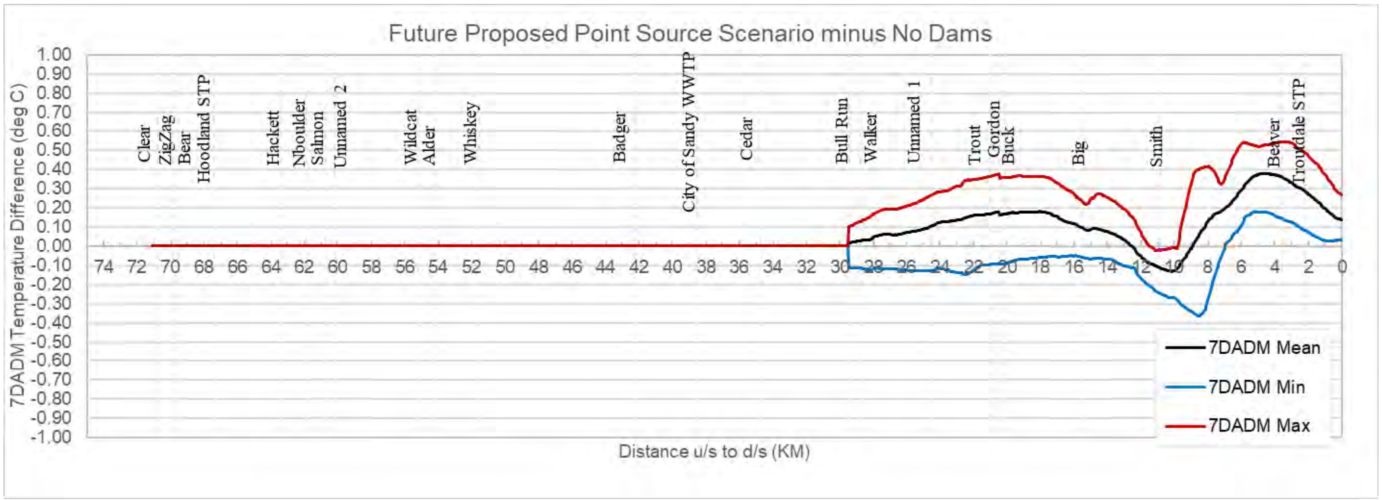


Figure 7-2. 7DADM temperature differences between the Sandy River future proposed point source and no dams scenarios.

Positive 7DADM differences indicates the 7DADM increase (heating effect) that the dam operations have on the Sandy River. Negative differences indicate that the dam operations have a relative cooling effect at the relevant nodes and days. For most segments, the mean 7DADM over the model period increased due to dam operations, while cooling occurred on average at some locations, e.g., between RKM 12.5 and RKM 9. The combined and temporally variable incoming flows and temperatures from the upstream Sandy River, the Bull Run River, and the downstream Sandy River tributaries likely resulted in these spatially and temporally variable Sandy River temperature results below the Bull Run River. Figure 7-3 shows the temporal variation along the Sandy River system (segments) during the model period. As evident in Figure 7-3, some locations showed cooling and warming at different times during the model period.

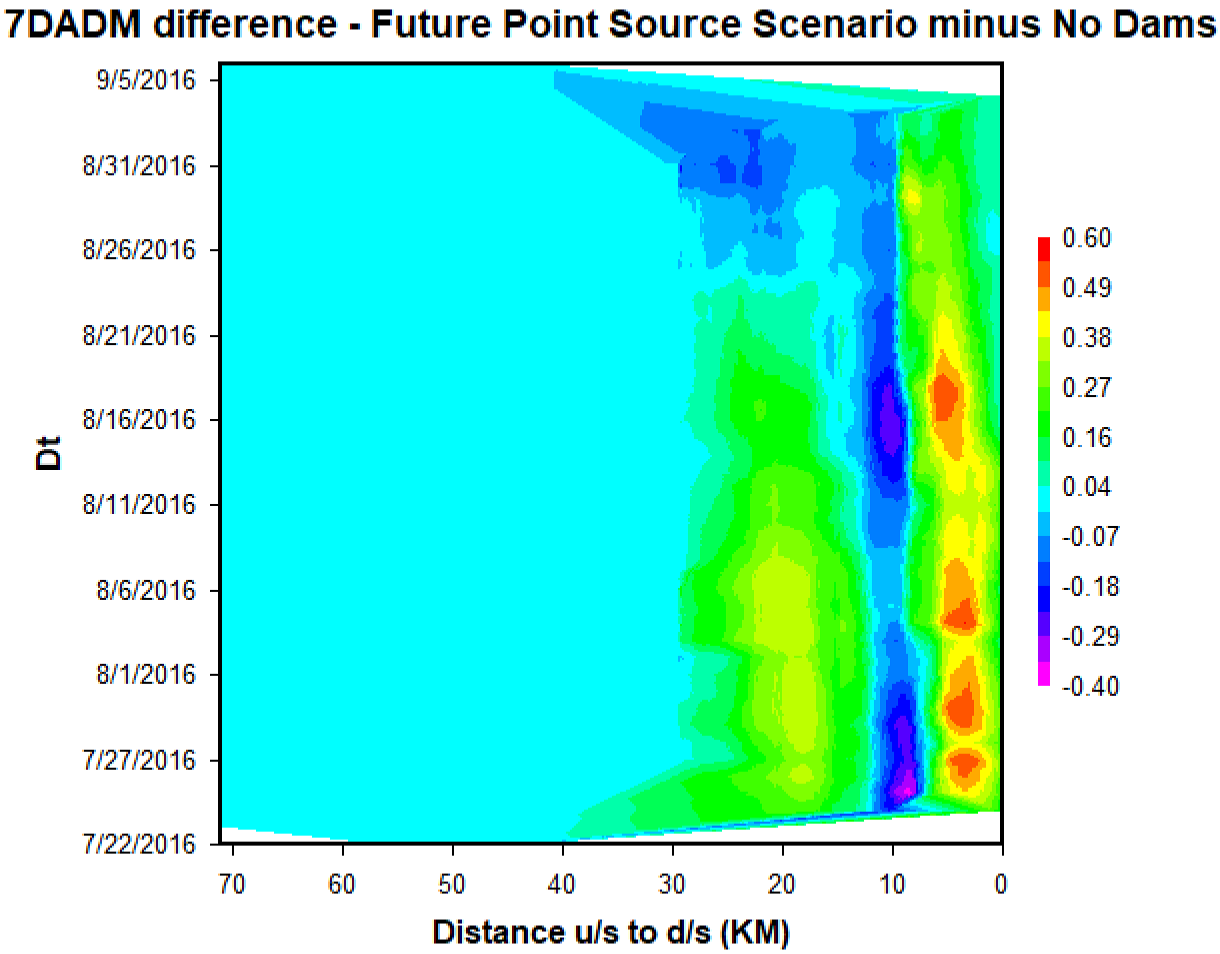


Figure 7-3. Spatial and temporal variation in the temperature difference for the no dams scenario along Sandy River.

The Bull Run flows and temperature from the existing condition W2 model and no dams scenario W2 model were also plotted to see how the conditions vary in the boundaries with and without dams (Figure 7-4 and Figure 7-5). Generally, the no dams flows were greater than the existing condition flows. The plots indicate that during the first half of July, the daily maximum temperatures under the no dams scenario were similar to or lower than the existing condition; were generally higher than the existing condition from around mid-July through August, especially during the last week of August; and were lower or similar to the existing condition for the remaining model period. The nighttime minimum temperatures, in contrast, were substantially lower in the no dams scenario for most of the simulation period.

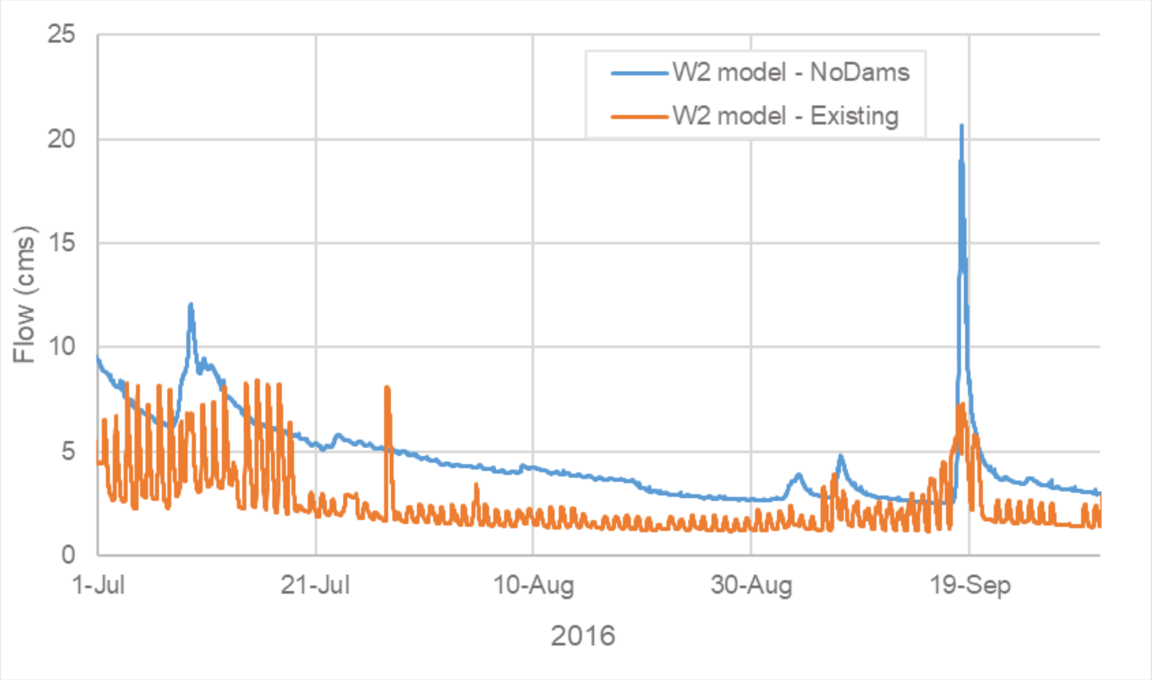


Figure 7-4. Modeled Bull Run existing condition and no dams condition flows.

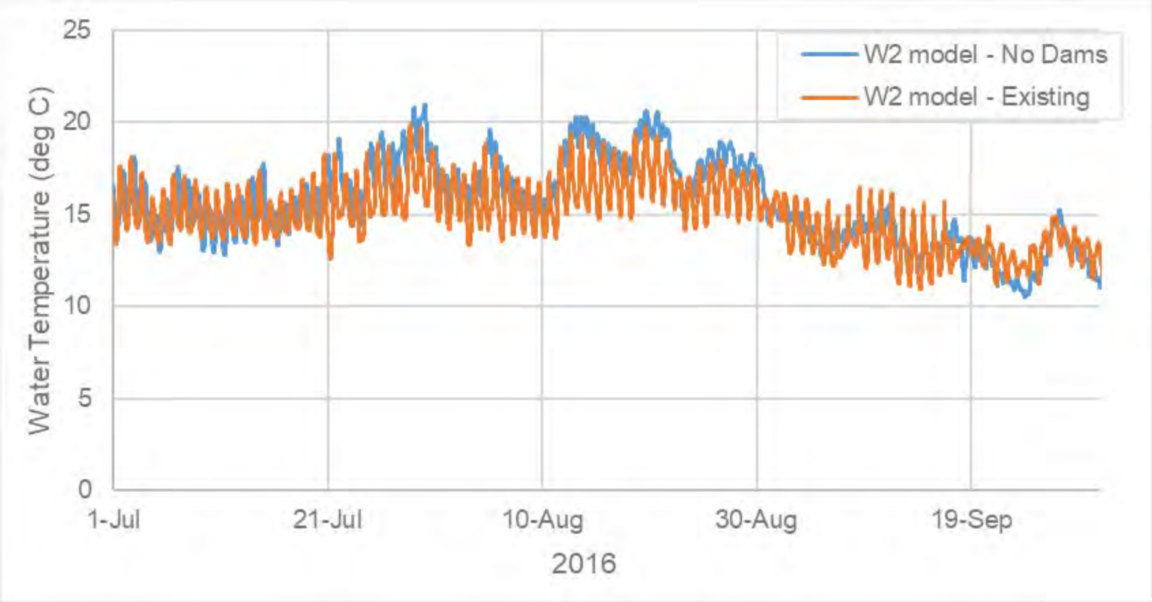


Figure 7-5. Modeled Bull Run existing condition and no dams condition water temperature.

8.0 RESTORED STREAM FLOW SCENARIO

This scenario evaluates the stream temperature response with the stream flow set to the median monthly natural stream flow. This scenario does not include point sources (effluent flows were set to zero). USGS StreamStats Application was used to generate a monthly (July, August, and September) Flow-Duration Statistics Report for the modeled stream at a reference point located within the model extent.

The chosen reference point was located at the most downstream USGS flow gage on the Sandy River closest to the mouth, which was USGS14142500 – Sandy River below Bull Run. The USGS StreamStats website was queried, and a flow statistics report was generated at this USGS station. Table 3 shows the 50th percentile flows for the summer months used in the modeling time period.

Table 3. Monthly Median (50th percentile duration) Flow-Duration Statistics Report from StreamStats.

Month	**Flow cfs [cms]**
July	1,020 [28.88]
August	557 [15.77]
September	483 [13.68]

The boundary condition and tributary flow inputs for the restored stream flow model scenario are calculated using Equation 1, shown below.

The restored stream flow scenario tributary flow rate at timestep *i,* assuming the relative flow contribution is the same as the current condition model.

$$\boldsymbol{Q_{Ni\_trib} = Q_{Ci\_trib} \cdot \left(1 + \frac{Q_{N\_ref} - Q_{Ci\_ref}}{Q_{Ci\_ref}}\right)} \qquad \text{Equation 1}$$

where,

Q_{Ni_trib} = The restored stream flow scenario tributary flow rate at timestep *i.*

Q_{Ci_trib} = The baseline condition tributary flow rate at timestep *i.*.

Q_{N_ref} = The monthly median natural flow rate at the reference location as derived from USGS StreamStats (Risley et al 2008).

Q_{Ci_ref} = The current condition flow rate at the reference location at timestep *i.*

Equation 1 assumes that the relative contribution is the same as the baseline conditions model scenario.

Figure 8-1 shows the maximum 7DADM temperature difference between the future point source scenario and the restored flow scenario. Note that the difference is calculated only when the restored stream flow scenario temperature exceeds the BBNC.

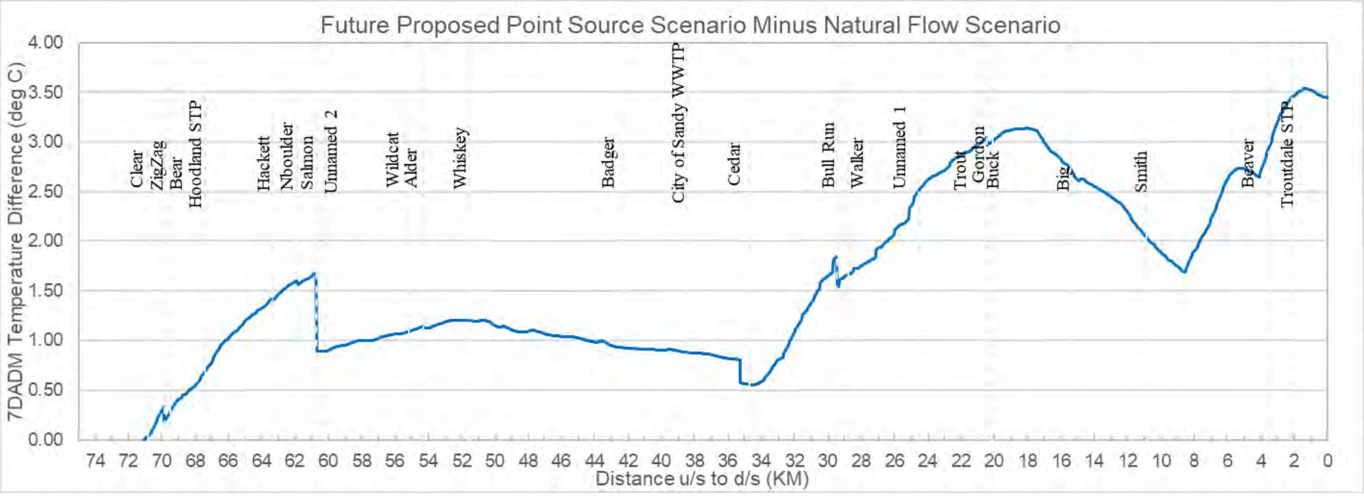


Figure 8-1. Impact due to restored stream flow scenario - maximum 7DADM difference.

9.0 WATER WITHDRAWAL SCENARIO

The water withdrawal scenario evaluates the temperature response assuming some percent consumptive flow reduction at the reference site chosen for the restored stream flow scenario. The reference site is located at RKM 29.1. This scenario does not include point sources (effluent flow was set to zero). The percent consumptive use is adjusted as needed to determine the flow reduction at the reference point that would attain the 0.3 °C HUA and the portion of the HUA that is allocated to water withdrawals (default is 0.05 °C). The tributary and boundary condition flow inputs are calculated using Equation 2.

The restored stream flow scenario tributary flow rate at timestep *i* assuming the relative flow contribution is the same as the current condition model.

$$\boldsymbol{Q_{Wi\_trib} = Q_{Ni\_trib} \cdot \left(1 - \frac{U}{100}\right)} \qquad \text{Equation 2}$$

where,

$Q_{Wi\_trib} =$ The water withdrawal flow scenario tributary flow rate at timestep *i.*

$Q_{Ni\_trib} =$ The restored stream flow scenario tributary flow rate at timestep *i.*

$U =$ The percent flow rate reduction at the reference site.

Iterative model runs were conducted by applying a percent flow rate reduction to all the restored stream flow of the tributaries and evaluating the resulting simulated temperatures at the reference point. Reductions of 9.70 percent (Figure 9-1) and 1.75 percent (Figure 9-2) were required to attain the 0.3 °C and 0.05 °C HUA respectively. The 7DADM warming from water withdrawals was determined by finding the difference in 7DADM temperature between the water withdrawal scenario and the restored stream flow model scenario.

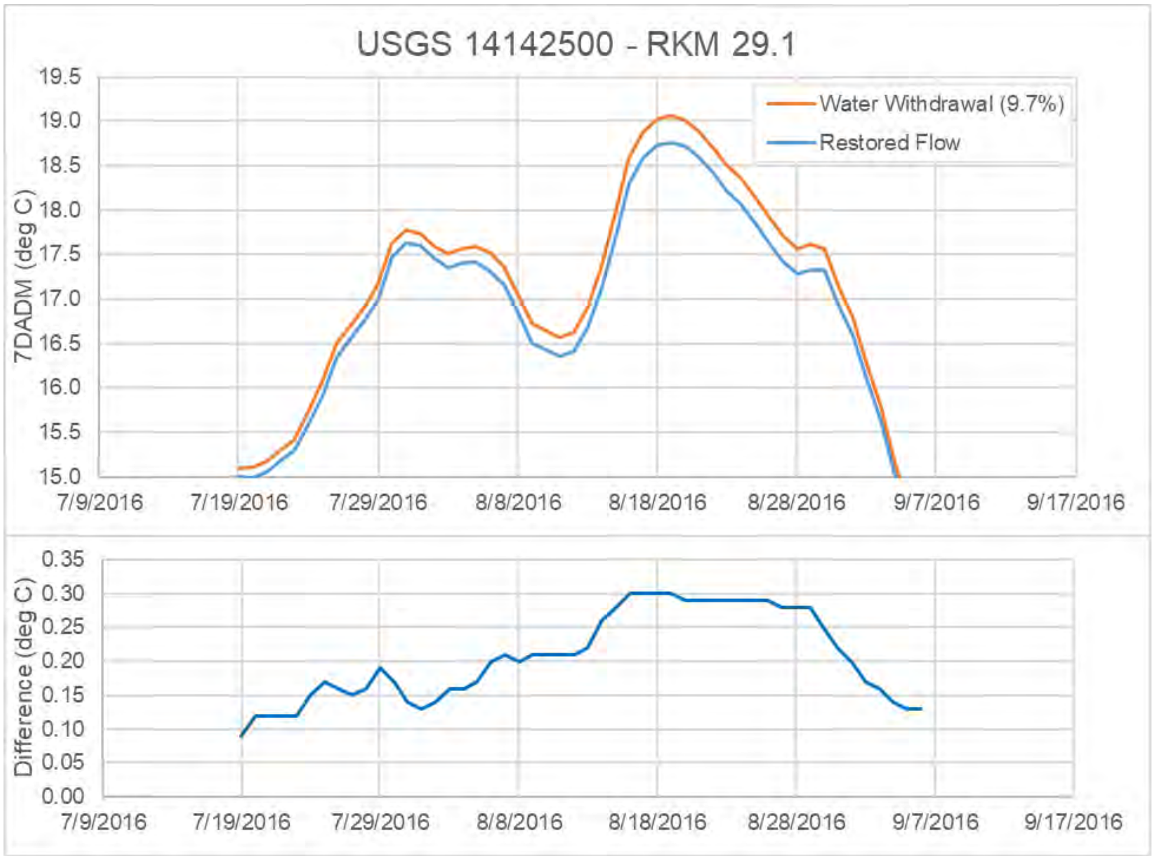


Figure 9-1. Restored Flow and Resulting water temperatures after 9.70 precent reduction to meet the 0.3 °C. HUA.

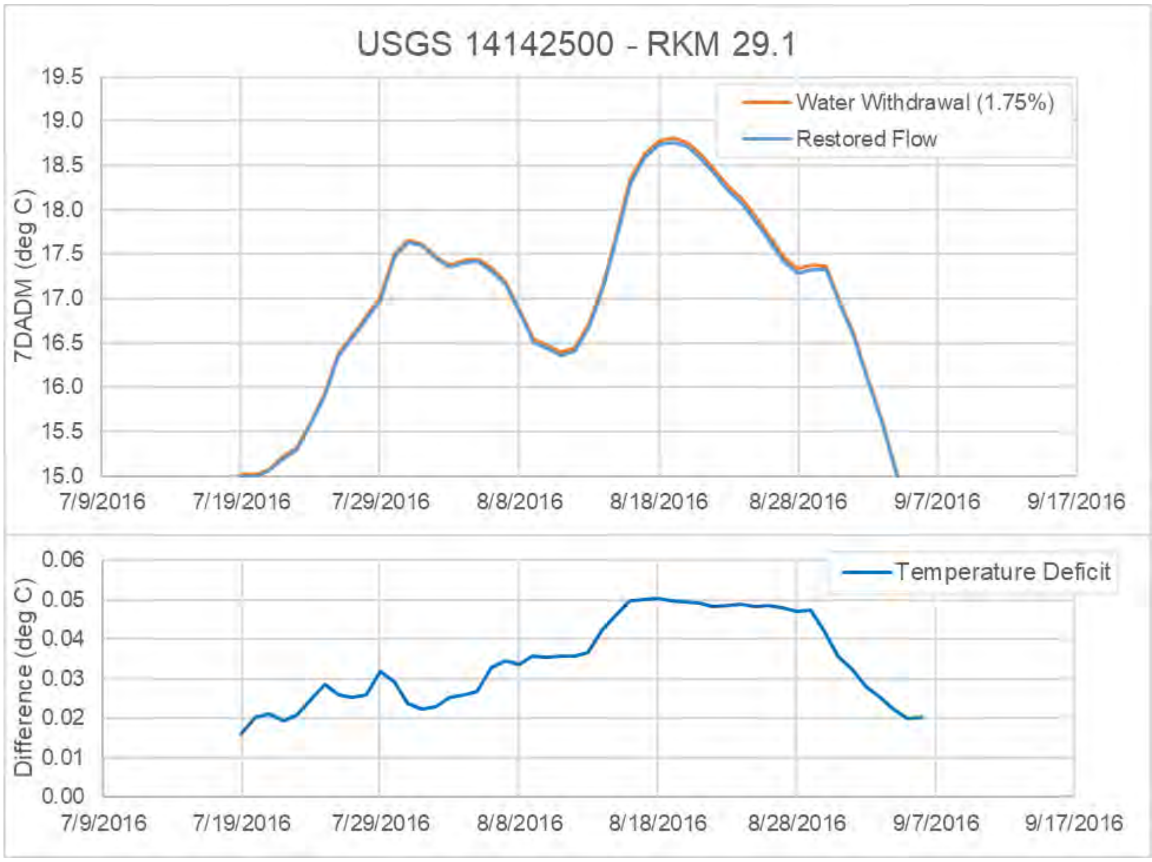


Figure 9-2. Restored Flow and Resulting water temperatures after 1.75 precent reduction to meet the 0.05 HUA allocated to water withdrawal.

10.0 BACKGROUND CONDITION SCENARIO

This scenario evaluates the stream temperature response from background sources only. Background sources include all sources of thermal loading not originating from human activities. This scenario is built upon the **restored vegetation scenario but with all point source discharges set to zero**. The Bull Run inputs for this scenario were set based on the no dams plus restored vegetation, flow and temperatures, provided by the City of Portland. Figure 10-1 shows the flow and water temperature extracted from the last segment of the Bull Run no dams plus restored vegetation condition W2 model provided by the City of Portland. Salmon River inputs were set based on the Salmon River restored vegetation Heat Source model outputs for flow and temperature provided by DEQ (Figure 6-1).

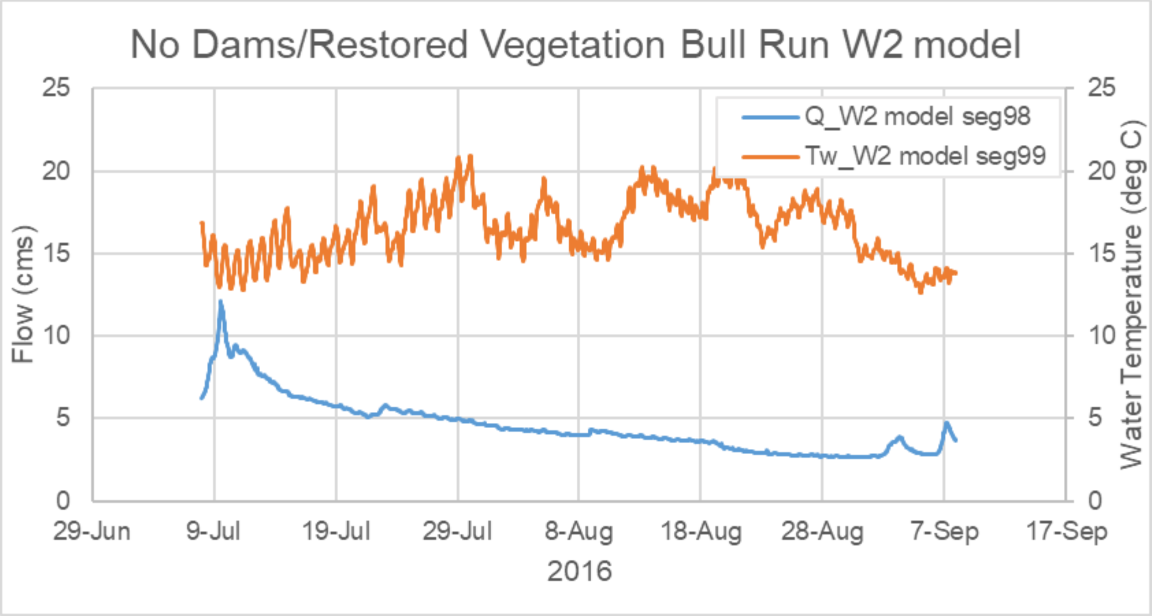


Figure 10-1. No dams/restored vegetation condition Bull Run W2 model output.

The background condition scenario was developed to estimate how much background excess load there is relative to anthropogenic load. The maximum 7DADM warming due to the background conditions was determined by finding the difference in 7DADM temperature between the future proposed point source scenario conditions and the background condition model scenarios. Figure 10-2 shows the warming impact from background conditions. A maximum impact of 3.17 °C is seen at the Troutdale STP location. Note that the difference is calculated only when the background condition scenario temperature exceeds the BBNC. An artifact of this can be seen in the longitudinal plots from RKM 41.25 to RKM 30.95 where the warming is shown as zero, since the temperature during the model simulation period did not exceed the BBNC because the BBNC increases from 16 to 18 °C from RKM 42.25 onwards (Figure 1-1)

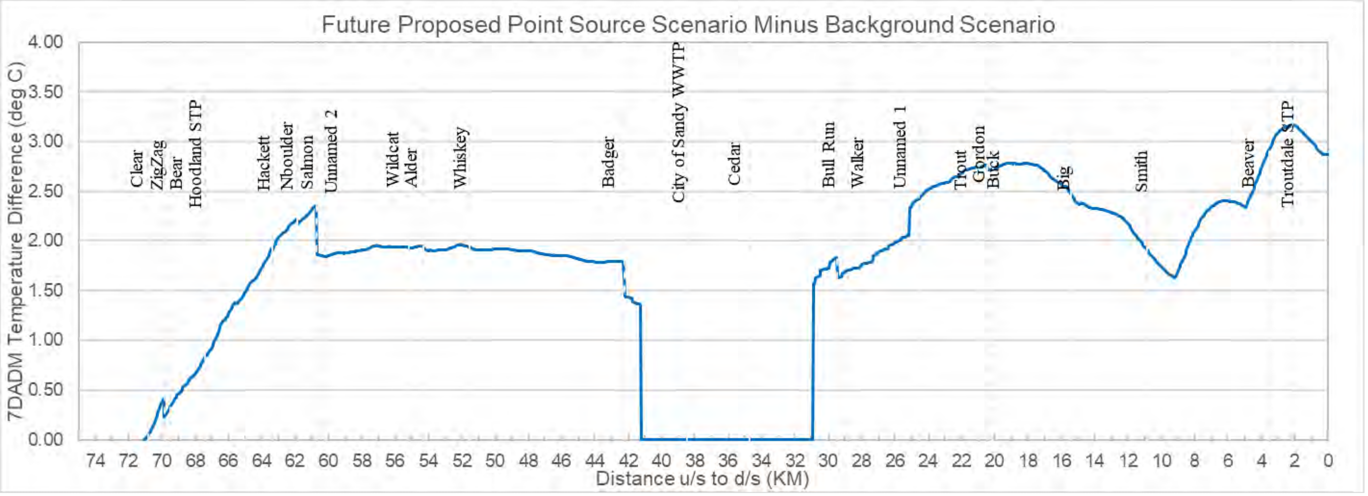


Figure 10-2. Stream temperature warming response from background conditions - maximum 7DADM difference.

11.0 SCENARIO COMPARISONS

Table 4. Scenario comparisons, effective shade results

			Shade Gap (%)	**Stream km Assessed**	**Stream km shade gap (%)**			
					0-15%	**16-25%**	**26-50%**	**51-100%**
Extent	**CCC**	**RV_A**						
Study Area	20	27	7	71.1	62	6	3.1	0
City of Portland	9	16	7	0.7	0.6	0.1	0	0
City of Sandy	26	30	4	0.7	0.6	0	0	0
City of Troutdale	14	20	6	3.2	2.9	0.2	0.1	0
Clackamas Cty.	19	30	11	18.3	13.1	3.3	1.9	0
Multnomah Cty.	17	20	3	2.3	2.2	0.1	0	0
ODA	24	29	5	0.9	0.8	0.1	0	0
ODFW	23	28	5	1.2	1.2	0	0	0
ODF - Private	20	25	5	25.5	23.6	1.2	0.7	0
OPRD	5	7	2	0.8	0.8	0	0	0
Port of Portland	3	9	6	0.7	0.7	0	0	0
State of Oregon	14	18	4	0.4	0.4	0	0	0
US BLM	28	33	5	14.3	13	0.9	0.4	0
USFS	3	7	4	1	1	0	0	0
US Gov't.	17	18	1	0.1	0.1	0	0	0
	1	2	1	1	1	0	0	0
Extent	**RV_B**	**RV_A**	**RV_B– Shade Results Tentative**					
Study Area	27	27	0	71.1	71	0.1	0	0
City of Portland	16	16	0	0.7	0.7	0	0	0
City of Sandy	30	30	0	0.7	0.7	0	0	0
City of Troutdale	19	20	1	3.2	3.2	0	0	0
Clackamas Cty.	30	30	0	18.3	18.3	0	0	0
Multnomah Cty.	19	20	1	2.3	2.3	0	0	0
ODA	29	29	0	0.9	0.9	0	0	0
ODFW	28	28	0	1.2	1.2	0	0	0
ODF - Private	25	25	0	25.5	25.4	0	0	0
OPRD	7	7	0	0.8	0.8	0	0	0
Port of Portland	9	9	0	0.7	0.7	0	0	0
State of Oregon	18	18	0	0.4	0.4	0	0	0
US BLM	33	33	0	14.3	14.3	0	0	0
USFS	7	7	0	1	1	0	0	0
US Gov't.	18	18	0	0.1	0.1	0	0	0
	2	2	0	1	1	0	0	0
Extent	**Topo**	**CCC**						
Study Area	7	20	13	71.1	47.6	12.1	10.4	1
City of Portland	4	9	5	0.7	0.7	0	0	0
City of Sandy	8	26	18	0.7	0.3	0.2	0.1	0
City of Troutdale	7	14	7	3.2	3	0.2	0	0
Clackamas Cty.	4	19	15	18.3	10.6	4.8	2.9	0
Multnomah Cty.	9	17	8	2.3	2.1	0.1	0	0
ODA	12	24	12	0.9	0.6	0.3	0	0
ODFW	5	23	18	1.2	0.6	0.4	0.2	0
ODF - Private	8	20	12	25.5	17.8	4.8	2.7	0.2
OPRD	4	5	1	0.8	0.8	0	0	0
Port of Portland	2	3	1	0.7	0.7	0	0	0
State of Oregon	4	14	10	0.4	0.4	0	0	0
US BLM	9	28	19	14.3	8	1.2	4.2	0.8
USFS	1	3	2	1	1	0	0	0
US Gov't.	9	17	8	0.1	0.1	0	0	0
	1	1	0	1	1	0	0	0

Table 5. Scenario comparisons, temperature results

Scenario	Value Type	Location	7DADM			Daily Max. Temp.		
			Model km	Date	WT (°C)	Model km	Date	WT (°C)
Current Cond.	CCC	Mouth	0	08/20/2016	23.08	0	08/18/2016	23.96
Restored Vegetation (RV_A)	RV_A	Mouth	0	08/20/2016	22.65	0	08/18/2016	23.5
	RV_A	Ref.	29.10	08/20/2016	19.59	29.10	07/29/2016	20.31
	RV_A vs. CCC	Mouth	0.00	09/01/2016	0.5	0.00	08/19/2016	0.56
	RV_A vs. CCC	POMI	61.15	08/29/2016	1.04	61.60	08/28/2016	1.13
	RV_A vs. CCC	Ref.	NEED	NEED	NEED	NEED	NEED	NEED
Restored Vegetation, Modified (RV_B) **Results Tentative**	RV_B	Mouth	0	08/20/2016	22.66	0	08/18/2016	23.51
	RV_B	Ref.	29.10	08/20/2016	19.60	29.10	07/29/2016	20.31
	RV_A vs. RV_B	Mouth	0.00	08/22/2016	0.02	0.00	08/19/2016	0.04
	RV_A vs. RV_B	POMI	3.0	08/18/2016	0.08	NEED	08/17/2016	0.11
	RV_A vs. RV_B	Ref.	29.10	07/20/2016	0.01	29.10	07/13/2016	0.00
Topography	Topo	Mouth	0	08/20/2016	23.71	0	08/18/2016	24.62
	Topo vs. CCC	Mouth	0	09/02/2016	0.81	0	09/02/2016	0.87
	Topo vs. CCC	POMI	39.3	08/29/2016	1.67	39.05	08/24/2016	1.85
Tributary Temperatures (TT)	TT	Mouth						
	TT vs. CCC	Mouth						
	TT vs. CCC	POMI						
Natural Flow	Natural Flow	Mouth	0	08/20/2016	21.54	0	08/18/2016	22
	Natural Flow	Ref.	29.1	08/19/2016	19.41	29.1	08/14/2016	20
	Nat. Flow vs. 2% WD	Mouth	0	08/14/2016	0.09	0	08/10/2016	0.11
	Nat. Flow vs. 2% WD	POMI	18.5	08/18/2016	0.11	Need	08/24/2016	0.12
	Nat. Flow vs. 2% WD	Ref.	29.1	08/14/2016	0.04	29.1	07/28/2016	0.05
Water Withdrawals (2% Consumptive)	WDs 2%	Mouth	0	08/19/2016	21.62	0	08/18/2016	22.11
	WDs 2%	Ref.	29.1	08/19/2016	19.45	29.1	08/14/2016	20.04
No Point Sources	No Point Sources	Mouth	0	08/20/2016	23.02	0	08/18/2016	23.89
WLAs	WLAs	Mouth	0	08/20/2016	23.09	0	08/18/2016	23.96
	WLAs vs. No PSs	Mouth	0	09/06/2016	0.16	0	09/04/2016	0.19
	WLAs vs. No PSs	POMI	41.1	08/23/2016	0.26	58.4	07/15/2016	-0.77
	WLAs vs. CCC	Mouth	0	07/19/2016	-0.10	0	07/19/2016	-0.12
	WLAs vs. CCC	POMI	34.75	09/06/2016	-0.13	NEED	09/05/2016	-0.15

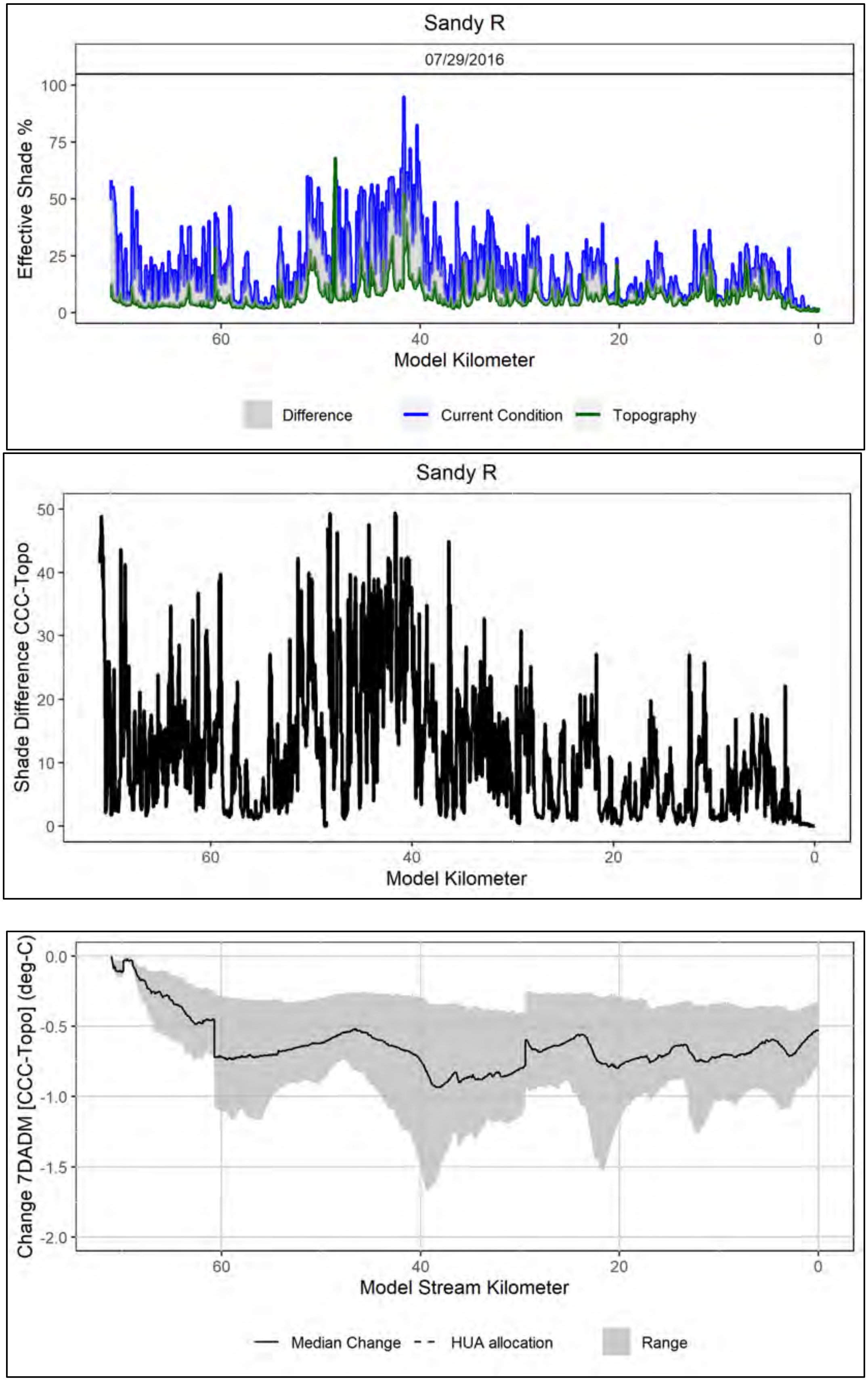


Figure 28. Topography scenario results vs. CCC.

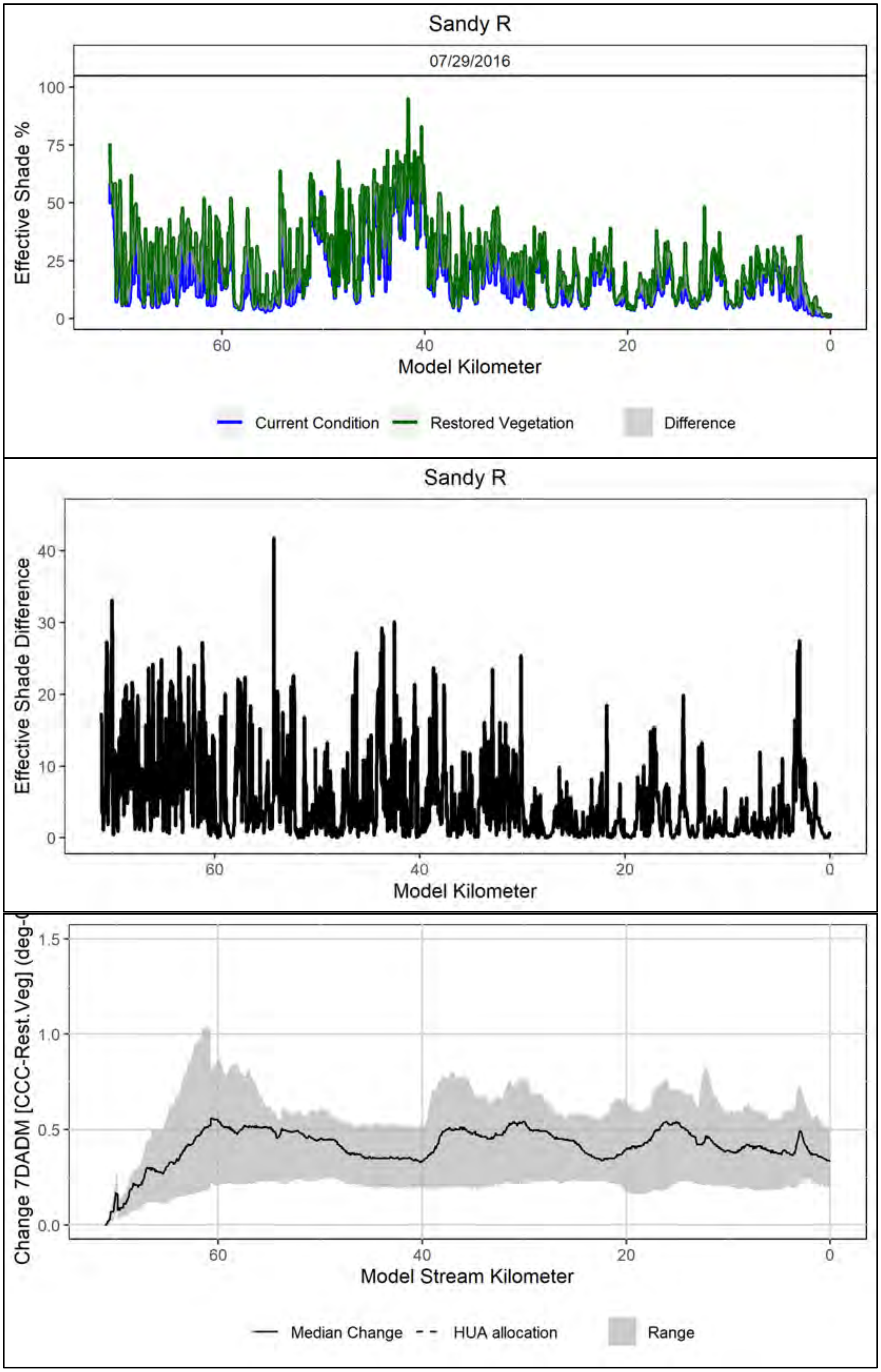


Figure 29. Restored vegetation A vs. CCC results.

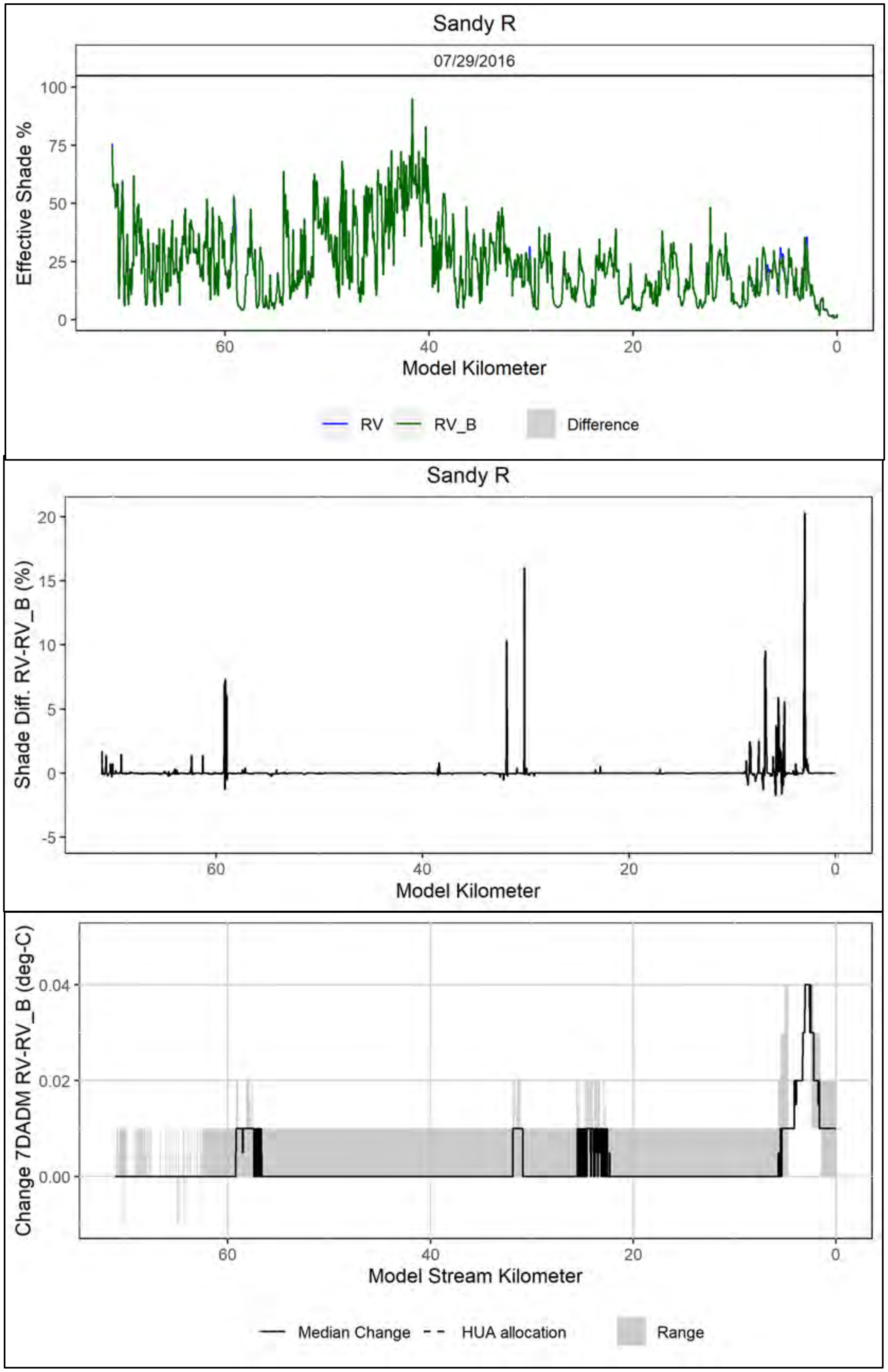


Figure 30. Restored vegetation A vs. Restored vegetation B results - PROVISIONAL.

12.0 REFERENCES

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Appendix D

Bull Run River (USGS 14138850 to confluence with Sandy River) Temperature Model Report

DRAFT

PWB Documentation – Benjamin Beal

Date: November, 2022

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1. Overview

This document contains changes made to the Middle River model and Lower River model of the Bull Run River in CEQUAL-W2. This report concentrates primarily on input data for the models, originally developed by Portland State University (Annear, Wells, & Evonuk, 1999). Changes to model boundary condition data was performed to update the model with the 2016 meteorological and flow conditions. Changes to the parameters of the models were in efforts to modernize aspects of the model to: increase model stability, bring parameter values within plausible bounds, and improve temperature calibration in 2016 in the Lower River model.

2. Available Data

2.1 Field Data

2.1.1 Continuous stream temperature

Continuous stream temperature data were used to:

- Evaluate if the waterbody achieves temperature water quality standards,
- As model input for tributary inflows or the upstream boundary condition,
- To assess model performance and goodness-of-fit by comparing the observed stream temperature data to the predicted stream temperature data

Continuous water temperature data was gathered from various sources for use in the 2016 model. Sources of stream temperature include:

1) PWB data temperature loggers at the diversion pool (location of headworks).
2) PWB temperature loggers at the Lamprey barrier (~300 ft downstream of the diversion pool).
3) PWB temperature loggers in the piping for the “south tower” (this is located inside the piping of the south tower which draws water from the lowest portion of reservoir two. The water is piped down past the diversion pool and is released into the Bull Run River ~250’ upstream of the lamprey barrier).
4) USGS temperature records from the stations: 14138850, 14139800, 14138900,14138870,14140020, and 14141500.
5) Three temporary in-situ probe installations located at: South Side Bridge (

Table 1. Stream temperature monitoring sites in the Bull Run supporting model development.

Monitoring Location ID	Monitoring Location Name	Latitude	Longitude	Source
14138850	Bull Run River near Multnomah Falls, OR	45°29'54"	122°00'40"	USGS
14139800	South Fork Bull Run River	45°26'41"	122°06'30"	USGS
14138900	North Fork Bull Run River	45°29'40"	122°02'05"	USGS
14138870	Fir Creek	45°28'49"	122°01'28"	USGS

Monitoring Location ID	Monitoring Location Name	Latitude	Longitude	Source
14141500	Little Sandy River	45°24'56"	122°10'13"	USGS
14140020	Larson’s Bridge	45°25'54.9"	122°11'39.2"	USGS
HDWTI024	Diversion Pool	45.449266	122.152702	PWB
HDWTI020	South Tower Wet Well	45.448601	122.146847	PWB
HDWTI025	Lamprey Barrier (primary)	45.448941	122.154977	PWB
HDWTI025B	Lamprey Barrier (backup)	45.448941	122.154977	PWB
PWB_BR_SS_BR	Bull Run South Side Bridge	45.437752	122.178867	PWB
PWB_BR_BWMN_BR	Bull Run Bowman’s Bridge	45.425093	122.216761	PWB
PWB_BR_DODGE	Bull Run at Dodge Park	45.443895	122.246630	PWB

2.1.2 Stream flow rate– continuous and instantaneous measurements

Continuous and instantaneous stream flow rates were collected by PWB/USGS at several sites during the 2016 model year. The measurements at these sites (Table A2 and Table A3) were used to support boundary condition flow inputs, and generation/validation of ungaged streamflows along the model domain.

Table 2. Continuous flow rate measurement sites in the Bull Run used to support model development.

Station ID	Station Name	Latitude	Longitude	Source
14138850	Bull Run River near Multnomah Falls, OR	45°29'54"	122°00'40"	USGS
14139800	South Fork Bull Run River	45°26'41"	122°06'30"	USGS
14138900	North Fork Bull Run River	45°29'40"	122°02'05"	USGS
14138870	Fir Creek	45°28'49"	122°01'28"	USGS
14141500	Little Sandy River	45°24'56"	122°10'13"	USGS
14140000	Bull Run River, Bull Run	45°26'14"	122°10'46"	USGS
HDWTI025	Lamprey Barrier (primary)	45.448941	122.154977	PWB

Table 3. Instantaneous flow rate measurements collected in the Bull Run used to support model development.

Site	Latitude	Longitude	Date	Time	Flow (cfs)
Bear Creek	45.486866	122.083788	Years 1979-1991	Various	Various
Deer Creek	45.491111	122.059411	Years 1979-1991	Various	Various
Cougar Creek	45.490428	122.061903	Years 1979-1991	Various	Various
Camp Creek	45.460585	122.099608	Years 1979-1991	Various	Various
Fivemile Creek	45.482657	122.092064	Years 1979-1991	Various	Various

2.1.3 Vegetation and habitat surveys

A vegetation survey was conducted along banks of the Bull Run River between headworks and the Sandy River in conjunction with the original development of the Lower River Model. Field data associated with this effort is no longer available, leaving only the compiled shade file for the Lower River Model as a product. It is understood that the level of effort and thoroughness put into this survey and the development of the shade file was very high, therefore we are using the shade file as is.

2.2 GIS and Remotely Sensed Data

2.2.1 Light Detection and Ranging (LiDAR)

Light Detection and Ranging (LiDAR) is a remote sensing method that uses pulses of light to calculate the elevation of ground and surface features with a high degree of accuracy and resolution. LiDAR data is used to develop high resolution digital surface models (DSM) and DEMs which can then be used to derive canopy height.

A 3 meter DEM of both bare earth and highest hit were used to establish vegetation heights and vegetation top elevations. This data was used in generating shading angles in the creation of the dynamic shading files.

2.2.2 Aerial Imagery

Aerial imagery was used to:

- Map stream features such as stream position, channel edges and wetted channel edges,
- Map near stream vegetation,
- Locate position of in-situ probes and stream gages and their relative location in the model domain.

2.3 Derived Data

Several datasets used for model setup were derived or sampled from landscape scale GIS data. Sampling density was user-defined and generally matched any GIS data resolution and accuracy. The derived parameters used in the stream temperature analysis were:

- Stream position and aspect
- Stream elevation and gradient
- Maximum topographic shade angles (Left and Right bank)
- Maximum vegetation shade elevations (Left and Right bank)
- Channel width
- Landcover classification and mapping

2.3.1 Stream Position and Channel Width

Stream position was estimated using the following steps:

Step 1. Stream geometry from the original rendition of the model (circa 2000) for the Lower and Middle river models were projected in a mapping tool (leaflet in R) based on length and angle of each segment, the linkage of segments in the W2 control file, and an estimated datum location (start point of the model) to achieve best fit between the model defined structure of the model and the readily available mapping of the stream from OpenMaps.

Step 2. Lengths and/or angles were adjusted the minimum possible to correct small errors in the original model stream geometry to generate a better fit.

Channel width was estimated using the following steps:

Step 1. Using aerial imagery, channel edges were digitized by hand in GIS.

Step 2. Using the corrected model segment lines from step 2.3.1 part 1, polygons were generated along the river with “tops” and “bottoms” based on the upstream and downstream locations of each stream segment from the model. The “sides” of the polygons are based on the left and right bank digitization of the stream in step 1.

Step 3. Area (in square meters) is calculated in GIS for every segment polygon generated in step 2, and the area is divided by the associated length of the stream segment (in meters) to generate the average channel width (in meters).

Figure 1: Example of digitized channel, flowline, and stream nodes.

2.3.2 Channel Bottom Width

Channel bottom width in CEQUAL-W2 is a user definable measurement. Bathymetry can be set at various vertical intervals to generate a triangular/trapezoidal shape. Original stream bathymetry in the models was coarse with vertical intervals of 1-2 meters and rather wide widths. This in general resulted in very wide and very thin wetted segments during the low flow portions of the model run. The shallow depths in the model appeared to be causing most of the model instability, which was keeping CEQUAL from completing a simulation, regardless of the maximum time step.

To combat this issue, the bathymetry was adjusted to represent a more trapezoidal shape by generating interpolated layers based on the original layer widths and vertical locations. The total number of vertical layers was set to 19 (KMZ) and the interval spacing in the Z direction for the layers was changed in order to increase the number of layers near the channel bottom and gradually increase the vertical interval spacing as the channel widens. This process in general creates many small layers on the bottom of the channel which appear to significantly assist in model stability during low flows.

During calibration, many different sets of vertical intervals were tested, with the final version providing good model stability for all years and scenarios tested as well as keeping the total number of layers small enough that the model does not take an unnecessarily long time to run. Below are the vertical layer intervals used in the final calibration, as well as several intervals sets that were tested, but not ultimately used. Note that for the Lower River Model, water body 4 uses the original bathymetry file from the PSU generation of the model. This is due to the somewhat odd bathymetry where a rather wide and deep plunge pool is connected to a relatively shallow and narrow active main channel.

Table 4: Vertical intervals for bathymetry files

Final Calibration		Test 1		Test 2		Test 3		Test 4	
Distance from BOT	**Interval**	**Distance from BOT**	**Interval**	**Distance from BOT**	**Interval**	**Distance from BOT**	**Interval**	**Distance from BOT**	**Interval**
0		0		0		0		0	
0.1	0.1	0.5	0.5	1	1	1	1	1	1
0.2	0.1	1	0.5	1.25	0.25	2	1	2	1
0.3	0.1	1.5	0.5	1.5	0.25	2.4	0.4	3	1
0.4	0.1	2	0.5	1.75	0.25	2.8	0.4	3.2	0.2
0.5	0.1	2.5	0.5	2	0.25	3.2	0.4	3.4	0.2
0.725	0.25	3	0.5	2.25	0.25	3.6	0.4	3.6	0.2
1	0.25	3.5	0.5	2.5	0.25	4	0.4	3.8	0.2
1.25	0.25	4	0.5	2.75	0.25	4.4	0.4	4	0.2
1.5	0.25	4.5	0.5	3	0.25	4.8	0.4	4.2	0.2
2	0.5	5	0.5	4	1	5.2	0.4	4.4	0.2
3	1	5.5	0.5	5	1	5.6	0.4	4.6	0.2
4	1	6	0.5	7	2	6	0.4	5	0.4
6	2	8	2	9	2	8	2	6	1
8	2	12	4	12	3	11	3	10	4

10	2	16	4	16	4	15	4	14	4
14	4	20	4	20	4	19	4	18	4
18	4	24	4	24	4	24	5	24	6

Stream Elevation and Gradient

Stream elevation and stream gradient were derived from the original PSU model, no adjustments were made to the elevation/gradient of EBOT (the bottom elevation of the channel) nor the slope of the channel. In some cases, slight adjustments were made to the length of a channel segment in order to bring the channel geometry into agreement with modern mapping of the stream. In these cases, the slope was not adjusted, nor were the EBOT values adjusted. This will have resulted in slightly different gradients (SLOPE) than the original PSU values.

More important than the SLOPE values are the SLOPEC values which are effectively the hydraulic grade line and has a substantial impact on the velocity of the flow. This value was changed considerably and served as a tuning factor for the model. By using a conservative tracer in the model, concentrations of tracer where released coinciding with the release of cold water pulses during the 2016 calibration. Due to considerable effort and experience with sending cold water down the Bull Run between Headworks and Larson’s bridge, PWB has developed approximate times of travel for pulses of cold water relative to the quantity of water released. Therefore, by measuring the model output of conservative tracer and calculating the time between half of the model release at headworks, and half of the tracer reaching Larson’s bridge, a time of travel is computed.

Several changes were made to the model associated with trying to improve the time of travel. First, due to changing the manning’s n values from the original values (as high as 0.21) down to 0.07 based on the recommendation by TetraTech in their review of the model, the velocity of the water increased greatly. To slow the water back down, the SlopeC values were reduced across the model domain in steps to attempt to match the timing between Headworks and Larson’s bridge tracer timing to that of our expected tracer timings. During this it was additionally discovered that the internal weirs which serve as a pool/riffle control in the model were causing a sort of damming of cold water within the channel. This was discovered by calculating the conservative tracer travel time between every segment and noticing that where some of these internal weirs existed, the time of travel would take exceptionally long moving between two segments split by a weir. To deal with this issue, the top elevation of the weir was gradually dropped by 0.5m at a time until the effect to the tracer timing was no longer considered to be erroneous. SlopeC values were dropped down to their current value of 0.0016 after a significant number of calibration runs using this iterative process of altering internal weirs and SlopeC values while keeping Manning’s n values constant.

Figure 2 below demonstrates an example of some results of the conservative tracer tests showing the tracer timing using the original model calibration (blue) alongside more modern versions of the model (green and red). Note the effect of internal weirs between segments 1&2, 4&6, and 9&10 from the original model calibration generating very large jumps in travel time (due to the internal weirs).

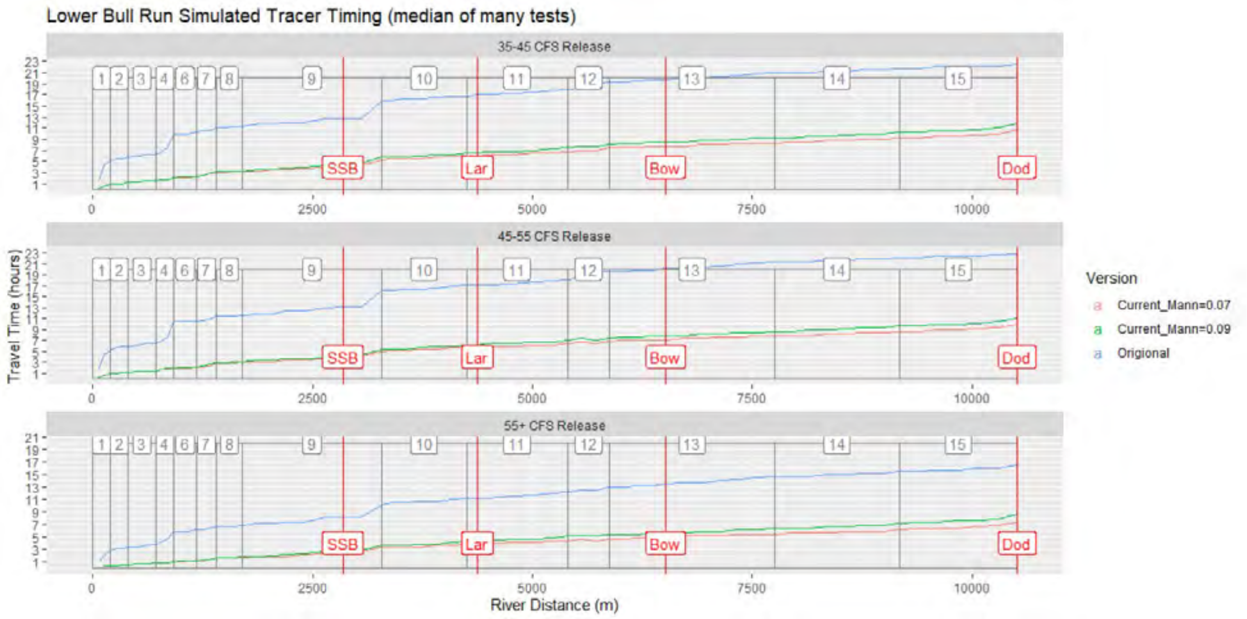


Figure 2: Examples of 2016 simulated tracer tests on different versions of the Lower River model

2.3.3 Topographic Shade Angles

The topographic shade angle represents the vertical angle to the highest topographic feature as measured from a flat horizon. At this angle and smaller the topographic feature will cast a shadow over the stream node as the sun moves behind it. Topographic shade angle was calculated using **Equation A2** below using sampled geometry statistics from Arcmap and solving for maximum angles of effect in R. Elevations were sampled from (Sciences, 2014). The maximum topographic shade angle in each direction for each stream node was found by sampling every raster cell out as far as 1000m in 18 directions (20 degree vectors) from each stream node.

$$\theta_T = \tan^{-1}\left(\frac{Z_T - Z_S}{d}\right)$$

Equation A1

where,

$\theta_T =$ The topographic shade angle (degrees)

$Z_T =$ The elevation (meters) at the topographic feature.

$Z_S =$ The elevation (meters) at the stream node.

$d =$ Horizontal distance (meters) from the stream node to the topographic feature.

2.3.4 Vegetation Shade Angles

The vegetation shade angle represents the vertical angle to the highest vegetation feature as measured from a flat horizon. At this angle and smaller the vegetation feature will cast a shadow over the stream node as the sun moves behind it. Vegetation shade angle was calculated using **Equation A2** above using sampled geometry statistics from Arcmap and solving for maximum angles of effect in R. Elevations were sampled from (Sciences, 2014). The maximum vegetation shade angle was computed for both left bank and right bank for each stream segment by sampling 3m wide polygon bands which conform to the shape of the shoreline and extend away from the stream. Vegetation was sampled out to 100m to find the highest vertical angle.

2.3.5 Land Cover Mapping

2.3.5.1 Modified No Dam DEM

A terrain dataset of Reservoirs 1 and 2 was created from bathymetry elevation data (Associates, 1991) and air borne lidar point cloud data (Sciences, 2014). The two reservoir terrain datasets were combined to create a continuous elevation model from Station 18 to Diversion Pool as a 3-ft grid in NAVD88. Dam structures were removed from landscape to reconstruct the river channel and to calculate shading in the Restored Condition and No Dam scenarios. The DEM was modified by hand digitizing polygons over the dams that were referenced to adjacent 10-ft contours. Each polygon was assigned an elevation and rasterized to create a modifier grid. The modifier grid was smoothed using local filters and then combined with the continuous DEM using conditional logic. The resulting modified DEM contains stair-step artifacts where the dams were located and is considered a rough approximation, but suitable for the scale of modeling.

2.3.5.2 Historic River Channel

The inundated historic channel centerline of the Bull Run River was hand digitized from the (Associates, 1991) point cloud by connecting the lowest value of each horizontal transect. The channel bottom elevations were interpolated from the reservoir bathymetry DEM. Historical maps were referenced to confirm the approximate river channel. ArcHydro Tools were applied to the modified DEM for additional confirmation of channel flow, and to identify sinks within the DEM. Minor adjustments were applied to the stream centerline based on the confirmation sources.

The riverbanks were approximated by creating a Relative Elevation Model (REM) using the Inverse Distance Weighting method. The REM is a detrended DEM based on the elevation of the stream centerline. A riverbank contour line was derived from the REM at an elevation that matched the channel bank above the influence of Dam 1. The left and right banks were hand digitized from the riverbank contour line to generalize and adjust areas around the dam. A polygon was created from the riverbank lines to represent the historic river channel.

2.3.5.3 Land Cover for Restored Conditions and No Dam

The Restored Conditions land cover codes were assigned using a combination of DEQ land cover restoration codes and the historical river channel polygon. DEQ provided a table with typical land cover code transitions from Current Conditions to Restored Conditions. This table was used to populate an attribute field of restored conditions land cover codes (RC_LCC) that are maintained separately from the current condition codes (CC_LCC). Geometry for the dam structures and areas inundated by the reservoirs were added by overlaying the historic river polygon with the land cover polygons. The new polygons were assigned a Restored Condition land cover code using nearby restored land cover.

The No Dam scenario is a combination of the Current Conditions and Restored Conditions. Two additional attribute fields were added to combine these fields. A dam filter field identified dam structures and reservoir inundated polygons (Dam Filter= ‘Yes’). The second field stored the No Dam land cover codes (ND_LCC) which were assigned using conditional logic (where: RC_LCC when Dam Filter is ‘Yes’, otherwise is CC_LCC).

2.3.6 Derived Tributary Stream Flow

Derived Tributary Stream Flows follows the process developed by PSU found in pages 61,62, & 67 (Annear, Wells, & Evonuk, 1999).

2.3.7 Derived Tributary Temperatures

Derived Tributary Stream Temperatures follows the process developed by PSU found in pages 67&68 (Annear, Wells, & Evonuk, 1999).

3. Model setup and calibration

3.1 Lower & Middle River Model

3.1.1 Model extent

Model extent for the Lower River model runs from present day headworks at the location of the diversion pool down to the confluence of the Sandy River. Model extent for the Middle River model runs from USGS station 14138850 on the Bull Run River down to present day headworks.

3.1.2 Spatial and temporal resolution

Spatial resolution of the lateral (length relative to the direction of flow) varies between about 50m and 250m per segment. Vertical resolution varies less for the entire model (except for waterbody 4, see section 2.3.2 for more details). Vertical resolution is between 0.1m and 4.0m. Temporal resolution for boundary condition data is hourly.

3.1.3 Meteorological inputs

Meteorological inputs are generated using a variety of different sensors and methods. See each subsection for an explanation.

Cloud data was extrapolated from PDX Airport area ASOS/AWOS Surface Weather Observation Station (KTTD). This entails converting descriptive cloud coverages from different samplings of the atmosphere (such as clear, overcast, cloudy, etc), and converting those to a density by using the highest density for any given timestep.

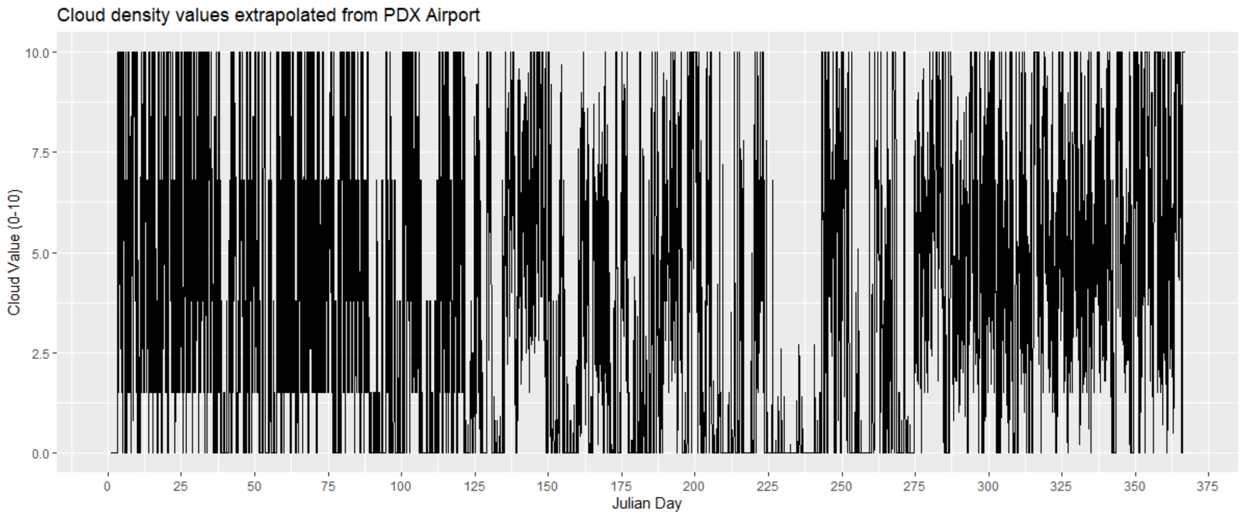


Figure 3: Cloud Data from near PDX airport

Air Temperature data comes from a meteorological station located on top of the dam at reservoir 2 which collects air temperature, relative humidity, wind speed, wind direction, and solar radiation. Air temperature data is screened for outliers. Single outliers are removed and replaced with linear interpolation.

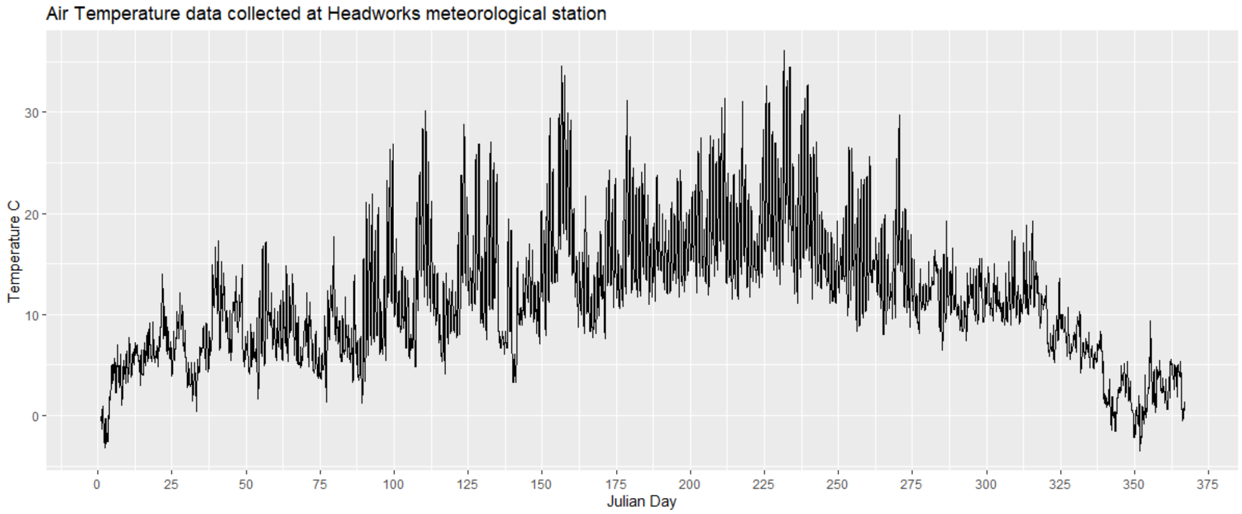


Figure 4: Air temperature data from Headworks/Dam 2

Model setup dew point temperature

Dew point temperatures are not collected at the Headworks/Dam2 weather gage, but are derived using Air Temperature and Relative Humidity using a function in R from the weathermetrics package (weathermetrics::humidity.to.dewpoint)

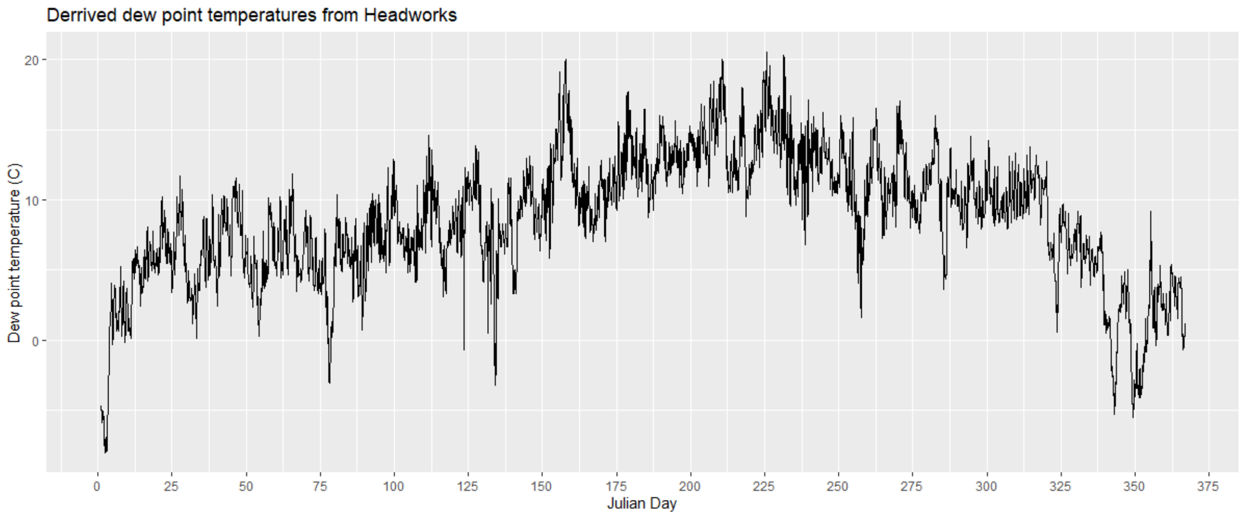


Figure 5: Derived dew point temperature data

Model setup solar radiation.

Solar radiation data at headworks is collected from the meteorological station located on top of Dam 2. Periodic spikes in the data are removed by comparing recorded data with a calibrated potential solar radiation model developed by GeoSyntec who were involved in the creation and updating of the Bull Run model. In the comparison with the potential solar radiation model, any observed solar radiation values that exceed the potential maximum solar radiation are reduced to the value of the potential maximum solar radiation.

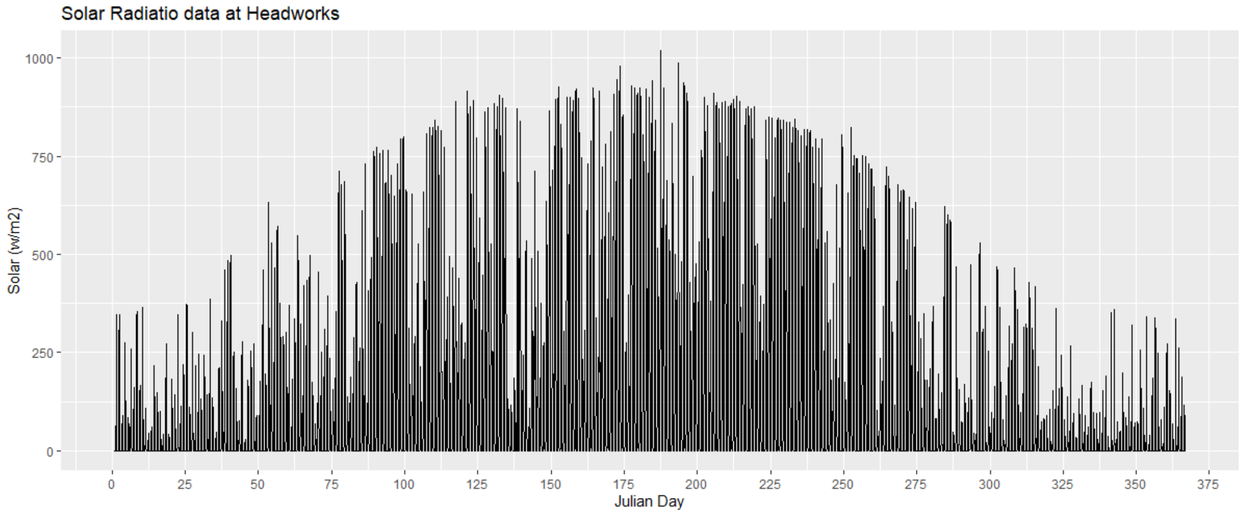


Figure 6: Derived solar radiation at Headworks

3.1.4 Temperature inputs

Model setup tributary and boundary condition temperatures.

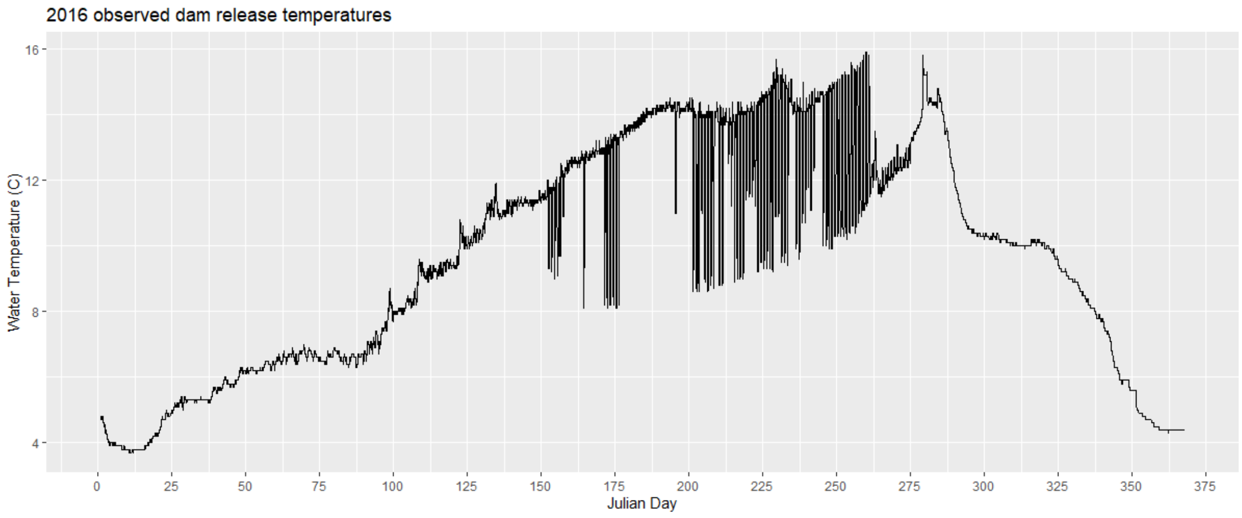


Figure 7: Observed 2016 Dam release temperatures (used for the 2016 model calibration)

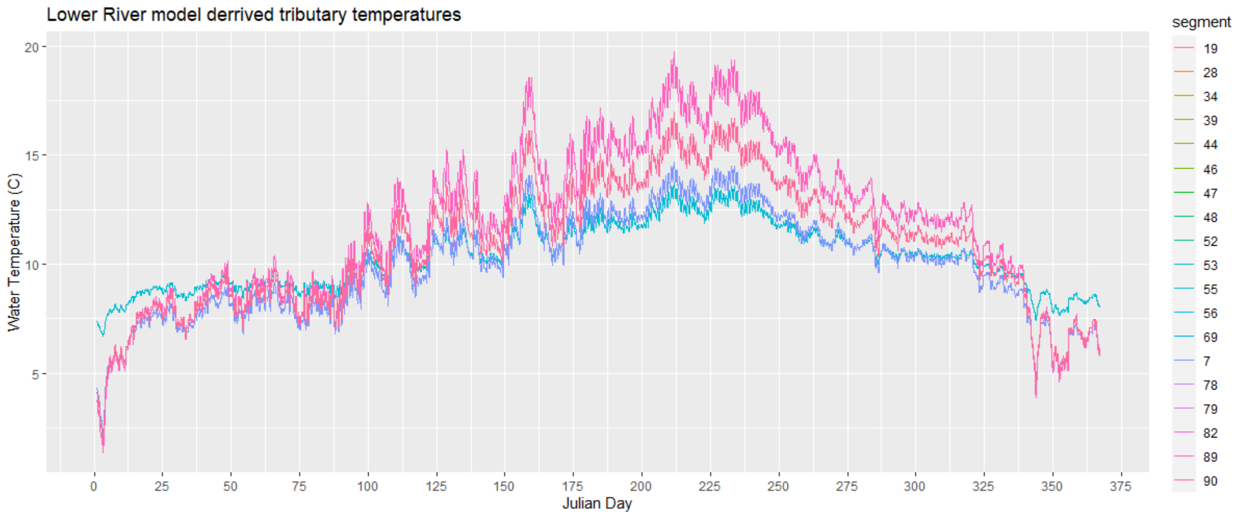


Figure 8: Derived tributary temperatures used for both calibration and scenario model runs

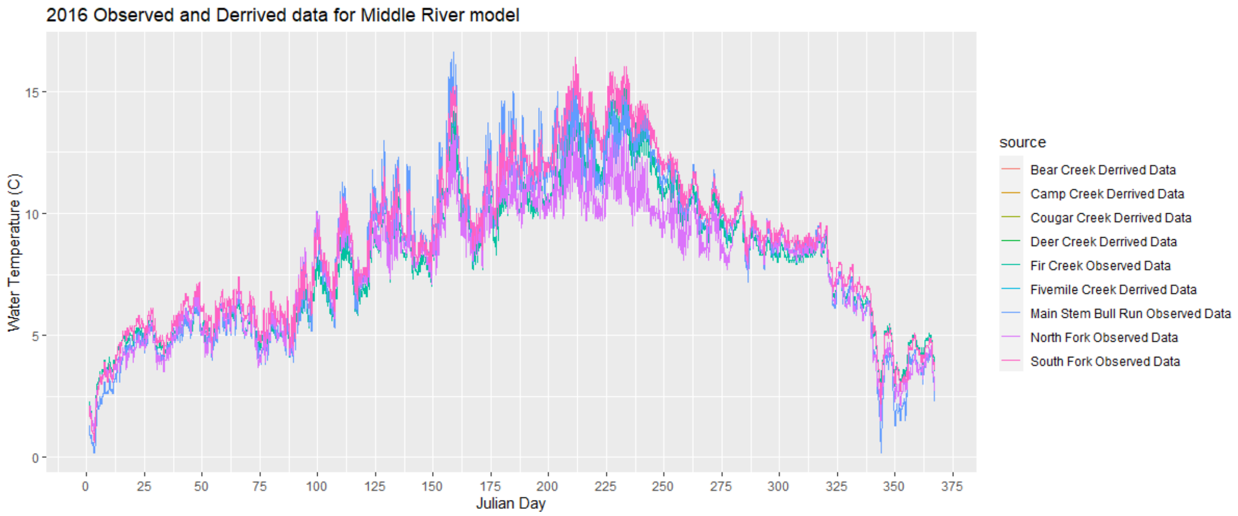


Figure 9: Derived and Observed tributary temperatures used for the Middle River model

3.1.5 Flow inputs

Model setup tributary and boundary condition flow rates.

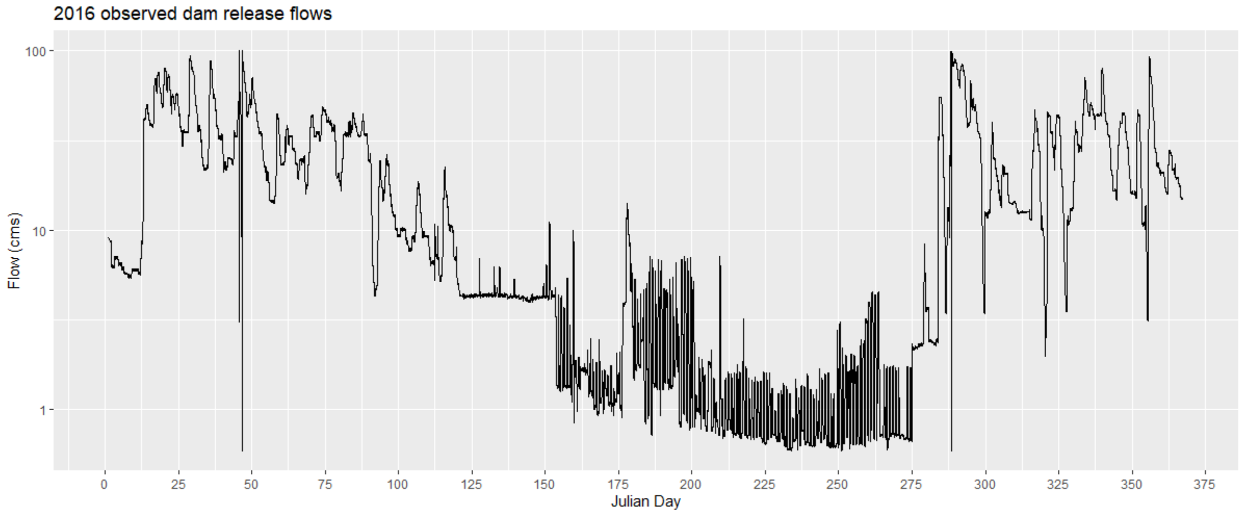


Figure 10: 2016 observed releases from Dam 2 in cubic meters per second

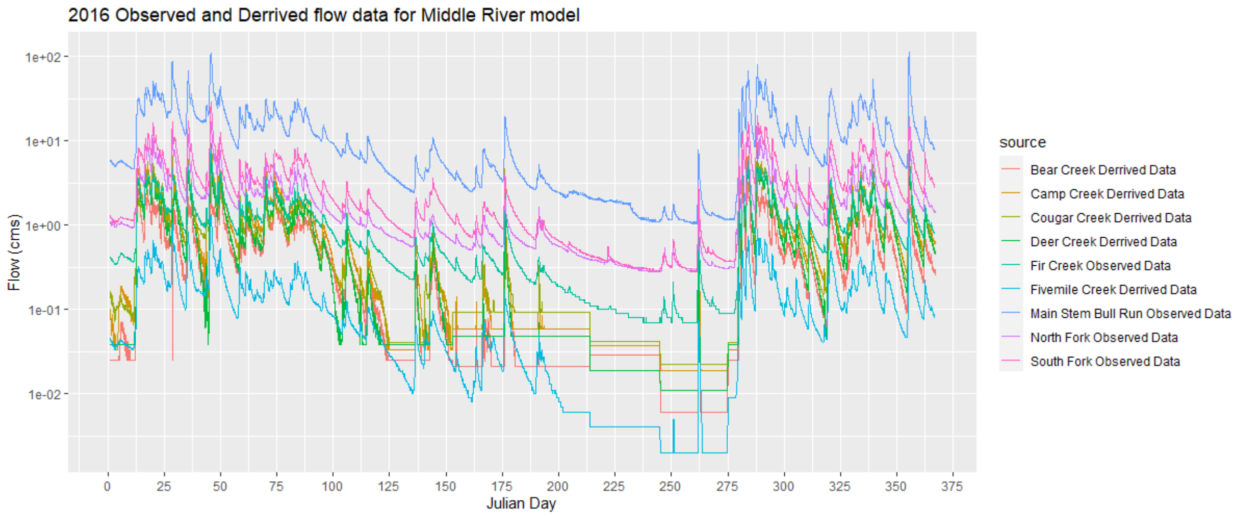


Figure 11: Observed and derived flows for the Middle River model in cubic meters per second

3.1.5.1 Model setup for groundwater/accretion/distributed flow rates.

Distributed/accretion/groundwater flows are included as tributary flows in the Middle and Lower river model.

3.1.5.2 Model setup for withdrawal flow rates.

There are no withdrawals in either the middle river or lower river model.

3.1.6 Point source inputs

There are no point source effluents in either the model domain for the middle and lower river models.

3.1.7 Topographic shade inputs

Model setup topographic shade angles.

Table 5: Topographic shading angles for Middle River model

Segment	0 degrees (North)	20 degrees	40 degrees	60 degrees	80 degrees	100 degrees	120 degrees	140 degrees	160 degrees	180 degrees (South)	200 degrees	220 degrees	240 degrees	260 degrees	280 degrees	300 degrees	320 degrees	340 degrees
2	0.291	0.227	0.091	0.415	0.641	0.798	0.874	0.88	0.804	0.636	0.227	0.087	0.181	0.261	0.376	0.419	0.383	0.379
3	0.28	0.207	0.084	0.374	0.464	0.47	0.392	0.304	0.253	0.166	0.078	0.144	0.263	0.31	0.37	0.395	0.424	0.386
4	0.23	0.171	0.177	0.219	0.157	0.225	0.308	0.298	0.248	0.14	0.085	0.183	0.325	0.4	0.474	0.412	0.384	0.278
7	0.183	0.152	0.135	0.135	0.158	0.266	0.331	0.316	0.263	0.191	0.113	0.06	0.107	0.165	0.268	0.24	0.19	0.254
8	0.171	0.139	0.102	0.118	0.255	0.311	0.384	0.38	0.364	0.335	0.214	0.119	0.038	0.088	0.184	0.229	0.227	0.243
9	0.286	0.253	0.123	0.102	0.145	0.274	0.299	0.282	0.228	0.226	0.202	0.132	0.03	0.121	0.233	0.284	0.294	0.315
10	0.402	0.333	0.173	0.081	0.129	0.244	0.279	0.245	0.204	0.199	0.133	0.1	0.045	0.218	0.359	0.436	0.46	0.457
11	0.462	0.366	0.21	0.065	0.116	0.323	0.507	0.732	0.858	0.808	0.56	0.377	0.053	0.198	0.312	0.42	0.489	0.498
12	0.386	0.296	0.19	0.138	0.185	0.346	0.377	0.357	0.31	0.3	0.195	0.085	0.071	0.242	0.341	0.38	0.421	0.427
13	0.258	0.202	0.116	0.067	0.211	0.361	0.391	0.417	0.509	0.437	0.329	0.068	0.095	0.192	0.238	0.3	0.303	0.308
14	0.126	0.133	0.093	0.172	0.419	0.628	0.76	0.74	0.643	0.541	0.272	0.081	0.097	0.157	0.215	0.239	0.233	0.128
17	0.201	0.114	0.087	0.215	0.328	0.389	0.359	0.348	0.264	0.237	0.151	0.096	0.22	0.273	0.302	0.337	0.317	0.272
18	0.444	0.126	0.069	0.15	0.207	0.237	0.292	0.318	0.274	0.258	0.218	0.137	0.319	0.527	0.596	0.667	0.707	0.629
19	0.132	0.13	0.096	0.124	0.231	0.335	0.474	0.567	0.664	0.65	0.55	0.385	0.193	0.053	0.08	0.146	0.141	0.129
20	0.122	0.105	0.095	0.086	0.137	0.244	0.352	0.417	0.491	0.552	0.495	0.498	0.38	0.107	0.09	0.148	0.153	0.142
21	0.21	0.2	0.168	0.101	0.098	0.135	0.224	0.258	0.266	0.24	0.19	0.133	0.053	0.083	0.18	0.229	0.242	0.204
22	0.467	0.332	0.142	0.076	0.086	0.132	0.223	0.261	0.25	0.248	0.165	0.106	0.063	0.095	0.295	0.4	0.476	0.486
23	0.26	0.236	0.158	0.086	0.075	0.144	0.412	0.537	0.61	0.475	0.357	0.185	0.047	0.147	0.175	0.227	0.298	0.261
24	0.324	0.259	0.168	0.084	0.1	0.159	0.219	0.193	0.181	0.147	0.072	0.09	0.313	0.479	0.611	0.581	0.52	0.45
25	0.203	0.159	0.125	0.185	0.207	0.215	0.239	0.206	0.189	0.157	0.25	0.325	0.322	0.217	0.133	0.204	0.272	0.267
26	0.206	0.139	0.07	0.121	0.154	0.298	0.422	0.484	0.482	0.39	0.26	0.067	0.047	0.116	0.146	0.195	0.25	0.263

27	0.226	0.132	0.067	0.092	0.243	0.329	0.385	0.415	0.363	0.245	0.121	0.059	0.081	0.187	0.282	0.336	0.347	0.324
28	0.169	0.109	0.057	0.138	0.171	0.279	0.334	0.27	0.243	0.193	0.138	0.078	0.042	0.107	0.181	0.213	0.223	0.196
29	0.116	0.086	0.062	0.072	0.124	0.221	0.327	0.411	0.359	0.28	0.165	0.094	0.048	0.084	0.156	0.221	0.231	0.167
30	0.193	0.111	0.061	0.055	0.103	0.168	0.208	0.211	0.201	0.188	0.137	0.109	0.062	0.096	0.131	0.229	0.26	0.271
31	0.226	0.127	0.056	0.05	0.094	0.165	0.214	0.236	0.177	0.251	0.222	0.127	0.073	0.11	0.141	0.178	0.249	0.245
32	0.204	0.142	0.051	0.053	0.108	0.193	0.282	0.386	0.443	0.424	0.362	0.16	0.073	0.136	0.158	0.185	0.204	0.231
33	0.198	0.151	0.05	0.053	0.299	0.534	0.627	0.667	0.593	0.487	0.408	0.214	0.078	0.154	0.165	0.187	0.168	0.215
34	0.206	0.151	0.046	0.045	0.229	0.347	0.464	0.502	0.469	0.437	0.385	0.223	0.108	0.201	0.234	0.196	0.19	0.184
37	0.206	0.151	0.046	0.045	0.229	0.347	0.464	0.502	0.469	0.437	0.385	0.223	0.108	0.201	0.234	0.196	0.19	0.184
38	0.206	0.151	0.046	0.045	0.229	0.347	0.464	0.502	0.469	0.437	0.385	0.223	0.108	0.201	0.234	0.196	0.19	0.184
39	0.206	0.151	0.046	0.045	0.229	0.347	0.464	0.502	0.469	0.437	0.385	0.223	0.108	0.201	0.234	0.196	0.19	0.184
40	0.206	0.151	0.046	0.045	0.229	0.347	0.464	0.502	0.469	0.437	0.385	0.223	0.108	0.201	0.234	0.196	0.19	0.184
41	0.206	0.151	0.046	0.045	0.229	0.347	0.464	0.502	0.469	0.437	0.385	0.223	0.108	0.201	0.234	0.196	0.19	0.184
44	0.185	0.147	0.054	0.158	0.527	0.666	0.765	0.795	0.715	0.513	0.175	0.028	0.145	0.27	0.339	0.355	0.275	0.242
45	0.206	0.137	0.083	0.321	0.482	0.49	0.615	0.529	0.504	0.447	0.287	0.033	0.13	0.272	0.37	0.41	0.394	0.331
46	0.238	0.125	0.1	0.431	0.617	0.691	0.75	0.722	0.616	0.502	0.246	0.03	0.15	0.203	0.274	0.326	0.372	0.336
47	0.214	0.113	0.17	0.29	0.394	0.493	0.515	0.493	0.458	0.28	0.178	0.031	0.158	0.202	0.202	0.209	0.246	0.233
48	0.164	0.104	0.102	0.225	0.333	0.397	0.392	0.375	0.408	0.374	0.216	0.03	0.145	0.271	0.3	0.258	0.212	0.16
49	0.244	0.118	0.064	0.143	0.287	0.439	0.485	0.479	0.431	0.286	0.098	0.068	0.229	0.34	0.435	0.501	0.48	0.402
50	0.262	0.106	0.061	0.28	0.41	0.471	0.509	0.489	0.372	0.25	0.132	0.123	0.302	0.394	0.441	0.431	0.41	0.378
51	0.258	0.215	0.054	0.222	0.292	0.333	0.357	0.4	0.384	0.339	0.202	0.104	0.128	0.191	0.211	0.275	0.282	0.218
52	0.172	0.129	0.107	0.107	0.128	0.178	0.198	0.237	0.238	0.208	0.204	0.149	0.175	0.221	0.242	0.257	0.23	0.207
53	0.226	0.133	0.078	0.108	0.157	0.204	0.251	0.275	0.285	0.24	0.117	0.109	0.2	0.248	0.27	0.28	0.259	0.249
54	0.256	0.179	0.059	0.098	0.245	0.357	0.508	0.488	0.481	0.405	0.213	0.15	0.22	0.275	0.279	0.282	0.276	0.244
55	0.187	0.104	0.049	0.191	0.21	0.241	0.202	0.131	0.092	0.098	0.291	0.332	0.37	0.396	0.391	0.354	0.342	0.27
56	0.121	0.117	0.206	0.248	0.258	0.261	0.233	0.188	0.13	0.083	0.309	0.471	0.567	0.593	0.568	0.412	0.254	0.202
57	0.106	0.16	0.33	0.466	0.545	0.544	0.49	0.294	0.193	0.122	0.071	0.202	0.24	0.305	0.289	0.267	0.249	0.181
58	0.094	0.09	0.142	0.18	0.206	0.199	0.23	0.263	0.197	0.135	0.146	0.269	0.365	0.458	0.485	0.444	0.326	0.206
59	0.086	0.115	0.159	0.259	0.358	0.42	0.426	0.386	0.301	0.215	0.165	0.341	0.369	0.403	0.394	0.312	0.244	0.169

60	0.139	0.075	0.236	0.402	0.518	0.604	0.624	0.607	0.516	0.392	0.156	0.084	0.151	0.26	0.272	0.266	0.215	0.161
61	0.131	0.063	0.13	0.263	0.394	0.498	0.503	0.461	0.372	0.249	0.155	0.1	0.165	0.275	0.332	0.336	0.313	0.225
62	0.241	0.178	0.078	0.189	0.279	0.333	0.341	0.304	0.253	0.252	0.135	0.131	0.18	0.296	0.32	0.328	0.297	0.271
63	0.242	0.16	0.067	0.161	0.215	0.239	0.326	0.351	0.271	0.149	0.099	0.186	0.254	0.345	0.37	0.329	0.315	0.339
64	0.434	0.23	0.06	0.124	0.233	0.273	0.28	0.227	0.118	0.094	0.167	0.286	0.389	0.405	0.488	0.56	0.569	0.516
65	0.162	0.072	0.109	0.201	0.272	0.287	0.259	0.148	0.129	0.211	0.297	0.403	0.512	0.585	0.599	0.526	0.417	0.287
66	0.123	0.165	0.25	0.354	0.404	0.419	0.307	0.168	0.141	0.218	0.332	0.392	0.389	0.378	0.377	0.347	0.291	0.207
67	0.264	0.477	0.596	0.603	0.646	0.567	0.476	0.332	0.159	0.125	0.1	0.193	0.284	0.353	0.306	0.297	0.254	0.161
68	0.084	0.268	0.34	0.386	0.378	0.331	0.242	0.182	0.178	0.137	0.152	0.079	0.028	0.111	0.197	0.24	0.259	0.176
69	0.246	0.225	0.186	0.204	0.166	0.111	0.158	0.179	0.234	0.247	0.153	0.122	0.071	0.124	0.212	0.258	0.289	0.243
70	0.444	0.349	0.192	0.139	0.12	0.175	0.243	0.28	0.274	0.225	0.171	0.113	0.146	0.24	0.292	0.368	0.449	0.466
71	0.292	0.265	0.167	0.103	0.098	0.128	0.154	0.168	0.151	0.134	0.107	0.174	0.303	0.409	0.463	0.495	0.513	0.431
72	0.201	0.148	0.092	0.099	0.109	0.111	0.164	0.179	0.181	0.147	0.127	0.086	0.142	0.167	0.212	0.264	0.318	0.275
73	0.157	0.094	0.073	0.087	0.107	0.149	0.196	0.207	0.23	0.19	0.197	0.133	0.059	0.069	0.17	0.209	0.242	0.223
74	0.183	0.103	0.064	0.068	0.103	0.16	0.202	0.254	0.358	0.374	0.323	0.233	0.111	0.096	0.163	0.212	0.239	0.217
75	0.222	0.152	0.083	0.06	0.06	0.116	0.16	0.185	0.197	0.171	0.105	0.072	0.044	0.146	0.2	0.256	0.292	0.285
76	0.277	0.193	0.093	0.041	0.057	0.104	0.155	0.169	0.18	0.133	0.094	0.101	0.149	0.199	0.234	0.285	0.317	0.324
77	0.288	0.288	0.104	0.07	0.172	0.248	0.362	0.427	0.453	0.438	0.352	0.222	0.197	0.289	0.288	0.305	0.386	0.369
78	0.379	0.377	0.263	0.117	0.088	0.208	0.343	0.43	0.547	0.619	0.631	0.584	0.451	0.291	0.271	0.279	0.301	0.328
81	0.084	0.268	0.34	0.386	0.378	0.331	0.242	0.182	0.178	0.137	0.152	0.079	0.028	0.111	0.197	0.24	0.259	0.176
82	0.084	0.268	0.34	0.386	0.378	0.331	0.242	0.182	0.178	0.137	0.152	0.079	0.028	0.111	0.197	0.24	0.259	0.176
83	0.084	0.268	0.34	0.386	0.378	0.331	0.242	0.182	0.178	0.137	0.152	0.079	0.028	0.111	0.197	0.24	0.259	0.176
84	0.084	0.268	0.34	0.386	0.378	0.331	0.242	0.182	0.178	0.137	0.152	0.079	0.028	0.111	0.197	0.24	0.259	0.176
85	0.084	0.268	0.34	0.386	0.378	0.331	0.242	0.182	0.178	0.137	0.152	0.079	0.028	0.111	0.197	0.24	0.259	0.176
86	0.084	0.268	0.34	0.386	0.378	0.331	0.242	0.182	0.178	0.137	0.152	0.079	0.028	0.111	0.197	0.24	0.259	0.176
87	0.084	0.268	0.34	0.386	0.378	0.331	0.242	0.182	0.178	0.137	0.152	0.079	0.028	0.111	0.197	0.24	0.259	0.176

Table 6: Lower River Model Topographic Angles

Segment	0 degrees (North)	20 degrees	40 degrees	60 degrees	80 degrees	100 degrees	120 degrees	140 degrees	160 degrees	180 degrees (South)	200 degrees	220 degrees	240 degrees	260 degrees	280 degrees	300 degrees	320 degrees	340 degrees

2	0.486	0.49	0.414	0.295	0.191	0.149	0.134	0.296	0.353	0.359	0.329	0.25	0.12	0.123	0.242	0.298	0.31	0.414
3	0.501	0.505	0.476	0.383	0.201	0.121	0.122	0.231	0.257	0.221	0.136	0.083	0.101	0.166	0.258	0.318	0.361	0.427
4	0.599	0.583	0.566	0.458	0.478	0.469	0.409	0.296	0.246	0.221	0.18	0.077	0.137	0.289	0.35	0.433	0.53	0.588
7	0.468	0.427	0.371	0.286	0.183	0.345	0.454	0.504	0.487	0.4	0.268	0.159	0.163	0.312	0.399	0.416	0.445	0.466
8	0.468	0.418	0.332	0.251	0.127	0.185	0.23	0.255	0.247	0.197	0.102	0.134	0.253	0.427	0.522	0.536	0.534	0.5
9	0.462	0.392	0.304	0.218	0.196	0.229	0.272	0.224	0.162	0.12	0.062	0.271	0.396	0.567	0.645	0.701	0.667	0.561
12	0.393	0.31	0.236	0.216	0.228	0.228	0.25	0.222	0.169	0.119	0.283	0.558	0.736	0.809	0.77	0.699	0.668	0.564
13	0.271	0.229	0.182	0.247	0.329	0.37	0.344	0.294	0.238	0.189	0.111	0.177	0.29	0.358	0.397	0.431	0.391	0.357
14	0.243	0.19	0.215	0.346	0.394	0.425	0.428	0.405	0.372	0.287	0.162	0.068	0.21	0.288	0.297	0.308	0.324	0.302
17	0.194	0.173	0.171	0.26	0.346	0.437	0.493	0.529	0.443	0.279	0.217	0.089	0.042	0.124	0.21	0.3	0.287	0.314
18	0.184	0.162	0.103	0.187	0.28	0.392	0.365	0.271	0.299	0.311	0.246	0.128	0.051	0.155	0.197	0.3	0.281	0.285
19	0.188	0.174	0.173	0.149	0.223	0.254	0.228	0.328	0.367	0.237	0.152	0.101	0.061	0.211	0.244	0.31	0.326	0.309
22	0.165	0.174	0.092	0.157	0.272	0.241	0.264	0.388	0.42	0.438	0.392	0.17	0.065	0.113	0.211	0.295	0.313	0.297
23	0.153	0.157	0.082	0.161	0.287	0.235	0.286	0.428	0.449	0.477	0.499	0.52	0.413	0.282	0.172	0.282	0.3	0.286
24	0.139	0.135	0.083	0.189	0.29	0.234	0.32	0.475	0.511	0.513	0.42	0.419	0.312	0.185	0.139	0.267	0.287	0.274
27	0.19	0.153	0.098	0.132	0.239	0.274	0.41	0.364	0.287	0.245	0.232	0.154	0.105	0.172	0.328	0.419	0.37	0.299
28	0.355	0.22	0.087	0.118	0.231	0.289	0.299	0.343	0.408	0.413	0.336	0.25	0.186	0.09	0.143	0.274	0.338	0.349
29	0.235	0.269	0.132	0.131	0.209	0.377	0.549	0.692	0.77	0.789	0.764	0.679	0.537	0.356	0.15	0.265	0.333	0.328
32	0.299	0.264	0.279	0.182	0.115	0.166	0.259	0.314	0.423	0.497	0.524	0.504	0.409	0.224	0.185	0.296	0.356	0.373
33	0.397	0.374	0.296	0.246	0.13	0.136	0.186	0.232	0.339	0.371	0.313	0.21	0.077	0.125	0.258	0.342	0.391	0.414
34	0.568	0.491	0.361	0.225	0.138	0.119	0.157	0.256	0.257	0.212	0.147	0.056	0.114	0.261	0.404	0.509	0.577	0.6
37	0.485	0.384	0.267	0.162	0.1	0.2	0.279	0.295	0.254	0.207	0.152	0.063	0.176	0.402	0.541	0.596	0.577	0.536
38	0.366	0.263	0.175	0.144	0.266	0.334	0.383	0.378	0.374	0.304	0.221	0.142	0.001	0.112	0.241	0.344	0.378	0.392
39	0.362	0.244	0.144	0.14	0.252	0.372	0.451	0.494	0.496	0.477	0.433	0.286	0.035	0.061	0.199	0.299	0.346	0.374
42	0.369	0.28	0.18	0.278	0.137	0.238	0.34	0.322	0.289	0.24	0.171	0.064	0.001	0.081	0.21	0.308	0.369	0.378
43	0.357	0.308	0.184	0.074	0.105	0.152	0.171	0.252	0.268	0.201	0.175	0.057	0.002	0.102	0.221	0.307	0.369	0.386
44	0.309	0.263	0.132	0.113	0.12	0.172	0.238	0.285	0.283	0.239	0.206	0.074	0	0.103	0.2	0.264	0.326	0.343
45	0.304	0.242	0.127	0.056	0.112	0.201	0.265	0.301	0.275	0.28	0.197	0.088	0.015	0.125	0.205	0.257	0.301	0.326
46	0.306	0.237	0.116	0.043	0.08	0.148	0.269	0.259	0.297	0.278	0.164	0.066	0.025	0.127	0.229	0.275	0.304	0.322

47	0.322	0.261	0.132	0.051	0.065	0.135	0.235	0.262	0.288	0.238	0.121	0.037	0.065	0.167	0.282	0.308	0.348	0.339
48	0.289	0.227	0.111	0.05	0.102	0.199	0.224	0.306	0.303	0.234	0.133	0.043	0.055	0.151	0.28	0.318	0.32	0.319
49	0.287	0.224	0.09	0.017	0.07	0.181	0.263	0.299	0.272	0.203	0.098	0.05	0.105	0.194	0.287	0.405	0.364	0.328
52	0.261	0.161	0.06	0.046	0.12	0.221	0.318	0.329	0.292	0.23	0.15	0.068	0.085	0.169	0.222	0.288	0.377	0.304
53	0.244	0.162	0.068	0.05	0.153	0.264	0.319	0.339	0.336	0.298	0.223	0.125	0.039	0.122	0.195	0.259	0.307	0.353
54	0.312	0.19	0.112	0.051	0.151	0.257	0.299	0.297	0.278	0.196	0.143	0.113	0.082	0.19	0.298	0.344	0.377	0.37
55	0.266	0.143	0.06	0.143	0.212	0.277	0.336	0.359	0.331	0.281	0.256	0.219	0.125	0.021	0.087	0.176	0.254	0.274
56	0.257	0.206	0.092	0.06	0.154	0.244	0.283	0.402	0.478	0.493	0.461	0.386	0.238	0.084	0.079	0.166	0.245	0.277
57	0.319	0.285	0.222	0.139	0.089	0.193	0.229	0.238	0.267	0.245	0.2	0.184	0.104	0.025	0.126	0.258	0.297	0.324
60	0.413	0.349	0.219	0.127	0.174	0.291	0.391	0.507	0.635	0.633	0.564	0.383	0.142	0.062	0.153	0.236	0.345	0.404
61	0.416	0.374	0.309	0.175	0.062	0.156	0.19	0.272	0.315	0.324	0.286	0.22	0.041	0.119	0.213	0.337	0.405	0.432
62	0.287	0.267	0.193	0.096	0.109	0.252	0.404	0.482	0.53	0.514	0.465	0.353	0.148	0.128	0.239	0.236	0.251	0.28
63	0.27	0.249	0.179	0.085	0.224	0.293	0.488	0.565	0.636	0.641	0.59	0.429	0.161	0.177	0.264	0.277	0.277	0.294
64	0.467	0.417	0.34	0.185	0.061	0.238	0.41	0.508	0.487	0.326	0.226	0.106	0.208	0.258	0.337	0.401	0.411	0.475
65	0.335	0.277	0.179	0.087	0.16	0.359	0.359	0.289	0.19	0.184	0.146	0.201	0.349	0.426	0.573	0.648	0.641	0.532
68	0.257	0.187	0.139	0.179	0.309	0.336	0.255	0.256	0.238	0.236	0.193	0.194	0.345	0.505	0.57	0.542	0.483	0.387
69	0.255	0.146	0.104	0.21	0.279	0.16	0.119	0.249	0.305	0.292	0.24	0.202	0.501	0.65	0.588	0.625	0.585	0.468
70	0.401	0.18	0.07	0.195	0.183	0.334	0.319	0.356	0.386	0.364	0.308	0.627	0.795	0.876	0.994	1.015	0.959	0.774
73	0.287	0.359	0.321	0.446	0.598	0.61	0.683	0.771	0.603	0.567	0.529	0.456	0.411	0.168	0.062	0.202	0.256	0.314
74	0.347	0.326	0.336	0.297	0.195	0.208	0.328	0.403	0.458	0.61	0.603	0.494	0.336	0.119	0.068	0.157	0.238	0.337
75	0.378	0.409	0.35	0.197	0.122	0.161	0.252	0.453	0.497	0.477	0.436	0.35	0.226	0.117	0.085	0.169	0.282	0.353
76	0.391	0.406	0.328	0.236	0.137	0.132	0.273	0.279	0.349	0.402	0.406	0.378	0.307	0.163	0.117	0.229	0.293	0.361
77	0.731	0.729	0.66	0.479	0.227	0.078	0.193	0.205	0.209	0.196	0.167	0.201	0.194	0.135	0.405	0.629	0.7	0.721
78	0.544	0.472	0.34	0.21	0.088	0.148	0.217	0.315	0.345	0.299	0.236	0.258	0.248	0.152	0.165	0.351	0.511	0.56
79	0.378	0.423	0.357	0.201	0.064	0.139	0.178	0.224	0.244	0.25	0.308	0.354	0.31	0.204	0.105	0.225	0.286	0.346
80	0.26	0.319	0.298	0.223	0.116	0.119	0.167	0.273	0.324	0.41	0.467	0.505	0.452	0.404	0.303	0.097	0.113	0.182
81	0.618	0.71	0.715	0.681	0.539	0.328	0.114	0.165	0.246	0.41	0.501	0.549	0.446	0.351	0.216	0.101	0.208	0.498
82	0.455	0.466	0.46	0.551	0.523	0.358	0.088	0.155	0.307	0.429	0.484	0.485	0.494	0.412	0.31	0.172	0.114	0.279
85	0.658	0.718	0.775	0.702	0.488	0.363	0.235	0.114	0.252	0.402	0.45	0.456	0.427	0.489	0.602	0.718	0.711	0.685

86	0.418	0.584	0.685	0.717	0.658	0.592	0.387	0.135	0.223	0.358	0.458	0.503	0.381	0.368	0.293	0.241	0.217	0.141
87	0.051	0.196	0.394	0.542	0.578	0.543	0.389	0.185	0.167	0.196	0.289	0.38	0.413	0.395	0.376	0.371	0.335	0.162
88	0.078	0.141	0.172	0.296	0.347	0.339	0.284	0.266	0.189	0.125	0.205	0.267	0.355	0.459	0.497	0.468	0.331	0.099
89	0.124	0.2	0.221	0.187	0.248	0.198	0.198	0.18	0.075	0.164	0.345	0.469	0.573	0.554	0.493	0.422	0.306	0.129
90	0.192	0.263	0.303	0.325	0.378	0.389	0.24	0.142	0.095	0.123	0.321	0.447	0.491	0.493	0.396	0.25	0.07	0.056
91	0.171	0.239	0.274	0.29	0.337	0.331	0.264	0.111	0.057	0.245	0.392	0.463	0.467	0.425	0.324	0.131	0.027	0.073
94	0.175	0.266	0.314	0.284	0.25	0.215	0.136	0.096	0.086	0.276	0.367	0.358	0.289	0.227	0.168	0.087	0.006	0.102
95	0.207	0.25	0.289	0.313	0.263	0.187	0.113	0.068	0.147	0.268	0.349	0.421	0.447	0.438	0.374	0.219	0.011	0.093
96	0.213	0.28	0.337	0.364	0.343	0.255	0.142	0.055	0.176	0.245	0.288	0.3	0.292	0.221	0.113	0.017	0.035	0.108
97	0.158	0.198	0.192	0.239	0.24	0.187	0.099	0.074	0.151	0.241	0.32	0.298	0.236	0.151	0	0.025	0.082	0.12
98	0.124	0.139	0.139	0.153	0.18	0.151	0.059	0.183	0.225	0.235	0.231	0.179	0.112	0.034	0.038	0.011	0.116	0.094
99	0.051	0.038	0.049	0.095	0.159	0.125	0.052	0.108	0.182	0.18	0.14	0.066	0.063	0.061	0.064	0.071	0.139	0.115

3.1.8 Channel setup

Model setup stream channel elevation (m) and gradient.

Table 7: Lower River Model - Channel bottom elevation and slope

Segment	Channel bottom elevation (m)	Slope	Angle	Mannings n
2	220	0	1.75	0.07
3	220	0	2.16	0.07
4	220	0	1.22	0.07
7	217.34583	0.001	1.28	0.07
8	217.27083	0.001	1.36	0.07
9	217.21	0.001	1.04	0.07
12	210.39994	0.009	5.82	0.07
13	209.46997	0.009	3.14	0.07
14	208.54	0.009	0.04	0.07
17	194.5	0	1.05	0.07
18	194.5	0	0.99	0.07
19	194.5	0	0.88	0.07
22	194.5	0	2.45	0.07
23	194.5	0	2.45	0.07
24	194.5	0	2.45	0.07
27	198.33	0.012	1.05	0.07
28	197.25	0.012	1.11	0.07
29	196.17	0.012	1.57	0.07
32	188.85	0	2.26	0.07
33	188.85	0	2.04	0.07
34	188.85	0	1.29	0.07
37	187.7775	0.011	0.41	0.07
38	186.6225	0.011	0.72	0.07
39	185.55	0.011	0.92	0.07
42	182.6024	0.00841	1.29	0.07
43	181.3409	0.00841	1.06	0.07
44	180.0794	0.00841	0.37	0.07
45	178.3133	0.00841	0.72	0.07
46	176.2949	0.00841	1.07	0.07
47	174.6129	0.00841	1.57	0.07
48	172.7627	0.00841	1.02	0.07
49	170.9125	0.00841	1.05	0.07
52	169.5625	0.01125	0.08	0.07
53	167.9875	0.01125	1.28	0.07
54	165.9625	0.01125	1.14	0.07
55	163.825	0.01125	0.73	0.07
56	161.8	0.01125	1.75	0.07
57	160	0.01125	1.91	0.07
60	135.3333	0.005	1.11	0.07
61	134.7333	0.005	1.01	0.07
62	133.39165	0.005	0.42	0.07
63	132.05	0.005	1	0.07
64	131	0.005	1.57	0.07
65	130.2	0.005	0.56	0.07
68	129.21	0	0.59	0.07
69	129.21	0	0.55	0.07
70	129.21	0	0.68	0.07
73	105.48125	0.0035	0.61	0.07
74	104.92125	0.0035	2.68	0.07
75	104.36125	0.0035	1.57	0.07
76	103.80125	0.0035	1.79	0.07

77	103.075	0.0035	1.47	0.07
78	102.34875	0.0035	1.02	0.07
79	101.6225	0.0035	1.2	0.07
80	100.9225	0.0035	1.88	0.07
81	100.19625	0.0035	1.93	0.07
82	99.47	0.0035	2.25	0.07
85	96.257546	0.01024	2.5	0.07
86	94.257059	0.01024	2.5	0.07
87	92.055459	0.01024	2.45	0.07
88	89.751459	0.01024	3.55	0.07
89	87.750973	0.01024	2.85	0.07
90	85.750486	0.01024	2.5	0.07
91	83.75	0.01024	2.73	0.07
94	80.710188	0.00663	2.68	0.07
95	79.293025	0.00663	2.5	0.07
96	77.701825	0.00663	2.5	0.07
97	76.284663	0.00663	1.87	0.07
98	74.627163	0.00663	1.79	0.07
99	73.21	0.00663	2.85	0.07

Table 8: Middle River Model - Channel bottom elevation, slope, orientation angle (phi), and roughness n

Segment	Channel bottom elevation (m)	Slope	Angle	Mannings n
2	312.91	0.00758	1.16	0.07
3	311.20	0.00758	0.84	0.07
4	309.50	0.00758	0.62	0.07
7	310.86	0.00636	0.75	0.07
8	309.43	0.00636	1.37	0.07
9	308.00	0.00636	1.78	0.07
10	306.57	0.00636	1.29	0.07
11	305.14	0.00636	1.39	0.07
12	303.71	0.00636	1.12	0.07
13	302.29	0.00636	1.09	0.07
14	300.86	0.00636	1.15	0.07
17	299.00	0.00825	0.97	0.07
18	297.15	0.00825	0.84	0.07
19	295.30	0.00825	1.7	0.07
20	293.44	0.00825	1.93	0.07
21	291.59	0.00825	1.86	0.07
22	289.74	0.00825	1.16	0.07
23	287.89	0.00825	1.68	0.07
24	286.03	0.00825	1.35	0.07
25	284.18	0.00825	0.34	0.07
26	282.33	0.00825	1.3	0.07
27	280.47	0.00825	1.09	0.07
28	278.62	0.00825	1.01	0.07
29	276.77	0.00825	1.33	0.07
30	274.91	0.00825	1.34	0.07
31	273.06	0.00825	1.18	0.07
32	271.21	0.00825	1.19	0.07
33	269.35	0.00825	1.37	0.07
34	267.50	0.00825	1.43	0.07
37	284.62	0.01024	0.31	0.07
38	283.59	0.01024	5.92	0.07
39	282.56	0.01024	5.63	0.07
40	281.53	0.01024	5.59	0.07
41	280.50	0.01024	5.18	0.07

44	267.03	0.00524	0.88	0.07
45	265.93	0.00524	0.9	0.07
46	264.83	0.00524	0.92	0.07
47	263.72	0.00524	1	0.07
48	262.62	0.00524	0.92	0.07
49	261.51	0.00524	0.78	0.07
50	260.41	0.00524	1.34	0.07
51	259.31	0.00524	1.48	0.07
52	258.20	0.00524	1.42	0.07
53	257.10	0.00524	0.79	0.07
54	256.00	0.00524	1.33	0.07
55	254.89	0.00524	0.71	0.07
56	253.79	0.00524	6.03	0.07
57	252.68	0.00524	0.34	0.07
58	251.58	0.00524	0.52	0.07
59	250.48	0.00524	0.15	0.07
60	249.37	0.00524	0.91	0.07
61	248.27	0.00524	1.02	0.07
62	247.16	0.00524	1.11	0.07
63	246.06	0.00524	1.18	0.07
64	244.96	0.00524	0.76	0.07
65	243.85	0.00524	0.21	0.07
66	242.75	0.00524	5.86	0.07
67	241.64	0.00524	0.1	0.07
68	240.54	0.00524	1.33	0.07
69	239.44	0.00524	1.77	0.07
70	238.33	0.00524	1.6	0.07
71	237.23	0.00524	0.81	0.07
72	236.12	0.00524	0.44	0.07
73	235.02	0.00524	0.58	0.07
74	233.92	0.00524	1.53	0.07
75	232.81	0.00524	1.77	0.07
76	231.71	0.00524	1.86	0.07
77	230.60	0.00524	1.56	0.07
78	229.50	0.00524	0.9	0.07
81	246.51	0.00501	1.96	0.07
82	245.67	0.00501	1.81	0.07
83	244.84	0.00501	2.2	0.07
84	244.00	0.00501	2.64	0.07
85	243.17	0.00501	1.86	0.07
86	242.33	0.00501	2.69	0.07
87	241.50	0.00501	2.7	0.07

3.1.9 Other model parameters

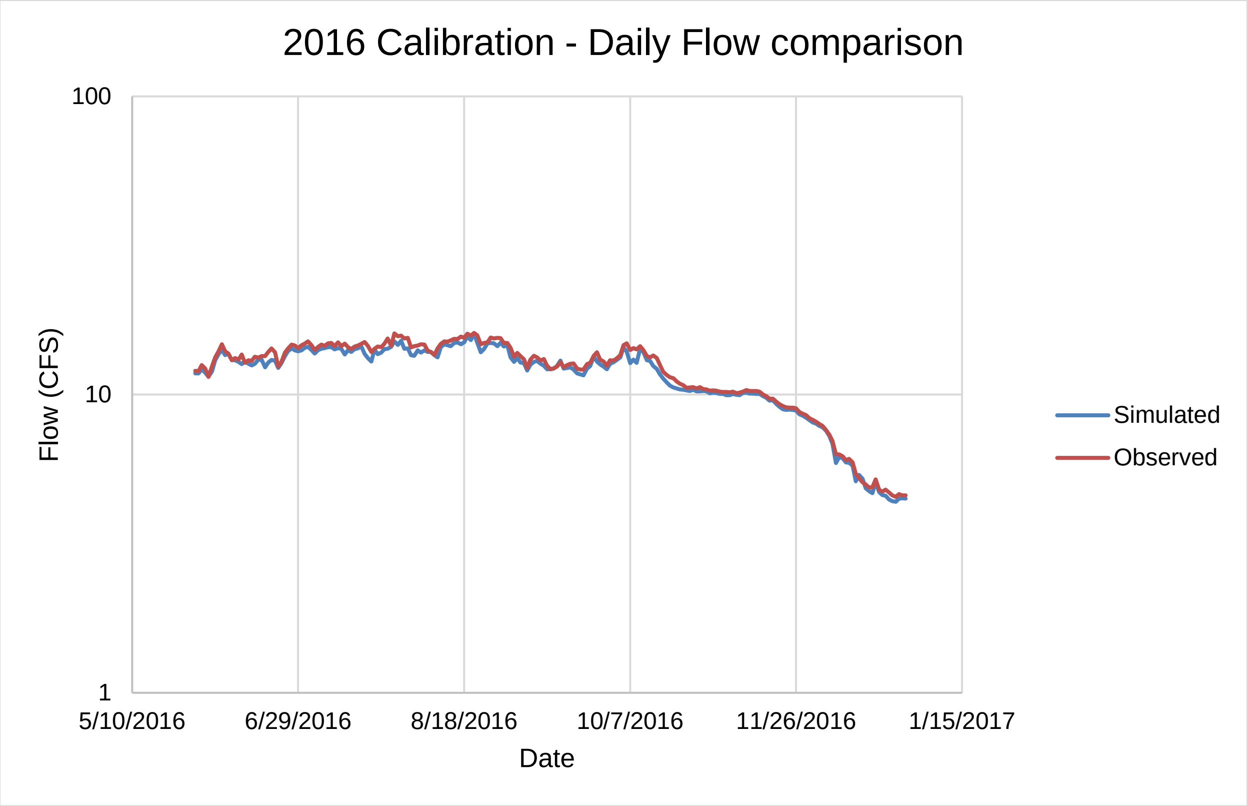
Most model parameters were kept as their original values from the PSU creation/calibration of the model. Of noteworthy change are:

TSEDF & TSED: These parameters which dictate the fraction of sediment temperature that is imparted on the water body (TSEDF 0-1) and temperature of the sediment in degrees C (TSED) were altered for the 2016 observed calibration of the model. TSED was set to the average annual air temperature of 2016 as recommended in the CEQUAL-W2 model literature. A range of TSEDF factors was tested between 0.1 to 1 (by 0.1 intervals) and results were compared. It was found that low values of TSEDF resulted in an overall cold bias to the calibration whereas high values of TSEDF resulted in an overall warm bias. A value of 0.5 for TSEDF (for all water bodies) was found to have the best results based on model goodness of fit tests. The Middle River model was therefore also given the same TSEDF and TSED parameters.

3.1.10 Calibration results

3.1.10.1 Flow

Figure A12. Field observed and model predicted mean daily flow rates.



Flow rate goodness of fit statistics comparing field observed and model flow rates

Table 9: Daily Flow Statistics comparing simulated and measured flows at Bowman's Bridge (USGS 14140000)

Daily Flow Statistics			
Bias	MAE	RMSE	NSE
-0.44	0.45	0.57	0.97

Temperature

Field observed and model predicted daily maximum temperatures at four different stations where in-situ probes collected continuous temperature data for most of 2016.

Table A10. Stream temperature goodness of fit statistics comparing field observed and model predicted temperatures.

Figure 13: Daily maximum water temperatures at 4 key observed stations for the 2016 calibration

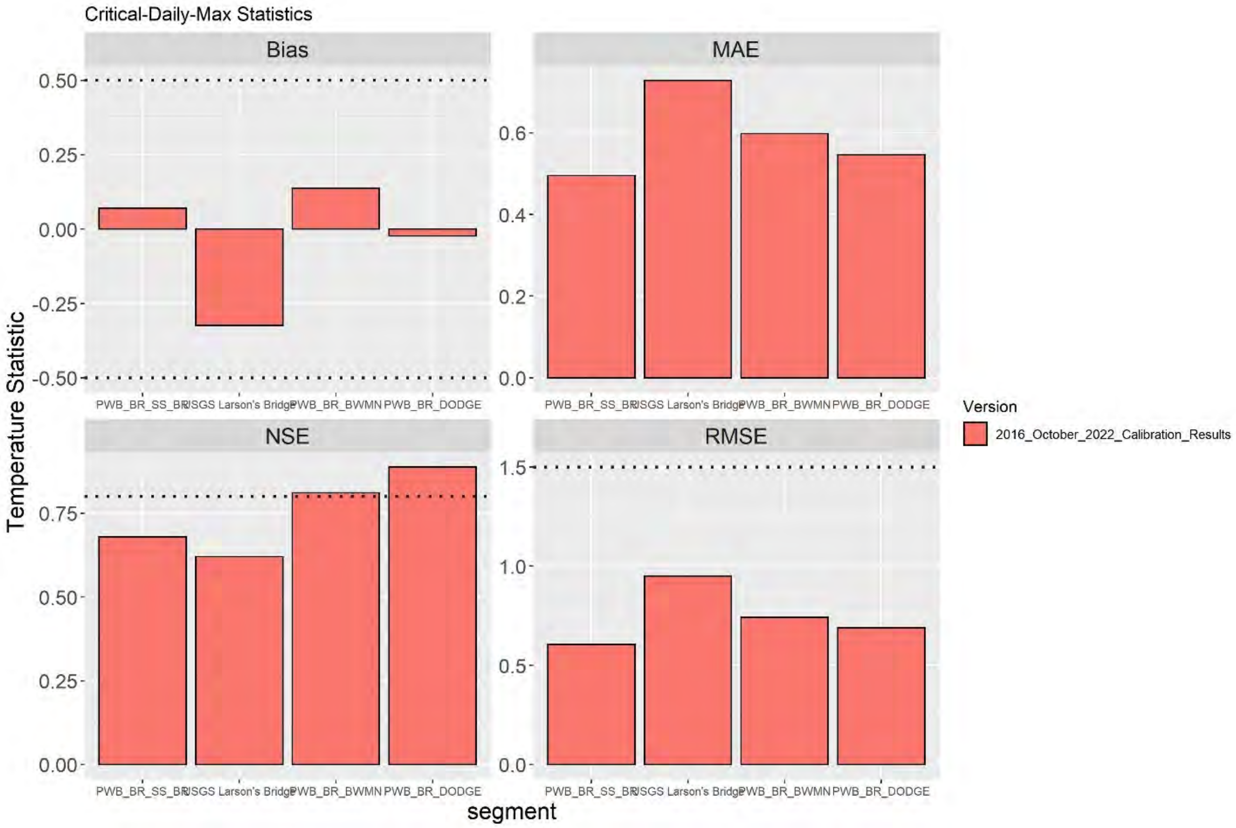


Figure 14: Goodness of fit statistics for observed vs. simulated daily maximum water temperatures at 4 key stations. Dates being considered are based on the "critical period" between 6/1/2016 - 10/15/2016

4. Model scenarios

4.1 Scenario descriptions

Three different scenarios were generated for this project utilizing two different models (Middle River model and Lower River model). All the scenarios utilize the weather year 2016 but differ in many ways.

2016 calibration – The model calibration scenario is based on 2016 as observed conditions. Therefore, this model considers the presence of the dams, the release of the dams, and is the basis for decisions made to the model parameters to make the best possible match for daily maximum temperatures. This scenario only considers the Lower River model. A significant difference between the 2016 calibration model and the other versions of the model apart from the shade files is the upstream boundary condition. Figure 15 below shows the relative locations of Branch 1 and 2 in the Lower River model. In this figure, Branch 1, also known as the diversion pool, is a short, controlled pool between Dam 2, and the diversion dam. Flow can pass either over the diversion dam or through the diversion dam via a valve. In addition, water from the reservoir can be routed either to the diversion pool, or just past the diversion pool in Branch 2. Branch 2 is a channel length with the upstream boundary being the downstream side of the diversion dam, and the downstream boundary being another weir called the Lamprey barrier. Since all flows that are sent downstream are accounted for at the Lamprey barrier (both flow and temperature), it makes a much more consistent point from which to use as the upstream boundary condition for the Lower River model instead of trying to accommodate the complicated routing associated with flows into branch 1 and routing that bypasses branch 1. The boundary condition data for the model is primarily based on the flow and temperature data from the Lamprey barrier (locations 3 & 4 on the figure below). Since the model already contains Branch 1, and branch 1 is still important for the scenarios which consider no dams, instead of rebuilding the model to exclude branch one from the geometry, the input boundary condition data is just set to start at Branch 2. Branch 1 in the 2016 calibration is essentially a stagnant pool of water with no inputs or outputs, all simulated results from Branch 1 (segment 2, 3, & 4) should be ignored.

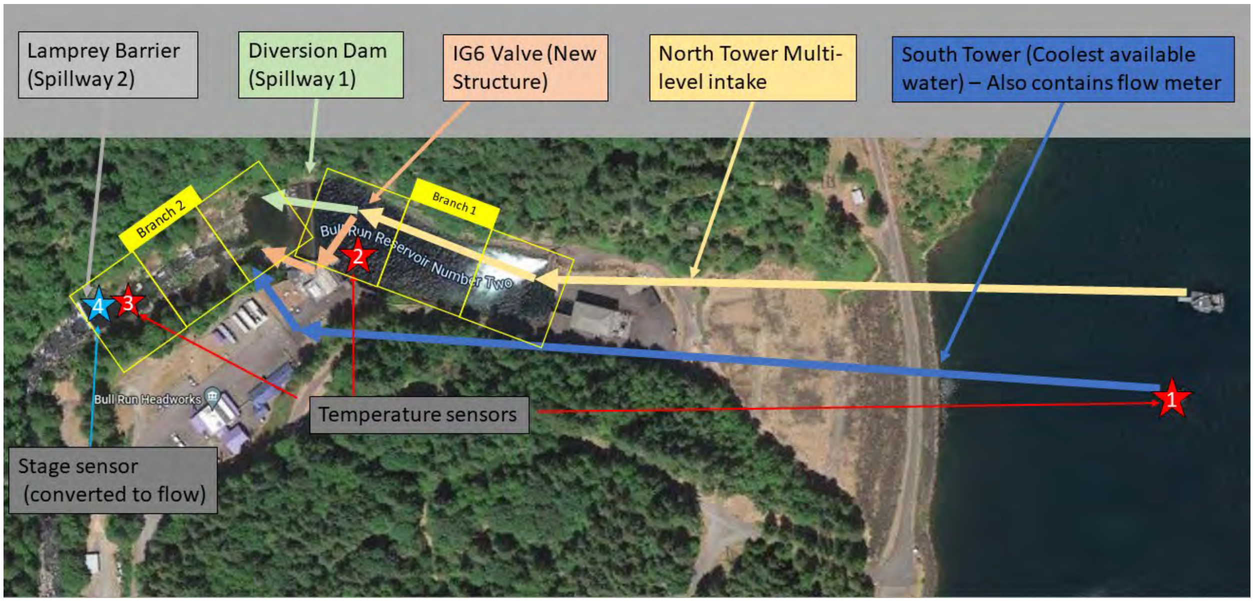


Figure 15: Headworks area of the Lower River model

2016 Current Conditions – This scenario considers both the Middle River model and Lower River model running in tandem. The Current Conditions model utilizes natural flows through the Middle River model through model channel morphology that is our best estimate of what a natural stream channel would look like in the absence of the two reservoirs and dams. The current conditions shade file considers current day vegetation elevations as measured using LiDAR where available and utilizing Restored Conditions vegetation elevations where the current day reservoirs are located (most of the Middle River Model). Temperature and flow outputs from the Middle River Model at spillway 4 are used as input data for the Lower River model at Tin_BR1 and Qin_BR1 respectively.

2016 Restored Conditions – This scenario considers both the Middle River model and Lower River model running in tandem. The restored conditions model utilizes natural flows through the Middle River model through model channel morphology that is our best estimate of what a natural stream channel would look like in the absence of the two reservoirs and dams. The restored conditions shade file considers current day vegetation elevations and restored condition vegetation elevations. In all areas, the higher of the two vegetation elevations is used for computing vegetation shade angles. Since the vegetation shade angles are based on a height of vegetation relative to a distance from centerline, vegetation elevations are not always higher in the restored conditions file, but the associated angle which takes into account elevation and distance from centerline is always higher (or the same) in the restored conditions file. Temperature and flow outputs from the Middle River Model at spillway 4 are used as input data for the Lower River model at Tin_BR1 and Qin_BR1 respectively.

4.2 Scenarios results

Two different scenarios were run using the Middle and Lower river model.

Scenario 1 was using a shade file that represented the No-Dam Conditions (current condition vegetation heights)

Scenario 2 was using a shade file that represented the Restored Conditions (restored condition vegetation, or current condition vegetation, whichever is higher)

Comparisons across the model domain for both scenarios showed very small differences in model results for temperature. The Middle River Model shade files for the two scenarios are nearly identical because most of the Middle River Model vegetation heights were given the Restored Condition vegetation heights because they reside underneath the current day reservoir. The Lower River Model therefore has upstream boundary conditions from the two different scenarios that are nearly identical. Interestingly, maximum daily temperatures did not differ significantly between the two scenarios in the Lower River Model.

The resulting daily maximum water temperatures for the Middle River and Lower River models were combined together. Extrapolating the DX (distance) values from the corresponding bathymetry files, daily maximum water temperature at each segment was converted to daily maximum water temperature at each segment centroid’s distance downstream (river mile) with the starting point being the upstream boundary of the Middle River model. Side branches from both models were removed from this analysis as their impact is incorporated in the main stem at their individual confluence points.

The figure below displays the daily maximum water temperature at all the points along the combined model domain (excluding side branches) for various dates throughout the “critical period” of June through mid-October. What is most evident is the increase in temperature from the Middle River model in the area just before headworks (where modern-day Reservoir 2 is). This location appears to see the maximum water temperatures during the Summer with daily maximum temperatures exceeding 22 C. At the end of the Middle River model, results indicate that water begins to cool off leading to the end of the model domain (headworks). The Lower River model continues to cool off the hot conditions from the Middle River model nearly until the end of the Lower River model.

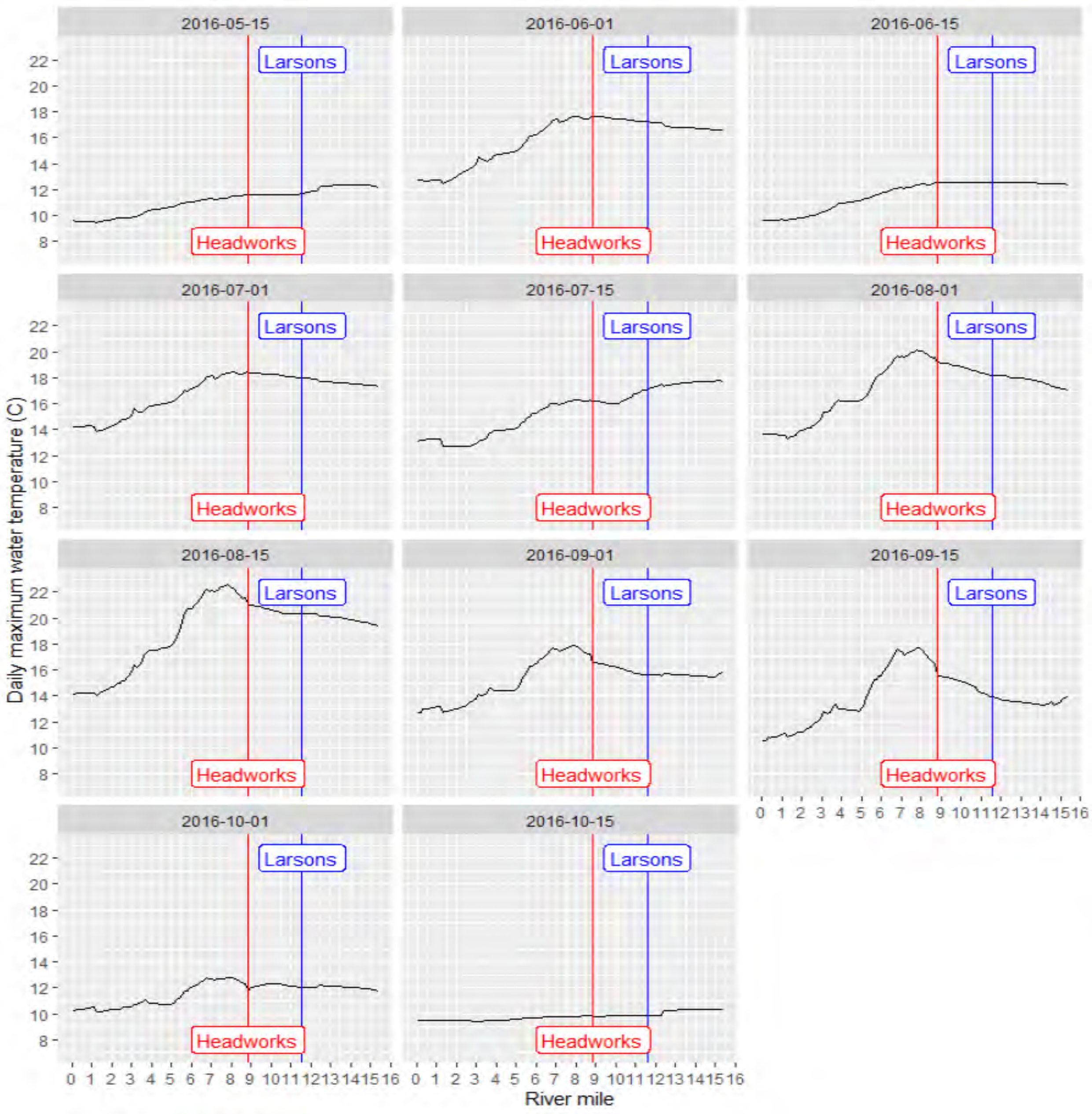


Figure 16: Combined Restored Conditions results for 2016 over various dates

5. References

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Associates, D. E. (1991). *Hydrographic Survey of Bull Run Reservoirs One and Two. Data collected for Portland Water Bureau, City of Portland.* Portland.

DOGAMI. (2009). *LiDAR remote sensing data collection, Oregon North Coast.* Portland: Oregon Department of Geology and Mineral Industries.

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Appendix E
Bull Run River Surrogate Measure Approach

March 21, 2023

Human Use Allowance

Oregon water quality standards also have provisions for human use (OAR 340-041-0028(12)(b)). The human use allowance is an insignificant addition of heat (0.3° C) authorized in waters that exceed the applicable temperature criteria. The applicable temperature criteria are defined in OAR 340-041-0002(4) to mean “the biologically based temperature criteria in OAR 340-041-0028(4), or the superseding cold water protection criteria in 340-041-0028(11)”. Following a temperature TMDL, or other cumulative effects analysis, waste load and load allocations will restrict all NPDES point sources and nonpoint sources to a cumulative increase of no greater than 0.3 degrees Celsius (0.5 Fahrenheit) above the applicable biological criterion after complete mixing in the waterbody, and at the point of maximum impact.

Surrogate Measure

The City of Portland Bull Run drinking water and hydroelectric project has been allocated 0.3 °C of the human use allowance and the equivalent load allocation on the Bull Run River. Monitoring stream temperature, rather than a thermal load, is often a more useful and meaningful approach for reservoir management. For this reason, DEQ is using a surrogate measure to implement the load allocation. OAR 340-042-0028(12)(a) states that anthropogenic sources are only responsible for controlling the thermal effects of their own discharge or activity in accordance with its overall heat contribution. For dam and reservoir operations, the minimum duties provision means that when 7-day average daily maximum temperatures upstream of the reservoirs exceed the applicable criteria plus the human use allowance the dam and reservoir operations must not contribute any additional warming above and beyond those upstream temperatures entering the reservoir. DEQ has developed a surrogate measure temperature target that implements this approach. The compliance point is at the lamprey barrier just downstream Reservoir #2.

The surrogate measure temperature target is the higher of either:

a) The estimated free flowing (no dam) 7DADM temperatures at the lamprey barrier; or
b) The allocated portion of the human use allowance (0.3 deg-C) plus the most restrictive applicable temperature criteria in the Bull Run River between Reservoir #2 and the confluence of the Bull Run River and Sandy River. If the applicable temperature criteria in this reach are updated and approved by EPA, the updated criteria and period when they apply shall be used instead.
    I. 16.3 °C June 16 - August 14
    II. 13.3 °C May 1 through June 15 and August 15 through November 15.

The transition to the 13 deg-C spawning use varies spatially and temporally in the Bull Run River. To be protective of these downstream spawning uses DEQ used the most restrictive temporal period to determine when to apply the spawning criterion for the surrogate measure target.

DEQ developed a regression equation (Equation 3) to predict the free flowing (no dam) daily maximum temperatures at the lamprey barrier downstream of Reservoir #2.

Two different regression approaches were evaluated. The first was to develop a regression to predict the daily maximum directly. The second regression approach is based on the concept that the daily maximum temperature can be calculated from the daily mean plus half the daily diel range as shown in Equation 2:

$$Daily\ Maximum = \ Daily\ Mean + \frac{Daily\ Diel\ Range}{2} \qquad \textbf{Equation 2}$$

Using this framework, a separate regression was developed for prediction of the two components of Equation 2: A regression to predict the daily mean no dam temperatures, and a regression to predict the daily no dam temperature diel range. Rounds (2010) used a similar approach to estimate no dam temperatures in the Willamette Basin.

For regression development, the response variables were derived from segment 7 of the Lower Bull Run No dam (background) CE-QUAL-W2 model for the period of 2014 to 2018. The explanatory variables include

- daily maximum temperature (t_max)
- daily mean temperature (t_mean)
- daily temperature diel range calculated as the daily maximum minus daily minimum (t_range)
- daily mean flow rate (q_mean)

Data for the explanatory variables were obtained from the following USGS gages near the Bull Run Project:

- 14138850 Bull Run River Near Multnomah Falls OR
- 14138900 North Fork Bull Run River Near Multnomah Falls OR
- 14139800 Fir Creek Near Brightwood, OR
- 14141500 Little Sandy River Near Bull Run, OR

Only data between May 1 and November 30 were used for regression development. The daily mean flow rates were transformed by taking the log of each value prior to regression development. Days with missing values were removed. There were 1070 total observations available for the five-year period.

The full set of models are described in Table 1. Model 1 and model 13 use the flow weighted daily mean temperatures or flow weighted daily max temperatures from all gages. The daily mean flow is the sum of flow from all gages.

Table 1 Summary of regression models.

Model #	Response Variable	Explanatory Variables
1	Daily Mean	t_mean + q_mean_log
2	Daily Mean	t_mean_14138850 + q_mean_14138850_log
3	Daily Mean	t_mean_14138870 + q_mean_14138870_log

4	Daily Mean	t_mean_14138900 + q_mean_14138900_log
5	Daily Mean	t_mean_14139800 + q_mean_14139800_log
6	Daily Mean	t_mean_14141500 + q_mean_14141500_log
7	Daily Range	t_range_14138850 + q_mean_14138850_log
8	Daily Range	t_range_14138870 + q_mean_log
9	Daily Range	t_range_14138870 + q_mean_14138870_log
10	Daily Range	t_range_14138900 + q_mean_14138900_log
11	Daily Range	t_range_14139800 + q_mean_14139800_log
12	Daily Range	t_range_14141500 + q_mean_14141500_log
13	Daily Maximum	t_max + q_mean_log
14	Daily Maximum	t_max_14138850 + q_mean_14138850_log
15	Daily Maximum	t_max_14138870 + q_mean_14138870_log
16	Daily Maximum	t_max_14138900 + q_mean_14138900_log
17	Daily Maximum	t_max_14139800 + q_mean_14139800_log
18	Daily Maximum	t_max_14141500 + q_mean_14141500_log

Each set of models were evaluated using the second order Akaike information criterion (AICc) (Sugiura 1978, Hurvich and Tsai 1989, 1991) as well as the coefficient of determination (R-squared). Regression

Table 2 Ranking models fitted to the daily mean temperature.

Model #	AICc	Delta_AICc	log-likelihood
6	1930.02	0	-960.99
1	2358.4	428.38	-1175.18
2	2472.3	542.27	-1232.13
5	2606.86	676.84	-1299.41
3	3081.72	1151.69	-1536.84
4	3628.93	1698.91	-1810.45

Table 3 Ranking models fitted to the daily diel temperature range.

Model #	AICc	Delta_AICc	log-likelihood
12	2684.02	0	-1337.99
8	2865.53	181.51	-1428.75
9	2900.73	216.71	-1446.34
10	3004.85	320.83	-1498.41
7	3015.47	331.44	-1503.71
11	3237.33	553.31	-1614.64

Table 4 Ranking models fitted to the daily maximum temperature.

Model #	AICc	Delta_AICc	log-likelihood
18	2834.19	0	-1413.08
13	3096.87	262.68	-1544.41
14	3254.42	420.23	-1623.19
17	3464.56	630.37	-1728.26

15	3828.7	994.51	-1910.33
16	3919.5	1085.31	-1955.73

The AICc results show the regression models 6 (daily mean) model 12 (daily range) and model 18 (daily max) utilizing data from the Little Sandy River gage 14141500 had the best fit based on AICc. After combining model 6 and 12 using the framework from Equation 2, the overall coefficient of determination was 0.97 and the residual standard error was 0.91. The coefficient of determination for the daily maximum model (model 18) was also 0.97and residual standard error was 0.91. Based on these metrics both models had the same goodness of fit.

Reviewing the residuals, the range between the 1st and 3rd quartile residuals for the combined models 6 and 12 was slightly smaller (1.1541) than the range for model 18 (1.2093) implying combined models 6 and 12 had a marginally better fit for at least 50 percent of the data points. The median residual for combined models 6 and 12 was slightly positive (0.1630) where model 18 had a slightly negative residual (-0.0767) implying the combined models 6 and 12 is slightly under predicting the daily maximum temperatures. While small, the under prediction represents a margin of safety so DEQ choose to utilize combined models 6 and 12 using daily mean and daily range from the Little Sandy River as the final model for prediction of the no dam temperatures. Equation 3 represents the combined final form.

Equation 3

$$T_{Max} = 0.1405173 + 1.1572642\overline{T_{LS}} + \; -0.3588068 \log \overline{Q_{LS}} + \left(\frac{3.7557135 + 1.1668769 T_{dLS} + -0.5969993 \log \overline{Q_{LS}}}{2}\right)$$

Where,

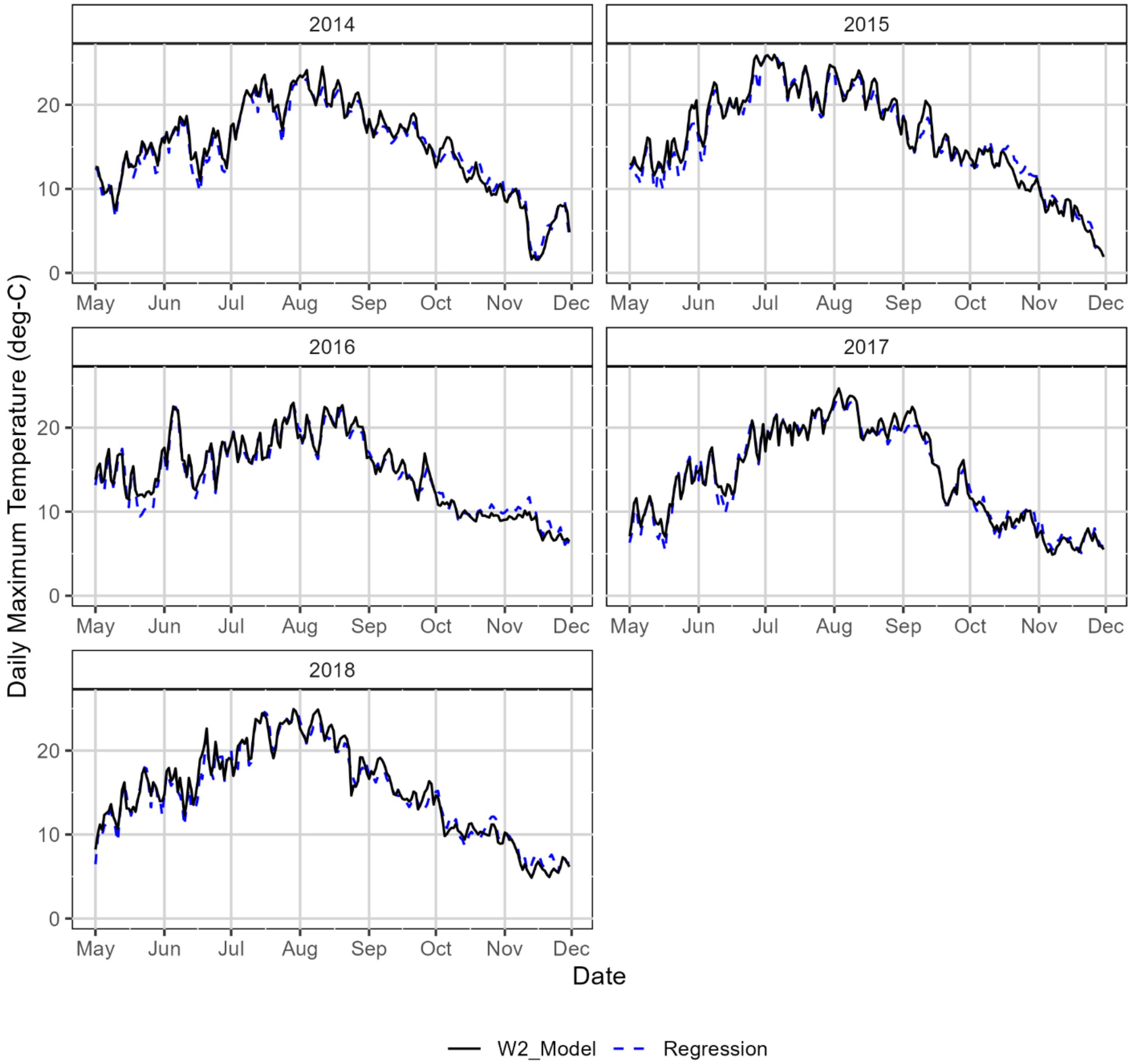
$T_{Max} =$ The no dam daily maximum stream temperature at the lamprey barrier downstream of Reservoir #2. (Lower Bull Run River model segment 7)

$\overline{T_{LS}} =$ The daily mean temperature (°C) at USGS Gage 14141500 Little Sandy River Near Bull Run.

$\overline{Q_{LS}} =$ The mean daily discharge (cfs) at USGS Gage 14141500 Little Sandy River Near Bull Run.

$T_{dLS} =$ The daily temperature range (°C) calculated as the daily maximum minus the daily minimum at USGS Gage 14141500 Little Sandy River Near Bull Run.

Figure 1 presents a plot of the predicted daily maximum at the lamprey barrier compared to the daily maximum derived from the CE-QUAL-W2 model for years 2014 – 2018.



References

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