Total Maximum Daily Loads for the Lower Columbia-Sandy Subbasin

Technical Support Document Appendix D: Bull Run Model Report

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State of Oregon
DEQ Department of Environmental Quality

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1. Overview

This report documents changes made to the pre-existing Middle River model and Lower River models 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 conditions data were performed to update the models with 2016 meteorological and flow conditions. Changes to model parameters were executed to modernize certain model aspects to increase model stability, bring parameter values within plausible bounds, and improve temperature calibration for 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 achieved temperature water quality standards,
- As model inputs for tributary inflows or upstream boundary condition,
- To assess model performance and goodness-of-fit by comparing observed stream temperature data to predicted stream temperature data

For the 2016 model, continuous water temperature data were gathered from various sources, including:.

1) Portland Water Bureau (PWB) data loggers at the diversion pool (location of headworks).
2) PWB data loggers at the Lamprey barrier (~300 ft downstream of the diversion pool).
3) PWB data 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 released into the Bull Run River ~250' upstream of the Lamprey barrier).
4) USGS temperature records for the stations: 14138850, 14139800, 14138900, 14138870, 14140020, and 14141500.
5) Three temporary *in-situ* probe installations located at: South Side Bridge (PWB_BR_SS, Bull Run Bowman's Bridge (PWB_BR_BWMN), and Bull Run at Dodge Park (PWB_BR_DODGE)

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
14141500	Little Sandy River	45°24'56"	122°10'13"	USGS
14140020	Larson's Bridge	45°25'55"	122°11'39"	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	Bull Run South Side Bridge	45.437752	122.178867	PWB
PWB_BR_BWMN	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 2 and Table 3) were used to support boundary condition flow inputs, and generation/validation of ungaged streamflows along the model domain.

Table 2: Continuous flow monitoring 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 measurements sites in the Bull Run used to support model development

Site	Latitude	Longitude	Date	Time
Bear Creek	45.486866	122.083788	Years 1979-1991	Various
Deer Creek	45.491111	122.059411	Years 1979-1991	Various
Cougar Creek	45.490428	122.061903	Years 1979-1991	Various
Camp Creek	45.460585	122.099608	Years 1979-1991	Various
Fivemile Creek	45.482657	122.092064	Years 1979-1991	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 are 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 used 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. These data were used to generate 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 positions of *in-situ* probes and stream gages and their relative locations 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 and the readily available mapping of the stream from OpenMaps.

Step 2. Lengths and/or angles were adjusted the least possible amount needed 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) was calculated in GIS for every segment polygon generated in step 2, and the area was divided by the associated length of the stream segment (in meters) to generate the average channel width (in meters).

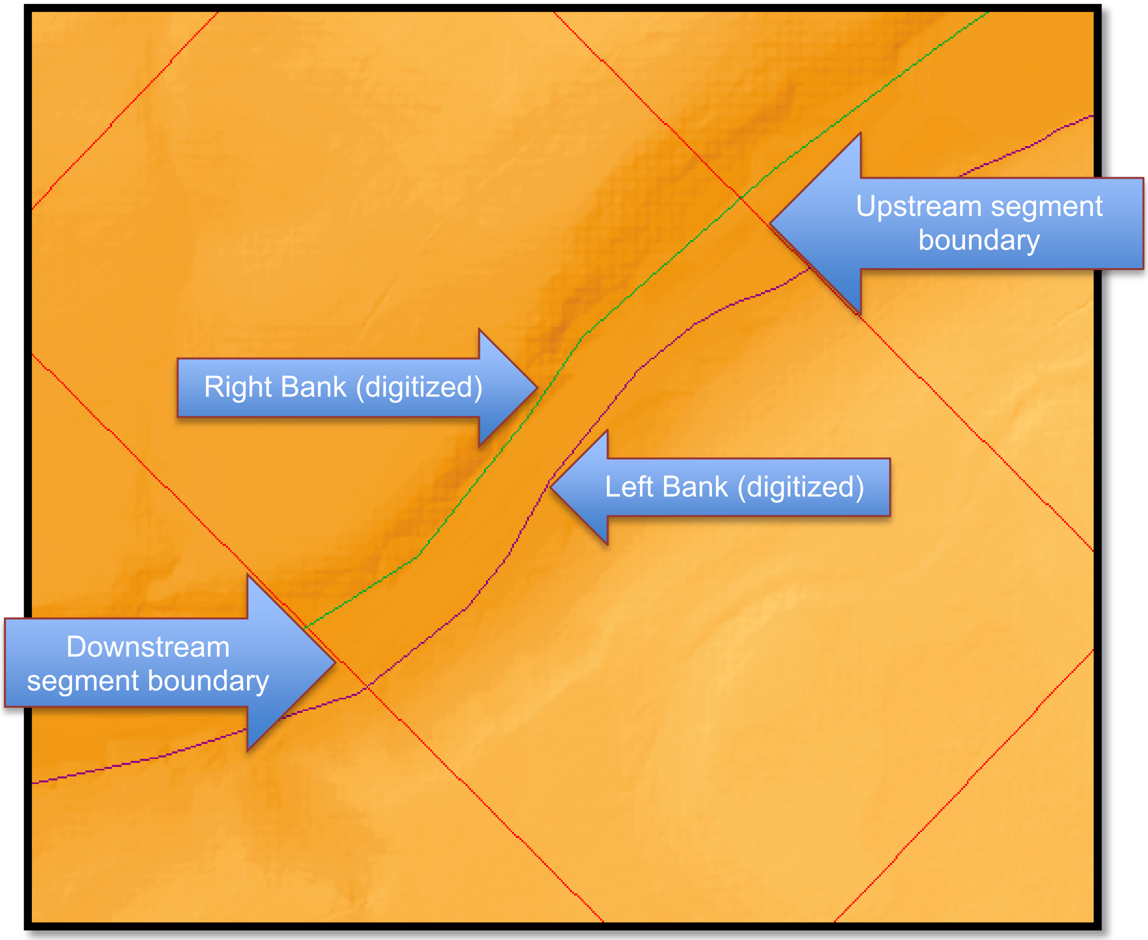

Figure 1: Example of digitized channel, flowline, and stream nodes

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 generally 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 cause most of the model instability, which kept CEQUAL from completing a simulation, regardless of the maximum time step.

To combat this issue, model 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 to (i) increase the number of layers near the channel bottom and (ii) gradually increase the vertical interval spacing as the channel widens. This process generally created many small layers on the bottom of the channel, which appeared to significantly improve model stability during low flows.

During calibration, many different sets of vertical intervals were tested; the final version provided good model stability for all years and scenarios tested, and kept the total number of layers small enough that the model did not take an unnecessarily long time to run. Table 4 shows the vertical layer intervals used in the final calibration, along with several interval sets that were tested but ultimately not used. Note that for the Lower River Model, water body 4 used 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

2.3.3 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 to bring the channel geometry into agreement with modern mapping of the stream. In these cases, neither the slope nor 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 have a substantial impact on the flow velocity. The SLOPEC parameter was changed considerably and served as a tuning factor for the model. By using a conservative tracer in the model, concentrations of tracer were released to coincide with the release of cold-water pulses during the 2016 calibration. Based on 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 was computed.

Several changes were made to the model to attempt to improve the time of travel. First, by reducing the Manning’s n values from the original values (as high as 0.21) to 0.07 based on TetraTech model review recommendations, the water velocities increased greatly. To reduce these velocities, the SLOPEC values were reduced stepwise across the model domain to attempt to match the travel time between Headworks and Larson's bridge tracer timing to expected tracer timings. During this process, it was discovered that the internal weirs, which served as pool/riffle controls in the model, had effectively caused "damming" of cold water in the channel. This was evident because calculated conservative tracer travel times were exceptionally long between various segments that were split by internal weirs. To address this issue, the top weir elevations were reduced in 0.5m increments until the effect on tracer timing was no longer observed to be erroneous. SLOPEC values were reduced to their current value (0.0016) after multiple model calibration runs via an iterative process of adjusting internal weirs and SLOPEC values while keeping Manning's n values constant.

Figure 2 shows example conservative tracer test results including tracer timing from the original model calibration (blue) alongside updated modern versions (green and red). Note the effect of internal weirs between segments 1&2, 4&6, and 9&10 from the original model calibration, evident in drastic travel time increases (due to the internal weirs).

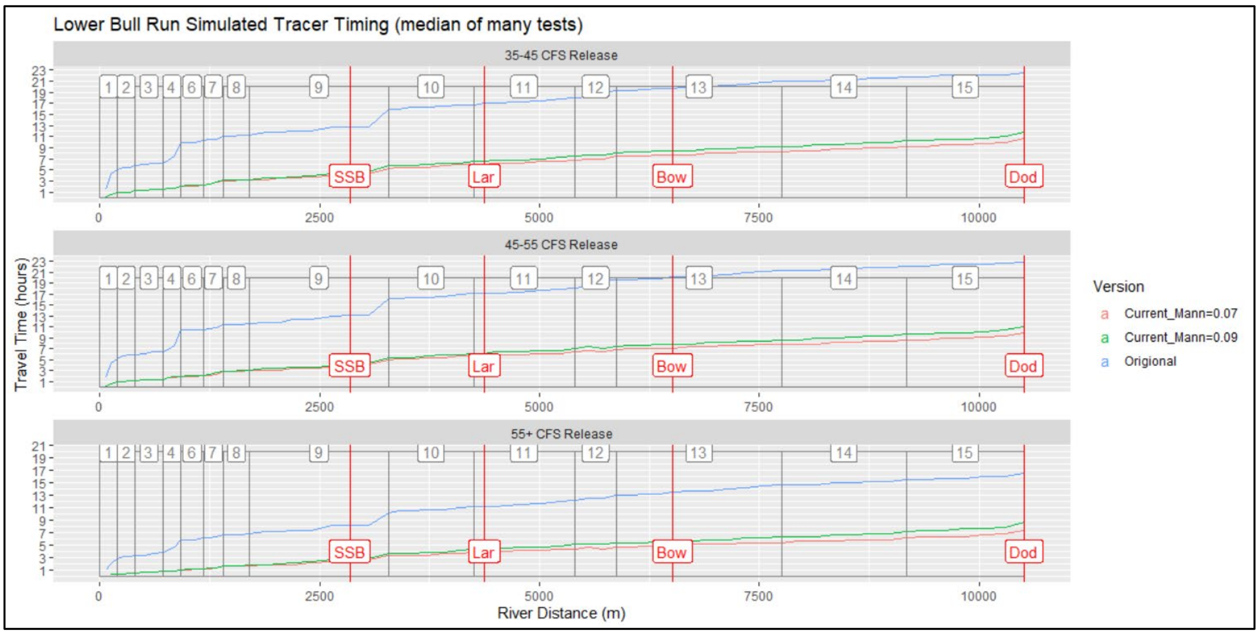

Figure 2: Examples of 2016 simulated tracer tests on different versions of the Lower River model

2.3.4 Topographic shade angles

The topographic shade angle (θ_T) represents the vertical angle to the highest topographic feature as measured from a flat horizon. At this angle and smaller, a topographic feature will cast a shadow over the stream node as the sun moves behind it. Topographic shade angles were calculated in R using **Equation A1** with sampled geometry statistics from ArcMap and solving for maximum angles of effect. Elevations were sampled from available LiDAR data (Sciences, 2014). The maximum topographic shade angle in each model direction for each stream node was found by sampling every raster cell out to 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.

2.3.5 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 angles were calculated using **Equation A1** in R with sampled geometry statistics from ArcMap and solving for maximum angles of effect. Elevations were sampled from available LiDAR data (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 that conformed to the shape of the shoreline and extended away from the stream. Vegetation was sampled out to 100m to find the highest vertical angle.

2.3.6 Land cover mapping

2.3.6.1 Modified "No Dam" digital elevation model (DEM)

A terrain dataset of Reservoirs 1 and 2 was created from bathymetry elevation data (Associates, 1991) and LiDAR point cloud data (Sciences, 2014). The two reservoir terrain datasets were combined to create a continuous digital elevation model (DEM) from Station 18 to Diversion Pool as a 3-ft grid in NAVD88. Dam structures were removed from landscape data to reconstruct the river channel and 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.

2.3.6.2 Historic river channel

The inundated historic channel centerline of the Bull Run River was hand-digitized from the LiDAR data (Associates, 1991) by connecting the lowest value of each horizontal transect. 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 in 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.

2.3.6.3 Land cover for Restored Conditions and No Dam scenarios

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 were 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 scenarios. 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).

2.3.7 Derived tributary flows

Tributary flow derivation followed a process developed by PSU (Annear, Wells, & Evonuk, 1999) (pages 61-67).

2.3.8 Derived tributary temperatures

Tributary temperature derivation followed a process developed by PSU (Annear, Wells, & Evonuk, 1999) (pages 67-68).

3. Model setup and calibration

3.1 Lower & Middle River models

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 50 m and 250 m 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 0.1 m and 4.0 m. 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 were 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.

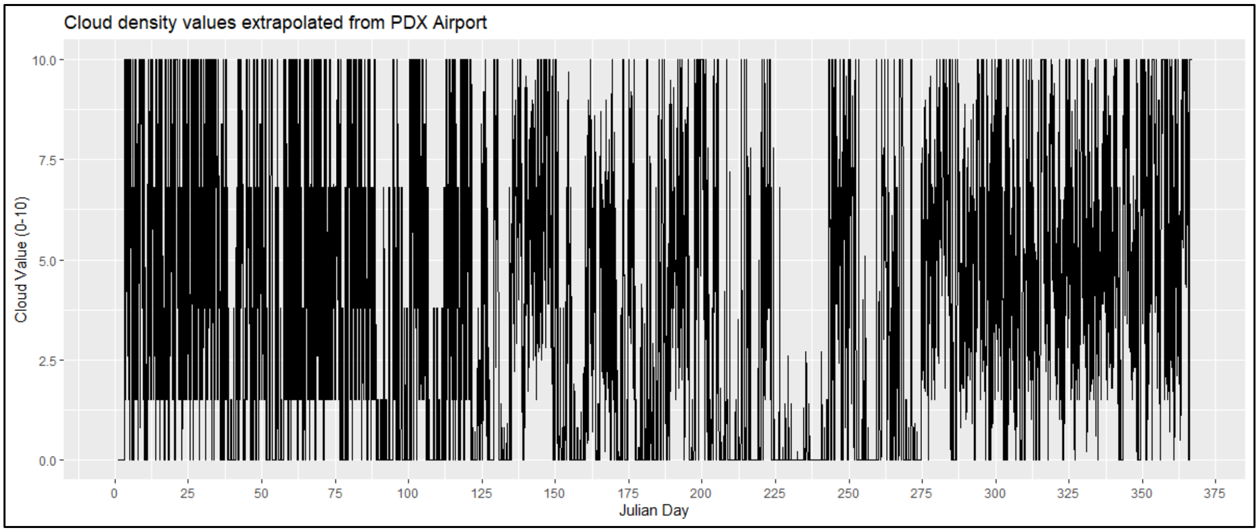

Figure 3: Cloud data, PDX airport

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

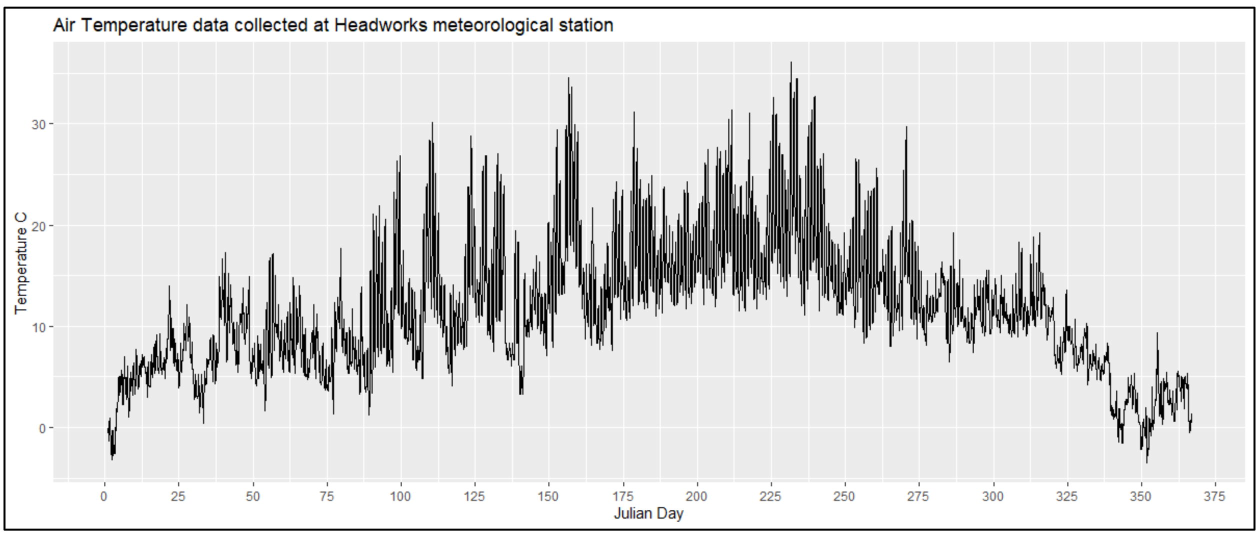

Figure 4: Air temperature data from Headworks/Dam 2

Dew point temperature data were not collected at the Headworks/Dam2 station but derived from air temperature and relative humidity with an R function (weathermetrics package "humidity to dewpoint")

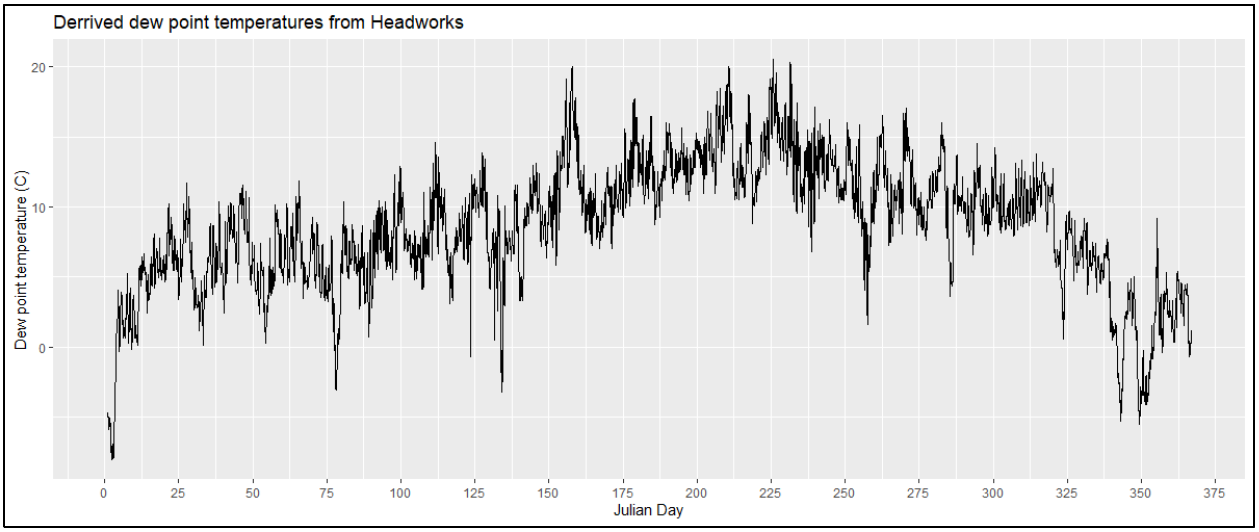

Figure 5: Derived dew point temperature data

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

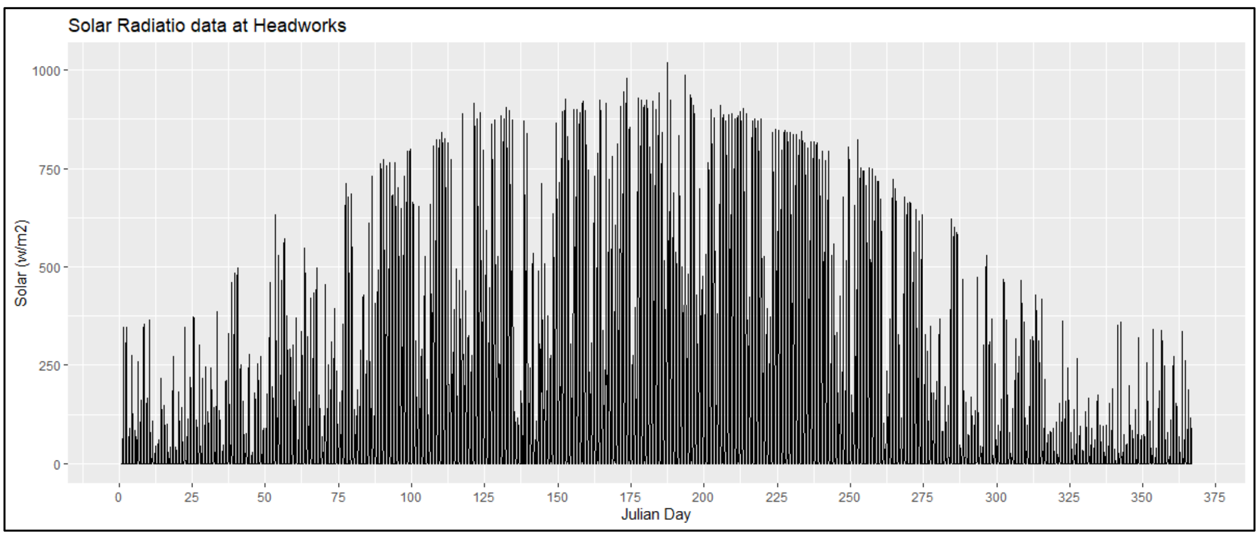

Figure 6: Derived solar radiation at Headworks

3.1.4 Temperature inputs: Tributaries and boundary conditions

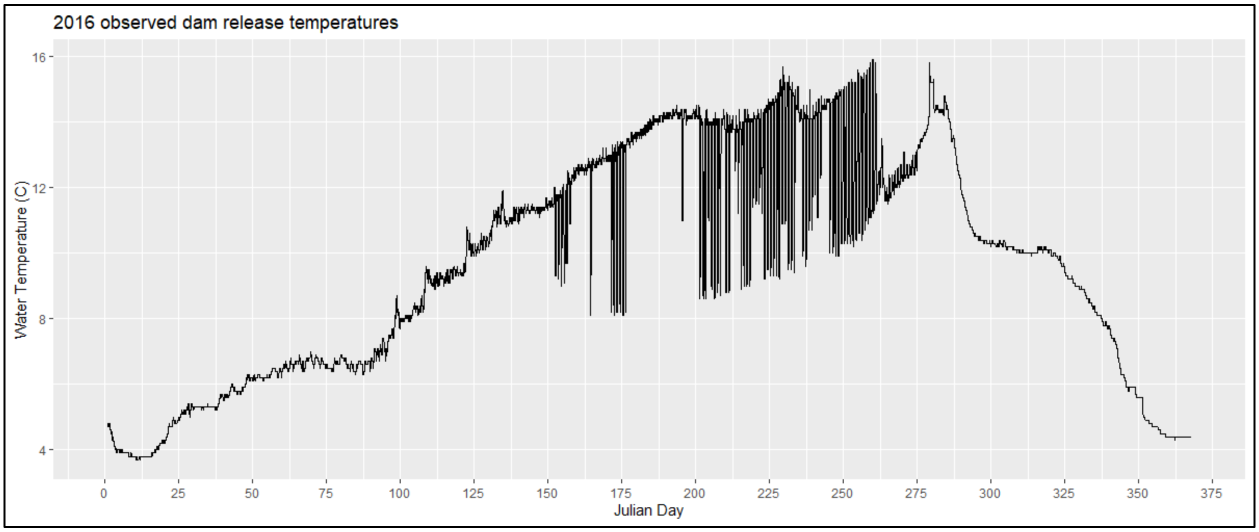

Figure 7: Observed 2016 dam release temperatures (used for model calibration)

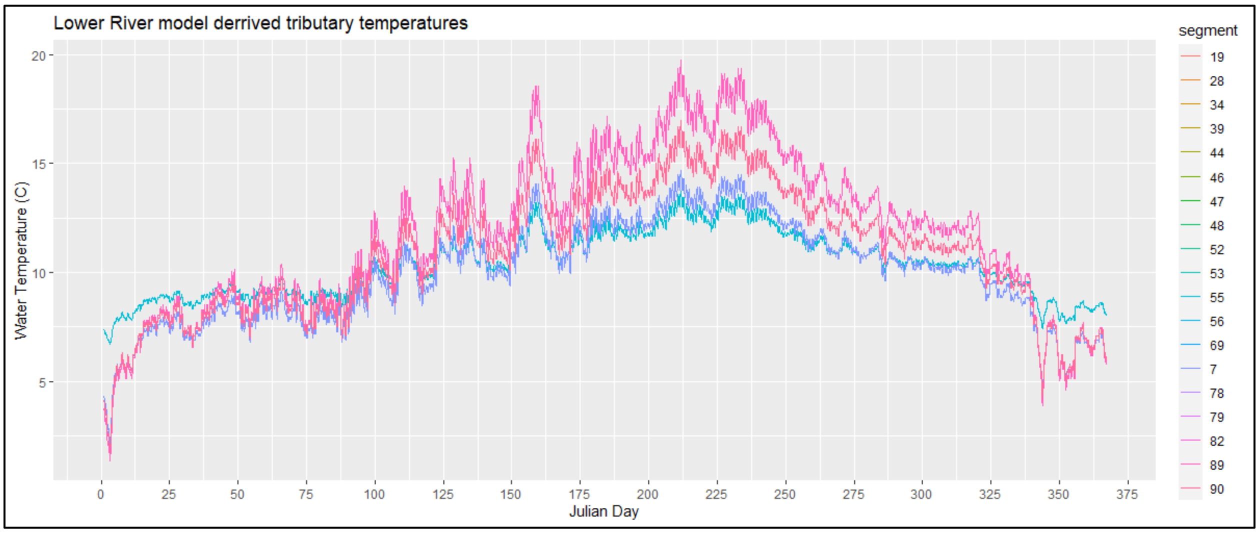

Figure 8: Derived tributary temperatures used for both calibration and scenario model runs

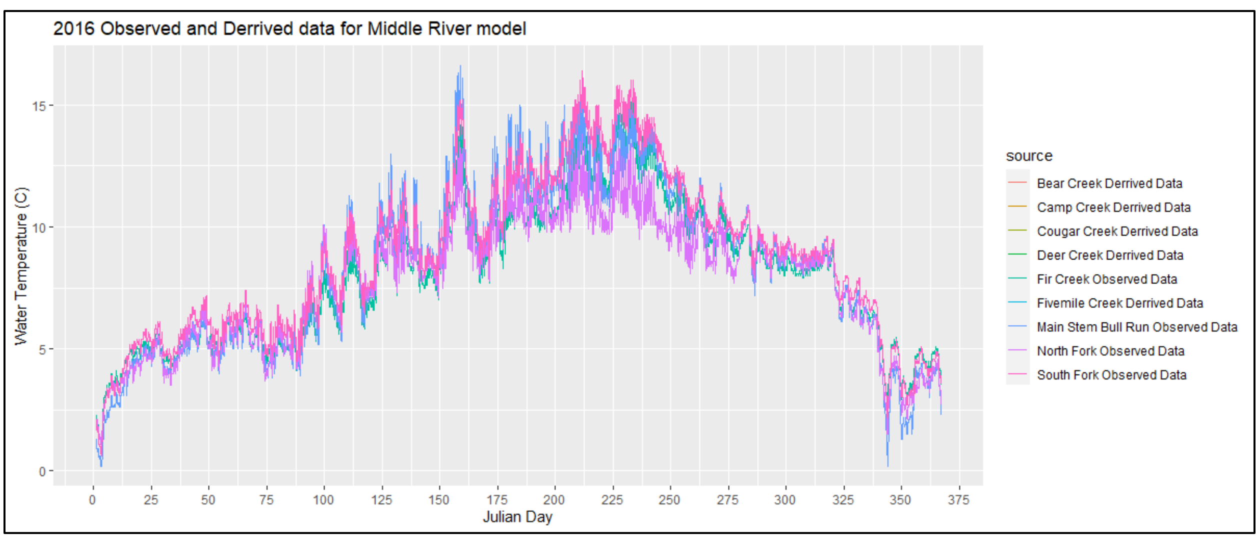

Figure 9: Derived and observed tributary temperatures used for the Middle River model

3.1.5 Flow inputs: Tributaries and boundary conditions

Model setup tributary and boundary condition flow rates are presented in Figure 10 and Figure 11.

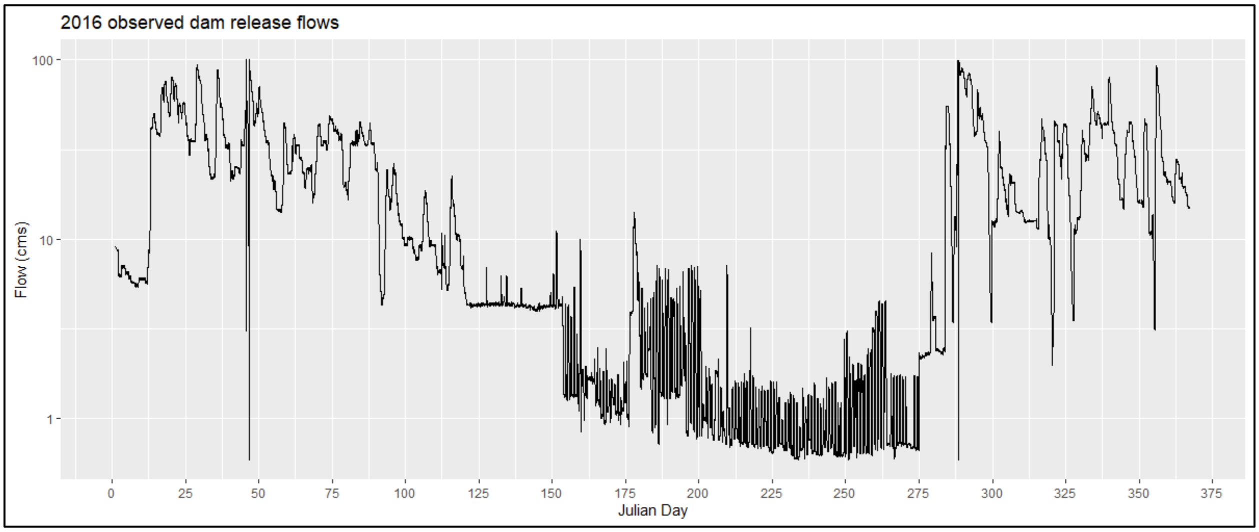

Figure 10: 2016 observed releases from Dam 2

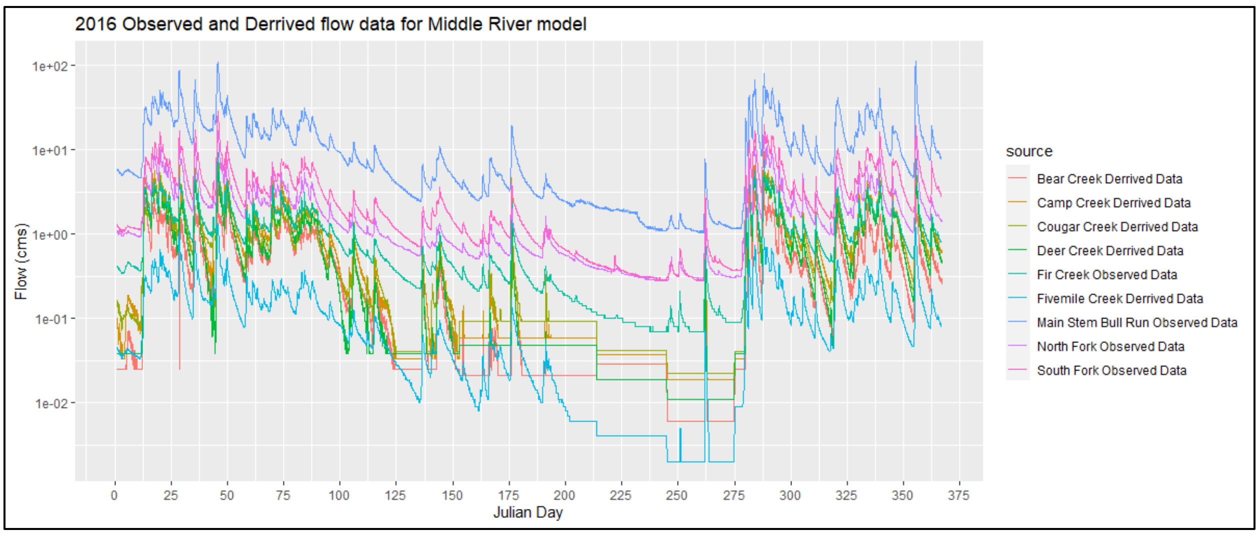

Figure 11: Observed and derived flows for the Middle River model

3.1.6 Model setup: Groundwater/accretion/distributed flow rates

Distributed/accretion/groundwater flows were input as tributaries in the Middle and Lower river model.

3.1.7 Model setup: Withdrawal rates

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

3.1.8 Model setup: Point source inputs

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

3.1.9 Model setup: Topographic shade angle inputs

Table 5: Topographic shading angles for Middle River model

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

3.1.10 Model setup: Stream channel elevation, gradient, and roughness

Table 7: Lower River Model - Channel bottom elevation, slope, orientation angle, and roughness

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

Segment	Channel bottom elevation (m)	Slope	Angle	Mannings n
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, and roughness

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

Segment	Channel bottom elevation (m)	Slope	Angle	Mannings n
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

3.1.11 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.

3.1.12 Model calibration results: Flow

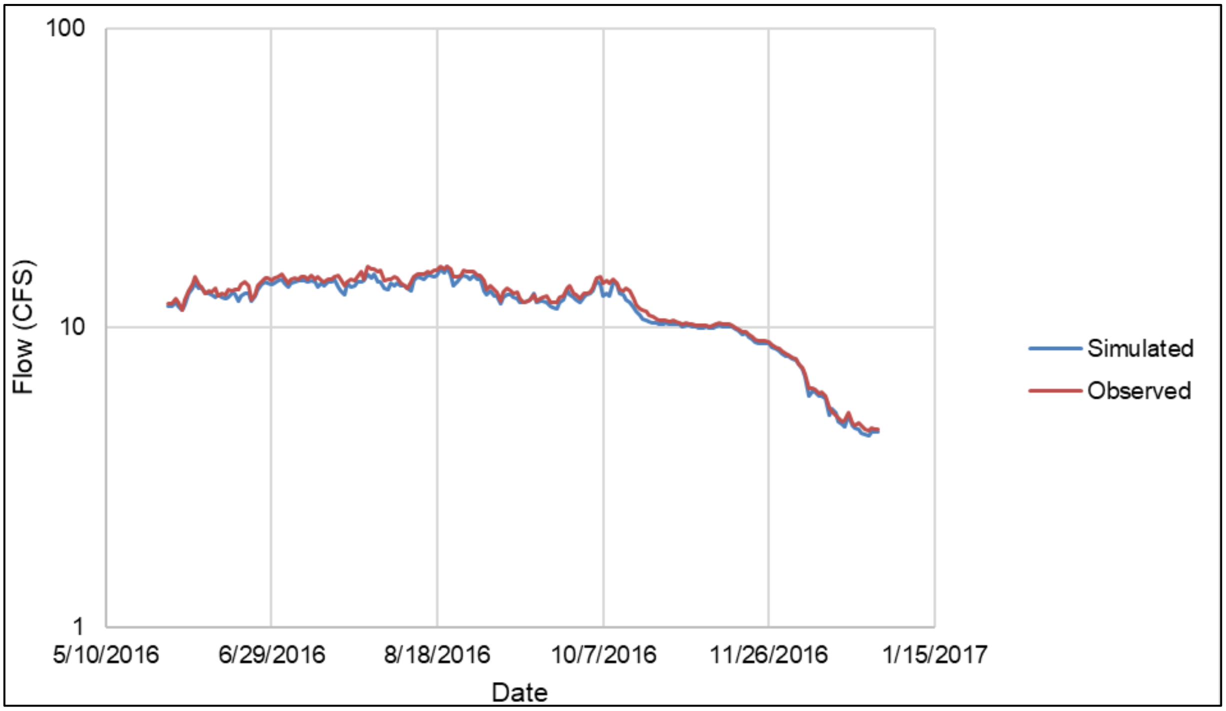

Figure 12. Observed and modeled mean daily flow rates at Bowman's Bridge (USGS 14140000), 2016 model calibration period

Table 9: Goodness-of-fit statistics comparing modeled and observed daily flows at Bowman's Bridge (USGS 14140000) , 2016 model calibration period

Daily flow statistics			
Bias	**MAE**	**RMSE**	**NSE**
-0.44	0.45	0.57	0.97

3.1.13 Model calibration results: Temperature

Table 10: Goodness-of-fit statistics comparing modeled and observed daily maximum temperatures at four sites from 6/1/2016 - 10/15/2016

Daily temperature statistics				
Site	**Bias**	**MAE**	**RMSE**	**NSE**
PWB_BR_SS	0.07	0.49	0.68	0.61
USGS Larson's Bridge	-0.32	0.73	0.62	0.95
PWB_BR_BWMN	0.14	0.60	0.81	0.74
PWB_BR_DODGE	-0.02	0.55	0.89	0.69

Figure 13: Observed and modeled daily maximum temperatures at four stations, 6/1/2016 - 10/15/2016

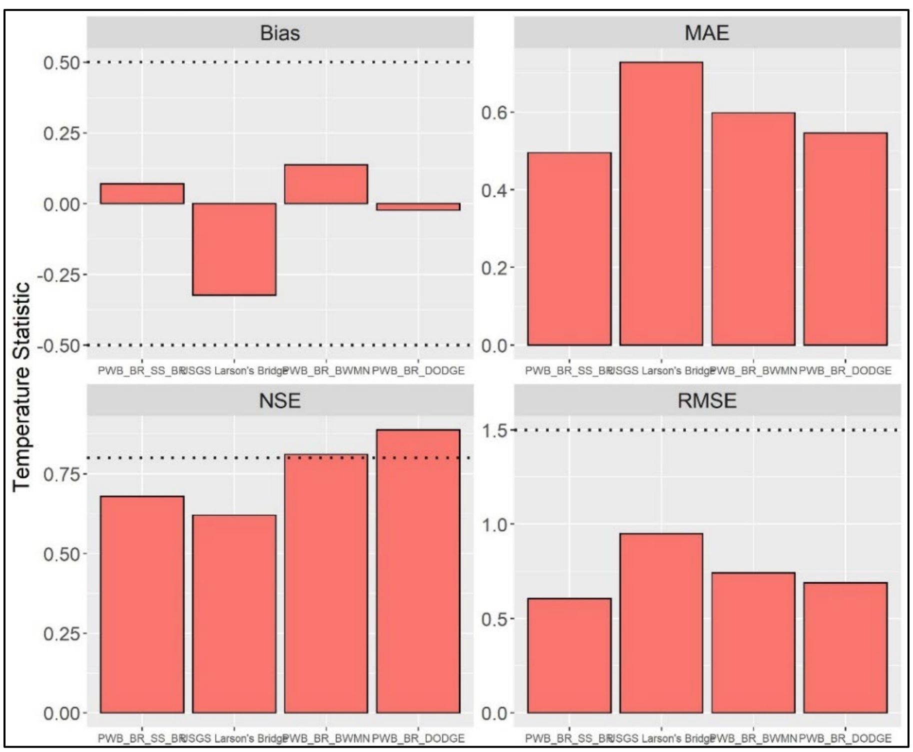

Figure 14: Goodness-of-fit statistics, observed vs. simulated daily maximum water temperatures, four stations for the critical period (6/1/2016 - 10/15/2016)

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 scenarios utilized 2016 weather 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 notable 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 shows the relative locations of Branch 1 and 2 in the Lower River model. Here, Branch 1 (aka 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 it via a valve. In addition, reservoir water can be routed either to the diversion pool or just past the diversion pool in Branch 2. Branch 2 is a channel stretch with an upstream boundary at the downstream side of the diversion dam and a downstream boundary at a weir called the "Lamprey barrier". Since all flows routed downstream are accounted for at the Lamprey barrier (both flow and temperature), this is a better point to use as the Lower River model's downstream boundary than Branch 1 flow plus its bypass, the latter of which would introduce error and complexity. Thus, the Lower River model downstream boundary is based primarily on flow and temperature data from the Lamprey barrier (Figure 15, locations 3 & 4). Since this model includes Branch 1, which is important to scenarios that simulate "no dams", instead of rebuilding the model to exclude Branch 1, the upstream boundary condition was set at Branch 2. Thus in the 2016 calibration, Branch 1 is basically a stagnant pool without inputs or outputs; all simulated Branch 1 results (model segment 2, 3, & 4) should be ignored.

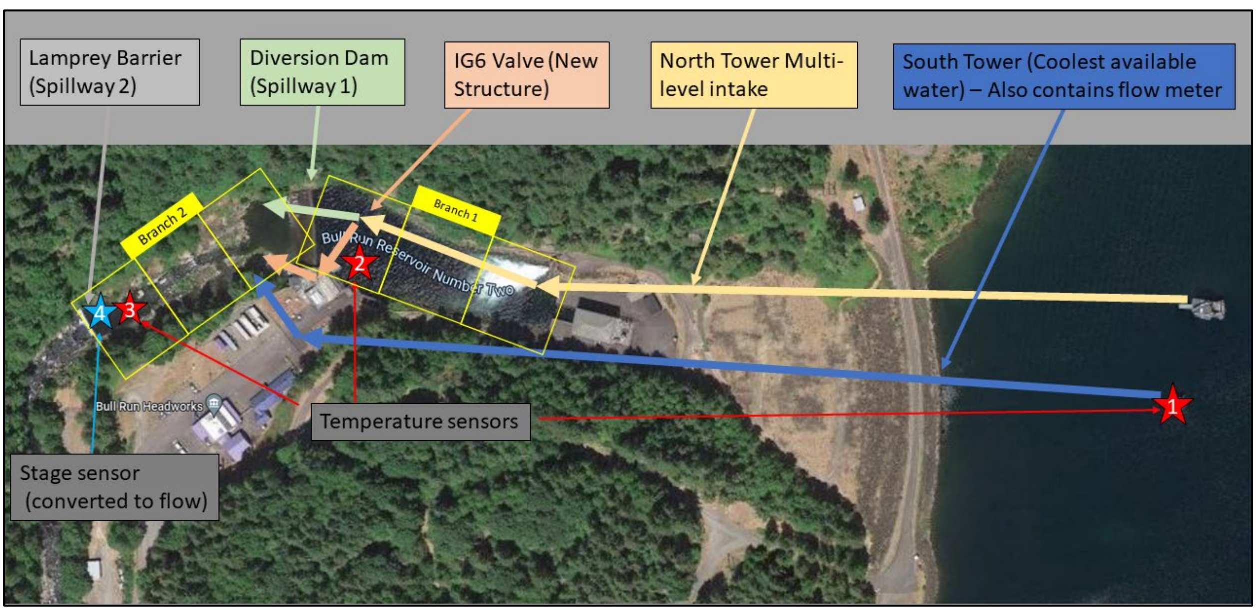

Figure 15: Headworks area of the Lower River model

2016 Current Conditions – This scenario considered both the Middle River model and Lower River models running in tandem. The Current Conditions model utilized natural flows in the Middle River by parameterizing its channel morphology with best estimates of natural conditions, i.e., without the two reservoirs and dams. The current conditions shade file included vegetation elevations measured with LiDAR where available, and with Restored Conditions scenario vegetation elevations where existing reservoirs are located (mostly within the Middle River Model). The Middle River Model's temperature and flow outputs at spillway 4 were used as inputs for the Lower River model at Tin_BR1 and Qin_BR1, respectively.

2016 Restored Conditions – This scenario considered both the Middle River model and Lower River models running in tandem. The Restored Conditions model utilized natural flows in the Middle River by parameterizing its channel morphology with best estimates of natural conditions, i.e., without the two reservoirs and dams. The restored conditions shade file considered both current and restored vegetation types and elevations; the higher of the two was used to compute vegetation shade angles. Since the vegetation shade angles are based on vegetation height at a distance from centerline, vegetation elevations are not always higher in the restored conditions file than in the current conditions file, but the associated angle that reflects elevation and distance from the centerline is always greater or equal in the restored conditions file. Temperature and flow outputs from the Middle River Model at spillway 4 were used as input data for the Lower River model at Tin_BR1 and Qin_BR1 respectively.

4.2 Scenario results

Two different scenarios were simulated using the Middle and Lower river models. Scenario 1 used a shade file representing "No-Dam Conditions" (current vegetation heights). Scenario 2 used a shade file representing Restored Conditions (greater of restored or current vegetation height)

Comparisons across the model domain for both scenarios showed minimal differences in modeled temperature results. For the two scenarios, the Middle River model shade files were nearly identical as most Middle River Model vegetation heights comprised the Restored Condition vegetation heights since they were co-located with/under the current day reservoir. Thus in both scenarios, the Lower River model's upstream boundary condition data were nearly identical. The Lower River model's maximum daily temperature results for the two scenarios did not differ substantially. See Sections 4.1 and 4.5.2 of Appendix A to the Technical Support Document for results and additional details.

The daily maximum water temperature results for the Middle River and Lower River models were assessed as a combined longitudinal set. Starting at the upstream Middle River model upstream boundary, the daily maximum water temperatures for each model segment were converted to daily maximum water temperatures for each segment's *centroid* location by extrapolating geographic data from the relevant bathymetry data. Side branches from both models were omitted from this analysis as their effects were already accounted for at their respective mainstem confluence locations.

Figure 16 shows daily maximum water temperatures along the combined longitudinal model domain for various dates in the June to mid-October critical period. Peak temperatures are evident just upstream of the headworks (i.e., Reservoir 2's location) in the Middle River, with maximum summertime daily water temperatures above 22°C. Toward the downstream end of the Middle River model, temperatures generally decrease before reaching the boundary (headworks) and continue to decrease through the Lower River model domain, on average and over most represented days.

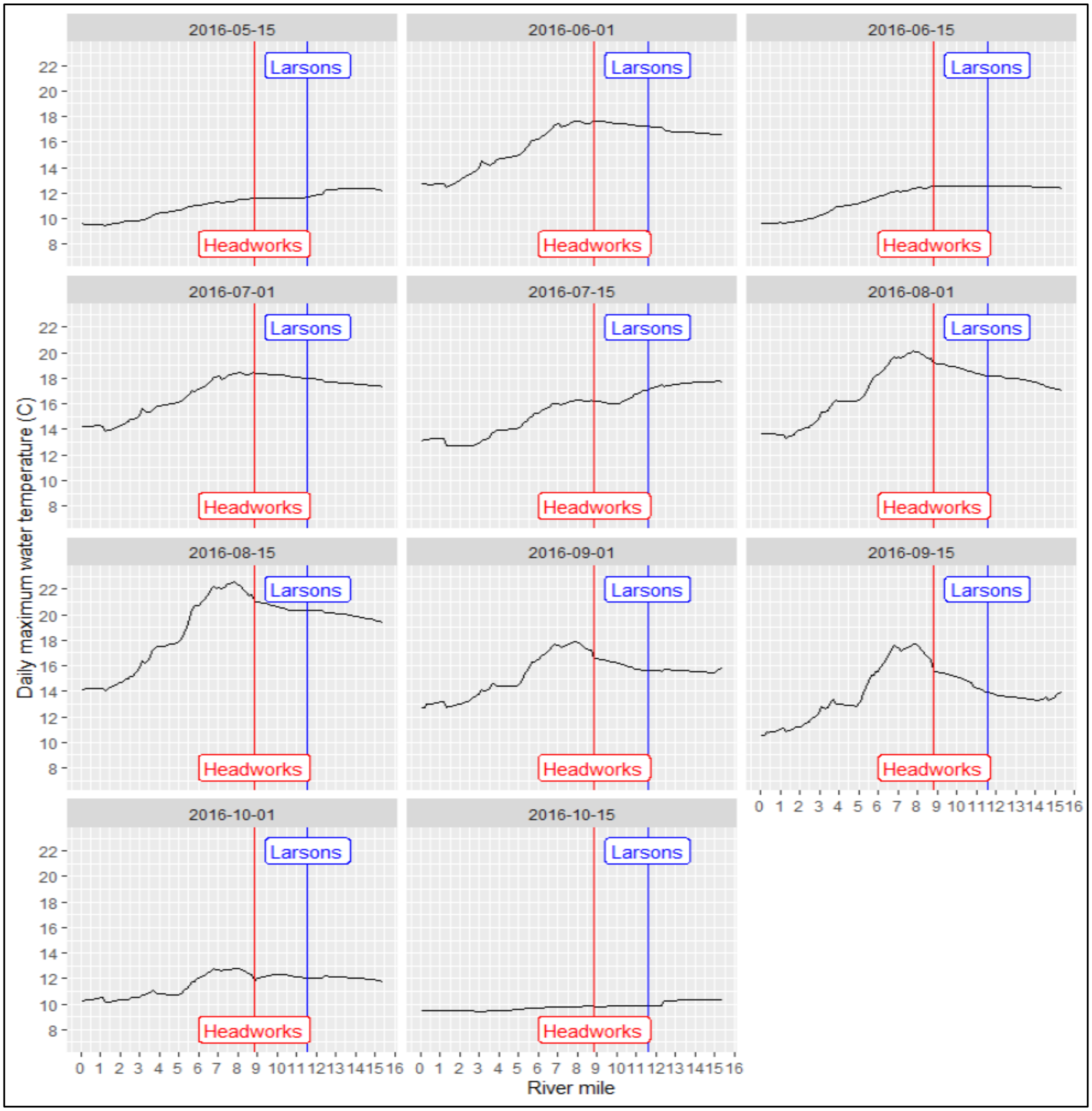

Figure 16: Restored Conditions results, select 2016 dates, Middle and Lower River models

5. References

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