Upper Deschutes and Little Deschutes Subbasins TMDLs

Context for Reviewing Watershed Sciences Temperature Modeling Reports

Overview and Scope

The Oregon Department of Environmental Quality (DEQ) contracted with Watershed Sciences, Inc. to conduct some of the preliminary temperature modeling analyses in the Upper Deschutes, Little Deschutes and Crooked River Subbasins. This work was done under two different contracts (2007-2008 and 2008-2011) and was designed to support TMDL development by DEQ at a later date. This work was funded by the U.S. Environmental Protection Agency.

Heat Source is the computer model DEQ uses to simulate stream thermodynamics and hydrology. Under the first contract, Watershed Sciences calibrated Heat Source temperature models for Tumalo Creek, Whychus Creek, and Deschutes River between Wickiup Reservoir and Lake Billy Chinook. Under the second contract, Watershed Sciences did additional modeling on Metolius River, Little Deschutes River, Crescent Creek, Deschutes River above Wickiup Reservoir and a number of streams in the Crooked River Subbasins. Under these contracts, Watershed Sciences wrote a series of reports providing background material on the data used in the Heat Source models and on model calibration.

DEQ began work on TMDL development in the Upper Deschutes and Little Deschutes Subbasins in 2011, with the expectation of completing these TMDLs by the end of 2012. During TMDL development, it is possible that some of the calibration and flow modeling results presented in this Watershed Sciences reports may be modified. The existing models may be revised to incorporate more site-specific input gathered from local stakeholders during the advisory committee process and/or public review. DEQ is not working on TMDLs in the Crooked River subbasins at this time so the information provided in the Watershed Sciences reports for the streams in this area are very preliminary in nature at this time.

The attached report describes the model calibration done under the second contract. Model calibration was identified as “Task 3” in the contract with Watershed Sciences. Until completion of the TMDLs, this document provides useful information about preliminary calibration of the Heat Source models.

Model Limitations

The temperature modeling effort undertaken in the Upper and Little Deschutes Subbasins provides some very interesting and meaningful results. However, it is worth identifying up-front some of the specific limitations of the models and the appropriate scale in which to interpret the results. Stream temperature dynamics are complex and analytical methods have limitations.

- <u>Heat Source simulations are only valid for the simulation time period</u> (which corresponds to the time period that ground level data was collected). Watershed Sciences calibrated the Heat Source models in the Upper and Little Deschutes Subbasins based on conditions in summer 2000 or summer 2001. It would not be appropriate to use these models to simulate stream temperature in another year without re-calibrating the model with input data from that other year.

State of Oregon
Department of Environmental Quality

Water Quality
Eastern Region
Bend Office
475 NE Bellevue, Suite 110
Bend, OR 97701
Phone: (541) 388-6146
(866) 863-6668
Fax: (541) 388-8283
Contact: Bonnie Lamb

www.oregon.gov/DEQ

DEQ is a leader in restoring, maintaining and enhancing the quality of Oregon’s air, land and water.

Last Updated:
04/02/2012
By: Bonnie lamb

Simulating other seasons or years introduces un-measurable uncertainty via a combination of climate, flow, and boundary condition assumptions. In addition, the existing flows in portions of Tumalo Creek and Whychus Creek were quite small (i.e. less than 10 cfs). Small flows equate to temperatures that are extra sensitive to climate and effective shade. Certain features such as vegetation growth or changes in flow can be simulated for the same time period, assuming that all other calibration inputs remain unchanged.

- Heat Source is not a groundwater model. The model has simulation inputs for groundwater and hyporheic exchange and attempts to include them in the heat flux, but Heat Source does not model far-field groundwater processes. Complex and wide-scale water table processes are not accounted for.

  Heat Source only includes groundwater contributions to surface water that were measured during the simulation time period. Alder Springs was the only spring where flows were measured during field data collection. Other springs were identified in the thermal infrared imagery and a flow mass balance was derived for those areas. The contain estimated flows and temperatures of springs that were observed in the TIR data. The uncertainty associated with such inputs is not directly quantifiable and therefore should not be used for simulating different spring flow scenarios.

- Heat Source results are only as good as the field data. Measured temperatures, flows, velocities, widths, effective shade, substrate, and other data are used as model validation. When these data types are sparse or absent, the user is required to make assumptions regarding channel morphology and hydrology. These assumptions introduce uncertainty and increase the model error. For some reaches there was limited field data due to lack of access. Verifying model accuracy in these reaches is difficult and is a source of uncertainty.

Deschutes Basin TMDL Modeling - Task 3

Stream Temperature Model Calibration

Contract No. 046-09 March 2011

Prepared for,

Oregon Department of Environmental Quality
475 NE Bellevue Dr., Suite 110
Bend, OR 97701

State of Oregon
Department of Environmental Quality

Prepared by,

Watershed Sciences, Inc.
529 SW Third Avenue, Suite 300
Portland, OR 97204

Watershed Sciences

Table of Contents

Introduction

This document summarizes the model inputs, assumptions, and calibration results for the streams shown in Figure 1.

The figures presented within this introduction are supplementary to the Task 2 report, *Data Summary & Digitization of Streams, Banks, and Riparian Corridor*.

Figure 1 displays the stream reaches where temperature and/or effective shade was simulated.

Figure 1 – Simulated stream reaches.

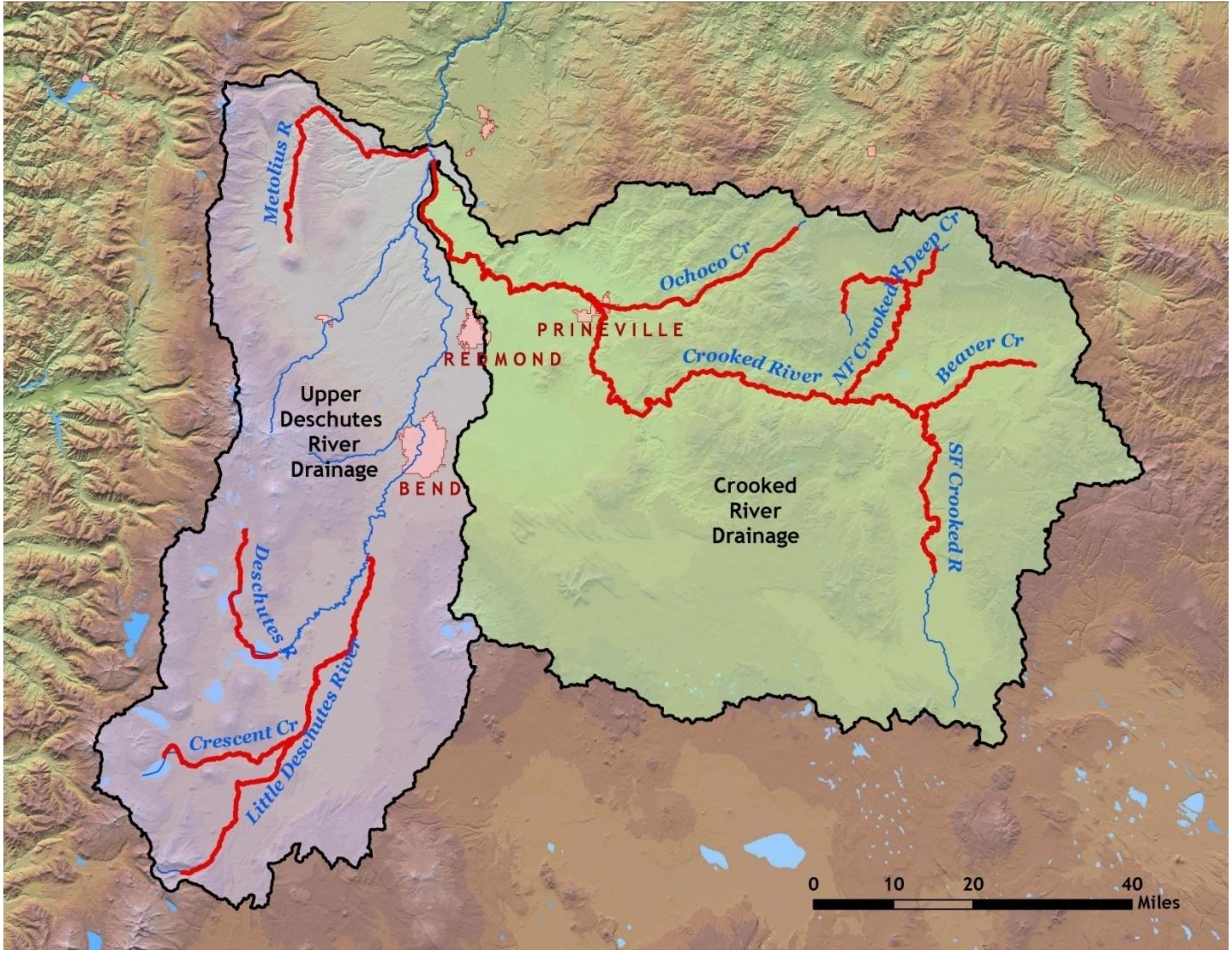


Figure 2 shows the U.S. Forest Service remote automated weather stations (RAWS) locations. Hourly air temperature, wind speed, relative humidity, and solar radiation data was obtained from the RAWS stations and used as model input.

Figure 2 – RAWS climate station locations.

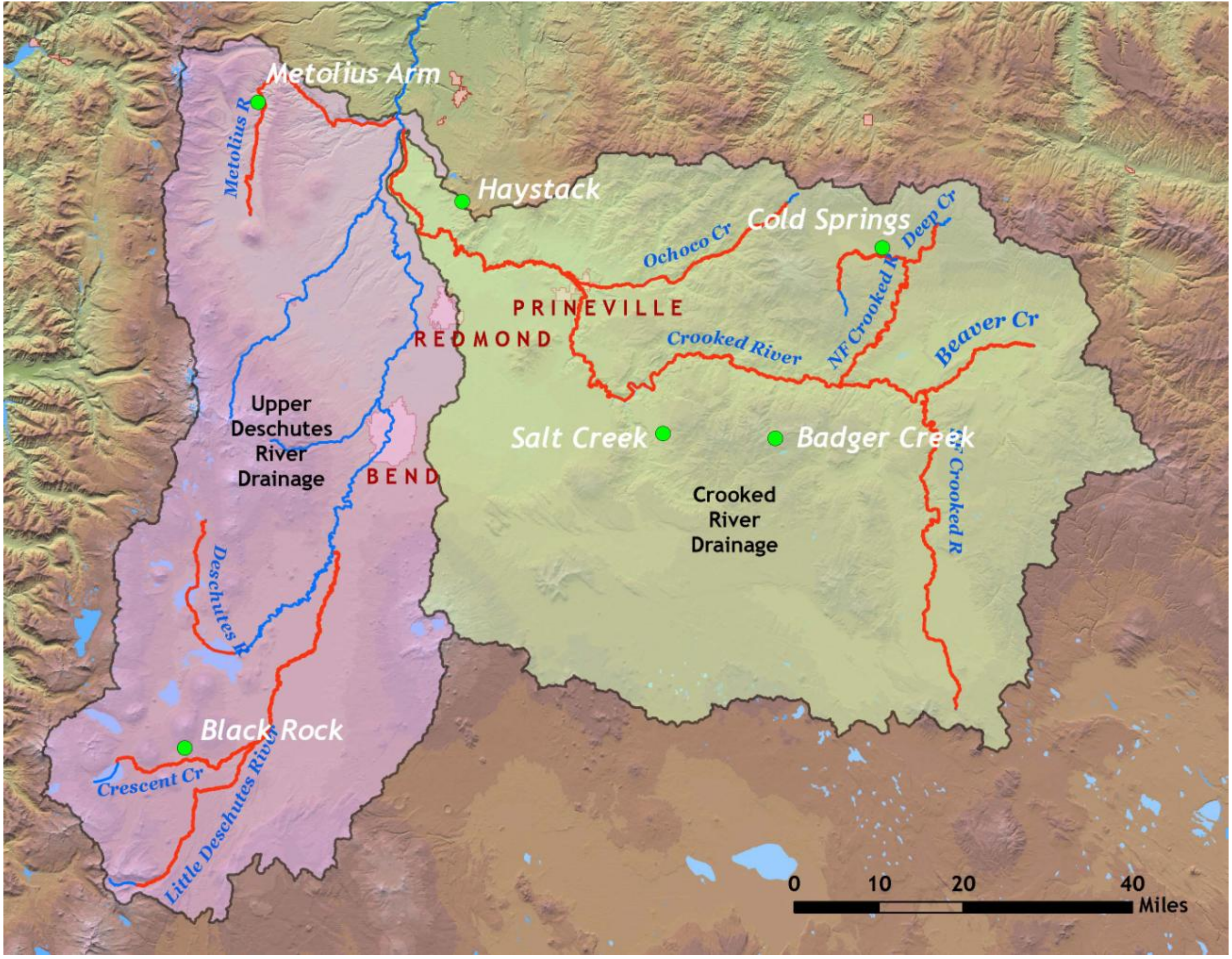
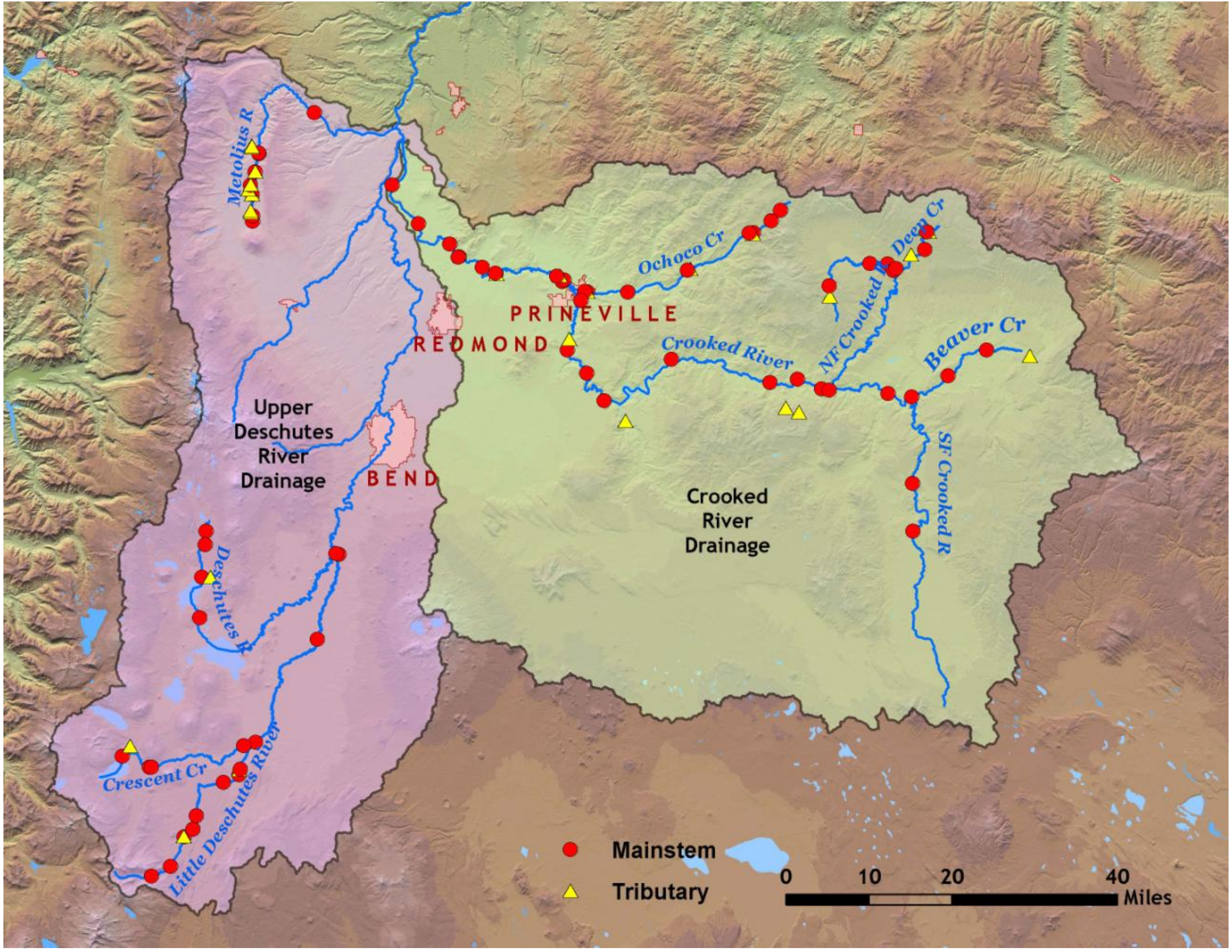


Figure 3 displays the locations where hourly stream temperature was recorded during the simulation period.

Figure 3 – Temperature monitoring locations.



Metolius River

The Metolius River was simulated from its headwater springs to the mouth (start of Lake Billy Chinook). The input parameters and assumptions used to calibrate the Heat Source model are shown in Table 1 and discussed below.

Table 1 - Metolius River Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 1 – August 31, 2001
TIR data:	7/27/01 15:06 – 7/27/01 15:50. Flown in downstream direction.
Simulation Extent:	45.95 km (headwater springs to the start of Lake Billy Chinook)
Time Step:	30 seconds
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	13
Continuous Data Sites:	7
Flush Initial Condition:	7 days
Deep Alluvium Temperature:	Option not used.
Climate Data Source:	RAWS – Metolius Arm
Land Cover Data Source:	Polygons were digitized from the NAIP imagery.
Evaporation Method:	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	1.6 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	1.0 m
Porosity:	35%

- The time step was 30 seconds (typical is one minute) in order to accommodate the high flow volumes and velocities.
- Cloud cover was estimated from the Metolius Arm RAWS solar radiation data. Inputs were either zero, 25, or 75% cloud cover.
- All climate data (air temperature, average wind speed, and relative humidity) are values from the Metolius Arm RAWS station. Air temperature was adjusted for the dry adiabatic lapse rate.
- Channel edges were digitized from the NAIP Orthophotographs.
- Jack Creek temperature data was missing 7/1-7/25. The gap was filled with measured data from Spring Creek minus 1°C because their diel variations had similar magnitudes.
- Wizard Falls discharge was missing temperature data 7/1-7/12. Lake Creek data was used to fill the gap since the effluent was composed mostly of spring water and later temperatures were very similar between the two sites.
- Wizard Falls discharge was 8.4 MGD according their discharge monitoring report.
- First Creek had temperature data, but records show it was dry in late July. Therefore no inflow was included for this tributary.
- Accretion flow values are the measured tributary or spring temperatures of inflows that appeared to be of significant size in the TIR imagery relative to the size of the Metolius River. Flows were estimated and mass balanced in order to match the measured gage data near the mouth of the Metolius. Smaller springs identified in the TIR were excluded and are considered accounted for by the larger mass inputs. The Metolius River is so large and cool, it is impossible to accurately calculate a mass balance at the smaller inputs because they do not measurably impact the bulk river temperatures.
- The end of the simulation ("mouth") was set at 1.1 kilometers below the USGS gage, which is where the last set of rapids is visible in the NAIP and TIR imagery above Lake Billy Chinook.
- Within the lower 30 stream kilometers that were simulated, there appears to be an upward

drift in the TIR temperature data. At the USGS gage near the mouth, the TIR data was over 3°F warmer than the instream hourly measurement. During model calibration, it was determined that that the TIR data was artificially high as it approached the mouth (possibly due to a drift in the radiance values in the TIR imagery which was not corrected to instream measurements in the lower river). Therefore, the model was calibrated to the hourly temperature data which had passed Oregon DEQ QA/QC tests.

- The boundary condition hourly temperature data were recorded at the headwater springs and the flow data were the value measured on 7/26/01 at the same location.
- There were no diversions included in this model due to a lack of data.
- Channel angle Z was assumed to be zero throughout the modeled stream. Thus the bottom width was equal to the surface width, assuming a rectangular cross-section of the channel.
- Manning's n values ranged from 0.033 to 0.25 and were adjusted based upon the measured gradients, velocities, and depths.

The Metolius River is a medium-sized river which flows predominately through forested lands (Figure 4). Summertime flow volumes are fairly large and the stream temperatures remain very cool due to the large contribution of spring water.

Figure 4 – Metolius River upstream of Wizard Falls fish hatchery.

Table 2 summarizes the calibration statistics. The model was calibrated to both the instantaneous longitudinal temperature profile and to the hourly data recorded at various sites during the 60-day simulation period.

Table 2 - Metolius River simulation calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	0-45.95	461	-0.77	0.80	0.93	0.31
Metolius @ headwaters spring footbridge	USFS	45.55	1,488	0.21	0.24	0.37	-1.03
Metolius u/s tract C bridge	DEQ	44.35	1,488	-0.35	0.42	0.50	0.73
Metolius u/s First Creek (Gorge CG)	USFS	39.70	1,488	0.59	0.59	0.71	0.64
Metolius u/s Canyon Creek	DEQ	37.15	1,488	0.18	0.27	0.32	0.80
Metolius u/s Bridge 99	USFS	28.80	1,488	0.39	0.40	0.49	0.75
Metolius d/s Bridge 99	DEQ	28.55	1,488	0.15	0.20	0.64	0.94
Metolius @ USGS Gauge Station (mouth)	DEQ	1.1	1,351	-0.33	0.42	0.48	0.85

Figure 5 shows the longitudinal temperature profile calibration for the Metolius River. The Metolius River is dominated by cold spring water inflow and its relatively large size helps it maintain cool temperatures throughout. As mentioned above, the TIR data deviated from the instream measurements toward the lower reaches. Since the measured hourly data at the lowest monitoring site passed Oregon DEQ quality assurance protocols, the model was calibrated to that data as opposed to the TIR in the lower reaches.

Figure 5 - Metolius River longitudinal temperature calibration results.

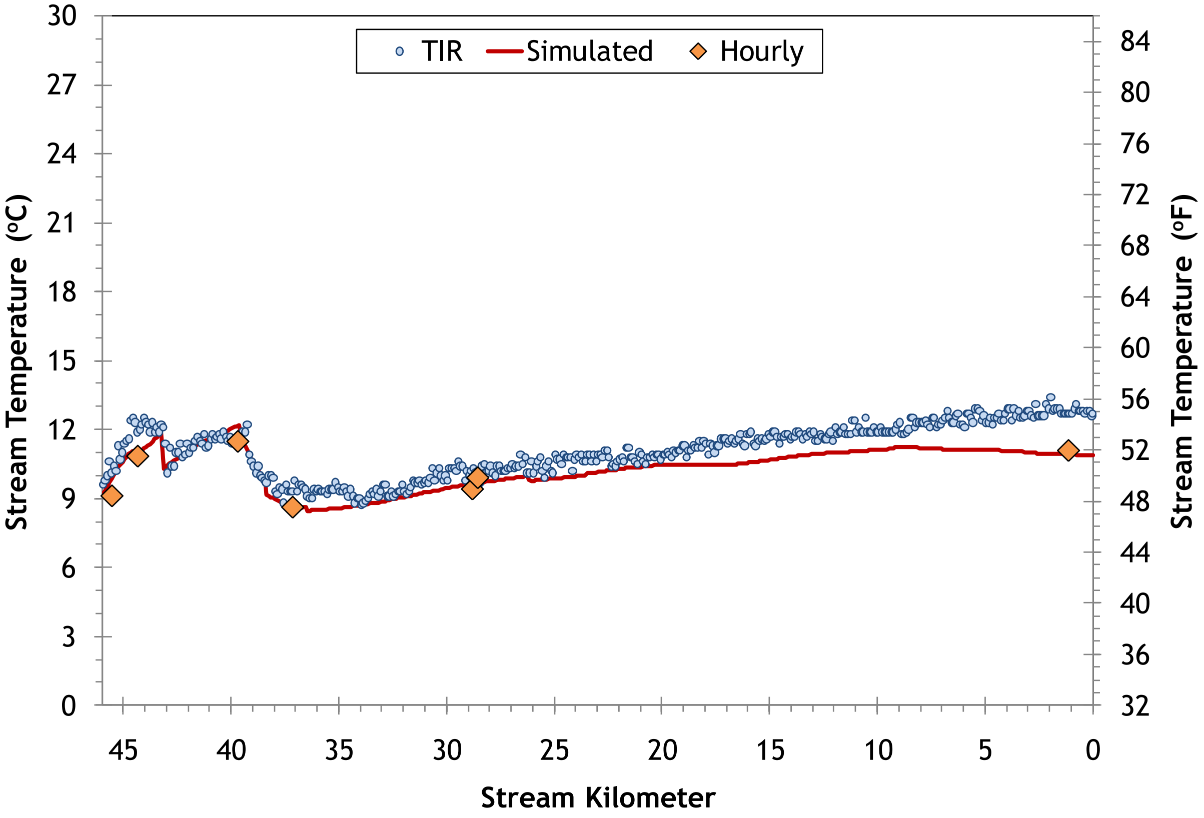
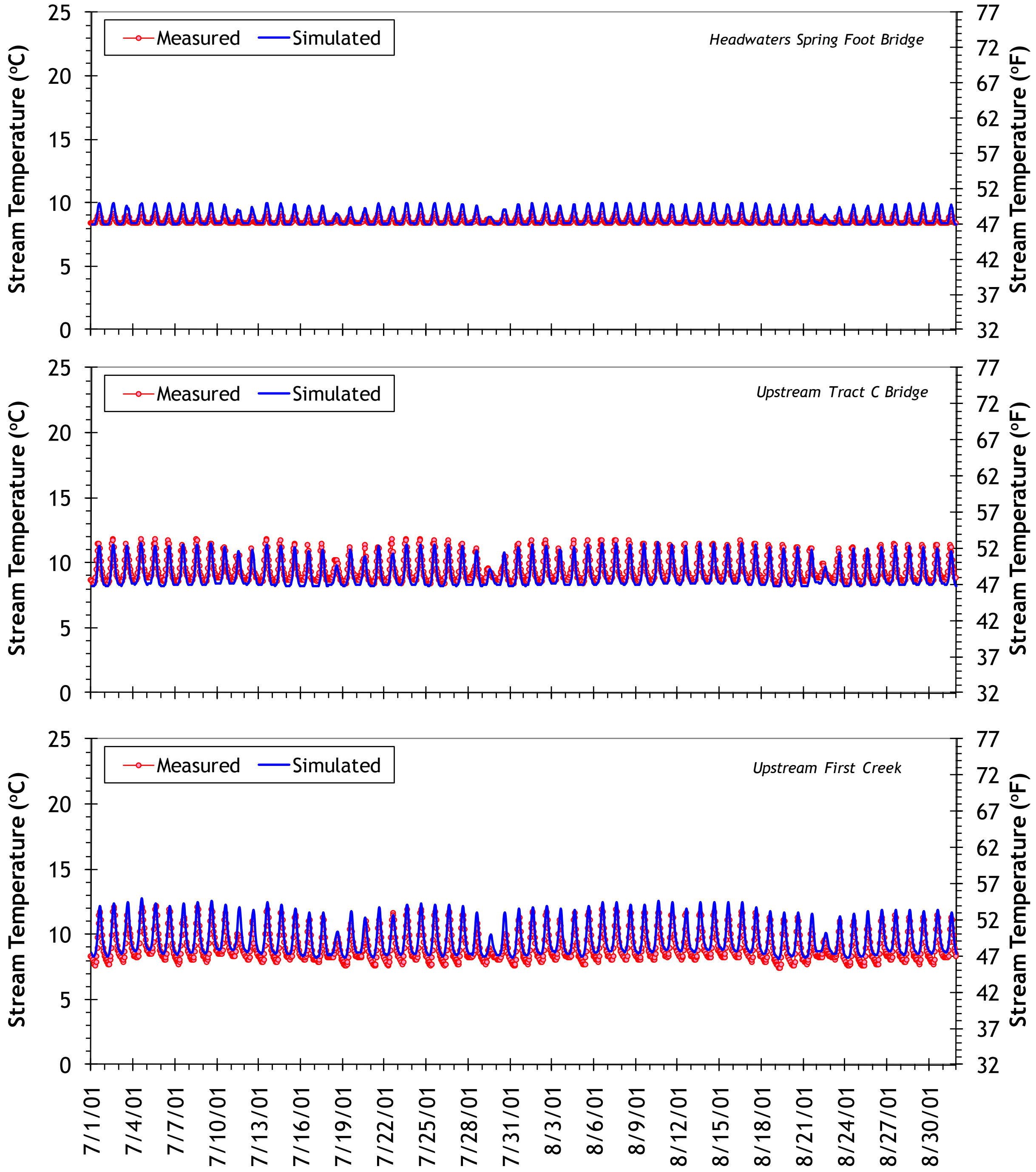
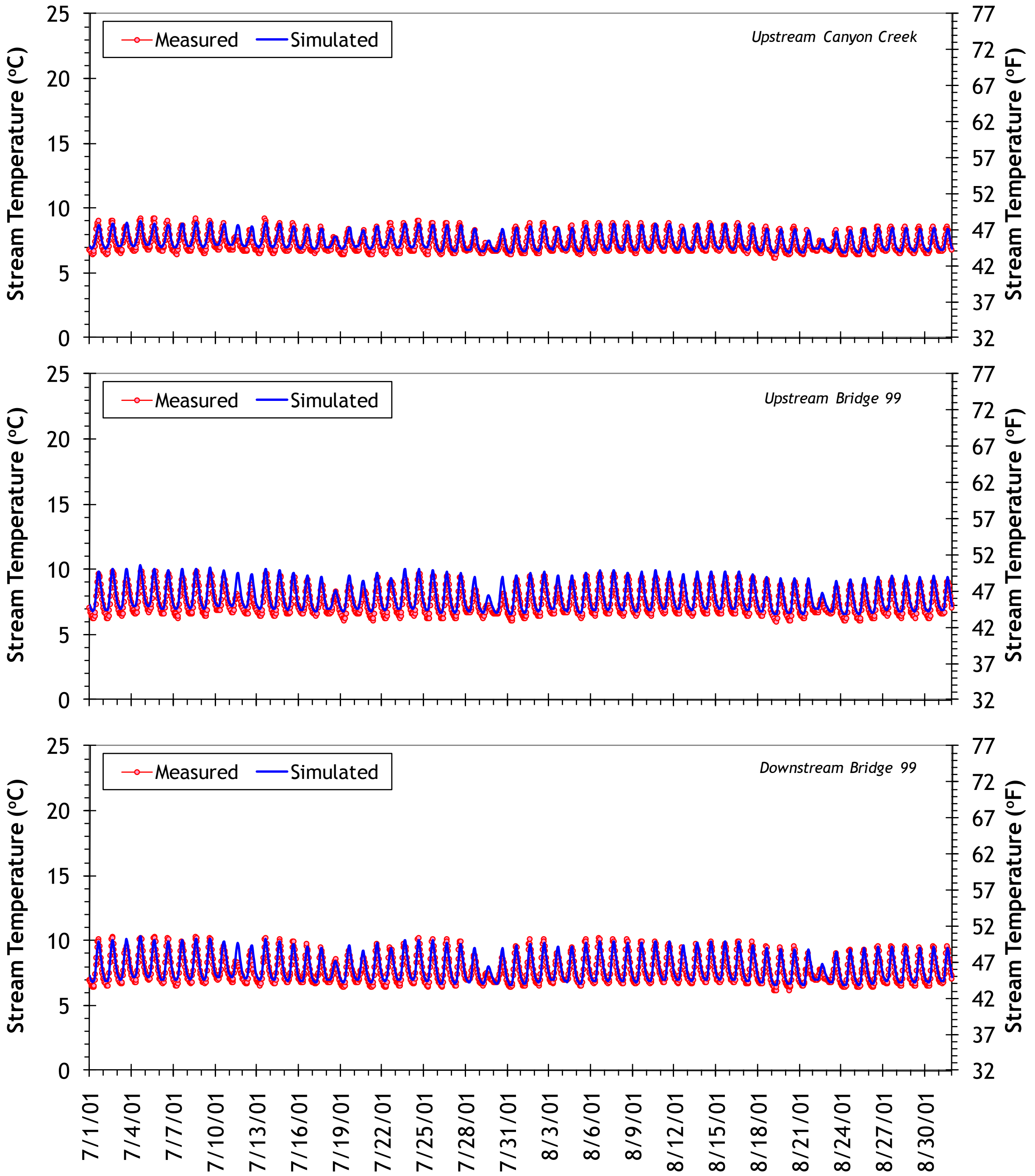


Figure 6 shows the simulated and measured hourly temperatures for the Metolius River. Since the river is dominated by cool groundwater inputs, the diel temperature variation is relatively small and steady during the simulation period.

Figure 6 - Metolius River simulated and measured hourly temperatures.




Measured
Simulated
Upstream Canyon Creek
Upstream Bridge 99
Downstream Bridge 99
Stream Temperature (°C)
Stream Temperature (°F)
0
5
10
15
20
25
32
37
42
47
52
57
62
67
72
77
7/1/01
7/4/01
7/7/01
7/10/01
7/13/01
7/16/01
7/19/01
7/22/01
7/25/01
7/28/01
7/31/01
8/3/01
8/6/01
8/9/01
8/12/01
8/15/01
8/18/01
8/21/01
8/24/01
8/27/01
8/30/01

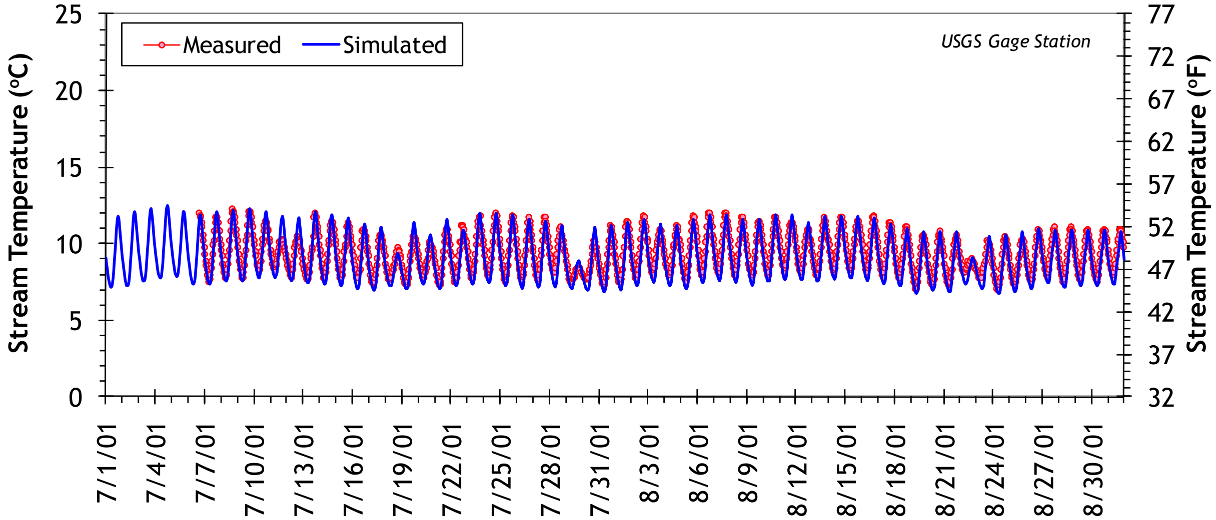


Figure 7- The Metolius River near Tract C Bridge.

Figure 8 through Figure 11 show the simulated and measured hydraulic parameters for the Metolius River. The simulated values in the charts are from July 27, 2001, when the TIR data was collected. The measured values were collected on July 25 and 26. Measurements were only able to be collected in the most upper reaches where the river was accessible and able to be waded. There was daily flow volume data available from the gage near the mouth.

Figure 8 - Metolius River simulated and measured flow volumes.

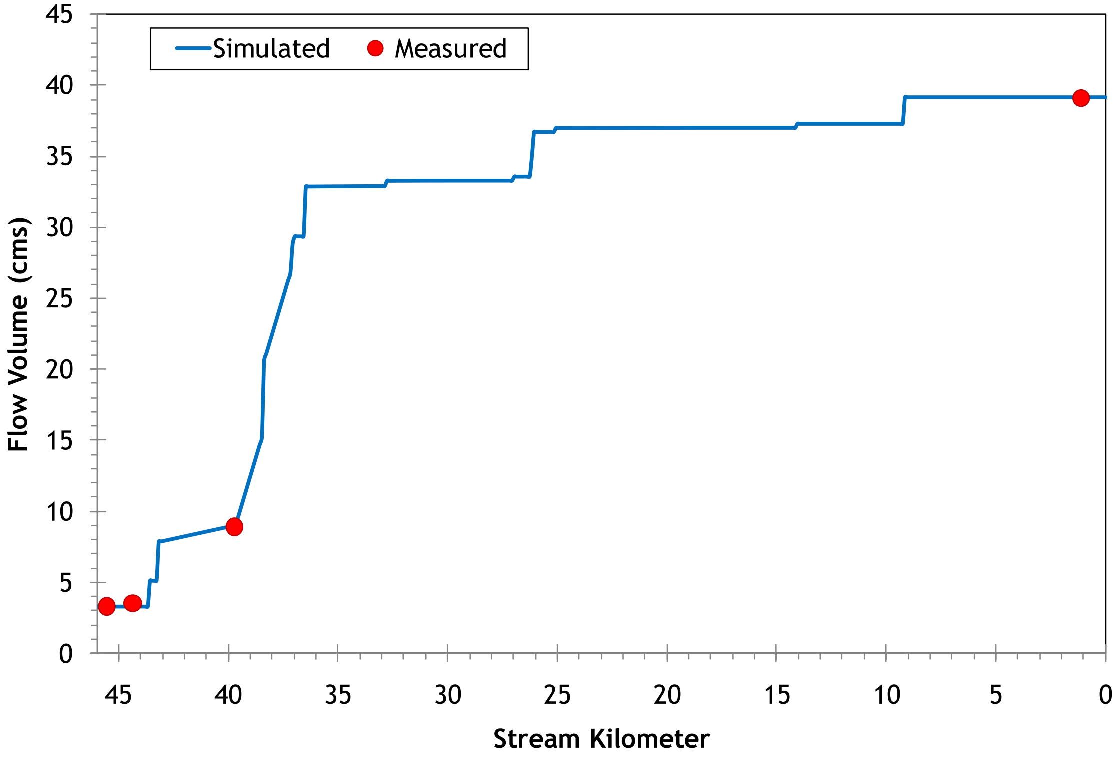


Table 3 summarizes the mass flow inputs that were included within the simulation. The upstream boundary condition was assumed constant and the various inflows were adjusted on a daily basis in order to calibrate the flow volume to match the measured values at the Grandview gage.

Table 3 - Metolius River simulated mass transfer locations and data sources.

Flow Input	Stream Km	Flow Data Source	Temperature Data Source
Lake Creek	43.6	DEQ	DEQ
Spring Creek	43.15	DEQ	DEQ
First Creek	39.6	Mass Balance Estimate	DEQ
Jack Creek	38.35	Mass Balance Estimate	DEQ
Canyon Creek	37.05	DEQ	DEQ
Spring (RB)	36.5	Mass Balance Estimate	TIR Estimate
Wizard Falls discharge	32.8	DEQ / Point Source DMR	DEQ / Point Source
Abbot Creek	26.95	Mass Balance Estimate	TIR Estimate
Candle Creek	26.15	DEQ	DEQ
Jefferson Creek	26.05	DEQ	DEQ
Mariel Creek	25.1	Mass Balance Estimate	TIR Estimate
Racing Creek	14.05	Mass Balance Estimate	TIR Estimate
Whitewater River	9.15	Mass Balance Estimate	TIR Estimate

The figure below compares the measured and simulated daily flow values at the Grandview gage. On average, the simulated daily values were within 0.1% of the gage data.

Figure 9 - Metolius River simulated and gaged flows at Grandview Gage.

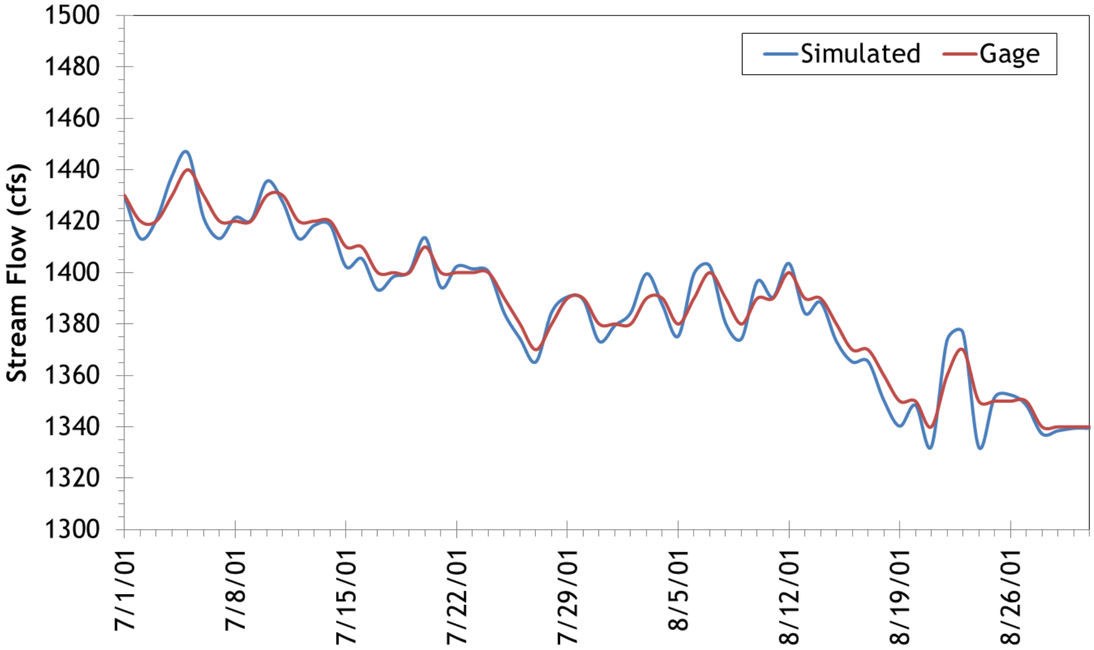


Figure 10 - Metolius River simulated and measured flow velocities.

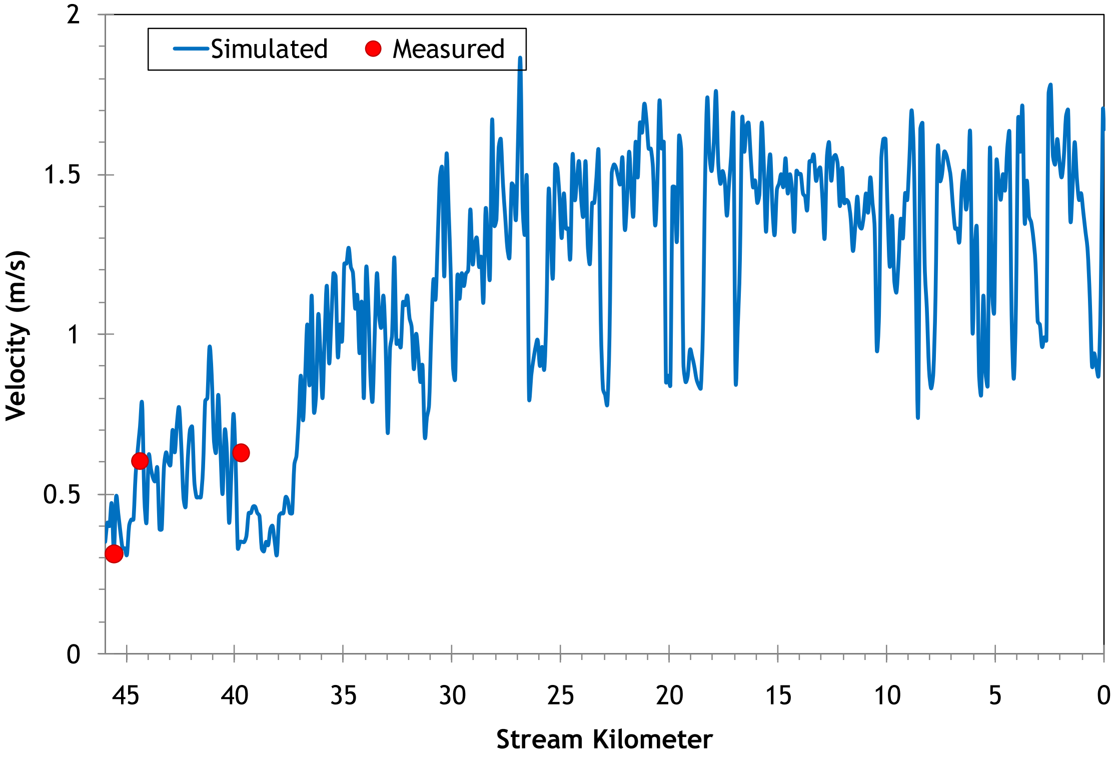


Figure 11 - Metolius River simulated and measured wetted widths.

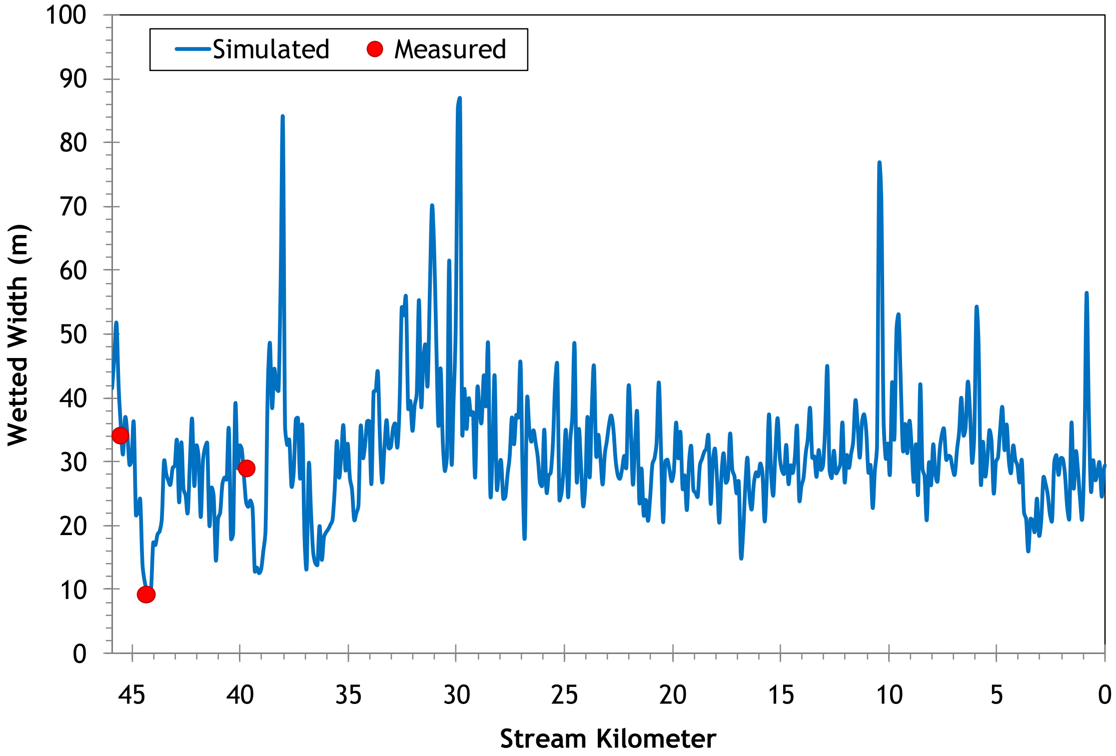
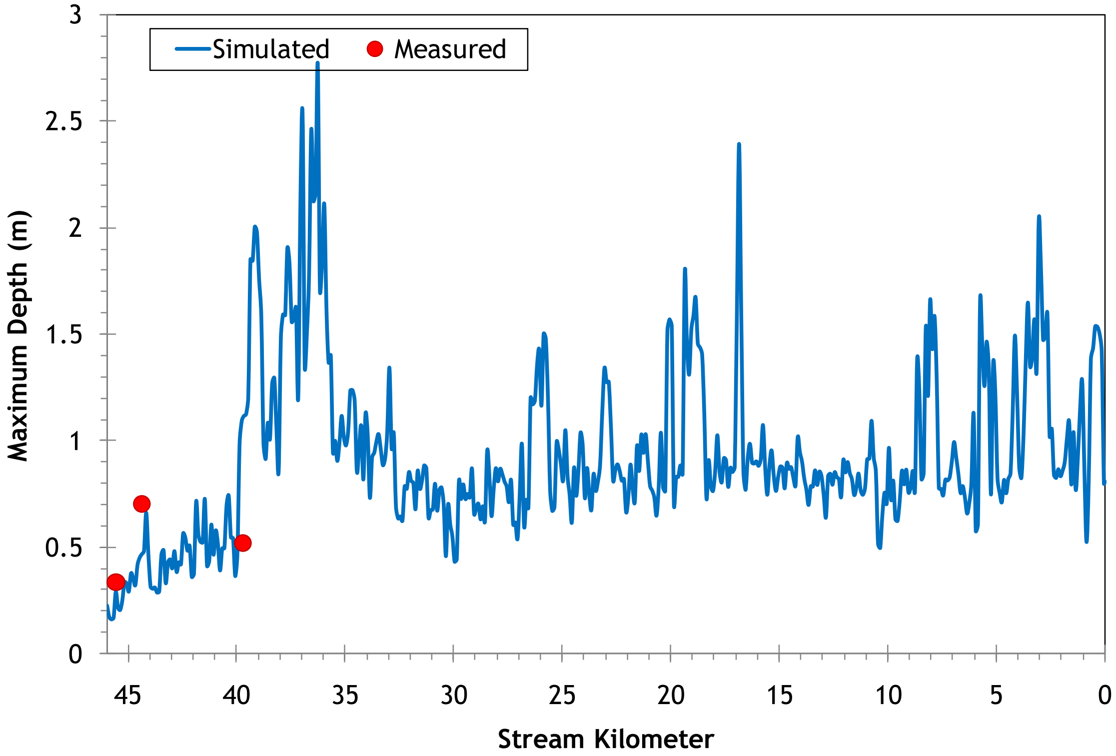


Figure 12 - Metolius River simulated and measured maximum depths.



The Metolius River simulated effective shade and solar fluxes are shown in Figure 13. The Metolius River is well forested. Effective shade is 30% on average. Topographic features generally account for less than 10% of the total effective shade. The Metolius River is a fairly large stream, with average widths around 30 meters. Wider streams are normally less shaded due to their larger surface area.

Figure 13 - Metolius River simulated and measured effective shade.

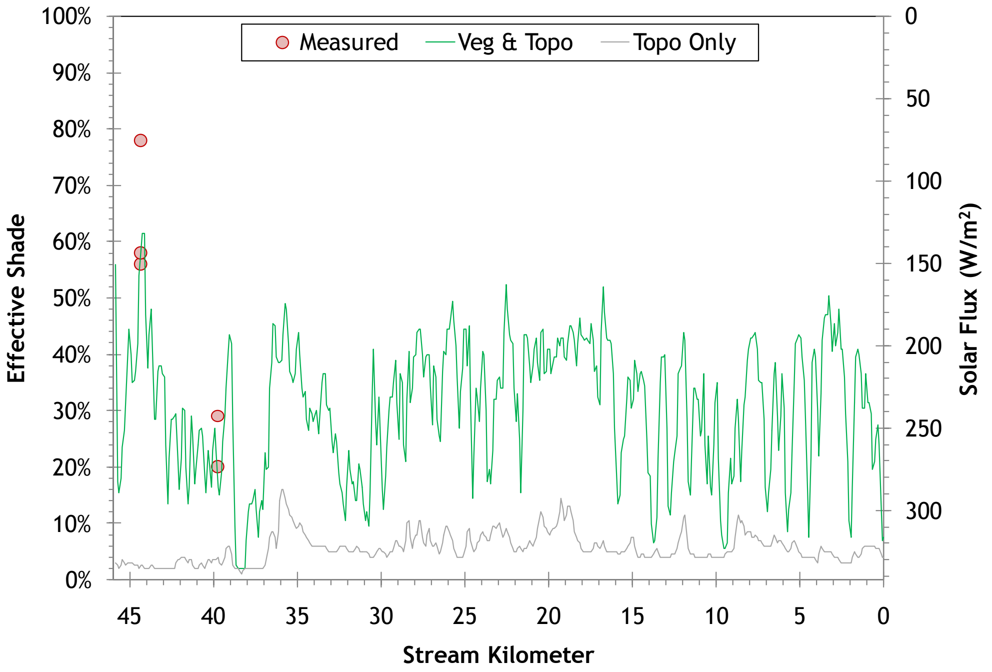
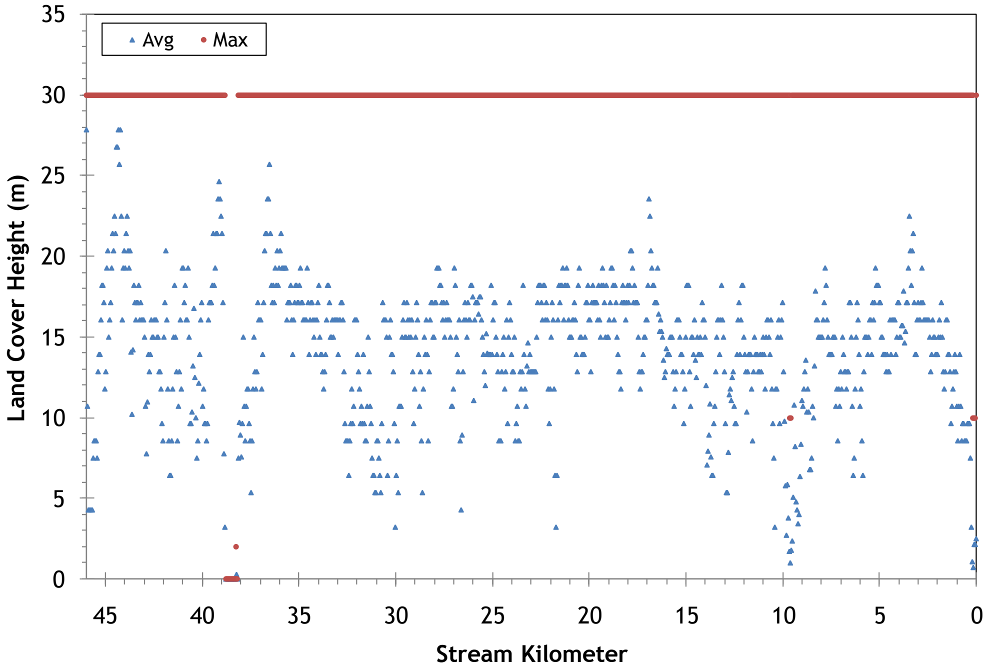


Figure 14 shows the average and maximum land cover heights sampled at each of the 50-meter model input segments. Land cover polygons were digitized from the NAIP imagery.

Figure 14 - Metolius River sampled land cover heights.



Deschutes River

The Deschutes River was simulated between Little Lava Lake and Crane Prairie Reservoir, and also between Crane Prairie Reservoir and Wickiup Reservoir. Since Heat Source is not a reservoir model, two separate models were set up and calibrated for these reaches. However the results from both models are presented together in single charts in order to simplify this report.

Deschutes River - Little Lava Lake to Crane Prairie Reservoir

Table 4 below summarizes the general Heat Source inputs for the Deschutes River between Little Lava Lake and Crane Prairie Reservoir.

Table 4 - Deschutes River (Little Lava Lake to Crane Prairie Reservoir) Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 1 – August 31, 2001
TIR data:	7/25/01 15:07 – 7/25/01 15:18. Flown in upstream direction.
Simulation Extent:	12.0 stream kilometers from Little Lava Lake to Crane Prairie Reservoir.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	1
Continuous Data Sites:	1
Flush Initial Conditions:	7 days
Deep Alluvium Temperature:	Option not used.
Climate Data Source:	RAWS – Black Rock
Land Cover Data Source:	Polygons were digitized from the NAIP imagery.
Evaporation Method:	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	0.35 m
Hyporheic Exchange:	1%
Porosity:	40%

- Since Heat Source cannot simulate reservoirs, two separate Heat Source models were set up for the free-flowing reaches – one between Little Lava Lake and Crane Prairie Reservoir, and one between Crane Prairie Reservoir and Wickiup Reservoir.
- Channel widths were digitized from the NAIP imagery.
- The first 3 days of hourly temperature data were not available for the downstream Lava Lake Blue Pool site, so July 4th hourly temperatures were used.
- The hourly air temperature, average wind speed, and relative humidity were recorded at the Black Rock RAWS station. Air temperatures were adjusted based on the dry adiabatic lapse rate.
- Solar radiation data was not recorded at the Black Rock RAWS site; therefore 75% cloud cover was estimated on days when the maximum daily temperature was noticeably cooler than the immediately surrounding days (see Figure 17).
- The measured hourly temperature data downstream of Blue Pool was approximately 1 °C warmer than the TIR data. It was used for the upstream boundary condition as-is.
- The boundary condition temperatures were hourly data measured downstream of Blue Pool. The record began on July 4th, 2001, so July 4th hourly data was copied to July 1-3.
- The boundary condition flow volume was measured on July 24, 2001 downstream of Little Lava

Lake. Since the daily gage data near Snow Creek exhibited only a 3 cfs variance (69-72 cfs) during the simulation period, a constant boundary flow was used throughout.

- There were no diversions or withdrawals included within this simulation.
- Bottom width inputs were the values measured between banks digitized from the NAIP orthophotos.
- Channel angle Z was zero throughout the simulated length.
- Manning's n values ranged from 0.08 to 0.10 in the simulated reach and were estimated in order to achieve a best-fit of the measured hydraulic velocities and depths.
- Accretion flow was estimated at 0.92 cms (32.5 cfs) between kilometers 11.6 and 11.0 in order for the flow profile to match the measured data upstream of Snow Creek. The TIR data revealed evidence of cold water inflow and cooling stream temperatures within that reach.

Figure 15 - Deschutes River upstream of Snow Creek.

Deschutes River – Crane Prairie Reservoir to Wickiup Reservoir

The general Heat Source inputs for the Deschutes River below Crane Prairie Reservoir are listed in Table 5.

Table 5 – Deschutes River (Crane Prairie Reservoir to Wickiup Reservoir) Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 1 – August 31, 2001
TIR data:	7/25/01 15:27 – 7/25/01 15:30. Flown in downstream direction.
Simulation Extent:	2.95 km from Crane Prairie Reservoir to Wickiup Reservoir
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	0
Continuous Data Sites:	1
Flush Initial Conditions:	7 days
Deep Alluvium Temperature:	Option not used.
Climate Data Source:	RAWS - Black Rock
Land Cover Data Source:	USGS LiDAR data
Evaporation Method:	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment / Hyporheic zone thickness:	0.35 meters
Hyporheic Exchange:	1%
Porosity:	40%

- The density of the LiDAR-sampled land cover was assumed to be 75%.
- Channel widths were digitized from the NAIP imagery.
- The hourly air temperature, average wind speed, and relative humidity were recorded at the Black Rock RAWS station. Air temperatures were adjusted based on the dry adiabatic lapse rate.
- Solar radiation data was not recorded at the Black Rock RAWS site; therefore 75% cloud cover was estimated on days when the maximum daily temperature was noticeably cooler than the immediately surrounding days (see Figure 17).
- Hourly temperature data measured at Brown's Crossing were used for the upstream boundary condition.
- The boundary condition flow volume was obtained from daily values measured at the Crane Prairie Reservoir outlet gage station.
- There were no diversions or withdrawals included within this simulation.
- Bottom width inputs were the values measured between the digitized banks from the NAIP orthophotos.
- Channel angle Z values were zero throughout the model.
- Manning's n values ranged from 0.2 to 0.3 in the simulated reach and were estimated in order to achieve a best-fit of the measured hydraulic velocities and depths.
- There was no accretion flow included within this modeled reach.

Table 6 summarizes the calibration statistics achieved in the calibrated Deschutes River simulations. The models were calibrated to both the instantaneous longitudinal temperature profile and to the hourly data recorded at various sites during the 60-day simulation period.

Table 6- Deschutes River calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	0-45.95	152	0.13	0.25	0.48	-0.04
Upstream Snow Creek	DEQ	45.55	1488	0.43	0.83	1.07	0.90
Brown's Crossing	DEQ	44.35	1488	0.03	0.18	0.24	0.98

Figure 16 shows the longitudinal stream temperature profile calibrations for the Deschutes River between Lava Lake and Wickiup Reservoir. Notice that the TIR temperatures were cooler than the hourly temperature data at the outlet of Lava Lake at Blue Pool. The hourly data was used to "seed" the upstream boundary condition.

Figure 16 - Deschutes River calibrated temperature profile.

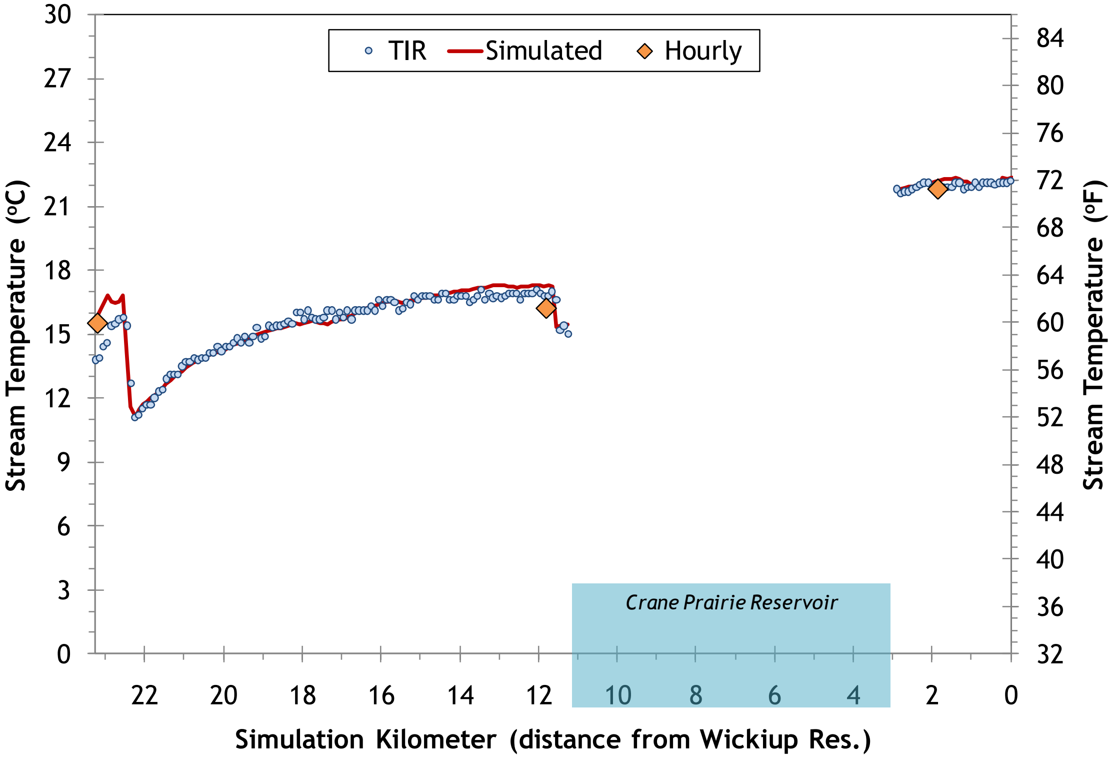


Figure 17 shows the Deschutes River simulated and measured hourly temperatures. Recall that the Brown's Crossing site data was also used as the upstream boundary condition for the reach between Crane Prairie Reservoir and Wickiup Reservoir.

Figure 17 - Deschutes River simulated and measured hourly temperatures.

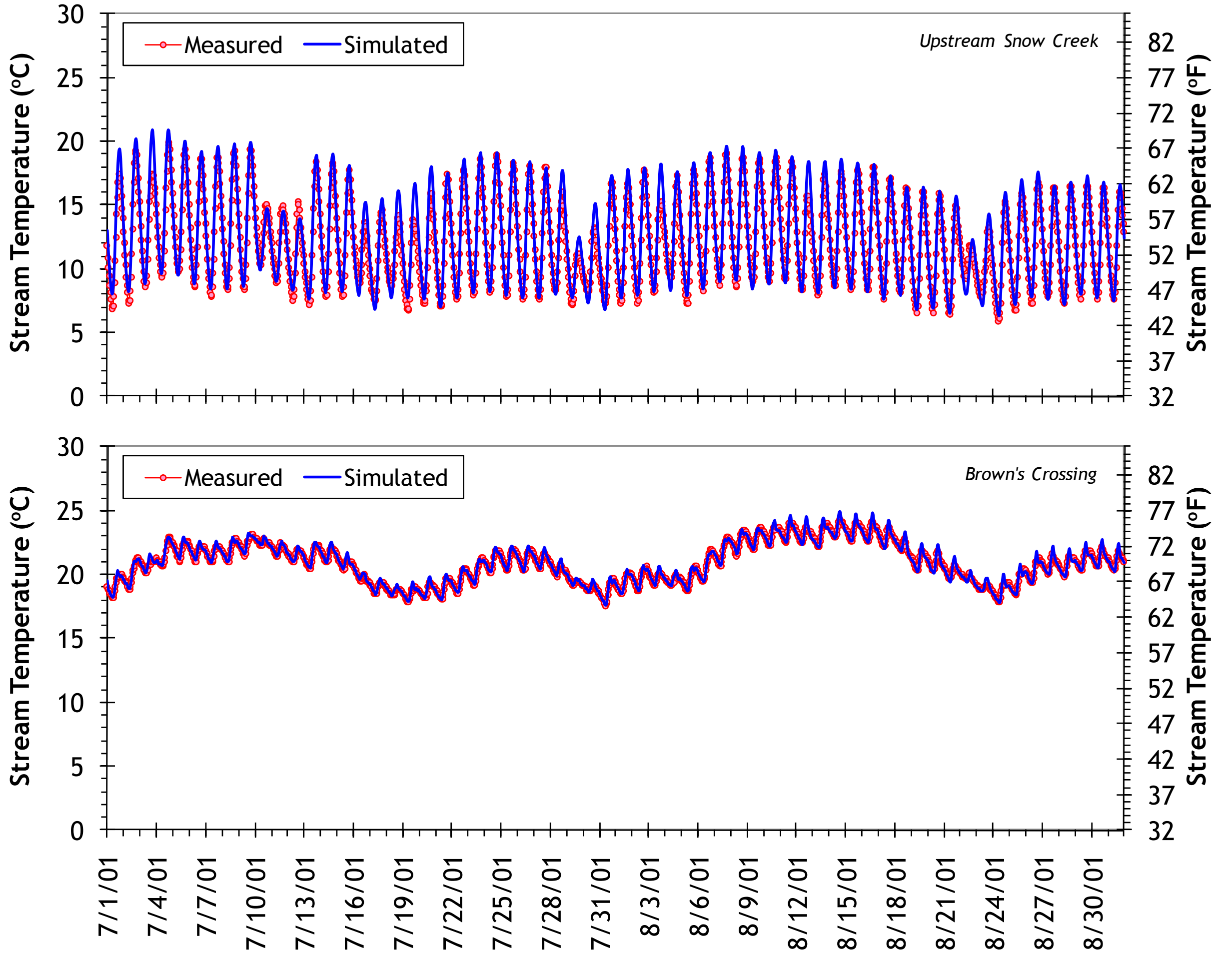


Figure 18 through Figure 21 present the simulated and measured hydraulic parameters from the calibrated models. Since the TIR was collected on July 25th, the simulation results are presented for that day. The ground level measurements were all collected on July 24th.

Figure 18 - Deschutes River simulated and measured flow volumes.

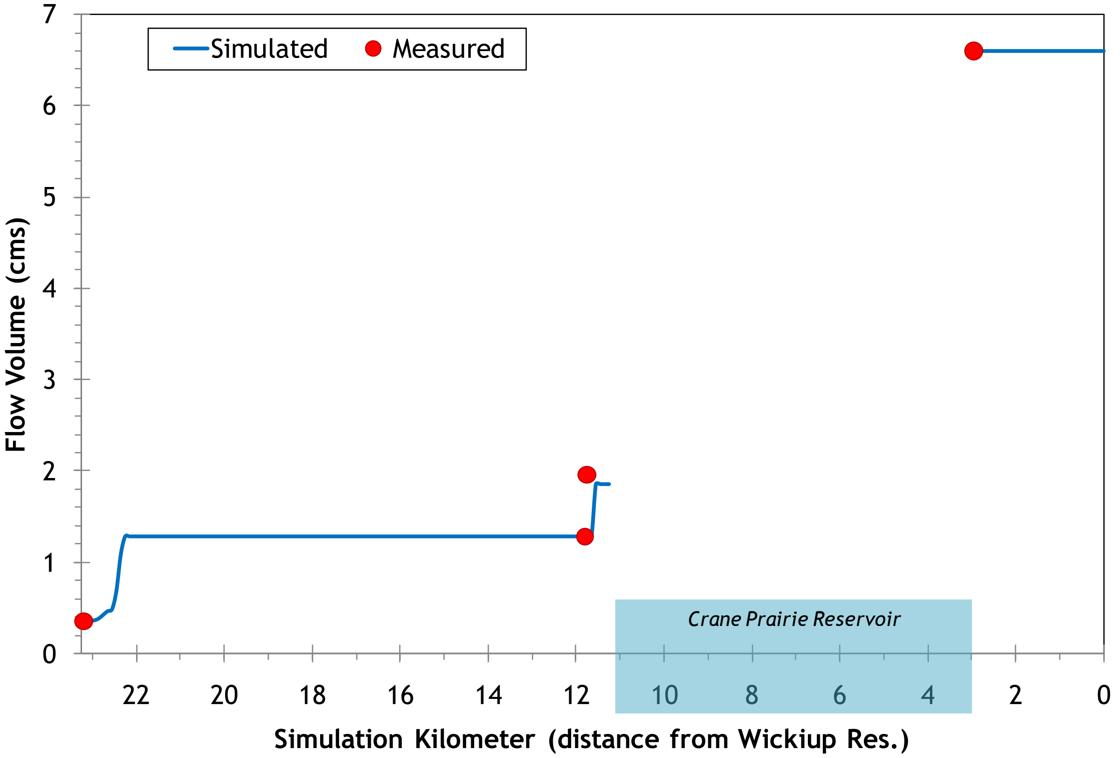


Table 7 summarizes the mass flow inputs that were included within the simulation. Accretion was estimated just downstream of Blue Pool, where there was evidence in the TIR data of a significant cooling reach. The inflow also raised the flow volume to match the measured data upstream of Snow Creek. The flow volumes from Crane Prairie Reservoir were obtained from daily gage data at that location.

Table 7 - Deschutes River simulated mass transfer locations and data sources.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Accretion / Spring	22.9-22.3	Mass Balance Estimate	TIR Estimate
Snow Creek	11.6	DEQ	DEQ

Figure 19 - Deschutes River simulated and measured velocities.

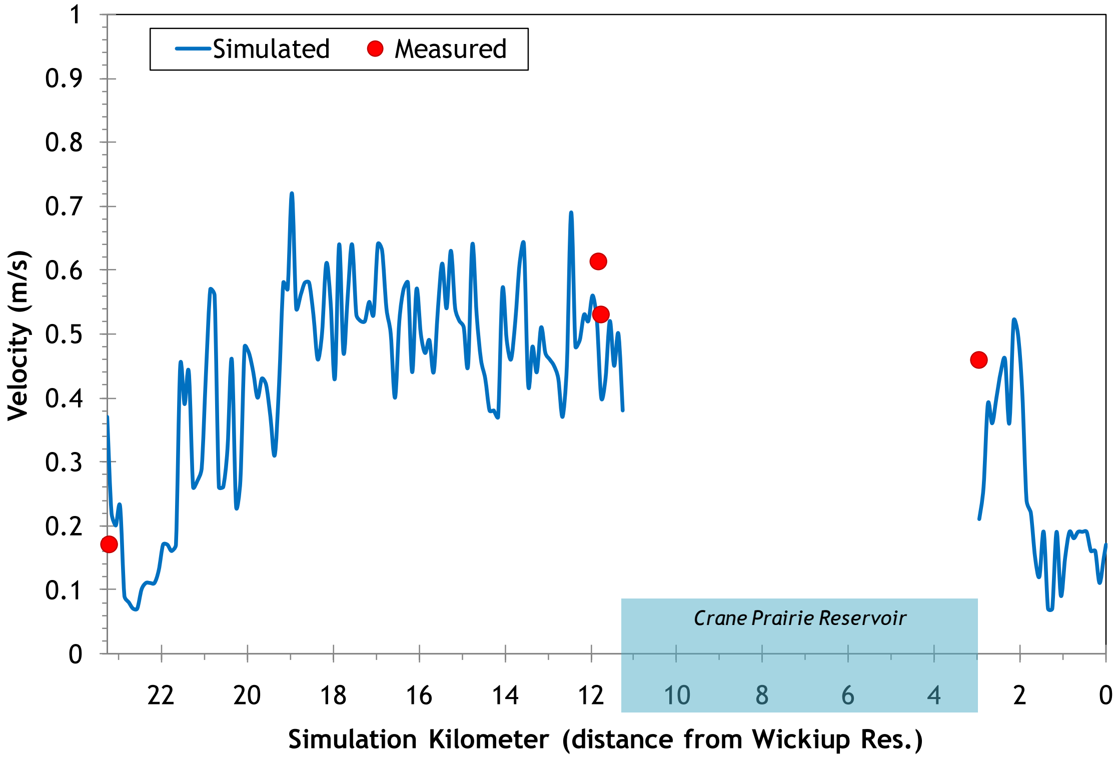


Figure 20 - Deschutes River simulated and measured wetted widths.

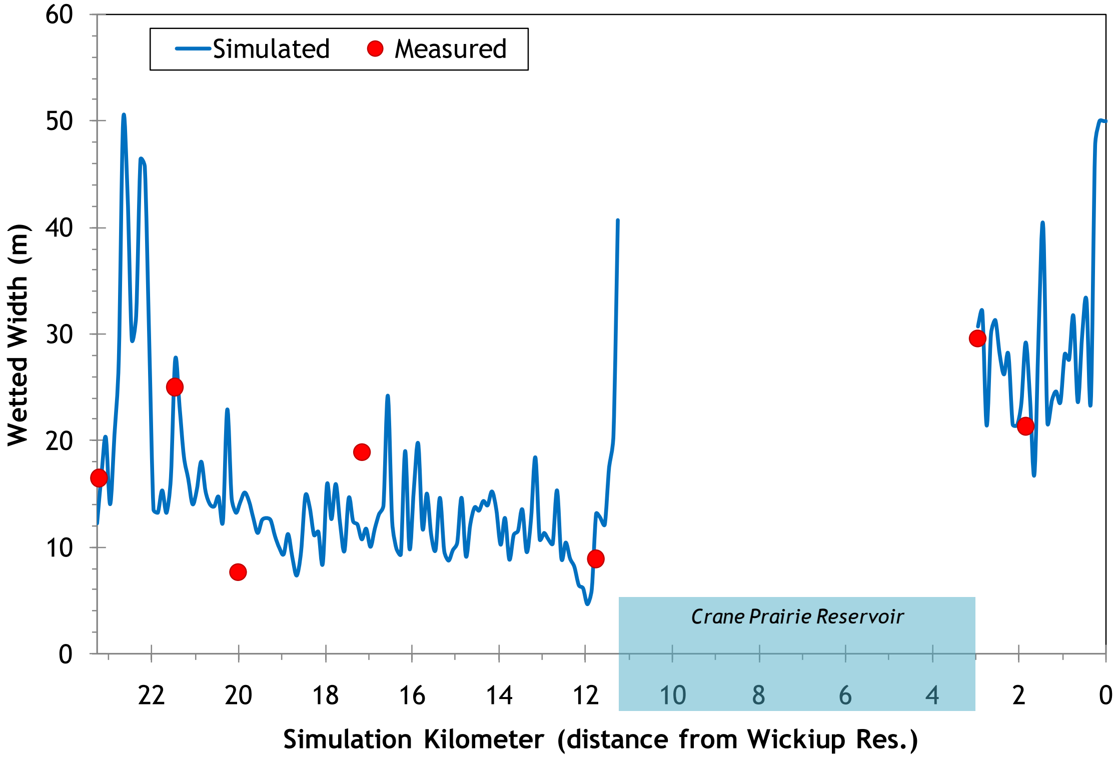


Figure 21 - Deschutes River simulated and measured maximum depths.

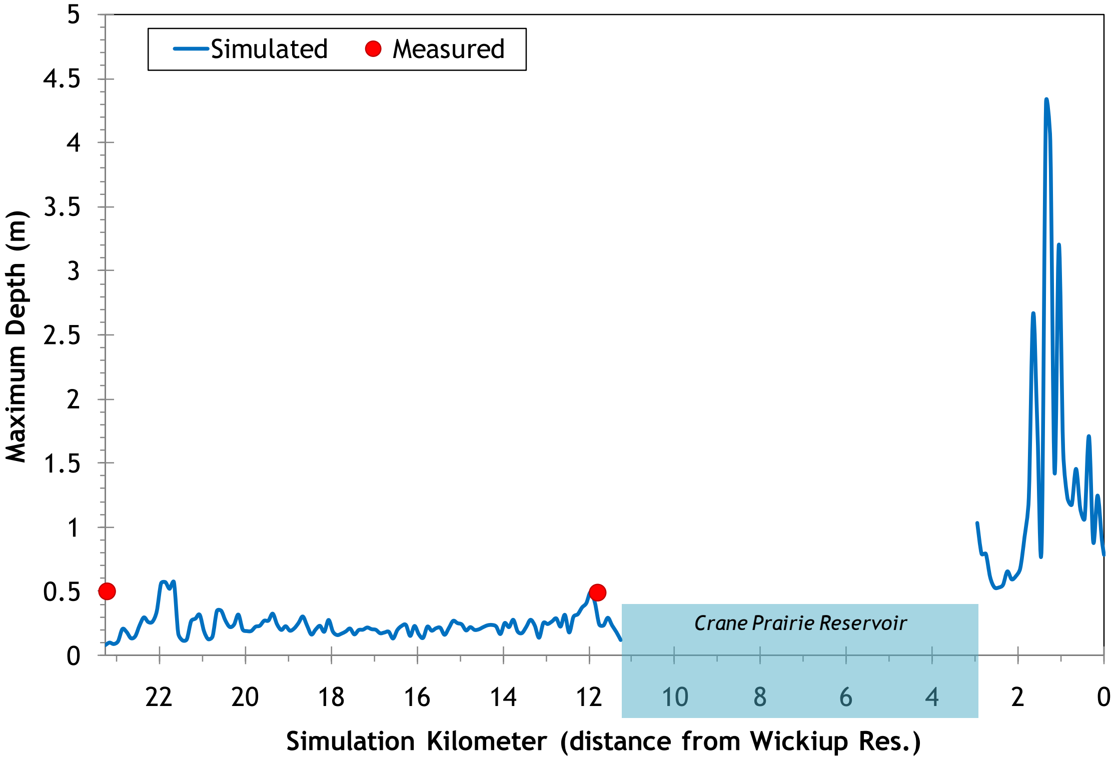


Figure 22 - Deschutes River at Brown's Crossing.

Figure 23 shows the simulated and measured effective shade along the Deschutes River. There is relatively little topographic shade along these reaches.

Figure 23 - Deschutes River simulated and measured effective shade.

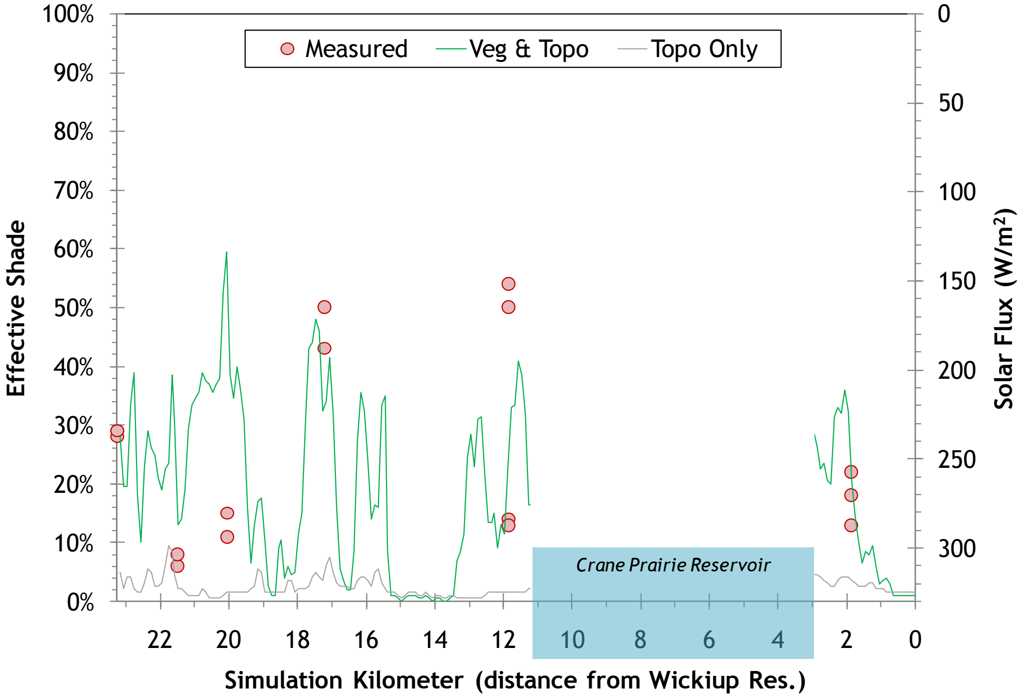
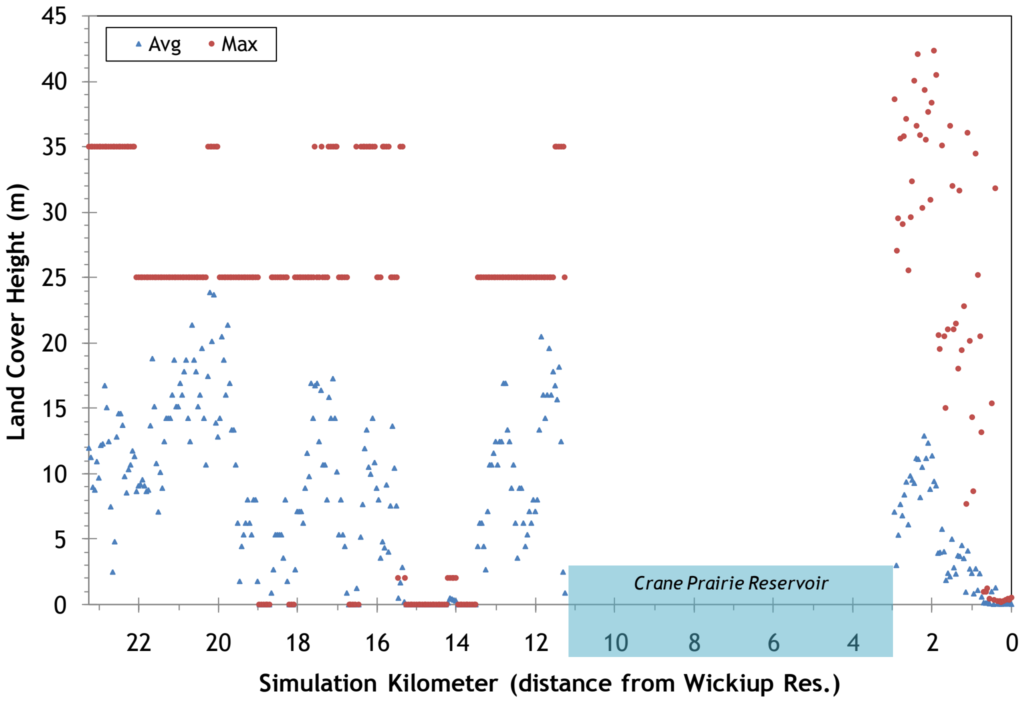


Figure 24 shows the average and maximum sampled land cover heights for the simulated Deschutes River reaches. The land cover between Lava Lake and Crane Prairie Reservoir was digitized from the NAIP imagery. USGS LiDAR data was sampled between Crane Prairie and Wickiup Reservoirs.

Figure 24 - Deschutes River sampled land cover heights.



Crescent Creek

Crescent Creek was simulated from Crescent Lake to the mouth. Listed in Table 8 are the model input parameters and assumptions used to calibrate the Heat Source model.

Table 8 - Crescent Creek Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 1 – August 31, 2001
TIR data:	7/25/01 14:02-14:36. Flown in upstream direction.
Simulation Extent:	48.45 stream kilometers from Crescent Lake to the mouth.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	7
Continuous Data Sites:	4
Flush Initial Condition:	7 days
Deep Alluvium Temperature:	Option not used.
Climate Data Source:	RAWS – Black Rock
Land Cover Data Source:	USGS LiDAR data
Evaporation Method	Penman
Wind Function, coefficient a	0.00000000151
Wind Function, coefficient b	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	0.35 meters
Hyporheic Exchange:	0%
Porosity:	40%

- The density of the LiDAR-sampled land cover was assumed to be 75%.
- Hourly average wind speed, air temperature, and relative humidity values were obtained from the Black Rock RAWS station. Air temperatures were adjusted based on the dry adiabatic lapse rate.
- Solar radiation data was not recorded at the Black Rock RAWS site; therefore 75% cloud cover was estimated on days when the maximum daily temperature was noticeably cooler than the immediately surrounding days.
- Channel widths were digitized from the NAIP imagery. The sampled values were reduced 33% in the upper 11 stream kilometers in order to facilitate a better calibration. (Note that the widths sampled from the NAIP imagery are starting estimates since the NAIP imagery was collected at a different time than the simulation period.)
- The upstream boundary was the outlet of Crescent Lake. Daily flow values were obtained from the gage and hourly stream temperatures were recorded by DEQ just downstream of the lake outlet.
- Based on measured flow data, there are un-verified losing reaches between Crescent Lake and stream kilometer 37.5 and between stream kilometers 29 and 4.8. Flow volume was removed evenly throughout those reaches in order to make the flow profile match the measured data points.
- Crescent Creek branches (or is diverted) in at least two locations downstream of the lake. It was assumed that the stream was flowing within the main channel, which corresponds to the channel that TIR was collected on (Figure 26).

Figure 25 – Stream channels and actual simulated Crescent Creek route.

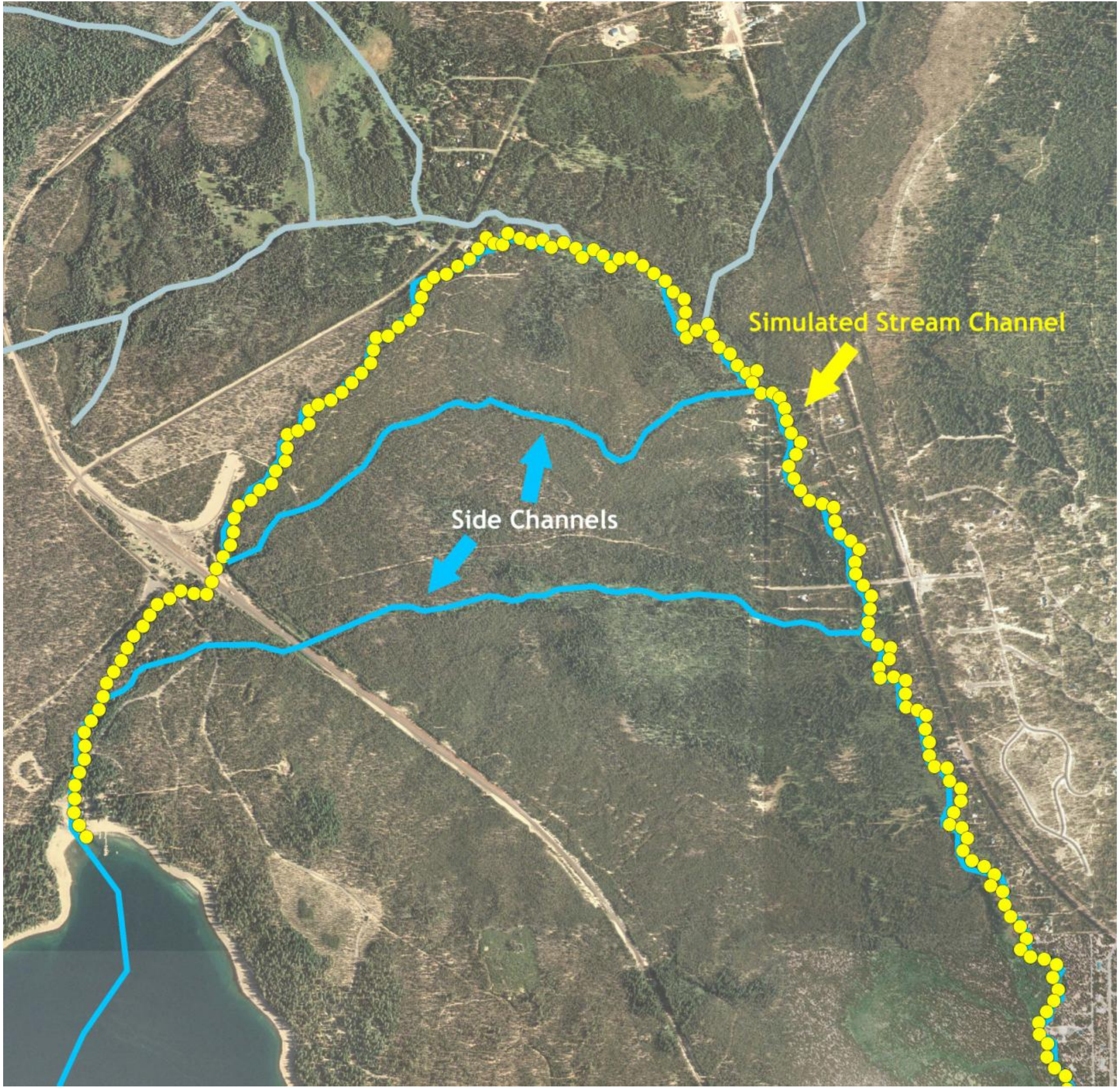


Table 9 summarizes the calibration statistics achieved in the calibrated Deschutes River simulations. The models were calibrated to both the instantaneous longitudinal temperature profile and to the hourly data recorded at various sites during the 60-day simulation period.

Table 9 - Crescent Creek simulation calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	48.45-0	486	-0.02	0.27	0.35	0.52
Upstream Big Marsh Creek	DEQ	37.50	1488	0.49	0.65	0.75	0.88
Downstream Big Marsh Creek	DEQ	36.90	1488	0.37	0.46	0.57	0.93
Road 62, near mouth	DEQ	4.80	1488	0.63	0.76	0.94	0.64

Figure 26 shows the calibrated longitudinal temperature profile of Crescent Creek. The TIR data was collected 7/25/01 14:02–14:36 in the upstream direction. The temperature profile of the creek was fairly stable throughout (i.e., there was little spatial variation).

Figure 26 - Crescent Creek calibrated longitudinal temperature profile.

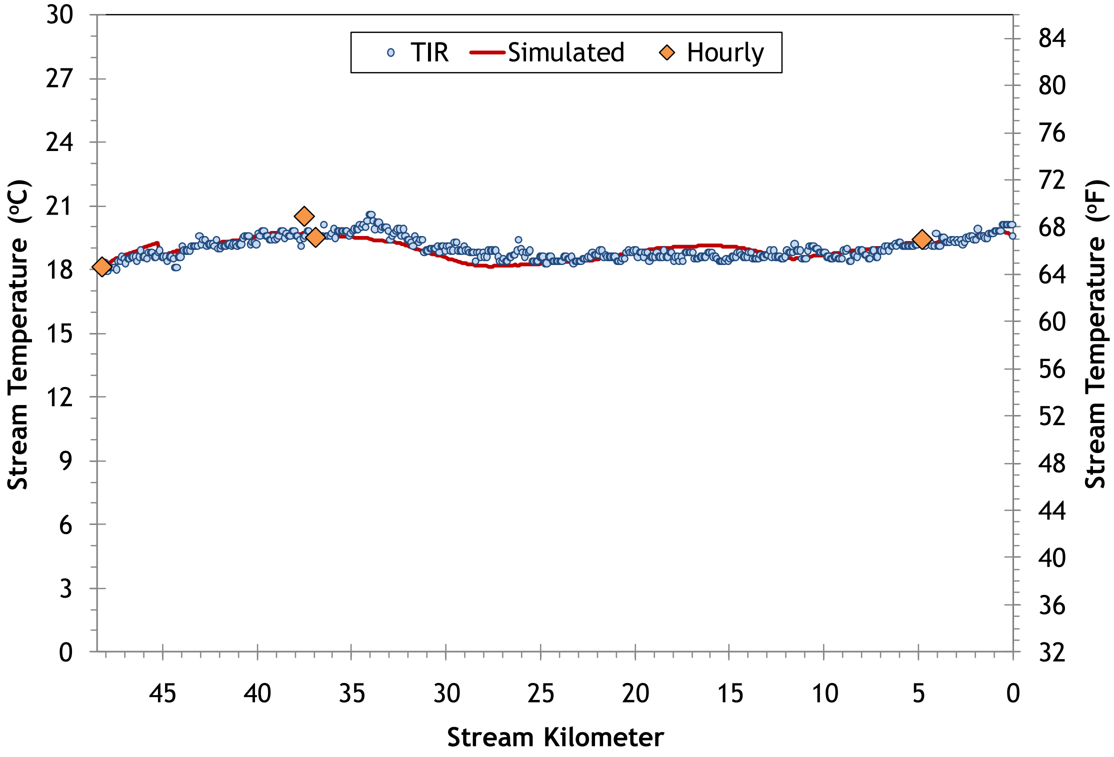


Figure 27 shows the simulated and measured hourly stream temperatures.

Figure 27 - Crescent Creek simulated and measured hourly temperatures.

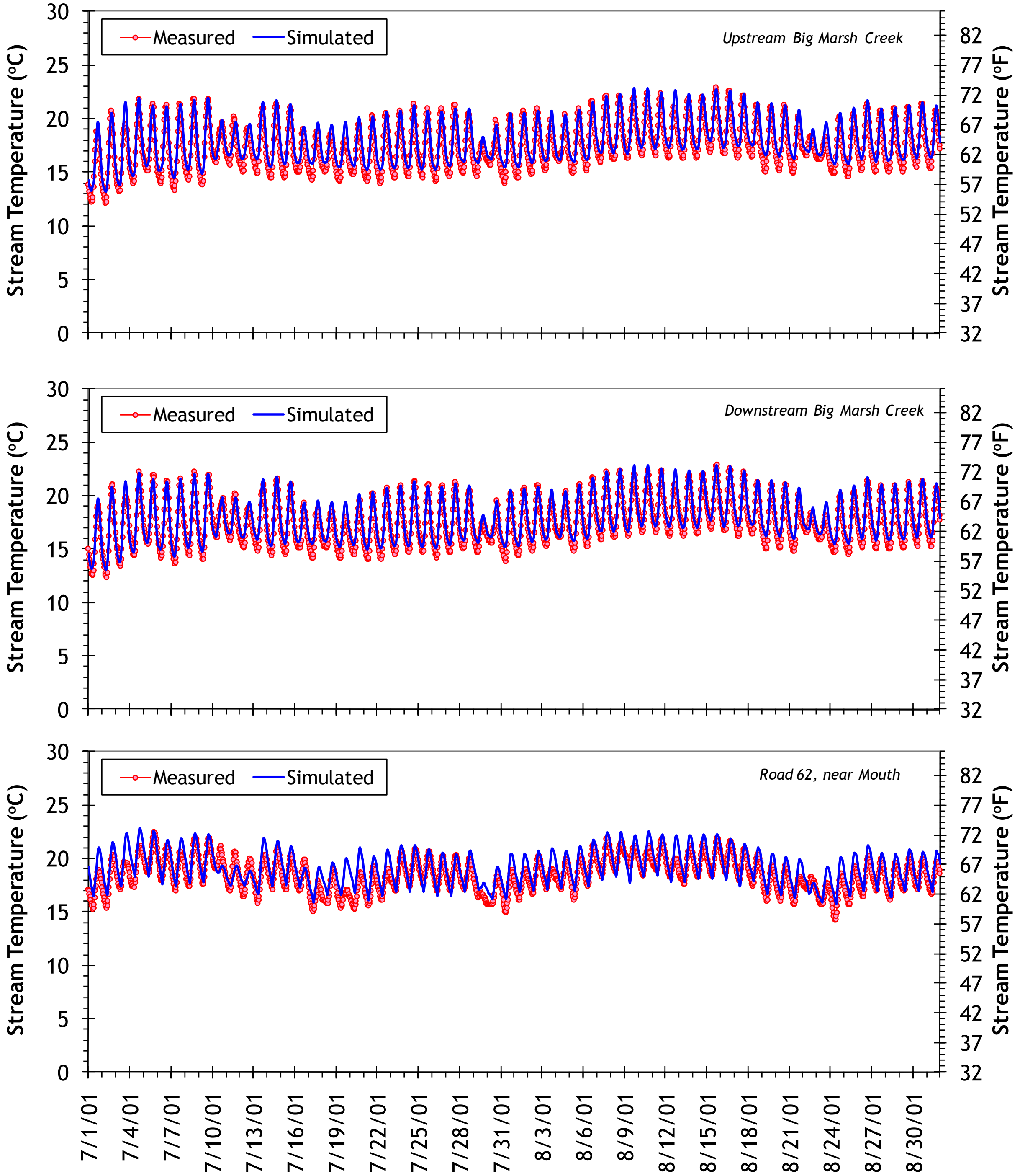


Figure 29 through Figure 32 show the simulated and measured hydraulic values for Crescent Creek. The simulated values presented are from July 25th, when the TIR data was collected. The measured values were collected on July 24 and 25, except for at the outlet of Crescent Lake, where daily gage data was available.

Figure 28 - Crescent Creek simulated and measured flow volumes.

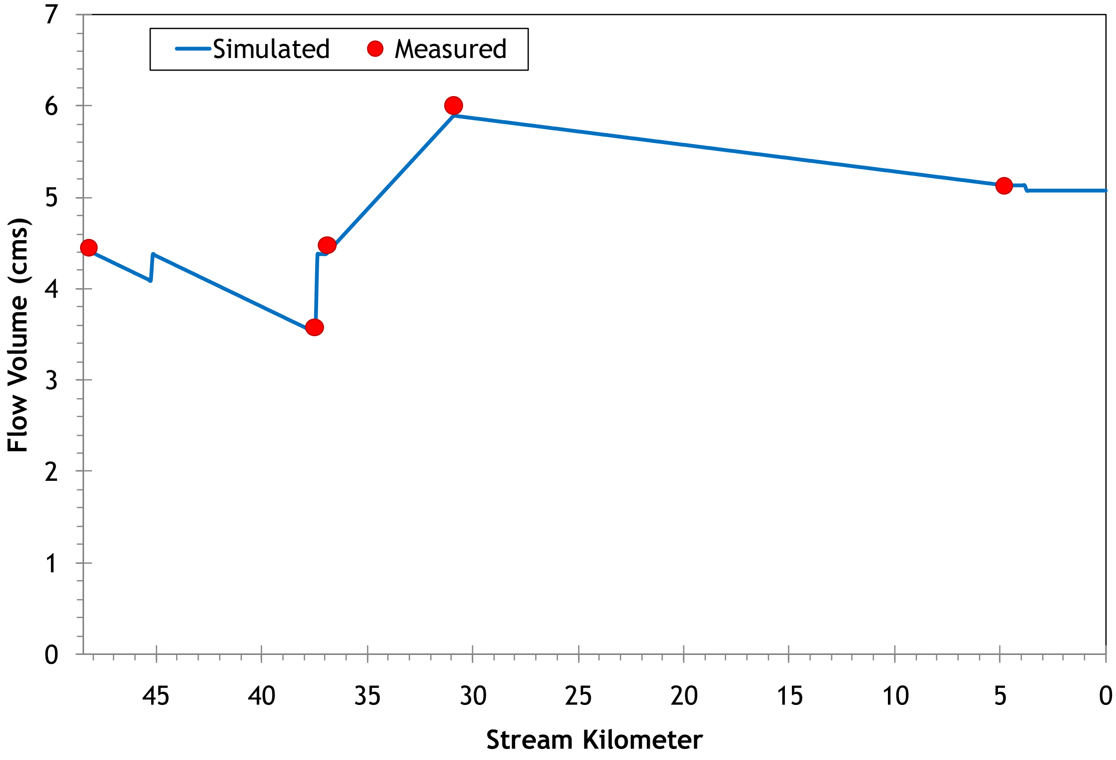


Table 10 summarizes the inflows and outflows included within the Crescent Creek simulation. Generally, mass balance calculations and interpolated gains and losses were included in order for the simulated flow to match the measured values.

Table 10 - Crescent Creek inflow locations and data sources.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Losing Reach	48.45-37.5	Mass Balance Estimate	NA
Cold Spring Creek (LB)	45.2	DEQ	DEQ
No Name (RB)	43.9	Dry	NA
No Name (RB)	42.55	Dry	NA
Marsh Creek (RB)	37.4	Estimated from historic gage	TIR Estimate
Gaining Reach	36.9-30.9	Mass Balance Estimate	Estimated at 15°C
Losing Reach	30.85-4.8	Mass Balance Estimate	NA
No Name (LB)	18.5	Dry	NA
No Name (LB)	7.25	Dry	NA
Withdrawal	3.8	Estimated at 2.0 cfs	NA
No Name (LB)	3.6	Dry	NA

Figure 29 - Crescent Creek simulated and measured velocities.

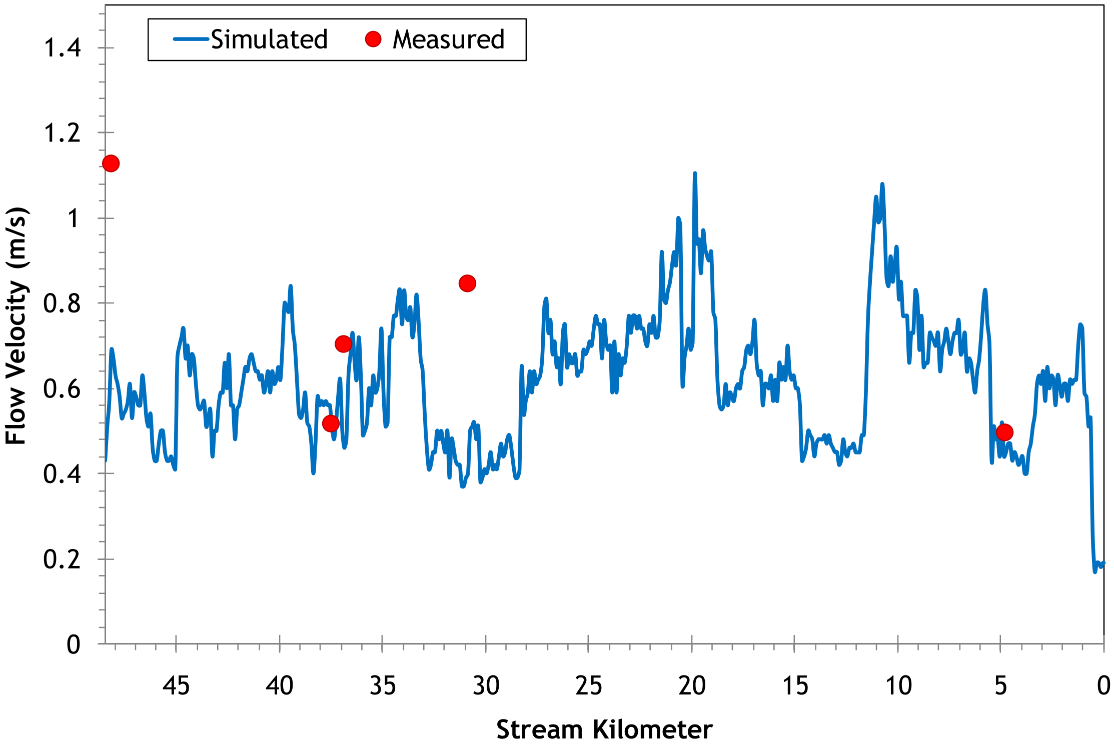


Figure 30 - Crescent Creek simulated and measured wetted widths.

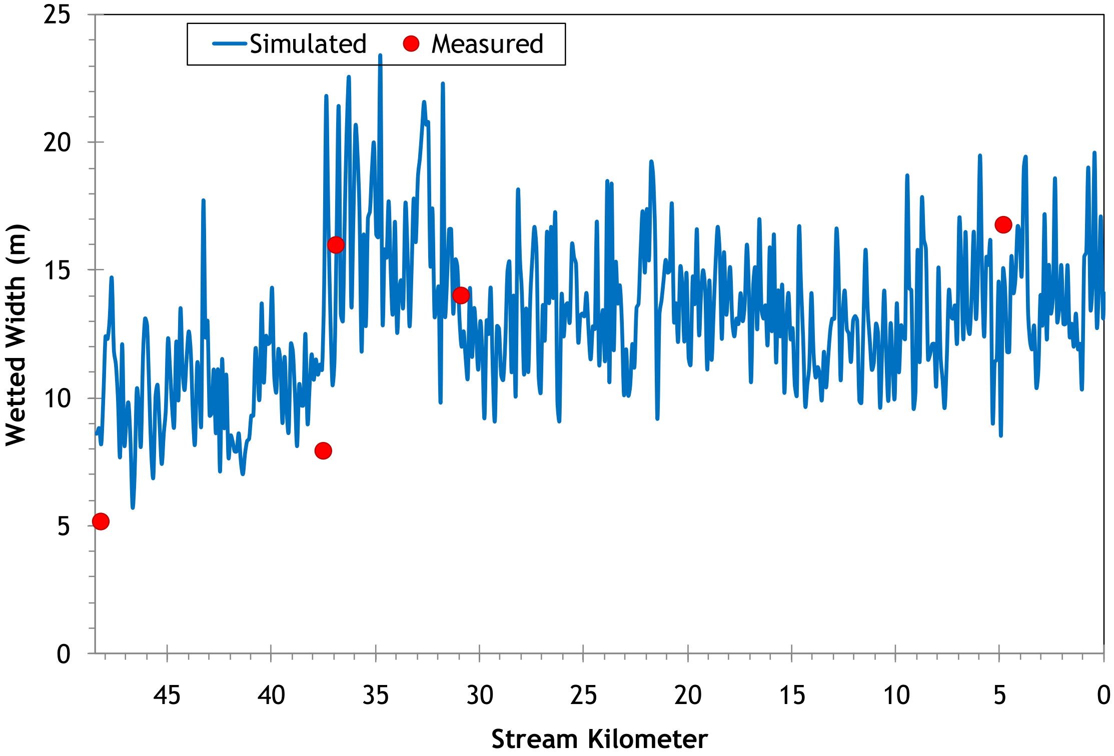


Figure 31 - Crescent Creek simulated and measured maximum depths.

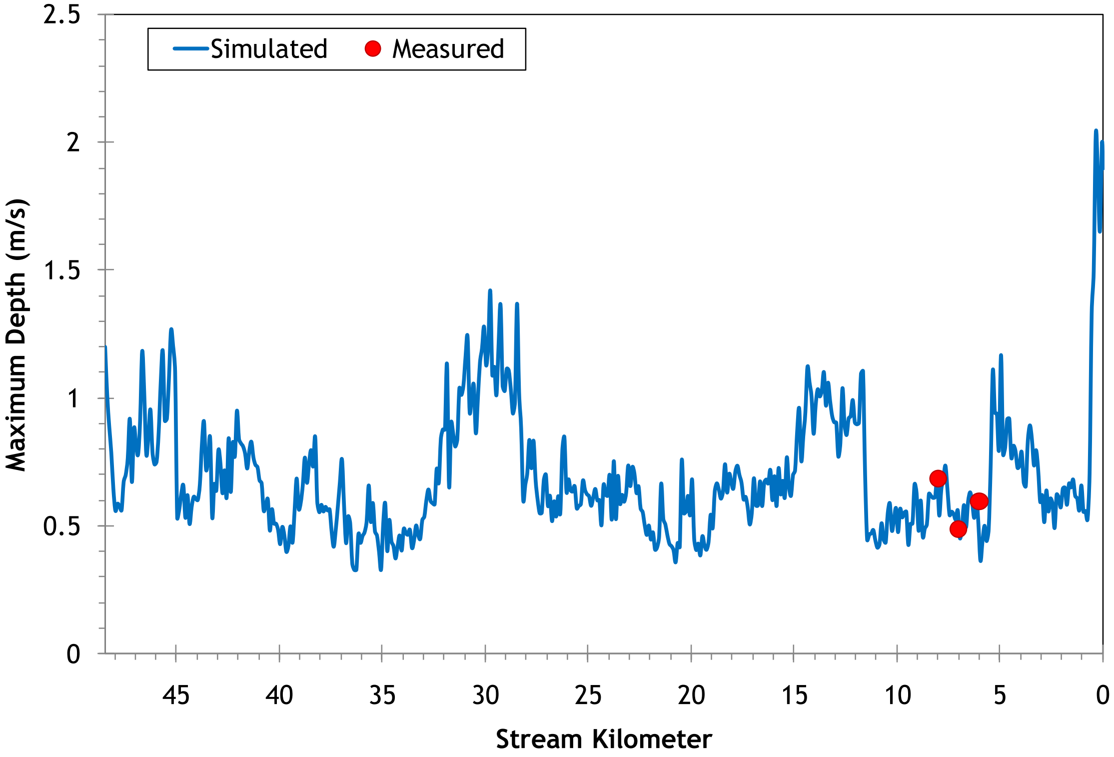


Figure 32 - Crescent Creek just downstream of Crescent Lake outlet gage station.

Figure 33 shows the simulated and measured effective shade along Crescent Creek. A large portion of the total effective shade is created by topographic features. Shade measurements were collected by Oregon DEQ and the USFS on Crescent Creek.

Figure 33 - Crescent Creek simulated and measured effective shade.

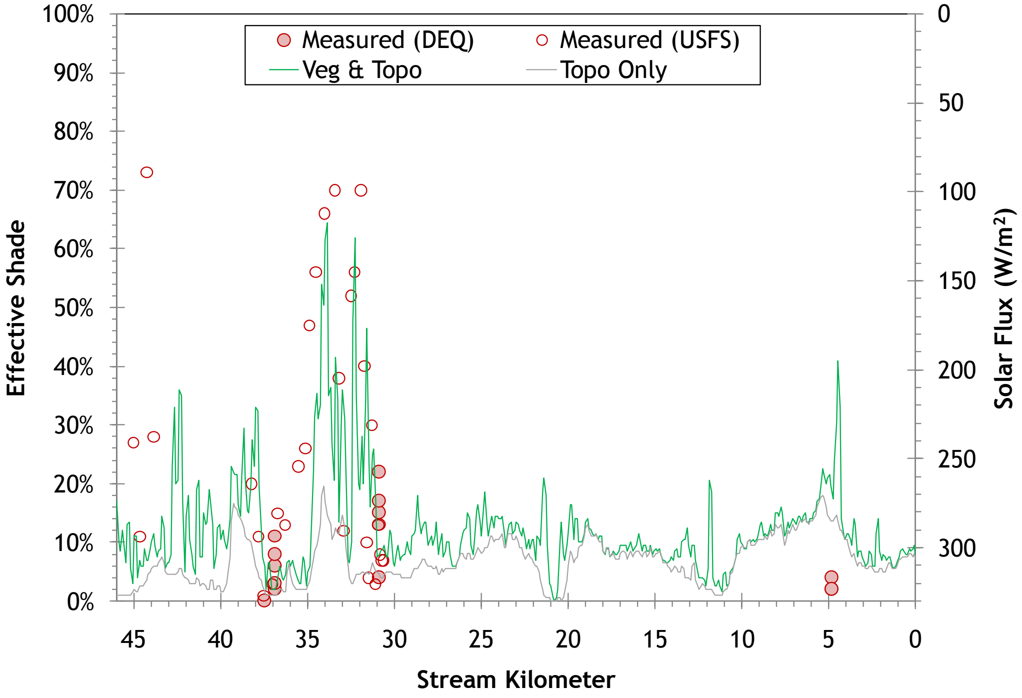
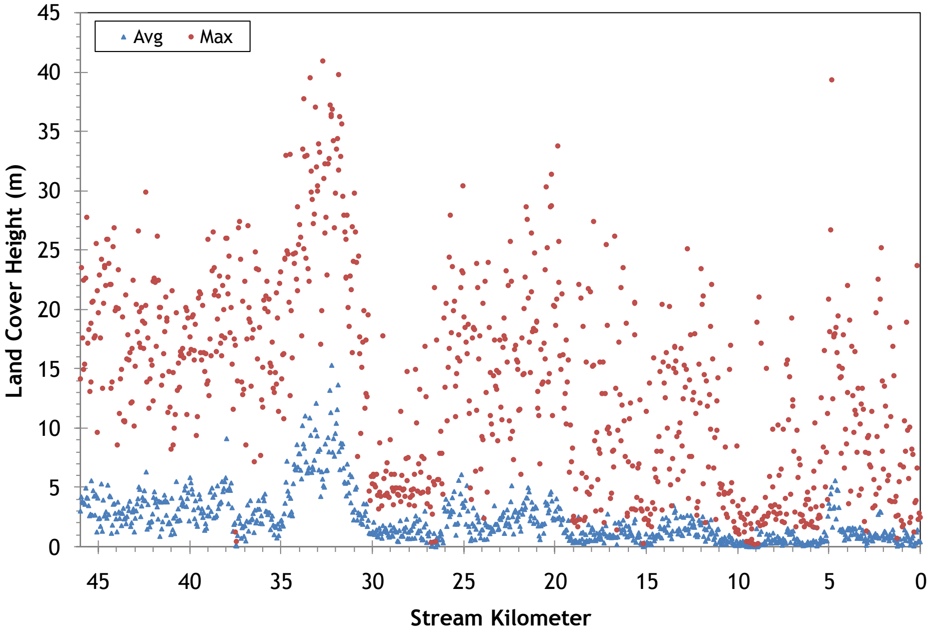


Figure 34 shows the sampled land cover heights along Crescent Creek. USGS LiDAR data was available the entire simulated length.

Figure 34 - Crescent Creek sampled land cover heights.



Little Deschutes River

The Little Deschutes River was simulated from Clover Creek to the mouth. The input parameters and assumptions used to calibrate Heat Source are summarized in Table 11 and described below.

Table 11 - Little Deschutes River Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 1 – August 31, 2001
TIR data:	7/24/01 13:59-16:00. Flown in downstream direction.
Simulation Extent:	168.2 stream kilometers from Clover Creek to the mouth.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	5
Continuous Data Sites:	11
Flush Initial Conditions:	7 days
Deep Alluvium Temperature:	True (15-17°C)
Climate Data Source:	RAWS – Black Rock
Land Cover Data Source:	Upstream of Crescent Creek: Polygons digitized from NAIP imagery. Downstream of Crescent Creek: USGS LiDAR data.
Evaporation Method:	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	0.5 – 3.0 meters
Hyporheic Exchange:	0-1%
Porosity:	35%

- Two separate Heat Source models were used to simulate the Little Deschutes River. One model was set up for the reach above Crescent Creek where there was no LiDAR data. Another model was set up for the reach below Crescent Creek where LiDAR data was available. (The current version of Heat Source can only use one type of land cover input at a time – either digitized polygon codes or LiDAR-sample vegetation heights.)
- The density of the LiDAR-sampled land cover was assumed to be 75%.
- Channel widths were digitized from the NAIP imagery.
- Cloud cover was estimated at 0, 25, or 75% based upon days when the daily maximum stream temperatures were significantly cooler than surround days.
- Simulated temperatures within the Gilchrist Mill Pond are not valid since the model cannot simulate a stratified water column. The TIR imagery revealed that the pond was stratified during the simulation period.
- The first 10 days of hourly temperature data at the Wilderness boundary did not exist, so data from the next downstream site (minus 1.9°C) were used.
- There were some un-verified losing and gaining reaches between flow measurement sites. Flow volume was evenly removed or added between flow measurement sites (see the flow profile chart).

Table 12 summarizes the calibration statistics for the Little Deschutes River simulation.

Table 12 - Little Deschutes River simulation calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	168.2-0	1,683	-0.02	0.38	0.50	0.63
Wilderness Boundary	DEQ	164.2	1,488	0.19	0.64	0.80	0.78
Spur Road off Road 300	DEQ	157.4	1,488	0.40	0.64	0.89	0.71
Upstream Hemlock Creek	DEQ	148.6	1,488	0.50	1.06	1.43	0.71
Off 090 Spur Road	USFS	145.7	1,488	0.55	1.30	1.65	0.54
Off 100 Road near Crescent	DEQ	119.7	910	0.54	0.94	1.23	0.71
Upstream Gilchrist Mill Pond	DEQ	113.2	1,212	0.73	1.06	1.35	0.78
Road 62, u/s Crescent Creek	USFS	100.9	1,488	0.64	1.76	2.38	0.35
Burgess Road	DEQ	44.0	1,488	-0.22	0.76	0.94	0.76
Crosswater Road Bridge	DEQ	1.6	1,488	-0.26	0.88	1.07	0.68
Crosswater Clubhouse	DEQ	0.3	1,488	-0.12	0.94	1.14	0.62

Figure 35 shows the calibrated stream temperature simulation results for the Little Deschutes River from Clover Creek to the mouth. The temperature decrease near stream kilometer 100 is the Crescent Creek confluence. Crescent Creek had much greater flow volumes than the Little Deschutes River during the simulation period. The increased flow volume, combined with low stream gradients and high sinuosity results in a more steady temperature profile in the lower 100 kilometers.

Figure 35 - Little Deschutes River calibrated longitudinal temperature profile.

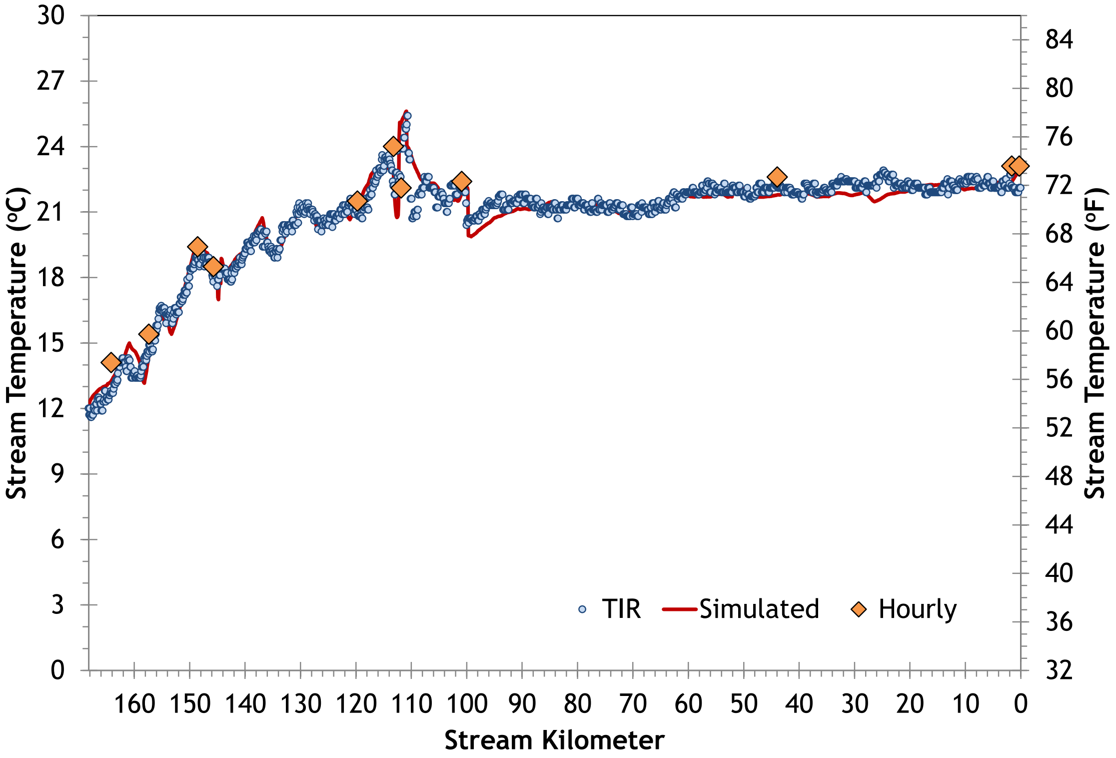
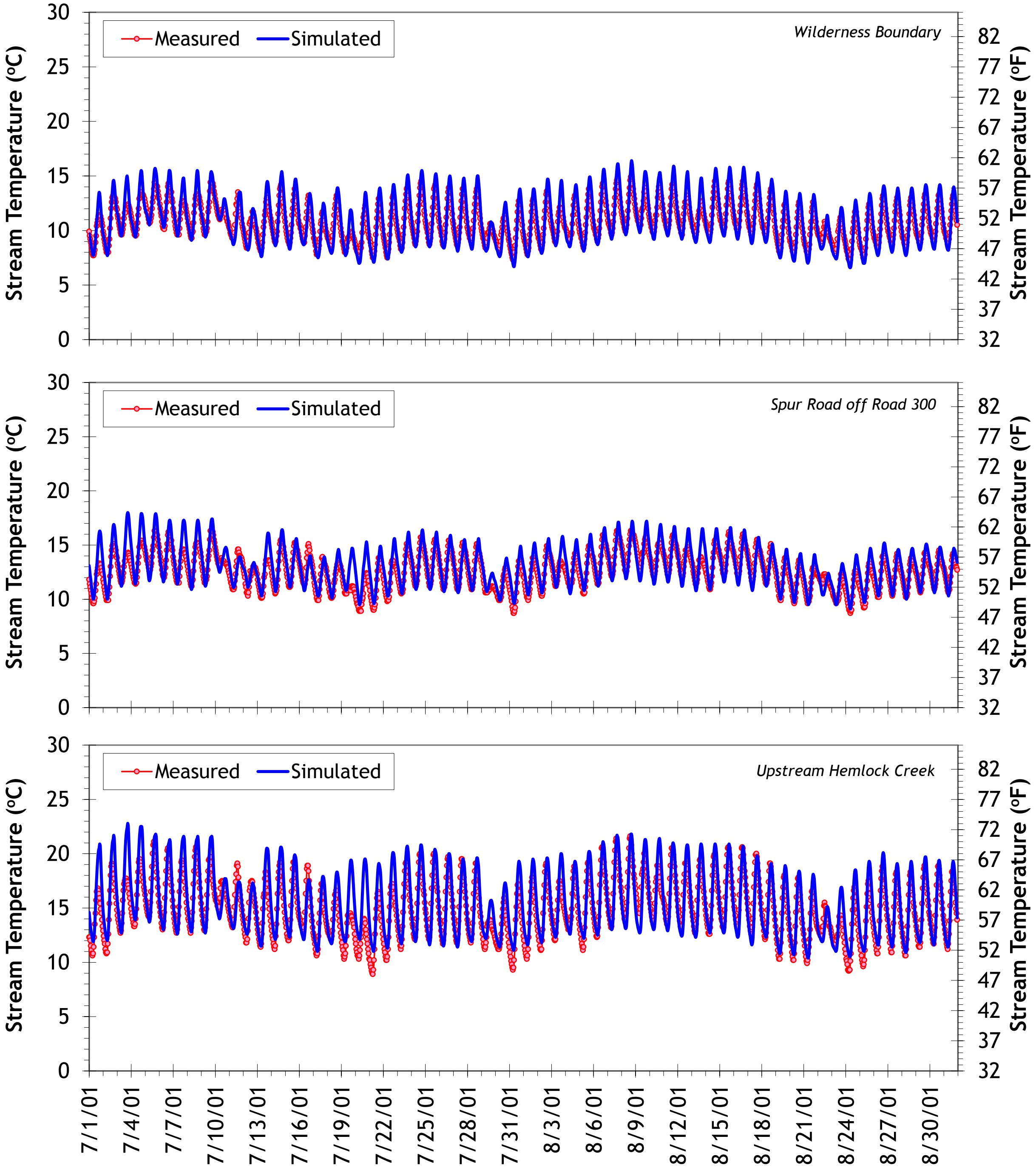
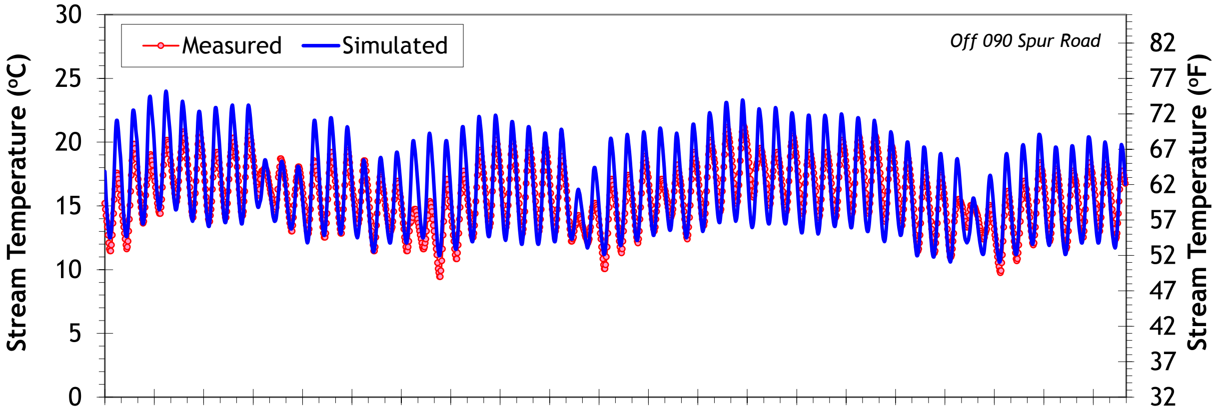
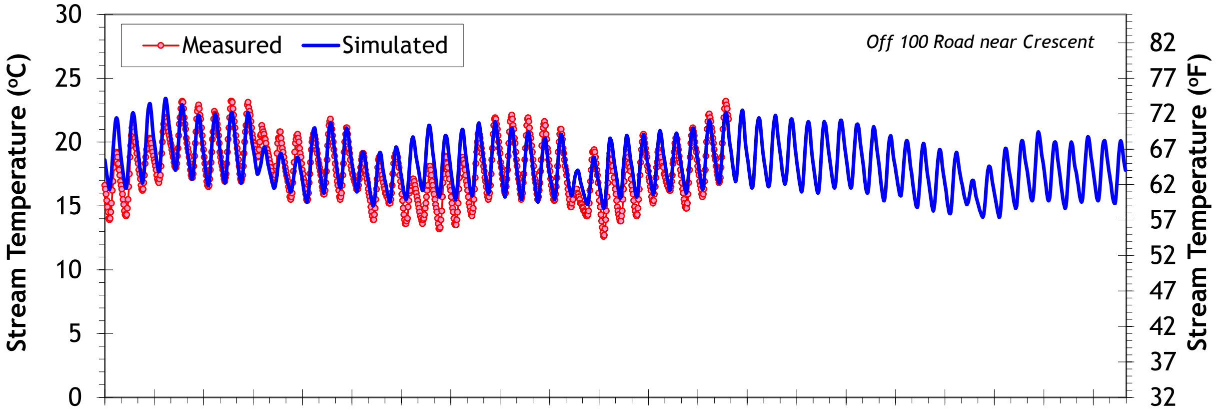


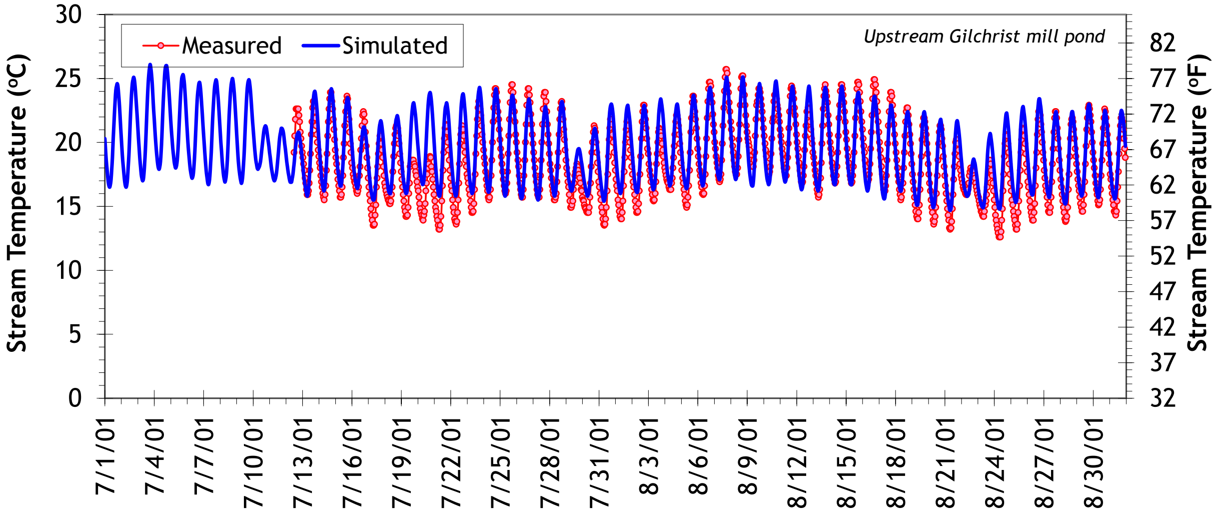
Figure 36 shows the simulated and measured hourly temperature data and RMSE statistics for the calibrated model. The measured data downstream Gilchrist Pond has suspect data quality.

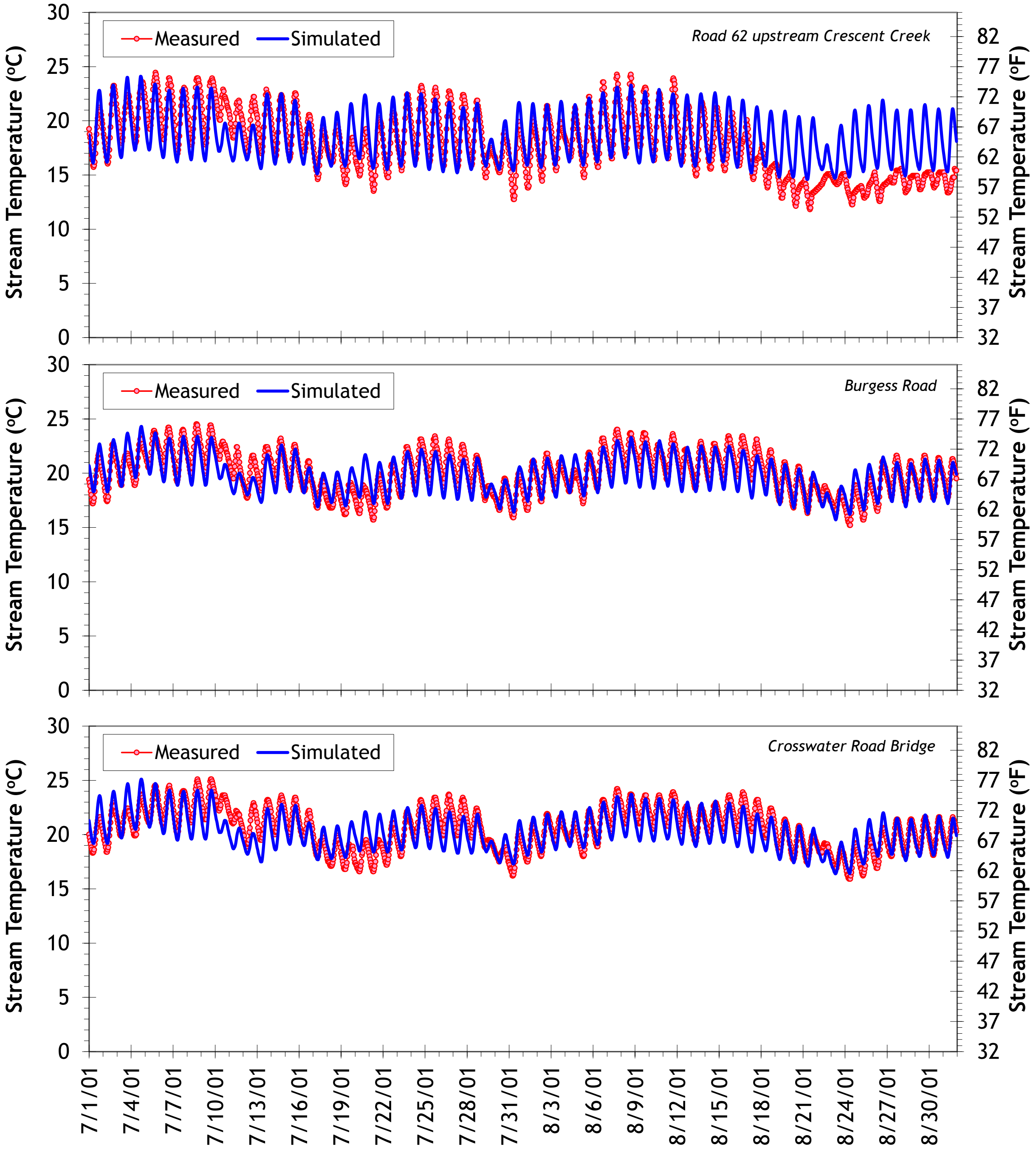
Figure 36 - Little Deschutes River simulated and measured temperatures.

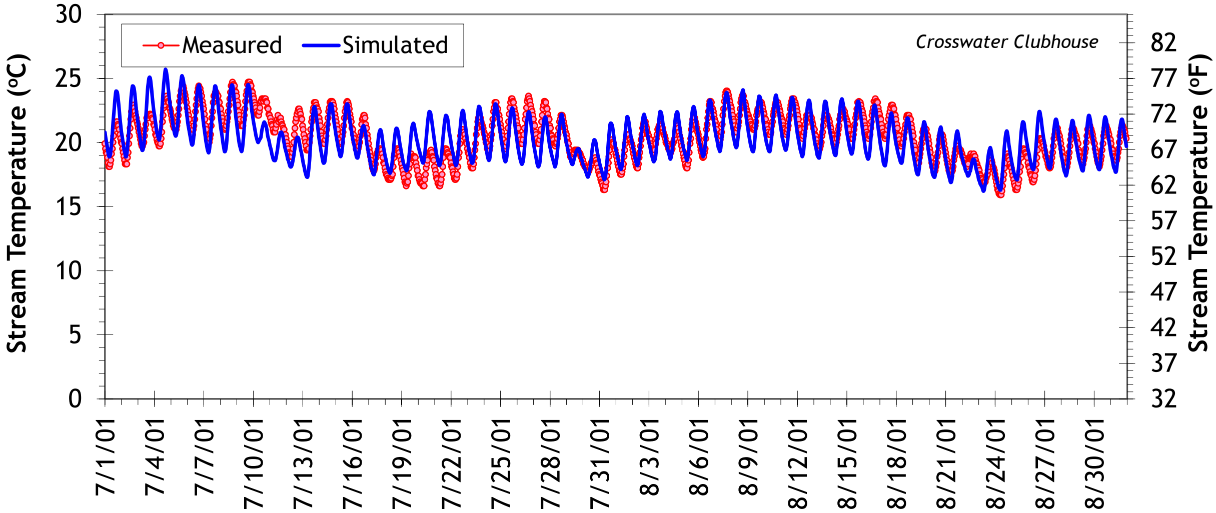



Stream Temperature (ºC)
30
25
20
15
10
5
0
Measured
Simulated
Off 090 Spur Road
82
77
72
67
62
57
52
47
42
37
32
Stream Temperature (ºF)


Stream Temperature (ºC)
30
25
20
15
10
5
0
Measured
Simulated
Off 100 Road near Crescent
82
77
72
67
62
57
52
47
42
37
32
Stream Temperature (ºF)


Stream Temperature (ºC)
30
25
20
15
10
5
0
Measured
Simulated
Upstream Gilchrist mill pond
82
77
72
67
62
57
52
47
42
37
32
Stream Temperature (ºF)
7/1/01
7/4/01
7/7/01
7/10/01
7/13/01
7/16/01
7/19/01
7/22/01
7/25/01
7/28/01
7/31/01
8/3/01
8/6/01
8/9/01
8/12/01
8/15/01
8/18/01
8/21/01
8/24/01
8/27/01
8/30/01


Measured
Simulated
Road 62 upstream Crescent Creek
Burgess Road
Crosswater Road Bridge
Stream Temperature (ºC)
Stream Temperature (ºF)
30
25
20
15
10
5
0
82
77
72
67
62
57
52
47
42
37
32
7/1/01
7/4/01
7/7/01
7/10/01
7/13/01
7/16/01
7/19/01
7/22/01
7/25/01
7/28/01
7/31/01
8/3/01
8/6/01
8/9/01
8/12/01
8/15/01
8/18/01
8/21/01
8/24/01
8/27/01
8/30/01


Measured
Simulated
Crosswater Clubhouse
Stream Temperature (ºC)
Stream Temperature (ºF)
30
25
20
15
10
5
0
82
77
72
67
62
57
52
47
42
37
32
7/1/01
7/4/01
7/7/01
7/10/01
7/13/01
7/16/01
7/19/01
7/22/01
7/25/01
7/28/01
7/31/01
8/3/01
8/6/01
8/9/01
8/12/01
8/15/01
8/18/01
8/21/01
8/24/01
8/27/01
8/30/01

Above the Crescent Creek confluence, the Little Deschutes River is very small and hydraulically, much different than the lower reaches. Crescent Creek contributes a significant amount of water to the Little Deschutes River, resulting in much different hydraulic properties in the lower 100 kilometers. All of the simulated and measured values are from July 24th.

Upstream of Crescent Creek, the simulated flows were steady-state and based upon the field measurements. Below Crescent Creek, the simulated flows vary on a daily basis and were calculated to match the OWRD La Pine gage data.

Figure 37 - Little Deschutes River simulated and measured flow volumes.

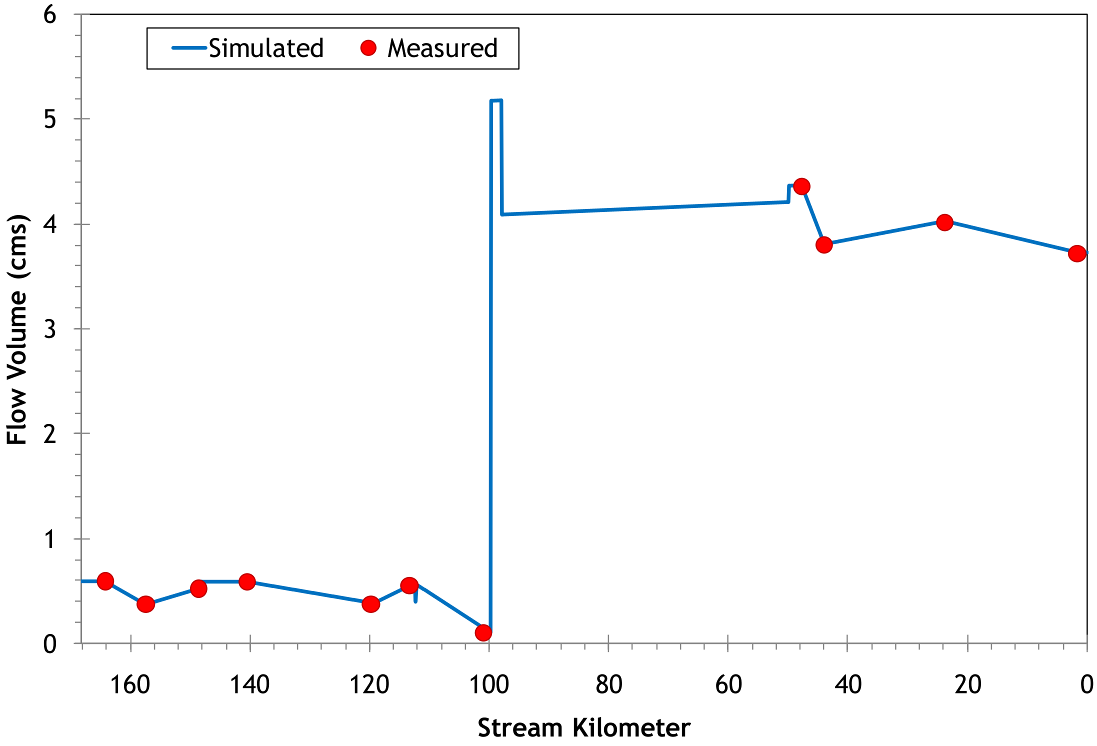


Table 13 - Inflows and outflows included within the Little Deschutes River simulation.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Losing reach	164.2-157.45	Mass Balance Estimate	NA
Gaining reach	157.4-148.65	Mass Balance Estimate	Estimated at 12-16°C
Hemlock Creek	148.1	DEQ	DEQ
Losing reach	140.35-119.85	Mass Balance Estimate	NA
Gaining reach	119.75-113.3	Mass Balance Estimate	Estimated at 15-20°C
***Gilchrist Pond*[1]**	***112.2***	***Reported at 5.5 cfs***	***Reported at 36.7°C***
Losing Reach	111.8-99.85	Mass Balance Estimate	NA
spring/trib	110.8	Mass Balance Estimate	TIR
Crescent Creek	99.7	DEQ	DEQ
Gaining Reach	99.7-47.75	Mass Balance Estimate	Estimated at 16°C
Walker Diversion	97.9	38.5 cfs (DEQ/OWRD)	NA
Long Prairie Slough	49.9	DEQ	TIR
Losing Reach	47.7-43.95	Mass Balance Estimate	NA
Gaining Reach	43.9-23.75	Mass Balance Estimate	Estimated at 16°C
Losing Reach	23.7-1.6	Mass Balance Estimate	NA

---

[1] The mill at Gilchrist Pond reportedly withdraws water from the pond and discharges its effluent back into the pond. Within the model, 5.5 cfs was withdrawn and then 5.5 cfs was returned within the pond (causing the small "blip" near kilometer 112).

Figure 38 shows the simulated and measured daily flow volumes at the La Pine gage. On average, the simulated values were within 4.4% of the measured daily flows. The flows in the lower Little Deschutes River are dominated by Crescent Creek and its reservoir releases.

Figure 38- Little Deschutes River simulated and gaged daily flows at the La Pine gage.

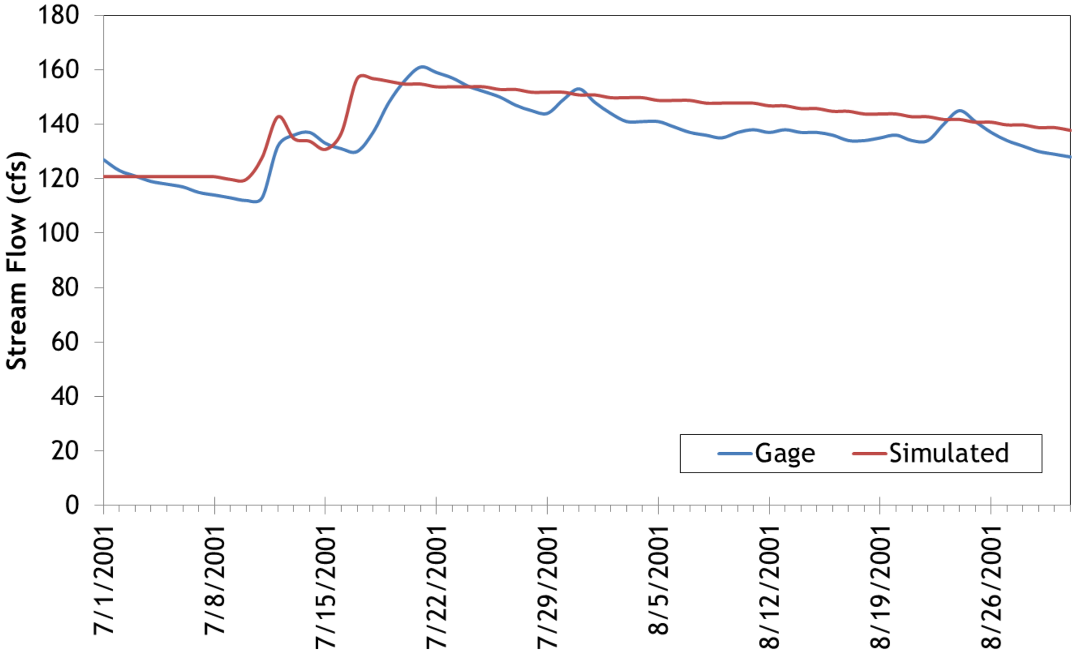


Figure 39 shows the simulated and measured velocities. Below Crescent Creek, the velocities are quicker due to the larger flow volume.

Figure 39 - Little Deschutes River simulated and measured velocities.

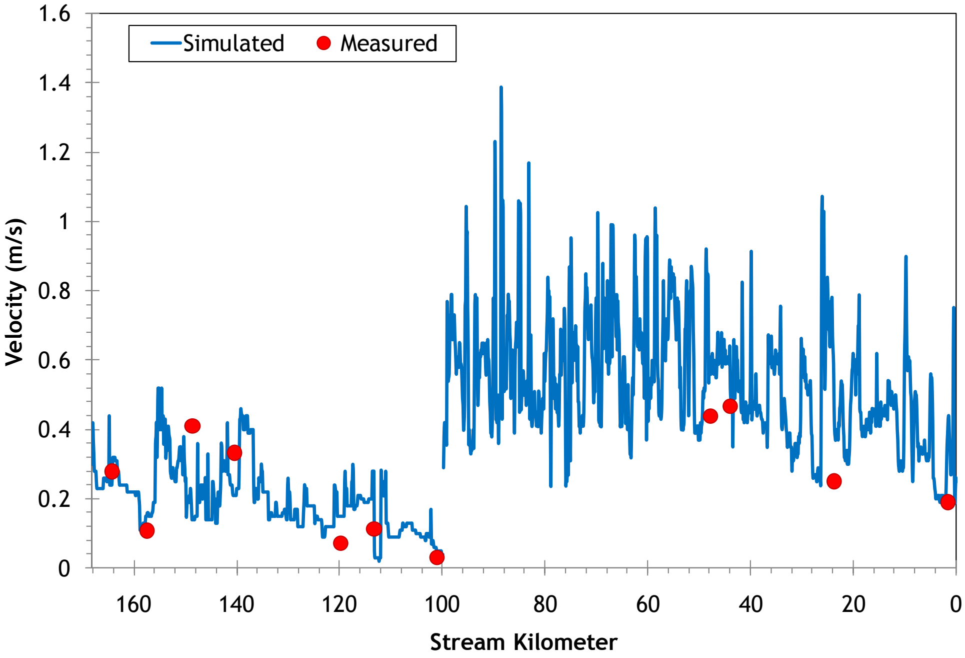


Figure 40 shows the simulated and measured wetted widths for Little Deschutes River. Upstream of Crescent Creek the stream was too narrow to be accurately digitized, so the channel widths were estimated based on the ground level and aerial photo measurements. Below Crescent Creek, the channel widths were digitized from the TIR imagery and the LiDAR data. Crescent Creek increases the flow within Little Deschutes River from about 0.5 cms to nearly 4.0 cms, resulting in a wider system.

Figure 40 - Little Deschutes River simulated and measured wetted widths.

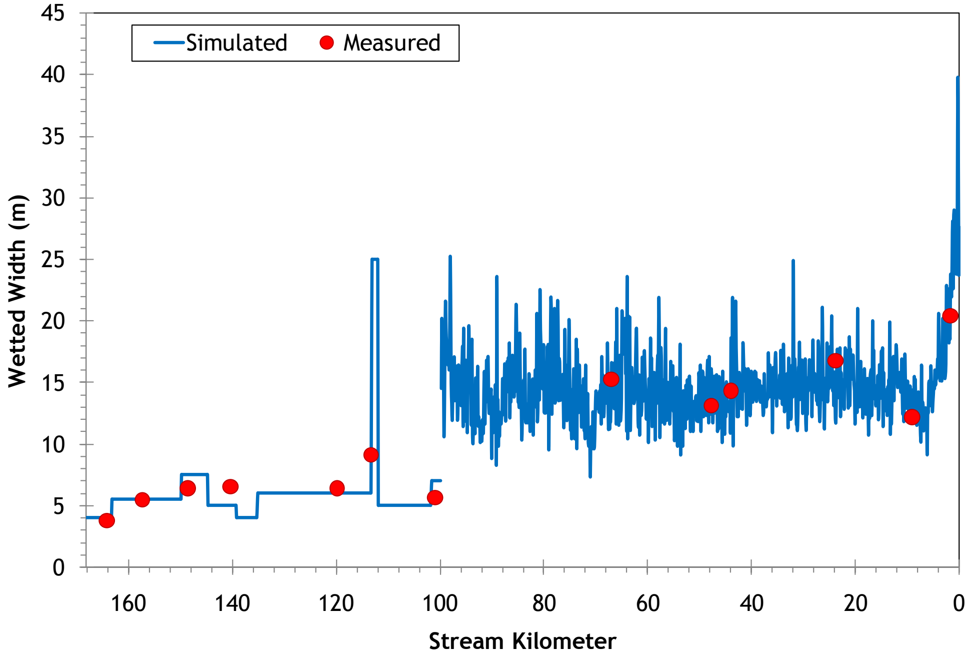


Figure 41summarized the maximum depths for the Little Deschutes River simulation. Depths are calculated by the model as a function of flow volume, velocity, and width.

Figure 41 - Little Deschutes River simulated and measured maximum depths.

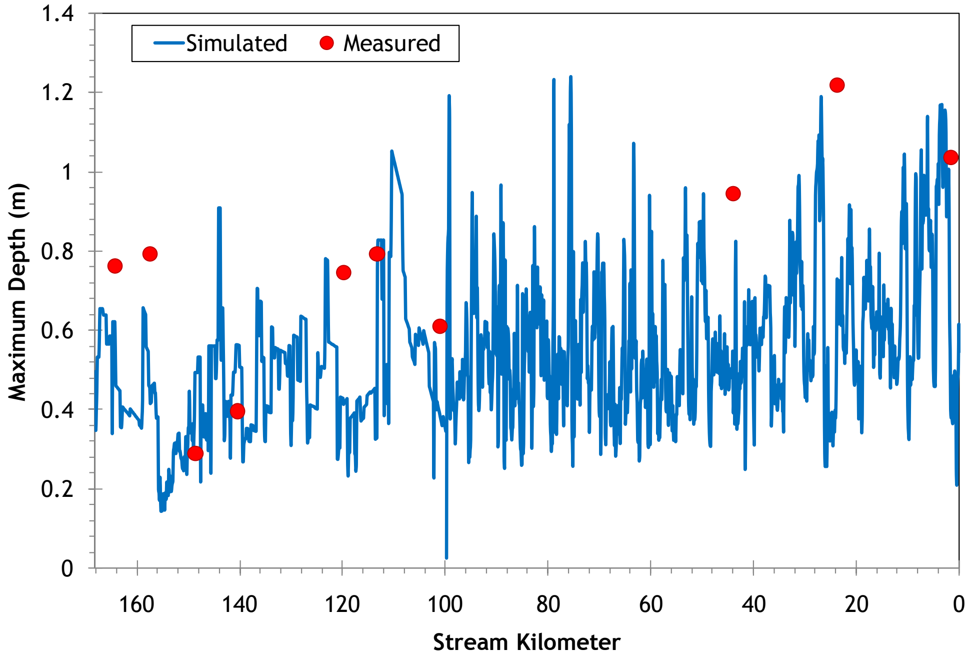


Figure 42 – Little Deschutes River upstream Hemlock Creek.

Figure 43 – Little Deschutes River at Crosswater Golf Course.

Figure 44 shows the simulated and measured effective shade of Little Deschutes River. The upper reaches tend to have higher effective shade values because there are more forested areas and the stream widths are narrower, which makes the surface more easily shaded.

Figure 44 - Little Deschutes River simulated and measured effective shade.

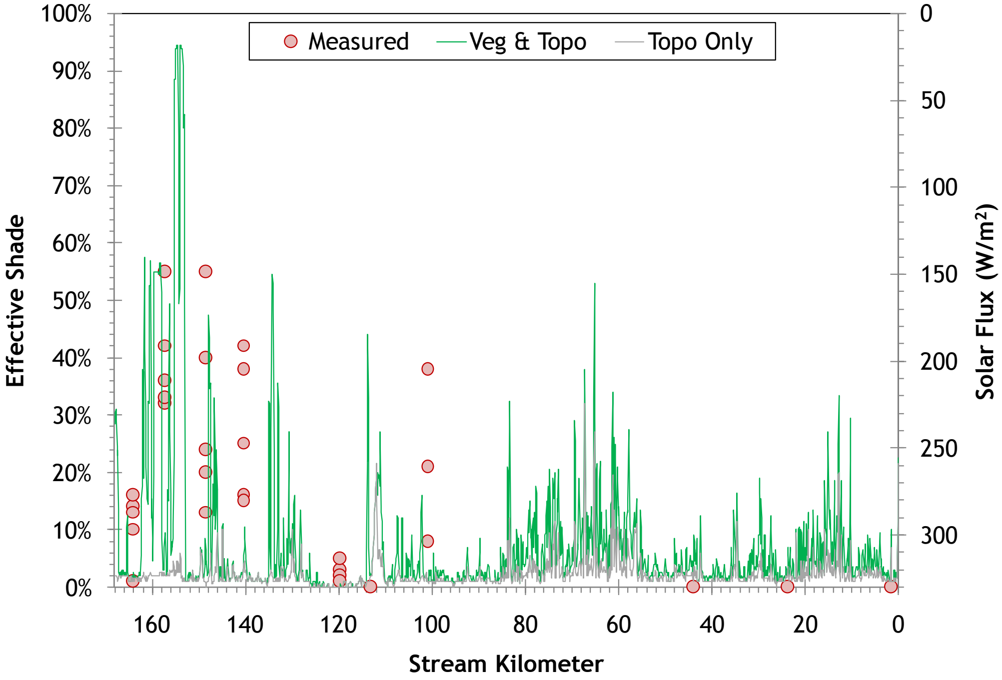
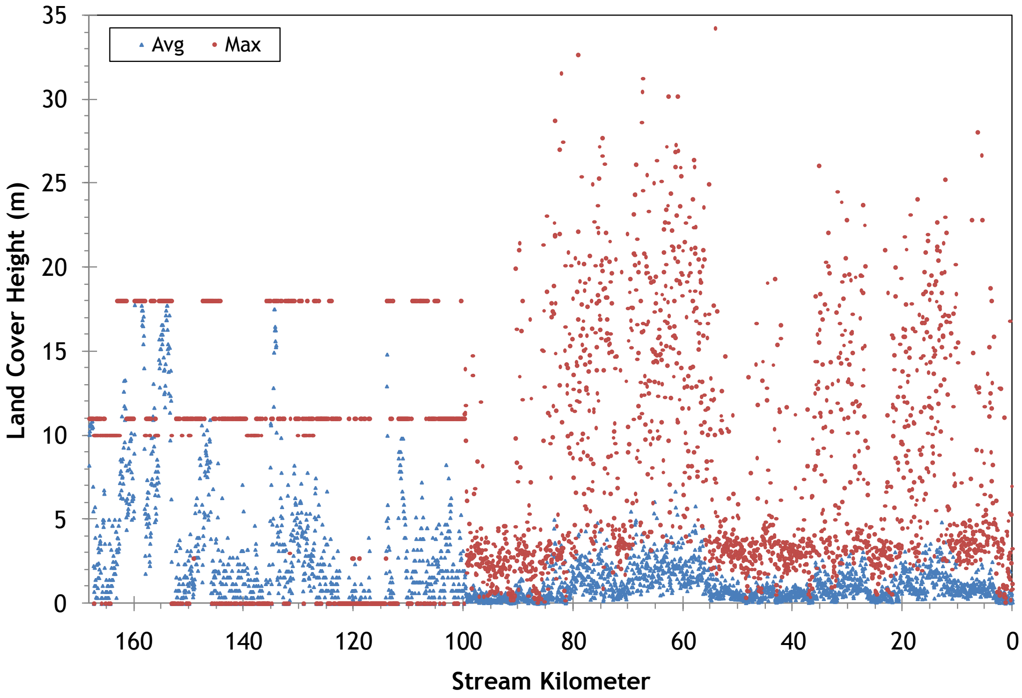


Figure 45 shows the sampled land cover heights along the Little Deschutes River. Upstream of Crescent Creek (kilometer 100), the land cover was sampled from polygons digitized from the NAIP imagery. Below Crescent Creek, the land cover heights were sampled from the USGS LiDAR data.

Figure 45 - Little Deschutes River sampled land cover heights.



South Fork Crooked River

The South Fork Crooked River was simulated from the outlet of the dam below Sears Creek to the mouth. The input parameters and assumptions used to calibrate the Heat Source model are summarized in Table 14 and described below.

Table 14 - South Fork Crooked River Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 25 – August 31, 2005
TIR data:	8/7/05, 13:10-14:07. Flown in upstream direction.
Simulation Extent:	60.9 stream kilometers to the mouth.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	1
Continuous Data Sites:	3
Flush Initial Condition:	7
Deep Alluvium Temperature:	True (15°C)
Climate Data Source:	RAWS – Badger Creek
Land Cover Data Source:	Polygons digitized from TIR mosaics and NAIP imagery.
Evaporation Method	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	0.7 – 1.5 meters
Hyporheic Exchange:	0 - 1%
Porosity:	40%

- Channel widths (wetted surface) were digitized from the mosaiced TIR imagery.
- Hourly air temperature, average wind speed, and relative humidity values were recorded at the Badger Creek RAWS station. Air temperatures were adjusted based on the dry adiabatic lapse rate.
- Based on solar radiation data collected at the Badger Creek RAWS site, cloud cover was estimated to be 75% on July 8 and 9.
- Hourly temperature data from the GI Ranch/BLM boundary monitoring site were used as the upstream boundary condition.
- The flow measurement at stream kilometer 15 (Jake Ford Place) was questionably high and therefore not used for calibration.
- The stream temperature was between 20 and 25°C throughout the simulated reach at the time that the TIR data was collected. The temperature profile itself is quite variable over short distances, indicating possible stratification throughout. In addition, the low gradients may contribute to stratification.
- The diversion rate of the canal upstream of Twelvemile Creek was estimated based on visual observation of its relative size in the TIR imagery. Point of diversion data supplied by OWRD was not helpful because it contains only permitted diversion rates, not actual rates for the simulation time period. (Permitted rates exceeded the existing stream flow.)
- Twelvemile Creek inflow volumes were estimated.

Table 15 summarizes the calibration statistics achieved for the instantaneous and hourly temperatures in the South Fork Crooked River model.

Table 15 - South Fork Crooked River calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	60.9-0	610	-0.05	0.51	0.66	0.01
GI Ranch / BLM Boundary	BLM	53.70	912	0.26	1.05	1.31	0.65
1.5 miles d/s Twelvemile Creek	BLM	30.10	912	0.13	0.97	1.19	0.85
Mouth	BLM	0.45	912	1.39	1.43	1.77	0.46

Figure 46 shows the calibrated longitudinal temperature profile of the South Fork Crooked River. The entire simulated reach was warm throughout, with areas of possible stratification.

Figure 46 - South Fork Crooked River calibrated longitudinal temperature profile.

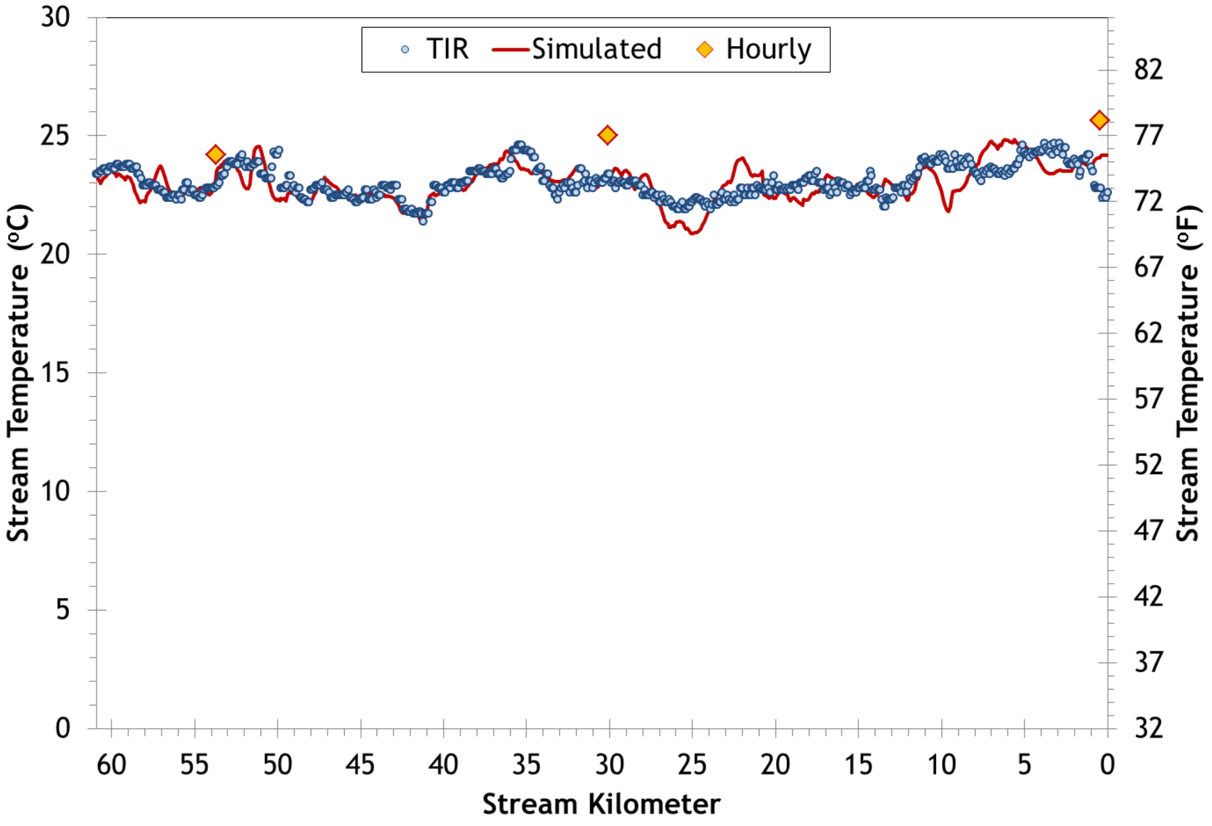


Figure 47 shows the simulated and measured hourly temperatures from the calibrated Heat source model. Due to the low flow volumes of the stream, hourly temperature calibration was challenging and the best attainable RMSE statistics were over 1°C. The hourly measured temperatures at the mouth were a few degrees higher than the TIR data for unknown reasons.

Figure 47 - South Fork Crooked River simulated and measured hourly temperatures.

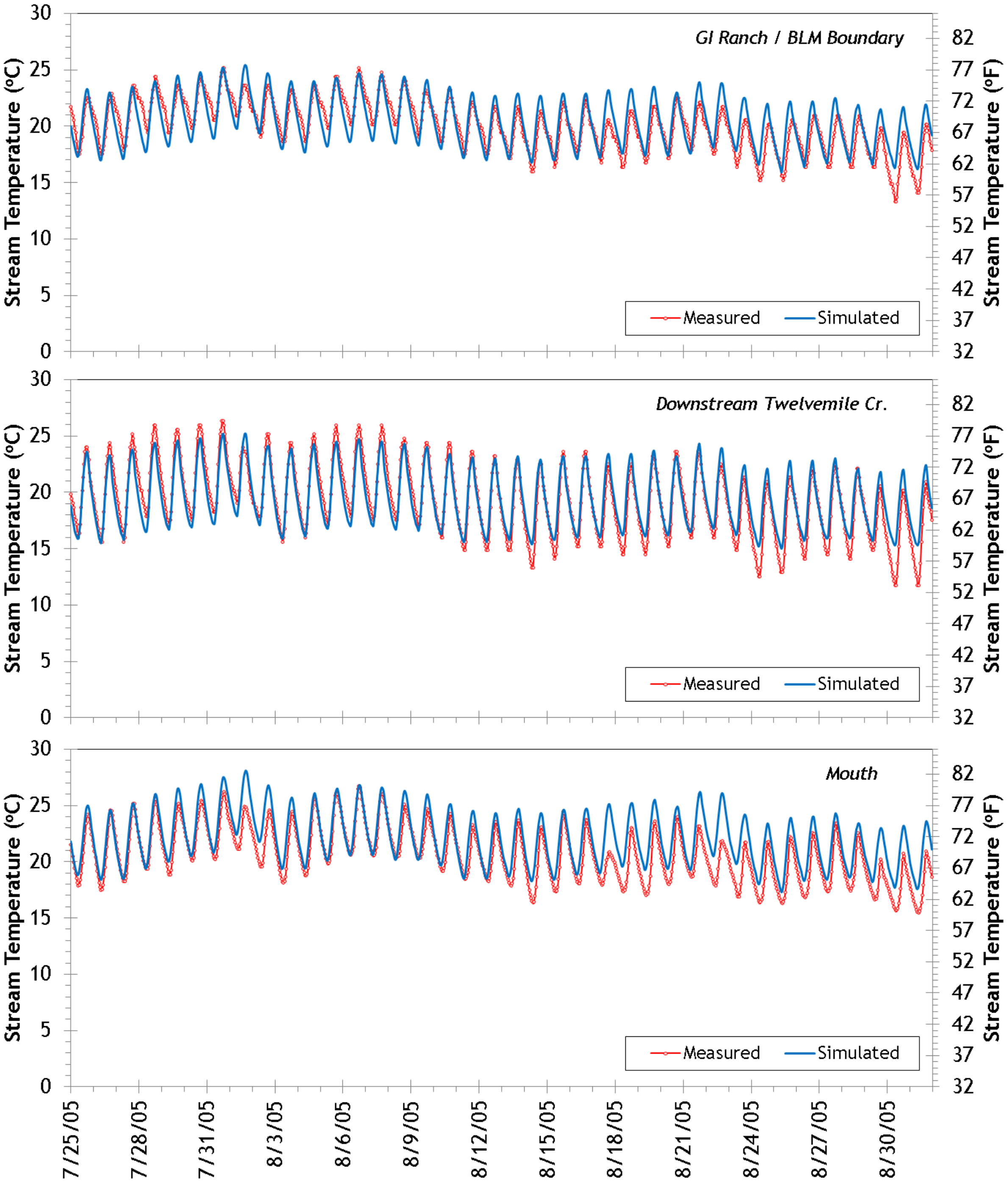


Figure 48 shows the simulated and measured flow volumes for the South Fork Crooked River. The simulated values are from August 7, 2005 when the TIR data was collected. The measured values were collected on August 4th and 11th. The upstream boundary was estimated at 0.09 cms (3.2 cfs). Diversions and gaining reaches were also estimated relative to the TIR imagery.

Figure 48 - South Fork Crooked River simulated and measured flow volumes.

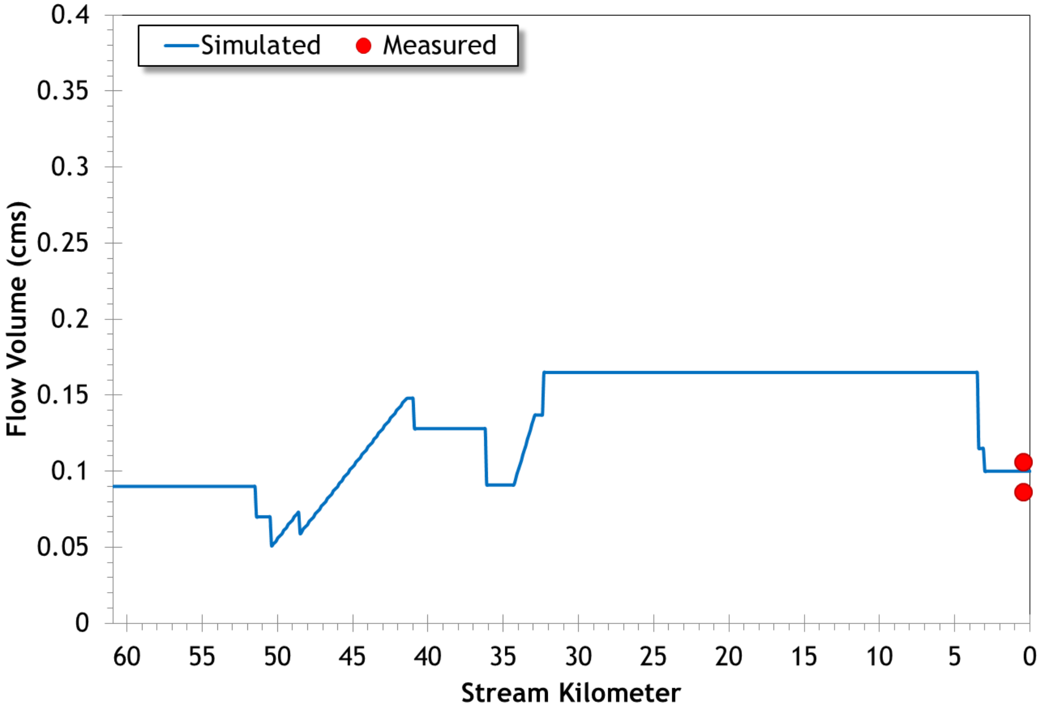


Table 16 summarizes the inflows and outflows that were estimated in the South Fork Crooked River simulation. Gains/returns were estimated based on TIR imagery and in order for the profile to match the measured data points.

Table 16 - Simulated inflow and accretion locations along the South Fork Crooked River.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Diversion	51.45	Estimated at 0.7 cfs	NA
Diversion	50.45	Estimated at 0.7 cfs	NA
Gain/Return	50.4-41.4	Estimate at 4.0 cfs	Estimated 22°C
Diversion	40.9	Estimated at 0.7 cfs	NA
Diversion	36.15	Estimated at 1.3 cfs	NA
Gain/Return	34.25-32.9	Estimated at 1.6 cfs	Estimated 22°C
Twelvemile Creek	32.3	Estimated at 1 cfs	Estimated
Diversion	3.45	Estimated at 1.8 cfs	NA
Diversion	3.05	Estimated at 0.5 cfs	NA

Figure 50 through Figure 53 show the simulated and measured hydraulic parameters of the South Fork Crooked River.

Figure 49 - South Fork Crooked River simulated and measured velocities.

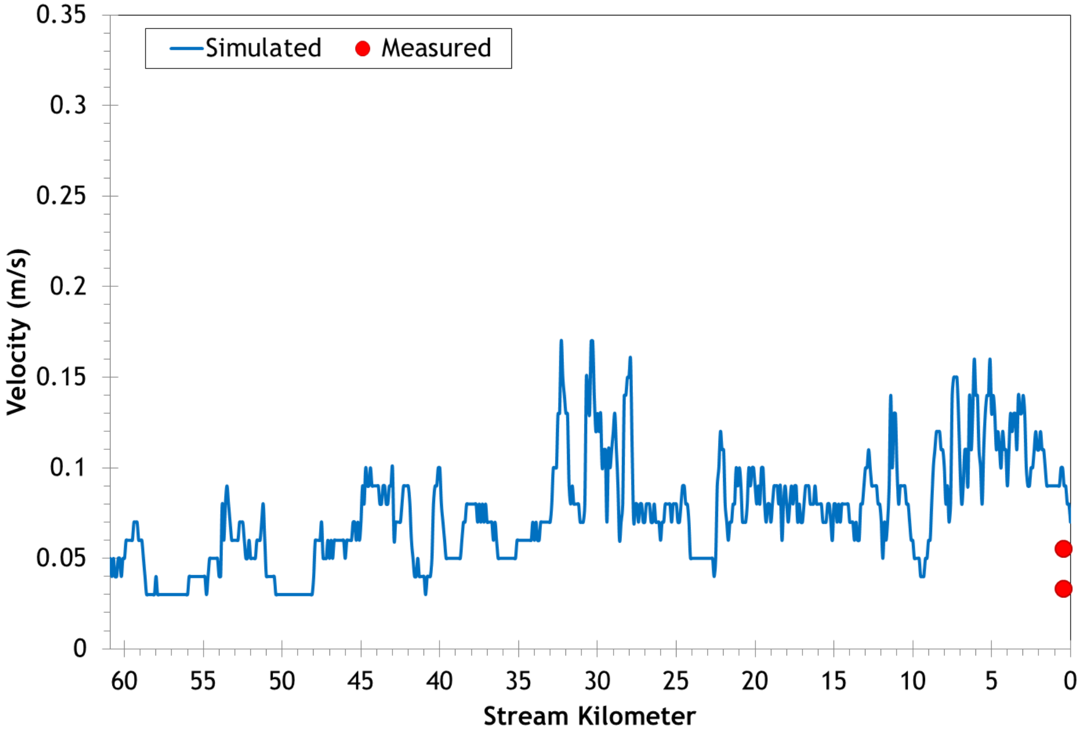


Figure 50 - South Fork Crooked River simulated and measured wetted widths.

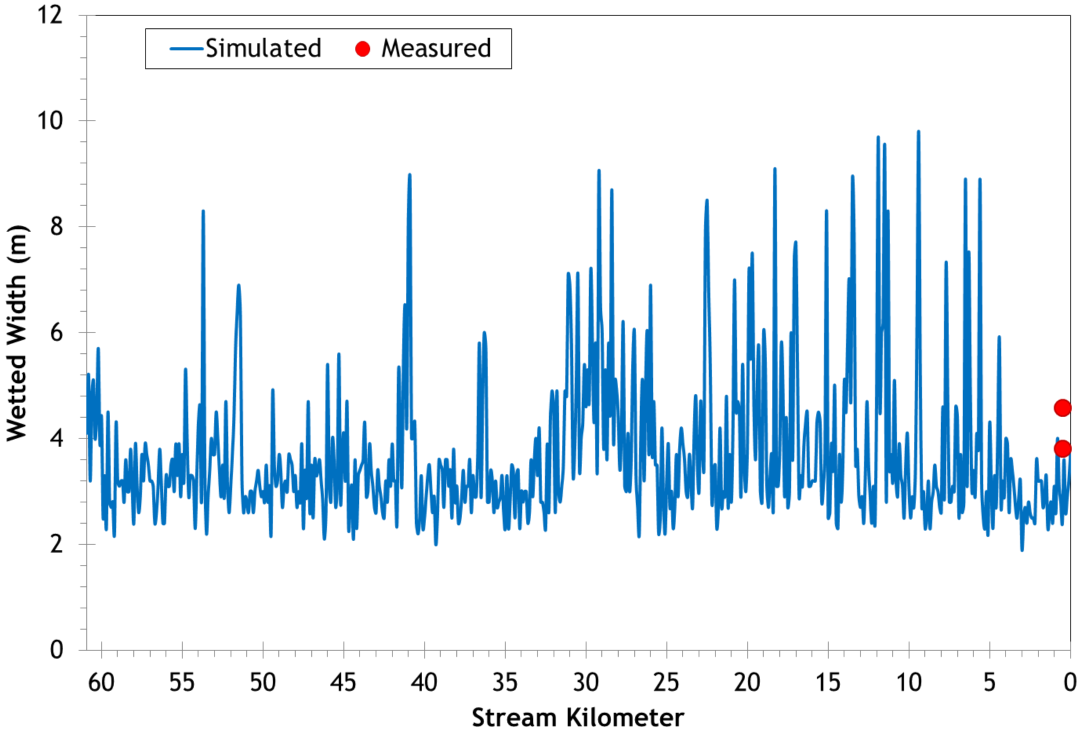


Figure 51 – South Fork Crooked River simulated and measured maximum depths.

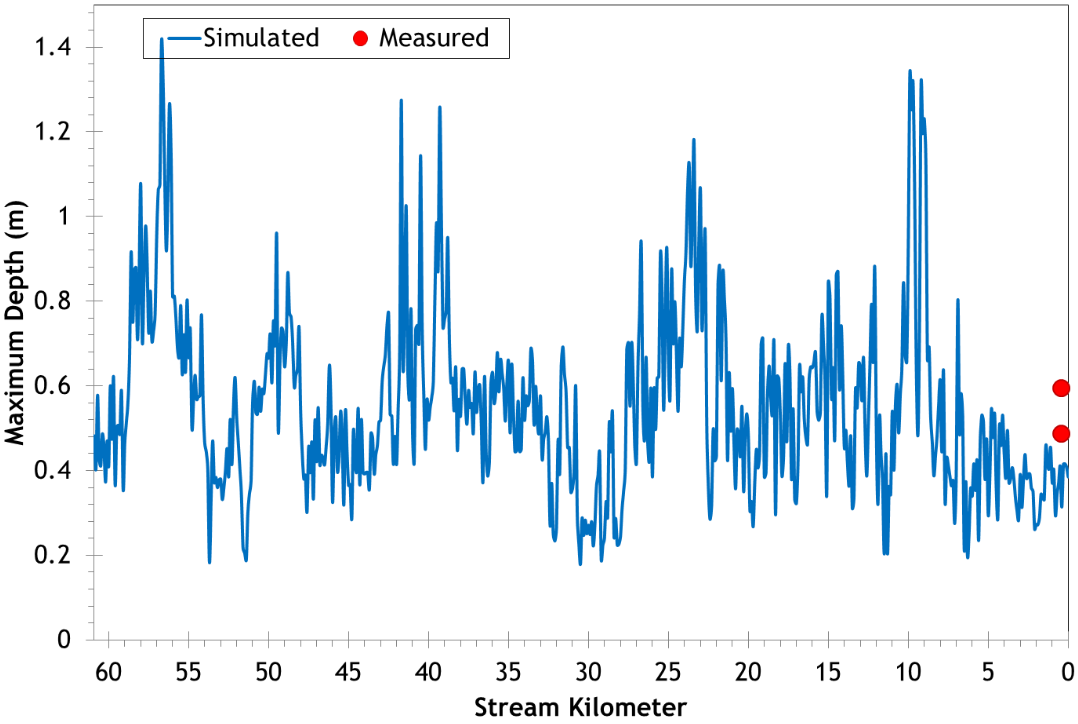


Figure 52 – South Fork Crooked River near stream kilometer 39.

The simulated effective shade for the South Fork Crooked River is shown in Figure 53. No ground level measurements had been collected. The entire South Fork simulated reach is surrounded by pasture, grassland, and wetland. Nearly all of the effective shade at the stream surface is created by topographic features. The small vegetation that does exist, contributes negligible shade compared to the topography.

Figure 53 - South Fork Crooked River simulated effective shade.

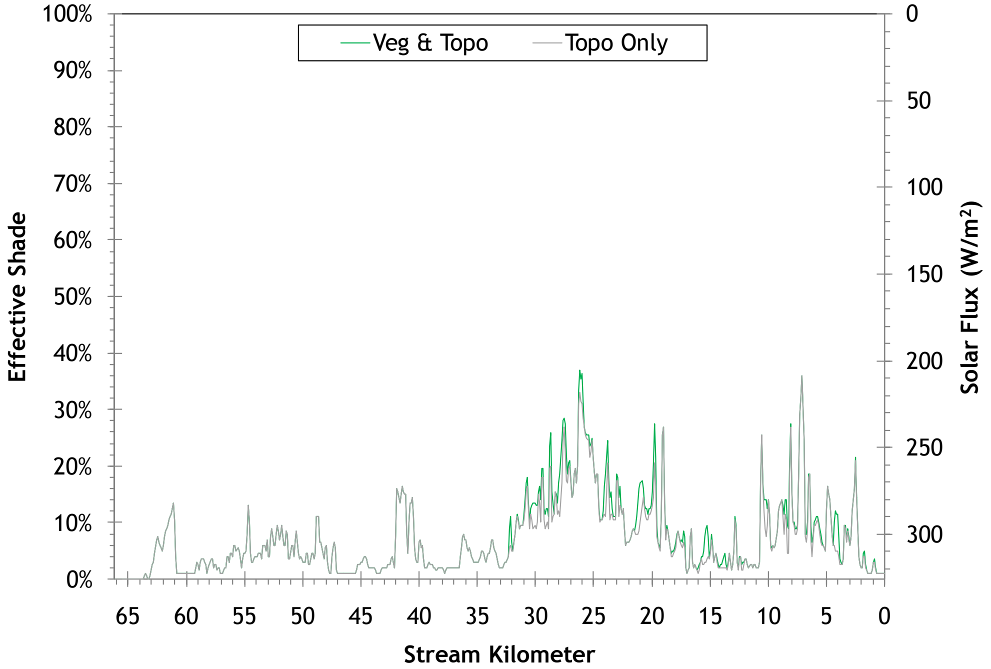
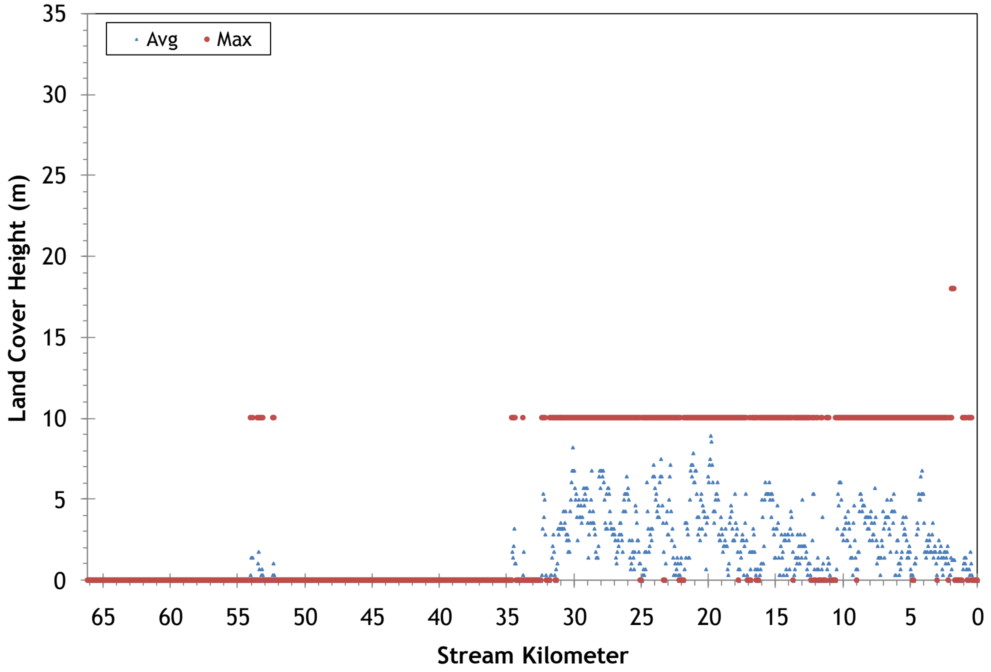


Figure 54 shows the sampled land cover heights along the South Fork Crooked River. Land cover polygons were digitized from the TIR mosaics and NAIP imagery for this simulation. The upper river is surrounded predominately by grasses, while the lower river flows through canyons with Juniper.

Figure 54 - South Fork Crooked River sampled land cover heights.



Beaver Creek

Beaver Creek was simulated from the South and North Fork confluence to the mouth. The input parameters and assumptions used to calibrate the model are listed in Table 17 and described below.

Table 17 - Beaver Creek Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 25 – August 31, 2005
TIR data:	8/7/05, 14:28-14:57. Flown in upstream direction.
Simulation Extent:	37.75 stream kilometers to the mouth.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	2
Continuous Data Sites:	2
Flush Initial Condition:	7 days
Deep Alluvium Temperature:	True (17°C)
Climate Data Source:	RAWS – Badger Creek
Land Cover Data Source:	Polygons digitized from TIR mosaics and NAIP imagery.
Evaporation Method	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	1.57 W/m/°C
Sediment Thermal Diffusivity:	0.0064 cm^2/sec
Sediment/Hyporheic zone thickness:	0.33-0.6 meters
Hyporheic Exchange:	2%
Porosity:	40%

- Channel widths (wetted surface) were digitized where possible from the mosaiced TIR imagery.
- Cloud cover was estimated to be 80% on days when hourly stream temperatures were markedly cooler than the remainder of the simulation period.
- Wolf Creek and Paulina Creek were estimated to be contributing 1.5 cfs each during the entire simulation period (based upon visual observation of the TIR imagery and their sizes relative to Beaver Creek). Constant temperature values were input for each of them, based upon the TIR measurements. (The diel temperature range of Beaver Creek was relatively narrow and rather than create diels for the tributaries, constant values were used.)
- The upstream boundary condition flow data was derived from an estimate observed on August 2, 2005 by a land owner downstream of the north and south fork confluence. The hourly temperature data was recorded in the South Fork Beaver Creek, just upstream of the confluence.

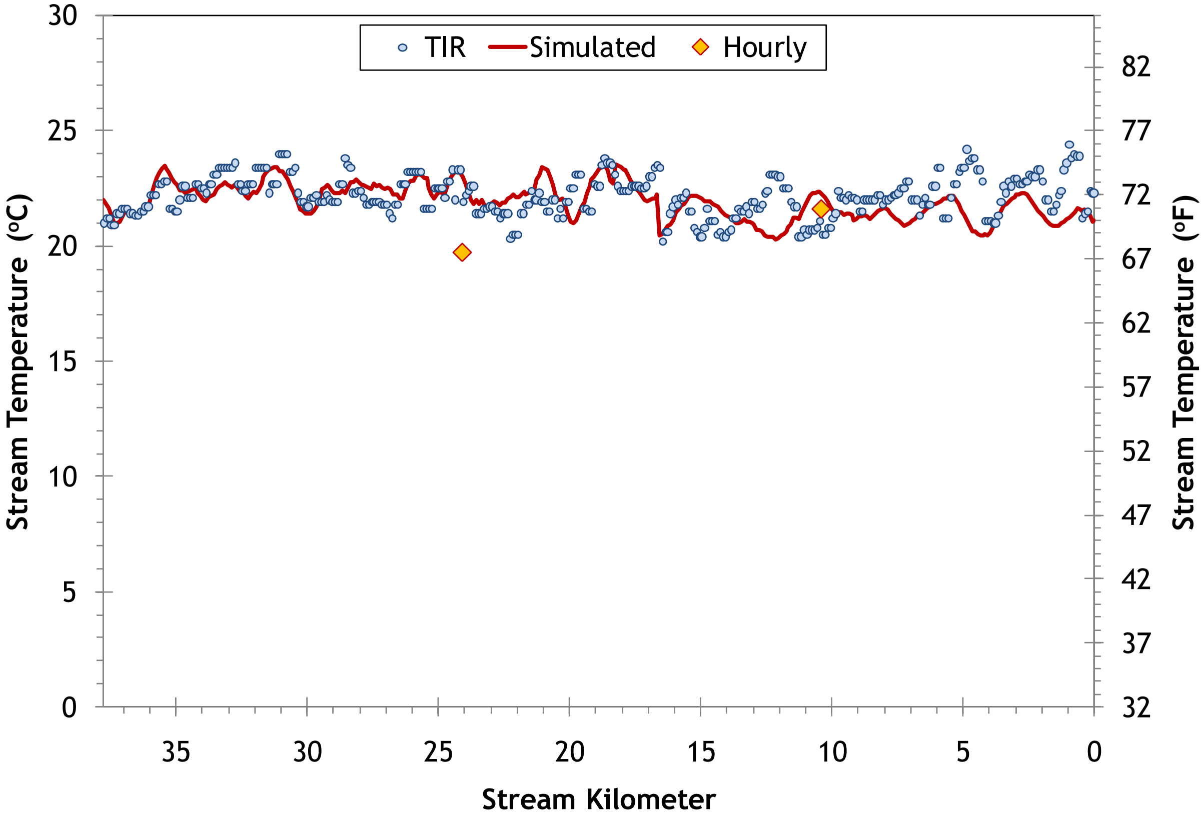
Table 18 summarizes the calibration statistics achieved for the instantaneous and longitudinal temperatures of the Beaver Creek simulation. Due to the very low flow and slow velocities, calibration to the hourly data was challenging. The hourly temperature data at Beaver Creek Road was cooler than the TIR measured temperatures, resulting in a lower RMSE.

Table 18 - Beaver Creek simulation calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	37.8-0	379	-0.21	0.81	1.04	-0.45
Beaver Creek Road	DEQ	24.1	912	1.78	2.06	2.46	-0.10
Post-Paulina Highway	DEQ	10.4	912	-0.09	1.33	1.60	0.40

The calibrated longitudinal temperature profile for Beaver Creek is shown in Figure 55. Similar to the South Fork Crooked River, Beaver Creek is low gradient, had a small flow volume, and little shade-producing vegetation. The entire stream was warm, with several areas of possible stratification.

Figure 55 - Beaver Creek calibrated longitudinal temperature profile.



Due to low flow volumes and the low gradient, it was difficult to calibrate the Heat Source model. Multiple factors influence stream temperature of small systems like Beaver Creek. The best hourly calibration results obtained had RMSE values of about 1.6°C (Figure 56).

Figure 56 - Beaver Creek simulated and measured hourly temperatures.

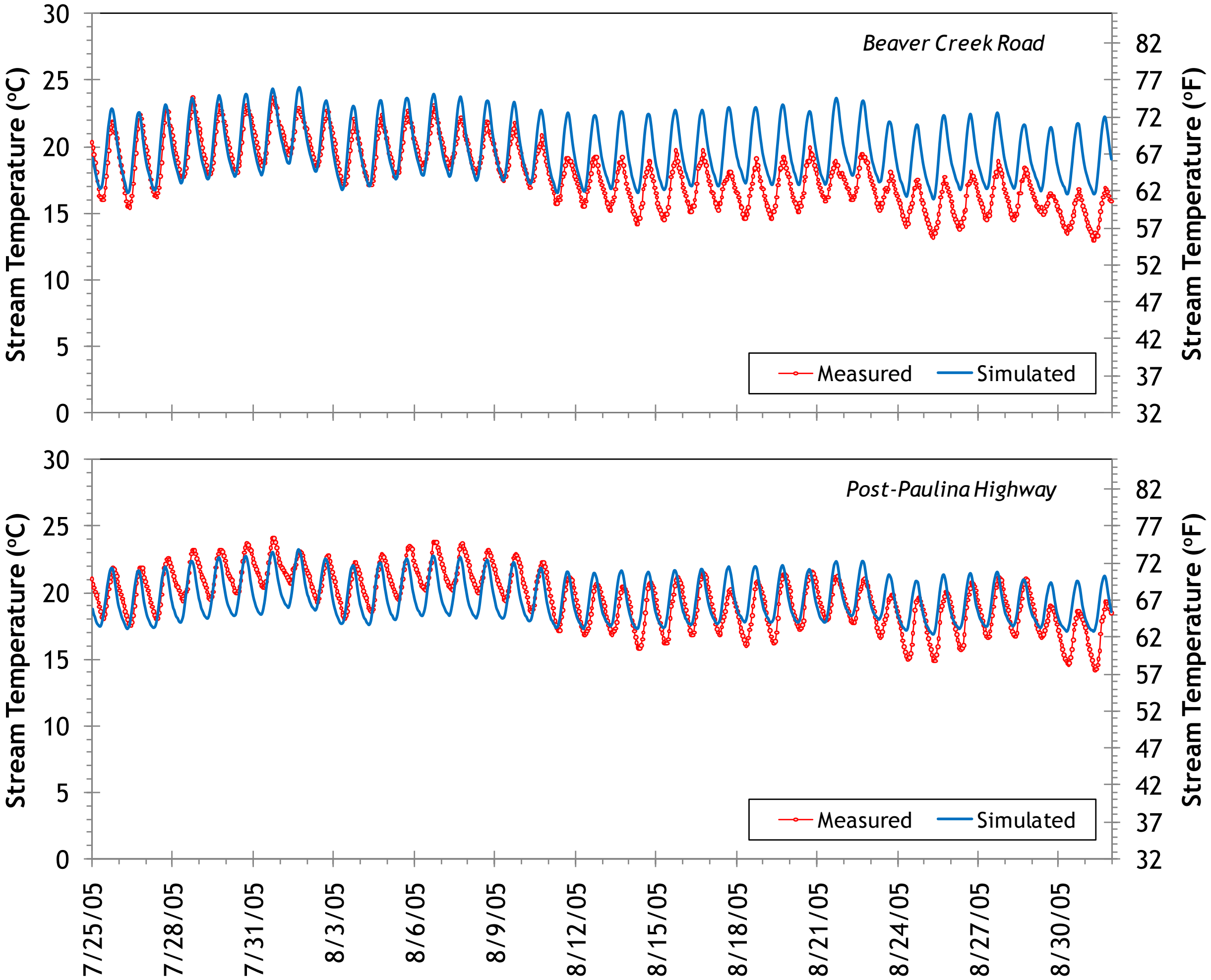


Figure 59 through Figure 62 present the simulated and measured hydraulic parameters of the Beaver Creek simulation. The simulated values presented are from August 7, 2005, which is the day that the TIR data was collected. The measured values were collected on August 2, 2005. There was very little measured data available for Beaver Creek. There were two tributaries and four active diversion canals observed within the TIR imagery. Estimated volumes for each of the inflows and outflows were estimated by the OWRD.

Figure 57 - Beaver Creek simulated and measured flow volume.

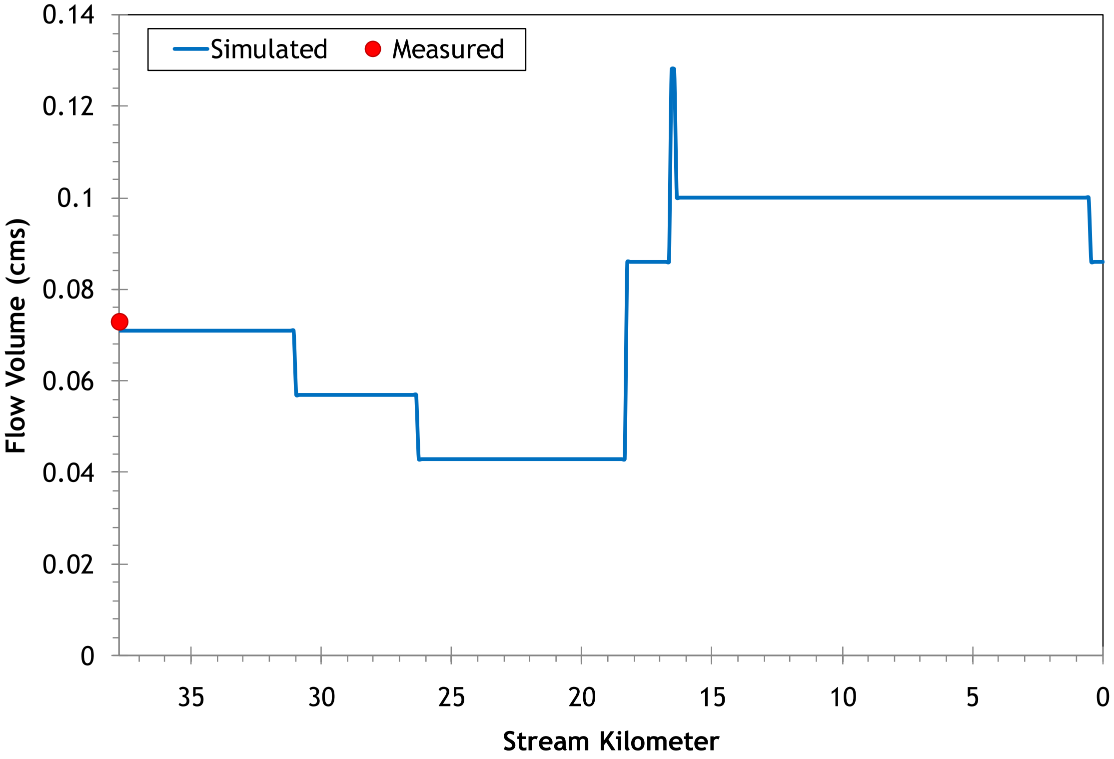


Table 19 summarizes the estimated inflows and diversions of the Beaver Creek simulation. There were no measured data available for springs or tributaries to Beaver Creek. Two tributaries were contributing visible flow as observed in the TIR imagery. There were three active diversion canals visible in the TIR imagery and their withdrawal rates were estimated.

Table 19 - Beaver Creek simulated inflows.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Withdrawal	31.0	Estimated at 0.5 cfs	NA
Withdrawal	26.3	Estimated at 0.5 cfs	NA
Wolf Creek	18.25	Mass Balance Estimate	Estimated from TIR
Paulina Creek	16.6	Mass Balance Estimate	Estimated from TIR
Withdrawal	16.4	Estimated at 1.0 cfs	NA
Withdrawal	0.5	Estimated at 0.5 cfs	NA

Figure 58 - Beaver Creek simulated and measured velocities.

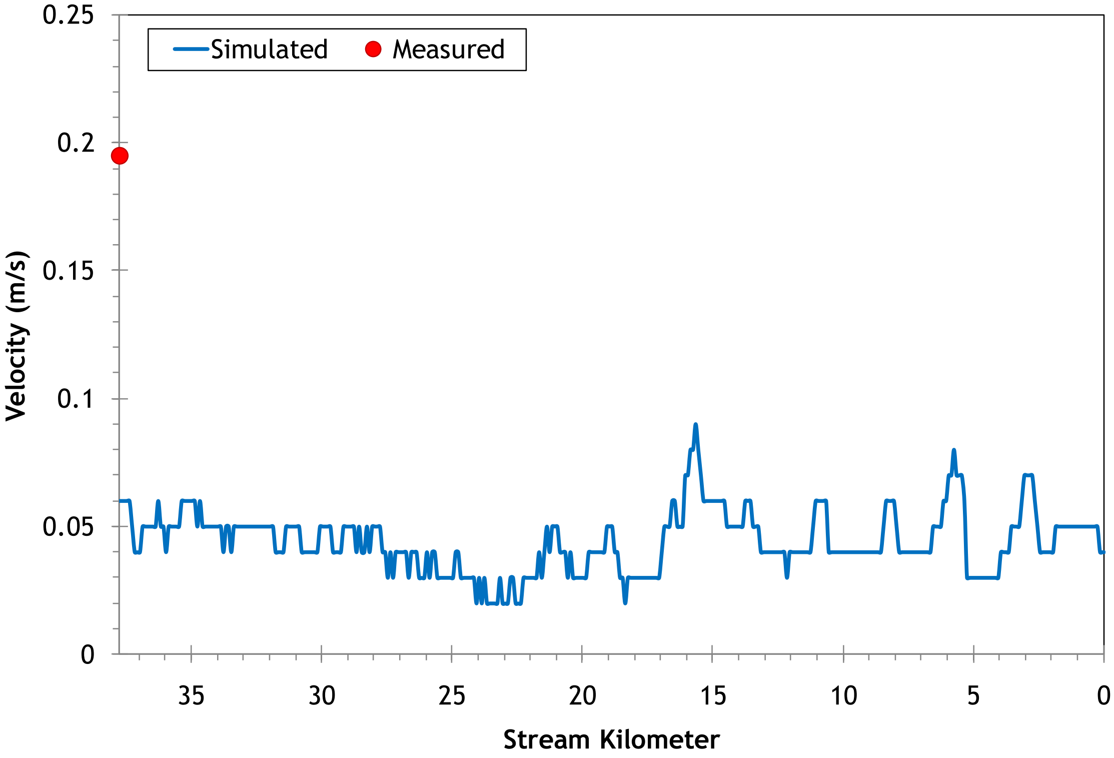


Figure 59 - Beaver Creek simulated and measured wetted widths.

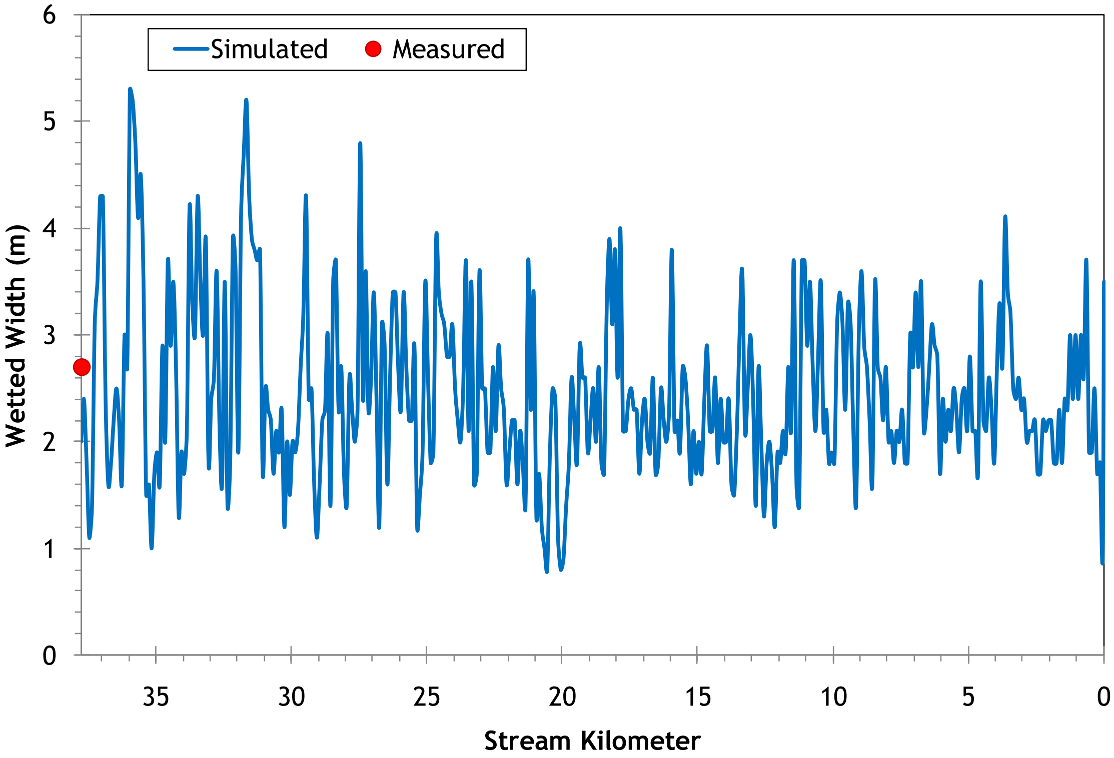


Figure 60 - Beaver Creek simulated and measured maximum depths.

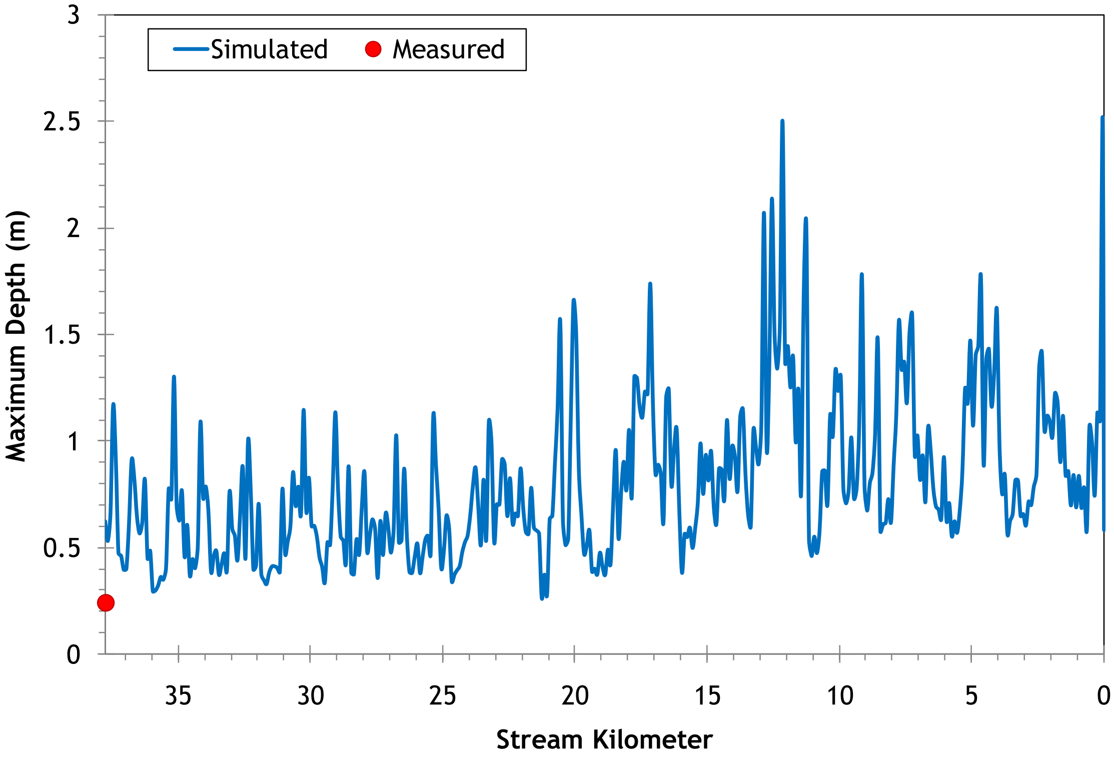


Figure 61 below is a typical reach along Beaver Creek. The stream flows through primarily cultivated and grazed lands.

Figure 61 - Typical reach along Beaver Creek.

Figure 62 shows the effective shade simulated along Beaver Creek. Like the South Fork Crooked River, Beaver Creek flows primarily through natural and agricultural grasslands. There is virtually no shade-producing vegetation (e.g., trees). Nearly 100% of the observed effective shade is produced by topographic features.

Figure 62 - Beaver Creek simulated effective shade.

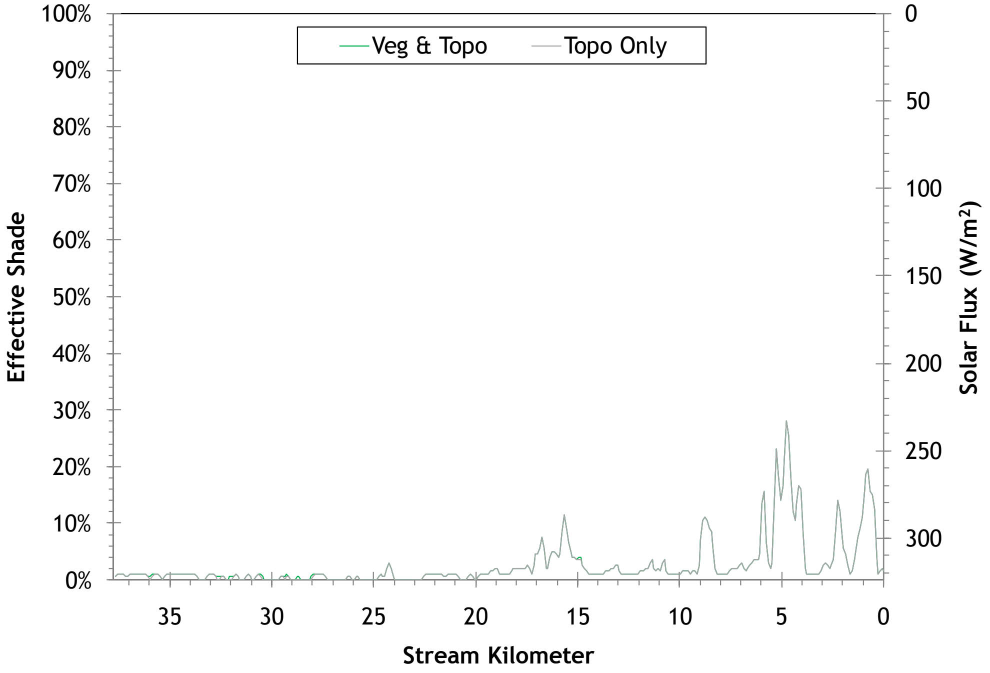
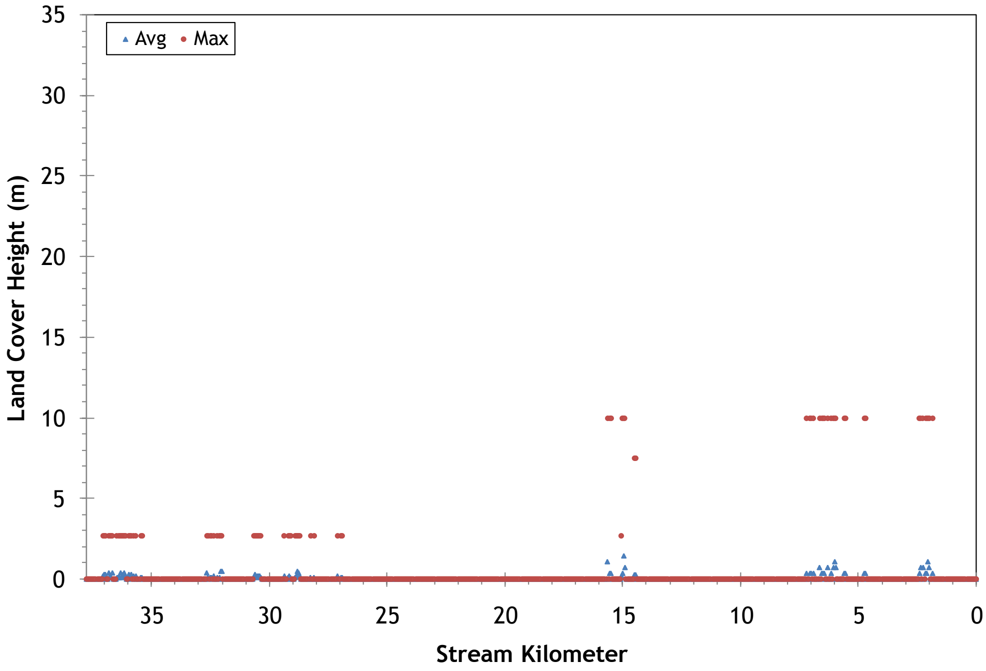


Figure 63 shows the sampled land cover heights for Beaver Creek. The mosaiced TIR imagery and the NAIP imagery was used to digitize land cover polygons for this simulation.

Figure 63 - Beaver Creek sampled land cover heights.



Deep Creek

Deep Creek was simulated from the Happy Camp and Jackson Creek confluence to the mouth. The input parameters and assumptions used to calibrate the Heat Source model are shown in Table 20 and described below.

Table 20 - Deep Creek Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 25 – August 31, 2005
TIR data:	8/8/05, 14:43-14:59. Flown in upstream direction.
Simulation Extent:	13.8 stream kilometers to the mouth.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	5
Continuous Data Sites:	2
Flush Initial Conditions:	7 days
Deep Alluvium Temperature:	Option not used.
Climate Data Source:	RAWS – Cold Springs
Land Cover Data Source:	Polygons digitized from TIR mosaics and NAIP imagery.
Evaporation Method	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	0.10 meters
Hyporheic Exchange:	1%
Porosity:	40%

- Channel widths (wetted surface) were digitized from the mosaiced TIR imagery.
- Cloud cover was estimated to be 75% on days when hourly stream temperatures were markedly cooler than the remainder of the simulation period. The Cold Springs RAWS station did not have solar radiation data available.
- The simulation begins just downstream of the Jackson/Happy Camp Creek confluence. Temperature data was only recorded from 8/5 – 8/31 at that site; therefore, hourly data from the mouth of Happy Creek was used for the boundary condition. Temperatures between the two sites were very similar.
- The boundary flow volume was from a field measurement downstream of the Jackson/Happy Creek confluence collected by DEQ on August 4, 2005.
- There were only 2 flow measurements available, one at Jackson/Happy Camp Creek confluence, and one at the mouth.
- No diversions or withdrawals were included within the simulation.

Table 21 summarizes the calibration statistics achieved for the instantaneous and longitudinal temperatures of the Beaver Creek simulation.

Table 21 - Deep Creek simulation calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	13.8-0	139	-0.32	0.64	0.78	0.68
Deep Creek d/s Happy Camp/Jackson confluence	USFS	13.7	634	0.33	0.86	0.94	0.96
Deep Creek above mouth	DEQ	0.1	912	-0.88	1.23	1.43	0.85

Figure 64 shows the Deep Creek longitudinal temperature calibration results. Deep Creek had a very low flow volume and little measured data was available. The RMSE value of the longitudinal calibration was 0.78°C.

Figure 64 - Deep Creek longitudinal temperature calibration.

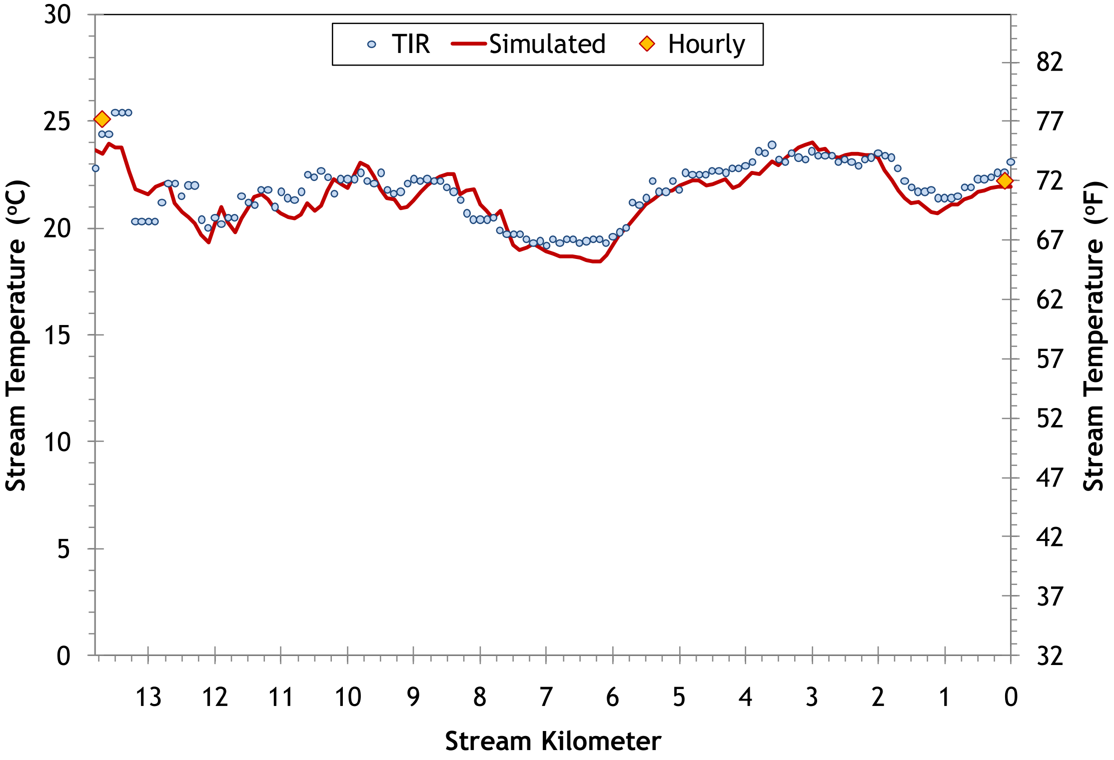


Figure 65 shows the simulated and measured hourly temperatures of the calibrated Deep Creek model. The data record downstream of the Jackson/Happy Camp Creek confluence began on August 5.

Figure 65 - Deep Creek simulated and measured hourly temperatures.

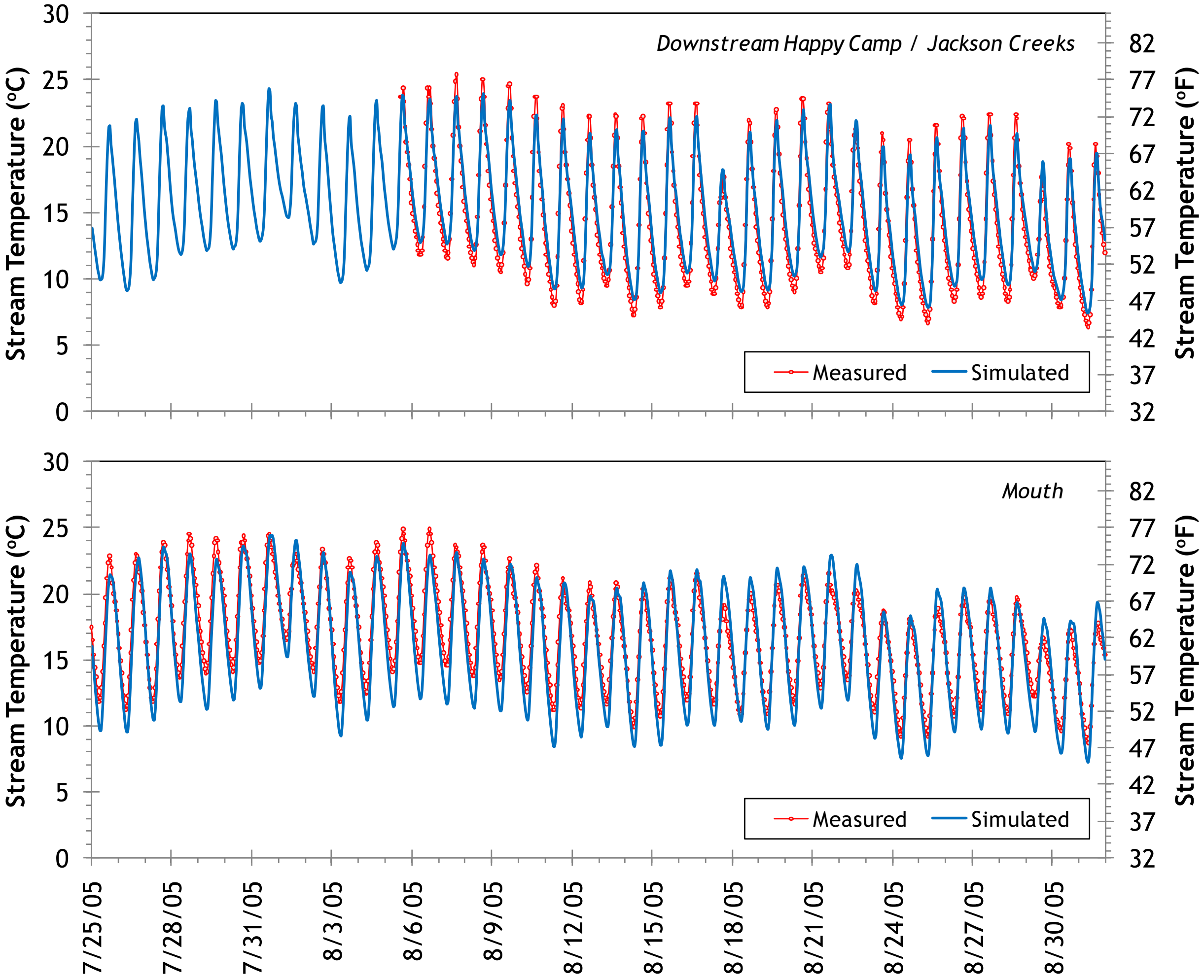


Figure 68 through Figure 71 show the simulated and measured hydraulic values for Deep Creek. The simulated values are from August 8, 2005 when the TIR data was collected. The measured values were collected on August 4, 2005. There was little measured data available, and the TIR imagery did not reveal significant tributary or spring inputs; therefor, flow several gaining reaches were interpolated in the flow profile.

Figure 66 - Deep Creek simulated and measured flow volume.

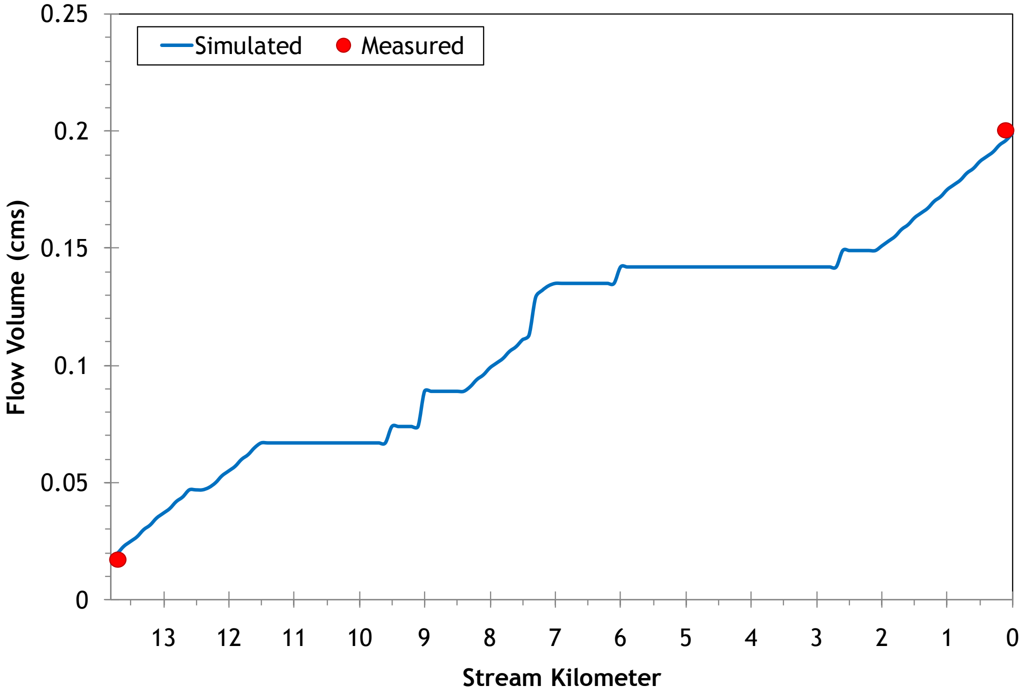


Table 22 summarizes the inflows used in the Deep Creek simulation. Little Summit Creek had measured flow and temperature data available. Other tributary inflow estimates were provided by OWRD. Gaining reaches were estimated via mass balance.

Table 22 - Deep Creek accretion and inflow summary.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Gaining Reach	13.8-12.6	Mass Balance Estimate	Estimated at 18°C
Gaining Reach	12.3-11.5	Mass Balance Estimate	Estimated at 18°C
Unnamed Tributary	9.55	OWRD/DEQ Estimate	Estimated
Little Summit Creek	9.0	DEQ	USFS
Gaining Reach	8.35-7.05	Mass Balance Estimate	Estimate at 18°C
Big Springs	7.3	OWRD/DEQ Estimate	Estimated
Crazy Creek	6	OWRD/DEQ Estimate	Estimated
Buck Hollow	2.65	OWRD/DEQ Estimate	Estimated
Gaining Reach	2.0-0.0	Mass Balance Estimate	Estimated at 18°C

Figure 67 - Deep Creek simulated and measured velocities.

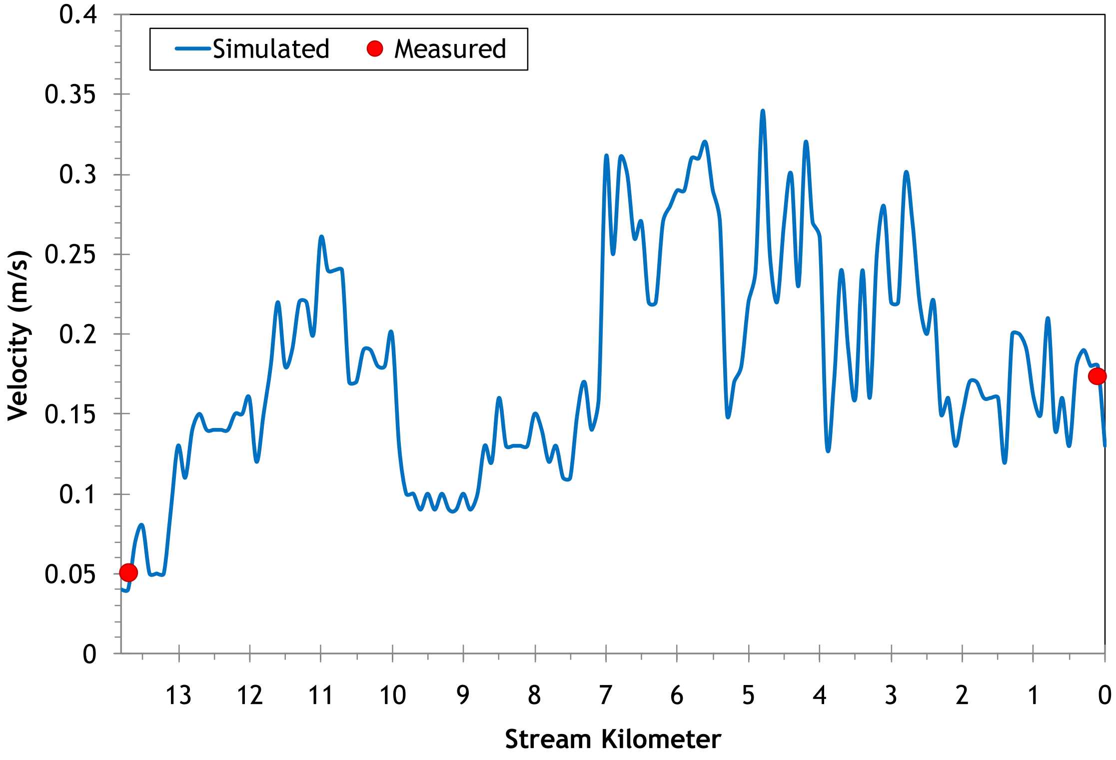


Figure 68 - Deep Creek simulated and measured wetted widths.

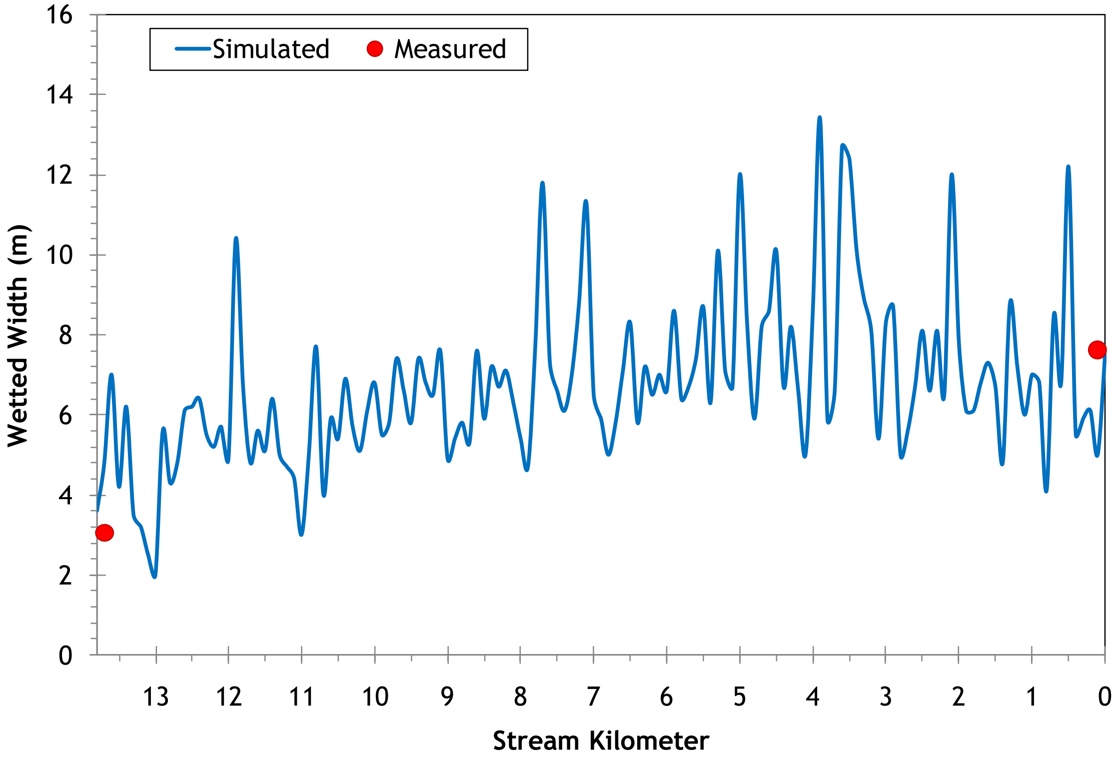


Figure 69 - Deep Creek simulated and measured maximum depths.

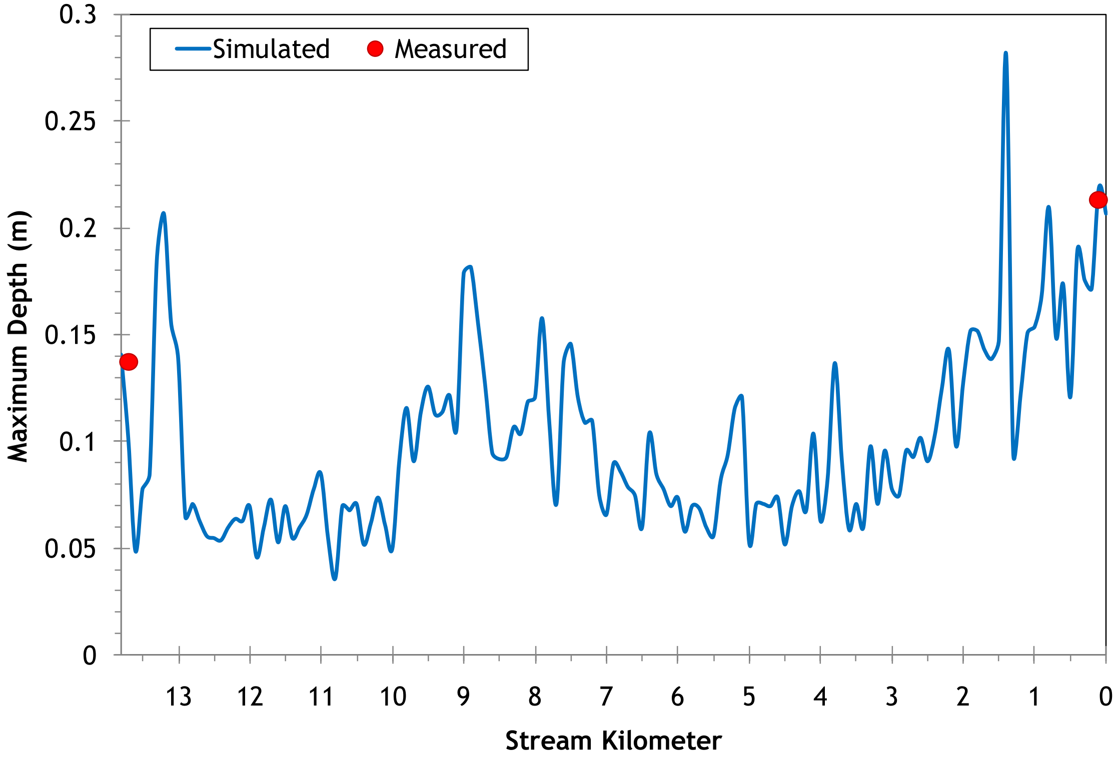


Figure 70 - Deep Creek at unknown location.

Figure 71 shows the simulated and measured effective shade for Deep Creek. Deep Creek is relatively well forested. On average, about 10-20% effective shade is produced by topographic features, with the remainder created by vegetation.

Figure 71 - Deep Creek simulated and measured effective shade.

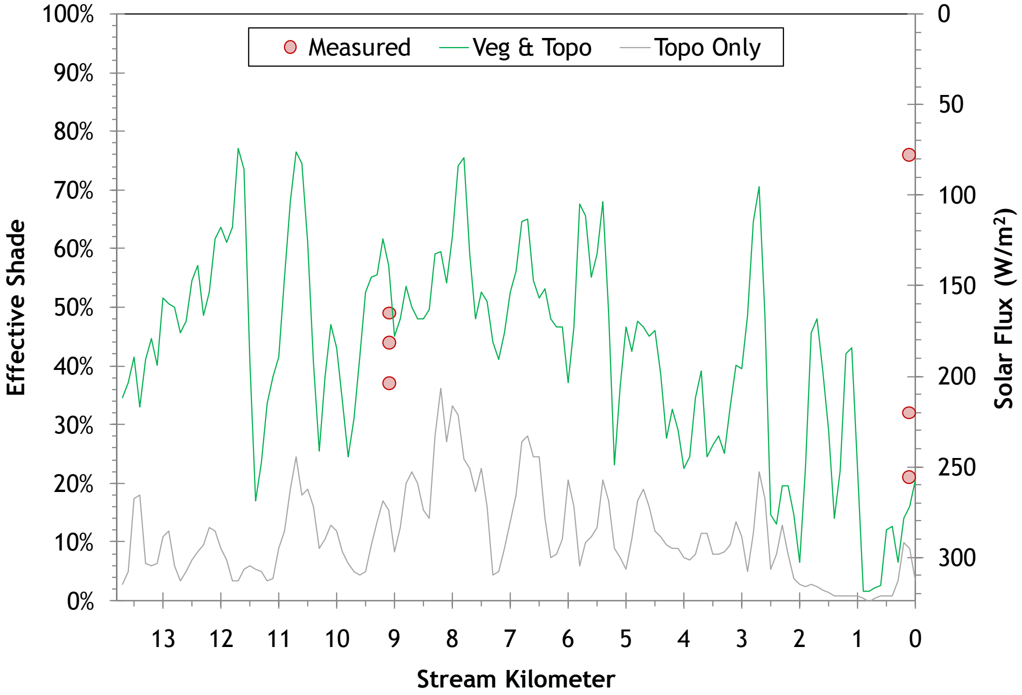
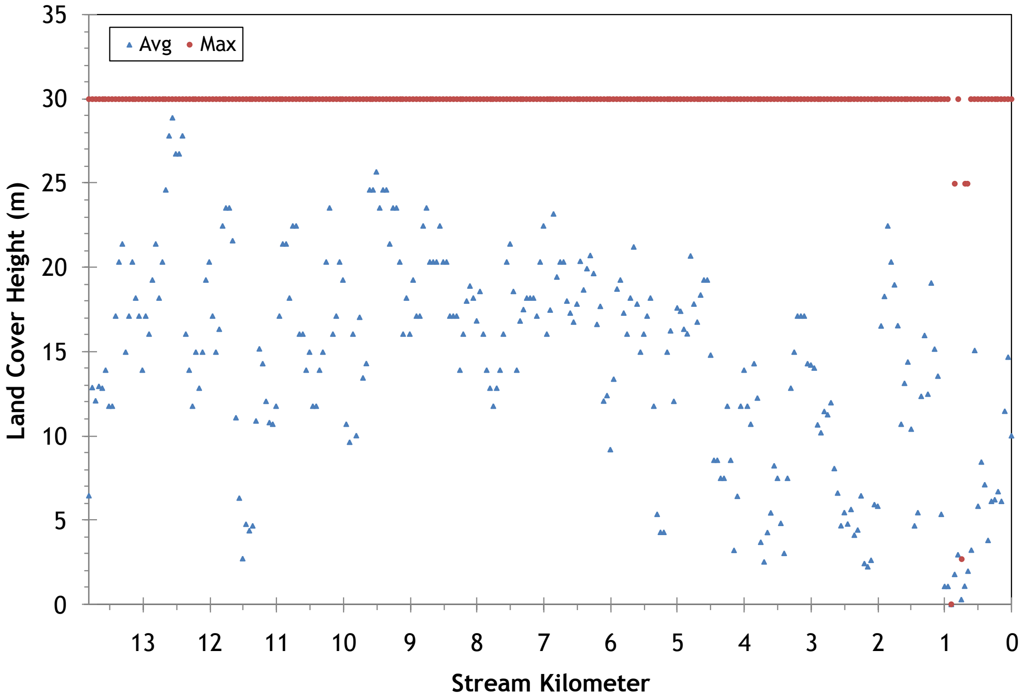


Figure 72 shows the sampled land cover heights for Deep Creek. The TIR mosaics and NAIP imagery were used to digitize land cover polygons for this simulation.

Figure 72 - Deep Creek sampled land cover heights.


Avg
Max
Land Cover Height (m)
35
30
25
20
15
10
5
0
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Stream Kilometer

North Fork Crooked River

The North Fork Crooked River temperature was simulated from Indian Creek to the mouth. The effective shade simulation was longer, beginning at Gray Creek and extending to the mouth. The reach between Gray Creek and Indian Creek had intermittent flow and therefore temperature was not simulated in that area. The input parameters and assumptions used to calibrate the Heat Source model are listed in Table 23 and described below.

Table 23 - North Fork Crooked River Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 25 – August 31, 2005
TIR data:	8/8/05, 13:19-14:35. Flown in upstream direction.
Simulation Extent:	Effective Shade: 73.85 stream kilometers to the mouth. Stream Temperature: 57.7 stream kilometers to the mouth.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	6
Continuous Data Sites:	5
Climate Data Source:	RAWS – Cold Springs
Flush Initial Conditions:	7 days
Deep Alluvium Temperature:	Option not used.
Land Cover Data Source:	Polygons digitized from TIR mosaics and NAIP imagery.
Evaporation Method:	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	0.10 meters
Hyporheic Exchange:	1%
Porosity:	40%

- Channel widths (wetted surface) were digitized from the mosaiced TIR imagery.
- Cloud cover was estimated to be 75% on days when hourly stream temperatures were markedly cooler than the remainder of the simulation period.
- Upstream of Indian Creek, the stream had intermittent flow. Only effective shade was simulated in that reach. (Heat Source cannot simulate dry or stagnant reaches and the model had some flow artificially included in order for it to run continuously from the upstream boundary.)
- The TIR imagery was examined to determine that the North Fork Crooked River had continuous flow starting at the Indian Creek confluence.
- There were two active diversion canals visible within the TIR imagery: Stream kilometers 10.7 and 2.2. Since no measured data was available, the diversion rates were estimated from the OWRD's point of diversion database.
- The upstream boundary for the temperature simulation is at Indian Creek.

Table 24 summarizes the calibration statistics for the TIR and the hourly temperatures simulated in the North Fork Crooked River.

Table 24 - North Fork Crooked River calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	73.85-0	577	-0.04	1.11	1.42	-0.13
N. Fork Crooked d/s 42/30 bridge	USFS	49.5	912	0.29	1.46	1.97	0.62
N. Fork Crooked above Deep Creek @ old USGS gauge	USFS	44.9	912	-0.61	1.06	1.31	0.89
N. Fork Crooked d/s Deep Cr. @ old USGS gauge station	USFS	42	912	-0.54	0.61	0.84	0.96
N. Fork Crooked near mouth @ Hwy 380	USFS	0.1	912	-0.98	2.10	2.57	0.66

Figure 73 shows the longitudinal temperature calibration results for the North Fork Crooked River. The North Fork flows through Big Summit Prairie between kilometers 61 and 48. Deep Creek enters the river near kilometer 43. From stream kilometers 40 to 25, there were several areas of possible stratification within naturally formed pools. Since Heat Source cannot simulate stratification, the longitudinal temperature profile was calibrated so that it roughly matched the lower values recorded in the TIR data. This increases the RMSE value and these regions should be carefully interpreted since model accuracy is compromised.

Figure 73 - North Fork Crooked River calibrated longitudinal temperature profile.

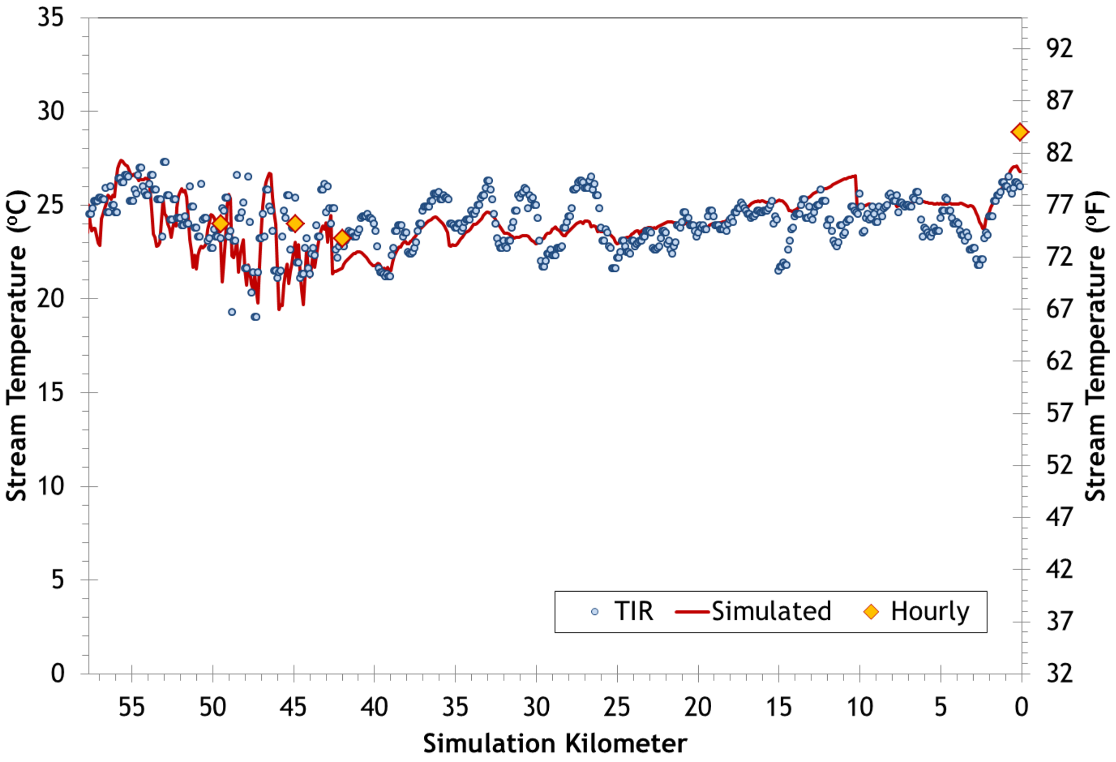
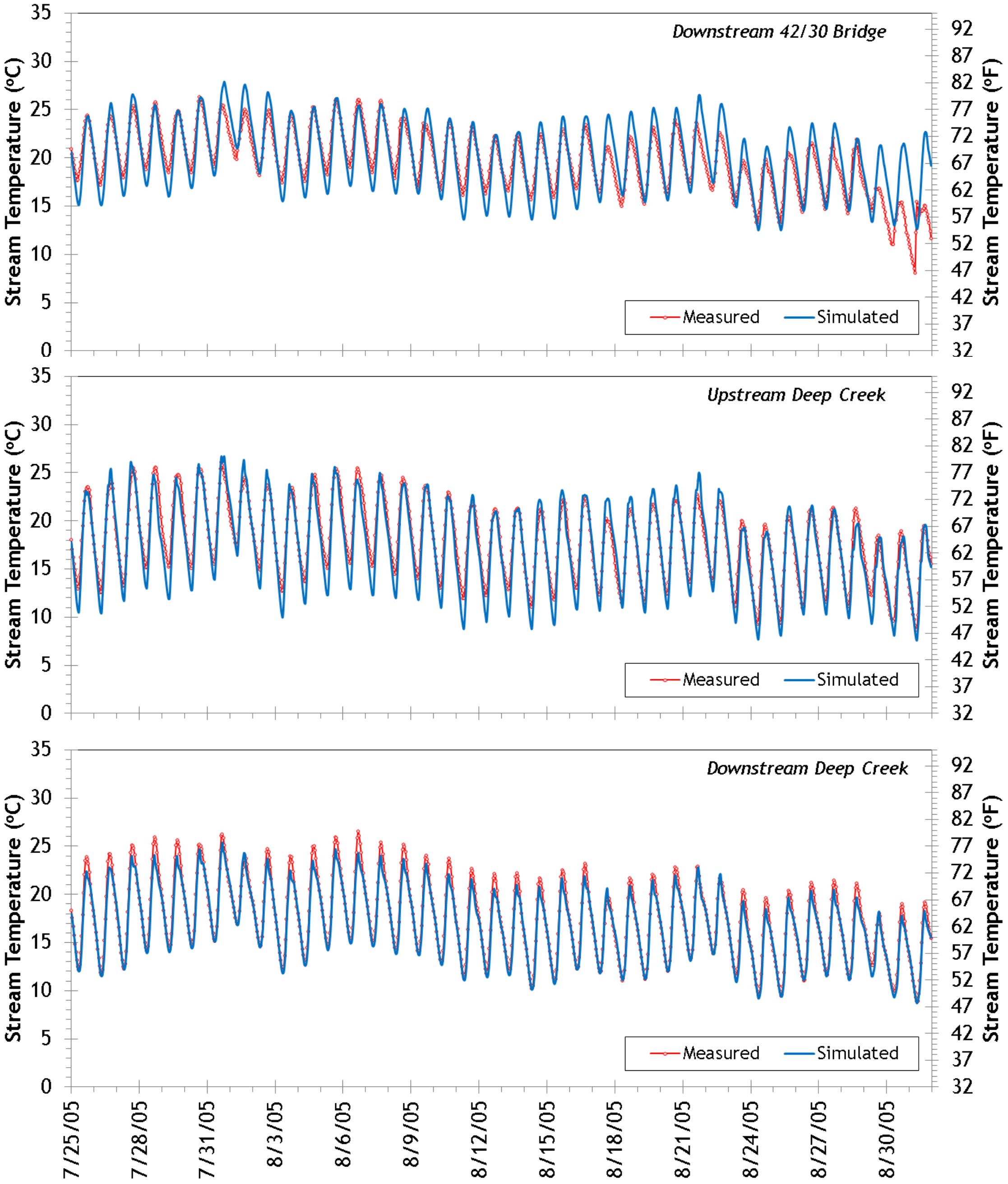


Figure 74 shows the simulated and measured hourly temperatures for the calibrated North Fork Crooked River model. The site near the mouth has questionable data quality. The hourly measurement was warmer than the TIR data and the entire record was approximately 5° warmer than the other hourly data collection locations. The TIR imagery reveals that the reach near the mouth appears to be a wide pool; therefore the data recorded within that pool may not be representative of stream conditions.

Figure 74 - North Fork Crooked River simulated and measured hourly temperatures.



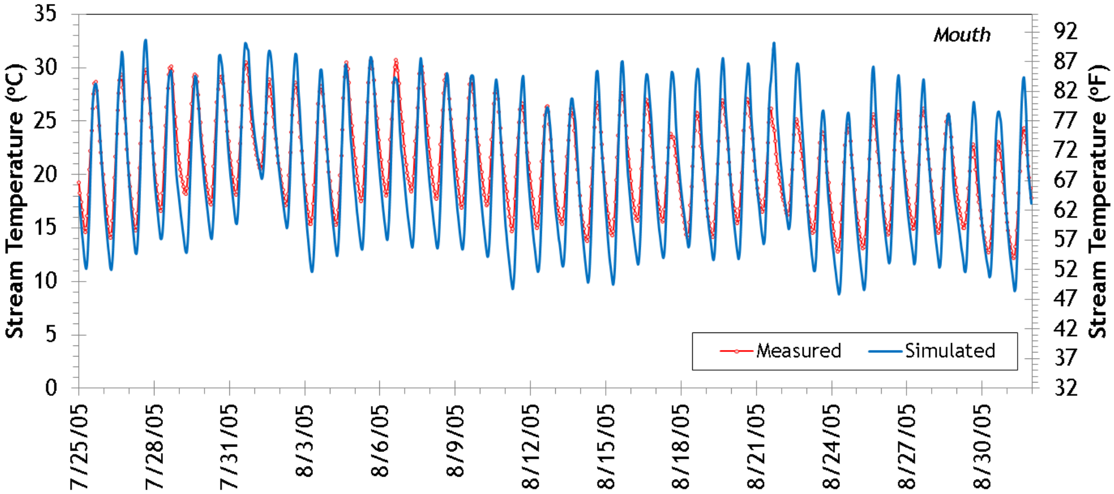


Figure 75 shows the mouth of the North Fork Crooked River (flowing from top right of the image toward the Crooked River in the lower left). There are several hundred yards of pool near the mouth of the river, with significant periphyton growth visible in the TIR imagery. The hourly temperature data recorded at this site had a much larger diel shift with highs about 5°C warmer than other areas. It is possible that the hourly temperatures recorded at the mouth are not representative of a fully mixed and free-flowing system, which is what Heat Source simulates. Therefore, the model was calibrated to the TIR data at the mouth rather than the hourly data.

Figure 75 - North Fork Crooked River near mouth.

Figure 78 through Figure 81 show the simulated and measured hydraulic parameters from the North Fork Crooked River simulation. The simulated values are from August 8, 2005 when the TIR data was collected. The measured values were collected on August 4th everywhere except at the mouth, which was collected on August 10th. Deep Creek enters the North Fork near stream kilometer 43 and greatly increases the flow volume.

Figure 76 - North Fork Crooked River simulated and measured flow volumes.

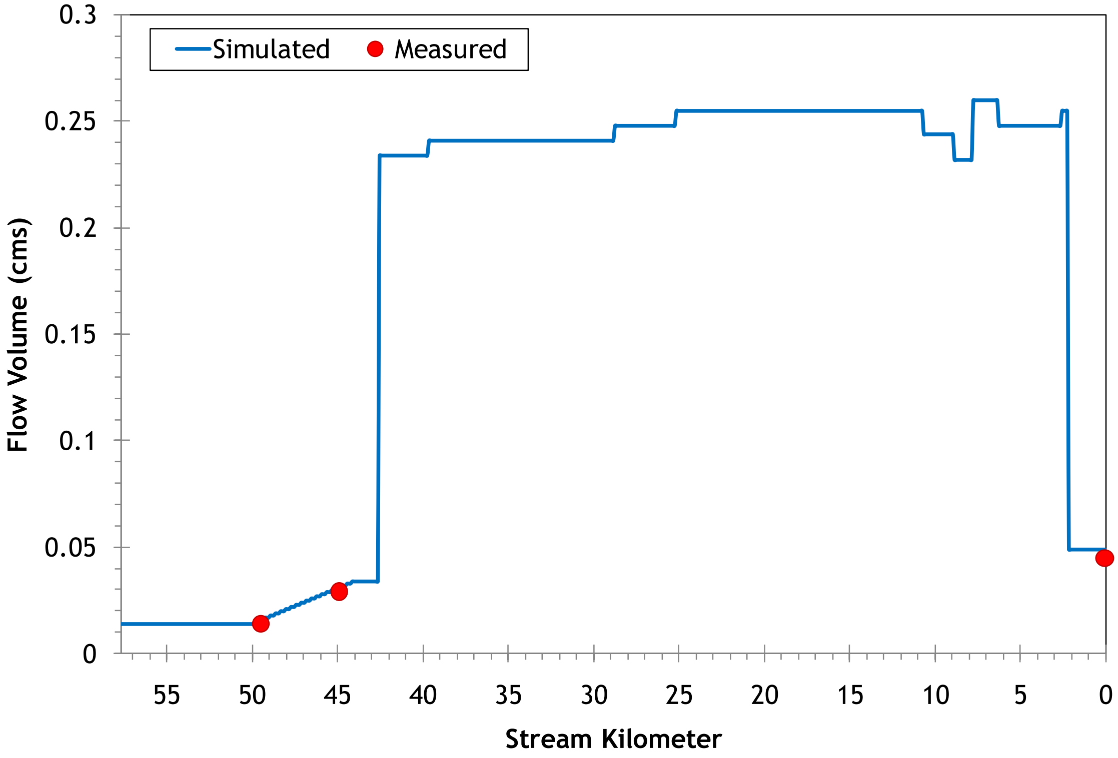


Table 25 summarizes the flow inputs included within the North Fork Crooked River simulation. There were few tributaries or springs visible within the TIR imagery and little ground level data to base inflow assumptions on. Diversion rates were estimated based on the OWRD point of diversion database.

Table 25 - North Fork Crooked River flow inputs.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Johnson Creek	57.7	Dry	NA
Peterson Creek	50.8	Dry	NA
Gaining Reach	50-44	Mass Balance Estimate	Estimated at 18°C
Deep Creek	42.6	DEQ	DEQ
Spring	39.65	Mass Balance Estimate	TIR Estimate
Spring	28.75	Mass Balance Estimate	TIR Estimate
Fox Canyon Creek	25.15	Mass Balance Estimate	TIR Estimate
Withdrawal	10.7	Estimated 0.4 cfs	NA
Committee Creek	9.35	Dry	NA
Withdrawal	8.9	Estimated 0.4 cfs	NA
Unnamed Tributary	7.75	Mass Balance Estimate	TIR Estimate
Withdrawal	6.3	Estimated 0.4 cfs	NA
spring	2.6	Mass Balance Estimate	TIR Estimate
Diversion Canal	2.2	Estimated 7.3 cfs	NA

Figure 77 - North Fork Crooked River simulated and measured velocities.

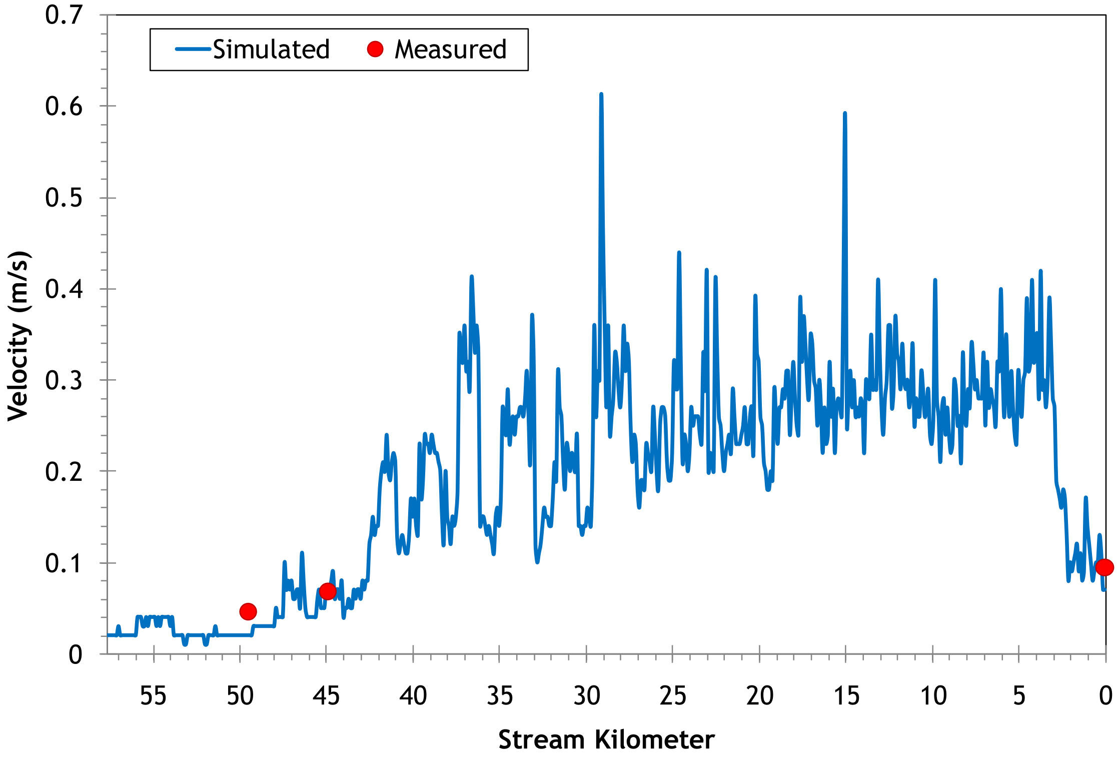


Figure 78 - North Fork Crooked River simulated and measured wetted widths.

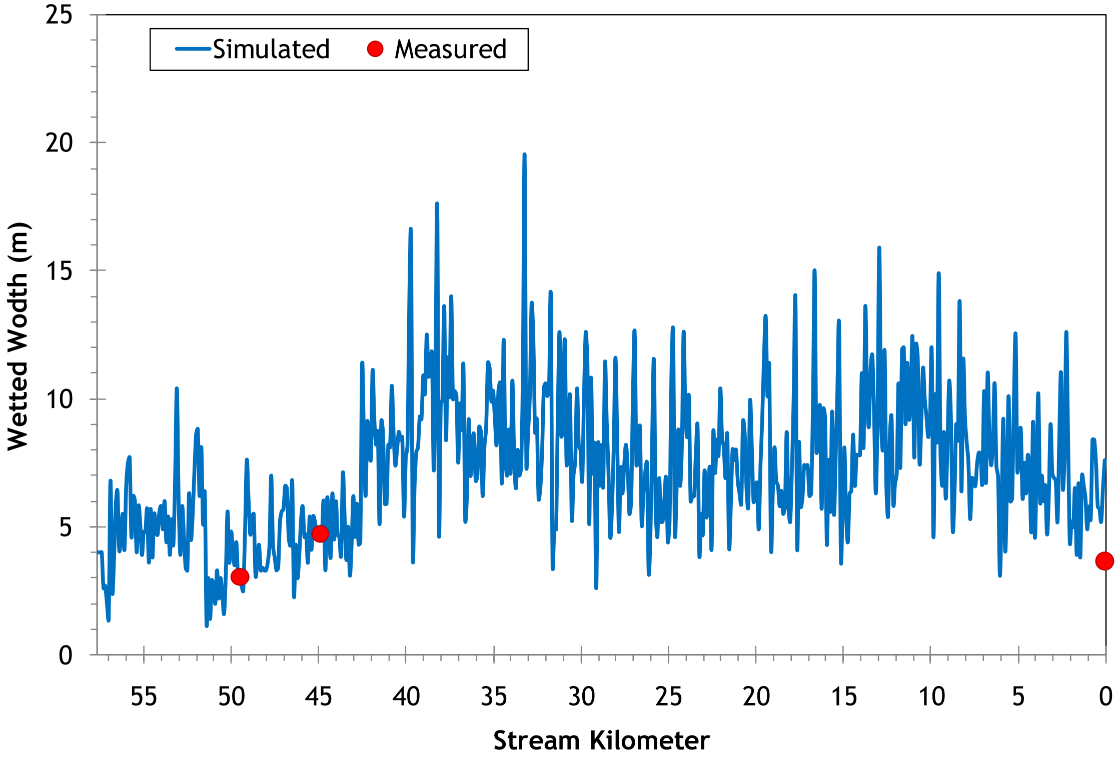


Figure 79 - North Fork Crooked River simulated and measured maximum depths.

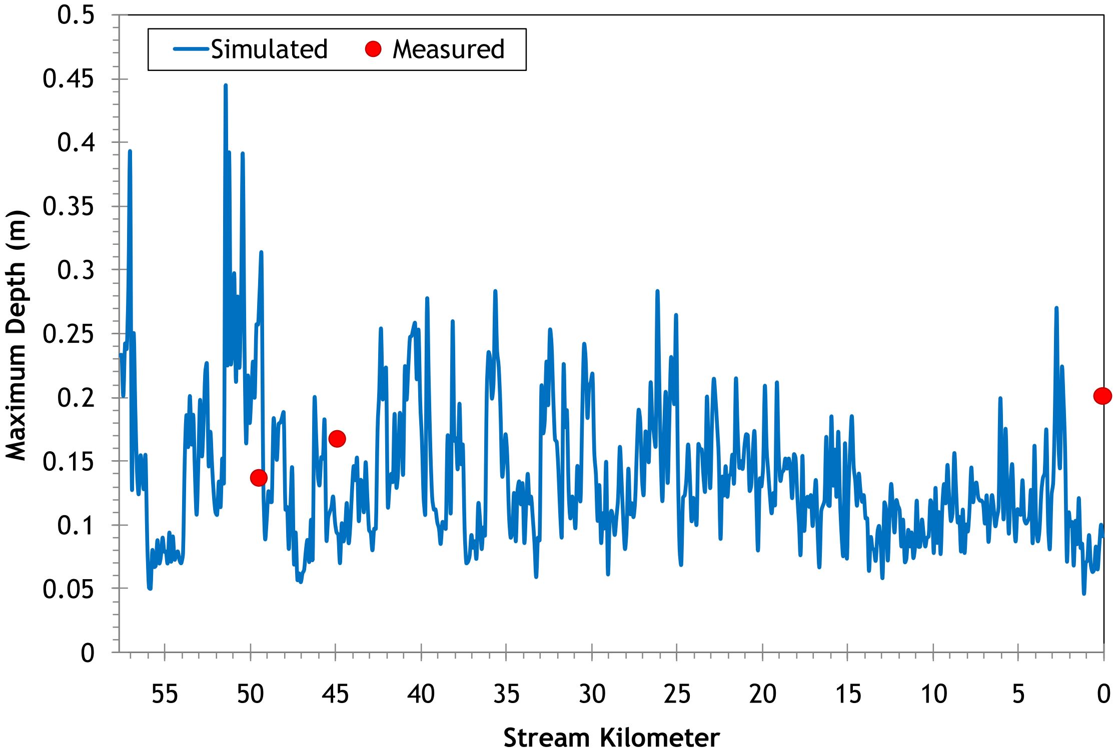


Figure 80 shows the simulated and measured effective shade for the North Fork Crooked River. Note that the effective shade simulation extends about 15 kilometers further upstream than the temperature simulation. The land use in the upper 38 stream kilometers is primarily cattle grazing and there is little effective shade. Below kilometer 50, there is more forest land and the stream flows through more confined canyons, which together result in more effective shade. In the lower 10 stream kilometers, the majority of the effective shade is produced by topography.

Figure 80 - North Fork Crooked River simulated and measured effective shade.

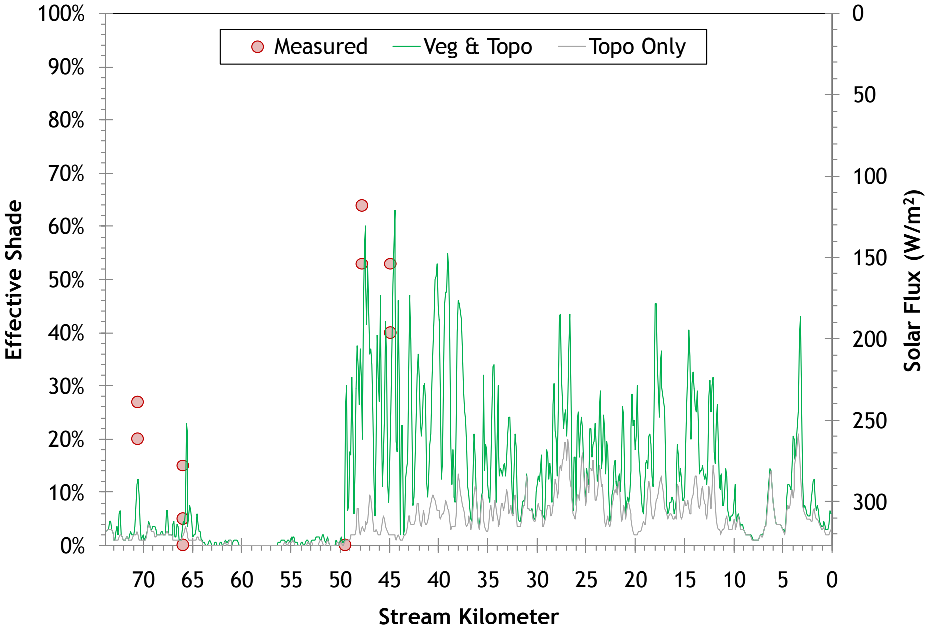
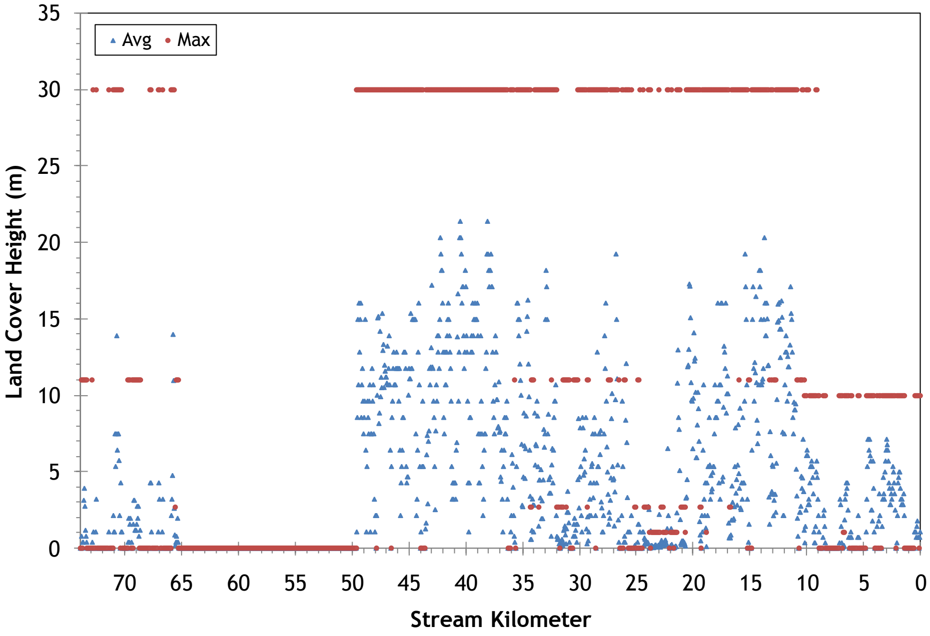


Figure 81 shows the sampled land cover heights for the North Fork Crooked River. Land cover polygons were digitized from the TIR mosaics and the NAIP imagery.

Figure 81 - North Fork Crooked River sampled land cover heights.



Upper Ochoco Creek

Ochoco Creek upstream of the reservoir had too little flow (less than one cfs) during the summer of 2005 and temperatures were unable to be simulated with Heat Source. However, the vegetation and stream channel were digitized and sampled with TTools in order to simulate effective shade. Table 26 summarizes the Heat Source parameters used to simulate effective shade.

Table 26 - Upper Ochoco Creek Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 1 – August 31, 2005
TIR data:	NA
Simulation Extent:	40.0 stream kilometers from Ahalt Creek to Ochoco Reservoir.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	NA
Continuous Data Sites:	NA
Climate Data Source:	NA
Land Cover Data Source:	Polygons were digitized from NAIP imagery.

Figure 82 shows the simulated and measured effective shade for Ochoco Creek above the reservoir. The upper 10 kilometers are mostly forested, while the lower 30 kilometers have a primarily grazed and cultivated flood plain. The high effective shade values measured in the upper reaches may be slight over-estimates because the Solar Pathfinder instrument assumes 100% density of the vegetation. The Heat Source effective shade simulation assumed a maximum of 75% density based on aerial photograph assessment.

Figure 82 - Upper Ochoco Creek simulated and measured effective shade.

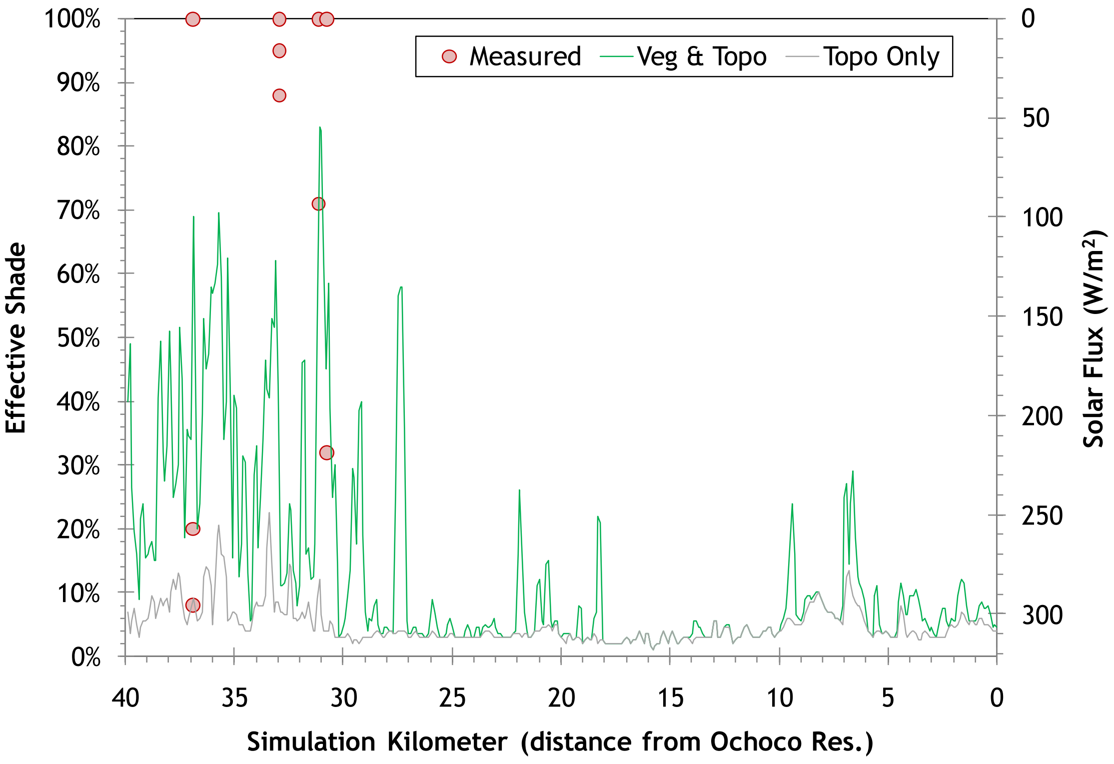
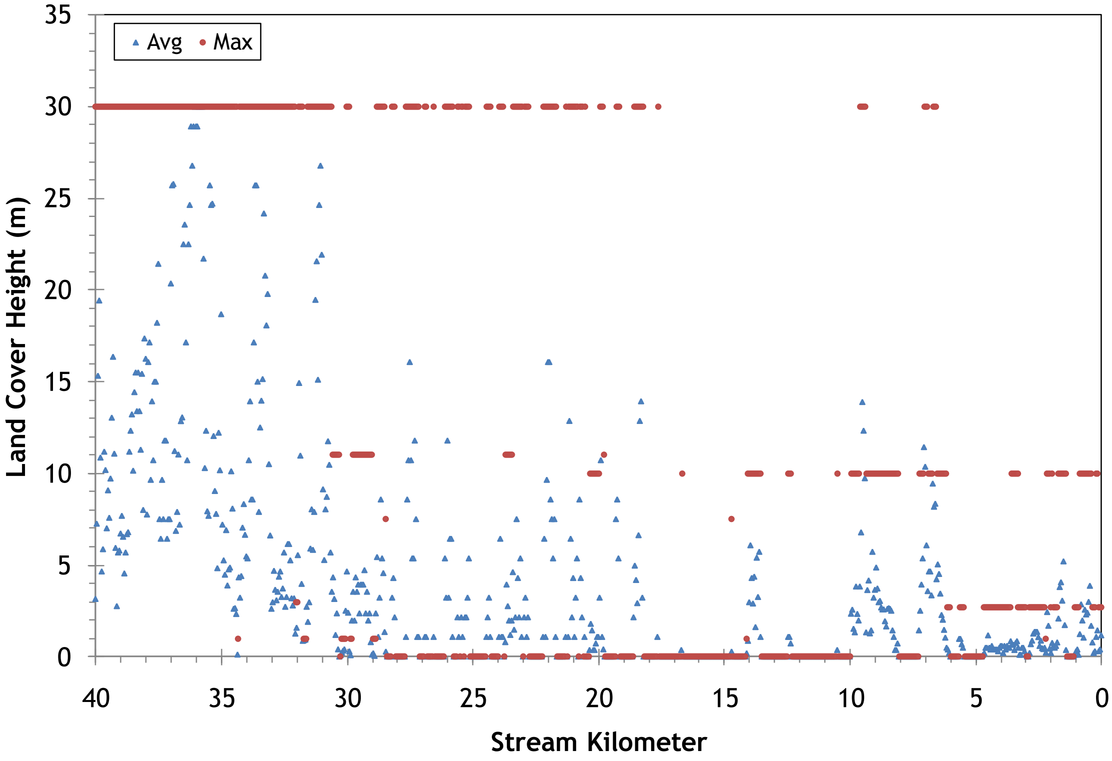


Figure 83 shows the sampled land cover heights for Upper Ochoco Creek. Land cover polygons were digitized from the TIR mosaics and NAIP imagery for this simulation.

Figure 83 - Upper Ochoco Creek sampled land cover heights.



Lower Ochoco Creek

Ochoco Creek had much higher flows below the reservoir due to water releases at the dam. Stream temperatures were simulated for lower Ochoco Creek, and the model inputs and assumptions are summarized in Table 27 and described below.

Table 27 - Lower Ochoco Creek Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 25 – August 31, 2005
TIR data:	8/5/05, 13:32-13:52. Flown in upstream direction.
Simulation Extent:	18.15 km from Ochoco Reservoir dam to the mouth.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	4
Continuous Data Sites:	3
Climate Data Source:	RAWS – Haystack
Flush Initial Conditions:	7 days
Deep Alluvium Temperature:	True (12°C)
Land Cover Data Source:	USGS LiDAR
Evaporation Method:	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	0.50 meters
Hyporheic Exchange:	1%
Porosity:	40%

- Channel widths (wetted surface) were digitized from the mosaiced TIR imagery.
- Cloud cover was estimated to be 75% on days when hourly stream temperatures were markedly cooler than the remainder of the simulation period.
- The upstream boundary is located just below the dam. It is assumed that the flow and temperature data were collected downstream of the diversion which is located at the base of the dam. Therefore, withdrawals from that diversion were not included as a separate input within the model.
- The thermistor deployed below the dam began recording on July 15. The hourly data from July 15 was copied to the first 14 days of the simulation period. This thermistor data was used as the upstream boundary condition.
- Boundary condition flows were the daily volumes measured by the gage just downstream of the reservoir.
- The OID return flow temperature data was only measured during August. The hourly values from August 1 were copied to each day in July. Generally, the August data were between 14 and 16°C.
- There is a pond located at stream kilometer 15.25 which appears to have been stratified at the time of TIR acquisition. Cooler water was being released at the lower end of that pond, resulting in a sudden temperature decrease. This was accounted for within the model by removing 0.2 cms at the pond and then adding 0.2 cms of 12°C water at that same location throughout the simulation period.

Table 28 summarizes the calibration statistics achieved for the Lower Ochoco Creek simulation.

Table 28 - Lower Ochoco Creek simulation calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	18.15-0	182	0.23	0.43	0.51	0.86
downstream Combs Flat Road	DEQ	8.25	912	-1.03	1.29	1.60	0.70
at Middle School	DEQ	7.70	912	-0.85	1.03	1.27	0.63
Near Mouth	DEQ	1.10	912	-1.52	1.66	2.03	-0.15

Figure 84 shows the calibrated longitudinal temperature profile of Ochoco Creek from the reservoir to the mouth.

Figure 84 - Lower Ochoco Creek longitudinal temperature calibration.

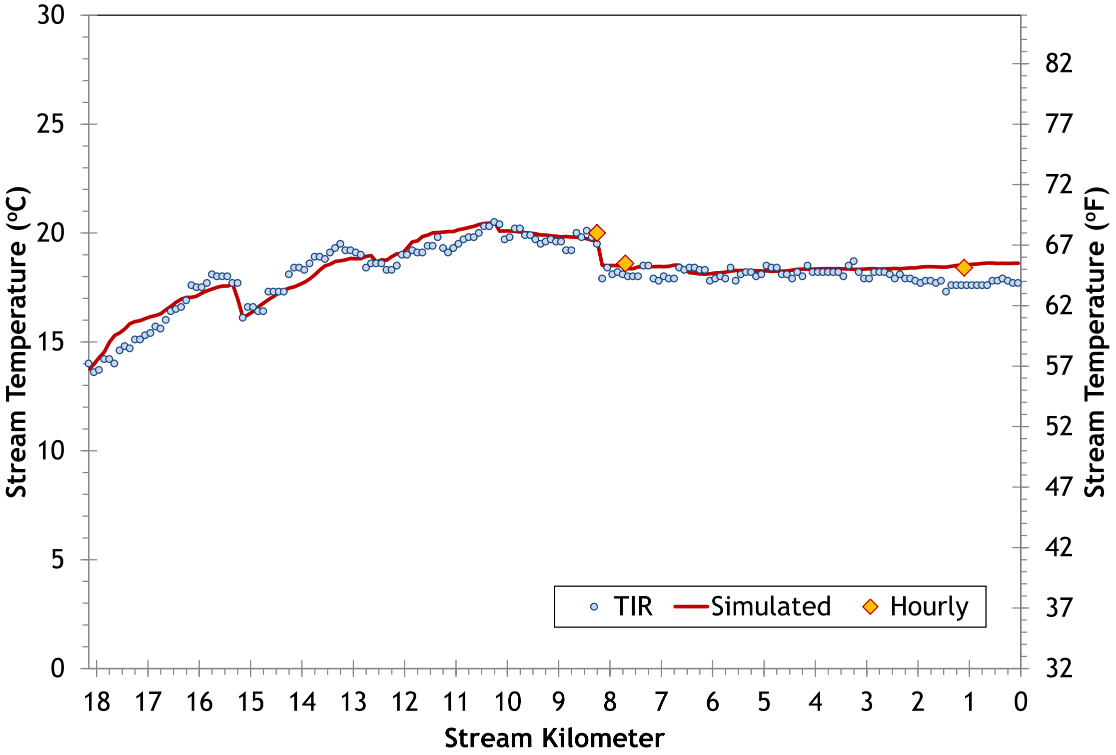


Figure 85 shows the simulated and measured hourly temperatures of the lower Ochoco Creek calibrated Heat Source model.

Figure 85 - Lower Ochoco Creek simulated and measured hourly temperatures.

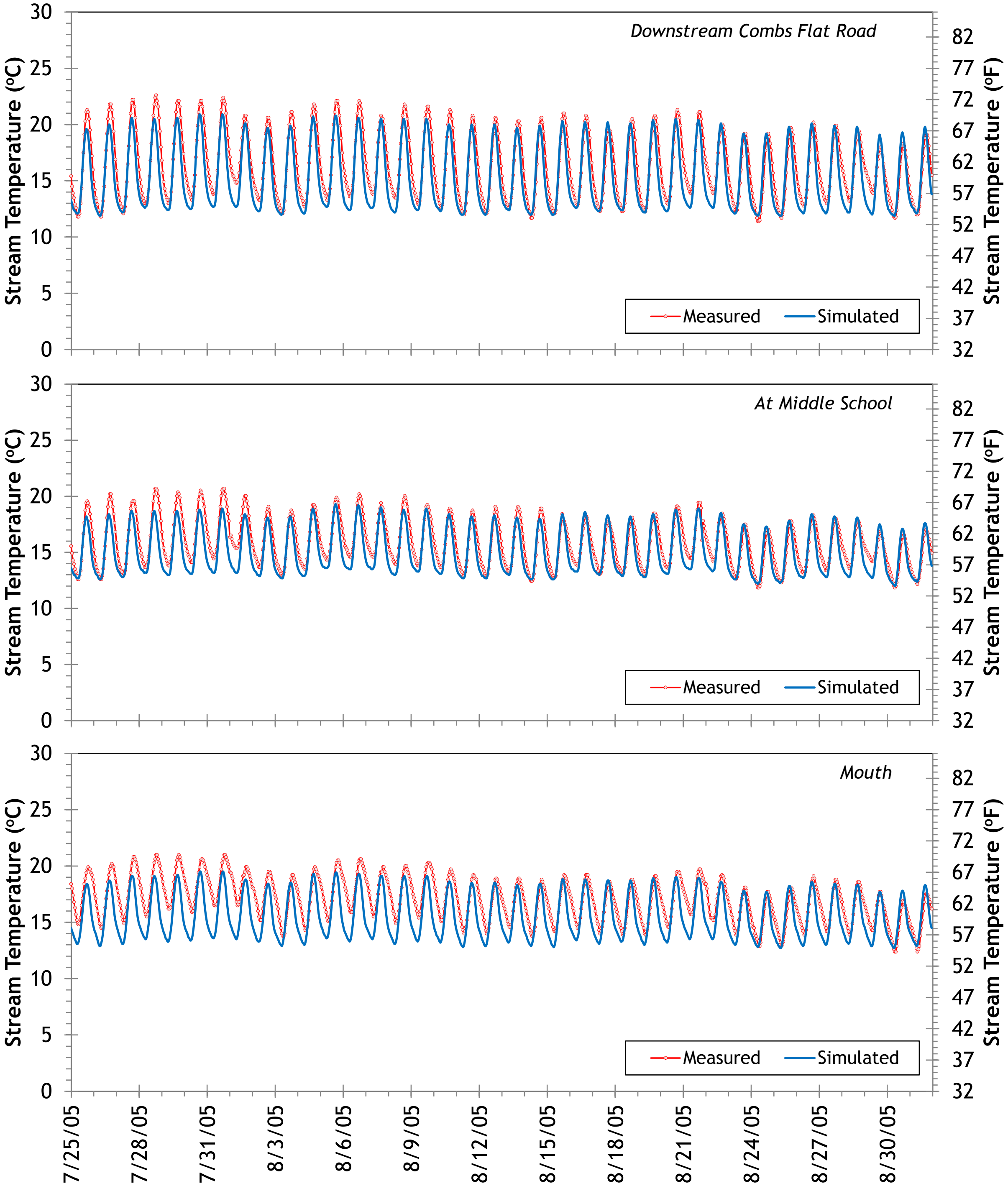


Figure 88 through Figure 91 show the simulated and measured hydraulic values from the lower Ochoco Creek simulation. The simulated values are from August 5, 2005 when the TIR data was collected. The measured values were also collected on August 5. The upstream boundary is the dam, where daily gaged volume data was available.

Figure 86 - Lower Ochoco Creek simulated and measured flow volumes.

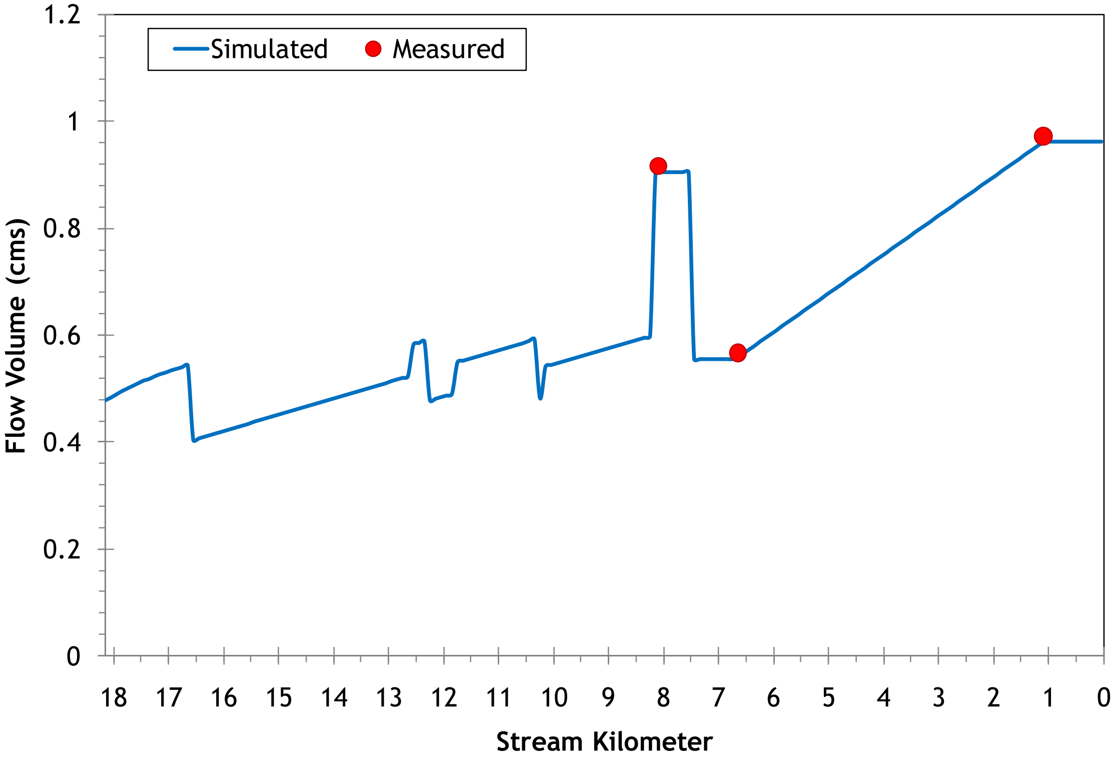


Table 29 summarizes the inflows included within the lower Ochoco Creek simulation. Accretion estimates (gaining reaches) were included within the model in order to match the measured flow values.

Table 29 - Lower Ochoco Creek simulated inflows.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Gaining Reach	18.15-8.2	Mass Balance Estimate	Estimated at 12-15°C
Spring	12.6	Mass Balance Estimate	TIR Estimate
Withdrawal	12.25	Estimated at 4.0 cfs	NA
Spring	11.8	Mass Balance Estimate	TIR Estimate
Withdrawal	10.25	Estimated at 4.0 cfs	NA
Spring	10.2	Mass Balance Estimate	TIR Estimate
OID Diversion Overflow	8.2	DEQ	DEQ
Withdrawal	7.5	Estimated at 12.3 cfs	NA
Gaining Reach	6.65-1.1	Mass Balance Estimate	Estimated at 16°C

Figure 87 – Lower Ochoco Creek simulated and measured velocities.

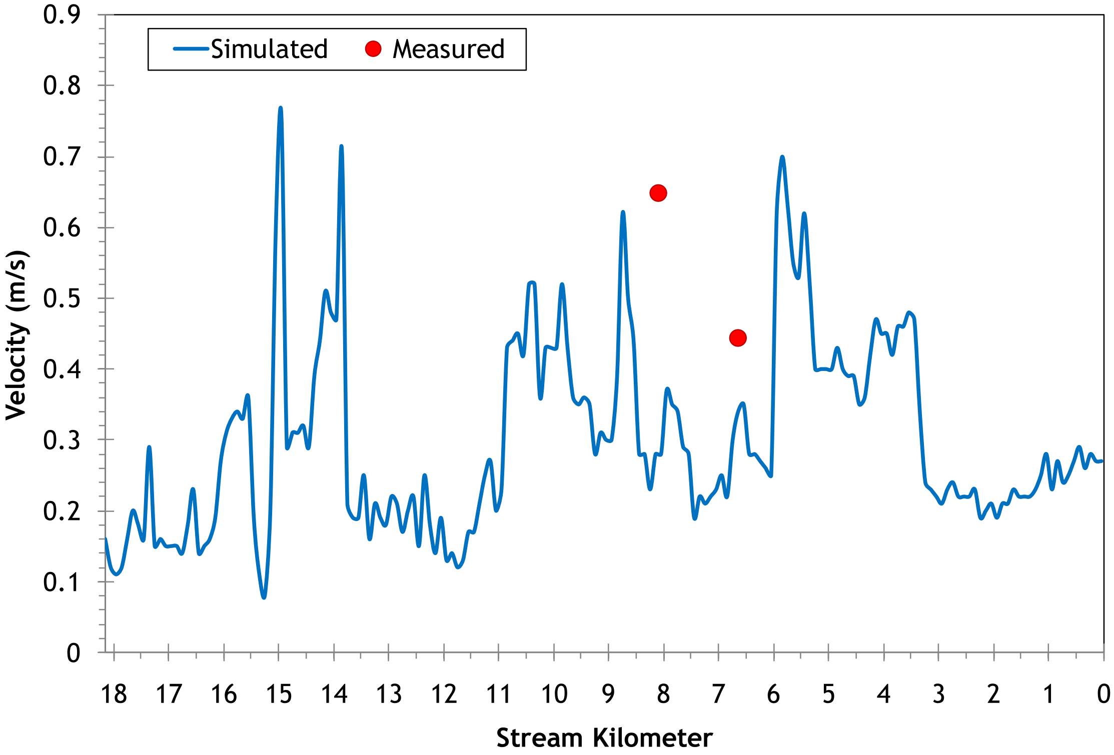


Figure 88 - Lower Ochoco Creek simulated and measured wetted widths.

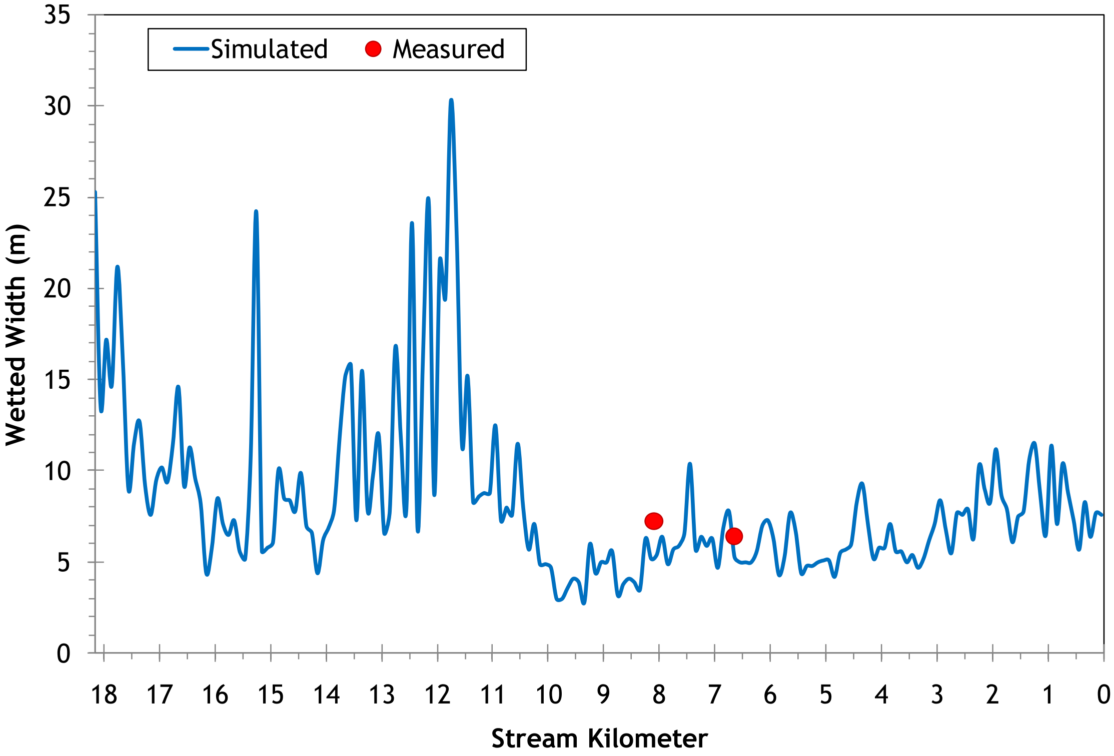


Figure 89 - Lower Ochoco Creek simulated and measured maximum depths.

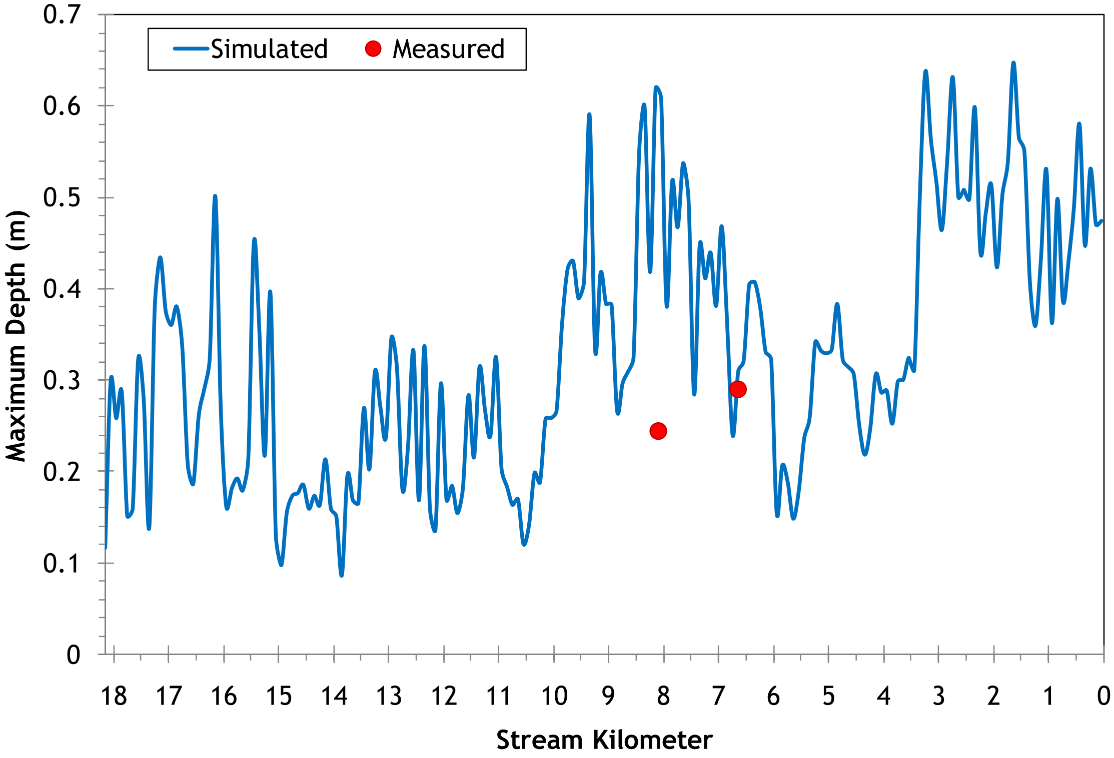
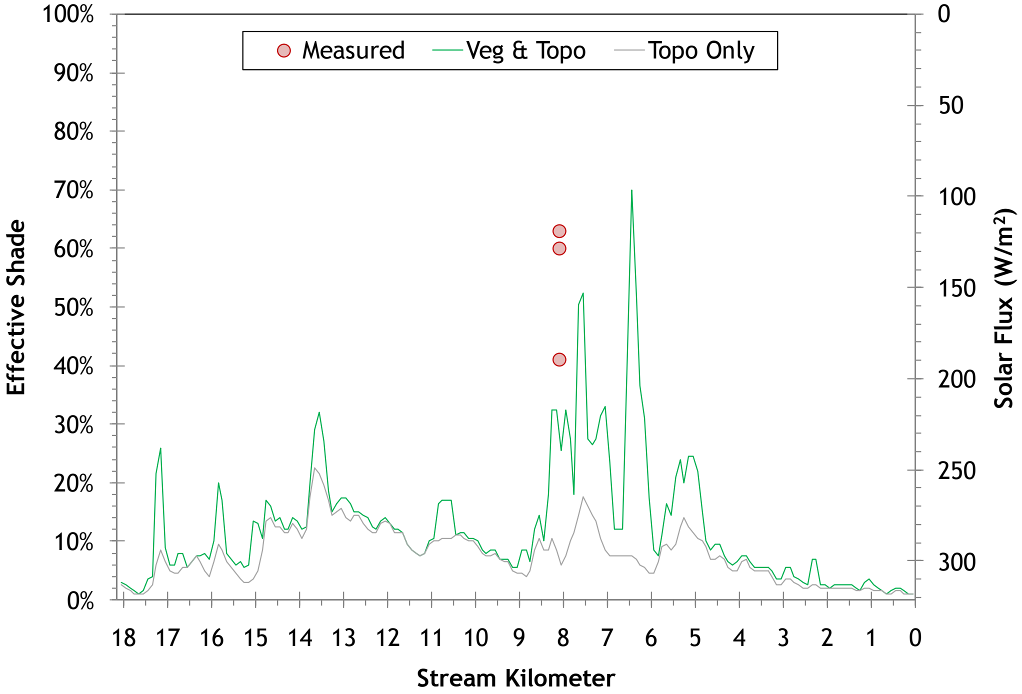


Figure 90 - Ochoco Irrigation District diversion on Ochoco Creek near stream kilometer 16.6.

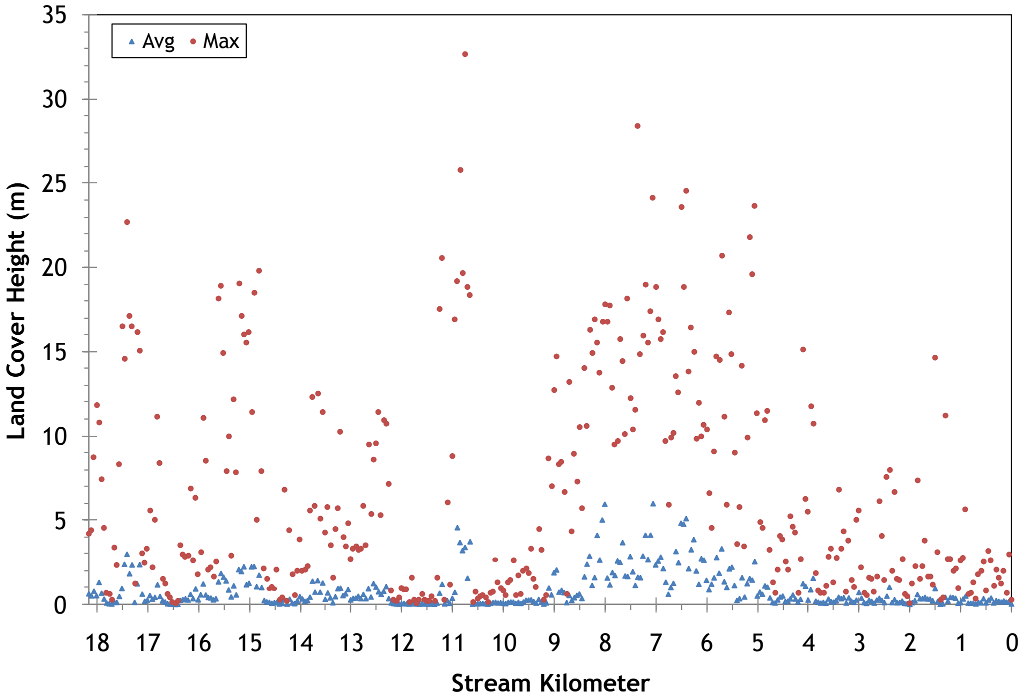
Figure 91 shows the simulated and measured effective shade for Ochoco Creek below the reservoir. For the most part, there is little effective shade produced by vegetation, except between stream kilometers 9 and 5. The remainder of the stream has effective shade that is primarily the result of topographic features.

Figure 91 - Lower Ochoco Creek simulated and measured effective shade.



Lower Ochoco Creek land cover heights were sampled from the USGS LiDAR data (Figure 92).

Figure 92 - Lower Ochoco Creek sampled land cover heights.


Avg
Max
Land Cover Height (m)
35
30
25
20
15
10
5
0
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Stream Kilometer

Upper Crooked River

The upper Crooked River was simulated from the forks to the Prineville Reservoir. The input parameters and assumptions used to calibrate Heat Source are listed in Table 30 and described below.

Table 30 - Upper Crooked River Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 25 – August 31, 2005
TIR data:	8/6/05, 16:26-17:32. Flown in upstream direction.
Simulation Extent:	68.75 km from SF/NF confluence to Prineville Reservoir.
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	6
Continuous Data Sites:	4
Climate Data Source:	RAWS – Badger Creek
Flush Initial Condition:	21 days
Deep Alluvium Temperature:	True (18°C)
Land Cover Data Source:	Polygons digitized from TIR mosaics and NAIP imagery.
Evaporation Method:	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	1.57 W/m/°C
Sediment Thermal Diffusivity:	0.0064 cm^2/sec
Sediment/Hyporheic zone thickness:	0.35 meters
Hyporheic Exchange:	1%
Porosity:	40%

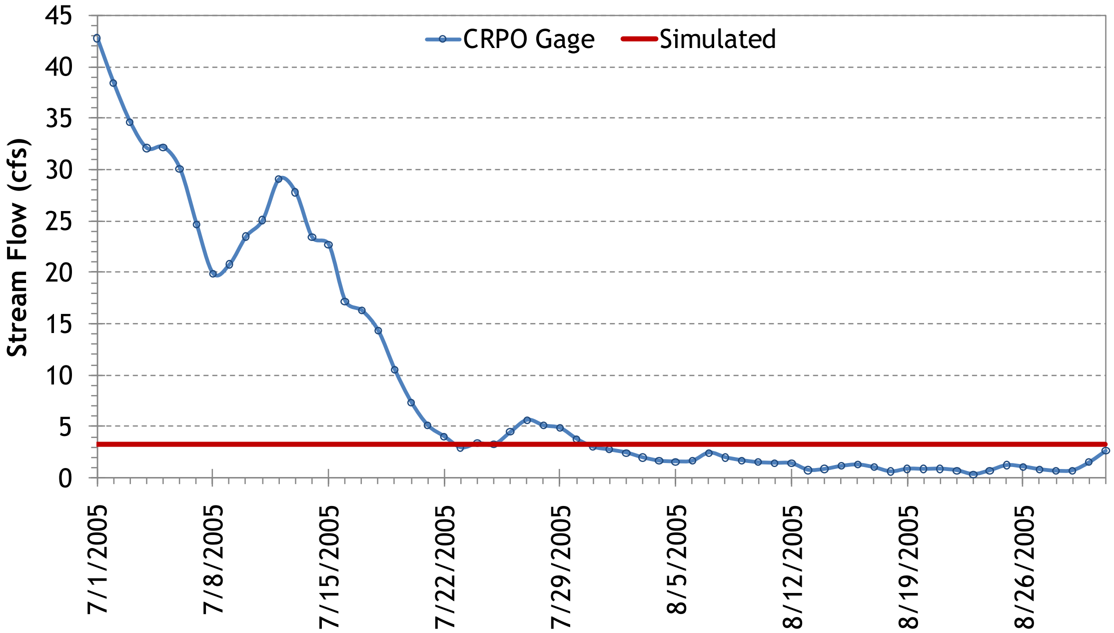
- The upper Crooked River has low flow, low gradients, and has very little shade-producing vegetation. Stratification occurs in many reaches. For these reasons, the stream temperature varies drastically over short distances and the TIR data may not accurately represent the bulk water column temperatures. The model was calibrated to generally fall within the ranges of surface temperatures recorded in the TIR flight; however, the results should be interpreted carefully with the understanding that there is a significant range of error.
- Channel widths (wetted surface) were digitized from the mosaiced TIR imagery.
- Based upon solar radiation data collected at the Badger Mountain RAWS station, cloud cover was estimated to be 75% on July 8th and 9th. All other days had zero cloud cover.
- Withdrawals that were identified within the TIR imagery were included within the simulation. Rates were approximated by assessing the OWRD point of diversion database permitted rates near each withdrawal.
- There was very little measured flow data available for the upper Crooked River. The CRPO gage revealed that late July and August flows were around 0.2 cfs.
- Climate data was from the Badger Creek RAWS station. Air temperatures were adjusted based on the dry adiabatic lapse rate.

The upper Crooked River was not an ideal system for modeling during the summer of 2005. Figure 93 shows the measured flow values at the CRPO gage, just upstream of the reservoir. The average flow volume during August 2005 was 1.3 cfs, which was too small for Heat Source to accurately model in this system. In addition, the flows were much greater during early July. Since the channel morphology inputs do not have a temporal option in Heat Source, the inputs would not be suitable for both July and August time periods (ideally, two separate modeling efforts would need to be completed for each month). However, there was no field data available to verify the source of higher flow volumes in July (it could have been greater spring and tributary inflows or fewer withdrawals occurring).

Rather than "create data" or make drastic assumptions for the higher July flows, a steady-state flow condition was simulated. The boundary flow volume, spring and tributary inputs, and withdrawals were all assumed to be the same throughout the simulation time period. As seen in Figure 93, the simulated flow volume at the gage was 3.3 cfs, which is generally greater than the August flows measured at that location. Heat Source became unstable and unable to be calibrated when the flow dropped below the 3.3 cfs threshold for this stream.

The upper Crooked River simulation results presented here should be interpreted with caution, while keeping in mind the major assumptions and the model's limitations. The results are most valid for the few days surrounding the TIR flight, when some flows were measured in the field. The further from the TIR flight date, the less valid the results.

Figure 93 - CRPO gage data and simulated flow at that location (6.9 kilometers from the reservoir).



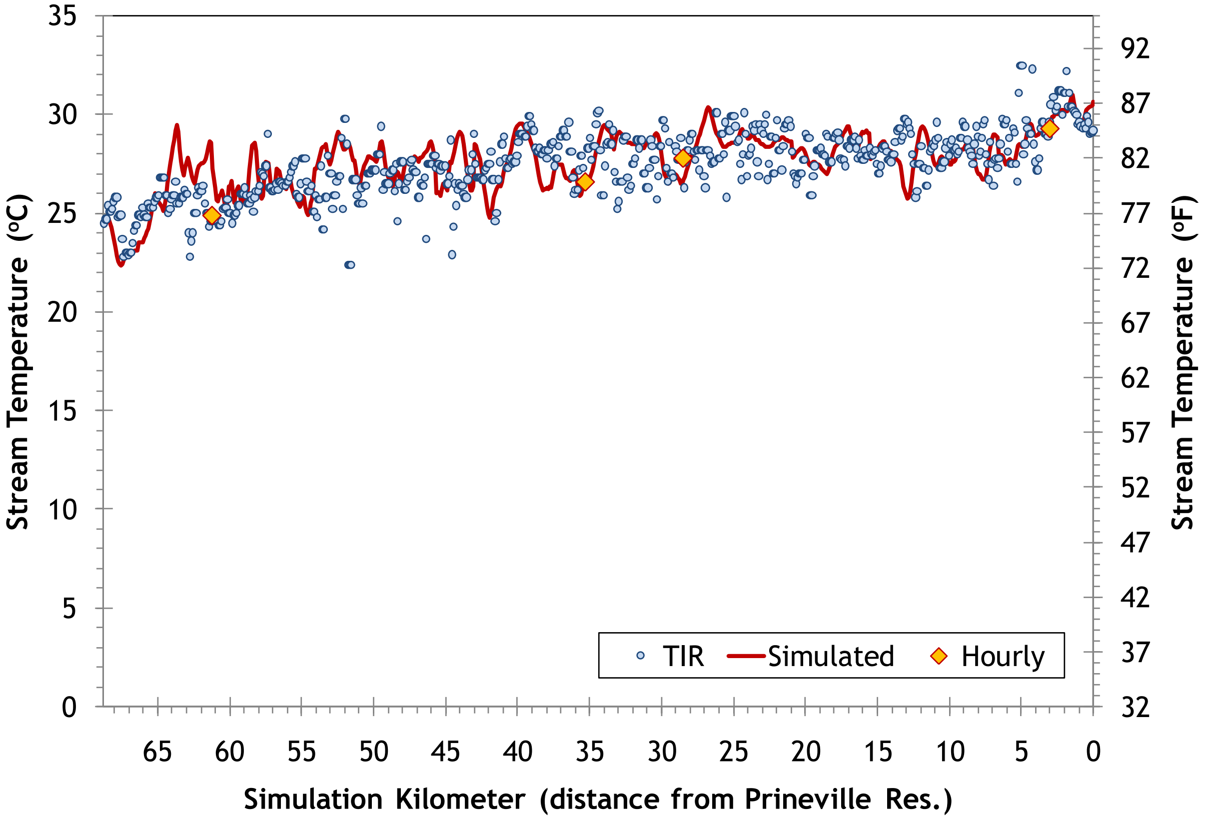
The upper Crooked River is very low gradient, has wide channels, little flow, not very much shade-producing vegetation, and is stratified in several areas. The river is heavily used for irrigation, with dozens of unmapped and unmonitored withdrawals and returns. Much of the river has thick periphyton growth during the summer, which affects flow properties as well as thermal dynamics. The simulation results should be interpreted with caution since Heat Source does not simulate stratification, periphyton growth, etc.

Table 31 - Upper Crooked River simulation calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	68-75-0	689	0.12	1.27	2.02	-0.49
BLM Guard Station	DEQ	61.25	912	2.38	2.48	2.94	0.01
TNC Property	DEQ	35.30	840	0.71	1.29	1.60	0.63
downstream FS Road 17	DEQ	28.50	912	0.45	1.20	1.50	0.80
North Shore Road Gate	USFS	3.00	840	-0.47	1.47	1.79	0.76

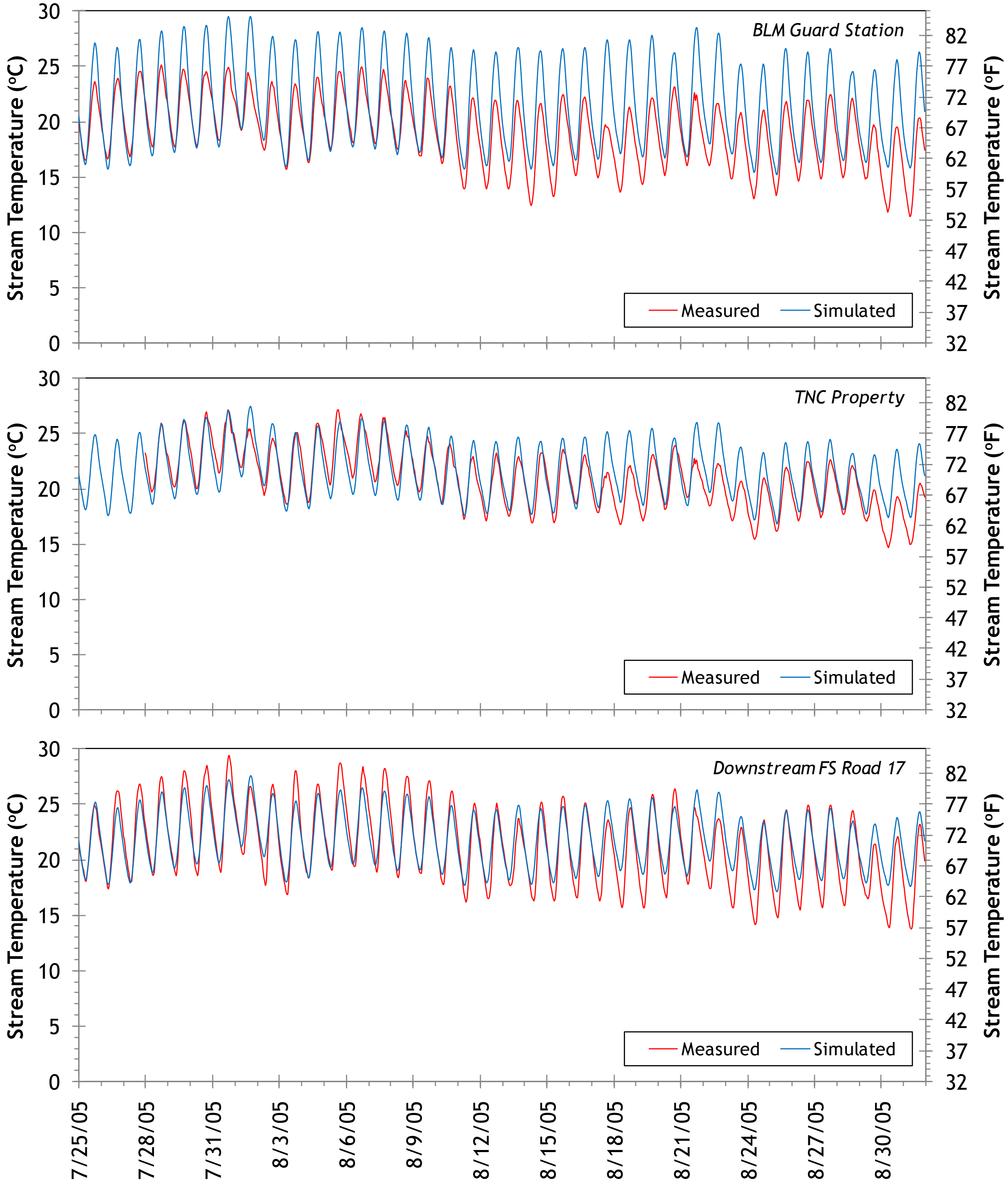
Figure 94 shows the calibrated longitudinal temperature profile of the upper Crooked River. The river is very warm throughout and has many areas of likely stratification. The low flow volume and wide channels make the temperature profile very sensitive and variable over short distances. The river is a less than ideal candidate for temperature modeling; however, the best attempt was made to roughly calibrate the model to the TIR profile.

Figure 94 - Upper Crooked River calibrated longitudinal temperature profile.



The measured and simulated hourly temperatures are shown in Figure 95.

Figure 95 - Upper Crooked River measured and simulated hourly temperatures.



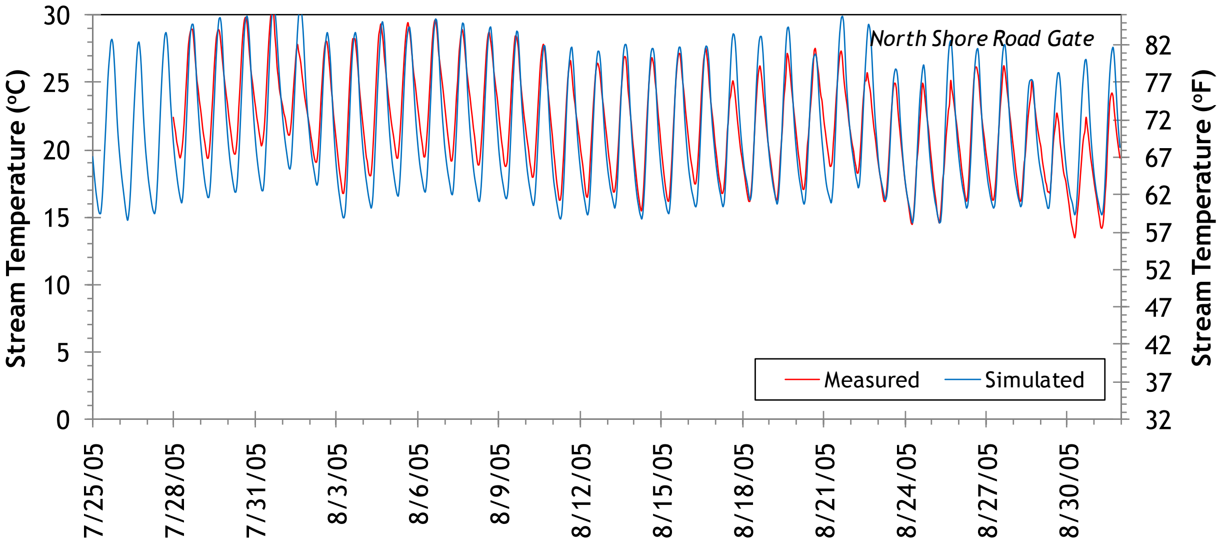
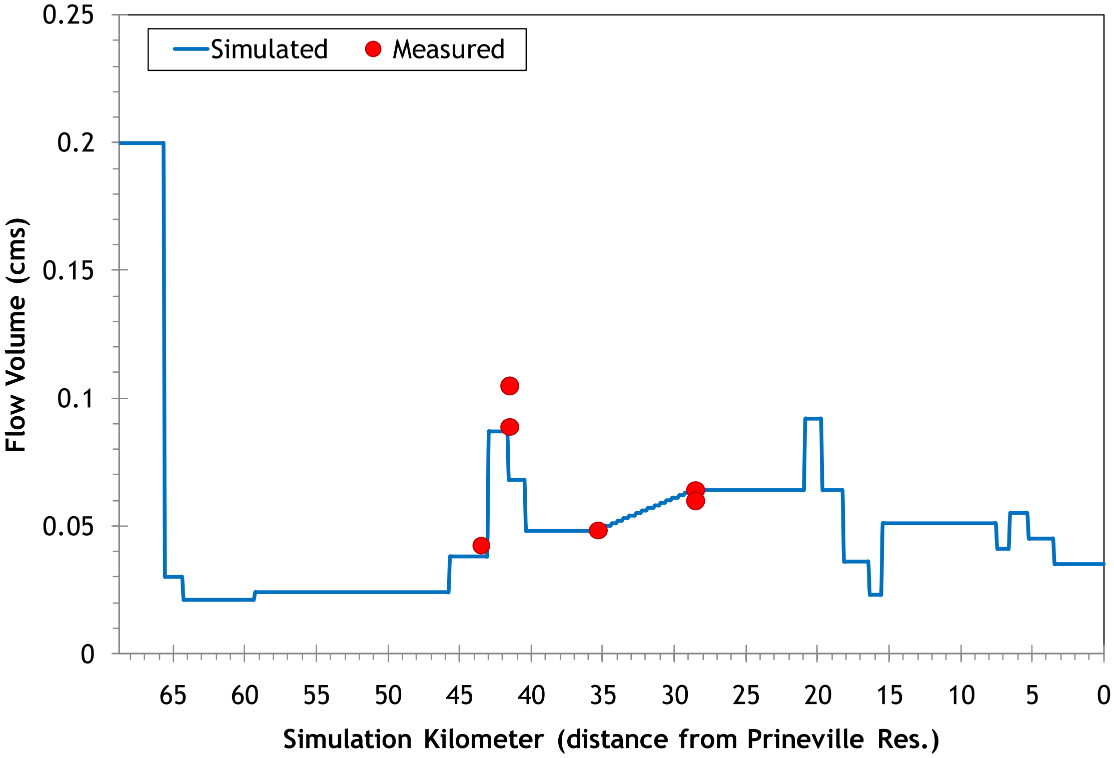


Figure 96 - Typical reach along the upper North Fork Crooked River.

Figure 97 displays the simulated and measured flow volumes for the Crooked River upstream of Prineville Reservoir. The simulated values are from August 6, 2005 when the TIR data was collected. The measured values were collected on August 4, 5, 10 and 11.

Figure 97 - Upper Crooked River simulated and measured flow volumes.



Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Withdrawal	65.6	Estimated at 6 cfs	NA
Withdrawal	64.3	Estimated at 3.2 cfs	NA
Spring	59.25	Estimated at 1 cfs	TIR Measurement
Camp Creek	54.05	Dry	NA
Spring	45.65	Estimated at 1 cfs	TIR Measurement
North Fork	43.0	DEQ	DEQ
Withdrawal	41.6	Estimated at 0.7 cfs	NA
Withdrawal	40.35	Estimated at 0.7 cfs	NA
Lost Creek	35.65	Dry	NA
Gaining Reach	35.3-28.5	Mass Balance Estimate	Estimated at 25°C
Newsome Creek	20.85	Estimated at 1 cfs	TIR Measurement
Withdrawal	19.7	Estimated at 1 cfs	NA
Withdrawal	18.15	Estimated at 1 cfs	NA
Withdrawal	16.4	Estimated at 0.5 cfs	NA
Horse Heaven Creek	15.5	Estimated at 1 cfs	TIR Measurement
Withdrawal	7.45	Estimated at 0.4 cfs	NA
Spring	6.6	Estimated at 1 cfs	TIR Measurement
Withdrawal	5.25	Estimated at 0.4 cfs	NA
Withdrawal	3.45	Estimated at 0.4 cfs	NA

Figure 98 through Figure 100 show the simulated and measured hydraulic data for the upper Crooked River. The simulated data shown is for August 6, 2005, when the TIR data was collected. The measured values were collected on August 4, 5, 10 and 11. Note that the velocities and depths may not necessarily represent the greater stream conditions. On the upper Crooked River, access was limited and flow measurements had to be collected at locations where there was sufficient flowing water to register on the equipment. Much of the river was too slow and/or deep to measure flow accurately.

Figure 98 - Upper Crooked River simulated and measured velocities.

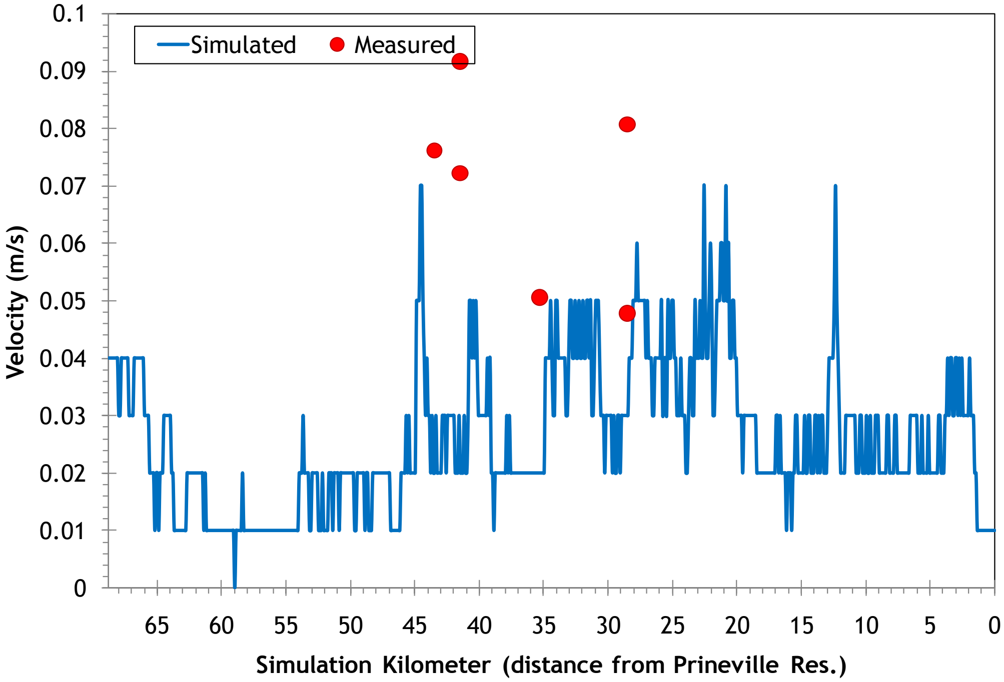


Figure 99 - Upper Crooked River simulated and measured wetted widths.

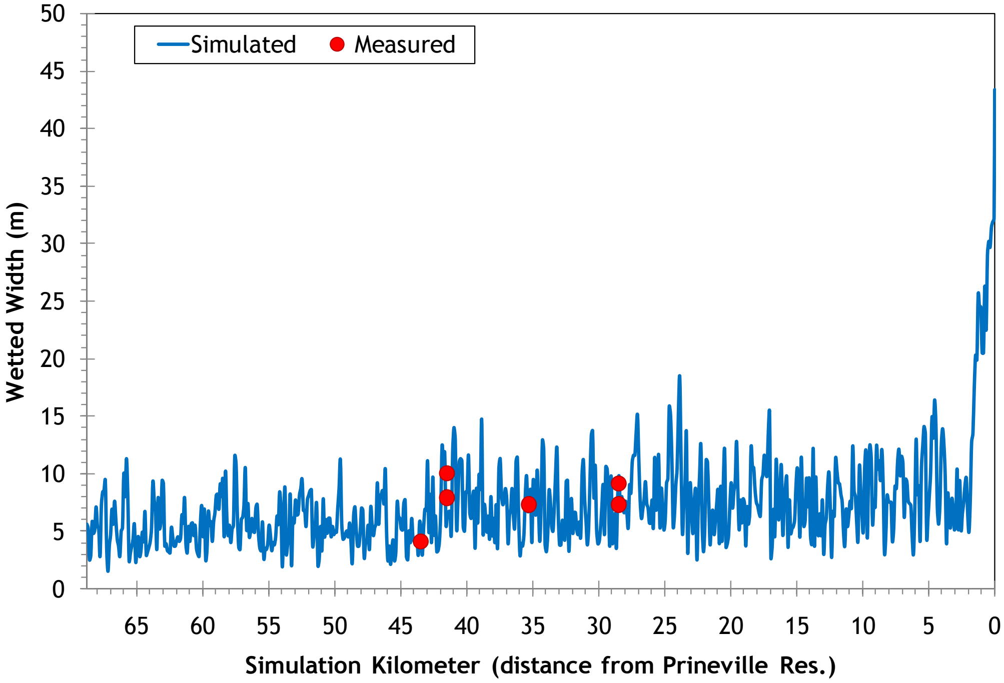


Figure 100 - Upper Crooked River simulated and measured maximum depths.

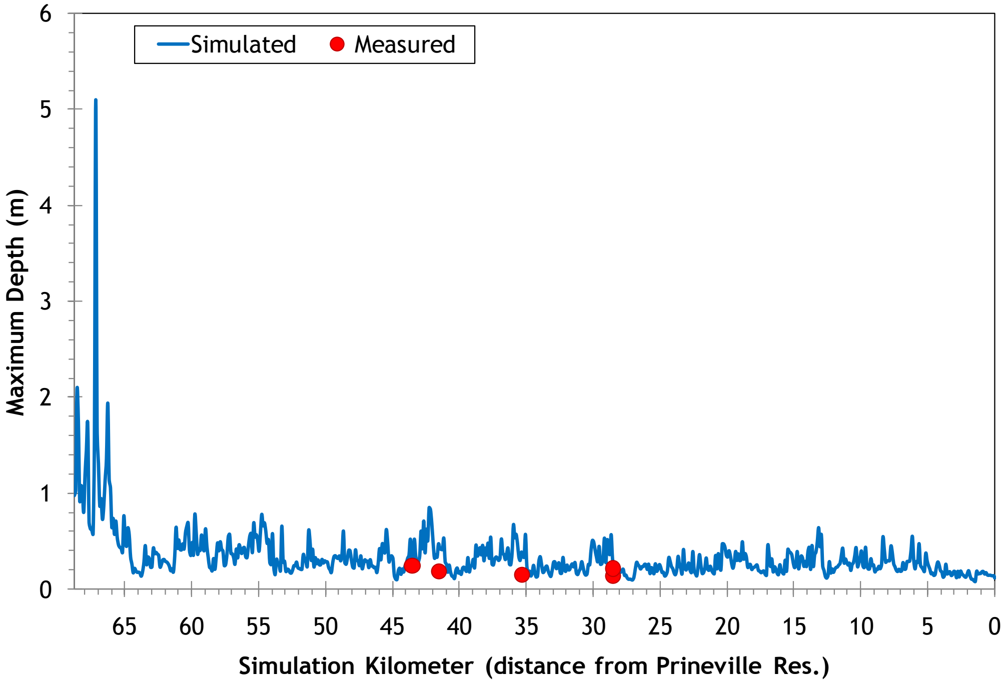
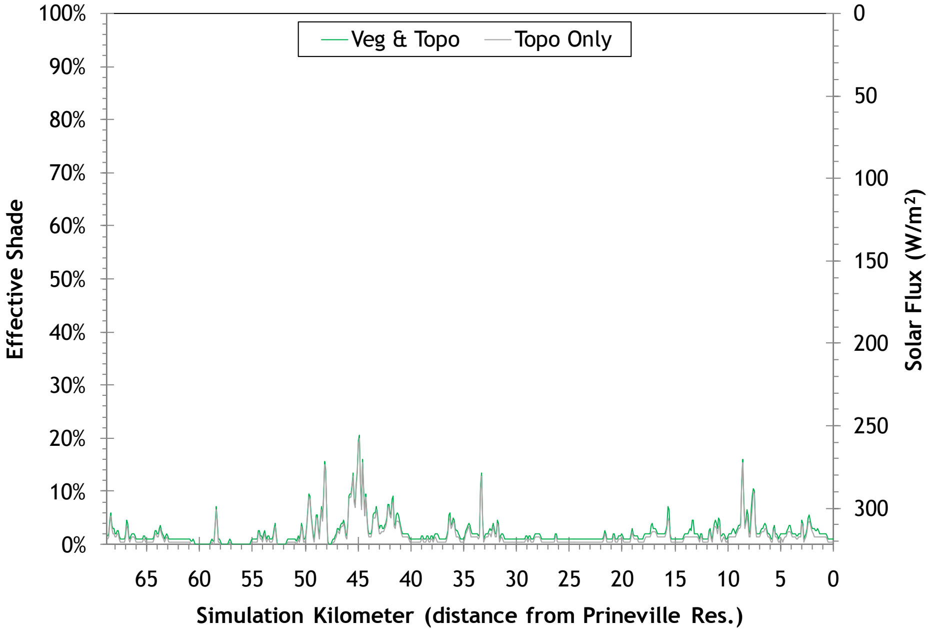


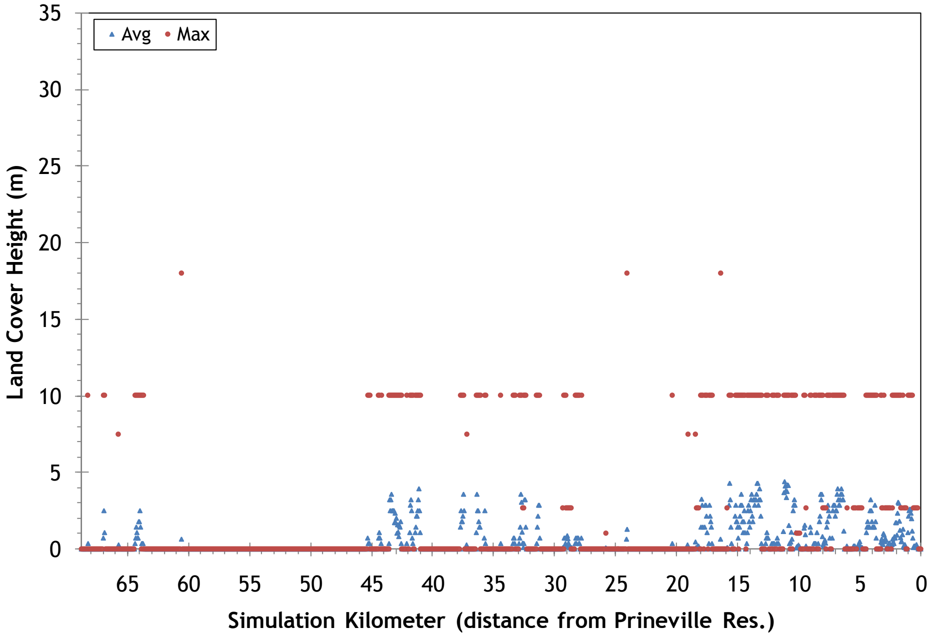
Figure 101 shows the simulated effective shade along the upper Crooked River. The upper Crooked River is very wide and flows through a flat valley with little topographic relief. The primary streamside vegetation is grass and small shrubs, which do not produce any significant effective shade. For these reasons, there is very little effective shade observed on the upper Crooked River.

Figure 101 - Upper Crooked River simulated effective shade.



Land cover polygons were digitized from the TIR mosaics and NAIP imagery for the upper Crooked River. The sampled land cover heights are shown in Figure 102.

Figure 102 - Upper Crooked River sampled land cover heights.



Lower Crooked River

The lower Crooked River was simulated from the Prineville Reservoir dam to Lake Billy Chinook. The input parameters and assumptions used to calibrate the Heat Source model listed in Table 32 and described below.

Table 32 - Lower Crooked River Heat Source inputs.

Model:	Heat Source version 8.0.4
Simulation Time Period:	July 25 – August 31, 2005
TIR data:	8/6/05, 13:32-15:34. Flown in upstream direction.
Simulation Extent:	105.45 km (Prineville Reservoir to Lake Billy Chinook)
Time Step:	1 minute
Distance Step:	100 meters
Longitudinal Sample Rate:	50 meters
Transverse Sample Rate:	15 meters
Inflow Sites:	47
Continuous Data Sites:	10
Climate Data Source:	RAWS – Haystack
Flush Initial Conditions:	14 days
Deep Alluvium Temperature:	True.
Land Cover Data Source:	USGS LiDAR
Evaporation Method:	Penman
Wind Function, coefficient a:	0.00000000151
Wind Function, coefficient b:	0.0000000016
Sediment Thermal Conductivity:	2.0 W/m/°C
Sediment Thermal Diffusivity:	0.0118 cm^2/sec
Sediment/Hyporheic zone thickness:	0.5 - 3.0 m
Hyporheic Exchange:	0 - 1%
Porosity:	35%

- Channel widths (wetted surface) were digitized from the mosaiced TIR imagery.
- Boundary condition flows were daily values recorded at the USGS gage below the dam.
- Boundary condition temperatures were hourly data recorded just below the dam.
- Data was not available for the Baldwin diversion and People's Irrigation diversion. Rates were assumed constant and estimated based upon mass balance calculations.
- Daily diversion data was available for the OID diversion canal from the US Bureau of Reclamation.
- Ochoco Creek temperature inputs were hourly measurements and the daily flow volumes were from the Ochoco Creek Heat Source simulation.
- McKay Creek had hourly temperature data available. Flow was measured at the mouth 4 times during the simulation time period. An average of the 4 measurements was used as the input for the entire simulation. Relative to the size of the Crooked River, McKay Creek was very small.
- The Hancock diversion had no data available. Diversion rate estimates were provided by OWRD.
- There were several spring inflows between stream kilometers 29 and 12. Simulation inputs were divided equally at 8 locations where larger springs were visible within the TIR imagery. Precise mass balance calculations were not possible because the springs did not influence Crooked River bulk temperatures enough.
- Between stream kilometers 10 and 2, there were 20 spring inputs included in the simulation. Each of the 20 inflows was estimated and distributed equally amongst themselves
- Opal Springs was estimated to contribute 28 cms (989 cfs) at 13.7°C during the simulation period. This estimate was based upon flow mass balance calculations and TIR imagery.

Table 33 summarizes the calibration statistics achieved for the lower Crooked River. There were ten locations where hourly temperature data was recorded for some of the calibration time period.

Table 33 - Lower Crooked River simulation calibration statistics.

Site	Source	Stream Kilometer	n	Mean Error	Abs. Mean Error	RMSE	Nash-Sutcliffe
Longitudinal TIR	DEQ	105.45-0	1,055	-0.20	0.47	0.60	0.97
Castle Rock	DEQ	92.70	720	-0.09	0.47	0.56	0.95
Upstream Stearns Dam	DEQ	85.15	841	-0.38	0.59	0.68	0.89
Les Schwab Park	DEQ	70.70	912	-0.43	1.96	2.31	-1.18
Upstream Ochoco Creek	DEQ	64.20	912	-0.21	0.71	0.85	0.87
Downstream McKay Creek	DEQ	62.50	912	-0.48	0.62	0.79	0.89
Upstream Dry Creek	DEQ	44.40	671	0.37	0.69	0.89	0.78
Downstream Dry Creek	DEQ	44.10	671	0.40	0.71	0.92	0.77
Lone Pine Road	DEQ	37.65	912	0.21	1.10	1.44	0.70
Downstream Osborne Canyon	DEQ	10.80	912	0.06	1.08	1.23	-0.09
Inflow to Lake Billy Chinook	DEQ	0.10	912	0.00	0.11	0.13	0.83

Figure 103 shows the Lower Crooked River longitudinal temperature calibration results. The Lower Crooked River has a much larger flow volume and higher gradient than the upper Crooked River. In addition, the Lower Crooked River is heavily influenced by cold spring water inflows, especially within the lower 20 kilometers.

Figure 103 - Lower Crooked River longitudinal temperature calibration.

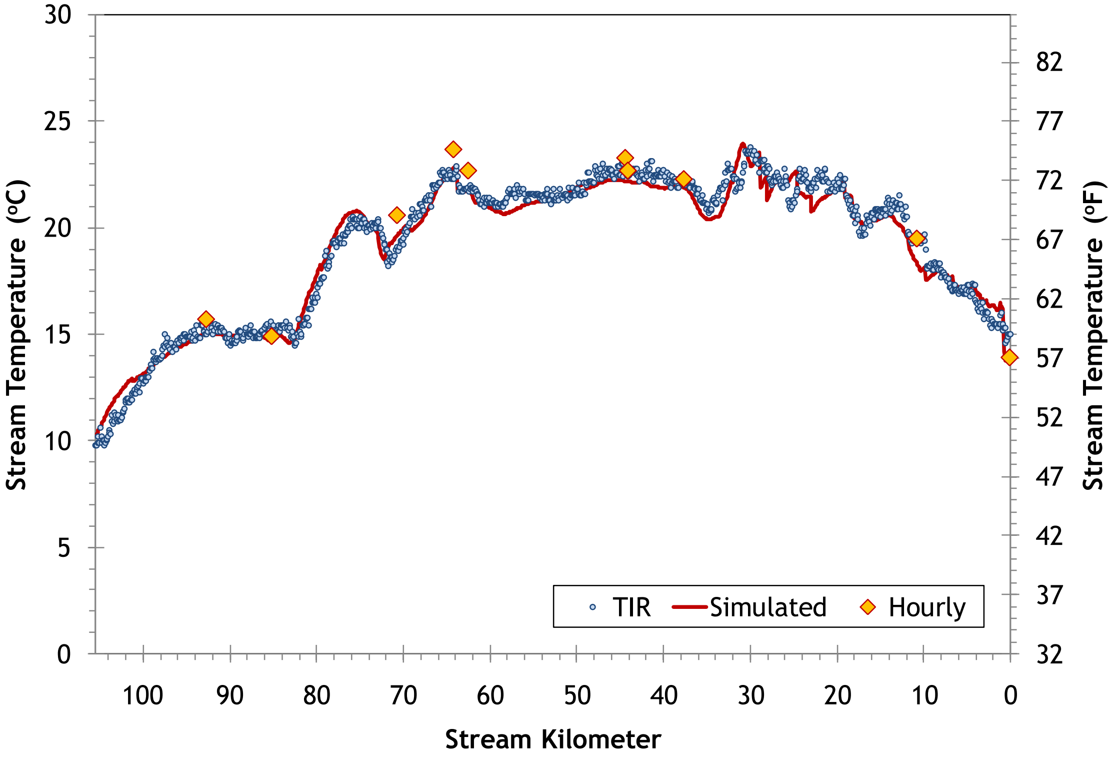
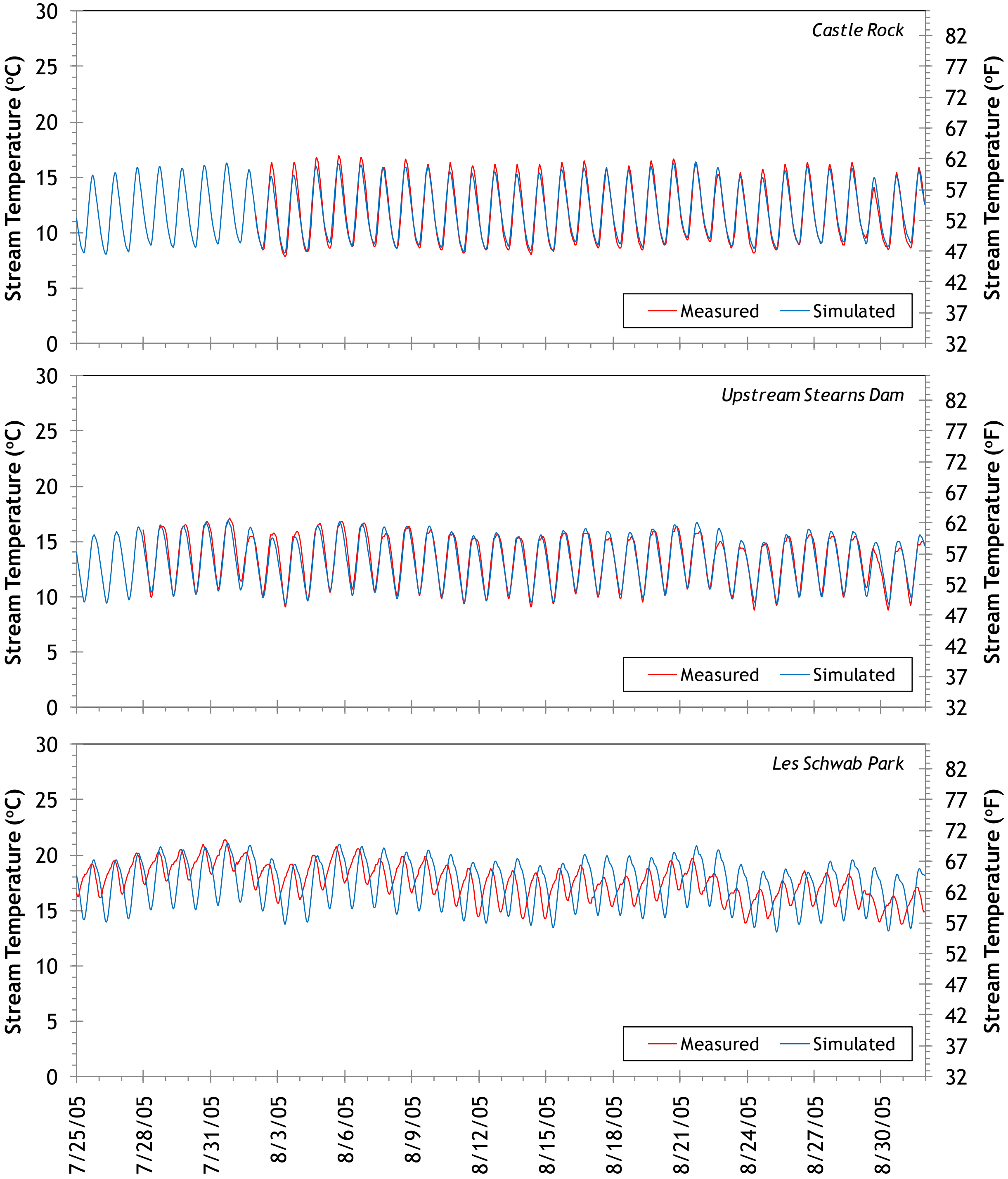
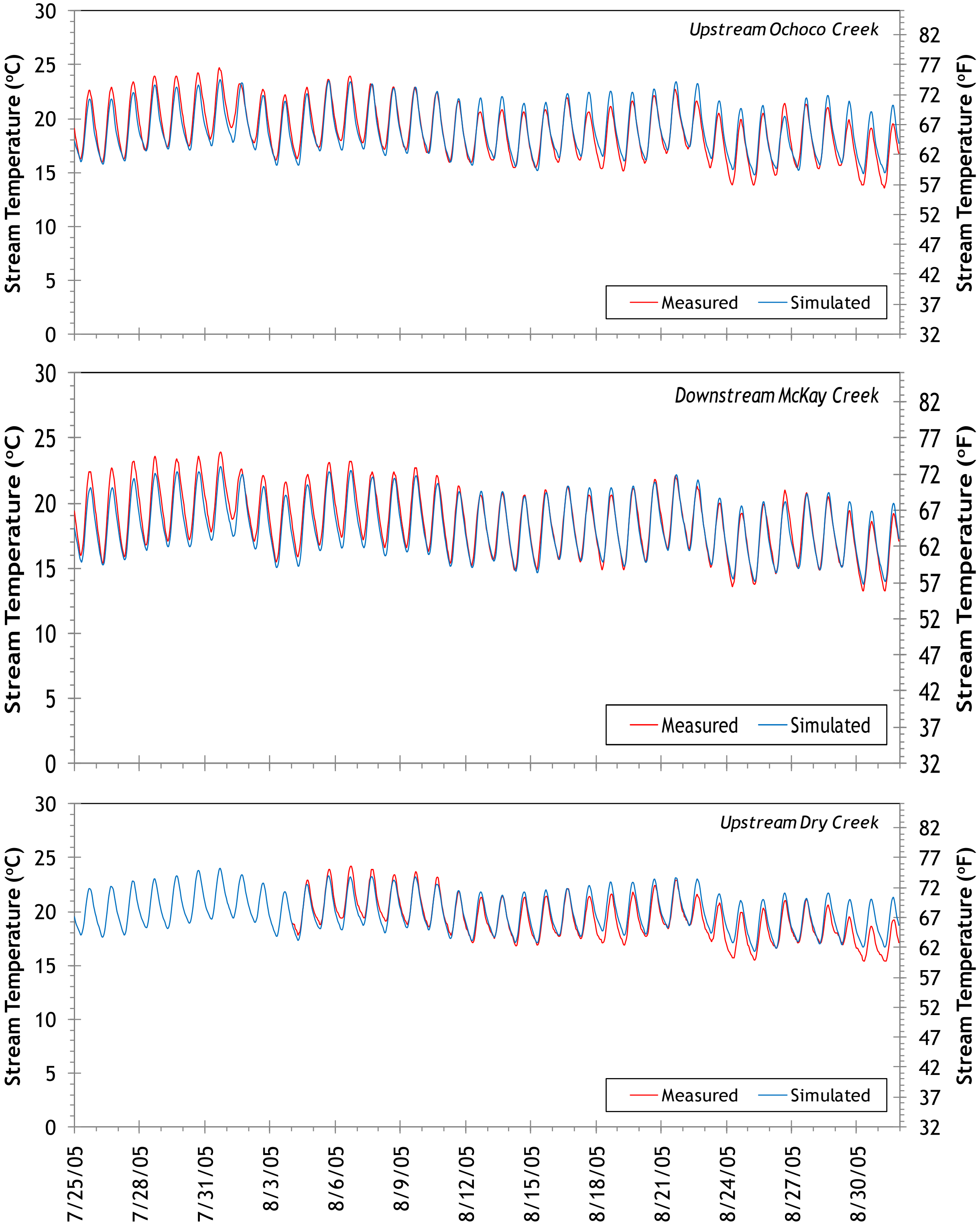
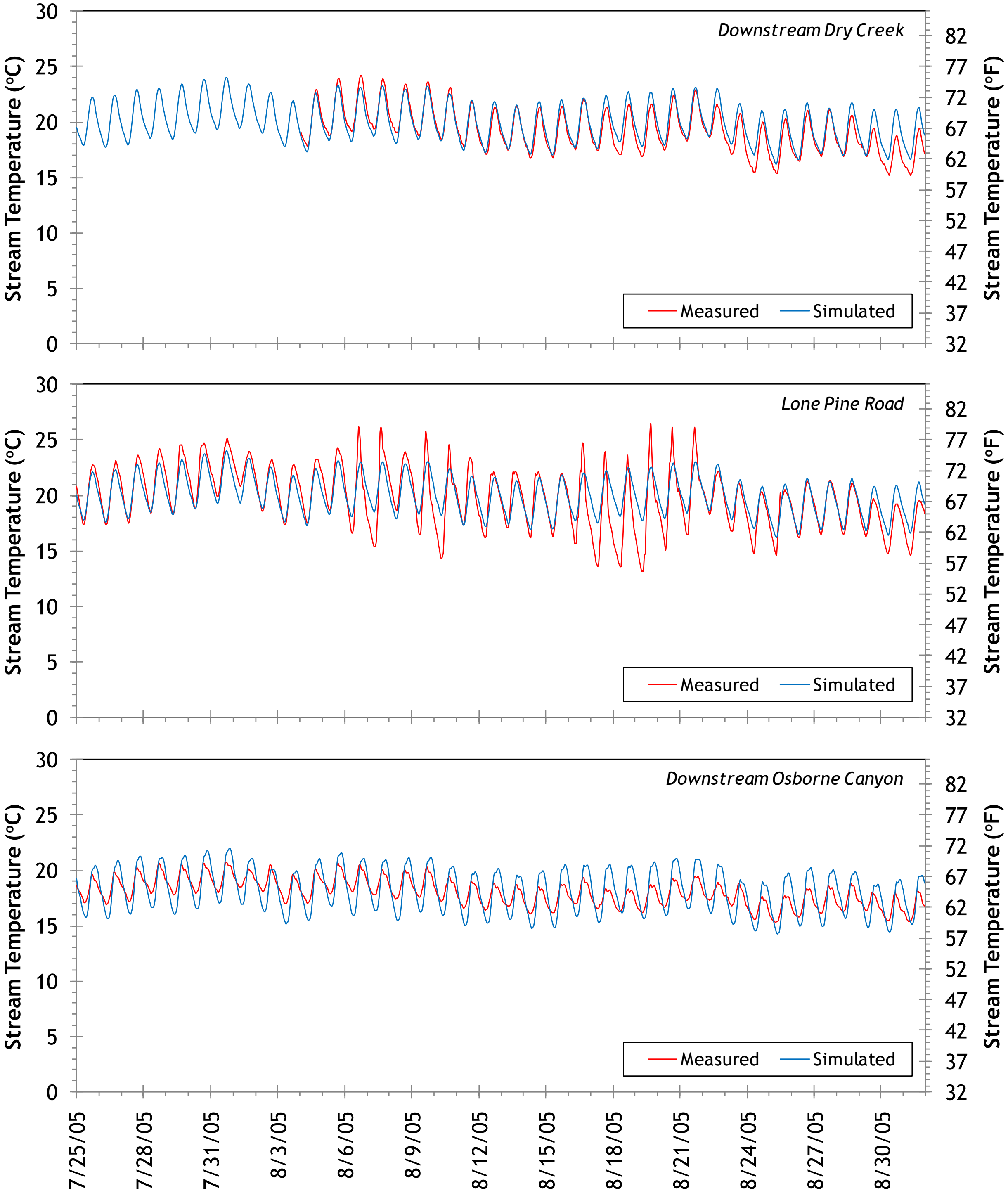


Figure 104 – Lower Crooked River simulated and measured hourly temperatures.

Figure 104 - Lower Crooked River simulated and measured hourly temperatures.




Upstream Ochoco Creek
Downstream McKay Creek
Upstream Dry Creek
Stream Temperature (°C)
Stream Temperature (°F)
30
25
20
15
10
5
0
82
77
72
67
62
57
52
47
42
37
32
Measured
Simulated
7/25/05
7/28/05
7/31/05
8/3/05
8/6/05
8/9/05
8/12/05
8/15/05
8/18/05
8/21/05
8/24/05
8/27/05
8/30/05


Downstream Dry Creek
Lone Pine Road
Downstream Osborne Canyon
Stream Temperature (°C)
Stream Temperature (°F)
30
25
20
15
10
5
0
82
77
72
67
62
57
52
47
42
37
32
Measured
Simulated
7/25/05
7/28/05
7/31/05
8/3/05
8/6/05
8/9/05
8/12/05
8/15/05
8/18/05
8/21/05
8/24/05
8/27/05
8/30/05

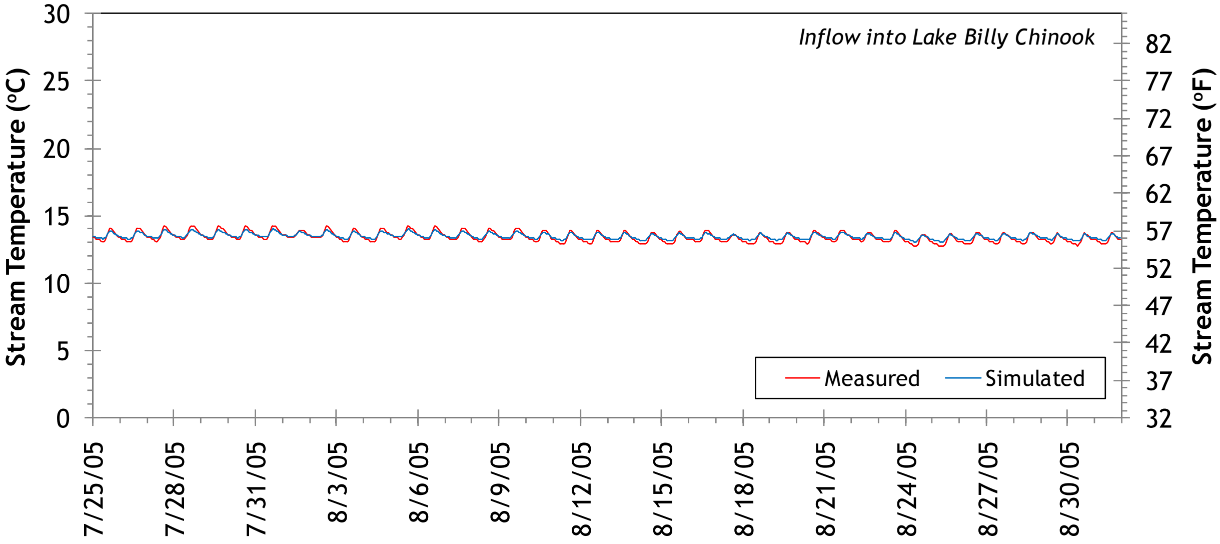


Figure 105 - Crooked River 4.6 stream kilometers from Lake Billy Chinook.

Figure 108 through Figure 112 show the simulated and measured hydraulic parameter values for the Lower Crooked River. The simulated values are from August 6, 2005 when the TIR data was collected. The measured values were collected on August 5, 6, and 11, 2005. Daily gage data was available for the Prineville dam outlet. Table 32 on the next page summarizes the inflow assumptions used for the simulation.

Figure 106 - Lower Crooked River simulated and measured flow volumes.

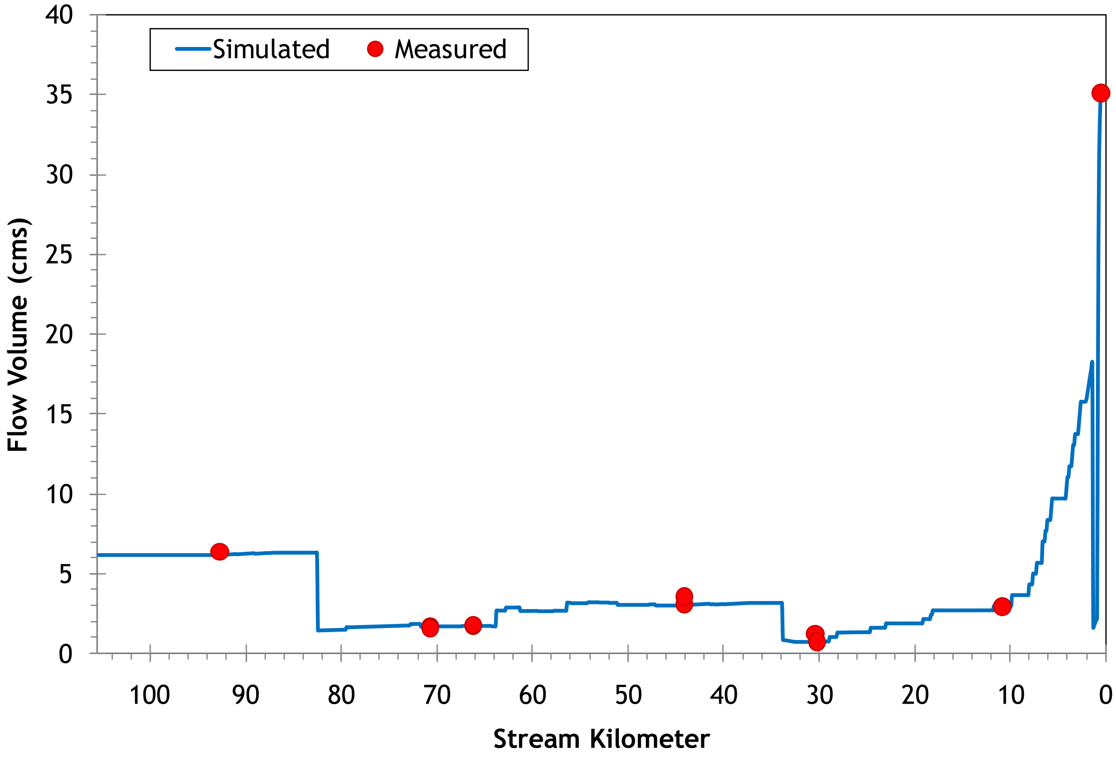


Table 34 - Lower Crooked River inflows.

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
Gaining Reach	92.65-87.05	Mass Balance	Estimated at 12°C
Withdrawal	90.95	Estimated at 0.7 cfs	NA
Withdrawal	89.05	Estimated at 1.4 cfs	NA
Withdrawal	87.75	Estimated at 0.4 cfs	NA
Baldwin / OID Diversion	82.5	BOR (daily)	NA
Gaining Reach	82.45-72.3	Mass Balance	Estimated at 12°C
Irrigation Return (RB)	79.5	Mass Balance	TIR
Withdrawal	79.4	Estimated at 0.5 cfs	NA
Baldwin Ditch Return	72.8	Mass Balance	TIR
People's ID	71.7	OWRD Estimate	NA
People's ID spill	70.3	OWRD Estimate	TIR
People's ID spill	67.35	OWRD Estimate	TIR
Withdrawal	64.25	Estimated at 1.0 cfs	NA
Ochoco Creek (RB)	63.75	DEQ	DEQ
McKay Creek (RB)	62.8	DEQ	DEQ
Crooked Central Diversion	61.25	OWRD Estimate	NA
Withdrawal	59.4	Estimated at 0.7 cfs	NA
Elliot Slough	57.75	Mass Balance	TIR
OID return #1	57.55	Mass Balance	TIR

Flow Input	Simulation Km	Flow Data Source	Temperature Data Source
OID return #2	57.15	Mass Balance	TIR
Lytle Creek (RB)	56.35	Mass Balance	TIR
Withdrawal	55.95	Estimated at 1.0 cfs	NA
OID main return	54.15	OID Estimate	TIR
Withdrawal	52.95	Estimated at 0.5 cfs	NA
Withdrawal	52.0	Estimated at 0.7 cfs	NA
Central canal return #3	51.05	Mass Balance	TIR
Withdrawal	51.05	Estimated at 8.0 cfs	NA
McAllister Slough (LB)	47.75	Mass Balance	TIR
Withdrawal	47.1	Estimated at 2.5 cfs	NA
Dry Canyon @ mouth/return flow	44.3	OWRD Estimate	USFS
Gaining Reach	44.0-37.3	Mass Balance	Estimated at 18°C
Withdrawal	41.35	Estimated at 1.5 cfs	NA
Withdrawal	40.9	Estimated at 0.7 cfs	NA
Withdrawal	40.0	Estimated at 0.5 cfs	NA
Primary Lone Pine return flow	37.9	Mass Balance	TIR
North Unit Pump	**33.8**	NUID Daily Record	NA
Spring (LB)	28.9	Mass Balance	TIR
Spring (LB)	28.05	Mass Balance	TIR
Spring (LB)	24.55	Mass Balance	TIR
Spring (RB)	22.95	Mass Balance	TIR
Unnamed Tributary (LB)	19.05	Mass Balance	TIR
Springs (LB)	18.25	Mass Balance	TIR
Spring (LB)	18.1	Mass Balance	TIR
Spring (LB)	11.7	Mass Balance	TIR
Spring (LB)	9.8	Mass Balance	TIR
Spring (LB)	7.95	Mass Balance	TIR
Seeps (LB)	7.6	Mass Balance	TIR
Seeps (LB)	7.2	Mass Balance	TIR
Spring (LB)	6.6	Mass Balance	TIR
Spring (LB)	6.55	Mass Balance	TIR
Spring (LB)	6.3	Mass Balance	TIR
Spring (LB)	6.05	Mass Balance	TIR
Spring (LB)	5.65	Mass Balance	TIR
Spring (LB)	5.6	Mass Balance	TIR
Spring (LB)	4.1	Mass Balance	TIR
Spring (LB)	4	Mass Balance	TIR
Spring (LB)	3.75	Mass Balance	TIR
Spring (LB)	3.5	Mass Balance	TIR
Spring (LB)	3.35	Mass Balance	TIR
Spring (LB)	3.2	Mass Balance	TIR
Spring (LB)	2.75	Mass Balance	TIR
Spring (RB)	2.65	Mass Balance	TIR
Spring (LB)	2.55	Mass Balance	TIR
Multiple Springs	1.95-1.25	Mass Balance (99 cfs)	Estimated from TIR at 13°C
Diversion	1.25	Estimated at 600 cfs	NA
Multiple Springs	1.2-0.75	Mass Balance (25 cfs)	Estimated from TIR at 13°C
Multiple Springs	0.7-0.5	Mass Balance (290 cfs)	Estimated from TIR at 13°C
Diversion Return	0.75	Mass Balance	TIR
Opal Spring (RB)	0.7	Mass Balance	TIR

Figure 107 and Figure 108 show the simulated and measured daily flow volumes at two gages. On average, the simulated values were within 6.1% of the Osborne gage and 0.9% of the Opal Springs gage.

Figure 107 - Crooked River simulated and measured flows at the Osborne Canyon gage.

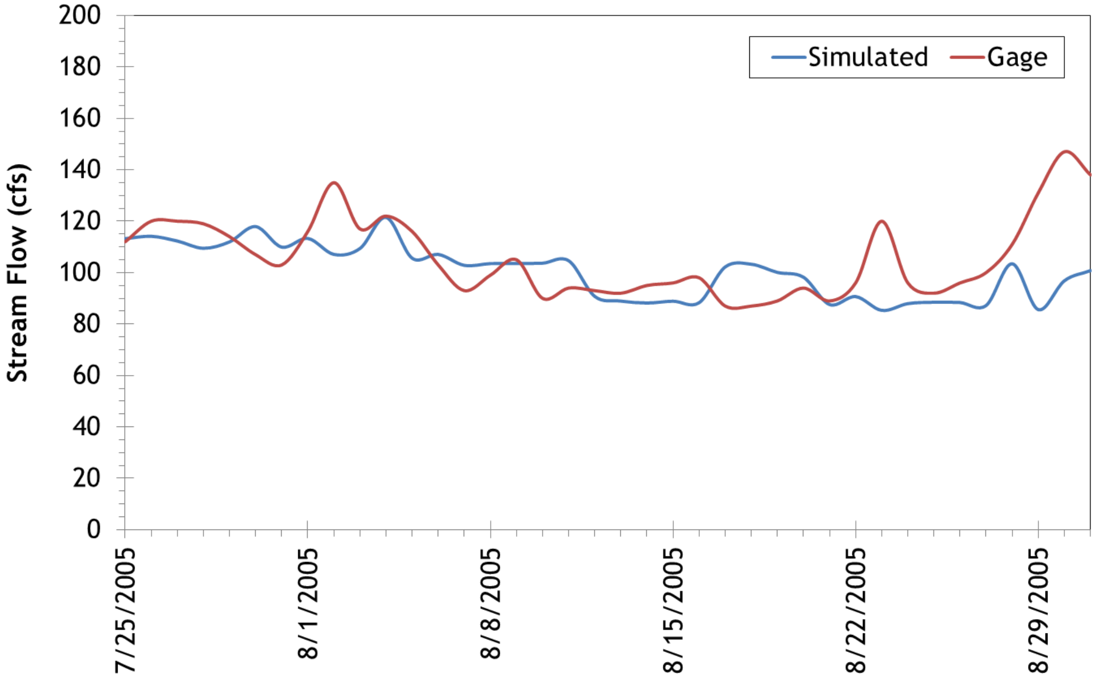


Figure 108 - Crooked River simulated and measured flows at the Opal Springs gage.

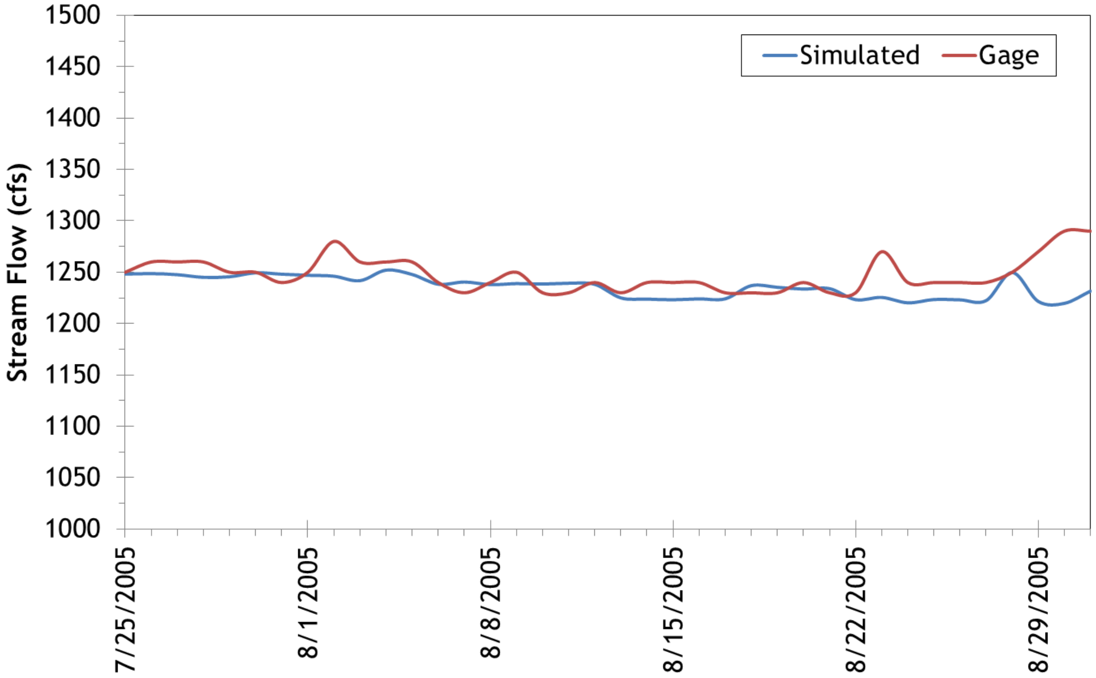


Figure 109 - Lower Crooked River simulated and measured velocities.

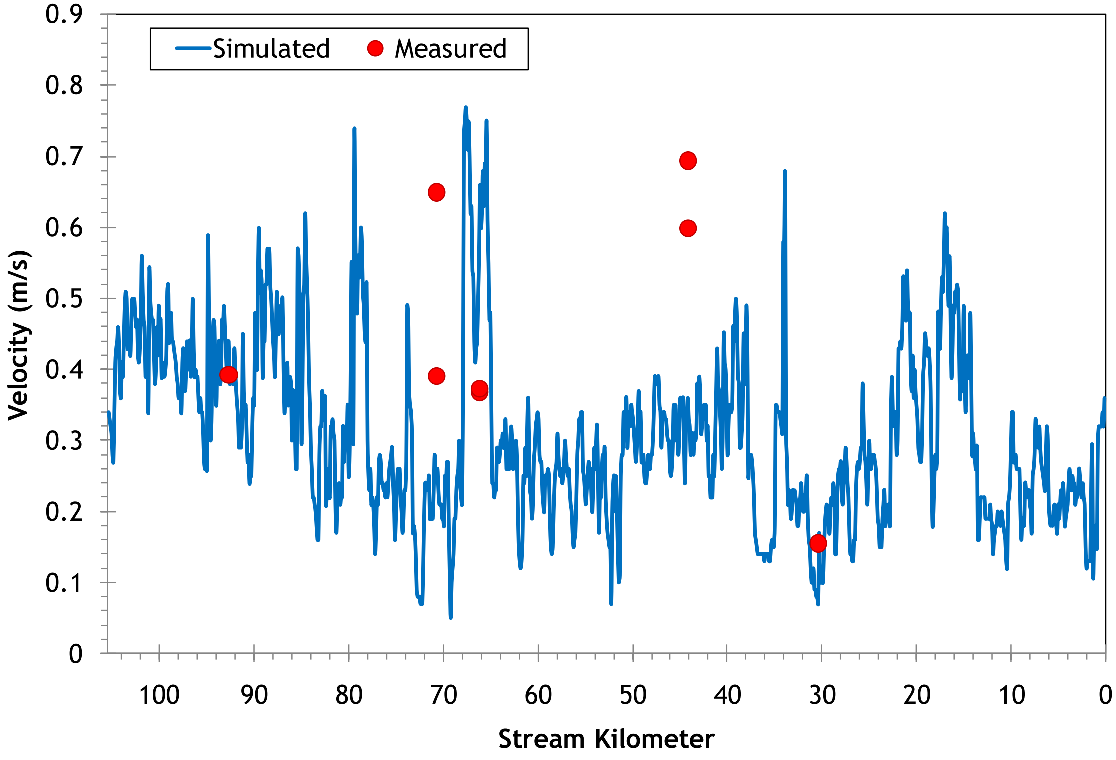


Figure 110 - Lower Crooked River simulated and measured wetted widths.

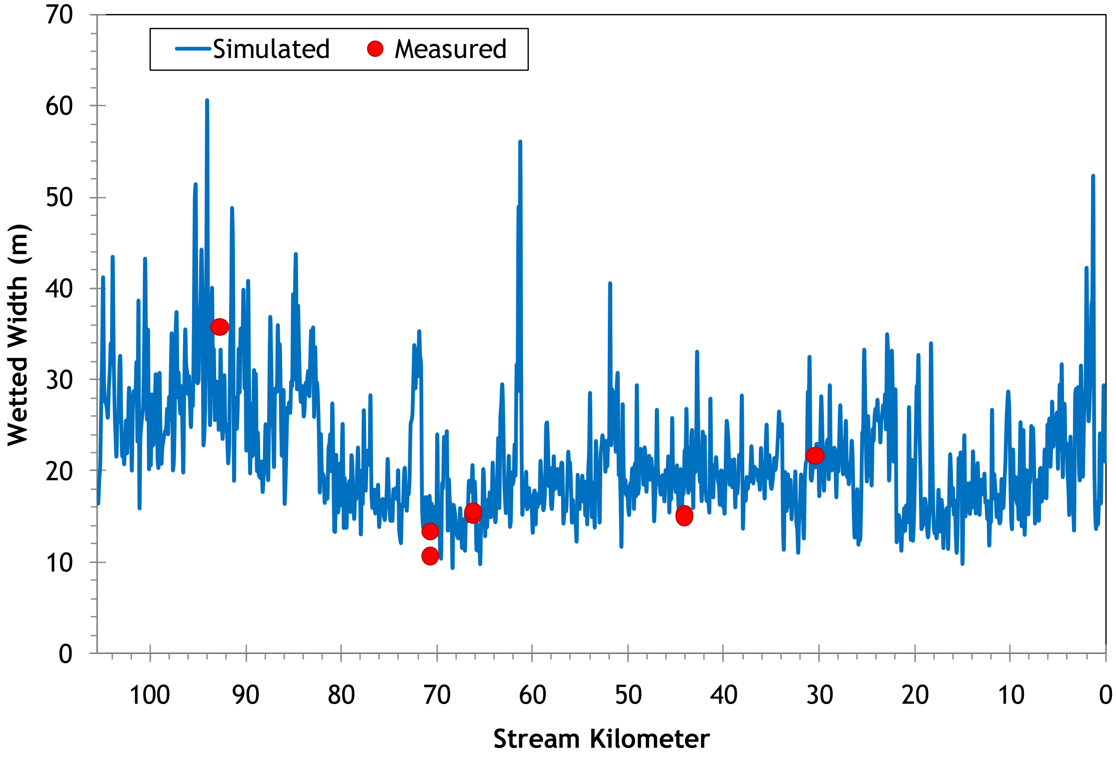


Figure 111 - Lower Crooked River simulated and measured maximum depths.

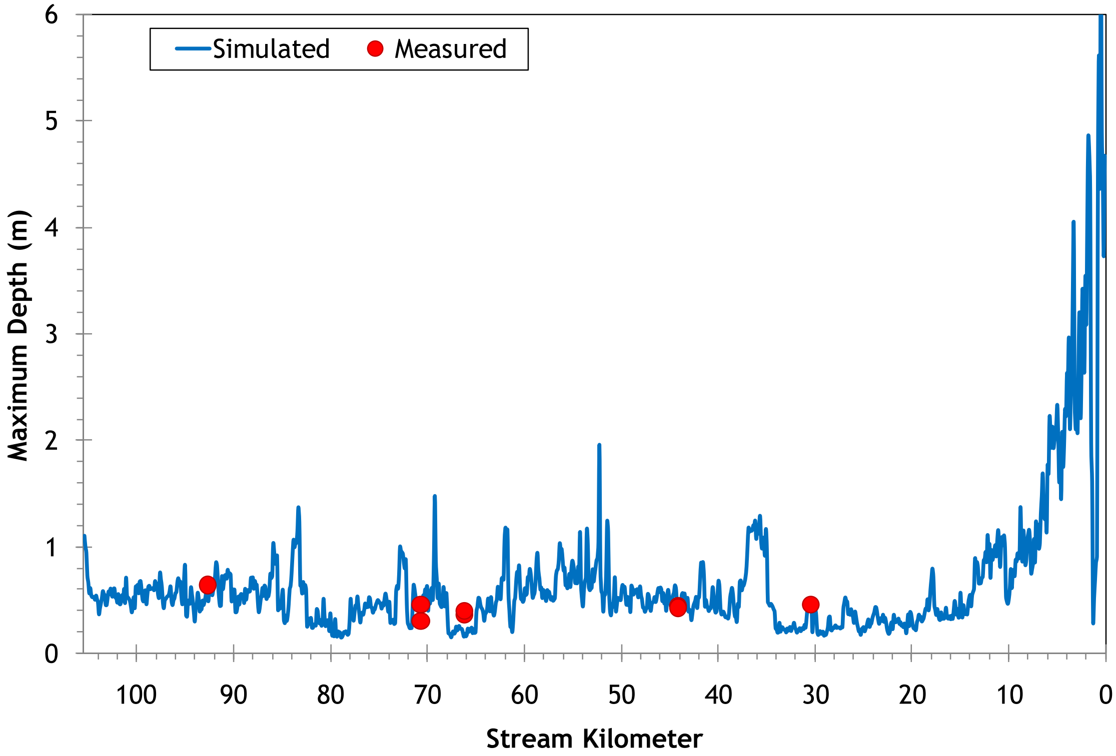


Figure 112 - Lower Crooked River at simulation at stream kilometer 56.

Figure 113 shows the lower Crooked River simulated effective shade. There were no ground level measurements available for this area due to the size of the river and lack of access. Nearly all of the effective shade on the lower Crooked River is the result of topographic features. Below stream kilometer 40, the river flows through a more confined and deep box-shaped canyon. The canyon walls within these lower 40 stream kilometers produce up to 50% effective shade in some areas.

Figure 113 - Lower Crooked River simulated effective shade.

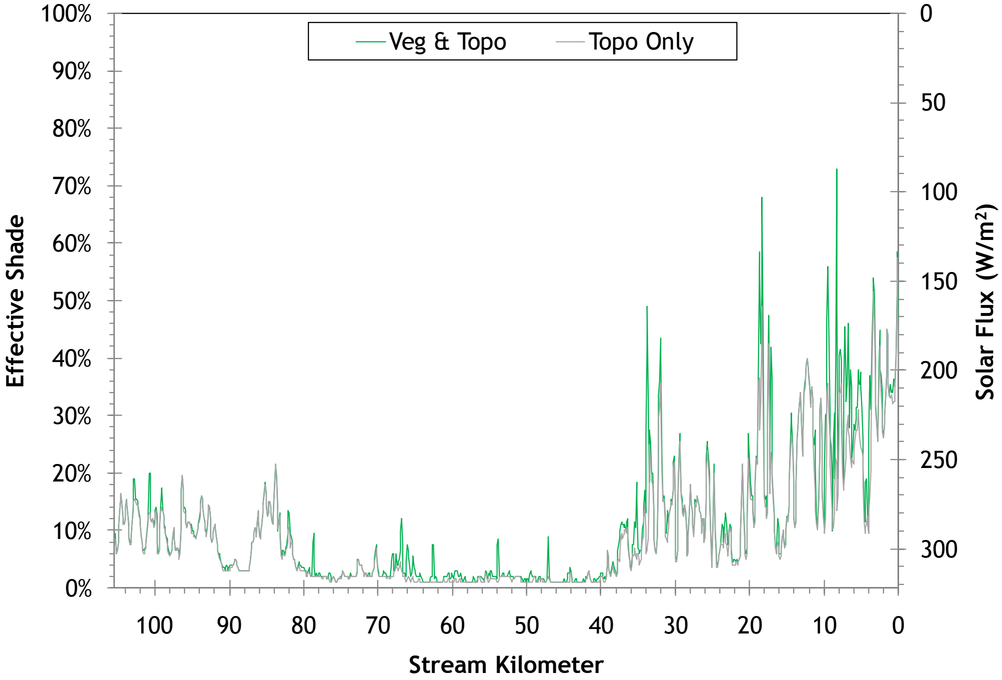


Figure 114 shows the land cover heights sampled from the USGS LiDAR data below Prineville Reservoir.

Figure 114 - Lower Crooked River sampled land cover heights.