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Development of a HEC-RAS Temperature Model for the North Santiam River, Northwestern Oregon

Open-File Report 2015–1006

U.S. Department of the Interior
U.S. Geological Survey

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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2015

Suggested citation:
Stonewall, A.J., and Buccola, N.L., 2015, Development of a HEC-RAS temperature model for the North Santiam River, northwestern Oregon: U.S. Geological Survey Open-File Report 2015-1006, 26 p., *http://dx.doi.org/10.3133/ofr20151006*.

ISSN 2331-1258 (online)

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
square meter (m^2)	0.0002471	acre

SI to Inch/Pound

Multiply	By	To obtain
cubic meter per second	0.3048	meter (m)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations and Acronyms

Name	Description
CE-QUAL-W2	two-dimensional hydrodynamic and water-quality model
MAE	mean absolute error
MAPE	mean absolute percentage error
ME	mean error
RKm	river kilometer
RM	river mile
RMSE	root mean square error
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

A one-dimensional, unsteady streamflow and temperature model (HEC-RAS) of the North Santiam and Santiam Rivers was developed by the U.S. Geological Survey to be used in conjunction with previously developed two-dimensional hydrodynamic water-quality models (CE-QUAL-W2) of Detroit and Big Cliff Lakes upstream of the study area. In conjunction with the output from the previously developed models, the HEC-RAS model can simulate streamflows and temperatures within acceptable limits (mean error [bias] near zero; typical streamflow errors less than 5 percent; typical water temperature errors less than 1.0 °C) for the length of the North Santiam River downstream of Big Cliff Dam under a series of potential future conditions in which dam structures and/or dam operations are modified to improve temperature conditions for threatened and endangered fish. Although a two-dimensional (longitudinal, vertical) CE-QUAL-W2 model for the North Santiam and Santiam Rivers downstream of Big Cliff Dam exists, that model proved unstable under highly variable flow conditions. The one-dimensional HEC-RAS model documented in this report can better simulate cross-sectional-averaged stream temperatures under a wide range of flow conditions.

The model was calibrated using 2011 streamflow and temperature data. Measured data were used as boundary conditions when possible, although several lateral inflows and their associated water temperatures, including the South Santiam River, were estimated using statistical models. Streamflow results showed high accuracy during low-flow periods, but predictions were biased low during large storm events when unmodeled ephemeral tributaries contributed to the actual streamflow. Temperature results showed low annual bias against measured data at two locations on the North Santiam River and one location on the Santiam River. Mean absolute errors using 2011 hourly data ranged from 0.4 to 0.7 °C. Model results were checked against 2012 data and showed a positive bias at the Santiam River station (+0.6 ˚C). Annual mean absolute errors using 2012 hourly data ranged from 0.4 to 0.8 °C.

Much of the error in temperature predictions resulted from the model's inability to accurately simulate the full range of diurnal fluctuations during the warmest months. Future iterations of the model could be improved by the collection and inclusion of additional streamflow and temperature data, especially near the mouth of the South Santiam River. Presently, the model is able to predict hourly and daily water temperatures under a wide variety of conditions with a typical error of 0.8 and 0.7 °C, respectively.

Introduction

The Detroit and Big Cliff Dams were constructed by the U.S. Army Corps of Engineers (USACE) on the North Santiam River; both dams were completed in 1953. The authorized primary purposes of the dams include flood risk management, hydropower, irrigation, water-quality improvement, recreation, and fish and wildlife habitat. Big Cliff Dam is a "re-regulating" dam that attenuates the highly variable flows from Detroit Dam caused by fluctuations during power generation.

The completion of the dams altered the natural hydrologic and thermal regime downstream. Winter streamflow peaks are smaller and summer streamflows are larger compared to pre-dam conditions. Water releases from the dams typically are cooler in spring and early summer, and warmer in the late summer and early fall, although since 2007, USACE has made operational modifications to minimize those thermal changes. The dams affect water temperatures for many miles downstream (Rounds, 2010).

The North Santiam River and some of its tributaries provide habitat for Upper Willamette River winter steelhead (*Oncorhynchus mykiss*) and Chinook salmon (*Oncorhynchus tshawytscha)*. To protect these fish during important life stages, the Oregon Department of Environmental Quality has set standards for maximum water temperatures of specific stream reaches, including the North Santiam and Santiam Rivers.

Previous modeling efforts have focused on determining how changes in dam operations and (or) changes to the elevation of water release points at Detroit Dam will affect temperatures directly downstream of Big Cliff Dam (Buccola and others, 2012). Although a two-dimensional hydrodynamic flow and temperature model (CE-QUAL-W2) was developed by Sullivan and others (2004) for the North Santiam and Santiam Rivers, the model proved inadequate under certain flow conditions because of numeric instabilities and excessive model run-times. This led to the development of a simpler, one-dimensional flow and temperature model alternative for this river reach using the HEC-RAS model (U.S. Army Corps of Engineers, 2008). Use of this HEC-RAS model will make it possible to estimate the thermal effects of hypothetical dam operations and structures at Detroit and/or Big Cliff Dams farther downstream in the North Santiam River Basin under a wide range of conditions.

Purpose and Scope

To inform operational and structural planning at Detroit and Big Cliff Dams, the USACE asked the U.S. Geological Survey (USGS) to assist with temperature modeling in the North Santiam River Basin. The purpose of this report is to document the calibration and development of a HEC-RAS temperature model of the North Santiam and Santiam Rivers. The model can be used to predict temperatures in the North Santiam River from the outlet of Big Cliff Dam, through the confluence with the South Santiam River, to near the mouth of the Santiam River. Model results are intended for use in conjunction with previously developed temperature models of Detroit and Big Cliff Lakes (Sullivan and others, 2007; Buccola and others, 2012) and allow hypothetical changes at Detroit Dam to be simulated downstream and assessed at points along the North Santiam and Santiam Rivers. The intended use of the model will be to evaluate the downstream impact of changes in streamflow and temperature released from the Big Cliff and Detroit Dams. The HEC-RAS temperature model was calibrated using 2011 data and independently tested using 2012 data.

Background

Study Area

The North Santiam River is located in northwestern Oregon (fig. 1), with headwaters in the Cascade Range near Duffy Lake. From there, the river flows generally northwestward to Detroit Lake, which is impounded by Detroit Dam. Streamflow is then re-regulated about 3 mi (5 km) downstream at Big Cliff Dam. From there, the North Santiam River flows generally westward until reaching its confluence with the Santiam River (around river mile 12 or river kilometer 19) near Jefferson, Oregon.

The Santiam River continues to the northwest, where it flows into the Willamette River just south of Salem, Oregon. The North Santiam River has one large tributary, the Little North Santiam River, and several smaller tributaries including Rock and Bear Branch Creeks. Important municipal and agricultural withdrawals occur near the city of Stayton, Oregon.

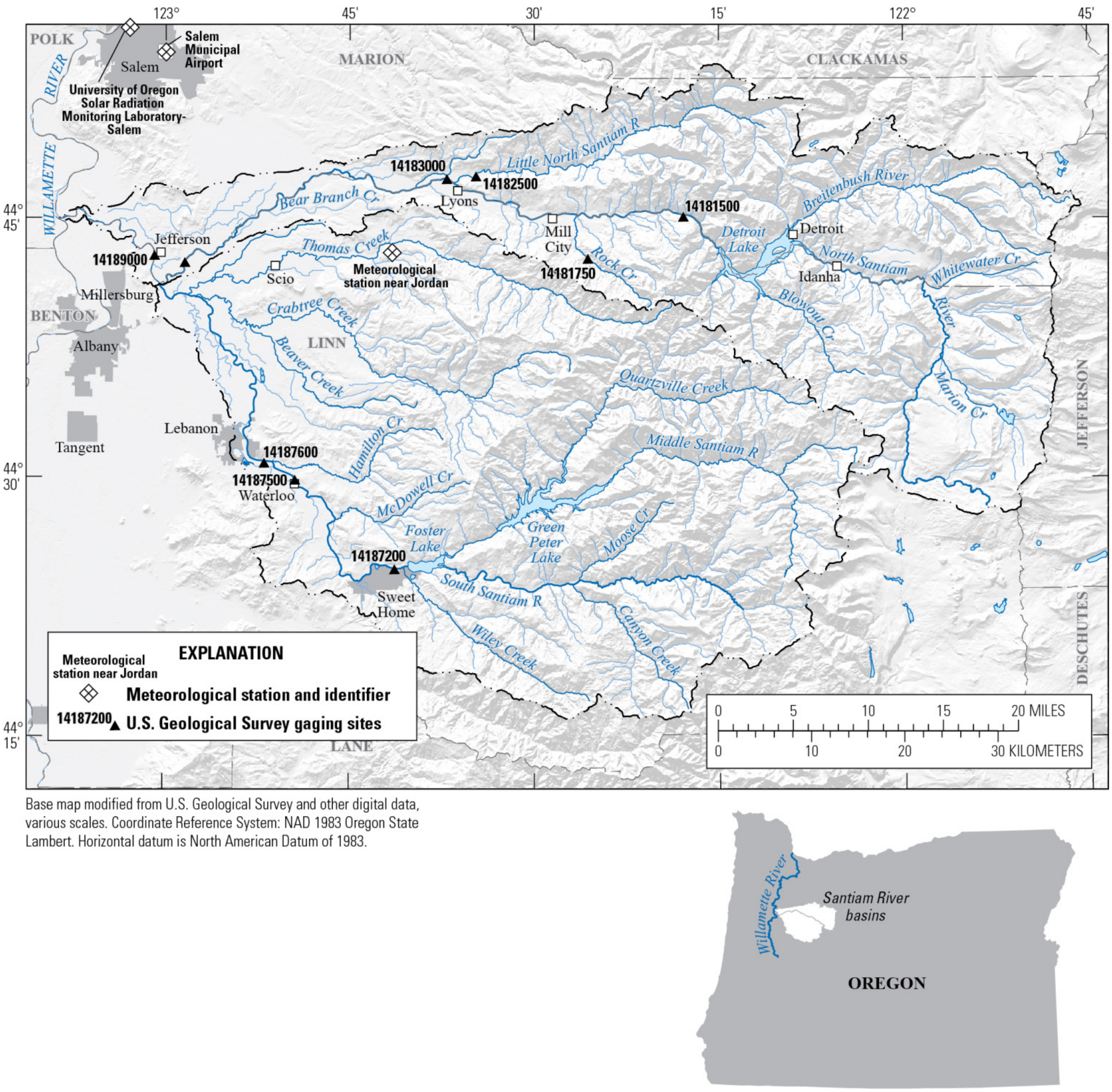

Figure 1. Santiam River Study area, northwestern Oregon.

The North Santiam, South Santiam, and Santiam Rivers drain 734 mi^2 (1,903 km^2), 1,040 mi^2 (2,696 km^2), and 1,810 mi^2 (4,692 km^2) at their respective mouths (U.S. Geological Survey, 2013a). The Santiam River Basin has a temperate, marine climate with warm, dry summers and cool, wet winters. Mean precipitation in the Santiam River Basin is 78.2 in. (199 cm) (U.S. Geological Survey, 2013a). Seventy-one percent of the Santiam River Basin is forested. The basin area is 1.8 percent urban and 0.4 percent impervious. North Santiam River Basin characteristics are similar to those for the entire Santiam River Basin (78 percent forest, 1.6 percent urban, 0.3 percent impervious).

Methods and Data

Model Description

The North Santiam River model was created using HEC-RAS, version 4.1.0 (U.S. Army Corps of Engineers, 2008). HEC-RAS is a one-dimensional hydraulic model developed by the USACE at the Hydrologic Engineering Center (HEC). The model allows for steady and unsteady river hydraulics calculations, water temperature estimation, and sediment transport-mobile bed modeling (U.S. Army Corps of Engineers, 2014). The HEC-RAS water quality computational module is run separately, but uses output from the hydraulic model. Development and calibration of a HEC-RAS model consists of three steps:

1. Development of river bathymetry and geometric data,
2. Compiling or estimating boundary conditions, and
3. Calibration of streamflow, water elevation, and water temperature.

Development of Bathymetry and Geometric Data

Bathymetric data were derived from an existing CE-QUAL-W2 model of the North Santiam River (Sullivan and Rounds, 2004). Bathymetric data in CE-QUAL-W2 are configured in layers (vertical grid direction) and segments (longitudinal flow direction) and can be described by location, cell width, cell slope and orientation, and cell height. HEC-RAS river bathymetry was developed using upstream, bottom edge points of each individual CE-QUAL-W2 cell and interpolating to the bottom edge points of each consecutive layer, creating a HEC-RAS cross section at the most upstream point of each CE-QUAL-W2 segment.

The process of constructing the HEC-RAS cross-sectional shape from the CE-QUAL-W2 cell geometries is best illustrated with a hypothetical example (fig. 2). In this example, the *x*, *y*, and *z* coordinates of the right bank of cell *A* can be determined using the latitude, longitude, and elevation of the center of cell *A*, and then applying a correction based on the orientation and width of the cell. The left bank of cell *A* can then be determined using the same procedure in the opposite direction. The banks of cell *B* are then determined by extending the distance from the center of the cell and adding the height of cell *A* to the determined elevation. The process is repeated until cell *F* is reached, after which the center of the next (downstream) cell *A* is determined using slope, orientation and reach length, and the process repeated.

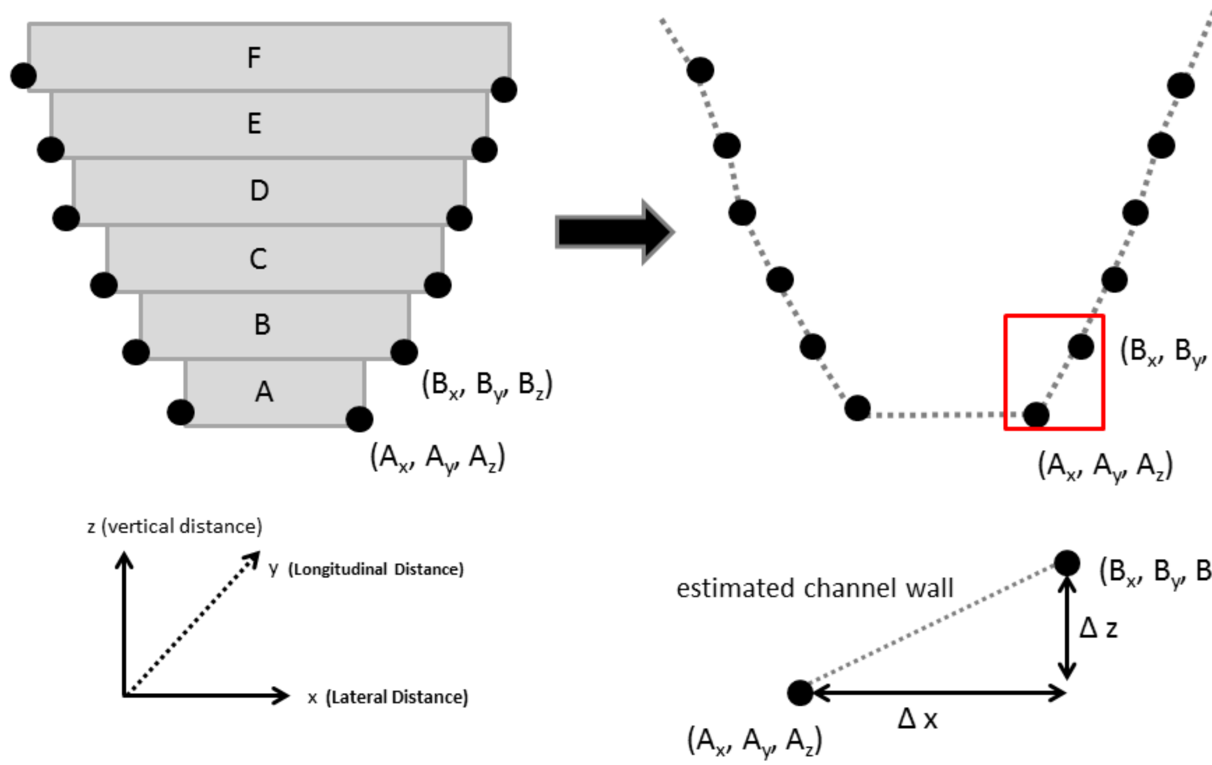

Figure 2. Example showing conversion of CE-QUAL-W2 model bathymetry to HEC-RAS model bathymetry.

Calculated HEC-RAS stream widths at 1 m of depth were compared against a database of stream widths between Big Cliff Dam and the Greens Bridge streamgage acquired by the USGS in the summer of 2002 (U.S. Geological Survey, 2013b). After calibration (see section, "Model Calibration") the HEC-RAS model was run at the same streamflow as those observed during width collection in 2002 (summer low flow). Measured stream widths showed more variability than the model stream widths (standard deviations of 15.3and 12.6 m, respectively). The average model stream width was within 2 percent of the average measured stream width. These results suggest that the model represents average stream widths well, but underrepresents stream width variability.

Streamflow

When possible, boundary conditions and lateral inflows were based on measured data (table 1, fig. 3). When measured data were not available, streamflow values were estimated using regression techniques from overlapping data periods prior to 2011, or as noted. For calendar year 2011, measured streamflow data for upstream boundary inputs were available at North Santiam River at Niagara (USGS streamgage 14181500) and the Little North Santiam River near Mehama (14182500). Other inputs were estimated as follows.

Table 1. Hydrological and meteorological stations in and near the Santiam River Basin, used for this study.

[Gaps in period of record are not denoted

USG stream gages					**Period of record**	
USGS ID	**Name**	**Abbreviated name**	**Lat**	**Long**	**Streamflow**	**Temperature**
14181500	North Santiam River at Niagara, OR	Niagra	44.75	-122.30	1905–2014	1953–2014
14181750	Rock Creek near Mill City, OR	Rock Creek	44.71	-122.43	2005–2008	2005–2009
14182500	Little North Santiam River near Mehama, OR	Little North Santiam	44.79	-122.58	1931–2014	2000–2014
14183000	North Santiam River at Mehama, OR	Mehama	44.79	-122.62	1905–2014	2000–2014[1]
14184100	North Santiam River at Greens Bridge, near Jefferson, OR	Greens Bridge	44.71	-122.97	1964–2014	1985–2014
14187200	South Santiam River near Foster, OR	Foster	44.41	-122.69	1973–2014	1973–2014
14187500	South Santiam River at Waterloo, OR	Waterloo	44.50	-122.82	1905–2014	1963–2014[2]
14187600	Lebanon Santiam Canal near Lebanon, OR	Lebanon Canal	44.51	-122.86	1992–2014	none
14189000	Santiam River at Jefferson, OR	Jefferson	44.71	-123.01	1907–2014	1963–2014[3]

Other stations	**Name**	**Abbreviated name**	**Lat**	**Long**
	Meteorological station near Jordan, OR	Jordan	44.72	-122.69
	University of Oregon Solar Radiation Monitoring Laboratory- Salem	UOSRML	44.94	-123.03
	Salem Municipal Airport.	Salem	44.91	-123.00

[1]Temperature period of record for streamgage 14183000 includes data from nearby streamgage 14183010, North Santiam River near Mehama, Oregon.

[2]Temperature data were not collected at streamgage 14187500 from Oct. 1, 2002, until Oct. 27, 2013.

[3]Temperature period of record for station 14189000 includes data from nearby station 14189050, Santiam River near Jefferson, Oregon.

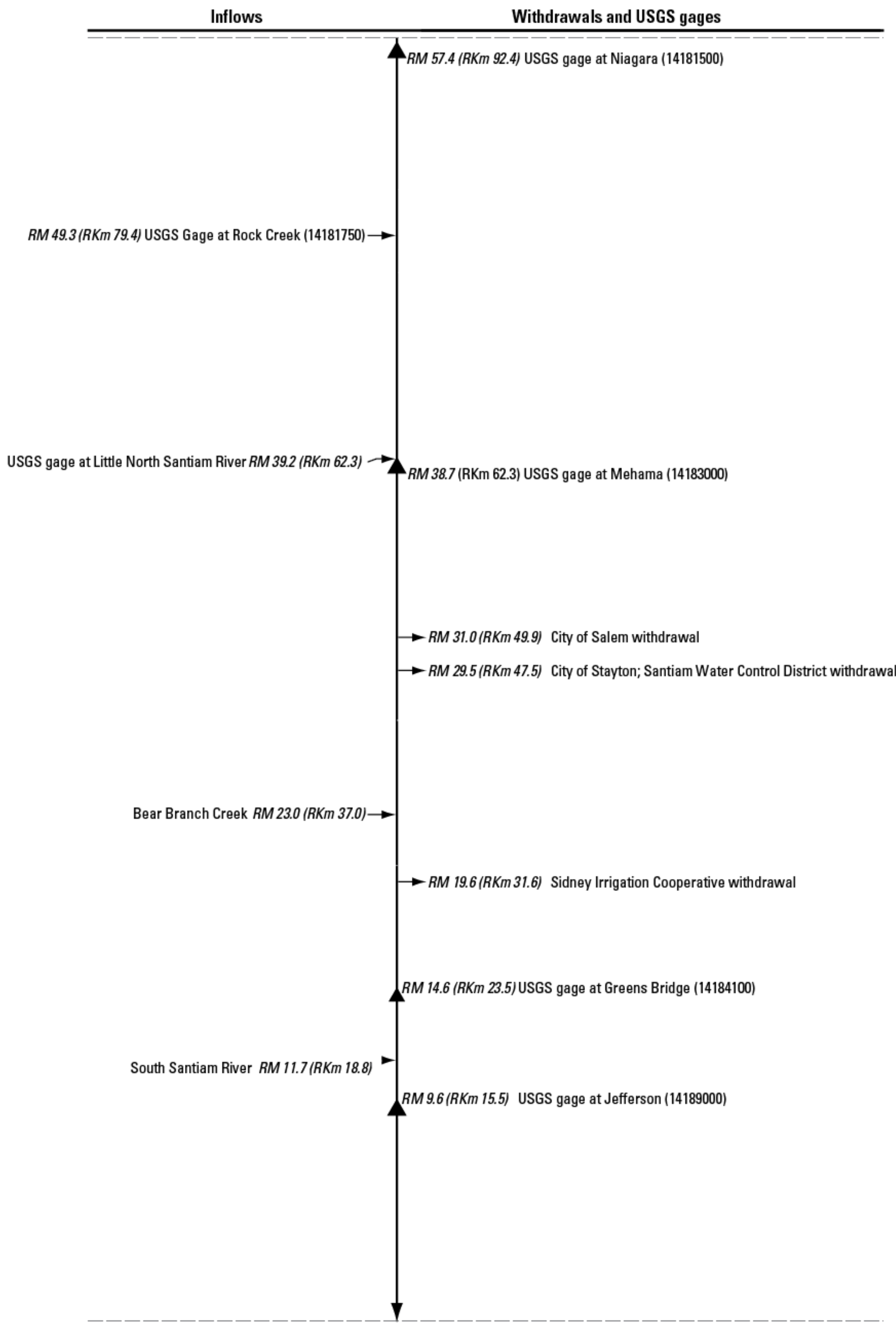

Figure 3. Locations of point-source and tributary inflows, withdrawals and USGS streamgages.

Bear Branch Creek

Streamflow at the mouth of Bear Branch Creek was estimated using the following equation:

$$Q_{BB} = 0.584 * Q_{LNS} \quad (1)$$

where:
Q_{BB} is the streamflow at Bear Branch Creek, in cubic meters per second, and
Q_{LNS} is the streamflow at Little North Santiam streamgage (14182500), in cubic meters per second

Rock Creek

Streamflow at the mouth of Rock Creek was estimated using the following equations:

$$Q_{RCL} = Q_{LNS} * 0.037 + 2.28 \quad (2)$$

$$Q_{RCH} = Q_{LNS} * 0.128 - 14.7 \quad (3)$$

$$\text{If } Q_{LNS} \leq 200 \text{ m}^3\text{/s, then } Q_{RC} = Q_{RCL} \quad (4)$$

$$\text{If } Q_{LNS} \geq 1{,}000 \text{ m}^3\text{/s, then } Q_{RC} = Q_{RCH} \quad (5)$$

$$\text{If } 200 \text{ m}^3\text{/s} < Q_{LNS} < 1{,}000 \text{ m}^3\text{/s, then } Q_{RC} = (Q_{LNS}\text{-}200)/800*(Q_{RCH})+ (1{,}000\text{-}Q_{LNS})/800*(Q_{RCL}) \quad (6)$$

where:
Q_{LNS} is the streamflow at Little North Santiam, in cubic meters per second,
Q_{RCL} is the streamflow at Rock Creek during low-flow conditions, in cubic meters per second,
Q_{RCH} is the streamflow at Rock Creek during high-flow conditions, in cubic meters per second, and
Q_{RC} is the final estimated streamflow at Rock Creek, in cubic meters per second.

Mean absolute percentage error (MAPE) for this regression equation is 32 percent. Errors tended to be highest (both MAPE and root mean-squared error [RMSE]) during flood events.

South Santiam River

Streamflow at the mouth of the South Santiam River was estimated using the following equation:

$$Q_{SSM} = Q_{SSW} * 1.23 - Q_{LSC} \quad (7)$$

where:
Q_{SSM} is the streamflow at mouth of the South Santiam River, in cubic meters per second,
Q_{SSW} is the streamflow at the South Santiam River at Waterloo streamgage (USGS 14187500), in cubic meters per second, and
Q_{LSC} is the streamflow at the Lebanon-Santiam Canal, in cubic meters per second.

Municipal Withdrawals

Municipal withdrawals at three locations, river mile 31.0 (rkm 49.9), 29.5 (rkm 47.5) and 19.6 (rkm 31.6), were estimated by the Oregon Water Resources Department and used without further modification.

Temperature

When possible, temperature was simulated using measured data as boundary conditions. USGS temperature data typically are collected at well-mixed sections, and checked for lateral variation at least twice a year. Consequently, temperatures were assumed well-mixed at recorded cross sections, and not corrected. When measured data were not available, temperature values were estimated using regression techniques, or as noted. For calendar year 2011, measured temperature data were available at the North Santiam River at Niagara streamgages. Measured temperature data were used from the Little North Santiam River near Mehama streamgage, with a monthly warming rate adjustment applied to water temperature data to account for thermal differences between the streamgage and the mouth of the river. Rounds (2010) documented a maximum summertime warming rate of 0.11 °C/mi for streams in the Willamette River Basin. Little North Santiam River and other temperature inputs were estimated as follows:

Rock Creek

Water temperature at the mouth of Rock Creek was estimated using the equation:

$$T_{RC} = 10^{(\log(TNS)*0.829+0.070} + 3.3\text{ miles} * WR \quad (8)$$

where:
T_{LNS} is the temperature at the Little North Santiam River streamgage, in degrees Celsius,
T_{RC} is the temperature at the mouth of Rock Creek, in degrees Celsius,
WR is the warming rate, in degrees Celsius per mile, using the following rates:

January: 0.02 ˚C/mi
February: 0.05 ˚C/mi
March: 0.07 ˚C/mi
April: 0.08 ˚C/mi
May: 0.09 ˚C/mi
June–September: 0.11 ˚C/mi
October: 0.09 ˚C/mi
November: 0.05 ˚C/mi
December: 0.02 ˚C/mi

Little North Santiam River

Temperature at the mouth of the Little North Santiam River was estimated using the following equation:

$$T_{LNSM} = T_{LNS} + 2.0\ miles * WR \tag{9}$$

where:

T_{LNSM} is the temperature at the mouth of the Little North Santiam River, in degrees Celsius,
T_{LNS} is the temperature at USGS streamgage 14182500 on the Little North Santiam River, in degrees Celsius,
WR is the warming rate, in degrees Celsius per mile, which is identical to the rate used for Rock Creek.

Bear Branch Creek and Municipal Withdrawals

Temperature data for Bear Branch Creek and all municipal withdrawals were not available, and were assigned to be identical to those at the mouth of the Little North Santiam River. (Withdrawals were represented as negative inflow hydrographs in HEC-RAS, and needed an accompanying temperature hydrograph).

South Santiam River

Water temperature at the mouth of the South Santiam River was estimated using the following equations:

$$T_{SSmin} = T_{SSF} + 0.4 * ((0.14 * T_{SSFmin} - 0.67)) \tag{10}$$

$$T_{SSMmean} = T_{SSF} + 0.4 * ((0.22 * T_{SSFmeam} - 1.04)) \tag{11}$$

$$T_{SSmax} = T_{SSF} + 0.4 * ((0.32 * T_{SSFmax} - 2.00)) \tag{12}$$

$$If, T_{SSF} = T_{SSFmin}; then\ T_{SSM} = T_{SSMmin} \tag{13}$$

$$If, T_{SSFmin} < T_{SSF} < T_{SSFmean}; then\ T_{SSM} = T_{SSMmin} + (T_{SSMmean} - T_{SSMmin}) \frac{T_{SSF} - T_{SSFmin}}{T_{SSFmean} - T_{SSFmin}} \tag{14}$$

$$If, T_{SSF} = T_{SSFmean}; then\ T_{SSM} = T_{SSMmean} \tag{15}$$

$$If, T_{SSFmean} < T_{SSF} < T_{SSFmax}; then\ T_{SSM} = T_{SSMmean} + (T_{SSMmax} - T_{SSMmean}) \frac{T_{SSF} - T_{SSFmean}}{T_{SSFmax} - T_{SSFmean}} \tag{16}$$

$$T_{SSFmax}; then\ T_{SSM} = T_{SSMmax} \tag{17}$$

where:

T_{SSMmin} is the daily minimum temperature at the mouth of the South Santiam River, in degrees Celsius,
$T_{SSMmean}$ is the daily mean temperature at the mouth of the South Santiam River, in degrees Celsius,
T_{SSMmax} is the daily maximum temperature at the mouth of the South Santiam River, in degrees Celsius,
T_{SSF} is the measured subdaily temperature of the South Santiam River at Foster, in degrees Celsius,
T_{SSFmin} is the daily minimum temperature of the South Santiam River at Foster, in degrees Celsius,
$T_{SSFmean}$ is the daily mean temperature of the South Santiam River at Foster, in degrees Celsius, and
T_{SSFmax} is the daily maximum temperature of the South Santiam River at Foster, in degrees Celsius.

Time of travel was not considered in this analysis. In other words, it was assumed that the maximum and minimum South Santiam River water temperature values occurred at the same time at both locations (Foster streamgage and mouth) and that the general patterns in water temperature were identical at both locations.

Meteorological Data

Water temperature simulation using HEC-RAS requires time series of atmospheric pressure, air temperature, humidity, short-wave solar radiation, cloudiness, and wind speed. In HEC-RAS, meteorological data can be associated with one or multiple station locations around the basin. Each cell of the HEC-RAS model then can be assigned to a specific meteorological station, or assigned automatically based on distance to the nearest meteorological station.

Initially, meteorological time series in the constructed model were allocated to one of three locations—the upper basin at Detroit Dam, the middle of the basin near the Jordan meteorological station, and the lower basin near the Salem Airport. Specific meteorological time series (for example, solar radiation and wind speed) not available at one location were copied from the nearest station.

Subsequent investigations found that specific meteorological time series were not necessarily representative of the surrounding region. For example, whereas most of the upper North Santiam River is moderately narrow, with large buffers of trees on either side, wind speeds recorded at Detroit Dam may be more indicative of the open space around the dam. Consequently, the three meteorological datasets were consolidated into one dataset for the most centralized location of the three stations (Jordan). The sources of data for each meteorological time series are listed in table 2.

Table 2. Meteorological data time series used in the HEC-RAS model of the North Santiam River.

Time series	Location	Source
Atmospheric Pressure	Salem Airport	MESOWEST
Air Temperature	Salem Airport	MESOWEST
Humidity	Jordan weather station	RAWS
Short Wave Radiation	Jordan weather station	RAWS
Cloudiness	Salem Airport	MESOWEST
Wind Speed	Jordan weather station	RAWS
reference-		
MesoWest	http://mesowest.utah.edu/	
RAWS USA Climate Archive	http://www.raws.dri.edu/	

Two of the six time series were modified slightly for use with the model. Short-wave radiation was adjusted using the following equations:

$$\text{If } SWR < 110, SWR = 110 \quad (18)$$

$$\text{If } T_{SWR} < 15{:}00, SWR = SWR * 0.8 \quad (19)$$

$$\text{If } T_{SWR} \geq 15{:}00, SWR = SWR * 0.65 \quad (20)$$

where:

SWR is short-wave solar radiation, in watts per square meter, and

T_{SWR} is the time-of-day of the short-wave radiation measurement using a 24-hour clock, and midnight is represented as 00:00.

These equations moderate the effect of short-wave radiation on stream water temperature. There is no algorithm in HEC-RAS version 4.1.0 to account for vegetative or topographic shading. The two coefficients in equations 19 and 20 are applied to the short-wave radiation time series to mimic shading patterns. Preliminary results indicated that more shading was needed in the afternoon to better match measured stream temperature data. Similarly, the minimum short-wave radiation value of 110 watts per square meter is designed to account for heat sources not accounted for in the HEC-RAS model, such inputs include internal friction, chemical and biological processes, forest radiation, condensation and transfer of sensible heat and the exchange of heat between the river and its bed. Evans and others (1998) showed that up to 24 percent of daily total energy transfer can occur at the channel bed.

Cloudiness data also were adjusted for model use. Cloudiness data are compiled by MesoWest (at *http://mesowest.utah.edu*, accessed July 22, 2013) in three variables representing cloud coverage at three different elevations. The three cloudiness time series were summed into a single time series, which was converted into percentiles (the highest value of the year was rated as 1, the lowest value 0.) Resulting percentiles were entered as cloudiness values between 0 and 1 (the fraction of cloudiness).

Model Calibration

The HEC-RAS model of the North Santiam and Santiam Rivers was calibrated using 2011 data, and the calibrated model was independently tested using 2012 data. 2011 and 2012 were selected for calibration and testing because of the relative abundance of streamflow, water temperature, and meteorological data available for those years.

Streamflow

Streamflow was calibrated by comparing measured streamflow at the Mehama, Greens Bridge, and Jefferson USGS streamgages with modeled streamflow, and adjusting model parameters to minimize the difference between measured and modeled values of streamflow and water temperature. Calibration was an iterative process. Emphasis was placed on achieving the best fit to measured water temperatures during summer and fall (June–November), when streamflow is typically lowest and the river is warmest. Little calibration was necessary, with the exception of the reach downstream of the confluence of the North Santiam and South Santiam Rivers. Streamflow was calibrated by adjusting Manning's n values (final values ranged from 0.03 to 0.07) and adjusting the contributions of ungaged streamflow between the South Santiam River at Waterloo streamgage (14187500) and the mouth of the South Santiam River.

Measured and modeled 2011 streamflow at Mehama, Greens Bridge, and Jefferson are shown in figures 4, 5, and 6, respectively, with goodness-of-fit metrics listed in table 3. In general, model errors increase from periods of low streamflows to periods of high streamflows. Model results typically show a negative bias during periods of high streamflow. This is likely due, at least in part, to under-representation of intermittent and ephemeral streams that are not included in the model. Such streams provide minimal streamflow contribution during low streamflow periods, but collectively can account for considerable streamflow during periods of high streamflow. For example, the drainage area at the Greens Bridge streamgage, as estimated by the USGS, is 736 mi^2 (1,096 km^2). Adding the upstream drainage area at the Niagara streamgage to the three largest tributaries between Niagara and Greens Bridge (Rock Creek, Little North Santiam River, Bear Branch Creek) sums to about 593 mi^2 (1,536 km^2), which is about 81 percent of the drainage area at Greens Bridge. Most, if not all, of these ungaged creeks that represent the remaining 19 percent of the drainage area upstream of Greens Bridge likely contribute little, if any streamflow during the dry summer and early fall. However, during moderate to extreme streamflow events, they likely contribute significant streamflow at the Greens Bridge streamgage. Because this model was designed to estimate streamflow temperatures that occur during periods of low streamflow (summer and fall), no effort was made to account for these ungaged tributaries.

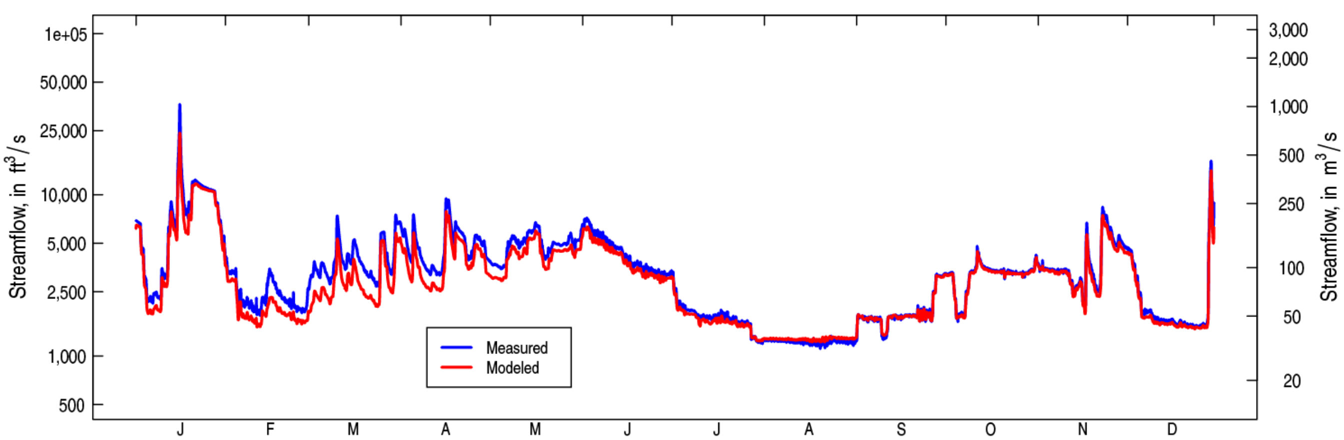

Figure 4. Measured and modeled streamflow in the North Santiam River at Mehama, Oregon (USGS streamgage 14183000), 2011.

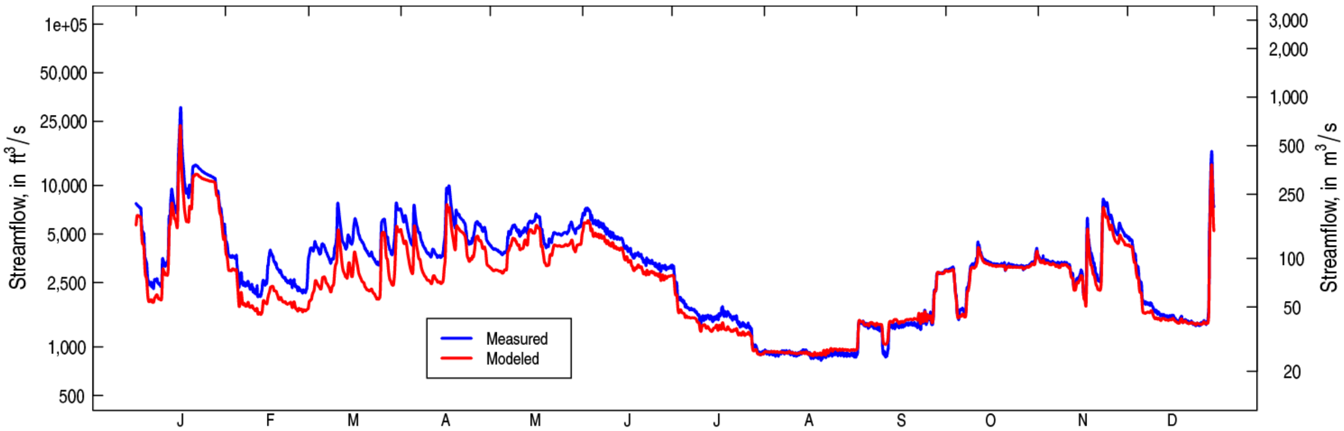

Figure 5. Measured and modeled streamflow in the North Santiam River at Greens Bridge, Oregon (USGS streamgage 14184100), 2011.

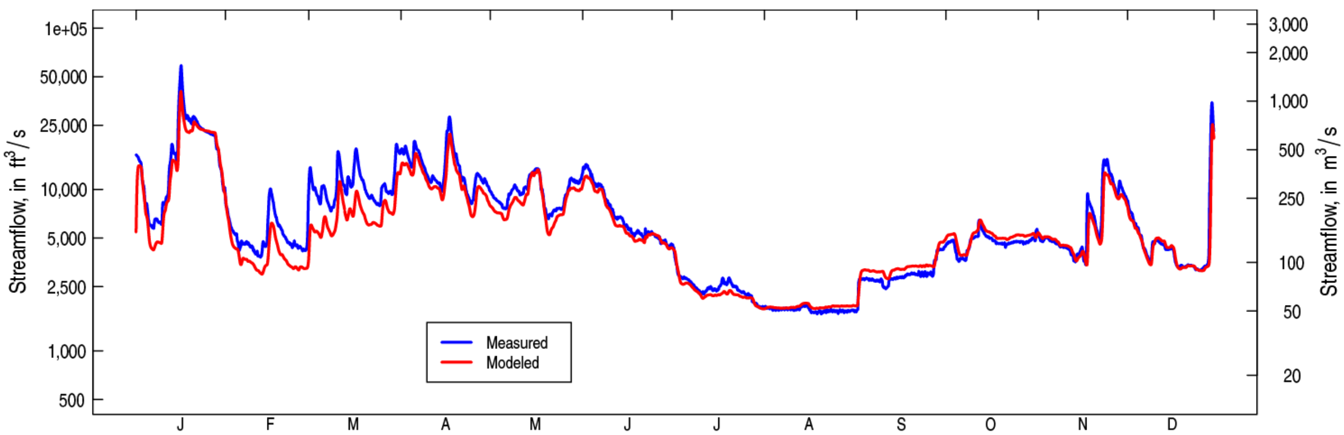

Figure 6. Measured and modeled streamflow in the Santiam River at Jefferson, Oregon (USGS streamgage 14189000), 2011.

Table 3. Goodness-of-fit statistics for modeled hourly North Santiam River streamflows for two periods during the 2011 calibration period.

[Abbreviations: ID, identification number; ME, mean error; MAE, mean absolute error; RMSE, root-mean squared error; MAPE, mean absolute percentage error; m^3/s, cubic meters per second]

Streamgage	USGS ID	ME (m^3/s)	MAE (m^3/s)	RMSE (m^3/s)	MAPE (percent)
Calendar year 2011					
Mehama	14183000	-11.0	11.3	19.1	9.6
Greens Bridge	14184100	-17.5	18.0	27.2	14.7
Jefferson	14189000	-26.7	31.8	57.7	12.4
June– October 2011					
Mehama	14183000	-2.6	3.3	5.4	3.9
Greens Bridge	14184100	-4.9	5.9	9.4	7.6
Jefferson	14189000	1.3	8.1	10.2	7.5

Modeled streamflow during June–November, when water temperatures typically are highest, suggests better agreement with measured values. MAPEs for the three locations during the dry period averaged about 4–8 percent. Mean errors for the three sites during the dry period averaged between about -5 and +1 percent, with sites upstream of the South Santiam River confluence showing a slight negative bias, and the comparison in the South Santiam River at the Jefferson streamgage showing a slight positive bias. Excellent measured streamflow data have an associated measurement error on the order of 5 percent for at least 95 percent of the record (Novak, 1985); therefore, this magnitude of low-flow bias in the model seems to be acceptable and should not greatly affect the water-temperature predictions.

Temperature

Model predictions of water temperature were calibrated for 2011 in a similar manner to streamflow. Measured values at Mehama, Greens Bridge, and Jefferson were compared to modeled values, and model parameters were adjusted to minimize the difference between the two. Adjusted model parameters that had the most effect on temperature values include Manning n values (channel roughness coefficients, which affect time of travel and consequently time of exposure to short-wave solar radiation), and short-wave solar radiation inputs (see section, "Meteorological Data").

A comparison of measured and modeled daily average temperatures for 2011 shows that the model captured the weekly and seasonal patterns in the data relatively well (figs. 7, 8, and 9 for Mehama, Greens Bridge, and Jefferson, respectively), with goodness-of-fit metrics showing a low overall seasonal bias and a mean absolute error less of 0.8 °C or less (table 4). Mean error values are 0.1 °C or less for the calendar year, suggesting little overall bias at all three sites, but a small amount of positive bias is present at the Greens Bridge and Jefferson sites for the warm-water period of June–November (0.3 and 0.2°C, respectively). Mean absolute errors are fairly consistent between the entire calendar year and the warm-water period. The best fit occurred at the most upstream site, Mehama.

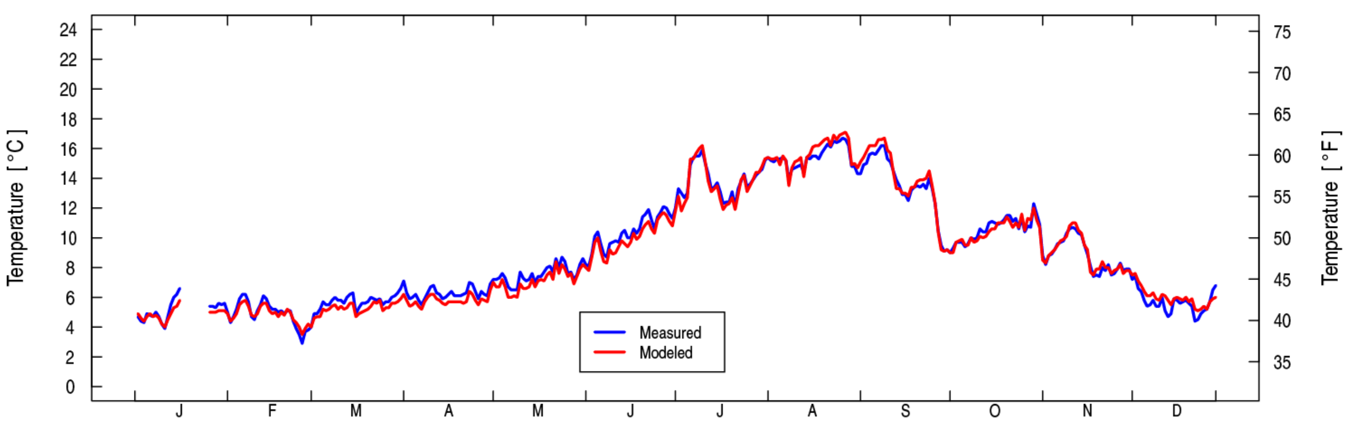

Figure 7. Measured and modeled mean daily values of temperature for the North Santiam River near Mehama, Oregon (USGS streamgage 14183010), 2011.

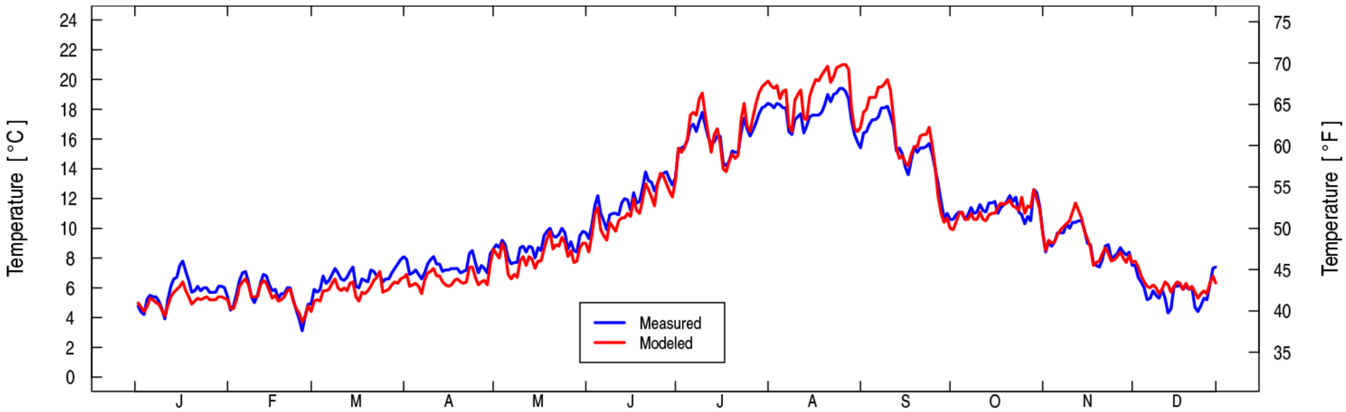

Figure 8. Measured and modeled mean daily values of temperature for the North Santiam River at Greens Bridge, Oregon (USGS streamgage 14184100), 2011.

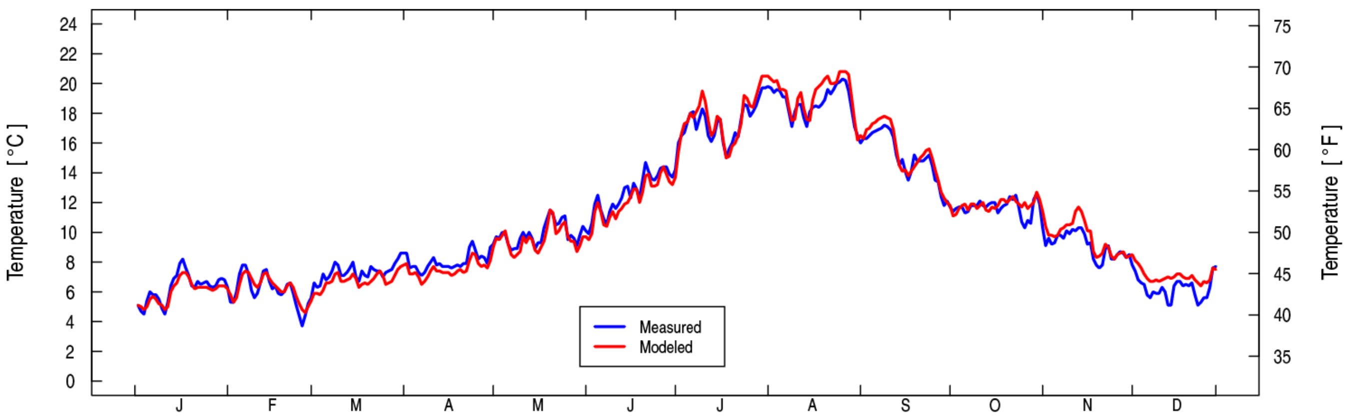

Figure 9. Measured and modeled mean daily values of temperature for the Santiam River near Jefferson, Oregon (USGS streamgage 14189050), 2011.

Table 4. Goodness-of-fit statistics using the modeled hourly temperatures for two periods in 2011.

[Abbreviations: ID, identification number; ME, mean error; MAE, mean absolute error; RMSE, root-mean squared error; MAPE, mean absolute percentage error; ˚C, degrees Celsius]

Streamgage	USGS ID	ME (˚C)	MAE (˚C)	RMSE (˚C)	MAPE (percent)
Calendar year 2011					
Mehama	14183010	-0.1	0.4	0.5	5.3
Greens Bridge	14184100	-0.1	0.7	0.9	7.7
Jefferson	14189050	0.1	0.6	0.7	6.2
June– October 2011					
Mehama	14183010	0.0	0.4	0.5	3.4
Greens Bridge	14184100	0.3	0.8	1.1	5.8
Jefferson	14189000	0.2	0.6	0.8	4.5

Goodness-of-fit metrics also were evaluated using daily average temperatures (table 5). Results are similar to those derived for the hourly temperatures in table 4, but the daily mean errors tended to be slightly lower. This is a reflection of the model's tendency to better-represent average daily conditions than the diurnal variation of temperature. Measured and modeled hourly temperatures for a typical warm-weather period in 2011 at Mehama demonstrate a strong daily variation (fig. 10). The model adequately simulates the timing of daily temperature extremes, but tends to over-predict daily temperature maximums during warm conditions.

Table 5. Goodness-of-fit statistics using the modeled mean daily temperatures for two periods during 2011.

[Abbreviations: ID, identification number; ME, mean error; MAE, mean absolute error; RMSE, root-mean squared error; MAPE, mean absolute percentage error; ˚C, degrees Celsius]

Streamgage	USGS ID	ME (˚C)	MAE (˚C)	RMSE (˚C)	MAPE (percent)
Calendar year 2011					
Mehama	14183010	-0.1	0.4	0.4	4.6
Greens Bridge	14184100	-0.1	0.7	0.8	7.0
Jefferson	14189050	0.1	0.5	0.6	5.4
June– October 2011					
Mehama	14183010	0.0	0.3	0.4	2.6
Greens Bridge	14184100	0.3	0.7	0.9	5.1
Jefferson	14189050	0.2	0.5	0.6	3.7

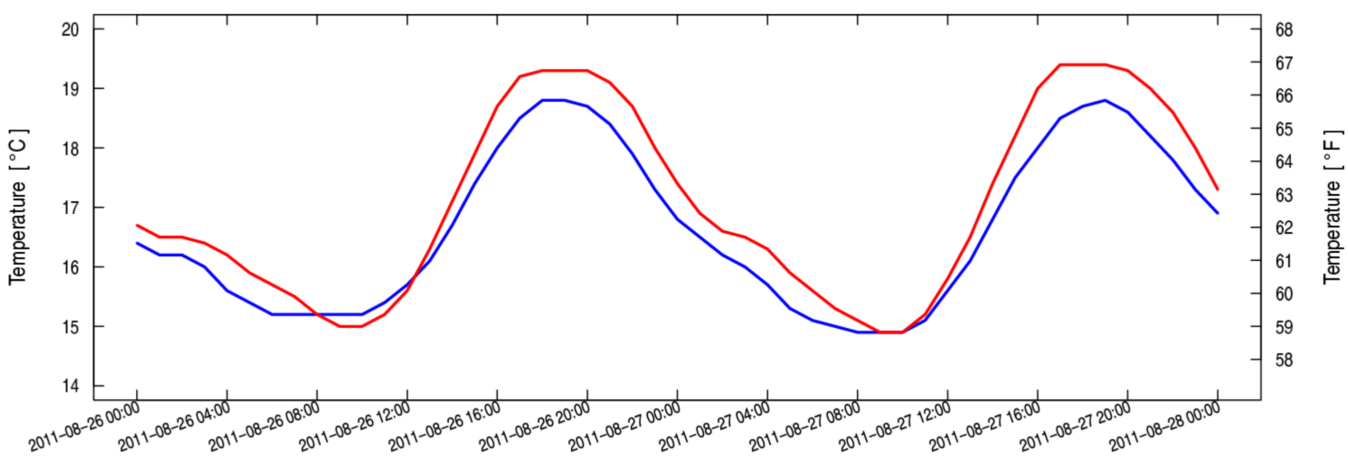

Figure 10. Measured and modeled values for 2 days of hourly temperature in late August 2011 for the North Santiam River near Mehama, Oregon (USGS streamgage 14183010).

Independent Calibration Check

In order to check the performance of the calibrated model, the model was tested with an independent dataset. Boundary condition and lateral inflow data from 2012 were entered into the same model using the same data sources and estimation techniques, and the results were checked against measured data. Measured and modeled 2012 streamflows at Mehama, Greens Bridge, and Jefferson showed relatively good agreement for most periods (figs. 11, 12, and 13, respectively), with goodness-of-fit metrics indicating slightly higher errors relative to the 2011 statistics (table 6). Streamflow errors for 2012 were comparable to 2011 rates at Mehama, and comparisons at all sites showed the same high-flow underprediction that was present with the 2011 data. During the low-flow season, the model significantly overpredicts streamflow at the Greens Bridge and Jefferson sites in 2012, a result that was not observed with the 2011 data; the difference is small, although it appears larger on the logarithmic scale of figures 11 and 12. The reason for this difference with the 2012 streamflow data is unknown. One possible source of the difference is the streamflow data from the Greens Bridge streamgage. Whereas streamflow data at the Mehama and Jefferson streamgages extend back to 1905 and 1907, respectively, streamflow data at Greens Bridge were collected from only 1964 to 1968, and again from 2005 onward. The stage-discharge relationships used to calculate streamflow data tend to improve with time. Consequently, streamflow data from Green Bridge may not be as accurate as data from the other two streamgages. Other potential sources of the discrepancy include unknown summer streamflow withdrawals or poor estimates of summer streamflow withdrawals, streamside transpiration, or an increase in uncertainty related to the contributions of ungaged and unmodeled tributaries between the Mehama and Greens Bridge streamgages.

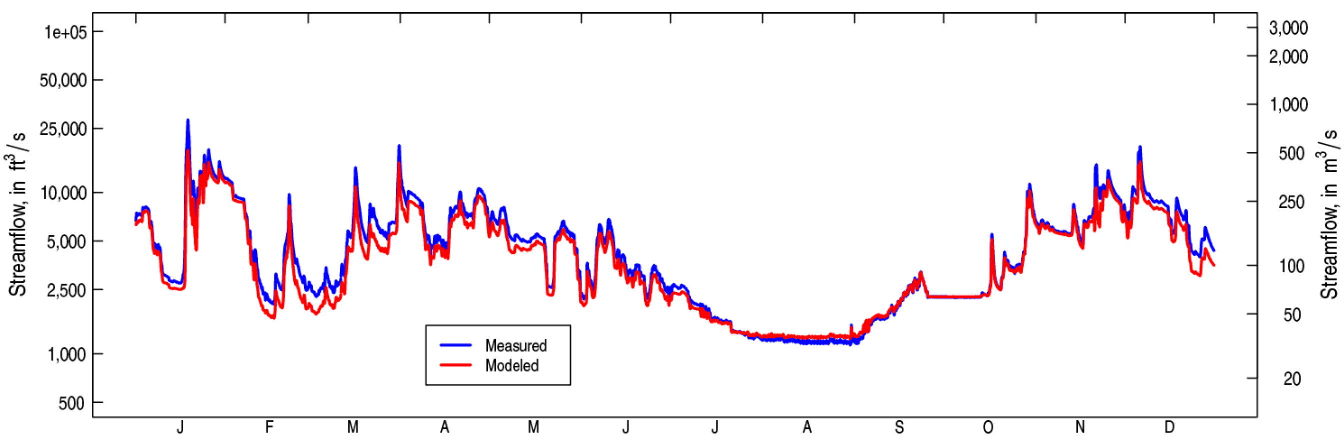

Figure 11. Measured and modeled streamflow for the North Santiam River at Mehama, Oregon (USGS streamgage 14183000), 2012.

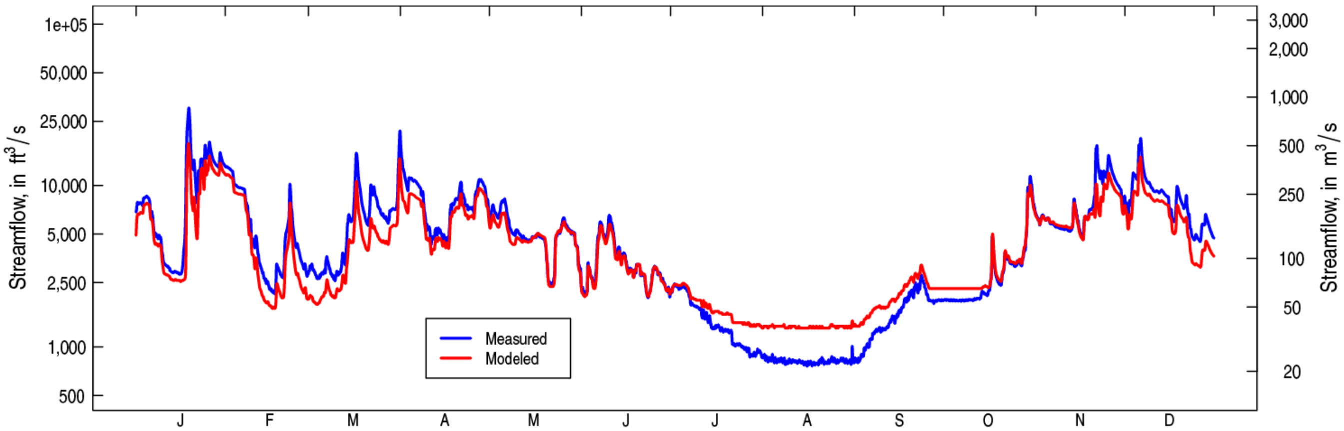

Figure 12. Measured and modeled streamflow for the North Santiam River at Greens Bridge, Oregon (USGS streamgage 14184100), 2012.

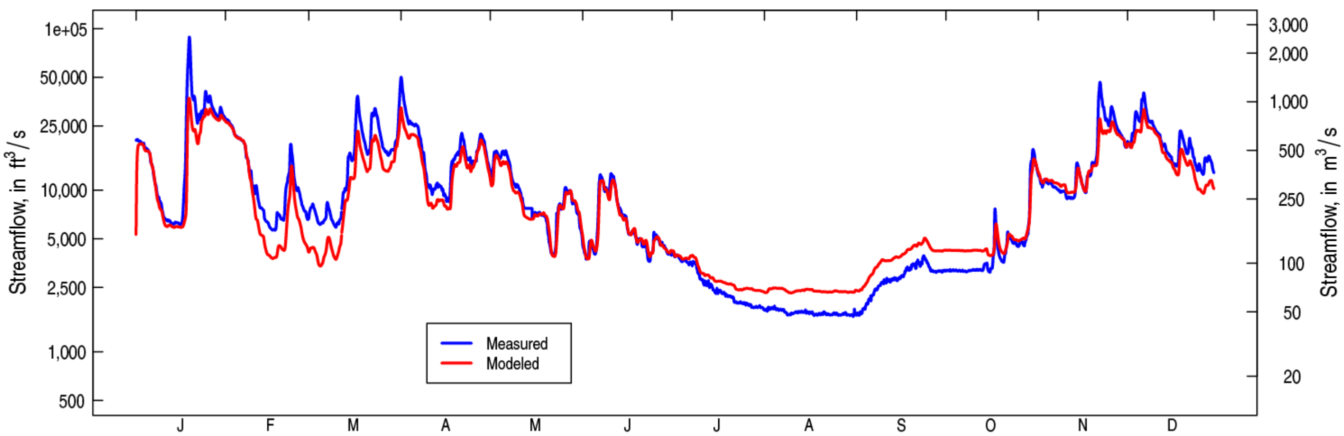

Figure 13. Measured and modeled streamflow for the Santiam River at Jefferson, Oregon (USGS streamgage 14189000), 2012.

Table 6. Goodness-of-fit statistics using modeled hourly streamflows for two periods in 2012.

[Abbreviations: ID, identification number; ME, mean error; MAE, mean absolute error; RMSE, root-mean squared error; MAPE, mean absolute percentage error; ˚C, degrees Celsius]

Streamgage	USGS ID	ME (m^3/s)	MAE (m^3/s)	RMSE (m^3/s)	MAPE (percent)
Calendar year 2012					
Mehama	14183000	-16.5	17.1	27.2	10.5
Greens Bridge	14184100	-18.3	25.6	41.8	21.2
Jefferson	14189000	-39.5	54.4	110	18.8
June–October 2012					
Mehama	14183000	-5.5	6.7	15.3	5.8
Greens Bridge	14184100	1.6	12.7	23.5	23.9
Jefferson	14189000	3.6	24.7	53.2	20.2

A comparison of measured and modeled 2012 water temperatures at the Mehama, Greens Bridge, and Jefferson sites shows that the model adequately captured the patterns in the data (figs. 14, 15, and 16, respectively), with goodness-of-fit metrics showing values that are similar to those from 2011 for the two upstream sites, and just slightly higher errors at the Jefferson site (compare table 7 to table 4). Summer and early fall temperature errors for 2012 were comparable to those in 2011 at Mehama and downstream at Greens Bridge, but higher at Jefferson. The higher error values at Jefferson are likely due to the increase in uncertainty resulting from the estimated lateral inflows and temperatures of the South Santiam River. All mean absolute error values were equal to or less than 0.7 ˚C for the periods of interest. This compares well with the North Santiam CE-QUAL-W2 river model developed by Sullivan and Rounds (2004), which resulted in absolute mean errors ranging from 0.5 to 1.0 °C.

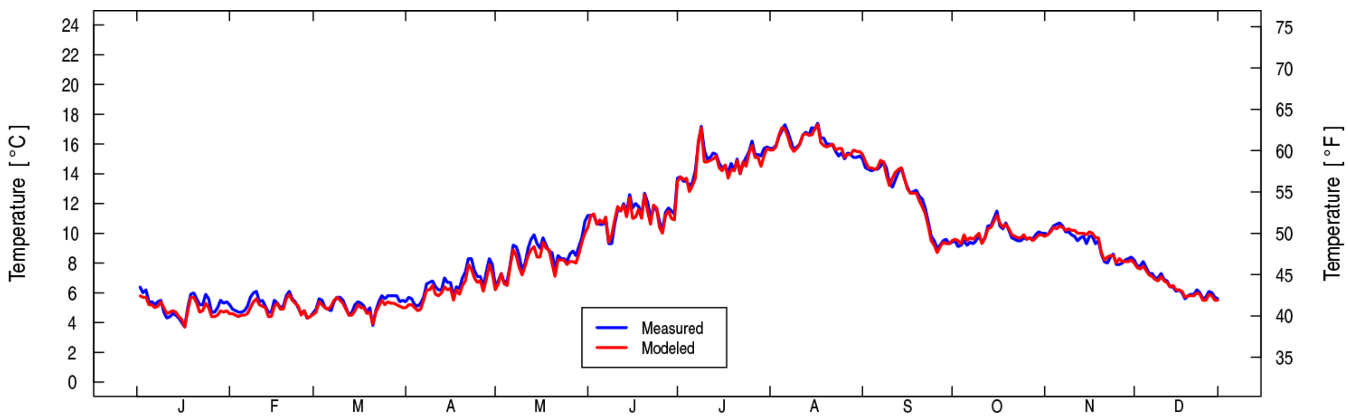

Figure 14. Measured and modeled mean daily values of temperature for the North Santiam River near Mehama, Oregon (USGS streamgage 14183010), 2012.

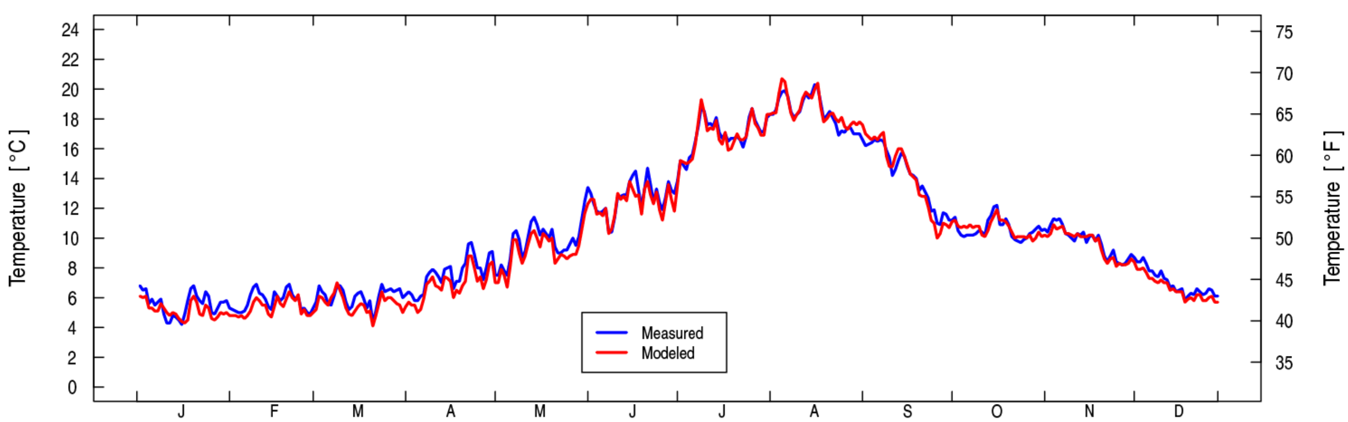

Figure 15. Measured and modeled mean daily values of temperature for the North Santiam River at Greens Bridge, Oregon (USGS streamgage 14184100), 2012.

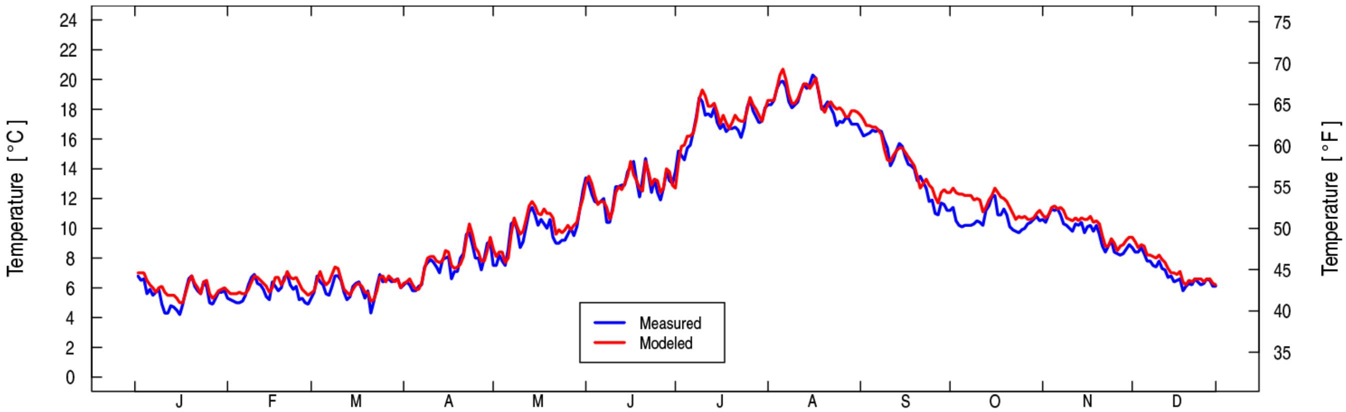

Figure 16. Measured and modeled mean daily values of temperature for the Santiam River near Jefferson, Oregon (USGS streamgage 14189050), 2012.

Table 7. Goodness-of-fit statistics using modeled hourly temperatures for two periods in 2012.

[Abbreviations: ID, identification number; ME, mean error; MAE, mean absolute error; RMSE, root-mean squared error; MAPE, mean absolute percentage error; ˚C, degrees Celsius]

Streamgage	USGS ID	ME (m^3/s)	MAE (m^3/s)	RMSE (m^3/s)	MAPE (percent)
Calendar year 2012					
Mehama	14183000	-0.2	0.4	0.5	4.1
Greens Bridge	14184100	-0.3	0.5	0.7	6.0
Jefferson	14189000	0.4	0.6	0.8	7.1
June–October 2012					
Mehama	14183000	0.0	0.4	0.6	3.3
Greens Bridge	14184100	-0.1	0.5	0.7	3.8
Jefferson	14189000	0.4	0.7	1.0	5.8

A plot of measured temperature versus modeled temperature for both 2011 and 2012 show that errors are fairly well-distributed at Mehama (fig. 17A). The same figure shows a bias at high temperatures at Greens Bridge in 2011 (fig. 17B), as previously discussed. However, this bias did not appear in 2012. The reason for the inconsistency is likely the positive bias of summer streamflow associated with the 2012 model. Results similar to Greens Bridge are seen at Jefferson, although the 2011 bias is not as strong (fig. 17C).

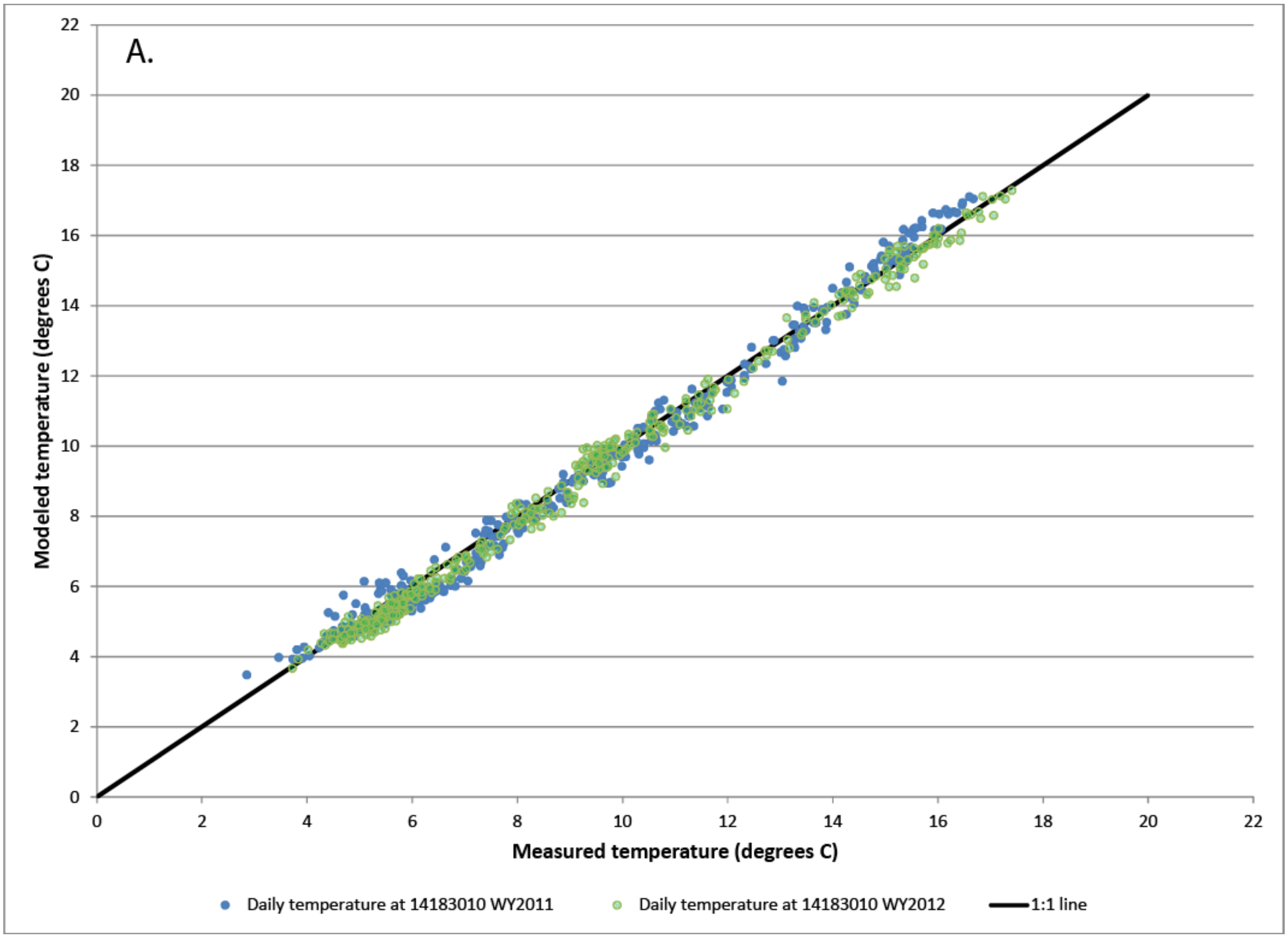

Figure 17. Measured and modeled mean daily values of temperature for 2011 and 2012 at USGS streamgages on the North Santiam River, Oregon.

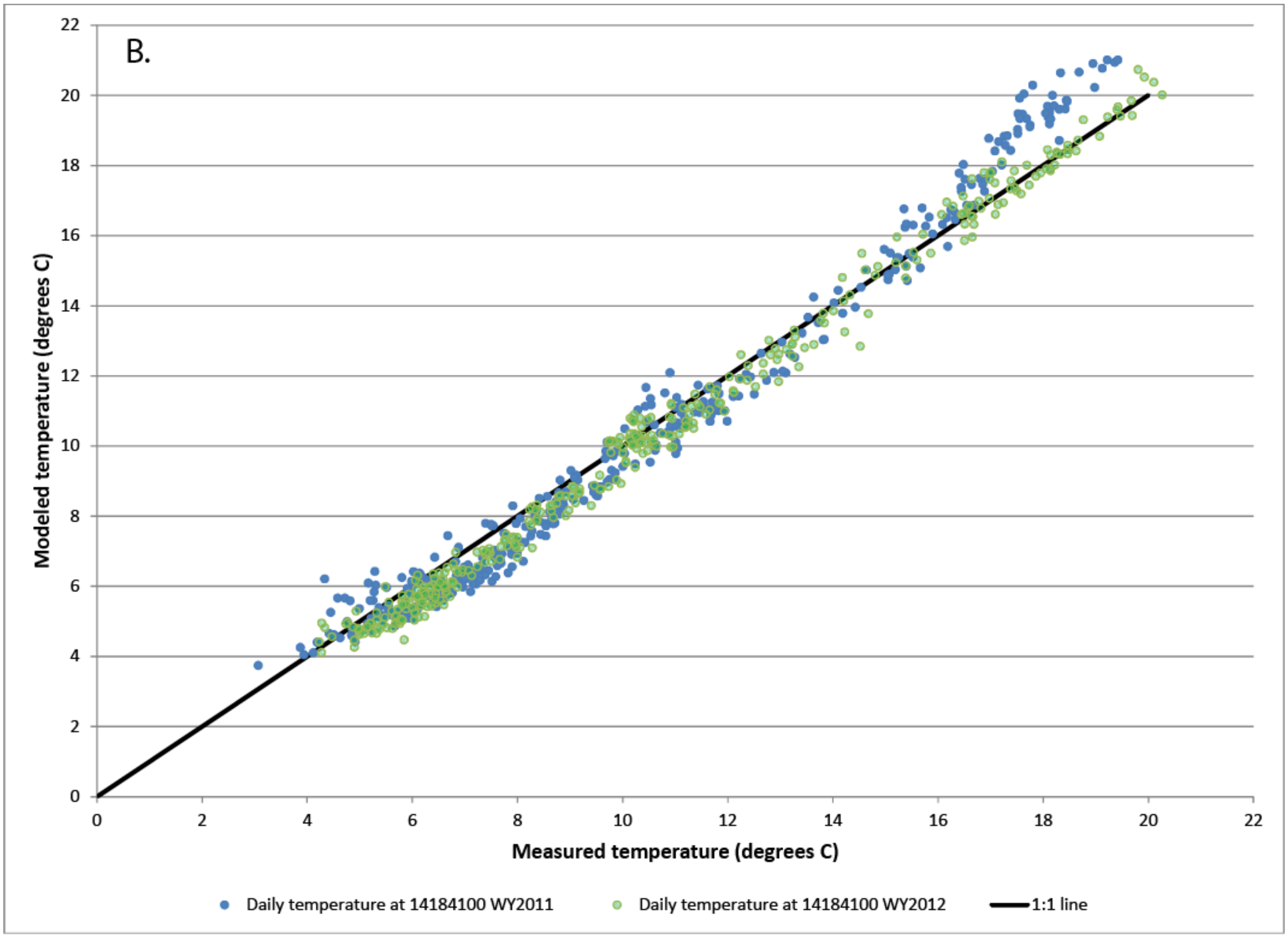

Figure 17.—Continued

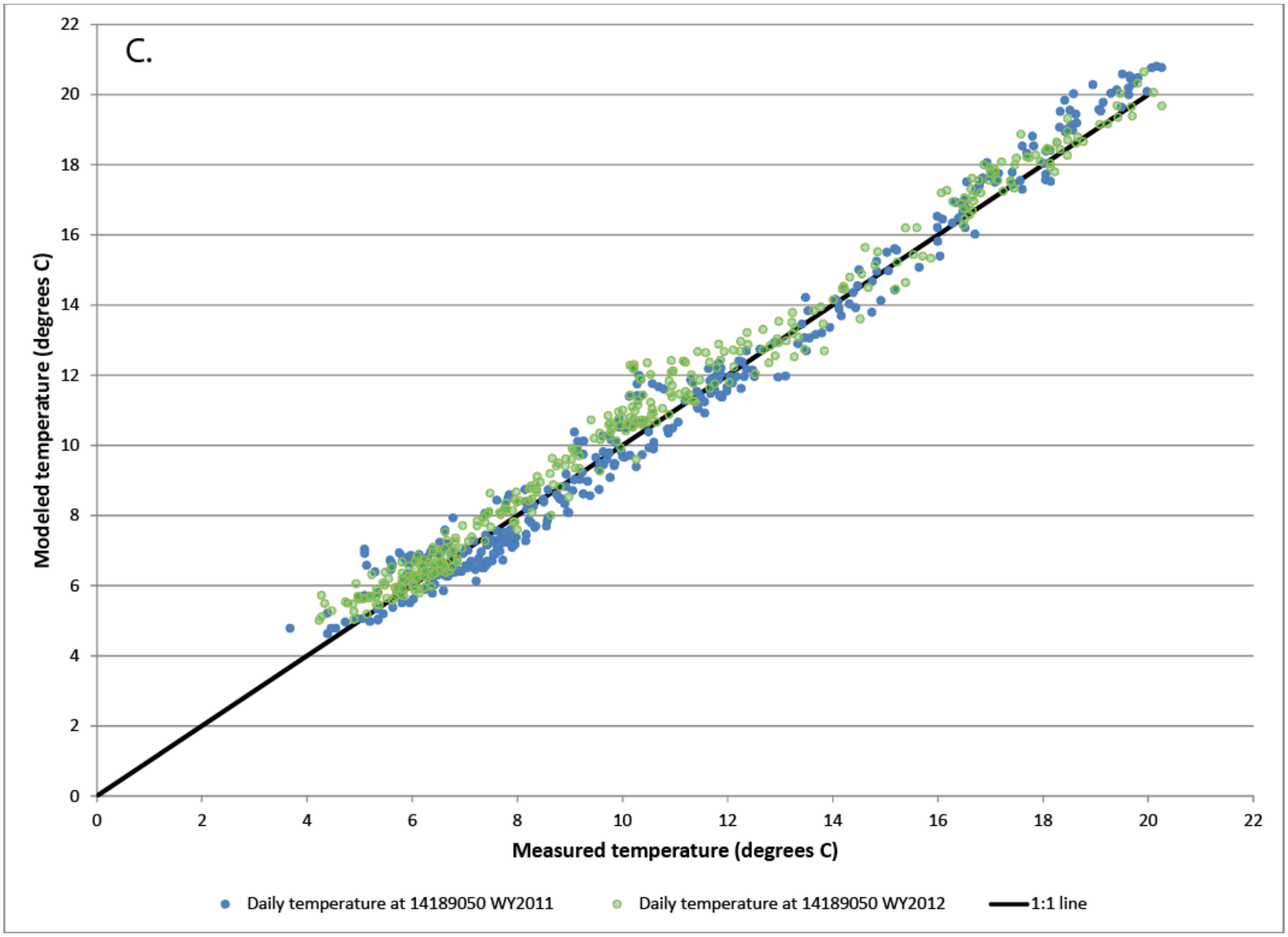

Figure 17.—Continued

Summary and Implications for Future Research and Monitoring

A river model of the North Santiam and Santiam Rivers was developed and calibrated to simulate streamflow and water temperature downstream of Detroit and Big Cliff Dams. Calibration was focused on 2011 conditions with particular interest on the June–November period. Hourly water temperature data were simulated with typical mean absolute errors from 0.4 to 0.8°C and little to no annual bias when compared to measured data, although bias levels are higher at specific locations during specific periods. A check using 2012 data in the model produced mean absolute errors ranging between 0.4 and 0.7 ˚C, with little or no bias at the Mehama and Greens Bridge streamgages, and a positive annual bias of about 0.4 ˚C at the Jefferson streamgage. The model tended to predict daily temperature averages with slightly more accuracy compared to the hourly data.

The model predictions generally are less accurate for more downstream locations, especially downstream of the confluence with the South Santiam River. This is expected, as temperature data at the mouth of the South Santiam River were estimated using a statistical model based on measured temperatures 37 mi (60 km) upstream of the confluence with the North Santiam River.

Much of the model's temperature error is attributable to the model's difficulty in fully simulating diurnal variability in the summer. Although overall errors fall within desired limits (mean absolute error less than 1.0 °C; mean error near zero), modeled summer water temperature maxima tend to show a small positive bias, especially at the downstream locations. The model simulated daily mean water temperature values to within acceptable limits.

The model can predict water temperatures to within a mean absolute error of 0.8 ˚C over the low-flow summer and early fall period and can be used to estimate impacts on streamflows and temperatures for the length of the North Santiam River downstream of Big Cliff Dam under a series of potential future conditions in which structures and/or operations at Detroit and Big Cliff Dams are changed. Further model refinement would be needed to reduce the positive bias in the prediction of daily summer and early fall temperature maxima and the negative bias in the prediction of winter high-streamflow events. Future model calibration also could be conducted using temperature or streamflow values that fall outside of the range used in this study.

Future model predictions could be improved with the availability of more streamflow and temperature data. Most useful to the improvement of the model would be temperature data near the mouth of the South Santiam River, which would eliminate the need for the statistical model built to estimate warming in that river between the Foster streamgage and its confluence with the North Santiam River. Other useful data that would improve the model include streamflow and temperature for the other modeled tributaries to the North Santiam River (Bear Branch Creek, Rock Creek) and measured municipal withdrawal rates.

Further model refinement also may be possible with the addition of more meteorological data, specifically short-wave radiation and wind speed data. Wind speed is likely highly variable throughout the watershed, and more representative wind stations might produce more accurate simulations of evaporative cooling. Short-wave solar radiation reaching the water surface also may be highly variable in the watershed, especially for partly cloudy weather conditions, where cloud cover low in the valley may not be identical to that closer to the headwaters. However, even with a more dense distribution of short-wave radiation datasets, the lack of a shading algorithm in HEC-RAS version 4.1.0 limits the ability of the model to effectively simulate daily summertime diurnal water temperature variation. Future versions of HEC-RAS may incorporate a shading algorithm, which would eliminate the need for manually manipulating short-wave radiation data to emulate shading and produce more accurate solar heating of the water surface.

Although the model is not intended for use in predicting high-streamflow events, additional calibration to account for small, ungaged tributaries could be implemented to reduce or remove the negative bias found during winter storm events. Additional considerations for summer sources and usage could improve summer streamflow estimates.

Acknowledgments

The authors thank Kathy Breen of the USGS Oregon Water Science Center for her assistance with figures used in this report. Discussions with Dan Turner and Kathryn Tackley of the U.S. Army Corps of Engineers were helpful in evaluating the performance and utility of the model.

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Publishing support provided by the U.S. Geological Survey
Science Publishing Network, Tacoma Publishing Service Center

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Stonewall and Buccola—**Development of a HEC-RAS Temperature Model for the North Santiam River, Northwestern Oregon**—Open-File Report 2015–1006

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20151006