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Modeling Streamflow and Water Temperature in the North Santiam and Santiam Rivers, Oregon, 2001–02

Scientific Investigations Report 2004-5001

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

Front cover:

Top:
The Santiam River at river mile 9.5, taken on August 7, 2002.

Lower:
The North Santiam River at river mile 57.3, taken on June 4, 2002.

Both photographs by Ian Wigger (U.S. Geological Survey).

Modeling Streamflow and Water Temperature in the North Santiam and Santiam Rivers, Oregon, 2001–02

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U.S. Geological Survey
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The calibrated models of the North Santiam and Santiam Rivers, as used in this investigation, are available for download from the Internet at http://oregon.usgs.gov/projs_dir/will_tmdl/model.html

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
	Area	
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (in^2)

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

°F = (1.8 x °C) + 32

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

Modeling Streamflow and Water Temperature in the North Santiam and Santiam Rivers, Oregon, 2001–02

By Annett B. Sullivan and Stewart A. Rounds

Abstract

To support the development of a total maximum daily load (TMDL) for water temperature in the Willamette Basin, the laterally averaged, two-dimensional model CE-QUAL-W2 was used to construct a water temperature and streamflow model of the Santiam and North Santiam Rivers. The rivers were simulated from downstream of Detroit and Big Cliff dams to the confluence with the Willamette River. Inputs to the model included bathymetric data, flow and temperature from dam releases, tributary flow and temperature, and meteorologic data. The model was calibrated for the period July 1 through November 21, 2001, and confirmed with data from April 1 through October 31, 2002. Flow calibration made use of data from two streamflow gages, and travel time and river-width data. Temperature calibration used data from 16 temperature monitoring locations in 2001 and 5 locations in 2002. A sensitivity analysis was completed by independently varying input parameters, including point-source flow, air temperature, flow and water temperature from dam releases, and riparian shading. Scenario analyses considered hypothetical river conditions without anthropogenic heat inputs, with restored riparian vegetation, with minimum streamflow from the dams, and with a more-natural seasonal water temperature regime from dam releases.

Significant Findings

1. Summertime river temperatures were generally coolest near the dams and increased downstream, with the warmest temperatures occurring in the Santiam River in both 2001 and 2002. In the fall, the releases from the dams typically were warmer than downstream temperatures.
2. Portions of both the North Santiam and Santiam Rivers exceeded the State of Oregon temperature standard for parts of 2001 and 2002. The 2001–02 temperature standards were 17.8°C (degrees Celsius) from July 1 through September 14, and 12.8°C from September 15 through June 30, measured as the 7-day average of daily maximum water temperature. Exceedances covered larger reaches and a longer time period in 2001, a low flow year. In both years, the greatest temperature exceedances occurred in the lower North Santiam River and Santiam River from late June through mid-October. Temperature standards were sometimes exceeded by more than 7°C.
3. The CE-QUAL-W2 model simulated both hourly and seasonal temperatures in these rivers with an acceptable level of accuracy. Comparison of hourly simulated river temperature to measured data from 16 temperature sensors in 2001 and 5 temperature sensors in 2002 produced mean absolute errors (MAE) between 0.41°C and 1.02°C and root mean square errors (RMSE) between 0.50°C and 1.16°C. Using a 7-day moving average of the daily maximum temperature, the MAE ranged from 0.15°C to 1.05°C, and the RMSE ranged from 0.21°C to 1.14°C. The largest differences between simulated and measured temperatures occurred in the lower Santiam River, where measured daily temperature variation became small close to the confluence with the Willamette River, while the model simulated a larger daily temperature variation. River temperatures may have been damped by hyporheic flow and exchange of shallow ground water with river water near the Willamette River, processes that were not simulated by the model.
4. Sensitivity analyses showed that river water temperature was most sensitive to a direct change in water temperature from dam releases, though this effect decreased downstream. Changes in air temperature, riparian vegetation and dam release flows also produced changes in water temperature, with different spatial patterns of change. Water temperature was not sensitive to the presence or absence of a minor point-source inflow at Stayton, Oregon.
5. A scenario to examine the effect of restored riparian shading and a set of minimum streamflow targets showed cooling in the North Santiam in summer and a slight warming in the fall. The overall simulated temperature change for July 1 through November 26, 2001, was -0.20°C.
6. A scenario to examine the effect of restored riparian shading, minimum streamflow targets from the dams, and a more-natural seasonal temperature regime from

dam releases showed slight warming in summer and significant cooling in fall compared to existing conditions. The overall simulated temperature change for July 1 through November 26, 2001, was -1.91°C.

7. Although the North Santiam and Santiam Rivers transported water from the dams to the Willamette River in only a few days in summer, the water temperature released from the dams was less important than meteorological conditions in determining the water temperature at the mouth of the Santiam River.

Introduction

The North Santiam and Santiam Rivers are located in the Willamette Basin in northwestern Oregon (fig. 1). The North Santiam originates in the Cascade Range and flows generally westward, passing through Detroit and Big Cliff dams. Near Jefferson, Oregon, it joins the South Santiam River to form the Santiam River, a tributary of the Willamette River. From the dams to the Willamette River, the North Santiam and Santiam Rivers are used for recreation, for municipal and industrial water supply, for irrigation, and for fish habitat.

The North Santiam and Santiam Rivers exceed State of Oregon water temperature criteria during portions of the year, and both are listed for temperature on Oregon's 2002 303(d) list (table 1). The statistical measure used for the temperature criteria is a 7-day moving average of the daily maximum water temperature (7dADM). The temperature criteria for these rivers were 17.8°C from July 1 through September 14 and 12.8°C from September 15 through June 30, measured as a 7dADM. The latter time period has a lower criterion to protect the rivers for salmonid spawning. The published 2002 303(d) listing (Oregon Department of Environmental Quality [ODEQ], 2003) has a typographical error which mistakenly lists the 17.8°C criterion for part of the North Santiam for July 1 to September 1, instead of September 15 (Marilyn Fonseca, ODEQ, written commun., 2003). In December of 2003, the ODEQ revised the water temperature standard for Oregon.

In addition to the North Santiam and Santiam Rivers, the entire Willamette River and most of its other major tributaries up to the first major dams also appear on Oregon's 2002 303(d) list for exceeding temperature criteria. To address the temperature issue, the State of Oregon was required to develop a TMDL for water temperature for these rivers by the end of 2003. A number of factors can influence river temperature, including meteorological conditions such as air temperature and solar radiation, riparian shade, point-source inflows from municipal or industrial facilities, and outflows from dams. Flow and water temperature models were developed as part of this TMDL process to clarify which factors were most important in affecting water temperature in these rivers and to provide a quantitative framework for heat-load allocations.

An important consideration in the application of Oregon's temperature standards and development of the TMDL is the concept of "system potential" conditions, the hypothetical river environment without anthropogenic heat inputs. Anthropogenic sources of heat can include loss of riparian vegetation and shade, municipal and industrial sources, dams, and diversions. If the water temperature standard cannot be met when these anthropogenic heat sources are removed (or minimized such that their effects cannot be measured), then system potential temperatures become the temperature standard. The temperature TMDL, therefore, must include a quantification of both current conditions as well as system potential conditions in order to set a proper framework for permitted heat discharges and future restoration of riparian vegetation areas.

Previous investigations have studied the temperature and streamflow regimes of the North Santiam and Santiam Rivers. Harris (1968) included these rivers in a study of water travel times in the Willamette Basin. Laenen and Hansen (1985) simulated North Santiam river temperatures using air temperature and wind speed as input. Hansen and Crumrine (1991) examined the effects of dams on the North and South Santiam Rivers by simulating daily mean water temperature with a one-dimensional model. Laenen and Risley (1997) produced a streamflow-routing model of the North Santiam and Santiam Rivers as part of their modeling of the Willamette Basin.

Site Description, Basin Characteristics, and Hydrology

The North Santiam River is dammed in its upper reach by Detroit and Big Cliff dams (fig. 1), both constructed in 1953. Detroit dam is the main storage structure and power generating facility, holding approximately 472,880 acre-feet of water at full pool (E & S Environmental Chemistry, Inc., and North Santiam Watershed Council, 2002). Big Cliff dam, with only 7,020 acre-feet of storage, lies downstream of Detroit dam and is primarily a reregulation dam, used to smooth the large daily variation in water releases from Detroit dam due to power generation and avoid large pulses in streamflow downstream.

Downstream of Detroit and Big Cliff dams, the river flows in a canyon where it is joined by tributaries, including Rock Creek, until reaching its confluence with the Little North Santiam River. Farther downstream, the topography is more open and agricultural uses are common. Near Jefferson, the North Santiam River joins the South Santiam River to form the Santiam River, which flows approximately 12 miles before reaching the Willamette River. Water flows from the dams to the mouth of the Santiam River in 1 or 2 days, depending on flow.

The North Santiam and Santiam Rivers from the dams to the Willamette are underlain by a complex, thick sequence of late Tertiary and Quaternary alluvial and fluvial deposits (O'Connor et al., 2001) on Tertiary volcanic and sedimentary rocks. The climate of this area is characterized by long, cool, rainy winters and warm, and dry summers. The average daily maximum temperature at Stayton from 1951 through 2001 was 17.2°C and the average daily minimum air temperature was 5.6 °C, with an average annual precipitation of 134.4 cm (centimeters) and an average annual snowfall of 6.4 cm.

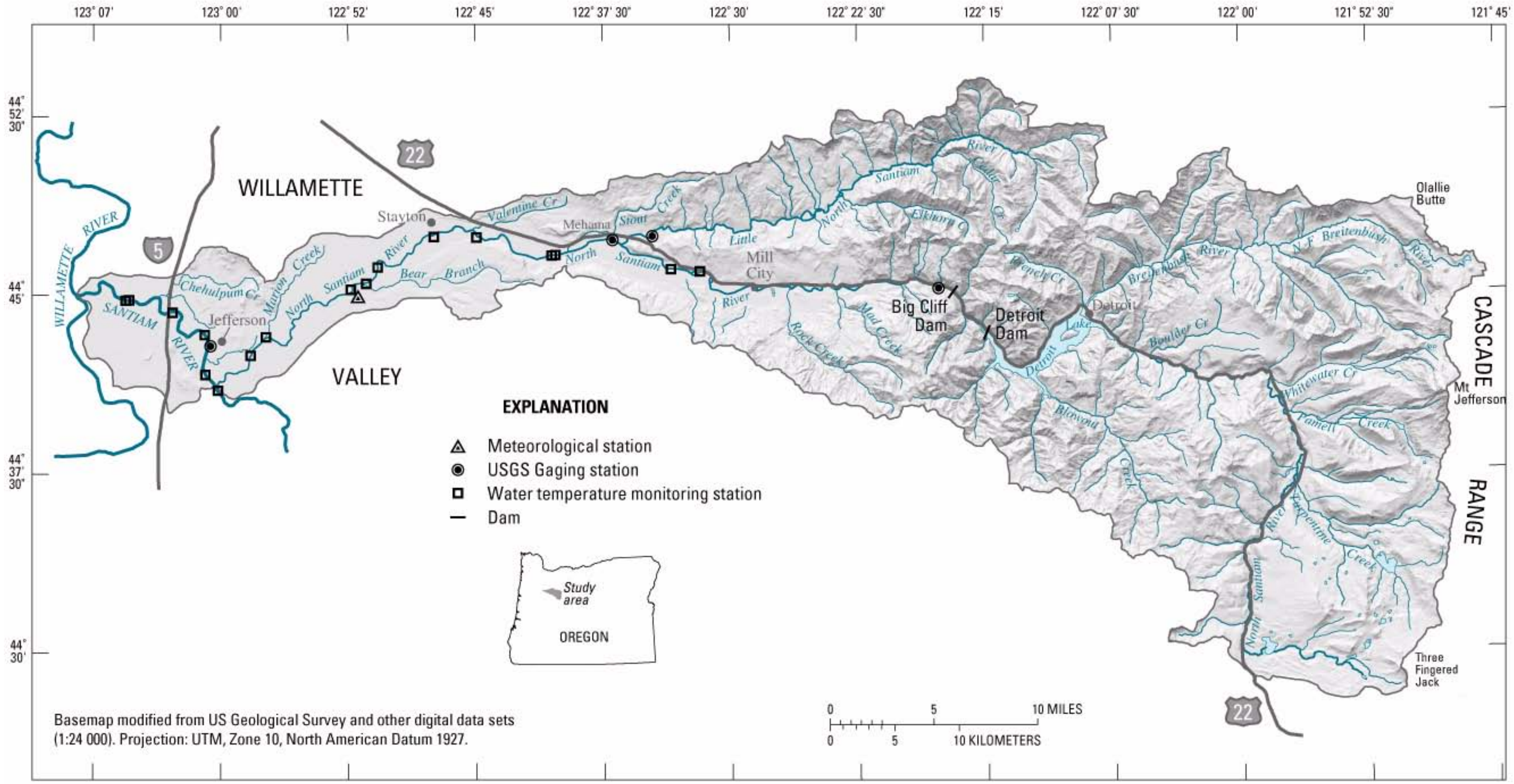

Figure 1. Map of the North Santiam and Santiam Rivers, Oregon, showing the locations of data-collection stations.

Table 1. Summary of North Santiam and Santiam Rivers 303(d) temperature listings in 2002 (Oregon Department of Environmental Quality [ODEQ], 2003). Temperature criteria have since changed in December of 2003.

[°C, degrees Celsius; SP, salmonid fish spawning; RR, salmonid fish rearing; RES, resident fish and aquatic life; AN, anadromous fish passage]

River	ODEQ river mile	Season	Criteria	Beneficial uses
North Santiam	0 to 10	July 1 to Sept. 14	17.8°C	SP, RR, RES, AN
	0 to 26.5	Sept. 15 to June 30	12.8°C	SP
Santiam	0 to 12	July 1 to Sept. 14	17.8°C	SP, RR, RES, AN
	0 to 12	Sept. 15 to June 30	12.8°C	SP

Water from the rivers is used for several purposes, including irrigation, municipal and industrial water supply, and recreation. The cities of Gates, Mill City, Mehama, Lyons, Stayton and Jefferson lie along these rivers, and the North Santiam River is also the source of drinking water for the city of Salem. The largest withdrawals from the river, including the Salem withdrawal, occur in the vicinity of Stayton.

In addition to anthropogenic uses of the water, a number of fish species live in these rivers. Spring-run Chinook salmon (*Oncorhynchus tshawytscha*) and winter-run steelhead trout (*O. mykiss*) are native to the rivers, and fall-run Chinook, summer-run steelhead, and coho salmon (*O. kisutch*) have been introduced. These salmonids use the river for spawning, rearing and migration. Resident salmonids include cutthroat trout (*O. clarki*) and rainbow trout (*O. mykiss*) (E & S Environmental Chemistry, Inc., and North Santiam Watershed Council, 2002).

Purpose and Scope

The objectives of this investigation were to (1) simulate hourly and seasonal streamflow and temperature conditions in the entire Santiam River and the North Santiam River below Big Cliff dam for parts of 2001 and 2002; (2) describe and document the model, including construction, calibration, sensitivity, and results; and (3) use the model to quantify current and system potential temperature conditions, and better understand the processes that influence water temperature in these rivers.

The study area included the North Santiam River from Big Cliff dam to its confluence with the South Santiam River, and the entire Santiam River from the mouth of the North Santiam River to the confluence of the Santiam River with the Willamette River. A model of the South Santiam River was constructed by ODEQ; streamflow results from that model were used as tributary input to the North Santiam-Santiam model. Besides the South Santiam, other tributaries included in the model were Rock Creek and the Little North Santiam River, both on the North Santiam. Anthropogenic inputs included outflows from the wastewater treatment plants for the cities of Stayton and Jefferson. Water withdrawals by agricultural and municipal users were included in the model.

In this investigation, USGS personnel collaborated with scientists from ODEQ, Portland State University (PSU), and the U.S. Army Corps of Engineers (USACE), all of whom were working in some capacity to create the tools necessary for ODEQ to create a water temperature TMDL for the Willamette River and its largest tributaries. The USGS was supported in this work through a scientific and financial partnership with the Oregon Association of Clean Water Agencies, a consortium of municipal agencies.

Methods

Model Description

The North Santiam and Santiam River flow and temperature model was constructed using CE-QUAL-W2 version 3.1 (Cole and Wells, 2002), a two-dimensional hydrodynamic and water-quality model from the USACE. This model is capable of simulating water levels, velocities, temperature, and a number of water-quality parameters, including dissolved oxygen, algae, and organic matter.

CE-QUAL-W2 originally was designed to simulate water quality in reservoirs; more than 400 reservoirs, lakes, and estuaries around the world have been simulated with this model. Version 3 of CE-QUAL-W2 includes the capability of modeling sloping river channels in addition to reservoirs. Application of this model to steeply sloping rivers like the North Santiam, however, is relatively new.

The model was developed by first constructing a grid based on river bathymetry information. Data were collected to quantify dam releases, tributary flow and temperatures, withdrawal rates, meteorology, and riparian vegetation. The model was first calibrated for flow by comparing simulated flows to data collected at monitoring locations along the river, by comparing simulated water travel time with published data, and by comparing simulated wetted width of the stream channel to available measurements. The model was calibrated for temperature after the water balance was complete by comparing independently collected temperature data with that simulated by the model.

The model was initially calibrated with data from July 1 through November 21, 2001. The model was confirmed and refined with data from April 1 through October 31, 2002. After calibration and testing were complete, simulations were run to examine the relative effect (sensitivity) of point sources, dam release flows, dam release temperatures, and riparian shade. Scenarios then were run to examine the effect of restored riparian vegetation, a set of proposed minimum streamflow targets, and a more-natural seasonal temperature pattern in dam releases.

Bathymetric Data and the Model Grid

A CE-QUAL-W2 model grid is made up of a sequence of longitudinal model segments, connected along the direction of flow. Each segment is divided into horizontal or sloping layers, each layer with a defined height. Widths of the layers for each segment are defined so that the cross-section of a model segment approximates the river's channel cross-section. Model segments are grouped together in branches, and each branch has its own channel slope. A branch or group of branches make up a waterbody, the largest entity in CE-QUAL-W2 bathymetry.

Bathymetric data from a number of sources were used to produce the model grid. Measured cross-sections were obtained from USGS gaging stations, from a HEC2 flood model of the North Santiam, and from a series of cross-sections measured along the lower 6 miles of the Santiam River by the USGS. River elevation data were taken from USGS 1:24,000 topographic maps.

ODEQ provided digitized information at 100 ft (foot) intervals along the North Santiam and Santiam Rivers derived from a grid of digital orthophoto quadrangles. This information included longitudinal centerline distance, wetted width, width of the near-stream-disturbance zone (zone with no vegetation), aspect, elevation, and riparian-vegetation data. The ODEQ data were derived from photographs taken on different dates and at different river flows, information that had to be considered when using the channel-width data. Because simulating the wetted width of the river is important in accurately simulating river temperatures, the USGS also measured channel widths at a number of locations along the rivers on three dates in 2002 during high-, medium-, and low-flow conditions for calibration purposes.

These bathymetry data were combined, averaged and interpolated into a CE-QUAL-W2 grid. In summary, the rivers first were divided into six branches based on slope changes. The ODEQ aspect data and USGS elevation data were averaged every 1,000 ft and a grid was generated to encompass the full dimensions of the river channel. Layer heights were set to a uniform 2 ft (0.61 m [meter]). Layer widths for each segment were initially determined by interpolating between available measured cross-sections. Extra layers were added to the top of the cross-sections to accomodate higher flows. Widths of the extra layers were estimated by extrapolating the average change in widths between lower layers. Finally, all cell widths were adjusted using 1,000-ft averaged ODEQ wetted widths to shrink or expand the cell widths between the measured cross-sections. As part of the model calibration, layer widths were further adjusted by comparing the model's wetted widths to field-measured wetted-channel widths on the same date or on dates with similar flows.

Application of CE-QUAL-W2 to steeply sloping rivers is a fairly new use of this model. During the construction of the North Santiam and Santiam River model, the CE-QUAL-W2 development team (Scott Wells [PSU] and Tom Cole [USACE]) was adjusting CE-QUAL-W2 to allow for easier application to sloping rivers. However, one issue required an accommodation to the North Santiam and Santiam model grid: CE-QUAL-W2 requires the same surface layer index for all segments in each of the model's waterbodies. The actual water level can be above or below the surface layer, but, for accounting purposes, it is always computed in relation to a single surface layer. When the river sloped steeply enough that the channel bottom in some segments was above the surface layer, the model considered these segments to be dry and would not run, even though the actual water level was well above the channel bottom. In order to overcome this issue, small-width (0.1 m) cells were added to the bottom of many of the segments to keep them from "drying out." The volume of these small-width cells was negligible compared to the water volume in the rest of the channel. The major drawback of this approach was that the model's timestep decreased, resulting in longer runtimes. On a 1.8 Ghz Pentium processor, a model run typically required between 12 and 44 hours; 2002 runs were longest due to the longer time period simulated and a large storm in April that further slowed the model timestep. Another approach to solve this issue might have been to break the model grid into a number of smaller waterbodies, as each waterbody can have a different surface layer index for accounting purposes. Because changes and improvements to CE-QUAL-W2 are made frequently, these kinds of accommodations to the model grid are likely to be unnecessary in the future.

The final model grid consisted of 1 waterbody, 6 branches, and 310 segments, of which 309 were 1,000 ft long and 1 was 500 ft, for a total distance of 309,500 ft, or approximately 58.6 miles (table 2). The model input format requires zero-width boundary segments at the start and end of the grid, and two boundary segments between branches, bringing the total number of segments in the grid to 322. A schematic of the grid is shown in figure 2, and the locations of all included inflows and withdrawals are shown in figure 3.

Temporal Inputs and Shading

The model requires meteorological data; streamflow and water temperature from dam releases, tributaries, and point sources; withdrawal rates; and information on shading from riparian vegetation.

Table 2. Summary of the CE-QUAL-W2 model grid used to represent the North Santiam and Santiam Rivers.

Branch	Distance from headwaters, river foot[1]	Distance from mouth, river mile[2]	Number of model segments	Average slope	River
1	14,750–35,750	58.1–54.1	21	0.0079	North Santiam
2	35,750–114,750	54.1–39.4	79	0.0042	North Santiam
3	114,750–179,750	39.4–27.0	65	0.0032	North Santiam
4	179,750–236,750	27.0–16.2	57	0.0027	North Santiam
5	236,750–260,750	16.2–11.7	24	0.0017	North Santiam
6	260,750–324,250	12.1–0.0	64	0.0011	Santiam

[1] Based on Oregon Department of Environmental Quality (ODEQ) data.

[2] Included for reference to USGS topo maps, on which the North Santiam River starts at RM 11.7 and the Santiam ends at RM 12.1.

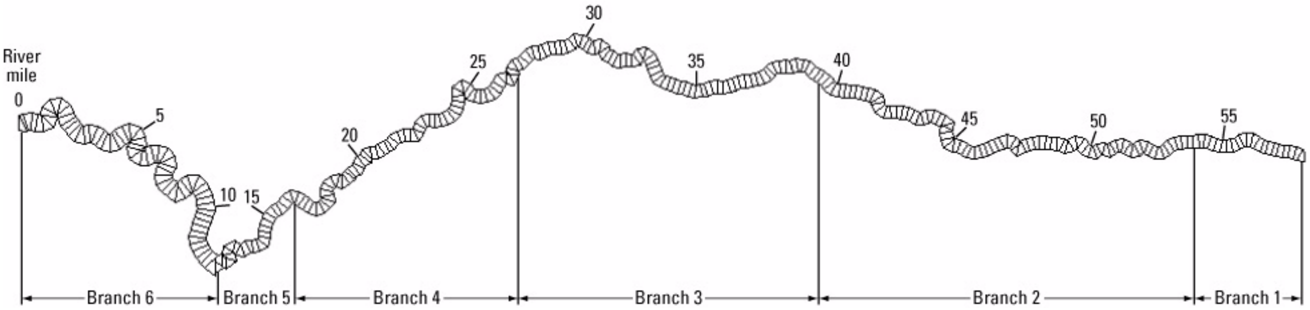

Figure 2. Schematic of the model grid, with branch boundaries and river miles from the mouth of the Santiam River.

Meteorology

Meteorological data needed for the model included air temperature, dewpoint temperature, wind speed and wind direction, cloud cover, and incident solar radiation. Many of these parameters, including air temperature, relative humidity (used to calculate dewpoint temperature), wind speed, and wind direction were measured hourly at a Remote Automated Weather Station (RAWS) site near Stayton (44° 45’ N, 122° 52’ W, 155 m elevation). Neither cloud cover nor solar radiation were measured at that site, so solar radiation data were obtained from the University of Oregon’s Solar Radiation Monitoring Laboratory (SRML) Eugene station (44° 03’ N, 123° 04’ W, 150 m elevation), which used an Ascension Technology Rotating Shadow Band Pyranometer to measure global irradiance. Daytime cloud cover was estimated by comparing the calculated theoretical solar radiation and measured solar radiation. Equations to calculate theoretical solar radiation and the effects of cloud cover were taken from the CE-QUAL-W2 code. Nighttime cloud cover was estimated relative to the day-time cloud cover at dusk and dawn.

Precipitation

Daily precipitation data were acquired from the Oregon Climate Service (OCS), a State repository for climate information. Precipitation data from Stayton were used for the Santiam and lower three branches of the North Santiam. Rainfall data from Detroit were used for the upper two branches on the North Santiam. Precipitation at Detroit was generally higher than that at Stayton.

Precipitation temperature also was required as CE-QUAL-W2 input, and while this was not directly measured, the daily median air temperature at the two precipitation sites was used as an estimate of precipitation temperature.

Streamflow and Stream Temperature

Big Cliff dam marked the upstream end of the model (RM 58.1; fig. 3). Data from the USGS gage on the North Santiam River at Niagara (USGS station 14181500), just downstream of the dam, were used as dam release flow and water temperatures. Temperature and streamflow were measured every half-hour at this location.

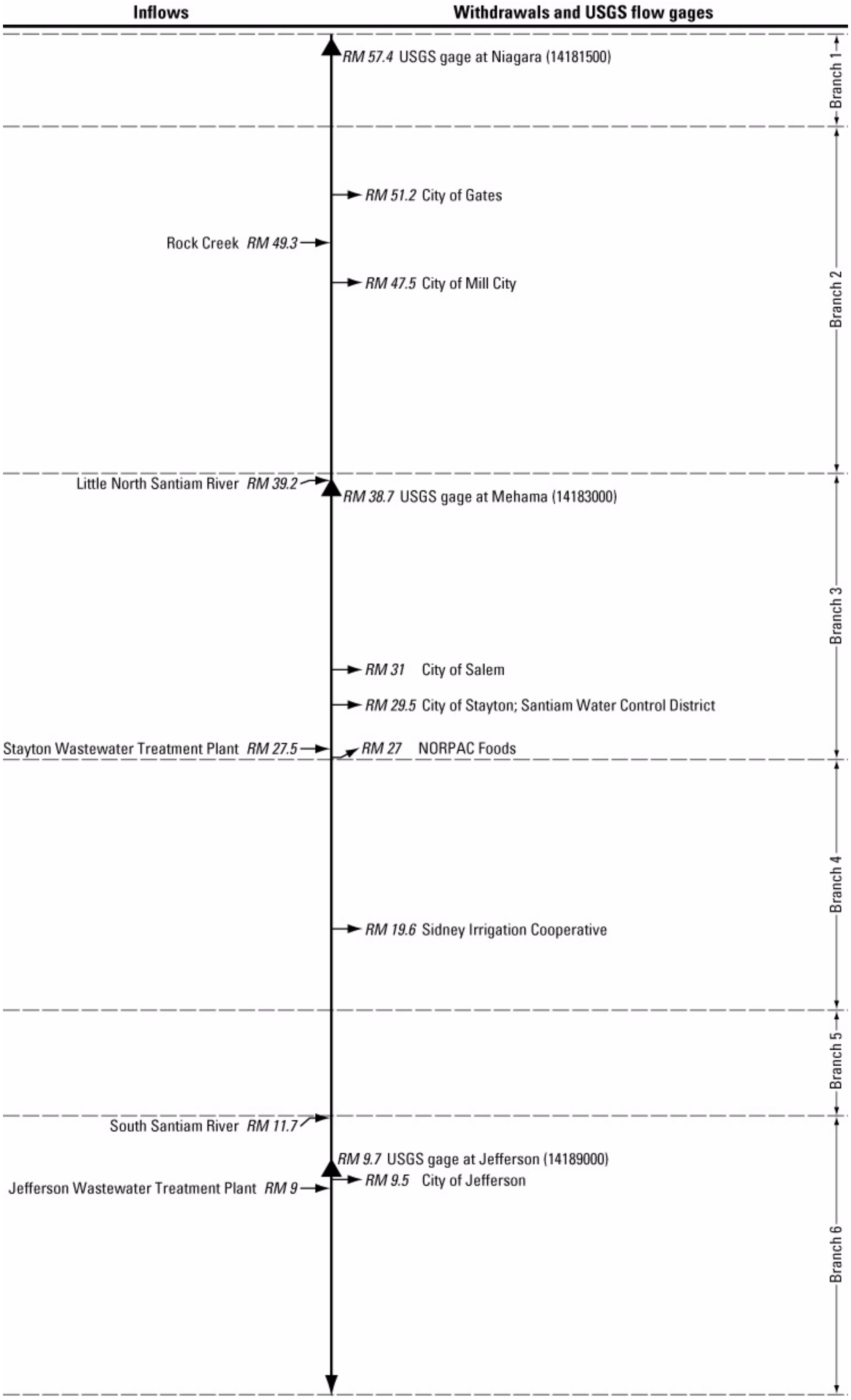

Figure 3. Locations of point-source and tributary inflows, withdrawals, and USGS streamflow gages.

The model included three significant tributaries. The Little North Santiam River flows into the North Santiam River at RM 39.2 (fig. 3) and has a USGS gage near its mouth (USGS station 14182500), which collected streamflow and temperature data at half-hour intervals.

A second, smaller tributary, Rock Creek, flows into the North Santiam River upstream of the Little North Santiam River, near RM 49.3. It was ungaged, so its streamflow was estimated by comparing estimated catchment areas of both Rock Creek and the Little North Santiam River, then using that ratio to estimate flow from Rock Creek as a proportion of the gaged flow of the Little North Santiam River. Stream temperature data were not measured at this site, so the stream temperature of Rock Creek was estimated to be equal to the temperature of the Little North Santiam River.

The third major tributary, the South Santiam River, converges with the North Santiam River to form the Santiam River at RM 11.7. Streamflow was not measured at the mouth of the South Santiam River, so simulated flows from the ODEQ CE-QUAL-W2 model of the South Santiam River (Jim Bloom, ODEQ, unpub. data, 2003) were used. For part of the time period simulated, half-hourly stream temperature was available from a temperature sensor at the mouth of the South Santiam River. That temperature monitor was not in the stream all year, so the available temperature data at the mouth of the South Santiam River were correlated to data from the USGS temperature gage on the Santiam River near Jefferson (station 14189050), which had a similar seasonal pattern. That correlation was used to estimate temperature in the South Santiam River for times when measured data were not available.

Streamflow in the North Santiam River at Niagara, in the Little North Santiam River, and at the mouth of the South Santiam River are shown in figure 4. The flow in the North Santiam River at Niagara, just downstream from the dams was controlled by the dams, with fairly constant minimum flows, and little daily variation. While larger releases did correspond to times of the year with higher precipitation, many of the smaller stormflows in the upper basin were absorbed by the reservoir and did not appear on this hydrograph. The Little North Santiam River hydrograph, on the other hand, was typical of a small unregulated river, with a definite response to storms, high flows during the rainy winter and low flows during the dry summer. The ODEQ-simulated hydrograph from the South Santiam River was a mix between the two types of hydrographs. The South Santiam River is dammed 35 miles upstream from its mouth, but the river also receives flow from unregulated tributaries before reaching the confluence with the North Santiam River.

Stream temperatures in the North Santiam River at Niagara and in the Little North Santiam River are shown in figure 5. The water temperature at Niagara just downstream from the dams had small 24-hour variations and reached an annual maximum later in the year, in late September or October. The temperature of the Little North Santiam River had larger 24-hour temperature cycles and maximum summer temperatures in August. For much of the year, the temperature at Niagara was cooler than that of the Little North Santiam River because the releases from Detroit dam are withdrawn from a depth in the lake where colder water collects. However, late in the year, the water temperature at Niagara was warmer than the Little North Santiam and other small unregulated tributaries. The water in Detroit Lake stores heat from the summer months and is slower to cool than the surrounding streams.

In addition to the dam releases and tributaries, flow and temperature from two municipal wastewater treatment plants (Stayton and Jefferson; fig. 3) were included in the model. Overall, few sources discharge into these rivers, as the North Santiam River is governed by the “Three Basin Rule” (Oregon Department of Environmental Quality, 2001) designed to protect the river as a source of drinking water. This rule severely restricts discharges into the river.

Withdrawals

Information on monthly withdrawals of water from the rivers by municipal and agricultural users was obtained from the Oregon Water Resources Department (OWRD) Water Use Reporting Database. Locations of the withdrawals included in the model are shown in figure 3. The withdrawals reported to OWRD are the total monthly withdrawals, including both consumptive and nonconsumptive uses. Discussions with representatives of the larger water users in the basins allowed a better estimate of consumptive withdrawals (Libby Barg, City of Salem, and Larry Trosi, Santiam Water Control District, oral commun., 2003) which were used in the model.

Riparian Shading

The representation of riparian vegetation for the shading component of the model was constructed using a technique modified from a method developed by Robert Annear (PSU), which used ODEQ-digitized vegetation information and the model bathymetry. For each of nine ODEQ vegetation zones along each river bank, the vegetation top elevation was calculated from tree height and thalweg elevation. Then the distance from the stream centerline to each vegetation zone, and a vegetation density for each zone, were calculated. The zone casting the longest shadow over the river was determined for each bank. Finally, the data were averaged longitudinally to correspond to the CE-QUAL-W2 model segment length. Final shading information was input to a CE-QUAL-W2 shade file, including Julian day, vegetation height, vegetation density, topographic shade inclination angles, and estimated leaf-out date and leaf-fall date. The original method accounted for shading from only one vegetation zone, which could underestimate shading. The method was modified in an attempt to better account for shading from all zones. This approach resulted in a better estimate of the vegetation density needed by the model.

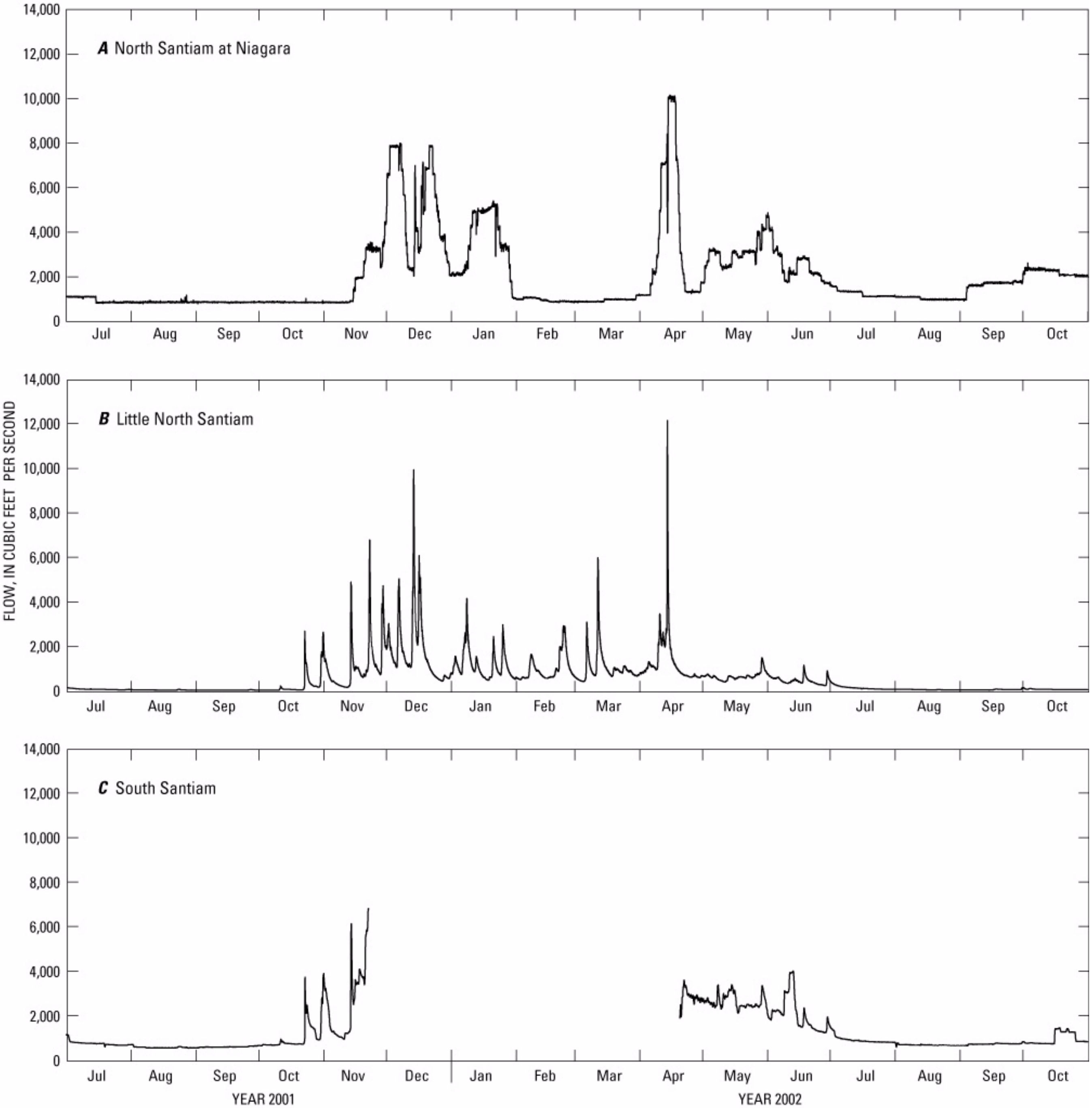

Figure 4. Streamflow in (*A*) the North Santiam River at Niagara (USGS station 14181500), just downstream from the dams, (*B*) the Little North Santiam River (USGS station 14182500), and (*C*) the South Santiam River for July 2001 through October 2002. Data in (*A*) and (*B*) were measured; data in (*C*) were from the Oregon Department of Environmental Quality model of the South Santiam River.

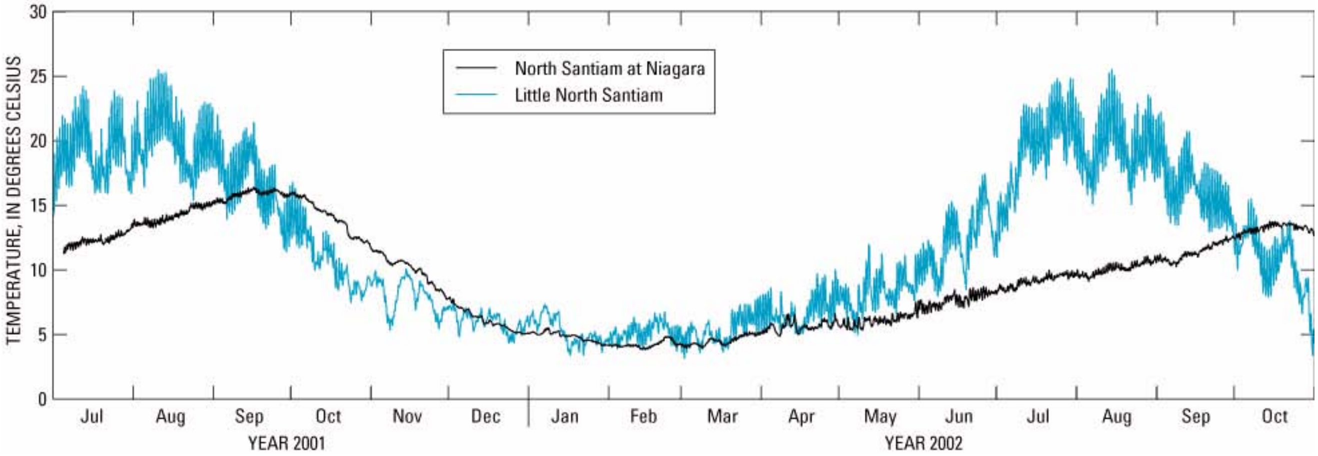

Figure 5. Water temperatures in the North Santiam River at Niagara (USGS station 14181500), just downstream from the dams, and at the Little North Santiam (USGS station 14182500) for July 2001 through October 2002.

In addition to the shade file based on the ODEQ digitized data (current conditions), shade files were prepared to represent the effect of no riparian vegetation and the effect of "system potential" vegetation. System potential vegetation is a representation of mature riparian vegetation with little natural disturbance and without anthropogenic influence. System potential vegetation characteristics were estimated by ODEQ by analyzing geology, historic vegetation, ecoregions and soils (ODEQ, unpub. data, 2003). Calculated vegetative shade under current and system potential conditions along the rivers on August 1, 2001, is shown in figure 6. Topographic shading was included in all model runs.

Ground Water and Ungaged Tributaries

The model allows for input of "distributed" tributaries that represent ungaged tributaries and inflows of ground water. Flows from a distributed tributary are spread out along an entire branch of the model rather than discharging at a specific location. Because neither ground-water inflow/outflow nor ungaged tributaries were monitored, the use of a distributed tributary was an integral part of the water balance calibration. The relative importance and application of these distributed tributaries is discussed further in the calibration section of this report.

Temperatures of these distributed tributaries were estimated to be a mix of ground-water inflow and ungaged tributaries. Ground-water temperature was estimated as 11°C for the upper two branches and 11.5°C for the lower four branches, based on annual mean air temperature at Detroit and Stayton, respectively. Ungaged tributaries were assigned a temperature equal to that of the Little North Santiam River.

Calibration Data

Calibration data consisted of a set of measured streamflow, travel time, wetted channel width, and temperature data along the two rivers. These data were compared to model output from the segment(s) corresponding to the measurement location to evaluate model performance.

Half-hourly streamflow data were obtained from two USGS gages. One gage was located on the North Santiam River at Mehama (USGS station 14183000) just downstream of the confluence with the Little North Santiam River. The other gage was located on the Santiam River at Jefferson (USGS station 14189000). Data were available for all the time periods simulated.

Dye studies were conducted by Harris (1968) to determine water travel times in 11 separate reaches of the North Santiam and Santiam Rivers. To compare these travel times to the model, a conservative tracer was simulated in the model at various flow conditions in 2001 and 2002, and the location of the tracer peak was tracked as it traveled downstream through the model segments. The time required for the simulated tracer peak to travel through segments corresponding to Harris' defined reaches and an average flow from these same segments were calculated from the model output.

USGS personnel measured wetted river widths with a laser rangefinder at 24 locations on the North Santiam River and 3 locations on the Santiam River at 3 times in 2002: April 9–10, June 4, and August 6. These data captured river widths at high, medium and low flow conditions, respectively. These field-measured widths were compared to simulated wetted width on the same dates.

Simulated water temperatures were compared to measured data at 16 locations in 2001 and at 5 locations in 2002. Information on the locations, corresponding model segments, source, and collection dates of these monitoring stations is summarized in table 3.

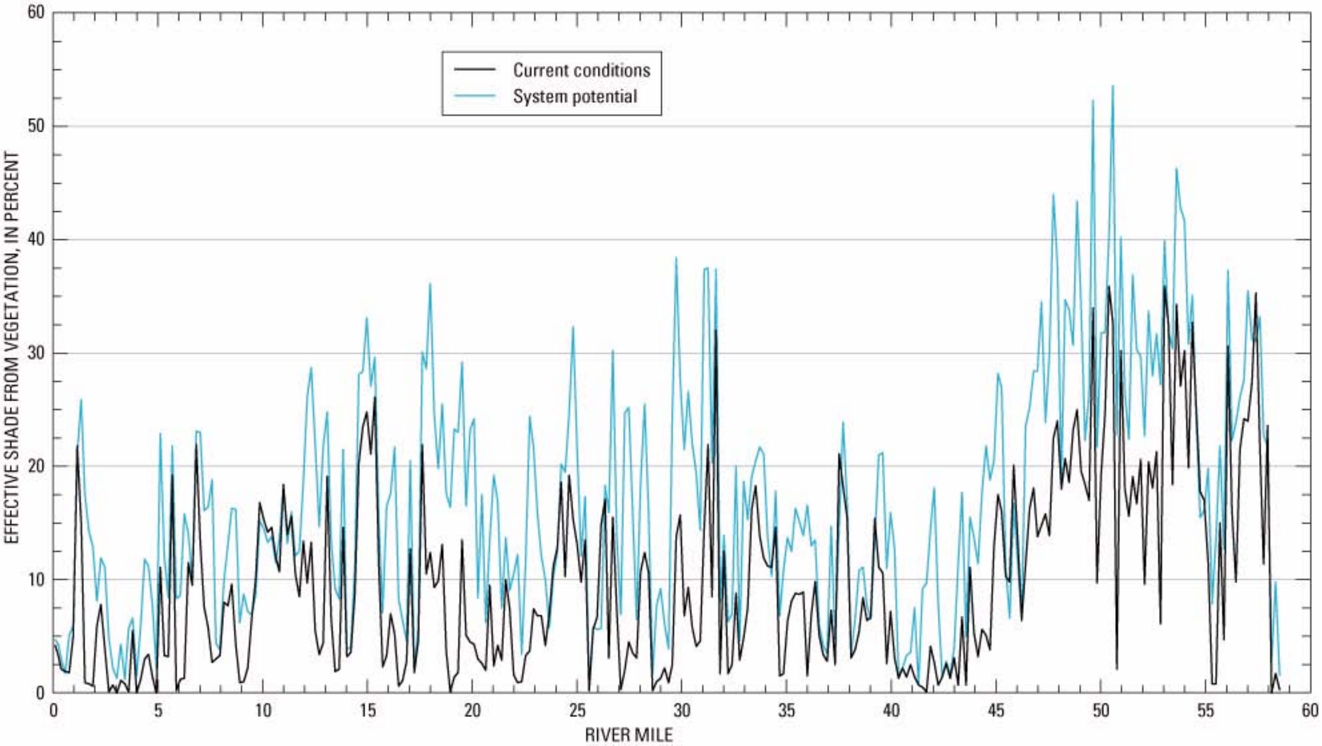

Figure 6. Vegetative shading for current conditions and system potential on August 1, 2001, for the North Santiam and Santiam Rivers. Shading is calculated as the percentage of the solar radiative flux that is blocked over the course of the entire day.

Model Calibration

Water Balance

The water-balance calibration was completed by comparing measured calibration data to model output and adjusting model parameters to achieve agreement between the two. This was an iterative process, using flows, wetted widths, and travel-time calibration data. Here, the results for each of these comparisons are presented sequentially.

Flow

After an initial simulation using 2001 data, the comparison of simulated flow to measured flow at the two USGS gages at Mehama and Jefferson demonstrated that the model was not accounting for enough flow. While each of the three major tributaries were included in the model, a number of small ungaged tributaries exist along the rivers. Some uncertainty also was inherent in the flows on the lower part of ODEQ’s South Santiam River model because no nearby gages existed with which to calibrate flow in the lower reach of that river. Also, ground-water exchange with the river was not measured. The sum of all of these unmeasured and uncertain flows were estimated using a distributed tributary inflow to achieve a reasonable agreement between measured and simulated flows.

Upstream of Mehama (RM 38.7) in 2001, the largest differences in flow occurred during precipitation events; a distributed tributary inflow was added to the upper two model branches to correct for the extra flow. These ungaged inflows were assumed to be a mix of 70 percent surface inflows with a temperature of the Little North Santiam River and 30 percent ground-water inflows with a temperature of 11°C.

At the Jefferson gage on the Santiam River (RM 9.7), the difference between simulated and measured flow was more constant through the time period simulated. The missing inflows were apportioned equally between the North Santiam and South Santiam Rivers. On the North Santiam River, the flows were distributed uniformly to the model branches between Mehama and the end of the river according to branch length. Temperatures were estimated by assuming a mix of 50 percent ground-water inflow at 11.5°C and 50 percent ungaged tributaries with the same temperature as the Little North Santiam River. The water balance after these adjustments for 2001 is shown in figure 7. The missing flows apportioned to the South Santiam River were added to the simulated flows from ODEQ’s model, and temperatures were not changed.

After calibrating the model with 2001 data, the model was tested with 2002 data. In the 2002 water balance, some unaccounted-for flows again were present during storm events. These flows were attributed to ungaged inflows and included as distributed tributaries, similar to the method used in 2001.

Table 3. Locations of monitors used to calibrate water temperature in the North Santiam and Santiam Rivers.

[SWC, Santiam Watershed Council; USGS, United States Geological Survey; SECOR, SECOR International, Inc.; n/a, not available]

Approximate river mile	Model segment	Latitude/Longitude	Source	Data availability (month/day)	
				[1]2001	[2]2002
43.6	81	44.76683/122.53149	SECOR	7/1–11/3	6/11–10/7
42.1	89	44.76836/122.55969	SWC	7/1–9/29	
38.7	110	44.7889/122.6167	USGS (gage 14183000)	7/1–11/21	4/1–10/31
35.6	126	44.08389/122.65931	SWC	7/1–9/28	
35.5	126	44.77828/122.67694	SWC	7/1–9/10	
31	150	44.79110/122.74997	SECOR	7/1–9/25	
28.7	167	n/a	SECOR	7/1–9/25	
24.3	186	44.77027/122.84771	SECOR		6/11–7/22
23	193	44.75333/122.85792	SWC	7/1–9/26	
22.3	196	44.75447/122.87389	SWC	7/1–9/26	
15.7	234	44.72133/122.95650	SWC	7/1–9/26	
14.6	240	44.70863/122.97207	SECOR	8/2–11/7	6/11–10/7
11	263	44.69528/123.01650	SWC	7/6–10/10	
9	274	44.72339/123.01672	SWC	7/6–10/10	
6.1	289	44.7389/123.0486	USGS (gage 14189050)	7/1–10/31	4/1–10/31
3.35	303	44.74747/123.09131	SWC	7/6–10/3	
3.25	304	44.74686/123.09467	SWC	7/6–10/3	

[1] Dates modeled in 2001 were 7/1 through 11/21.

[2] Dates modeled in 2002 were 4/1 through 10/31.

At Mehama, for 2001 and 2002, the distributed tributary flows were generally less than 3 percent of the total flows. During spring and winter storms, the distributed tributary flow was larger and could be up to 18 percent of the total flow. At Jefferson for 2001 and 2002, the distributed tributary flows generally were between zero and 10 percent of the total flows. During spring and winter storms, distributed tributary flows accounted for up to 22 percent of the total flow. In addition, during low flow in 2002 only, the measured flow at the upstream gage at Niagara was higher than that further downstream at Mehama, necessitating the inclusion of a withdrawal of water between those two locations. No withdrawals of that magnitude were recorded by OWRD, and this phenomenon is unusual. Gage data were double-checked, but no measurement errors were found. The discrepancy may represent an unreported withdrawal from the river, pumping from ground water near the river, or a natural loss of river water to ground water. The final 2002 water balance is shown in figure 7.

Channel Width

Field-measured wetted-channel widths were compared to simulated wetted-channel widths, and results of that comparison were used to adjust layer widths in the model grid. A comparison of the final wetted-channel widths simulated by the model and those measured in the field by USGS on the same date, August 6, 2002, is shown in figure 8. The USGS measurements were at discrete points along the river, while the simulated widths represent averages for 1000-ft long segments. The ODEQ channel widths in figure 8 are included for comparison, and while they were digitized at a relatively fine interval of 100 ft, the dataset includes channel widths on different dates and at different flows. The final model bathymetry was able to represent the wetted channel widths of the rivers at different flows with sufficient accuracy for the purposes of this investigation.

Travel Times

Simulated travel times at different flows for model simulations in 2001 and 2002 were compared to measured travel times for a tracer peak in the reaches measured by Harris (1968) (fig. 9). The simulated travel times compare well with the measured values, but in some reaches the slopes of simulated and measured travel times show a difference. The slopes of the simulated travel time versus discharge data were similar for all 11 reaches. Dunne and Leopold (1978) show that for stations along a river system, the slopes of these curves should be similar, while their ordinate position may differ. On the other hand,

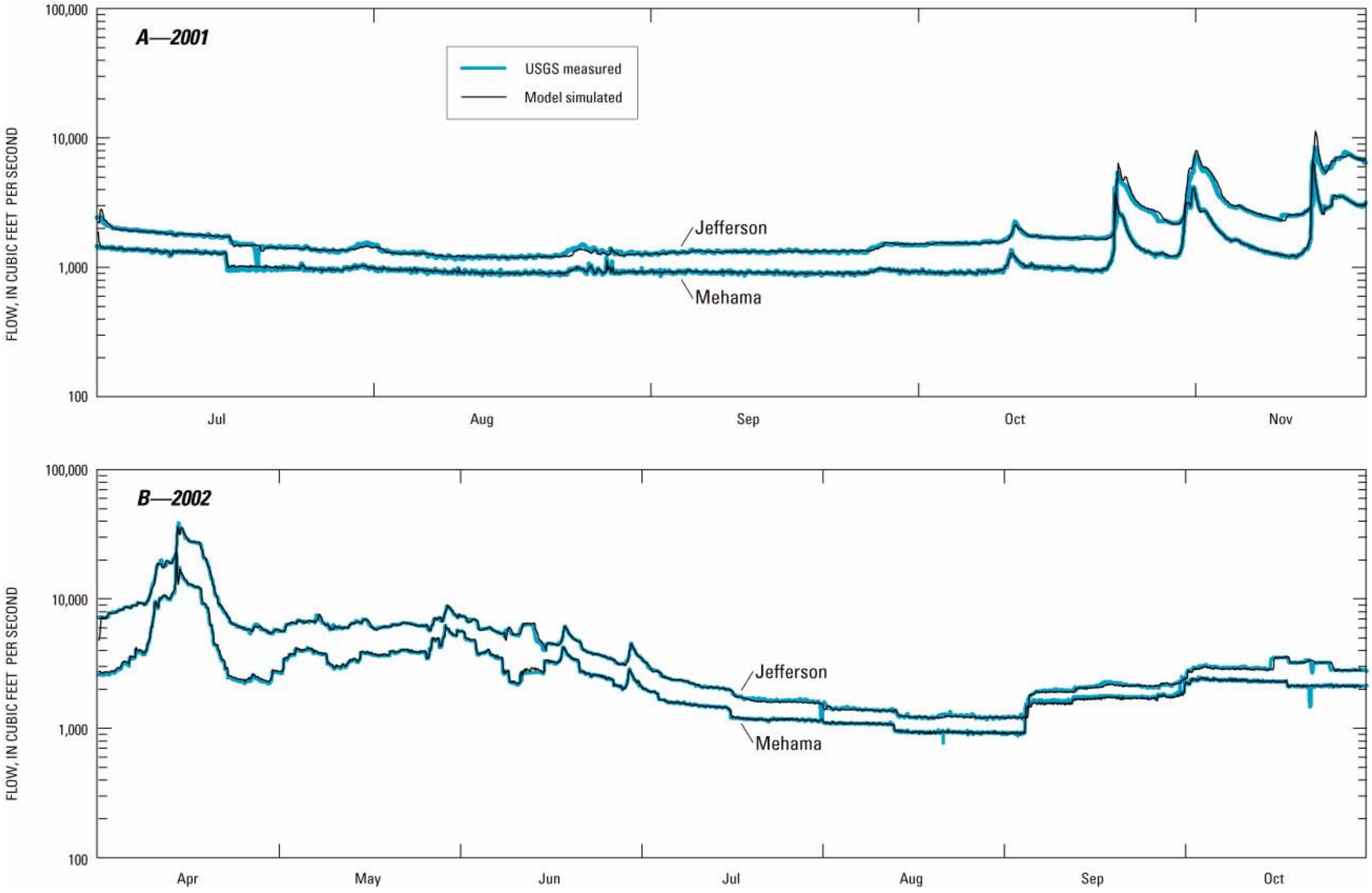

Figure 7. Comparison of measured streamflow at the USGS gages at Mehama (USGS station 14183000) and Jefferson (USGS station 14189000) to calibrated model output for (*A*) 2001 and (*B*) 2002.

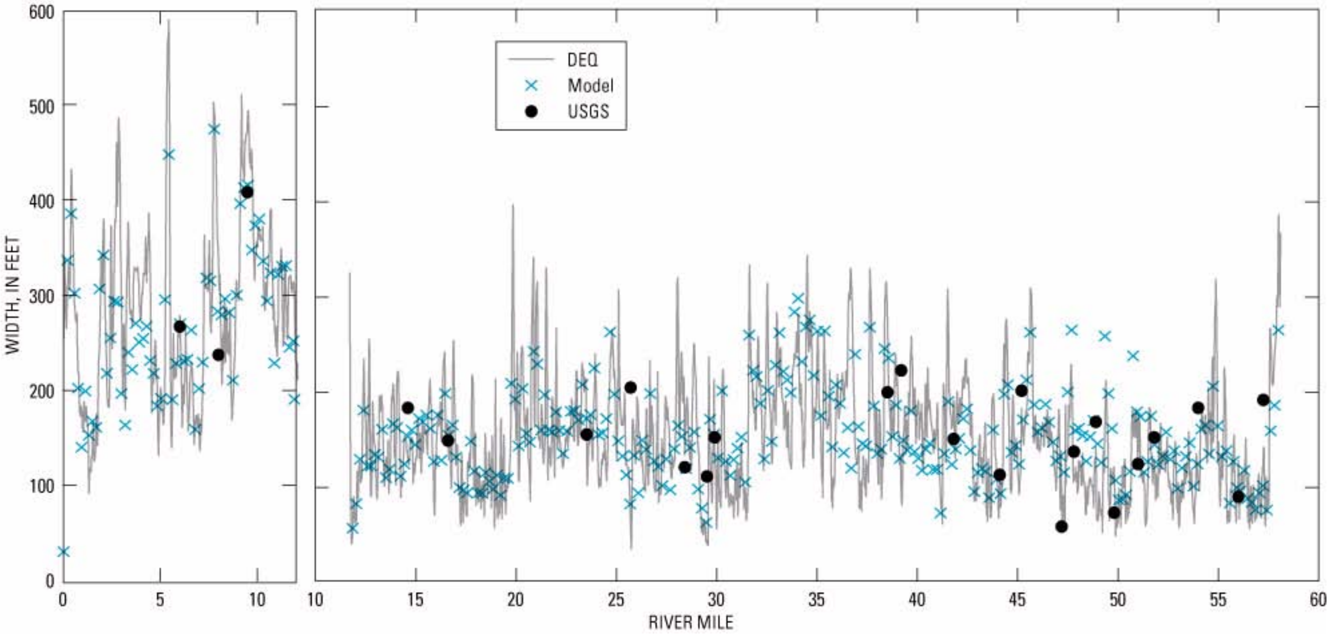

Figure 8. Comparison of USGS field-measured channel width to Oregon Department of Environmental Quality digitized channel width and to wetted width from the calibrated model. The USGS field-measured data and model data output are for the same date (August 6, 2002) and flow, while the ODEQ widths are from a range of dates and flows.

results from the Harris (1968) travel time study show a range in slopes. The reason for this is not clear, but it may be related to the fact that the North Santiam River channel becomes braided in some portions of the reach below Mehama (RM 38.7). Routing of the river water through a system of smaller side channels would probably change water travel time behavior compared to the one-channel representation of the model. The travel time comparison, while certainly not perfect, was deemed to be sufficiently accurate for the needs of this study.

Water Temperature

After the water-balance calibration was complete, very little calibration was needed to simulate water temperatures accurately. A comparison of daily average and hourly measured and simulated temperature is shown in figure 10 for selected stations in 2001 and in figure 11 for all stations in 2002. Because the daily temperature variations were large, a seasonal comparison between simulated and measured temperature is shown using daily average temperatures. Hourly water temperatures are shown for a 2-month period. Error statistics, including mean absolute error (MAE) and root mean square error (RMSE), for the comparison between the hourly model output and measured data for the 16 temperature stations are shown in table 4. These MAEs ranged from 0.41°C to 1.02°C and the RMSEs ranged from 0.50°C to 1.16°C. Similar error statistics for the 7dADM, the 7-day moving average of the daily maximum water temperature, used in the water temperature standard, are shown in table 5. These MAEs ranged from 0.15°C to 1.05°C and RMSEs ranged from 0.21°C to 1.14°C. The smoothing effect of the 7dADM, and the fact that the model was more successful at matching daily maxima compared to daily minima, made for a better fit.

Differences between measured and simulated water temperatures can be due to several factors. First, the measurements and model output are at different scales, as temperature measurements were from discrete points in the river, while model output was laterally and vertically averaged through the water-column and longitudinally averaged through each 1,000-ft segment.

Temperature monitors also can be affected by local environmental conditions. The temperature monitor at RM 9 (not included in fig. 10 or 11) in the Santiam River appeared to show local effects. From early July through mid-August, the measured and simulated hourly temperature cycles were of similar magnitude. Thereafter, the measured hourly temperature signal became increasingly damped, until by early October, very little daily variation remained in the measured temperature. Measurements both upstream and downstream of this station did not show a similar decrease in the magnitude of the daily temperature cycle. The monitor may have become covered by sediment or algae, buffering it from daily heating and cooling cycles.

Some of the largest differences between measured and simulated water temperature on the North Santiam River occurred in 2002 at RM 38.7, just downstream of the inflow of the Little North Santiam River. From mid-May to mid-June, the measured temperature was higher than the simulated temperature. The most plausible explanation for this is that the Little North Santiam River may not have completely mixed into the

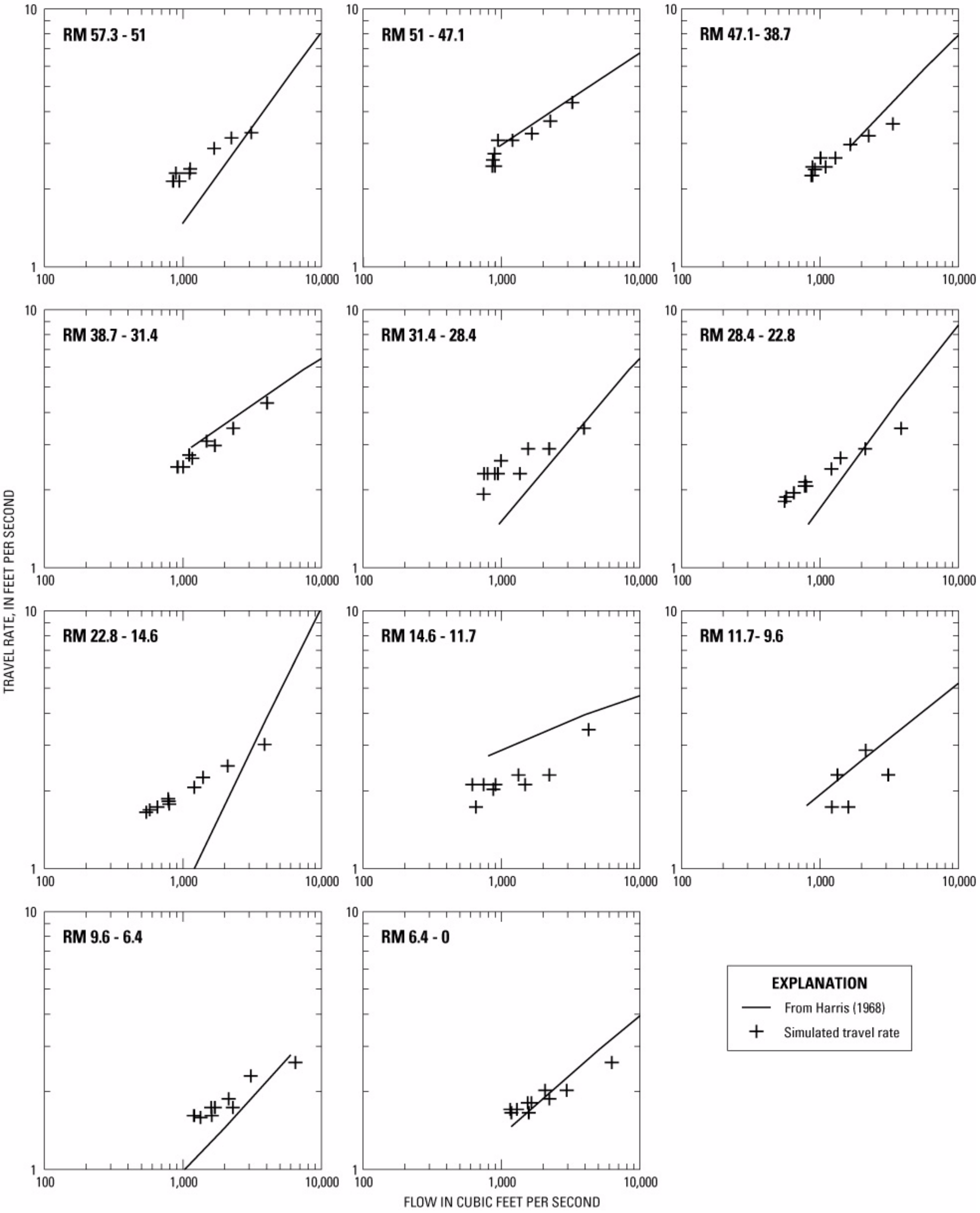

Figure 9. Comparison of simulated travel times to field measurements by Harris (1968). Data represent the velocity of the peak concentration of an injection of a nonreactive dye tracer.

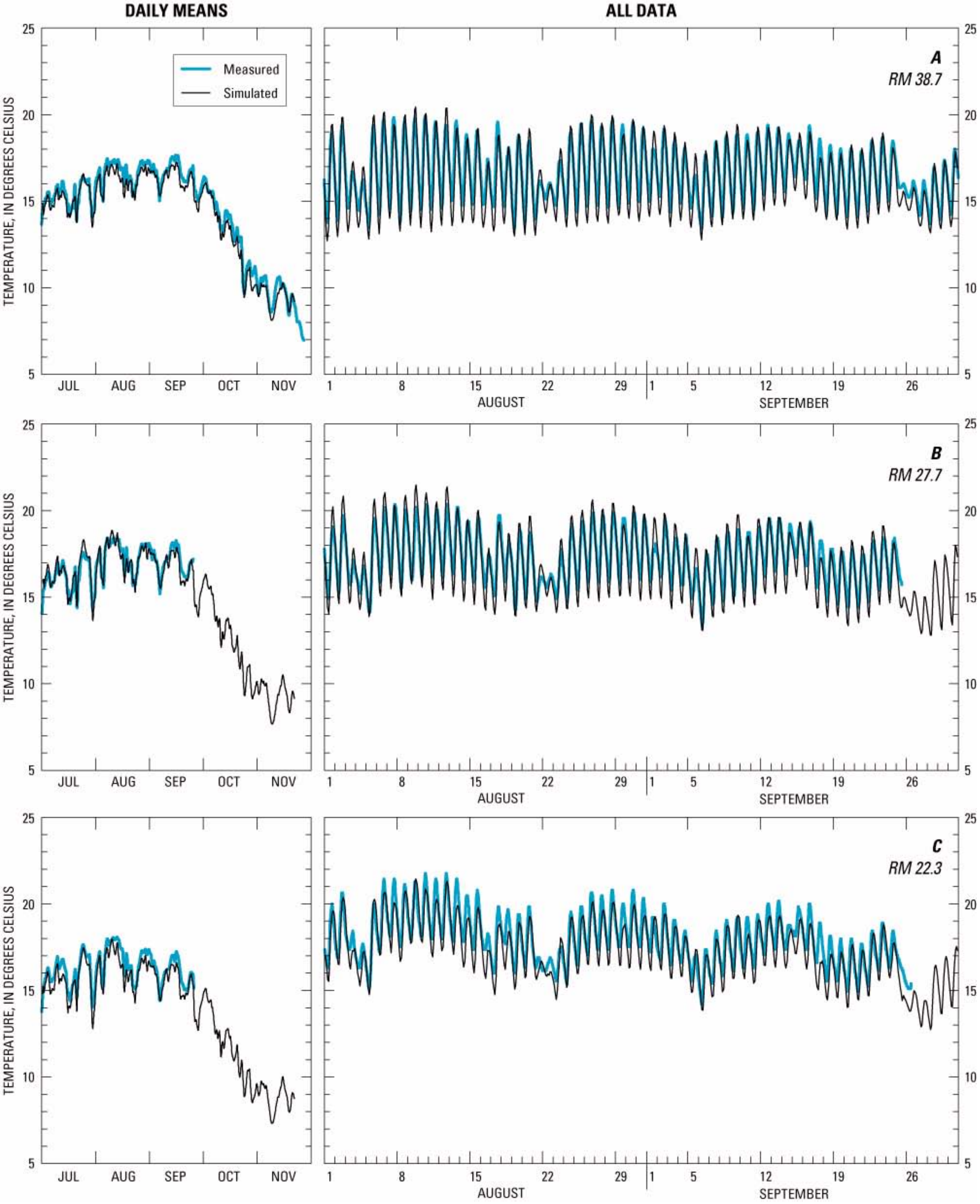

Figure 10. Daily average and hourly comparison of model output to measured temperature at calibration stations in 2001. River mile (RM) locations are noted: (*A*) river mile 38.7, (*B*) river mile 27.7, (*C*) river mile 22.3, (*D*) river mile 11, (*E*) river mile 6.1, (*F*) river mile 3.25.

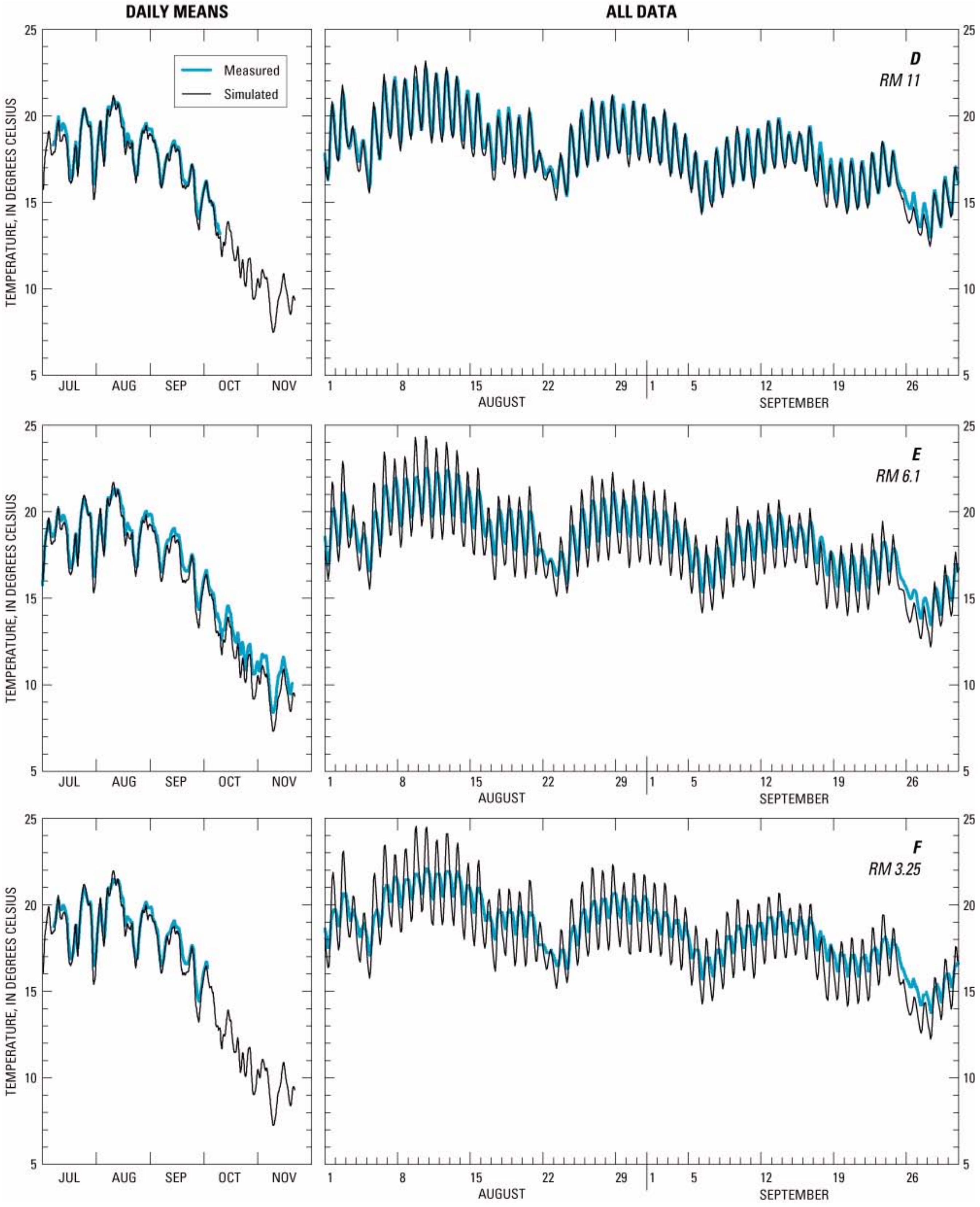

Figure 10. Daily average and hourly comparison of model output to measured temperature at calibration stations in 2001. River mile (RM) locations are noted: (*A*) river mile 38.7, (*B*) river mile 27.7, (*C*) river mile 22.3, (*D*) river mile 11, (*E*) river mile 6.1, (*F*) river mile 3.25—Continued.

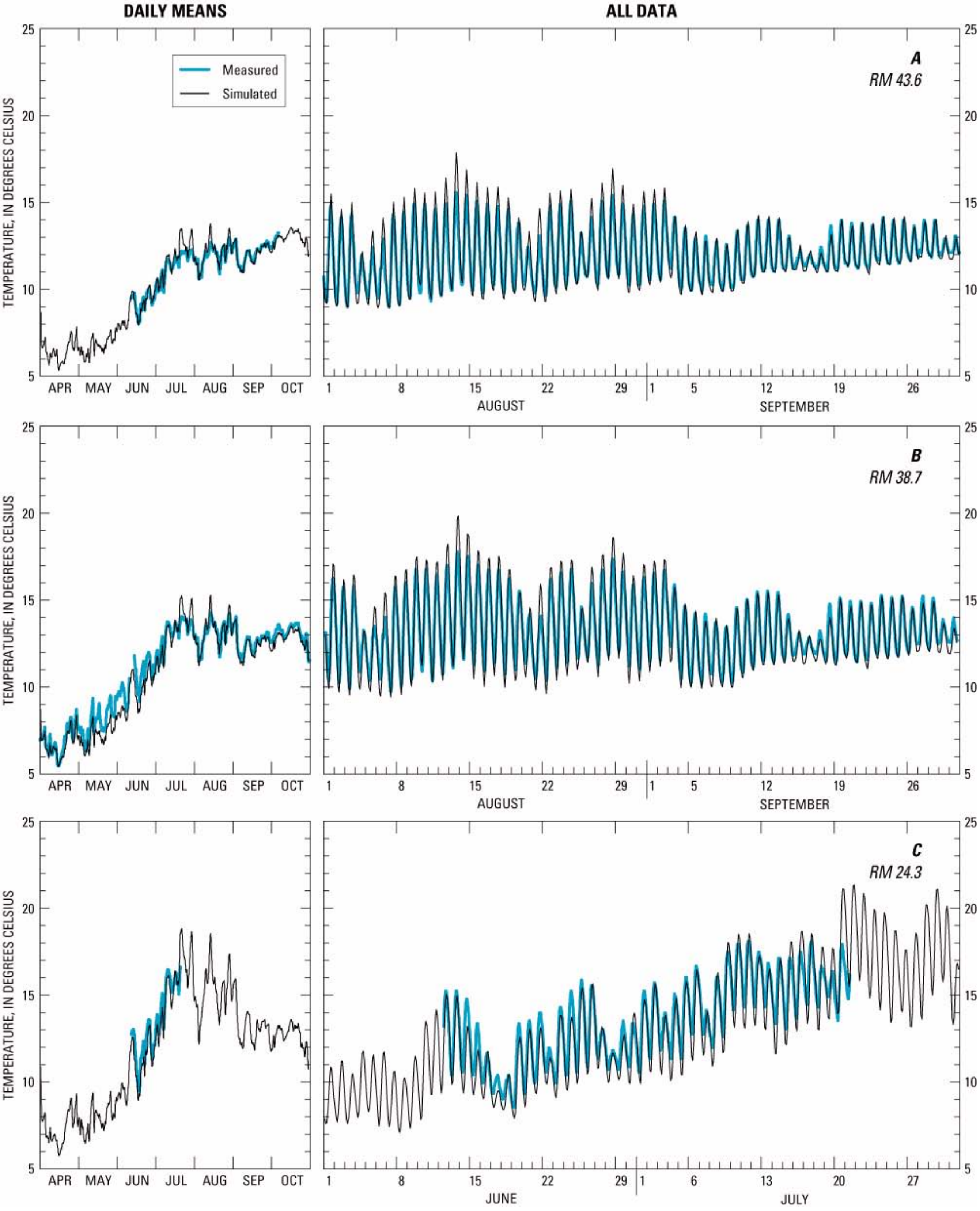

Figure 11. Daily average and hourly comparison of model output to measured temperature at calibration stations in 2002. River mile (RM) locations are noted: (*A*) river mile 43.6, (*B*) river mile 38.7, (*C*) river mile 24.3, (*D*) river mile 14.6, (*E*) river mile 6.1.

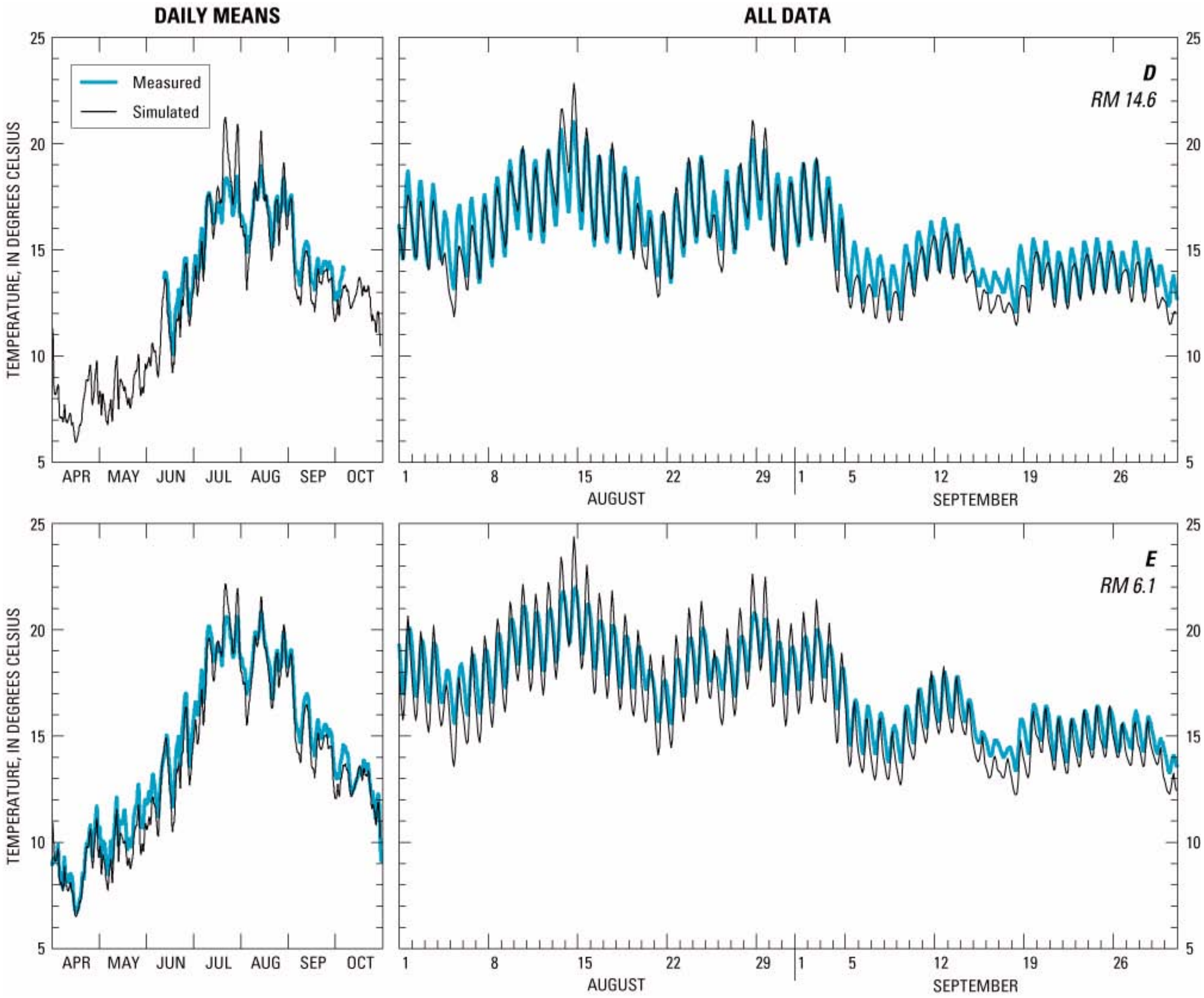

Figure 11. Daily average and hourly comparison of model output to measured temperature at calibration stations in 2002. River mile (RM) locations are noted: (*A*) river mile 43.6, (*B*) river mile 38.7, (*C*) river mile 24.3, (*D*) river mile 14.6, (*E*) river mile 6.1—Continued.

North Santiam River; the Little North Santiam River joins the North Santiam River on the north bank (the right bank, looking downstream), the same bank where the temperature monitor is located. At that time, the temperature of the tributary was higher than that of the North Santiam River, and tributary inflows were relatively high. Prior to this time period, tributary and main-stem temperatures were similar, while after July, the flow from the Little North Santiam River was small and less significant. This explanation was corroborated through an examination of measured temperature cross-sections during these time periods.

Overall, the largest differences between measured and simulated hourly temperatures in both years were in the lower portions of the Santiam River. On an hourly timescale, the measured temperature signal was damped compared to the simulated temperature, and this effect increased with increasing proximity to the confluence of the Santiam River with the Willamette River. One possible explanation for this is that the thick gravels that underlie this portion of the river allowed a large amount of hyporheic flow. Interaction of the river water with ground water would have buffered the daily temperature variation. The lower reach of the Santiam River is known to have a large amount of hyporheic exchange (Hinkle and others, 2001; Laenen and Bencala, 2001). The direction of the exchange was found to alternate between ground-water discharge to the river and river-water flow into the subsurface in the lower Santiam River, depending on flow and channel characteristics.

The water temperature standard for these rivers is based on a 7dADM water temperature. This information is shown for the calibrated model for the North Santiam River and Santiam River in both 2001 and 2002 in figure 12. Each point on these

Table 4. Goodness of fit statistics for hourly water temperature (in degrees Celsius).

River	Approximate river mile	Model segment	2001, mean absolute error	2001, root mean square error	2002, mean absolute error	2002, root mean square error
North Santiam	43.6	81	0.50	0.60	0.43	0.66
	42.1	89	0.67	0.86		
	38.7	110	0.57	0.68	0.56	0.70
	35.6	126	0.71	0.86		
	35.5	126	0.80	0.98		
	31	150	0.67	0.81		
	28.7	167	0.58	0.70		
	24.3	186			0.83	1.09
	23	193	0.76	0.93		
	22.3	196	0.74	0.91		
	15.7	234	0.58	0.73		
	14.6	240	0.65	0.81	0.78	1.01
Santiam	11	263	0.41	0.50		
	†9	274	0.55	0.66		
	6.1	289	0.86	0.96	0.84	0.98
	3.35	303	0.98	1.12		
	3.25	304	1.02	1.16		

†Statistics for this location computed using only data from before sensor became buried.

Table 5. Goodness of fit statistics for 7dADM water temperature (in degrees Celsius).

[7dADM, 7-day average of daily maximum]

River	Approximate river mile	Model segment	2001, mean absolute error	2001, root mean square error	2002, mean absolute error	2002, root mean square error
North Santiam	43.6	81	0.47	0.59	0.65	0.82
	42.1	89	0.51	0.59		
	38.7	110	0.27	0.32	0.49	0.63
	35.6	126	0.35	0.42		
	35.5	126	0.24	0.27		
	31	150	0.44	0.50		
	28.7	167	0.44	0.53		
	24.3	186			0.32	0.41
	23	193	0.55	0.61		
	22.3	196	0.39	0.45		
	15.7	234	0.32	0.44		
	14.6	240	0.49	0.62	0.59	0.67
Santiam	11	263	0.15	0.21		
	†9	274	0.56	0.62		
	6.1	289	0.69	0.77	0.79	0.95
	3.35	303	1.05	1.14		
	3.25	304	1.04	1.14		

†Statistics for this location computed using only data from before sensor became buried.

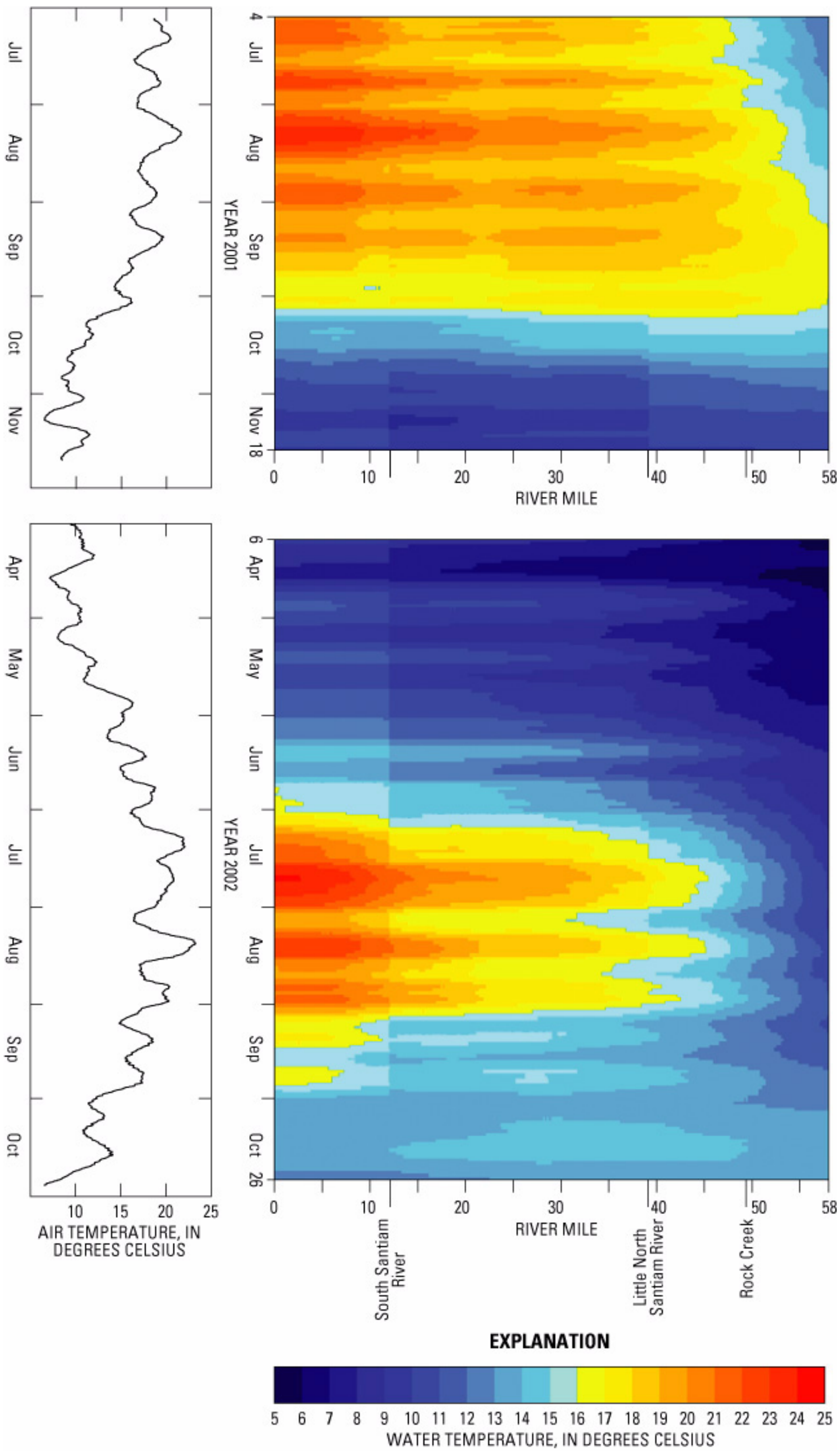

Figure 12. Simulated 7-day moving average of daily maximum water temperature in degrees Celsius for 2001 and 2002. A time series of the 7-day moving average of air temperature shows the correlation of temporal patterns in both datasets.

graphs uses a color to represent the 7-day moving average of daily maximum temperature for a particular location and time. During summer, the water just below the dams (right side of figure) was generally the coldest in the whole system. Discharges from Detroit Lake were drawn from deeper, colder water during summer. Late in the year, in October, the pattern reversed, and the outflow from the dam was warmer than other parts of the North Santiam River downstream. At this time of year Detroit Lake is drawn down, and the reservoir is discharging water with stored summer heat. Overall, the warmest temperatures in the system were in the Santiam River during the summer, often reaching well above 20°C. Water temperatures in 2001, a low-flow year, were warmer further upstream and for a longer time period than in 2002, a more typical flow year.

A strong water temperature cycle of approximately a 2-week timescale is obvious in both 2001 and 2002. Air temperature showed similar temporal cycles in both years. The air temperature and water temperature cycles seen in figure 12 are indicative of the strong influence of meteorological factors in controlling water temperature. Releases from the dams provide an initial temperature to a parcel of water as it travels through the system, but the influence of the release temperature diminishes as the water travels downstream. Generally, water travels through the system in 1 or 2 days, depending on flow. In that short time, 7dADM water temperatures can be warmed by over 10°C in summer from the dams to the mouth of the Santiam River. Tributary inflows did not have a large influence on 7dADM water temperatures in this system. The location of the inflows of Rock Creek, the Little North Santiam River and the South Santiam River are noted in figure 12, and the changes in 7dADM water temperatures at the mixing locations of these tributaries is small.

Considering the water temperature standards of 17.8°C in summer and 12.8°C in winter (table 1), the rivers exceeded the water temperature standards for long periods in summer and fall, as shown in figure 13. In these graphs, simulated temperatures in the Santiam River and North Santiam Rivers were compared to the 17.8°C standard from July 1 through September 14, and to the 12.8°C temperature standard from September 15 through June 30. In parts of 2001 and 2002, most or all of these rivers exceeded the standards. Areas of greatest exceedance typically occurred near the mouth of the Santiam River or when the standard switched from 17.8°C to 12.8°C in fall. The low-flow year, 2001, had longer reaches with higher exceedances than 2002.

Sensitivity Analysis

To determine the relative effect of individual model parameters or dam releases on simulated river temperatures, a series of sensitivity tests was run by taking the calibrated model and adjusting one input parameter or condition at a time. Sensitivity runs were conducted for 2001 only using the North

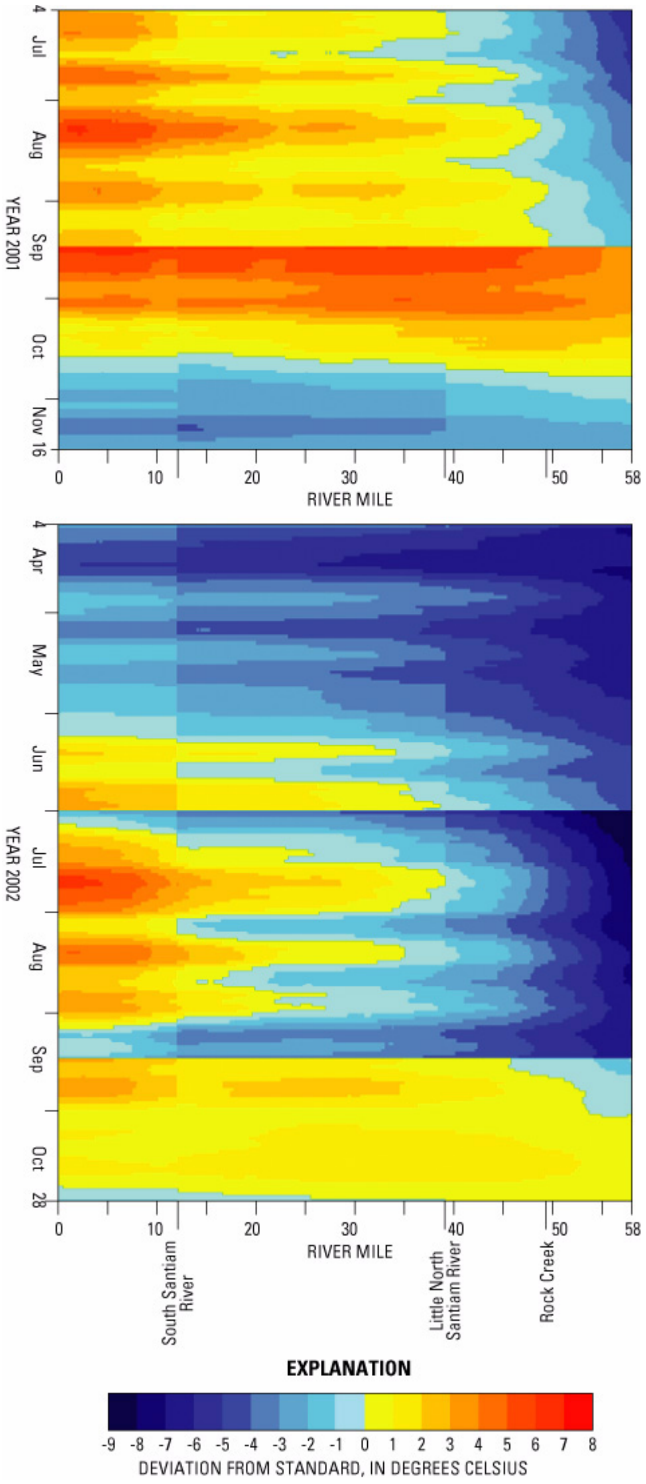

Figure 13. Difference between the simulated 7-day moving average of daily maximum water temperature and the applicable water temperature standard in degrees Celsius. The temperature standard was 17.8°C from July 1 through September 14, and 12.8°C for the rest of the year. (Note that the temperature standard has since changed. See Appendix 1.)

Santiam River part of the model. Parameters were changed as follows:

1. Removal of the point source at Stayton
2a. Dam release temperature increased by 5°C
2b. Dam release temperature decreased by 5°C
3a. Air temperature increased by 5°C
3b. Air temperature decreased by 5°C
4a. Riparian vegetation at system potential
4b. No riparian vegetation
5a. Dam release flow increased by 20 percent
5b. Dam release flow decreased by 20 percent

The greatest overall change in river temperature was produced by changing the temperature of the dam releases. However, the magnitude of that change decreased significantly with distance downstream. The effect of changing air temperature increased with distance from the dams. Changes to riparian shade, which affects the amount of solar radiation reaching the stream, produced small temperature changes along most of the river. Changes to dam release flows produced both warming and cooling in each simulation, depending on the time of year. The point source at Stayton was small enough that its removal had no effect on river temperature. Further details of the results from the sensitivity analyses are given below.

Point Sources

The base model was adjusted by removing the wastewater treatment plant point-source input at Stayton on the North Santiam at river mile 27.5. This produced no change (<0.01°C) in the simulated 7dADM water temperature from July 1 to November 26, 2001 (table 6). The point source at Stayton was small compared to the flow in the river, and effluent temperatures were similar to river temperatures. The North Santiam River channel is braided in this part of the river, however, and Stayton discharges only into the smaller north channel. The effect of the effluent in a smaller channel may be more significant, as the current model considers all flow to occur in only one channel. Further analysis regarding the effects of this point-source discharge on its receiving water may be merited.

Dam Release Temperature

The base model was adjusted by first increasing and then decreasing the dam release water temperatures at Big Cliff dam by 5°C. These changes produced a measurable change in water temperatures throughout the North Santiam River for the entire time period simulated (fig. 14 and table 6).

The 5°C increase in dam release temperatures produced an average 7dADM temperature change of +2.74°C for July 1 through November 26, 2001 (table 6). The magnitude of that temperature change was greatest near the dams (fig. 14) with a +4°C to +5°C increase in temperature. The effect decreased with downstream distance as the river had more time to exchange heat with its surroundings. At the mouth of the North Santiam River, the temperature change had been reduced to between +1°C and +3°C, depending on the time of year, showing that more than half of the temperature increase had dissipated. The fact that this change is dissipated in only about 1.5 days of travel time attests to the rapid exchange of heat between the river and the atmosphere. The seasonal variation in the tem-

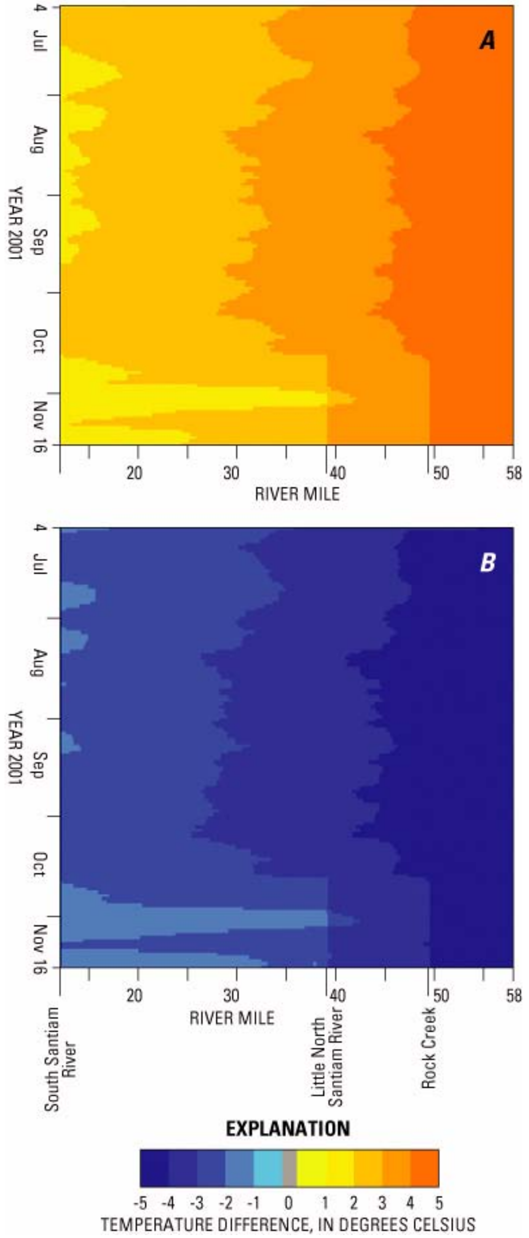

Figure 14. Difference in water temperature between the base model and the model with dam release temperatures (*A*) increased by 5°C and (*B*) decreased by 5°C, using the 7-day moving average of daily maximum water temperature in degrees Celsius. The gray color zone includes all temperature differences within 0.05°C of 0°C.

Table 6. Summary of the model sensitivity analysis for the North Santiam River in 2001.

[Values are averages of simulated 7dADM water temperatures compared to the base case for all segments on all days in each month. 7dADM, 7-day average of daily maximum; °C, degrees Celsius]

		Average change in 7dADM water temperature, °C					Overall
Parameter	**Change**	**July**	**August**	**September**	**October**	**November**	**July–November**
Point sources	No point sources	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Inflow temperature	+5°C	+2.75	+2.84	+2.86	+2.70	+2.43	+2.74
	-5°C	-2.83	-2.94	-2.96	-2.77	-2.47	-2.82
Air temperature	+5°C	+0.72	+0.82	+0.79	+0.67	+0.43	+0.70
	-5°C	-0.69	-0.78	-0.76	-0.64	-0.41	-0.67
Riparian shade	System potential	-0.21	-0.26	-0.28	-0.09	-0.03	-0.18
	No vegetative shade	+0.31	+0.38	+0.46	+0.19	+0.09	+0.30
Inflows	+20%	-0.33	-0.28	-0.05	+0.11	+0.09	-0.09
	-20%	+0.42	+0.34	+0.07	-0.22	-0.10	+0.12

perature change was small, with the greatest monthly average change of +2.86°C in September and the smallest, +2.43°C, in November. After mid-October, flows from the unregulated tributaries, Rock Creek and the Little North Santiam River, became significant (fig. 4B), causing obvious cooling to the warmer upstream water.

Imposing a 5°C decrease in dam release temperatures produced an average 7dADM temperature change of -2.82°C on the North Santiam River between July and November 2001. The spatial and seasonal patterns of the decrease in temperature were similar to those for the increase in dam release temperatures. The greatest decrease in temperature was -2.96°C in September, and the smallest decrease, -2.47°C, was in November. Note that temperature changes downstream of the Little North Santiam River in November 2001 were smaller (less affected by dam releases) because of higher flows from the Little North Santiam River Basin.

Air Temperature

The relative effect of air temperature on 7dADM water temperature was examined by increasing and then decreasing air temperature by 5°C in separate model simulations. The results of these sensitivity tests are shown in figure 15 and table 6.

Increasing air temperature produced a +0.70°C overall average change in water temperature in the North Santiam River from July 1 through November 26, 2001. The spatial pattern was opposite of that of changing dam release temperatures. The water temperature change was negligible just downstream of the dams, and increased with distance away from the dams. This result makes sense because time must pass in order to allow a change in air temperature to affect the simulated water temperatures. No change occurred near the dams because an insufficient amount of time had elapsed to observe an effect. The greatest monthly average temperature change was +0.82°C in August, and the smallest change was +0.43°C in November, due to higher flows and shorter travel times.

Decreasing air temperature produced a -0.67°C overall 7dADM water temperature change. The spatial pattern of the change in the North Santiam River was similar to that for the increase in air temperature. The decrease in temperature was greatest in August, -0.78°C, and least in November, -0.41°C.

Riparian Vegetation

The base model was adjusted by first considering system-potential riparian vegetation, and then examining the effect of removing all riparian vegetation. Topographic shading information, a separate model input, was unchanged in all of these shade sensitivity analyses. The results of the riparian-vegetation sensitivity analysis are presented in figure 16 and table 6.

System potential shade, a mature vegetative shade without anthropogenic influence and little natural disturbance, cooled the 7dADM water temperature on average by -0.18°C between July 1 and November 26, 2001. The change was fairly consistent spatially, producing a change of between 0°C and -1°C throughout the North Santiam River, with the largest changes occurring at the most downstream site. The greatest cooling occurred in September, with a -0.28°C average change, while the temperature change was very small in November, -0.03°C. The smaller temperature changes in November are attributable

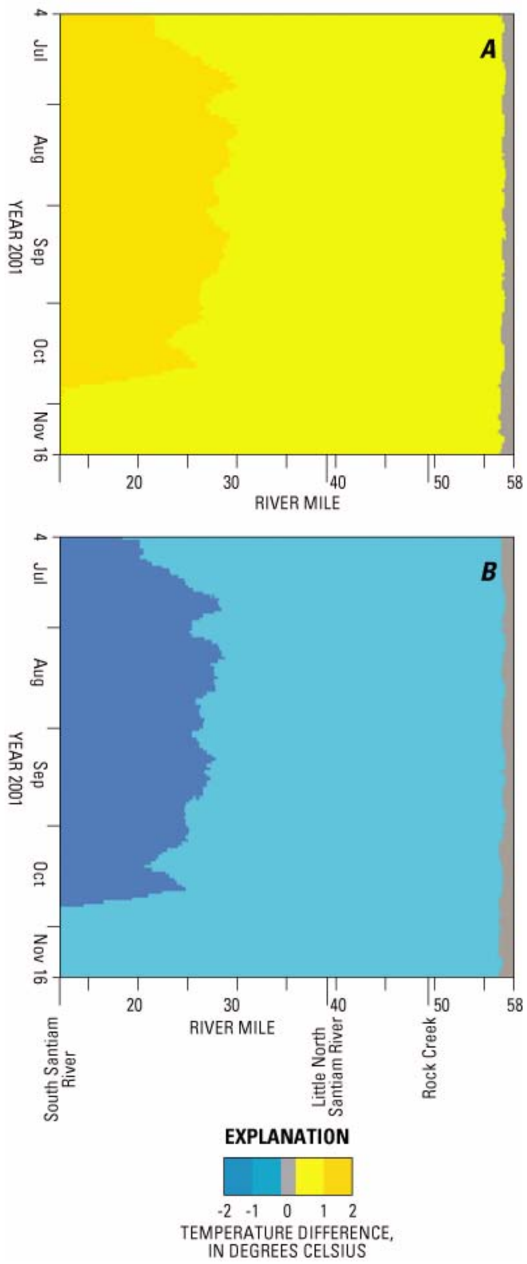

Figure 15. Difference in water temperature between the base model and the model with air temperature (*A*) increased by 5°C and (*B*) decreased by 5°C, using the 7-day moving average of daily maximum water temperature in degrees Celsius. The gray color zone includes all temperature differences within 0.05°C of 0°C.

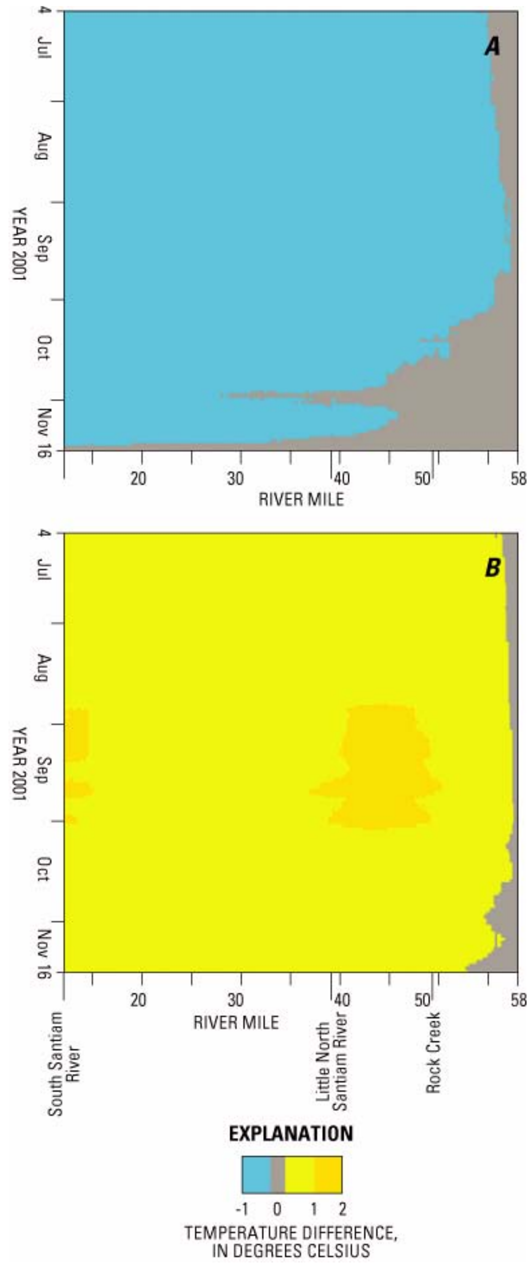

Figure 16. Difference in water temperature between the base model and the model (*A*) with system potential shade and (*B*) without any riparian shade, using the 7-day moving average of daily maximum water temperature in degrees Celsius. The gray color zone includes all temperature differences within 0.05°C of 0°C.

to the decreased importance of solar radiation (and therefore shade) at that time of year, the loss of leaves from some riparian vegetation in the fall, and the higher flows and corresponding shorter travel times. System potential vegetation information was provided by ODEQ (Oregon Department of Environmental Quality, unpub. data, 2003).

Removing all riparian shade warmed the river over almost the entire model reach. The overall average temperature change was +0.30°C, with the greatest monthly change in September, +0.46°C, and the smallest in November, +0.09°C. Clearly, the effect of riparian shading in the North Santiam River is not as important to the temperature of the river as some other influences, such as dam release temperature or meteorological factors.

Dam Release Flow

The base model was adjusted by increasing and then decreasing the dam release flows at Big Cliff dam by 20% in separate runs. Results are presented in figure 17 and table 6.

The average 7dADM water temperature change for increased dam release flows was only -0.09°C from July 1 through November 26, 2001, but this effect showed fairly significant seasonal differences. In summer, when outflows from Detroit Lake were relatively cool, a flow increase cooled much of the North Santiam River. Later in the year, when the outflows from the lake were relatively warm, increasing those flows warmed much of the simulated reach. The water temperature change was -0.33°C in July and +0.11°C in October.

The seasonal effects of changing dam release flows could be caused by both travel time and volume effects. For instance, larger outflows from the dams travel more quickly downstream and have less time to be affected by meteorological conditions. The larger volume and greater depth of an increased outflow also would be less susceptible to heating or cooling by meteorologic conditions.

Decreasing the dam release flows (fig. 17B) produced the opposite effects. In summer, a decrease in dam release flow warmed the river, and in fall it cooled the river. The temperature change was +0.42°C in July and -0.22°C in October. The average water temperature change was +0.12°C from July 1 through November 26, 2001, for decreased dam release flows. Smaller outflows from the dams would be more affected by meteorological conditions compared to the base case, due to longer travel times and the presence of less water to absorb inputs of solar radiation.

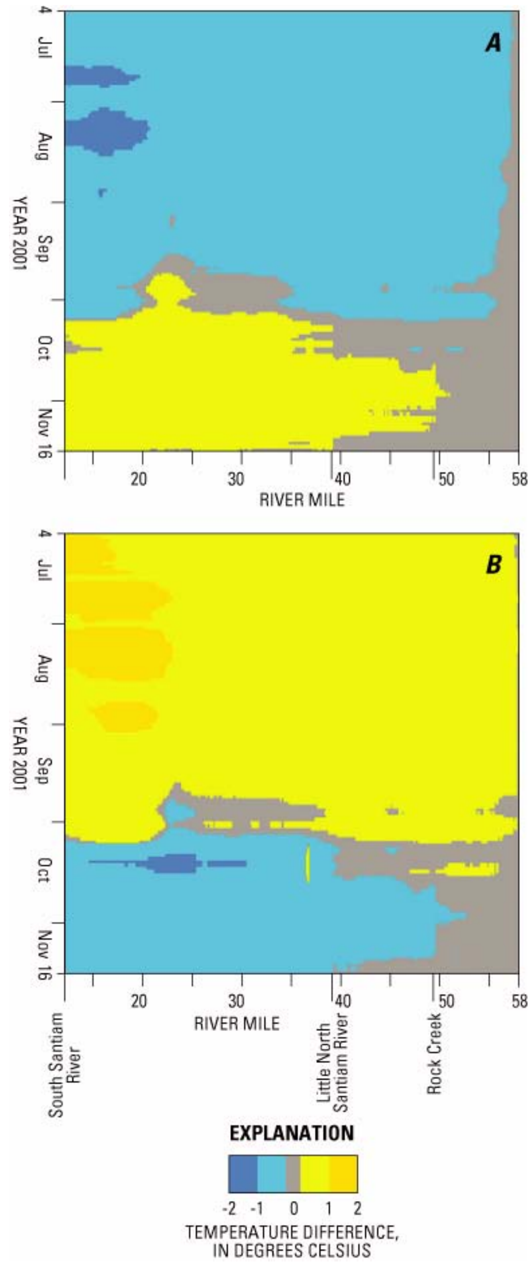

Figure 17. Difference in temperature between the base model and the model with dam release flows (*A*) increased by 20 percent and (*B*) decreased by 20 percent, using the 7-day moving average of daily maximum water temperature in degrees Celsius. The gray color zone includes all temperature differences within 0.05°C of 0°C.

Several other authors have examined the sensitivity of input parameters to Willamette River tributary water-temperature models. Laenen and Hansen (1985) examined the sensitivity of simulated water temperature in the North Santiam River downstream of the dams to wind speed, dam releases, channel width and area, tributary inflows and withdrawals, and equilibrium temperature—the temperature that a waterbody would move towards at steady state. Of those influences, they found that equilibrium temperature and wind speed affected water temperature the most. Hansen (1988) evaluated the sensitivity of a temperature model of the McKenzie River by varying equilibrium temperature, wind speed, upstream inflow, top-width, cross-sectional area and tributary inflows. Of those parameters, equilibrium temperature was found to produce the greatest effect on water temperature, followed by discharge and top-width.

Simulation of System Potential Conditions

The calibrated model was used to examine two scenarios designed to provide insight into the behavior of these rivers at system potential. Both of the scenarios used system potential riparian vegetation from ODEQ and dam release flows from USACE operational modeling of flows from the dams to meet proposed National Oceanic and Atmospheric Administration (NOAA) Fisheries minimum flow targets (fig. 18). These flow targets were designed to improve fish habitat downstream from the dams. A second scenario additionally replaced measured temperatures released from the dams with an estimated, more-natural seasonal temperature regime (fig. 19). This temperature regime was estimated by mixing the three major tributaries to Detroit Lake: the North Santiam River (USGS gage 14178000), Breitenbush River (14179000) and Blowout Creek (14180300), weighted according to their measured flows. The mixing did not take travel time differences into account, resulting in an incorrect daily temperature variation; therefore, a daily average temperature input was used for this analysis. This estimate of a more-natural seasonal temperature regime did not take into account any anthropogenic disturbances upstream of the dam that might have increased the measured temperatures.

System-Potential Vegetation with Proposed NOAA Fisheries Target Flows

The first scenario was designed to examine the effect of combined system potential shade and proposed Detroit dam minimum outflow requirements on the temperature of the North Santiam River. The new USACE modeled releases for 2001 were between 10% and 73% higher than the flows from the base model, depending on the date. The resulting changes in temperature compared to the base-calibrated model are shown in figure 20A. The pattern of temperature change was very similar to that seen in the sensitivity run of increasing flows by 20% (fig. 17A). Cooler temperatures were predicted from July through October, and slightly warmer temperatures were predicted through most of the river from early October through mid-November. Just as in the flow-sensitivity analysis, these effects are mainly a function of changes in travel time. Higher flows during a time when the river is gaining heat means that less time is available for that gain, resulting in cooler water relative to the base case. August had the most cooling with an average temperature drop of -0.47°C (table 7), and October showed the most warming with an average temperature increase of +0.18°C. The overall temperature change for this period in 2001 was -0.20°C.

System-Potential Vegetation with Proposed NOAA Fisheries Target Flows and a More-Natural Seasonal Temperature Regime in Dam Releases

This scenario was similar to the first, but also replaced the measured dam release temperatures with an estimated, more-natural seasonal temperature regime. Compared to the measured temperatures, the more-natural seasonal temperature regime did not have significantly different yearly maximum or minimum temperatures. However, the timing of the maximum temperature shifted to earlier in the year from late September-October to July-August (fig. 19). Thus, the more-natural seasonal temperature input was warmer in late spring and summer and cooler in the fall and early winter, compared to the base case. The results from this scenario compared to the base case are shown in figure 20B. Some warming occurred in July and August, between 0° and 2°C, but the most significant feature of this scenario was the large cooling effect near the dams in September through November of between -1°C and -7°C. The magnitude of this cooling effect decreased with distance from the dam. The month of October had the greatest cooling, -3.74°C, while the temperatures in the month of July warmed by an average of +0.12°C. The overall temperature change with this scenario was -1.91°C. A comparison of the results in figure 20B to

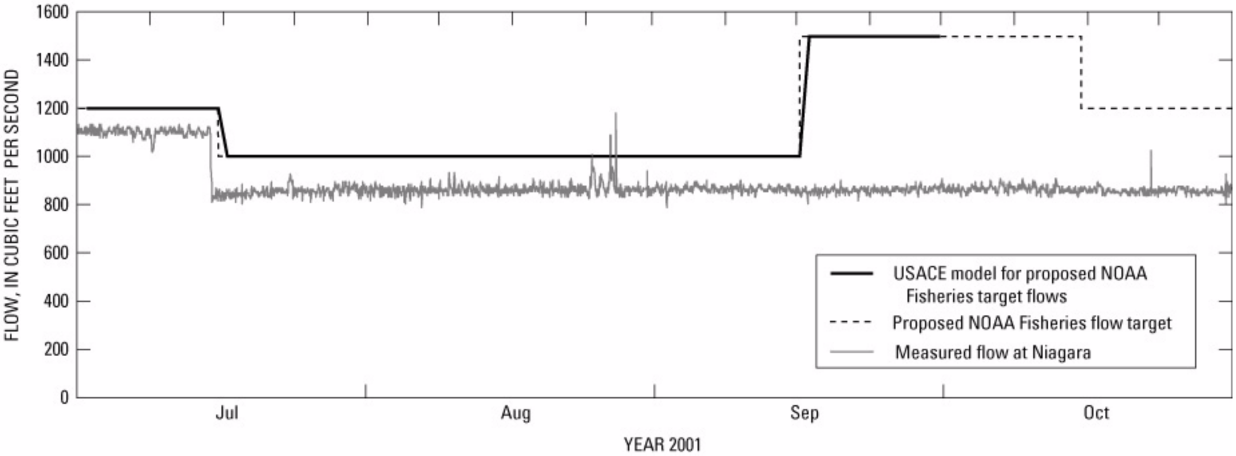

Figure 18. Proposed NOAA Fisheries minimum flow targets for releases from the Detroit and Big Cliff dam complex, U.S. Army Corps of Engineers simulated flow from Detroit Dam using those targets, and measured flow at Niagara for 2001.

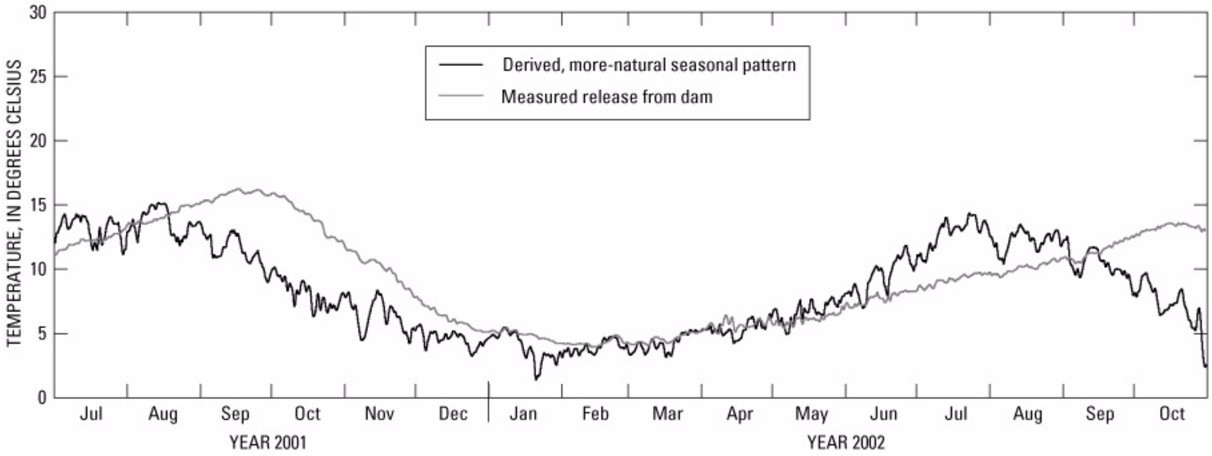

Figure 19. Estimated more-natural seasonal water temperature and measured temperature (as released from the dam) in the North Santiam River at Niagara.

Table 7. Summary of results from system potential simulations for 2001.

[Values are averages of simulated 7dADM water temperatures compared to the base case for all segments on all days in each month. 7dADM, 7-day average of daily maximum; °C, degrees Celsius]

		Average change in 7dADM water temperature, °C					
Scenario	**Changes to base case**	**July**	**August**	**September**	**October**	**November**	**Overall (July–November)**
1	System potential vegetation, new minimum inflows	-0.42	-0.47	-0.25	+0.18	+0.04	-0.20
2	System potential vegetation, new minimum inflows, natural seasonal inflow temperatures	+0.12	-0.80	-3.17	-3.74	-2.02	-1.91

those in figure 13 indicate that the temperature standard still would have been exceeded in this scenario, though the extent of that exceedance would be decreased substantially in both magnitude, spatial extent, and timing. If anthropogenic disturbances upstream of Detroit Lake were minimized, the resulting temperatures might even be cooler.

Other studies have found similar effects downstream from Willamette Basin dams. Hansen (1988) found similar results on the McKenzie River downstream of Cougar and Blue River dams. The dam produced little effect on river temperatures from January through May, cooled the river in June through September and warmed the river from September through the end of November; Cougar and Blue River dams are similar to Detroit dam in that the discharge point is deep enough to access cold stored water in midsummer. Hansen and Crumrine (1991) used a one-dimensional model to examine the effect of flow and temperature without the dam on the temperatures downstream of Detroit and Big Cliff dams. They also found that the temperature changes attenuated with distance downstream from Detroit.

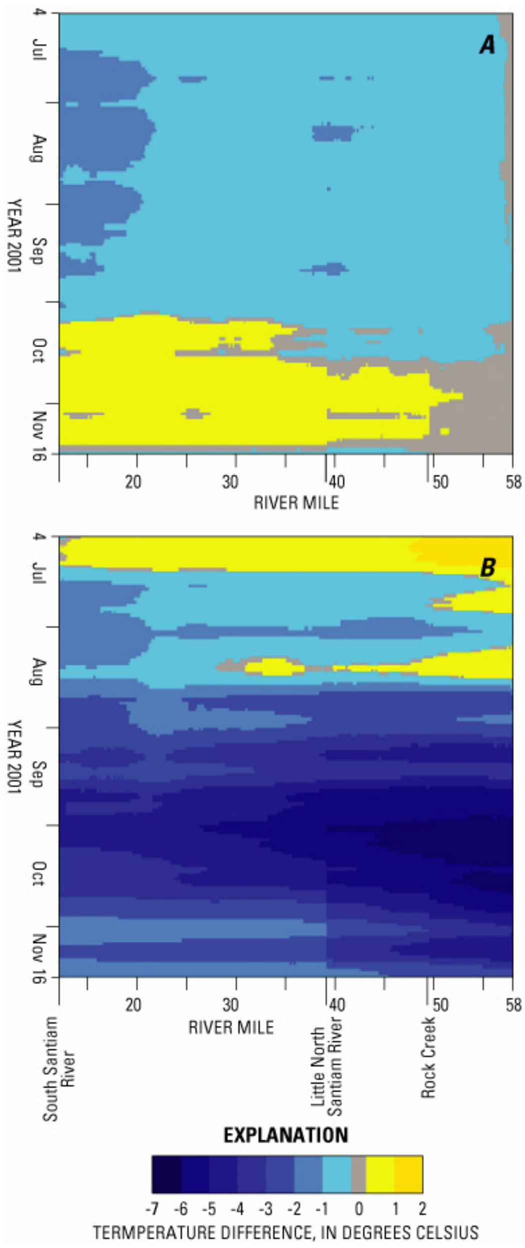

Figure 20. Temperature change for (*A*) system-potential scenario 1 and (*B*) system-potential scenario 2 for 2001, using the 7-day moving average of daily maximum water temperature. The gray color zone includes all temperature differences within 0.05°C of 0°C.

Summary

A CE-QUAL-W2 model of the North Santiam and Santiam Rivers was constructed and calibrated for July 1 to November 26, 2001, and confirmed for April 1 through October 31, 2002. The model effectively simulated flow and water temperature on both hourly and seasonal timescales. The mean absolute error (MAE) and root mean square error (RMSE) statistics for water temperature were below 1°C for all stations except those on the lower parts of the Santiam River. There, the simulated daily temperature variation was larger than the measured variation, and provided indirect evidence of hyporheic flow, corroborating the conclusions of previous hydrological studies.

To complete the water balance, extra flows were added to account for ungaged tributaries and ground-water inflows. The extra flows were most important during the rainy season and storm events. Although the river becomes braided in the vicinity of Stayton, the model simulated the rivers as a one-channel system. The temperature simulation did well despite the difference, but there was some deviation in measured versus simulated travel times in that reach. This could be explained by river braiding or the presence of small check dams in the vicinity of Stayton.

The Detroit-Big Cliff dam complex released cold water from Detroit Lake in the summer, and river temperatures were coldest near the dams at that time of year and could increase by as much as 10°C before discharging into the Willamette River. In fall, the dams discharged water with stored summer heat; river temperatures near the dams at that time were often the warmest of the whole system, and cooling occurred as the water traveled downstream.

Observed water temperatures were produced by a combination of releases from Detroit and Big Cliff dams, meteorological factors (including air temperature and solar radiation), temperatures of tributary rivers and streams, and riparian shade. Anthropogenic point-source inflows were unimportant in determining water temperature in these rivers because such sources were relatively small. During summer, the temperatures released from the dam did not propagate far downstream before being affected by meteorological factors. Daily water temperature variations of up to 7°C at some sites also attest to the importance of radiative heat exchange with the atmosphere. Changes in travel time at different flow conditions affected water temperatures by affecting the amount of time available for the river to exchange heat with its surroundings.

During summer and early fall, the downstream parts of the North Santiam and the Santiam Rivers were often above Oregon's water temperature standards. Exceedance of water temperature standards in this system was due to both anthropogenic and natural causes. The presence of the dams affected both flow and temperature and contributed to exceedances of the temperature standard in the fall, especially in the upper reaches of the river. Simulation of a more-natural seasonal temperature regime from the dams resulted in significant cooling in the fall and some warming in the summer compared to current conditions. This cooling effect was greatest in the upper portion of the North Santiam River, and decreased downstream; this was not enough to put the lower North Santiam River and Santiam River in compliance with temperature standards for the years simulated in this study. Disturbances to the river's riparian vegetation also contributes somewhat to higher temperatures. Restoring riparian vegetation along the river would provide some cooling to the river, but that effect would be smaller than changing the temperature regime from the dams. In the lower reaches of these rivers, meteorological factors account for most of the temperature standard exceedances in midsummer. If the water temperature standard cannot be met when anthropogenic heat sources are removed—by restoring riparian vegetation and removing the heating effects of point sources—then the "system potential" becomes the temperature standard. That is to say, the temperature standard stipulates a condition of no measurable anthropogenic heating. The system potential model runs shown in this report provide some insight into the types of temperatures that might be achieved in the absence of human disturbances other than the presence of the dams.

Besides providing an understanding of the river temperature regime and the factors that influence it, this model can be used to asses the effects of future changes on the rivers, including restoration of riparian vegetation, different dam operations or changes in climate. A CE-QUAL-W2 model of Detroit Lake that includes a selective withdrawal tower for the regulation of released water temperature is currently being constructed by the USGS and will connect to the North Santiam/Santiam River model. A selective withdrawal tower would allow releases from both reservoir bottom and surface water. This would allow dam operators some flexibility to release warmer water in summer and cooler water in fall in order to approach a more natural seasonal temperature regime in the North Santiam River. Together, the river and reservoir models will allow detailed investigations into how dam operations will affect downstream river temperatures.

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Appendix 1

Appendix 1. Revised Water Temperature Standards

In this report, it was noted that the water temperature standards were expected to change. The standards were indeed revised, and this appendix provides an update with the new temperature criteria. The revisions in the standards were initiated by a court case brought by Northwest Environmental Advocates, which resulted in the Federal District Court of Oregon overturning the 1999 U.S. Environmental Protection Agency (USEPA) approval of Oregon's existing temperature criteria in March 2003. In order to protect salmonid populations, the USEPA provided guidance to Oregon in formulating new water temperature criteria. The Oregon Department of Environmental Quality (ODEQ) used the USEPA guidance along with advice from stakeholders, the Oregon Department of Fish and Wildlife, NOAA Fisheries and the U.S. Fish and Wildlife Service to formulate proposed standards. Input from the public was received through an open comment period and via public hearings across the State. The Oregon Environmental Quality Commission adopted the new water temperature criteria in December 2003, and the USEPA approved them on March 2, 2004.

Under these new criteria, based on the 7-day moving average of the daily maximum water temperature (7dADM), the North Santiam River has been designated as core cold-water habitat, with water temperature not to exceed 16.0°C during the period June 16–August 31. From September 1 through June 15, the river was designated for salmon and steelhead spawning use, with a stricter 13.0°C standard in effect. The Santiam River was designated as salmon and trout rearing and migration habitat with a maximum 7dADM water temperature of 18.0°C for the period May 16–October 14. From October 15 through May 15, the Santiam River was designated as salmon and steelhead spawning use with a maximum 7dADM water temperature of 13°C.

Figure 13 of this report, showing the difference between the simulated 7dADM and the applicable water standard, has been updated with these new temperature standards, and is shown here as figure A-1.

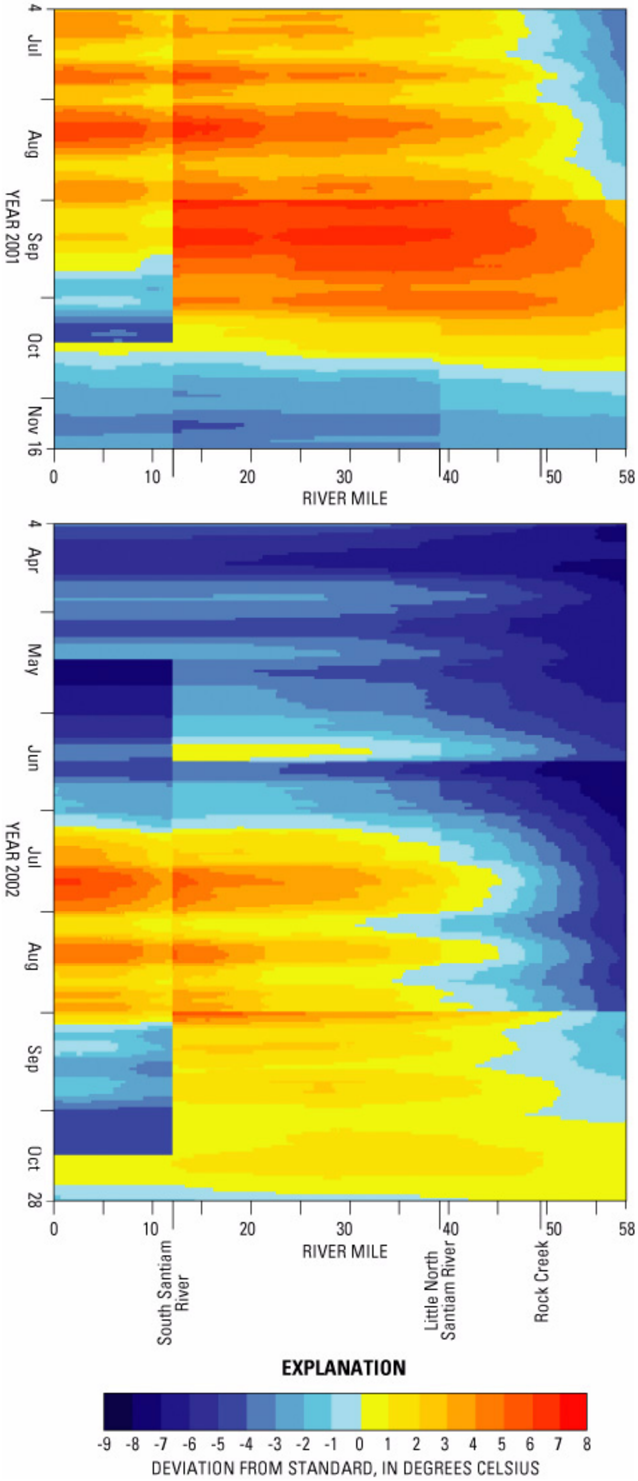

Figure A-1. Difference between the simulated 7-day moving average of daily maximum water temperature and the revised water temperature standard, in degrees Celsius.

Back cover:

The North Santiam River at river mile 29.5, taken on June 4, 2002 (*photograph by Ian Wigger, U.S. Geological Survey*).

USGS

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