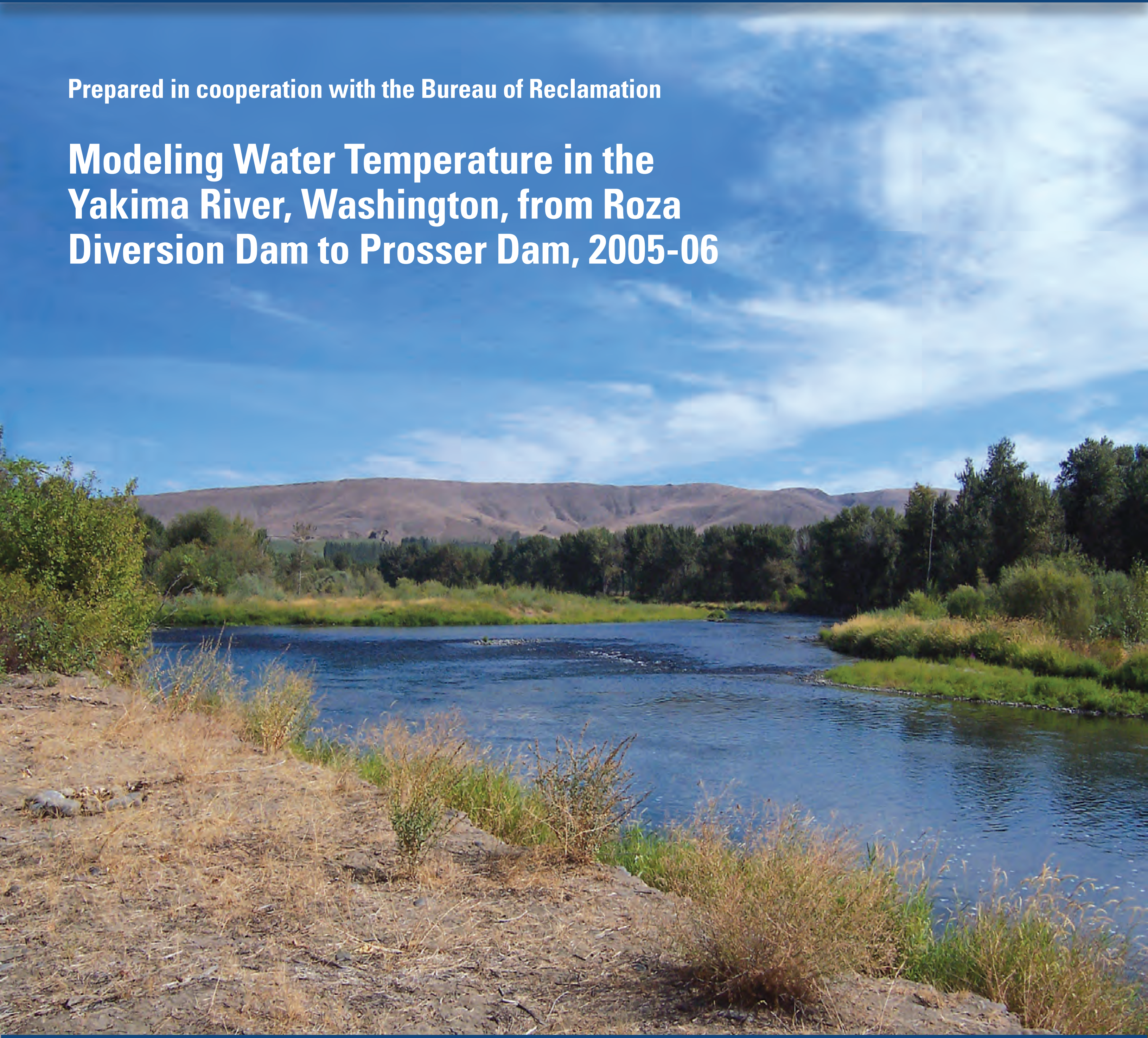
Prepared in cooperation with the Bureau of Reclamation

Modeling Water Temperature in the Yakima River, Washington, from Roza Diversion Dam to Prosser Dam, 2005-06



Scientific Investigations Report 2008–5070

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

Cover: Photograph of the Yakima River near Wapato, Washington. (Photograph taken by M. Eleno, U.S. Geological Survey, Tacoma, Washington, 2005.)

Modeling Water Temperature in the Yakima River, Washington, from Roza Diversion Dam to Prosser Dam, 2005–06

By Frank D. Voss, Christopher A. Curran, and Mark C. Mastin

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Conversion Factors and Datums

Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
cubic centimeter per second (cm^3/s)	3.531	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
joule (J)	0.0000002	kilowatt hour (kWh)
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
meter per second (m/s)	3.281	foot per second (ft/s)
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)

Datums

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).

Elevation, as used in this report, refers to distance above the vertical datum.

Modeling Water Temperature in the Yakima River, Washington, from Roza Diversion Dam to Prosser Dam, 2005–06

By Frank D. Voss, Christopher A. Curran, and Mark C. Mastin

Abstract

A mechanistic water-temperature model was constructed by the U.S. Geological Survey for use by the Bureau of Reclamation for studying the effect of potential water management decisions on water temperature in the Yakima River between Roza and Prosser, Washington. Flow and water temperature data for model input were obtained from the Bureau of Reclamation Hydromet database and from measurements collected by the U.S. Geological Survey during field trips in autumn 2005. Shading data for the model were collected by the U.S. Geological Survey in autumn 2006. The model was calibrated with data collected from April 1 through October 31, 2005, and tested with data collected from April 1 through October 31, 2006. Sensitivity analysis results showed that for the parameters tested, daily maximum water temperature was most sensitive to changes in air temperature and solar radiation. Root mean squared error for the five sites used for model calibration ranged from 1.3 to 1.9 degrees Celsius (°C) and mean error ranged from –1.3 to 1.6°C. The root mean squared error for the five sites used for testing simulation ranged from 1.6 to 2.2°C and mean error ranged from 0.1 to 1.3°C.

The accuracy of the stream temperatures estimated by the model is limited by four errors (model error, data error, parameter error, and user error).

Introduction

The Bureau of Reclamation tries to maintain river conditions conducive to salmon recovery while also regulating flows in the Yakima River to meet urban and agricultural water allocation demands in the Yakima River basin. The Bureau of Reclamation is considering water management plans that could potentially change the amount and timing of flows in the Yakima River. For example, the Yakima Basin Storage Project (known as the Black Rock Project) involves the construction of a new reservoir about 48 km east of Yakima, Washington. Under this project, the reservoir would have a maximum capacity of 1,973 hm^3 and be filled by water pumped from the Columbia River. Between 616 to 986 hm^3 of water from the reservoir would be delivered directly to irrigation canals supplying the Yakima River basin, thereby, freeing up an equivalent volume of water from the Yakima River for enhancing fish and wildlife habitat. The Bureau of Reclamation plans to use the Ecosystem Diagnosis and Treatment (EDT) method described at http://www.mobrand.com/MBI/edt.html to estimate results of the enhancements to habitat quality and quantity from water management alternatives such as the Black Rock Project. The EDT analytical model is a major component of the EDT method and is used to analyze environmental information.

Daily maximum water temperature is a necessary input for the EDT analytical model. In this cooperative study with the Bureau of Reclamation, the U.S. Geological Survey (USGS) used a water-temperature model to generate simulated daily maximum water temperature data for the Yakima River mainstem between the Roza Diversion Dam and the Prosser Dam (Roza–Prosser Reach) (fig. 1) for input into the EDT analytical model.

Purpose and Scope

The purpose of this report is to document a water-temperature model for simulating daily maximum water temperatures along the Roza–Prosser Reach for any given year from April 1 through October 31. This is the approximate time range when water is diverted from the river to irrigate agricultural areas. The model is intended to assess general trends in daily maximum water temperature that may occur when different proposed water management alternatives are used. The model is not intended to simulate daily maximum water temperature with an accuracy of 1.0°C or less on any given day.

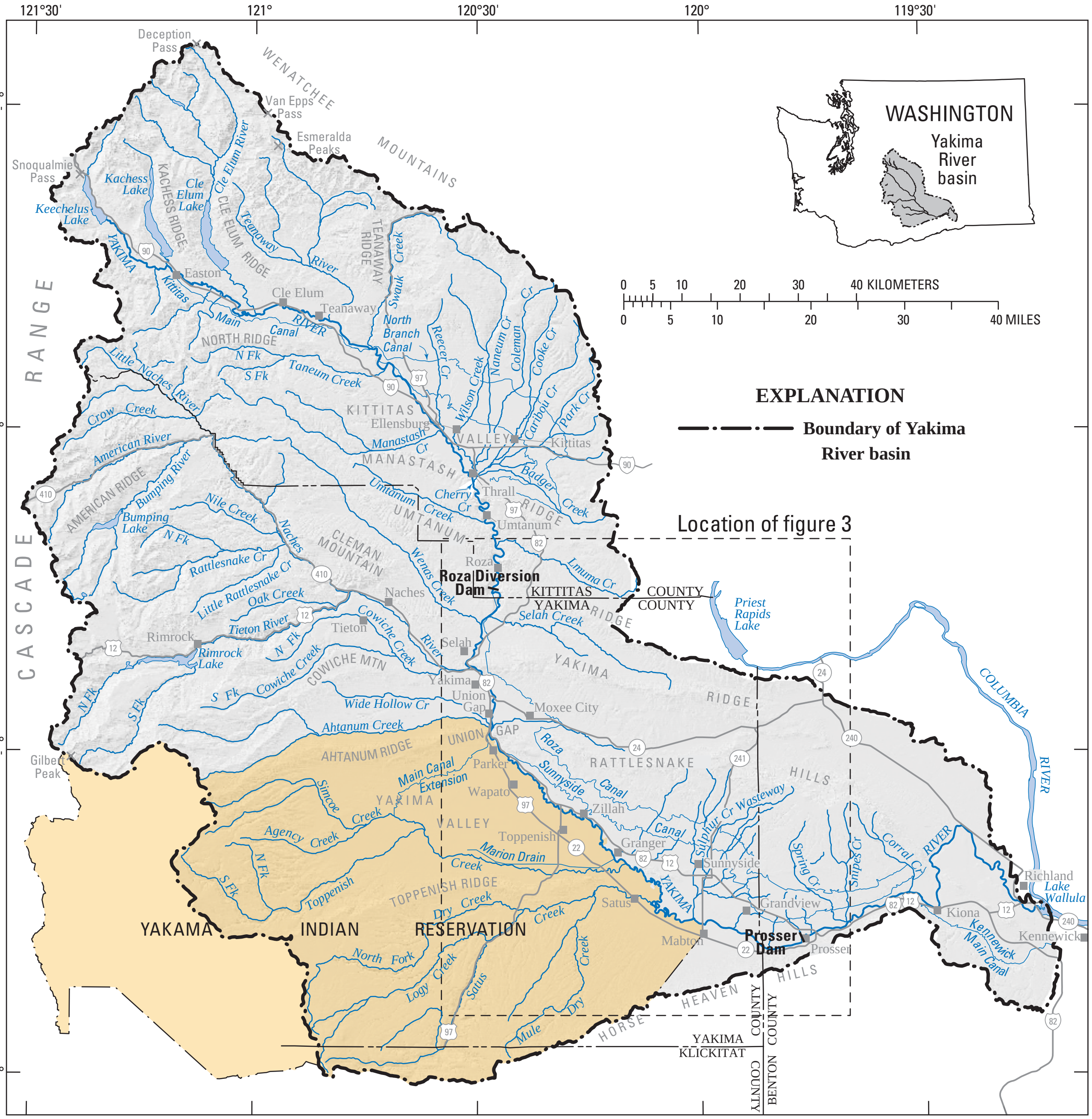


Figure 1. Location of Yakima River basin and study area, Washington.

The objectives of the project were to (1) collect discharge, water-temperature, and related data along the Roza–Prosser Reach of the Yakima River; (2) develop methods for estimating water temperatures at the Roza Diversion Dam on the Yakima River and at a point on the lower Naches River; (3) apply an existing process-based water-temperature model to the Roza–Prosser Reach to simulate daily maximum water temperature; and (4) document the model.

The USGS was supported in this work through a scientific and financial partnership with the Bureau of Reclamation.

Description of Study Area

The Yakima River is located in south-central Washington and is a tributary of the Columbia River (fig. 1). The Yakima River originates in the central Cascade Range near Snoqualmie Pass (at an elevation of about 914 m) and flows 354 km southeast out of the Cascade Range and onto the Columbia Plateau. The Yakima River then flows into the Columbia River near Richland (at an elevation of 104 m), draining a total drainage basin area of 15,941 km^2.

Precipitation in the Yakima River basin varies substantially with elevation and season. The high elevations at the crest of the Cascade Range in the western part of the basin normally receive more than 305 cm of annual precipitation (mostly as snow); whereas, low elevations in the rain shadow of the mountains only receive 18 cm of annual precipitation. Most of the precipitation occurs during the late autumn, winter, and early spring seasons; the summers typically are dry. Peak river discharge under natural conditions generally occurs during late spring and early summer because of snowmelt. The Bureau of Reclamation manages six lakes and reservoirs (with a total active storage capacity of about 1,233 hm^3) to retain the spring and summer snowmelt from the mountains and to deliver water to agriculture in the lowlands between April and October (Kent, 2004).

The Yakima River basin contains a diverse range of land cover types. About 30 percent of the basin is forested, mostly in the western mountains; 50 percent is rangeland, where sagebrush and bunch grass are the dominant vegetation; and 20 percent is agricultural, mostly irrigated land along the main valley of the Yakima River (Kent, 2004).

The study area for this project is the Yakima River mainstem extending from the Roza Diversion Dam located at river kilometer (RKM) 214 to the Prosser Dam located at RKM 74. From the Roza Diversion Dam, the Yakima River flows in a general southeasterly course past Selah, Washington, to the city of Yakima where the river is joined by the Naches River, then flows past a series of towns including Moxee City, Union Gap, Wapato, Zillah, Toppenish, Granger, Sunnyside, Satus, Mabton, Grandview, and finally Prosser. (For populations of these towns, see table 1.) The river forms the eastern boundary of the 5,260 km^2 Yakama Reservation (population 31,799), which occupies 23 percent of the southwestern section of the Yakima River basin. The main roads running alongside the river are State Route 82 to the north and State Routes 97 and 22 to the south.

Table 1. Population estimates for cities and towns adjacent to the Roza–Prosser Reach, Washington.

[U.S. Census Bureau, 2000. Cities and towns ordered from upstream to downstream]

Cities and towns	Population estimate
Selah	6,310
Yakima (city)	71,845
Yakima (metro area)	229,094
Moxee	821
Union Gap	5,621
Wapato	4,582
Zillah	2,198
Toppenish	8,946
Granger	2,530
Sunnyside	13,905
Satus	746
Mabton	1,905
Grandview	8,377
Prosser	5,138

Development of Water-Temperature Model

Description of Stream Network Temperature Model

The Stream Network Temperature model (SNTEMP) is a mechanistic, one-dimensional heat transport model that simulates the daily mean and maximum water temperatures as a function of stream distance and environmental heat flux. The model was developed in the early 1980s for the U.S. Department of Agriculture, Soil Conservation Service (Theurer and others, 1984) and has since been used in studies to analyze the effects of reservoir discharge timing, release temperature, and release volume (or some combination of all three) on downstream water temperatures (Bartholow, 2000). The DOS-based SNTEMP (Version 2.0) was used to develop the water-temperature model for this study. The USGS supports and distributes SNTEMP and offers an online course on how to use the model at http://www.fort.usgs.gov/Products/Training/IF312.asp. The SNTEMP software used for this study was obtained online from the USGS Fort Collins Science Center at http://www.fort.usgs.gov/Products/Software/SNTEMP/. The user's manual (Theurer and others, 1984) contains equations used by the model and describes how to construct model input files. In addition, answers to frequently asked questions about SNTEMP are provided at URL http://www.fort.usgs.gov/products/Publications/4037/4037.asp

The SNTEMP model is composed of the six modules listed in table 2. This table also includes a description of the functionality associated with each module.

The heat flux module forms the core of the SNTEMP model (Theurer and others, 1984). Processes that affect the amount of heat entering or leaving a stream are represented by the following equation:

$$\begin{aligned}\text{Net heat flux} = {} & \text{solar radiation} + \text{atmospheric radiation} \\ & + \text{vegetative and topographic radiation} \\ & + \text{evaporation} + \text{convection} + \text{conduction} \\ & + \text{fluid friction} - \text{water's back radiation}\end{aligned} \tag{1}$$

The processes represented by the heat flux equation are shown in figure 2. (Energy fluxes directed at the water body are positive and those directed away from the water body are negative.)

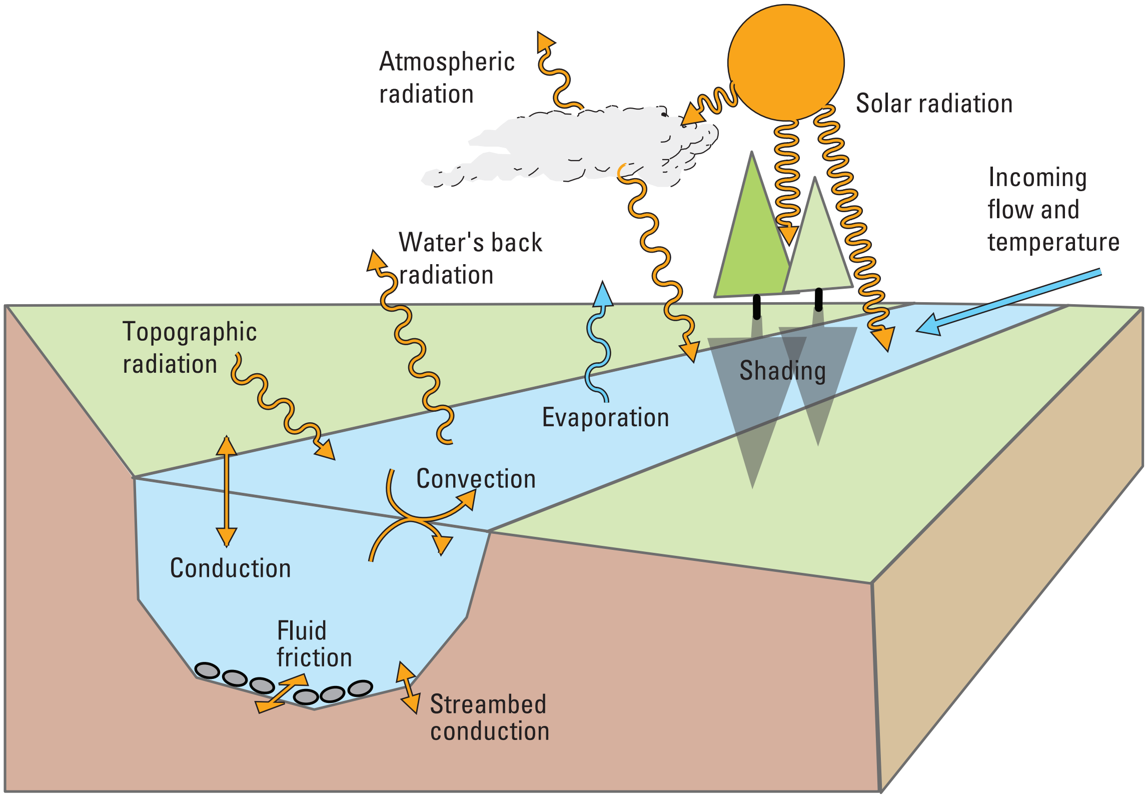
The SNTEMP model has several advantages. These advantages include (1) the capability to simulate stream networks of any size or order, and (2) the capability to use a simulation time step ranging from 1 month to 1 day. SNTEMP documentation states that the model is capable of simulating mean water temperatures to within 0.5°C of measured mean water temperatures given representational data for a user selected time step. The model also uses readily available input data and is well documented (Bartholow, 2000).

Table 2. Modules of the Stream Network Temperature Model and description of the functionality associated with each module.

Module	Functionality
Heat flux	Calculates incoming and outgoing energy fluxes
Heat transport	Calculates daily mean and maximum water temperatures as a function of stream distance
Solar	Calculates solar radiation penetrating the water as a function of latitude, time of year, and meteorological conditions
Shade	Calculates interception of solar radiation due to topography and riparian vegetation
Meteorological correction	Calculates changes in air temperature, relative humidity, and atmospheric pressure as a function of watershed elevation
Regression	Smooths water temperature data and estimates missing water temperature values

HDR Engineering, Inc., as part of a study for the State of Idaho Department of Environmental Quality compared several water-temperature models (SNTEMP, Heat Source, Basin Temp, CE-QUAL-W2, CE-QUAL-RIV1, RMA-11, MIKE-11, and hybrid model combinations) and selected SNTEMP to simulate water temperature in the Lochsa River in north-central Idaho based on the criteria that the model should (1) simulate daily maximum stream temperature, (2) be peer-reviewed and used within the scientific community, (3) not require an inordinate amount of time for data collection, and (4) have documentation that is easy to follow and reasonably available technical support (HDR Engineering Inc., 2002).

The SNTEMP model also has limitations. SNTEMP uses a regression equation to estimate daily maximum air temperature, which is used to calculate daily maximum water temperature. The effect of regression equation error on simulation results is discussed in section, "Limitations of Water-Temperature Model". Technical staff is no longer available as of February 2006 to answer users' questions about the theory and application of the model. One important fact is that the SNTEMP model does not simulate hydrology—flow data and initial water temperatures are required for all input locations.



Modified from Theurer and others, 1984

Figure 2. Energy fluxes simulated for solution of the stream energy balance by the SNTEMP model.

Model Structure for the Yakima River

Five SNTEMP modeled reaches were linked in a series (fig. 3) to simulate daily maximum water temperatures at any given location on the Roza–Prosser Reach, which was required for generating input data for the EDT analytical model.

The equations used in SNTEMP required the length of the modeled reach to approximately equal the distance that a “parcel” of water travels in the reach for the selected simulation time step. For example, if the selected time step is 1 week, then the length of the reach being modeled would be the distance that water would travel in 1 week; if the selected

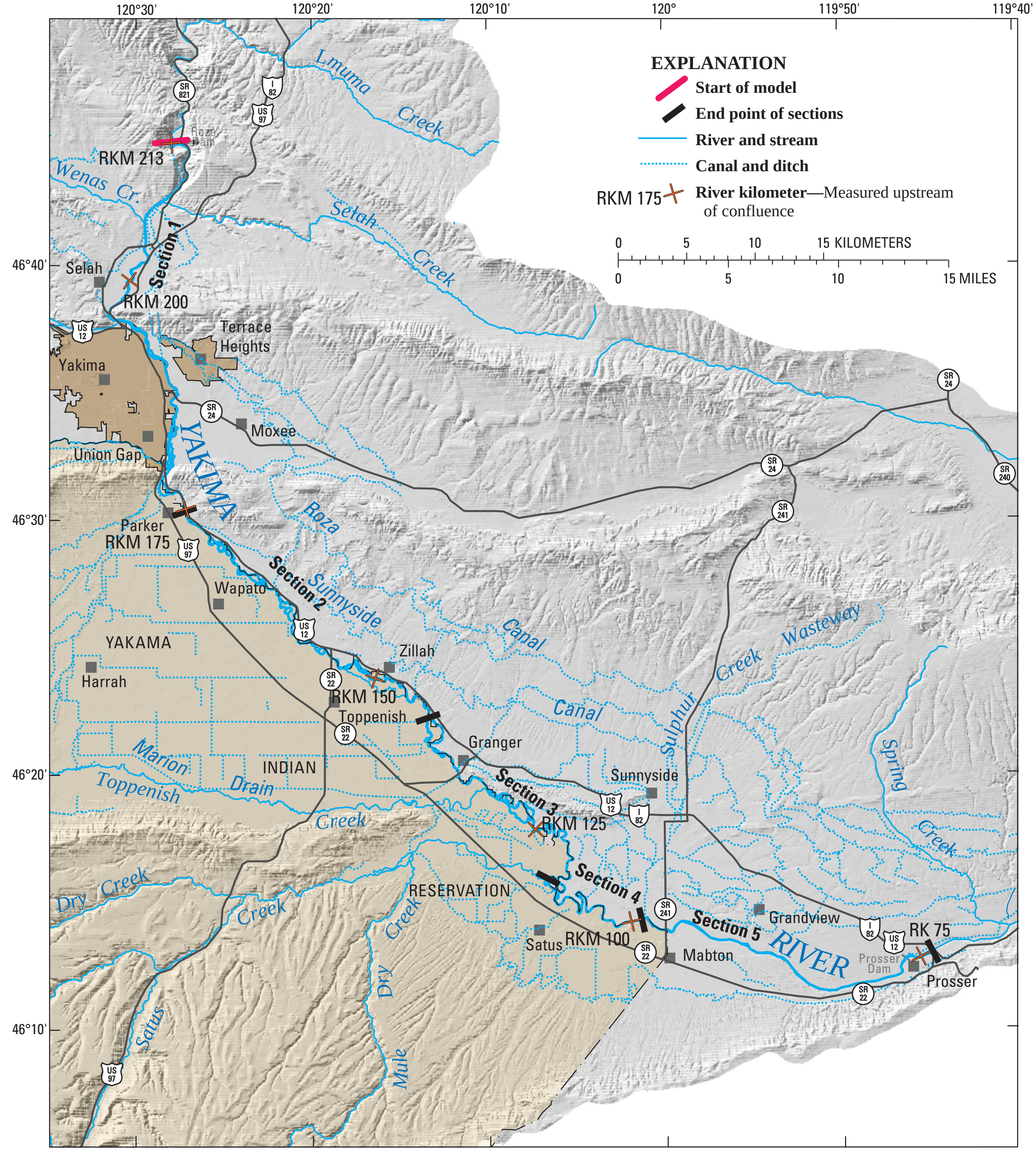


Figure 3. Extent of the five SNTEMP models used to simulate water temperature in the Roza–Prosser Reach, Washington.

time step is 1 day, then the length of the reach would be the distance that the water would travel in 1 day. The travel time for the Roza–Prosser Reach was determined to be 5 days using water velocity measurements collected by the USGS during field trips in September 2005; therefore, five modeled reaches were necessary to run the model using a daily time step. Because the SNTEMP model is not designed to be linked in series, the USGS linked the modeled reaches by developing software to transform output data from an upstream modeled reach into input for the next downstream modeled reach. The end points for the modeled reaches are shown in figure 3.

The model developed for this study did not use the branch configuration (fig. 4) typical for most stream networks because water temperatures were not simulated for tributaries entering the Roza–Prosser Reach. Instead, the Roza–Prosser Reach was represented as a single channel. Streams, drains, and wasteways carrying water to the Roza–Prosser Reach were designated as point sources; whereas, canals carrying water from the Roza–Prosser Reach were designated as diversions. The water-temperature model requires input of water temperature and flow data for every point source and diversion for every day of the entire simulation period. The structure of the model for the Roza–Prosser Reach with all point sources and diversions is shown in figure 5. The vertical line in figure 5 represents the Roza–Prosser Reach. Entities listed left of the vertical line are adding water to the Roza–Prosser Reach; whereas, sites listed to the right of the vertical line are entities diverting water from the Roza–Prosser Reach.

Simulated daily maximum water temperature from SNTEMP was generated for locations that correspond to the input locations for the EDT analytical model (fig. 6). An example of the output file generated for input into the EDT analytical model is shown in appendix A.

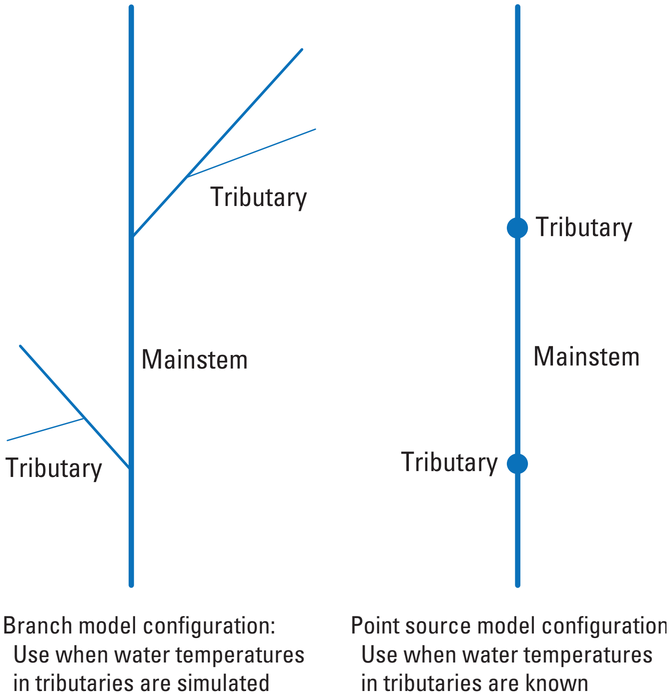


Figure 4. Difference between the SNTEMP branch and point source model configurations.

Input Data

SNTEMP model was designed to use data that are relatively easy to gather from maps and Federal data sources (Bartholow, 2000). Because SNTEMP is a steady-state model and uses a daily time step, the model requires daily mean data as input.

Meteorology

SNTEMP model requires daily mean values for air temperature, relative humidity, wind speed, and solar radiation or percent cloud cover for each day of the simulation period. Precipitation data are not used because the model does not simulate flows. The AgriMet weather station in Harrah, Washington (fig. 7) was used to obtain values for mean air temperature, relative humidity, wind speed, and solar radiation, which were used for calibration and testing simulations. The weather data were downloaded from the web site http://www.usbr.gov/pn/agrimet/webarcread.html for the station code HRHW. Data for these four meteorology parameters from January 1, 1988, through October 31, 2006, are shown in figure 8. The boxplots illustrate general weather patterns for the Roza–Prosser Reach; namely, relative humidity is inversely related to air temperature and solar radiation. The boxplot for wind speed shows that wind speed is fairly constant throughout the simulation period.

Solar radiation, daily mean air temperature, and daily mean relative humidity data from July 4 through September 30, 2006, were collected at four USGS weather stations at Roza, Parker, Granger, and Prosser, Washington. (fig. 7). These weather data were compared to weather data from the AgriMet weather station (Harrah, Washington) to determine whether data from the AgriMet station represented conditions near the river. If the data did not represent these conditions, then appropriate adjustments to the data were needed before the data were used as input to the model. Scatter plots showing these comparisons are shown in figure 9. Correlation coefficients for the weather data from the AgriMet weather station at Harrah, Washington, and data from the four USGS weather stations were 0.97 or greater for daily mean air temperature (fig. 9*A*), 0.94 or greater for solar radiation (fig. 9*B*), and 0.83 or greater for relative humidity (fig. 9*C*). The high correlations provide evidence that the weather data from the AgriMet weather station at Harrah, Washington, is representative of weather conditions along the Roza–Prosser Reach, and adjustments were not made to the AgriMet weather data before using the data for model input.

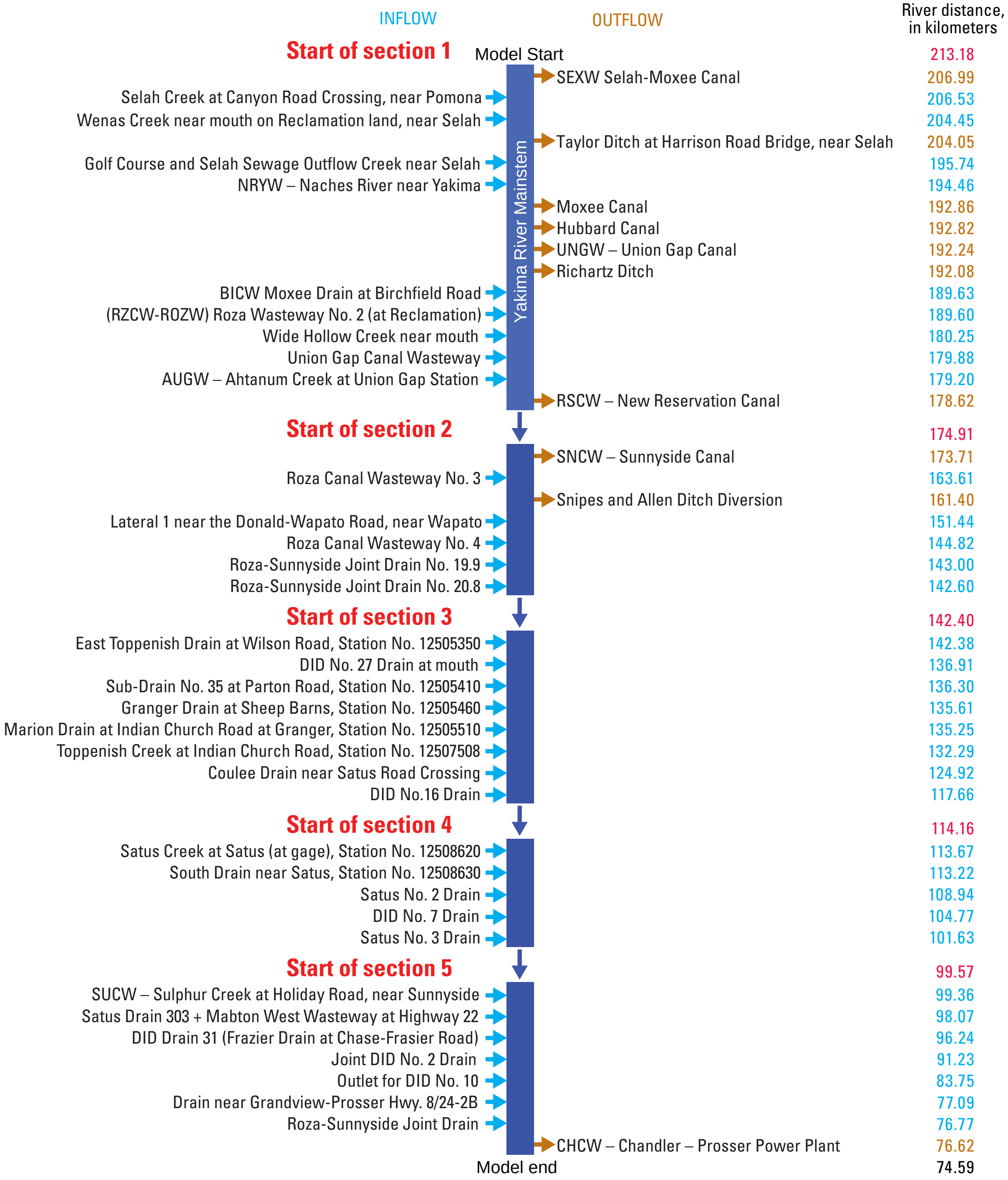


Figure 5. Model structure showing flows to and from the Roza–Prosser Reach, Washington.

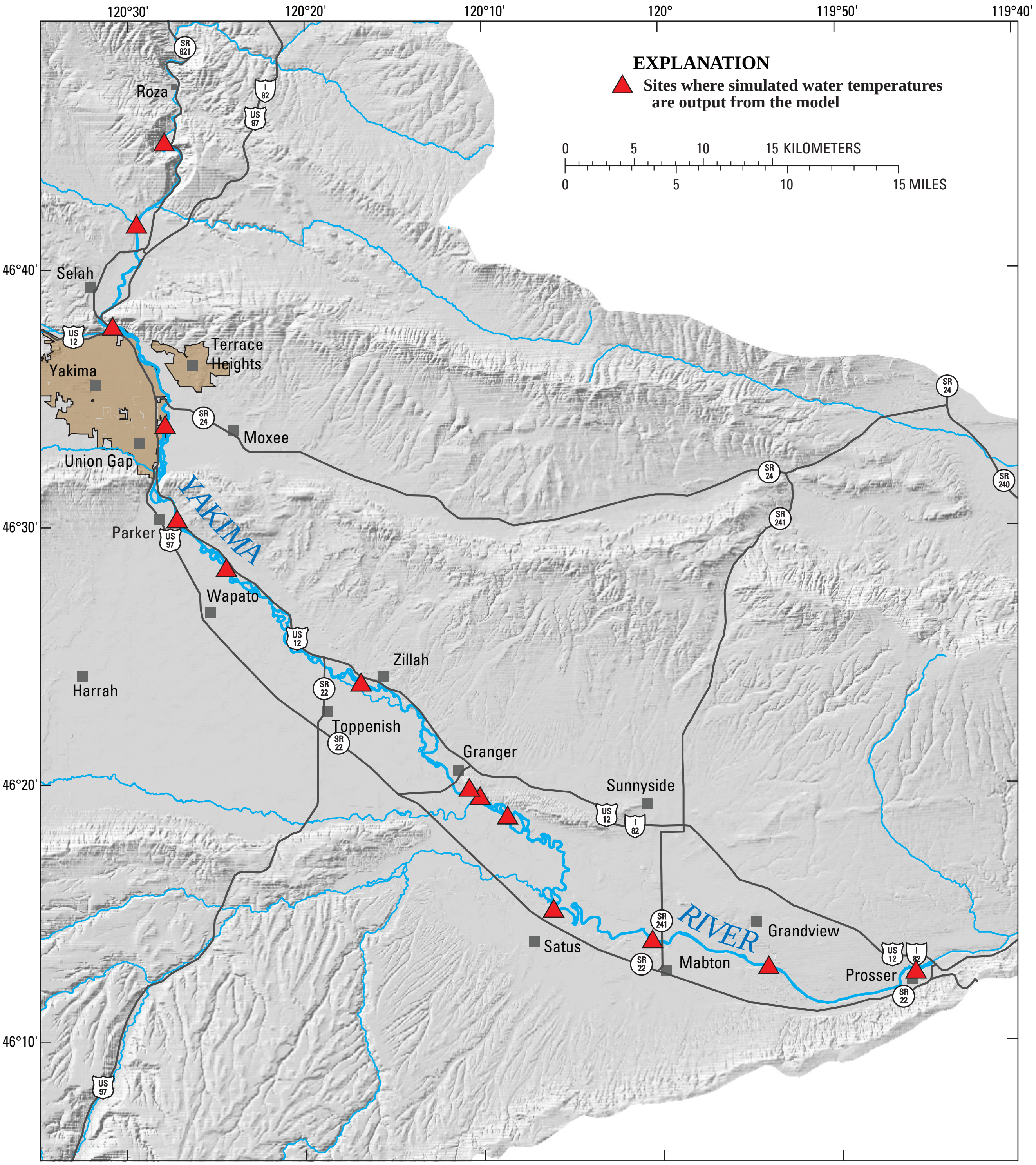


Figure 6. Sites where simulated water temperatures are output from the model, Roza–Prosser Reach, Washington.

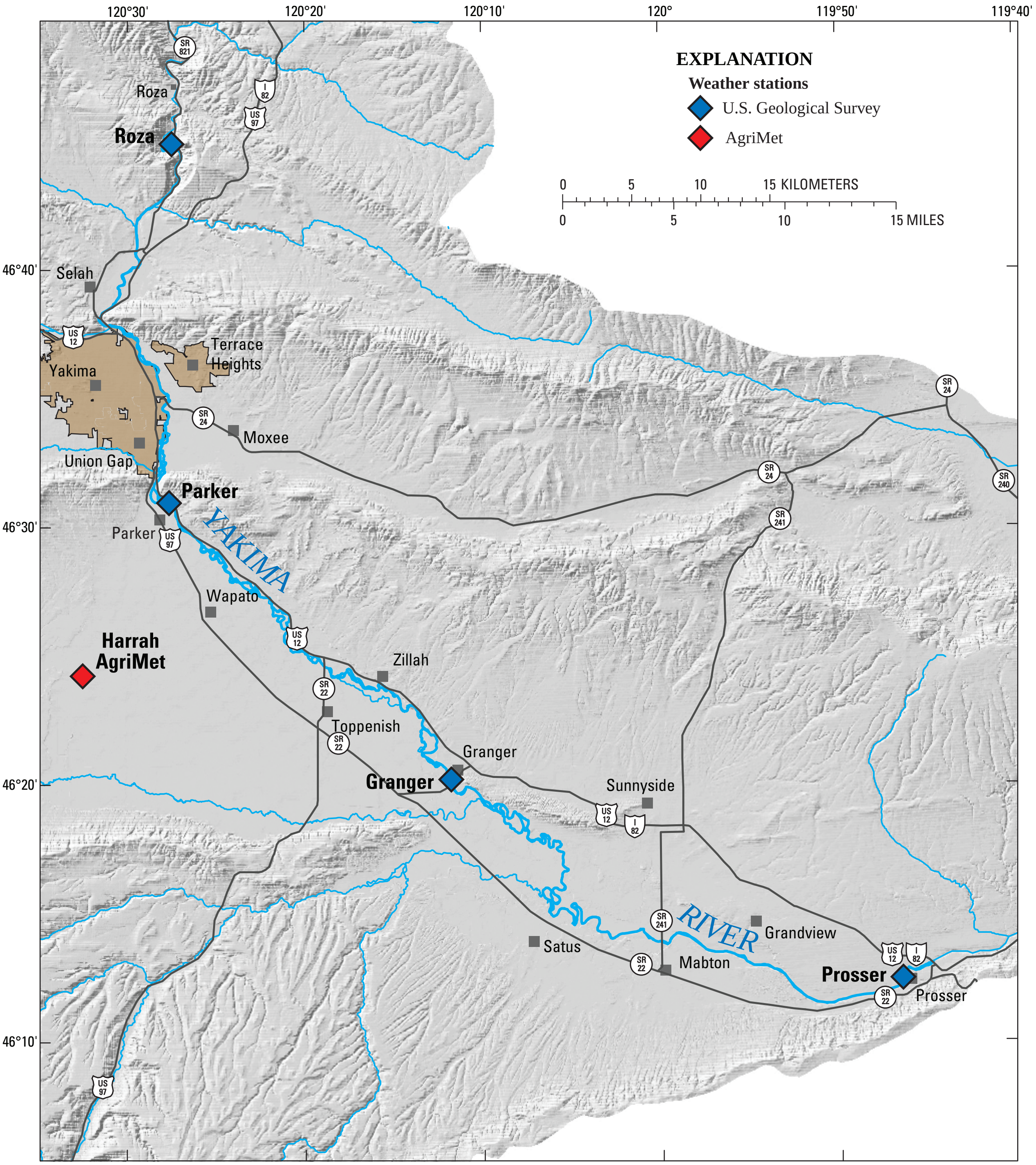


Figure 7. Location of AgriMet weather station (Harrah, Washington) and four U.S. Geological Survey weather stations at Roza, Parker, Granger, and Prosser, Washington.

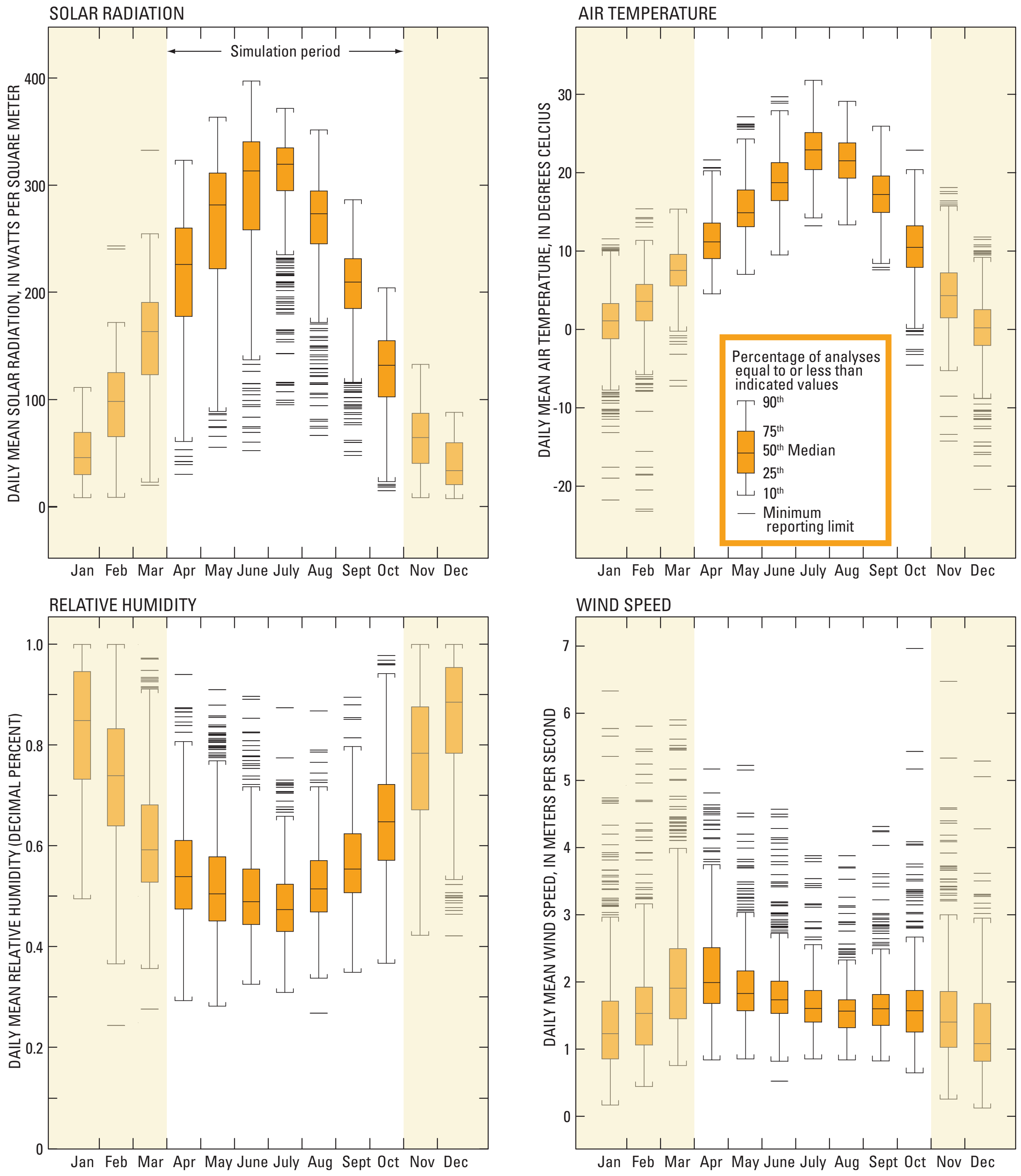
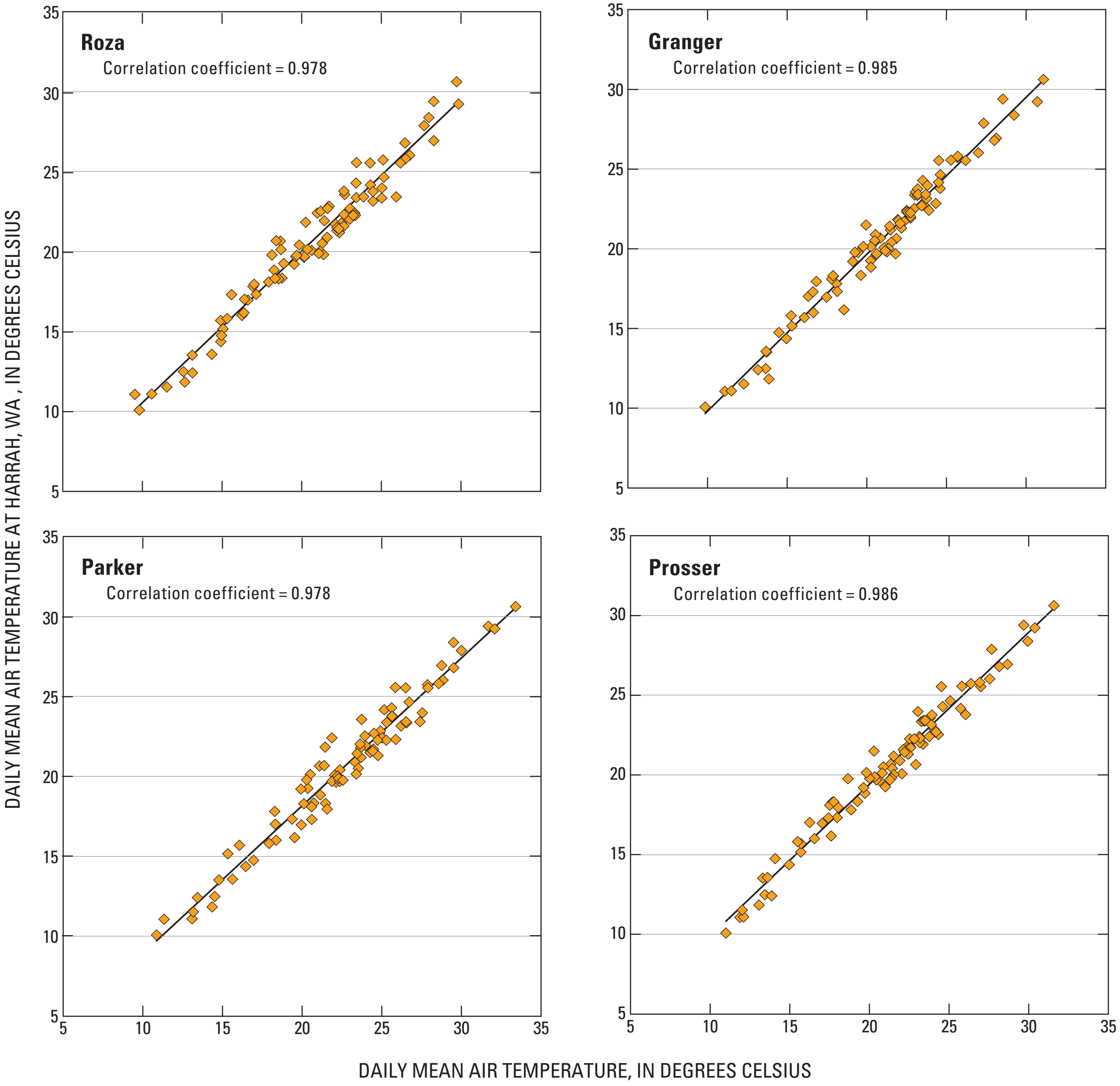
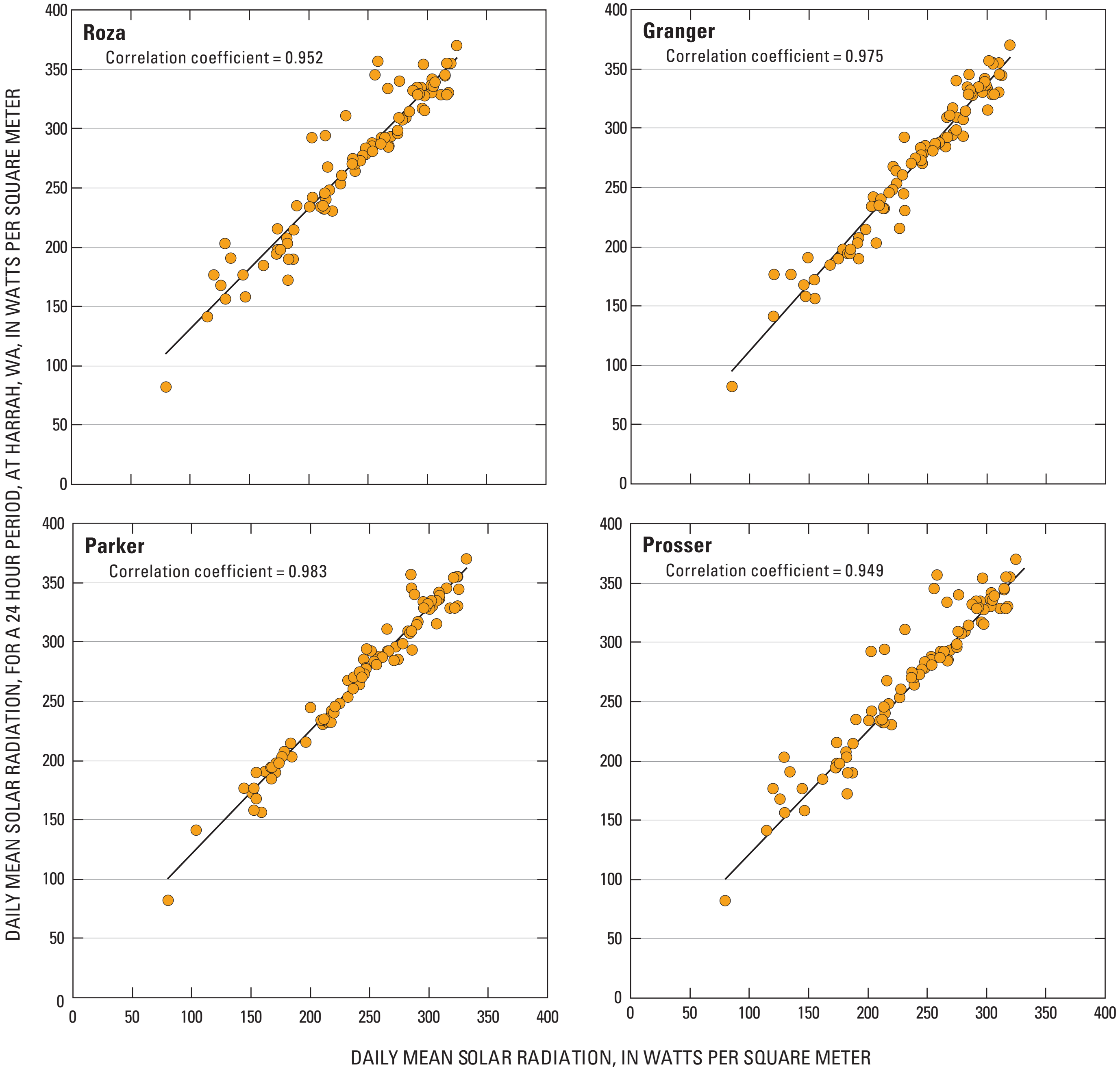


Figure 8. Monthly distributions of solar radiation, daily mean air temperature, daily mean relative humidity, and daily mean wind speed at the AgriMet weather station (Harrah, Washington), January 1, 1988, through October 30, 2006.



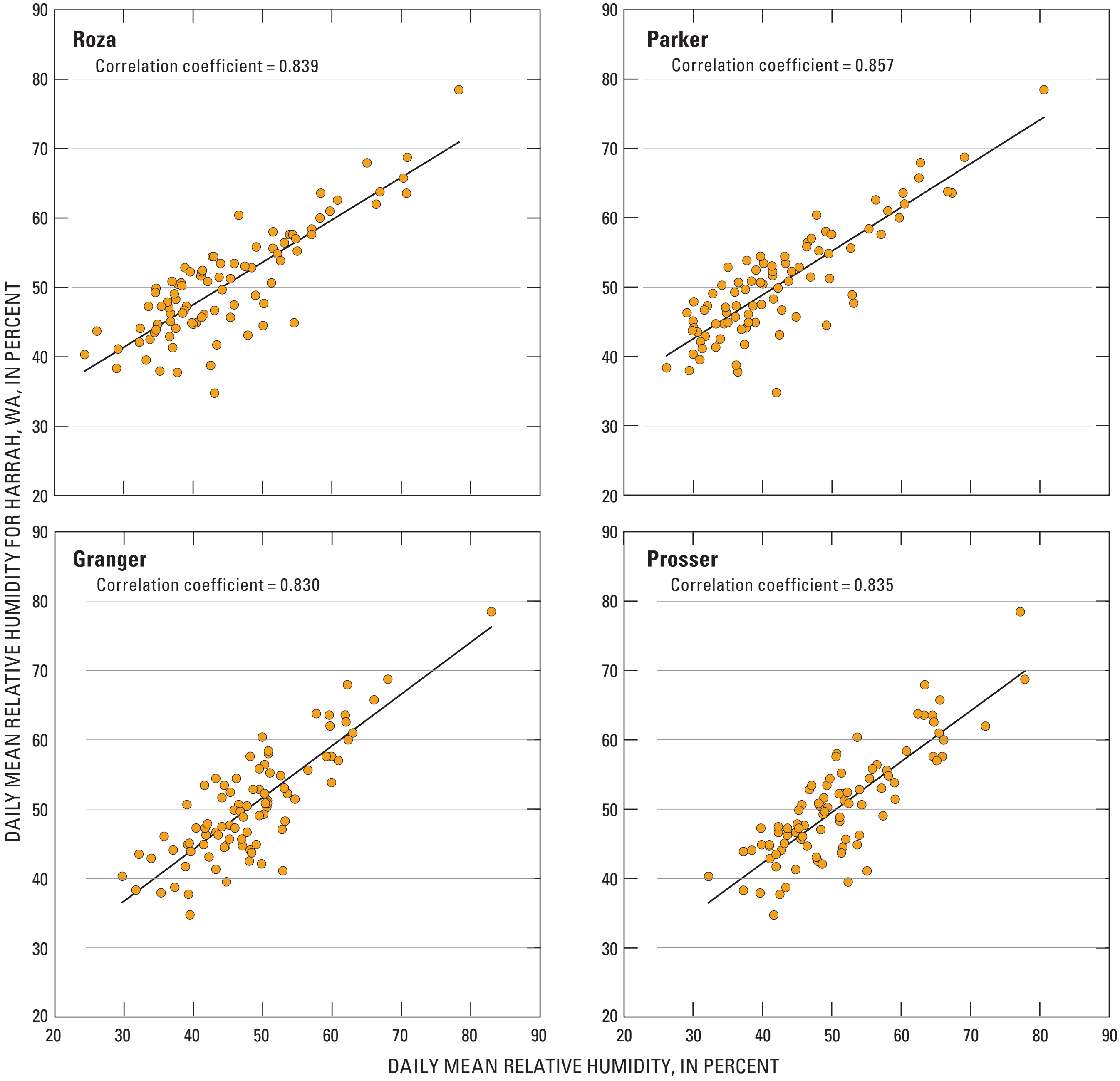
A. **AIR TEMPERATURE**

Figure 9. Measured air temperature, solar radiation, and relative humidity at the AgriMet weather station (Harrah,) and four USGS weather stations (Roza, Parker, Granger, and Prosser), Roza–Prosser Reach, Washington, July 4 through September 30, 2006.



***B*. SOLAR RADIATION**

Figure 9.—Continued.



***C.* RELATIVE HUMIDITY**

Figure 9.—Continued.

Hydrology

SNTEMP model does not simulate hydrology. Therefore, before the model could be run, flow data needed to be determined at all locations where flow enters or leaves the Roza–Prosser Reach for each time step during the simulation period. Flow data were obtained from two sources: Hydromet gaging stations maintained by the Bureau of Reclamation and field measurements collected in September 2005 by the USGS.

Average daily flow data for model calibration and testing were downloaded for 15 gages from the Bureau of Reclamation's Yakima Project Hydromet System Web page at http://www.usbr.gov/pn/hydromet/yakima/index.html. The Hydromet system is a network of automated hydrologic and meteorological monitoring stations located throughout the Pacific Northwest. Remote data collection platforms transmit water and environmental data by using point-to-point radio or satellite communications to provide near-real-time water management capability. The sites used to supply data to the model are listed in table 3.

From September 14 through September 16, 2005, the USGS measured flows in the Roza–Prosser Reach and at more than 40 joining creeks, diversions, wasteways, and drains, which are referred to as laterals. Sites used to estimate flows for the water-temperature model are listed in table 4, and the locations of the sites are shown in figure 10.

A database table was developed to include columns for flow and water temperature for each of the 15 Hydromet gaging stations and for the laterals sampled by the USGS. Data for the 15 Hydromet gaging stations were then imported into this database table. The flow to and from the Roza–Prosser Reach from ungaged laterals was calculated using the following methods:

Roza Diversion Dam to Parker, Washington

- Flow in ungaged diversions was assigned a proportion of the flow at the nearest gaging station. This proportion of flow was based on USGS field measurements collected in September 2005. For example, if flow in an ungaged diversion was 10 percent of the flow from the nearest gaged diversion, then the ungaged flow would always be set to 10 percent of the flow from the gaged diversion for each day of the simulation period. The equations for estimating flow in the ungaged diversions are included in appendix B.

- Flow for ungaged laterals that added water to the Roza–Prosser Reach was estimated by subtracting all gaged inflow from outflow for the Roza–Prosser Reach. The difference in flow was assumed to be the total inflow from ungaged laterals.

- A percentage of the difference in flow was assigned to each ungaged lateral based on proportions of flow measured during USGS field trips in September 2005. For example, if measurements showed that flow in a lateral was 10 percent of the total inflow to the Roza–Prosser Reach on the day of the measurement, then the ungaged lateral was assigned 10 percent of the difference between inflow and outflow to the Roza–Prosser Reach for each day of the simulation period. The equations used to assign flow in ungaged inflowing laterals are included in appendix B.

Table 3. Bureau of Reclamation Hydromet gaging stations used to estimate flow in the Yakima River mainstem from Roza Diversion Dam to Prosser Dam, Washington.

[Locations of gaging stations are shown in figure 10. NA, not applicable]

Station name	Station identification	River kilometer
Yakima River below Roza Dam	RBDW	213.18
Roza Canal at Headworks	RZCW	NA
Selah Moxee Canal	SEXW	206.99
Naches River near Yakima	NRYW	194.46
Union Gap Canal	UNGW	192.24
Moxee Drain at Birchfield Road	BICW	189.63
Ahtanum Creek at Union Gap	AUGW	179.20
Roza Canal at 11.0 mile	ROZW	NA
New Reservation Canal	RSCW	178.62
Sunnyside Canal	SNCW	173.71
Yakima River near Parker	PARW	173.37
Sulpher Creek at Holiday Road, near Sunnyside	SUCW	99.36
Yakima River at Euclid Road Bridge, near Grandview	YGVW	89.77
Chandler–Prosser Power Canal	CHCW	76.62
Yakima River near Prosser	YRPW	74.64

Parker to Grandview, Washington

There are no diversions for this section of the Roza–Prosser Reach. Inflow from April through September is mostly water used for irrigation returning to the Roza–Prosser Reach through laterals.

- Flow measured at the Yakima River near Parker Hydromet gaging station (PARW) was subtracted from the flow measured at the Yakima River at Euclid Road, near Grandview Hydromet gaging station (YGVW). The difference in flow was assumed to be the total inflow from ungaged laterals.
- A percentage of the difference in flow was assigned to each ungaged inflowing lateral based on proportions of flow measured during USGS field trips in September 2005. The equations used to assign flow in ungaged inflowing laterals are included in appendix B.

Grandview to Prosser, Washington

There is one gaged diversion for this section of the Roza–Prosser Reach. Inflow from April through September is mostly water used for irrigation returning to the reach through laterals.

Table 4. U.S. Geological Survey surface-water sites measured for flow, velocity, and water temperature in the Yakima River mainstem from Roza Diversion Dam to Prosser Dam, Washington, and joining creeks, diversions, wasteways, and drains, September 14–16, 2005.

[Locations of surface-water sites are shown in figure 10. Inflow is flow from a lateral to the Roza-Prosser Reach. Outflow is flow from the Roza-Prosser Reach to a lateral. **Abbreviations:** Reclamation, Bureau of Reclamation; m^3/s, cubic meter per second]

Site description	Inflow/Outflow	Flow (m^3/s)	River kilometer
Selah Creek at Canyon Road crossing, near Pomona	Inflow	0.00	206.53
Wenas Creek near mouth on Reclamation land, near Selah	Inflow	.05	204.45
Taylor Ditch at Harrison Road Bridge, near Selah	Outflow	.11	204.05
Golf course and Selah Sewage Outflow Creek near Selah	Inflow	.30	195.74
Moxee Canal	Outflow	.09	192.86
Hubbard and Moxee Canals	Outflow	.33	192.82
Richartz Ditch	Outflow	.00	192.08
Wide Hollow Creek near mouth	Inflow	.99	180.25
Union Gap Canal Wasteway	Inflow	.17	179.88
Roza Canal Wasteway No. 3	Inflow	.19	163.61
Snipes and Allen Ditch Diversion	Outflow	.28	161.40
Lateral 1 near the Donald-Wapato Road, near Wapato	Inflow	.18	151.44
Roza Canal Wasteway No. 4	Inflow	.04	144.82
Roza-Sunnyside Joint Drain No. 19.9	Inflow	.01	143.00
Roza-Sunnyside Joint Drain No. 20.8	Inflow	.02	142.60
East Toppenish Drain at Wilson Road Station No. 12505350	Inflow	.65	142.38
DID Drain No 27 at mouth	Inflow	.03	136.91
Sub-Drain No. 35 at Parton Road Station No. 12505410	Inflow	1.17	136.30
Granger Drain at Sheep Barns Station No. 12505460	Inflow	.64	135.61
Marion Drain at Indian Church Road at Granger, Station No. 12505510	Inflow	.43	135.25
Toppenish Creek at Indian Church Road, Station No. 12507508	Inflow	1.22	132.29
Coulee Drain near Satus Road Crossing	Inflow	.36	124.92
DID No. 16 Drain	Inflow	.40	117.66
Satus Creek at Satus (at gage), Station No. 12508620	Inflow	1.53	113.67
South Drain near Satus, Station No. 12508630	Inflow	1.31	113.22
Satus No. 2 Drain	Inflow	.00	108.94
DID No. 7 Drain	Inflow	.09	104.77
Satus No. 3 Drain	Inflow	.42	101.63
Satus Drain 303 + Mabton West Wasteway at Highway 22	Inflow	1.24	98.07
DID Drain 31 (Frazier Drain at Chase-Frasier Road)	Inflow	.48	96.24
Joint DID No. 2 Drain	Inflow	.51	91.23
Outlet for DID No. 10	Inflow	.10	83.75
Drain near Grandview-Prosser Highway 8/24-2B	Inflow	.01	77.09
Roza-Sunnyside Joint Drain	Inflow	.09	76.77

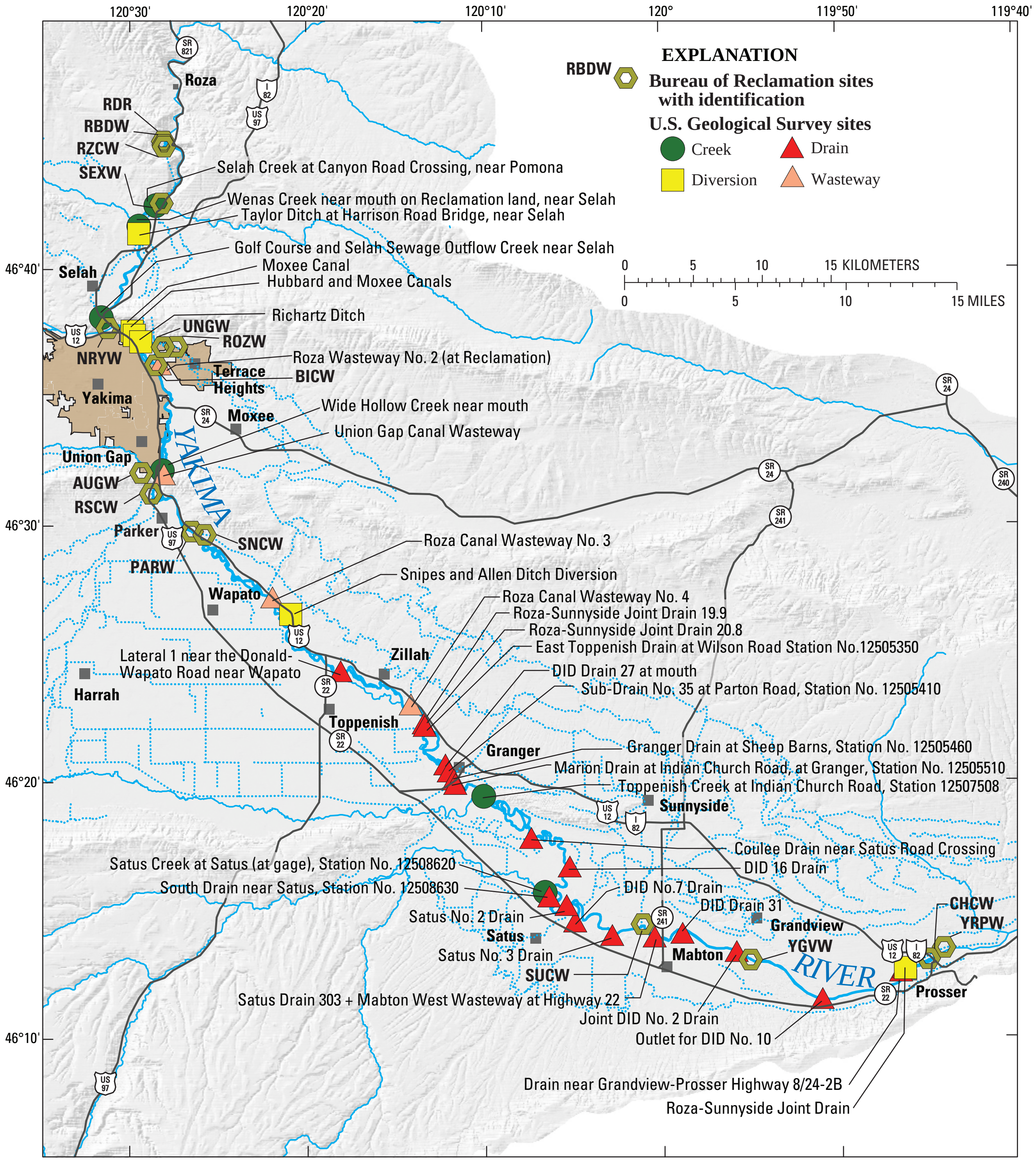


Figure 10. Locations of Bureau of Reclamation Hydromet sites and U.S. Geological Survey sites used to estimate flow to and from the Roza–Prosser Reach, Yakima River, Washington.

- Flow measured at the YGVW Hydromet gaging station (Grandview) was subtracted from the flow measured at the YRPW Hydromet gaging station (Prosser) minus the flow measured at the Hydromet gaging station for the Chandler Canal (CHCW). The difference in flow was assumed to be the total inflow from ungaged laterals.

- A percentage of the difference in flow was assigned to each ungaged inflowing lateral based on proportions of flow measured during the USGS field trips in September 200 The equations used to assign flow in ungaged inflowing laterals are included in appendix B.

Ground water flowing to and from a river affects water temperature (Poole and Berman, 2001) and is an important process, but difficult to measure. The SNTEMP model sets ground-water flow equal to the difference between inflow and outflow. For example, if flow into the model is 20 m^3/s and the outflow from the model is 21 m^3/s, then the model will add 1 m^3/s as ground-water inflow. The model sets the temperature of the ground water equal to the mean annual air temperature for the simulation period, unless the user specifies another value. Ground-water temperature was set to 11.2ºC for calibration and testing simulations based on the calculated average daily mean air temperature at the AgriMet weather station (Harrah) from January 1, 1988, through December 31, 2005. SNTEMP adds ground water to a model as a distributed flow, meaning that flow in a reach was added equally throughout the reach of the entire model instead of being discharged at a specific location.

Water Temperature

Water temperature, as with flow, must be determined for all inflows before the SNTEMP model can be run. However, consistent water-temperature data for flows into the Roza–Prosser Reach were not available, and methods needed to be developed for estimating inflow water temperatures. Water temperatures leaving the Roza–Prosser Reach do not need to be calculated because those temperatures do not affect the temperature of the Roza–Prosser Reach, and outflow water temperatures are not used in other calculations. Two methods were developed by the USGS to estimate the water temperature of flows entering the Roza–Prosser Reach: (1) regression equations to estimate water temperatures for rivers entering the Roza–Prosser Reach (namely the upper Yakima River above Roza Diversion Dam and the Naches River where the river joins the Roza–Prosser Reach just north of Yakima) and (2) a set of regression equations to estimate water temperature for all streams, wasteways, and drains entering the length of the Roza–Prosser Reach.

To develop the regression equations for the Yakima River above Roza Diversion Dam and the Naches River where the river joins the Roza–Prosser Reach, existing datasets were required for water temperature (response variable) at both locations as well as for other parameters used to explain the variations in water temperature over time (explanatory variables). Daily records of average water temperature at both locations were obtained from the Bureau of Reclamation Hydromet database (table 5).

The primary dataset used to derive explanatory variables for Roza Diversion Dam and Naches River regressions was obtained from the National Climate Data Center (NCDC). Specifically, the daily mean air temperature recorded at Yakima Air Terminal (Site ID: YKM) was used. Previous studies have concluded that in the absence of other data, mean air temperature (above freezing) can explain most variations in water temperature (Bartholow, 1989). For the Naches River regression, river discharge recorded at the Naches River at Yakima gaging station also was used. Because the model alternatives were seasonal and limited to the 7-month period April 1 through October 31, only data collected during this period were used to develop the regression equations.

Regression equations were derived by using S-PLUS statistical software (Insightful Corp., 2002). Ordinary least-squares (OLS) linear regression as well as linear robust (least trimmed squares, LTS) and nonlinear methods were considered. Initially, a regression equation was developed to estimate water temperature, using only daily mean air temperature as an explanatory variable. Residual plots for these regressions (residual versus fit) showed slight curvature (heteroscadasticity) that resulted in a relation between residuals and the explanatory variable that was not desirable and likely the result of seasonality. To incorporate the effect

Table 5. Data sources used to develop regression equations for the Yakima River above Roza Diversion Dam and the Naches River where the river joins the Roza–Prosser Reach, Washington.

[Locations of sites are shown in figure 10. Reclamation, Bureau of Reclamation; ºC, degrees Celsius; m^3/s, cubic meter per second]

Site	Site identification	Source	Parameter	Type of data	Period of record
Roza Reservoir	RDR	Reclamation-Hydromet	Water temperature (ºC)	Daily mean	April 1999 to present
Naches River at Yakima	NRYW	Reclamation-Hydromet	Water temperature (ºC)	Daily mean	August 1987 to July 2004
Naches River at Yakima	NRYW	Reclamation-Hydromet	Flow (m^3/s)	Daily mean	October 1981 to present
Yakima air terminal	YKM	National Climate Data Center	Air temperature (ºC)	Daily mean	March 1909 to present

of seasonality, regressions were examined using 3-, 7-, 15-, 30-, and 45-day moving averages of air temperature and a time-dependent parameter based on a function of Julian day. In the case of the Naches River regression, river flow also was added. Then a stepwise regression technique was used to select variables that best explain the data variance, thereby reducing the total number of variables. An evaluation of multicolinearity between variables (Helsel and Hirsch, 1995) also was performed and further reduced the number of variables.

The resulting linear regression equations for estimating water temperature at Roza Diversion Dam and Naches River at Yakima are:

$$\mathrm{RDR} = 4.0 + \mathrm{AT45dav}*0.2991 + \mathrm{AT}*0.3448; \quad (2)$$
$$R^2 = 0.80, \mathrm{N}=1605, \text{Std. Err.} = 1.6\ (^\circ\mathrm{C})$$

$$\mathrm{NRYW} = 2.4 + \mathrm{AT45dav}*0.4635 + \mathrm{AT}*0.2992 - 0.002*\mathrm{Q}; \quad (3)$$
$$R^2 = 0.90, \mathrm{N} = 2302, \text{Std. Err.} = 1.4\ (^\circ\mathrm{C}),$$

where

RDR and
NRYW are water temperature (°C) at Roza Diversion Dam and Naches River at Yakima, respectively,
AT45dav is the simple 45-day moving average of daily mean air temperature (°C) at the Yakima Air Terminal,
AT is the daily mean air temperature at the same location, and
Q is the discharge (cubic meters per second) at the Naches River at Yakima gaging station.

Explanatory variables need not be independent of each other (Helsel and Hirsch, 1995), and although the explanatory variables AT45dav and AT are derivations of the same parameter, these variables are only modestly correlated ($r = 0.65$).

The proportion of variability (R^2) explained by using robust LTS or nonlinear regression methods did not increase appreciably, nor was there a substantial decrease in standard error; therefore these methods were not used.

An important assumption for the regression equation for the Roza Diversion Dam is that water temperature near the surface of the reservoir (at the location of the sensor) is representative of water temperature in the river immediately downstream of the spillway. The water temperature sensor was located just west of the gage structure on the dam, about 46 meters from the edge of the spillway (Q. Kreutler, U.S. Bureau of Reclamation, written commun., 2006). Water temperature data collected by the USGS between April 1 and July 20, 2006, indicated that on average the water temperature at the gaging station was within 0.2ºC of water temperature in the river immediately downstream of the spillway.

Water temperature for inflowing lateral sites was estimated by developing regression equations for 11 inflowing laterals that had limited measured water temperature data available (table 6). Other inflowing laterals to the Roza–Prosser Reach were then assigned the same water temperature as the nearest lateral with a developed regression equation for water temperature (see appendix C).

Table 6. Inflowing laterals to the Roza–Prosser Reach, Washington, where regression equations were developed to estimate water temperature.

[Locations of sites are shown in figure 10. *Ta*, daily mean air temperature at Harrah, Wash., in degrees Celsius; *Tw*, daily mean water temperature, in degrees Celsius]

Site description	Regression equations	R^2
Wide Hollow Creek near mouth	$Tw = (0.5768*Ta) + 20.8$	0.9115
Lateral 1 near the Donald-Wapato Road, near Wapato	$Tw = (1.1037*Ta) + 26.4$	.8797
East Toppenish Drain at Wilson Road, Station No. 12505350	$Tw = (0.5567*Ta) + 20.6$	.8308
Sub-Drain No. 35 at Parton Road, Station No. 12505410	$Tw = (0.5074*Ta) + 20.1$	.8738
Marion Drain at Indian Church Road, at Granger, Station No. 12505510	$Tw = (0.7477*Ta) + 23.1$	.8634
Toppenish Creek at Indian Church Road, Station No. 12507508	$Tw = (1.0704*Ta) + 22.0$	.8769
Coulee Drain near Satus Road Crossing	$Tw = (0.7312*Ta) + 22.8$	.8363
Satus Creek at Satus (at gage), Station No. 12508620	$Tw = (0.8225*Ta) + 23.4$	.8519
South Drain near Satus, Station No. 12508630	$Tw = (0.915*Ta) + 24.5$	.8979
DID No. 7 Drain	$Tw = (0.9929*Ta) + 24.3$	.8092
Satus Drain 303 + Mabton West Wasteway at Highway 22	$Tw = (1.1977*Ta) + 27.5$	.7853

Stream Geometry

Stream geometry data were developed to define characteristics of the Roza–Prosser Reach. The SNTEMP model requires descriptive data for the model nodes and the river sections between the nodes. Model nodes are used in the Roza–Prosser Reach to define where model sections begin and end, where water enters or leaves the reach, where simulation results are output, and where substantial changes occur in reach characteristics. Each model node must be assigned a site location (distance upstream for some arbitrary downstream site), latitude, and elevation, which were derived using a Geographic Information System (GIS) in this study. Reaches between points require data for the reach azimuth (defined as the deviation of a channel from a true north-south axis), the river roughness coefficient called Manning's *N*, and width of the river. Reach properties are set at the starting node and are considered constant until these properties are changed at a node farther downstream.

A GIS was used to determine the azimuth for sections of the Roza–Prosser Reach. A Manning's *N* value of 0.04 (the value for large natural channels) was selected from the SNTEMP user's manual (Table II, page II-3) and was assigned to all channels in the Roza–Prosser Reach. The width of a river can be set to a constant value or can vary with flow. The equation $W = aQ^b$ (where W is stream width in meters, Q is flow in cubic meters per second, and a and b are coefficients) was used to change the width of reaches as the flow changed. The equation coefficients a and b were determined by using the results of the Bureau of Reclamation's HEC-RAS model, which estimates channel width for a set of flow conditions for hundreds of cross sections along the length of the Roza–Prosser Reach. The equations derived from the HEC-RAS model also represent sections of the reach that had braided channels.

Shading

Shading lowers water temperature by reducing the amount of solar radiation that enters the water. To test for the effect that shading might have on water temperature in the Roza–Prosser Reach, a shading survey was conducted by the USGS on October 26–28, 2006, at 37 stations, covering a total river distance of 62 km.

The shading survey methods used were developed by previous researchers (Quigley, 1981; Theurer and others, 1984) and outlined more recently by Bartholow (1989). Parameters measured at each station were date, time, location, stream azimuth, stream width, topographic altitude, vegetation shade parameters, and incident solar radiation. Location and stream azimuth were determined using a standard compass and Global Positioning System (GPS). A hand-held LaserAce Hypsometer was used to measure stream width, topographic altitude, and vegetation shade parameters, including height above water surface, crown width, distance from the edge of the water, and vegetation density. Vegetation density is partly subjective and was determined by estimating the percentage of continuity of vegetation (quantity) along the river reach and multiplying this by the percentage of incident solar radiation filtered through the vegetation (quality).

Incident solar radiation measurements were made by using a hand-held solarimeter. Direct solar radiation was measured from the center of the river, exposure measurement in sunlight (E_o), and diffuse solar radiation was measured at the riverbank, exposure measurement in shade (E_i). Bartholow (1989) used both incident solar radiation measurements to determine a relative shade quality index:

$$\text{Shade quality} = 1.0 - (E_i \,/\, E_o)$$

In addition to the above measurements, digital photographs were taken at each station, and the water temperature was measured.

Two hydrographers collected measurements from a 5-m jet boat with a 35-horsepower outboard motor. The river generally was navigable at the time of the survey, and the boat was used to travel between stations, allowing observation of various riparian terrain and vegetation.

Weather conditions at the time of the survey were mild, dry, and generally clear. The level of sunlight was not constant during the survey and changed frequently during the days because of intermittent clouds. Following the suggestion of Bartholow (1989), shade data mostly were collected between 0900 and 1500 hours. The locations where shade measurements were collected are shown in figure 11, and an example of the field sheet is in appendix D.

For this project, shading data were entered into the model for locations where shade was directly measured. Estimates of shading at other locations were based on relating shading measurements to orthophotographs. Sections of the Roza–Prosser Reach that appeared similar to measured sections were given average values of the measured sections.

Topographic shading was not estimated in the field by the USGS because topographic shading is difficult to measure and is usually not a factor for large rivers in a floodplain. However, the upper regions of the study area are in a canyon where topographic shading may contribute to a decrease in water temperature. In the future, topographic shading in the canyon could potentially be calculated using a GIS and digital elevation data, but this calculation was beyond the scope of this study.

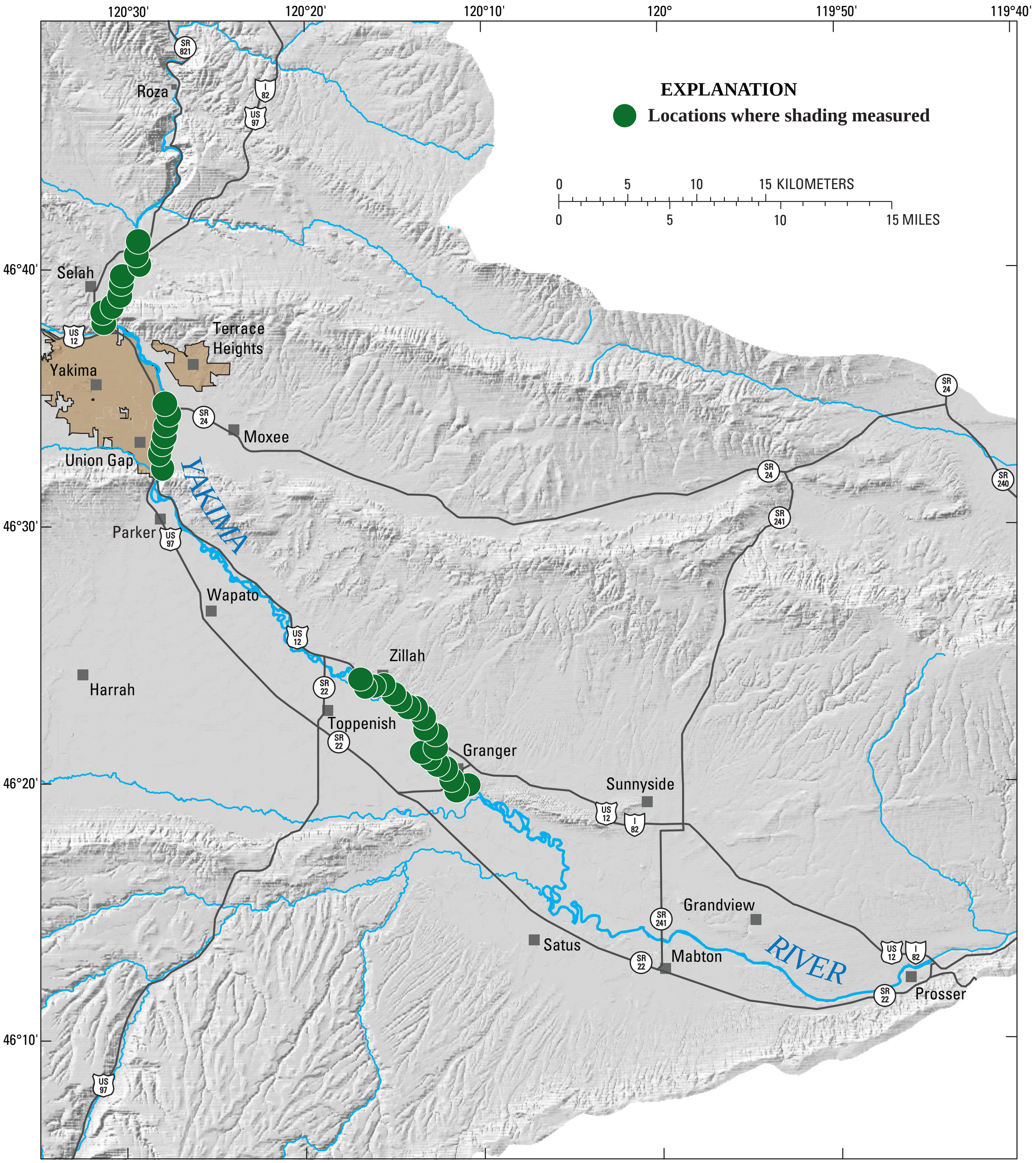


Figure 11. Locations where shade parameters were measured by the U.S. Geological Survey, Roza–Prosser Reach, Washington, October 2006.

Water-Temperature Model Calibration and Testing

A simulation period from April 1 through October 31, 2005, was used to calibrate the water-temperature model for the Roza–Prosser Reach. Daily mean water temperature data used to calibrate the model were obtained for Hydromet gaging stations at Parker, and at Grandview. Daily maximum water temperature data were obtained for sites maintained by the Bureau of Reclamation (fig. 12) where small temperature sensors (TidbiTs) were installed. Monthly distributions of weather variables measured at the AgriMet weather station (Harrah) that were used as model input during the calibration period are shown in figure 13. Weather coefficients in the SNTEMP program control file, which can be set to systematically increase or decrease the magnitude of SNTEMP climate input data (air temperature, wind speed, relative humidity, and solar radiation) by a user-specified percentage, were adjusted to obtain the best agreement between simulated and measured water temperature. The best agreement was obtained when the coefficients for air temperature, wind speed, and relative humidity were set to 1.0 and the coefficient for solar radiation set to 0.95. Because adjustments to Manning's *N* did not produce better agreement between simulated and measured water temperatures, Manning's *N* was left at the original value of 0.04.

The two statistics used for assessing the goodness-of-fit between simulated and measured water temperatures at the calibration and testing sites were root mean squared error (RMSE) and mean error. RMSE is the standard deviation of the simulated water-temperature values about the measured water-temperature values. For example, a RMSE value of 1.4°C for the Mabton site for the calibration simulation period indicates that approximately 68 percent of the simulated daily maximum water temperatures are within one standard deviation (+1.4°C) of the measured daily maximum water temperatures at Mabton, 95 percent are within two standard deviations (+2.7°C), and 99 percent are within three standard deviations (+3.6°C). RMSE is a measure of how accurately the model simulates water temperature; the lower the RMSE, the more accurate the simulations. The RMSE was calculated using the following steps: (1) subtracting simulated from measured water temperatures for each day of the period of interest (which could be a week, a month, or the entire simulation period) and squaring the differences (so that negative values do not cancel positive values), (2) sum all squared differences and divide by the number of days in the period of interest, and (3) take the square root of the value calculated in step 2 to get the RMSE.

Mean error is the average error of a number of observations by taking the mean value of the positive and negative errors without regard to sign. Therefore, mean error can be positive or negative and is an indicator of bias in simulation results. For example, if the mean error for the TidbiT site at Mabton is –0.8ºC, then on average, the model simulated daily maximum water temperatures that were 0.8ºC lower than the measured daily maximum water temperature at Mabton. Ideally, mean error should be zero, meaning that the model over-simulates and under-simulates water temperature equally and, therefore, has no bias. Possible reasons for bias in the calibration and testing simulations are discussed in section, "Limitations of Water-Temperature Model". Mean error is calculated by subtracting the measured daily (mean or maximum) water temperature from the simulated daily (mean or maximum) water temperature for the period of interest, summing the differences, and then dividing the summed differences by the number of days in the period of interest. Table 7 shows the goodness-of-fit statistics for the five calibration sites of the final calibration simulation. Simulated and measured daily mean water temperatures for the calibration period at two Hydromet gaging stations are shown in figure 14. Simulated and measured daily maximum water temperatures at three TidbiT sites maintained by Bureau of Reclamation are shown in figure 15.

A simulation period from April 1 through October 31, 2006, was used to test the water-temperature model for the Roza–Prosser Reach. Daily mean water temperature data for testing were obtained from Hydromet gaging stations at Parker and Grandview, Washington, which were the same sites used to obtain data for the calibration simulation. Daily maximum water temperature data were obtained for three TidbiT sites maintained by the Bureau of Reclamation (fig. 12). The Mabton TidbiT site also was used to obtain data for the calibration simulations; however, data from TidbiT sites at Harlin Landing and Wapato were used only for the testing simulation. Monthly distributions of weather variables used as model input during the testing period measured at the AgriMet weather station (Harrah) are shown in figure 16. Model parameters were not adjusted for the testing simulation.

The goodness-of-fit statistics for the testing simulation at two Hydromet gaging stations and three TidbiT sites are shown in table 8. Graphs of simulated and measured daily mean water temperature for the calibration period at two Hydromet gages are shown in figure 17. Graphs of simulated and measured daily maximum water temperatures at three TidbiT sites maintained by the Bureau of Reclamation are shown in figure 18.

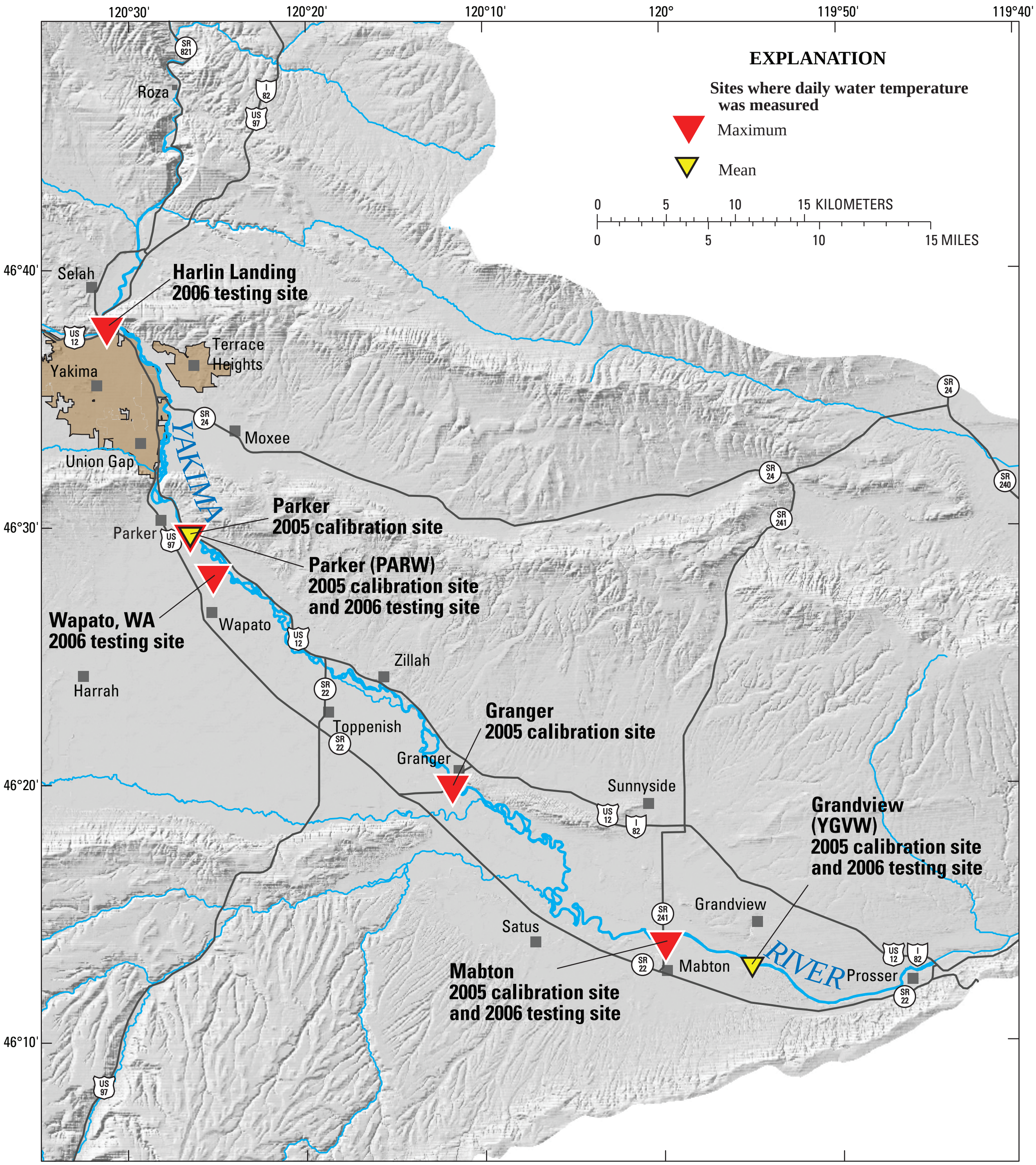


Figure 12. Locations of sites where mean and maximum daily water temperature used for model calibration and testing were measured, Roza–Prosser Reach, Washington.

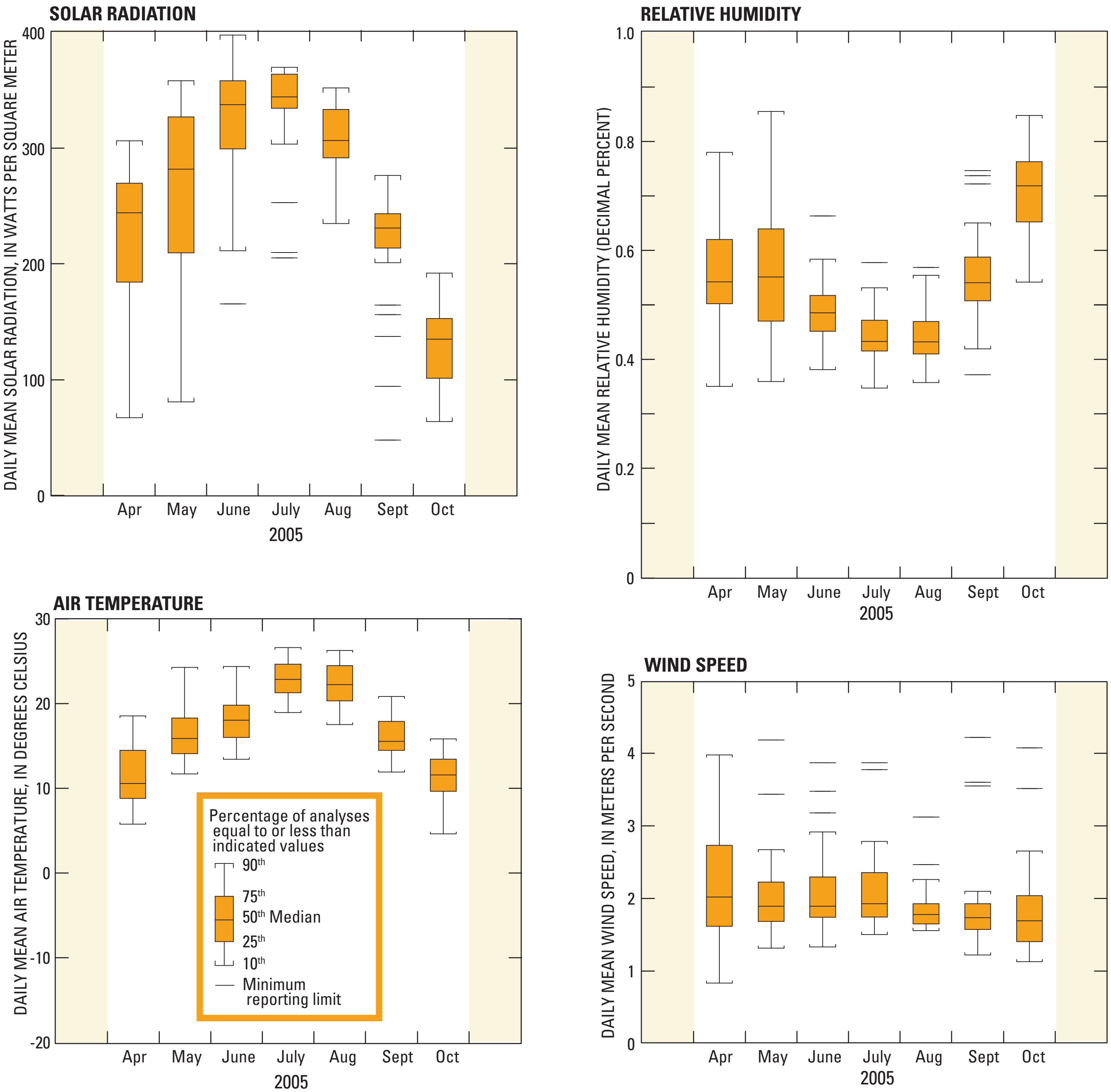


Figure 13. Monthly distributions of solar radiation, air temperature, relative humidity, and wind speed measured at the AgriMet weather station (Harrah), Roza–Prosser Reach, Washington, April through October 31, 2005.

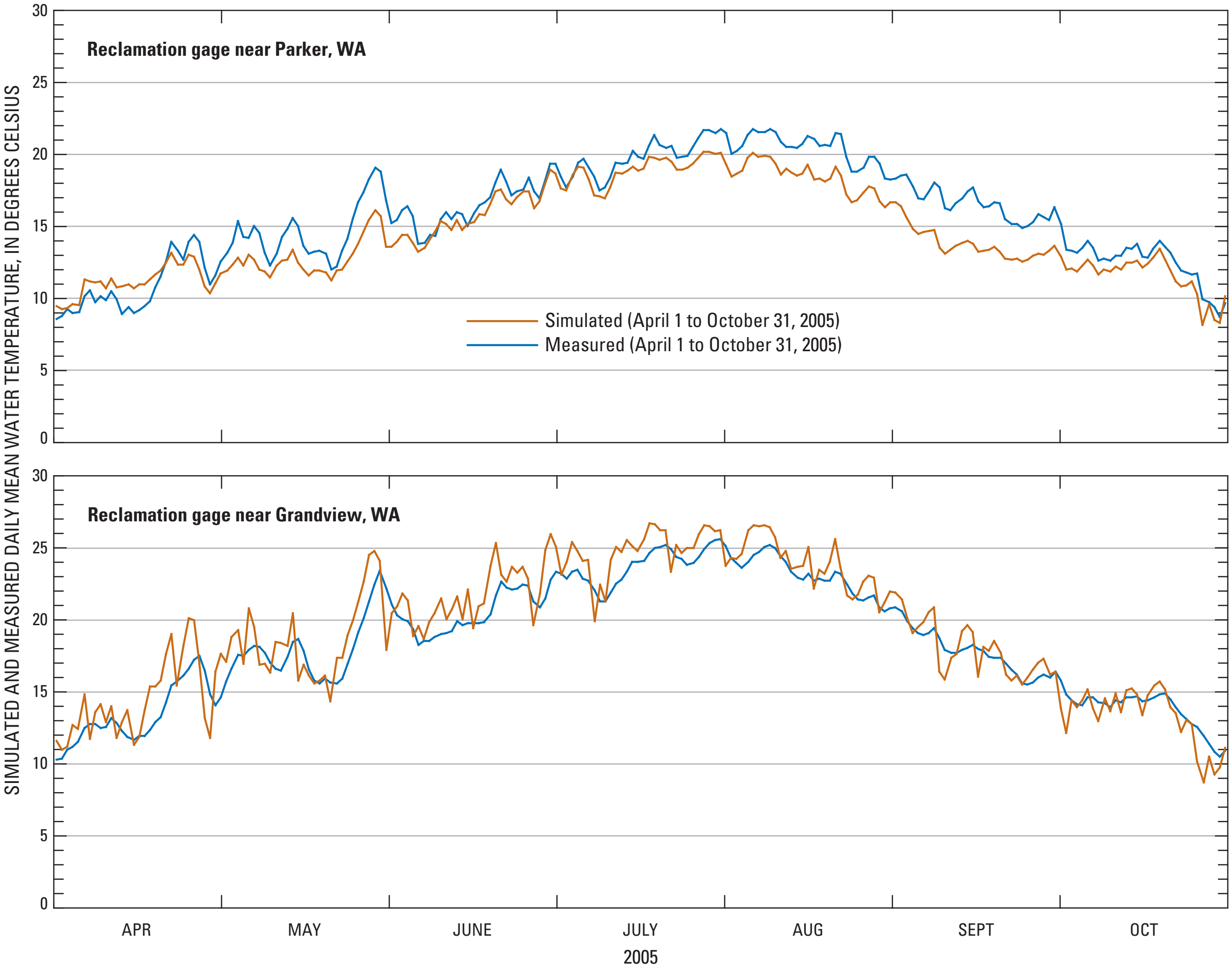


Figure 14. Simulated and measured daily mean water temperature at Bureau of Reclamation gaging stations at Parker and Grandview, Roza–Prosser Reach, Washington, April 1 to October 31, 2005.

Table 7. Goodness-of-fit statistics for the final calibration simulation, Roza–Prosser Reach, Washington.

[**Abbreviations:** RMSE, root mean square error; ºC, degrees Celsius; Reclamation, Bureau of Reclamation]

Site description	RMSE (ºC)	Mean error (ºC)
Sites where daily mean water temperatures were measured		
Hydromet gage at Parker (station identification–PARW)	1.7	-1.3
Hydromet gage at Grandview (station identification–YGVW)	1.5	.7
Sites where daily maximum water temperatures were measured		
Reclamation TidbiT near Parker	1.9	1.6
Reclamation TidbiT near Granger	1.4	-.4
Reclamation TidbiT near Mabton	1.3	-.8

Table 8. Goodness-of-fit statistics for testing simulations, Roza–Prosser Reach, Washington.

[**Abbreviations:** RMSE, root mean square error; ºC, degrees Celsius; Reclamation, Bureau of Reclamation]

Site description	RMSE (ºC)	Mean error (ºC)
Sites where daily mean water temperatures were measured		
Hydromet gage at Parker (station identification–PARW)	1.6	0.7
Hydromet gage at Grandview (station identification–YGVW)	2.0	1.2
Sites where daily maximum water temperatures were measured		
Reclamation TidbiT near Harlin	2.2	1.2
Reclamation TidbiT near Wapato	1.8	1.3
Reclamation TidbiT near Mabton	1.9	.1

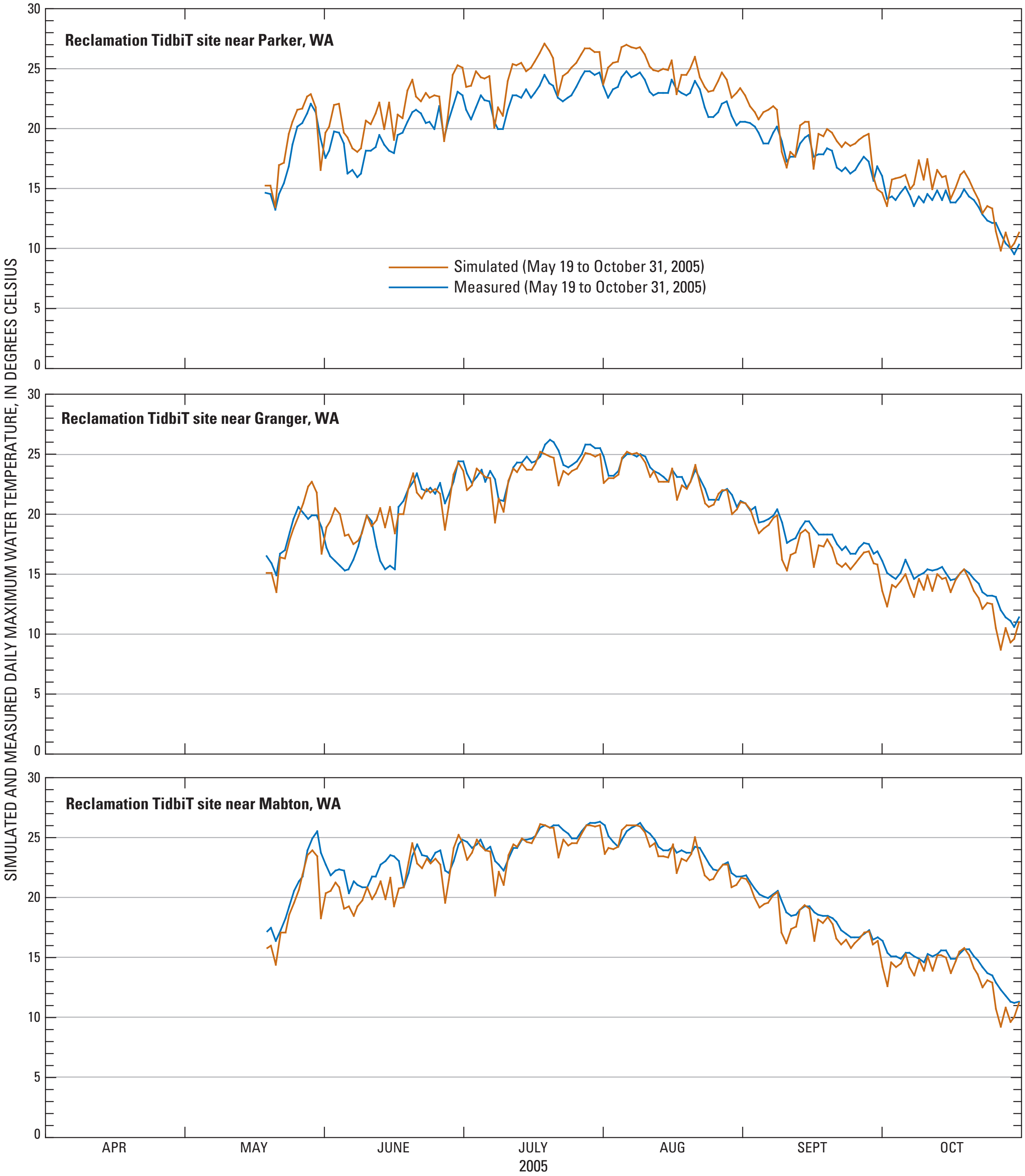


Figure 15. Simulated and measured daily maximum water temperature at three Bureau of Reclamation TidbiT sites near Parker, Granger, and Mabton, Washington, May 15 to October 31, 2005.

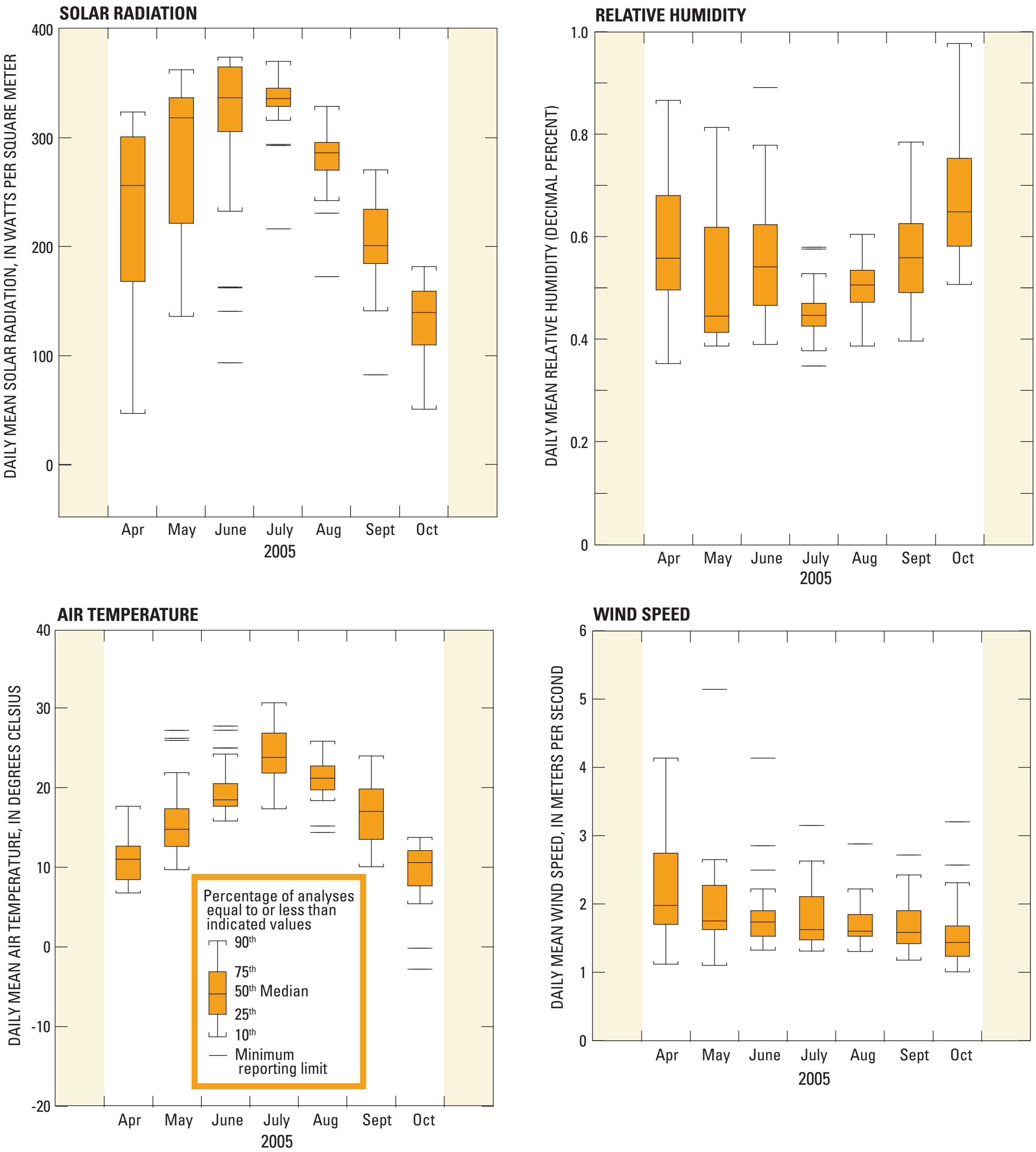


Figure 16. Monthly distributions of solar radiation, air temperature, relative humidity, and wind speed measured at the AgriMet weather station (Harrah), Roza–Prosser Reach, Washington, April 1 to October 31, 2006.

The graphs in figures 17 and 18 show that the Roza–Prosser Reach model simulates seasonal patterns in measured daily mean and maximum water temperatures at the testing sites indicating that flows generally are characterized correctly and the model is responding correctly to meteorological inputs. The RMSE for the testing simulation sites ranged from 1.6 to 2.2°C and mean error ranged from –1.3 to 1.6°C; whereas, RMSE for the calibration simulation sites range from 1.3 to 1.9°C and mean error ranged from 0.1 to 1.3°C, showing that the model is capable of simulating water temperature for growing seasons with differing flow and climate conditions with generally the same degree of accuracy.

Monthly RMSE and mean error values were calculated for the testing sites to investigate seasonal patterns in simulation error. Statistics were not generated for October because data for October from the TidbiT site contained errors. Monthly goodness-of-fit statistics for the testing sites are shown in table 9.

The mean error shows a general seasonal pattern where the model over-predicts water temperature from April through June of the simulation period and obtains greater accuracy or under-predicts water temperature from July through September (table 9). The seasonal pattern in error also can be seen in figures 17 and 18. This seasonal bias may indicate model sensitivity to air temperature, possibly caused by underestimating flow in the system resulting in less thermal buffering; overestimating stream width resulting in overexposure to solar radiation and air temperature input; or incorrect model-section lengths, resulting in errors in climate input. Errors and the effect on simulation results are discussed in section, “Limitations of Water-Temperature Model”.

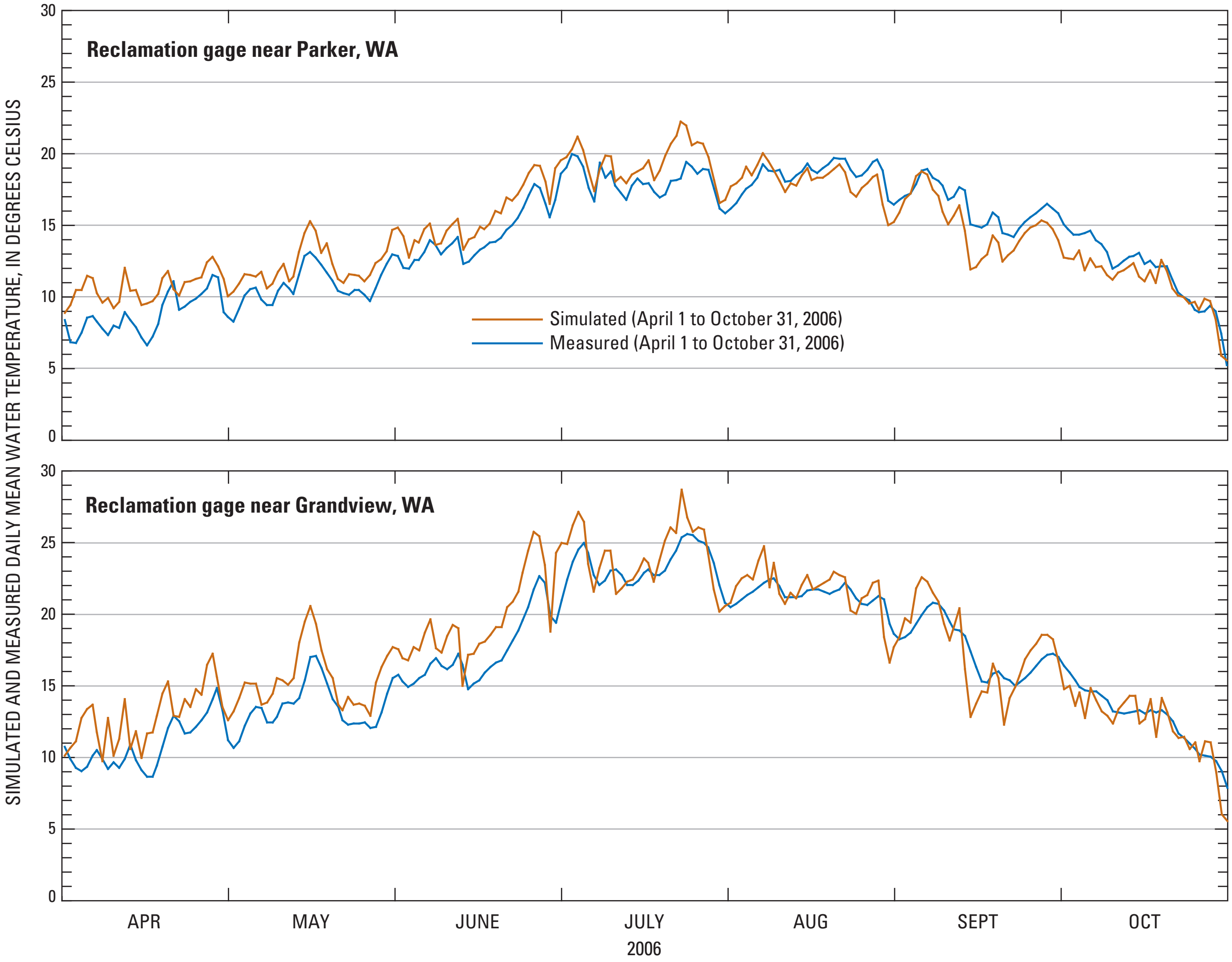


Figure 17. Tested simulated and measured daily mean water temperature at Bureau of Reclamation gaging stations at Parker and Grandview, Washington, April 1 to October 31, 2006.

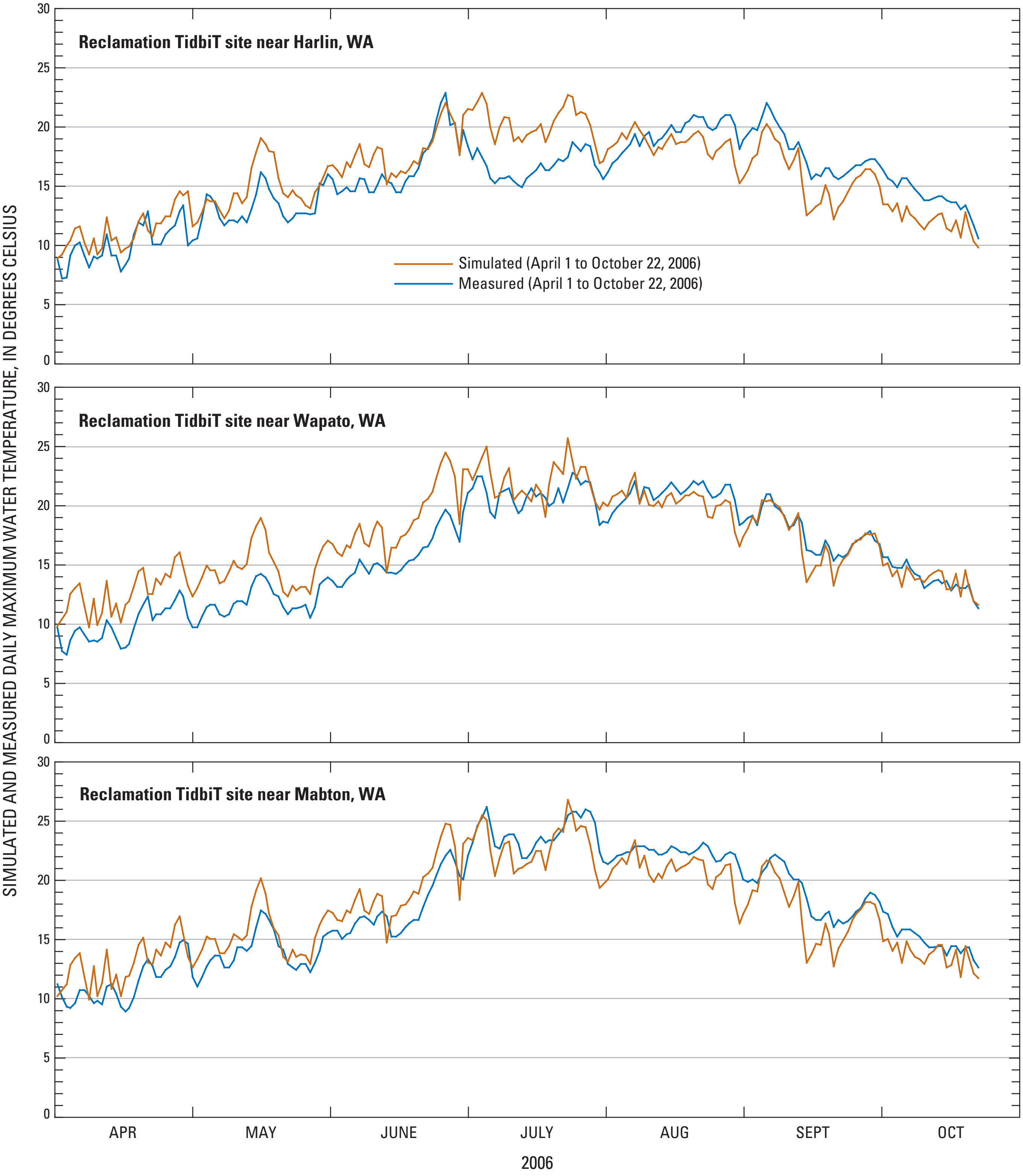


Figure 18. Tested simulated and measured daily maximum water temperature at three TidbiT sites, Washington, April 1 to October 22, 2006.

Table 9. Monthly goodness-of-fit statistics for testing simulations, Roza-Prosser Reach, Washington.

Testing period	Water temperature, in degrees Celsius							
	Parker	Grandview	Harlin Landing		Wapato		Mabton	
	Mean	Mean	Mean	Maximum	Mean	Maximum	Mean	Maximum
Mean Error								
April through September	0.7	1.2	1.9	0.8	1.1	1.3	0.3	0.1
April	1.9	2.0	2.4	1.2	2.0	2.1	1.7	1.6
May	1.3	2.0	2.7	1.5	1.4	1.8	1.5	1.4
June	1.4	2.2	2.5	1.1	1.6	1.8	1.7	1.6
July	1.3	.8	4.4	3.5	2.2	2.1	-.8	-1.1
August	-.4	.4	.5	-.9	.4	.3	-1.2	-1.5
September	-1.3	.1	-.8	-1.9	-.8	-.5	-.9	-1.5
Root Mean Square Error								
April through September	1.6	2.0	2.8	2.2	1.7	1.8	1.8	1.9
April	2.1	2.5	2.6	1.6	2.1	2.3	2.2	2.1
May	1.4	2.2	2.8	1.9	1.5	1.9	1.7	1.7
June	1.5	2.5	2.6	1.6	1.7	2.0	2.0	2.0
July	1.6	1.7	4.6	3.7	2.3	2.2	1.6	1.7
August	1.0	1.2	1.4	1.8	1.1	.9	1.6	1.9
September	1.5	1.7	1.3	2.1	1.3	1.2	1.6	1.9

Sensitivity Analysis

A series of simulations were conducted to determine the relative effect of selected input variables and model parameters on simulated water temperatures. One input variable or model parameter in the calibrated Roza–Prosser Reach model was changed for each simulation by a percentage, although all other variables and parameters were held constant. As shown in table 10, the resulting percentage of change in daily mean water temperature for the simulation period was measured and recorded for one Hydromet site (Grandview) and two TidbiT sites maintained by Bureau of Reclamation. The period for the sensitivity simulations was from April 1 through October 31, 2005, and used weather data from the AgriMet weather station (Harrah). Simulations for July were run to determine seasonal patterns of sensitivity.

Daily maximum and mean water temperatures for the Roza–Prosser Reach model were most sensitive to daily mean air temperature. Daily maximum water temperatures were more sensitive than daily mean water temperatures to solar radiation, and both simulated daily maximum and daily mean water temperatures were more sensitive to solar radiation than to relative humidity.

Table 10. Results of sensitivity analysis, Roza–Prosser Reach, Washington.

[Irrigation season = April 1 to October 31, 2005; July = July 1 through July 31, 2005. All values are in percent. **Abbreviations:** Reclamation, Bureau of Reclamation; YGVW, Yakima River at Euclid Road Bridge, near Grandview; °C, degrees Celsius; Wm^{-2}, Watts per square meter; m/s, meter per second; m, meter]

Parameter or variable	Percent change to input value	Resulting percent change in maximum water temperature at sites				Resulting percent change in mean water temperature at site	
		Reclamation Tidbit site near Granger		Reclamation Tidbit site near Mabton		Hydromet gage at Grandview (station identification – YGVW)	
		Irrigation season	July	Irrigation season	July	Irrigation season	July
Daily mean air temperature (°C)	+ 5	+ 1.71	2.02	1.72	1.95	2.03	2.47
	- 5	- 1.67	-2.02	-1.69	-1.95	-2.00	-2.06
Daily mean solar radiation (Wm^{-2})	+ 5	+ 1.31	1.62	1.40	1.56	1.22	1.65
	- 5	- 1.31	-1.21	-1.41	-1.56	-1.23	-1.23
Relative humidity (percent)	+ 5	+ .61	.81	.62	.78	.76	.82
	- 5	- .61	-.40	-.63	-.39	-.77	-.82
Wind speed (m/s)	+ 5	+ .24	.00	-.26	-.39	-.28	-.41
Channel width (m)	+ 10	.00	.00	.21	.39	.18	.41
	- 10	.00	.00	-.22	-.39	-.19	.00

Limitations of Water-Temperature Model

The accuracy of the water temperatures estimated by the SNTEMP model is limited by four types of error: model, data, parameter, and user errors.

Model error occurs when the equations used to represent physical processes are flawed or incomplete. This happens in all models in varying degrees because a model by definition is a simplified version of a real system. Model error can result from the use of an improper equation, use of the wrong numerical method to represent the equation, and calculation errors in the computer code that might make a model overly sensitive to certain input parameters. A potentially significant source of model error in SNTEMP is the method used to calculate daily maximum water temperature (Bartholow, 2000). The form of the equation used to calculate daily maximum water temperature (Theurer and others, 1984, equation II(116)) is the same as that used for daily mean water temperature (Theurer and others, 1984, equation II(115)). However, because of limitations in the model computer code, daily maximum air temperature cannot be used in place of the daily mean air temperature. Instead, a regression equation that includes relative humidity, wind speed, and solar radiation is used to predict the daily maximum air temperature, which is used as input into equation II(116). The coefficients for the regression equation (Theurer and others, 1984, table II.3 page II-32) are based on measurements collected throughout the country. A method exists to estimate regression coefficients by using local weather data (Bartholow, 2000). This was attempted by using data from the AgriMet weather station (Harrah). However, when the results from the regression equation were compared against measured data, the local coefficients did not predict daily maximum air temperature as well as the coefficients from table II.3 in the User's Manual (Theurer and others, 1984).

Data error occurs when the input data used in the model do not accurately represent actual conditions. Input data for the Roza–Prosser Reach contained data errors because much of the input data were estimated.

Input flow data contain data errors for at least four reasons:

1. Flow estimates in all ungaged laterals (for example. streams, canals, drains, returns) were based on flow measurements from one USGS September 2005 seepage run. The proportion of flow in the laterals measured in September 2005 generally was assumed to be the same throughout the growing season but the actual proportion of flow varies over the growing season and adds error to water temperature estimates on any given day.

2. All flow estimates for the model were based on daily flow measurements made at 13 gages maintained by the Bureau of Reclamation. Data errors at these gages (especially during large runoff events) add data error to flow estimates.

3. Ground-water flow to or from a reach is based on estimated surface-water flows. When inflow to a reach is less than outflow, SNTEMP adds ground water to maintain the water balance in the reach. Therefore, errors in surface-water flow estimates are related to errors in ground-water estimates. The work required to characterize ground-water exchange more accurately in the Roza–Prosser Reach was beyond the scope of this project.

(4) Data error may occur because inflow to the Yakima River mainstem from holding ponds and oxbow lakes may not be accurately represented. The exchange between those bodies of water is not well understood. Therefore, greater data error could occur during low-flow conditions in the mainstem when inflow from ponds and oxbow lakes may be proportionally higher. Characterizing the flow exchange between the mainstem and adjacent ponds and lakes also was beyond the scope of this study.

Input water temperatures contain data errors because these data were generated using regression equations, which are approximations of actual conditions. Data also were not available to develop a regression equation for every inflowing lateral. Many laterals were assigned water temperature values from a nearby lateral (with a developed regression equation), which increases data error.

Input meteorology data contain data errors because actual conditions along the mainstem vary from conditions at the AgriMet weather station at Harrah. Differences between meteorological data at Harrah and at four USGS weather stations along the mainstem are discussed in the section, "Meteorology".

Parameter error occurs when variables adjusted to calibrate a model are set to values that do not represent actual conditions. For example, Manning's *N* can be adjusted to improve the agreement between measured and simulated water temperatures, but instead of obtaining a better representation of the system, the adjustment might be concealing poorly represented processes in the model that caused the poor agreement.

User error can occur when the user makes a mistake. This can happen when a user assumes a condition exists when in fact it does not or when a user makes a programming error or enters incorrect data.

Summary

Water temperatures in the Roza–Prosser Reach affect aquatic habitat and the viability of native fish populations. However, water demand for increasing population and agriculture in the Yakima River basin has caused the Bureau of Reclamation to consider water-allocation management plans that could potentially alter water temperatures in the Roza–Prosser Reach. A mechanistic water-temperature model was constructed by the U.S. Geological Survey (USGS) for use by the Bureau of Reclamation to study the relative effects that various water-management plans might have on water temperature during a growing season (April 1 through October 31). The DOS-based Stream Network Temperature model (SNTEMP version 2.0) was selected for the simulation because input data for the model were readily available, and the model has been successfully used in water temperature studies since the mid-1980s. Five SNTEMP modeled reaches were linked in series to simulate the daily maximum water temperatures at locations selected by the Bureau of Reclamation for input into the Ecosystem Diagnosis and Treatment analytical model. Meteorological data for model input were collected from an AgriMet weather station (Harrah). Streamflow data collected from 15 Bureau of Reclamation Hydromet gaging stations and field measurements collected by the USGS in September 2005 were used to estimate flow in the Roza–Prosser Reach. Regression equations were used to estimate water temperature data for flow entering the Roza–Prosser Reach from the upper Yakima River upstream of the Roza Dam and the Naches River and for all inflowing laterals under current operating conditions. Shading data for model input were collected by the USGS in October 2006. The model was calibrated using a simulation period, April 1 through October 31, 2005, and tested using a simulation period, April 1 through October 31, 2006. A sensitivity analysis indicated that daily maximum water temperatures are most influenced by daily mean air temperature and solar radiation.

Graphs comparing daily simulated and measured water temperatures at calibration and testing sites show that the model simulated seasonal patterns of measured water temperature. Root mean squared error (RMSE) for the five sites used for model calibration ranged from 1.3 to 1.9 degrees Celsius (°C), and mean error ranged from –1.3 to 1.6°C. For the five sites used for testing simulation, the RMSE ranged from 1.6 to 2.2°C, and mean error ranged from 0.1 to 1.3°C. Similar RMSE and mean error for the calibration and testing simulations indicate the model simulated differing flow and climate conditions with the same level of accuracy and that the model is suitable for studying the effect of potential water management decisions on water temperature in the Roza–Prosser Reach.

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References Cited

Bartholow, J.M., 1989, Stream temperature investigations—Field and analytic methods: U.S. Fish and Wildlife Service, Biological Report, v. 89, no. 17, 139 p.

Bartholow, J.M., 2000, The stream segment and stream network temperature models—A self-study course: U.S. Geological Survey Open-File Report 99-112, 276 p.

HDR Engineering Inc., 2002, Water temperature of Lochsa River and selected tributaries (QRP00023) – final report, 55 p., accessed March 12, 2008, at http://www.deq.state.id.us/water/data_reports/surface_water/water_bodies/lochsa_river_temp_cs.pdf

Helsel, D.R., and Hirsch, R.M., 1995, Statistical methods in water resources: Studies in Environmental Science, New York, Elsevier, v. 49, 529 p.

Insightful Corporation, 2002, S-PLUS, v. 6.1, for Windows [computer software], Professional Edition: Insightful Corporation.

Kent, C.A., 2004, Water resource planning in the Yakima River Basin—Development versus Sustainability: Yearbook of the Association of Pacific Coast Geographers, v. 66, p. 27-60.

Poole, G.C., and Berman, C.H., 2001, An ecological perspective on in-stream temperature—Natural heat dynamics and mechanisms of human-caused thermal degradation: Environmental Management, v. 27, no. 6, p. 787-802.

Quigley, T.M., 1981, Estimating contribution of overstory vegetation to stream surface shade: Wildlife Society Bulletin, v. 9, no. 1, p. 22-27.

Systat Software, Inc. SYSTAT 10.2, Statistics I. Point Richmond, Calif.: Systat Software, Inc; 2002.

Theurer, F.D., Voos, K.A., and Miller, W.J., 1984, Instream water-temperature model—Instream flow information Paper 16: U.S. Fish and Wildlife Service, FWS/OBS-84/15, 335 p.

U.S. Census Bureau, 2000, Census 2000 data for the state of Washington, accessed June 5, 2006, at http://www.census.gov/census2000/states/wa.html

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Appendix A. Example of Input File to the EDT Analytical Model

The following is an example of the output file format that will be generated from the Roza-Prosser Reach water-temperature model for input to the EDT analytical model. The first column is the identifier code for the output site, the second column is the output data code (MAX_WATER_TEMP_C is daily maximum simulated water temperature in degrees Celsius [°C]), the third column is the date (in Afrikaans date format), and the fourth column is the simulated daily maximum water temperature in °C.

```
H-2C   MAX_WATER_TEMP_C     1984/04/01     12.02
H-2C   MAX_WATER_TEMP_C     1984/04/02     12.62
H-2C   MAX_WATER_TEMP_C     1984/04/03     11.91
H-2C   MAX_WATER_TEMP_C     1984/04/04     11.03
H-2C   MAX_WATER_TEMP_C     1984/04/05     11.46
H-2C   MAX_WATER_TEMP_C     1984/04/06     12.72
H-2C   MAX_WATER_TEMP_C     1984/04/07     11.25
H-2C   MAX_WATER_TEMP_C     1984/04/08     12.29
```

Appendix B. Method for Deriving Daily Mean Flow for Sites Used to Define Flow for the Roza-Prosser Reach Water-Temperature Model

Tables B1 and B2 show methods used to derive values for daily mean flow for sites used to define flow for the Roza–Prosser Reach water-temperature model. Sites at Hydromet gaging stations used daily mean flow measurements from those stations. Sites between Hydromet stations were assigned a percentage of the difference in flow between the stations. The assigned percentages were based on flow measurements made by the USGS during field trips in September 2005.

Table B1. Method used to assign daily mean flow to sites used to define flow for the Roza–Prosser Reach water-temperature model.

[**Flow calculation** abbreviations are listed in table B2; SUM1 = All inflow between Roza Dam and Parker, Washington, minus flow to diversions. **Abbreviations:** Reclamation, Bureau of Reclamation; NA, not applicable]

Location	Flow calculation	Decimal percent used in calculations
Yakima River below Roza Dam, near Roza	Used daily values measured at RBDW	NA
Selah-Moxee Canal	Used daily values measured at SEXW	NA
Selah Creek at Canyon Road Crossing, near Pomona	Set daily values equal to percent of PARW - (SUM1)	0.003
Wenas Creek near mouth on Reclamation land, near Selah	Set daily values equal to percent of PARW - (SUM1)	.031
Taylor Ditch at Harrison Road Bridge, near Selah	Set daily values equal to percent of SEXW	.080
Golf Course and Selah Sewage Outflow Creek, near Selah	Set daily values equal to percent of PARW - (SUM1)	.197
Naches River near North Yakima, near mouth at Reclamation gaging site 12499900	Used daily values measured at NRYW	NA
Moxee Canal	Set daily values equal to percent of UNGW	.050
Hubbard Canal	Set daily values equal to percent of UNGW	.200
Union Gap Canal	Set daily values measured at UNGW	NA
Richartz Ditch	Set daily values equal to percent of UNGW	.000
Roza Wasteway No. 2 (at Reclamation)	Set daily values equal to RZCW-ROZW	NA
Moxee Drain at Thrope Road	Use daily values measured at BICW	NA
Wide Hollow Creek near mouth	Set daily values equal to percent of PARW - (SUM1)	.658
Ahtanum Creek at Union Gap, Station No. 12502500	Use daily values measured at AUGW	NA
Union Gap Canal Wasteway	Set daily values equal to percent of PARW - (SUM1)	.111
New Reservation Canal Headworks (Wapato Canal)	Use daily values measured at RSCW	NA
Sunnyside Canal near Parker	Use daily values measured at SNCW	NA
Yakima River at Parker, Station No. 1250500	Use daily values measured at PARW	NA
Roza Canal Wasteway No. 3	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0174
Snipes and Allen Ditch Diversion	Set daily values equal to percent of SEXW	.2065
Lateral 1 near the Donald-Wapato Road, near Wapato	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0161
Roza Canal Wasteway No. 4	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0039
Roza-Sunnyside Joint Drain 19.9	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0011
Roza-Sunnyside Joint Drain 20.8	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0017
East Toppenish Drain at Wilson Road, Station No 12505350	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0592
DID Drain 27 at mouth	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0026
Sub-Drain No. 35 at Parton Road, Station No. 12505410	Set daily values equal to percent of (YGVW-SUCW)-PARW	.1073
Granger Drain at Sheep Barns, Station No. 12505460?	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0584
Marion Drain at Indian Church Road, at Granger, Station No. 12505510	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0392
Coulee Drain near Satus Road Crossing (2 Drains?)	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0327

Table B1. Method used to assign daily mean flow to sites used to define flow for the Roza-Prosser Reach water-temperature model.—Continued

[**Flow calculation** abbreviations are listed in table B2; SUM1 = All inflow between Roza Dam and Parker, Washington, minus flow to diversions. **Abbreviations:** Reclamation, Bureau of Reclamation; NA, not applicable]

Location	Flow calculation	Decimal percent used in calculations
Toppenish Creek at Indian Church Road, Station 12507508	Set daily values equal to percent of (YGVW-SUCW)-PARW	0.1122
DID 16 Drain	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0364
Satus Creek at Satus (at gage), Station No. 12508620	Set daily values equal to percent of (YGVW-SUCW)-PARW	.1402
South Drain near Satus, Station No. 12508630	Set daily values equal to percent of (YGVW-SUCW)-PARW	.1205
Satus No. 2 Drain	Set daily values equal to percent of (YGVW-SUCW)-PARW	0.00
DID No. 7 Drain	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0085
Satus No. 3 Drain	Set daily values equal to percent of (YGVW-SUCW)-PARW	.039
Sulphur Creek Wasteway	Use daily values measured at SUCW	NA
Satus Drain 303 + Mabton West Wasteway at Highway 22	Set daily values equal to percent of (YGVW-SUCW)-PARW	.1135
DID Drain 31 (Frazier Drain at Chase-Frasier Road)	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0436
Joint DID 2 Drain	Set daily values equal to percent of (YGVW-SUCW)-PARW	.0465
Outlet for DID No. 10	Set daily values equal to percent of (YRPW+CHCW)-YGVW	.5075
Drain near Grandview-Prosser Highway 8/24-2B	Set daily values equal to percent of (YRPW+CHCW)-YGVW	.0374
Roza-Sunnyside Joint Drain	Set daily values equal to percent of (YRPW+CHCW)-YGVW	.4551
Chandler Canal at Prosser Dam, Station No. 12509499	Use daily values measured at CHCW	NA
Yakima River at Prosser	Use daily values measured at YRPW	NA

Table B2. U.S. Bureau of Reclamation gaging stations used in calculations for the Roza–Prosser Reach water-temperature model.

[Data obtained from Hydromet database]

Station identification	Station description
RBDW	Yakima River below Roza Dam
RZCW	Roza Canal at Headworks
SEXW	Selah Moxee Canal
NRYW	Naches River near Yakima
UNGW	Union Gap Canal
BICW	Moxee Drain at Birchfield Road
AUGW	Ahtanum Creek at Union Gap
ROZW	Roza Canal at 11.0 mile
RSCW	New Reservation Canal
SNCW	Sunnyside Canal
PARW	Yakima River near Parker
SUCW	Sulpher Creek at Holiday Road, near Sunnyside
YGVW	Yakima River at Euclid Road Bridge, near Grandview
CHCW	Chandler–Prosser Power Canal
YRPW	Yakima River near Prosser

Appendix C. Regression Equations Used to Estimate Water Temperature for Each Surface-Water Source of the Roza–Prosser Reach, Washington.

Table C1. Regression equations used to estimate water temperature for each surface-water source of the Roza–Prosser Reach, Washington.

[**Abbreviations:** NA, Water temperature is not assigned to diversions; *Tw*, daily mean water temperature in degrees Celsius; m^3/s, cubic meter per second]

Location	Water temperature calculation
Yakima River below Roza Dam, near Roza	*Tw* = 4.0+ 0.2991*(45-day moving average of daily mean air temperature) + 0.3448*(daily mean average of air temperature)
Selah-Moxee Canal	NA
Selah Creek at Canyon Road Crossing, near Pomona	*Tw* = *Tw* at Wide Hollow Creek near mouth
Wenas Creek near mouth on Reclamation land, near Selah	*Tw* = *Tw* at Wide Hollow Creek near mouth
Taylor Ditch at Harrison Road Bridge, near Selah	*Tw* = *Tw* at Wide Hollow Creek near mouth
Golf Course and Selah Sewage Outflow Creek near Selah	*Tw* = *Tw* at Wide Hollow Creek near mouth
Naches River near North Yakima, near mouth at Reclamation gaging station 12499900	*Tw* = 2.4 + 0.4635*(45-day moving average of daily mean air temperature) + 0.2992*(daily mean average of air temperature) – 0.002*(flow (m^3/s) at the Naches River at Yakima gaging station)
Moxee Canal	NA
Hubbard Canal	NA
Union Gap Canal	NA
Richartz Ditch	*Tw* = *Tw* at Wide Hollow Creek near Mouth
Roza Wasteway No. 2 (at Reclamation)	*Tw* = *Tw* at Wide Hollow Creek near Mouth
Moxee Drain at Thrope Road	*Tw* = *Tw* at Wide Hollow Creek near Mouth
Wide Hollow Creek near mouth	*Tw* = (0.5768*daily mean air temperature) + 20.8
Ahtanum Creek at Union Gap, Station No. 12502500	*Tw* = *Tw* at Wide Hollow Creek near Mouth
Union Gap Canal Wasteway	*Tw* = *Tw* at Wide Hollow Creek near Mouth
New Reservation Canal Headworks (Wapato Canal)	NA
Sunnyside Canal near Parker	NA
Yakima River at Parker, Station No. 1250500	NA
Roza Canal Wasteway No. 3	*Tw* = *Tw* at Lateral 1 near the Donald-Wapato Road near Wapato
Snipes and Allen Ditch Diversion	NA
Lateral 1 near the Donald-Wapato Road, near Wapato	*Tw* = (1.1037*daily mean air temperature) + 26.4
Roza Canal Wasteway No. 4	*Tw* = *Tw* at Lateral 1 near the Donald-Wapato Road near Wapato
Roza-Sunnyside Joint Drain 19.9	*Tw* = *Tw* at Lateral 1 near the Donald-Wapato Road near Wapato
Roza-Sunnyside Joint Drain 20.8	*Tw* = *Tw* at Lateral 1 near the Donald-Wapato Road near Wapato
East Toppenish Drain at Wilson Road, Station No 12505350	*Tw* = (0.5567*daily mean air temperature) + 20.6
DID Drain 27 at mouth	*Tw* = *Tw* at Sub-Drain No. 35 at Parton Road, Station No. 12505410
Sub-Drain No. 35 at Parton Road, Station No. 12505410	*Tw* = (0.5074*daily mean air temperature) + 20.1
Granger Drain at Sheep Barns, Station No. 12505460	*Tw* = *Tw* at Sub-Drain No. 35 at Parton Road, Station No. 12505410
Marion Drain at Indian Church Road, at Granger, Station No. 12505510	*Tw* = (0.7477*daily mean air temperature) + 23.1
Coulee Drain near Satus Road Crossing	*Tw* = (0.7312*daily mean air temperature) + 22.8
Toppenish Creek at Indian Church Road, Station 12507508	*Tw* = (1.0704*daily mean air temperature) + 22.0
DID 16 Drain	*Tw* = Tw at Coulee Drain near Satus Road Crossing
Satus Creek at Satus (at gage), Station No. 12508620	*Tw* = (0.8225*daily mean air temperature) + 23.4
South Drain near Satus, Station No. 12508630	*Tw* = (0.915*daily mean air temperature) + 24.5
Satus No. 2 Drain	*Tw* = *Tw* at South Drain near Satus, Station No. 12508630
DID No. 7 Drain	*Tw* = (0.9929*daily mean air temperature) + 24.3
Satus No. 3 Drain	*Tw* = *Tw* at DID No. 7 Drain
Sulphur Creek Wasteway	*Tw* = Tw at DID No. 7 Drain
Satus Drain 303 + Mabton West Wasteway at Highway 22	*Tw* = (1.1977*daily mean air temperature) + 27.5
DID Drain 31 (Frazier Drain at Chase-Frasier Road)	*Tw* = *Tw* at Satus Drain 303 + Mabton West Wasteway at Highway 22
Joint DID 2 Drain	*Tw* = *Tw* at Satus Drain 303 + Mabton West Wasteway at Highway 22
Outlet for DID No. 10	*Tw* = *Tw* at Satus Drain 303 + Mabton West Wasteway at Highway 22
Drain near Grandview-Prosser Highway 8/24-2B	*Tw* = *Tw* at Satus Drain 303 + Mabton West Wasteway at Highway 22
Roza-Sunnyside Joint Drain	*Tw* = *Tw* at Satus Drain 303 + Mabton West Wasteway at Highway 22
Chandler Canal at Prosser Dam, Station No. 12509499	NA
Yakima River at Prosser	NA

Appendix D. Example of the Shading Effects Field Sheet.

Shading Effects Field Sheet

Location____
____
Date: _________ Time: _______ Hydrographer(s) _____________
GPS Coordinates: N ____° ____’ _____” accuracy +/-_______ft
(at center of river) W____° ____’ _____”
Stream Azimulth (-90° to 90°) ______° Magnetic or True North?
Stream Width _____________ft

	West Bank	East Bank
Topographic Altitude	__________°	__________°
Vegetation height (Vh)	__________ft	__________ft
Vegetation crown (Vc)	__________ft	__________ft
Vegetation offset (Vo)	__________ft	__________ft
Vegetation density (Vd)	__________%	__________%
Maximum light	__________Fc	__________Fc
Shaded light	__________Fc	__________Fc

Remarks____

Appendix E. Regression Equations Used to Estimate Daily Mean Water Temperature in Outflow from Five Reservoirs in the Yakima River Basin

The following section shows regression equations that were used to estimate daily mean water temperature in outflow from five reservoirs in the Yakima River basin. The equations were originally intended for generating input to the Roza–Prosser Reach water-temperature model but were not included in the final version of the model. The equations are included here for documentation purposes.

Regression equations were examined by using S-PLUS (Insightful Corp., 2002) and TableCurve 3D (Systat Software, Inc., 2002) for the purpose of estimating stream water temperatures downstream of five reservoirs. The process of variable selection for the regressions was identical to the process used in Roza Dam and Naches River regression development.

Bumping: (Linear Robust LTS, S-PLUS)

BUM = -1.809 + AT * 0.1449 + AT45dav * 0.7177

Robust multiple R^2 = 0.89, Scale estimate of residual = 1.5 (°C), N = 1620

Cle Elum: (Linear Robust LTS, S-PLUS)

CLE = 16.28 + AT * 0.0518 - J’ * 0.09 - Q * 0.004

Robust multiple R^2 = 0.89, Scale estimate of residual = 2.56, N = 1279

Kachess: (Linear OLS, S-PLUS)

KAC = -2.1 + AT * 0.1729 + AT45dav * 0.7995

Multiple R^2 = 0.95, Residual Standard Error = 1.0 (°C), N = 460

Keechelus: (Linear OLS, S-PLUS)

KEE = 3.5 + AT * 0.2028 + AT45dav * 0.4633

Multiple R^2 = 0.91, Residual Standard Error = 1.4 (°C), N = 742

Rimrock: (Linear Robust LTS, S-PLUS)

RIM = 15.85 – AT45dav * 0.1071 – J’ * 0.073 + Q * 0.004

Robust multiple R^2 = 0.98, Scale estimate of residual = 0.90, N = 360

Explanation of variables:

AT = Air temperature at Yakima Air Terminal as provided from NOAA (°C).

AT45dav = 45 day moving average of air temperature at Yakima Air Terminal (°C).

Q = Flow downstream of dam (cubic meters per second).

J’ = Number of days from warmest average water day (for CleElum J’= ABS(Julian day – 233), for Rimrock, J’ = ABS(Julian day – 258).

(°C) = degree Celsius.

N = Number of data sets used in regression development.

Appendix F. Daily Maximum, Mean, and Minimum Water Temperature for Sites in the Yakima River Basin, Washington

As a part of this project, water temperature data were collected at 20 sites within the Yakima River basin. Data were collected from May 27, 2005, to December 6, 2006, but the actual period of record for individual sites varies during this period. The data have been entered into the U.S. Geological Survey database (Automated Data Processing System, ADAPS) and are available in an Excel spreadsheet at the USGS Washington Water Science Center Yakima River Temperature Model project website at http://wa.water.usgs.gov/projects/yakimatemp/data.htm.

Several sites were located in the upper parts of the watershed and were not used in the development of the model, but they are included here for possible use in other studies. Water temperatures were recorded by Onset StowAway TidbiT thermistors or Onset Optic StowAway thermistors set in enclosures, usually a 1- x 3-inch PVC pipe, tied to something solid on the river bank and placed on the bottom of the river- or creek-channel. Either 30- or 60-minute recording cycles were used to log the data. Recorded values were checked with field measurements during visits to the gaging station.

Table F1. U.S. Geological Survey gaging stations where daily maximum, mean, and minimum water temperature data were collected, Yakima River basin, Washington.

[Data are available at http://wa.water.usgs.gov/projects/yakimatemp/data.htm. NAD27, North American Datum of 1927; NAD83, North American Datum of 1983]

Gaging station name	Gaging station No.	Latitude	Longitude	Datum
Gold Creek above Keechelus Lake near Hyak	12473980	47º 23' 25"	121º 22' 54"	NAD27
Box Canyon Creek near Hyak	12473985	47º 21' 32.4"	121º 14' 44.4"	NAD83
Cle Elum River above Cle Elum Lake, near Roslyn	12478300	47º 21' 19"	121º 06' 22"	NAD27
American River near Nile	12488500	46º 58' 40"	121º 10' 03"	NAD27
Tieton River below Oak Creek, near Naches	12493005	46º 43' 39"	120º 8' 35.5"	NAD83
Naches River above Divrsion Dam, near Yakima	12498690	46º 37' 56"	120º 35' 15"	NAD27
Cowiche Creek near Yakima	12498986	46º 37' 38"	120º 34' 52"	NAD83
Wide Hollow Creek near Union Gap	12500447	46º 32' 20"	120º 28' 22"	NAD27
Yakima River above Ahtanum Creek, at Union Gap	12500450	46º 32' 04"	120º 27' 58"	NAD27
Yakima River near Wapato	12505050	46º 29' 09"	120º 25' 49"	NAD27
East Toppenish Drain at Wilson Road, near Toppenish	12505350	46º 22' 04"	120º 15' 00"	NAD27
Sub 35 Drain at Connie Road, near Granger	12505410	46º 20' 11"	120º 13' 48"	NAD27
Lateral 1 Drain near Wapato	1250547010	46º 27' 45"	120º 24' 31"	NAD83
Marion Drain at Indian Church Road and Highway 223	12505510	46º 19' 52"	120º 11' 54"	NAD27
Toppenish Creek at Indain Church Road, near Granger	12507508	46º 18' 52"	120º 11' 53"	NAD27
Coulee Drain at North Satus Road, near Satus	12507560	46º 17' 49"	120º 08' 42"	NAD27
South Drain near Satus	12508630	46º 15' 35"	120º 07' 57"	NAD27
Satus Creek below North Drain, near Satus	1250862050	46º 16' 32"	120º 08' 16"	NAD27
DID 7 Drain near Mabton	12508670	46º 15' 32"	120º 03' 56"	NAD83
Satus Drain 303 near Mabton	12508694	46º 13' 00"	120º 01' 14.5"	NAD83

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Voss and others— **Modeling Water Temperature, Yakima River, Washington, Roza Diversion Dam to Prosser Dam, 2005–06** —Scientific Investigations Report 2008–5070