Willamette River Basin Temperature TMDL Modeling Study

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ABSTRACT

The Corps of Engineers dynamic 2-D model CE-QUAL-W2 Version 3.1 was applied to the Willamette River basin in Oregon. The Corps of Engineers and the State of Oregon Department of Environmental Quality (DEQ) funded the modeling and TMDL study. The study area included about 872 km (545 miles) of river. The model domain included the main stem Willamette River, the North and South Santiam Rivers, the Long Tom River, the McKenzie River and the Coast and Middle Forks of the Willamette River. The model domain also included about 146 km (90.7 miles) of the Columbia River since it affects the tidally influenced portion of the lower Willamette basin. This TMDL project focused on meeting temperature standards and will form the basis for a water quality study at a later time.

The study included model construction (grid development, shading data analysis, meteorological data, and dynamic inflow boundary conditions of flow and temperature), model calibration (model-data comparisons of flow rate and water level at monitoring stations, dye studies performed throughout the basin, and continuous temperature data at dozens of monitoring locations), and evaluation of modeling strategies for temperature improvement. These management scenarios included evaluating the impacts of stream shading, different flow management practices from storage reservoirs in the headwaters of the Willamette, and the impact of point source discharges (primarily wastewater treatment plants, pulp and paper mills, and various industries).

The model development and evaluation of alternatives was also reviewed by the Willamette River TMDL Council, an Oregon citizen and stakeholder group evaluating the Willamette River water quality. The USGS, DEQ, and Portland State University modeling team worked together to provide peer review and model refinement, although DEQ ultimately had responsibility to establish the TMDL assessment approach.

KEYWORDS

Temperature, river basin modeling, TMDL, hydrodynamic and temperature modeling, CE-QUAL-W2

INTRODUCTION

The State of Oregon Department of Environmental Quality (DEQ) is developing a TMDL for temperature in the Willamette River basin shown in Figure 1. The study area included the Willamette River and all major tributaries (except the Tualatin River where a TMDL process was already concluded). A large section of the Columbia River was also modeled to provide adequate boundary representation of tidal flows in the lower Willamette River. The Willamette River below the Willamette Falls in the Portland metropolitan area has a typical diurnal tidal range of 1 m. The development of a dynamic model of temperature and hydrodynamics of the entire river basin incorporating shading were primary requirements of this modeling study. The model would be used by DEQ to set temperature limits on point source dischargers and to evaluate the impact of management strategies on river temperatures to improve fish habitat. Some of these strategies included modifications of the dam at the Willamette River Falls south of Portland and channel reconfigurations.

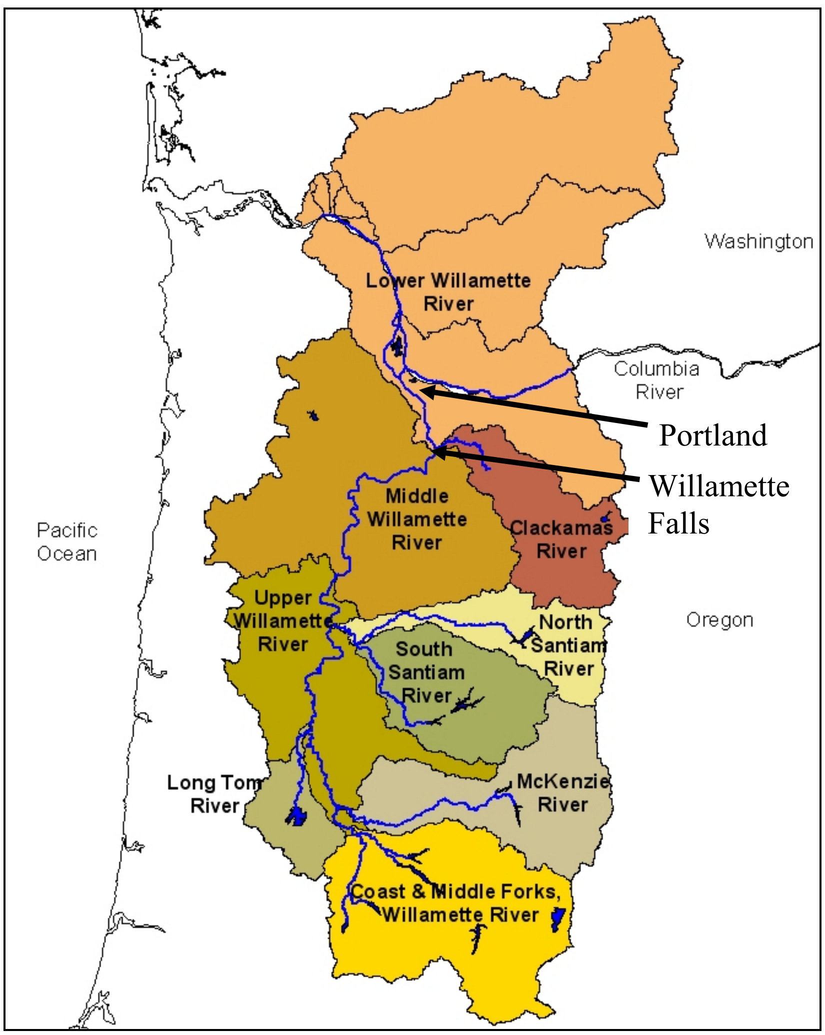

Figure 1 TMDL study area - the Willamette River basin with drainage basins delineated.

This project involved the following elements:

- Model selection
- Model development
- Model calibration
- Management strategies with the model for TMDL development.

MODEL SELECTION

CE-QUAL-W2 Version 3.1 (Cole and Wells, 2002) was chosen as the appropriate model tool for this system for the following reasons:

- Dynamic temperature predictive capability
- Dynamic shading prediction based on detailed topographic and vegetative shading information
- Ability of the model to be used for water quality after the temperature study where parameters of interest are algae, periphyton, pH, dissolved oxygen
- Ability to model complex hydraulic flow paths with multiple interconnected branches using hydraulic elements (weirs, pumps, spillways) between branches
- Ability to evaluate the stratification potential of deep pools in the Willamette River where water quality and temperature data have shown significant stratification
- Ability to model estuary hydrodynamics
- Ability to model an entire river basin including upstream deep-density stratified reservoirs
- Public domain executable and source code for quality-assurance and testing

MODEL DEVELOPMENT

The river basin model was originally divided into several reaches. Individual models were developed for each reach. These reaches were (see also Figure 2):

- **Columbia River** - from Beaver Army Terminal (Columbia River Mile 53.8) to Bonneville Dam (RM 144.5) (Willamette River enters the Columbia River at Columbia River Miles 87 and 101);
- **Tidal Willamette River** – Lower Willamette River from mouth to Willamette Falls (RM 26.5), including the Willamette Channel and the Multnomah Channel;
- **Non-tidal Willamette River** – Willamette Falls (RM 26.5) to confluence of Coast and Middle Forks (RM 187); this section was divided further into the following reaches:
  - Middle Willamette from the Willamette Falls (RM 26.5) to the city of Salem (RM 85);

    - Upper Willamette from the City of Salem (RM 85) to the confluence of Coast and Middle Forks (RM 187)
- **Clackamas River** up to River Mill Dam/Estacada Lake (RM 26);
- **Santiam River** (all 12 miles), North Santiam River up to Detroit Dam (RM 49), South Santiam River up to Foster Dam (RM 38);
- **Long Tom River** to Fern Ridge Dam (RM 26);
- **McKenzie River** to RM 56, and South Fork McKenzie River to Cougar Dam (RM 4);
- **Middle Fork Willamette** to Dexter Dam (RM 17), Fall Creek to Fall Creek Dam (RM 7);
- **Coast Fork Willamette** to Cottage Grove Dam (RM 30), Row River to Dorena Dam (RM 7.5);
- **Columbia Slough** in the tidal portion of the Willamette River (about 9 miles in length)

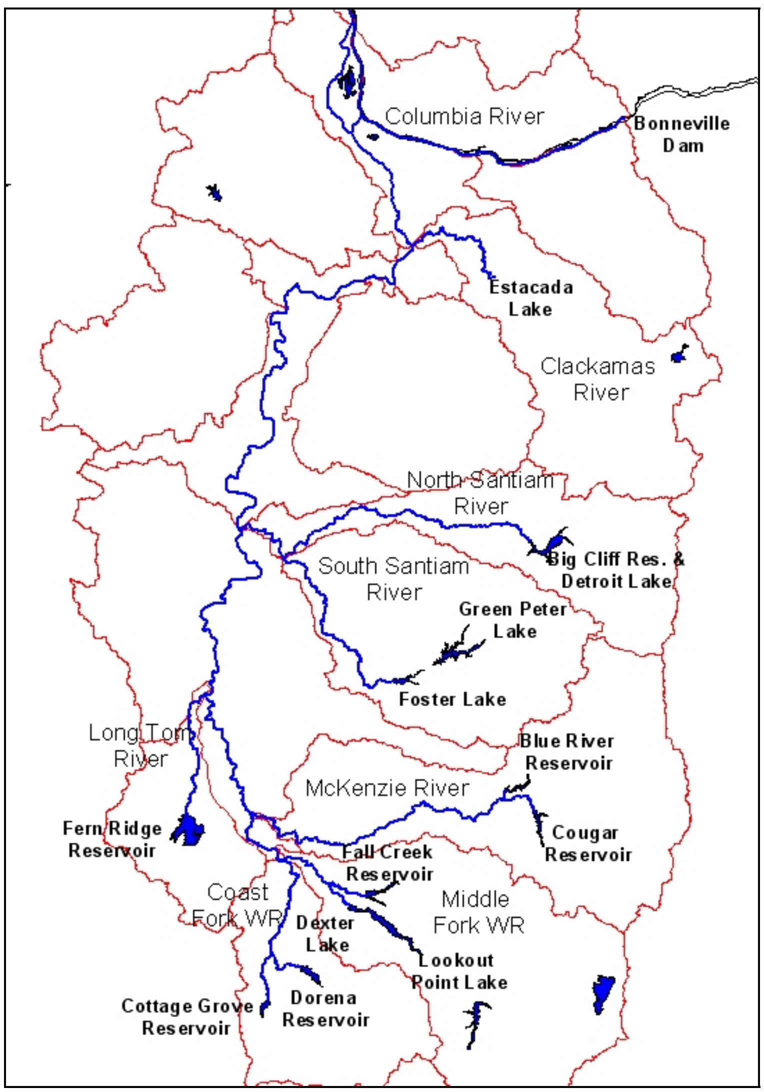

Figure 2. Willamette River and modeled tributaries.

The model development consisted of obtaining data for:

- river channel morphology or bathymetry
- meteorological data (air temperature, dew point temperature or relative humidity, wind speed/direction, solar radiation and/or cloud cover)
- flow and temperature upstream boundary conditions (in most cases determined by continuously monitored dam release flows)
- water level and temperature downstream boundary conditions in the tidal Columbia River

The river channel was divided into longitudinal model segments of approximately 250 m with a vertical grid resolution of between 0.2 to 1 m. An example of the river channel segmentation is shown in Figure 3.

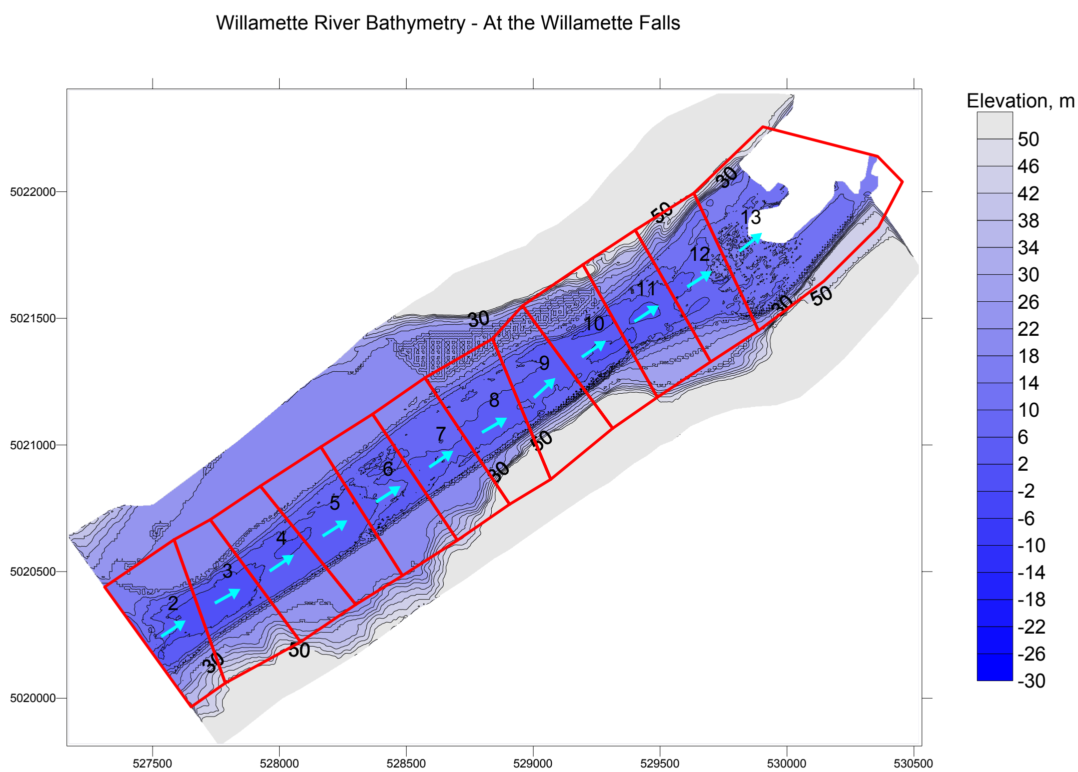

Figure 3. Longitudinal segments of the Willamette River model near the Willamette Falls at RM26.

An example of the vertical and longitudinal grid layout for a section of the Willamette River where there were deep holes is shown in Figure 4.

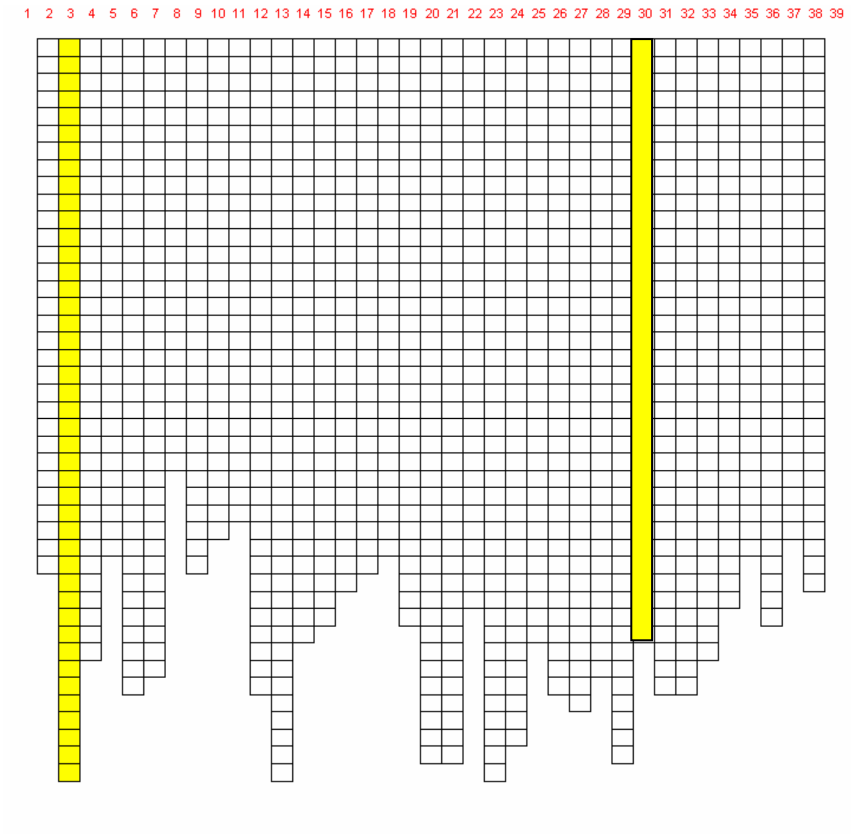

Figure 4. Model grid for Middle Willamette showing longitudinal segments and vertical layers (side view).

Individual segments had varying segment widths with depth, such as those shown in Figure 5.

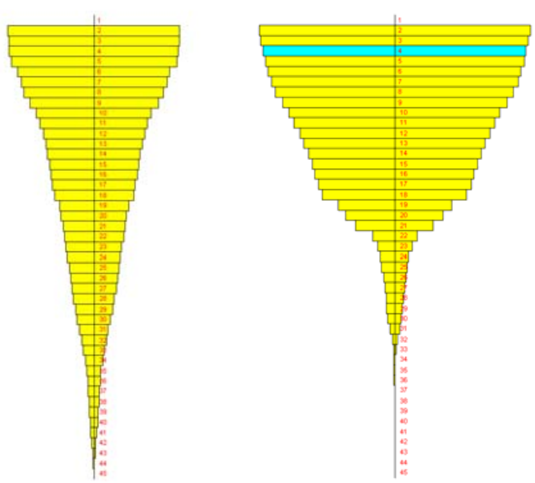

Figure 5. Typical variation of layer widths with depth for longitudinal segment 3 (left) and segment 30 (right) from Figure 4.

A typical section of the Willamette River is shown below in Figure 6.

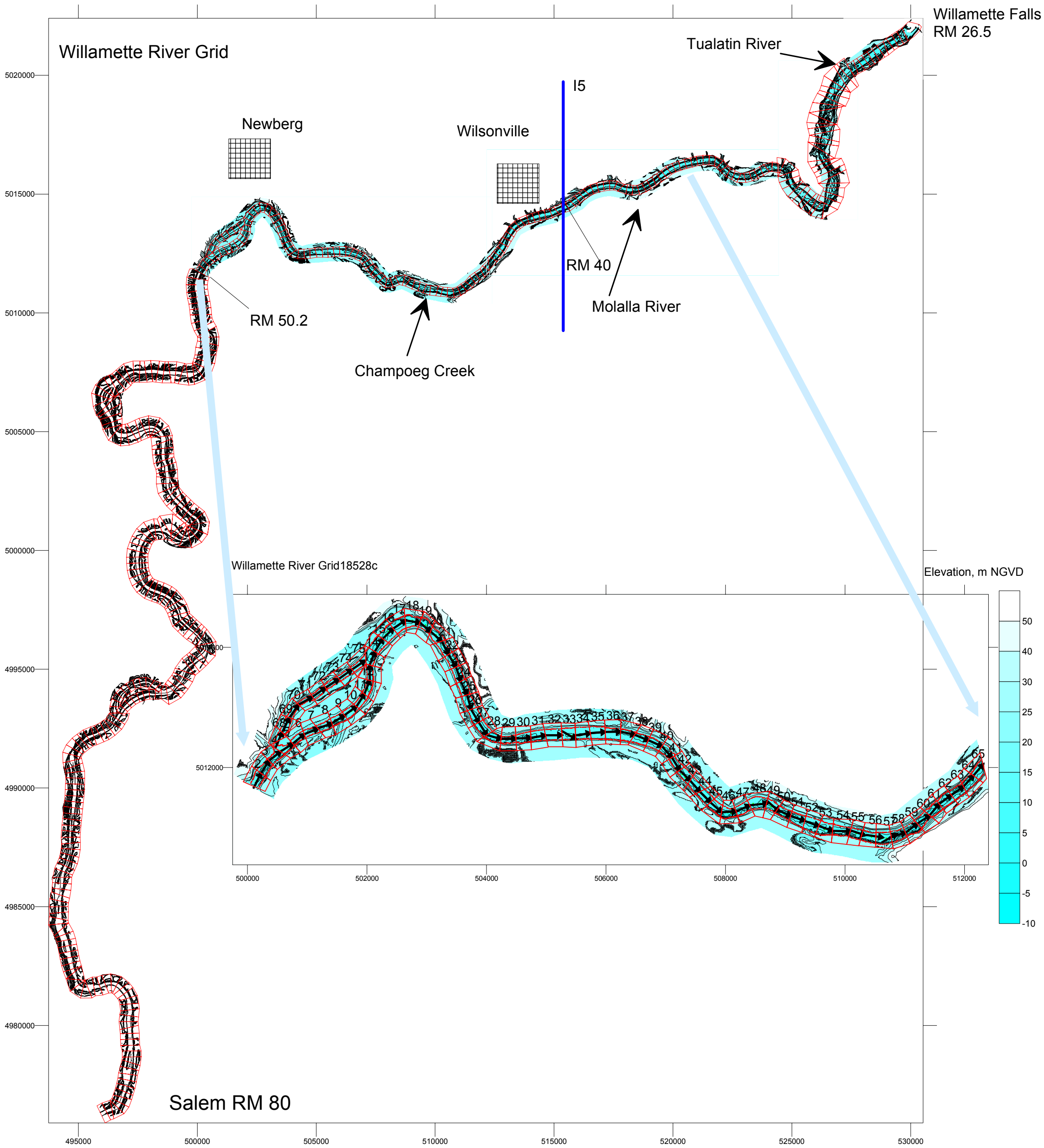

Figure 6. Section of the grid for the Mid Willamette River.

Since this project was a cooperative project between the Oregon DEQ, USGS and Portland State University, the model development was divided into the following areas of responsibility:

- DEQ: overall TMDL responsibility, model development of South Santiam basin, data collection, coordination and quality assurance checks for entire river basin, determination of management strategies for TMDL development, development of shade (vegetation cover) for the entire basin
- USGS: model development of the North Santiam and Santiam River, flow, stage and temperature monitoring, river channel bathymetry determination and dye studies in selected portions of the river system
- PSU: model development for Lower Willamette and Columbia Rivers, Clackamas River, Mid Willamette River, Upper Willamette River, Middle Fork Willamette River, Coast Fork Willamette River, Long Tom River, McKenzie River, Row River (tributary of Coast Fork, see Figure 7), and Fall Creek (tributary of Middle Fork, see Figure 7)

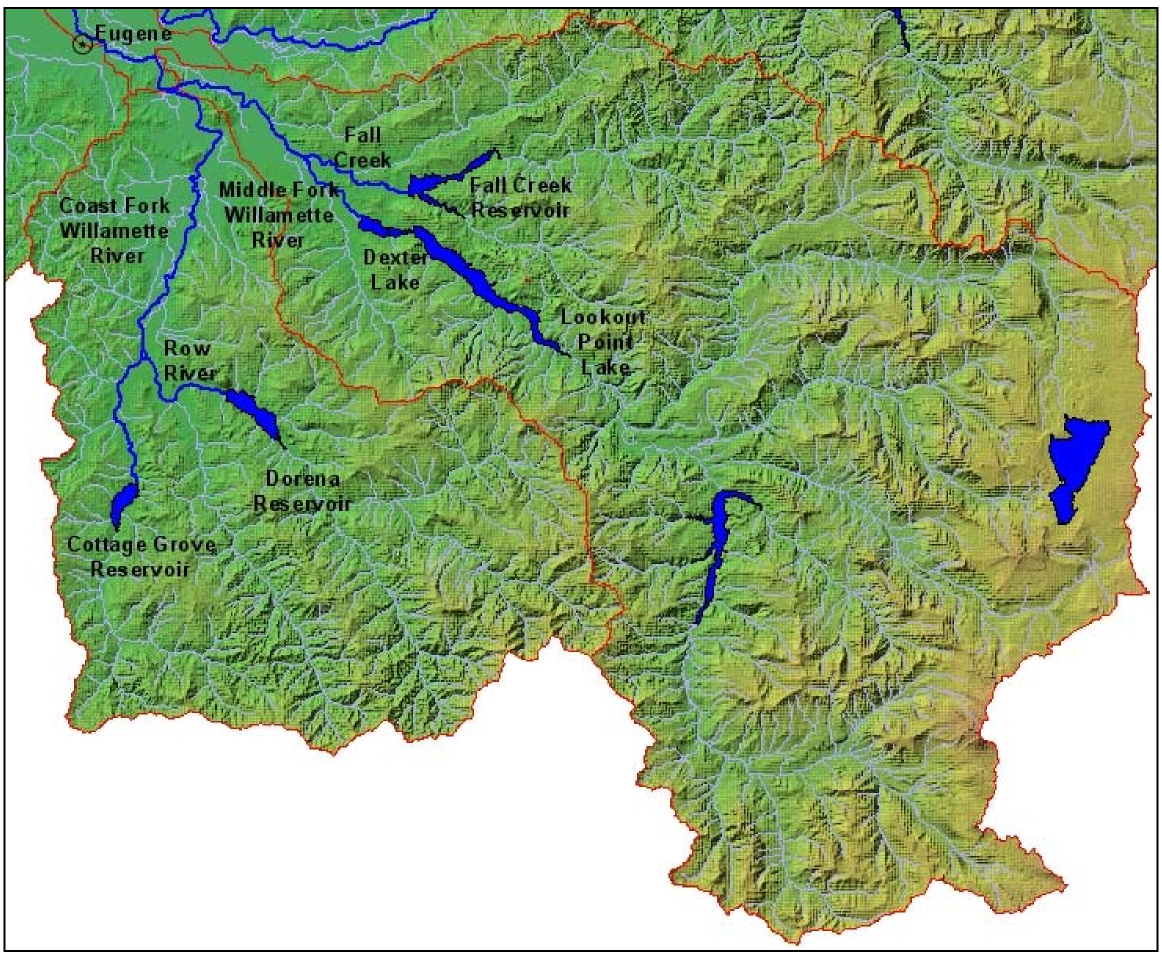

Figure 7. Coast and Middle Forks of the Willamette River with headwater storage reservoirs.

MODEL CALIBRATION

After obtaining the model grid and all boundary condition data, the model calibration consisted of model-data comparisons of hydrodynamic and temperature data for the periods of 2001 and 2002:

- Hydrodynamics
    - Flow rate
    - Stage or water level
    - Dye study travel times
    - Channel widths
- Temperature

Hydrodynamic calibration involved adjustment and re-examination of model friction factors (Manning's friction factors) and model bathymetry (in many cases model channel morphology was rare). Once model hydrodynamics were reasonable, temperature calibration was obtained by (again) re-examining channel morphology (for example, was the channel too deep or too wide?), meteorological data source (how close was the metrological station used for this reach, is it representative?), adjusting model predicted evaporation usually by adjusting wind sheltering.

Statistics were also developed to estimate how good the model calibration was. These included the mean error, absolute mean error, and the root-mean-square error. Also, the model was compared to all instantaneous data collected in the field. This involved model data comparisons of continuous flow, stage, and temperature at over 100 locations in the basin. Figure 8 shows locations of many of the temperature monitoring locations scattered throughout the basin.

Lower Willamette and Columbia Rivers

These tidally influenced rivers were initially studied by Berger et al. (1999) who applied a CE-QUAL-W2 model for the years 1993, 1994, 1998, 1999, and 2000. This model was updated with data from 2001 and 2002 and model-data comparisons were made for flow and stage and temperature. Figure 9 shows typical tidal flow model-data comparisons in the Columbia River, and Figure 10 shows typical water level variability in the Willamette River. Continuous temperatures were compared at 8 locations. Average absolute mean error and root mean square errors for all these locations were 0.29^{o}C and 0.39^{o}C, respectively for 2001 and 2002.

Mid Willamette River

In this reach, flow and stage was monitored only at 1 location, but 22 continuous temperature gages were used for model-data comparisons. The average AME and RMS

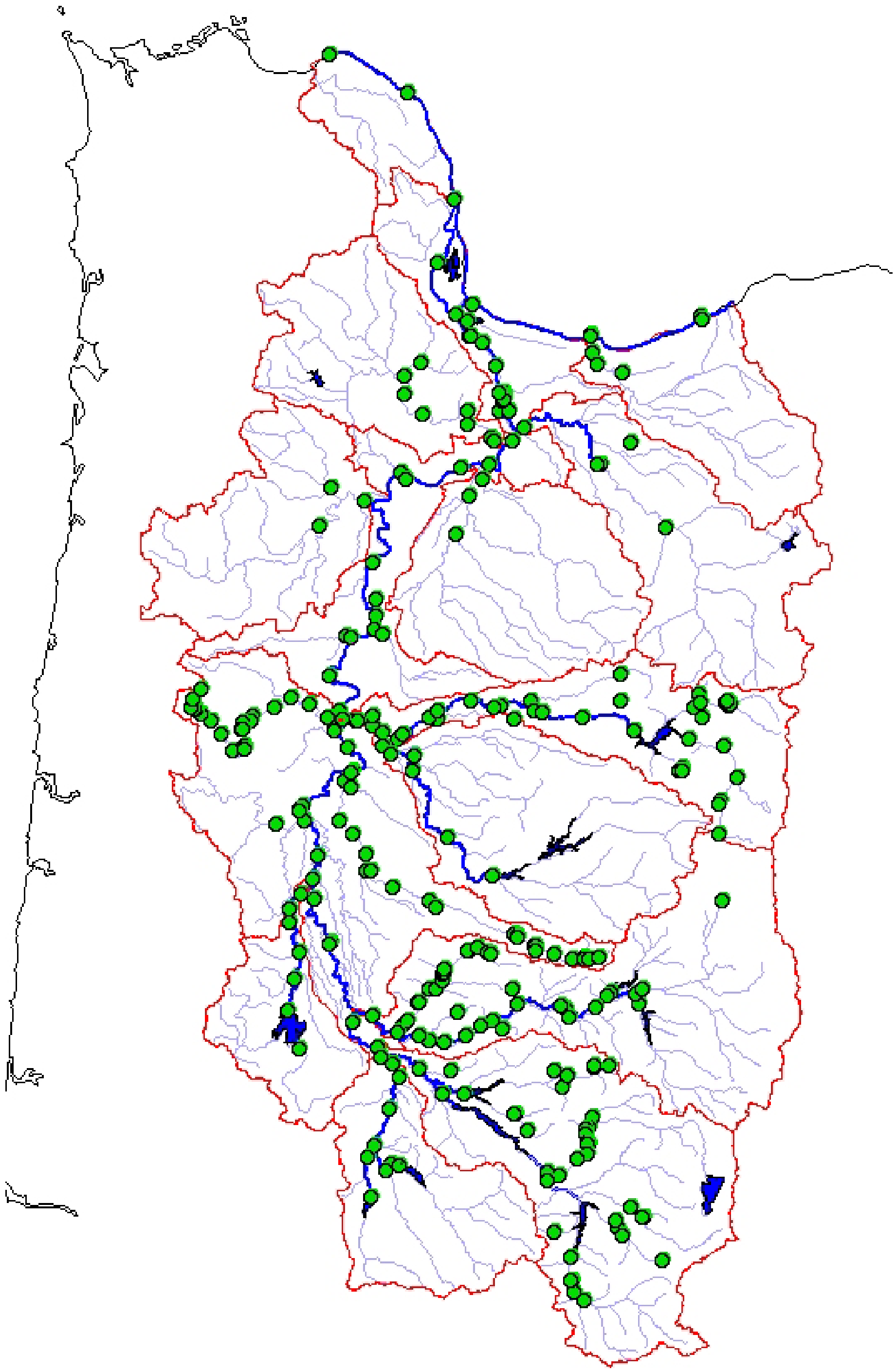

Figure 8. Temperature monitoring stations in the Willamette Basin.

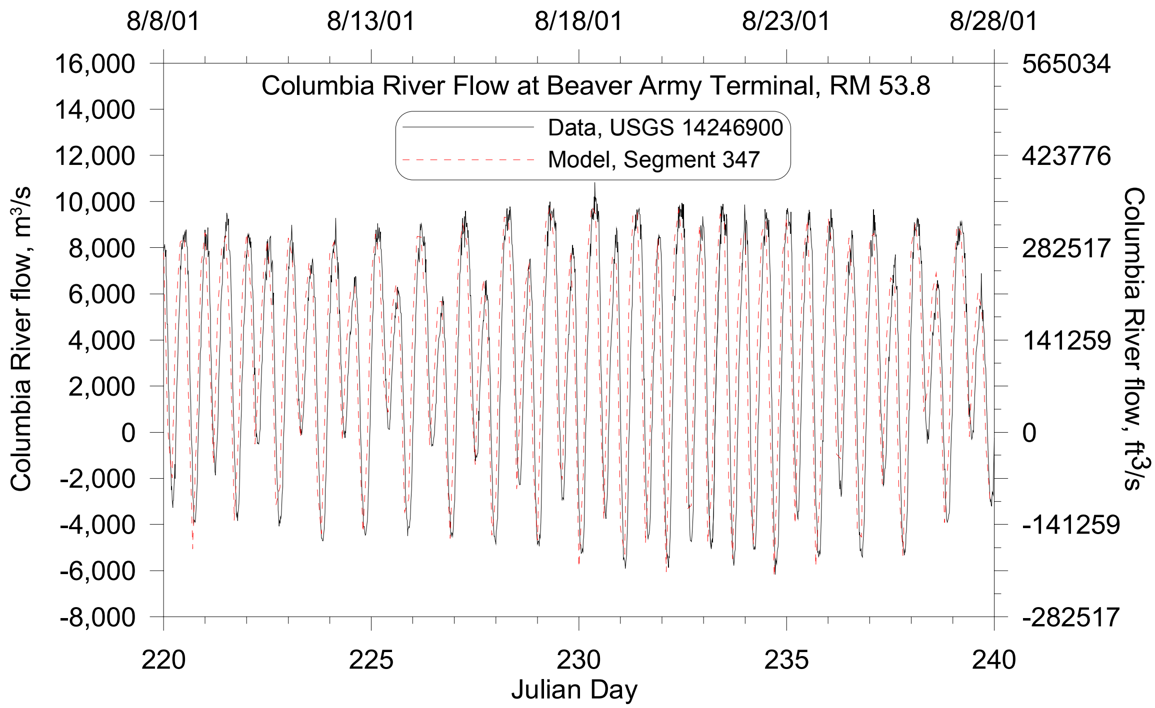

Figure 9. Columbia River model-data tidal flow comparison, 2001.

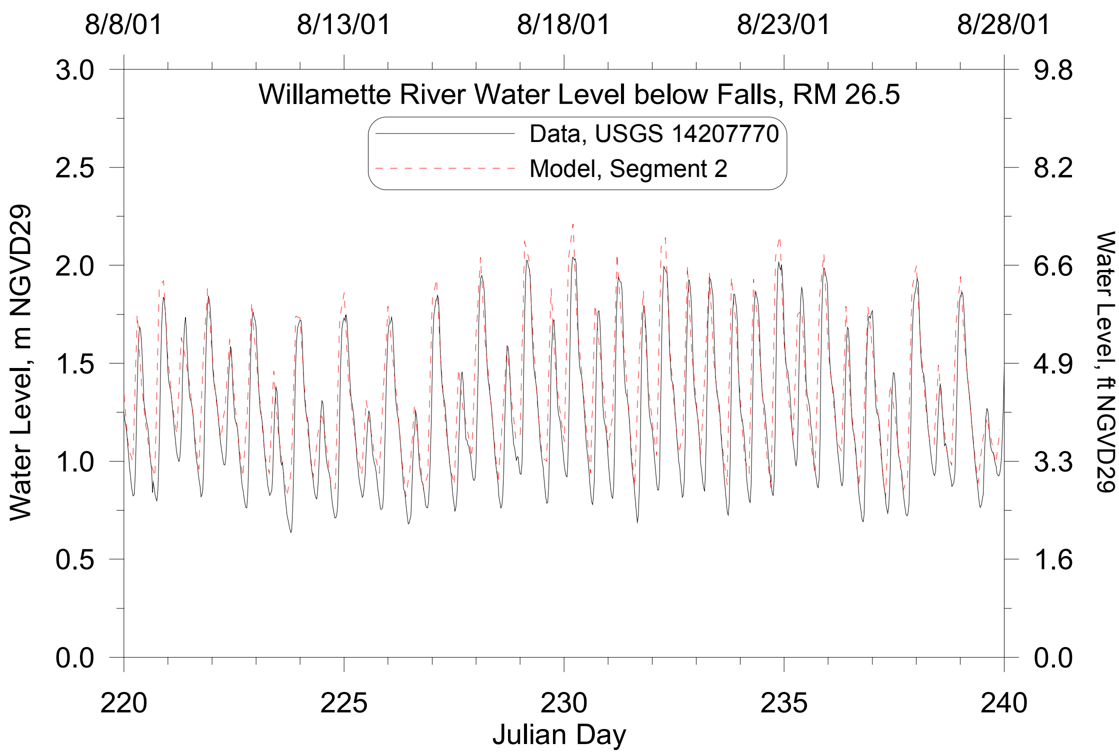

Figure 10. Typical water level model-data comparison in Willamette River below the Willamette River Falls, 2001.

error for temperature were 0.56°C and 0.68°C, respectively. An example of this comparison is shown in Figure 11.

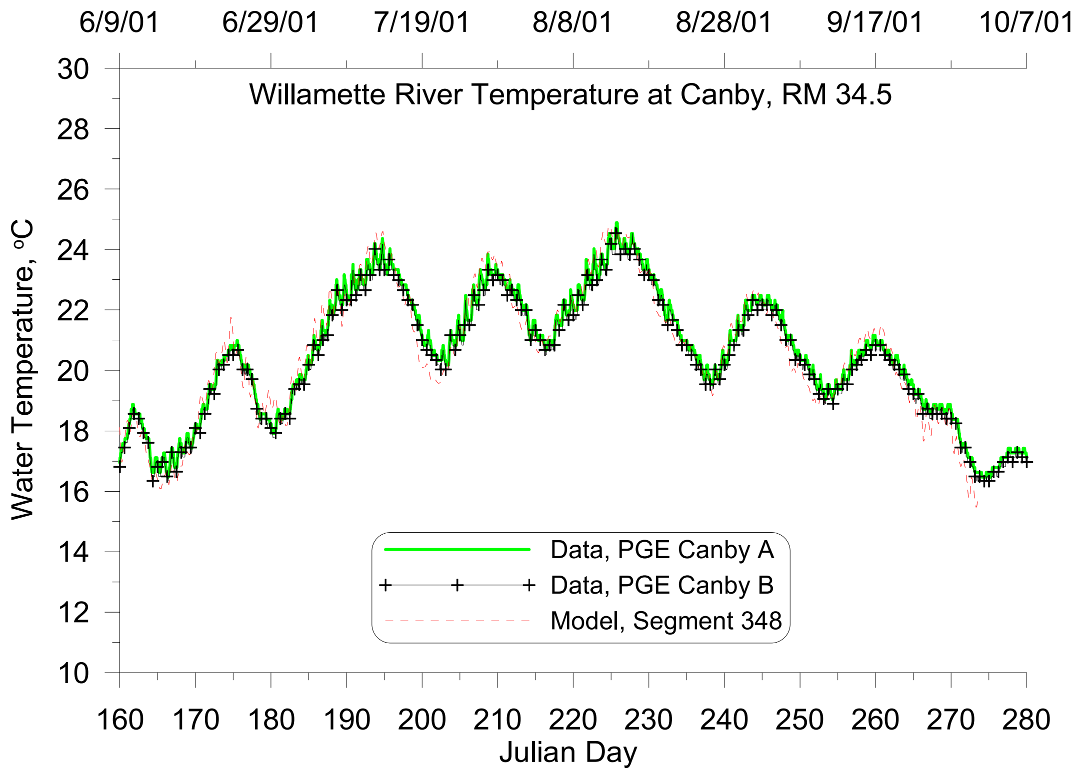

Figure 11. Temperature model-data comparison in the Mid Willamette River for 2001.

Upper Willamette River

The model domain for the Upper Willamette River is shown in Figure 12. For 2001, model-data statistics for water level and flow are shown in Table 1. Similar results were obtained for 2002. Typical flow and water level comparisons for 2002 are shown in Figure 13 and 14 for the Harrisburg gage, respectively. Another important comparison is that the model surface widths represent the actual surface widths. Figure 15 shows the model predictions of surface width compared to measurements of surface widths from physical measurements.

The longitudinal variation of water surface elevation for this section of the Willamette River and the location of the dye studies are shown in Figure 16.

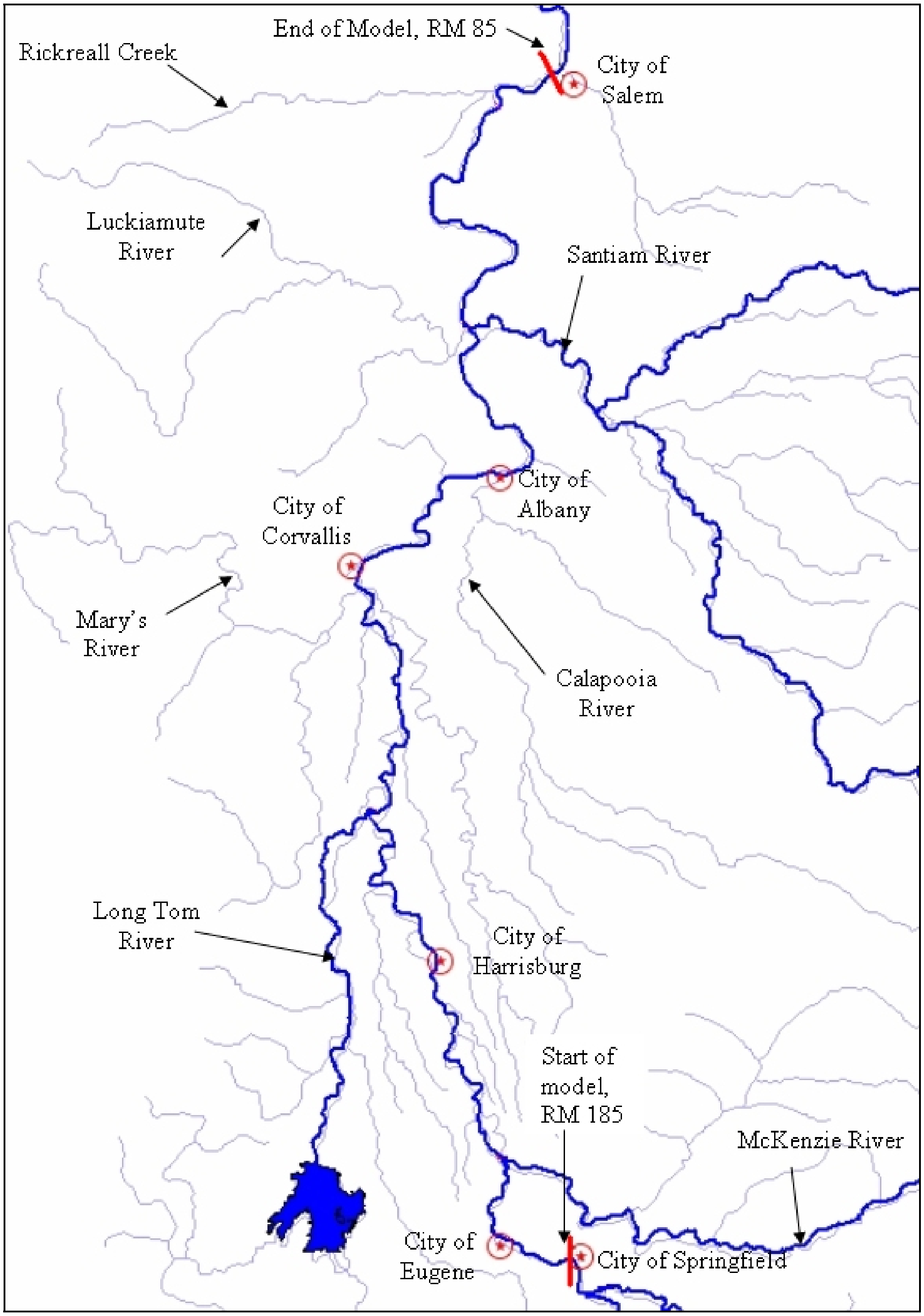

Figure 12. Model domain for the Upper Willamette River model.

Table 1: Hydrodynamic calibration statistics at 5 sites along the Upper Willamette River, 2001

Flow							
Station Name	Gage ID	RM	Model Segment	Sample size, N	Mean Error, m^3/s	Absolute ME, m^3/s	RMS Error, m^3/s
Eugene	ACOE EUGO3	181	19	5721	0.228	0.488	0.701
Harrisburg	USGS 14166000	161	156	5760	-0.214	0.463	0.620
Corvallis	ACOE CORO3	132	352	11081	*	*	*
Albany	USGS 14174000	119	434	5760	-0.226	0.890	1.147
Salem	USGS 14191000	85	665*	5760	-0.022	0.301	0.430
Water Level							
Station Name	Gage ID	RM	Model Segment	Sample size, N	Mean Error, m	Absolute ME, m	RMS Error, m
Eugene	ACOE EUGO3	181	19	5721	-0.043	0.047	0.052
Harrisburg	USGS 14166000	161	156	5760	0.227	0.227	0.227
Corvallis	ACOE CORO3	132	352	11081	-0.060	0.067	0.075
Albany	USGS 14174000	119	434	5760	-0.184	0.184	0.189
Salem	USGS 14191000	85	665*	5760	*	*	*

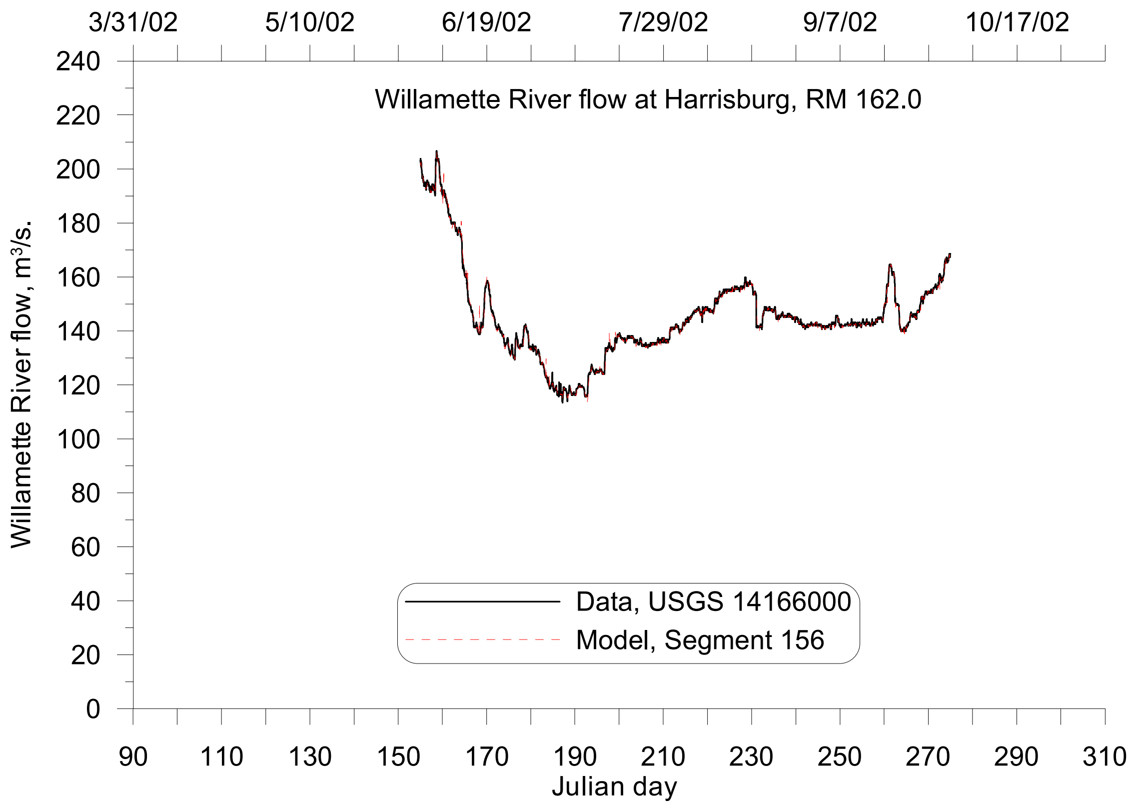

Figure 13: Willamette River at Harrisburg model-data flow comparison, 2002.

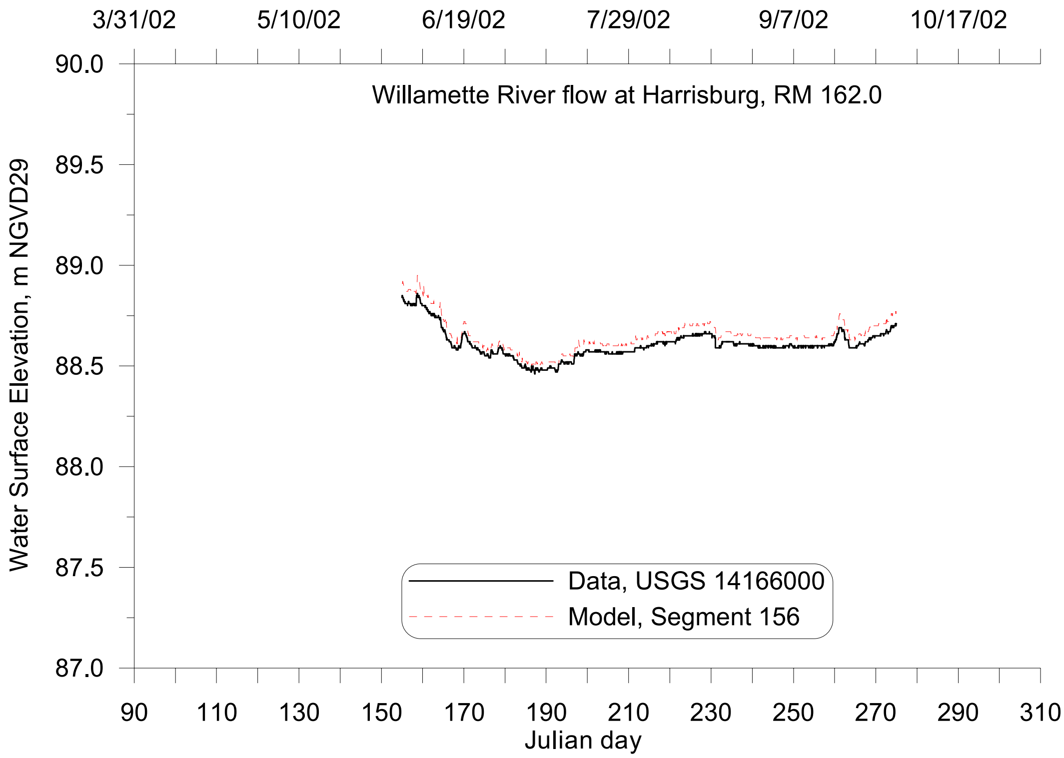

Figure 14: Upper Willamette River at Harrisburg model-data flow comparison, 2002.

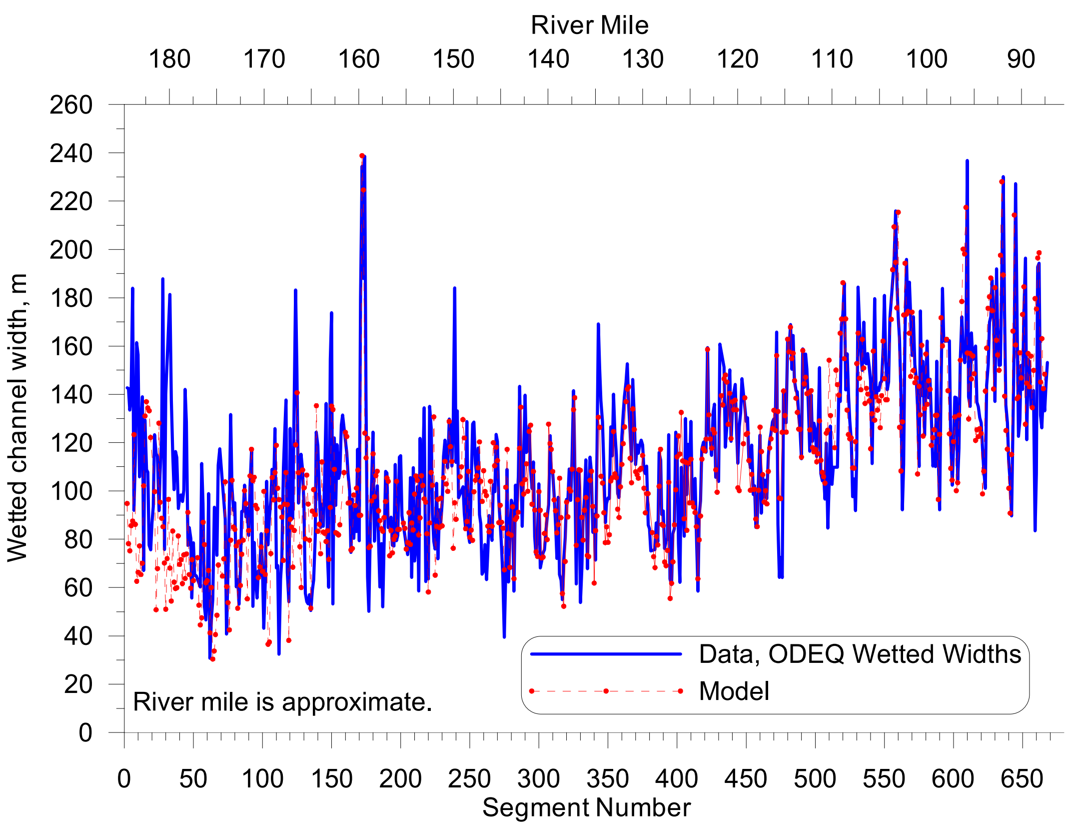

Figure 15: Upper Willamette River model-data wetted-width comparison.

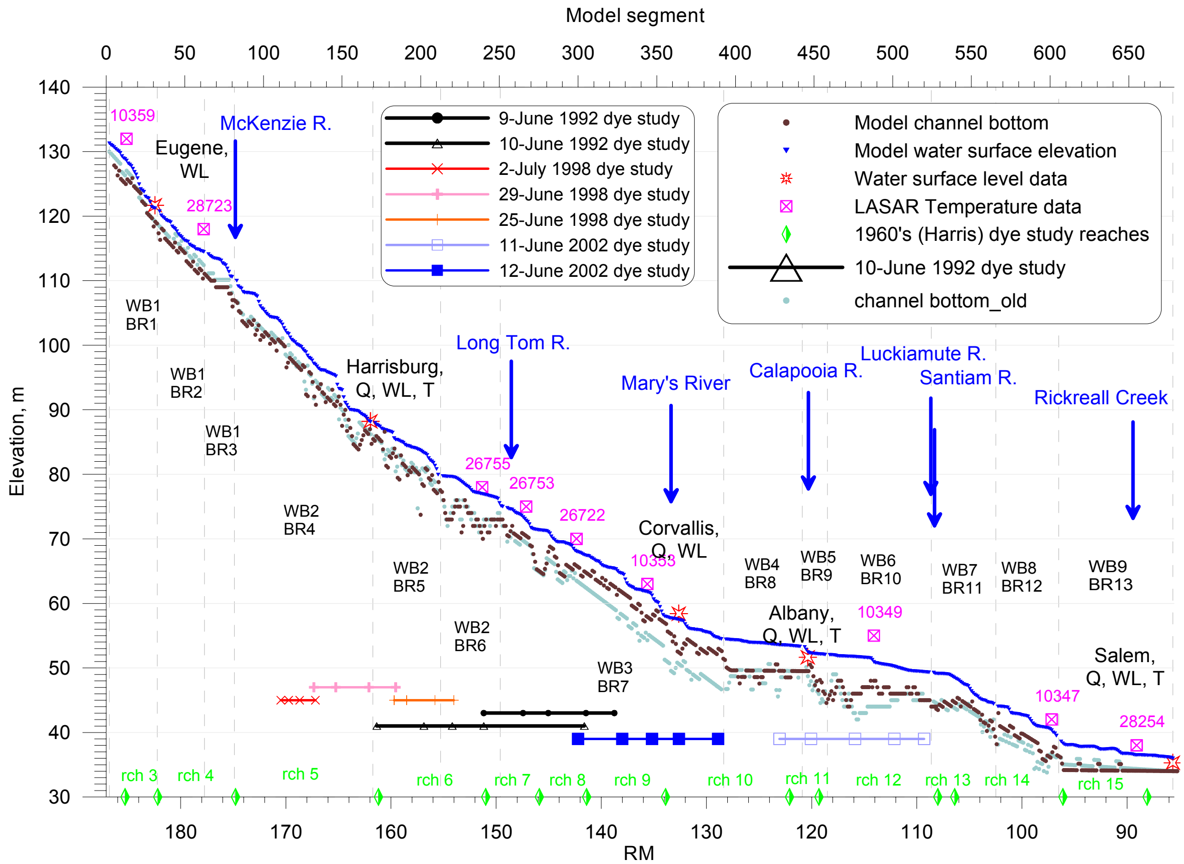

Figure 16. Longitudinal water surface profile and location of dye studies and gaging stations.

A 1968 travel time study by the USGS was used to compare to model predictions at 14 different model reaches. Model travel rates as a function of flow rate are shown in Figure 17 for 4 of these reaches. Also, dye studies were performed in 1992, 1998, and 2002 for various reaches at different flow rates. A model-data comparison of dye profiles are shown in Figure 18 and Figure 19 for a dye study on the Willamette main-stem in 1998 and in 2002, respectively.

There were 12 continuous model-data comparison sites for temperature. Table 2 shows a list of these sites and model-data errors for 2001. Similar results were also obtained for 2002. Typical model predictions of temperature compared to continuous measurements for 2001 and 2002 at RM 135 are shown in Figure 20 and Figure 21, respectively.

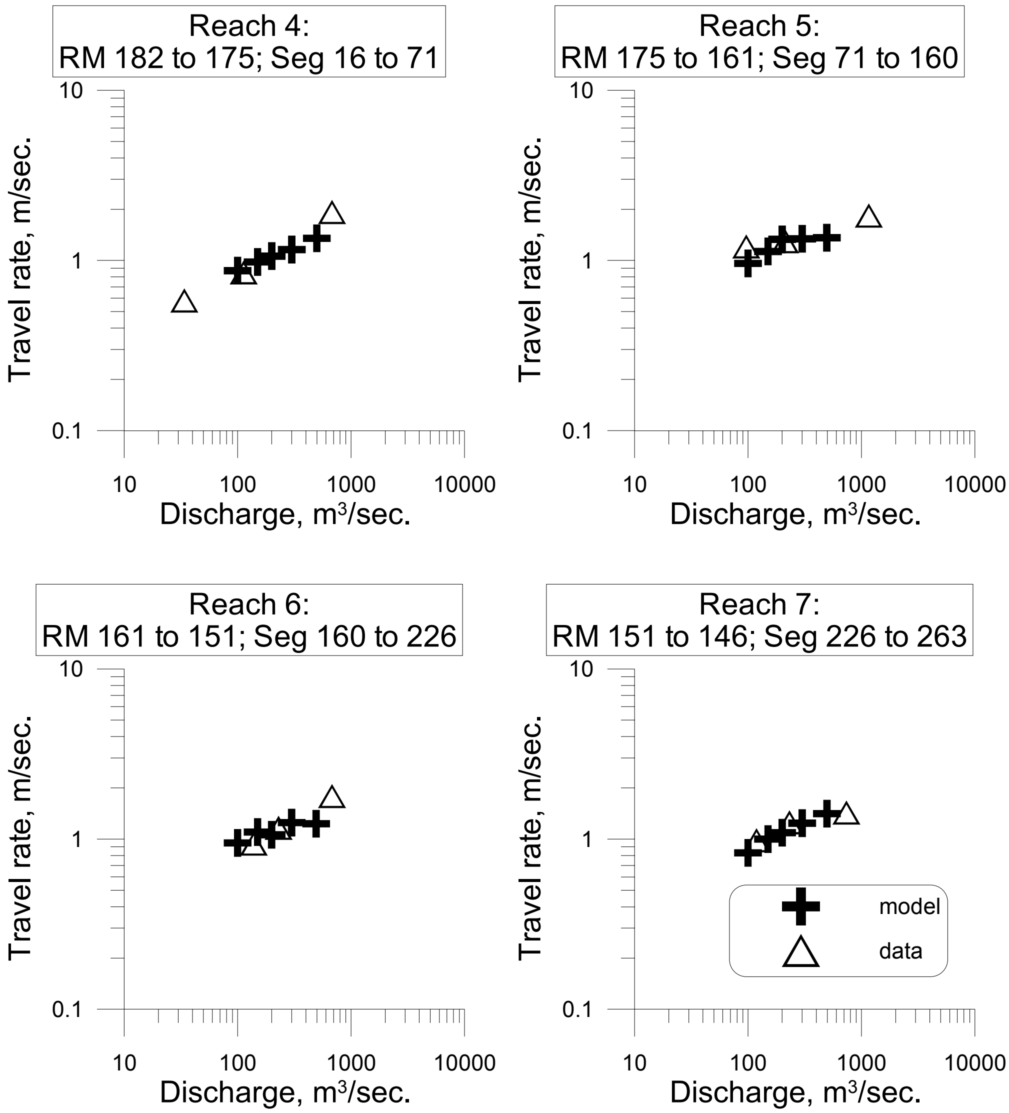

Figure 17: Model-data comparisons of 1968 Harris Study travel rates over RM 182 to 146.

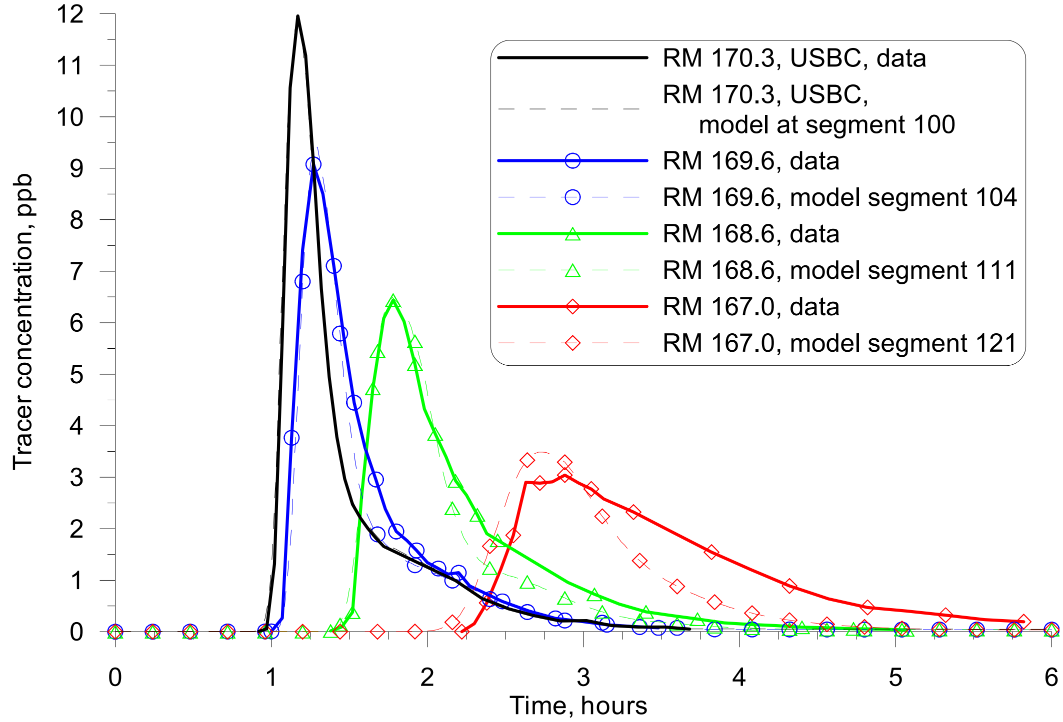

Figure 18: July 2, 1998 dye study model simulation.

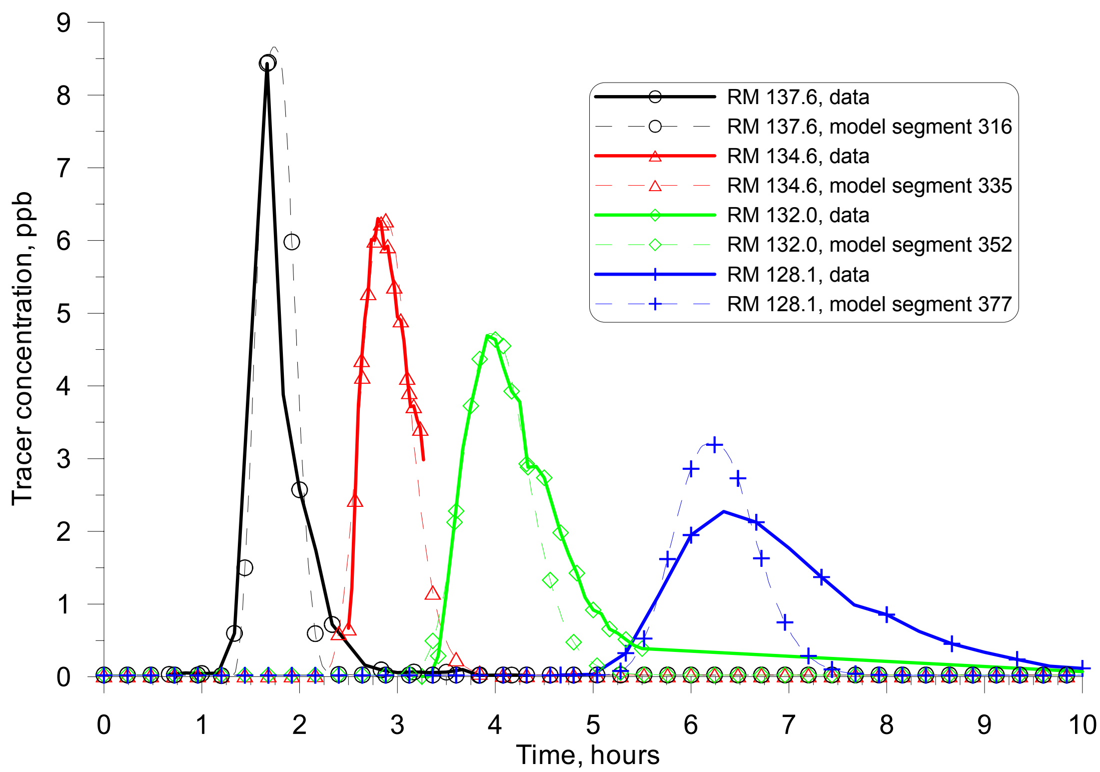

Figure 19: June 12, 2002 dye study model simulation.

Table 2: Continuous water temperature calibration statistics, 2001.

Site ID	RM	Model Segment	Continuous Temperature			
			Number of Comparisons	ME, °C	AME, °C	RMS, °C
LASAR 10359	185.3	2	5040	0.016	0.040	0.051
LASAR 28723	177.7	53	2362	-0.183	0.400	0.514
USGS 14166000	162.0	156	5040	0.149	0.615	0.736
LASAR 26755	151.6	227	5040	0.381	0.577	0.738
LASAR 26753	147.4	255	5040	0.490	0.638	0.812
LASAR 26772	142.4	287	5040	0.359	0.603	0.752
LASAR 10353	135.2	334	2520	0.206	0.485	0.619
USGS 14174000	120.2	434	2179	-0.109	0.370	0.472
LASAR 10349	113.9	476	4967	0.023	0.454	0.580
LASAR 10347	96.9	589	4958	-0.167	0.424	0.523
LASAR 28254	88.9	643	2520	0.126	0.630	0.824
USGS 14191000	84.7	666	600	0.167	0.514	0.641

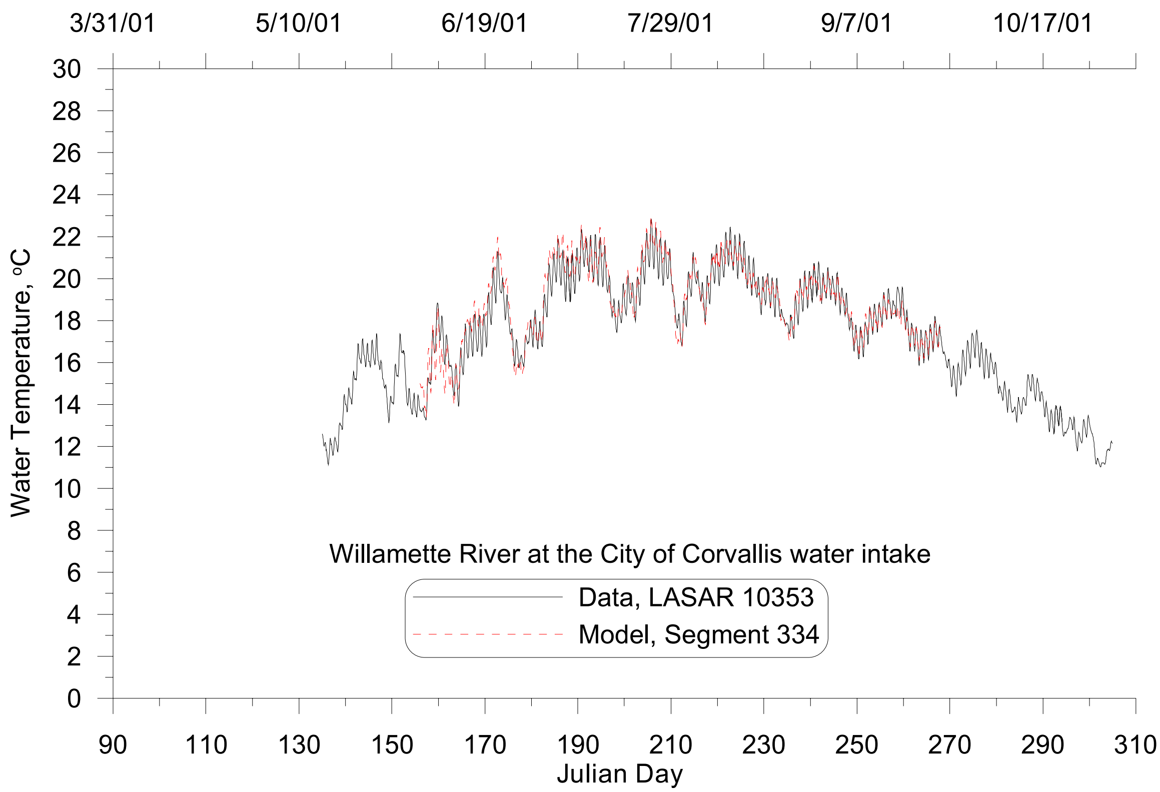

Figure 20: Upper Willamette River at City of Corvallis water intake water temperature, 2001.

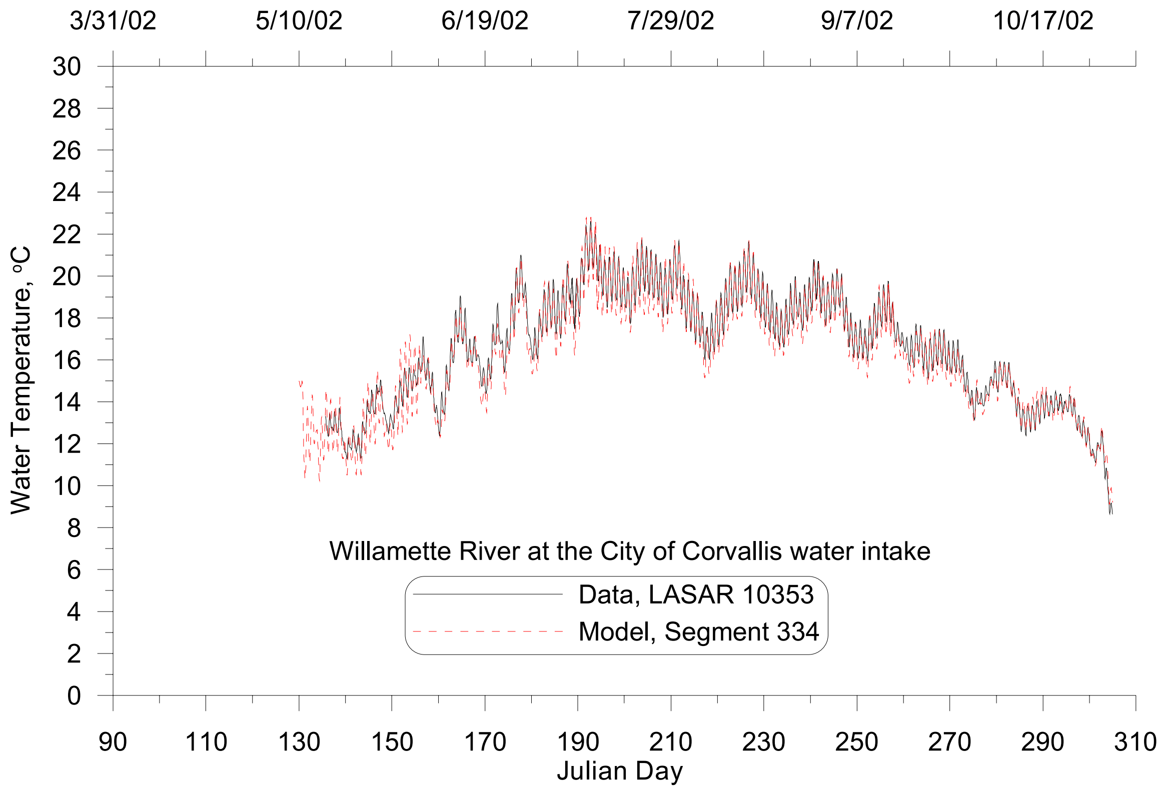

Figure 21: Upper Willamette River at City of Corvallis water intake water temperature, 2002.

Long Tom River

The Long Tom River had only 1 flow and stage comparison point and several continuous temperature monitoring points. Figure 22 shows a model-data comparison for temperature in the Long Tom River near the confluence with the Willamette River for 2002. Typical model errors in temperature were all less than 1°C with mean errors close to 0.5°C.

Clackamas River

The Clackamas River below River Mill Dam was modeled for temperature and compared to 4 continuous monitoring stations for 2001 and 2002. Typical results for August 2001 are shown in Figure 23.

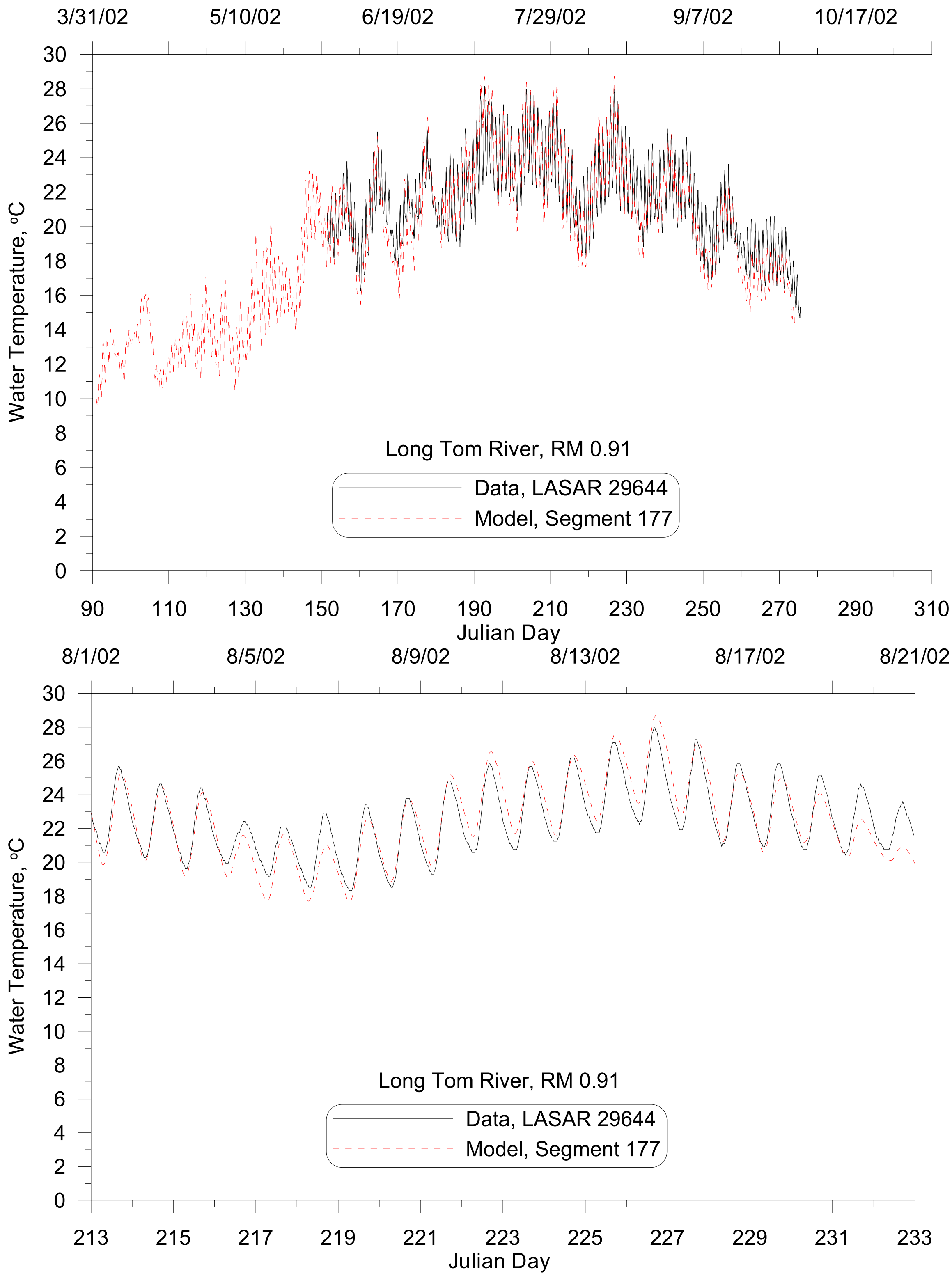

Figure 22. Long Tom River model-data temperature comparison, 2002.

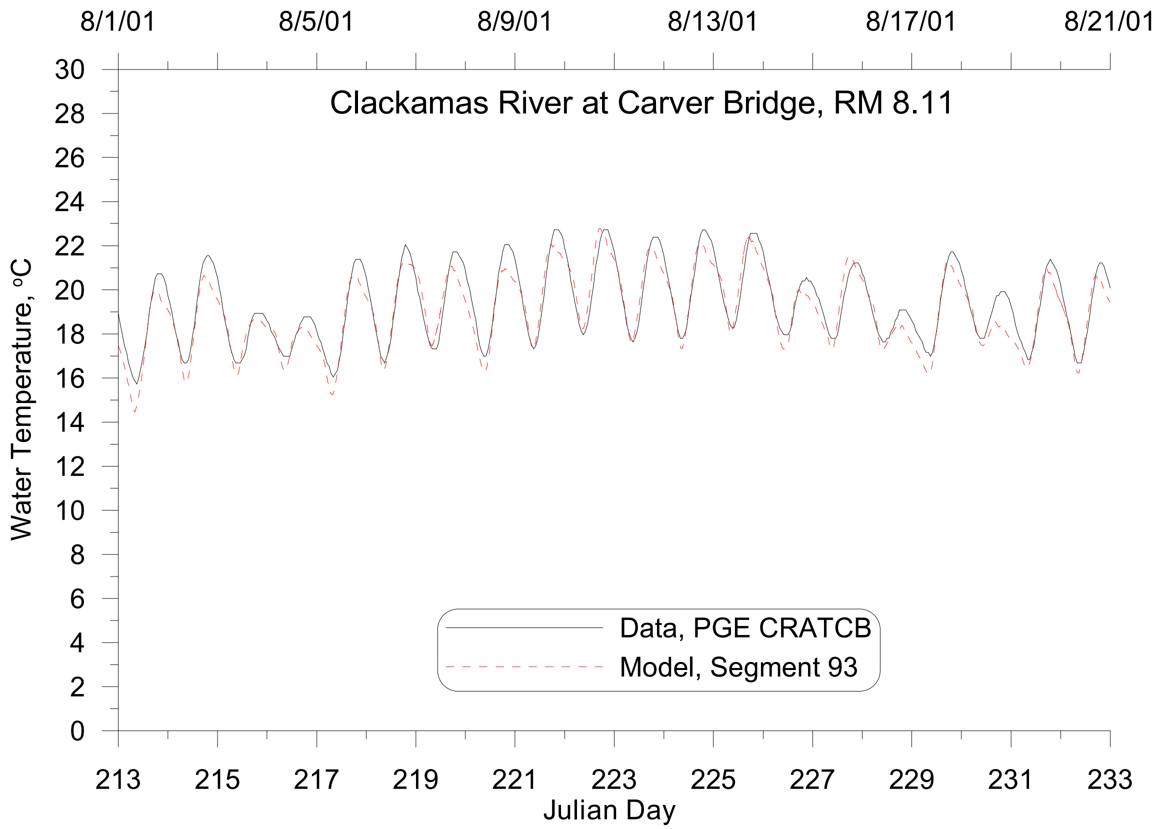

Figure 23. Clackamas River model-data temperature comparison, 2002.

McKenzie River

The McKenzie River had 4 flow and water level comparison stations. Statistics of model-data errors for continuous flow and water level data are shown in Table 3 and Table 4 for 2001 and 2002, respectively.

At McKenzie River RM 44.56, Figure 24 shows water level comparison of model and data for 2001, and Figure 25 shows flow rate comparison of model and data for 2002.

Table 3. McKenzie River model-data flow rate and water level error statistics, 2001.

Flow							
Station Name	Gage ID	RM	Model Segment	Sample size, N	Mean Error, m^3/s	Absolute ME, m^3/s	RMS Error, m^3/s
South Fork McKenzie	USGS 14159500	60.39	4	7008	0.00	0.03	0.07
McKenzie River near Vida	USGS 14162500	44.56	108	7008	0.00	0.27	0.46
McKenzie River below Leaburg Dam	USGS 14163150	34.11	177	7008	-0.02	0.22	0.51
McKenzie River near Walterville	USGS 14163900	24.97	240	6996	-0.01	0.25	0.49
Water Level							
Station Name	Gage ID	RM	Model Segment	Sample size, N	Mean Error, m	Absolute ME, m	RMS Error, m
South Fork McKenzie	USGS 14159500	60.39	4	7008	0.00	0.02	0.04
McKenzie River near Vida	USGS 14162500	44.56	108	7008	0.01	0.01	0.02
McKenzie River below Leaburg Dam	USGS 14163150	34.11	177	7008	0.04	0.04	0.04
McKenzie River near Walterville	USGS 14163900	24.97	240	6996	0.25	0.25	0.25

Table 4. McKenzie River model-data flow rate and water level error statistics, 2002.

Flow							
Station Name	Gage ID	RM	Model Segment	Sample size, N	Mean Error, m^3/s	Absolute ME, m^3/s	RMS Error, m^3/s
South Fork McKenzie	USGS 14159500	60.39	4	10175	0.00	0.05	0.29
McKenzie River near Vida	USGS 14162500	44.56	108	10174	0.01	0.46	0.90
McKenzie River below Leaburg Dam	USGS 14163150	34.11	177	10174	-0.01	0.85	2.05
McKenzie River near Walterville	USGS 14163900	24.97	240	10174	0.00	0.60	1.91
Water Level							
Station Name	Gage ID	RM	Model Segment	Sample size, N	Mean Error, m	Absolute ME, m	RMS Error, m
South Fork McKenzie	USGS 14159500	60.39	4	10175	0.08	0.08	0.14
McKenzie River near Vida	USGS 14162500	44.56	108	10174	0.05	0.05	0.11
McKenzie River below Leaburg Dam	USGS 14163150	34.11	177	10174	0.00	0.04	0.04
McKenzie River near Walterville	USGS 14163900	24.97	240	10174	-0.03	0.04	0.09

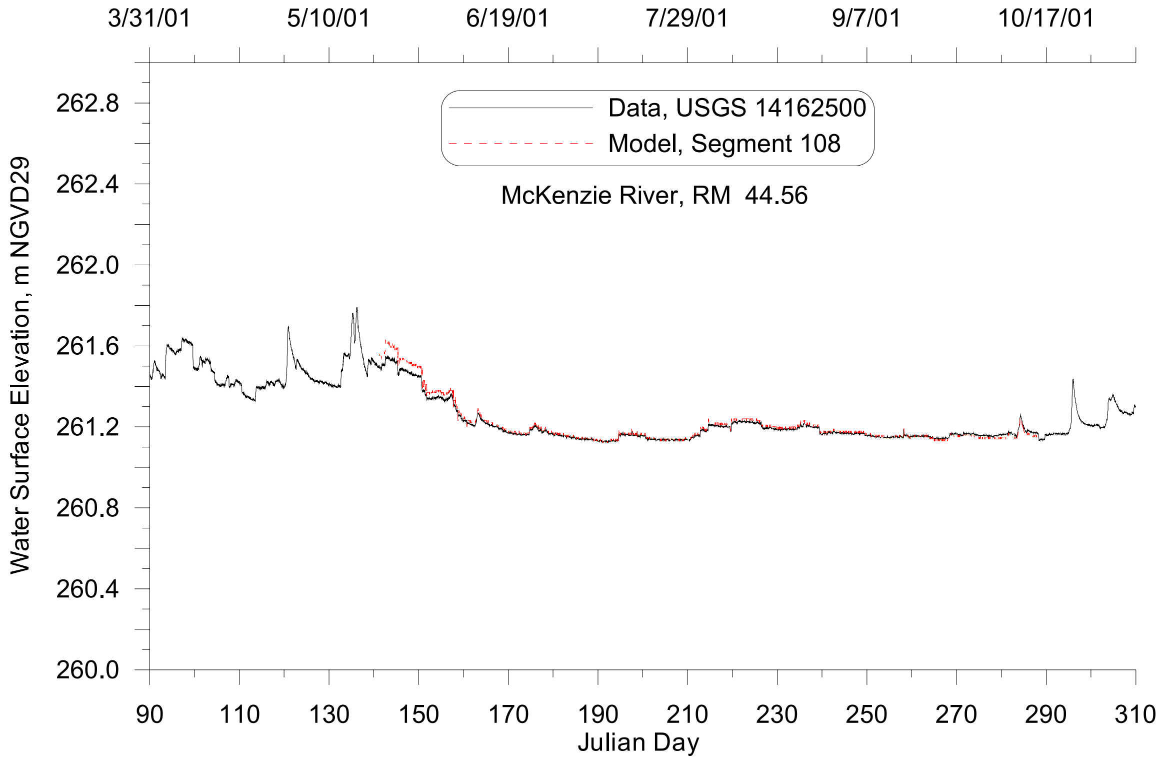

Figure 24. McKenzie River model-data water level comparison, 2001.

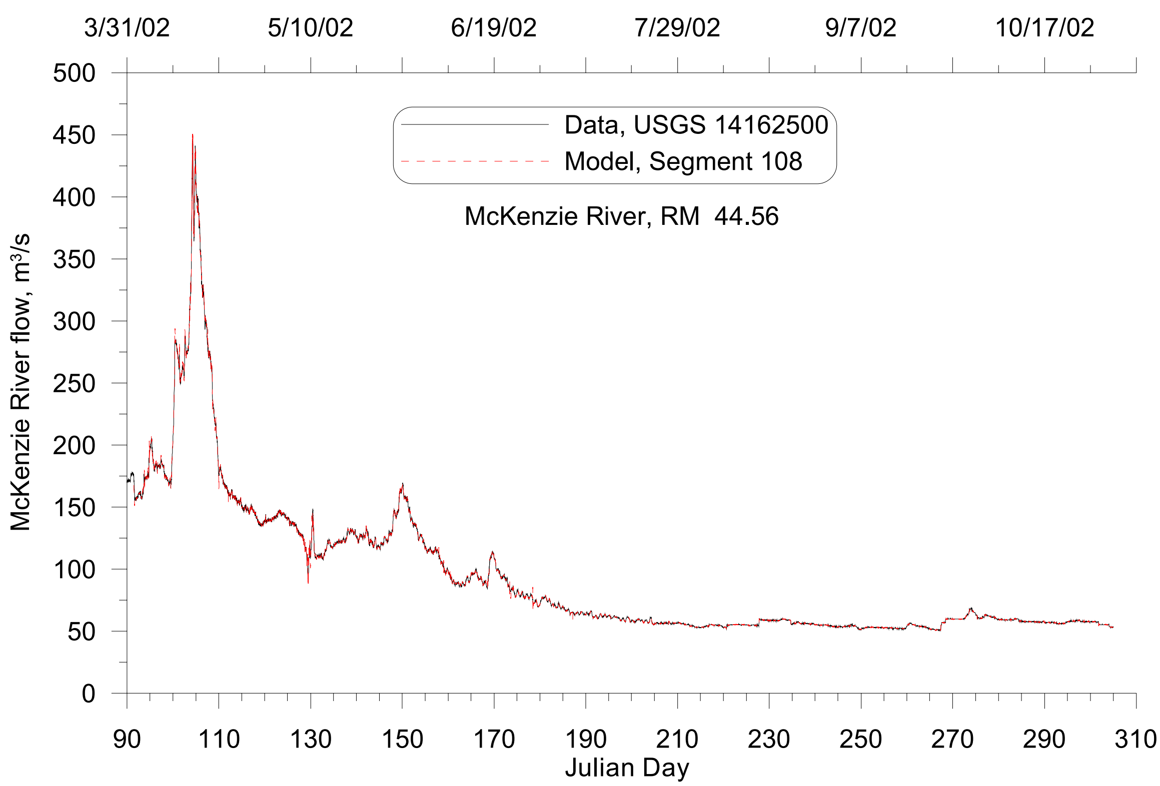

Figure 25. McKenzie River model-data flow comparison, 2002.

Temperature statistics at 12 locations on the river are shown in Table 4, and a model-data temperature comparison for 2002 at RM 44.56 is shown in Figure 26.

Table 5. McKenzie River continuous water temperature calibration model-data error statistics, 2002

Site ID	RM	Model Segment	Continuous Temperature			
			Number of Comparisons	ME, °C	AME, °C	RMS, °C
USGS 14159500	60.39	4	10271	0.05	0.13	0.20
LASAR 26770	50.99	65	5856	-0.17	0.31	0.38
USGS 14162500	44.56	108	10270	0.42	0.49	0.64
LASAR 28504	40.74	132	3385	0.45	0.50	0.64
LASAR 25610	35.72	167	5668	0.31	0.70	0.88
LASAR 26758	28.45	215	5666	0.14	0.72	0.87
USGS 14163900	24.97	240	10270	0.25	0.59	0.74
LASAR 26757	15.61	299	5669	0.07	0.49	0.63
LASAR 29645	10.40	333	5857	0.06	0.54	0.68
LASAR 10376	3.38	378	5715	0.22	0.56	0.72

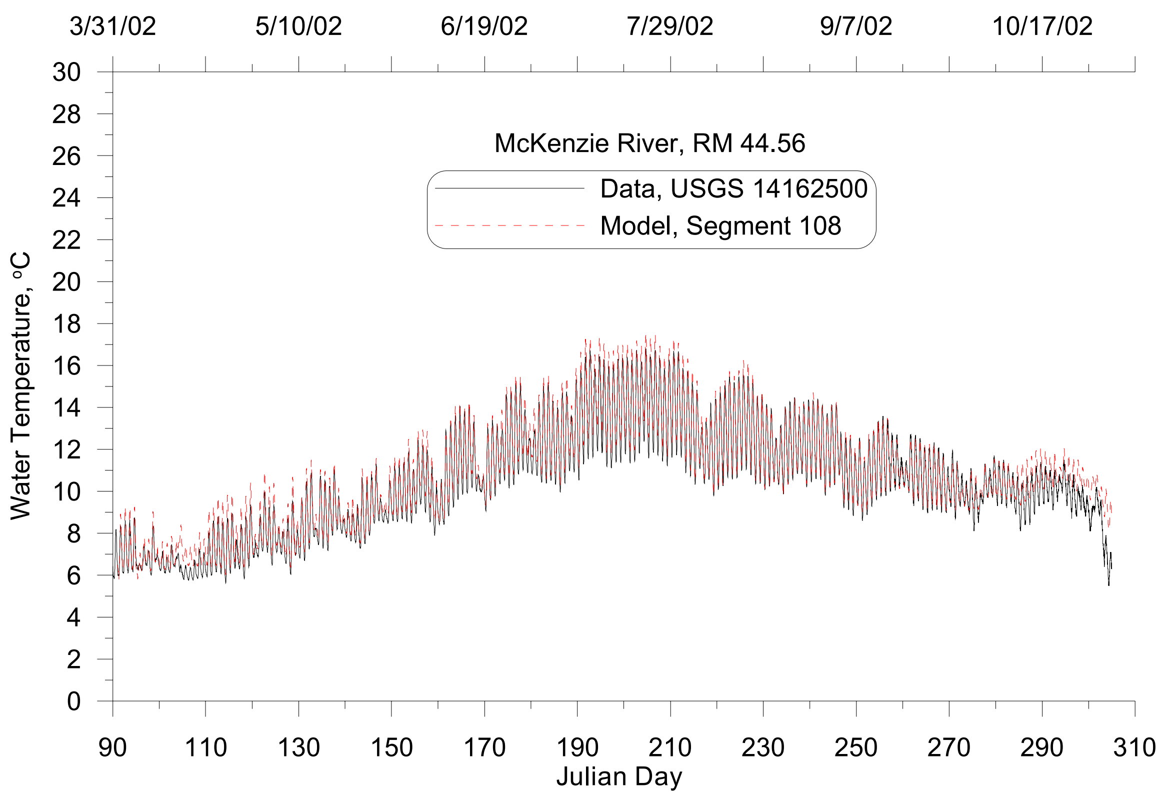

Figure 26. McKenzie River model-data continuous temperature comparison, 2002.

Coast and Middle Fork of the Willamette River, Row River, and Fall Creek

Typical comparisons of flow, water level and temperature are shown in 2001 for the Middle Fork in Figures 27, 28, and 29, respectively. Similar results were obtained for the Coast Fork, Row River and Fall Creek.

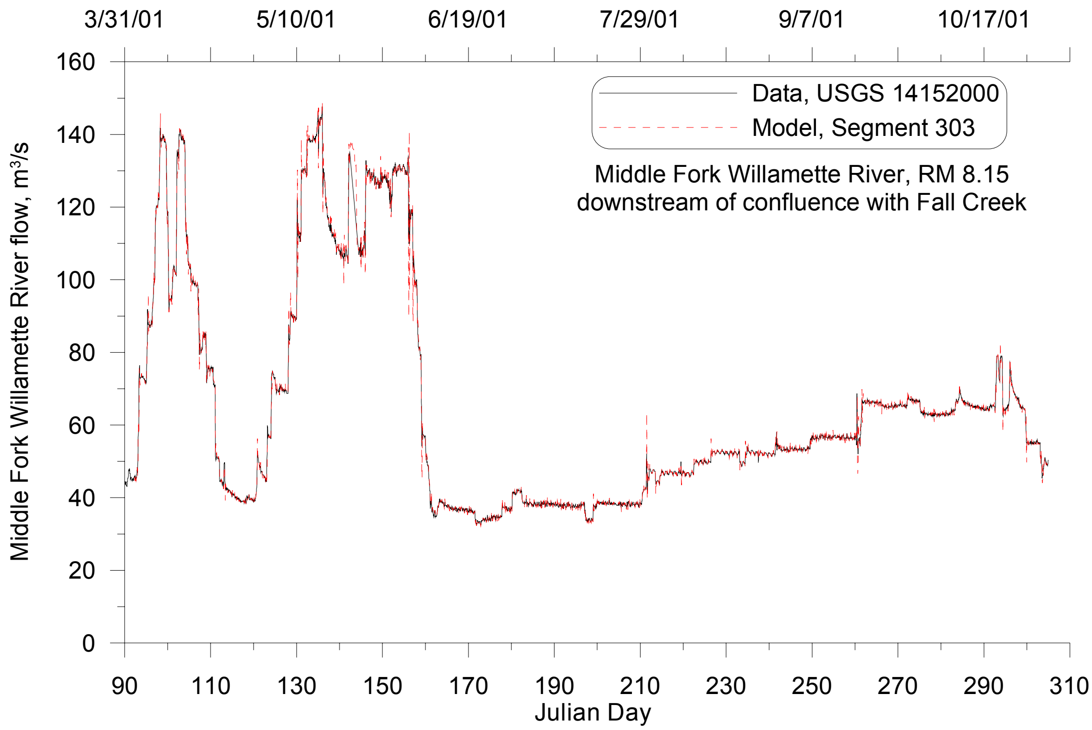

Figure 27. Middle Fork Willamette River model-data flow comparison, 2001.

DISCUSSION OF MODEL CALIBRATION

In general, calibration results were deemed acceptable based on the data for which the model was constructed. A goal of the calibration was to have flow data to be in almost exact agreement, water levels to be within the error of the finest grid resolution, dye travel times to be in agreement, and instantaneous AME/RMS errors for temperature below 1°C.

Most of the calibration effort was snot directed toward adjusting model parameters. This was only a small part of the calibration exercise. Most of the effort was directed at representing the system more accurately. One example involved re-evaluating channel morphology and finding that there had been errors in reducing the data from field surveys. Once the new channel morphology was used, model-data predictions improved. This is typical of a good model – the more accurately one describes the prototype, the

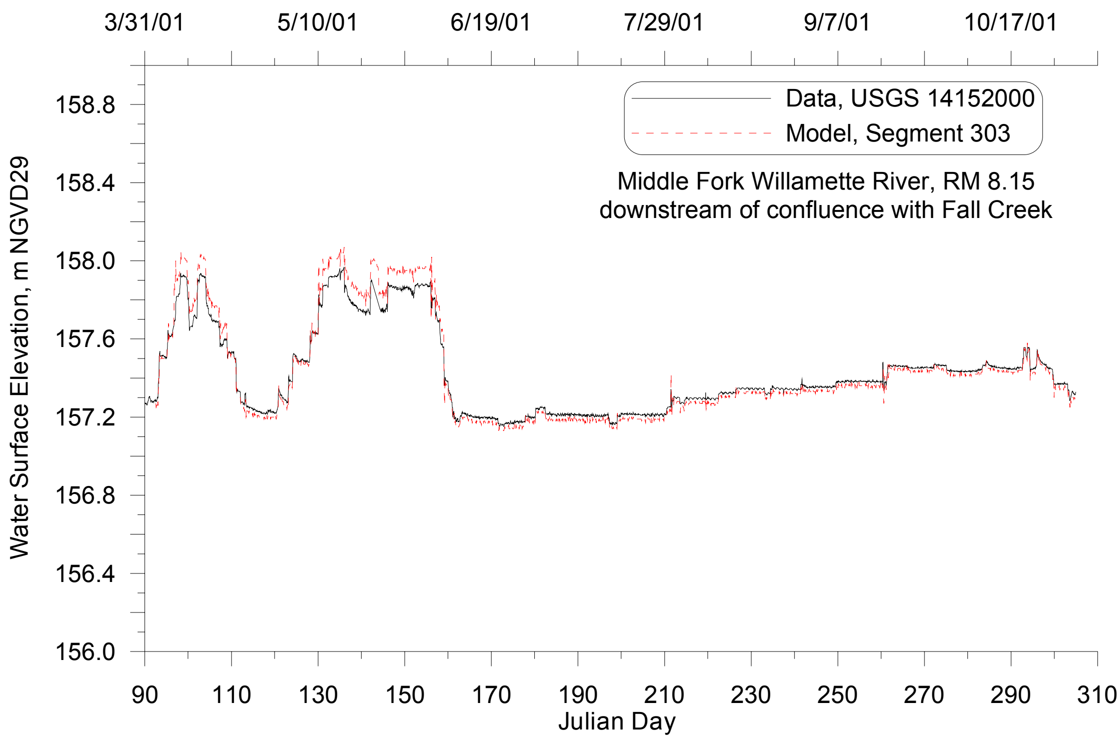

Figure 28. Middle Fork Willamette River model-data water level comparison, 2001.

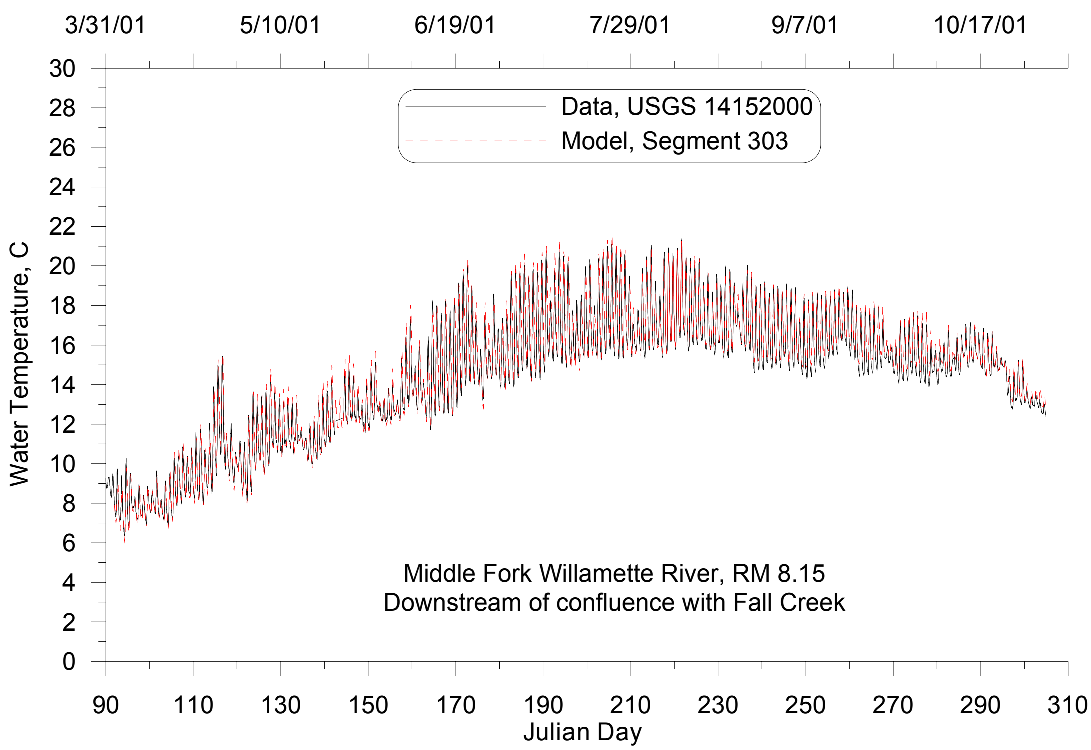

Figure 29. Middle Fork Willamette River model-data continuous temperature comparison, 2001.

more accurate the model will be in predicting field data. The goal of such modeling is to reduce the calibration “knobs” available to the modeler since most of the error in modeling is based on poor understanding of boundary conditions and conditions within the model domain.

MODEL MANAGEMENT SCENARIOS IN SUPPORT OF THE TEMPERATURE TMDL

In support of the TMDL, a series of model scenarios were proposed. The modeling scenarios in support of the TMDL were organized in two categories, those needed to establish point source waste load allocations and those needed for other informational purposes in support of the TMDL narrative.

Point Source Wasteload Allocation Scenarios

1. No point sources with different “system potential” scenarios (defined below)
2. Existing point sources with different system potential scenarios
3. Point sources at design flow with different system potential scenarios

Additional informational Scenarios

1. Sensitivity to boundary flow rates
2. Sensitivity to boundary temperature
3. Sensitivity to shade
4. Sensitivity to channel complexity

The term “system potential” was defined as the maximum potential shade along the river channels and included other assumptions relating to tributary temperatures (both historical observed and estimated ‘best’ temperature for the basin with maximum shade) and upstream boundary condition temperatures and flows (assuming historical observations and estimated flows and temperatures in the absence of upstream dams). Point sources that were included in the model included 27 primary sources which were primarily wastewater treatment plant dischargers, pulp and paper mills, and a steel mill.

Besides evaluating these scenarios with hourly model output for temperature and flow rate at each critical location (28 different locations as defined by DEQ), 7-day average daily maximums temperatures and 7-day average flow rates were also determined for each location. Also, 2 seasons were simulated: 2001 from June 1 to October 31 and 2002 from April 1 to October 31. An example of this evaluating the impact of point sources is shown in Figure 30 and Figure 31 for August 10, 2001 and September 27, 2001, respectively, for the Lower Willamette River. In this example, little impact is seen from the point sources.

CONCLUSIONS

Over 600 miles of rivers in the Willamette River basin were modeled using CE-QUAL-W2 in support of a temperature TMDL. The TMDL was to have been finished by December 2003, but changes in the Oregon temperature standard have delayed the implementation. The results of the current modeling effort were deemed acceptable to use for setting the TMDL. Often the determination of temperature in a river system is a function of the travel time of the water in the river. This was a critical element in successfully modeling a river system since the travel time determines the daily maximum and minimum. For example, downstream from a dam discharge, the daily maximum and minimum will usually occur at a travel time approximately 12 hours downstream if conditions of shade are similar over this stretch of river and there are no appreciable tributary inflows.

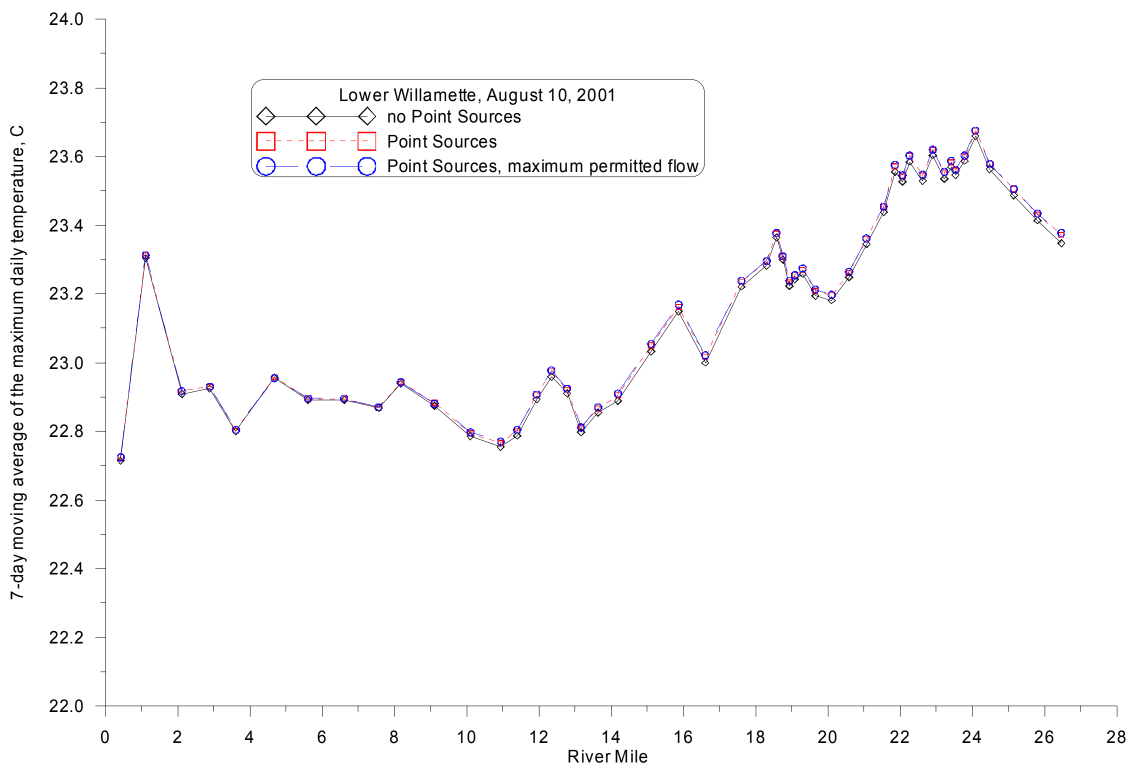

Figure 30. Model predicted 7-day average daily maximum on August 10, 2001 for the Lower Willamette River between RM 0 and RM 28.

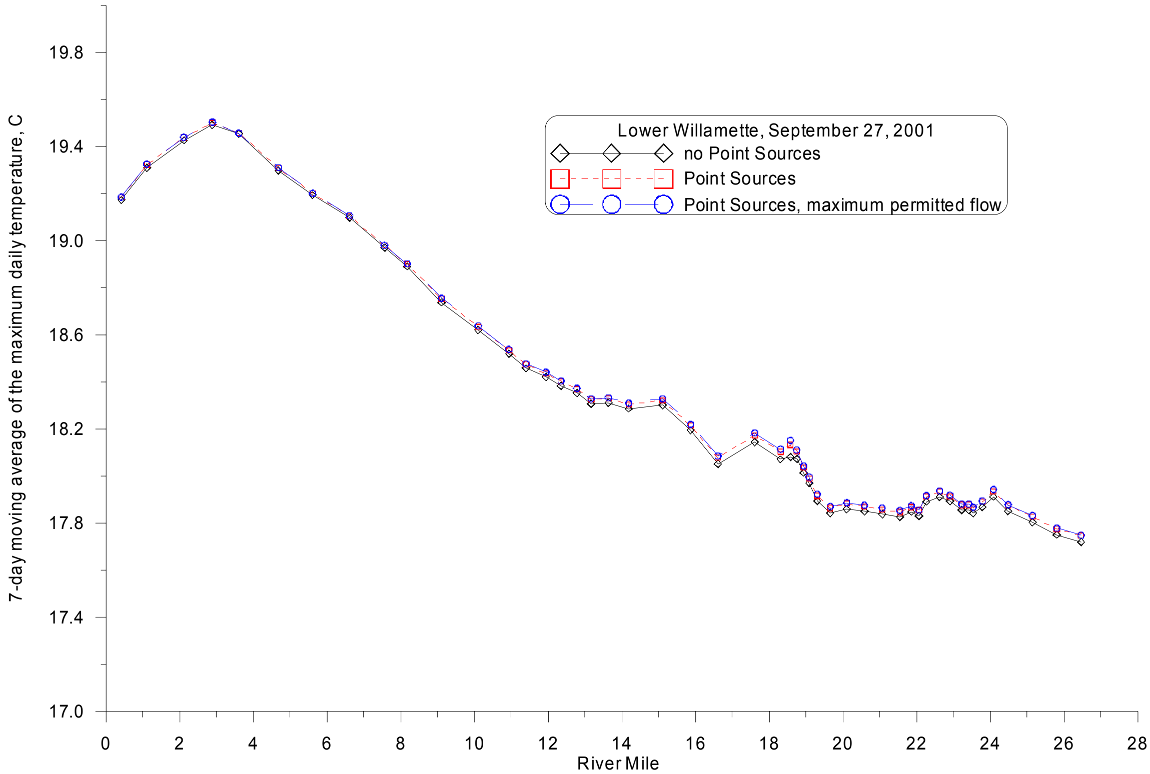

Figure 31. Model predicted 7-day average daily maximum on August 10, 2001 for the Lower Willamette River between RM 0 and RM 28.

As the modeling study progressed over the 600 miles of river, it became apparent where there were data gaps, and it was usually in these areas that poor model-data agreement was seen. The modeling effort itself was an excellent tool to focus effort on understanding whether the knowledge base on which the model was based was adequate or not. Further work on this TMDL effort will include eventually modeling water quality conditions (eutrophication parameters) and resolving model-data uncertainties.

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