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Temperature Effects of Point Sources, Riparian Shading, and Dam Operations on the Willamette River, Oregon

Scientific Investigations Report 2007–5185

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

Front cover: Photograph of McKenzie River near Coburg, Oregon (U.S. Geological Survey gaging station 14165500) looking downstream from Coburg Road bridge. (Photograph taken by Glen Hess, U.S. Geological Survey, June 19, 2007.)

Back cover:

Top: Photograph showing Middle Fork Willamette River at Jasper Road near Jasper, Oregon (river mile 196.5 from mouth of Willamette River) looking upstream from right bank. (Photograph taken by Anna Buckley, formerly U.S. Geological Survey, August 7, 2002.)

Middle: Photograph showing Willamette River at Newberg, Oregon (U.S. Geological Survey gaging station 14197900) looking downstream from pipeline bridge. (Photograph taken by Roy Wellman, U.S. Geological Survey, June 13, 2005.)

Bottom: Photograph showing McKenzie River above Hayden Bridge at Springfield, Oregon (U.S. Geological Survey gaging station 14164900) looking downstream toward confluence with Mohawk River. (Photograph taken by Doug Cushman, U.S. Geological Survey, September 12, 2005.)

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Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

$$°F=(1.8\times°C)+32.$$

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).

Conversion Factors, Datums, and Acronyms and Abbreviations—Continued

Acronyms and Abbreviations

Acronyms and Abbreviations	Meaning
7dADM	7-day moving average of the daily maximum, usually referring to water temperature.
$7Q_{10}$	Lowest 7-day average streamflow that would be expected to occur once in 10 years.
ACWA	Oregon Association of Clean Water Agencies.
HUA	Human Use Allowance, defined in the State of Oregon water-temperature standard as the maximum allowable increase in water temperature attributable to anthropogenic influences and quantified as 0.3°C.
NTP	Natural Thermal Potential, defined in the State of Oregon water-temperature standard as the condition which serves as a pseudo-natural baseline for comparisons of point-source and non-point-source heating effects in the Total Maximum Daily Load.
ODEQ	Oregon Department of Environmental Quality.
POMI	Point of Maximum Impact, defined as the location of a cumulative point-source heating maximum determined on the basis of model results.
PSU	Portland State University.
TMDL	Total Maximum Daily Load, defined either as the maximum allowable load of a pollutant that a water body can carry without violating water-quality standards, or more commonly, the plan created by a regulatory agency to bring a water body back into compliance with water-quality standards.
TSRF	Time series output frequency
USACE	U.S. Army Corps of Engineers.
USGS	U.S. Geological Survey.

Temperature Effects of Point Sources, Riparian Shading, and Dam Operations on the Willamette River, Oregon

By Stewart A. Rounds

Abstract

Water temperature is an important factor influencing the migration, rearing, and spawning of several important fish species in rivers of the Pacific Northwest. To protect these fish populations and to fulfill its responsibilities under the Federal Clean Water Act, the Oregon Department of Environmental Quality set a water temperature Total Maximum Daily Load (TMDL) in 2006 for the Willamette River and the lower reaches of its largest tributaries in northwestern Oregon. As a result, the thermal discharges of the largest point sources of heat to the Willamette River now are limited at certain times of the year, riparian vegetation has been targeted for restoration, and upstream dams are recognized as important influences on downstream temperatures. Many of the prescribed point-source heat-load allocations are sufficiently restrictive that management agencies may need to expend considerable resources to meet those allocations.

Trading heat allocations among point-source dischargers may be a more economical and efficient means of meeting the cumulative point-source temperature limits set by the TMDL. The cumulative nature of these limits, however, precludes simple one-to-one trades of heat from one point source to another; a more detailed spatial analysis is needed. In this investigation, the flow and temperature models that formed the basis of the Willamette temperature TMDL were used to determine a spatially indexed "heating signature" for each of the modeled point sources, and those signatures then were combined into a user-friendly, spreadsheet-based screening tool. The Willamette River Point-Source Heat-Trading Tool allows the user to increase or decrease the heating signature of each source and thereby evaluate the effects of a wide range of potential point-source heat trades. The predictions of the Trading Tool were verified by running the Willamette flow and temperature models under four different trading scenarios, and the predictions typically were accurate to within about 0.005 degrees Celsius (°C).

In addition to assessing the effects of point-source heat trades, the models were used to evaluate the temperature effects of several shade-restoration scenarios. Restoration of riparian shade along the entire Long Tom River, from its mouth to Fern Ridge Dam, was calculated to have a small but significant effect on daily maximum temperatures in the main-stem Willamette River, on the order of 0.03°C where the Long Tom River enters the Willamette River, and diminishing downstream. Model scenarios also were run to assess the effects of restoring selected 5-mile reaches of riparian vegetation along the main-stem Willamette River from river mile (RM) 176.80, just upstream of the point where the McKenzie River joins the Willamette River, to RM 116.87 near Albany, which is one location where cumulative point-source heating effects are at a maximum. Restoration of riparian vegetation along the main-stem Willamette River was shown by model runs to have a significant local effect on daily maximum river temperatures (0.046 to 0.194°C) at the site of restoration. The magnitude of the cooling depends on many factors including river width, flow, time of year, and the difference in vegetation characteristics between current and restored conditions. Downstream of the restored reach, the cooling effects are complex and have a nodal nature: at one-half day of travel time downstream, shade restoration has little effect on daily maximum temperature because water passes the restoration site at night; at 1 full day of travel time downstream, cooling effects increase to a second, diminished maximum. Such spatial complexities may complicate the trading of heat allocations between point and nonpoint sources.

Upstream dams have an important effect on water temperature in the Willamette River system as a result of augmented flows as well as modified temperature releases over the course of the summer and autumn. The TMDL was formulated prior to the installation of a selective withdrawal tower at Cougar Dam on the South Fork McKenzie River; construction was completed early in 2005. Model runs were used to evaluate the likely effects of the new tower

on downstream water temperatures, which were quantified using the 7-day moving average of the daily maximum. The changes were determined to be largest in the South Fork McKenzie River, with maximum mid-summer warming of 6.0–6.5°C and maximum cooling of more than 5.0°C in October. The effect was diluted in the main-stem McKenzie River, with mid-summer warming of as much as 1.5 or 2.0°C and autumn cooling of more than 1.5°C. The effects were further diminished downstream in the Willamette River, with temperature changes as large as 0.4–0.5°C upstream of the Santiam River confluence (RM 108.5) and no more than 0.3°C downstream of that point.

Introduction

Background

The water-temperature standard for the State of Oregon was designed to protect the needs of targeted fish species during critical periods when they use rivers for spawning, rearing, migration, or other life stages (Oregon Department of Environmental Quality, 2007a). Many rivers in western Oregon, including the Willamette River and many of its tributaries, exceed the maximum water-temperature standard, most typically during summer when salmonids are rearing or migrating, or during spring or autumn when salmonids are spawning. The Federal Clean Water Act requires that exceedances of water-quality standards be addressed, and in this case a plan of remediation was required for the Willamette River under the Act’s Total Maximum Daily Load (TMDL) provisions.

In September of 2006, after many years of data collection and modeling, the Oregon Department of Environmental Quality (ODEQ) finalized the Willamette temperature TMDL (Oregon Department of Environmental Quality, 2006a and 2006b). A large part of the TMDL focuses on the main-stem Willamette River and selected major tributaries (Fall Creek as well as the Clackamas, Santiam, North Santiam, South Santiam, Long Tom, McKenzie, South Fork McKenzie, Coast and Middle Fork Willamette, and Row Rivers) as far upstream as the first major dam on each tributary (fig. 1). The TMDL is meant to regulate several important sources of temperature alteration in this system, including upstream and instream dams, riparian vegetation, and point-source discharges.

Dams have an important effect on flow and temperature in the rivers downstream of those projects (Collier and others, 1996). The U.S. Army Corp of Engineers built and operates a system of 13 dams in the Willamette River basin that provides flood control, recreation, power production, and summertime flow augmentation for navigation, among other uses. Many of these dams are tall enough, and their point of release is low enough, that the temperature of water releases in July and August typically is far cooler and the temperature of releases in September and October typically is far warmer than what would occur in the absence of the dam (Sullivan and Rounds, 2004). The direct temperature effect diminishes with distance downstream, though the effect is still measurable for many tens of miles or more, depending on various factors. The upstream dams in the Willamette River system were given monthly temperature targets under the TMDL in an attempt to restore a more natural seasonal temperature pattern and ensure compliance with the temperature standard at that point and in nearby downstream reaches.

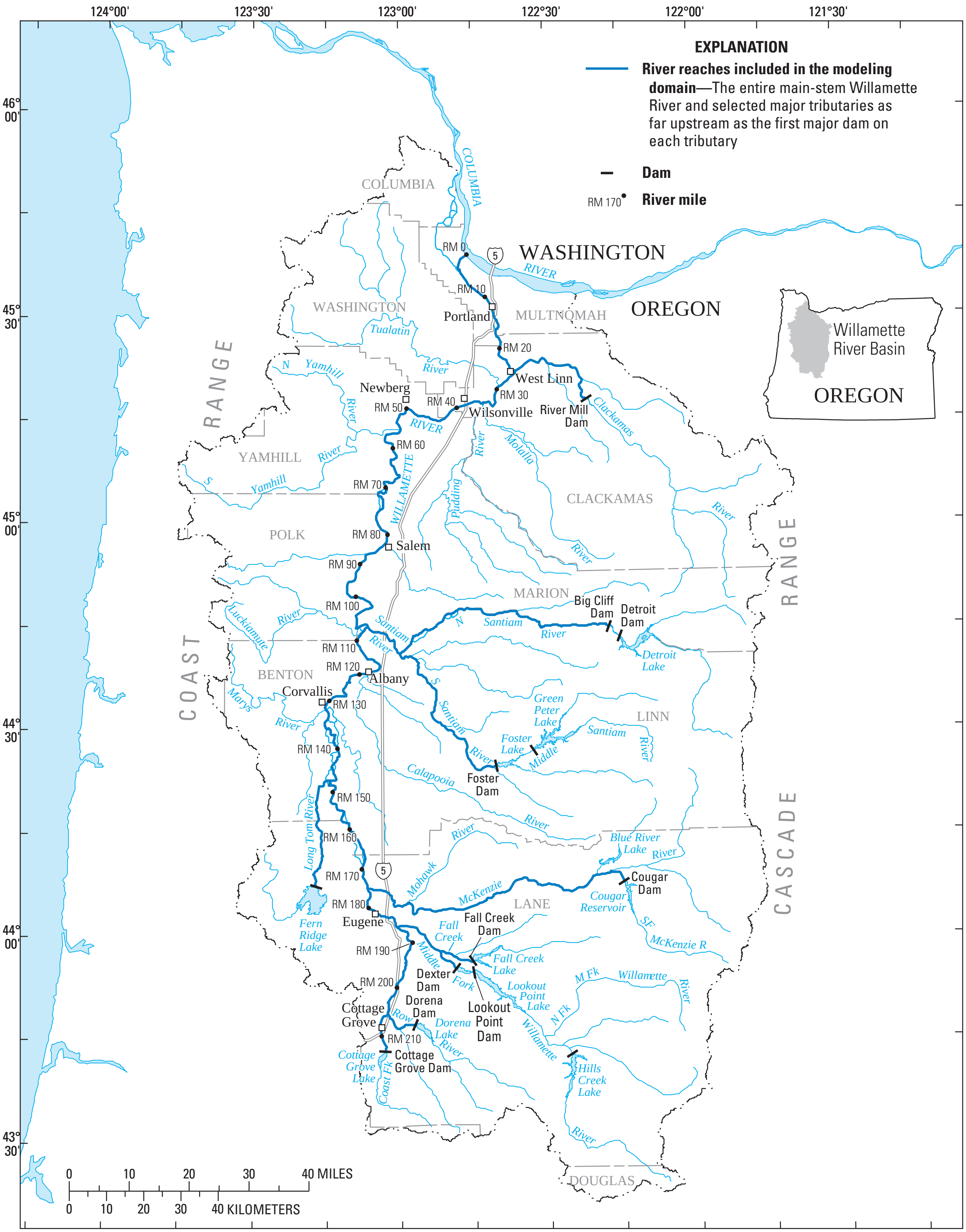
A major nonpoint source of heat to the Willamette River and its tributaries is a degraded level of riparian shading that allows a greater amount of solar radiation to be absorbed by adjacent rivers. Under the TMDL, riparian vegetation is required to be restored to a more natural level, calculated using information on the types of vegetation that typically grow on certain surficial geologic units and accounting for some natural level of disturbance.

The thermal effects of both point-source discharges and riparian shading were assessed for the TMDL by using a set of flow and temperature models developed for that application. The effects of the point sources were evaluated relative to a baseline condition termed Natural Thermal Potential (NTP), defined under the State of Oregon water-temperature standard (Oregon Department of Environmental Quality, 2007b) as

> “the determination of the thermal profile of a water body using best available methods of analysis and the best available information on the site-potential riparian vegetation, stream geomorphology, stream flows, and other measures to reflect natural conditions.”

Essentially, NTP represents the water temperature that would occur in a stream if certain anthropogenic influences were either minimized or eliminated. For the Willamette temperature TMDL, NTP conditions were defined as the water temperatures that would occur in the absence of point sources, with restored riparian vegetation, without Portland General Electric’s cap and flashboards at Willamette Falls, and without the Eugene Water and Electric Board’s hydroelectric diversions on the McKenzie River. Water withdrawals for municipal, agricultural, and industrial uses were included in the NTP baseline conditions, as were the effects of upstream dams. A more historic channel shape was not included in the TMDL definition of NTP.

Using the Willamette flow and temperature models, NTP conditions were defined for a modeled time period in 2001 and 2002, and the cumulative thermal effects of the largest point sources were assessed. That assessment was done only for the most critical conditions, when the rivers exceeded the numeric criteria of the temperature standard under NTP conditions.



Base map modified from U.S. Geological Survey and other digital data sets (1:2,000,000; 1:100,000). Projection: Oregon Lambert Conformal Conic, NAD1983, NAVD1988.

Figure 1. Location of the river network, the modeled river reaches, and major reservoirs in the Willamette River basin, Oregon.

Under such conditions, Oregon's temperature standard specifies that NTP temperatures become the applicable temperature criteria, and anthropogenic heating effects must be limited to a small amount (0.3°C), called the Human Use Allowance (HUA). Using this type of analysis and a policy decision specifying that 0.23°C of the HUA could be assigned to the point sources, ODEQ used the models iteratively to determine maximum heat-load allocations for each of the permitted point-source facilities.

In the final TMDL, many of the point sources' heat allocations are sufficiently restrictive that accommodating current conditions and future growth may be difficult without corrective action or an increased heat-load allocation. Several different strategies are being proposed in an attempt to accommodate existing and future heat loads. One alternative is for each point source to find ways to reduce their heat load, possibly by decreasing the amount of water discharged. For example, many municipalities have programs in which treated wastewater is piped to nearby golf courses for use as irrigation water. If the heat load contributed by a point source could be decreased, then that point source might no longer need all of its heat allocation under the TMDL. By accepting a lower allocation, a "credit" could be created that might be traded or sold to another point source that needs a higher allocation. This sort of trading is allowed under the Willamette temperature TMDL.

Trading of heat allocations among the dischargers and designated management agencies, including direct point-source trading or point-source to nonpoint-source trading, may be an efficient means of meeting the obligations of the point sources under the Willamette temperature TMDL while also improving the river ecosystem. A framework for creating a marketplace for trading "ecosystem service" credits, including temperature credits, is being pursued by the Willamette Partnership (http://willamettepartnership.org/). Quantitative tools are needed, however, to assess the temperature effects of any proposed action or trade. In this investigation, the U.S. Geological Survey (USGS) worked in cooperation with the Oregon Association of Clean Water Agencies (ACWA) and the Willamette Partnership to address some of these temperature-related issues under the TMDL.

Purpose and Scope

The purpose of this investigation was to develop a better understanding of the effects of point and nonpoint sources of heat as well as upstream dam operations on water temperature in the Willamette River and the lower reaches of its largest tributaries. The investigation was geared primarily toward quantifying these effects in the context of the thermal allocations set by the Willamette temperature TMDL. Specifically, the objectives of this investigation were to:

- Evaluate the efficacy of various point-source heat allocation trading scenarios, including the partial or complete removal of selected point-source discharges from the river, with the goal of allowing for future growth and the efficient use of existing capacity by other point sources;
- Evaluate the effect of increased point-source heat allocations on the temperature regime of the Willamette River;
- Evaluate the effect of selected riparian shade-restoration projects on the thermal characteristics of the Willamette River system; and
- Evaluate the effect of changed operations at Cougar Dam on downstream water temperatures, including the potential effect of those operations on downstream point-source heat allocations.

Through these objectives, this investigation was designed to develop a better overall understanding of anthropogenic influences on water temperature in the main-stem Willamette River, and provide information and tools that might be used in the development of a heat-trading system that operates within the limits set by the Willamette temperature TMDL. This report documents the results of this investigation.

Both the spatial and temporal scopes of this investigation were aligned with those used in the development of the TMDL. The Willamette flow and temperature models, developed previously to form the basis for the temperature TMDL, were used to simulate the time periods from June 1 through October 31 of 2001 and from April 1 through October 31 of 2002. The models include the entire main-stem Willamette River as well as the lower reaches of selected tributaries (Clackamas, Santiam, North Santiam, South Santiam, Long Tom, McKenzie, South Fork McKenzie, Middle and Coast Fork Willamette, and Row Rivers, as well as Fall Creek) up to their first major dams (fig. 1); the McKenzie River was modeled only up to the point where it is joined by the South Fork McKenzie River. By keeping the same spatial and temporal domains as those used in the Willamette temperature TMDL, the results of this investigation can be directly compared to and augment the information and results created during the TMDL process.

Description of Models

The Willamette flow and temperature models were constructed using CE-QUAL-W2, a two-dimensional (longitudinal, vertical) model from the U.S. Army Corps of Engineers (Cole and Wells, 2002). CE-QUAL-W2 is a physically based mechanistic model that simulates gravity- and wind-driven flow through a network of interconnected river channels or reservoir reaches by using channel geometry and slope, bottom friction, wind shear, density effects, and upstream/downstream flow or water-level data. Algorithms to calculate the effect of hydraulic structures such as weirs, pumps, and spillways are included. Horizontal and vertical velocities, flow, and stage are simulated.

Water temperature is modeled in CE-QUAL-W2 by using a detailed expression of the energy budget of the water body. The model includes algorithms to calculate the effects of both topographic and vegetative shading. Using latitude, longitude, time of day, and the water body's orientation, the model determines at each time step the presence or absence of a topographic or vegetative shadow on the water surface, the length of any shadow, and the degree to which that shadow shields the water body from solar radiation. Model inputs include meteorological data, topographic shading angles, tree-top elevations, distance to the vegetation, and solar-reduction factors associated with the riparian canopy that vary by location. This detailed representation of the heat budget and the effects of riparian shading was one of the major reasons that ODEQ chose to use CE-QUAL-W2 for the Willamette temperature TMDL analysis.

In addition to modeling flow and water temperature, CE-QUAL-W2 can simulate many water-quality constituents, including conservative and nonconservative tracers, bacteria, different forms of nitrogen (nitrate and ammonia) and phosphorus, multiple phytoplankton and epiphyton groups, dissolved oxygen, multiple suspended-sediment groups, and dissolved and particulate organic matter. These capabilities were not used in the Willamette temperature TMDL application but may be used to build on these models in the future. CE-QUAL-W2 has open source code, good documentation, and a large user community. In addition, it has a long history of successful application to a wide range of lake, reservoir, estuary, and river systems (Cole and Wells, 2002). USGS users have found that CE-QUAL-W2 is capable of simulating water temperature with a mean absolute error of 0.5 to 1.0°C (Bales and others, 2001; Green, 2001; Rounds and Wood, 2001; Sullivan and Rounds, 2005 and 2006).

The Willamette modeling suite is composed of nine submodels. These models can be linked together by passing the output of any upstream models to the input of downstream models. Such connections can be made using filters and scripts so that the linkages are automatic and transparent. The nine submodels include:

- Lower Willamette River, with connections to the Columbia River
- Middle Willamette River, from RM 26.5 (Willamette Falls) to RM 85.5 upstream of Salem
- Upper Willamette River, as far upstream as the confluence of the Coast and Middle Forks
- Clackamas River, the lower 26 miles downstream of River Mill Dam
- Santiam and North Santiam Rivers, downstream of Big Cliff Dam
- South Santiam River, downstream of Foster Dam
- Long Tom River, downstream of Fern Ridge Dam
- McKenzie River as far upstream as its confluence with the South Fork McKenzie River, plus the South Fork downstream of Cougar Dam
- Coast and Middle Forks Willamette River, downstream of Cottage Grove Dam on the Coast Fork and Dexter Dam on the Middle Fork, including the Row River downstream of Dorena Dam and Fall Creek downstream of Fall Creek Dam.

In general, these models include the entire main-stem Willamette River and most of its major tributaries as far upstream as the first major dam on each tributary (fig. 1). Version 3.12 of CE-QUAL-W2 was used to build all submodels. The Santiam and North Santiam River model was constructed by USGS (Sullivan and Rounds, 2004). The South Santiam River model was constructed by ODEQ with assistance from Dr. Scott Wells' research team at Portland State University (PSU). The rest of the models were constructed by the PSU modeling team (Annear and others, 2004a and 2004b; Berger and others, 2004).

All models were calibrated to measured temperatures at many locations for June 1 to October 31, 2001, and April 1 to October 31, 2002. The summer of 2001 was a drought period, with low flows at or near post-dam $7Q_{10}$ low-flow levels in many of the modeled rivers. The $7Q_{10}$ is the lowest 7-day average streamflow that would be expected to occur once in 10 years. Hydrologic conditions in 2002, in contrast, were more typical. The models' water-temperature predictions were in good agreement with measured data; mean absolute errors generally were less than 1.0°C (Berger and others, 2004; Sullivan and Rounds, 2004).

Code Changes

All submodels originally were calibrated and run with a slightly modified form of CE-QUAL-W2, based on version 3.12 from August 19, 2003. The PSU modeling team made one enhancement to that code, which created several new output files. These custom outputs contained the daily maximum water temperature from each segment in the model at a user-specified output frequency, calculated using either the surface temperature, a volume-weighted temperature, or a flow-weighted temperature. Having these quantities pre-calculated by the model simplified the post-processing of model results. Further modifications were made to the model code by the USGS for this investigation to make the models easier to use and to eliminate some minor problems. The details of the USGS code changes are described in appendix A. The models used in this investigation are available online from the USGS project website (see section, "Supplemental Material").

Model Modifications

After receiving the Willamette models from ODEQ, USGS staff performed a detailed review and found a few problems that required attention. Several modifications were made to the models to correct errors, remove instabilities, and make the results more usable.

Point-Source Spreadsheet Errors

For each of the modeled point sources, a spreadsheet was crafted by ODEQ staff to calculate the allowable effluent flows and temperatures that result from each source's wasteload allocation formula. The resulting time series of flow and temperature were used in the Willamette temperature models. The spreadsheet calculations, however, were not entirely consistent with the TMDL's final wasteload allocation formulas. Two errors were discovered, both of which relate to the calculation and use of an adjustment factor ("a") in the point-source flow-scaling equation of the TMDL (see Oregon Department of Environmental Quality, 2006b, for more details on the TMDL's point-source allocation framework). USGS staff corrected these errors in the point-source spreadsheets, and the allowable point-source flows and temperatures were recalculated. The changes were largest for those point sources that discharge to the Willamette River and its tributaries upstream of the Santiam River (river mile [RM] 108.5); the modeled point-source discharges increased slightly at certain times of the year. For the rest of the point sources, the changes were small and typically negligible.

Tri-City WWTP Oversight

The Tri-City wastewater treatment plant (WWTP), which discharges to the lower Willamette River at about RM 25.5, was inadvertently modeled by ODEQ with flows and temperatures calculated for the Wacker Siltronics point source. The Tri-City WWTP is a larger source than Wacker, with higher flows and somewhat similar temperatures. After correcting this error, the modeled cumulative temperature effect of the point sources increased slightly in the lower Willamette River.

Travel-Time Offsets

The additional flow in a river contributed by a point-source discharge has an effect on downstream temperatures—the magnitude of which depends on river flow and point-source flow. Downstream of dams, increasing streamflow through point-source additions can slightly modify downstream patterns in the 7-day moving average of the daily maximum (7dADM) temperature. Such changes in downstream temperature patterns can complicate the analysis of cumulative point-source heating effects because temperature changes resulting from travel-time modifications are complex and difficult to disentangle from the more straightforward point-source heating effects. Because of this problem, ODEQ modeled most of the point sources with an associated upstream withdrawal of the same magnitude in an attempt to eliminate the travel-time artifact. The Cottage Grove WWTP did not have an associated time-of-travel offset (withdrawal) in the original ODEQ model. By adding such an offset, a slight travel-time anomaly in the Coast Fork model results was eliminated.

Model Instabilities

Two specific model instabilities were identified and eliminated. The first occurred in the Coast Fork model and affected the simulated 7dADM water temperature for RMs 195.6–186.4 for April 18–24, 2002. This instability was eliminated by reducing the model's maximum allowable time step from April 16–26, 2002. The second instability occurred in the upper Willamette model and affected the 7dADM water temperature for RMs 94.8–85.5 for October 2–27, 2002. The problem was caused by slightly increased flows on day 277, and only occurred for model runs that included point sources in the Santiam River system. The Santiam sources (WWTPs at Jefferson, Stayton, Lebanon, and Sweet Home), though small, were large enough to cause the slightly elevated Willamette flows that triggered the instability. These sources had not been given time-of-travel offsets by ODEQ in the original model runs; adding such offsets was sufficient to eliminate the instability. By removing these instabilities and their associated artifacts in the modeled 7dADM temperatures, the model results were more usable.

Upper Willamette Distributed Tributary Temperatures

The temperatures assigned to the distributed tributaries (ground water and ungaged tributaries) of the upper Willamette model for branches 1-6 were not consistent in the ODEQ models. Different temperatures were used for the model runs that included point sources, as compared to model runs that had no point sources. The distributed tributary temperatures in the former were slightly higher than those used in the latter, resulting in a small additional temperature increase in the “with point sources” model run that was not caused by the point sources. This problem was fixed by consistently assigning these temperatures to those used in the “without point sources” run.

Lower Willamette Timing Artifacts

Because of the relatively large time steps used in the lower Willamette River model, different model runs did not necessarily calculate their daily maximum water temperatures from the same time of day. The maxima could have been extracted from model results that were several minutes apart. This timing discrepancy led to temperature differences, when comparing two model runs, on the order of several hundredths of a degree or more, which in turn led to problems in subsequent data analysis, particularly when adding together the results of many model runs. The solution was to decrease the maximum time step in the lower Willamette River model from 360 to 60 seconds, and use a slightly different version of the model that determined the daily maximum temperature by using information from every time step rather than a user-specified number of times per day (see appendix A).

Flow-Weighted Daily Maximum Temperatures

In assessing the heating effects of point and nonpoint sources on the river system, ODEQ opted to use daily temperature maxima from the river surface for every submodel except the upper, middle, and lower Willamette River. In those three submodels, the flow-weighted daily maxima were used. The lower Willamette River model, however, produces some anomalies in the flow-weighted daily maximum water temperatures that appear when 7dADM temperatures from two different model runs are subtracted. This “noise” is compounded when adding the effects from multiple model runs, making those results unusable for some purposes. Tests showed that the volume-weighted daily maximum temperatures, which do not contain this sort of noise, could be used in place of the flow-weighted daily maximum temperatures for the lower Willamette River without losing any pertinent information. In this work, therefore, USGS used the volume-weighted daily maxima rather than the flow-weighted daily maxima from the lower Willamette River model.

Methods

Model results were analyzed using the same general method used by ODEQ in the development of the Willamette temperature TMDL. That method may be summarized as follows:

1. Determine the 7-day moving average of the daily maximum (7dADM) water temperature for every model segment and every day simulated in each model run. Flow-weighted daily maximum temperatures were used for the upper and middle Willamette River models. Volume-weighted daily maximum temperatures were used for the lower Willamette River model (ODEQ used flow-weighted, as discussed previously). Surface daily maximum temperatures were used for all other submodels.

2. Subtract the 7dADM temperatures for the “without point sources” baseline model run from the 7dADM temperatures for the target model run (for example, a “with point sources” run) for every model segment and every simulated day. The result is a distribution of 7dADM temperature differences at each location in the model. The “without point sources” baseline run typically was the Natural Thermal Potential, or NTP, run.

3. Determine the 95th percentile of the 7dADM temperature differences at each location. Data were grouped together in several different ways to calculate these percentiles, either for all of 2001 and 2002, or by month, or by a fish-use designation time period defined in Oregon’s temperature standard. In the calculation of the 95th percentile, data points were included from a particular location and time only if they adhered to two particular criteria. If the criteria are met, then the data point is included; if either is not met, then the data point is excluded from the computation of the 95th percentile. Those criteria are:

   a. The 7dADM temperature from the NTP run at that time exceeds the numeric criteria of the temperature standard at some point downstream. The focus is on the most critical conditions, when the allowable temperature increase is most restricted by the standard.

   b. The modeled daily average flow at the appropriate point of maximum impact (POMI) is equal to or greater than the post-dam $7Q_{10}$ low-flow statistic at that location. The POMI is the location of a cumulative point-source heating maximum determined on the basis of model results. POMI locations are at or near Albany in the upper

Willamette River model, in the Newberg pool or at Salem in the middle Willamette River model, and in the Portland Harbor for the lower Willamette River model. Local POMIs were used for the Coast Fork and McKenzie River models. $7Q_{10}$ flow values were obtained from the ODEQ's Willamette temperature TMDL document (Oregon Department of Environmental Quality, 2006b).

This analysis method was discussed with ODEQ staff prior to its use, and it was agreed that this method was very similar, if not identical, to the method used by ODEQ to analyze model results for the TMDL.

Note that at least six different common methods can be used to compute percentiles, and no good agreement exists as to which is preferred. The SAS statistics package alone offers five separate methods for calculating percentiles (SAS Institute, 1990). ODEQ staff relied on Microsoft© Excel to compute percentiles, and Excel's method, though related, does not match any of those offered by SAS. Most of these percentile methods differ in their assumptions for the intervals that surround each ranked data point; as a result, the computations differ most when applied at the extremes of the distribution, such as at the 5th or 95th percentile. In this analysis, the method documented by Helsel and Hirsch (2002) and identical to SAS Proc Univariate's definition 4 was used to compute the 95th percentiles. This method is widely applied, but may result in slightly higher 95th percentiles with some datasets, as compared to those computed by Excel.

Temperature Effects of Point Sources

The Willamette temperature TMDL quantified the cumulative heating effects of a set of 27 point-source discharges to the Willamette River and selected tributaries, set maximum heat-loading limits for each, and provided for the potential trading of such heat-load allocations, among other things. The TMDL did not provide any tools or spatially linked quantifications of individual point-source heating effects, however, that might be used to assess potential point-source heat-allocation trades. To assess the efficacy of such trades, the Willamette flow and temperature models were used in this investigation to determine individual "heating signatures" for each of the 27 modeled point sources listed in table 1. Those signatures then were used to create a screening tool in which the magnitude of the heating signature for each point source can be increased or decreased to simulate the effects of potential changes in point-source heat-load allocations. The aim of the screening tool was to facilitate the evaluation of point-source to point-source heat-allocation trading.

Table 1. Point sources of heat included in the Willamette River flow and temperature models.

[Locations are provided for point sources that discharge to the Willamette or Coast Fork Willamette Rivers. **Abbreviations:** RM, river mile; MWMC, Metropolitan Wastewater Management Commission; WWTP, wastewater treatment plant; U of O, University of Oregon; NA, not applicable]

Entity	Location (RM)	Receiving stream
Cottage Grove WWTP	207.4	Coast Fork
U of O Heat Plant	181.6	Willamette
MWMC (Eugene/Springfield)	177.9	Willamette
Weyerhaeuser Springfield	NA	McKenzie
Fort James Halsey	147.6	Willamette
Pope and Talbot	147.6	Willamette
Evanite Fiber	132.8	Willamette
Corvallis WWTP	131.0	Willamette
Albany WWTP	118.4	Willamette
Teledyne Wah Chang	117.2	Willamette
Weyerhaeuser Albany	117.2	Willamette
Sweet Home WWTP	NA	South Santiam
Lebanon WWTP	NA	South Santiam
Stayton WWTP	NA	North Santiam
Jefferson WWTP	NA	Santiam
Salem WWTP	78.9	Willamette
S&P Newsprint	50.2	Willamette
Newberg WWTP	50.0	Willamette
Wilsonville WWTP	38.9	Willamette
West Linn Paper	26.2	Willamette
Blue Heron Paper	26.4	Willamette
Tri City WWTP	25.5	Willamette
Clackamas Fish Hatchery	NA	Clackamas
Tryon Creek WWTP	20.4	Willamette
Oak Lodge WWTP	20.1	Willamette
Kellogg Creek WWTP	18.7	Willamette
Wacker Siltronics	6.6	Willamette

The heating signature for each point source was determined by running the Willamette temperature models under the TMDL's NTP baseline conditions, but with the addition of that single point source at its maximum wasteload allocation under the TMDL. The model results then were processed as described in the section "Methods" to obtain the 95th percentile of the 7dADM temperature differences caused by that point source; that 95th percentile as a function of downstream distance is the point source's heating signature. The process was repeated with each of the 27 point sources to determine each of the 27 heating signatures. A spreadsheet-based screening tool was created to add the heating signatures together and thereby estimate the cumulative heating effects of all modeled point sources.

Heating Signature Summation Issues

Point-Source Independence

The summation of individual point-source heating signatures by the screening tool is only valid in predicting the cumulative point-source heating effect if the temperature changes that result from each point source are largely independent of one another. The temperature changes caused by many of these point sources, however, do not completely dissipate by the time a downstream point source adds its heat to the river. To the extent that an upstream point source increases the temperature of the river at the location of a downstream point-source discharge, the temperature increase caused by the downstream source is slightly less than it would be in the absence of the upstream source. Therefore, the individual point sources are not completely independent, and the summation of the individual point-source heating signatures will not be a completely accurate prediction of the cumulative temperature effect of all point sources if they were modeled together; instead, the sum is likely to be slightly larger.

The magnitude of this point-source dependence problem diminishes as the temperature change associated with each point source decreases. Given that the point sources included in this investigation all have discharge flows that are small relative to the flow in their respective receiving streams, and that the temperature increases caused by each point source also are small (typically less than a few tenths of a degree Celsius), the point-source dependence problem also is likely small. Indeed, the effect was estimated for this investigation using a range of point-source flows (as much as 1/50th of the receiving stream's flow) and a range of independent point-source temperature increases (as large as 0.2°C). Under these conditions, the point-source dependence error is only on the order of a few thousandths of a degree Celsius. This error is small compared to the actual discrepancy between the sum of the individual point-source heating signatures and the cumulative temperature increase as predicted by a model run with all point sources included (fig. 2). Most of the observed error in using the sum of the point-source heating signatures, then, is not a result of point-source dependence issues.

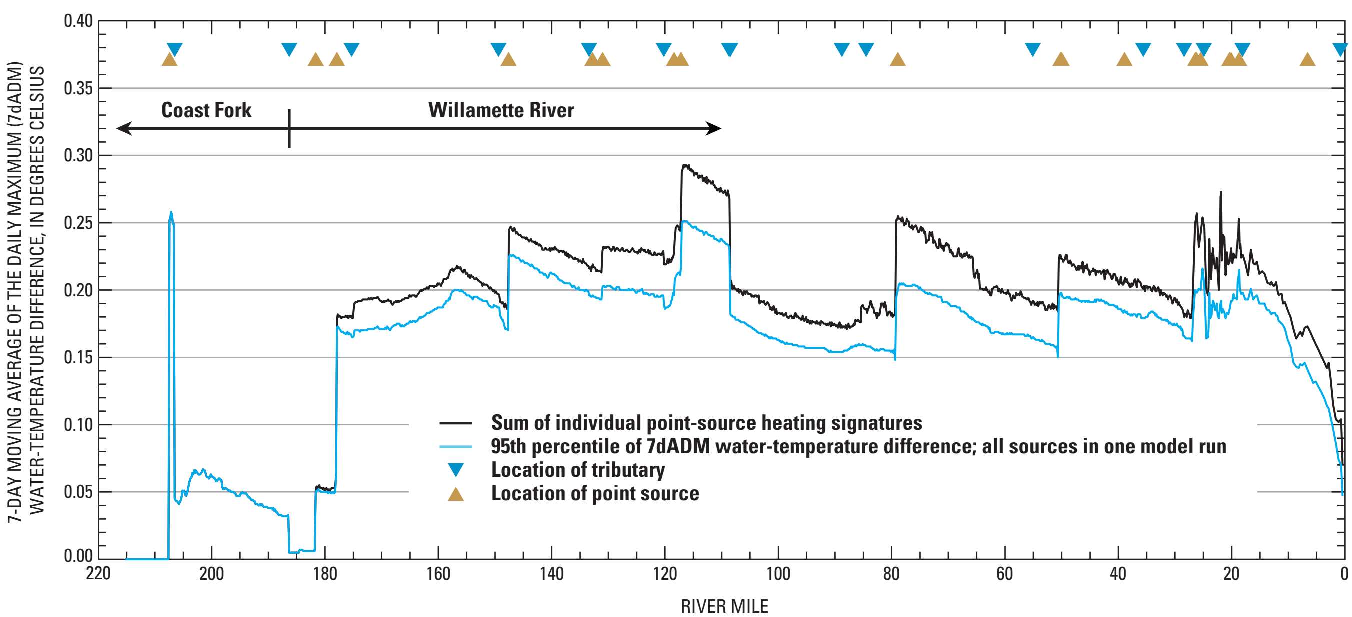


Figure 2. Comparison of the sum of the individual point-source heating signatures to the results from one model run containing all point sources. The difference is caused by (a) interdependence among the point-source heating signatures, and (b) the fact that the heating signatures, because they are defined as 95th percentiles, are not additive unless point-source heating effects are completely synchronized in time.

Addition of 95th Percentiles

The summation of the point-source heating signatures is complicated by the fact that each signature is defined as a 95th percentile, and such percentiles from separate data distributions are only additive under certain conditions. This problem is illustrated in figure 3, in which two data distributions were added together in two different ways. In that figure, distributions A and B are normal distributions with means of 0.15 and 0.10, respectively, and identical standard deviations of 0.03. Distributions C and D represent the “random sum” and the “ranked sum” of A and B, respectively. The random sum is defined as the sum of members of distributions A and B, chosen randomly. In contrast, the ranked sum was created by first ranking the members of A and B, pairing them according to their ranks, and then adding them together. Statistical methods dictate that the standard deviation of the random sum, distribution C, is the square root of the sum of the variances of the distributions being added, giving a value of 0.042. In contrast, the standard deviation of the ranked sum, distribution D, is simply the sum of the standard deviations of A and B, resulting in a value of 0.06. Regardless of whether the distributions are normal, the fact remains that the ranked sums produce a wider distribution, and therefore have larger 95th percentiles than those resulting from the random sum. One particularly useful result is that the 95th percentile of the ranked sum distribution is exactly equal to the sum of the 95th percentiles of distributions A and B.

The example using ranked and random sums illustrates that 95th percentiles from many datasets are only additive when the members of those datasets are tied together with similar ranks. Heating signatures from different point sources, therefore, may be added together only if the temperature changes caused by each of the point sources are not random, but “synchronized” with one another. So, in order for the sum of the heating signatures to be a good prediction of the results from a single model run that includes all point sources together, the modeled temperature change resulting from each point source can not be random relative to those that result from other point sources. The temperature change caused by a point-source discharge is determined by a number of factors, but streamflow and weather conditions are prime influences, and those flow and weather conditions are likely to be similar across the entire model domain. Therefore, when any one point source is modeled to have its greatest heating effect on the river, it is likely that all other point sources also have large, if not their largest, heating effects on the river. In this way, the point-source heating effects are somewhat synchronized rather than random, and their heating signatures, though they are defined as 95th percentiles, probably can be added together without incurring a large amount of predictive error.

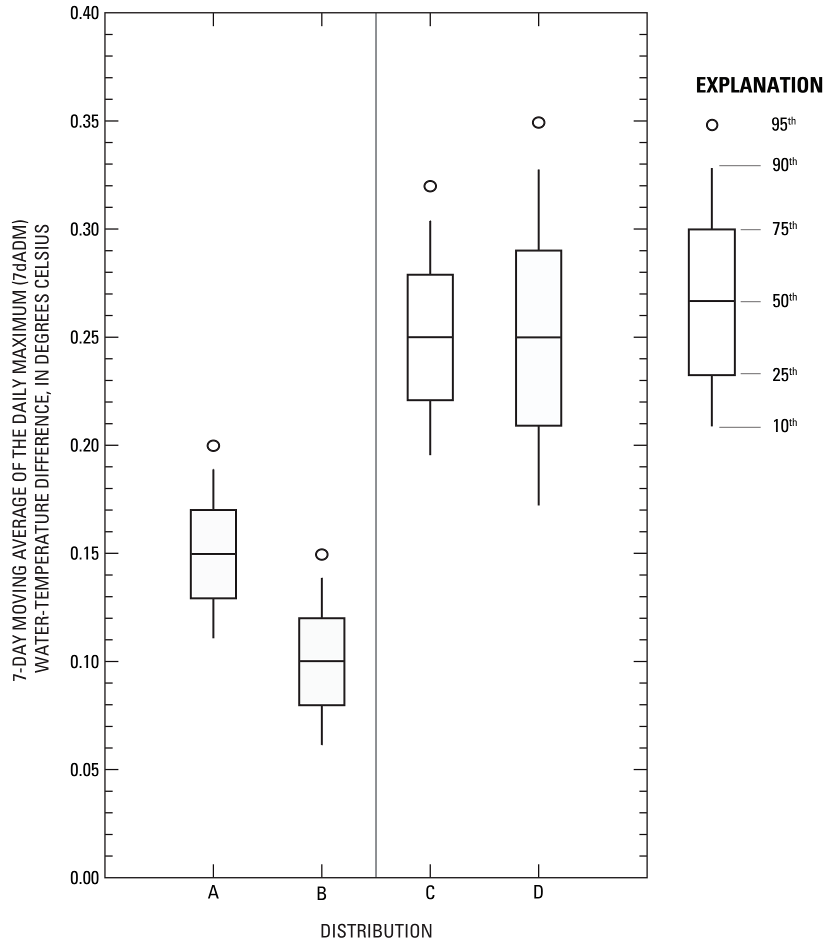


Figure 3. Percentiles from two hypothetical normal distributions, A and B, as well as two distributions resulting from the addition of A and B. Distribution C is the random sum, in which members of distributions A and B were chosen randomly and added together. Distribution D is the ranked sum, in which the members of distributions A and B first were ranked, then paired according to their ranks and summed. The ranked sum results in the same mean but a wider distribution, resulting in larger 95th percentiles. The 95th percentile of D is equal to the sum of the 95th percentiles of A and B.

Despite the fact that the point-source heating effects are largely synchronized, the sum of the 27 point-source heating signatures is slightly larger than the 95th percentile of temperature increases resulting from a single model run containing all 27 point sources (fig. 2). The difference probably is because the heating effects from each point source are not completely synchronized in time with those from other point sources. The flow conditions that occur at each point-source discharge location have similar seasonal and annual patterns, but may not conform to exactly the same patterns because of the influence of varying releases from upstream dams. Therefore, the heating effects of point sources that discharge to the Willamette River upstream and downstream of the McKenzie River confluence are affected by slightly different patterns in streamflow, which contributes to the difference shown in figure 2.

Adjustments and Strength Factors

The sum of the 27 heating signatures may be slightly larger than the results from one model run containing all point sources, but the difference is small enough that a correction factor can be formulated to adjust each of the heating signatures until the sum of all signatures is exactly equal to the results from that one model run. The formulation of the correction factor must be relatively simple and defensible, and yet still produce the desired result. One simple and logical way to adjust the heating signatures is to decrease each by a certain percentage, where the percentage varies as a function of location along the river because the required adjustment, as a percentage of the model results, also varies across the model domain. This adjustment by itself, however, is not enough because the sum of the heating signatures also needs to collapse to a single heating signature if all but one point source is removed from the analysis. If the percentage adjustment still remains in that case, then the prediction would be too low. So, the correction factor needs to include not only a factor that causes a percentage decrease, but also a second term that causes the correction factor to gradually be eliminated as any one point-source heating signature becomes the dominant member of the sum.

In addition to the correction factors, each heating signature was assigned a corresponding “strength factor” for use in the screening tool. The strength factor is simply a multiplicative factor that is used to linearly vary the magnitude of a particular heating signature. A strength factor of 1.0 leaves the point source at its full wasteload allocation as specified in the Willamette temperature TMDL. A strength factor of 0.0 has the effect of removing that point source from the river. A strength factor of 0.5 cuts its effect in half, and a factor of 1.5 increases its effect by 50 percent. The strength factor may be thought of as a modification to its allowable flow, without a change in its temperature.

Accounting for the strength factors and correction terms, the resulting framework for the screening tool is manifested in the following equations. The sum of the heating signatures, multiplied by their strength factors and adjusted by a correction factor results in a prediction of the cumulative heating effect caused by the point sources:

$$\Delta T = \sum s_i h_i \left(1-\alpha\right), \qquad (1)$$

where

ΔT is the predicted cumulative temperature increase or heating effect of the point sources at any one location,

s_i is the strength factor for point source i,

h_i is the temperature increase (heating signature) at that location caused by point source i at its full TMDL allocation, and

α is a correction factor at that location.

The correction factor is defined by:

$$\alpha = \left(\frac{\sum h_i - \Delta T^*}{\sum h_i} \right) \beta, \qquad (2)$$

where ΔT^* is the cumulative point-source temperature increase (heating effect) as calculated from one model run containing all point sources at their full TMDL heat-load allocations. The term in parentheses is a fractional adjustment and is the same for each point source, but varies by location. The second factor in that equation, β, also varies with location and is the term that causes the correction factor to become zero when any one point source dominates the strength-weighted sum of heating signatures; it is defined with the following asymptotic formula:

$$\beta = \left(\frac{1.5\left(1-\lambda\right)}{0.5\left(1-\gamma\right)+\left(1-\lambda\right)} \right), \qquad (3)$$

where

λ is the largest fraction of the strength-weighted sum of heating signatures resulting from any one point source at that location:

$$\lambda = \frac{\max(s_i h_i)}{\sum s_i h_i}, \quad (4)$$

and

γ is the largest fraction of the non-weighted sum of heating signatures resulting from any one point source at that location:

$$\gamma = \frac{\max(h_i)}{\sum h_i}. \quad (5)$$

Formulated in this way, the β factor is near 1.0 under most conditions and quickly decreases toward 0.0 whenever any one point source begins to dominate the strength-weighted sum of heating signatures. This means that the adjustment factor α typically is equal to a simple percentage reduction and is only eliminated when the strength-weighted sum of heating signatures approaches the strength-weighted signature from just one point source.

Use of the Trading Tool

A spreadsheet-based screening tool was created to calculate the sum of the 27 adjusted and strength-weighted point-source heating signatures. This screening tool, termed the "Willamette Point-Source Heat-Trading Tool" or just the "Trading Tool" for short, was crafted to allow resource managers, city engineers, plant operators, and regulators to quickly and accurately evaluate the thermal effects of potential heat-allocation trades among the point sources regulated by the Willamette temperature TMDL. By simply selecting a target time period and modifying the strength factors associated with each point source in an iterative fashion, potential trades can be defined and the effects on the temperature of the river can be estimated. The latest version of the Trading Tool may be downloaded from the project website; the website address is listed in section, "Supplemental Material."

The Trading Tool not only calculates the sum of the strength-weighted point-source heating signatures, but also provides graphs of the results and several types of metrics that might be useful in evaluating potential trades. Graphs include the predicted 7dADM temperature difference that results from point sources as a function of river mile along the Coast Fork Willamette, McKenzie, and Willamette Rivers, with a comparison to the TMDL's fully allocated condition, as well as the difference between the two. The tool also includes a graph showing the contribution of each point source to the total 7dADM temperature difference, and a cumulative frequency plot showing the distribution of 7dADM temperature differences for the potential trade compared to the fully allocated condition.

Several metrics are calculated by the Trading Tool to assist in evaluating the effects of a potential trade. A set of screening criteria are evaluated, one for each of several subreaches of the modeled domain. These criteria help to determine whether the potential trade would cause the temperature to increase above the level that occurred at any of the local points of maximum impact (POMI) for the fully allocated condition. Presumably, if the magnitude of the cumulative point-source heating effect at any POMI is estimated to increase to a level that is higher than what was modeled for the TMDL under fully allocated conditions, then that trade might not be desirable. In addition to these screening criteria, the number of miles of river that are expected to be heated or cooled by certain amounts as a result of the trade is quantified. Lastly, an integrated heating or cooling effect for the river and several subreaches is calculated. This overall heating or cooling effect is quantified in terms of "degree-miles," where one degree-mile is equivalent to a change in temperature of one degree over the entire length of one mile of river. This metric is useful in providing an overall measure of the heating or cooling effect of the trade, regardless of any localized temperature changes.

Finally, the changes in point-source heat-load allocations are quantified by the Trading Tool in a set of tables that mirrors the wasteload allocations provided in the TMDL. For each point source, one or two tables show that source's maximum allowable heating effect both in terms of a change in temperature of the receiving stream, and as an added heat load in millions of kilocalories per day; each of these measures is a function of the flow in the river. These tables may prove to be particularly useful to permit writers and to engineers and planners that need to quantify a potential trade in units that they can measure or calculate.

Patterns in the Temperature Differences

The patterns in the predicted cumulative point-source temperature effects can be explained primarily by the locations of point-source and tributary inflows. The 7dADM temperature difference usually increases where a point-source discharge is located (the upward-pointing triangles in figure 2**,** for example). The magnitude of the increase depends on several factors such as the size of the point source, the flow in the river at that location, and the temperature of both the river and the point-source discharge. Tributary inflows (table 2) are notable particularly where they cause the 7dADM temperature difference to decrease in response to additional flow that dilutes upstream point-source heating effects; this is the case for the inflows of the Row River (RM 206.5), the Middle Fork Willamette (RM 186.3), and the Santiam River (RM 108.5). The McKenzie River inflow at RM 174.9, though it contributes a large flow to the Willamette River, shows an increase in the 7dADM temperature difference in figure 2; this

Table 2. Locations of tributaries included in the Willamette River flow and temperature models that discharge to the Willamette or Coast Fork Willamette Rivers.

[RM, river mile]

Tributary	Location (RM)	Receiving stream
Row River	206.5	Coast Fork
Middle Fork Willamette River	186.3	Willamette
McKenzie River	174.9	Willamette
Long Tom River	149.4	Willamette
Marys River	133.4	Willamette
Calapooia River	120.2	Willamette
Luckiamute River	108.7	Willamette
Santiam River	108.5	Willamette
Rickreal Creek	88.8	Willamette
Mill Creek	84.5	Willamette
Yamhill River	55.1	Willamette
Molalla River	35.6	Willamette
Tualatin River	28.4	Willamette
Clackamas River	24.9	Willamette
Johnson Creek	18.1	Willamette
Columbia Slough	0.8	Willamette

results from the presence of a point source on the McKenzie River upstream. Downstream of point-source inflows, the 7dADM temperature difference typically diminishes slightly with downstream distance as the river dissipates some of the heat from the point sources to the atmosphere.

A few anomalies do not follow this pattern of point-source heating, downstream heat dissipation, and tributary dilution. A small increase and decrease in the 7dADM temperature difference, a "hump" in the pattern, occurs between roughly RMs 150 and 160. This anomaly, which does not coincide with any point-source or tributary inflow, has more than one potential explanation. First and most likely, it may be caused by the fact that point-source temperatures often are relatively constant while receiving water temperatures can vary over the course of a day. Any increase in river temperature at the point-source's discharge location, therefore, also varies and is greatest when the receiving water temperature is at its daily minimum. This increased daily minimum water temperature at the point of discharge then can result in an increased daily maximum water temperature at a location approximately one-half day of travel time downstream. This effect can only occur when the receiving stream has a sufficiently large daily variation in its water temperature at the point of discharge, thus making it a transient anomaly. In this case, the anomaly between RMs 150 and 160 is indeed approximately one-half day of travel time downstream of the Metropolitan Wastewater Management Commission (MWMC) point source at RM 177.9, and the anomaly is associated primarily with that point source's heating signature.

A second possible explanation is that this anomaly was caused by a slight change in travel time associated with the MWMC and possibly the Weyerhaeuser Springfield (McKenzie River) point sources upstream. Downstream of dams that release relatively constant flows and temperatures, the daily maximum temperature of a river tends to exhibit a nodal pattern with downstream distance, where the nodes are spaced at intervals of approximately one day of travel time (Lowney, 2000). The introduction of point sources changes the travel time and therefore the distance between nodes. When the 7dADM temperature results of two model runs are subtracted, this change in the nodal pattern causes some interesting patterns to appear downstream of the larger point sources. ODEQ staff tried to remove all such travel-time artifacts by artificially withdrawing flow from the river upstream of each point source, but it is possible that not all of the travel-time artifacts were completely eliminated.

The "hump" in the 7dADM temperature difference between RMs 200 and 205 might be another anomaly caused by travel-time changes or daily variations in heating effects associated with an upstream point source. The hump also could be a numerical modeling artifact caused by the large change in temperature that occurs just upstream; slight numerical anomalies just downstream of abrupt changes in temperature are not uncommon in numerical model predictions, though improvements in numerical solution techniques in CE-QUAL-W2 have minimized or eliminated most such artifacts.

Predictions and Test Results

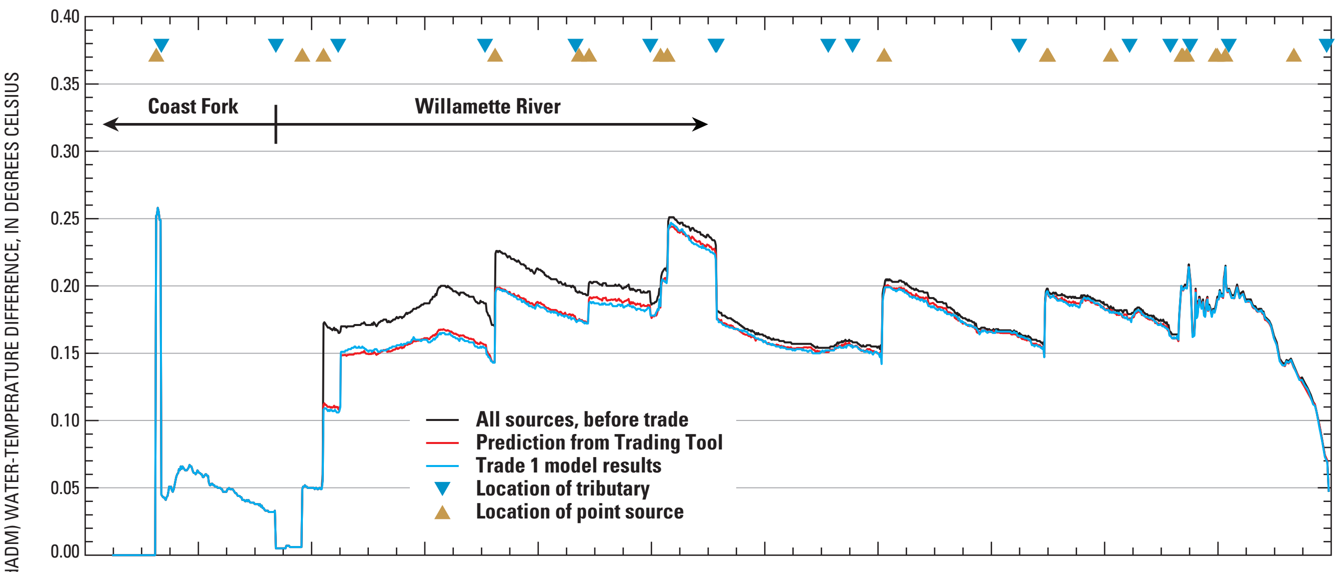
A screening tool such as the Trading Tool is only useful if it can be shown to be accurate in its predictions. To test the tool's predictions, four test cases were created and evaluated with the Trading Tool. Then, the exact same conditions were simulated with the Willamette flow and temperature models. By comparing the results, the error associated with the Trading Tool estimates can be quantified. The Trading Tool is envisioned to be used only as an easy-to-use screening tool to quickly define potentially useful point-source heat-allocation trades. Each identified trade, then, can be evaluated with the Willamette River flow and temperature models. Only if the Trading Tool predictions are shown to be accurate over a wide range of conditions might its predictions be used without verification; at this time, verification runs with the full suite of models is still advisable.

The first test case postulates a purely hypothetical heat trade between three point sources in the upper Willamette River. In this trade, MWMC's allocation is decreased by 50 percent by setting its strength factor in the Trading Tool to 0.5. In concert with this heat-load decrease, the screening tool shows that the heat-load allocations for the cities of both Corvallis and Albany might be increased by 50 percent; their strength factors were both set to 1.5. All other strength factors were kept at 1.0 to represent their fully allocated condition under the TMDL. This test case was modeled with the full suite of flow and temperature models by simply changing the modeled flow for each of these three point sources; each was changed by multiplying their point-source flow time series by each source's strength factor, but leaving the temperature associated with each source unchanged. Time-of-travel offset withdrawals also were adjusted for each of these point sources, as in the TMDL model runs. The resulting comparison shows that, for this test case, the Trading Tool predictions agree with the model results to within 0.005°C, with a mean error of 0.001°C and a mean absolute error of 0.002°C (fig. 4, table 3). Mean error is a measure of bias in the predictions, and the mean absolute error may be thought of as a typical error associated with any point along the river. Given the magnitude of the temperature changes being modeled, these errors seem small enough to be acceptable.

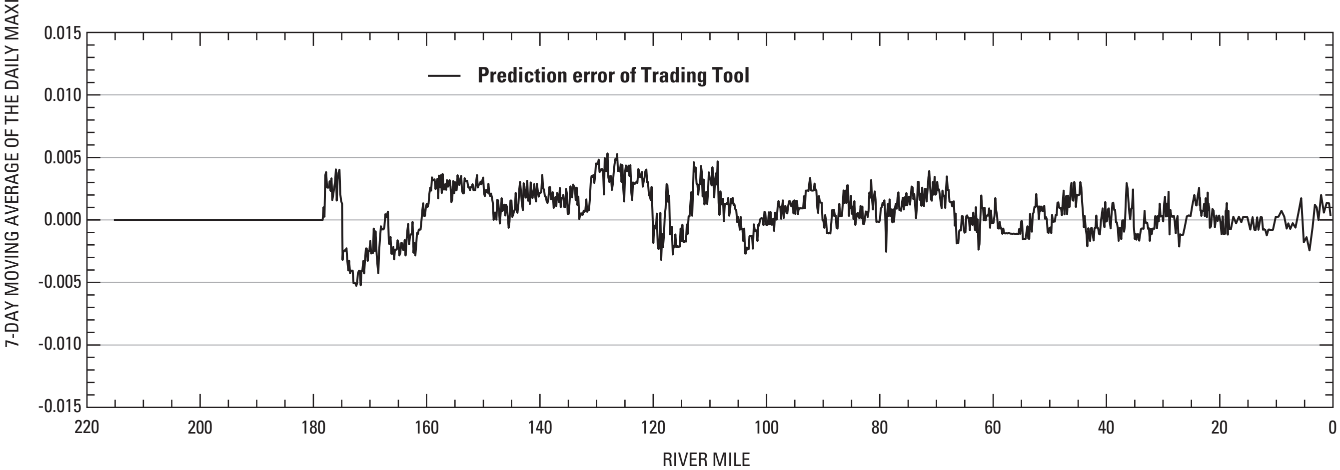
Table 3. Prediction errors of the Trading Tool when used to estimate the effects of several hypothetical heat-trading test cases.

[A positive mean, minimum, or maximum error indicates that the tool gave a result that was larger than that predicted by the Willamette River flow and temperature models. All results are based on the 95th percentile of the 7dADM water-temperature difference, as described in the section, "Methods." Abbreviations: 7dADM, 7-day moving average of the daily maximum; °C, degrees Celsius]

Heat-trading test case	Error (°C)			
	Mean	Mean absolute	Minimum	Maximum
1	0.001	0.002	-0.005	0.005
2	-0.002	0.002	-0.011	0.004
3	-0.001	0.001	-0.005	0.002
4	-0.003	0.003	-0.014	0.002



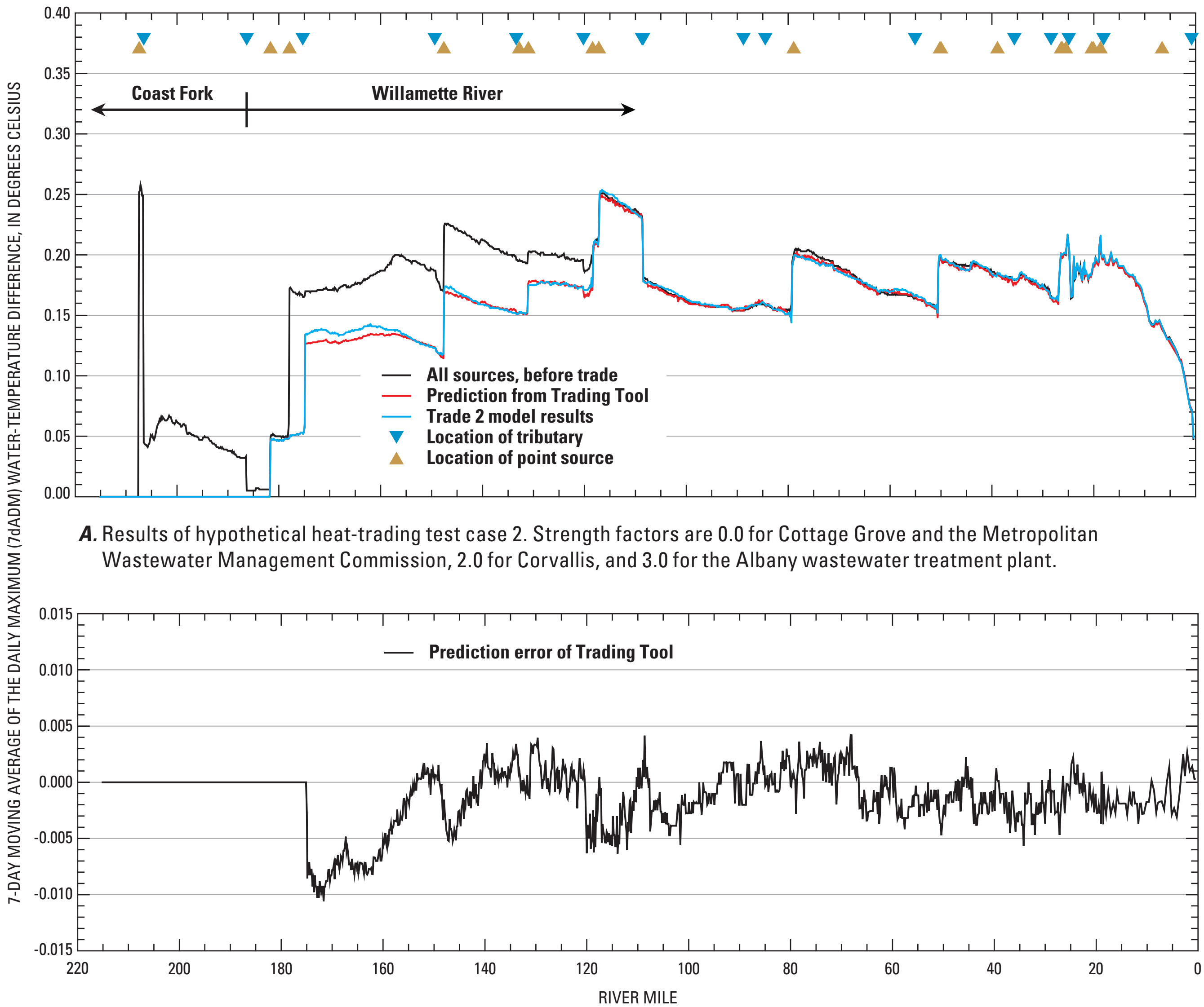
A. Results of hypothetical heat-trading test case 1. Strength factors are 0.5 for the Metropolitan Wastewater Management Commission and 1.5 for the Corvallis and Albany wastewater treatment plants.



B. Errors associated with Trading Tool estimate.

Figure 4. Results of hypothetical heat-trading test case 1, showing 7dADM point-source temperature effects from the test case's model run and errors associated with the Trading Tool estimate.

Test case 2, also hypothetical, involves four point sources upstream of the Santiam River confluence. In this test case, Cottage Grove no longer discharges to the Coast Fork Willamette River and MWMC removes its discharge from the Willamette River (each strength factor = 0.0). Because of this decrease in heat inputs upstream, the cities of Corvallis and Albany are able to increase their heat discharges, in this case by factors of 2.0 and 3.0, respectively. These strength factors were set in the Trading Tool to estimate the cumulative point-source heating effect. The Willamette flow and temperature models also were run to determine the result of this change in point-source discharges; the flows of the point sources were modified while the temperature of those sources were left unchanged. A comparison of the results of the models to the predictions of the Trading Tool shows that the Trading Tool's predictions were fairly accurate, with a mean error of -0.002°C and a mean absolute error of 0.002°C (fig. 5, table 3). The tool's predicted patterns of 7dADM temperature effects generally were within 0.005°C of the model results. The match was not quite as accurate in the 15 miles or so downstream of the McKenzie River confluence (RM 174.9), probably due to the different flow conditions that affect the point sources discharging to the McKenzie River versus those along the Willamette River.



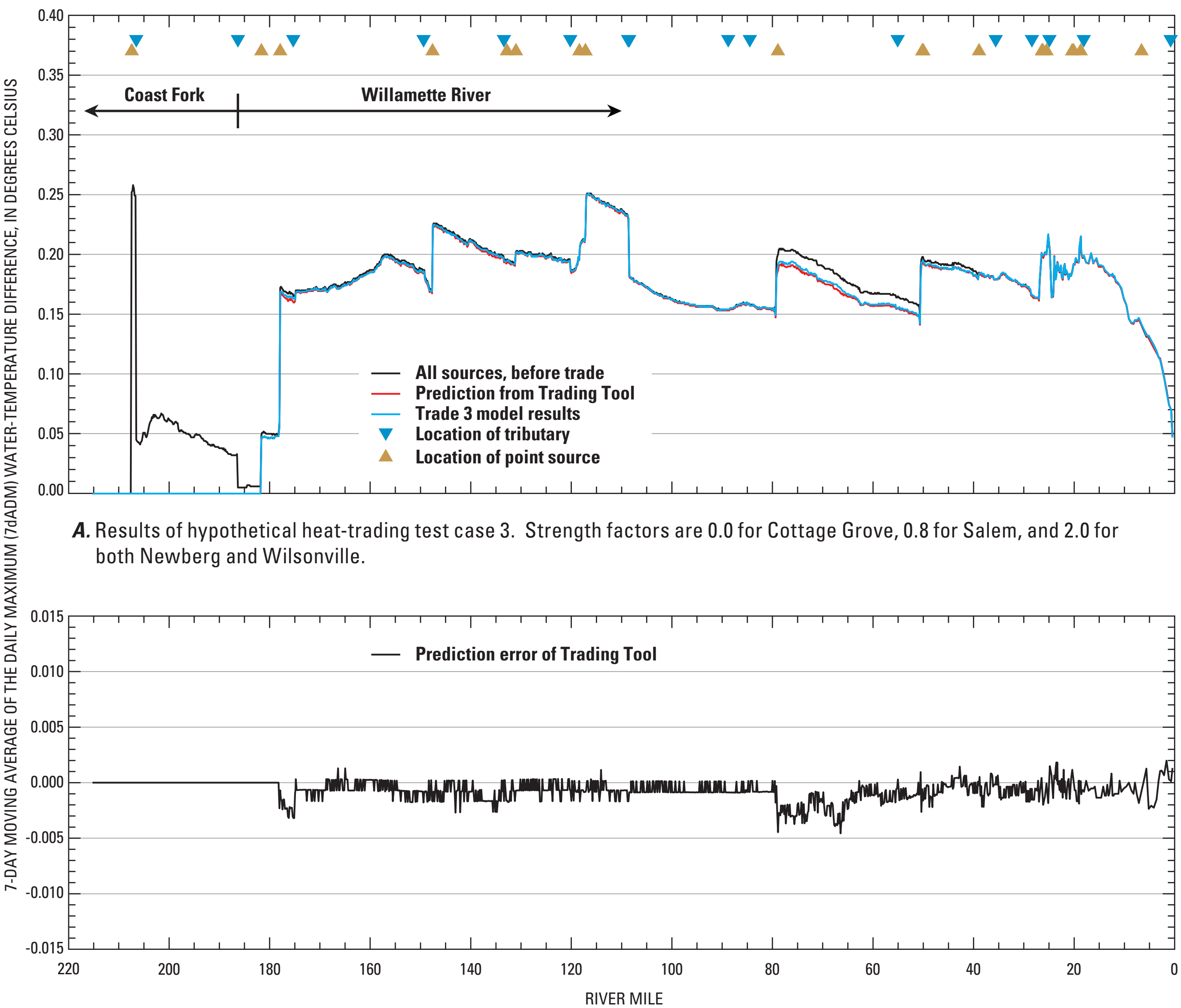
A. Results of hypothetical heat-trading test case 2. Strength factors are 0.0 for Cottage Grove and the Metropolitan Wastewater Management Commission, 2.0 for Corvallis, and 3.0 for the Albany wastewater treatment plant.

B. Errors associated with Trading Tool estimate.

Figure 5. Results of hypothetical heat-trading test case 2, showing 7dADM point-source temperature effects from the test case's model run and errors associated with the Trading Tool estimate.

In test case 3, the predictions of the Trading Tool were tested for sources located in the middle Willamette subreach. Again, Cottage Grove's flow was removed from the river (strength factor set to 0.0). The city of Salem's discharge was scaled back by 20 percent (strength factor = 0.8). Then, the heat-load allocations for the cities of Newberg and Wilsonville were doubled (strength factor = 2.0). The Willamette flow and temperature models were used to assess this new condition by changing the point-source flows as before. For this test case, the Trading Tool predicted the change in temperature conditions along the Willamette River quite well, with a mean error of -0.001°C and a mean absolute error of 0.001°C (fig. 6, table 3). The screening tool's prediction errors in this case were well within ±0.005°C for the entire model domain.

For hypothetical test case 4, the Cottage Grove WWTP effluent was removed from the river, and Weyerhaeuser Springfield traded some of its heat-load allocation with the Weyerhaeuser Albany plant downstream. The Springfield plant reduced its load by one-half (strength factor = 0.5), thus allowing the Albany plant to double its load (strength factor = 2.0). The flow and temperature models were run with the modified point-source and travel-time offset flows;



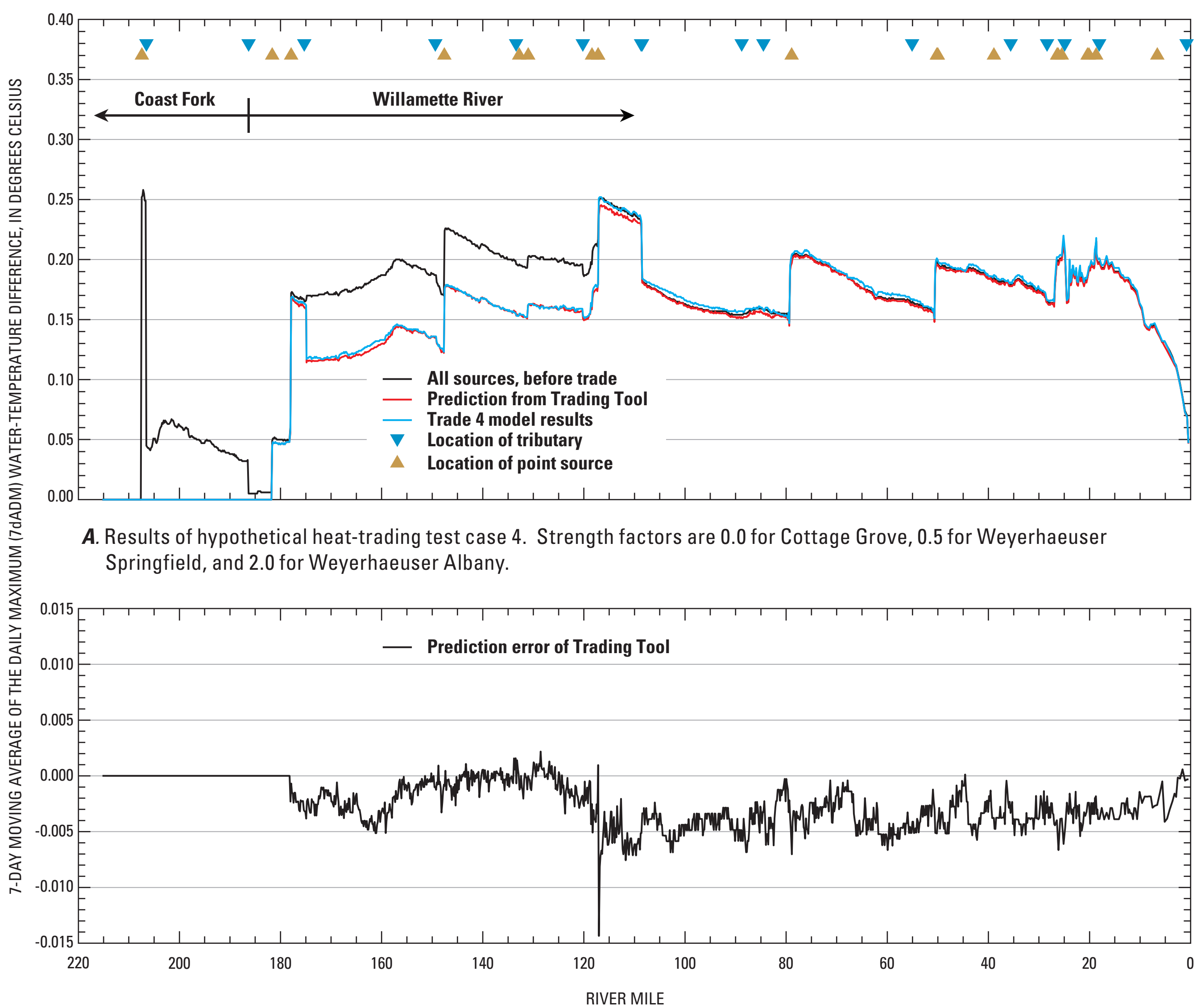
A. Results of hypothetical heat-trading test case 3. Strength factors are 0.0 for Cottage Grove, 0.8 for Salem, and 2.0 for both Newberg and Wilsonville.

B. Errors associated with Trading Tool estimate.

Figure 6. Results of hypothetical heat-trading test case 3, showing 7dADM point-source temperature effects from the test case's model run and errors associated with the Trading Tool estimate.

the results are compared to the predictions of the Trading Tool in figure 7, with error statistics listed in table 3. For this test case, the mean error and the mean absolute error for the tool's predictions were -0.003°C and 0.003°C, respectively. In this case, the Trading Tool accurately predicted the modified patterns in the cumulative point-source heating effects, but the predictions were biased very slightly negative for most of the length of the Willamette River. This inaccuracy is small (less than 2 percent), however, compared to the types of temperature differences being modeled, so the predictions of the Trading Tool still appear to be reliable in this case.

On the basis of these four hypothetical test cases, the Trading Tool predictions are sufficiently accurate to be useful in its intended purpose as a tool for screening potential point-source heat-allocation trades. The tool's prediction errors typically are within ±0.005°C, which is small compared to both the calculated cumulative point-source heating effects of the TMDL and the typical changes in 7dADM temperature patterns associated with many potential trades. Though it appears that the Trading Tool is both accurate and reliable in its predictions, a verification of all potential point-source heat-allocation trades with the full suite of Willamette River flow and temperature models is still advised.



A. Results of hypothetical heat-trading test case 4. Strength factors are 0.0 for Cottage Grove, 0.5 for Weyerhaeuser Springfield, and 2.0 for Weyerhaeuser Albany.

B. Errors associated with Trading Tool estimate.

Figure 7. Results of hypothetical heat-trading test case 4, showing 7dADM point-source temperature effects from the test case's model run and errors associated with the Trading Tool estimate.

Temperature Effects of Riparian Shading

The Willamette River flow and temperature models were used to assess the effects of restoring riparian vegetation along the Long Tom River, and along selected reaches of the upper Willamette River. These effects were modeled by changing several model inputs: the tree-top elevation, the distance from the center of the river to the vegetation, and the fraction of solar radiation intercepted by that vegetation. These three model inputs vary as a function of location and are assigned separately for the vegetation on each bank of the river. The characteristics of the riparian vegetation, translated into input files for the models, were developed during model construction. Current vegetation characteristics were derived from aerial photographs and GIS techniques by ODEQ staff, then translated into model input files using methods developed by PSU, ODEQ, and USGS (Annear and others, 2004a; Sullivan and Rounds, 2004). "System potential" vegetation, or the potential near-stream land cover, is the mature vegetation that should occur at a particular location, based on the soils and geologic materials that occur there. ODEQ conducted a study of potential near-stream land cover as part of the Willamette River temperature TMDL, and the results were used to predict the height and shading characteristics of system potential vegetation along the banks of all modeled river reaches (Oregon Department of Environmental Quality, 2006c). System potential vegetation was used in the modeling of Natural Thermal Potential baseline conditions in the TMDL and in this investigation. System potential shade input files for the models were used as received from ODEQ; shade files representing current conditions were obtained from PSU as used in the latest model calibration runs.

Long Tom River Shading

The effect of restoring riparian vegetation along the entire Long Tom River, from Fern Ridge Dam to the mouth of the Long Tom, was simulated with the Willamette temperature TMDL models by switching the shade input files of the Long Tom model between current conditions and system potential and running the suite of models under those conditions. The 7dADM water-temperature differences between these two model runs then were calculated, and the 95th percentile of that difference was computed according to the procedure described in section, "Methods." Plotting these results as a function of downstream distance along the Willamette River, the effects of cooling the Long Tom River with shade restoration are apparent (fig. 8). A maximum cooling of about 0.034°C was modeled in the Willamette River as a result of shade restoration on the Long Tom River; greater cooling effects occur in the Long Tom, but its flow is small relative to flow in the Willamette and therefore the cooling effect from the Long Tom River is diluted when its waters mix with those of the Willamette River. Restoring all riparian vegetation along the Long Tom River, though probably very beneficial for that river, has a limited effect on temperatures in the Willamette River. Still, a decrease of about 0.02°C at the upper Willamette's POMI near Albany might enable one or more of the point sources upstream of Albany to increase its allowable heat load substantially through a point-source to nonpoint-source trade.

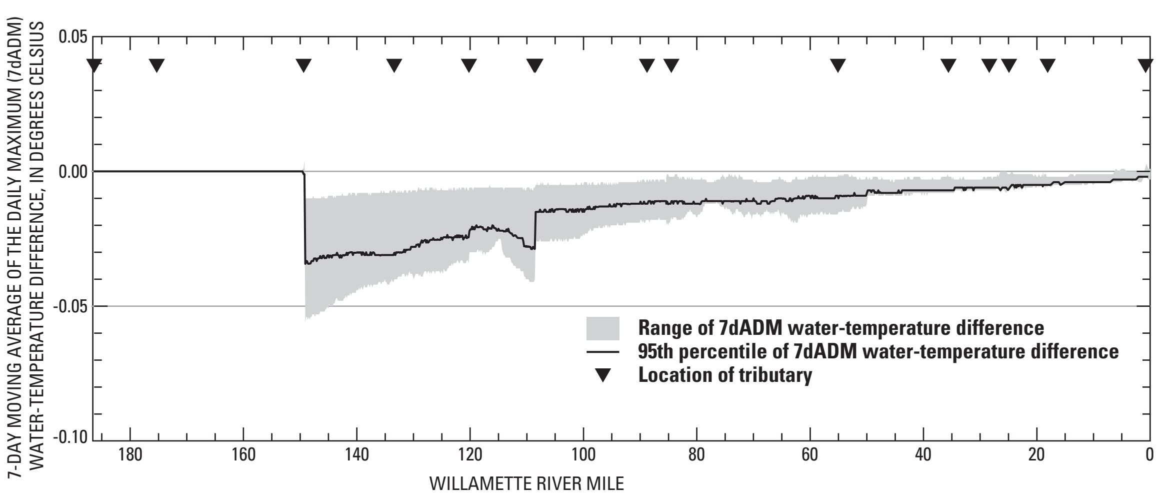


Figure 8. Thermal effects of restoring riparian vegetation along the Long Tom River, as manifested by a water-temperature change in the Willamette River. Vegetation restoration represents the change from current to system potential conditions along the Long Tom River downstream of Fern Ridge Dam.

Upper Willamette River Shading

The thermal effect of restoring riparian vegetation along the upper Willamette River upstream of Albany was explored through a series of model runs. As in the Long Tom River model runs, these scenarios simply modified the model's shade input file for a baseline model run—in this case, the fully allocated point-source model run with system potential vegetation. In each run, the vegetation characteristics were changed from system potential back to current conditions for a selected 5-mile reach along the upper Willamette River. The results for each model run then were subtracted from those for the baseline model run, thus producing an estimate of the cooling effect resulting from the restoration of vegetation in that reach. Twelve model runs were performed, each with 5-mile reaches of restored vegetation between RM 116.87, near the upper Willamette River's POMI at Albany, and RM 176.80, just upstream of the McKenzie River confluence.

The use of a 5-mile restoration reach has interesting implications for the Willamette River system. A 5-mile restoration reach was selected because typical restoration projects may be relatively limited in their spatial extent, yet this amount of restoration was thought to be large enough to produce measurable results. Given the velocities in the Willamette River during summer, however, a parcel of water can travel past an entire 5-mile restoration reach in the span of a few hours. One-half day downstream of the restoration reach, therefore, the 7dADM water temperature is largely unaffected by the restoration project because the water traveled past the restored reach at night, when increased shading has little effect on water temperature. Similarly, the water at a point one full day downstream of the restoration project has a decreased 7dADM water temperature because some solar energy was prevented from entering the water when it passed by the project. These facts manifest themselves in a "nodal" pattern of cooling downstream of the restored reach, where the greatest cooling occurs at or just downstream of the project, followed by nodes of decreasing magnitude that are spaced roughly at daily travel-time distances downstream. Indeed, this pattern was predicted by the model results (fig. 9.). The predicted nodal patterns are not perfectly symmetrical and smooth because variations in flow cause the spacing between nodes to change over time, and only the model results that met certain criteria were used in the analysis of the 95th percentiles (see the "Methods" section of this report).

The cooling effects predicted in the upper Willamette River as a result of any one 5-mile restoration project appear to be significant, relative to the types of temperature changes specified by the point-source heat allocations in the Willamette River temperature TMDL. The maximum 7dADM water-temperature change ranged from -0.046 to -0.194°C (fig. 9, table 4). The magnitude of the effect depends on several factors, including river width as well as the amount of shade that must be added to restore the reach to system potential conditions. The modeled cooling effects, however, vary greatly with downstream distance. If the aim of riparian shade restoration is to cool the upper Willamette River's point-source POMI so that one or more point-source heat allocation might be increased, then the location of the restoration project becomes critical. The shading scenario that produced the maximum amount of cooling at any one location (scenario UW-H, -0.194°C, table 4) actually produced only a small amount of cooling at RM 116.87 (-0.023°C). Scenario UW-K, in which the restored reach was located quite close to the POMI, produced the greatest cooling there (-0.094°C) among this set of shading scenarios.

An alternate means of quantifying the cooling effect of riparian shade restoration is to integrate the predicted cooling effect over the entire length of the Willamette River. This is done by summing the products of reach length and 7dADM water-temperature change (95th percentile) for each segment in the upper, middle, and lower Willamette River models. The result is an overall measure of the modeled heating or cooling effect (in units of "degree-miles") regardless of any localized patterns or maxima. Such an integrated value may prove to be a useful metric for comparing model results. With this metric, it appears that restoring the riparian vegetation in the RM 146.92 to 136.80 reach (scenarios UW-G and UW-H, table 4), provides the greatest overall cooling to the Willamette River (more than 1°C-mile of cooling per mile of restoration), among the model runs tested, despite the fact that these model runs provide among the least cooling at the upper Willamette River's POMI near Albany.

As a comparison to point-source heating effects, the models were used to quantify the effects of restoring riparian vegetation along the upper Willamette River for the entire length of all 5-mile reaches that were modeled separately. This one model run, in which approximately 60 miles (RMs 176.80–116.87) of riparian vegetation was restored from current to system potential condition, was useful in providing context relative to the cumulative heating effects of the point sources. This model run, denoted as UW-AL in table 4, demonstrated that the nonpoint-source heating effects caused by less than system potential shading are substantial, with a maximum modeled 7dADM temperature change of -0.419°C. Clearly, then, the restoration of riparian shading along the upper Willamette River might provide opportunities for trading heat credits between point and nonpoint sources under the Willamette temperature TMDL.

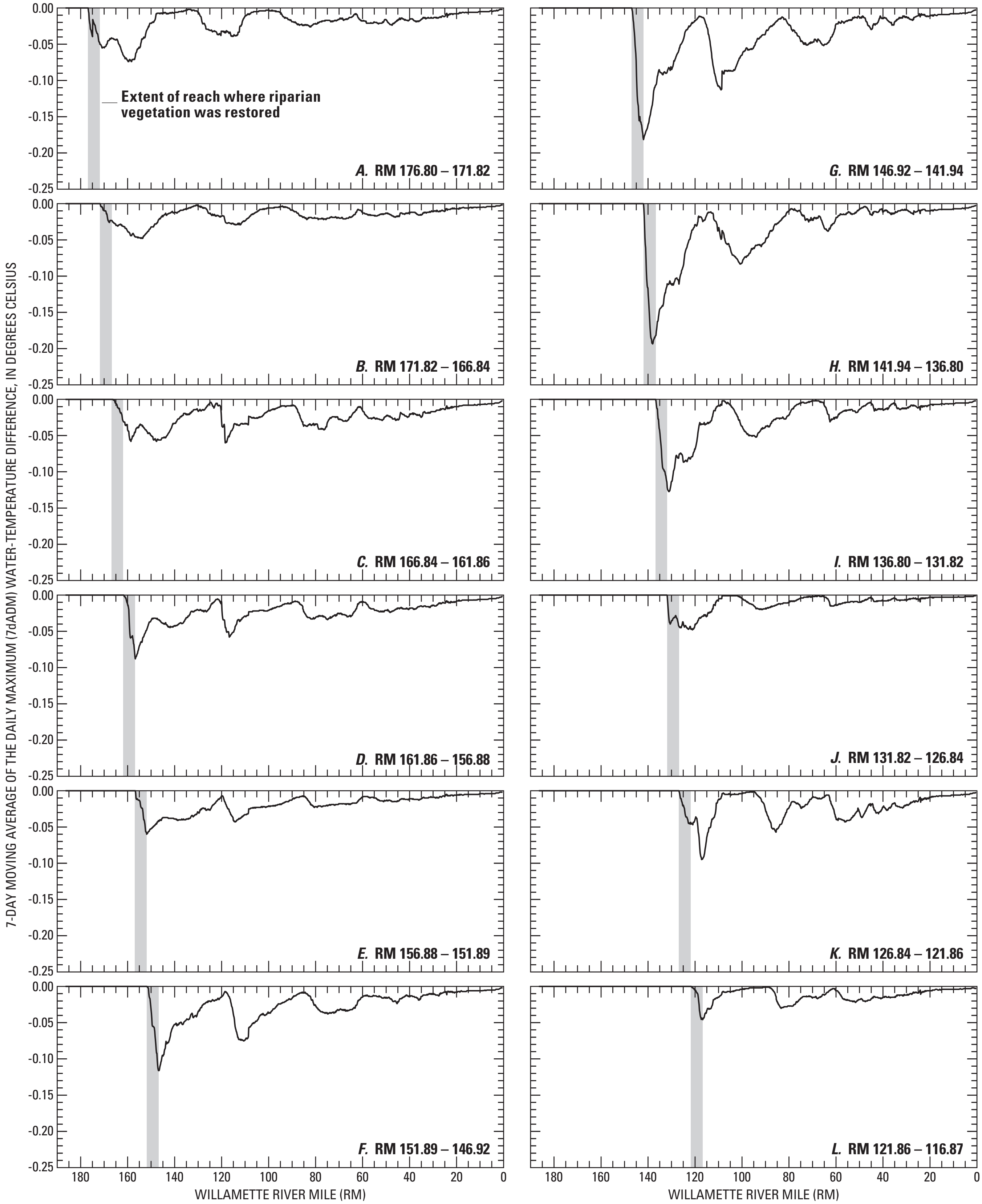


Figure 9. Modeled temperature changes associated with shade restoration along selected 5-mile reaches of the upper Willamette River, from river mile 116.87 near Albany to river mile 176.80 just upstream of the McKenzie River confluence.

Table 4. Cooling effects of several shading scenarios on the Willamette River, Oregon.

[Effects were measured relative to the 95th percentile of the 7dADM water temperature difference due to changes in shading. **Abbreviations**: 7dADM, 7-day moving average of the daily maximum; RM, river mile; ΔT, change in temperature; °C, degree Celsius]

Shading scenario	Shaded reach (RM)	Maximum ΔT in Willamette River (°C)	ΔT at RM 116.9 (°C)	Integrated change for Willamette River (°C-mile)
UW - A	176.80 – 171.82	-0.074	-0.035	-3.432
UW - B	171.82 – 166.84	-0.048	-0.026	-2.655
UW - C	166.84 – 161.86	-0.060	-0.052	-3.893
UW - D	161.86 – 156.88	-0.088	-0.054	-3.731
UW - E	156.88 – 151.89	-0.060	-0.026	-2.954
UW - F	151.89 – 146.92	-0.116	-0.014	-4.043
UW - G	146.92 – 141.94	-0.182	-0.013	-5.977
UW - H	141.94 – 136.80	-0.194	-0.023	-5.111
UW - I	136.80 – 131.82	-0.127	-0.035	-3.364
UW - J	131.82 – 126.84	-0.048	-0.029	-1.467
UW - K	126.84 – 121.86	-0.095	-0.094	-2.731
UW - L	121.86 – 116.87	-0.046	-0.045	-1.459
UW - AL	176.80 – 116.87	-0.419	-0.273	-29.557
Long Tom	all in Long Tom	-0.034	-0.021	-2.055

Temperature Effects of Dam Operations

In addition to assessing the effects of point-source heat discharges and riparian shading, the Willamette River flow and temperature models were used to assess the thermal effects of changed operations at Cougar Dam, which is one of the upper boundaries for the McKenzie River model. Situated on the South Fork McKenzie River and completed in 1963, Cougar Dam is the second highest dam (452 ft) and impounds the fifth largest reservoir (219,000 acre-ft) in the Willamette River basin (fig. 10).

Figure 10. Aerial view of Cougar Dam and Reservoir, looking south. Photograph taken by Bob Heims, U.S. Army Corps of Engineers, July 12, 1989.

Cougar Dam controls the flow and greatly influences the temperature in the South Fork McKenzie River downstream of the dam. Cougar Reservoir becomes thermally stratified in summer, with warmer, less-dense water near the surface and colder, more-dense water at the bottom (Resource Management Associates, 2003). Western Oregon's warm and sunny summer weather adds additional heat to the reservoir's surface, stabilizing its stratification throughout the summer. Because the dam was built with its major release point at a relatively low elevation, the dam historically released relatively cold water from near the bottom of the reservoir in mid-summer. As the reservoir was drawn down in autumn to make room for flood-control storage, the heat that was captured in the reservoir's upper layer during the summer was released downstream. As a result, the seasonal temperature pattern downstream of Cougar Dam through 2001 was quite different from the pattern upstream of Cougar Reservoir (fig. 11.).

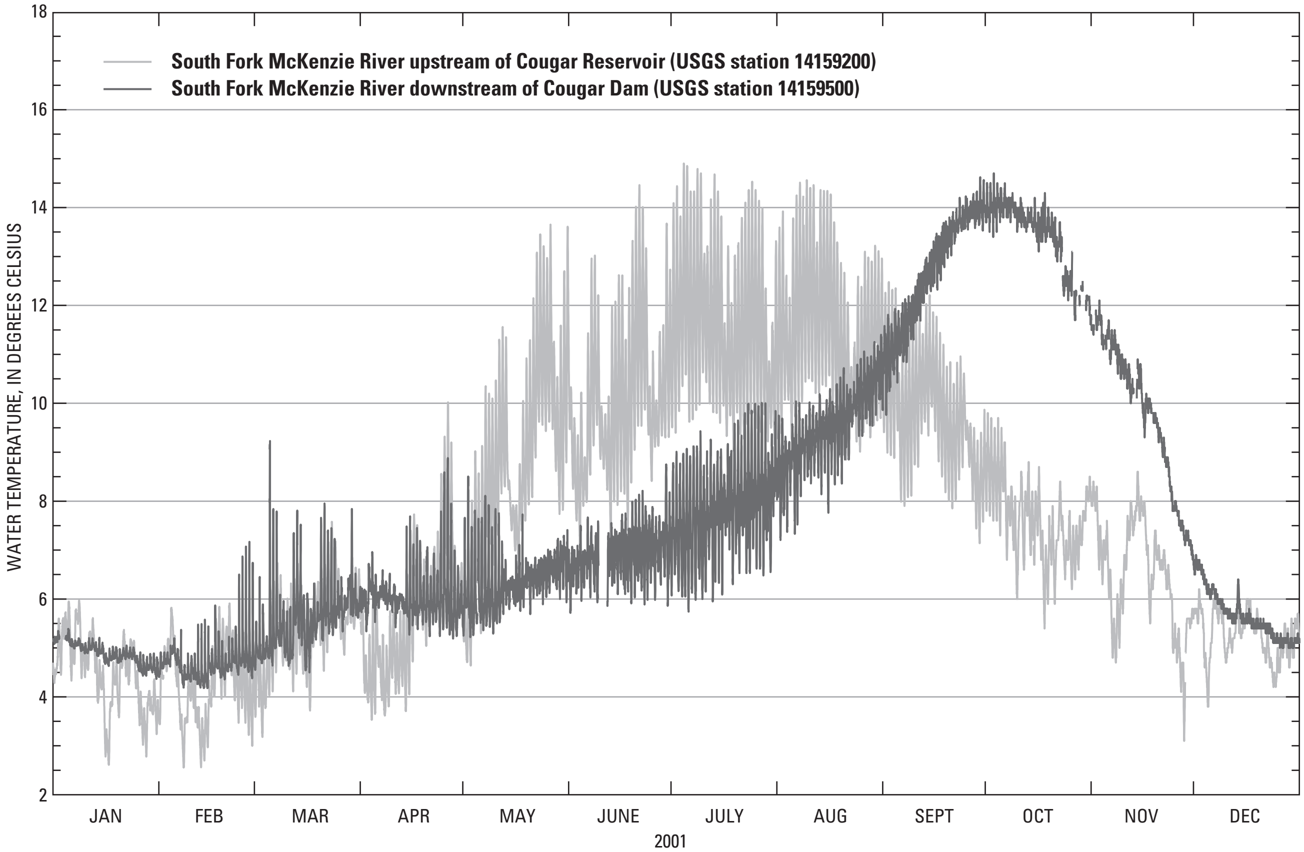


Figure 11. Seasonal water temperature patterns in the South Fork McKenzie River upstream and downstream of Cougar Reservoir, prior to the construction of a selective withdrawal tower at Cougar Dam, Oregon, 2001.

The McKenzie River supports the largest remaining wild population of Chinook salmon (*Oncorhynchus tshawytscha*) in the upper Willamette River basin (Good and others, 2005), and the South Fork McKenzie River provides good spawning habitat. The altered temperature pattern downstream of Cougar Dam, however, can create problems with regard to the timing of migration, spawning, and egg hatching (Caissie, 2006). To restore the suitability of this reach for salmonid spawning, the U.S. Army Corps of Engineers (USACE) added a sliding gate assembly to the intake structure at Cougar Dam. To allow for construction, the reservoir was drawn down from 2002 through 2004; construction was completed in early 2005. The new selective withdrawal tower allows dam operators to blend warm water from the top of the reservoir with cooler water at other levels, or to simply select a depth from which to withdraw water, in an attempt to match a downstream temperature target. The selective withdrawal tower was used successfully in 2005 and 2006 to restore a more-natural seasonal temperature pattern to the South Fork McKenzie River downstream of Cougar dam (fig. 12).

The time periods modeled as the basis for the Willamette temperature TMDL included one summer in which Cougar Dam operated without a selective withdrawal tower (2001), and one summer during which Cougar Reservoir was drawn down for construction (2002). Release temperatures in 2001 were typical of the pre-selective-withdrawal-tower period, with cool releases in mid-summer and warmer releases in autumn. In 2002, the greatly reduced storage and shallower depth in Cougar Reservoir resulted in a short residence time and less stratification that might affect release temperatures. As a result, 2002 release temperatures from Cougar Dam mirrored the seasonal temperature pattern upstream, with limited warming in the smaller reservoir. These measured temperatures were used as upstream boundary conditions for the South Fork portion of the McKenzie River model used for the Willamette temperature TMDL. Cougar Dam's current and future release temperatures, however, are unlikely to resemble those that occurred in 2001; therefore, it is instructive to explore how these seasonal changes in Cougar Dam release temperatures affect downstream temperatures in the McKenzie

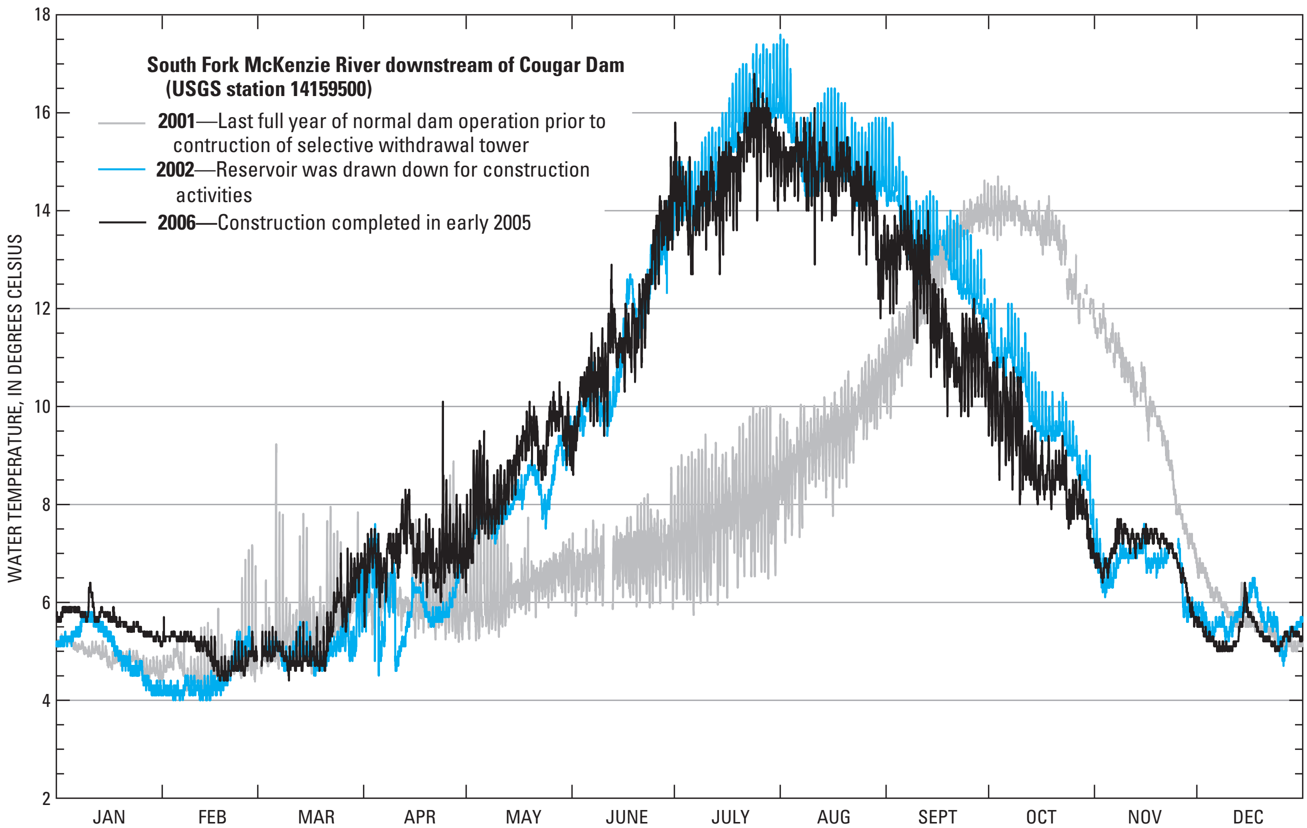


Figure 12. Seasonal water temperature patterns in the South Fork McKenzie River downstream of Cougar Dam in 2001, 2002, and 2006.

and Willamette Rivers, and whether such changes might affect future point-source heat allocations under the Willamette temperature TMDL.

To determine the effect of changed operations at Cougar Dam on downstream water temperatures, the Willamette flow and temperature models were used to answer one simple question: "What might the temperatures downstream of Cougar Dam have been during 2001 and 2002 if the released temperatures during those periods had been equal to those measured in 2006?" Release temperatures in 2005 and 2006, the first full years after completion of the selective withdrawal tower, were similar; the 2006 water temperatures were selected because the second year had fewer operational glitches and should be more representative of future seasonal patterns. Obviously, superimposing 2006 release temperatures upon flow conditions from 2001 and 2002 is imperfect. Release temperatures are tied somewhat to the flows, as a stratified reservoir has a limited supply of warm and cool water. In addition, the 2006 release temperatures are tied somewhat to the meteorological conditions that occurred during 2006. Still, running the 2001 and 2002 models with 2006 release temperatures is a good first step toward quantifying the thermal effects of changed operations at Cougar Dam. Further refinement of these results can be an objective for future research.

Imposing 2006 release temperatures on the 2001 modeled conditions has a greater effect than when imposed on the 2002 conditions, for two main reasons. First, differences between 2001 and 2006 water temperatures are greater than differences between 2002 and 2006 water temperatures (fig. 12). Second, the amount of water discharged from Cougar Reservoir was much less than normal during August–October 2002 because the reservoir was drawn down for construction. Late summer releases in 2002 were less than 250 ft^3/s, while releases during that time period in 2001 exceeded 700 ft^3/s. The greater flows in 2001 have a greater effect on downstream temperatures once those flows are mixed into the McKenzie and Willamette Rivers.

The Willamette River flow and temperature models first were used to determine the change in 7dADM water temperature downstream of Cougar Dam in the absence of point sources. All other conditions, except for the modified temperatures released from Cougar Dam, were identical to those used in the Willamette TMDL. Results from those model runs showed that Cougar Dam's selective withdrawal tower has the greatest effect on water temperatures in the South Fork McKenzie River, with mid-summer 7dADM temperature increases as large as 6.0–6.5°C and decreases of 5.0°C or more in October, as compared to the original 2001 model results (fig. 13). As expected, the modeled temperature changes for the 2002 model runs were smaller than those for 2001. Downstream of the confluence of the South Fork McKenzie

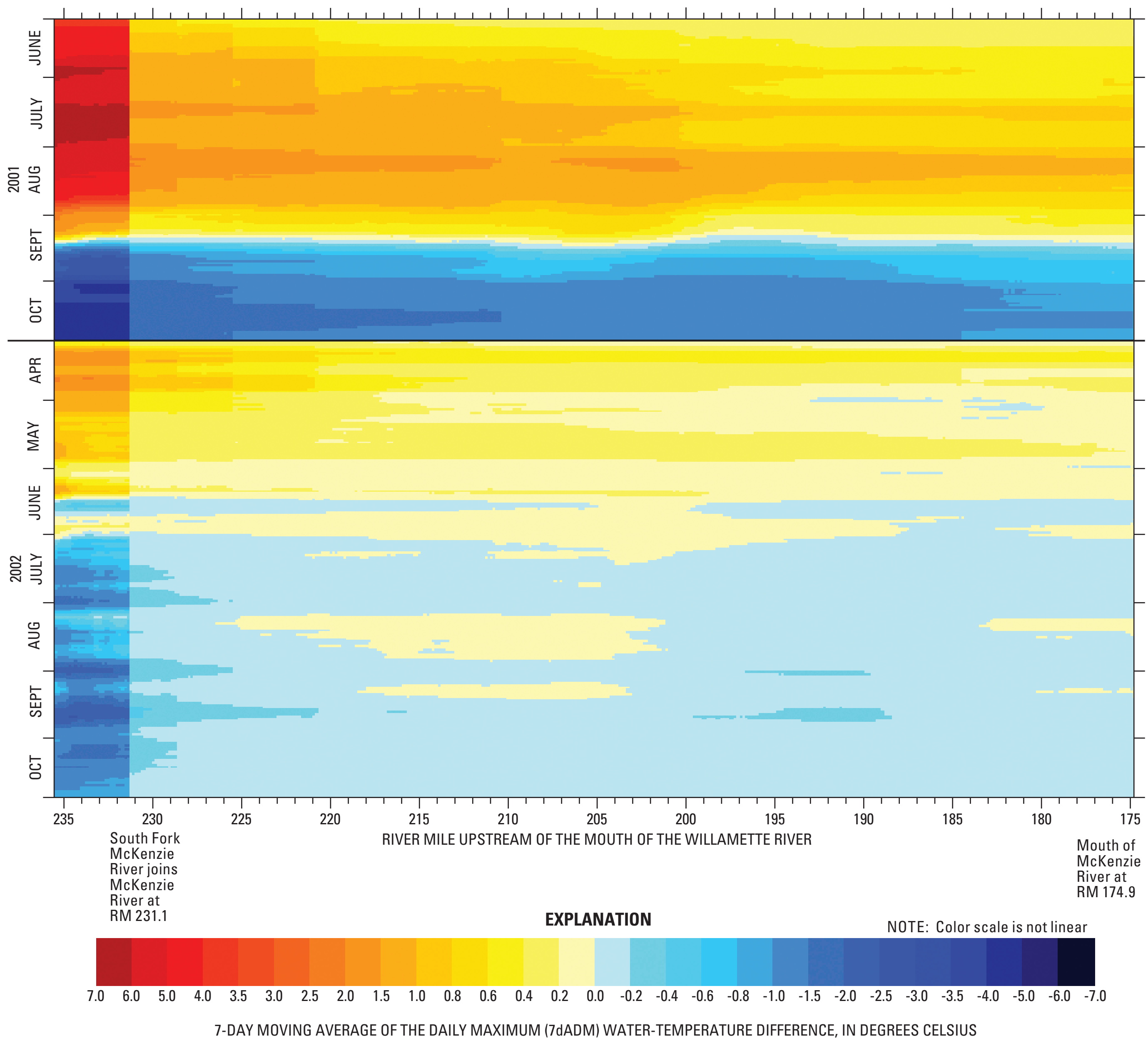


Figure 13. Modeled changes in the 7-day moving average of the daily maximum water-temperature difference in the South Fork McKenzie and McKenzie Rivers in response to the construction of a selective withdrawal tower at Cougar Dam, Oregon.

River with the McKenzie River, the thermal effects are somewhat diluted, though the 7dADM temperature changes in the McKenzie River were still large enough to be important, relative to the temperature modifications mandated by the TMDL. McKenzie River 7dADM temperatures were warmed in mid-summer as much as 1.5 or 2.0°C, depending on time of year and location, and cooling in autumn was sometimes more than 1.5°C. Because of additional dilution and time for heat exchange with the atmosphere, the magnitude of the temperature effect decreased downstream of the confluence of the McKenzie River with the Willamette River (fig. 14). In the Willamette River, 7dADM water-temperature changes as large as 0.4–0.5°C (warming in summer, cooling in autumn) were predicted upstream of the Santiam River confluence (RM 108.5). The effect diminished to no more than 0.3°C downstream of that point.

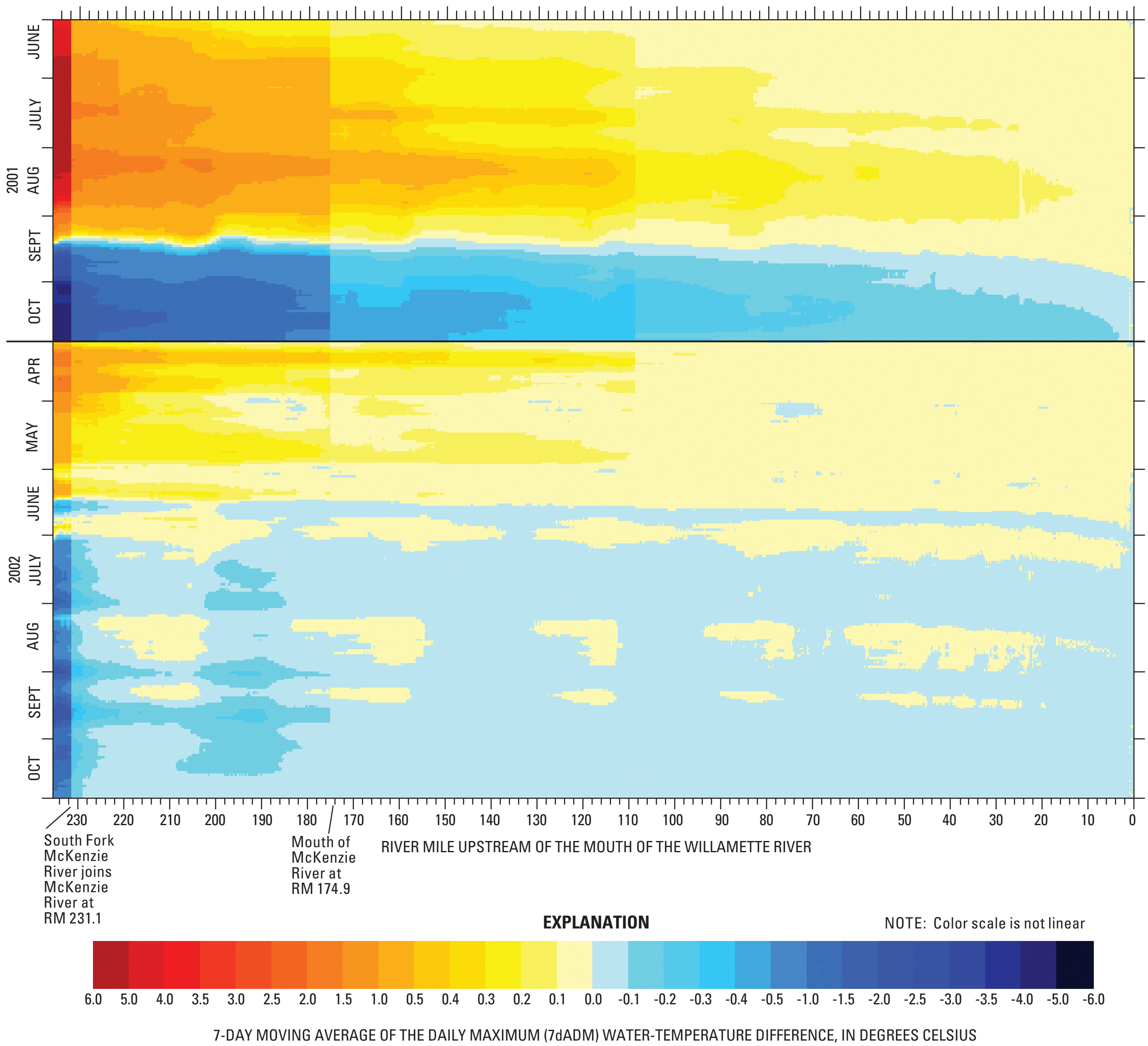


Figure 14. Modeled changes in the 7-day moving average of the daily maximum water-temperature difference in the South Fork McKenzie, McKenzie, and Willamette Rivers in response to the construction of a selective withdrawal tower at Cougar Dam, Oregon.

In addition to imposing 2006 release temperatures, the models were run both with and without the point sources to determine their cumulative heating effect under the modified baseline conditions. As in the TMDL analysis, the cumulative heating effect was determined by first calculating the 7-day mean of the modeled daily maximum temperature for each location in the models and for each day that was simulated. Then, the difference in the 7dADM temperature for each day and location was calculated by subtracting the without-point-sources results from the with-point-sources results. Finally, the 95th percentile of the 7dADM temperature-difference data at each location was calculated and plotted against downstream distance along the McKenzie and Willamette Rivers. These results for both the original TMDL point-source model runs ("TMDL base case") and for the model runs where the 2006 Cougar Dam release temperatures were imposed ("Cougar retrofit") are shown in figure 15.

Although the changed operations at Cougar Dam were shown to have a significant effect on downstream temperature in the McKenzie River system and potentially measurable effects in the Willamette River, incorporating the Cougar Dam retrofit into the cumulative point-source temperature assessment had little effect. The difference between the "base case" and "Cougar retrofit" point-source temperature effects was determined to be small, ranging from -0.006 to 0.008°C, with less than a 0.001°C decrease at the POMI near RM 117 (fig. 15). The effect is small because the Cougar Dam retrofit was incorporated into both the with- and without-point-sources model runs. The temperature of the river receiving the point-source flows was slightly different as a result of the Cougar Dam retrofit, but not so different that the cumulative point-source effects were greatly affected. Because the cumulative point-source heating effects were not greatly affected by the Cougar Dam retrofit, the point-source heat allocations of the Willamette temperature TMDL would not likely change appreciably if the Cougar Dam retrofit had been included in the TMDL analysis. Only for those point sources closest to Cougar Dam, and particularly for those located on the McKenzie River, might a more detailed analysis be warranted.

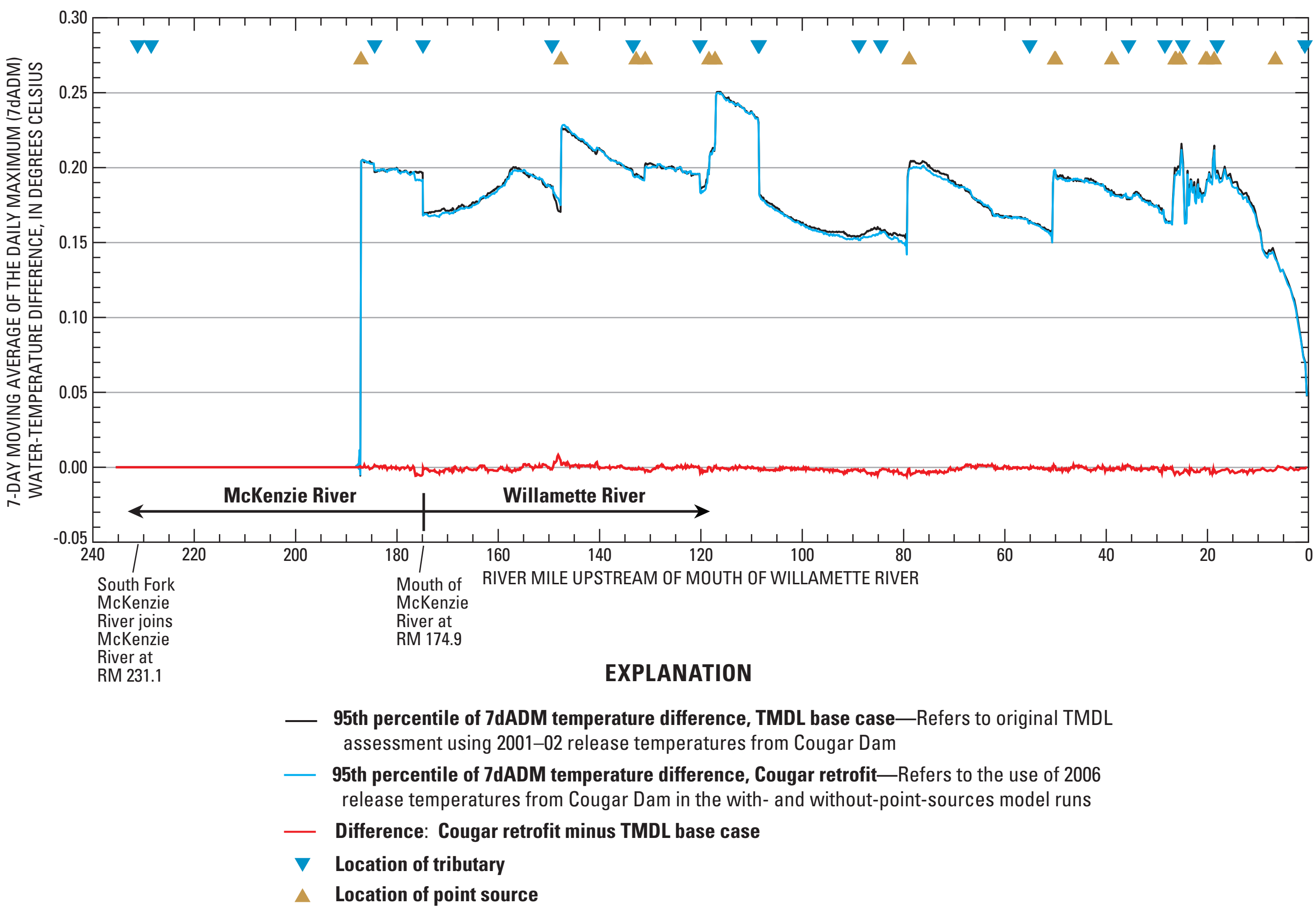


Figure 15. Effects of the Cougar Dam selective withdrawal tower on the cumulative heating effects of the modeled point sources.

Summary and Conclusions

The Willamette River flow and temperature models were used to explore and quantify the thermal effects of point-source discharges, riparian shading, and upstream dam operations on water temperature in the Willamette River and portions of its largest tributaries. The models, which form the basis of the Willamette temperature Total Maximum Daily Load (TMDL), were reviewed prior to their use, and several modifications were made to correct errors, remove instabilities, and make the models and their results more usable. Model results were evaluated using methods very similar to those used in the construction of the TMDL, in which the results of a model scenario were compared to model results from a baseline scenario and the 95th percentile of the 7-day moving average of the daily maximum (7dADM) water-temperature difference was calculated as a function of location along the modeled river reaches. In this way, the cumulative heating effects of one or more point sources or the thermal effect of restoring riparian shade along a particular river reach, for example, could be quantified relative to a Natural Thermal Potential baseline condition. Because the results of each model run were evaluated as a difference between that run and a baseline model run, any errors that occurred in both were largely eliminated via that subtraction. The predicted temperature *differences*, therefore, were expected to be far more precise than the modeled prediction of actual river conditions, meaning that predicted temperature differences as small as hundredths of a degree Celsius might be real and useful.

The flow and temperature models first were used to examine the cumulative heating effects of the 27 point sources included in the TMDL. The models were run for each point source separately to quantify the “heating signature” of each source. These signatures then were incorporated into a spreadsheet-based screening tool in which each signature could be linearly increased or decreased using a multiplicative “strength factor.” The sum of the strength-weighted point-source heating signatures was used as an estimate of the cumulative point-source heating effect, such that when the strength factor for each point source was set to 1.0, the sum equaled the results from one model run that included all point sources at their full TMDL heat allocation. This screening tool allows users to quickly evaluate the effects of potential changes to point-source heat allocations, including the trading of such allocations among the point sources. Graphs and various metrics are calculated to facilitate the evaluation of potential heat-load trades. Once a potential trade is identified through the use of the screening tool, the modified point-source conditions can be evaluated with the full suite of flow and temperature models. Four test trades were evaluated, and the screening tool was shown to accurately predict the resulting cumulative point-source heating effects when compared to the exact same conditions simulated with the Willamette flow and temperature models, with mean absolute errors on the order of 0.002 degrees Celsius (°C) and maximum prediction errors of roughly plus-or-minus 0.005°C.

The cooling effects of riparian shading were quantified with the Willamette River flow and temperature models. Model results showed that restoring all riparian shading along the Long Tom River could cool the Willamette River at its point of inflow by approximately 0.03°C, which is small but potentially useful for heat-load trades with some of the point sources upstream of Albany. Shade restoration along selected 5-mile reaches of the Willamette River upstream of Albany showed cooling effects as large as 0.19°C at certain locations. A 5-mile reach can be traversed in a few hours, however, which caused the cooling effects to exhibit a nodal pattern with downstream distance. The cooling effect was minimal at one-half day of travel time downstream of the restored reach because the water passed by that reach during the night when shading does not particularly affect the heat budget of the river. This pattern in downstream cooling effects has potentially important ramifications for heat-load trading and the siting of riparian restoration projects.

Finally, the downstream temperature effects of changed operations at Cougar Dam on the South Fork McKenzie River were evaluated using the TMDL models. Since 2005, temperature releases from Cougar Dam have been controlled through the use of a selective withdrawal tower; this change occurred after the 2001-2002 time period modeled for the temperature TMDL. The downstream thermal effects were estimated by substituting 2006 measured temperatures downstream of Cougar Dam for the measured 2001 and 2002 temperatures used in the TMDL models. The model results showed that the modified operations at Cougar Dam have an important effect on downstream temperatures, with warming in mid-summer and cooling in autumn. Predicted 7dADM temperature shifts in the South Fork McKenzie River were greatest, with changes as large as 6.0°C. Downstream, the models showed 7dADM temperature changes in the McKenzie River of close to 2.0°C at times. In the Willamette River upstream of the Santiam River confluence, predicted 7dADM temperature changes were as large as 0.5°C, while downstream of the Santiam River the changes were less than 0.3°C. Although large temperature shifts were apparent as a result of the change in operations at Cougar Dam, if those changes also were incorporated into the Natural Thermal Potential baseline conditions, the modeled cumulative point-source heating effect was not significantly altered.

This investigation has helped to quantify the heating effects of several important influences on water temperature in the Willamette River and several of its major tributaries. Only through a detailed understanding of the river's heat budget and the factors that influence it can scientists, resource managers, and regulators construct defensible plans for optimizing the river's thermal regime to protect its beneficial uses and aquatic resources. The results of this investigation, and the tools produced by it, should prove useful as these managers and regulators move forward to implement the Willamette temperature TMDL.

Acknowledgments

This investigation was the result of a collaboration between the USGS and the Oregon Association of Clean Water Agencies (ACWA) with additional assistance from the Willamette Partnership. Janet Gillaspie, Executive Director of ACWA, aided this investigation through her leadership and coordination. A group termed the Scenario Development Team (SDT) provided useful discussions, insight, information, and guidance. The SDT was composed of USGS staff and ACWA members as well as representatives from the Oregon Department of Environmental Quality (ODEQ), the U.S. Army Corps of Engineers (USACE), and the Willamette Partnership. Thanks to ACWA members Mark Yeager (city of Albany), Steve Downs (city of Salem), Tom Mendes (Metropolitan Wastewater Management Commission of Eugene/Springfield), Larry Lamperti and Dan Hanthorn (city of Corvallis), Andrew Swanson (Clackamas Water Environment Services), Brett Arvidson (Oak Lodge Sanitary District), and Garry Ott (city of Portland). Thanks also to Jim Britton (USACE), Jim Bloom and Neil Mullane (ODEQ), and David Primozich and Charlie Logue (Willamette Partnership).

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Supplemental Material

A website has been created to provide additional information and supplemental material associated with this investigation. Visitors to http://or.water.usgs.gov/proj/will_temp/ will be able to:

- Download this report;
- Download the Willamette River flow and temperature models used in this investigation, complete with the data files to run them;
- Download the Willamette River Point-Source Heat-Trading Tool;
- View selected sets of results;
- Download or view selected animations of model output; and
- Follow links to related information and data.

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Appendix A. CE-QUAL-W2 Code Changes

USGS personnel obtained the Willamette River temperature TMDL models and model source code from ODEQ staff. ODEQ used CE-QUAL-W2 version 3.12 from August 19, 2003, for each of the submodels, with one modification by the PSU model development team. That “Tmax” modification enabled the model to internally calculate and output the daily maximum water temperature for every segment in the model in three different ways: (a) surface-water temperature only, (b) volume-weighted water temperature for the entire cross section, and (c) flow-weighted water temperature for the entire cross section. ODEQ used this “Tmax” version for almost all of its Willamette TMDL modeling. The Tmax version was not used on the North Santiam and Santiam Rivers; the version used there did not have the Tmax code additions, but the model computations were otherwise identical.

When USGS staff needed to run the Willamette River models, several code changes were necessary to make the models easier to use or to eliminate problems. Great restraint was exercised in keeping code changes to a minimum, so as to ensure that the model calibration would remain unchanged. All code changes were checked extensively and are described and justified in this appendix. In the end, USGS used its “generic Tmax3” version for all Willamette River temperature models except the lower Willamette River, where the “generic Tmax3a” version was applied. The details behind these versions, and the reasons for their use, are described below.

Removal of Visual Interface

The models as provided by ODEQ to USGS contained a “visual interface” such that when they were run under Microsoft© Windows, a new window opened to display selected model inputs and results during the model run. When the model run was completed, however, the display window did not close itself and did not return control to the operating system. Therefore, the model version that contains this visual interface was not amenable to unattended operation in which batch files are used to run the submodels in sequence, passing the output of one model as input to the next model downstream without active human intervention.

To enable unattended linkages between submodels, USGS staff removed the visual interface from the source code obtained from ODEQ. The code modifications were designed to create a “generic” version of CE-QUAL-W2. When CE-QUAL-W2 is distributed to the public by the PSU model development team, two versions typically are provided: the “cvf” version with the visual interface, and a generic version without the visual interface. This generic version of the model code created by USGS was different from the version with the visual interface in exactly the same way that the PSU cvf and generic versions differ.

This code change has no effect on the model’s computations and therefore has absolutely no effect on the model results. This was checked by running the cvf and generic versions of the Willamette models and comparing their output. No significant differences were observed. The minor differences that did exist were easily attributable to the use of slightly different compilation options.

Artificial Raising and Lowering of the River Bottom

The version of CE-QUAL-W2 used in the Willamette River temperature models includes a clever bit of coding by the PSU model development team that helps sloping river models to continue running under a wide range of flow conditions. In each of the model’s “water bodies,” the model keeps track of a “surface-layer index.” The water surface, though, can actually reside in a model layer that is above the surface-layer index. To enable the model to continue running when a model segment still has flow, but its bottom is above the surface layer index, the PSU team added some code that tells the model that the river bottom is lower in that segment than originally specified. This “trick” works fairly well, but was only partially implemented by the PSU model development team at the time the Willamette temperature models were being developed.

In running one of the Willamette River models under slightly different conditions, USGS staff observed that the model could crash because this “trick” was not sufficiently robust. The trick allows the surface layer index to drop below the bottom-most active layer in a model segment, assigning a small nonzero width to the next lower layer to keep the water flowing in a sloping reach. This originally was not allowed to occur if the segment had the largest Z value in the water body – if the water surface in that segment was the lowest in the water body, relative to the layer boundaries and irrespective of slope.

The code was changed so that all segments in a water body could have their bottoms “lowered,” as long as they are not lowered past the bottom-most active layer in that water body. Without this fix, the original trick is insufficient to keep the river from “drying up” under certain conditions, and the model could crash unnecessarily. This modification was tested originally by the USGS on another river system (the Tualatin River), and it was determined to work as intended. The code changes were shared with the PSU model development team at that time and have since been incorporated into the latest public release version of CE-QUAL-W2. So, in the interest of keeping the model from crashing unnecessarily, this change was made to the code. In the model code, these modifications are denoted with the comments “!SR 08/01/05” and “!SR 08/08/05,” which are the dates of modification for when these fixes were made to USGS versions of the code. This change does not affect the computations of the model. It simply keeps it from crashing.

Minor Bug Fixes

As stated previously, great care was taken to minimize the number of code changes that were made to the Willamette models, in order to preserve the model calibration and ensure that the models were essentially the same as those used to develop the TMDL. In a few instances, though, it made sense to correct a couple of small coding errors.

First, in the LATERAL_WITHDRAWAL subroutine, several fixes were applied. The statement:

```
IF (KBOT > KB(ID)) KBOT = KB(ID)
```

incorrectly referenced the most-downstream segment in the branch (ID), when it should have referenced the segment where the withdrawal is located (I). The line was changed to

```
IF (KBOT > KB(I)) KBOT = KB(I)
```

The original statement could result in the improper allocation of a withdrawal flow rate as a function of model layer. This error was fixed by the PSU model development team in later versions, but was never changed in the Willamette models. Next, the following code was added:

```
IF (QWD(JWD) == 0.0) THEN
 KTW(JWD) = KTOP
 KBW(JWD) = KBOT
 RETURN
END IF
```

This helps to avoid problems with the calculation of KTOP and KBOT, and streamlines the code slightly. This might have been the source of problems in which the original code would hang if the withdrawal flow rate was zero. In any case, the change explicitly enables the model to handle withdrawal flow rates of zero.

Elsewhere in the LATERAL_WITHDRAWAL subroutine, the distribution of the withdrawal flow rate among the relevant model layers utilized values of BHR() and BHRKT2() in the original code. These were carry-overs from the DOWNSTREAM_WITHDRAWAL routine and were not appropriate for a lateral withdrawal. These variables were changed to BH() and BHKT2(). These fixes were cleared with the PSU development team in 2004. In addition, two further slight code modifications were added to help avoid potential divide-by-zero errors in this routine. Those fixes are labeled with the comment “!SR 09/16/04,” which was the date when these errors were originally fixed in other versions of the code.

In the DOWNSTREAM_WITHDRAWAL subroutine, two snippets of code were added in an effort to avoid divide-by-zero errors, mirroring code that was added to the LATERAL_WITHDRAWAL routine. Look for comments with the label “!SR 09/16/04.”

Finally, a problem was fixed in the setting of the BHKT1(IU-1) variable when segments are being subtracted after a layer is subtracted. There was an extra set of parentheses in that computation that would cause the water depth in that cell to be computed incorrectly. Look for the comment “!SR 07/29/05.” This change is inconsequential, because segments are never subtracted in the Willamette temperature model applications. Still, this was an obvious coding error that has since been corrected by the PSU model development team.

All changes up to this point were incorporated into the USGS model version named “generic Tmax3,” or “Tmax3” for short. The effect of these changes was tested, and no significant changes to the model output resulted. Most of the coding changes were minor, would rarely be invoked, or were “defensive” in nature, guarding against divide-by-zero errors, for example, and therefore would not normally be expected to cause a change in the model results. Mainly, these bug fixes serve to keep the model running under extraordinary circumstances, and to keep its computations more correct. Many more bug fixes and upgrades could be applied to the Willamette temperature models (the public release version of CE-QUAL-W2 is at version 3.5 as of April of 2007, and the Willamette models were built on version 3.12), but a major upgrade to the model code would require a re-evaluation of the model calibration, which is beyond the scope and need of this investigation. The Tmax3 version was used by USGS to run all Willamette submodels except the lower Willamette River, as explained below.

Daily Water Temperature Maxima in the Lower Willamette River

In version Tmax3 and in the original CE-QUAL-W2 version obtained from ODEQ, the calculations that determine the daily maximum surface temperature, the daily maximum volume-weighted temperature, and the daily maximum flow-weighted temperature for every segment only calculated those quantities when the “time series” output was printed. So, if the user specified that the model should write time-series output 20 times per day (time series output frequency (TSRF) = 0.05), then the modeled temperatures would be queried only 20 times per day to find the daily maxima. At times, this may not be frequent enough. It particularly can be a problem when the model time steps are large, such that different model runs might not calculate daily maxima using information from the exact same times. If the user-specified maximum time step is, say, 360 seconds, as it was in the lower Willamette River model, then the typical time step might be several minutes, and different model runs (no point sources versus all point sources, for example) might end up using information from several minutes apart in determining the daily maxima, simply due to variations in the model’s variable time steps. As a result, two different model runs might show daily maximum temperature differences of several hundredths of a degree or more, when such differences are only an artifact of the number of times per day that the model checked to determine whether a daily maximum had occurred. This “timing artifact” is not real and can be minimized or eliminated in one of several ways.

Simply increasing the number of times per day that the model checks for a daily maximum helps to minimize this timing artifact. As a test, the lower Willamette River model was run with a time-series output frequency of 200 points per day (TSRF = 0.005) and the results were compared to those from a model run using a time-series output frequency of only 20 points per day. The magnitude of the artifact was decreased, but not eliminated. Similarly, tests were run using a user-specified maximum time step (DLTMAX) of 60 seconds rather than 360 seconds for the lower Willamette River model, and this also decreased the magnitude of the timing artifact. In fact, decreasing the maximum time step to 60 seconds was more effective than checking more frequently.

In an attempt to minimize this artifact to the greatest extent possible, two things were changed for the lower Willamette River model. First, the maximum time step was decreased from 360 seconds to 60 seconds. That did not entail a code change. Second, a change was made to the model code so that the model would determine the daily maximum water temperatures (surface, volume-weighted, flow-weighted) using information from each and every time step, rather than only a certain number of times per day. This change means that the daily maximum temperature calculation is no longer tied to the TSRF. This new version of the model was named “generic Tmax3a” and was used only for the lower Willamette River submodel, because that model had the longest time steps and was the most susceptible to this timing artifact.

Tests showed that the new Tmax3a code had smaller timing artifacts in the computed daily maximum water temperatures. Separate tests showed that the Tmax3a version did not produce results that were any different from the Tmax3 version for the upper Willamette model, where the typical time step is much smaller.

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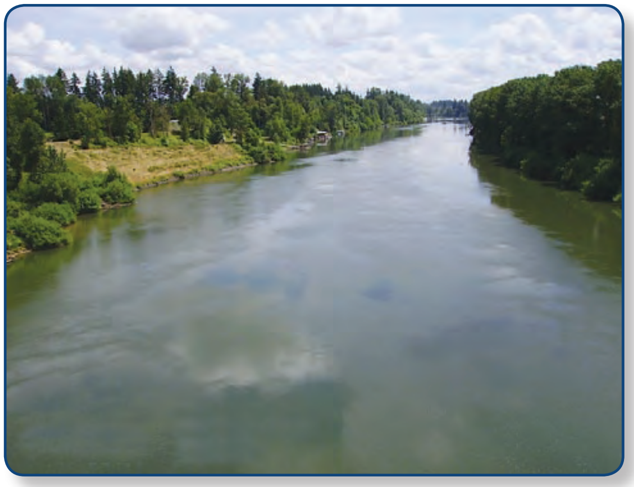

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