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Missouri River Recovery Program (MRRP)

Hydrologic Engineering Center-River Analysis System (HEC-RAS) Water Temperature Models Developed for the Missouri River Recovery Management Plan and Environmental Impact Statement

Zhonglong Zhang and Billy E. Johnson

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Hydrologic Engineering Center-River Analysis System (HEC-RAS) Water Temperature Models Developed for the Missouri River Recovery Management Plan and Environmental Impact Statement

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Final report

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Abstract

This report describes the Hydrologic Engineering Center-River Analysis System (HEC-RAS) water temperature models developed for five Missouri river reaches (e.g., Fort Peck Dam to Garrison Dam; Garrison Dam to Oahe; Fort Randall Dam to Gavins Point Dam; Gavins Point Dam to Rulo, NE; and Rulo, NE to the mouth of the Missouri River). These models were developed based on calibrated HEC-RAS flow models that the Omaha and Kansas City Districts of the U.S. Army Corps of Engineers (USACE) provided. Of five HEC-RAS water temperature models, three models were run for an 18-year period (1995–2012) for six alternatives in support of developing the Missouri River recovery program (MRRP) management plan (ManPlan) and environmental impact statement (EIS). The HEC-RAS water temperature model results for each river reach and each alternative are presented in this report. Likewise, the sources of model uncertainty are discussed in this report as well.

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Preface

This study was conducted as part of the Missouri River Recovery Program (MRRP), Project Number 396939, "MRRP Management Plan (ManPlan) and Environmental Impact Statement (EIS)." Mr. Jeff Tripe of USACE Kansas City District was the Program Manager.

This report was prepared by Dr. Zhonglong Zhang of LimnoTech, under contract to the U.S. Army Engineer Research and Development Center (ERDC) and Dr. Billy Johnson of the Water Quality and Contaminant Modeling Branch (WQCMB), Environmental Processes and Engineering Division (EPED), Environmental Laboratory (EL) of ERDC. At the time of publication, Mr. Mark Noel was acting chief, WQCMB; and Mr. Warren Lorentz was chief, EPED. The Deputy Director of ERDC-EL was Dr. Jack Davis and the Director was Dr. Beth Fleming.

Additionally, Mr. Mark Jensen and Mr. Todd Steissberg of the HEC, Mr. Zachary Jelenek of the Sacramento District, and Mr. Barry Bunch of WQCMB provided support for the HEC-RAS model improvement, model input data processing, and model execution. Mr. Mark Dortch of WQMCB and Ms. Laurel Hamilton of the Omaha District reviewed the report

COL Bryan S. Green was Commander of ERDC, and Dr. David W. Pittman was the Director

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit (°F)	(F-32)/1.8	degrees Celsius (°C)
day (d)	86400	second (s)
feet (ft)	0.3048	meters (m)
cubic feet (ft^3)	0.02831685	cubic meters (m^3)
liter (L)	0.001	cubic meters (m^3)
gram (g)	10^{-6}	micrograms (µg)
gram (g)	10^{-9}	nanograms (ng)
pounds (mass) (lb)	453.59	grams (g)
pounds (mass) (lb)	0.45359237	Kilograms (kg)
pounds (mass) per cubic foot (lb/ft^3)	16.01846	kilograms per cubic meter (kg/m^3)
pounds (mass) per square foot (lb/ft^2)	4.882428	kilograms per square meter (kg/m^2)
gallons (U.S. liquid) (gal)	3.785412 E-03	cubic meters (m^3)
calories (Cal)	4.184	joule (J)

Acronyms and Abbreviations

1-D	One dimensional
2-D	Two dimensional
ATEM	air temperature
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BC	Boundary Condition
BiOp	Biological Opinion of the U.S. Fish and Wildlife Service
CLOU	cloud cover
DEWP	dew point
EA	Effects Analysis
EIS	Environmental Impact Statement
ERDC	U.S. Army Engineer Research and Development Center
ESH	Emergent Sandbar Habitat
ESA	Endangered Species Act
HEC-DSS	Hydrologic Engineering Center-Data Storage System
HEC-EFM	Hydrologic Engineering Center-Ecosystem Functions Model
HEC-RAS	Hydrologic Engineering Center-River Analysis Systems
HEC-ResSim	Hydrologic Engineering Center-Reservoir System Simulation
HSPF	Hydrological Simulation Program--Fortran
IRC	Interception Rearing Complex

MAF	million acre feet
ManPlan	Management Plan
MRRIC	Missouri River Recovery Implementation Committee
MRRP	Missouri River Recovery Program
NSM	Nutrient Simulation Module
NWS	National Weather Service
QUICKEST	Quadratic Upwind Interpolation for Convection Kinematics with Estimated Streaming Terms
RM	River Mile
RMSE	Root Mean Square Error
SOLR	short wave solar radiation
SWAT	Soil and Water Assessment Tool
SWH	Shallow Water Habitat
ULTIMATE	Universal Limiter for Transient Interpolation Modeling of Advective Transport Equation
USACE	U.S. Army Corps of Engineers
USAFETAC	U.S. Air Force Environmental Technical Applications Center
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WIND	wind speed

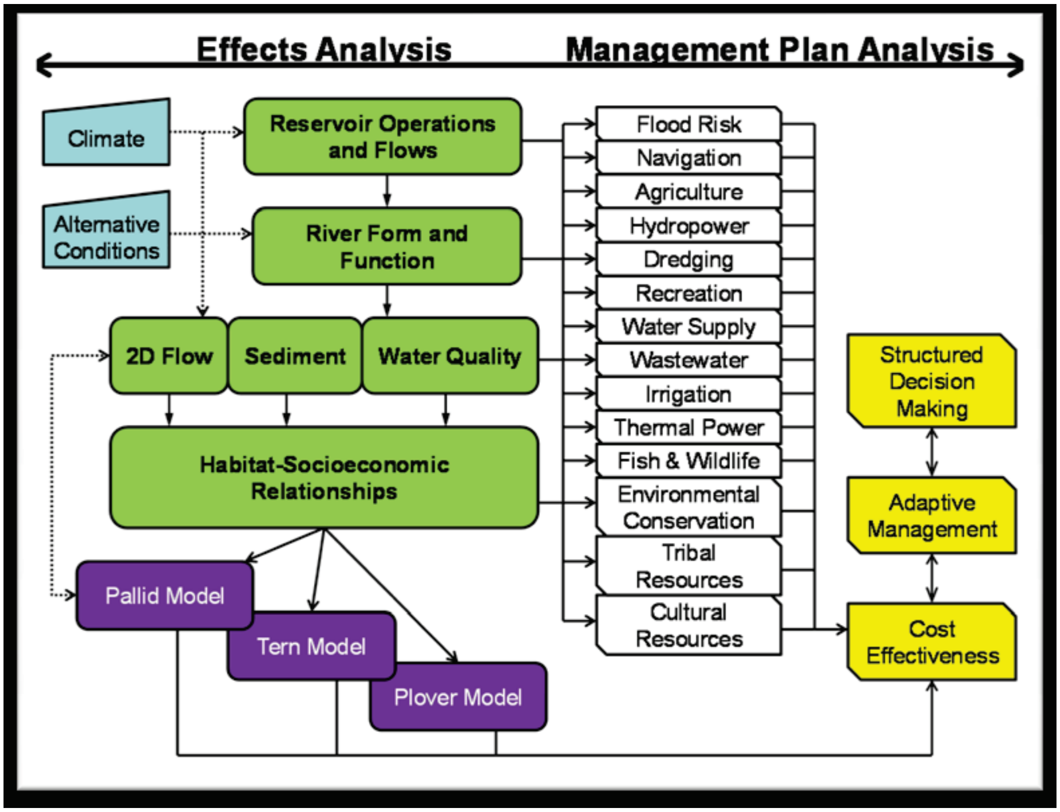
1 Introduction

1.1 Background

The Kansas City and Omaha Districts of the U.S. Army Corps of Engineers (USACE), in cooperation with the U.S. Fish and Wildlife Service (USFWS), have developed the MRRP ManPlan and EIS. As stated in "*Draft Missouri River Recovery Management Plan and Environmental Impact Statement*" (USACE 2016), USACE has a responsibility under the Endangered Species Act (ESA) to take actions to ensure that the operation of the Missouri River is not likely to jeopardize the continued existence of threatened and endangered species or adversely modify critical habitat. The purpose of the ManPlan and EIS is to develop a suite of actions that meets ESA responsibilities for the threatened and endangered species (e.g., Pallid Sturgeon, Least Tern and Piping Plover). The geographic scope of the ManPlan and EIS is limited to the Missouri River main stem from Fort Peck Reservoir to the confluence of the Mississippi River and the Yellowstone River from Intake Dam at Intake, Montana, to the confluence with the Missouri River (USACE 2016).

As Fischenich et al. (2014) outlined, ManPlan and EIS analyses are accomplished through a series of models recommended by technical working groups. These models will quantify the relationships among habitat conditions, habitat requirements, and species' demographics as well as evaluate the effectiveness of current habitat development and recommend any needed modifications to more effectively create habitat and avoid peril of threatened and endangered species. Specifically, predictions of future population size, growth, and distribution must be quantified as a function of past and future management actions, such as habitat alteration/manipulation through flow management and habitat creation as well as other drivers and stressors, which include climate and predation. Figure 1 presents the Missouri River modeling framework for the effects analysis (EA) and ManPlan analysis. The framework shown in Figure 1 includes components specific to the ManPlan in addition to those serving both the EA and the ManPlan. Outputs from the species models and the ManPlan models will feed into a structured decision process to consider impacts, benefits, and tradeoffs among the objectives.

Figure 1. Missouri River modeling framework for the effects analysis and the management plan analysis (Fischenich et al. 2014).



The above framework utilizes several HEC models. Main stem Missouri River reservoir operations are modeled using HEC-Reservoir System Simulation (ResSim); HEC-RAS models of riverine reaches are used to support flow, sediment transport and water quality analyses. HEC-ResSim model outputs are used as inputs to the HEC-RAS flow models. The HEC-Ecosystems Function Model (EFM) is used to integrate time series flow data from the HEC-RAS models with other relevant information to quantify habitat availability. Two-dimensional (2-D) hydrodynamic and sediment modeling of representative reaches will supplement the HEC models, providing critical insight into important processes that cannot be properly assessed using one dimensional (1-D) models alone.

As the water quality group identified (USACE 2014b), the 1-D longitudinal (i.e., along river flow axis) HEC-RAS along with the aquatic nutrient simulation module (NSM) was chosen as the preferred riverine water quality model for simulating current conditions and evaluating management strategies for the river reaches on the Missouri River. The HEC-RAS-NSM was chosen based on its capability and compatibility with existing Missouri River HEC-RAS flow models USACE developed (USACE

2015). HEC-RAS-NSM can model water temperature, nutrients, and eutrophication in 1-D riverine systems.

ERDC-EL was tasked to apply the latest HEC-RAS-NSM model to simulate the water temperature for the river reaches of the Missouri River, from Fort Peck, MT, to St. Louis, MO, in support of the ManPlan and the EIS. Water temperature is a primary indicator of the physical, chemical, and biological health of aquatic ecosystems. Modeled water temperatures along the Missouri River have been used for alternative analysis under the ManPlan and the EIS. USACE Omaha and Kansas City Districts developed five discrete HEC-RAS flow models for simulating river reaches of the Missouri River's main stem. These river reaches are Fort Peck Dam to Garrison Dam; Garrison Dam to Oahe Dam; Fort Randall Dam to Gavins Point Dam; Gavins Point Dam to Rulo, NE, and Rulo, NE, to the mouth of the Missouri River at St. Louis, MO. HEC-RAS models described in the report only simulate river reaches and do not simulate the reservoirs on the Missouri River. The HEC-RAS water temperature models were developed based on the calibrated flow models the USACE Omaha and Kansas City Districts provided. Likewise, the HEC-RAS water temperature models were used to simulate current conditions on the Missouri River, with the intention of running management scenarios to compare alternatives.

1.2 Objectives

Water temperature in streams and rivers is an important attribute of water quality and controls the health of freshwater ecosystems. Various human activities such as industrial production, deforestation and thermal pollution, will affect water temperature, and hence impact fish habitats and aquatic organisms. The overall goal of the project is to expand the existing HEC-RAS flow models for simulating current conditions of water temperature along the Missouri River, with the intention of running management scenarios to compare alternatives.

This study is a work in progress. Useful data will be pursued to revise the models as necessary to meet the study objectives. As additional information is identified, or otherwise becomes available, the HEC-RAS water temperature models discussed in this report will be updated and improved.

1.3 Approaches

The tool used in this study was the 1-D HEC-RAS model. HEC-RAS water temperature models were developed based on the calibrated HEC-RAS flow models that USACE Omaha and Kansas City Districts provided. These HEC-RAS flow models are described in a separate USACE report (USACE 2015). Meteorological data and inflow water temperatures are primary model inputs for running a HEC-RAS water temperature model. Hourly meteorological data were obtained from the U.S. Air Force Environmental Technical Applications Center (USAFETAC) in Asheville, NC and the U.S. Environmental Protection Agency (USEPA) website. Because of limited observed water temperature data, boundary conditions for all inflow water temperatures used in the HEC-RAS models were computed from multiple air – water temperature regression relationships. Regression methods were used to estimate missing data and compute long-term time series (18 years) boundary conditions along the Missouri River for the HEC-RAS water temperature models in support of conducting the ManPlan and EIS analysis.

2 Missouri River HEC-RAS Flow Models

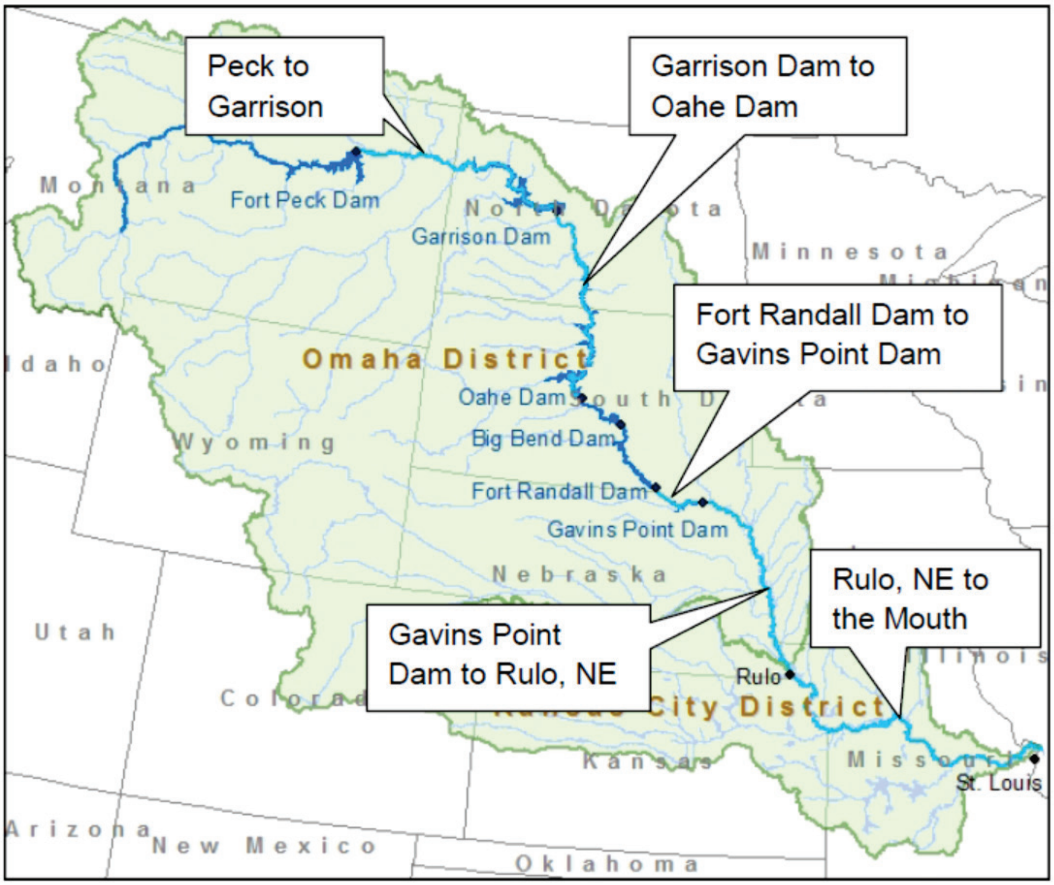
The Missouri River flows for 2,341 miles from Three Forks, MT through the states of Montana, North Dakota, South Dakota, Nebraska, Iowa, Kansas, and Missouri. It is the longest river in the United States and drains one sixth of the contiguous United States, an area of 529,350 square miles. USACE operates six dams and reservoirs with a capacity to store 72.4 million acre feet (MAF) of water, the largest reservoir system in North America. USACE operates the system to serve eight congressionally authorized project purposes of flood control, navigation, irrigation, hydropower, water supply, water quality, recreation, and fish and wildlife. Runoff from the upper Missouri River Basin is stored in reservoirs behind the main stem dams: Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point. Released water from the lowest dam in the system, Gavins Point Dam, flows down the lower Missouri River from Sioux City, IA to St. Louis, MO (Figure 2).

USACE Omaha and Kansas City Districts developed five separate HEC-RAS unsteady flow models for discrete reaches of the main stem of the Missouri River in support of ManPlan and EIS (USACE 2015). Figure 2 lays out the model extent and locations of the five individual HEC-RAS models. The geographic domains of the five HEC-RAS models are defined as follows.

- Fort Peck Dam to Garrison Dam river reach: begins with the regulated outflow from Fort Peck Dam in MT and extends approximately 382 miles downstream, to just upstream of Garrison Dam on Lake Sakakawea, ND.
- Garrison Dam to Oahe Dam river reach: begins with the regulated outflow from Garrison Dam in ND and extends approximately 318 miles downstream to just upstream of Oahe Dam on Lake Oahe, SD.
- Fort Randall Dam to Gavins Point Dam river reach: begins with the regulated outflow from Fort Randall Dam in SD and extends 69 miles downstream to just upstream of Gavins Point Dam on Lewis and Clark Lake.
- Gavins Point Dam to Rulo, NE of the Missouri River: begins with the regulated outflow from Gavins Point Dam in SD at river mile (RM) 811.1 and extends approximately 313 miles downstream to Rulo, NE, at RM 498.0.

- Rulo, NE to the mouth of the Missouri River: includes the lower 498-mile stretch contained within the boundary of the USACE Kansas City District as well as the Mississippi River between Grafton and St. Louis.

Figure 2. HEC-RAS modeled reaches on the Missouri River (USACE 2015).



The HEC-RAS model was only used for simulating the free-flowing river reaches, not reservoirs on the Missouri River. Six reservoirs were modeled using HEC-ResSim and CE-QUAL-W2 models. A separate ManPlan and EIS report describes the five Missouri River HEC-RAS flow models (USACE 2015). In addition to the modeling the Missouri River, major tributaries were included as separate routing reaches within the HEC-RAS model in order to more accurately route flows from the tributary gage to the main stem. Minor tributaries that have U.S. Geological Survey (USGS) gage data were included as lateral inflow to the model. Numerous ungaged inflows were also included in these HEC-RAS flow models. Ungaged inflow represents that portion of the flow that is not captured by the gage station records and then calculated between two gages on the main stem, which has a continuous record of both stage and flow. As described in the district report (USACE 2015), the HEC-RAS flow models were developed using the best available ground LIDAR and hydrographic survey data. These models were calibrated by using relatively recent high and low flow events (within bank), as well as recent mid-level flooding, and extreme events (e.g., 1993 and/ or 2011).

These HEC-RAS flow models were used to support riverine modeling needs associated with the ManPlan and EIS. The HEC-RAS modeling effort outputs support conceptual and quantitative ecological models that evaluate species responses to management actions, examine the effects to basin stakeholder interests, and assess authorized purposes in the ManPlan and EIS analysis. The HEC-RAS flow models were also used as flow drivers for corresponding reach water temperature models described in this report. Water temperature analysis for the study period has been undertaken to produce temperature information that serves as a baseline (no action condition) against which alternatives were assessed.

3 HEC-RAS Water Temperature Model Description and Input Requirements

The HEC-RAS water temperature model simulates hydraulics as well as in-stream heat and mass transfer processes related to stream temperature dynamics. This chapter briefly discusses the water temperature transport and source/sink formulation and its input requirements.

3.1 Water temperature model description

Heat storage capacity, along with a stream's response to thermal energy inputs and the influence of inflow water temperatures, is a function of stream velocity and water depth, which are determined by the spatial and temporal variations in the hydrologic regime. Additionally, surface and subsurface runoff entering or interacting with stream networks can be significant sources of thermal energy (Nelson and Palmer 2007; Herb and Stefan 2011). Variability in topography, channel morphology (width, depth, slope, and orientation), along with bankside vegetation characteristics affect the stream surface area available for solar heating and, in turn, control the instream energy and water balances.

The HEC-RAS water temperature model solves the 1-D advection-dispersion equation for thermal energy with additional terms to account for lateral inflow, solar radiation, and the heat exchange with the atmosphere and streambed. Lateral inflow represents additional water entering the model domain as surface inflow, overland flow, interflow, and groundwater discharge. The 1D heat transport equation is given as (HEC 2016):

$$\frac{\partial}{\partial t}(VT_w) = -\frac{\partial}{\partial x}(QT_w)\Delta x + \frac{\partial}{\partial x}\left(AD_x\frac{\partial T_w}{\partial x}\right)\Delta x + S_L + S \qquad 3.1$$

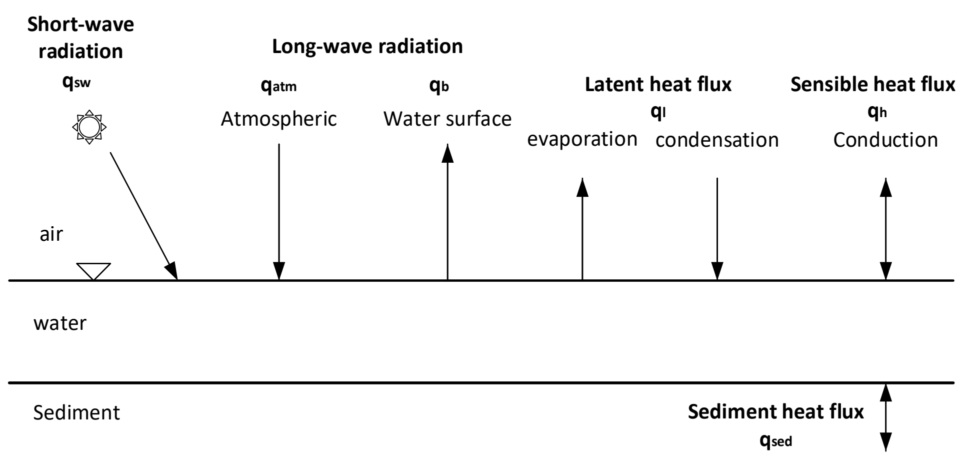
where

V = volume of the computational cell (m^3)
T_w = water temperature (^oC)
t = time (s)
Q = flow rate ($m^3\ s^{-1}$)
A = channel cross-sectional area (m^2)
x = distance along channel (m)

Δx = distance between cross sections (m)
Dx = dispersion coefficient (m^2 s^{-1})
S_L = source/sink term representing the time rate of inflow heat exchange (^oC m^3 s^{-1})
S = source/sink term representing the time rate of change of local external heat exchange (^oC m^3 s^{-1}).

The above thermal transport model tracks heat and water fluxes along the model domain. The magnitude and rate of change in water temperature will depend on meteorological conditions and hydraulics. The main sources of heat exchange at the water surface in the S term are short-wave solar radiation, long-wave atmospheric radiation, and conduction of heat from the atmosphere to the water. The main sinks of heat exchange are long-wave radiation emitted by the water, evaporation, and conduction from the water to the atmosphere. Heat exchange at the sediment-water interface is via conduction. The schematic of sources and sinks of heat at the air- and sediment-water interfaces is shown in Figure 3.

Figure 3. Sources and sinks of heat energy at the atmospheric and sediment interfaces (Deas and Lowney 2000).



Units of heat flux (W m^{-2}) are used to describe heat exchange at the air-water and sediment-water interfaces. The sign convention used herein is positive (+) for heat entering the water column, and negative (-) for heat leaving the water column. Net heat flux (q_{net}) for the water column is

$$q_{net} = q_{sw} + q_{atm} - q_b \pm q_h \pm q_l \pm q_{sed} \quad 3.2$$

where

q_{sw} = short-wave solar radiation flux (W m^{-2})
q_{atm} = atmospheric (downwelling) long-wave radiation flux (W m^{-2})
q_b = back (upwelling) long-wave radiation flux (W m^{-2})
q_h = sensible heat flux (W m^{-2})
q_l = latent heat flux (W m^{-2})
q_{sed} = sediment–water heat flux (W m^{-2}).

Each of the heat fluxes in equation 3.2 can be computed from user-specified meteorological data from the HEC-RAS user interface. Heat and temperature are related by the specific heat of water. The following equation describes the change in water temperature due to a change in net heat flux (q_{net})

$$\rho_w C_{pw} \frac{\partial T_w}{\partial t} = \frac{A_s}{V} q_{net} \quad 3.3$$

where
T_w = water temperature (°C)
ρ_w = density of water (kg m^{-3})
C_{pw} = specific heat capacity of water (J kg^{-1} °C^{-1})
A_s = surface area of the water column cell (m^2)
q_{net} = net heat flux at (W m^{-2}).

The density of water is dependent on the dissolved and suspended matter as well as the temperature of the water. The HEC-RAS water temperature model does not account for ice. Therefore, model results for winter conditions should be viewed with caution, and recognize that results do not reflect observed conditions.

The heat transport equation 3.1 is solved in two steps. In the first step, a source/sink term (S) is computed from the net heat flux. The source/sink value includes the effects of local heat change in a cell volume. In the second step, the effects of longitudinal transport in equation 3.1 are computed. For reasons of accuracy, efficiency, and stability, equation 3.1 is solved using the Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms–-Universal Limiter for Transient Interpolation Modeling of Advective Transport Equation (QUICKEST–ULTIMATE) explicit numerical scheme. The QUICKEST–ULTIMATE form of the 1-D water quality transport solved in HEC-RAS (HEC 2016) is:

$$V^{n+1}C^{n+1} = V^nC^n + \Delta t\left(Q_{up}C_{up}^* - Q_{dn}C_{dn}^* + D_{dn}A_{dn}\frac{\partial C^*}{\partial x}_{dn} - D_{up}A_{up}\frac{\partial C^*}{\partial x}_{up}\right) + \Delta t(S_L + S) \tag{3.4}$$

where

C^{n+1} = concentration of a constituent at present time step (g m^{-3})
C^n = concentration of a constituent at previous time step (g m^{-3})
C_{up}^* = QUICKEST concentration of a constituent at upstream cell face (g m^{-3})
$\frac{\partial C^*}{\partial x}_{up}$ = QUICKEST derivative of a constituent at upstream cell face (g m^{-4})
C_{dn}^* = QUICKEST concentration of a constituent at downstream cell face (g m^{-3})
$\frac{\partial C^*}{\partial x}_{dn}$ = QUICKEST derivative of a constituent at downstream cells face (g m^{-4})
D_{up} = upstream face dispersion coefficient (m^2 s^{-1})
V^{n+1} = volume of the computational cell at present time step (m^3)
V^n = volume of the computational cell at previous time step (m^3)
Q_{up} = upstream face flow (m^3 s^{-1})
A_{up} = upstream face cross sectional area (m^2)
Q_{dn} = downstream face flow rate (m^3 s^{-1})
A_{dn} = downstream face cross sectional area (m^2).

The above equation in HEC-RAS is used for solving all water quality constituents including water temperature (T_w). C will be substituted by T_w for water temperature. Leonard (1979, 1991) provides details of QUICKEST- ULTIMATE formulae for solving unsteady flows on a non-uniform grid. The water quality model's time step is dynamically recalculated and adjusted in HEC-RAS so that subsequent Courant and Peclet constraints are automatically met. This differs from the flow model where the user must specify the time step (HEC 2016).

$$C_{us} = u_{us}\frac{\Delta t}{\Delta x} £ \ 0.9 \tag{3.5a}$$

$$\alpha_{us} = D_{us}\frac{\Delta t}{\Delta x^2} £ \ 0.4 \tag{3.5b}$$

where

C_{us} = Courant number
u_{us} = velocity at water quality cell face (m s^{-1})
α_{us} = local Peclet number
D_{us} = dispersion coefficient at water quality cell face (m^2 s^{-1}).

The Courant and Peclet numbers are cross section face properties. Both constraints can force a short time step if water quality cells are small. Therefore, small water quality cells within the model domain should be avoided.

The numerical solution of equation 3.4 requires initial and boundary conditions for simulated water quality constituents. In this study, the initial condition is the water temperature profile along the modeled river domain at the beginning of the simulation. Water temperatures for all inflow entering the modeled domain must be provided to the model. The upstream boundary condition is the water temperature at the upstream end of the domain during the period of simulation.

3.2 Water temperature model input requirements

The water temperature simulation in HEC-RAS uses the schematization that is already set up for the flow model. The HEC-RAS model computes water temperatures from a calibrated flow model. This means that the user only has to specify a limited amount of input data including:

- time frame of the water quality simulation
- definition of the water quality computational cells
- initial temperatures
- meteorological data
- temperatures at the inflow boundaries
- information about the numerical method and the time step.

When the water quality model is set up for the first time in HEC-RAS, water quality computational cells are initially established between cross sections. Water quality computational points are located exactly between cross section pairs. However, a single small water quality cell will force the model to choose a small time step in order to satisfy the stability conditions. The HEC-RAS allows users to combine small water quality cells together into larger ones and redefine the water quality computational cells. Meteorological data and inflow boundary conditions are primary model inputs for running a water quality model. They are time and space dependent and discussed below.

3.2.1 Meteorological data

Meteorological data influence water quality processes in aquatic systems. At least one full meteorological data set must be provided to run the HEC-RAS water temperature model. Hourly meteorological data are typically required for modeling water temperature due to large fluctuations in air temperature and solar radiation. A time series of the following parameters at a local meteorological station is required:

- Atmospheric pressure (mb)
- Air temperature (^oC)
- Dew point [°C] or relative humidity (%)
- Short wave radiation (W m^{-2})
- Cloud cover [%]
- Wind speed (m s^{-1})

Meteorological data should be determined from the nearest recording meteorological station that is close to the river water surface elevation.

3.2.2 Water temperature boundaries

Complete sets of temperature data at the appropriate time intervals are required for all low flow or high flow conditions used for the model set up and calibration. Hourly, or at least daily, average inflow temperatures on major branch and tributary inflows are needed for all flow boundaries. Obtaining usable long-term stream water temperature records is not as easy as might be assumed. Water temperature records of many streams throughout the United States are available from the USGS web site. A major problem, however, is that stream temperature records frequently lack continuity over a whole year. The water temperature to be used as inflow boundary conditions for a long-term simulation is often not available and must be estimated. In this study, observed water temperature data for many boundaries is limited and of questionable quality. Historical water temperature data for several major tributaries in each model were not available, thus, they were substituted with observed data from other nearby monitoring stations. Observed water temperatures in many stations were monthly based, they were interpolated internally to the model computation time step to provide required data. This deficiency in observed data contributes to model error and uncertainty.

4 Missouri River HEC-RAS Water Temperature Models

This chapter describes the HEC-RAS water temperature model development and calibration for the five modeled reaches of the Missouri River. The Fort Peck Dam to Garrison Dam and Fort Randall Dam to Gavins Point Dam reaches were only set up and calibrated for approximately two years (2011 – 2012). The HEC-RAS water temperature model results were not used in the current ManPlan and EIS nalysis. The reaches for Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the mouth of the Missouri River were set up and ran for an 18-year simulation period (1995 – 2012). Model results from the latter three river reaches were used for conducting the ManPlan and EIS analysis.

4.1 Meteorological data

In this study, historical meteorological data were obtained from USAFETAC in Asheville, NC and the USEPA website. Hourly meteorological data were processed and compiled into one Hydrologic Engineering Center–Data Storage System (HEC-DSS) file (MoRmet.dss) for 14 meteorological stations along the main stem Missouri River. Figure 4 shows the spatial distribution of meteorological stations along the Missouri River used in the HEC-RAS temperature models. Table 1 lists the 14 meteorological stations and their locations and elevations. Each station includes the following five parameters: ATEM (air temperature), DEWP (dew point), SOLR (solar radiation/short wave radiation), CLOU (cloud cover), and WIND (wind speed). These parameters are included in the HEC-DSS file (MoRmet.dss), and their data records cover the period from 1975 – 2013 at hourly intervals. Atmospheric pressure data was not available from USAFETAC and was calculated based on the elevation of meteorological stations specified in the model.

Figure 4. Distribution of meteorological stations used in the Missouri River HEC-RAS models.

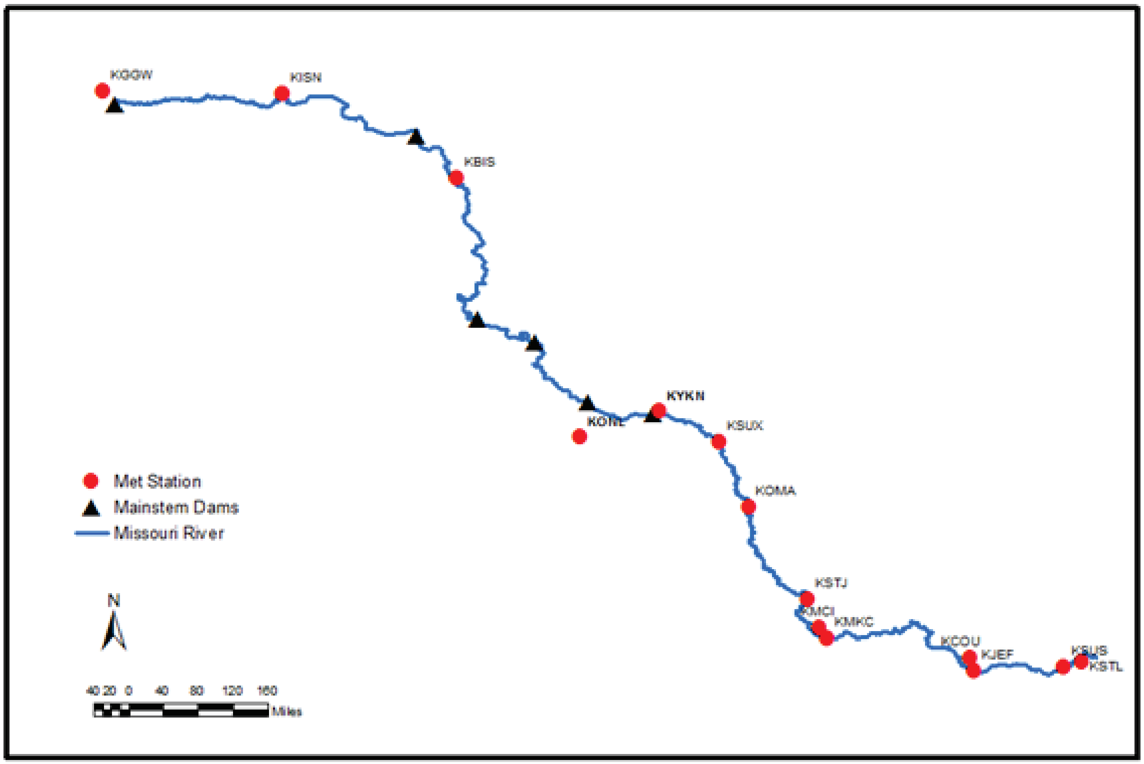


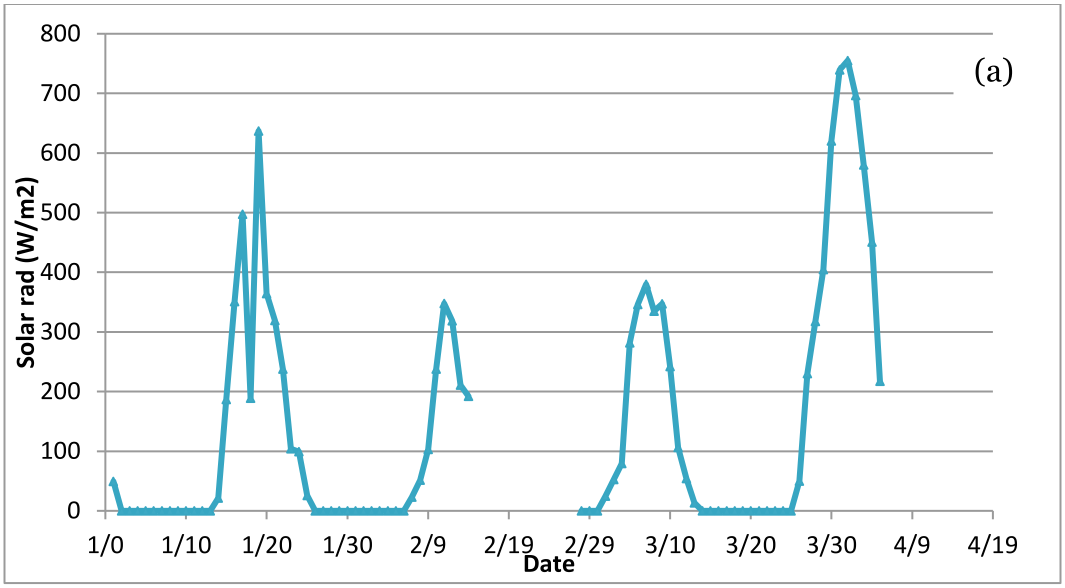
Table 1. Meteorological stations along the Missouri river and their locations and elevations.

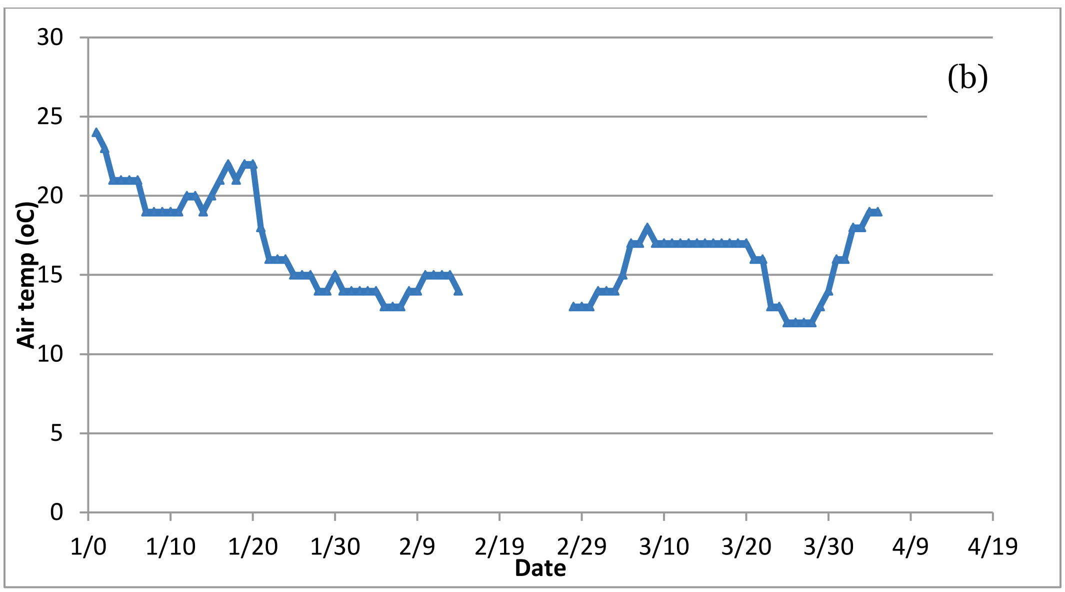
USAFETAC ID	BASINS ID	Station Location	Latitude	Longitude	Elevation (ft)
KGGW	MT243558	WOKAL FLD GLASGOW INTL, MT	48.2125	-106.61472	2296
KISN	ND329425	SLOULIN FLD INTL, ND	48.17793	-103.64234	1982
KBIS	ND320819	BISMARCK MUNI, ND	46.77273	-100.74573	1661
KONL	n/a	ONeillMuni John L Baker FLD, NE	42.46989	-98.6881	2031
KYKN	SD726525	Chan Gurney Muni, SD	42.91669	-97.3859	1306
KSUX	IA137708	Sioux City AP, IA	42.4026	-96.384367	1098
KOMA	NE256255	Omaha Eppley Airfield, NE	41.30317	-95.894069	984
KSTJ	MO237435	Kansas City Intl AP, MO	39.77194	-94.909706	826
KMCI	MO234358	St Louis Lambert Intl, MO	39.29761	-94.713905	1026
KMKC	MO234359[1]	St Joseph Rosecrans AP, MO	39.12325	-94.59275	759
KCOU	MO231791	Kansas City Charles Wheeler Downtown AP, MO	38.81809	-92.219631	889
KJEF	MO724458	St Louis Spirit of St Louis AP, MO	38.59118	-92.156144	549
KSUS	MO724345	Jefferson City MEM, MO	38.66212	-90.652044	463
KSTL	MO237455	Columbia Regional AP, MO	38.74717	-90.361389	605

[1] SOLR, CLOU, DEWP, WIND are missing from 1/1/2007 – 12/31/2009. They are substituted with corresponding data from MO234358 station.

The HEC-RAS temperature model requires meteorological data to be stored in HEC-DSS with a constant time interval (hourly in this case). There were often gaps in source data obtained from USAFETAC and the National Weather Service (NWS). Sometimes the data gaps were small, less than a day, and sometimes the data gaps were large, several days or months. For example, Figure 5 shows some of the gaps in hourly solar radiation and air temperature data at KOMA, NE.

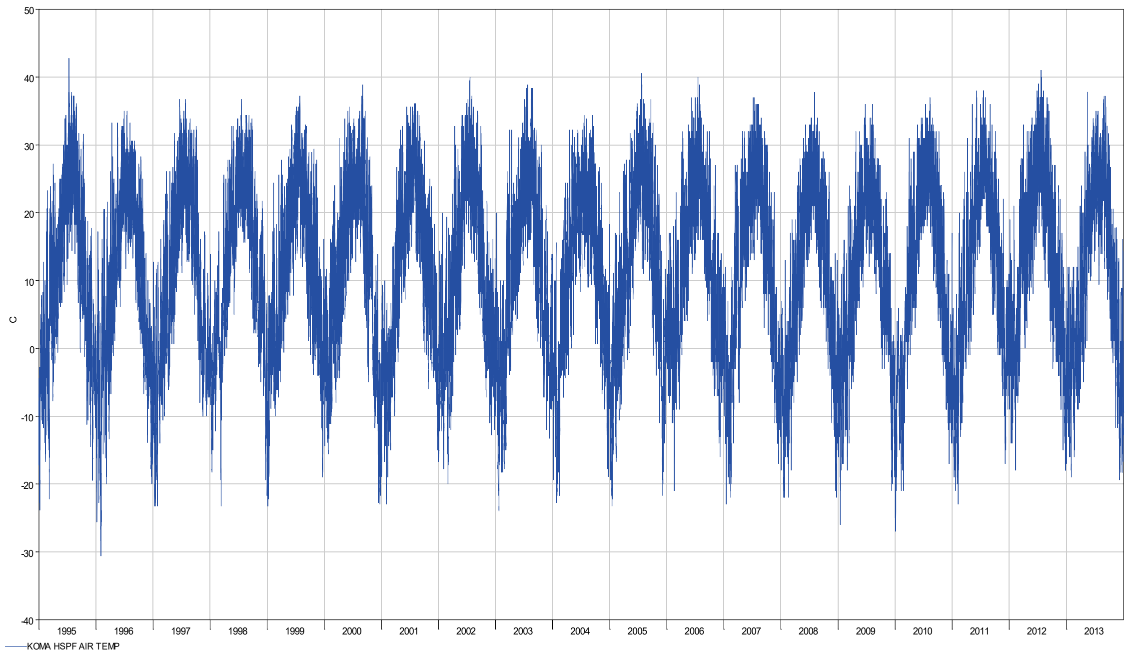
Figure 5. Data gaps of observed hourly (a) solar radiation and (b) air temperature at KOMA, NE.





All gaps in meteorological data obtained from the above stations were linearly interpolated in HEC-DSS in order to use them as model inputs. Thus, the data gaps were filled with a straight line between the two bounding values. All meteorological data (after filling gaps) were compiled into one single HEC-DSS file (MoRmet.dss). For example, Figure 6 shows the time series plot of hourly air temperature at the Columbia Regional AP, MO station.

Figure 6. Hourly air temperature at KOMA, NE.



4.2 Water temperature boundary conditions

As described in the district report (USACE 2015), major tributaries discharging into the Missouri River were simulated in each HEC-RAS model. Minor tributaries were included as lateral inflow to the model. Numerous ungaged inflows were also included in the HEC-RAS models. Flow discharging into the main stem Missouri River from point sources was taken into account as part of ungagged flow.

In this study, the primary source for observed water temperature data was the USGS website. USACE Omaha and Kansas City Districts also provided observed data collected for 2010 – 2014 (USACE 2014a). Overall, observed water temperature data for the Missouri River as well as major tributaries were limited for the simulation period from 1995 – 2012. After reviewing existing water quality data, water temperature measurements generally were taken only once a month during the summer season. Water temperature data at most of the water quality monitoring locations only covered a five-year period from 2009 – 2013. Some locations have a longer period of record for water temperature measurements. There were almost no observed data before 2009 for all inflow tributaries.

Due to limited observed data, water temperatures for all inflow boundaries were generated from other methods. A basin wide watershed model such as the Soil and Water Assessment Tool (SWAT) or the Hydrological Simulation Program-Fortran (HSPF) can be used to compute water temperatures for all inflow boundaries discharging into the Missouri River. However, a watershed model for the Missouri River basin did not exist. Development and calibration of a watershed model for the Missouri River basin was not feasible under this project due to limited resources (i.e., funding and time). Alternatively, the project team proposed an air - water temperature regression relationship for computing water temperatures for all inflow boundaries discharging into the Missouri River. Under the scope of this project, all boundary conditions of water temperature required in the HEC-RAS models in support of conducting current ManPlan and EIS were computed from the regression relationships and fed into the model.

Many factors influence stream temperature. Air temperature has often been used as an independent variable in regression analysis of stream temperature because it can be viewed as a surrogate for the net heat exchange (Webb et al. 2003). Previous researchers have successfully developed and applied linear and non-linear regression relationships between air and stream temperatures. Table 2 provides a summary of air-water temperature regression relationships that have been used in the past.

Table 2. Summary of air and water temperature regression models for rivers and streams

Regression type	Application region	Time scale	Reference
Linear	40 groundwater-fed streams in MN, USA	Weekly	Krider et al. (2013)
	Red deer river in Canada	Daily	Saffran and Anderson (1997)
	39 stream stations in MN, USA	Daily, weekly, monthly, yearly	Pilgrim et al. (1998)
	43 U.S. and international sites	Daily	Morrill et al. (2005)
	USGS stations, USA	Daily, weekly, monthly, yearly	Erickson and Stefan (2000)
	A small catchment in north-central Austria	Monthly, yearly	Webb and Nobilis (1997)
	11 streams Mississippi River basin, USA	Daily, weekly	
	Several rivers in UK	Monthly, yearly	Stefan and Preud'homme (1993)
	4 chalk streams in UK	Monthly	Smith (1981)
	A Devon river system in UK	Hourly, daily, weekly	Mackey and Berrie (1991)

Regression type	Application region	Time scale	Reference
	River Drava, Croatia	Daily	Webb et al. (2003)
	8 Alabama Rivers, USA	Hourly	Rabi et al. (2015) Chen G. and Fang X. (2015)
Non-linear	584 USGS stations, USA	Weekly	Mohseni et al. (1998)
	Large river basins all over the world	Daily	Van Vliet et al. (2012)
	43 U.S. and international sites	Hourly, daily, weekly	Morrill et al. (2005)
	A Devon river system in UK	Hourly	Webb et al. (2003)
	8 Alabama Rivers, USA		Chen G. and Fang X. (2015)

Water temperature results from the HEC-RAS models for the Fort Peck Dam to Garrison Dam and Fort Randall Dam to Gavins Point Dam reaches were not required in conducting ManPlan and EIS. Therefore, only water temperatures from tributary boundaries included in the three reaches for Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the mouth of the Missouri River were computed from daily air and water temperature regression relationships as explained in the next section.

4.2.1 Regression relationship between air and water temperatures

In this study, two air-temperature regression approaches were evaluated for use with the periodic water temperature measurements: (1) linear regression, and (2) nonlinear regression. The first step was to evaluate which regression method (linear or nonlinear) to use. These two regression approaches were evaluated using two data sets over a seven year period (2007 – 2013), where one includes fewer observed water temperature values, and the other includes more observed water temperature values. If there are multiple meteorological stations around a stream temperature monitoring station, the closest meteorological station was used in developing the regression relationships. The first data set includes water temperature in the main stem Missouri River at Kansas City, MO (USGS 0689300) and air temperature at station MO234359. The second data set includes water temperature from the Mississippi River at Grafton, IL (USGS 05587455) and air temperature at MO232591. This reach of the Mississippi River was simulated in the lower Missouri River HEC-RAS model. After choosing the better regression approach, the selected approach was applied to develop regressions for each inflow boundary using observed water temperature data from that boundary, if available, and the nearest meteorological station for observed air temperatures.

Stream temperatures fluctuate at time scales ranging from diurnal to seasonal. Previous research showed that weekly and monthly averages of stream temperature and air temperature are better correlated with each other than are daily values (Stefan and Preud'homme 1993; Pilgrim et al. 1998; Erickson and Stefan 2000). Therefore, a 3 – 12 day moving average (the same day plus the next 6, and past 6 days for the 12-day moving average) of air temperatures were used in developing regression relationships in this study.

4.2.1.1 Linear regression

As listed in Table 2, a simple linear regression was used to estimate water temperature as a function of one or more independent variables. When air temperature is specified as the only independent variable, the general linear regression equation is written as

$$T_w(\mathrm{t}) = a_0 + a_1 T_a(t) + \varepsilon(t) \quad (4.1)$$

where

T_a = measured 3 – 12 day moving average air temperature for the day t (^oC)

T_w = measure (or predicted) daily water temperature (^oC)

a_0 a_1 = regression coefficients

$\varepsilon(t)$ = error term.

All temperatures in the above equation are in degree Centigrade. The model calibration and validation to determine the two parameters a_o, a_1 was performed by minimizing the root mean square error (RMSE) between estimated regressions and observed water temperatures. RMSE is defined as

$$RMSE = \sqrt{\frac{1}{n}\sum_i (OV_i - MV_i)^2} \quad (4.2)$$

where

$RMSE$ = root mean square error

n = number of observations

OV_i = observed value
MV_i = model computed value.

To evaluate the goodness of fit and model performance of various regression relationships, the coefficient of determination (R^2) is used in addition to regression scatter plots of model predicted and observed data sets. R^2 is calculated with the following formula,

$$R^2 = \frac{\left(\sum_i (OV_i - \overline{OV})(MV_i - \overline{MV})\right)^2}{\sum_i (OV_i - \overline{OV})^2 \sum_i (MV_i - \overline{MV})^2} \tag{4.3}$$

where

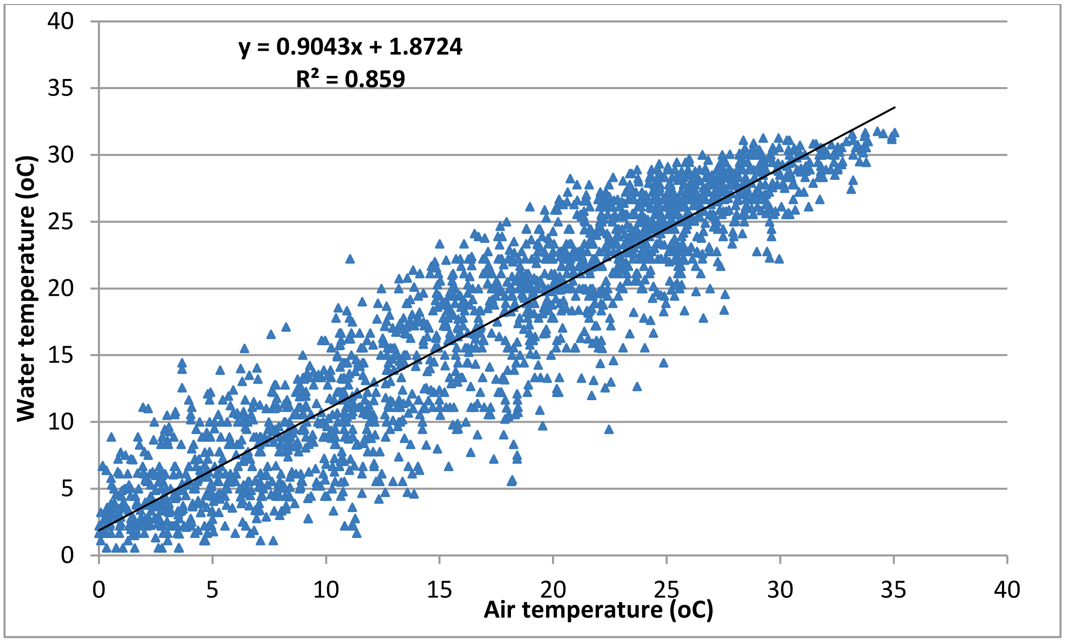
$\overline{OV}$ = mean of observed values
$\overline{MV}$ = mean of model computed values.

R^2 is an indicator of the strength of the linear relationship between the predicted and observed values. The R^2 values can vary from zero – one, which describes how much of the observed dispersion the model explains. A value of zero means no correlation at all; whereas a value of one means that the dispersion of the model is equal to that of the observation, which indicates a perfect fit.

Langan et al. (2001) indicated that the best fit between air and water temperature occurred in the summer. Stream temperatures during the summer seasons can be more accurately predicted from the linear regression relationship. Webb et al. (2003) also indicated that air and water temperatures are more strongly correlated when flows are below median levels.

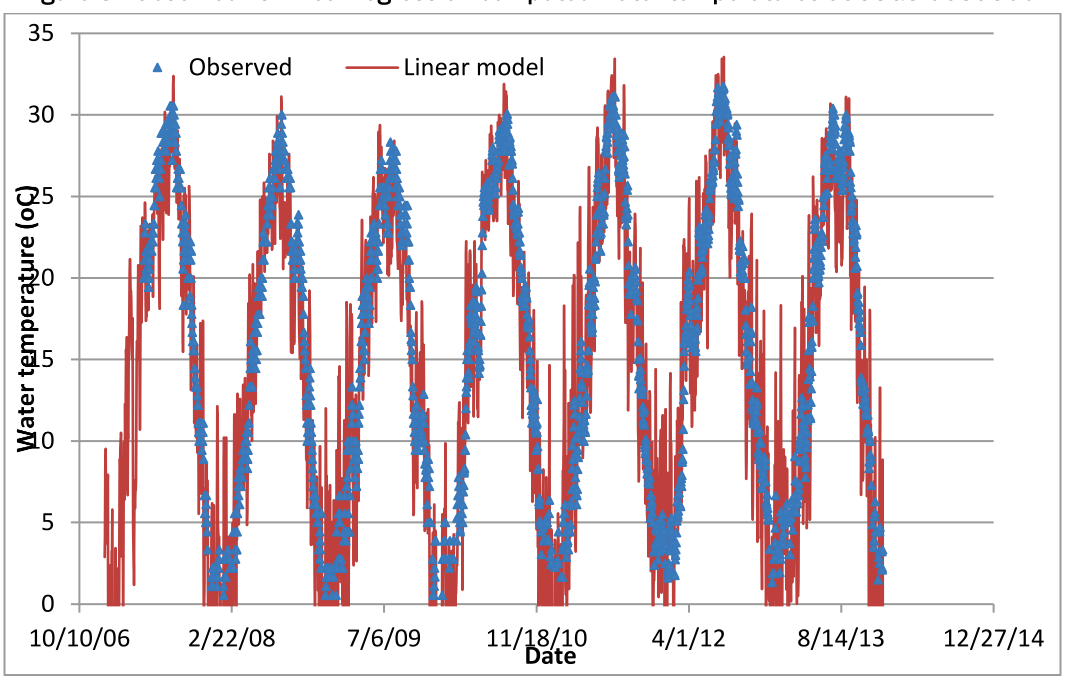
First, the authors evaluated the linear regression relationship between observed water versus air temperatures. Figure 7 shows the scatter plot of observed water and air temperatures at USGS 0689300 with a linear regression relationship. Both visual comparison and statistics (R^2) indicate that there is a strong linear co-relationship between water and air temperatures at this location.

Figure 7. Scatter plot of observed water versus air temperatures at USGS 0689300.



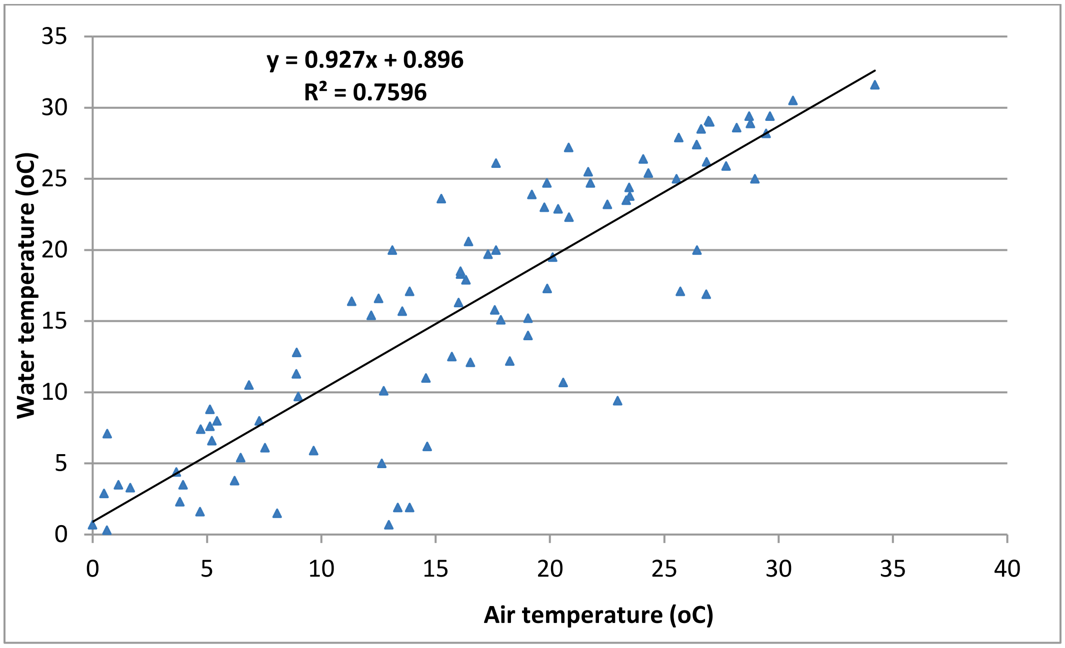
Seven year time series plot of observed and linear-regression-computed water temperatures with six day moving average air temperature at USGS 0689300 is presented in Figure 8.

Figure 8. Observed vs. linear-regression-computed water temperatures at USGS 0689300.



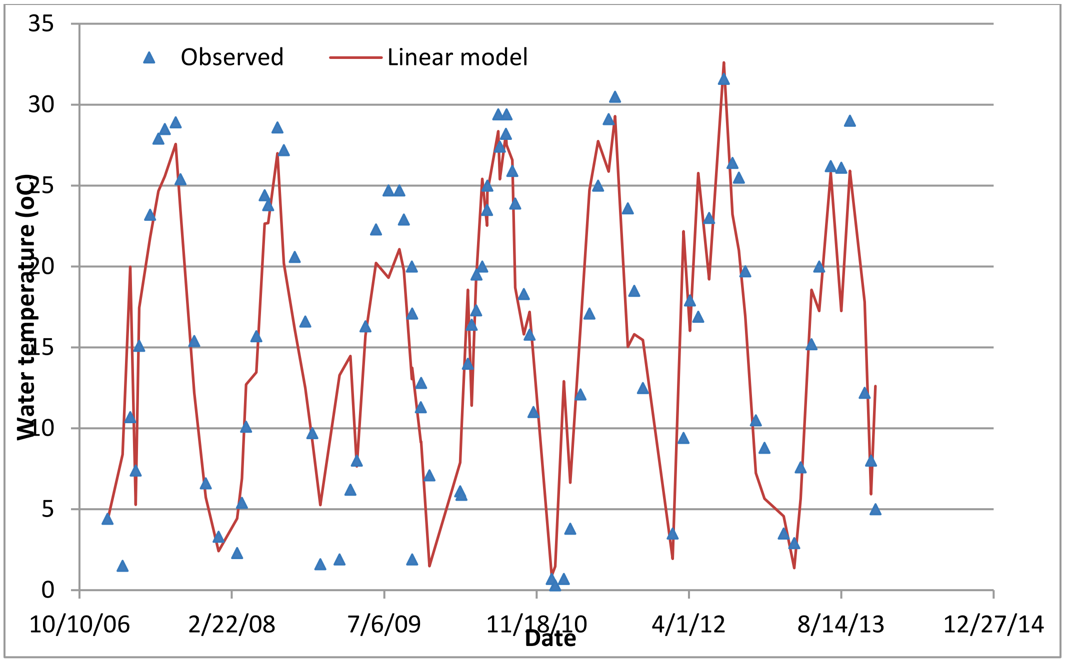
The second data set includes water temperature from the Mississippi River at Grafton, IL (USGS 05587455) and air temperature at MO232591. Figure 9 shows the scatter plot of observed water and air temperatures at this location with a linear regression relationship. The linear co-relationship between water and air temperatures is relatively weak.

Figure 9. Scatter plot of observed water versus air temperatures at USGS 05587455.



Seven year time series comparison of observed and linear-regression-computed water temperatures at USGS 05587455 is presented in Figure 10.

Figure 10. Observed vs. regression-computed water temperatures at USGS 05587455.



4.2.1.2 Non-linear regression

A significant non-linear relation between air and water temperatures was also observed at hourly, daily, or weekly intervals (Mohseni et al. 1998). Accordingly, an S-shaped logistic function to predict daily stream temperatures (using 3–12 day moving average air temperatures) at different locations in the U.S. was developed (Mohseni et al. 1998). This function is expressed as:

$$T_w = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \quad (4.3)$$

where

α = estimated maximum water temperature
β = air temperature at the inflexion point
μ = estimated minimum water temperature
γ = steepest slope of the logistic function.

The parameters μ, γ, and β are calculated iteratively to minimize RMSE.

The non-linear regression was also evaluated using two data sets (USGS gages 0689300 and 05587455) discussed above. Seven year time series comparison of observed and nonlinear regression estimated water temperatures for these two locations are presented in Figure 11 and Figure 12. Calibrated non-linear regression equations for USGS gages 0689300 and 05587455 are defined as follows:

$$T_w = -0.24328 + \frac{33.7026 + 0.24328}{1 + e^{0.12533(16.50901 - T_a)}} \quad (4.4a)$$

$$T_w = -1.02148 + \frac{34.51232 + 1.02148}{1 + e^{0.12318(17.25027 - T_a)}} \quad (4.4b)$$

Figure 11. Observed vs regression computed water temperatures at USGS 0689300.

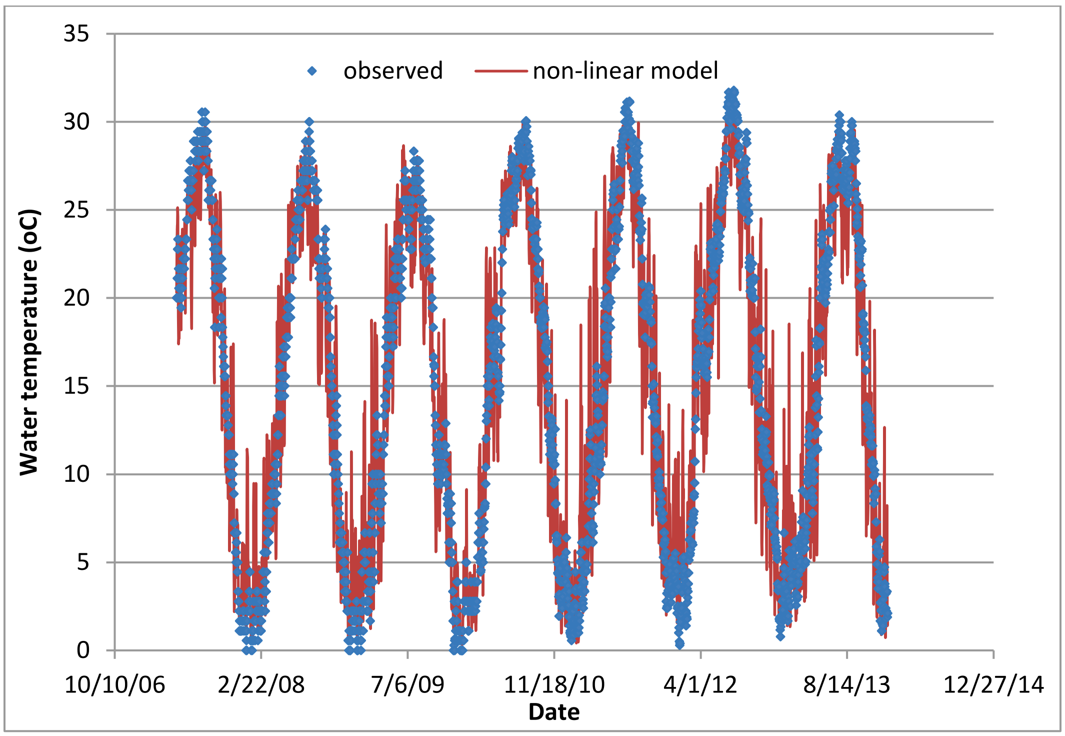
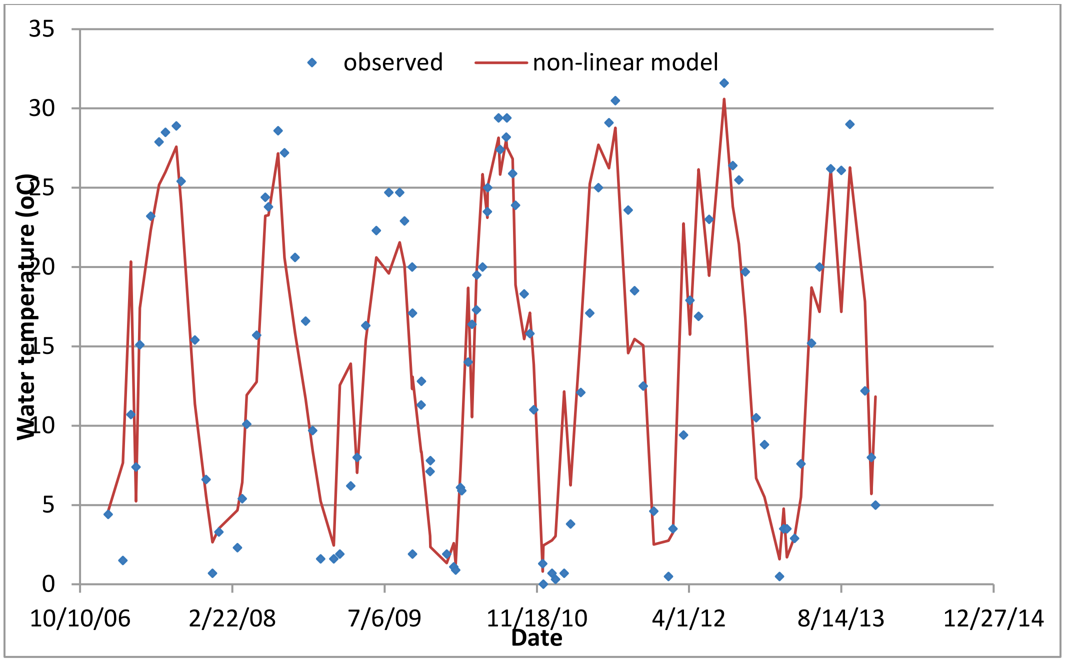


Figure 12. Observed and regression computed water temperatures at USGS 05587455.



As shown in the above figures, nonlinear regression equations for both locations perform better than their linear regression equations when air temperatures are close to 0 °C. The liner regression RMSE values for USGS gages 0689300 and 05587455 are 3.30 and 4.49. Their respective non-linear regression RMSE values are 3.087 and 4.258. Warmer temperatures, predicted using the two regression approaches discussed above, are pretty much the same for the two data sets. However, calibrating μ, γ, and β parameters included in the nonlinear regression is a challenge for multiple locations as well as long-term data sets (i.e., more than ten years). For efficiency, a piecewise linear regression was an adequate approach to explain the nonlinear relationship between water and air temperatures.

The piecewise linear regression equation for each location was developed as follows. Water temperatures were observed for a specific tributary and for a given day. All years with observed water temperature data were assembled together along with the day of the observation. A best-fit linear regression was developed using water temperature for that day and 3–12 day moving averages of previous air temperatures. RMSE and R^2 values were used as statistic evaluators of the fitted regression relationship. The moving average of air temperatures that produced the best fit for the tributary and the associated regression equation was used to generate the daily water temperatures for the entire simulation period (1995–2012).

Thus, a linear regression equation was developed for each inflow boundary, and these regression equations were used to generate daily water temperatures for all inflow boundaries throughout the year for the simulation period 1995–2012. These daily inflow water temperatures were then fed into the HEC-RAS models for the three reaches, Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the mouth of the Missouri River.

4.2.2 Application of the regression equations to compute water temperatures of inflowing tributaries

As explained above, a series of linear regression equations were applied to compute daily stream temperatures of inflowing tributaries as a function of daily air temperatures. Figure 13 is a map of the water quality monitoring gages and meteorological stations used in the regression relationship for the Garrison Dam to Oahe Dam reach. Figure 14 is a map of the water quality monitoring gages and meteorological stations used for Gavins Point Dam to Rulo and Rulo to the mouth of the Missouri River reaches. Table 3 lists all water temperature boundaries computed from the regression relationships. Fifty-one boundary conditions of inflowing water temperatures were created for the three HEC-RAS water temperature models (Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, Rulo to the mouth of the Missouri River). Mean daily air temperatures using the regressions were computed from observed hourly data stored in the HEC-DSS file (MoRMet.dss).

Figure 13. Water quality monitoring gages and correlated meteorological stations for the Garrison Dam to Oahe Dam reach.

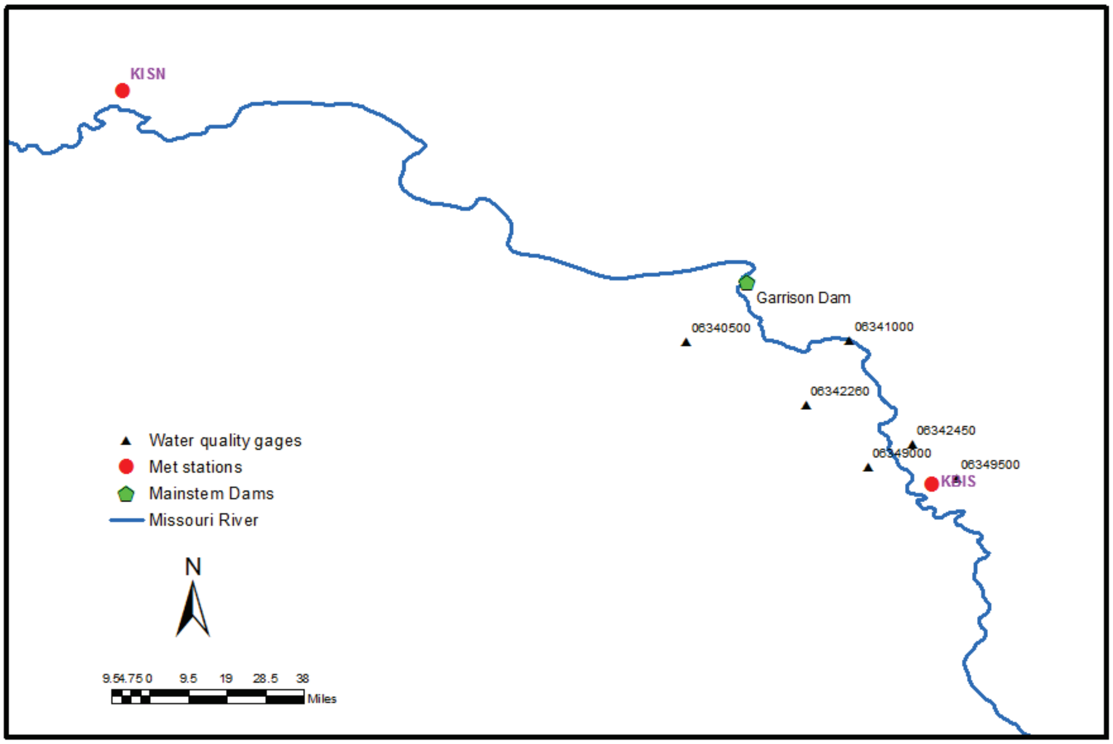


Figure 14. Water quality monitoring gages and correlated meteorological stations for the lower Missouri River from the Givens Point Dam to the mouth of the Missouri River.

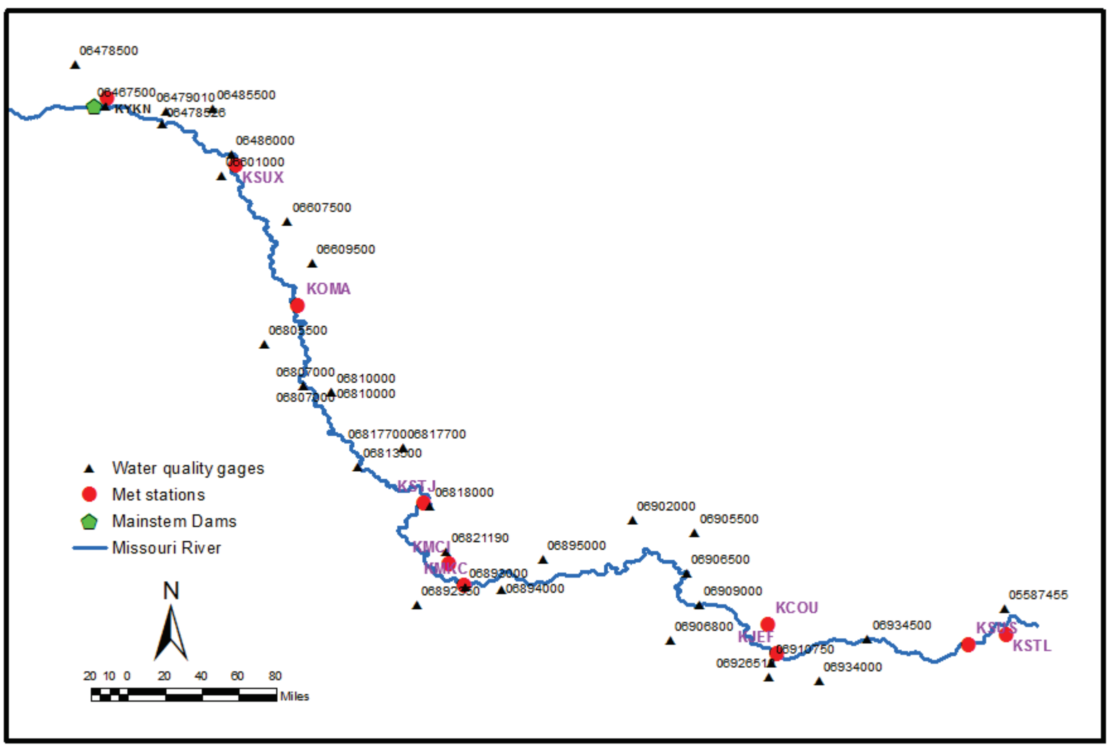


Table 3. Water temperature boundaries derived from water quality monitoring gages and meteorological stations.

Water quality Boundary*	Water quality gage	Water quality gage location	Record of observed data	No of samples	Met station
Garrison Dam to Oahe Dam reach					
BC1	06349500	Apple Creek Nr Menoken, ND	2/17/2000 – 11/7/2013	67	KBIS
BC2	06349000	Heart River Nr Mandan, ND	3/7/2000 – 7/26/2012	57	KBIS
BC3	06340500	Knife River at Hazen, ND	1/18/2000 – 7/24/2012	56	KBIS
BC4	06349500	Apple Creek Nr Menoken, ND	2/17/2000 – 11/7/2013	67	KBIS
BC5	06349500	Apple Creek Nr Menoken, ND	2/17/2000 – 11/7/2013	67	KBIS
BC6	06342260	Square Butte Creek below Center, ND	2/23/2000 – 10/25/2013	58	KBIS
BC7	06342450	Burnt Creek Nr Bismarck, ND	2/26/2000 – 7/25/2012	42	KBIS
BC8	06349500	Apple Creek Nr Menoken, ND	2/17/2000 – 11/7/2013	67	KBIS
Gavins Point Dam to Rulo reach					
BC1	06813500	Missouri River at Rulo, NE	1/4/2000 – 12/31/2013	661	KSTJ
BC2	06485500	Big Sioux River at Akron, IA	1/5/2000 – 9/4/2013	246	KSUX
BC3	06609500	Boyer River at Logan, IA	1/25/2000 – 12/17/2013	145	KOMA
BC4	06478500	James River near Scotland, SD	1/4/2000 – 9/4/2013	176	KYKN
BC5	06607500	Little Sioux River near Turin, IA	1/28/2000 – 12/18/2013	132	KOMA
BC6	06467500	Missouri River at Yankton SD	10/1/2010 – 7/16/2013	1000	KYKN
BC7	06478526	Missouri River near Maskell NE	7/16/2009 – 10/16/2013	36	KYKN
BC8	06486000	Missouri River at Sioux City, IA	1/3/2000 – 12/2/2013	871	KYKN
BC9	06486000	Missouri River at Sioux City, IA	1/3/2000 – 12/2/2013	871	KSUX
BC10	06601200	Missouri River at Decatur, NE	5/28/2009 – 10/15/2013	201	KSUX
BC11	06610000	Omaha Creek at Homer, NE	1/3/2000 – 12/28/2013	1157	KOMA
BC12	06805500	Platte River at Louisville NE	1/21/2000 – 12/18/2013	252	KOMA
BC13	06807000	Missouri River at Nebraska City, NE	1/3/2000 – 12/18/2013	1453	KOMA
BC14	06810000	Nishnabotna River above Hamburg, IA	2/22/2000 – 12/16/2013	135	KOMA
BC15	06817700	Nodaway River near Graham, MO	3/15/2000 – 10/22/2013	91	KSTJ
BC16	06479010	Vermillion River near Vermillion SD	1/5/2000 – 9/4/2013	183	KYKN

Rulo to the mouth of the Missouri River reach					
BC1	06810000	Nishnabotna River above Hamburg, IA	7/16/2009 – 10/15/2013	35	KSTJ
BC2	06906800	Lamine River near Otterville, MO	7/16/2009 – 10/16/2013	36	KCOU
BC3	06910750	Moreau River near Jefferson City, MO	7/16/2009 – 10/15/2013	35	KCOU
BC4	06934000	Gasconade River near Rich Fountain, MO	7/16/2009 – 10/17/2013	33	KJEF
BC5	06902000	Grand River near Sumner, MO	7/16/2009 – 10/16/2013	36	KMKC
BC6	06892350	Kansas River, Desoto, KS	5/17/2010 – 10/15/2013	29	KMKC
BC7	06906800	Lamine River near Otterville, MO	7/16/2009 – 10/16/2013	36	KCOU
BC8	06934500	Missouri River at Hermann, MO	6/13/2005 – 12/3/2013	103	KSTL
BC9	06807000	Missouri River, Nebraska City, NE	1/10/2007 – 12/4/2013	358	KSTJ
BC10	06818000	Missouri River, St. Joseph, MO	1/10/2009 – 10/16/2013	358	KMCI
BC11	06893000	Missouri River, Kansas City, MO	1/3/2007 – 12/18/2013	670	KMKC
BC12	06894000	Little Blue River near Lake City, MO	1/3/2007 – 12/18/2013	670	KMKC
BC13	06895000	Crooked River near Richmond, MO.	1/3/2007 – 12/18/2013	670	KMKC
BC14	06906500	Missouri River at Glasgow, MO	5/28/2009 – 10/15/2013	201	KCOU
BC15	06900900	Missouri River at Boonville, MO	5/9/2007 – 12/30/2013	2428	KJEF
BC16	06934500	Missouri River at Hermann, MO	6/13/2005 – 12/3/2013	103	KSUS
BC17	06910750	Moreau River near Jefferson City, MO	7/16/2009 – 10/15/2013	35	KJEF
BC18	06810000	Nishnabotna River above Hamburg, IA	7/16/2009 – 10/15/2013	35	KSTJ
BC19	06810000	Nishnabotna River above Hamburg, IA	7/16/2009 – 10/15/2013	35	KSTJ
BC20	06910750	Moreau River near Jefferson City, MO	7/16/2009 – 10/15/2013	35	KJEF
BC21	06910750	Moreau River near Jefferson City, MO	7/16/2009 – 10/15/2013	35	KJEF
BC22	06934500	Missouri River at Hermann, MO	9/10/2009 – 10/17/2013	33	KJEF
BC23	06910750	Moreau River near Jefferson City, MO	4/8/2010 – 10/16/2013	31	KJEF
BC24	06810000	Nishnabotna River above Hamburg, IA	1/9/2007 – 12/16/2013	81	KSTJ

BC25	06817700	Nodaway River near Graham, MO	4/5/2010 – 10/15/2013	27	KJEF
BC26	06926510	Osage River below St. Thomas, MO	4/8/2010 – 10/16/2013	31	KJEF
BC27	06821190	Platte River at Sharps Station, MO	1/10/2007 – 10/21/2013	45	KMCI

* BC represents boundary condition.

Time series plots of regression approach predicted and observed water temperatures for each of the inflow boundary sites included in the three HEC-RAS water temperature models are provided in Appendix A through C. The accuracy of the regression relationships were assessed through a visual comparison between regressions estimated, observed water temperatures, and error statistics. RMSE values calculated for each boundary condition (BC) location and each linear regression equation are listed in Table 4.

Table 4. Statistics for each boundary condition and each regression equation.

Water quality Boundary*	Water quality gage	No of samples	Met station	RMSE
Garrison Dam to Oahe Dam reach				
BC1	06349500	67	KBIS	2.614
BC2	06349000	57	KBIS	3.491
BC3	06340500	56	KBIS	3.532
BC4	06349500	67	KBIS	2.325
BC5	06349500	67	KBIS	2.407
BC6	06342260	58	KBIS	3.272
BC7	06342450	42	KBIS	2.550
BC8	06349500	67	KBIS	2.410
Gavins Point Dam to Rulo reach				
BC1	06813500	661	KSTJ	2.73
BC2	06485500	246	KSUX	2.763
BC3	06609500	145	KOMA	2.835
BC4	06478500	176	KYKN	2.530
BC5	06607500	132	KOMA	2.385
BC6	06467500	1000	KYKN	1.934
BC7	06478526	36	KYKN	1.744
BC8	06486000	871	KYKN	2.975

BC9	06486000	871	KSUX	2.795
BC10	06601200	201	KSUX	3.253
BC11	06610000	1157	KOMA	3.228
BC12	06805500	252	KOMA	2.438
BC13	06807000	1453	KOMA	1.839
BC14	06810000	135	KOMA	2.265
BC15	06817700	91	KSTJ	2.734
BC16	06479010	183	KYKN	2.767
Rulo to the mouth of the Missouri River reach				
BC1	06810000	35	KSTJ	1.892
BC2	06906800	36	KCOU	1.735
BC3	06910750	35	KCOU	2.552
BC4	06934000	33	KJEF	2.074
BC5	06902000	36	KMKC	1.567
BC6	06892350	29	KMKC	1.193
BC7	06906800	36	KCOU	1.740
BC8	06934500	103	KSTL	2.827
BC9	06807000	358	KSTJ	2.910
BC10	06818000	358	KMCI	2.715
BC11	06893000	670	KMKC	2.509
BC12	06894000	670	KMKC	2.468
BC13	06895000	670	KMKC	2.417
BC14	06906500	201	KCOU	2.461
BC15	06900900	2428	KJEF	1.785
BC16	06934500	103	KSUS	1.896
BC17	06910750	35	KJEF	1.509
BC18	06810000	35	KSTJ	1.708
BC19	06810000	35	KSTJ	1.284
BC20	06910750	35	KJEF	1.284
BC21	06910750	35	KJEF	1.748
BC22	06934500	33	KJEF	2.540
BC23	06910750	31	KJEF	1.436
BC24	06810000	81	KSTJ	2.638

BC25	06817700	27	KJEF	2.034
BC26	06926510	31	KJEF	2.350
BC27	06821190	45	KMCI	1.983

In general, stream temperatures reflect the combined influence of both meteorological and hydrological factors. Meteorological conditions, such as air temperature, has a large influence on stream temperatures; however, other factors such as solar radiation, wind speed, relative humidity, water depth, and water flow rate are also important factors. Additionally, stream temperature is greatly influenced by the source characteristics of the water, including where snowmelt occurs, surface runoff, groundwater inflow, or cultural heat inputs. Each source characteristic has a different temperature signature, with surface runoff ranging close to the ambient air temperature and snowmelt ranging just above freezing. As a result, the relative influence of meteorological and hydrologic factors on stream temperature can vary greatly with watershed and/or season.

After reviewing all comparisons of regression approach predicted water temperature and observed data presented in Appendix A–C, the water temperature computed by the regression approach was satisfactory in general. For a few stream gaging stations, the fitted regression equations were, however, questionable if not useless (i.e., their R^2 values were below 0.5). Stefan and Preud'homme (1993) developed an air-water regression model based on daily and weekly water temperature data from 11 streams in the central United States. Their study indicated that the dependence of regression coefficients on stream characteristics and weather parameters other than air temperature is evident in some streams. Not being able to capture the temporal variations in observed water temperature for some locations within the Missouri River basin may be a result of the weak air-water temperature correlations or lack of observed data. In these locations, air-water temperature correlations may not be appropriate for computing water temperature boundary conditions. Therefore, the authors recommend using the current HEC-RAS water temperature model for assessing the relative changes of water temperatures associated with management alternatives along the Missouri River instead of using them to assess absolute deterministic values.

4.3 Model development and calibration

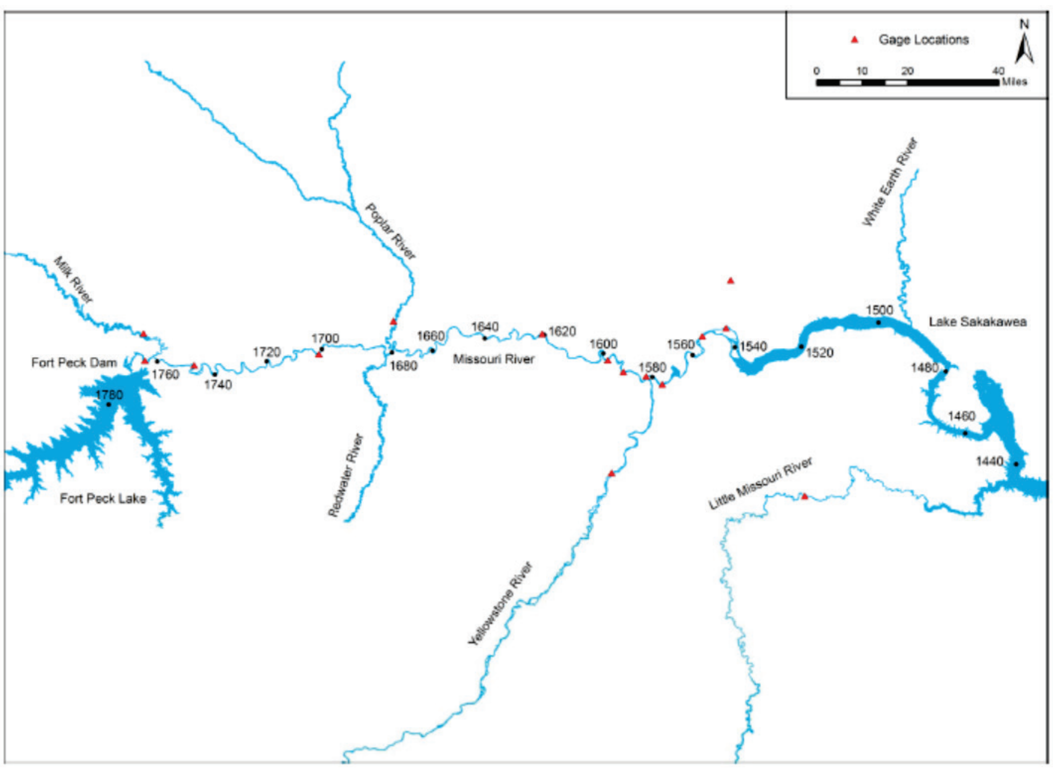
All HEC-RAS water temperature models were constructed based on the calibrated HEC-RAS flow models the USACE Omaha and Kansas City Districts provided. The following sections discuss each modeled river reach separately.

4.3.1 Fort Peck Dam to Garrison Dam River Reach

4.3.1.1 HEC-RAS flow model

The Fort Peck Dam to Garrison Dam reach of the Missouri River begins at RM 1769.04, located just downstream of Fort Peck Dam in MT, and extend to RM 1391.08, located upstream of Garrison Dam on Lake Sakakawea, Pick City, ND. The reach is approximately 365 miles long. This is the most upstream portion of the Missouri River being modeled with HEC-RAS. USACE Omaha District developed and calibrated the unsteady HEC-RAS flow model for the Fort Peck Dam to Garrison Dam reach (USACE 2015). The model extent and tributaries entering the Missouri River within this reach are shown in Figure 15.

Figure 15. HEC-RAS model extent for the Fort Peck Dam to Garrison Dam reach (USACE 2015).



In addition to the Missouri River, three tributary reaches were included within the HEC-RAS model to route flow from the gage station to the Missouri River. The three tributary routing reaches are:

- Milk River, which extends approximately 24 miles from the confluence within the Missouri River to Nashua, MT
- Poplar River, near Poplar, Montana, extends 14 miles upstream from the confluence within the Missouri River
- Yellowstone River, which extends approximately 62 miles from the confluence within the Missouri River to Sydney, MT.

4.3.1.2 Water temperature model inputs

Once a HEC-RAS flow model is calibrated, meteorological data and inflow temperature boundary conditions are primary model inputs for the water temperature model. They are time and space dependent and discussed below.

Meteorological data

Two meteorological stations (KGGW and KISN), shown in Figure 1, were used in the Fort Peck Dam to Garrison Dam reach of the HEC-RAS water temperature model. In HEC-RAS, the dataset from the nearest station was automatically assigned to water quality computational cells within the river reach.

Boundary conditions

The required boundary conditions for the HEC-RAS water temperature model are the water temperatures at the upstream boundary (Fort Peck Dam release temperatures), and water temperatures from all lateral and distributed inflow discharging into this reach. Table 5 below provides a list of flow boundary locations in the HEC-RAS model and observed water temperature records at these locations. If a water quality monitoring station was not available for the inflow boundary, observed data collected from adjacent water quality stations were used. Thus, the same water quality station is listed in Table 5 for different inflow boundaries.

Since the HEC-RAS water temperature model results for this reach were not needed for conducting current ManPlan and EIS, the regression relationships described previously were not developed and applied to compute inflow water temperature boundary conditions for this river reach. Observed water temperatures for each boundary listed in Table 5 were directly used in the water temperature model.

Table 5. Flow and temperature boundaries included in the HEC-RAS model for the Fort Peck Dam to Garrison Dam reach

Inflow boundary	Flow boundary type	Water quality boundary	Water quality station ID	Water quality station location	Temperature Records	Number of samples
Milk River XS 23.54	Tributary	BC1	06174500[3]	Milk River, Nashua, MT	5/7/2010 - 10/20/2013	643
Poplar River XS14.18	Tributary	BC2	06181000[3]	Poplar River, Poplar, MT	1/26/2000 - 7/30/2013	128
Yellowstone River XS 103500	Tributary	BC3	06329500[3]	Yellowstone River, Sidney, MT	1/11/2000 – 10/30/2013	615
Little Missouri XS 81.59	Tributary	BC4	GARNFMORR1[1]	Garrison Reservoir inflow	4/6/2010 - 10/29/2013	24
Missouri River XS 1769	Upstream boundary	BC5	FTPlake[1]	Fort Peck Lake	6/14/2010 - 10/1/2012	420
Missouri River XS 1768	Lateral inflow	BC5	FTPlake	Fort Peck Lake	6/14/2010 - 10/1/2012	420
Missouri River XS 1762	Lateral inflow	BC5	FTPlake	Fort Peck Lake	6/14/2010 - 10/1/2012	420
Missouri River XS 1761	Lateral inflow	BC6	FTPPP1[1]	Fort Peck Dam Powerplant, MT	1/1/2010 – 1/1/2014	35065
Missouri River XS 1760	Lateral inflow	BC7	USGS (1761.4)[2]	Missouri River, Fort Peck Dam, MT	5/7/2010 - 8/4/2013	265
Missouri River XS 1744	Lateral inflow	BC8	USGS (1744.8)[2]	Missouri River, Frazer, MT	5/7/2010 - 9/1/2013	474
Missouri River XS 1725	Lateral inflow	BC9	USGS (1741)[2]	Missouri River, Grant Champs, MT	5/7/2010 - 9/1/2013	643
Missouri River XS 1717	Lateral inflow	BC10	USGS (1696.9)[2]	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1708	Lateral inflow	BC10	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1701	Lateral inflow	BC10	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1689	Lateral inflow	BC10	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1681	Lateral inflow	BC10	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1678	Lateral inflow	BC10	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656

Missouri River XS 1645	Lateral inflow	BC11	USGS (1615.1) [2]	Missouri River, Culbertson, MT	5/7/2010 - 10/1/2013	502
Missouri River XS 1630	Lateral inflow	BC11	USGS (1615.1)	Missouri River, Culbertson, MT	5/7/2010 - 10/1/2013	502
Missouri River XS 1627	Lateral inflow	BC11	USGS (1615.1)	Missouri River, Culbertson, MT	5/7/2010 - 10/1/2013	502
Missouri River XS 1623	Lateral inflow	BC11	USGS (1615.1)	Missouri River, Culbertson, MT	5/7/2010 - 10/1/2013	502
Missouri River XS 1545	Lateral inflow	BC12	USGS (1573.6) [2]	Missouri River below Yellowstone River, MT	5/7/2010 - 10/1/2013	330

1. USACE Omaha District provided water temperature data for these locations
2. The USGS provided water temperature data for these locations
3. USGS gage.

4.3.1.3 Water temperature model set up and calibration

When the water temperature model for the Fort Peck Dam to Garrison Dam reach is opened, water quality computational cells are initially established between cross sections along this river reach. However, in situations where hydraulic cross sections have been placed very close together (such as around bridges or other hydraulic structures), default water quality cells may be very small. A single small water quality cell will force the model to choose a correspondingly small time step. For this river reach, the minimum water quality cell length was set as 1000 ft., which directs the model to combine water quality cells to ensure that the all cells are at least as long as this user specified minimum.

After specifying above meteorological data and boundary conditions, the HEC-RAS water temperature model for the Fort Peck Dam to Garrison Dam reach was set up and run using an hourly time step from January 1, 2011–September 30, 2012 based on available water temperature boundary data. All gaps in observed water temperature data used for boundary conditions were linearly interpolated in the HEC-RAS water temperature model. The model results generated using this approach are questionable if gaps in observed water temperature are big, for example, a month or longer time interval. An hourly time step was also used in the other HEC-RAS water temperature models described in this chapter.

The HEC-RAS water temperature model for the Fort Peck Dam to Garrison Dam reach was not used in conducting current ManPlan and EIS.

The water temperature model for this river reach was preliminarily calibrated with available observed data. During the model calibration, solar radiation and coefficients in the wind speed function were adjusted. Time series plots of HEC-RAS predicted and observed water temperatures at five USGS stations along the Fort Peck Dam to Garrison Dam reach are presented in Figures 16–20.

Figure 16. HEC-RAS predicted versus observed water temperatures of the Missouri River at Frazer, MT.

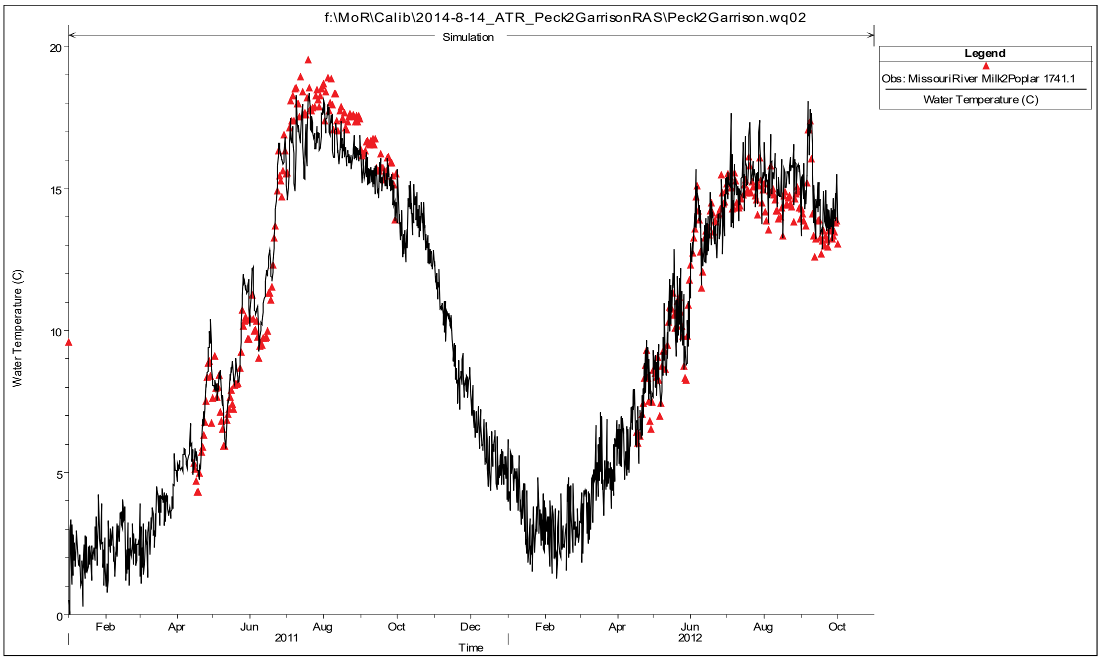


Figure 17. HEC-RAS predicted versus observed water temperatures of the Missouri River at Wolf, MT.

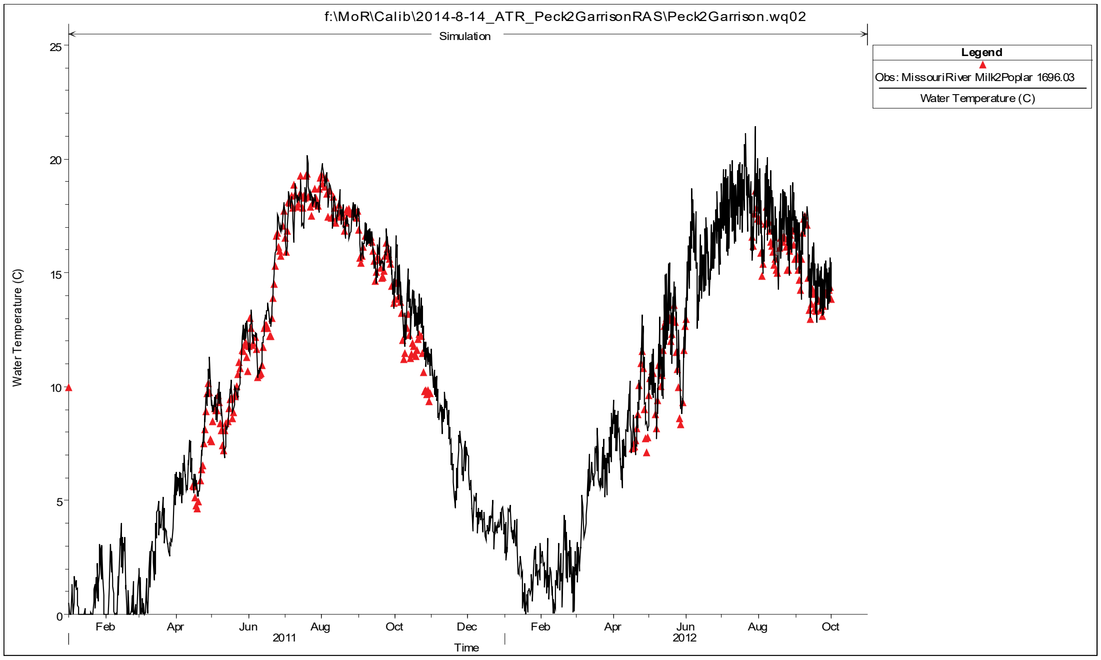


Figure 18. HEC-RAS predicted versus observed water temperatures of the Missouri River at Culbertson, MT.

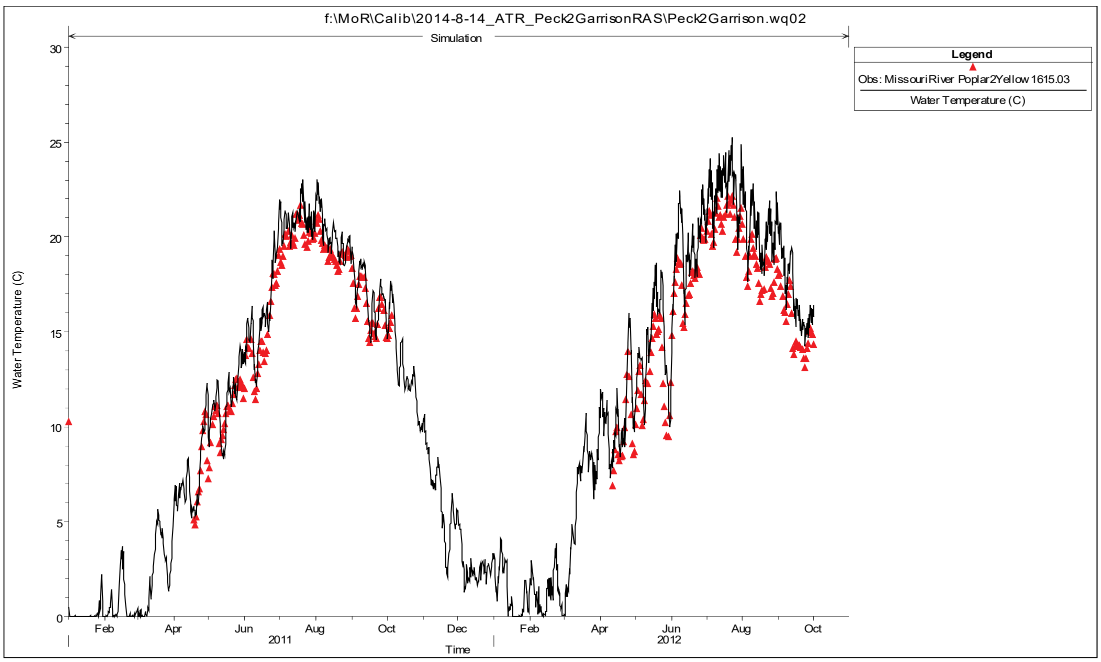


Figure 19. HEC-RAS predicted versus observed water temperatures of the Missouri River at Nohly, MT.

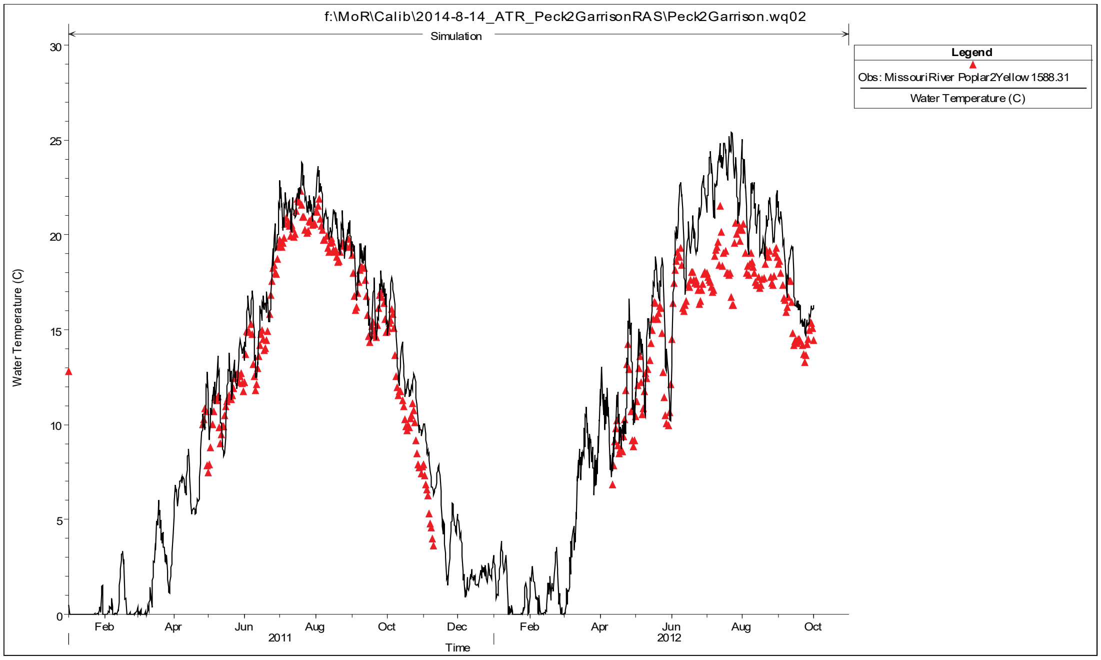
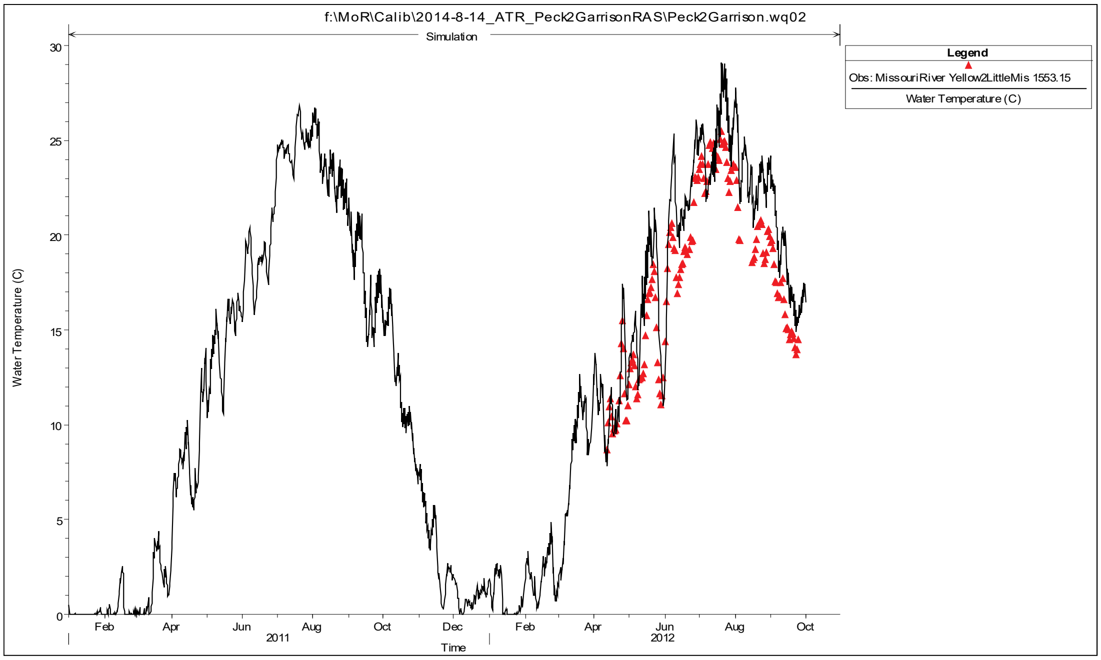


Figure 20. HEC-RAS predicted versus observed water temperatures of the Missouri River at Williston, MT.



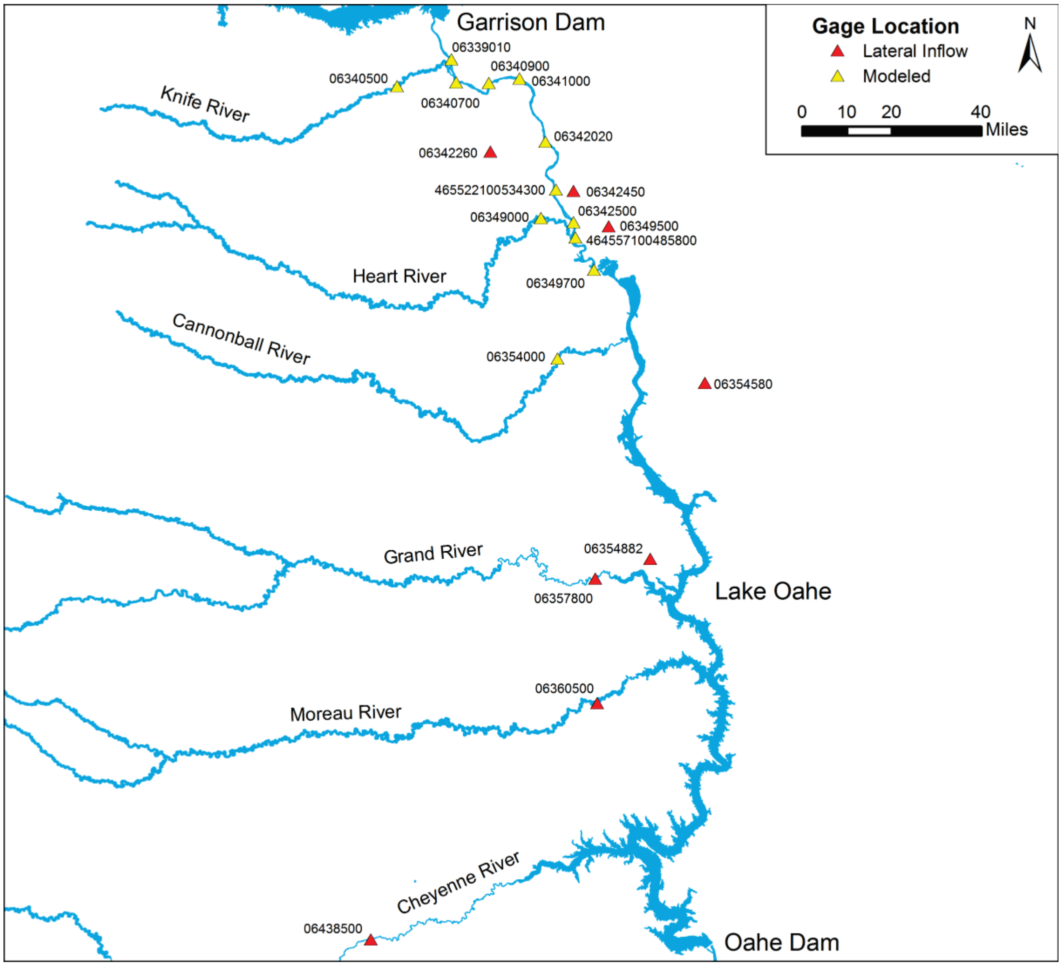
These figures show a scatter plot of instantaneous temperature predictions against time-stamped temperature observations. Comparisons of model predictions and observed data at USGS stations along this river reach demonstrate the degree that the HEC-RAS model captures the instantaneous water temperature observations at these locations. The main differences between modeled and observed values occur during summer seasons when the model predictions tend to be higher than the observed temperatures.

4.3.2 Garrison Dam to Oahe Dam River Reach

4.3.2.1 HEC-RAS flow model

The Garrison Dam to Oahe Dam reach of the Missouri River begins from RM 1388.30, located just downstream of Garrison Dam, ND, to RM 1073.04, located upstream of Oahe Dam, Pierre, SD. The reach is approximately 318 miles long. The Garrison Dam to Oahe Dam reach of the Missouri River is the second reach being modeled with HEC-RAS. USACE Omaha District developed and calibrated the unsteady HEC-RAS flow model (USACE 2015). Figure 21 shows the extent of the model as well as tributaries entering the Missouri River within this reach. USGS stations shown in this figure are only flow gages.

Figure 21. HEC-RAS model extent for the Garrison Dam to Oahe Dam reach (USACE 2015).



In addition to modeling the Missouri River, three tributary reaches were included within the HEC-RAS model to route flow from the gage station to the Missouri River. The three tributary routing reaches are:

- The Knife River, which extends approximately 26 miles from the confluence within the Missouri River to Hazen, ND
- The Heart River, which extends approximately 11 miles from the confluence within the Missouri River to near Mandan, ND
- The Cannonball River, which extends approximately 30 miles from the confluence within the Missouri River to Breien, ND.

4.3.2.2 Water temperature model Inputs

Meteorological data and inflow temperature boundary conditions for the Garrison Dam to Oahe Dam reach HEC-RAS water temperature model are discussed below.

Meteorological data

One meteorological station (KBIS) at Bismarck Muni, ND, shown in Figure 1, was used in the Garrison Dam to Oahe Dam reach HEC-RAS water temperature model.

Boundary conditions

Figure 22 presents approximate locations of inflow boundaries included in the Garrison Dam to Oahe Dam reach HEC-RAS model. Water temperatures associated with each inflow boundary for the simulation period (1995–2012) were computed using regression relationships as explained previously. The water temperatures from Garrison Dam release and inflow temperatures for all tributaries along the reach were specified in the model through a HEC-DSS file. Table 6 lists 25 water temperature boundary conditions, which correspond to their inflow boundaries included in the HEC-RAS model for the Garrison Dam to Oahe Dam reach.

Figure 22. Schematic representation of inflow boundary locations included in the HEC-RAS model for the Garrison Dam to Oahe Dam reach.

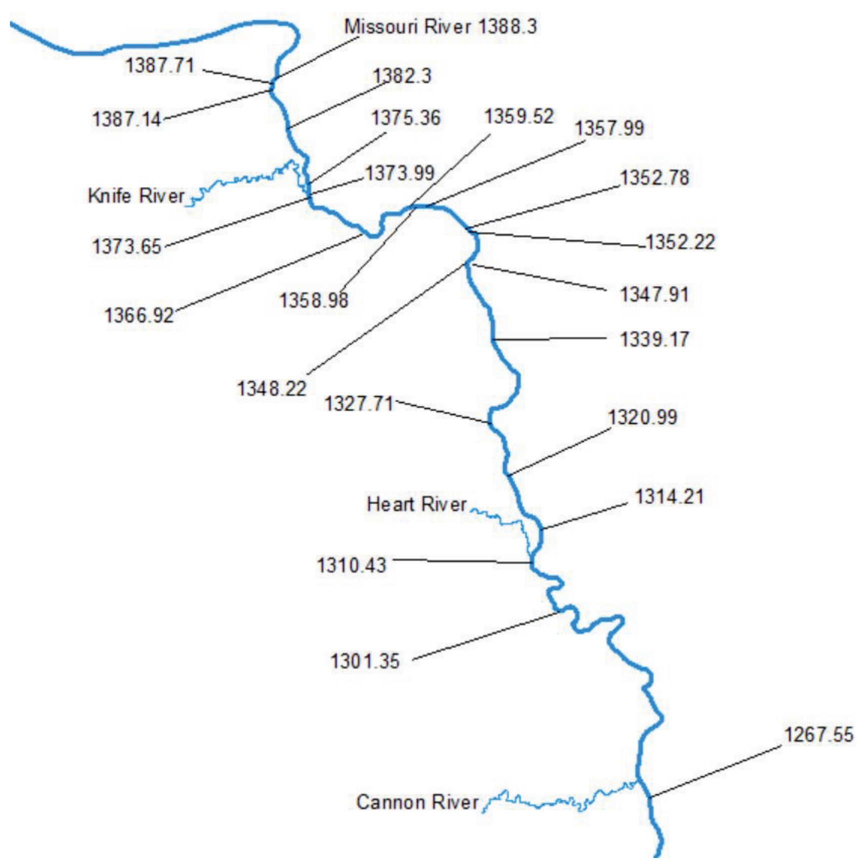


Table 6. Inflow and temperature boundaries included in the HEC-RAS model for the Garrison Dam to Oahe Dam reach.

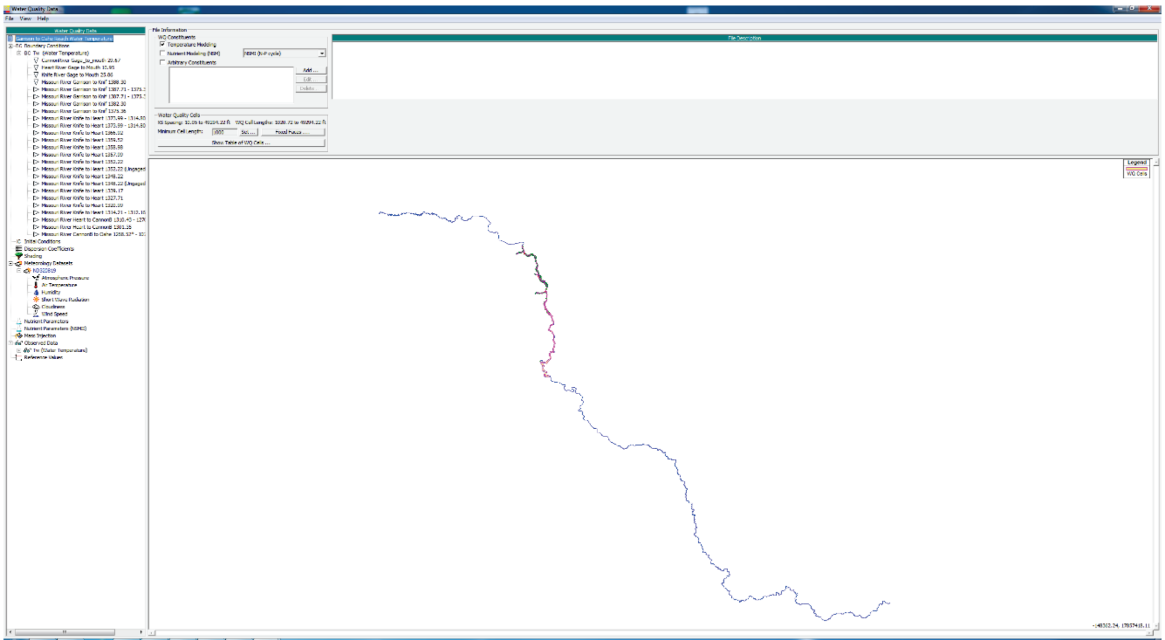
NO	Flow boundary	Flow boundary type	Water quality boundary
1	Cannon River RS 29.67	Tributary	BC1
2	Heart River RS 10.95	Tributary	BC2
3	Knife River RS 25.86	Tributary	BC3
4	Missouri River RS 1388.30	Upstream boundary from dam release	BC4
5	Missouri River RS 1387.71	Uniform lateral inflow	BC3
6	Missouri River RS 1387.71	Uniform lateral inflow	BC3
7	Missouri River RS 1382.30	Lateral inflow	BC3
8	Missouri River RS 1375.36	Lateral inflow	BC3
9	Missouri River RS 1373.99	Uniform lateral inflow	BC3
10	Missouri River RS 1373.99	Uniform lateral inflow	BC3
11	Missouri River RS 1366.92	Lateral inflow	BC5
12	Missouri River RS 1359.52	Lateral inflow	BC5
13	Missouri River RS 1358.98	Lateral inflow	BC5
14	Missouri River RS 1357.99	Lateral inflow	BC5
15	Missouri River RS 1352.22	Lateral inflow	BC5
16	Missouri River RS 1352.22	Lateral inflow	BC5
17	Missouri River RS 1348.22	Lateral inflow	BC5
18	Missouri River RS 1348.22	Lateral inflow	BC5
19	Missouri River RS 1339.17	Lateral inflow	BC5
20	Missouri River RS 1327.71	Lateral inflow	BC6
21	Missouri River RS 1320.99	Lateral inflow	BC7
22	Missouri River RS 1314.21	Uniform lateral inflow	BC7
23	Missouri River RS 1310.43	Uniform lateral inflow	BC8
24	Missouri River RS 1301.35	Lateral inflow	BC8
25	Missouri River RS 1267.55	Uniform lateral inflow	BC8

4.3.2.3 Water temperature model set up and calibration

After specifying above meteorological data and boundary conditions, the HEC-RAS temperature model for the Garrison Dam to Oahe Dam reach was set up and run using an hourly time step from January 1, 1995–

December 31, 2012. Figure 23 shows the schematic and data plan of the HEC-RAS temperature model for this reach. The minimum water quality cell length in HEC-RAS was set as 1000 ft.

Figure 23. Schematic and data plan of the HEC-RAS temperature model for the Garrison Dam to Oahe Dam reach.



The HEC-RAS water temperature model for the Garrison Dam to Oahe Dam reach was preliminarily calibrated at two USGS stations (06341000 and 06342500) on the main stem Missouri River. Their locations can be found in Figure 21. Time series plots of HEC-RAS predicted and observed data at these two stations are presented in Figure 24 and Figure 25.

Figure 24. HEC-RAS predicted versus observed water temperatures of the Missouri River at Washburn, ND (USGS 06341000).

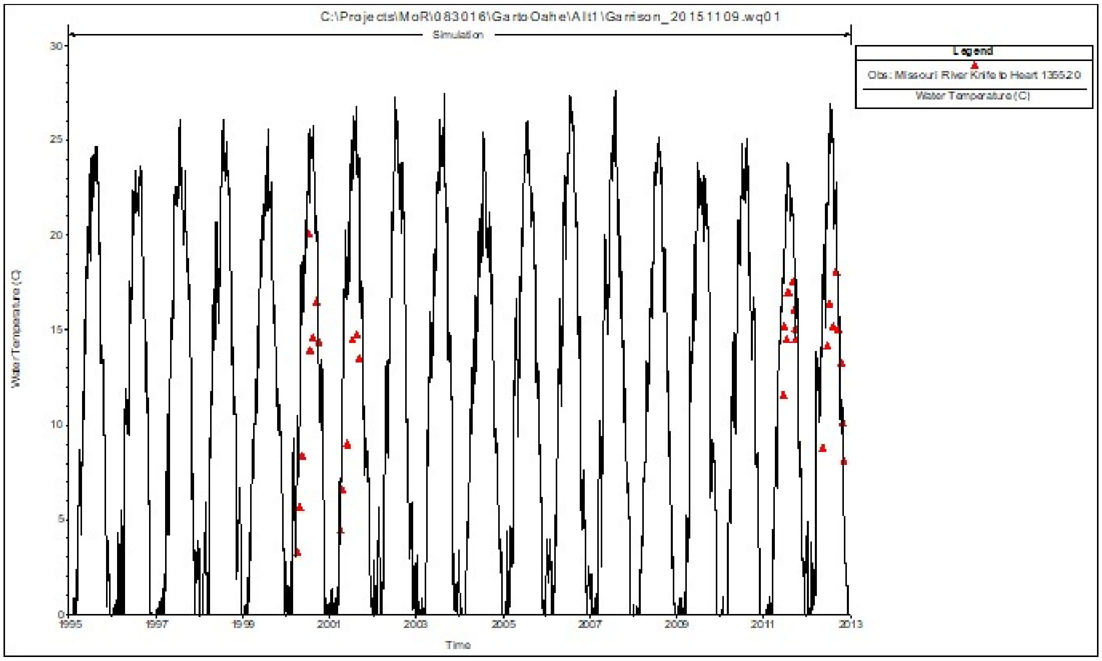
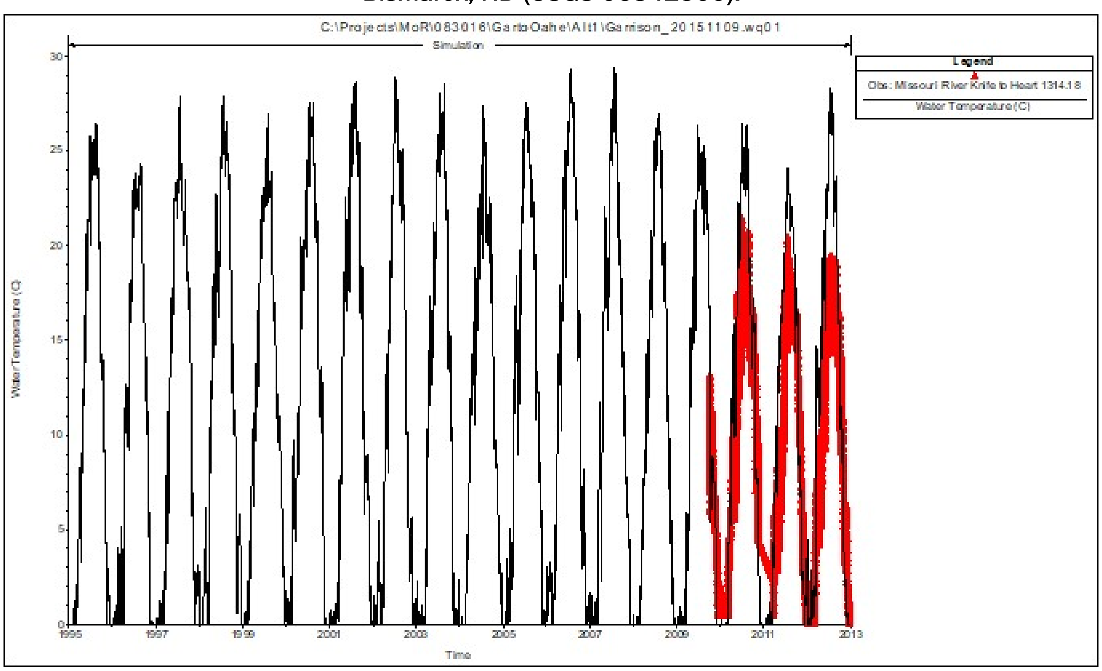


Figure 25. HEC-RAS predicted versus observed water temperatures of the Missouri River at Bismarck, ND (USGS 06342500).



The HEC-RAS model for the Fort Peck Dam to Garrison Dam reach captured the seasonal variations of observed water temperatures well;

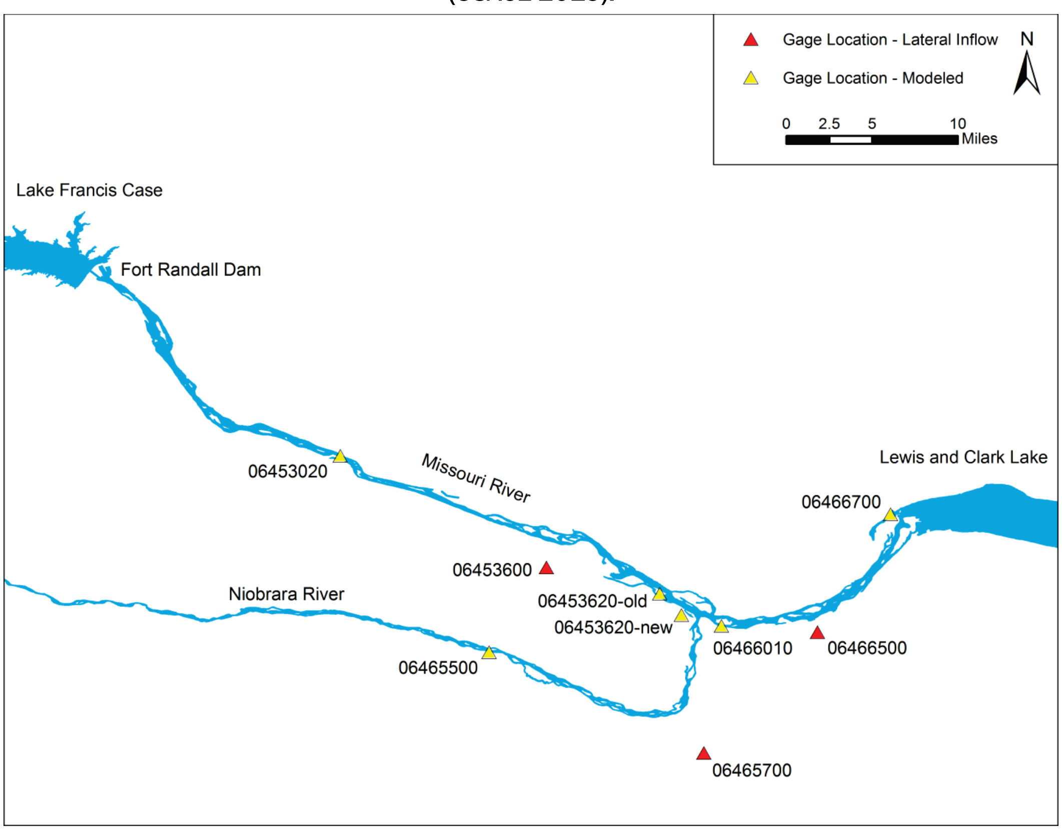
however, the model over predicted summer temperatures at both locations along this reach.

4.3.3 Fort Randall Dam to Gavins Point Dam River Reach

4.3.3.1 HEC-RAS flow model

The Fort Randall Dam to Gavins Point Dam reach of the Missouri River begins from RM 879.04, located just downstream of Fort Randall Dam, SD, to RM 812.74, located upstream of Gavins Point Dam on Lewis and Clark Lake, Yankton, SD. The reach is approximately 70 miles long. The Fort Randall Dam to Gavins Point Dam reach is the third reach of the Missouri River being modeled with HEC-RAS. USACE Omaha District developed and calibrated the unsteady HEC-RAS flow model (USACE 2015). The model extent and tributaries entering the Missouri River within this reach are shown in Figure 26. USGS stations shown in this figure are only flow gages.

Figure 26. HEC-RAS model extent for the Fort Randall Dam to Gavins Point Dam reach (USACE 2015).



In addition to modeling the Missouri River, there is one tributary modeled in HEC-RAS. The Niobrara River model extends approximately 15 miles upstream from the confluence within the Missouri River to near Verdel, NE. The Niobrara River watershed is approximately 12,000 square miles.

4.3.3.2 Water temperature model Inputs

Meteorological data and inflow temperature boundary conditions for the Fort Randall Dam to Gavins Point Dam reach HEC-RAS model are discussed below.

Meteorological data

Two meteorological stations (NYKN and KONL), shown in Figure 1, were used in the Fort Randall Dam to Gavins Point Dam reach HEC-RAS water temperature model. In HEC-RAS, the data from each meteorological station was automatically assigned to the closest water quality computational cells within the river reach.

Boundary conditions

Table 7 below provides a list of inflow boundary locations and their water temperature inputs included in the Fort Randall Dam to Gavins Point Dam reach HEC-RAS model. USGS 06465500 was used twice because it was the only water quality station on the Niobrara River.

The HEC-RAS water temperature model results for this reach were not needed for the ManPlan analysis. In addition, the air-water temperature regression approach was not applied to all inflow boundaries for computing the water temperatures. Observed water temperatures for each boundary listed in Table 5 were directly used in the HEC-RAS water temperature model. All gaps in observed water temperature data used for boundary conditions were linearly interpolated in the HEC-RAS model.

Table 7. Flow and temperature boundaries included in the HEC-RAS model for the Fort Randall Dam to Gavins Point Dam reach

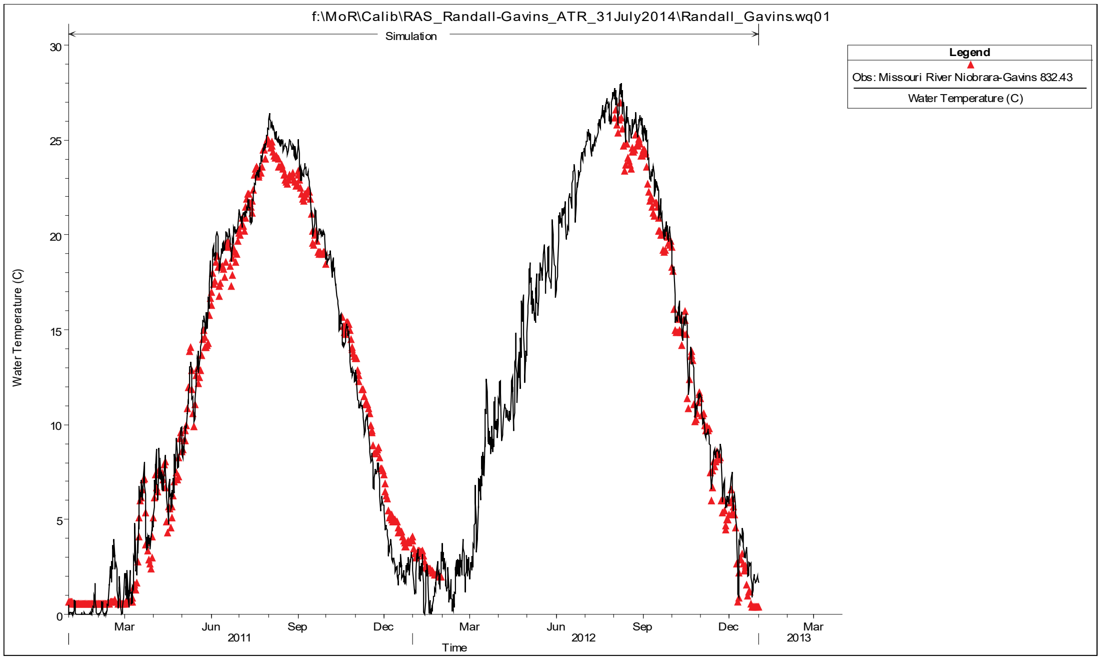
Inflow boundary	Flow boundary type	Water quality boundary	Water quality station ID	Water quality station location	Temperature records	Number of samples
Niobrara River	Tributary	BC1	06465500[1]	Niobrara River near Verdel, NE	10/10/2010 – 12/31/2013	81540
Niobrara River	Tributary to Niobrara River	BC1	06465500[1]	Niobrara River near Verdel, NE	10/10/2010 – 12/31/2013	81540
Missouri River XS 879.04	Upstream boundary	BC2	FTRRRTW1B[2]	Fort Randall Dam tailwater	1/12/2010 – 12/9/2013	46
Missouri River XS 849.37	Lateral inflow	BC3	MORRR0851B[2]	Missouri River near Verdell, NE	3/16/2010 – 12/31/2013	35
Missouri River XS 838.06	Lateral inflow	BC4	GPTNFMORR1[2]	Gavins Point Reservoir inflow	3/16/2010 – 10/28/2013	86

1. USGS gage
2. USACE Omaha District provided water temperature data for these locations

4.3.3.3 Water temperature model set up and calibration

The HEC-RAS water temperature model for the Fort Randall Dam to Gavins Point Dam reach was not used in conducting current ManPlan and EIS The model was set up and run using an hourly time step for two years, from January 1, 2011–December 31, 2012. The minimum water quality cell length in HEC-RAS was set as 1000 ft. Only one location (USGS 06466700) on this river reach had observed water temperature data. A time series plot of HEC-RAS predicted and observed water temperatures at this location is presented in Figure 27.

Figure 27. HEC-RAS predicted versus observed water temperatures of the Missouri River at Springfield, SD (USGS 06466700).



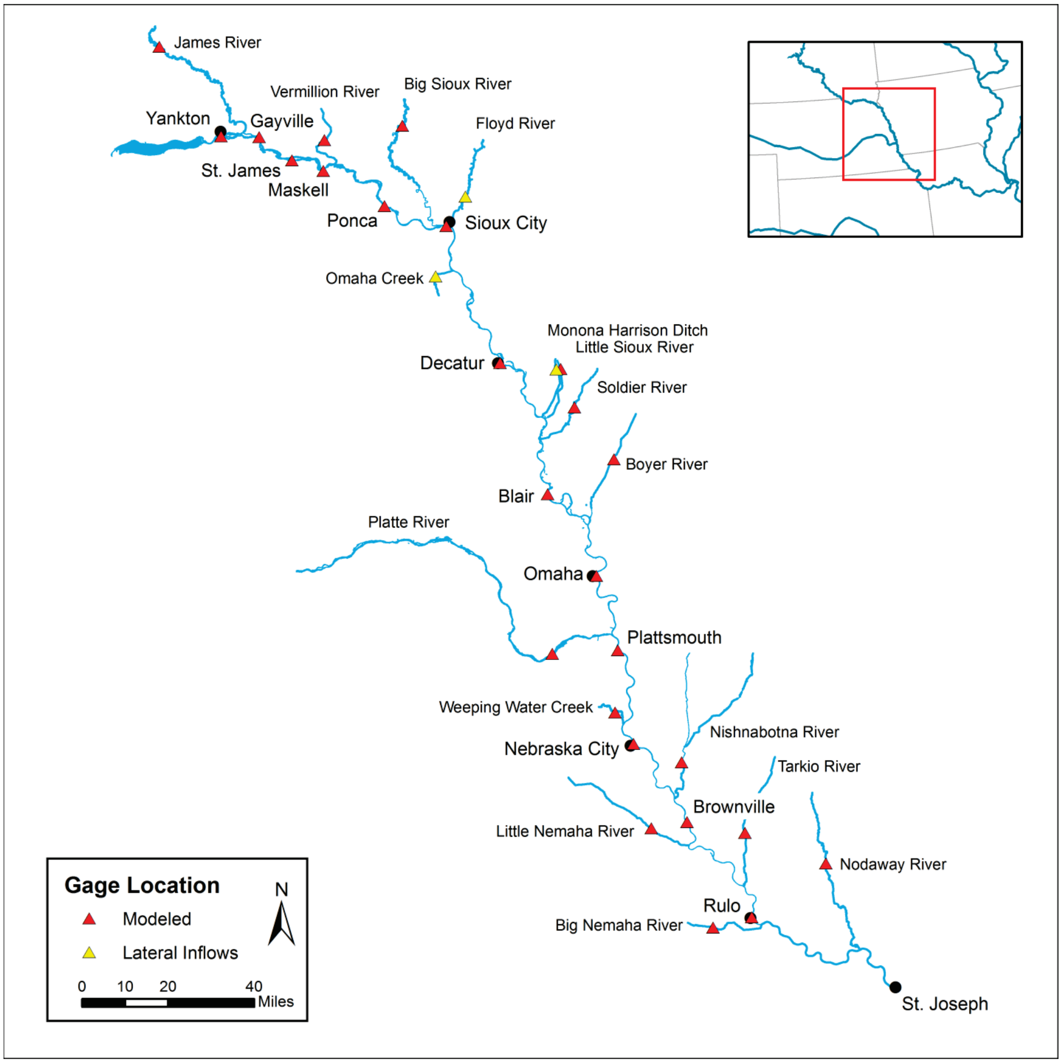
Comparisons of model predictions and observed data at this location show that the Fort Randall Dam to Gavins Point Dam HEC-RAS model was able to capture water temperature observation patterns. The minor differences between modeled and observed values occur during summer seasons when the model predictions tend to be slightly higher than the observed temperature.

4.3.4 Gavins Point Dam to Rulo River Reach

4.3.4.1 HEC-RAS flow model

The Gavins Point Dam to Rulo, NE, reach of the Missouri River begins with the regulated outflow from Gavins Point Dam in SD at RM 811.1. The reach extends approximately 250 miles downstream to Rulo, NE at RM 498.0. The USACE Omaha District developed and calibrated the unsteady HEC-RAS flow model for this reach (USACE 2015). The model extent and tributaries entering the Missouri River for the Gavins Point Dam to Rulo reach are shown in Figure 28. USGS stations shown in this figure are only flow gages.

Figure 28. HEC-RAS model extent for the Gavins Point Dam to Rulo reach (USACE 2015).



Refer to the model schematic shown in Figure 28 for the locations of significant tributaries, many tributaries enter the Gavins Point Dam to Rulo reach. Major tributaries were simulated as separate routing reaches within the HEC-RAS model. Minor tributaries that have USGS gage data were included as lateral inflow to the model.

4.3.4.2 Water temperature model inputs

Meteorological data and inflow temperature boundary conditions for the Gavins Point Dam to Rulo reach HEC-RAS model are discussed below.

Meteorological Data

Four meteorological stations (NYKN, KSUX, KOMA, and KSTJ), shown in Figure 1, were used in the Gavins Point Dam to Rulo reach HEC-RAS temperature model. In HEC-RAS, the meteorological data from each station was automatically assigned to the closest water quality computational cells within the river reach.

Boundary conditions

Figure 29 presents approximate locations of inflow boundaries included in the Gavins Point Dam to Rulo reach HEC-RAS model. Water temperatures associated with each inflow boundary for the simulation period (1995–2012) were computed using regression relationships as explained previously in this chapter. The water temperatures from Gavins Point Dam release and inflow temperatures for all tributaries along the reach were specified in the model through a HEC-DSS file. Table 8. Inflow and temperature boundaries included in the HEC-RAS model for the Gavins Point Dam to Rulo reach. lists all water temperature boundaries corresponding to inflow boundaries along this river reach. If a water quality monitoring station was not available for the inflow boundary, observed data collected from adjacent water quality stations were used in the HEC-RAS water temperature model.

Figure 29. Schematic representation of inflow boundary locations included in the HEC-RAS model for the Gavins Point Dam to the Rulo reach.

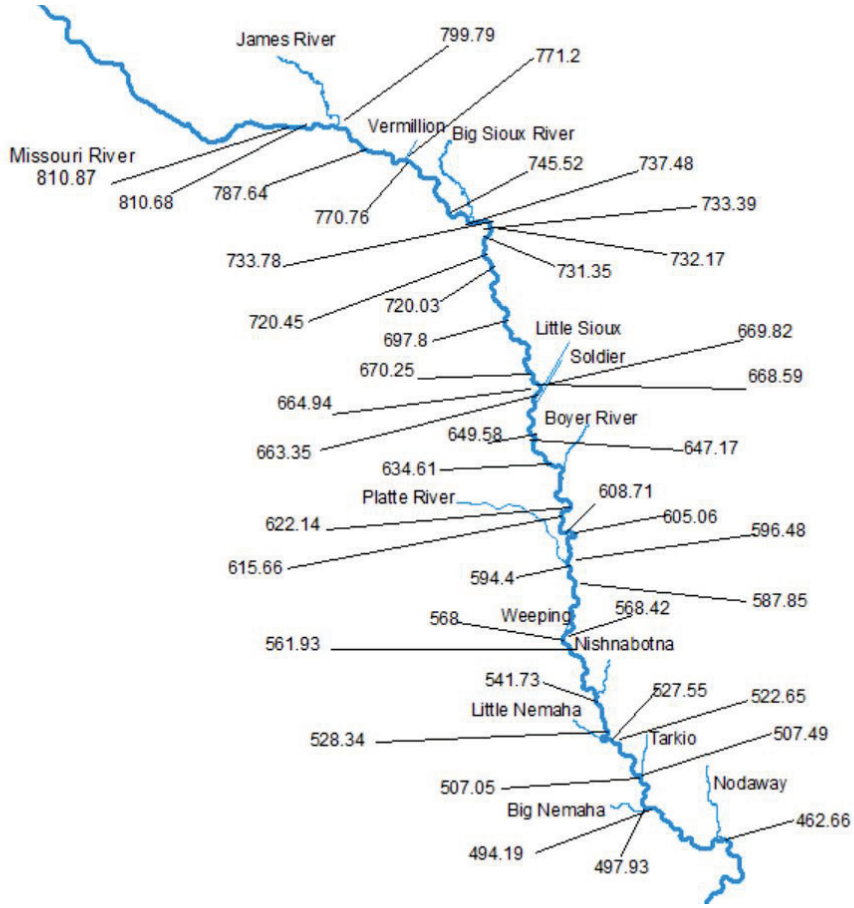


Table 8. Inflow and temperature boundaries included in the HEC-RAS model for the Gavins Point Dam to Rulo reach.

No	Inflow boundary	Flow boundary type	Water quality boundary
1	Big Nemaha River RS 13.66	Tributary	BC1
2	Big Sioux River RS 50.93	Tributary	BC2
3	Boyer River RS 15.75	Tributary	BC3
4	James River RS 55.606	Tributary	BC4
5	Little Nemaha River RS 10.52	Tributary	BC1
6	Little Sioux River RS 13.35	Tributary	BC5
7	Missouri River RS 810.87	Upstream boundary from dam release	BC6
8	Missouri River RS 810.68	Uniform lateral inflow	BC6
9	Missouri River RS 810.68	Uniform lateral inflow (withdraw)	
10	Missouri River RS 799.79	Uniform lateral inflow (withdraw)	

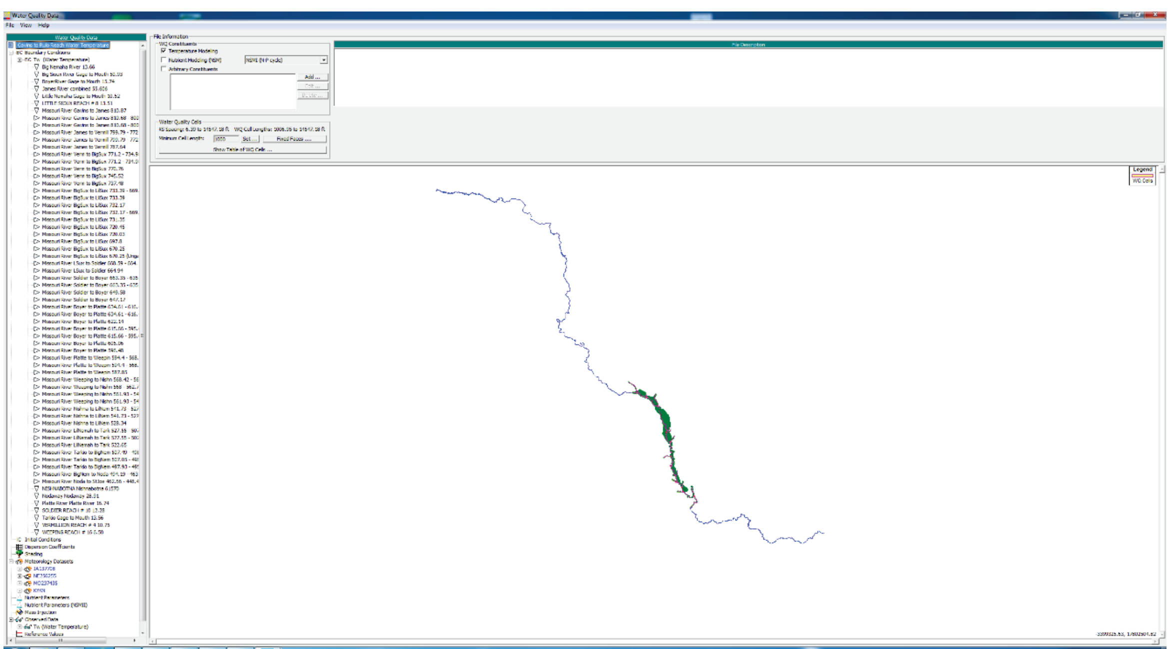
11	Missouri River RS 799.79	Uniform lateral inflow	BC7
12	Missouri River RS 787.64	Lateral inflow	BC7
13	Missouri River RS 771.20	Uniform lateral inflow	BC8
14	Missouri River RS 771.20	Uniform lateral inflow (withdraw)	
15	Missouri River RS 770.76	Lateral inflow	BC8
16	Missouri River RS 745.52	Lateral inflow	BC9
17	Missouri River RS 737.48	Lateral inflow	BC9
18	Missouri River RS 733.39	Lateral inflow	BC9
19	Missouri River RS 733.39	Uniform lateral inflow	BC9
20	Missouri River RS 732.17	Lateral inflow	BC9
21	Missouri River RS 732.17	Uniform lateral inflow	BC9
22	Missouri River RS 731.35	Lateral inflow	BC9
23	Missouri River RS 720.45	Lateral inflow	BC9
24	Missouri River RS 720.03	Lateral inflow	BC9
25	Missouri River RS 697.80	Lateral inflow	BC10
26	Missouri River RS 670.25	Lateral inflow	BC10
27	Missouri River RS 670.25	Lateral inflow	BC10
28	Missouri River RS 668.59	Uniform lateral inflow	BC10
29	Missouri River RS 664.94	Lateral inflow	BC3
30	Missouri River RS 663.35	Uniform lateral inflow (withdraw)	
31	Missouri River RS 663.35	Uniform lateral inflow	BC3
32	Missouri River RS 649.58	Lateral inflow	BC3
33	Missouri River RS 647.17	Lateral inflow	BC3
34	Missouri River RS 634.61	Uniform lateral inflow	BC11
35	Missouri River RS 622.14	Lateral inflow	BC11
36	Missouri River RS 615.66	Uniform lateral inflow	BC11
37	Missouri River RS 605.06	Lateral inflow	BC12
38	Missouri River RS 596.48	Lateral inflow	BC12
39	Missouri River RS 594.4	Uniform lateral inflow	BC12
40	Missouri River RS 587.85	Lateral inflow	BC12
41	Missouri River RS 568	Uniform lateral inflow	BC13
42	Missouri River RS 561.93	Uniform lateral inflow	BC13
43	Missouri River RS 541.73	Uniform lateral inflow	BC14
44	Missouri River RS 528.34	Lateral inflow	BC1

45	Missouri River RS 527.55	Uniform lateral inflow	BC1
46	Missouri River RS 522.65	Uniform lateral inflow	BC1
47	Missouri River RS 507.49	Uniform lateral inflow	BC1
48	Missouri River RS 507.05	Uniform lateral inflow	BC1
49	Nishnabotna River RS 61570	Tributary	BC14
50	Nodaway River RS 28.91	Tributary	BC15
51	Platte River RS 16.74	Tributary	BC13
52	Soldier River RS 13.09	Tributary	BC5
53	Tarkio River RS 13.56	Tributary	BC1
54	Vermillion River RS 10.17	Tributary	BC16
55	Weeping River RS 6.19	Tributary	BC13

4.3.4.3 Water temperature model set up and calibration

The HEC-RAS temperature model for the Gavins Point Dam to Rulo reach was set up and run using an hourly time step from January 1, 1995–December 31, 2012. Figure 30 shows the schematic and data plan of the HEC-RAS temperature model for this reach. The minimum water quality cell length in HEC-RAS was set as 1000 ft.

Figure 30. Schematic and data plan of the HEC-RAS temperature model for the Gavins Point Dam to Rulo reach.



The HEC-RAS water temperature model calibration for the Gavins Point Dam to Rulo reach primarily focused on six USGS stations with observed data along this reach. These six USGS stations are 06478526, 06486000, 06601200, 06610000, 06807000, and 06813500. Their locations on the main stem Missouri River are shown in Figure 31. Time series plots of HEC-RAS predicted and observed data are presented in Figures 32–37.

Figure 31. HEC-RAS water temperature calibration locations from the Gavins Point Dam to the mouth of the Missouri River.

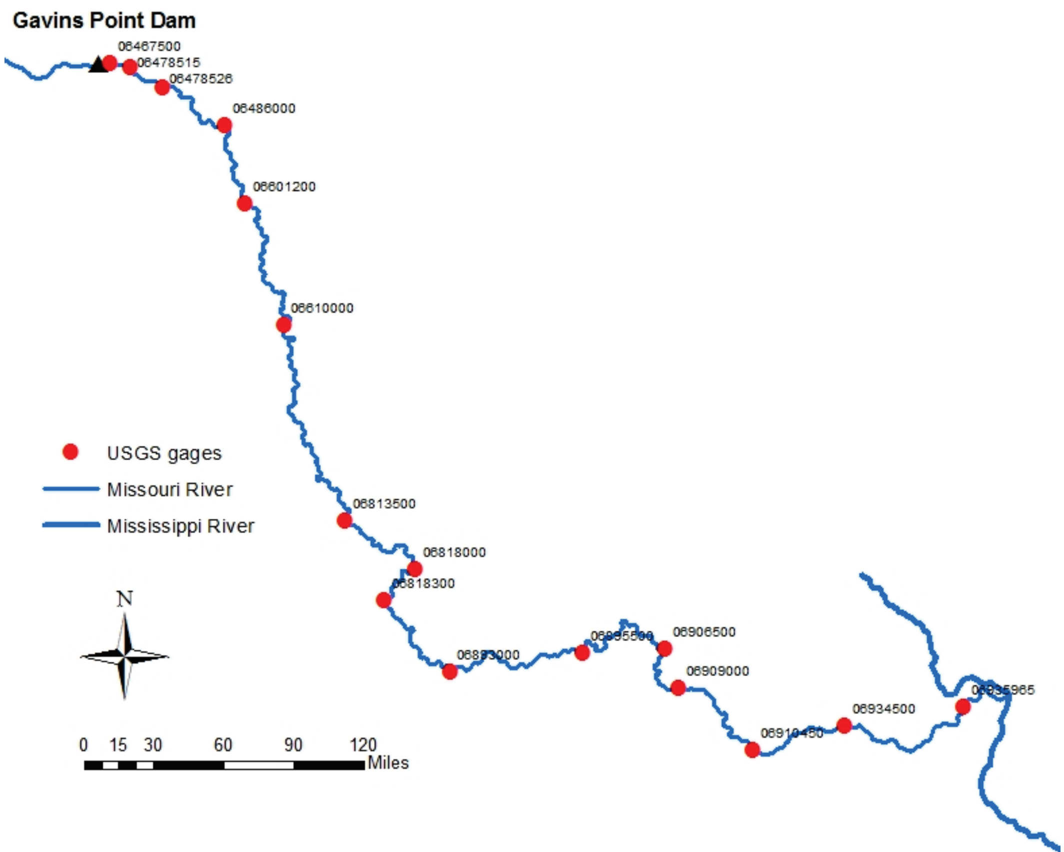


Figure 32. HEC-RAS predicted versus observed water temperatures of the Missouri River near Maskell, NE (USGS 06478526).

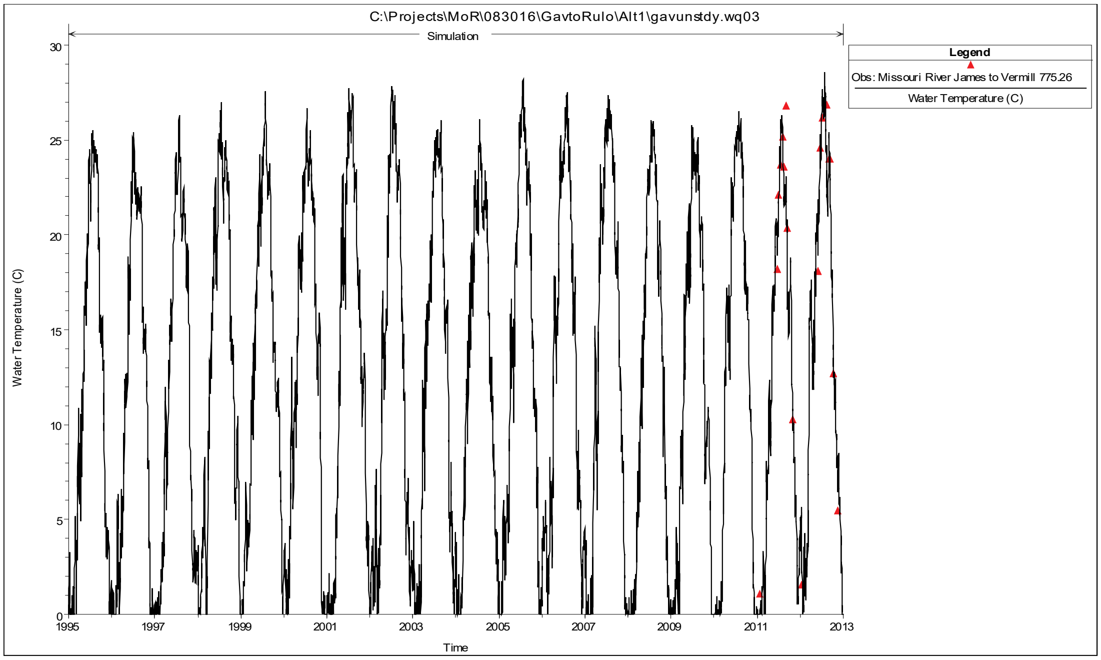


Figure 33. HEC-RAS predicted versus observed water temperatures of the Missouri River at Sioux City, IA (USGS 06486000).

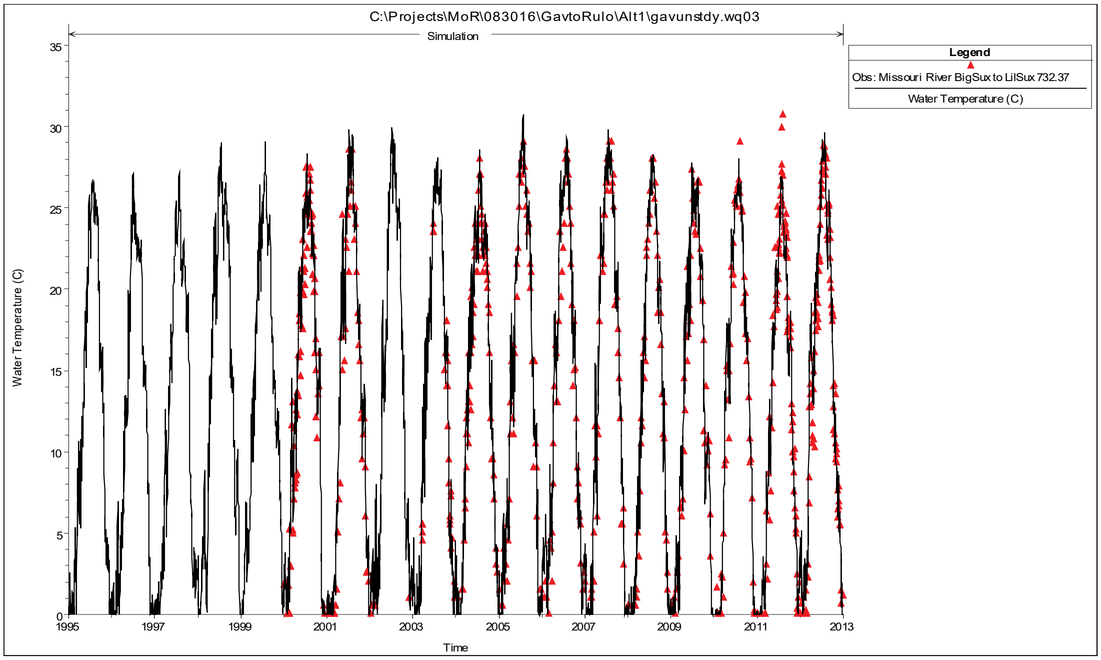


Figure 34. HEC-RAS predicted versus observed water temperatures of the Missouri River at Decatur, NE (USGS 06601200).

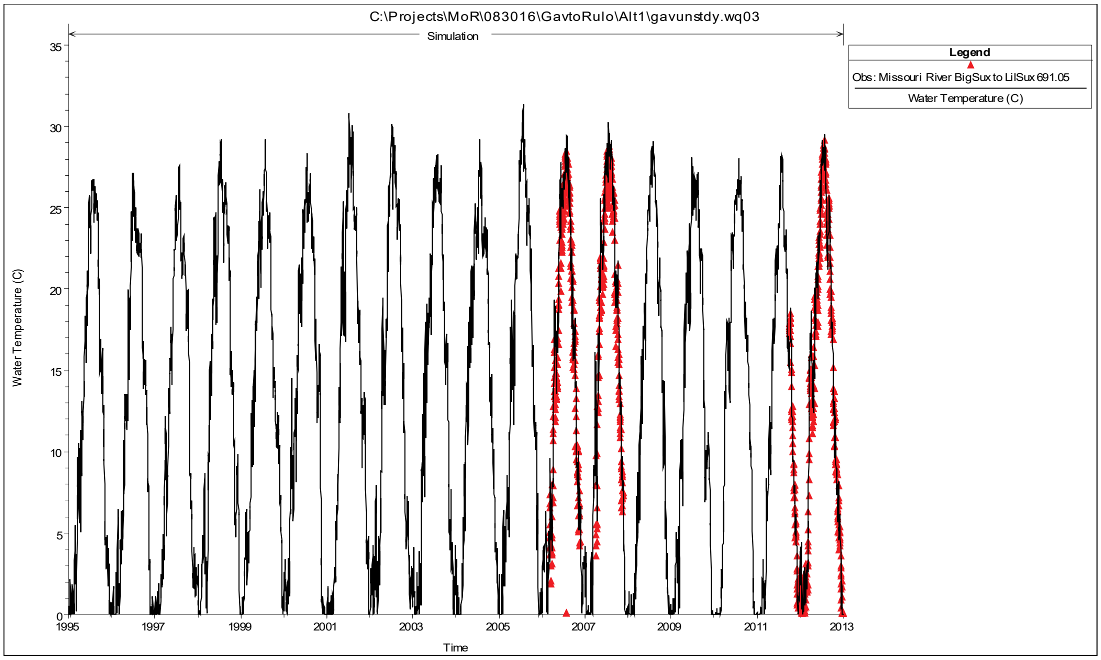


Figure 35. HEC-RAS predicted versus observed water temperatures of the Missouri River at Omaha, NE (USGS 06610000).

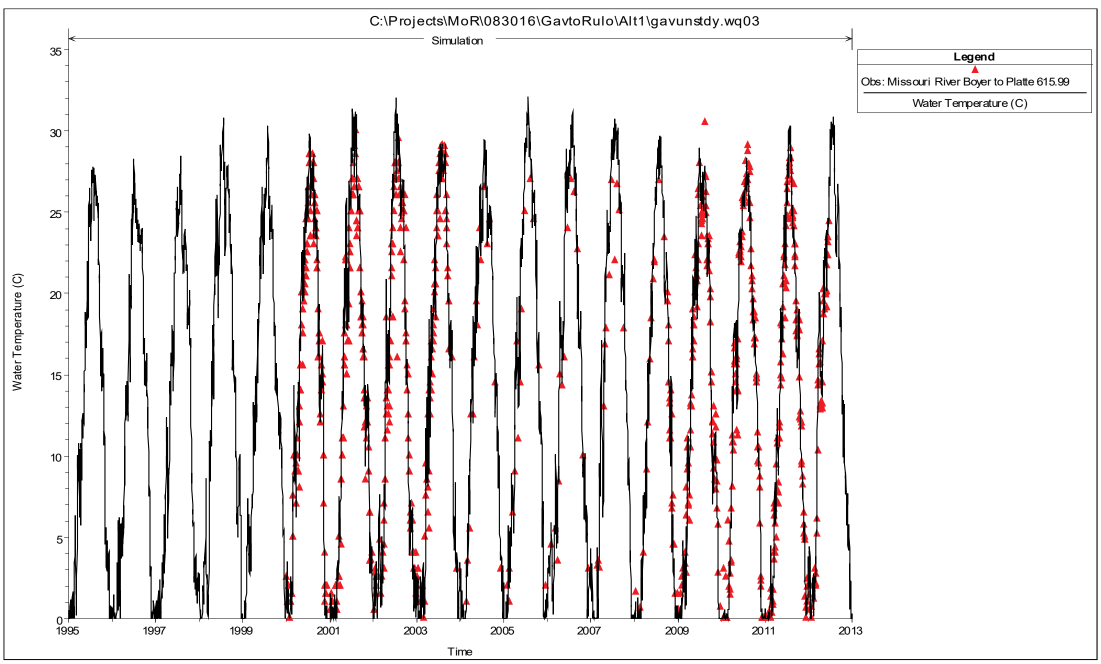


Figure 36. HEC-RAS predicted versus observed water temperatures of the Missouri River at Nebraska City, NE (USGS 06807000).

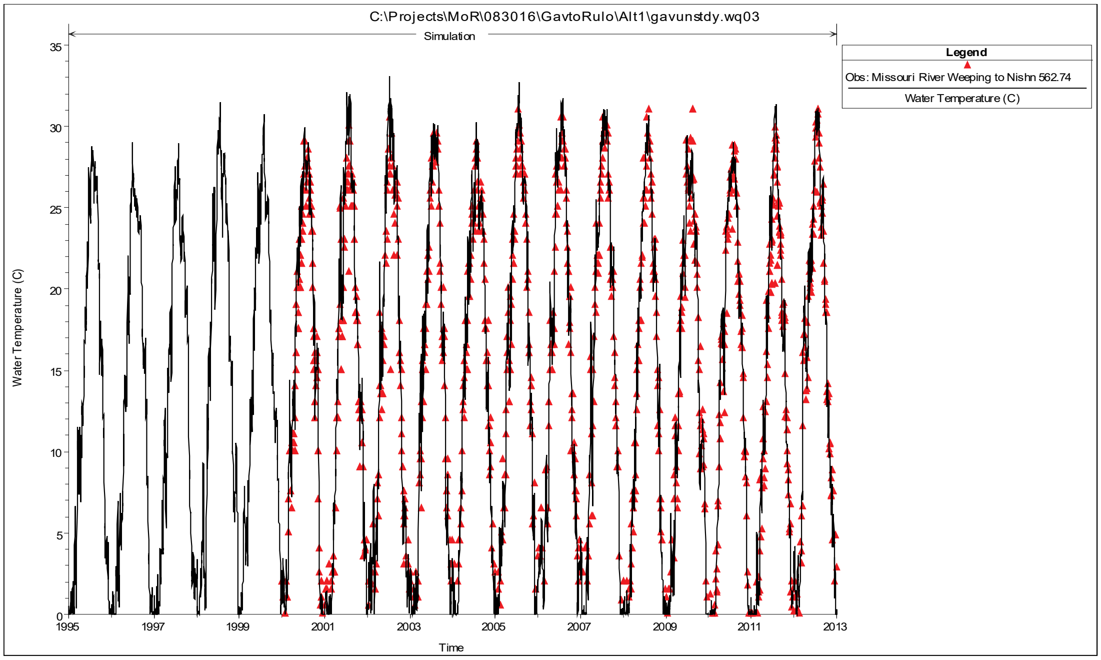
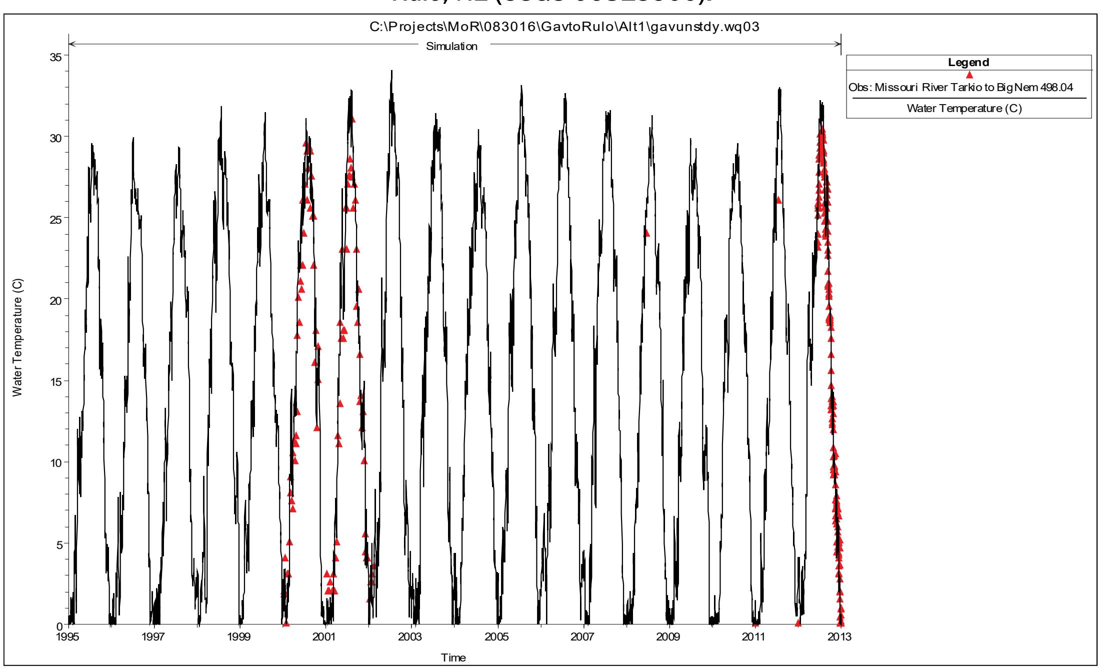


Figure 37. HEC-RAS predicted versus observed water temperatures of the Missouri River at Rulo, NE (USGS 06813500).



The above time series plots suggest a fairly good agreement between the HEC-RAS predictions and observations for all six calibration locations along this river reach, except that the model tends to over predict the peak water temperatures during summer seasons.

4.3.5 Rulo to the Mouth of the Missouri River

4.3.5.1 HEC-RAS flow model

From the Rulo (Rulo, NE) to the mouth reach of the Missouri River (near St. Louis, MO) is approximately 498 miles. This reach meanders south through the dissected till plaines of the central lowlands to Kansas City, then traverses east along the northern border of the Osage Plains and Ozark Plateau until it empties into the Mississippi River. Major tributaries include the Kansas, Grand, Chariton, Osage, and Gasconade. USACE Kansas City District developed and calibrated the unsteady HEC-RAS flow model for the Rulo to the mouth reach of the Missouri River (USACE 2015). The model extent and tributaries entering the Missouri River within this reach are shown in Figure 38.

Figure 38. HEC-RAS model extent for the Rulo to the Mouth of the Missouri River reach (USACE 2015).

In the HEC-RAS flow model, the model area was extended upstream and downstream because of the complicated nature of modeling extreme floods such as experienced in 1993 and 2011 at both Rulo and the confluence. Approximately 70 miles of the Mississippi River was included, with the upstream limit at the tailwater of Lock and Dam 25 and the downstream boundary approximately 10 miles downstream of the St. Louis USGS gage. Upstream, the model limits of the Missouri River were extended approximately 60 miles to Nebraska City, NE.

Fourteen tributary reaches were also simulated in the Rulo to the mouth of the Missouri River reach HEC-RAS model. The primary purposes of including tributary reaches were to route flows from the gage to the confluence with the Missouri. Other small tributaries entering the Missouri were specified as lateral inflow boundaries in the HEC-RAS model. In the HEC-RAS model, all ungaged inflow is uniformly distributed between gages based on basin area. Modeled tributaries include:

- Nishnabotna River
- Little Nemaha River
- Tarkio River
- Big Nemaha River
- Nodaway River
- Platte River
- Kansas River
- Grand River
- Chariton River
- Blackwater River
- Moreau River
- Osage River
- Gasconade River

4.3.5.2 Water temperature model Inputs

Meteorological data and inflow temperature boundary conditions for the Rulo to the mouth of the Missouri River reach HEC-RAS model are discussed below.

Meteorological data

Seven meteorological stations (KSTJ, KCOU, KSTL, KMCI, KMKC, KSUS, KJEF), shown in Figure 1, were used in the Rulo to the mouth of the Missouri River reach of the HEC-RAS water temperature model. In HEC-RAS, the meteorological data from each station was automatically assigned to water quality computational cells within the river reach based on the closest distance.

Boundary conditions

Figure 39 presents approximate locations of flow boundaries included in the Rulo to the mouth of the Missouri River reach of the HEC-RAS model.

Water temperatures associated with each inflow boundary for the simulation period (1995–2012) were computed using the developed regressions as explained previously and specified in the model through a HEC-DSS file. Table 9 lists all water temperature boundaries corresponding to inflow boundaries along this river reach.

Figure 39. Schematic representation of inflow boundary locations included in the HEC-RAS model from Rulo to the mouth of the Missouri River.

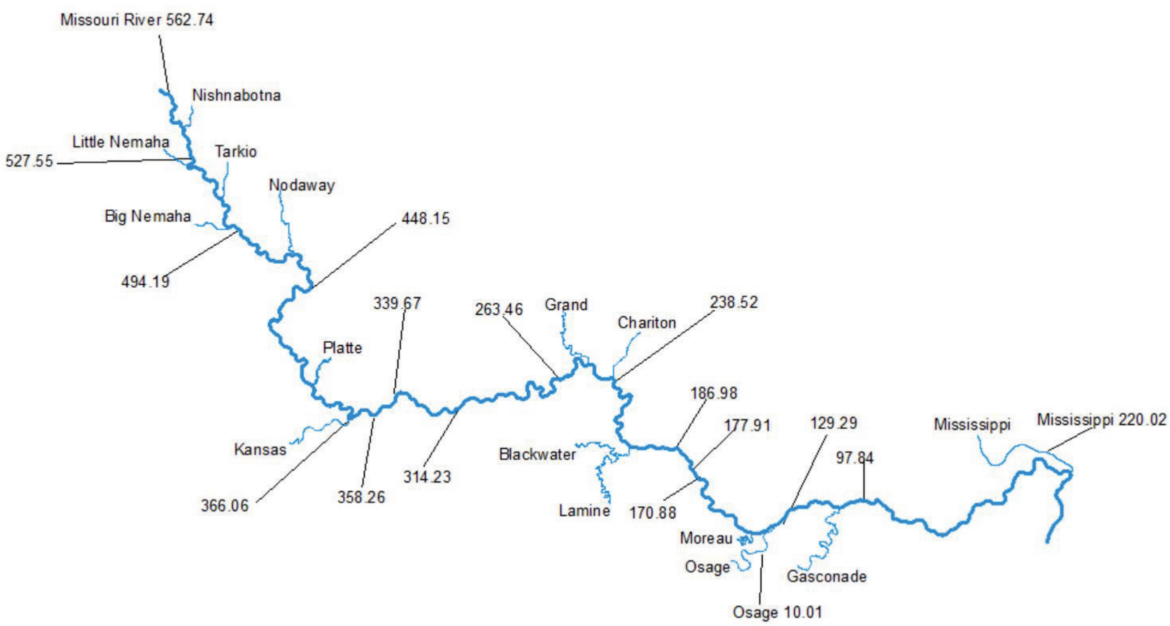


Table 9. Inflow and temperature boundaries included in the HEC-RAS model from Rulo to the mouth of the Missouri River.

No	Inflow boundary	Flow boundary type	Water quality boundary
1	Big Nemaha River RS 13.66	Tributary	BC1
2	Blackwater River RS 25.77	Tributary	BC2
3	Chariton RS 19.64	Tributary	BC3
4	Gasconade RS 51.64	Tributary	BC4
5	Grand RS 34.87	Tributary	BC5
6	Kansas RS 30.42	Tributary	BC6
7	Lamine RS 56.99	Tributary	BC7
8	Little Nemaha River RS 10.47	Tributary	BC1
9	Mississippi River RS 241.33	Tributary	BC8
10	Mississippi River RS 220.02	Lateral inflow	BC8
11	Missouri River RS 562.74	Upstream boundary	BC11

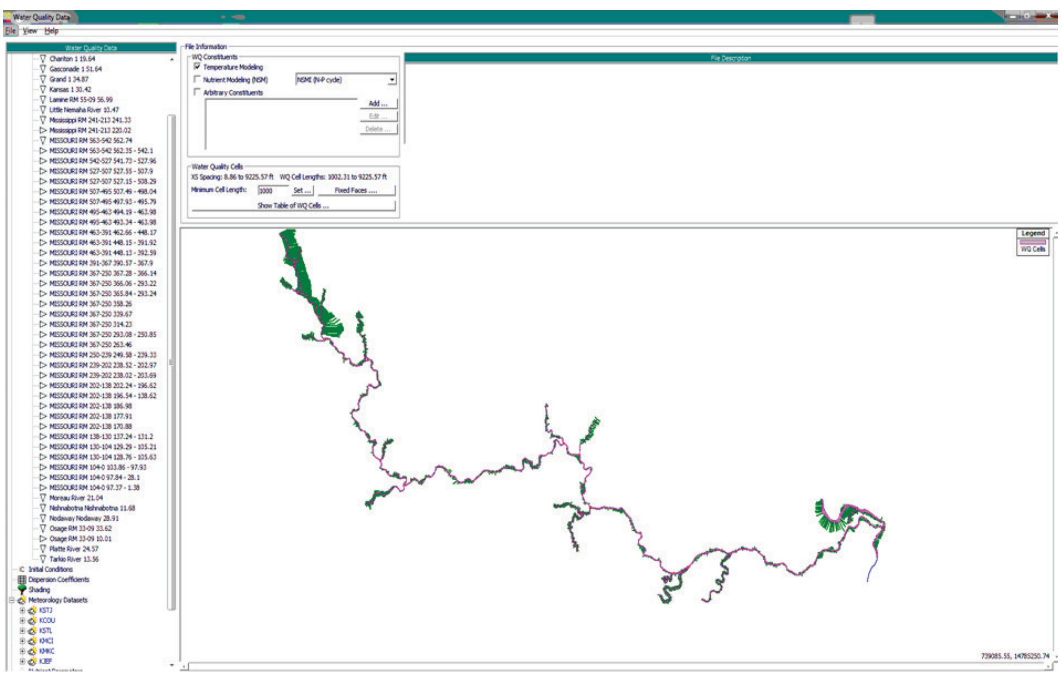
12	Missouri River RS 562.35	Uniform lateral inflow (withdraw)	
13	Missouri River RS 541.73	Uniform lateral inflow (withdraw)	
14	Missouri River RS 527.55	Uniform lateral inflow	BC12
15	Missouri River RS 527.15	Uniform lateral inflow (withdraw)	
16	Missouri River RS 507.49	Uniform lateral inflow (withdraw)	
17	Missouri River RS 497.93	Uniform lateral inflow (withdraw)	
18	Missouri River RS 494.19	Uniform lateral inflow	BC13
19	Missouri River RS 493.34	Uniform lateral inflow (withdraw)	
20	Missouri River RS 462.66	Uniform lateral inflow (withdraw)	
21	Missouri River RS 448.15	Uniform lateral inflow	BC14
22	Missouri River RS 448.13	Uniform lateral inflow (withdraw)	
23	Missouri River RS 390.57	Uniform lateral inflow (withdraw)	
24	Missouri River RS 367.28	Uniform lateral inflow (withdraw)	
25	Missouri River RS 366.06	Uniform lateral inflow	BC15
26	Missouri River RS 365.84	Uniform lateral inflow (withdraw)	
27	Missouri River RS 358.26	Lateral inflow	BC15
28	Missouri River RS 339.67	Lateral inflow	BC16
29	Missouri River RS 314.23	Lateral inflow	BC17
30	Missouri River RS 293.08	Uniform lateral inflow (withdraw)	
31	Missouri River RS 263.46	Lateral inflow	BC18
32	Missouri River RS 249.58	Uniform lateral inflow (withdraw)	
33	Missouri River RS 238.52	Uniform lateral inflow	BC18
34	Missouri River RS 238.02	Uniform lateral inflow (withdraw)	
35	Missouri River RS 202.24	Uniform lateral inflow (withdraw)	
36	Missouri River RS 196.54	Uniform lateral inflow (withdraw)	
37	Missouri River RS 186.98	Lateral inflow	BC19
38	Missouri River RS 177.91	Lateral inflow	BC20
39	Missouri River RS 170.88	Lateral inflow	BC20
40	Missouri River RS 137.24	Uniform lateral inflow (withdraw)	
41	Missouri River RS 129.29	Uniform lateral inflow	BC21
42	Missouri River RS 128.76	Uniform lateral inflow (withdraw)	
43	Missouri River RS 103.86	Uniform lateral inflow (withdraw)	
44	Missouri River RS 97.84	Uniform lateral inflow	BC22
45	Missouri River RS 97.37	Uniform lateral inflow (withdraw)	

46	Moreau River RS 21.04	Tributary	BC23
47	Nishnabotna RS 11.68	Tributary	BC24
48	Nodaway RS 28.91	Tributary	BC25
49	Osage RS 33.62	Tributary	BC26
50	Osage RS 10.01	Lateral inflow	BC26
51	Platte River RS 24.57	Tributary	BC27
52	Tarkio River RS 13.56	Tributary	BC8

4.3.5.3 Water temperature model set up and calibration

The HEC-RAS temperature model from Rulo to the mouth of the Missouri River was set up and run using an hourly time step from January 1, 1995–December 31, 2012. Figure 40 shows the schematic and data plan of the HEC-RAS temperature model for this reach. The minimum water quality cell length in HEC-RAS was set as 1000 ft.

Figure 40. Schematic and data plan of the HEC-RAS temperature model for the Rulo to the Mouth of the Missouri River.



The water temperature model calibration primarily focused on five USGS stations with limited observed data along this reach. These five USGS stations are 06818000, 06893000, 06895500, 06906500, and 06934500. Their locations on the main stem Missouri River can be found in Figure 31. Time series plots of HEC-RAS modeled and observed data are presented in

Figures 41–45. These figures show the comparison of HEC-RAS predicted and observed mean daily stream temperatures.

Figure 41. HEC-RAS predicted versus observed water temperatures of the Missouri River at St. Joseph, MO (USGS 06818000).

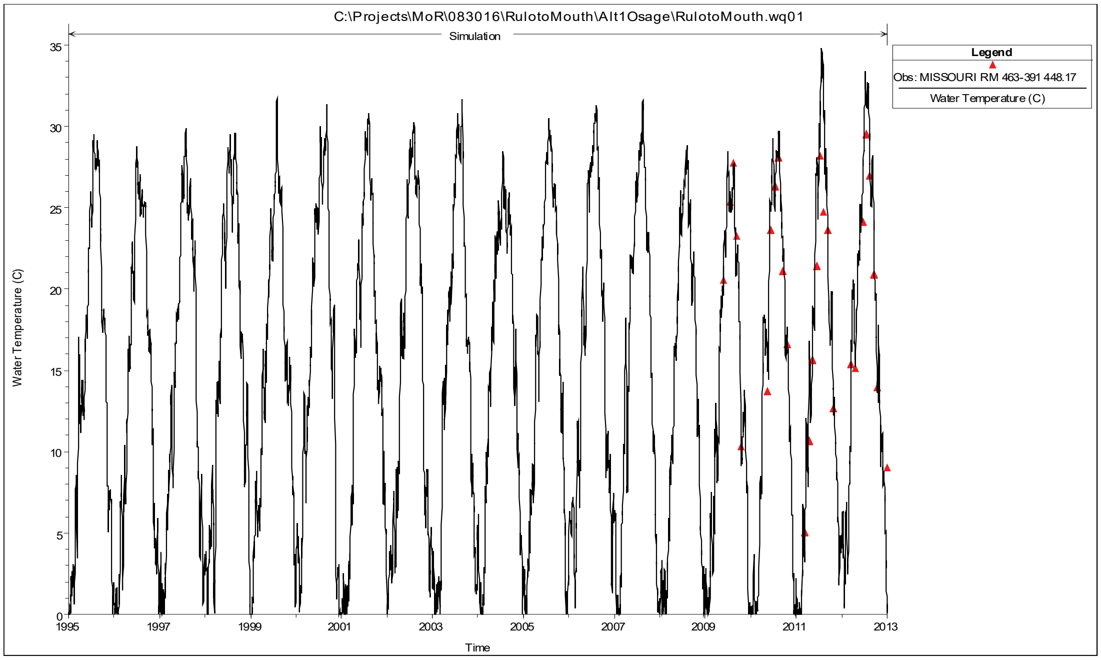


Figure 42. HEC-RAS predicted versus observed water temperatures of the Missouri River at Kansas City, MO (USGS 06893000).

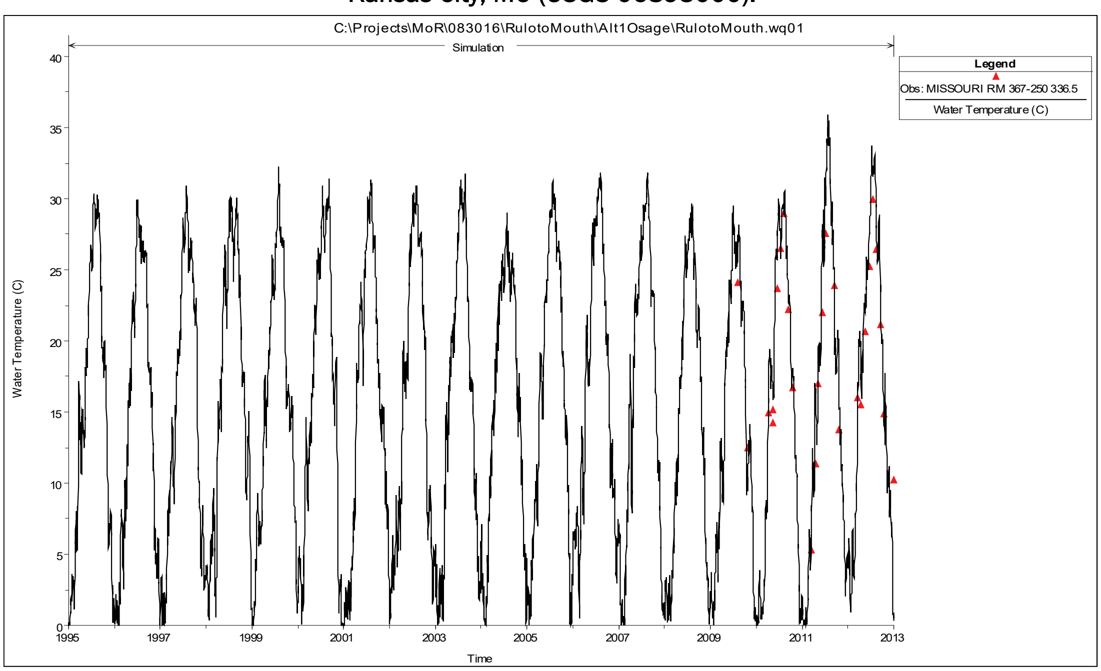


Figure 43. HEC-RAS predicted versus observed water temperatures of the Missouri River at Waverly, MO (USGS 06895500).

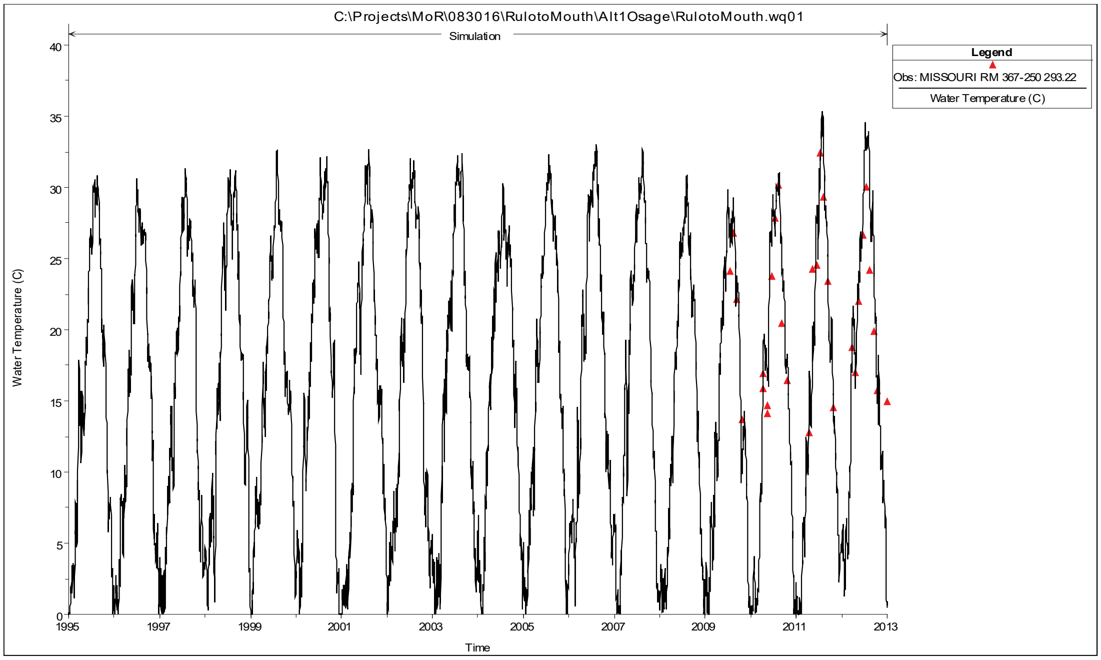


Figure 44. HEC-RAS predicted versus observed water temperatures of the Missouri River at Gasgow, MO (USGS 06906500).

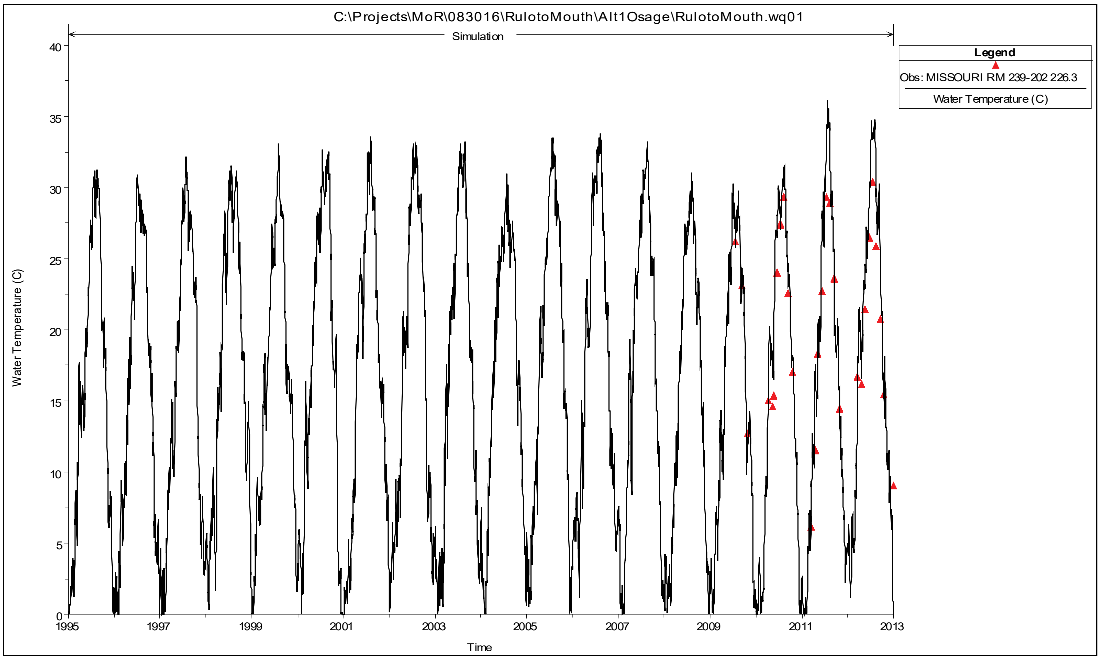
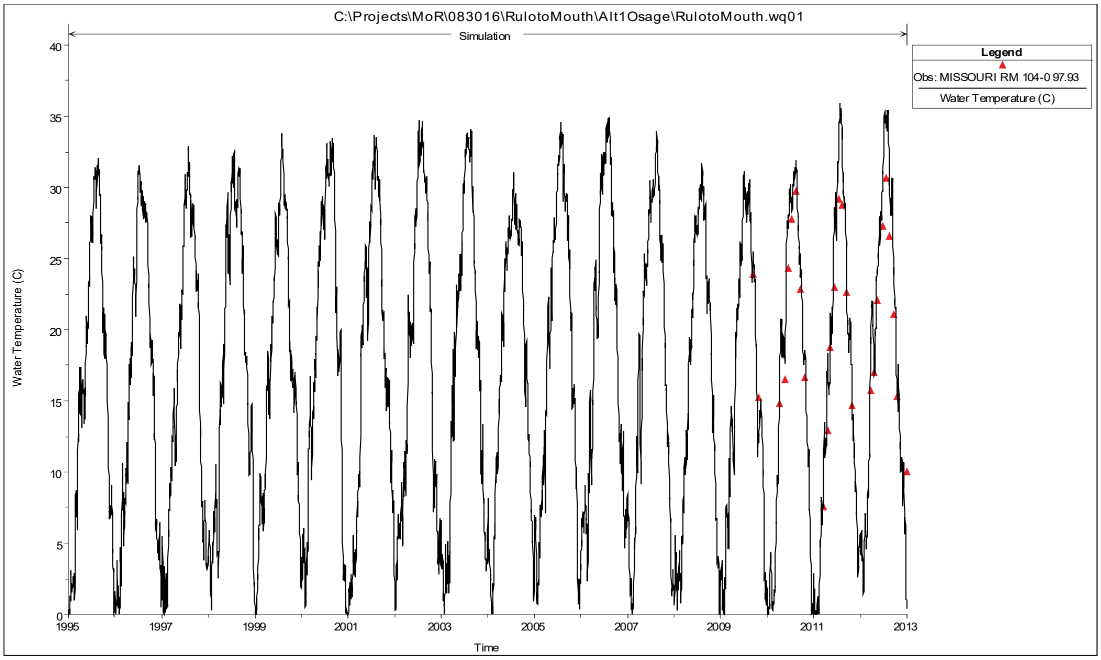


Figure 45. HEC-RAS predicted versus observed water temperatures of the Missouri River at Hermann, MO (USGS 06934500).



The above time series plots suggest a fairly good agreement between the HEC-RAS predictions and observations for five calibration locations, except that the model tends to over predict the peak water temperatures during summer seasons.

In summary, HEC-RAS water temperature models described above were preliminarily calibrated due to limited observed data and approximate boundary conditions. The sources of model uncertainty originate from the accuracy and temporal resolution of inflow water temperature boundary conditions included in the HEC-RAS models. Several water temperature boundary conditions computed from the regression relationships are quite uncertain due to limited observed data and use of air temperature as the only independent variable in developed regression relationships in this chapter. Additionally, water temperature model uncertainty also comes from the scarcity of stream water quality monitoring gages within the basin and the limited record available at these gages. Most water quality sample measurements for this study were obtained monthly during the summer. Additional observed water temperature data are necessary to improve and refine Missouri River HEC-RAS water temperature models described here.

5 Missouri River HEC-RAS Water Temperature Model Results for Alternatives

This chapter briefly describes the ManPlan and EIS alternatives (scenarios) USACE provided for use in three reach HEC-RAS water temperature models. These three river reaches are Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the mouth of the Missouri River. The HEC-RAS water temperature results for each reach and each alternative were stored in their corresponding HEC-DSS files and provided to the project team.

Alternatives evaluated in the ManPlan and EIS were informed by the best available science and shaped through collaboration among the USACE, USFWS, and the Missouri River Recovery Implementation Committee (MRRIC). The alternatives are collections of management actions aimed at providing habitat conditions to avoid a finding of jeopardy for the three listed species. Detailed description of the alternatives is provided in *Draft Missouri River Recovery Management Plan and Environmental Impact Statement* (USACE 2016). Table 10 provides a list of recently developed ManPlan and EIS alternatives conducted with the existing HEC-RAS flow models.

Table 10. List of alternatives evaluated with the Missouri River HEC-RAS models.

Alt	Geometry
1	No Action (Year 2012) (2012 geometry + new Shallow Water Habitat (SWH) + mechanical Emergent Sandbar Habitat (ESH)
2	Biological Opinion of the U.S. Fish and Wildlife Service (BiOp) As Projected (Year 2012) (2012 geometry + USFWS SWH/ESH/Inundation/Bi-modal Pulse)
3	All Mechanical (Year 2012) (2012 geometry + new Interception Rearing Complex (IRC) + mechanical ESH)
4	Spring 2, 42 MAF (Year 2012) (2012 geometry + new IRC + Spring Bird ESH Release + mechanical ESH)
5	Fall 5, 35 SL (Year 2012) (2012 geometry + new IRC + Fall Bird ESH Release + mechanical ESH)
7	Spawning cue (Year 2012) (2012 geometry + new IRC + Bi-modal spawning cue + mechanical ESH)

USACE Omaha and Kansas City Districts developed the HEC-RAS flow models for each river reach as well as each alternative. When constructing corresponding HEC-RAS water temperature models for three river reaches (e.g., Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the mouth of the Missouri River) and all alternatives listed in Table 10, the following assumptions were made:

- The HEC-RAS flow models for each river reach and all alternatives, were run in conjunction with the same historical meteorological and water temperature boundary forcings (1995–2012).
- Water quality parameters that were calibrated in the baseline HEC-RAS water temperature model for each reach were not adjusted while conducting alternative model runs.

The HEC-RAS water temperature models for each river reach and each alternative were then employed to compute the daily mean water temperatures for the 18-year (1995-2012) simulation period. The water temperature results at specified locations of the Missouri River (Table 11) were written into a HEC-DSS file for each reach and each alternative.

Table 11. List of HEC-RAS water temperature model output locations along the Missouri River.

River Mile (RM)	Location
Rulo to the mouth of the Missouri River reach	
57.85	Labadie Power Plant, Labadie, MO
115.39	Callaway Nuclear Power Plant, Portland, MO
336.50	KCP&L Sibley Power Station, Sibley, MO
345.67	Independence, MO Power (decommissioned 1/2016)
358.26	KCP&L Hawthorne Power Station, Kansas City, MO
365.84	Veolia Energy Grand Ave-summer PKG
373.45	Quindaro Power Station, Kansas City, KS
378.84	Nearman Creek Power Station, Nearman Creek Power Station, Kansas City, KS
410.70	KCPL-latan Power Station, Latan, MO
445.88	KCP&L St.Joseph-Lake Road Power Station, St Joseph, MO
Gavins Point Dam to Rulo reach	
532.50	NPPD-Cooper Nuclear Power Plant, Brownville, NE

556.37	OPPD-Power Plant, Nebraska City, NE
605.86	MidAmerican -- Walter Scott Energy Center, Council Bluffs, IA
625.22	OPPD-No.Omaha Power Station
645.99	OPPD-Ft.Calhoun Nuclear Power Plant, Council Bluffs, IA
716.83	Neal South-Unit 4 (MidAmerican), Sioux City, IA
718.44	Neal North-Unit 1-3 (MidAmerican), Sioux City, IA
Garrison Dam to Oahe Dam reach	
1319.46	Montana Dakota Utilities Heskett
1362.68	Great River Energy-Coal Creek
1364.56	Minnkota Power-Milton Young (Square Butte Electric)
1371.83	Basin Electric-Leland Olds Station and Great River Energy Stanton Station
1372.38	Montana Dakota Utilities Coyote

The HEC-RAS model predicted water temperatures stored in the HEC-DSS files can be used to produce a baseline condition (no action condition) against which alternatives will be assessed. As an illustration, Figure 46 shows the over 18-year time series plots of HEC-RAS model predicted daily flow at Missouri River RM 625.22 for alternatives 1 and 7. Figure 47 shows a comparison of HEC-RAS model predicted daily mean water temperatures at this location for alternatives 1 and 7. Local flow changes do not affect water temperature very much at this location under Alternative 7. The project team has assessed the potential impacts associated with each of the alternatives and the findings are discussed in technical reports available at www.moriverrecovery.org.

Figure 46. Model predicted daily mean flow discharge at Missouri River RM 625.22 for alternatives 1 and 7.

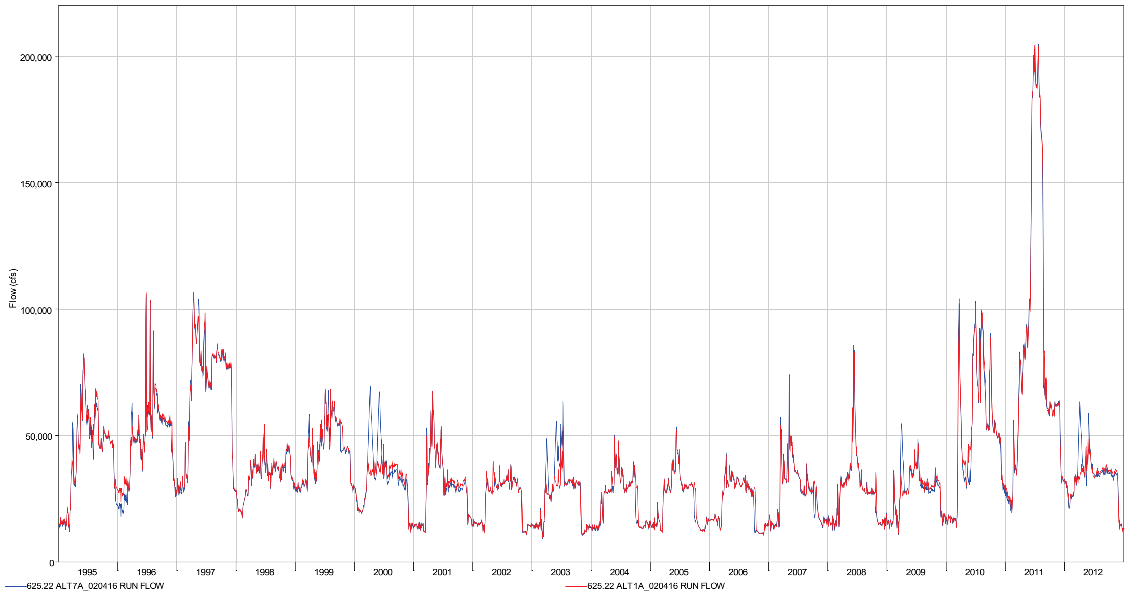
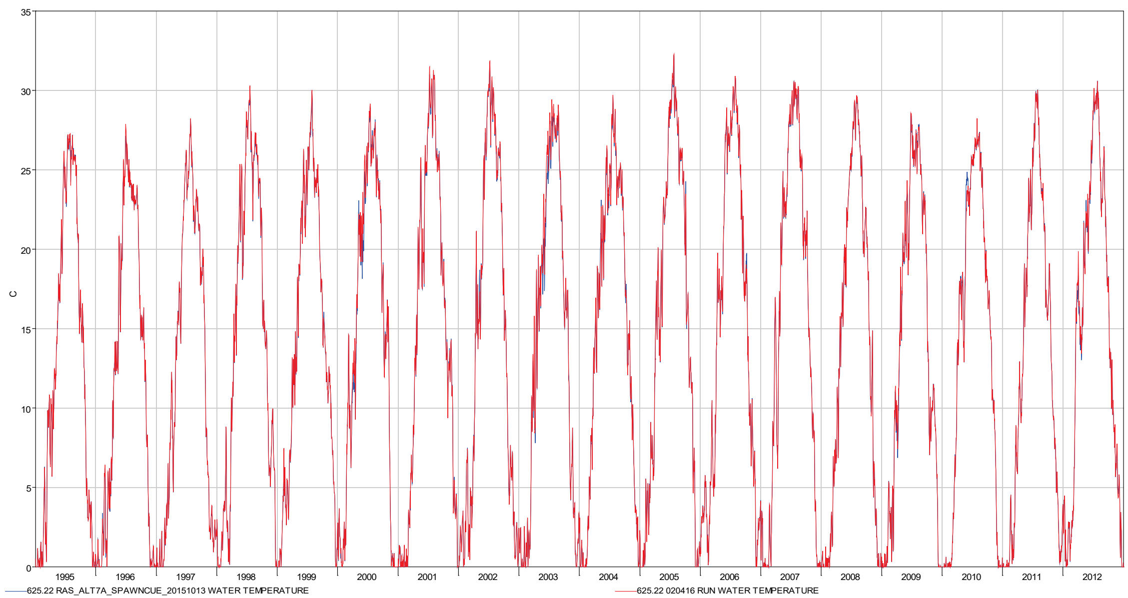


Figure 47. Model predicted daily mean water temperatures at Missouri River RM 625.22 for alternatives 1 and 7.



6 Conclusions and Summary

The HEC-RAS water temperature models for five reaches of the Missouri River (e.g., Fort Peck Dam to Garrison Dam, Garrison Dam to Oahe, Fort Randall Dam to Gavins Point Dam, Gavins Point Dam to Rulo, and Rulo to the mouth of the Missouri River) were developed and calibrated using available observed data. Of five models, multiple linear regression relationships of air-water temperatures were developed and used to compute long-term inflowing water temperature boundary conditions for three HEC-RAS models (e.g., Garrison Dam to Oahe, Gavins Point Dam to Rulo, and Rulo to the mouth of the Missouri River). The HEC-RAS water temperature models for these three reaches were set up and run from January 1, 1995–December 31, 2012, and the model results for three river reaches were used in support of conducting current ManPlan and EIS analysis.

In this study, various factors contributed to model error for water temperature predictions in the HEC-RAS models. The largest sources of model input uncertainty contributing to model error were the accuracy and temporal resolution of inflow water temperature boundary conditions. Water temperature boundary conditions computed from regression relationships showed errors because of limited observed data and the best-fit regression equation, which uses only air temperature as the single independent variable for predicting water temperature. Observed data sets used for each reach only covered the period 2009–2012. Additionally, most of the water temperature measurements were conducted monthly during the summer. These data limitations can certainly impact the accuracy of computed water temperatures.

Since this study is a work in progress, the following recommendations are provided for future model updates and improvement. Inflow water temperature predictions can be improved when watershed hydrology is incorporated into the model; thus, a basin wide watershed model is especially useful for generating accurate boundary conditions where varying inflow components propel differences in stream temperatures, and a lack of sufficient data is observed. Furthermore, watershed models that simulate the influence of all hydrologic sources (e.g., snowmelt, groundwater inflow, surface runoff, and stream discharge) and water quality together possess the capability to project the effects of hydrologic changes on stream temperature.

The existence of point sources along the Missouri River may have significant effects on stream temperatures. Flow boundary conditions for wastewater treatment plants and other industries discharging into the Missouri River were grouped together as ungaged flow in the current HEC-RAS flow models. Ungaged inflow represents that portion of the flow that is not captured by the gage station records, and then is calculated within HEC-RAS. Thus, point source flows and temperatures were not specified in the HEC-RAS models. It is recommended that all major point sources should be included as inflow boundary conditions in the Missouri River HEC-RAS models.

Due to the limited observed water temperature data available for this study, additional data should be collected for all inflow tributaries and the main stem Missouri River. Once additional observed data are available, regression relationships and boundary conditions for the HEC-RAS models can be improved and refined. Missouri River HEC-RAS water temperature model results will be updated with improved data sets.

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Appendix A: Time Series Plots of Regression Computed versus Observed Water Temperatures for the Garrison Dam to Oahe Dam River Reach

Figures A1–A8 show the 18 year (1995-2012) time series plots of regression computed and observed inflow boundary water temperatures for the Garrison Dam to Oahe Dam reach HEC-RAS model.

Figure A1. Regression computed versus observed water temperatures at BC1.

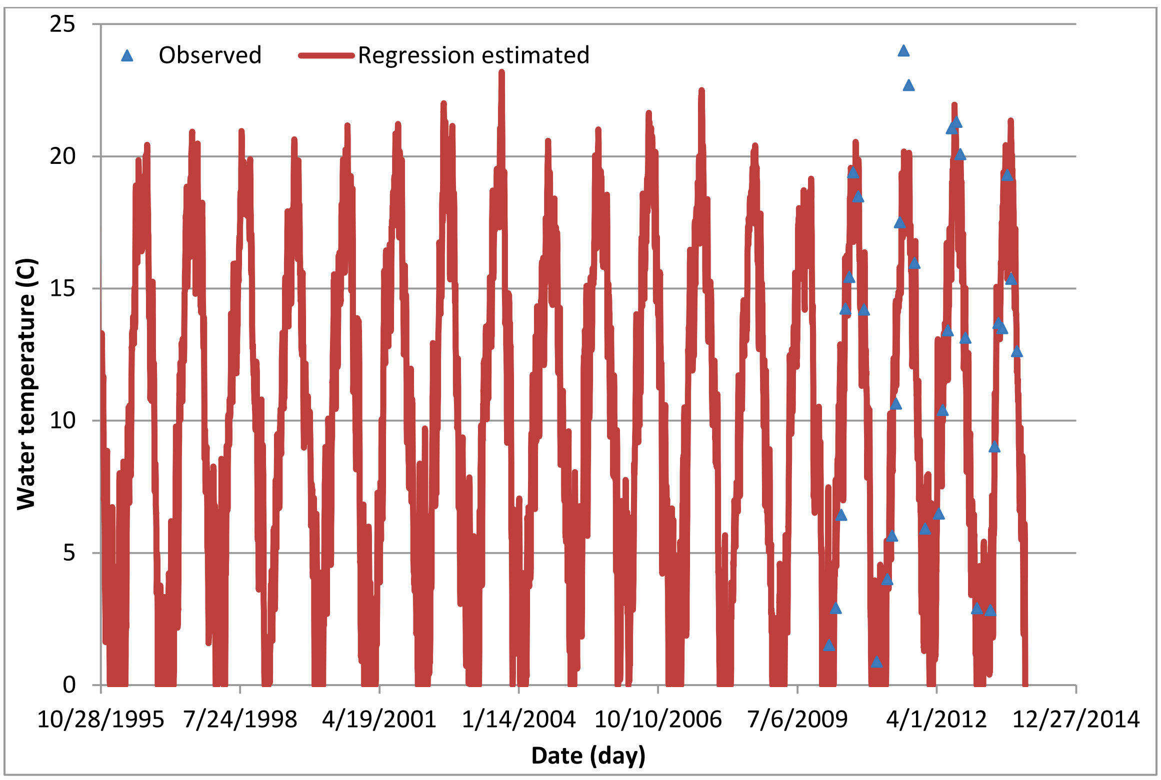


Figure A2. Regression computed versus observed water temperatures at BC2.

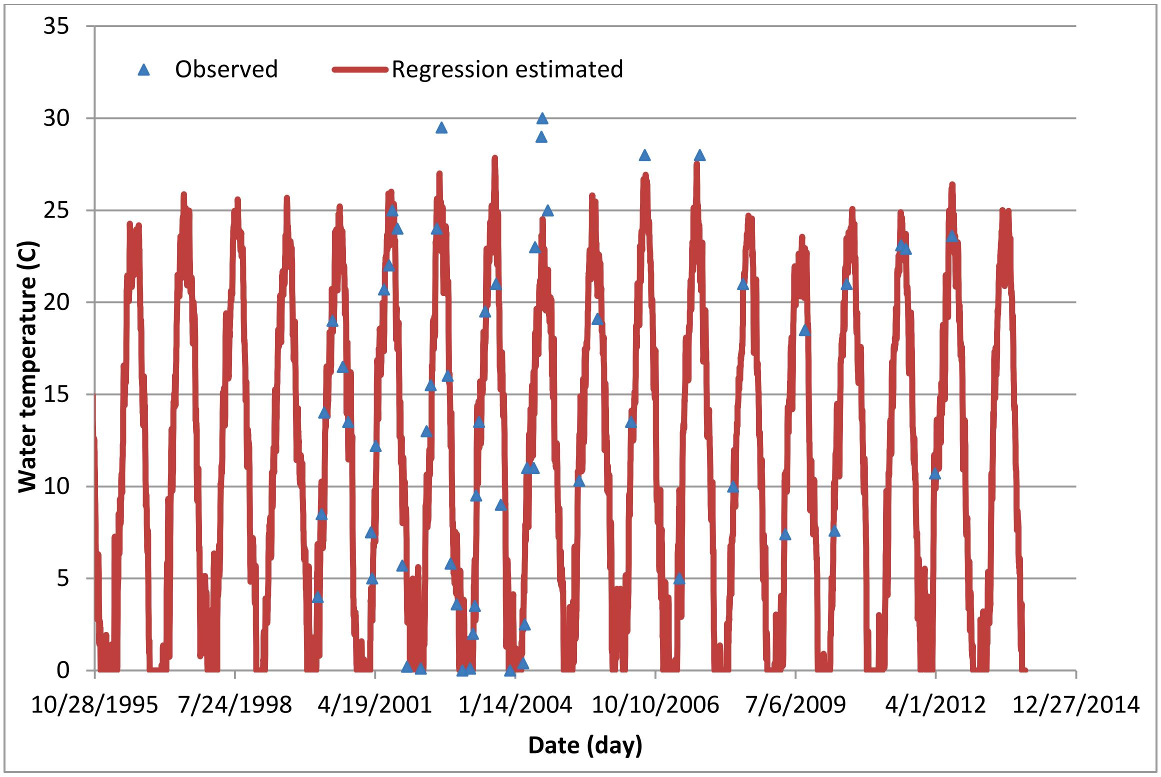


Figure A3. Regression computed versus observed water temperatures at BC3.

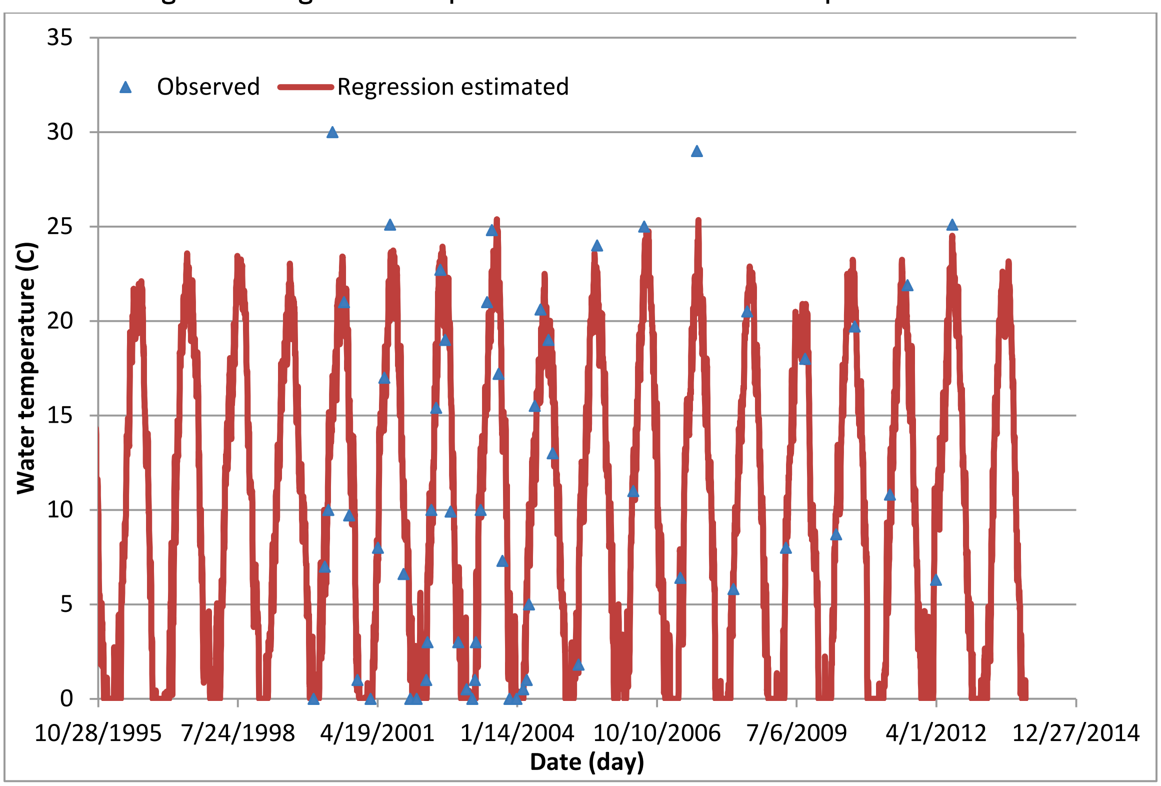


Figure A4. Regression computed versus observed water temperatures at BC4.

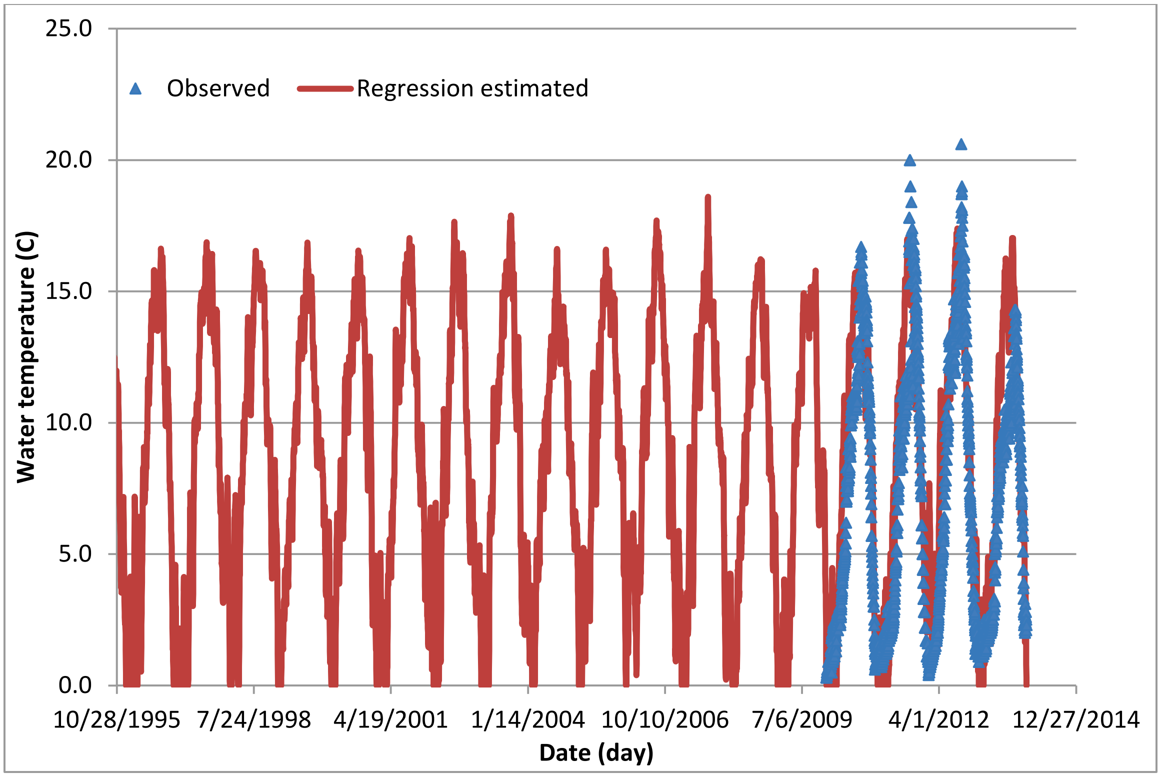


Figure A5. Regression computed versus observed water temperatures at BC5.

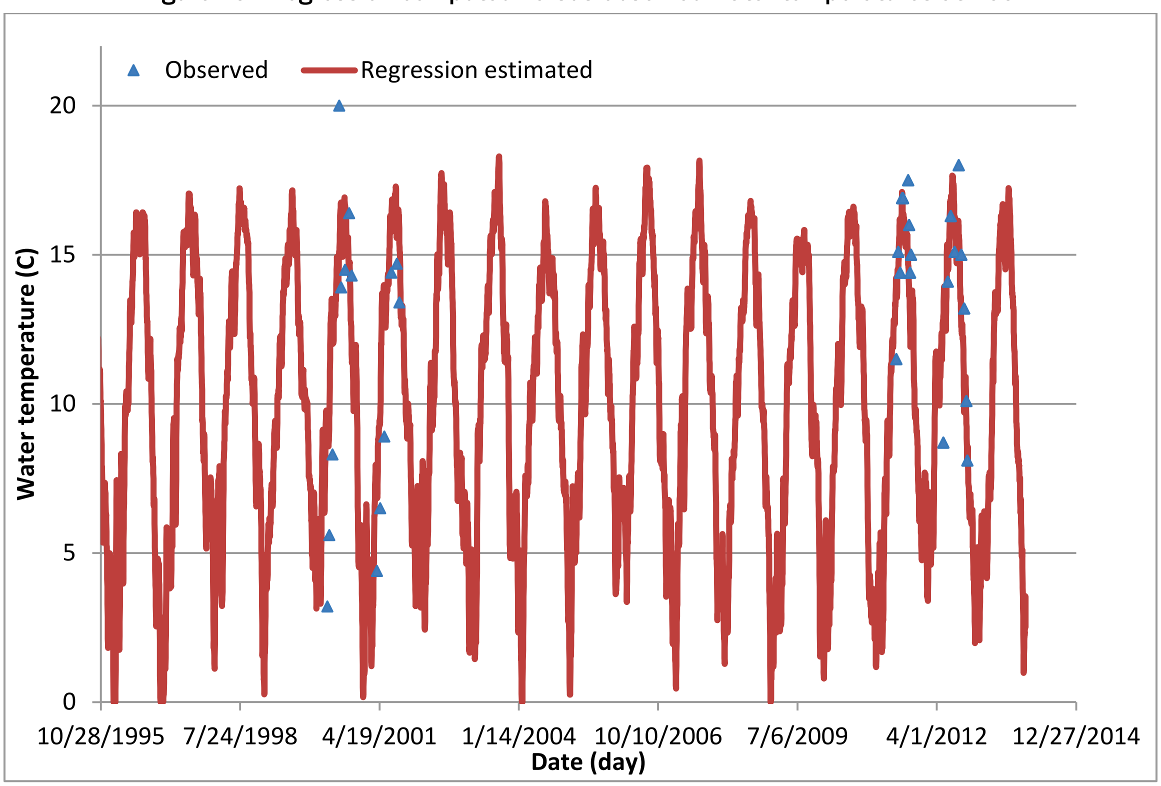


Figure A6. Regression computed versus observed water temperatures at BC6.

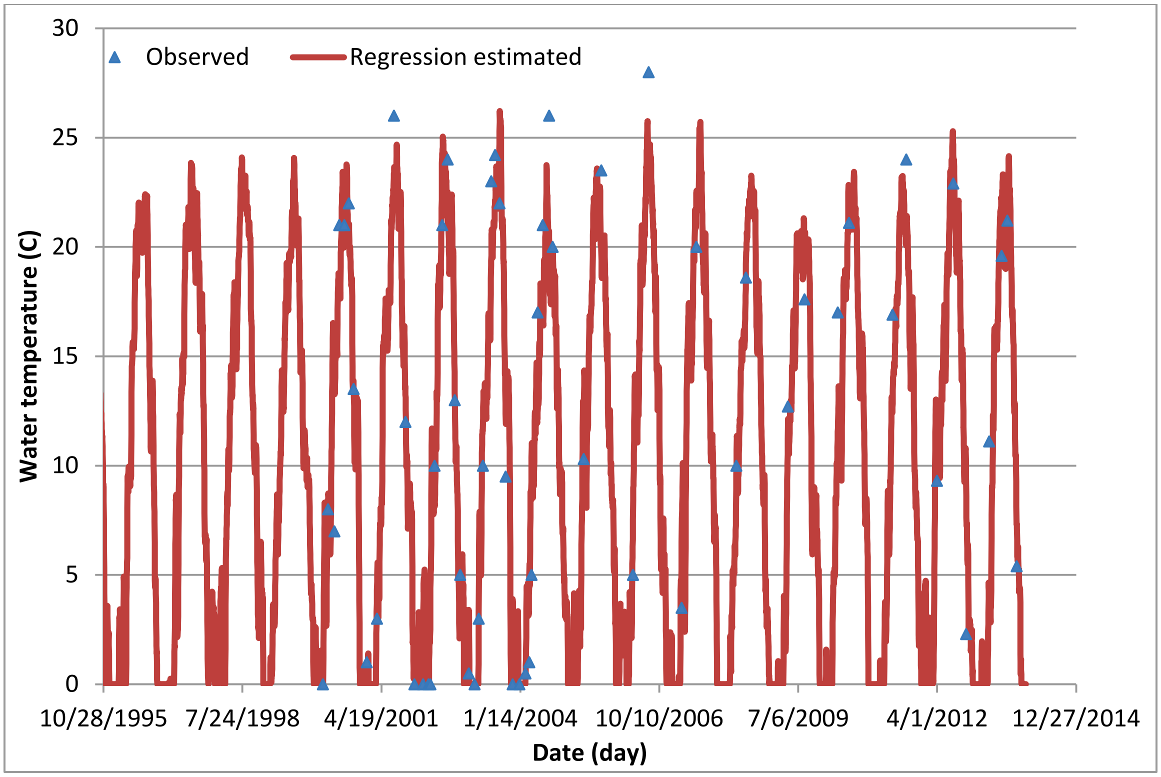


Figure A7. Regression computed versus observed water temperatures at BC7.

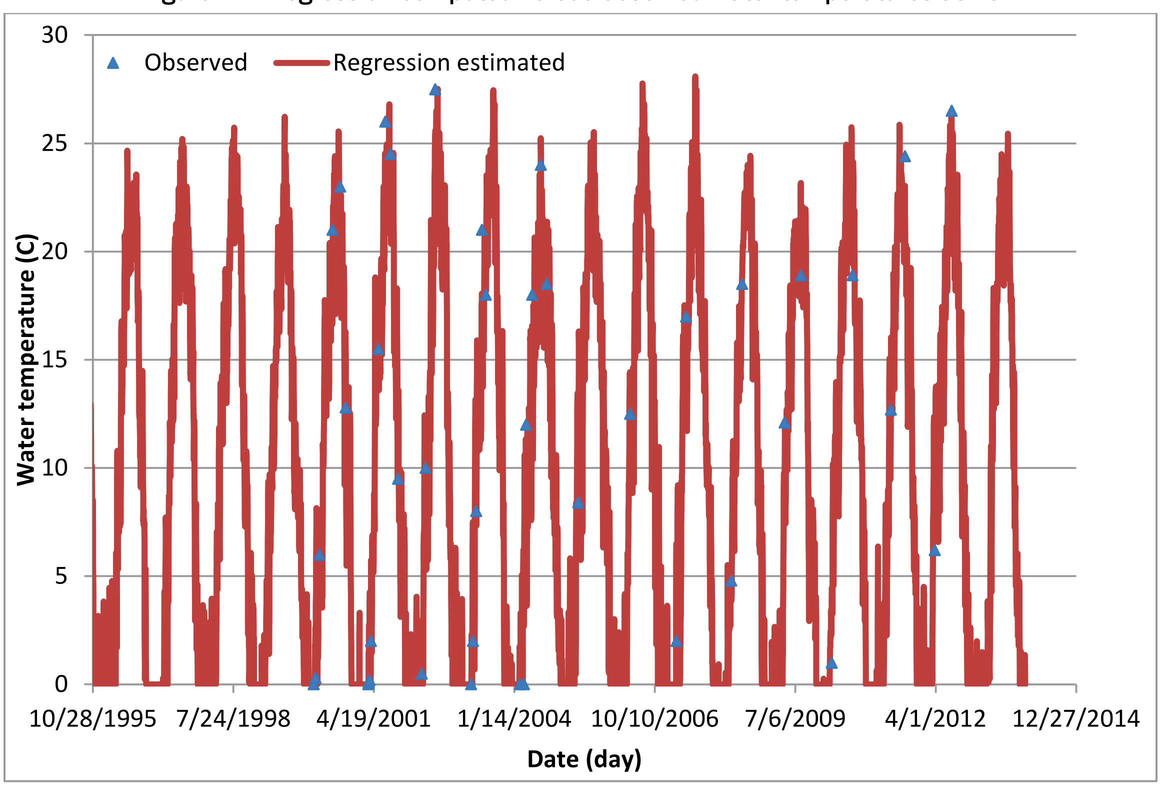
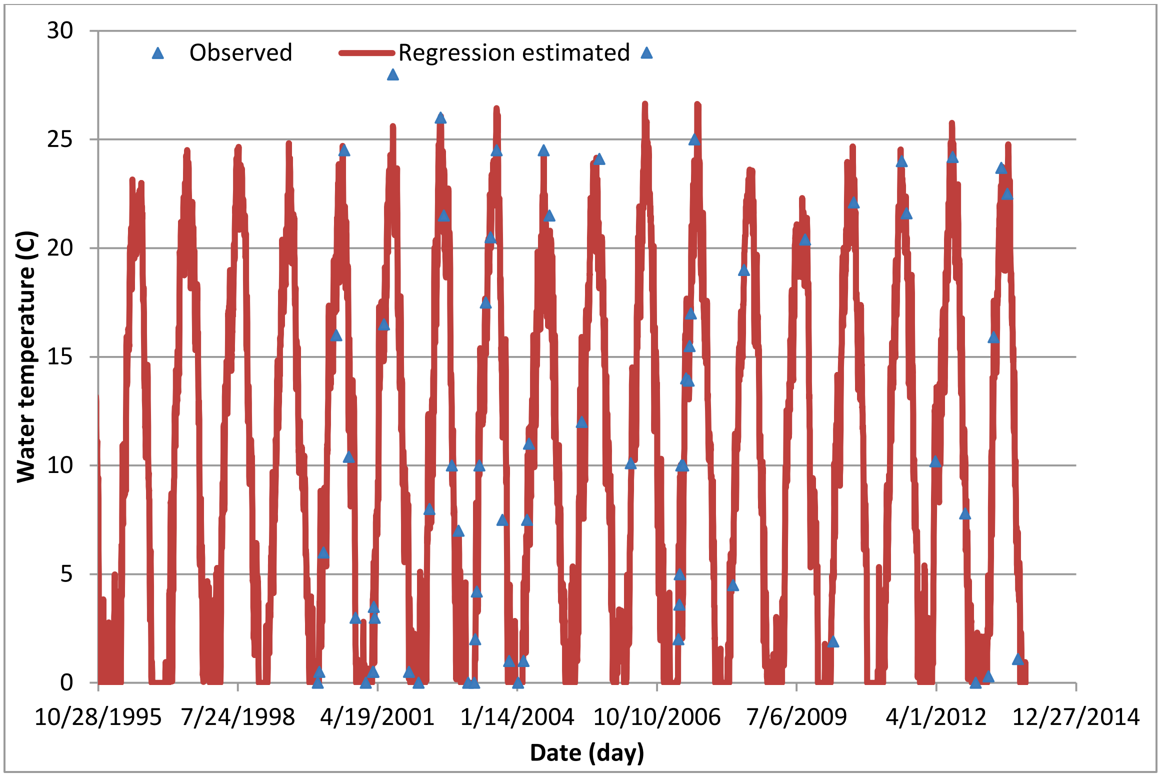


Figure A8. Regression computed versus observed water temperatures at BC8.



Appendix B: Time Series Plots of Regression Computed versus Observed Water Temperatures for the Gavins Point Dam to Rulo River Reach

Figures B1–B16 show the 18 year (1995–2012) time series plots of regression computed and observed inflow boundary water temperatures for the Gavins Point Dam to Rulo reach HEC-RAS model.

Figure B1. Regression computed versus observed water temperatures at BC1.

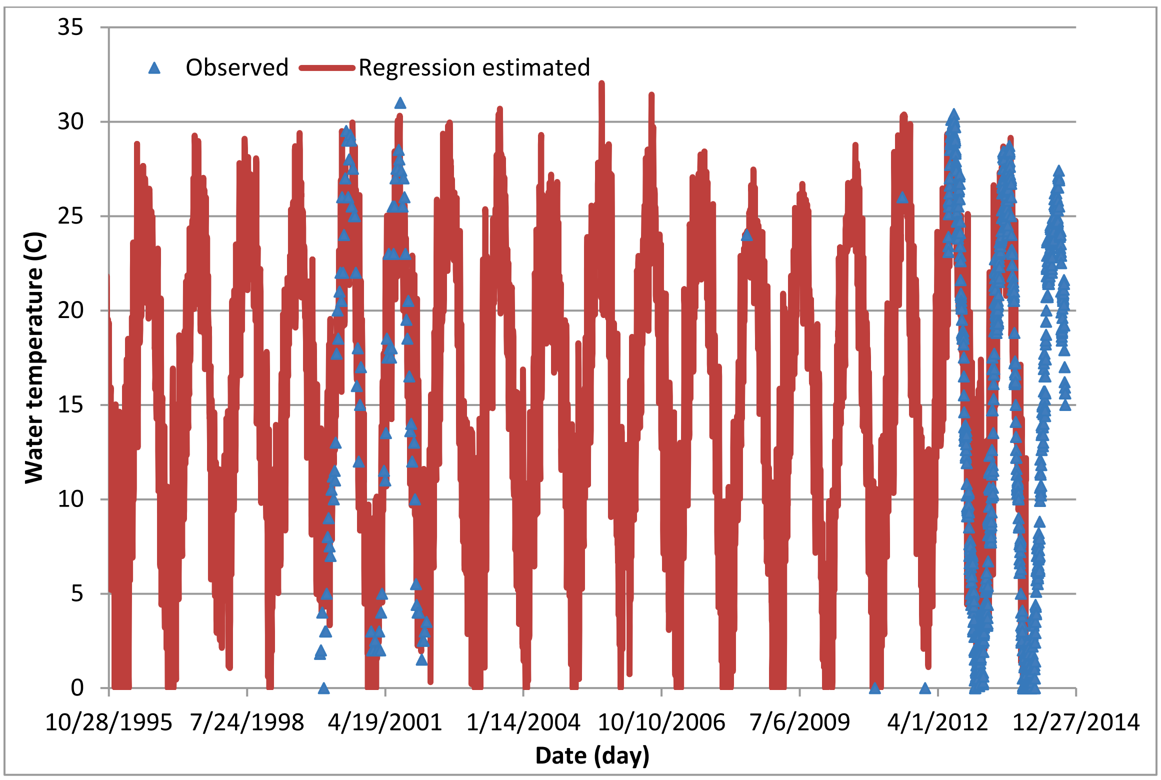


Figure B2. Regression computed versus observed water temperatures at BC2.

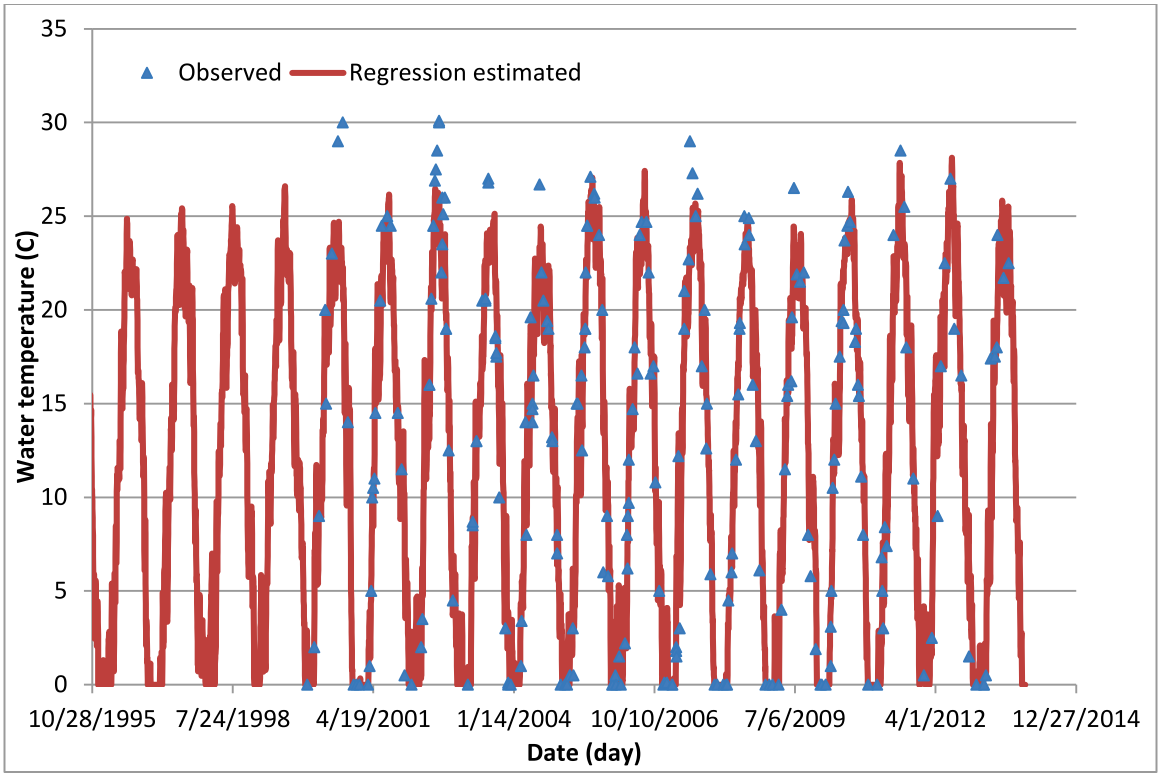


Figure B3. Regression computed versus observed water temperatures at BC3.

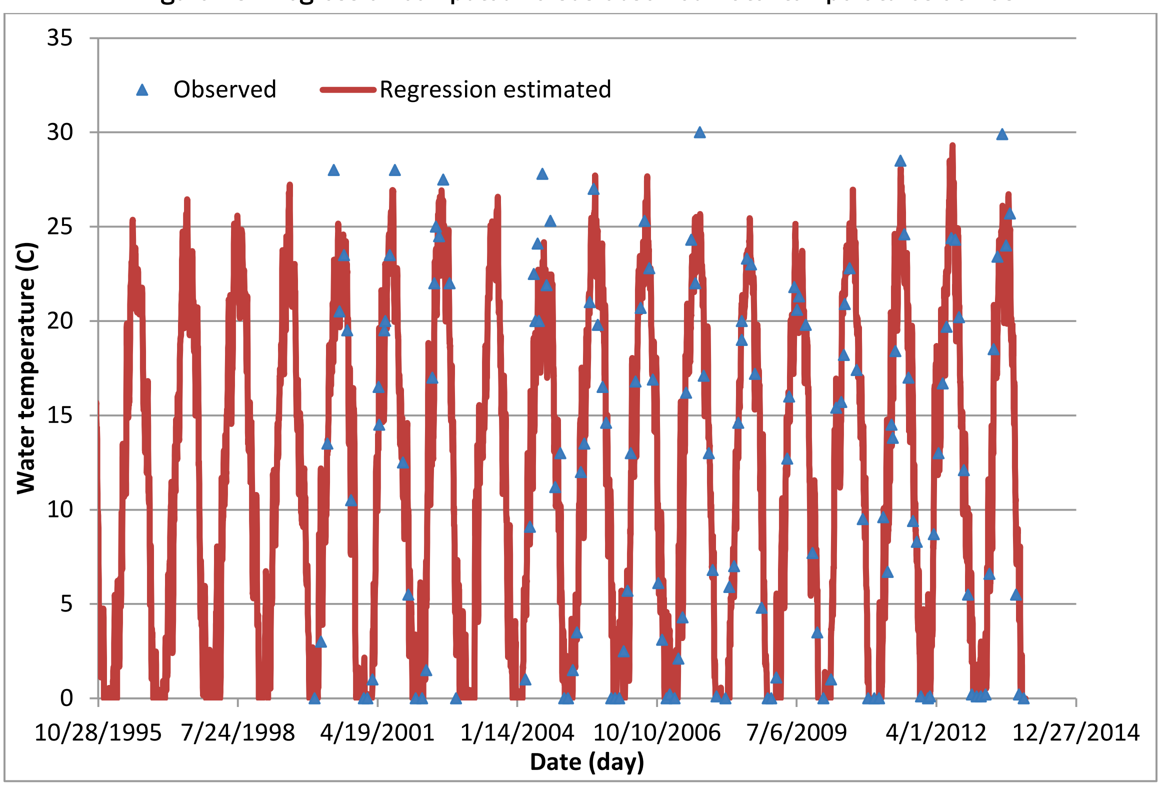


Figure B4. Regression computed versus observed water temperatures at BC4.

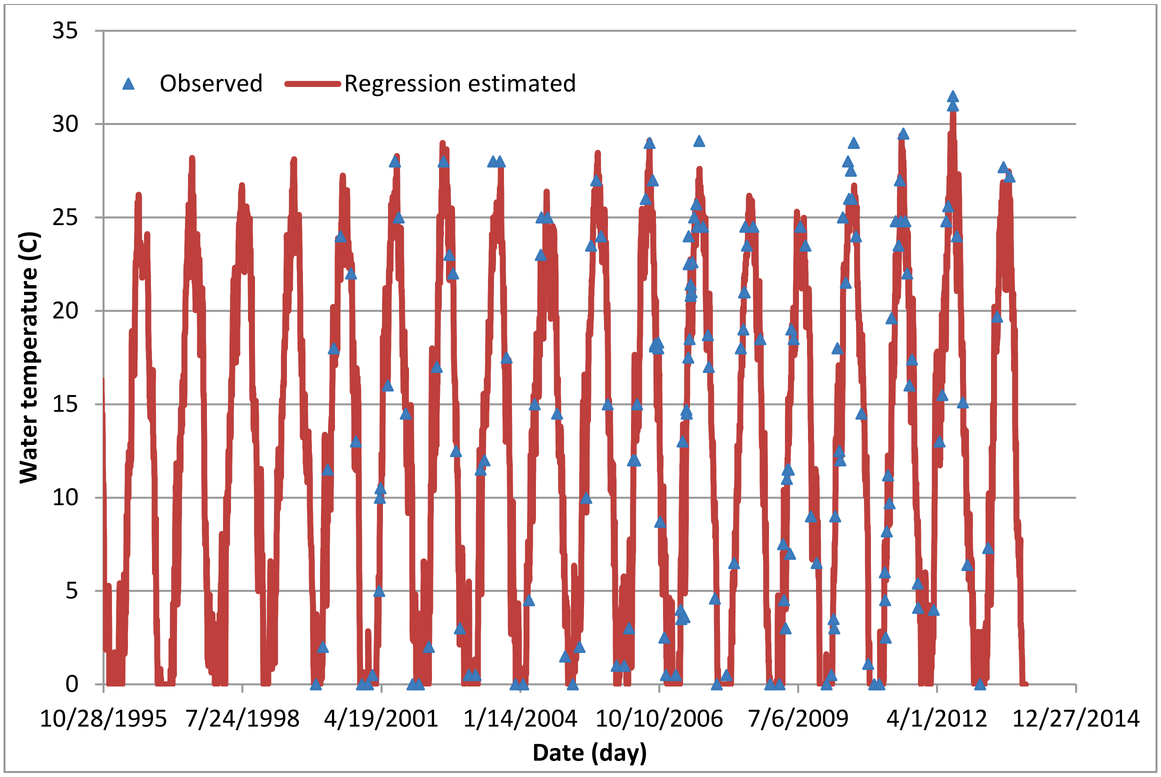


Figure B5. Regression computed versus observed water temperatures at BC5.

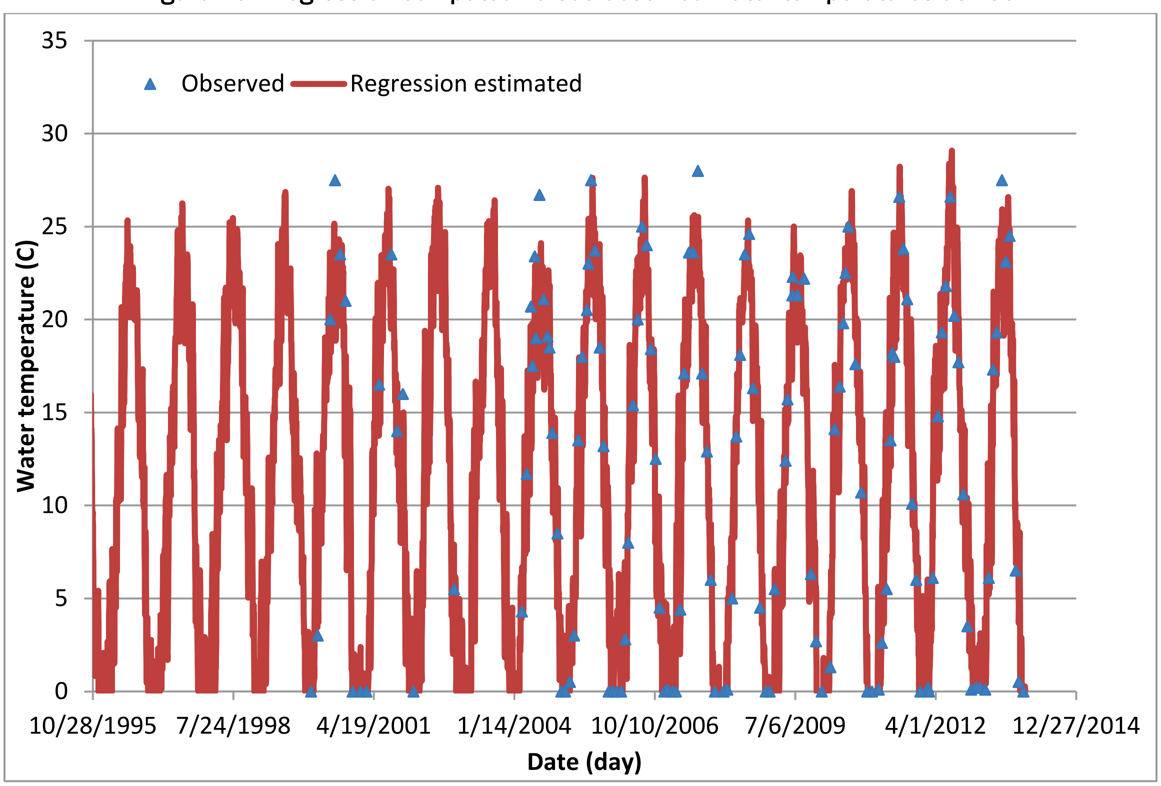


Figure B6. Regression computed versus observed water temperatures at BC6.

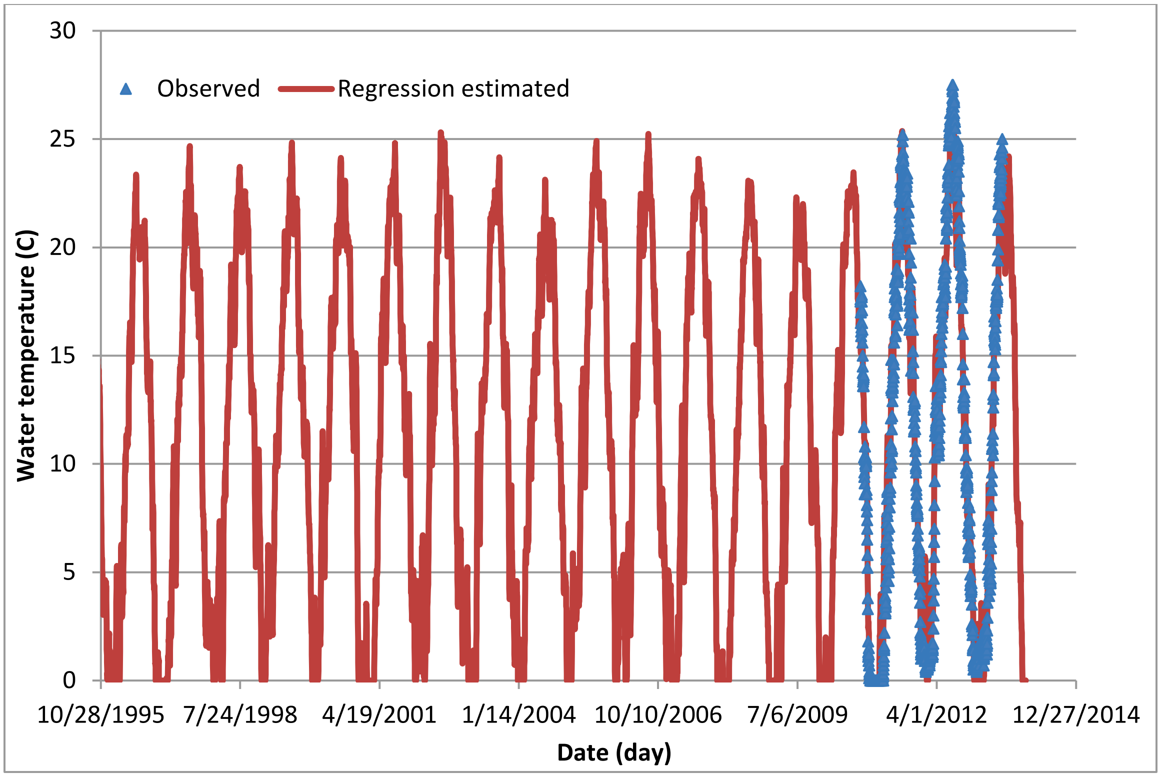


Figure B7. Regression computed versus observed water temperatures at BC7.

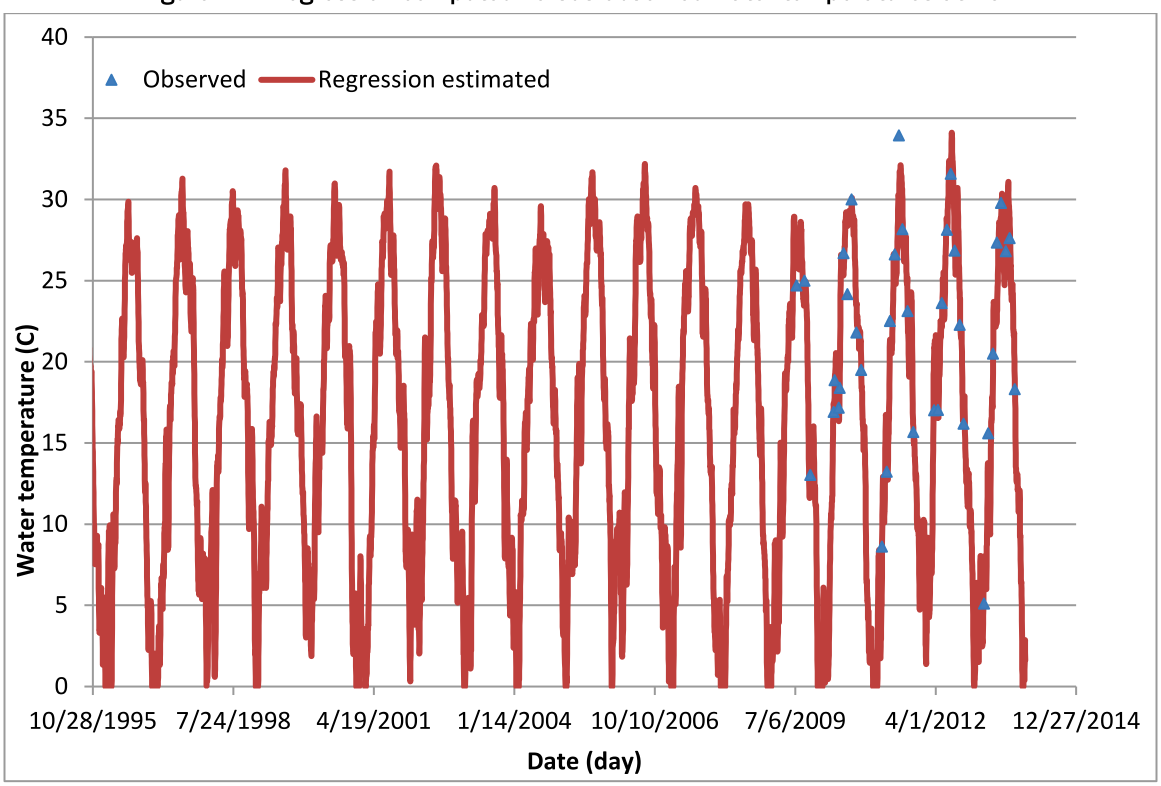


Figure B8. Regression computed versus observed water temperatures at BC8.

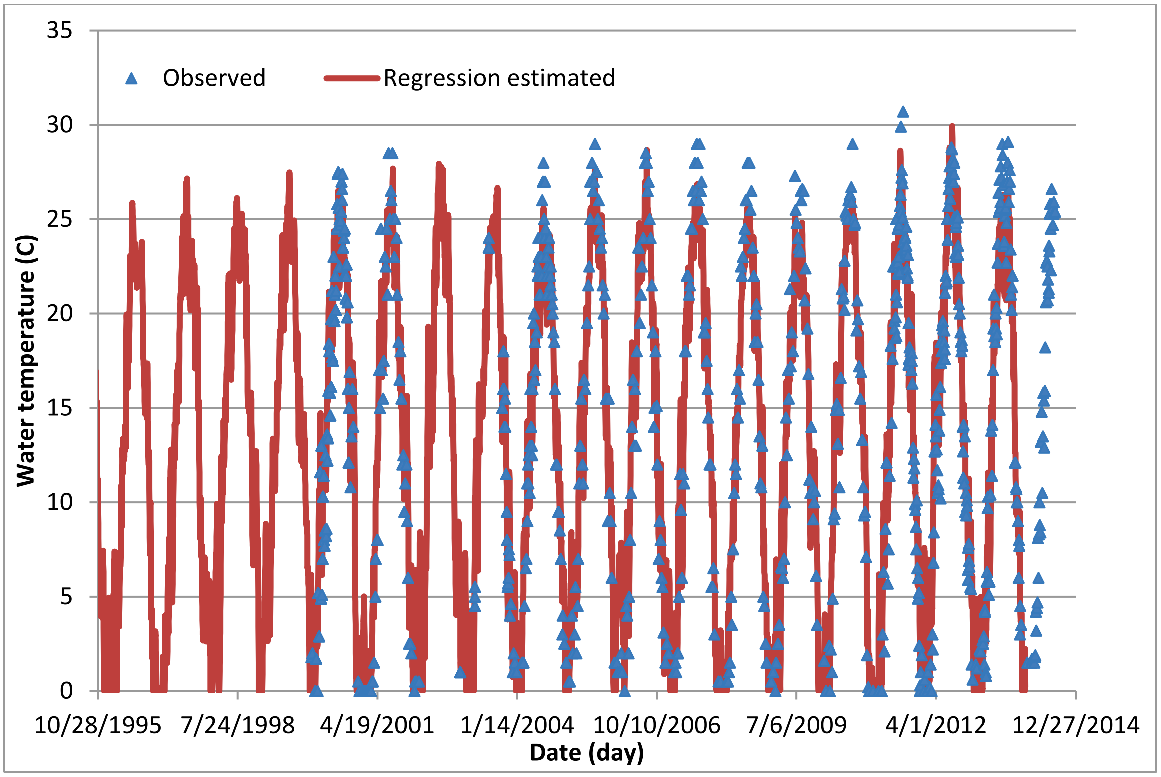


Figure B9. Regression computed versus observed water temperatures at BC9.

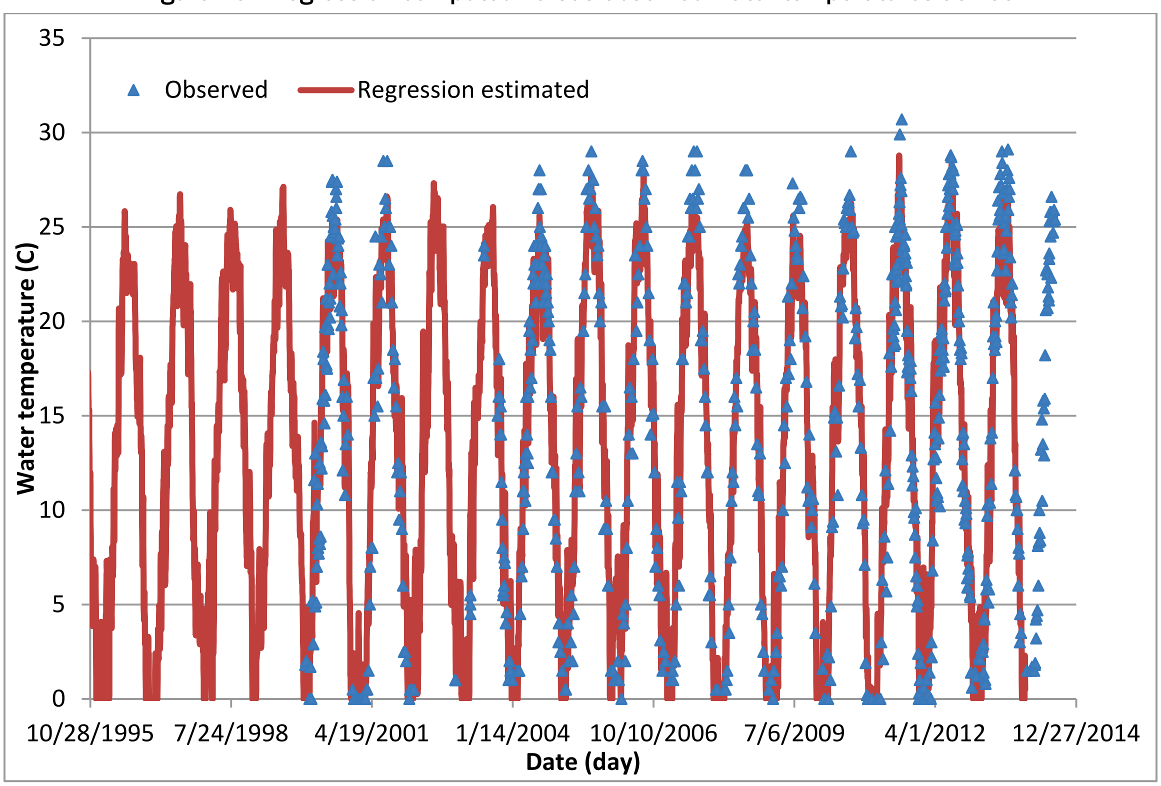


Figure B10. Regression computed versus observed water temperatures at BC10.

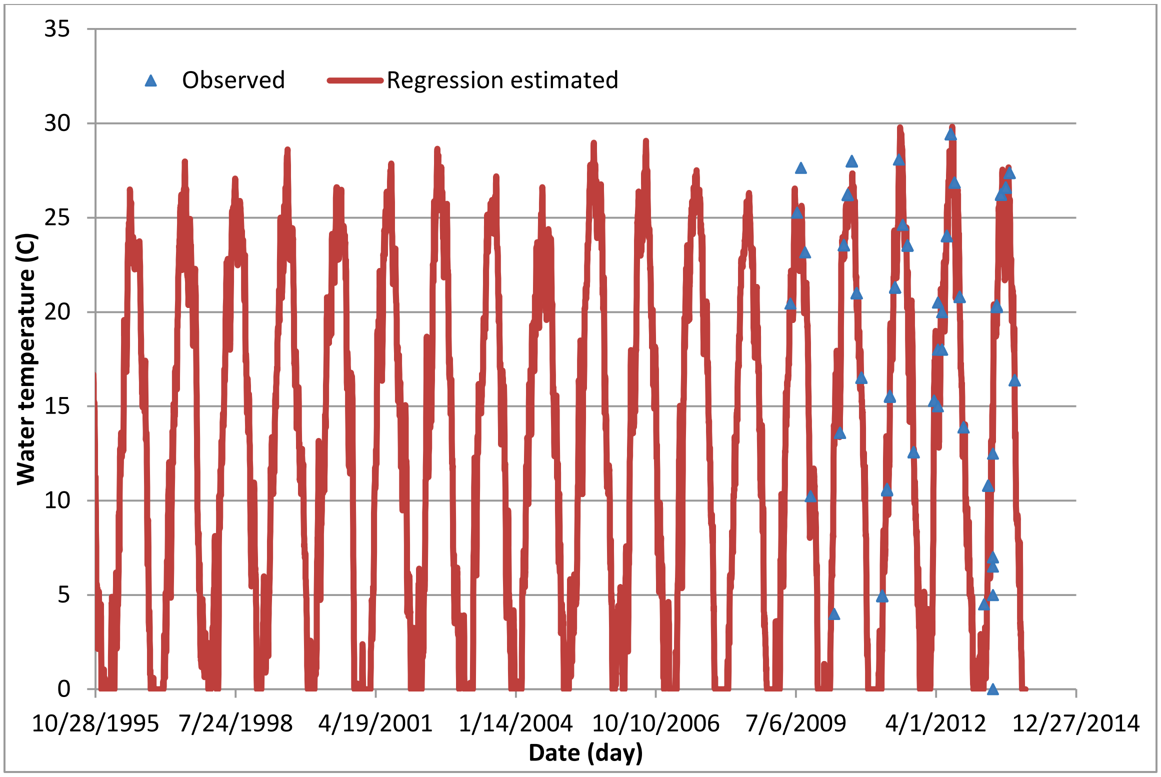


Figure B11. Regression computed versus observed water temperatures at BC11.

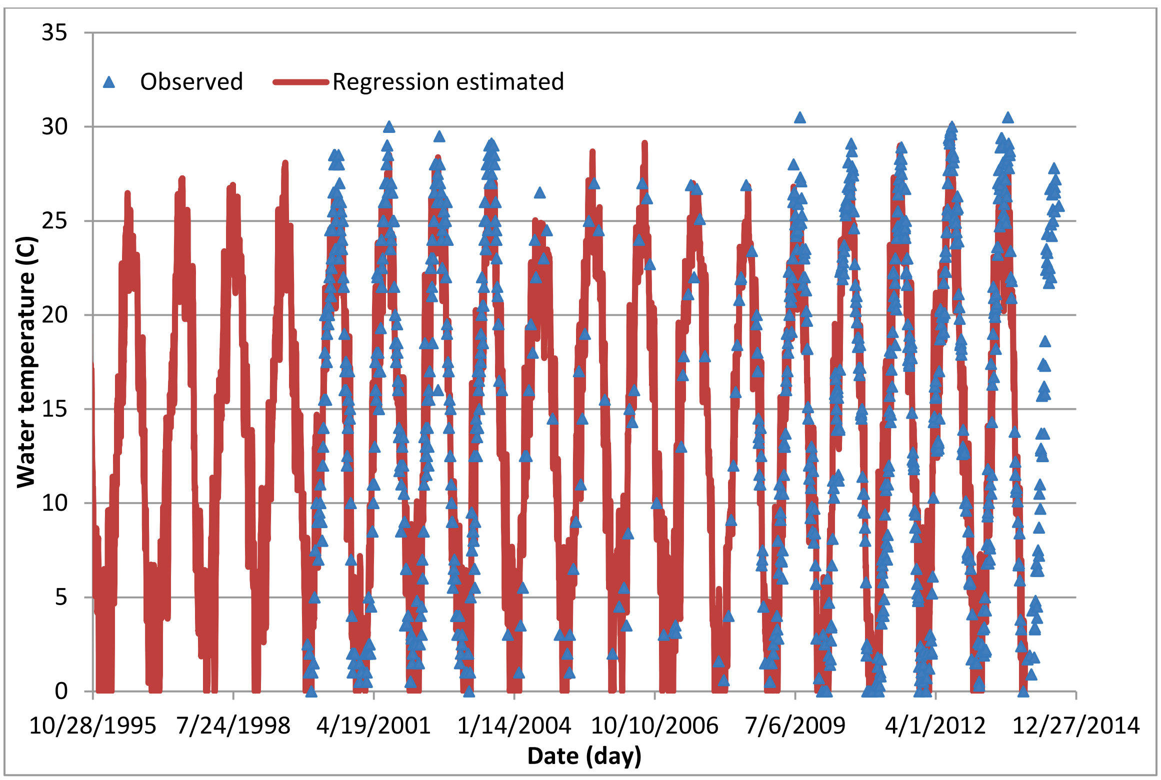


Figure B12. Regression computed versus observed water temperatures at BC12.

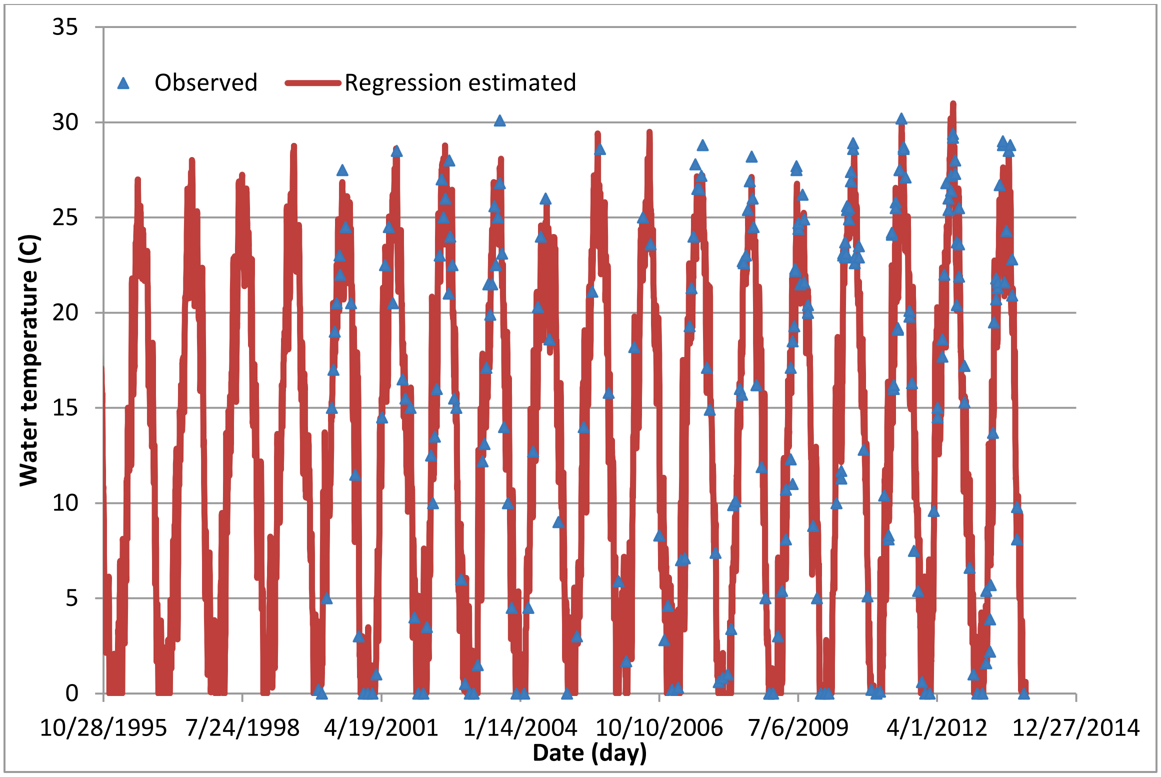


Figure B13. Regression computed versus observed water temperatures at BC13.

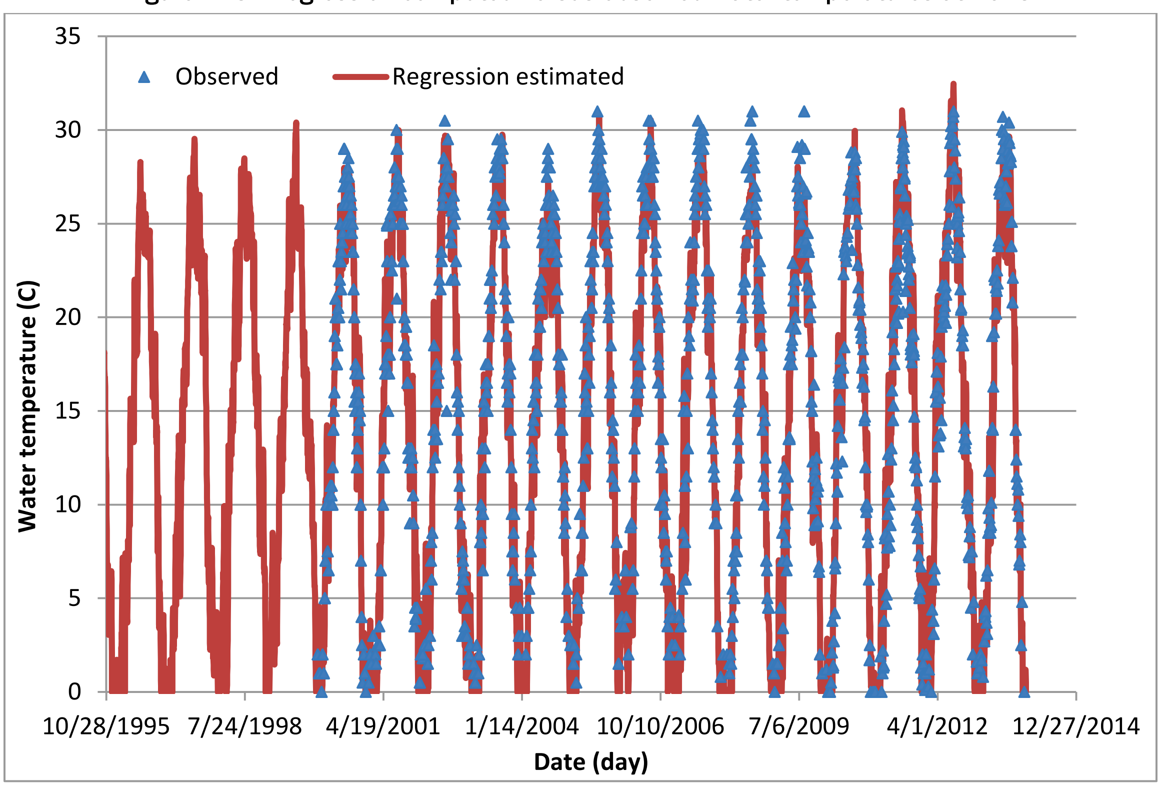


Figure B14. Regression computed versus observed water temperatures at BC14.

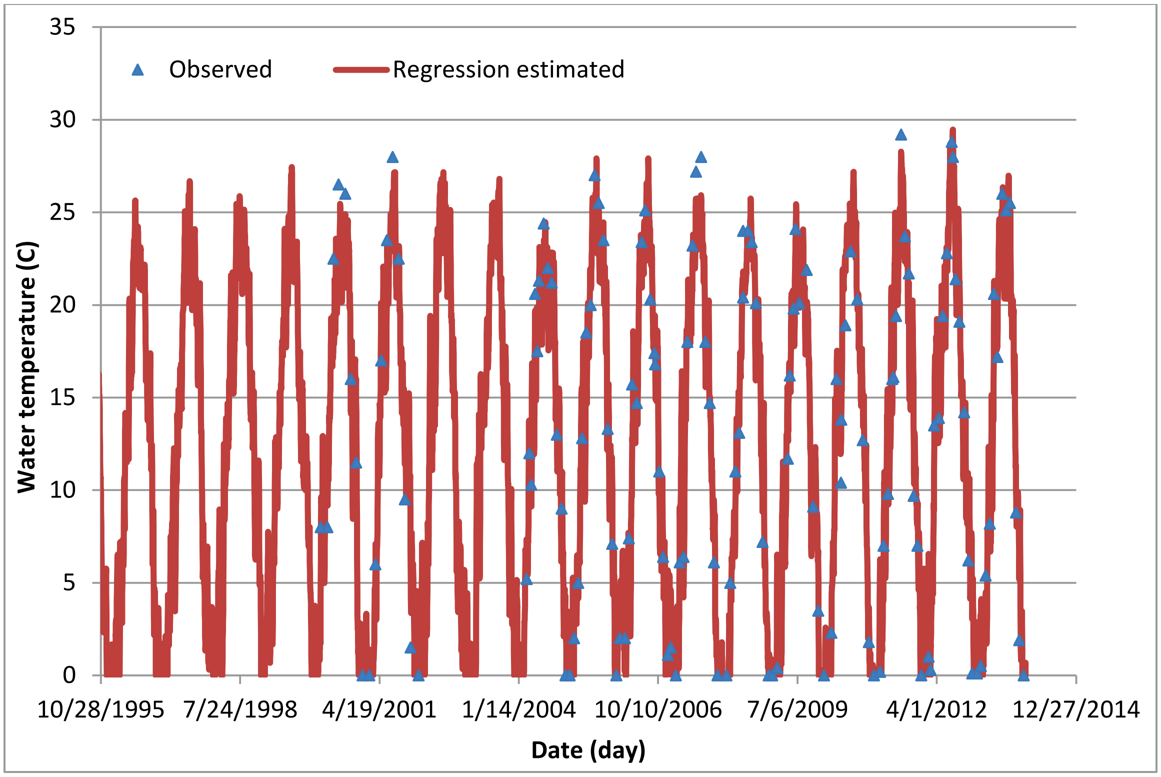


Figure B15. Regression computed versus observed water temperatures at BC15.

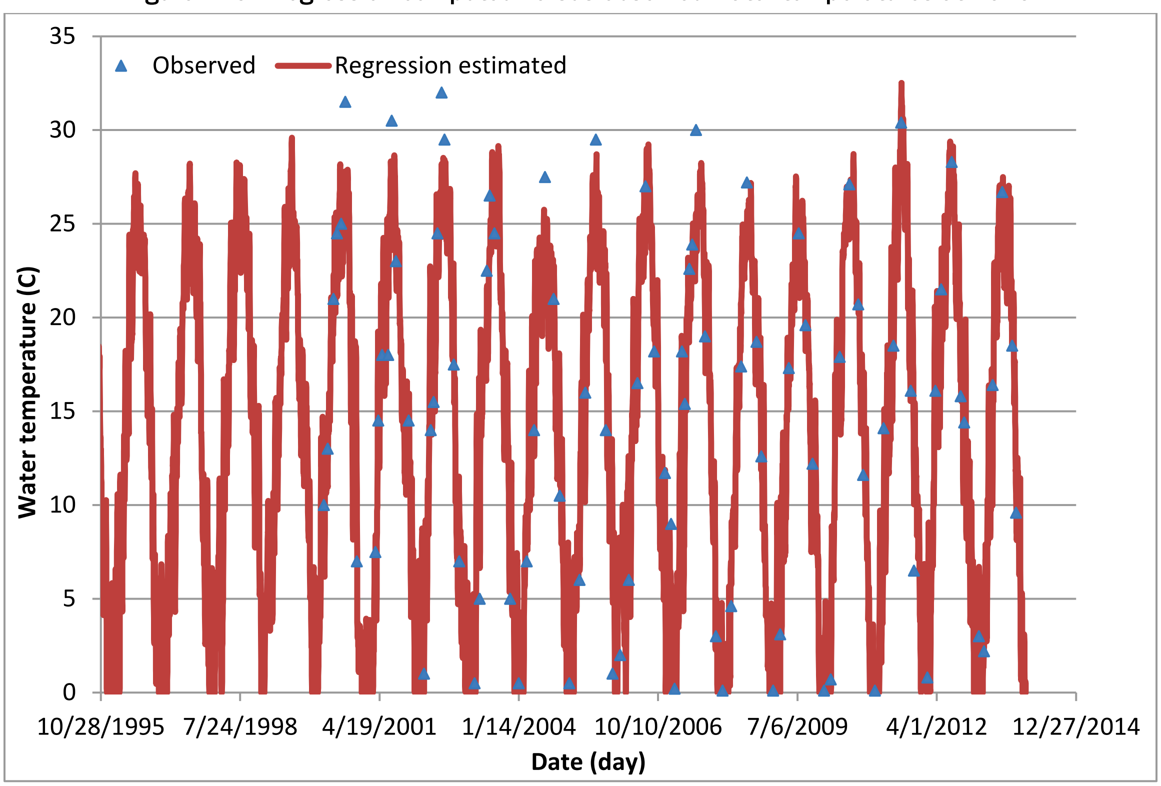
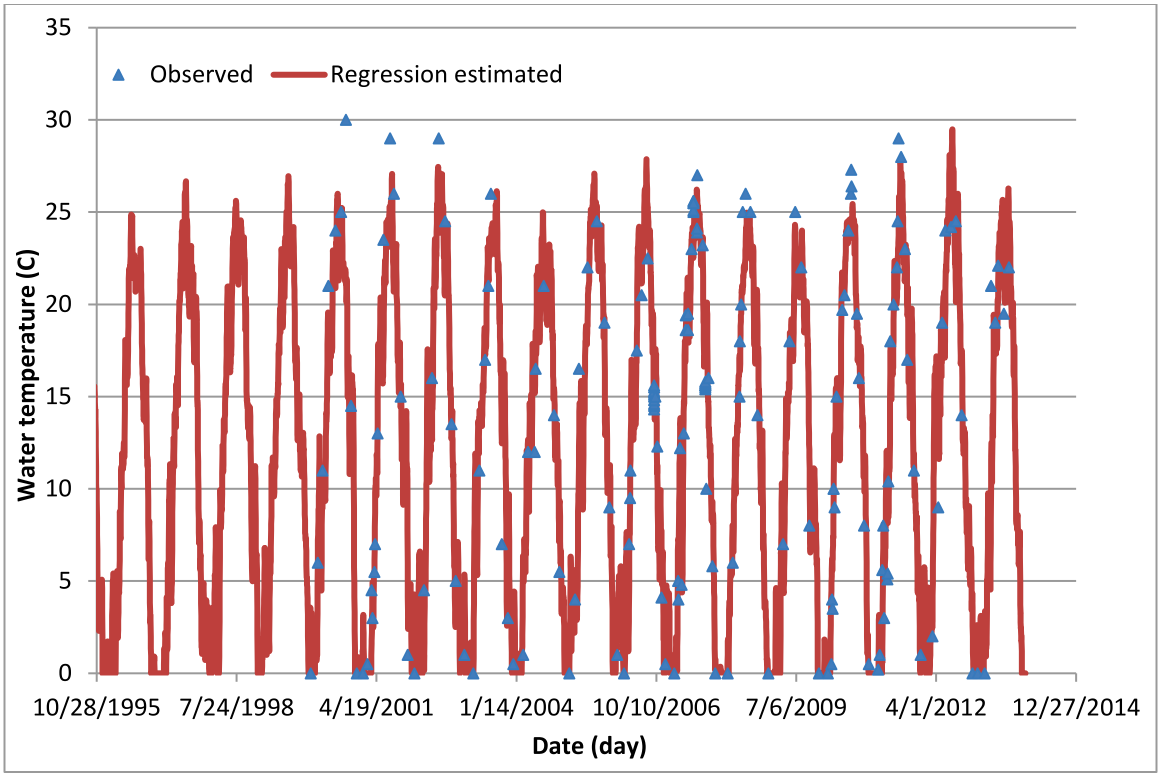


Figure B16. Regression computed versus observed water temperatures at BC16.



Appendix C: Time Series Plots of Regression Computed versus Observed Water Temperatures for the Rulo to the mouth of the Missouri River

Figures C1 –C27 present 18 year (1995-2012) time series plots of regression computed and observed inflow boundary water temperatures for the HEC-RAS model from Rulo to the mouth of the Missouri River.

Figure C1. Regression computed versus observed water temperatures at BC1.

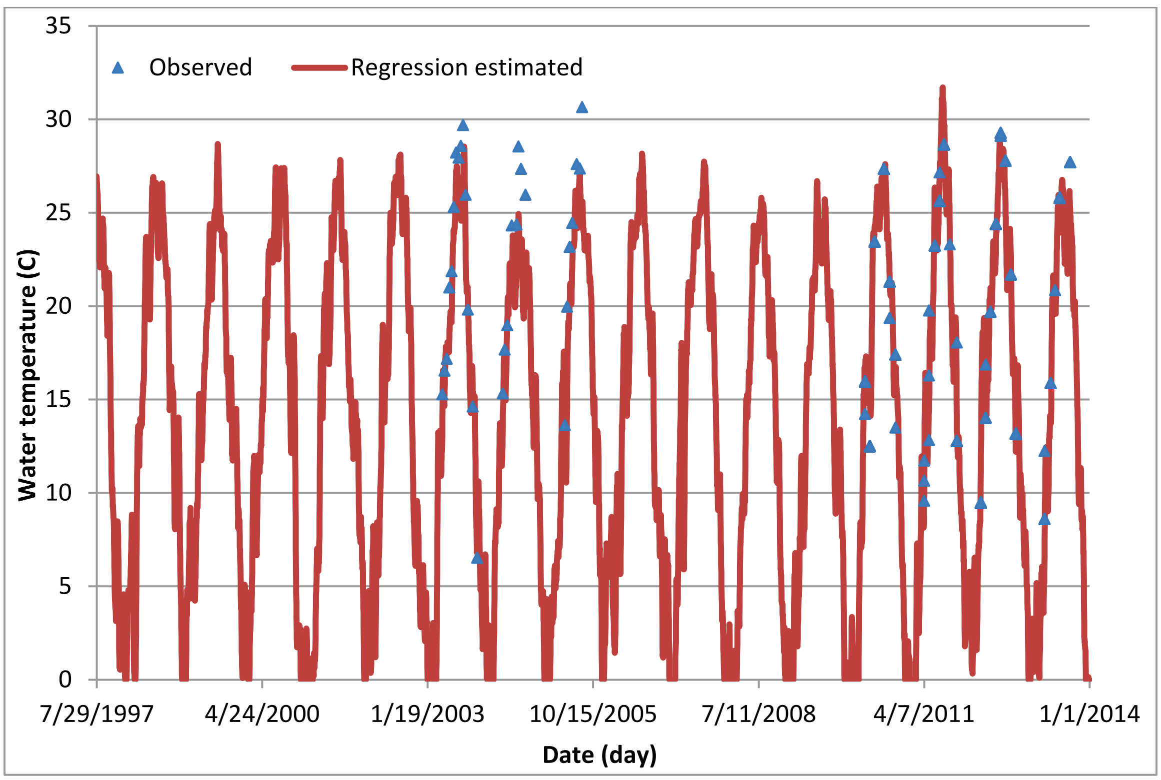


Figure C2. Regression computed versus observed water temperatures at BC2.

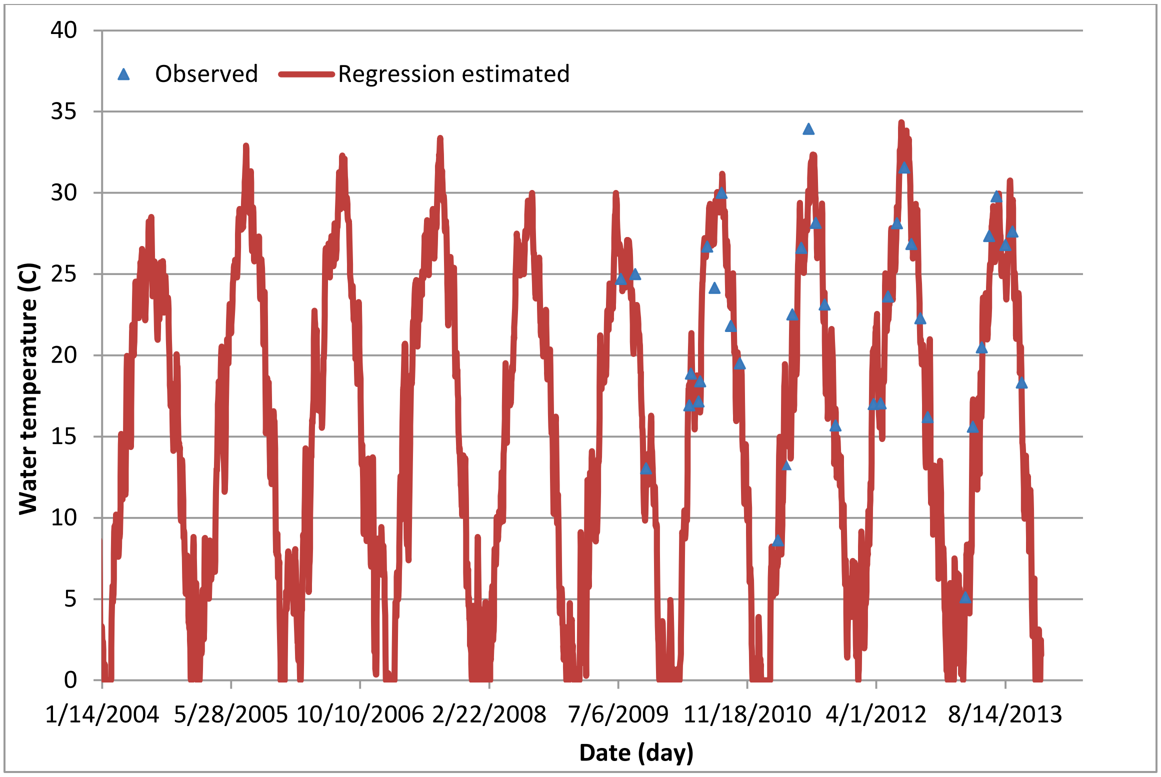


Figure C3. Regression computed versus observed water temperatures at BC3.

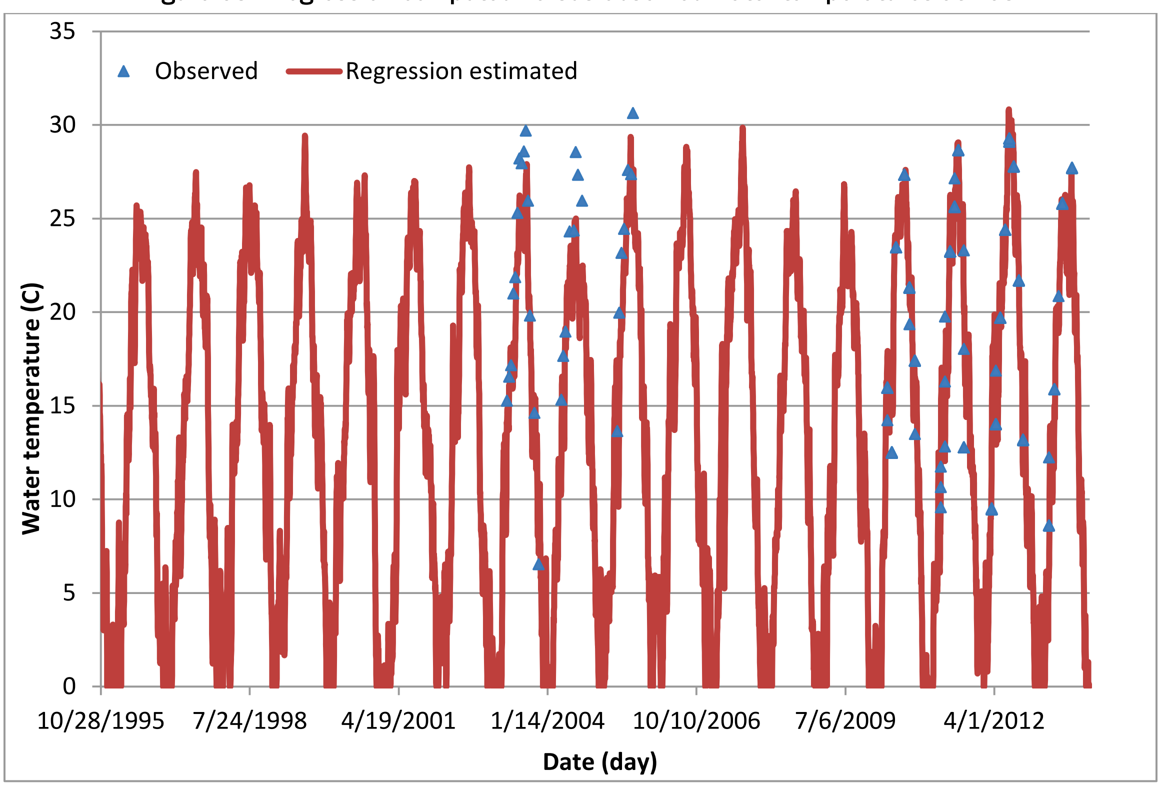


Figure C4. Regression computed versus observed water temperatures at BC4.

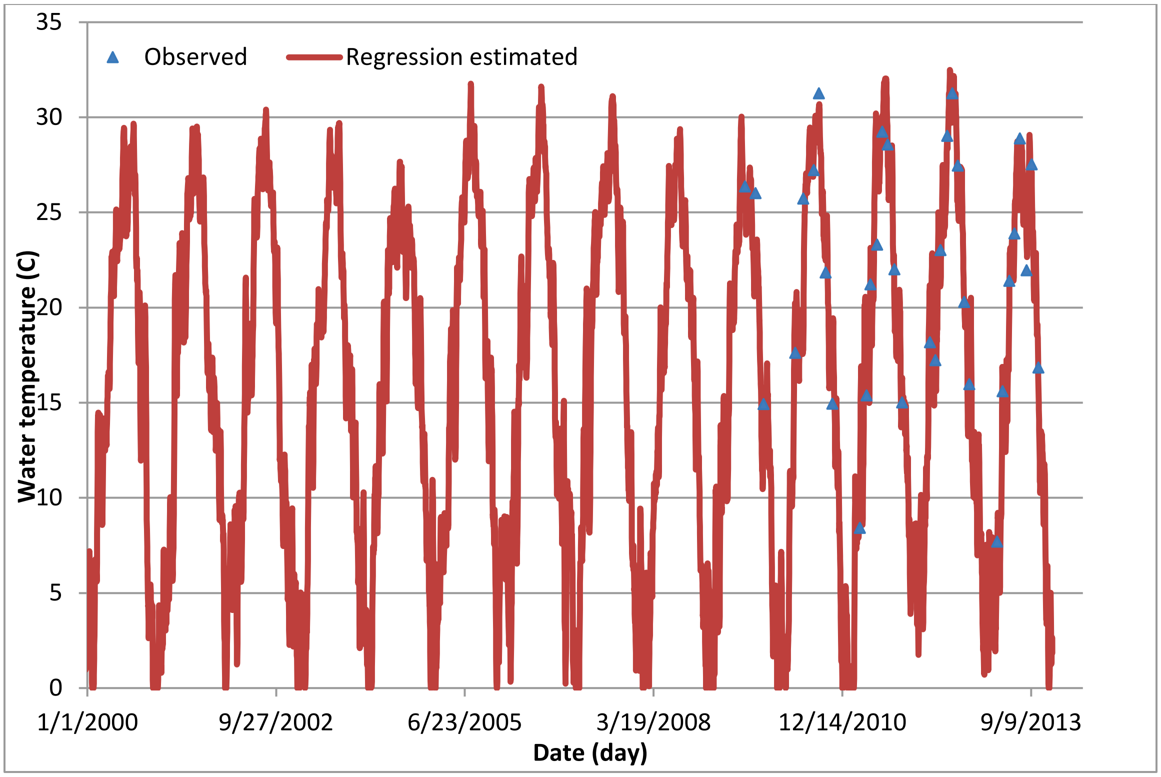


Figure C5. Regression computed versus observed water temperatures at BC5.

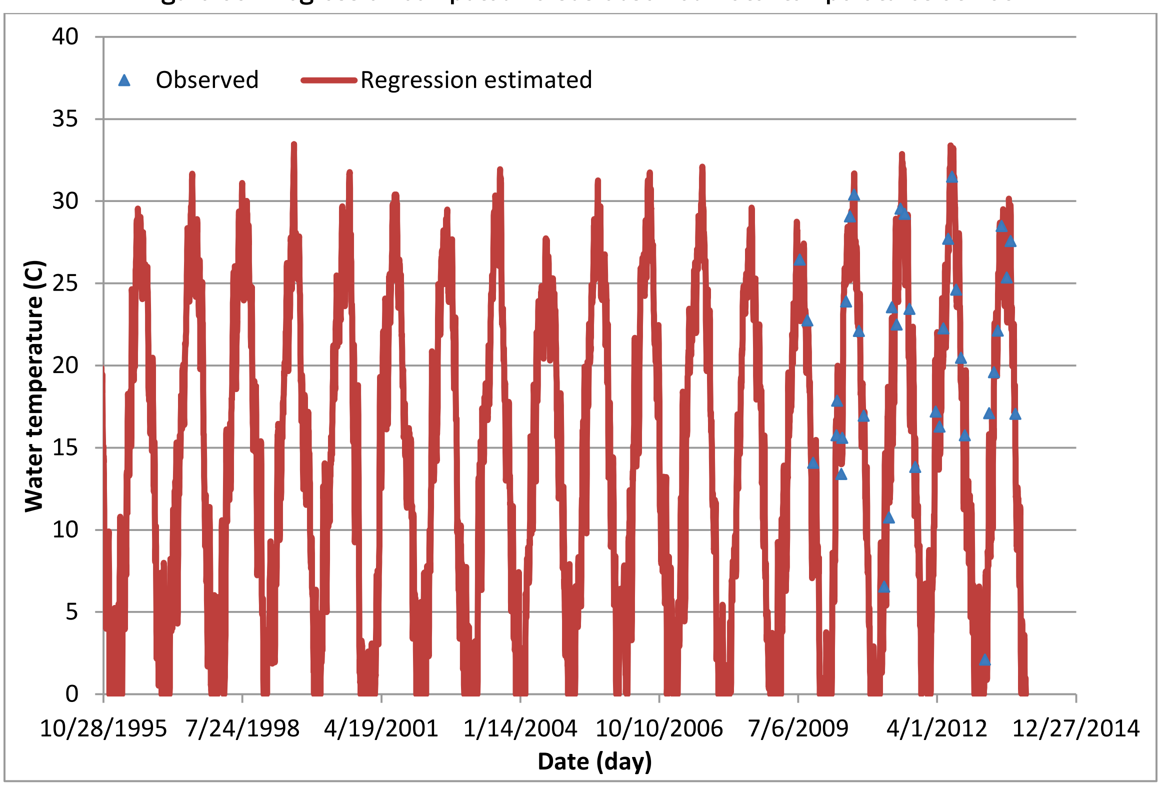


Figure C6. Regression computed versus observed water temperatures at BC6.

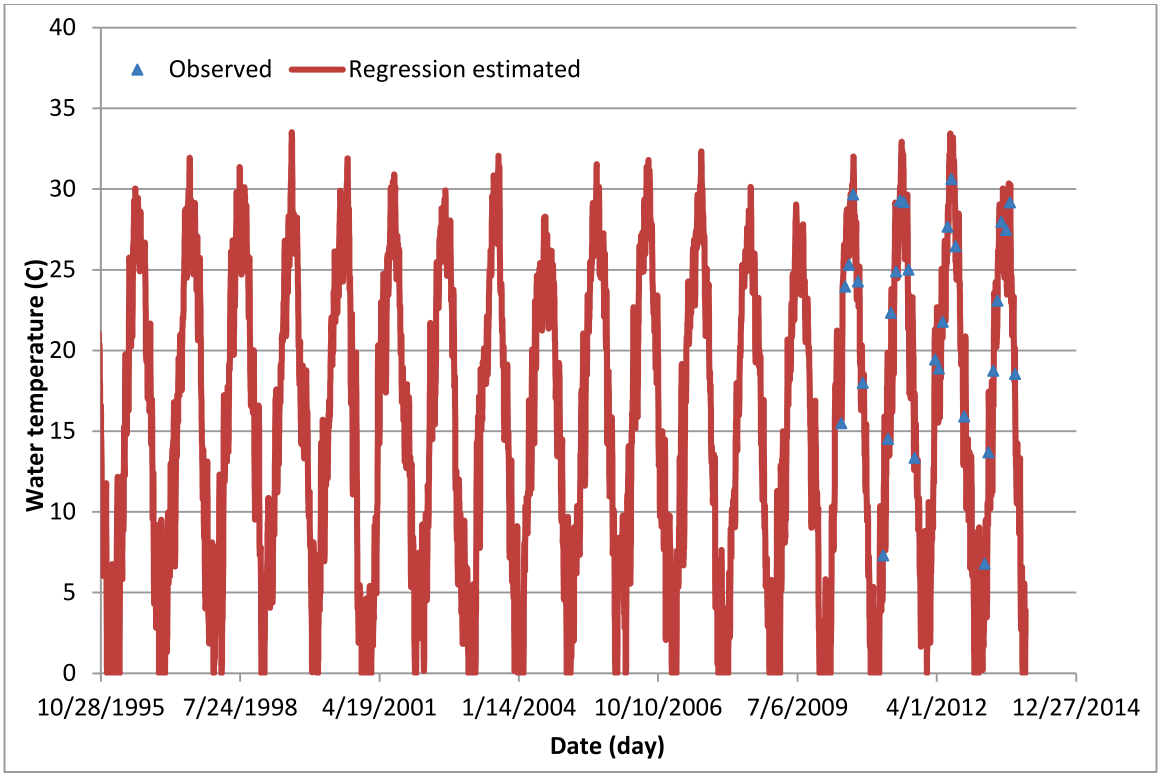


Figure C7. Regression computed versus observed water temperatures at BC7.

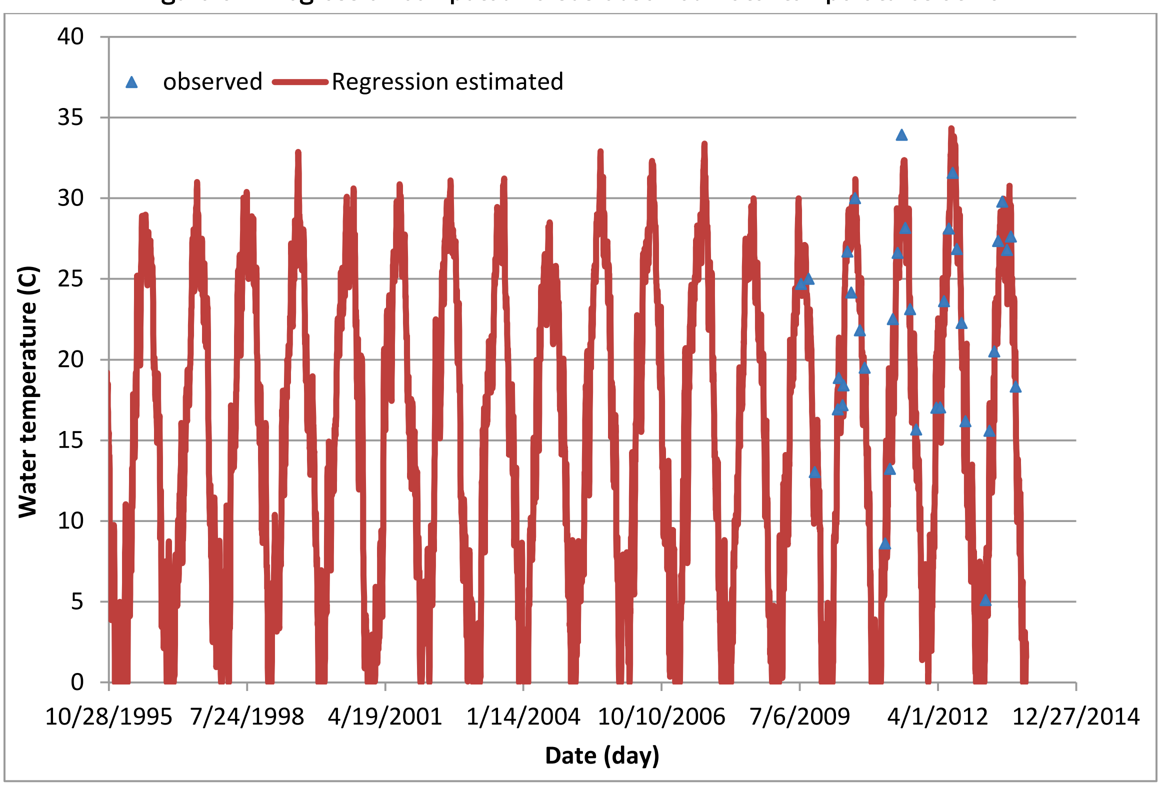


Figure C8. Regression computed versus observed water temperatures at BC8.

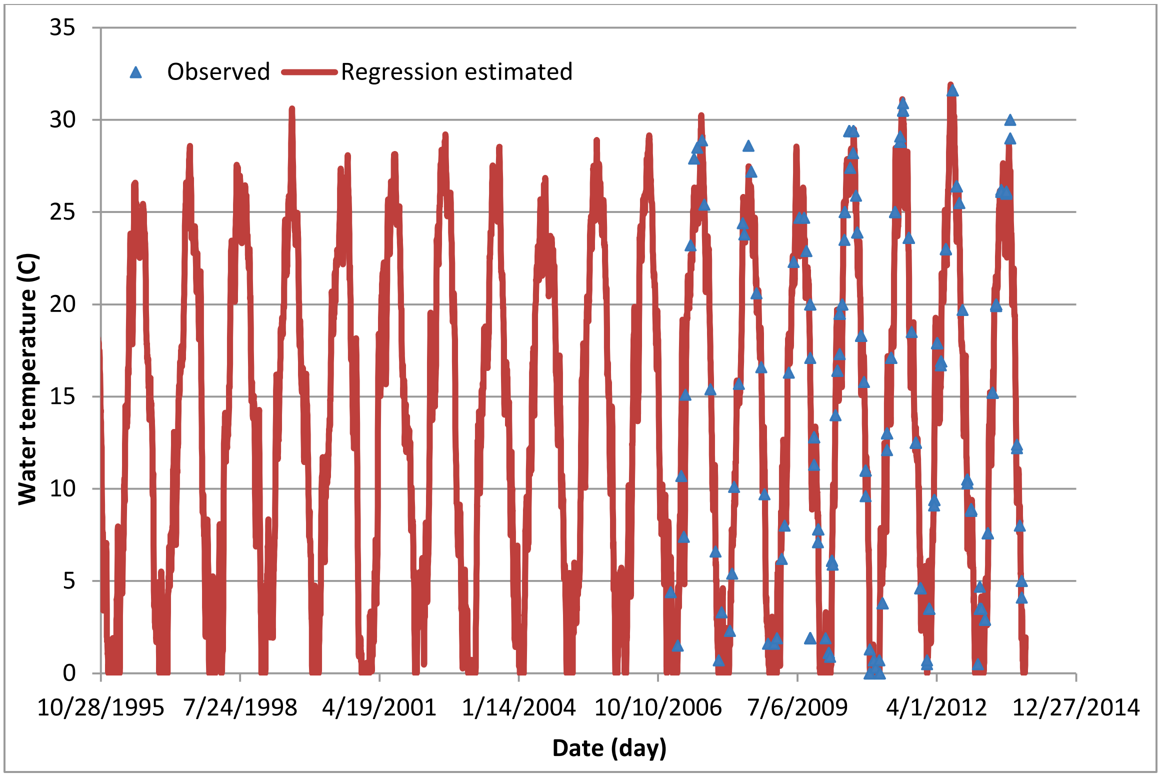


Figure C9. Regression computed versus observed water temperatures at BC9.

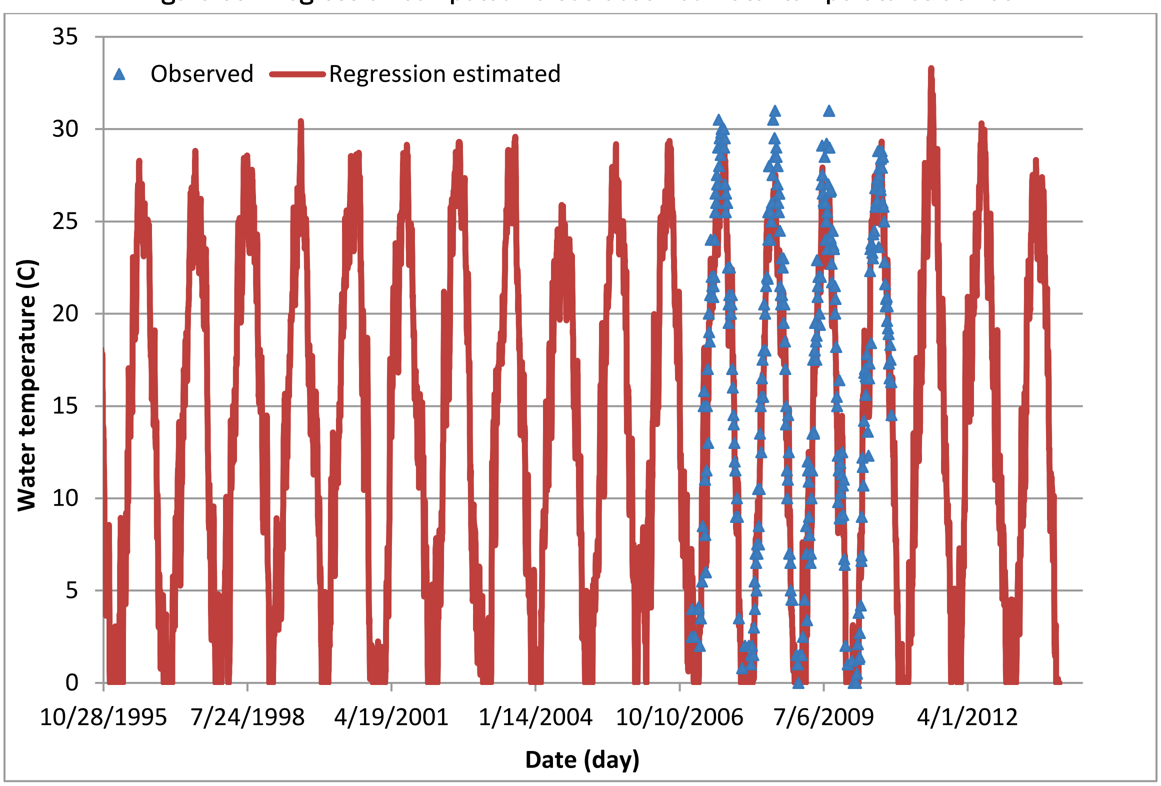


Figure C10. Regression computed versus observed water temperatures at BC10.

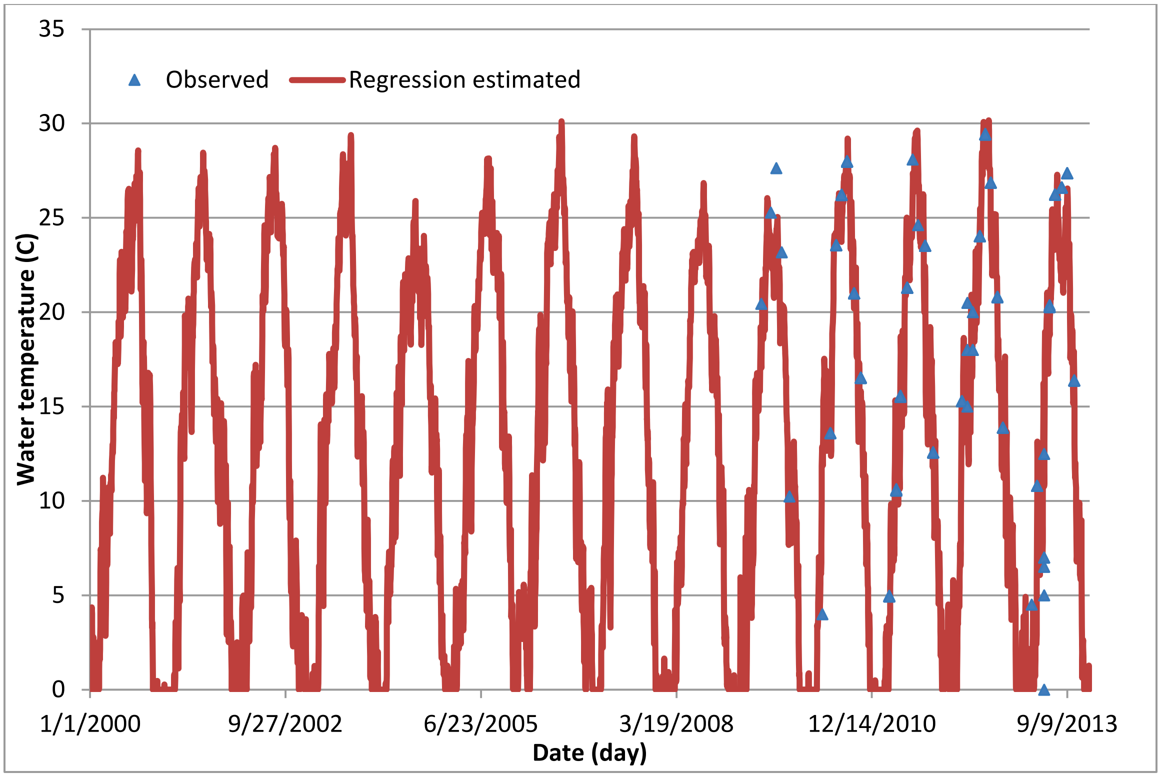


Figure C11. Regression computed versus observed water temperatures at BC11.

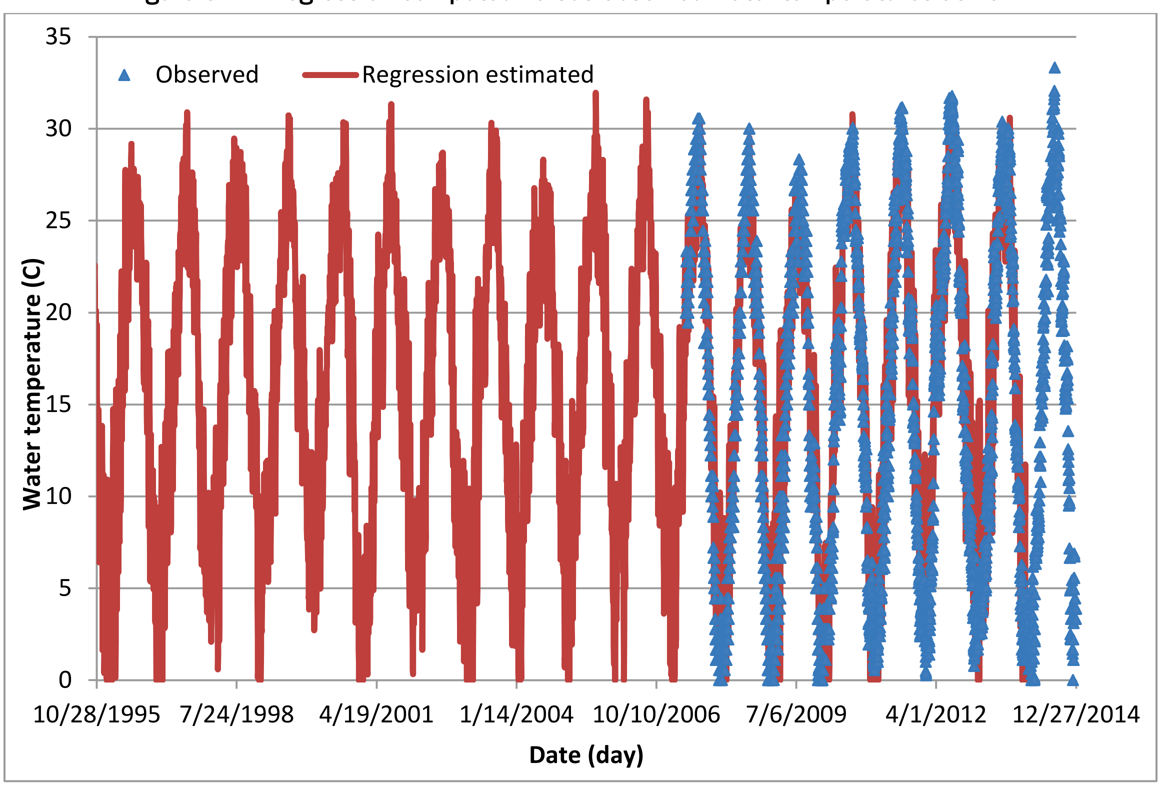


Figure C12. Regression computed versus observed water temperatures at BC12.

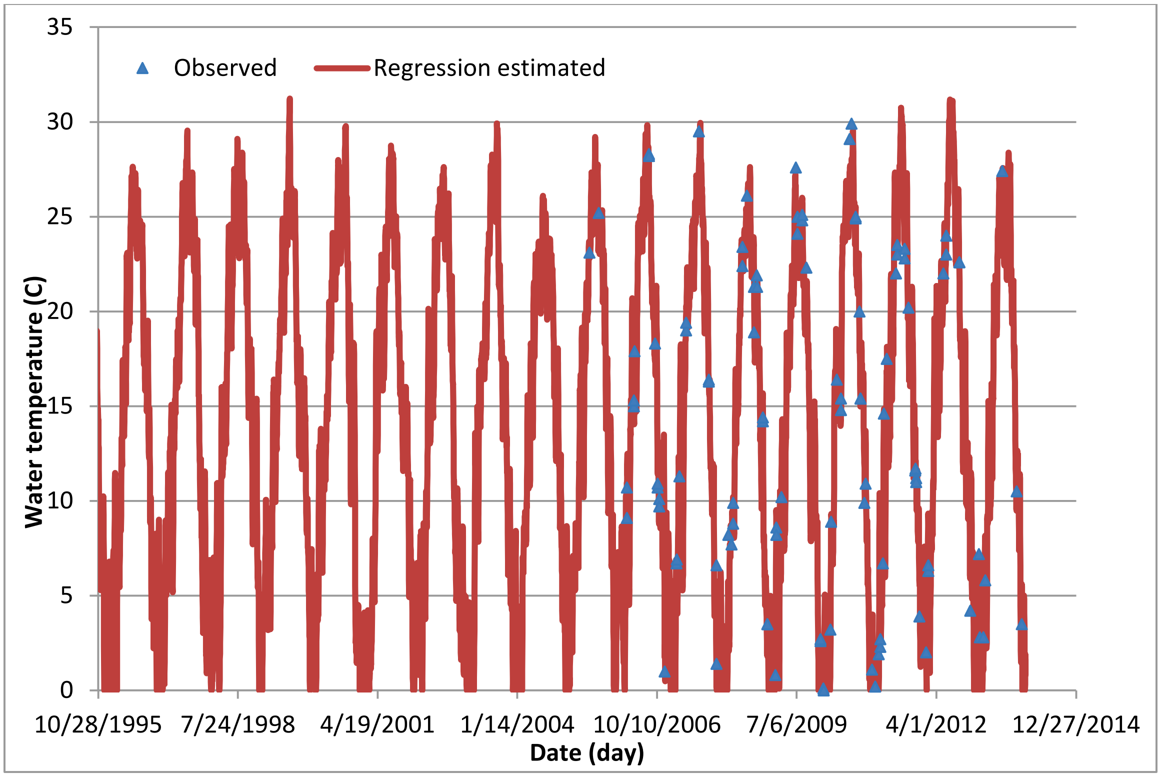


Figure C13. Regression computed versus observed water temperatures at BC13.

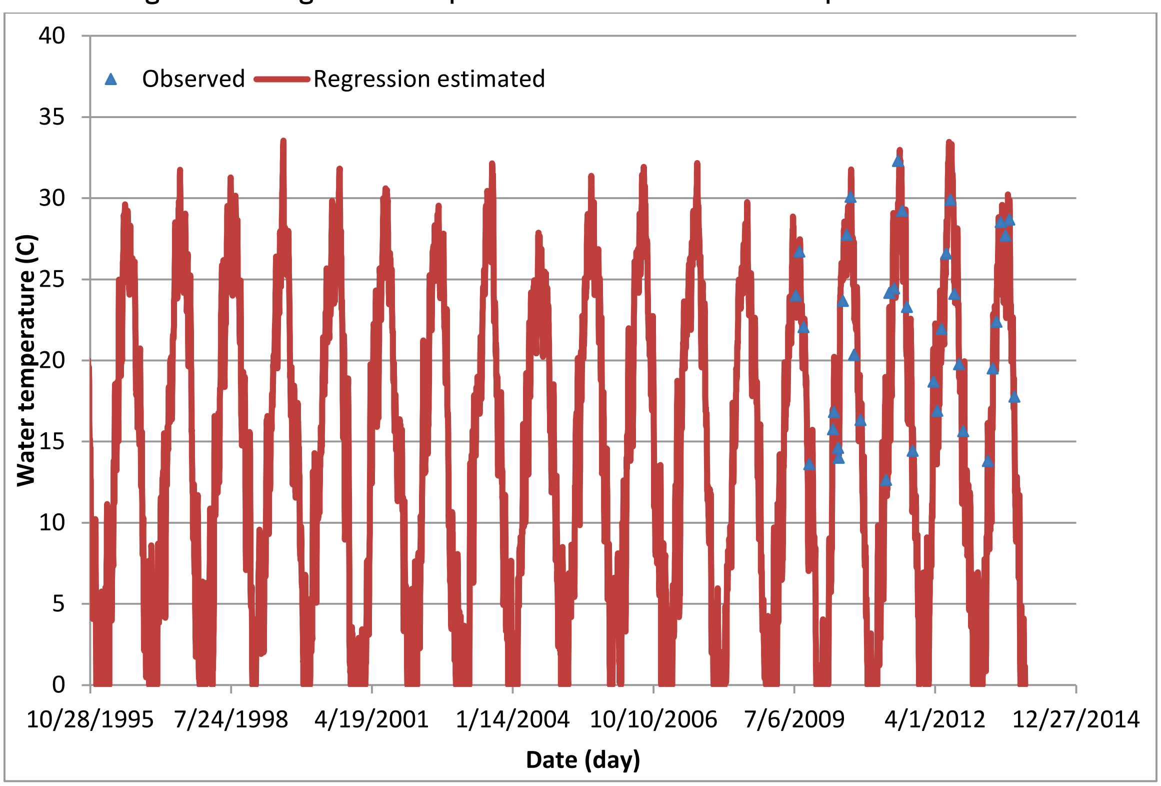


Figure C14. Regression computed versus observed water temperatures at BC14.

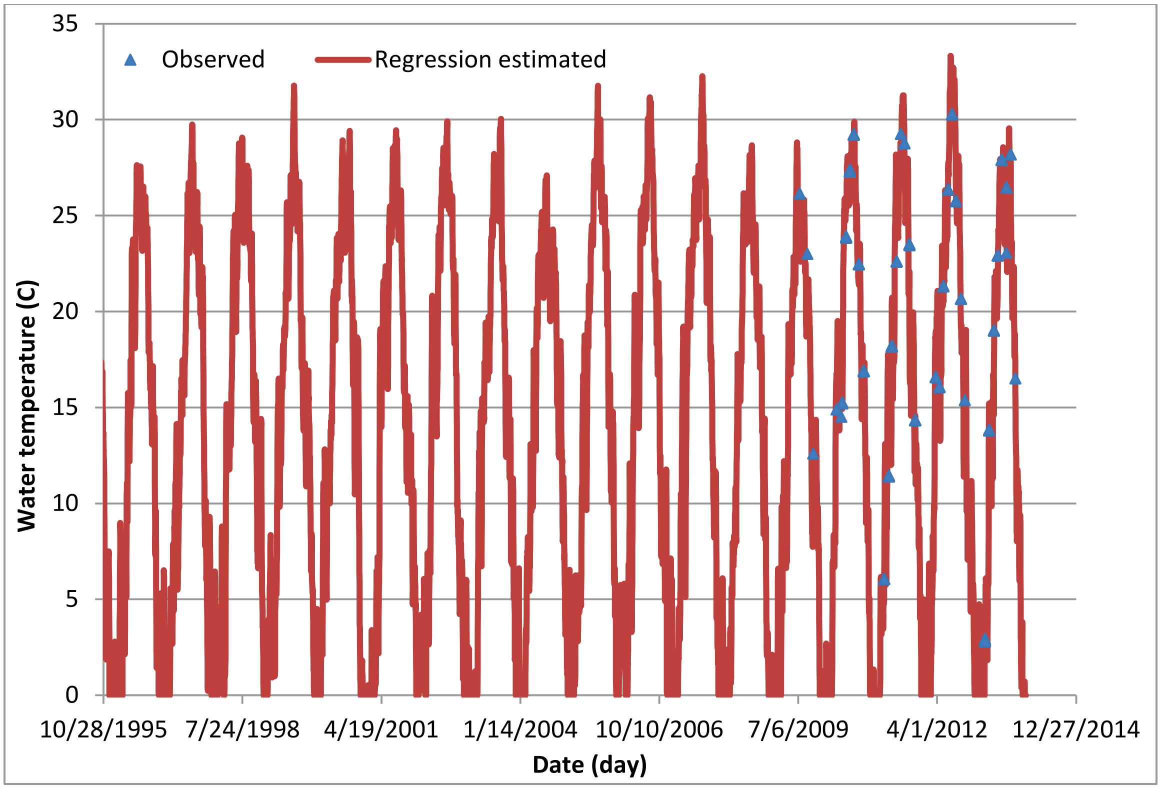


Figure C15. Regression computed versus observed water temperatures at BC15.

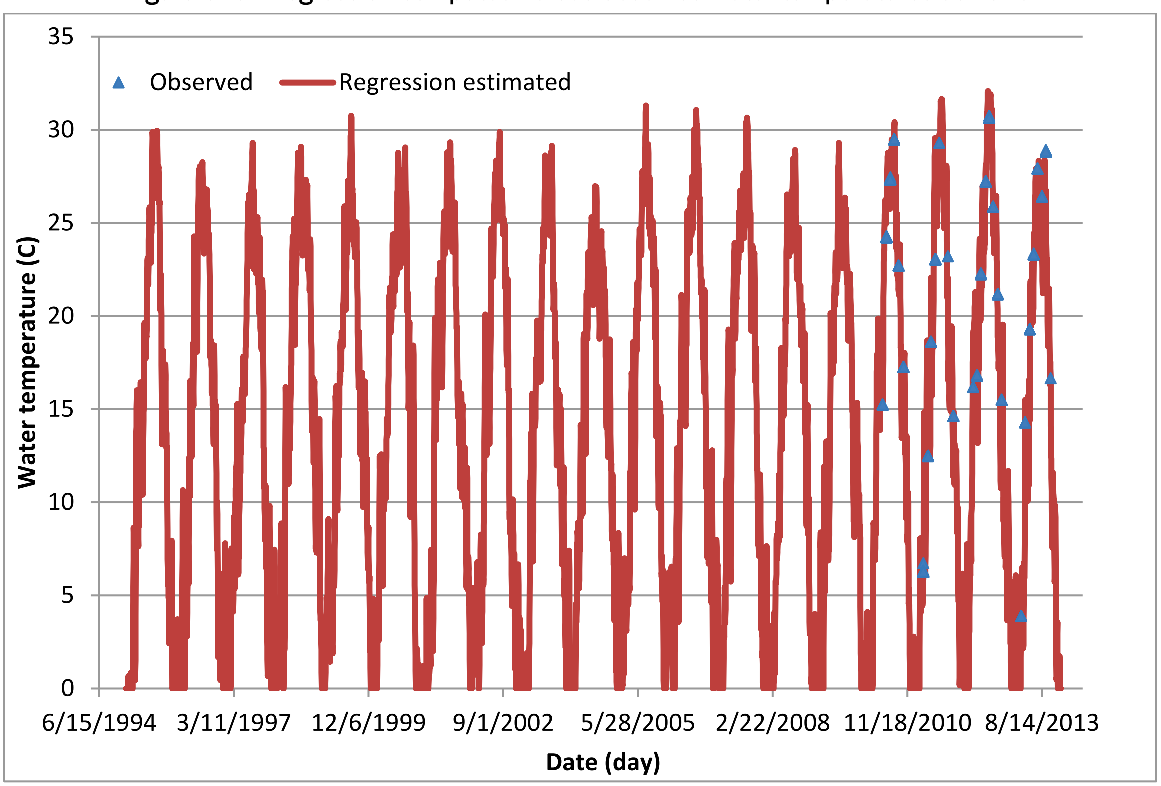


Figure C16. Regression computed versus observed water temperatures at BC16.

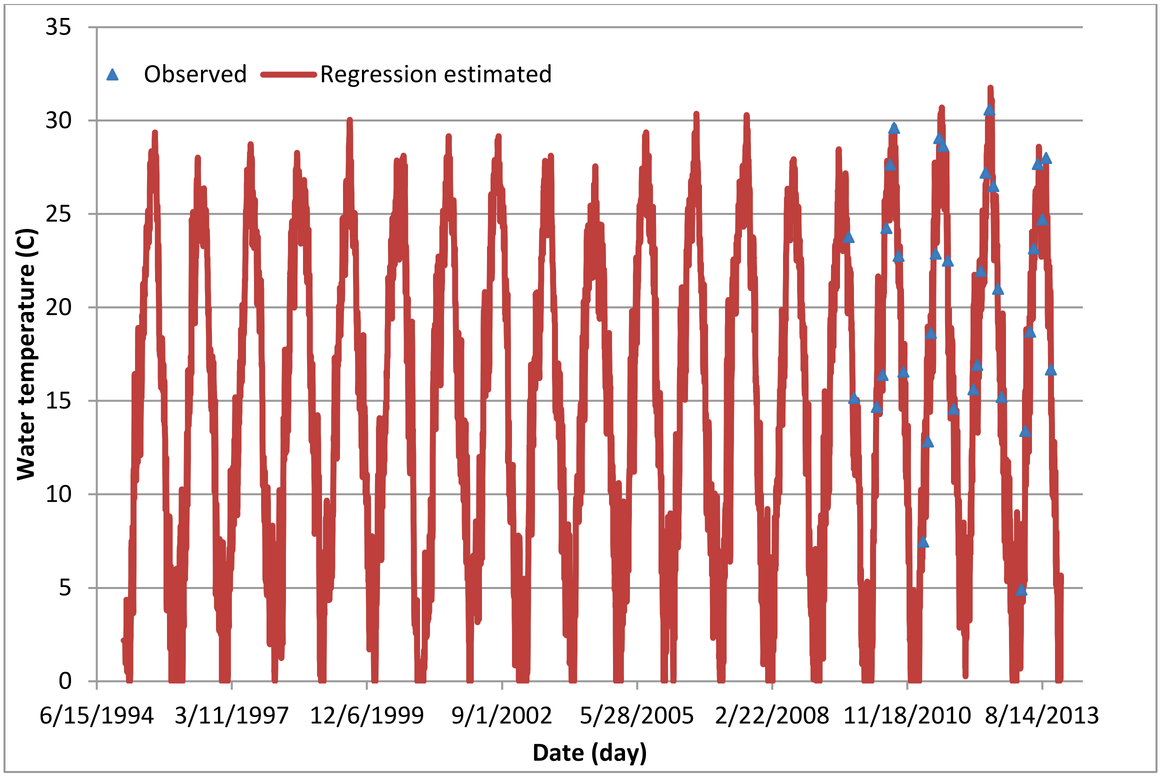


Figure C17. Regression computed versus observed water temperatures at BC17.

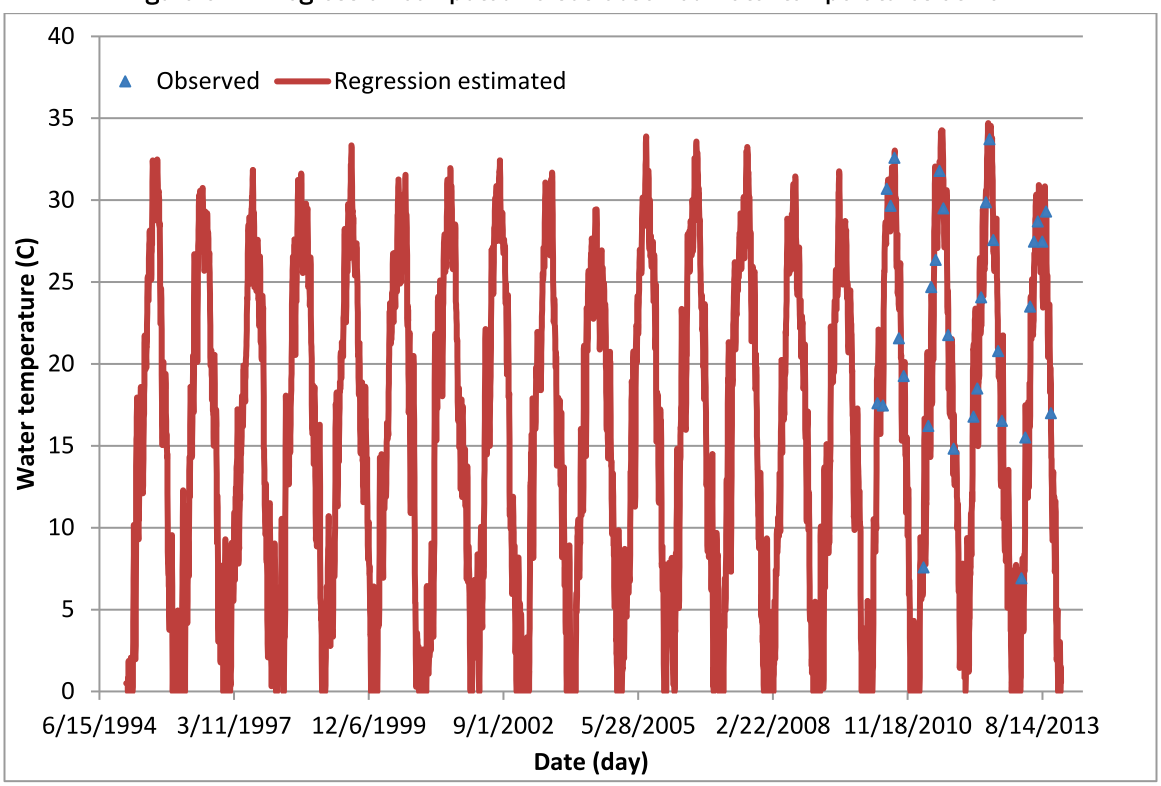


Figure C18. Regression computed versus observed water temperatures at BC18.

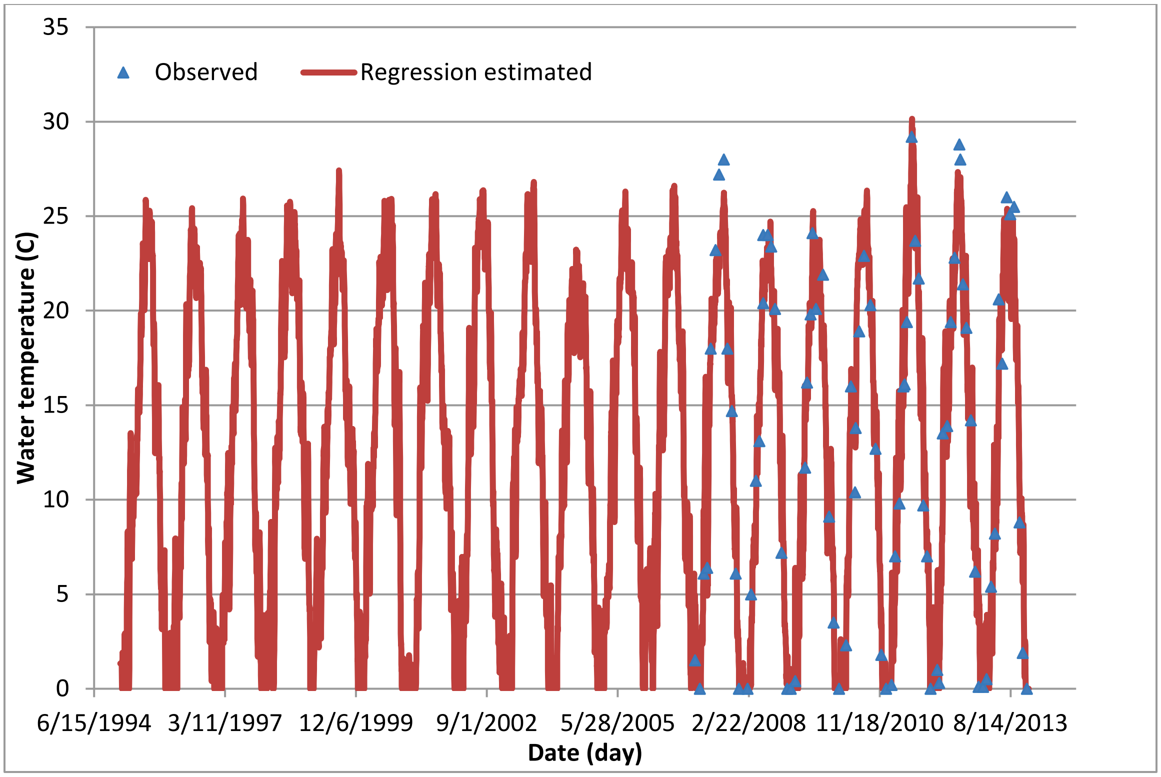


Figure C19. Regression computed versus observed water temperatures at BC19.

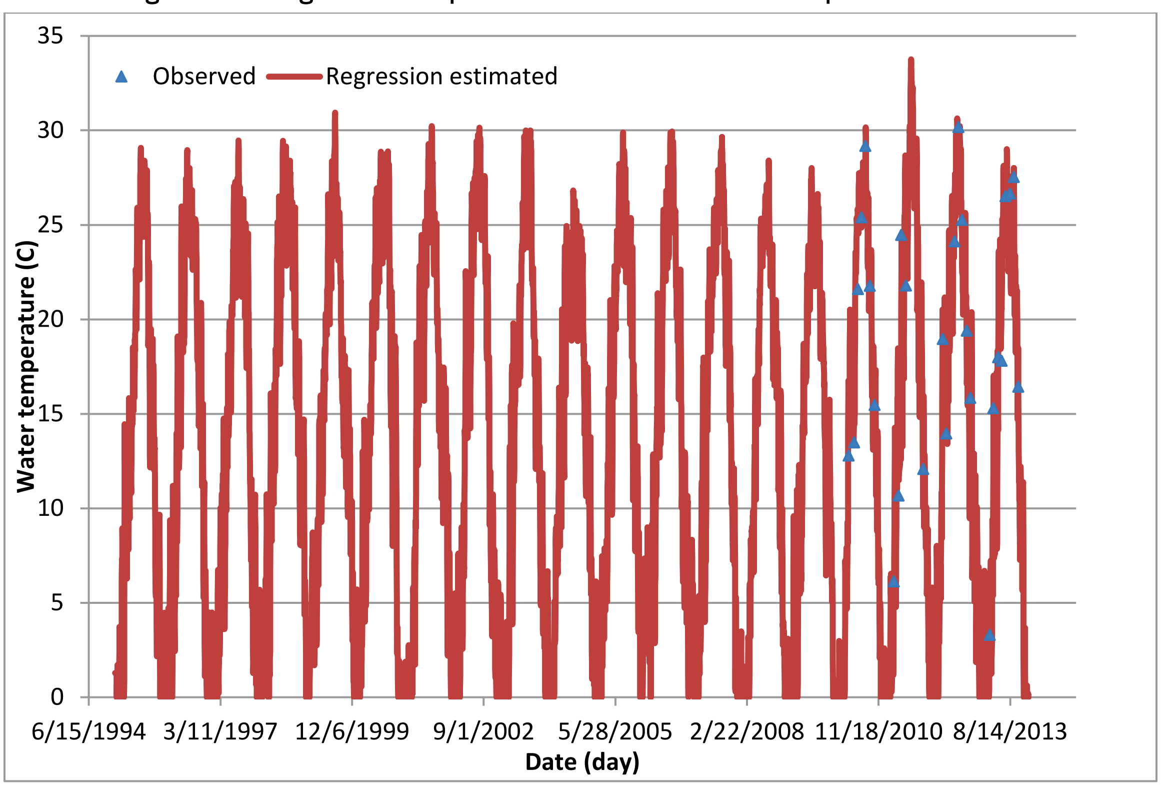


Figure C20. Regression computed versus observed water temperatures at BC20.

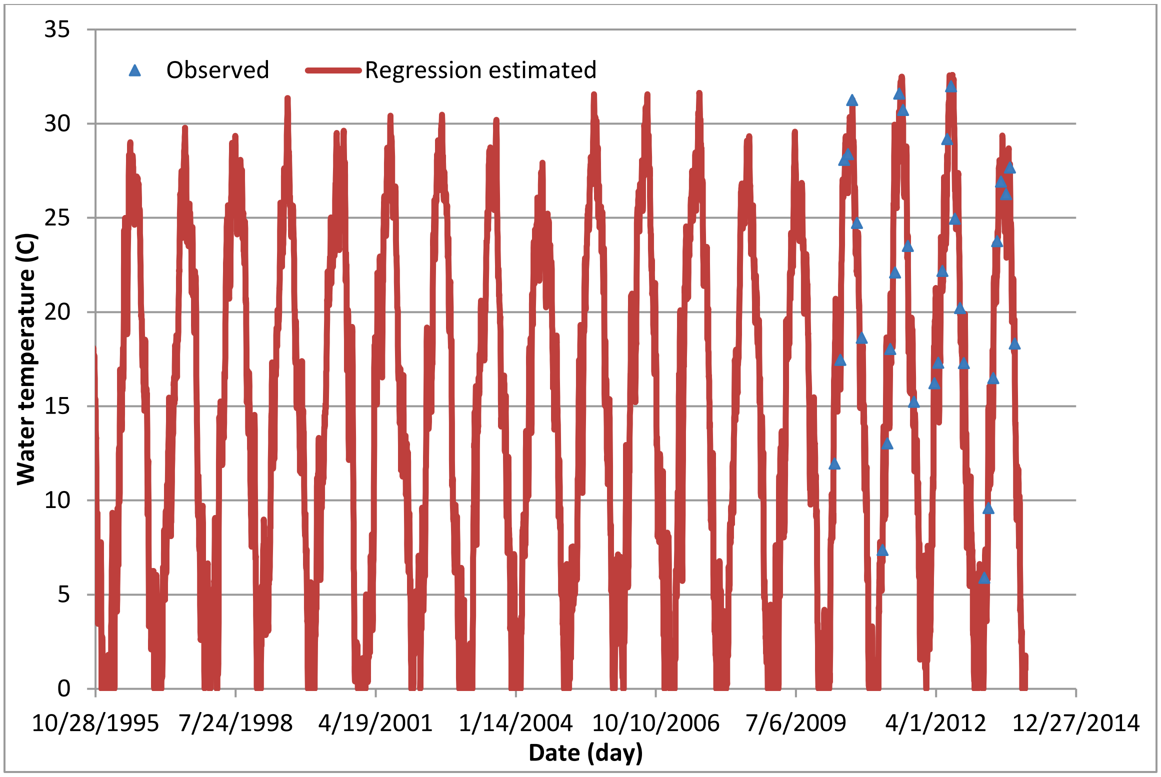


Figure C21. Regression computed versus observed water temperatures at BC21.

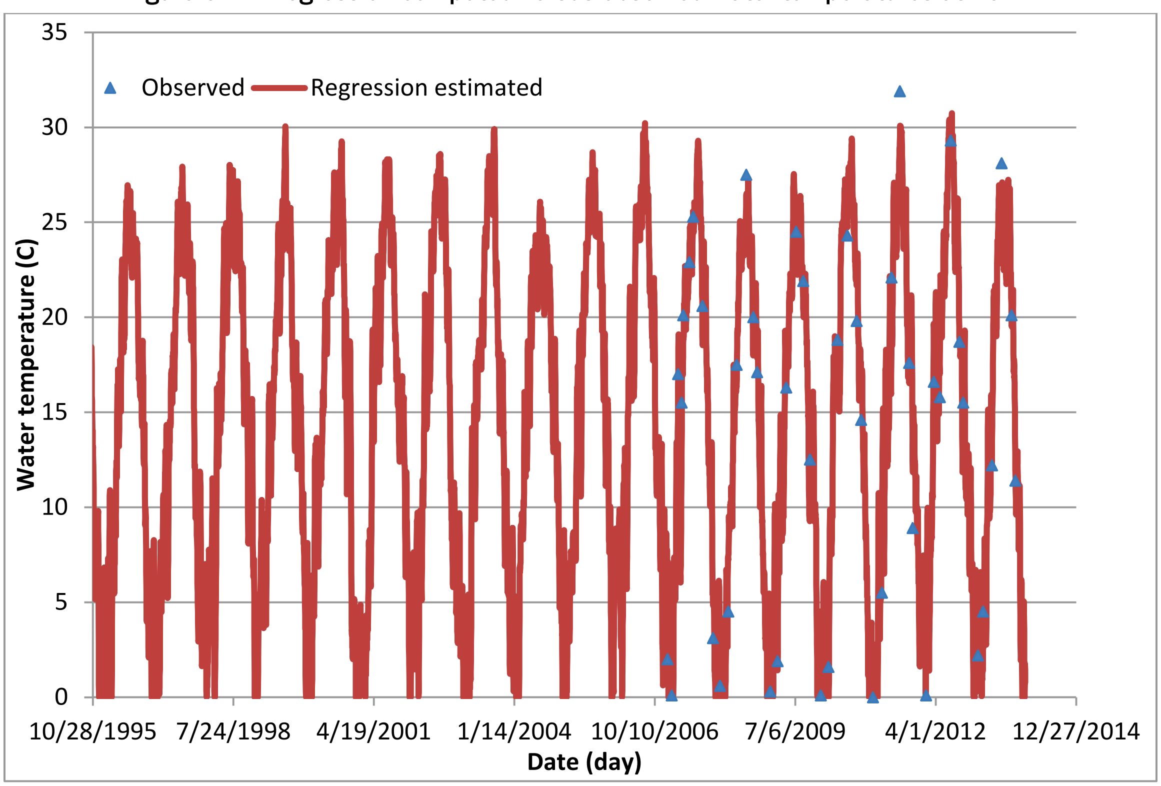


Figure C22. Regression computed versus observed water temperatures at BC22.

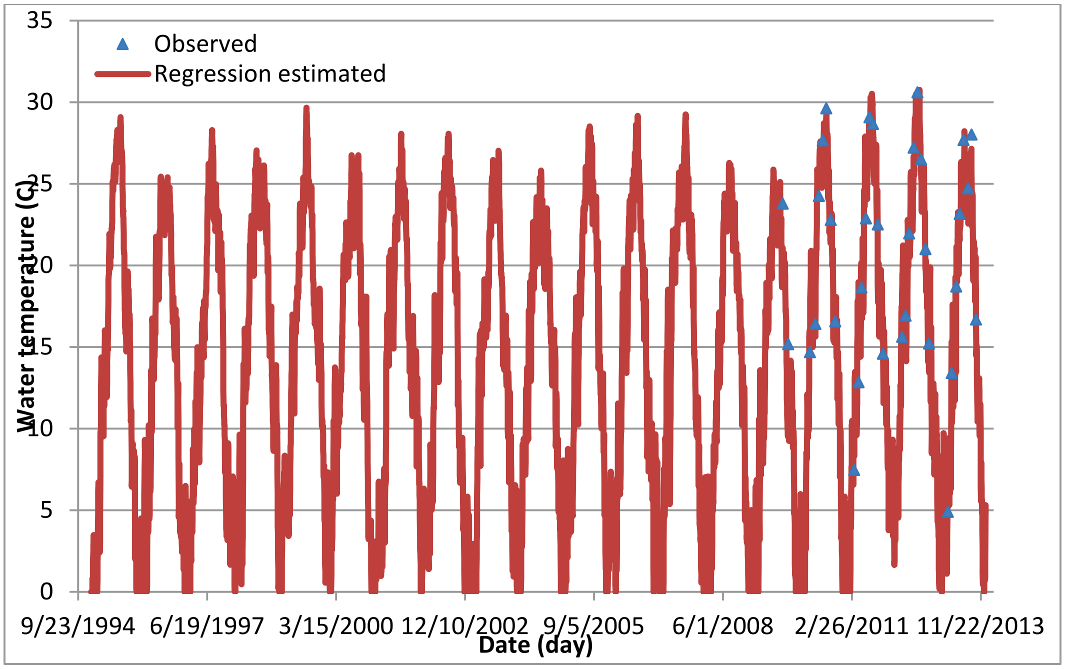


Figure C23. Regression computed versus observed water temperatures at BC23.

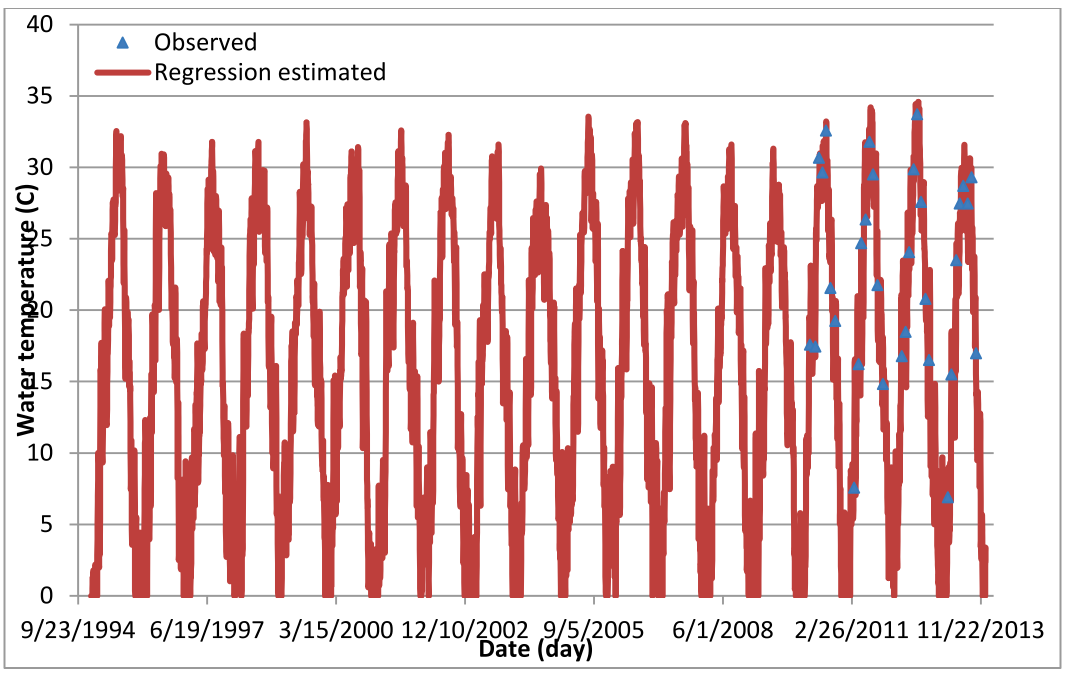


Figure C24. Regression computed versus observed water temperatures at BC24.

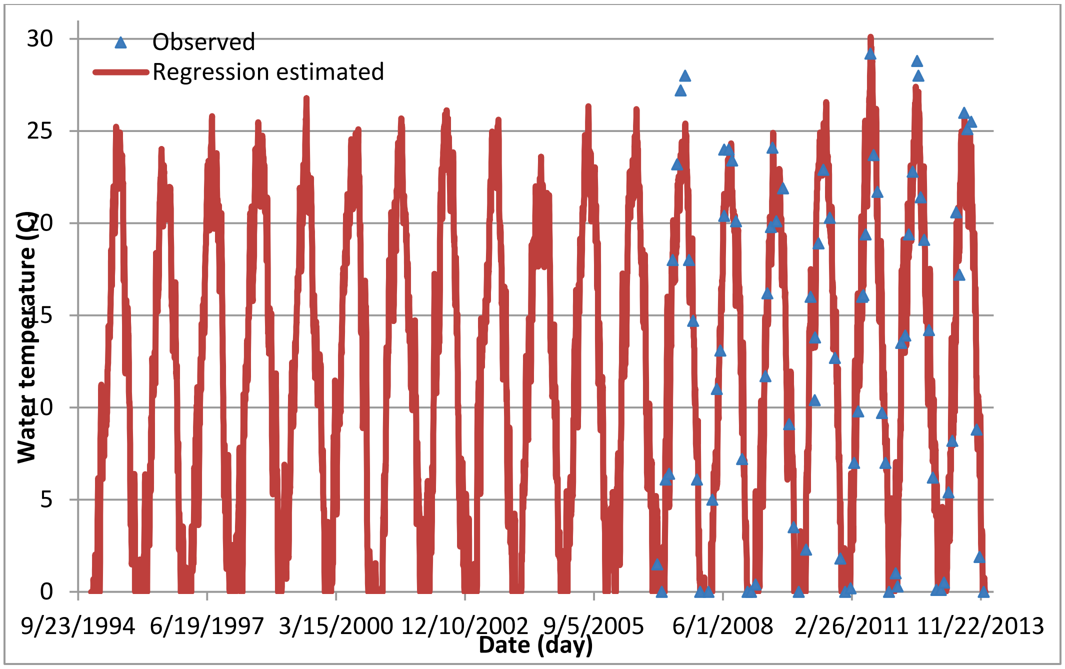


Figure C25. Regression computed versus observed water temperatures at BC25.

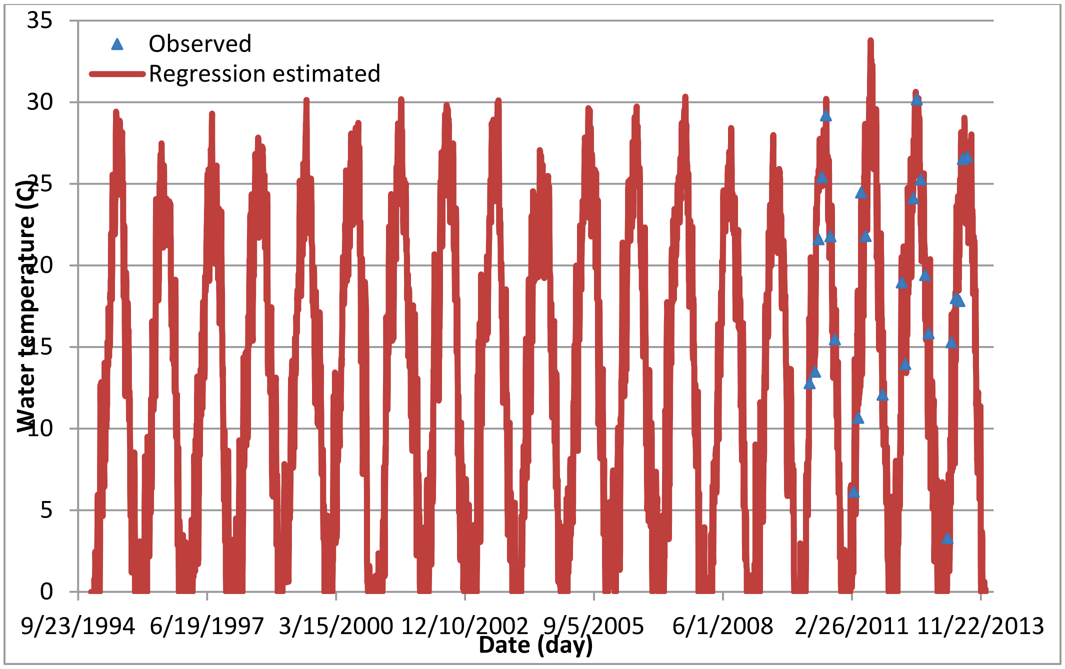


Figure C26. Regression computed versus observed water temperatures at BC26.

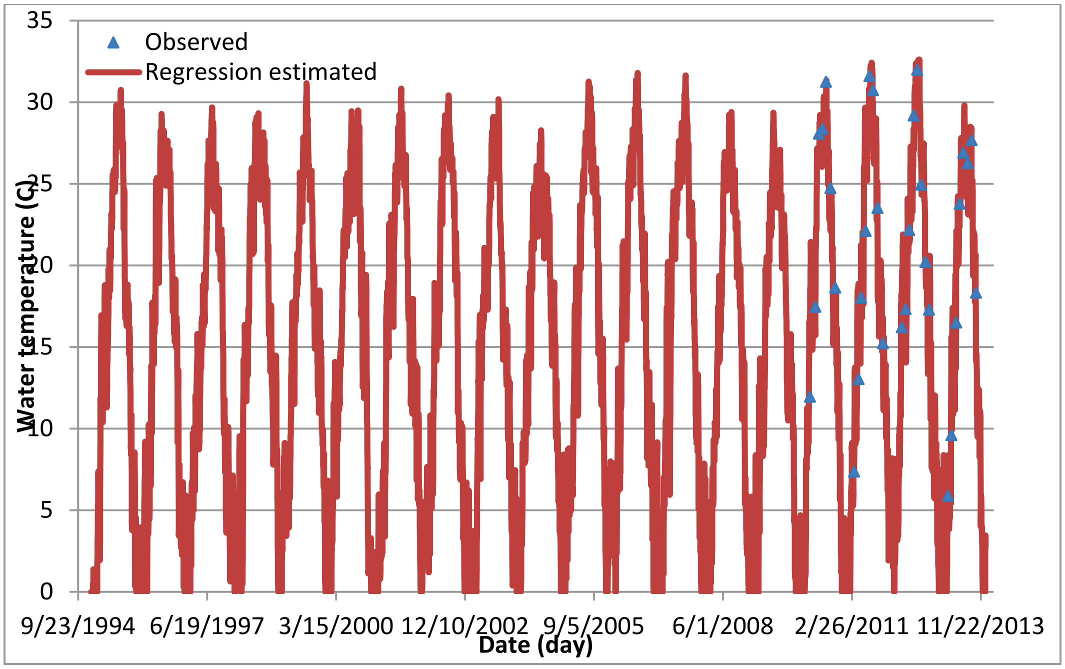
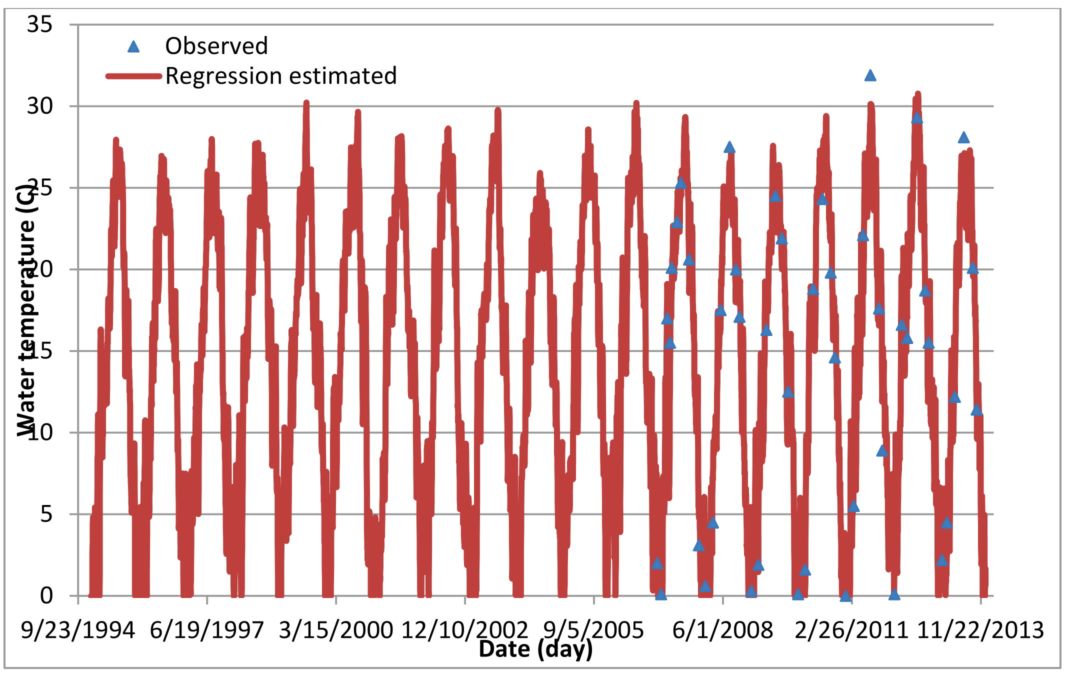


Figure C27. Regression computed versus observed water temperatures at BC27.



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Zhonglong Zhang and Billy E. Johnson

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14. ABSTRACT
This report describes the Hydrologic Engineering Center-River Analysis System (HEC-RAS) water temperature models for five Missouri river reaches (e.g., Fort Peck Dam to Garrison Dam; Garrison Dam to Oahe; Fort Randall Dam to Gavins Point Dam; Gavins Point Dam to Rulo, NE; and Rulo, NE to the mouth of the Missouri River). These models were developed based on calibrated HEC-RAS flow models that the Omaha and Kansas City Districts of U.S. Army Corps of Engineers (USACE) provided. Of five HEC-RAS water temperature models, three models were run for an 18-year period (1995 – 2012) for six alternatives in support of developing the Missouri River recovery program (MRRP) management plan (ManPlan) and environmental impact statement (EIS). The HEC-RAS water temperature model results that were used to establish a baseline and management alternative scenarios are presented in this report. Likewise, the sources of model uncertainty are discussed in this report as well.

15. SUBJECT TERMS
HEC-RAS
Water temperature
Missouri River
Recovery program
Management plans
Environmental impact statement

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