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Missouri River Recovery Program (MRRP)

DRAFT 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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Environmental Laboratory

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Environmental Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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Abstract

This report describes the HEC-RAS water temperature model development and calibration 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. The water temperature model results conducted for the baseline and management alternative scenarios are presented along the Missouri River. The sources of model uncertainty are discussed in the report. The HEC-RAS hydraulic models for five Missouri River reaches were developed and calibrated by USACE Omaha and Kansas City Districts. These models were further expanded to simulate the water temperature along the Missouri River. The HEC-RAS water temperature models were set up and preliminarily calibrated with limited observed data to simulate current conditions of water temperature along the Missouri River, with the intention of running management scenarios to compare alternatives in support of developing the Missouri River recovery management plans and environmental impact statement.

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Preface

This study was conducted for and funded by the Missouri River Recovery Program (MRRP) – Management Plan and Environmental Impact Statement. Jeff Tripe and Lisa Rabbe of USACE Kansas City District were Program Managers.

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. The study was conducted under the general direction of Dr. Beth Fleming, Director, EL; Mr. Warren Lorentz, Chief, EPED; and Dr. Dorothy Tillman, Chief, WQCMB.

Additionaly, Mark Jensen and Todd Steissberg (Hydrologic Enginnering Center), Zachary Jelenek of Sacramento District and Barry Bunch of WQCMB provided support for the HEC-RAS model improvement, model input data processing, and model execution.

At the time of publication, COL Bryan S. Green was Commander of ERDC and Dr. Jeffery P. Holland 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
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BiOp	Biological Opinion of the U.S. Fish and Wildlife Service
EA	Effects Analysis
EIS	Environmental Impact Statement
ERDC	U.S. Army Engineer Research and Development Center
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
MAF	million acre-feet
ManPlan	Management Plan
MRRP	Missouri River Recovery Program
NOAA	National Oceanic and Atmospheric Administration
NSM	Nutrient Simulation Module
NWS	National Weather Service
QUICKEST	Quadratic Upwind Interpolation for Convection Kinematics with Estimated Streaming Terms

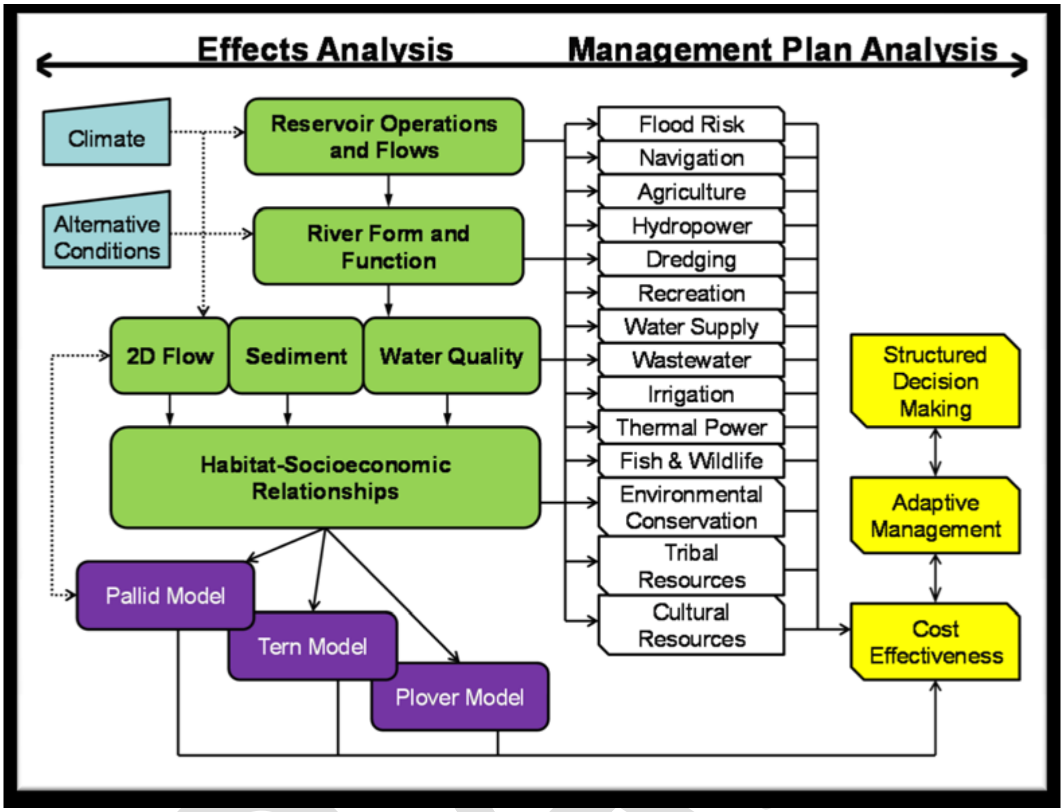
RM	River Mile
RMSE	root mean square error
SWAT	Soil and Water Assessment Tool
ULTIMATE	Universal Limiter for Transient Interpolation Modeling of Advective Transport Equation
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

1 Introduction

1.1 Background

Under the Missouri River Recovery Program (MRRP), the Kansas City and Omaha Districts of the U.S. Army Corps of Engineers (USACE) are leading the development of the Missouri River Recovery Management Plan (ManPlan) and Environmental Impact Statement (EIS) to address mitigation efforts, Biological Opinion (BiOp) compliance, and cumulative effects of USACE actions along the Missouri River. This effort will quantify the relationships among habitat conditions, habitat requirements, and species' demographics and evaluate the effectiveness of current habitat development and recommend any needed modifications to more effectively create habitat and avoid jeopardy to threatened and endangered species (Pallid Sturgeon, Least Tern and Piping Plover). 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 such as climate and predation. As outlined by Fischenich et al. (2014), these analyses are accomplished through a series of models recommended by technical working groups. Figure 1 illustrates 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 Hydrologic Engineering Center (HEC) models; mainstem Missouri River reservoir operations are modeled using HEC-ResSim; HEC-RAS models of riverine reaches are used to support hydraulic, sediment transport and water quality analyses. HEC-ResSim model outputs are used as inputs to the HEC-RAS hydraulic models. The HEC-EFM is used to integrate time series flow data from the 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 1-D models alone.

As identified by the water quality group (USACE, 2014), the one-dimensional (1-D), longitudinal (i.e., along river flow axis) Hydrologic Engineering Center-River Analysis System (HEC-RAS) with the aquatic Nutrient Simulation Modules (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 exsiting Missouri River HEC-RAS hydraulic models developed by the USACE (2015). HEC-RAS-NSM can model water temperature, nutrients and eutrophication in 1-D riverine systems.

The Environmental Laboratory of the U.S. Army Engineer Research and development Center (ERDC) 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. Five discrete HEC-RAS hydraulic models were developed by the USACE Omaha and Kansas City Districts for simulating river reaches of the mainstem Missouri River. 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 hydraulic models provided from the USACE Omaha and Kansas City Disctricts and 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 work in progress. We will continue to pursue useful data and 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

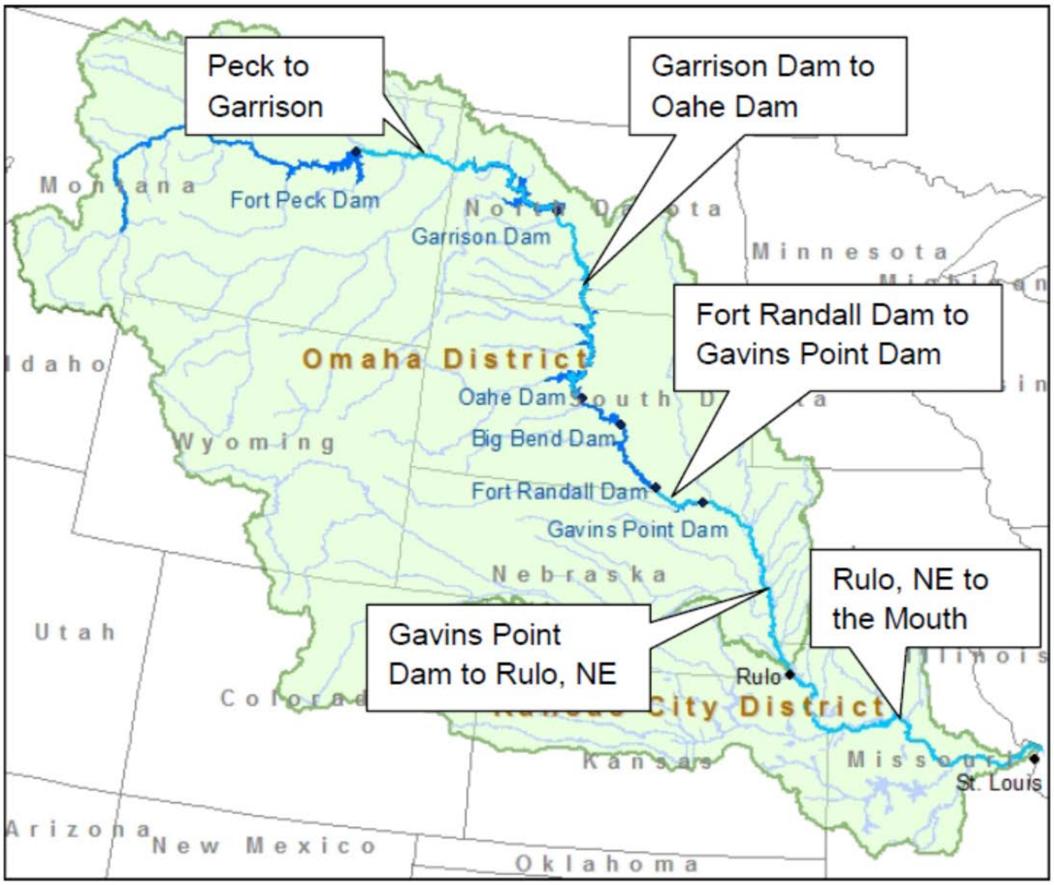
The tool used in this study was the 1-D HEC-RAS model. HEC-RAS water temperature models were developed based on the calibrated HEC-RAS flow models provided by USACE Omaha and Kansas City Districts. These HEC-RAS flow models are described in a separate USACE report (USACE 2015). Meteorological and inflow boundary conditions are primary model inputs for running a HEC-RAS water temperature model. Hourly meteorological data were obtained from from the U.S. Air Force Environmental Technical Applications Center in Asheville, NC and U.S. Environmental Protection Agency (EPA) web site. The inflows to the Missouri River HEC-RAS model domain include tributary inflows, distributed flows, and discharges from point sources. Because of limited observed water temperature data are available, boundary conditions for all inflow water temperatures used in the HEC-RAS models were computed from the multiple air – water temperature regression relationships. Regression methods were used to estimate missing data and compute long-term time series boundary conditions for the HEC-RAS water temperature models. The goal was to have a long-term simulation of water temperatures along the Missouri River in support of the ManPlan analysis.

2 HEC-RAS Flow Models for the Missouri River Management Plan and Environmental Impact Statement

The Missouri River is 2,341 miles long and drains one sixth of the contiguous United States, an area of 529,350 square miles. Its origin is south of the Canadian border in Montana and flows into the Mississippi River slightly north of St. Louis, Missouri. The Missouri River mainstem reservoir system includes six USACE's mainstem dams with a total storage capacity of 73.1 million acre-feet (MAF) and carry-over storage of 39 MAF of water, which makes it the largest reservoir system in North America. Six main stem dams consisting of Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point (in downstream order) regulate the flow in the Missouri River.

Five separate HEC-RAS unsteady flow models were developed by the USACE Omaha and Kansas City Districts for discrete reaches of the mainstem of the Missouri River in support of management plan and environmental impact statement. 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. Gavins Point Dam to Rulo reach and Rulo to Mouth reach HEC-RAS models overlap between Nebraska City, NE, and St. Joseph, MO. Figure 2 lays out the model extent and locations of the individual HEC-RAS models.

Figure 2. HEC-RAS Modeled Reaches on the Missouri River (USACE 2015).



The HEC-RAS model was only used for simulating the river reaches, not reservoirs on the Missouri River. Six reservoirs were modeled using HEC-ResSim and CE-QUAL-W2 models. Five HEC-RAS flow models for simulating free-flowing reaches of the Missouri River are described in a separate report (USACE 2015). In addition to the modeling of 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 mainstem. Minor tributaries that have USGS gage data were included as lateral inflow to the model. Numerious ungaged inflows are also included in the HEC-RAS flow model. The HEC-RAS flow models were developed from the best available ground, LIDAR and hydrographic survey data. These models have been 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).

Theses HEC-RAS models were used to support riverine modeling needs associated with the ManPlan and EIS. Outputs from the HEC-RAS modeling effort support conceptual and quantitative ecological models for evaluating species responses to management actions and evaluation of the effects to basin stakeholder interests and authorized purposes in the ManPlan 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 will be assessed.

3 HEC-RAS Water Temperature Model Formulation 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 module formulation and its input requirements.

3.1 Water Temperature Model Formulation

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 et al. 2008). 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 dvection-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 heat transport equation is given as:

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

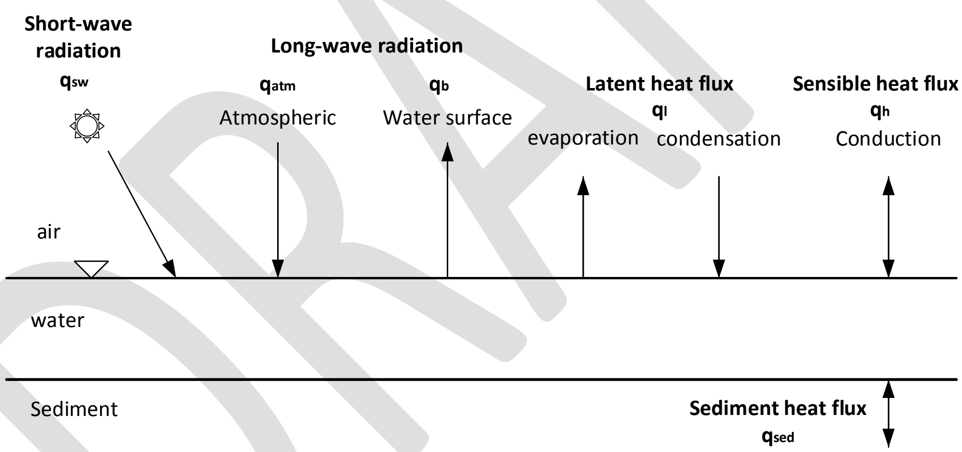
where

- V = volume of the computational cell (m^3)
- T_w = water temperature (^{o}C)
- 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 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 (after 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

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

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 change in water temperature due to a change in net heat flux (q_{net}) is described by the following equation

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

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 QUICKEST–ULTIMATE (Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms) explicit numerical scheme. The QUICKEST–ULTIMATE form of the 1-D water quality transport solved in HEC-RAS is:

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

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 can be substituented by T_w. Details of QUICKEST- ULTIMATE formulae for unsteady flows on a non-uniform grid, are provided by Leonard (1979, 1991). The water quality model's time step is dynamically recalculated and adjusted in HEC-RAS so that following Courant and Peclet constraints are automatically met. This differs from the flow model where the user may specify the time step (HEC, 2016a).

$$C_{us} = u_{us}\frac{\Delta t}{\Delta x} \pounds\ 0.9 \qquad (3.5a)$$

$$\alpha_{us} = D_{us}\frac{\Delta t}{\Delta x^2} \pounds\ 0.4 \qquad (3.5b)$$

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 constituents. In this study, ithe initial condition is the temperature profile along the modeled river domain at the beginning of the simulation. Water temperature in flow 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

A HEC-RAS water quality model requires an extensive array of coefficients and measured data that are used to describe hydraulic transport, transfer, and biochemical transformation properties of the simulated reaches. The physical factors that affect stream temperature regime include climate, hydrology, topography, channel morphology, and near-stream vegetation (Story et al. 2003). The water temperature module uses the schematization already set up for the flow model. The flow inputs for computing water temperature are computed by the HEC-RAS 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 detup 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 U.S. Geological Survey (USGS). 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 tempearature 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 HEC-RAS Water Temperature Model Development and Calibration

This chapter describes the HEC-RAS water temperature model development and calibration for the five modeled reachs 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 reaches for Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the Mouth were set up and run for an 18 year simulation period (1995 – 2012). Model results from these three river reaches have been used for the ManPlan analysis.

4.1 Meteorological Data

In this study, historical meteorological data were obtained from the U.S. Air Force Environmental Technical Applications Center (AFETAC) in Asheville, NC and U.S. Environmental Protection Agency (EPA) web site. Hourly meteorological data were processed and compiled into one HEC-DSS file (MoRMet.dss) for 14 meteorological stations along the lower Yellowstone River and Missouri River. Figure 4 shows the spatial distribution of meteorological stations used in the HEC-RAS temperature models. Table 1 lists 14 meteorological stations, their parameters and data records. Each station includes the following parameters: ATEM (air temperature), DEWP (dew point), SOLR (short wave radiation), CLOU (cloud cover), and WIND (wind speed). These parameters are included in the HEC-DSS file, their data records cover the period from 1975 to 2013.

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

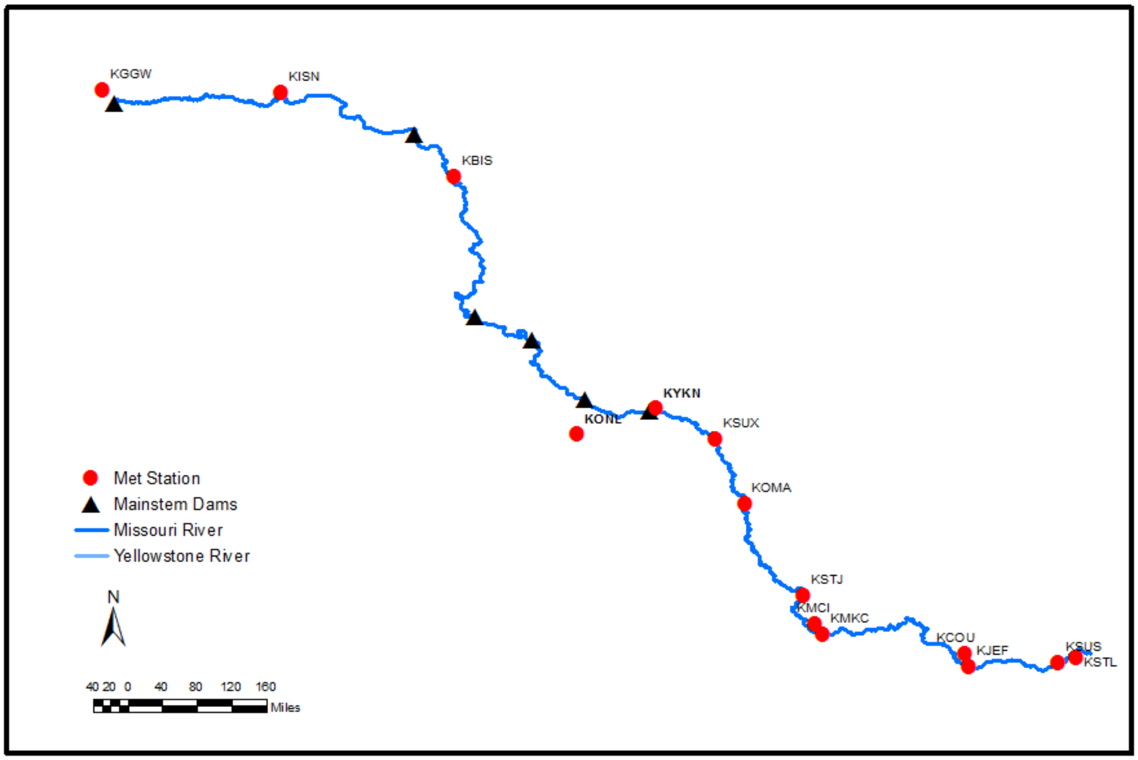


Table 1. Meteorological stations along the Missouri river and their properties.

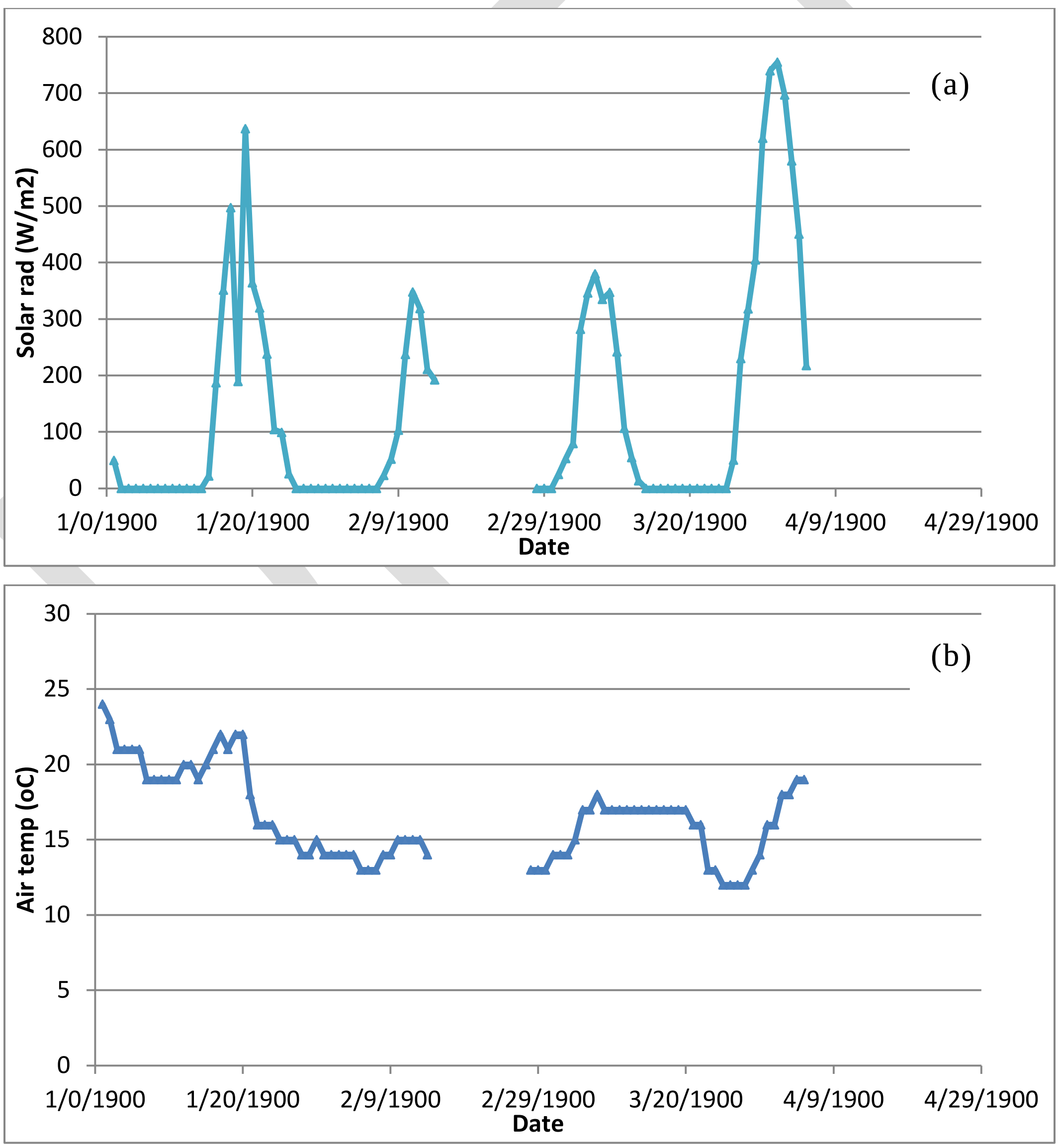
AFETAC ID	BASINS ID	Station Location	Latitude	Longitude	Elevation (ft)
KGGW	MT243558	WOKAL FLD GLASGOW INTL, MT	48.2125	-106.61472	2296
KISN	ND329425	SLOULIN FLD INTL, ND	48.17793	-103.64234	1982
KBIS	ND320819	BISMARCK MUNI, ND	46.77273	-100.74573	1661
KONL	n/a	ONeillMuni John L Baker FLD, NE	42.46989	-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

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

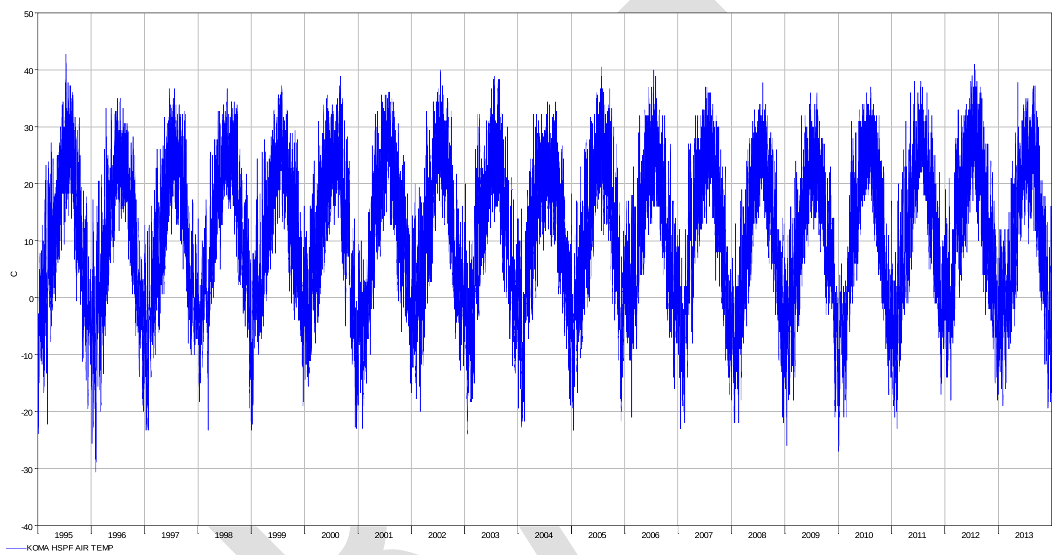
The HEC-RAS temperature model requires meteorological data to be stored in HEC-DSS with a constant time interval. There were often gaps in source data obtained from AFETAC and National Weather Service (NWS). Sometimes the data gaps are small, less than a day, and sometimes the data gaps are large, several days or months. For example, Figure 5 shows some of the gaps in hourly solar radiation and air tempearure 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, th data gaps were filled with a straight line between the two bounding values. In this study, all meteorological data with gaps filled was compiled into one single HEC-DSS file (MoRMet.dss). For example, Figure 6 shows the time series plot of hourly air tempearure at the KSTL station.

Figure 6. Hourly air temperature at KOMA, NE.



4.2 Water Temperature Boundary Conditions

The inflows to the Missouri River HEC-RAS model domain include tributary inflows, distributed flows, and discharges from point sources. Flow discharging from point sources was taken into account as part of ungagged flow in the Missouri River HEC-RAS flow models. Therefore, boundary conditions for all point source water tempeartures were not specified in the Missouri River HEC-RAS water temperature models.

In this study, the primary source for observed water temperature data was the USGS web site. USACE Omaha and Kansas City Districts also provided temperature data for 2010 to 2014 (USACE 2014). Overall, observed water temperature data for the Missouri River and major tributaries were limited for the simulation period frrom 1995 to 2012. From 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 water quality monitoring locations only covered a five year period record from2009 to 2013. Some locations have a longer period of record for water temperature measurements.

Due to limited observed data, water temperatures for all inflow boundaries had to be generated from other methods. A basin wide watershed model such as Soil and Water Assessment Tool (SWAT) or HSPF (Hydrological Simulation Program-Fortran) can be used to compute water temperatures for all inflow boundaries discharging into the Missouri River. However, a watershed model for the Misssouri River basin did not exit. Development and calibration of a watershed model for the Misssouri River basin was not feasible under this project due to limited resources (funding and time). Alternatively, an air - water temperature regression relationship was proposed by the project team 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 for the ManPlan analysis were computed from the regression relationships and feed into the model.

Even many factors will 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). Linear and non linear regression relationships between air and stream temperatures have been developed and applied successfully by previous researchers. Table 2 provides a summary of air-water temperature regression relationships that have been used before.

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)
	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 Fort Peck Dam to Garrison Dam and Fort Randall Dam to Gavins Point Dam reache HEC-RAS models were not required in the ManPlan analysis. 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 were computed from daily air and water temperature regressions 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) non-linear regression. 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 to 12 day average (the same day plus the next six and past six days) 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 has been 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 can be writtern as

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

where

T_a = measured daily average air temperature for the day t (°C)
T_w = water temperature for the same day t (°C)
a_0□a_1 = regression coefficients
$\varepsilon(t)$ = error term.

The model calibration and validation to determine the two parameters a_0, a_1 is performed by minimizing the root mean square error (RMSE) between regression estimated and observed water temperatures. RMSE is defined as

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

where

$RMSE$ = root mean squaree 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 0 to 1 which describes how much of the observed dispersion is explained by the model. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the model is equal to that of the observation, indicating a perfect fit.

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

In this study, the linear regression was evaluated using two data sets, where one includes fewer observed water temperature values, and the other includes more observed water temperature values. If there are multiple meterological stations around the stream temeperature monitoring station, the closest meterological station was used in developing the regression relationships. The first data set includes water temepearutre in the Missouri River at Kansas City, MO (USGS 0689300) and air temperature at station - MO234359. Figure 7 shows the linear regression relationship between air and water temperature. Time series plot of observed and linear regression computed water temperatures at this location is presented in Figure 8.

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

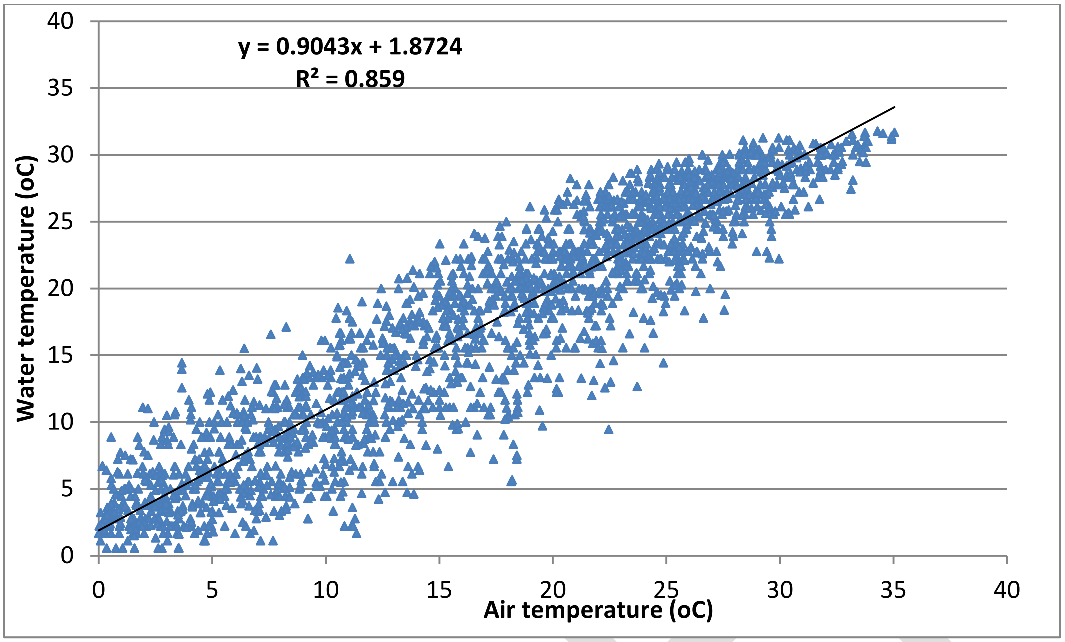
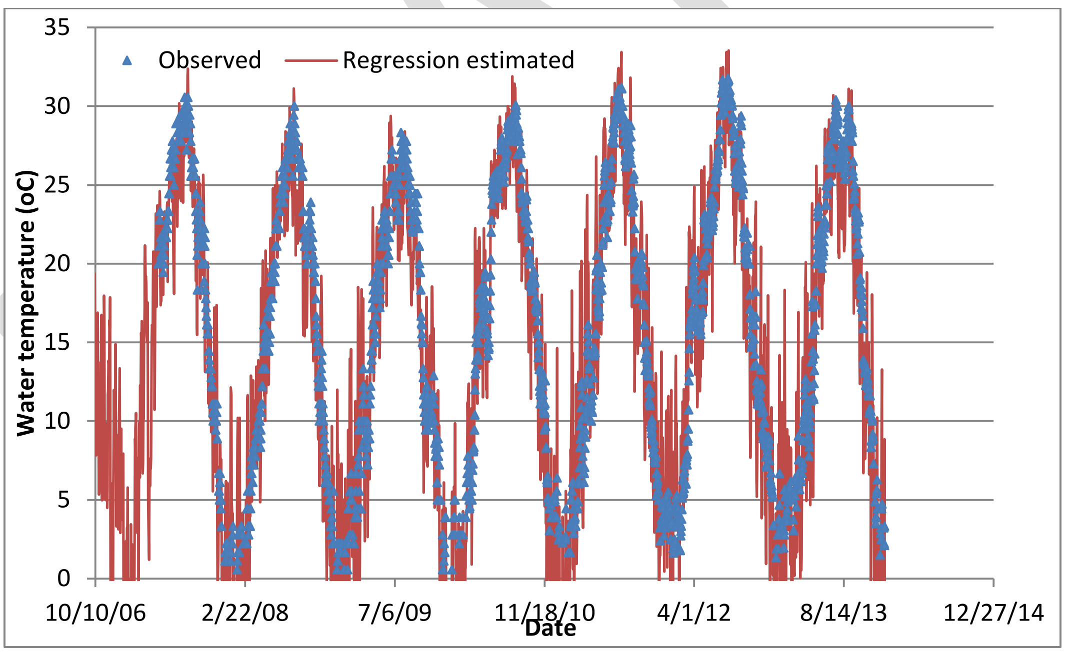


Figure 8. Observed vs. regression computed water temperatures at USGS 0689300.



The second data set includes water temepearutre from the Mississippi River at Grafton, IL (USGS 05587455) and air temperature at MO232591. Figure 9 shows the regression relationship between air and water temperature. Comparison of observed and linear regression computed water temperatures at this location is presented in Figure 10.

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

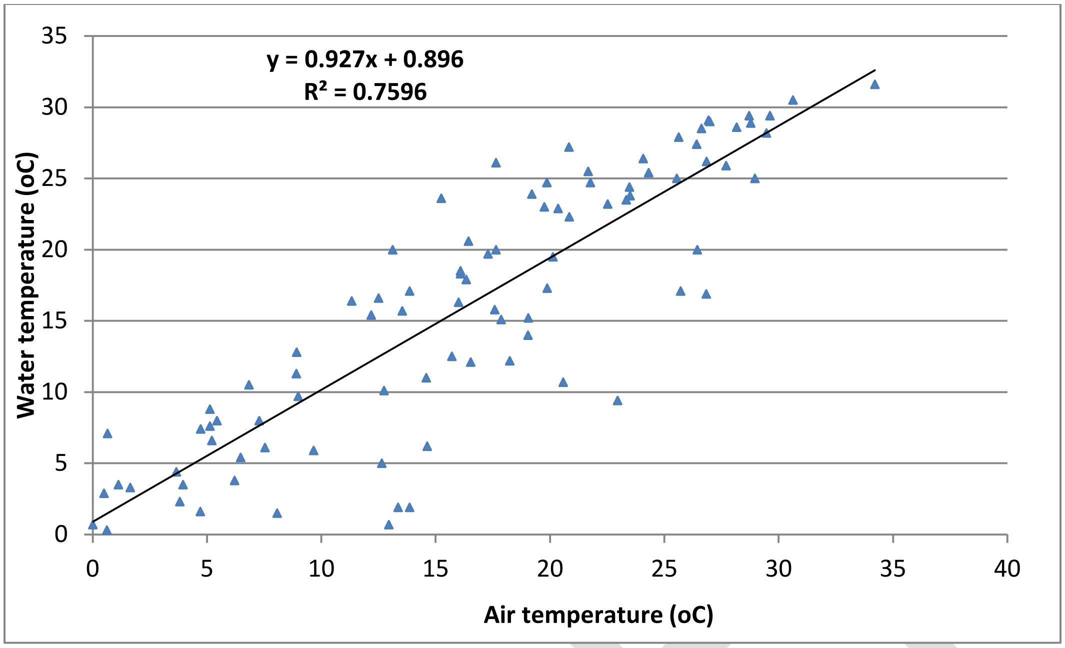
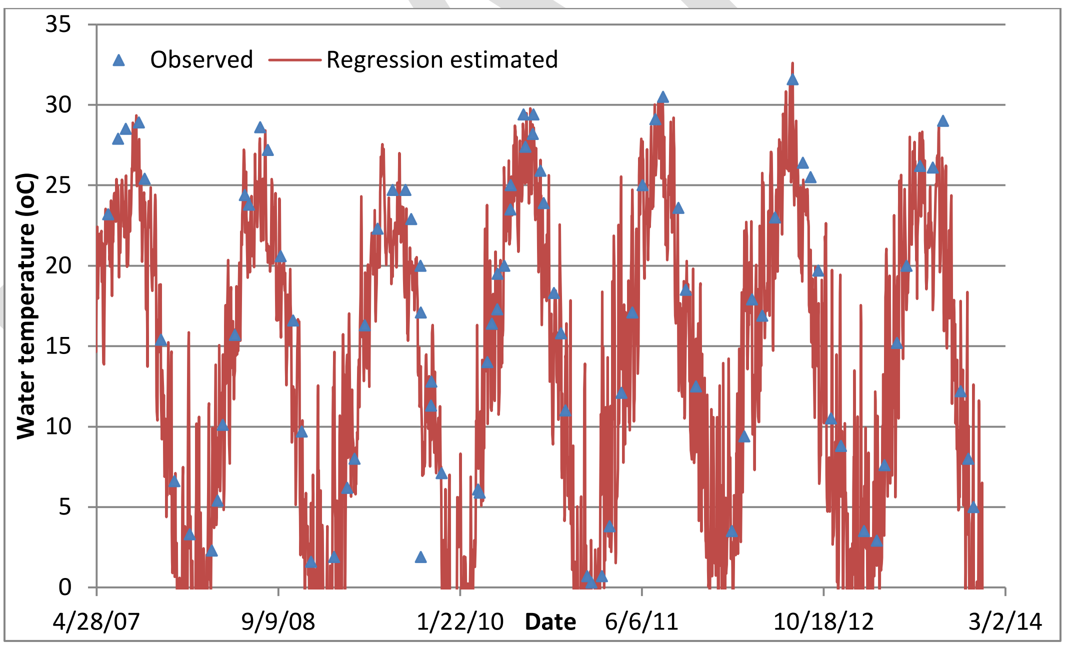


Figure 10. Observed vs. regression computed water temperatures at USGS 05587455.



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, a S-shaped logistic function to predict average weekly stream temepeartures at different locations in the U.S. was developed (Mohseni et al. 1998). This function is expressed as:

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

where

a = estimated maximium water temperature
β = air temperature at the inflexion point
μ = estimated minium water temperature
γ = steepest slope of the logistic function.

The parameters μ, γ and β are calculated iteratively to minimize RMSE. Comparison of observed and non-linear regression estimated water temperatures for two locations (USGS gages 0689300 and 05587455) discussed above are shown in Figures 11 and 12.

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

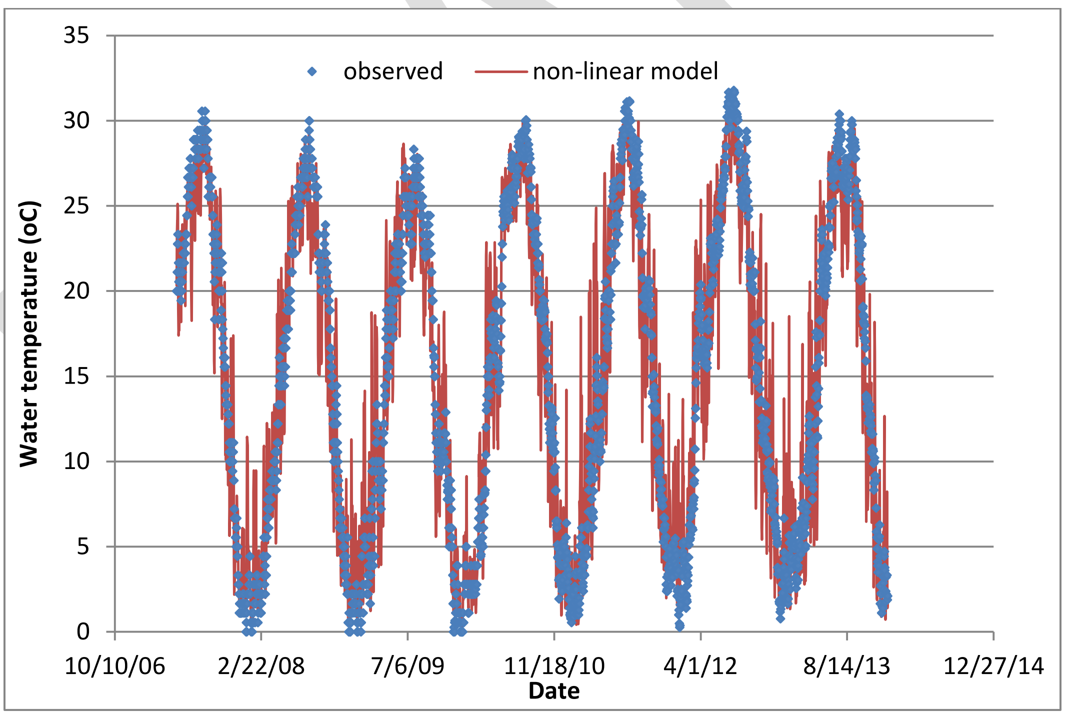
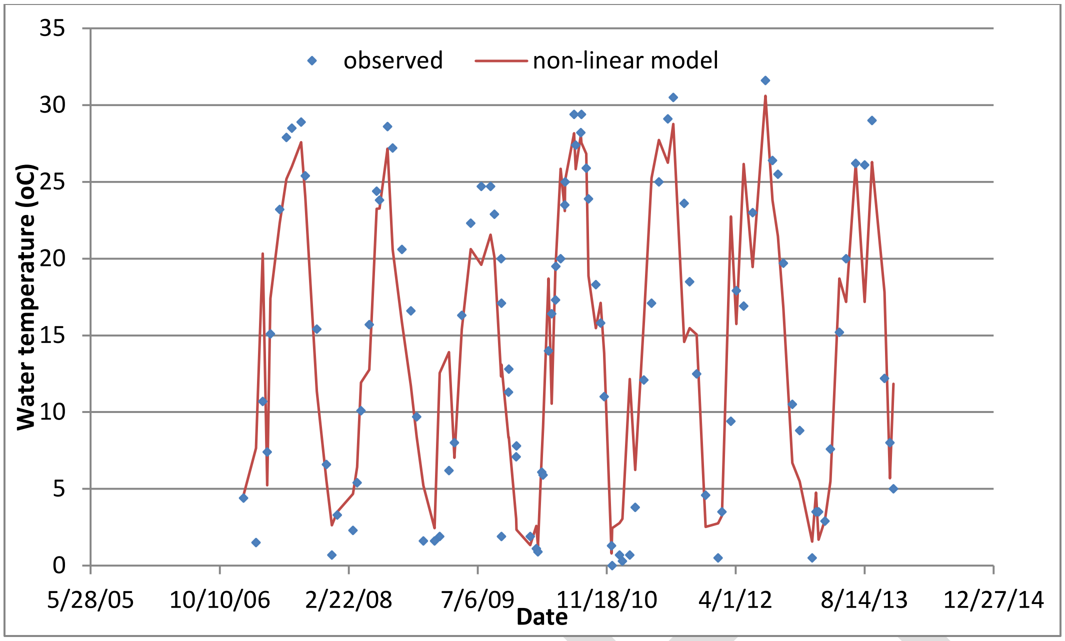


Figure 12. Observed and regression computed water temperatures at USGS 05587455.



As shown in above figures, the non-linear regression performs better than the linear regression when air temperatures close or drop below 0 ^{0}C. Warmer temperatures predicted using the two regression approaches discussed above are pretty much same for the two data sets. However, calibrating μ , γ and β parameters included in the non-linear regression is a challenge for multiple locations and long-term simulation (more than ten years) in this study. For efficiency, a piece-wise linear regression was an adequate appropriate approach to explain the nonlinear relationship between water and air temperatures. Thus, the observed water temperature data set was divided and calibrated using the multiple linear regression approach for each location. After the multiple linear regression relationships were developed, they were used to compute mean daily water temeperatures and feed into the HEC-RAS models for the three modeled reaches, Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the Mouth.

4.2.2 Application of the regression equations to the inflow tributaries for the Missouri River

In this study, a series of linear regression relationship was applied to compute daily stream temperatures as a function of daily air temperatures. Figure 13 is a map of the water quality monitoring gages and meterological 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 meterological stations used for Gavins Point Dam to Rulo and Rulo to the Mouth reaches. Table 3 provides a list of water temperature boundaries computed from the regression relationships. The total 51 boundary conditions for water temperature were created for three HEC-RAS water temperature models. In all regression relationships, the mean daily air temperatures are computed from observed hourly data .stored in MoRMet.dss.

Figure 13. Water quality monitoring gage locations and correlated meterological stations along the Garrison Dam to Oahe Dam reach.

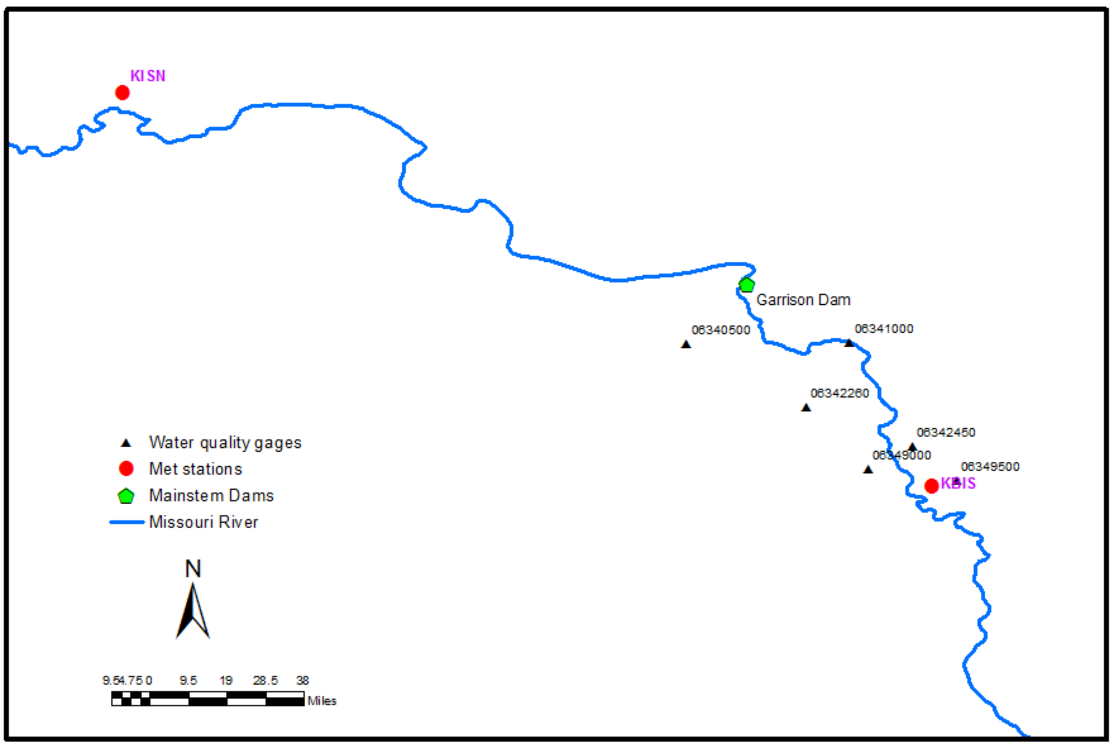


Figure 14. Water quality monitoring gage locations and correlated meterological stations along the lower Missouri River.

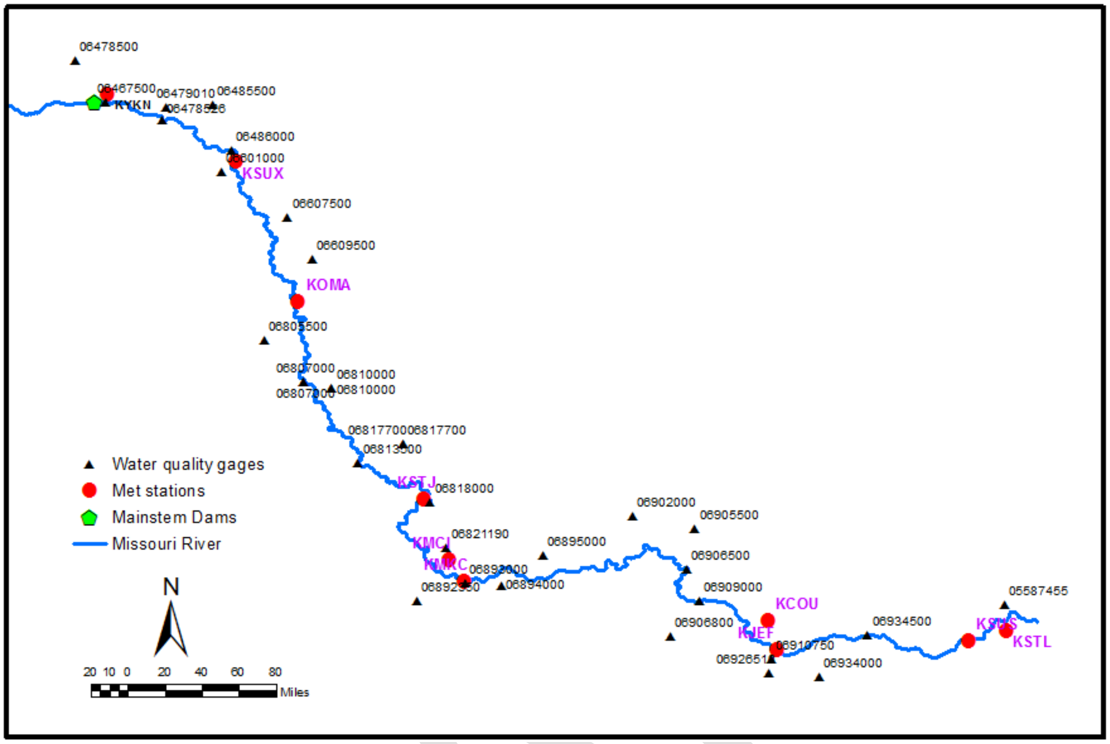


Table 3. Water temperature boundaries derived from water quality monitoring gages and meterological stations.

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 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

Time series of regression model predicted and observed water temperatures for each of the boundary sites included in the HEC-RAS water temperature models are provided in Appexdix A to C. The performance of the regression relationships were assessed through a visual comparison between regression estimated and observed water temperatures and statistics. 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, but other factors such as solar radiation, wind speed, relative humidity, water depth, and water flow rate are also important. Additionally, stream temperature is greatly influenced by the source characteristics of the water, where snowmelt, surface runoff, groundwater inflow, or cultural heat inputs have different temperature signatures, with surface runoff close to the ambient air temperature and snowmelt 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. From reviewing all comparisons of regression predicted water temperature and observed data presented in Appendix A to C, the regression model 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. The dependence of regression coefficients on stream characteristics and weather parameters other than air temperature is also evident in their results. Not being able to capture the temporal variations in observed water temperature 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 predicting water temperature boundary conditions. Therefore, we recommend the current HEC-RAS model results are best used for assessing the relative changes of water temperatures along the Missouri River rather than using them to assess absolute deterministic values.

4.3 Model Development and Calibration

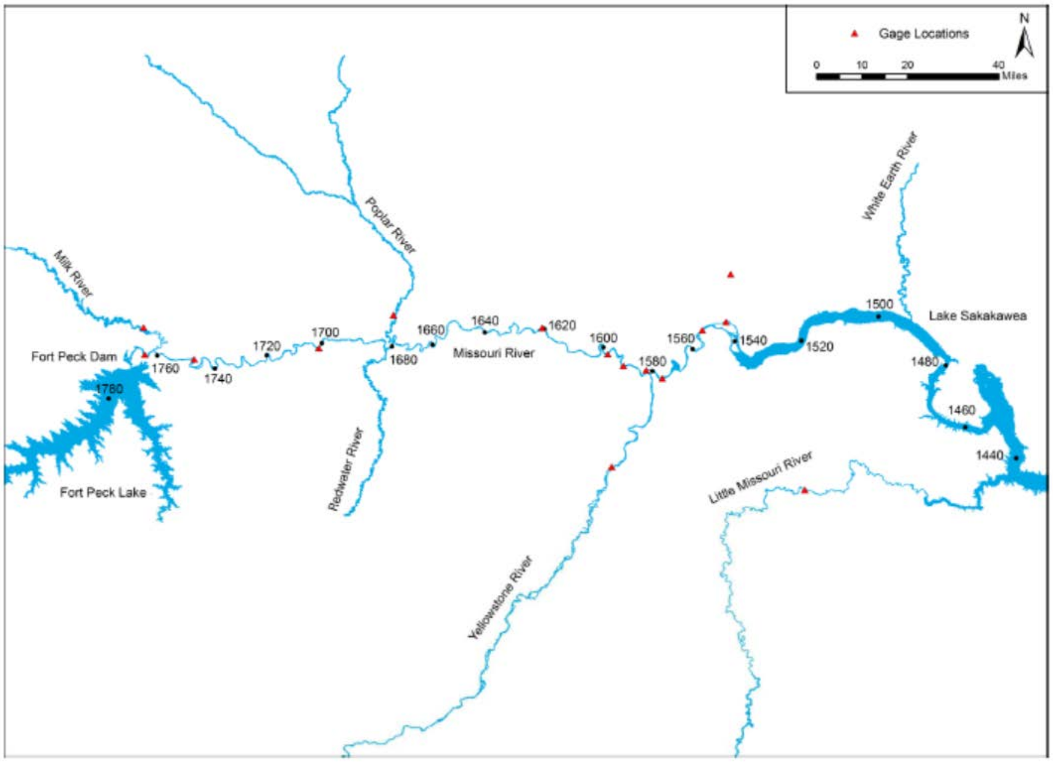
All HEC-RAS water temperature models were constructed based on the calibrated HEC-RAS flow models provided by the USACE Districts. The following sections discuss each modeled river reach separately.

4.3.1 Fort Peck Dam to Garrison Dam Reach

4.3.1.1 HEC-RAS flow model

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

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



In addition to the modeling of 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 extending approximately 24 miles from the confluence with the Missouri River to Nashua, MT.
- Poplar River near Poplar, Montana extending 14 miles upstream from the confluence with the Missouri River.
- Yellowstone River extending approximately 62 miles from the confluence with the Missouri River to Sydney, MT.

4.3.1.2 Water temperature model inputs

Meteorological data

Two meteorological stations KGGW and KISN 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 modeled water quality 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), water discharges and inflow temperatures for all tributaries along the reach. Table 4 below provides a list of flow boundary locations and their water temperature inputs included in the HEC-RAS model. If there is no water quality monitoring station available for the inflow boundary, observed data collected from adjacent water quality stations were used. For example, the same water quality station is listed in Table 4 for different inflow boundaries.

Table 4. Flow and temperature boundaries included in the Fort Peck Dam to Garrison Dam HEC-RAS model

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

Missouri River XS 1701	Lateral inflow	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1689	Lateral inflow	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1681	Lateral inflow	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1678	Lateral inflow	USGS (1696.9)	Missouri River, Wolf Point, MT	5/7/2010 - 10/20/2013	656
Missouri River XS 1645	Lateral inflow	USGS (1615.1) [2]	Missouri River, Culbertson, MT	5/7/2010 - 10/1/2013	502
Missouri River XS 1630	Lateral inflow	USGS (1615.1)	Missouri River, Culbertson, MT	5/7/2010 - 10/1/2013	502
Missouri River XS 1627	Lateral inflow	USGS (1615.1)	Missouri River, Culbertson, MT	5/7/2010 - 10/1/2013	502
Missouri River XS 1623	Lateral inflow	USGS (1615.1)	Missouri River, Culbertson, MT	5/7/2010 - 10/1/2013	502
Missouri River XS 1545	Lateral inflow	USGS (1573.6) [2]	Missouri River below Yellowstone River, MT	5/7/2010 - 10/1/2013	330

1. Water temperature data for these locations were provided by the USACE Omaha District.

2. Water temperature data for these locations were provided by the USGS.

3. USGS gage.

4.3.1.3 Water temperature model set up and calibration

The HEC-RAS water temperature model for the Fort Peck Dam to Garrison Dam reach was not used in conducting ManPlan analysis. The model was set up and run only from January 1, 2011 to September 30, 2012 due to availability of water temperature boundary conditions. The model operated on an hourly time step. Hourly time step was also used in other HEC-RAS water temperature models described in this chapter. The water temperature model for this river reach was only preliminarily calibrated due to limited observed data and approximate boundary condition inputs. During the model calibration, solar radiation, coefficients in the wind speed function are adjusted.

Time series plots of model predicted and observed water temperatures at five USGS stations along the Fort Peck Dam to Garrison Dam reach are presented in Figures 16 to 20. In these figures model results were compared to observed water temperature data where available.

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

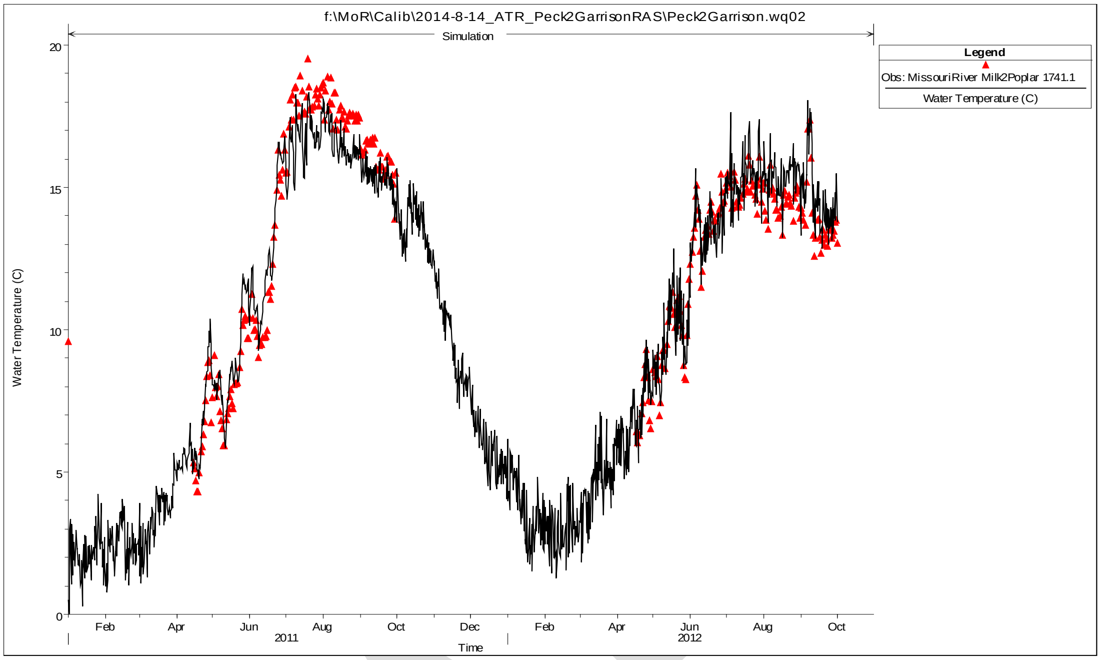


Figure 17. Model predicted versus observed water temperatures of the Missouri River at Wolf, MT.

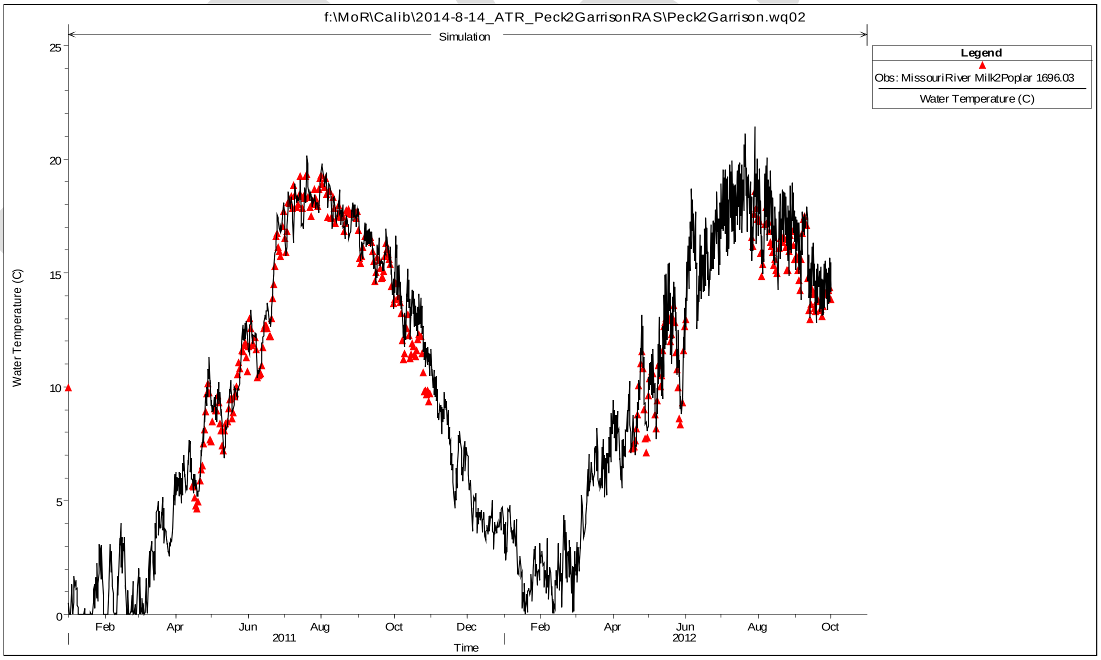


Figure 18. Model predicted versus observed water temperatures of the Missouri River at Culbertson, MT.

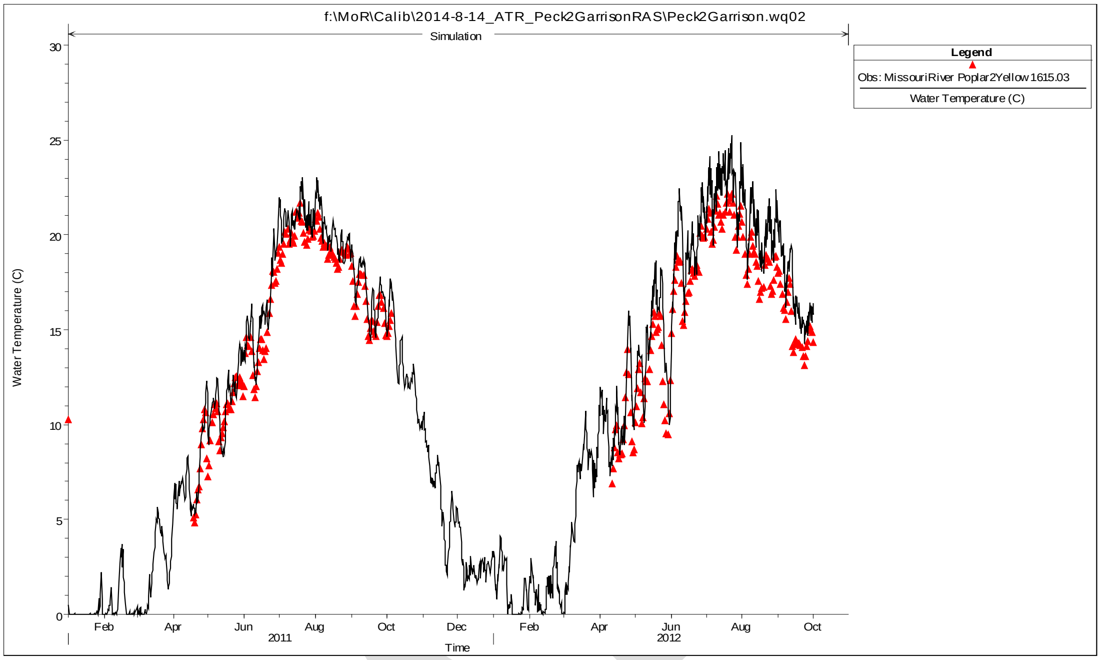


Figure 19. Model predicted versus observed water temperatures of the Missouri River at Nohly, MT.

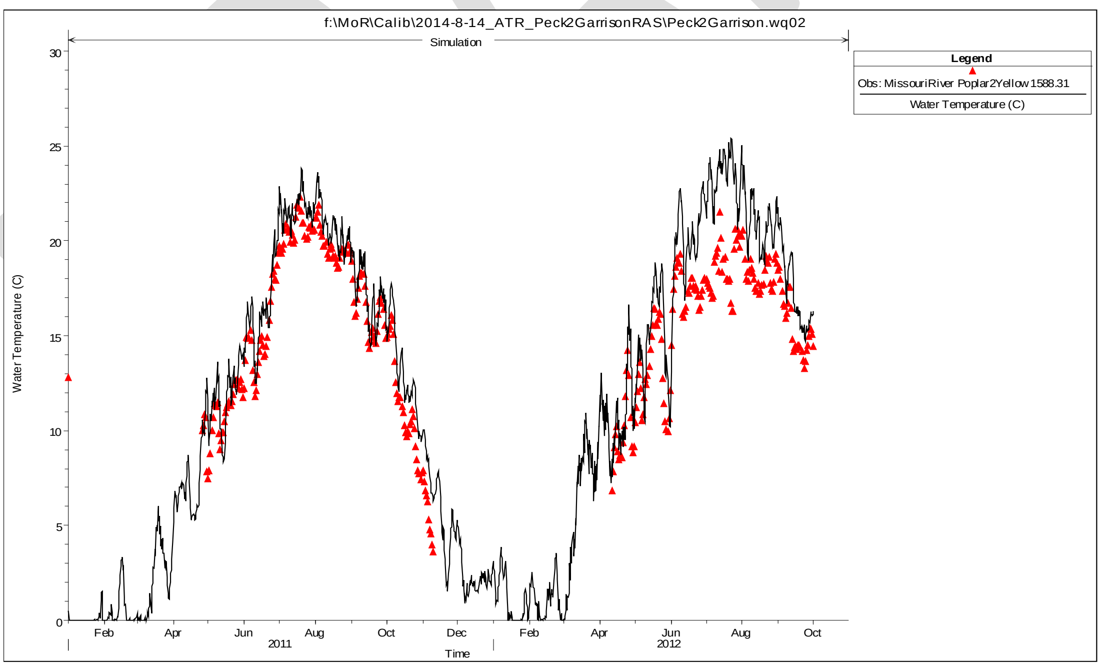
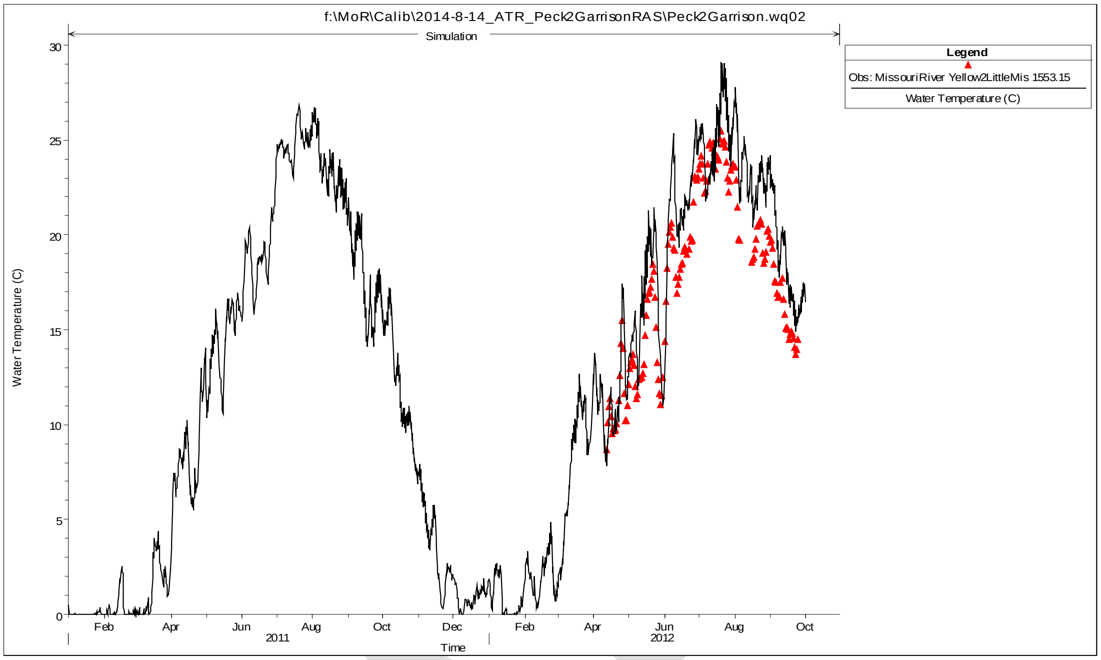


Figure 20. Model predicted versus observed water temperatures of the Missouri River at Williston, MT.



These figures show a scatterplot of instantaneous temperature predictions against time-stamped temperature observations collected once a month, where the hourly temperature simulation closest to each observation point in time was selected for comparison. 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 during the 2012 summer season.

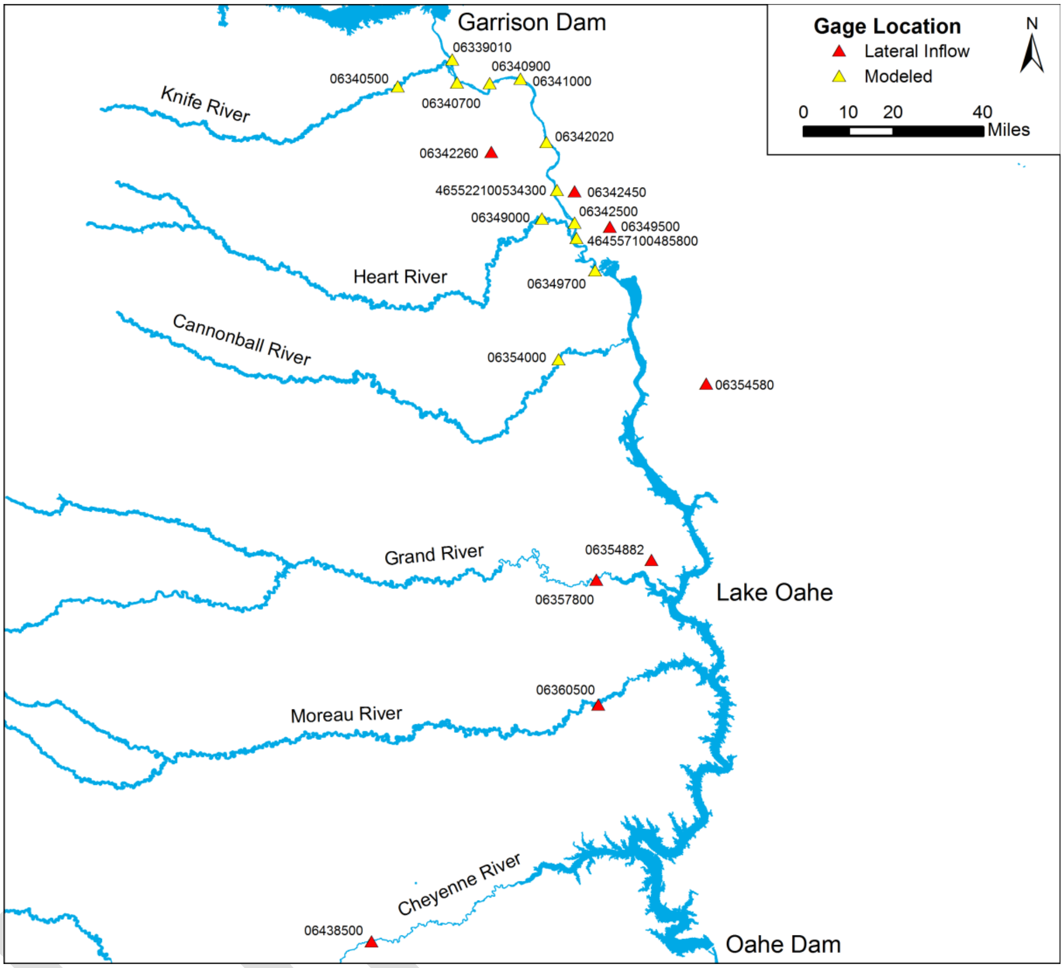
4.3.2 Garrison Dam to Oahe Dam Reach

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 just upstream of Oahe Dam, Pierre, SD. The reach is approximately 318 mile long. The Garrison Dam to Oahe Dam reach of the Missouri River is the second reach being modeled with HEC-RAS. The unsteady HEC-RAS flow model was developed and calibrated by the

USACE Omaha District. The model extent and tributaries entering the Missouri River within this reach are showned in Figure 21.

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



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

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

4.3.2.2 Water temperature model Inputs

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 flow 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 included in MoRWQBCs.dss. The water temperatures from Garrison Dam release and inflow temperatures for all tributaries along the reach were specified in the model. Table 5 provides a list of 25 water temperature boundaries corresponding to inflow boundaries included in the Garrison Dam to Oahe Dam reach of the HEC-RAS model.

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

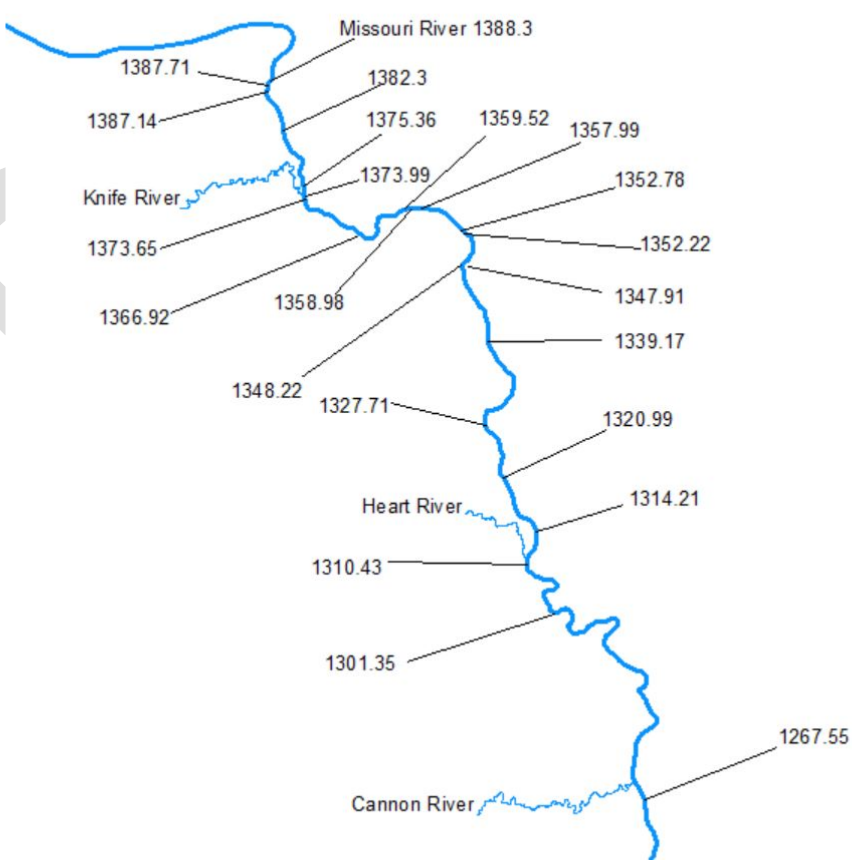


Table 5. Inflow and temperature boundaries included in the Garrison Dam to Oahe Dam HEC-RAS model

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

The HEC-RAS temperature model for the Garrison Dam to Oahe Dam reach was set up and run from January 1, 1995 to December 31, 2012.

Model predicted and observed water temperatures were compared at three USGS stations along the Garrison Dam to Oahe Dam reach. Time series plots of modeled and observed data are presented in Figures 23 and 24. The water temperature model for this river reach was only preliminarily calibrated due to limited observed data and approximate boundary condition inputs computed from the regression relationships.

Figure 23. Model predicted versus observed water temperatures of the Missouri River at Washburn, ND (USGS 06341000).

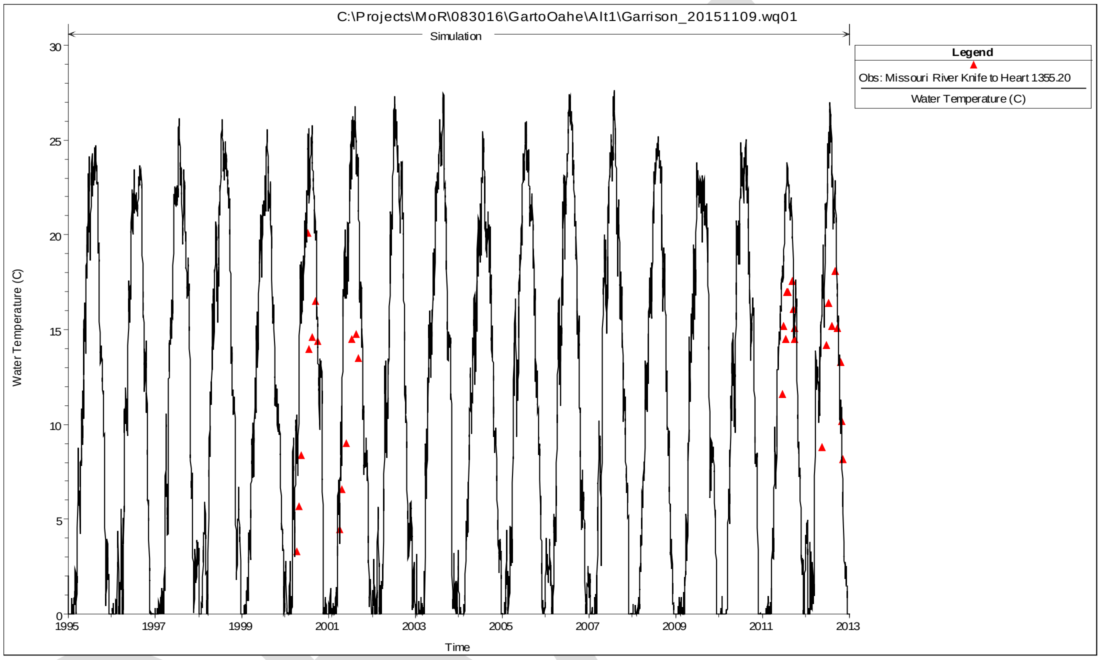
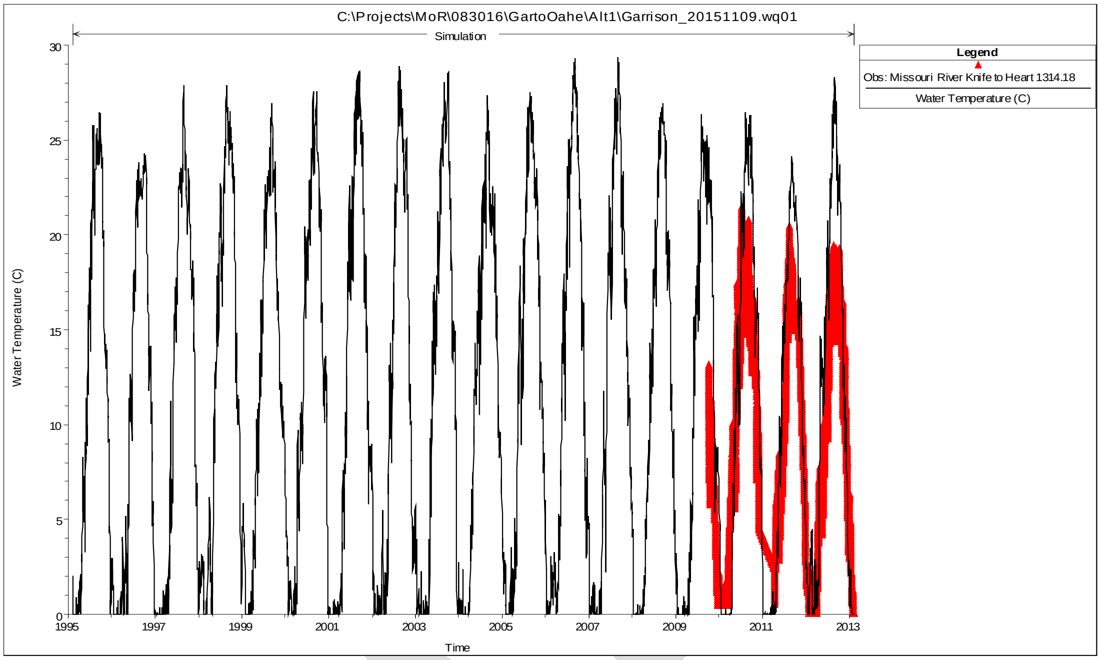


Figure 24. Model predicted versus observed water temperatures of the Missouri River at Bismarck, ND (USGS 06342500).



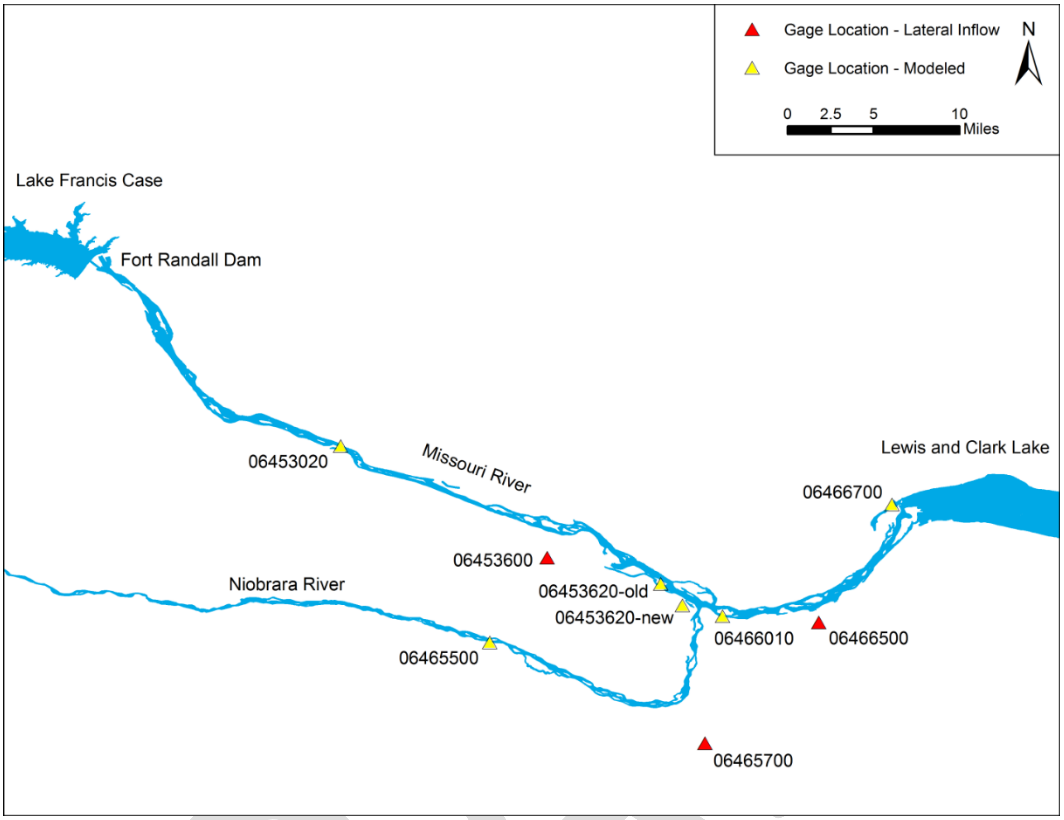
From comparing modeled results and observed data where avialble over the simulation period, the seasonal variations of observed data were captured well by the model. However, the model underpredicted and overpredicted some high temperatures at Bismarck, ND along the Fort Peck Dam to Garrison Dam reach.

4.3.3 Fort Randall Dam to Gavins Point Dam 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 just upstream of Gavins Point Dam on Lewis and Clark Lake, Yankton, SD. The reach is approximately 70 mile long. The Fort Randall Dam to Gavins Point Dam reach is the third reach of the Missouri River being modeled with HEC-RAS. The unsteady HEC-RAS flow model was developed and calibrated by the USACE Omaha Distrcit. The model extent and tributaries entering the Missouri River within this reach are showned in Figure 25.

Figure 25. HEC-RAS model extent for the Fort Randall Dam to Gavins Point Dam reach (USACe 2015).



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

4.3.3.2 Temperature model Inputs

Meteorological data

Two meteorological stations NYKN and KONL 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 station was automatically assigned to modeled water quality cells within the river reach based on the closest distance.

Boundary conditions

Table 6 below provides a list of flow 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.

Table 6. Flow and temperature boundaries included in the Fort Randall Dam to Gavins Point Dam HEC-RAS model

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

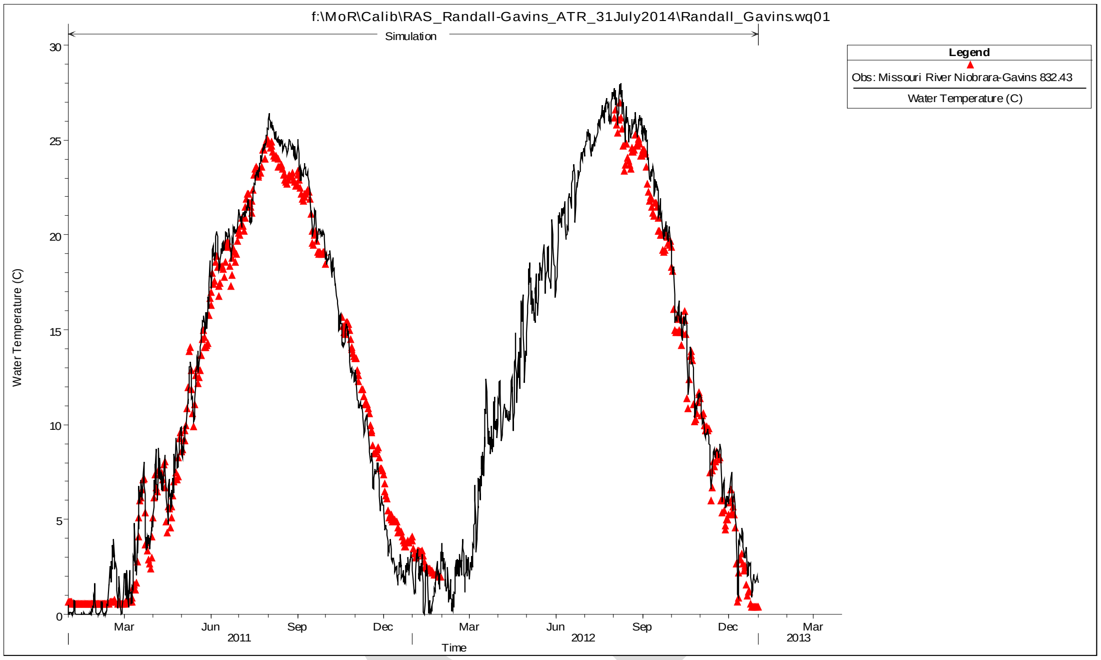
1. USGS gage

2. Water temperature data for these locations were provided by the USACE Omaha District.

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 ManPlan analysis. The model was set up and run for the two years from January 1, 2011 to December 31, 2012. Only one location on this river reach had observed water temperature data. Time series plot of model predicted and observed water temperatures at this location is presented in Figure 26.

Figure 26. Model predicted versus observed water temperatures of the Missouri River at Springfield, SD (USGS 06466700).



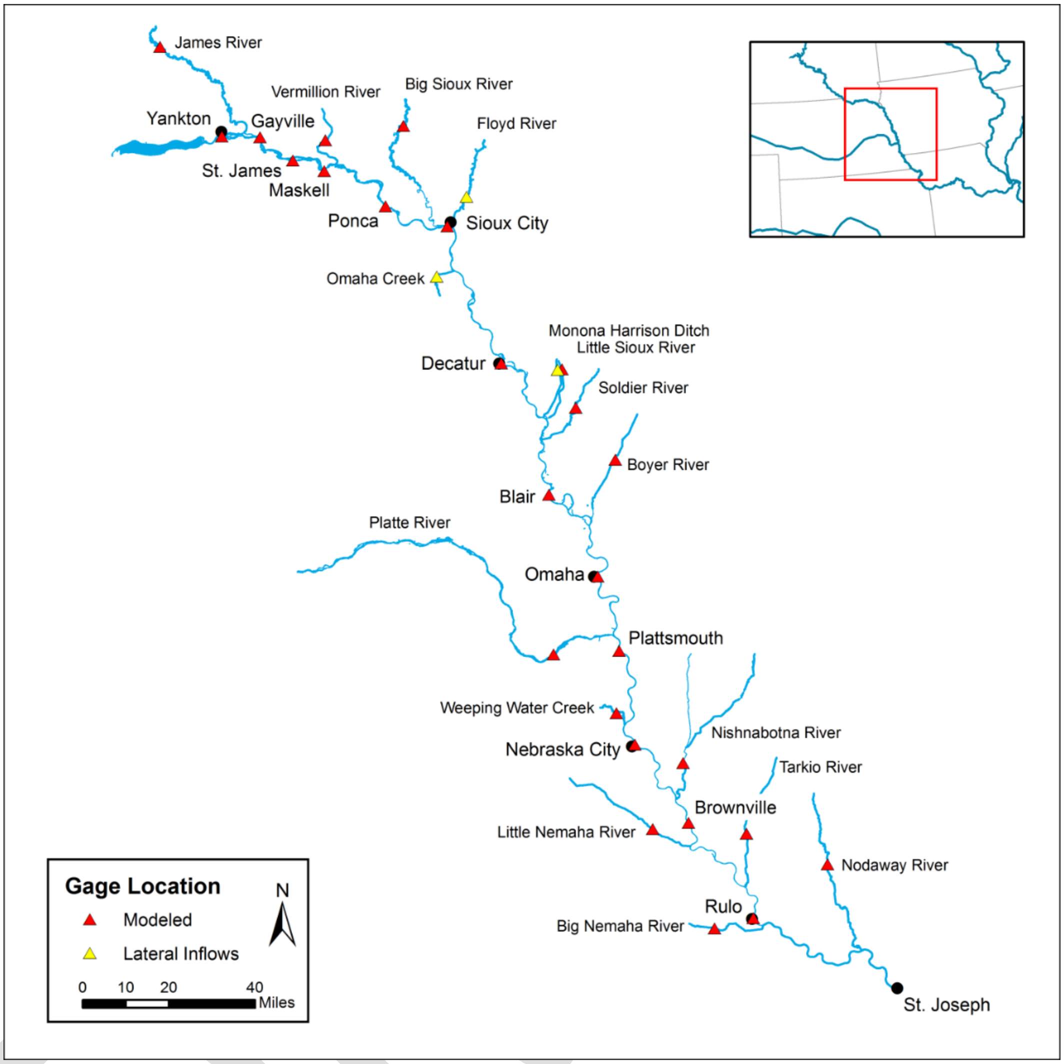
Comparisons of model predictions and observed data at this location show that the Fort Randall Dam to Gavins Point Dam HEC-RAS model was able to capture water temperature observation pattern. The minor differences between modeled and observed values occur during summer seasons when the model predictions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

4.3.4 Gavins Point Dam to Rulo Reach

4.3.3.4 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 unsteady HEC-RAS flow model for this reach was developed and calibrated by the USACE Omaha District. The model extent and tributaries entering the Missouri River for the Gavins Point Dam to Rulo reach are showned in Figure 27.

Figure 27. HEC-RAS model extent for the Gavins Point Dam to Rulo reach (USACE 2015).



Numerous tributaries enter the Missouri River within the model reach. Refer to the model schematic shown in Figure 32 for the locations of significant tributaries. Major tributaries were included as separate routing reaches within the model. Minor tributaries that have USGS gage data were included as lateral inflow to the model.

4.3.3.5 Water temperature model inputs

Meteorological Data

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

Boundary conditions

Figure 28 presents approximate locations of flow 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 defined in MoRWQBCs.dss. The water temperatures from Gavins Point Dam release and inflow temperatures for all tributaries along the reach are sepecified in the model. Table 7 provides a list of water temperature boundaries corresponding to inflow boundaries. If there is no water quality monitoring station available for the inflow boundary, observed data collected from adjacent water quality stations were used.

Figure 28. Schematic representation of inflow boundary locations included in the Gavins Point Dam to the Rulo reach HEC-RAS model.

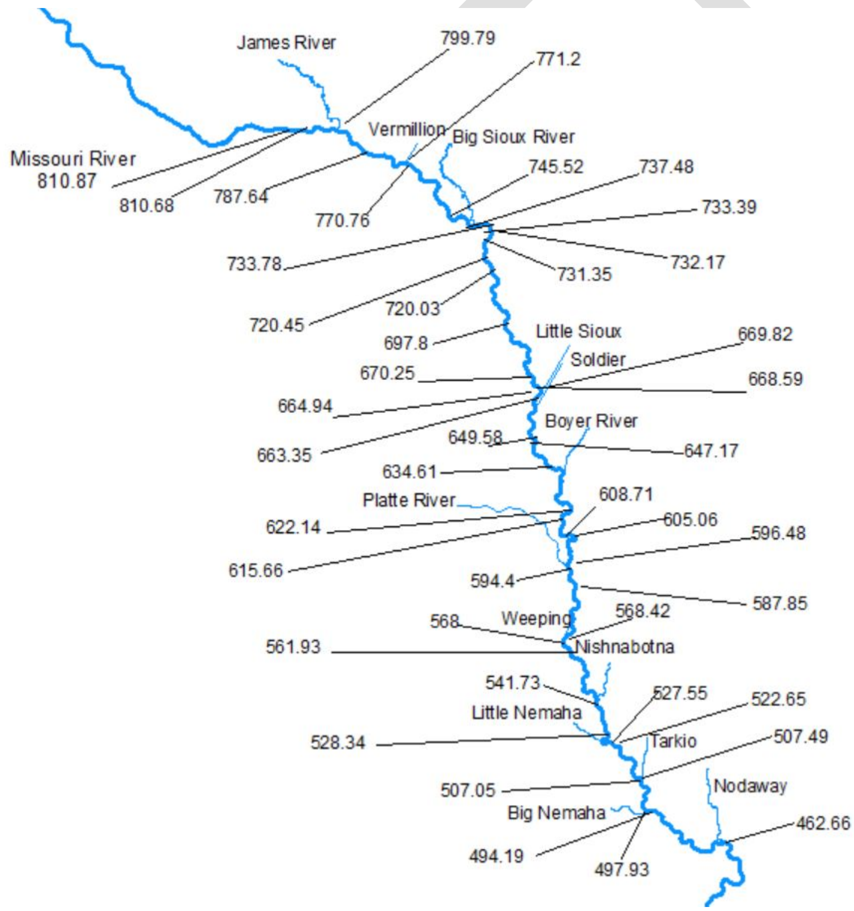


Table 7. Inflow and temperature boundaries included in the Gavins Point Dam to Rulo reach HEC-RAS model.

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

4.3.3.6 Water temeprature model set up and calibration

The HEC-RAS temperature model for the Gavins Point Dam to Rulo reach was set up and run from January 1, 1995 to December 31, 2012. The model calibration primarily focused on five USGS stations with limited observed data along this reach. These five USGS stations are 06478526, 06486000, 06601200, 06610000, 06807000, 06813500. Time series plots of modeled and observed data are presented in Figures 29 to 34.

Figure 29. Model predicted versus observed water temperatures of the Missouri River near Maskell, NE (USGS 06478526)

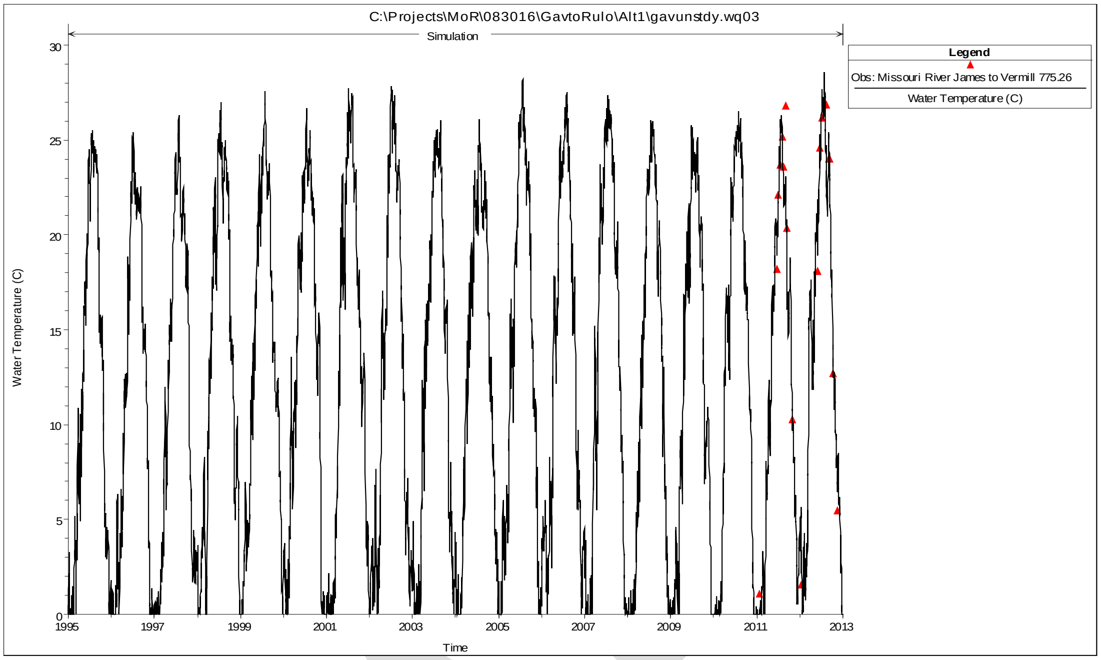


Figure 30. Model predicted versus observed water temperatures of the Missouri River at Sioux City, IA (USGS 06486000)

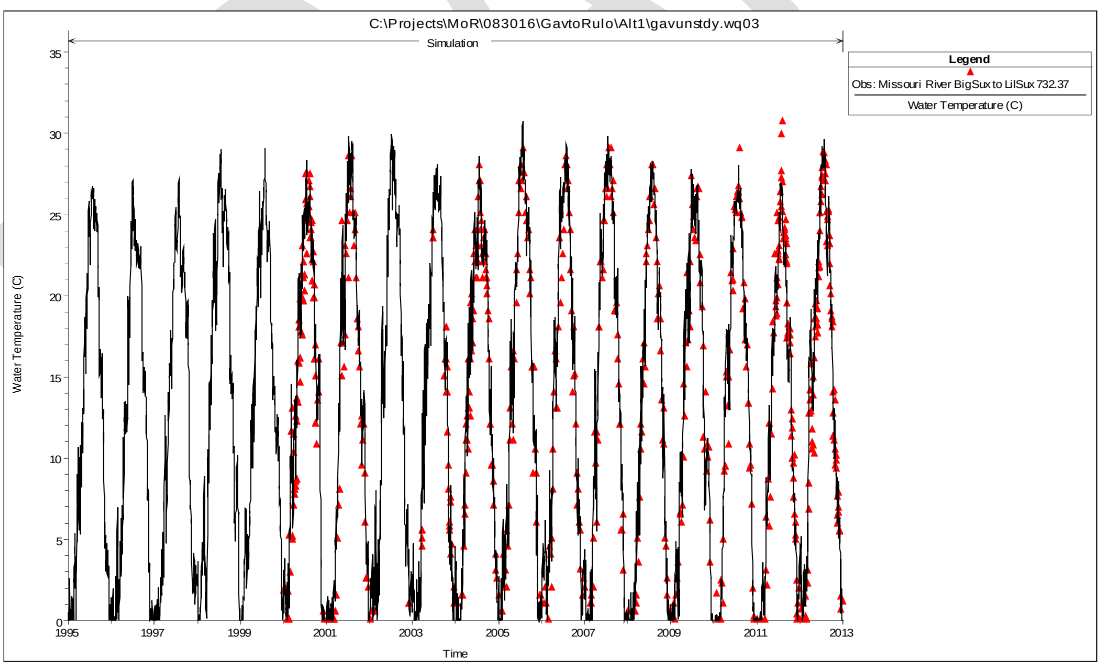


Figure 31. Model predicted versus observed water temperatures of the Missouri River at Decatur, NE (USGS 06601200)

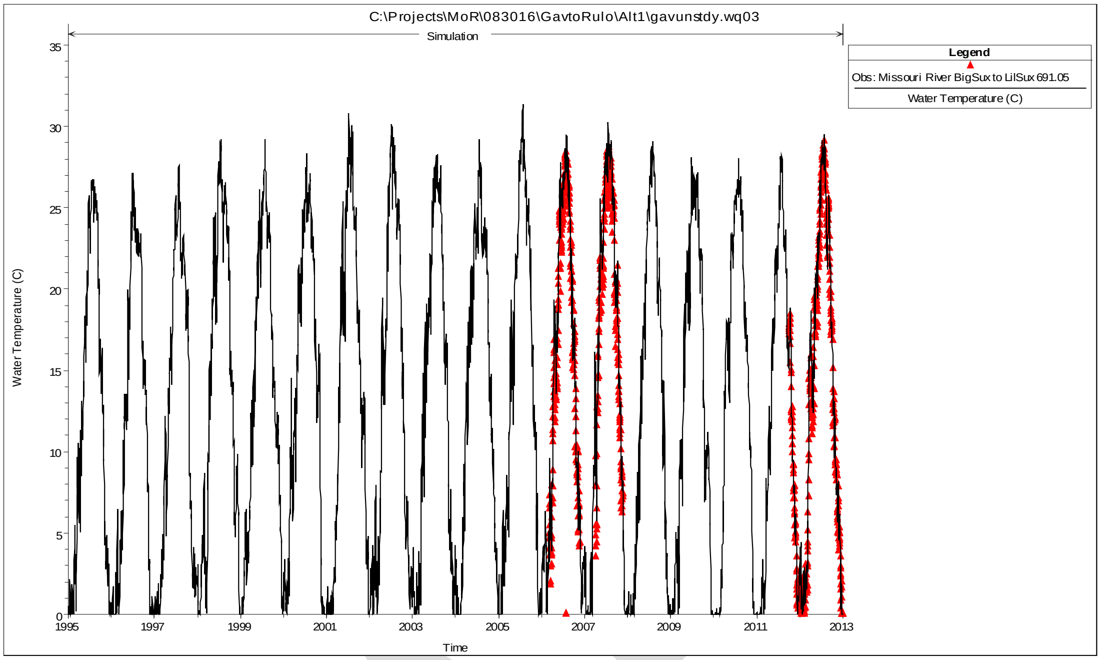


Figure 32. Model predicted versus observed water temperatures of the Missouri River at Omaha, NE (USGS 06610000)

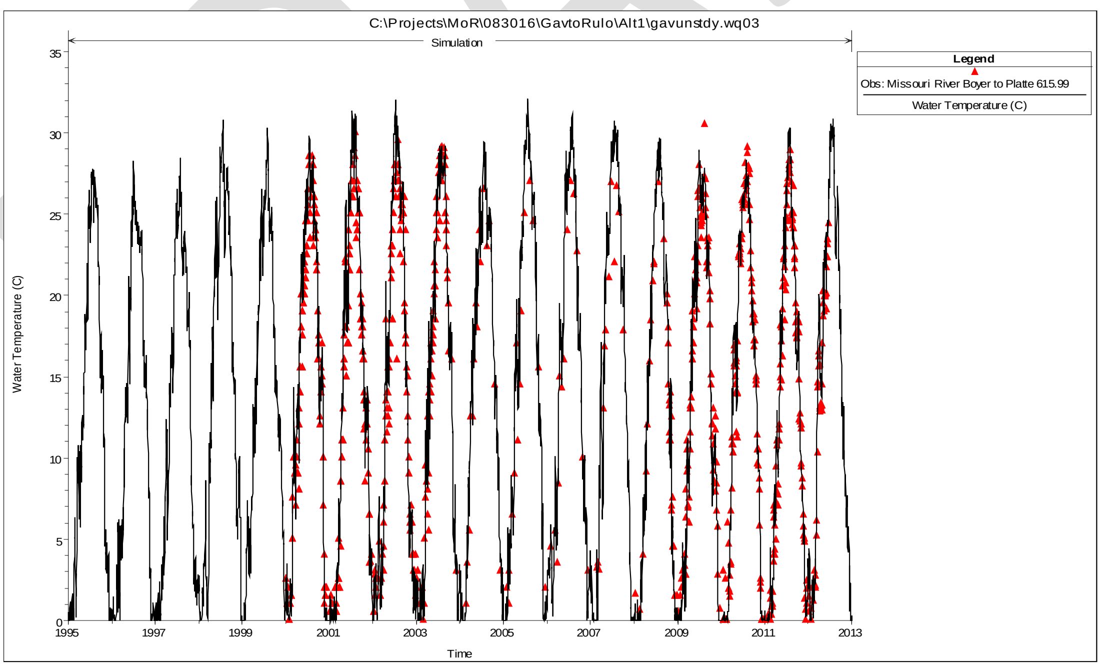


Figure 33. Model predicted versus observed water temperatures of the Missouri River at Nebraska City, NE (USGS 06807000)

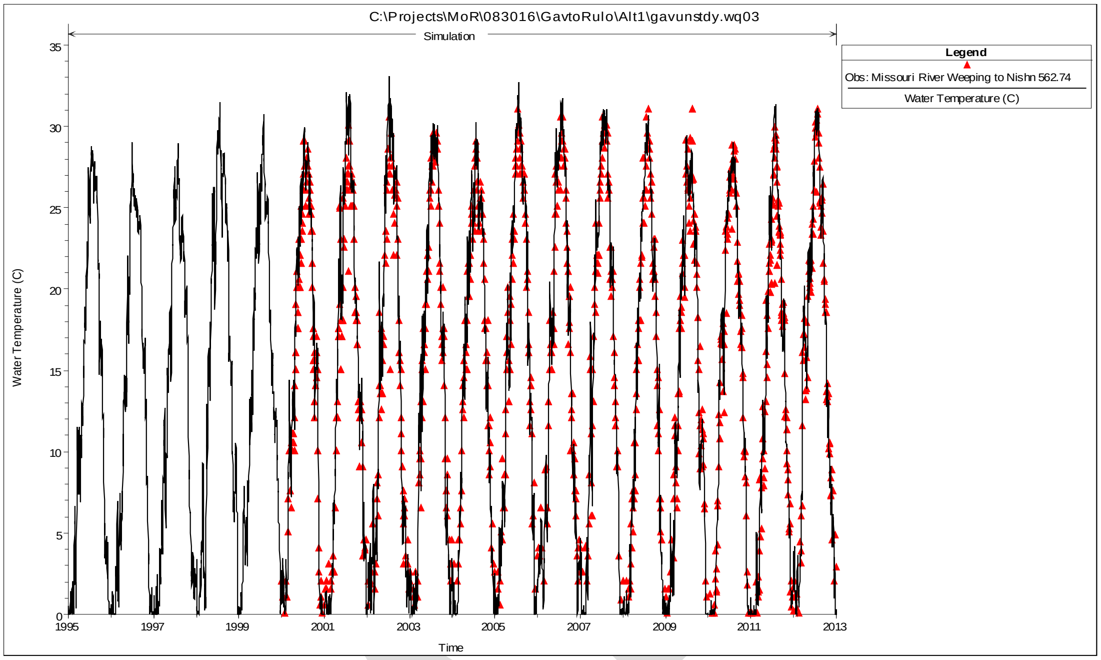
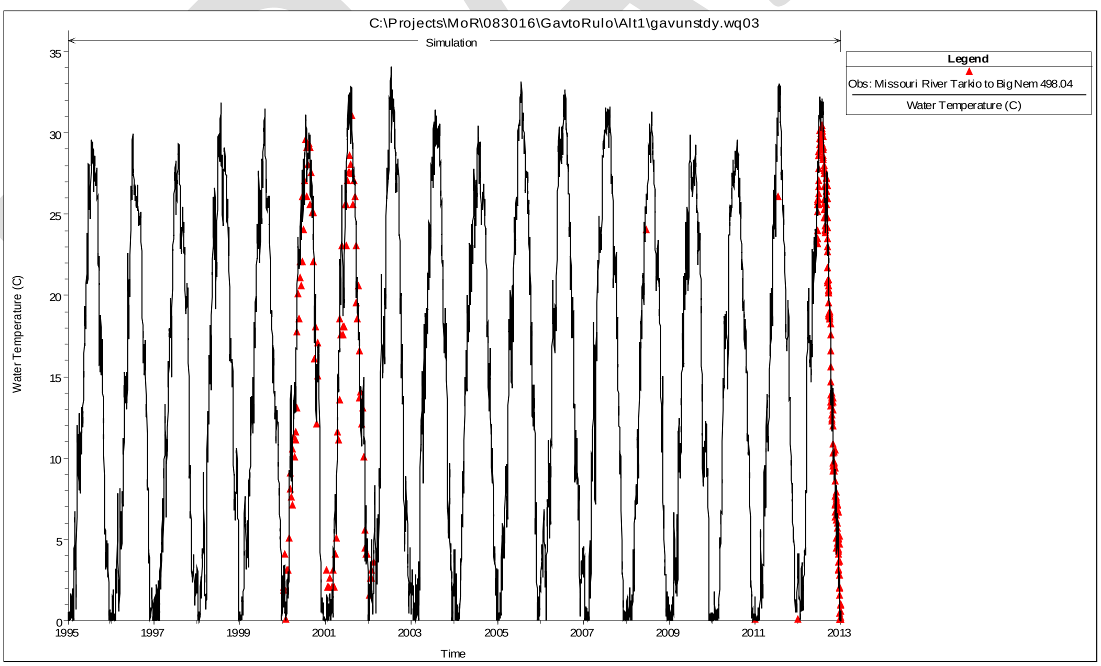


Figure 34. Model predicted versus observed water temperatures of the Missouri River at Rulo, NE (USGS 06813500)



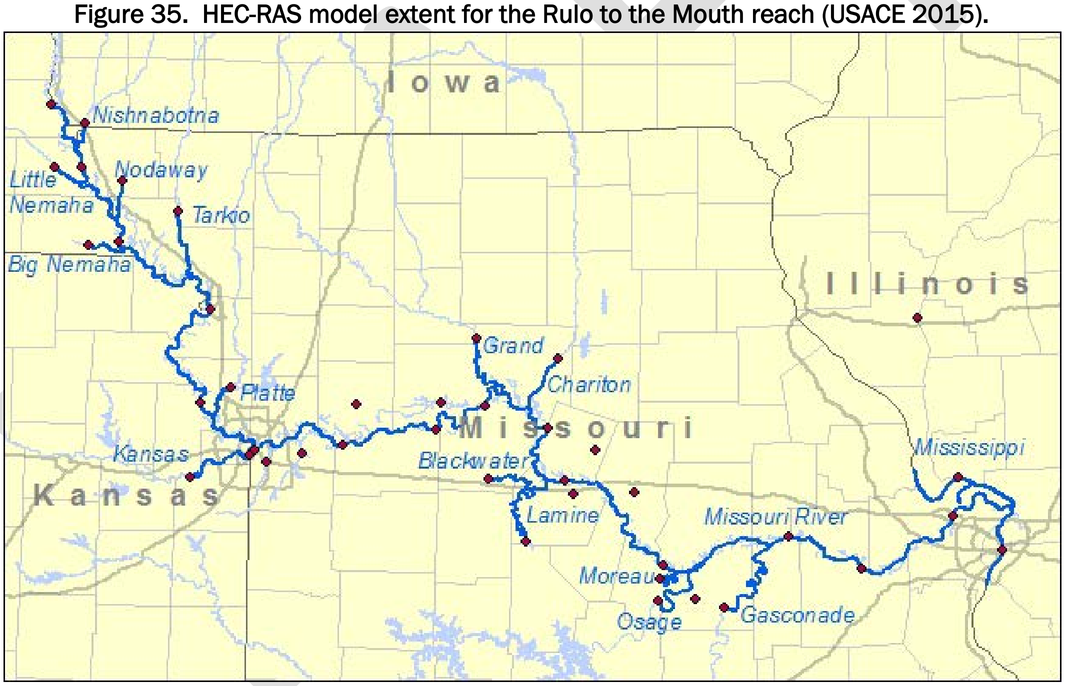
The above time series plots suggest a fairly good agreement between the model simulations and observations for all six calibration locations with observed data except that the model tends to overpredict the peak water temperatures during summer seasons.

4.3.4 Rulo to the Mouth Reach

4.3.4.1 HEC-RAS flow model

The Rulo to the Mouth reach of the Missouri River is approximately 498 mile from Rulo, NE to the mouth near St. Louis, MO. This reach meanders south through the dissected till planes 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 (USACE, Kansas City District, 1994). Major tributaries include the Kansas, Grand, Chariton, Osage, and Gasconade. The unsteady HEC-RAS flow model for the Rulo to the Mouth reach was developed and calibrated by the USACE Kansas City District. The model extent and tributaries entering the Missouri River within this reach are showned in Figure 35.

Figure 35. HEC-RAS model extent for the Rulo to the Mouth reach (USACE 2015).



In the HEC-RAS flow model, modeled area was extend upstream and downstream because of the complicated nature of modeling extreme floods such as 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 & Dam 25 and the downstream boundary approximately 10 miles downstream of the St. Louis USGS gage.

Upstream, the model limits were extended approximately 60 miles to Nebraska City, NE.

Fourteen tributary reaches were also simulated in the Rulo to the Mouth 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

4.3.4.2 Water temperature model Inputs

Meteorological data

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

Boundary conditions

Figure 36 presents approximate locations of flow boundaries included in the Rulo to the Mouth reach HEC-RAS model. Water temperatures associated with each inflow boundary for the simulation period (1995-2012) were specified through MoRWQBCs.dss. Table 8 provides a list of water temperature boundaries corresponding to inflow boundaries.

Figure 36. Schematic representation of inflow boundary locations included in the Rulo to the the Mouth reach HEC-RAS model.

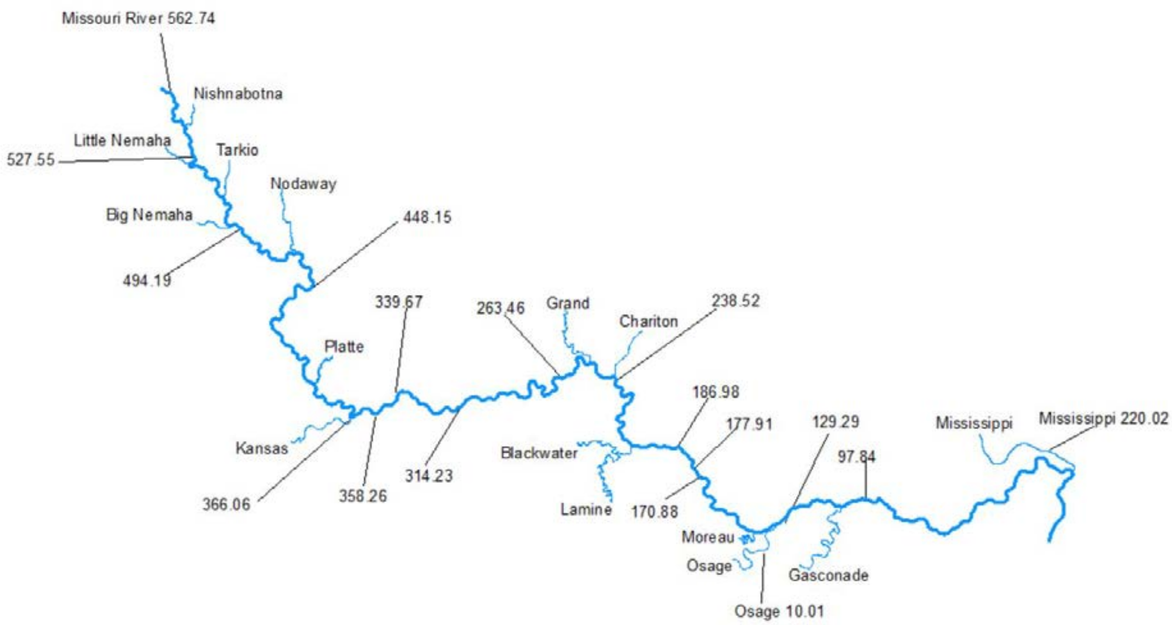


Table 8. Inflow and temperature boundaries included in the Rulo to the Mouth reach HEC-RAS model.

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

4.3.4.3 Water temperature model set up and calibration

The HEC-RAS temperature model for the Rulo to the Mouth reach was set up and run from January 1, 1995 to December 31, 2012. The model calibration primarily focused on five USGS stations with limited observed data along this reach. These five USGS stations include 06893000, 06893000, 06895500, 06906500, 06934500. Time series plots of modeled and observed data are presented in Figures 37 to 41. These figures compare the model predicted and observed mean daily stream temperatures.

Figure 37. Model predicted versus observed water temperatures of the Missouri River at St. Joseph MO (USGS 06818000)

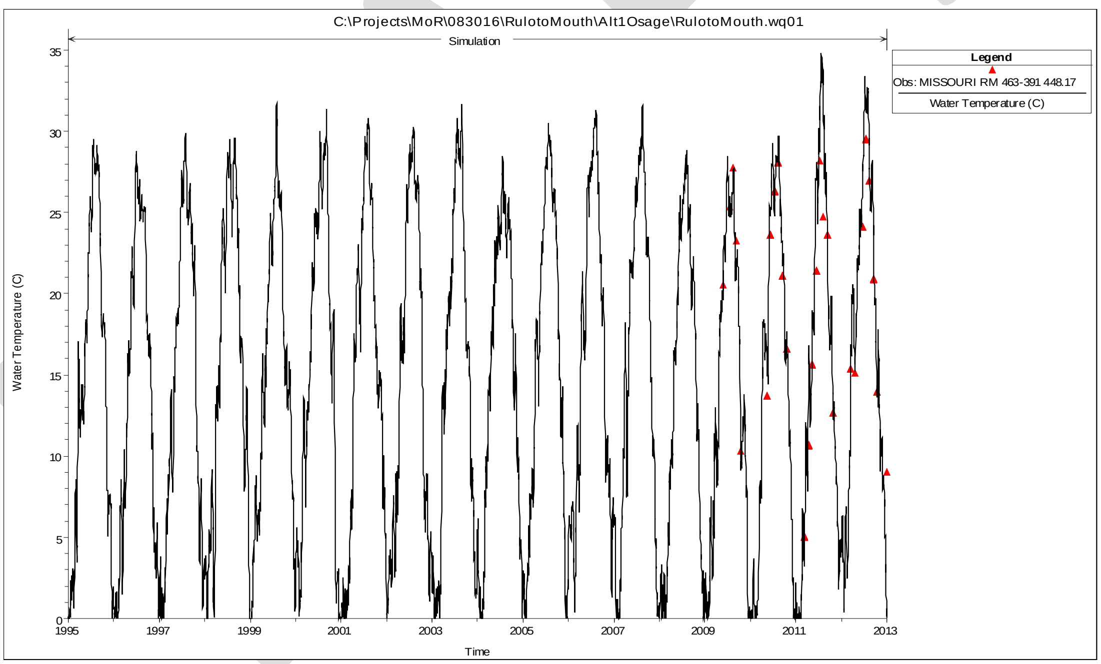


Figure 38. Model predicted versus observed water temperatures of the Missouri River at Kansas City, MO (USGS 06893000)

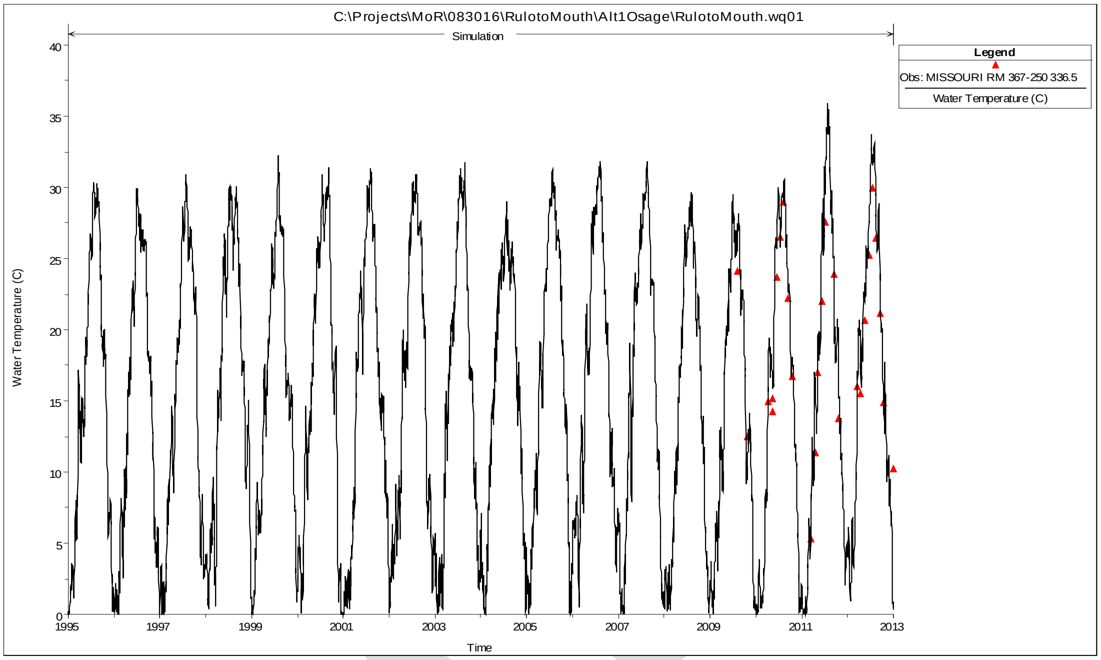


Figure 39. Model predicted versus observed water temperatures of the Missouri River at Waverly, MO (USGS 06895500)

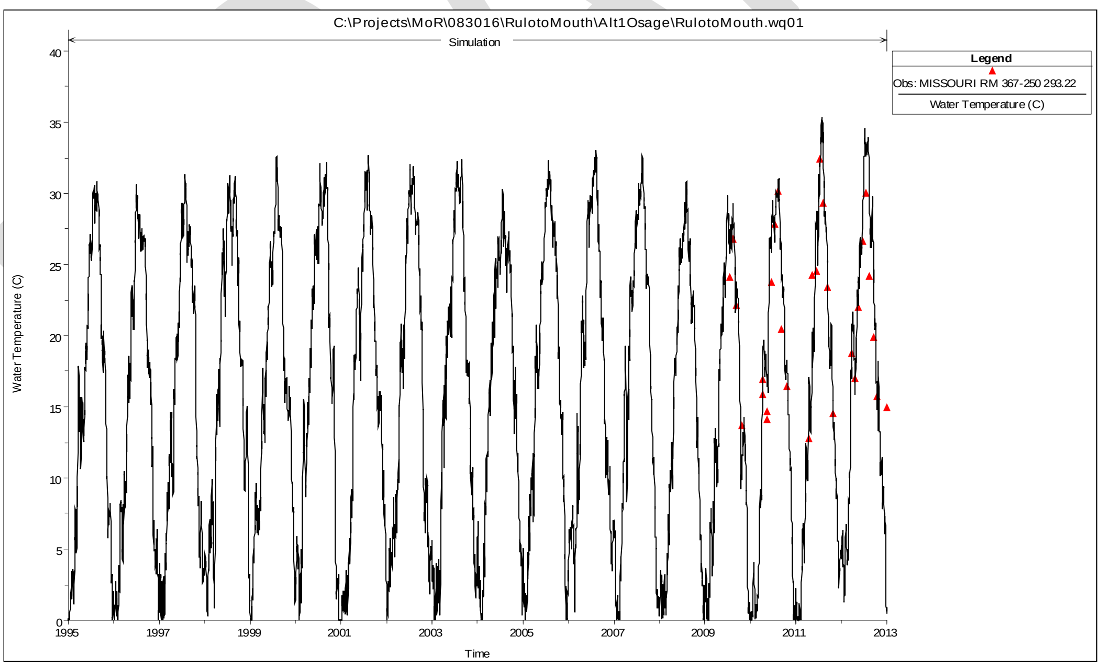


Figure 40. Model predicted versus observed water temperatures of the Missouri River at Gasgow, MO (USGS 06906500)

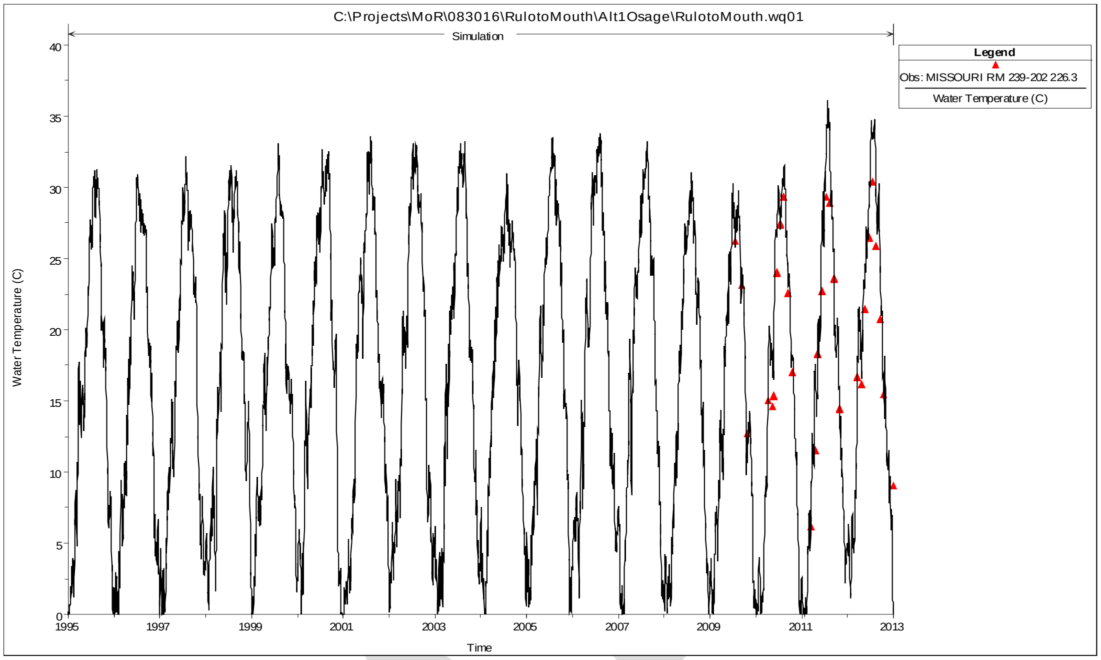
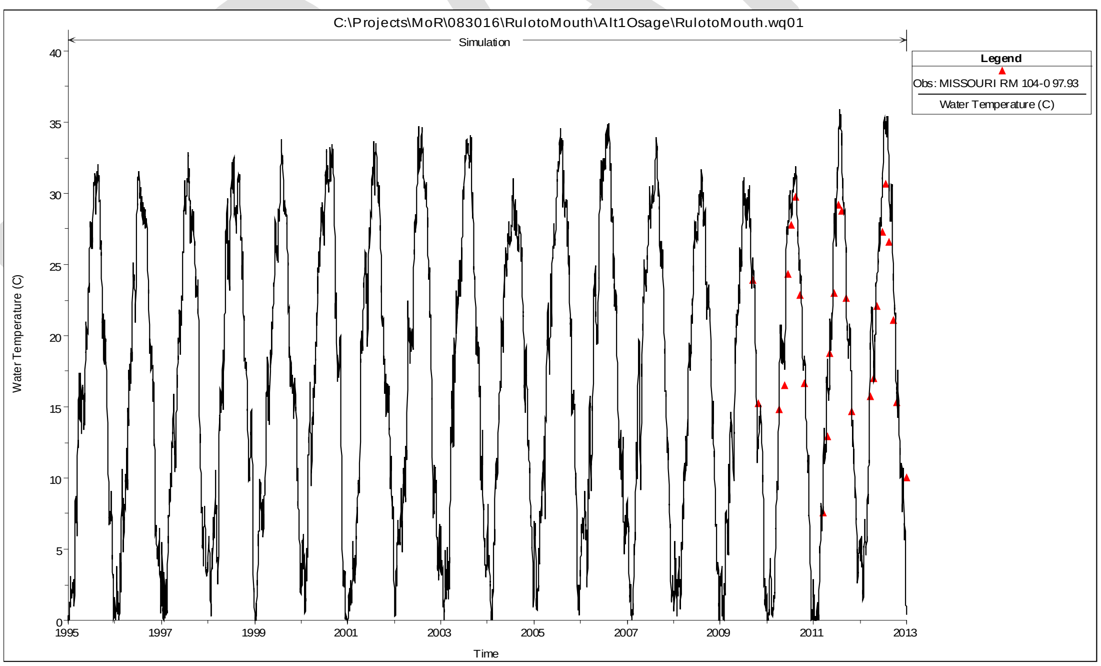


Figure 41. Model predicted versus observed water temperatures of the Missouri River at Hermann, MO (USGS 06934500)



The above time series plots suggest a fairly good agreement between the model simulations and observations for five calibration locations with observed data except that the model tends to overpredict the peak water temperatures during summer seasons. In summary, all HEC-RAS water temperature models described above were only preliminarily calibrated due to limited observed data and approximate boundary conditions computed from the regression relationships for the 18 year simulation period. The sources of model uncertainty come from the accuracy and temporal resolution of inflow 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 uncertainty in use of air temperature as a soley dependent variable in the regression relationships. Additionally, the model uncertainty also come from the scarcity of stream water quality monitoring gages within the basin and the limited record available at these gages. Most of water quality sample measurements were obtained monthly during the summer. This large uncertainty would impact the accuracy of water temperatures along the Missouri River predicted by the HEC-RAS models, when compared to observed data.

5 HEC-RAS Water Temperature Model Results for Management Plans

This chapter briefly describes the management alternatives (scenarios) provided by the USACE for use in the HEC-RAS water temperature model simulations for the reaches of Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the Mouth. The results of these scenario simulations have been used for evaluating implications of ManPlan alternative scenarios.

Table 9 below provides a list of all the sets of management alternative runs conducted with the existing HEC-RAS flow models. The HEC-RAS flow models for each river reach and each alternative were set up and provided by the USACE Omaha and Kansas City Districts.

Table 9. Management alternative scenarios simulated in the HEC-RAS models.

Alt	Geometry	Description
1	No Action (Year 2012) (2012 geometry + new SWH + mech ESH)	Model is based on current 2012 geometry. Includes all mechanical ESH construction and 20 acre/mile SWH that would add to the system through 2032 (based on MRRP 2014 SWH Accounting estimates).
2	BiOp As Projected (Year 2012) (2012 geometry + USFWS SWH/ESH/Inundation/Bi-modal Pulse)	Model is based on current 2012 geometry. Includes all mechanical ESH construction and 30 acre/mile SWH that would be added to the system through 2032 (based on USFWS 2003 Amended BiOp and 2015 PAL). Includes 77,410 acres of inundation area based on 5-year flood frequency. Includes a bi-model Spawning Cue for the Pallid.
3	All Mechanical (Year 2012) (2012 geometry + new IRC + mech ESH)	Model is based on current 2012 geometry. Includes 5 acre/mile IRC and all mechancial ESH (based on EA team descriptions) that would be added to the system through 2032.
4	Spring 2, 42 MAF (Year 2012) (2012 geometry + new IRC + Spring Bird ESH Release + mech ESH)	Model is based on current 2012 geometry. Includes a Fall Bird ESH Release. Includes 5 acre/mile IRC and mechancial ESH (based on EA team descriptions) that would be added to the system through 2032.
5	Fall 5, 35 SL (Year 2012) (2012 geometry + new IRC + Fall Bird ESH Release + mech ESH)	Model is based on current 2012 geometry. Includes a Fall Bird ESH Release + LSFs. Includes 5 acre/mile IRC and mechancial ESH (based on EA team descriptions) that would be added to the system through 2032.
7	Spawning Cue (Year 2012) (2012 geometry + new IRC + Bi-modal Spawning Cue + mech ESH)	Model is based on current 2012 geometry. Includes a Pallid Bi-modal Spawning Cue. Includes 5 acre/mile IRC and all mechancial ESH (based on EA team descriptions) that would be added to the system through 2032.

For all seven scenarios, the HEC-RAS flow models for three reaches, e.g. Garrison Dam to Oahe Dam, Gavins Point Dam to Rulo, and Rulo to the Mouth, were forced with the same historical meteorological and water temperature boundary forcings (1995-2012), and identical water quality parameters included in their baseline HEC-RAS water temeperature models. The HEC-RAS water temeperature models for each river reach and each alternative were then employed to compute the daily mean water temperatures at specified locations of the Missouri River (Table 10) for the 18-year (1995−2012) simulation perieod. Water temperature model results for the simulation period have been use to produce a baseline condition (No Action condition) against which alternatives will be assessed. Detailed water temperature model results for each river reach and each alternative can be found in the attached HEC-DSS files.

Table 10. List of RM locations of the Missouri River in HEC-RAS water temperature model outputs.

River Mile (RM)	**Location**
Rulo to the Mouth 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-Iatan 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

6 Conclusions and Summary

The HEC-RAS water temperature models for five reachs 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) have been developed and calibrated using limited observed data. Linear regression relationships were developed and used to compute inflowing water temeperature 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 to December 31, 2012, and the model results for these river reaches have been used in support of the Missouri River ManPlan and EIS analysis.

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 are the accuracy and temporal resolution of inflow boundary conditions for temperature. Water temperature boundary conditions computed from the regression relationships have errors due to limited observed data and limitation of the regression formulation that uses only air temperature as the single dependent variable for predicting inflow temperature. Observed data sets used for each reach only covered the period 2009 - 2012. Additionally, the most of sample measurements were conducted monthly during the summer. These data limitations can certainly impact the accuracy of water temperature regressions.

Since this study is work in progress, the following recommendations are provided for the future model update 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 where varying inflow components drive differences in stream temperatures and lack of sufficient observed water temperature data. Furthermore, watershed models that simulate the influence of all hydrologic sources (e.g., snowmelt, groundwater inflow, surface runoff, 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 the stream temperatures. Flow boundary conditions for wastewater treatment plants and other industries discharging into the Missouri River were taken into accout and lumped into ungaged flow in current HEC-RAS flow models. Thus, point source flows were not specified separately in the models. This component is recommended to be separated from the ungagged flow in the current HEC-RAS models.

Limited observed water temperature data available for this study means that additional data needs to be collected for all inflow tributaries and the mainstem Missouri River. Once more observed data are available, existing air-water temperature regression relationsips and boundary conditions for the HEC-RAS models can be improved and updated with more observed water temeperature data.

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Appendix

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

Figure 42 to Figure 49 show the time series plots of regression computed and observed water temperatures for the Garrison Dam to Oahe Dam reach HEC-RAS model.

Figure 42. Regression computed versus observed water temperature at BC1

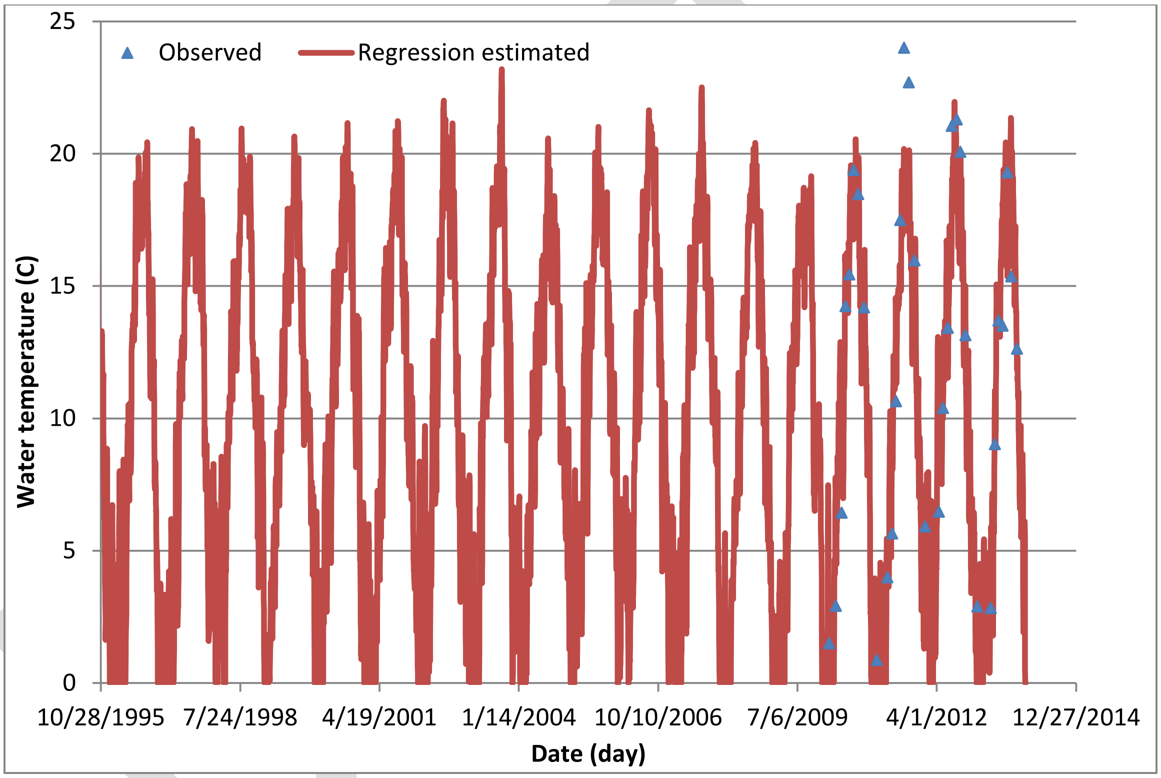


Figure 43. Regression computed versus observed water temperature at BC2

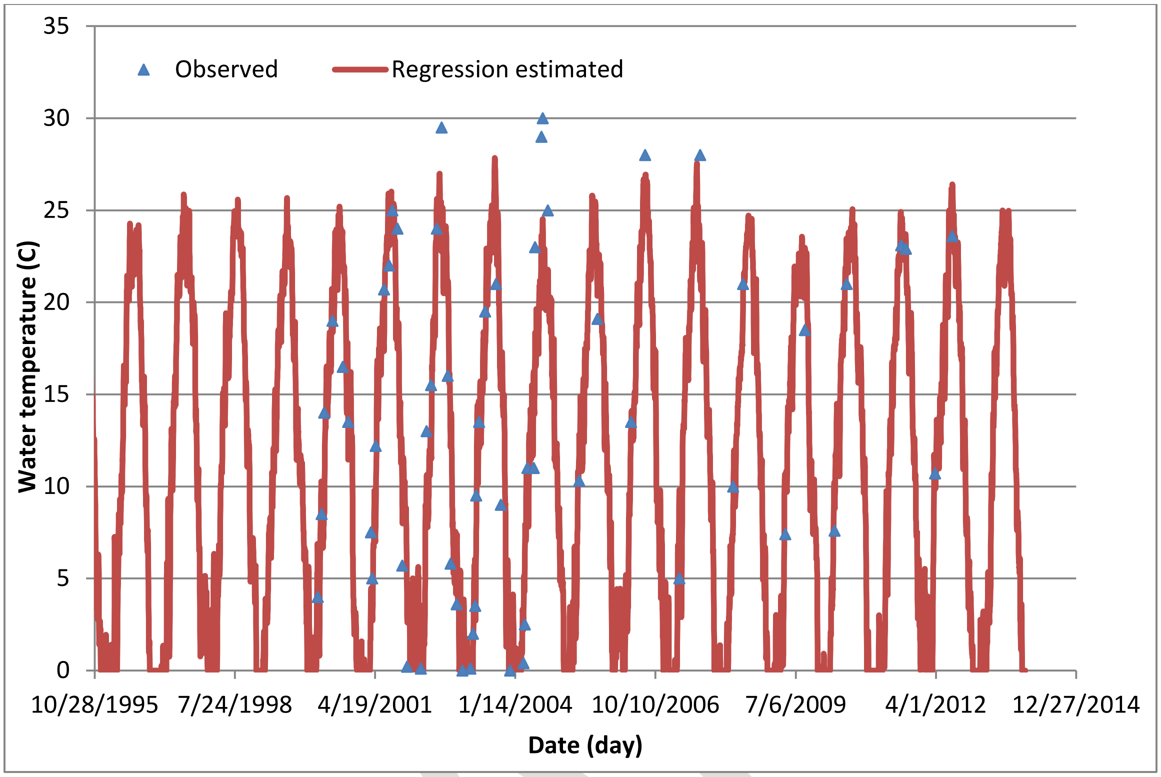


Figure 44. Regression computed versus observed water temperature at BC3

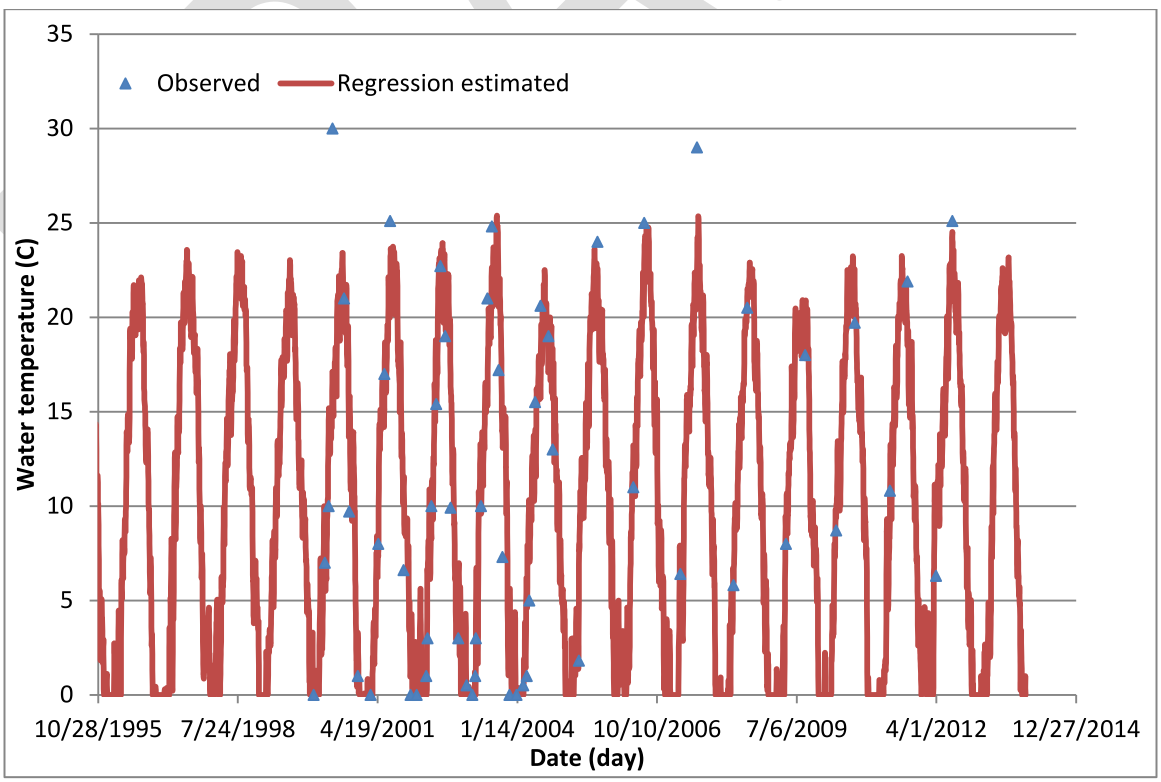


Figure 45. Regression computed versus observed water temperature at BC4

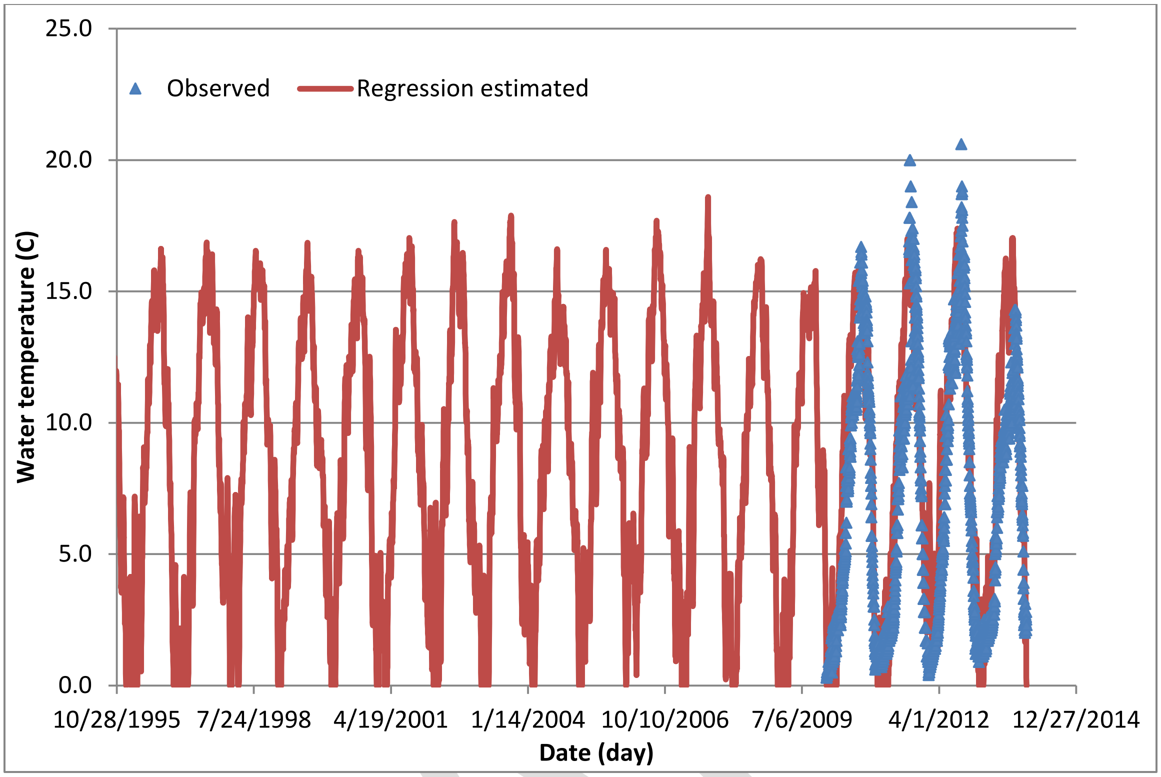


Figure 46. Regression computed versus observed water temperature at BC5

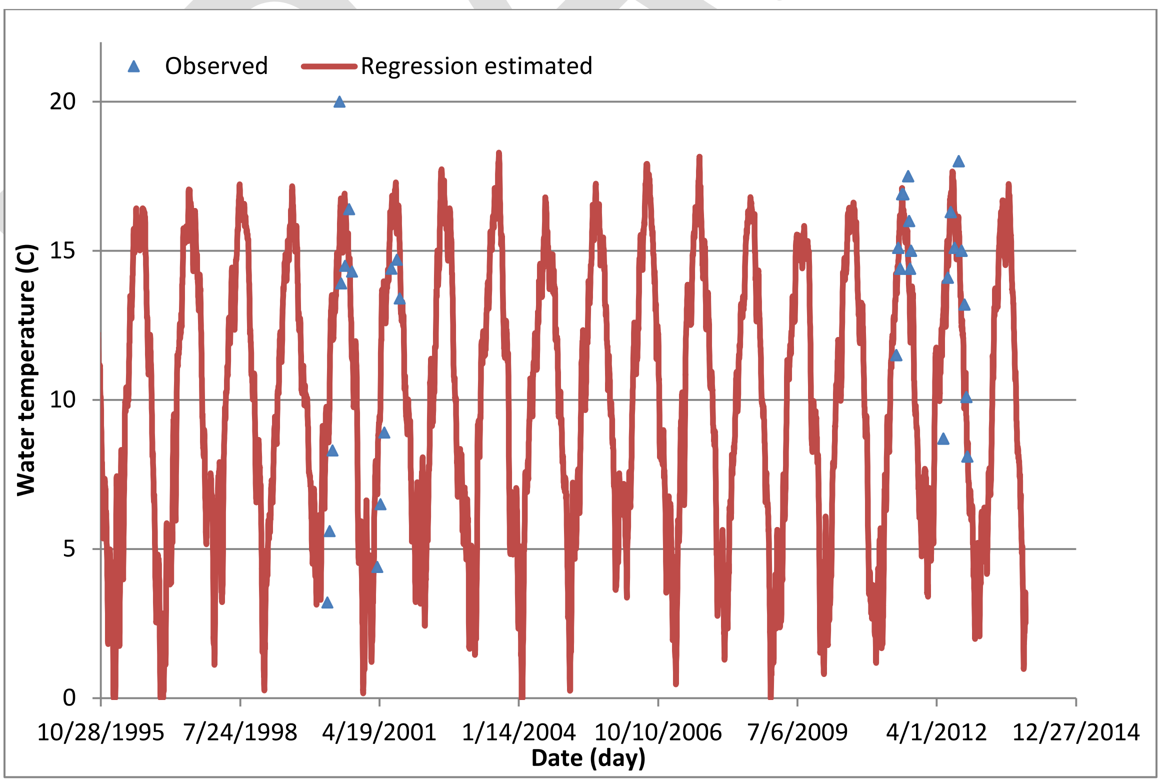


Figure 47. Regression computed versus observed water temperature at BC6

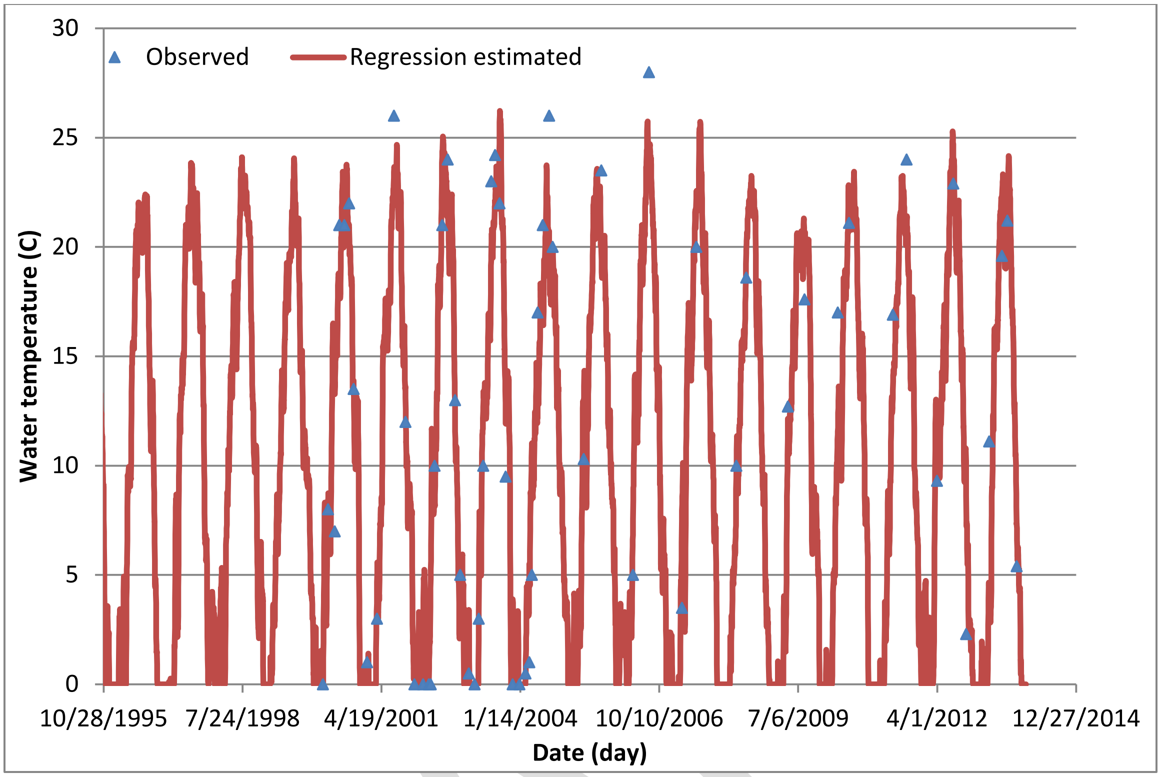


Figure 48. Regression computed versus observed water temperature at BC7

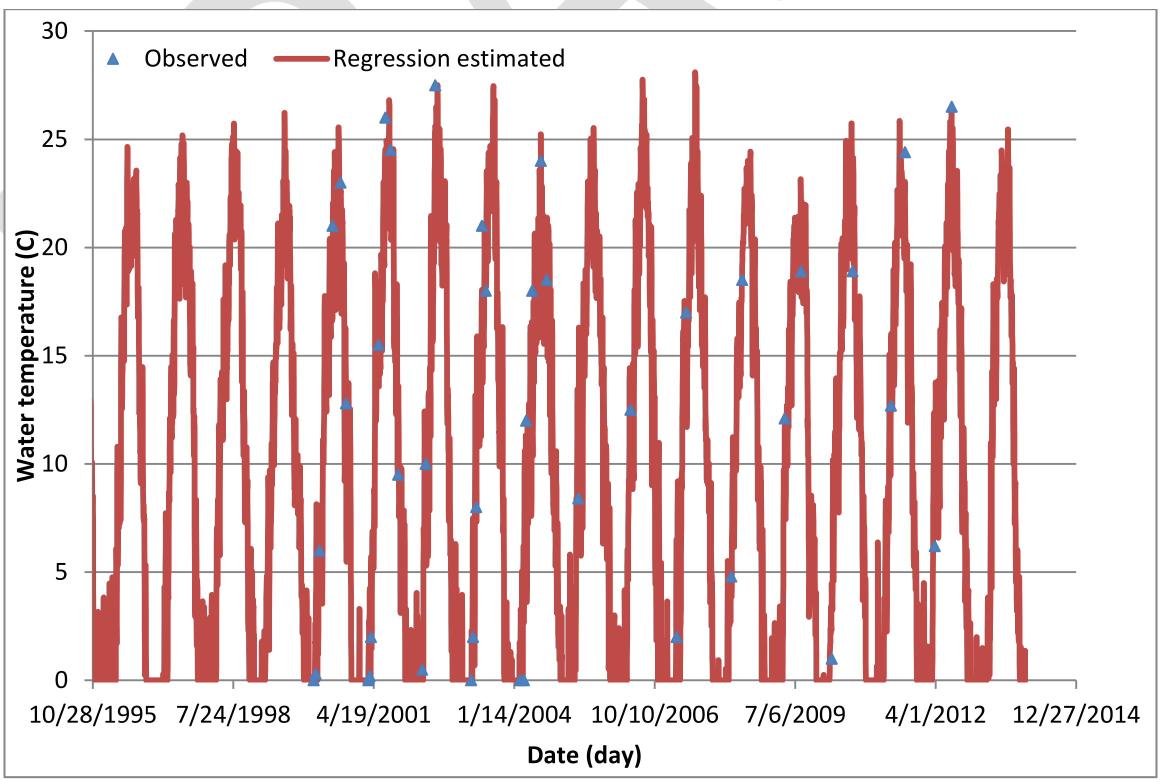
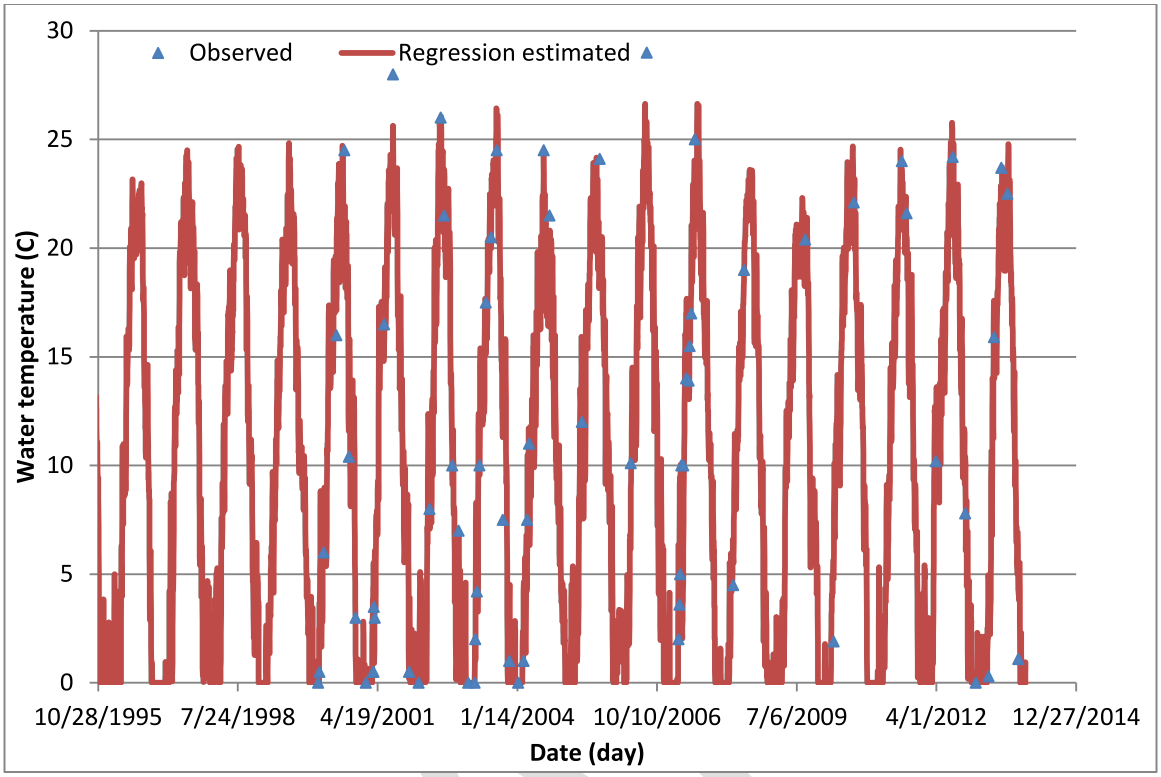


Figure 49. Regression computed versus observed water temperature at BC8



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

Figure 50 to Figure 65 show time series plots of regression computed and observed water temperatures for the Gavins Point Dam to Rulo reach HEC-RAS model.

Figure 50. Regression computed versus observed water temperature at BC1

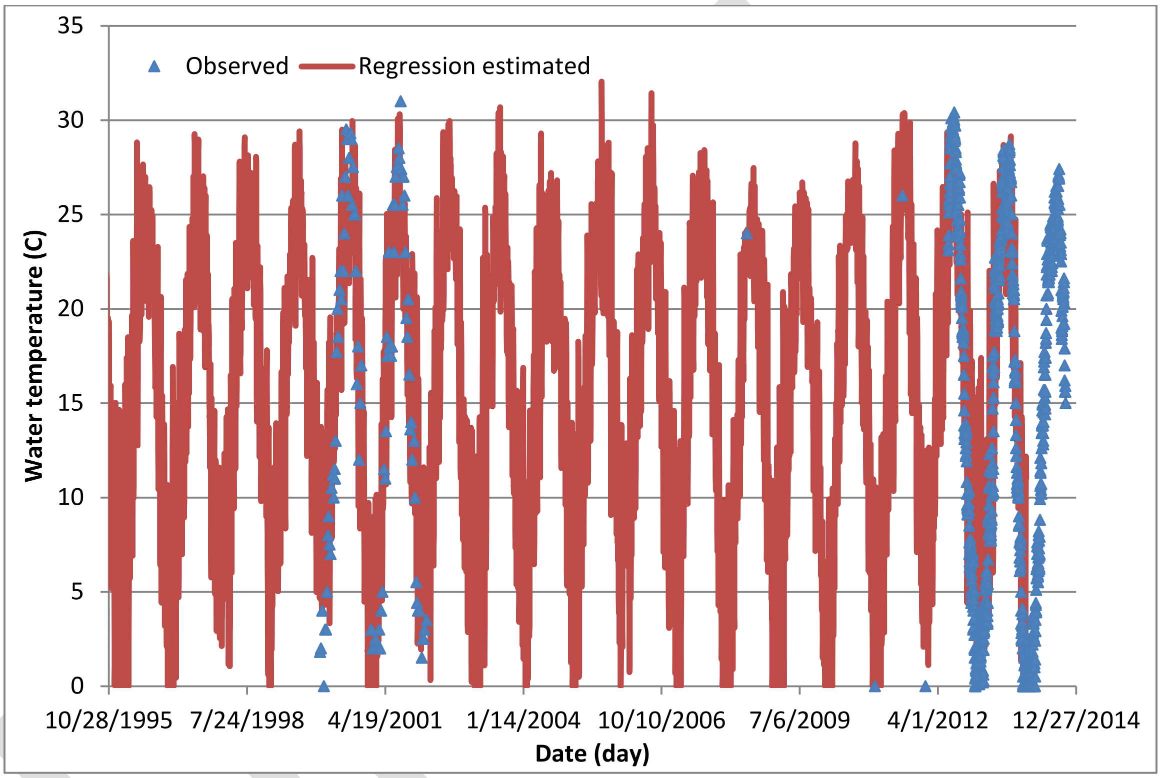


Figure 51. Regression computed versus observed water temperature at BC2

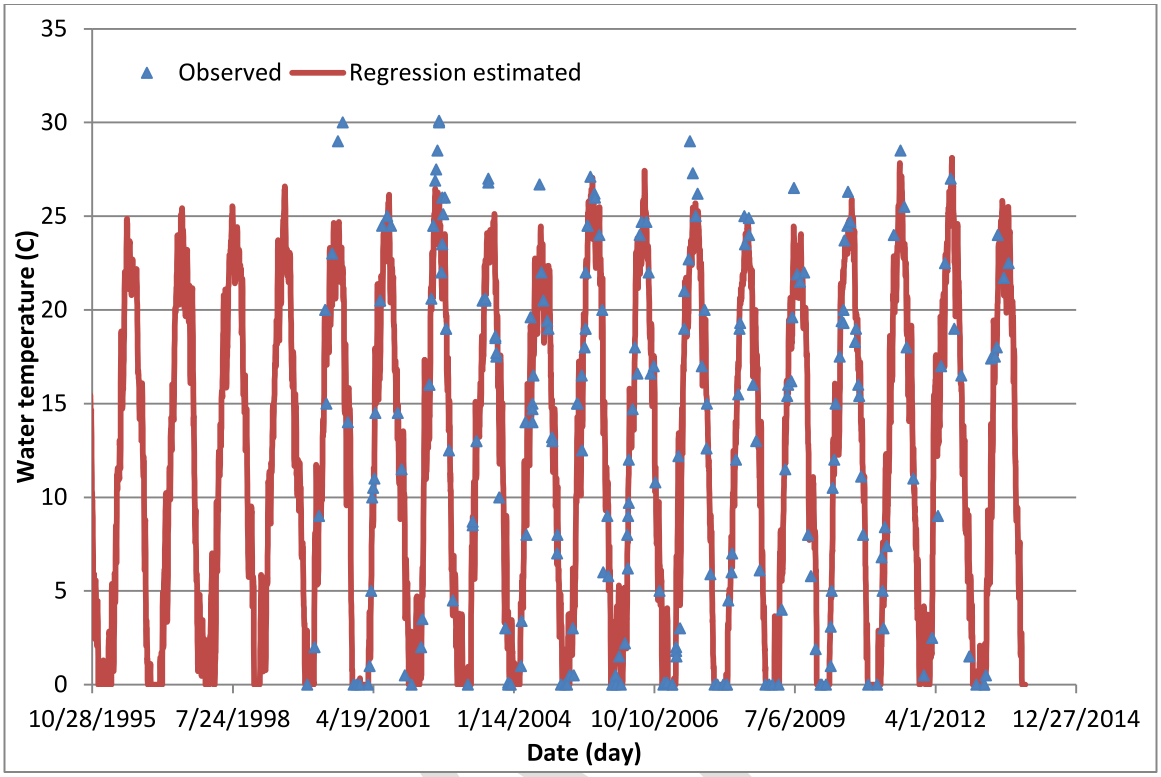


Figure 52. Regression computed versus observed water temperature at BC3

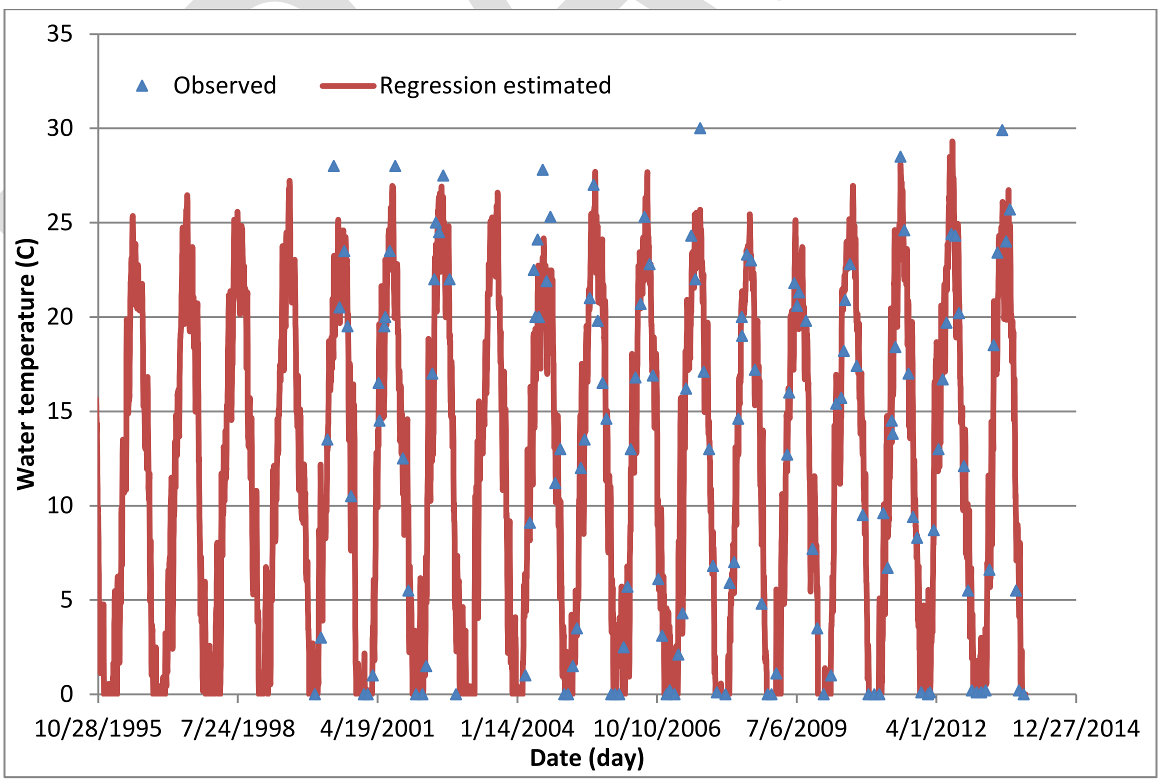


Figure 53. Regression computed versus observed water temperature at BC4

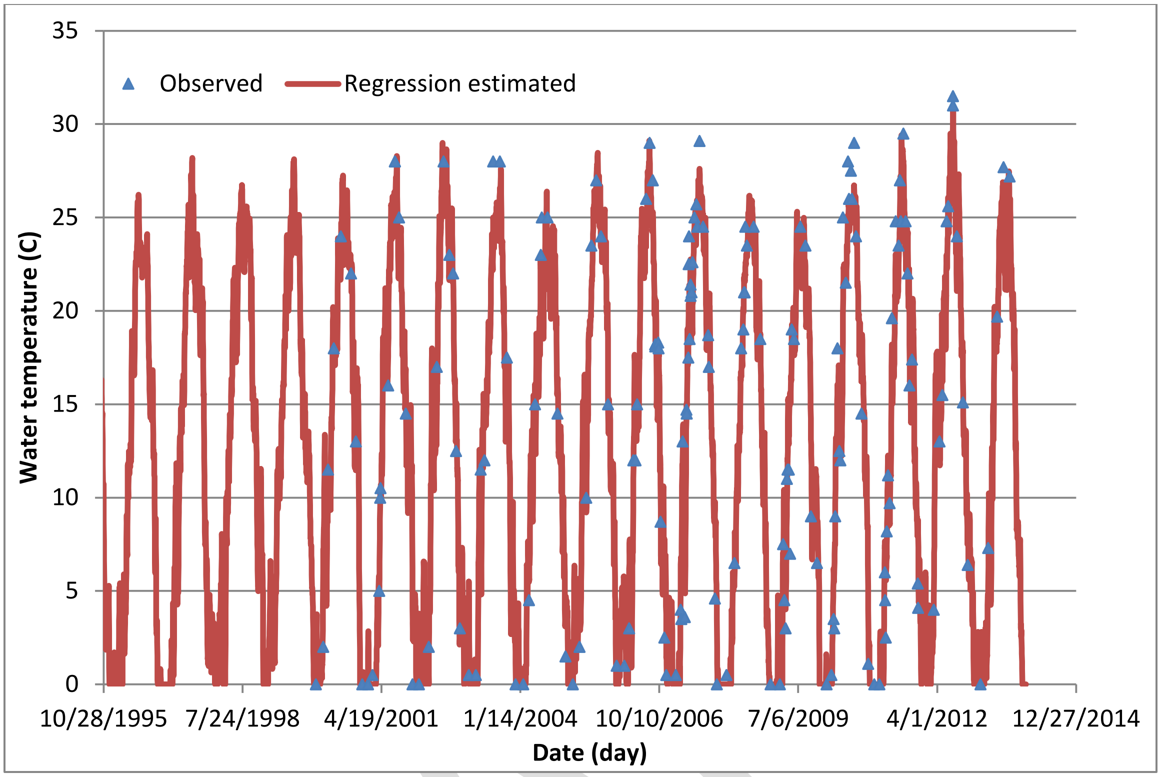


Figure 54. Regression computed versus observed water temperature at BC5

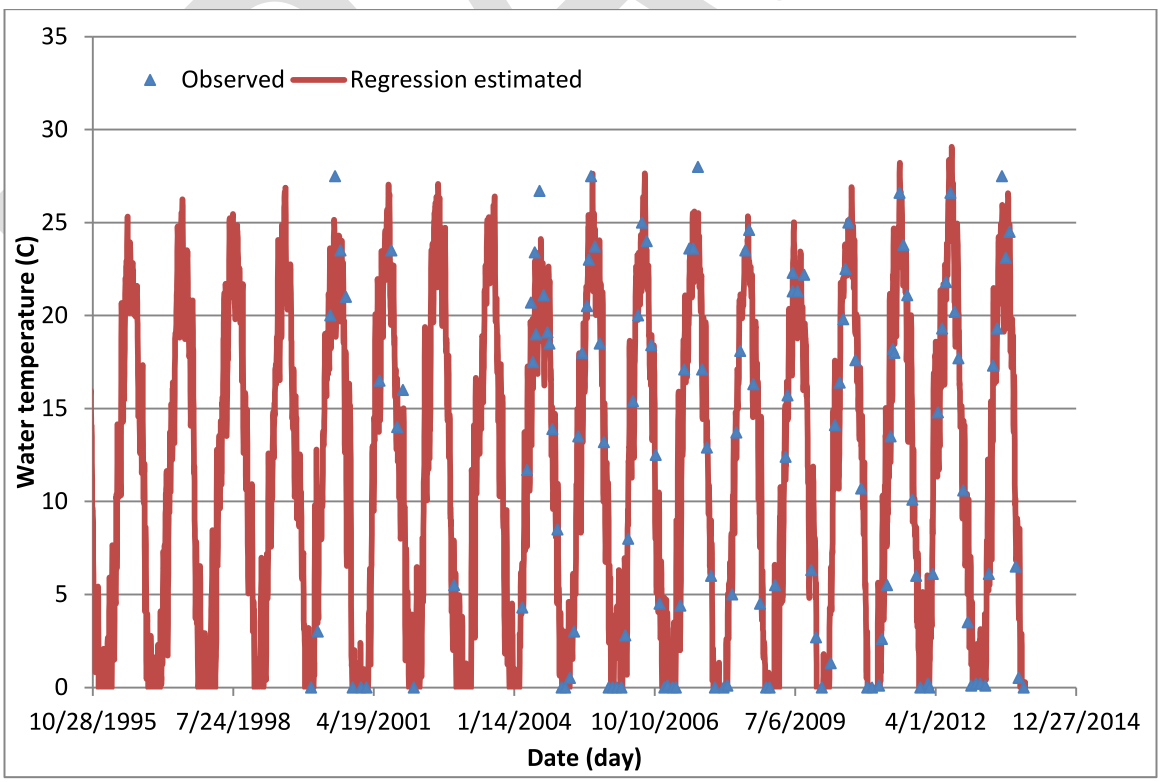


Figure 55. Regression computed versus observed water temperature at BC6

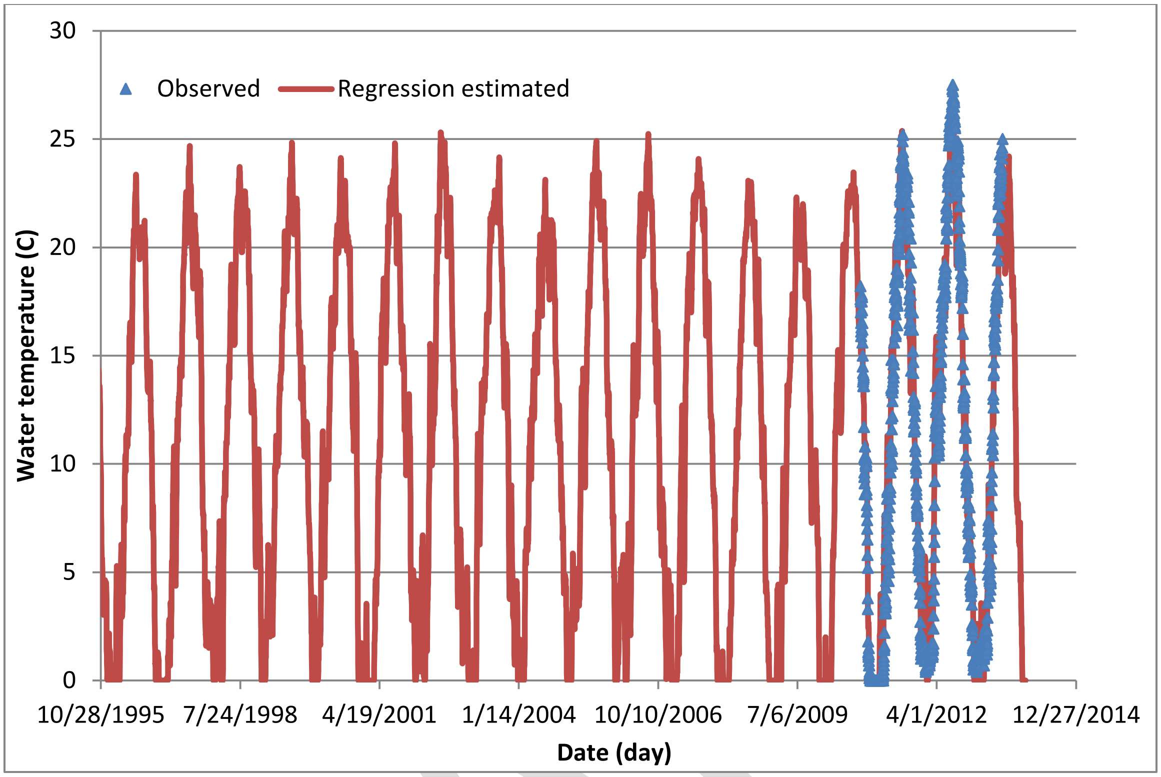


Figure 56. Regression computed versus observed water temperature at BC7

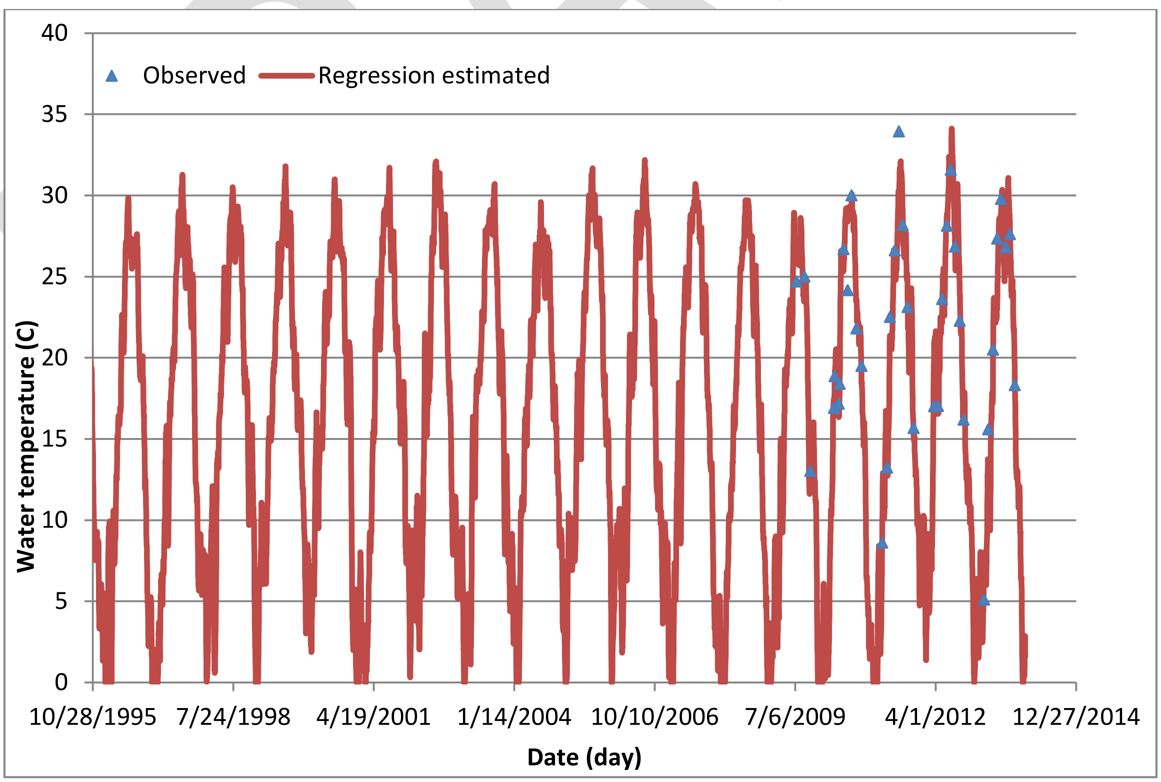


Figure 57. Regression computed versus observed water temperature at BC8

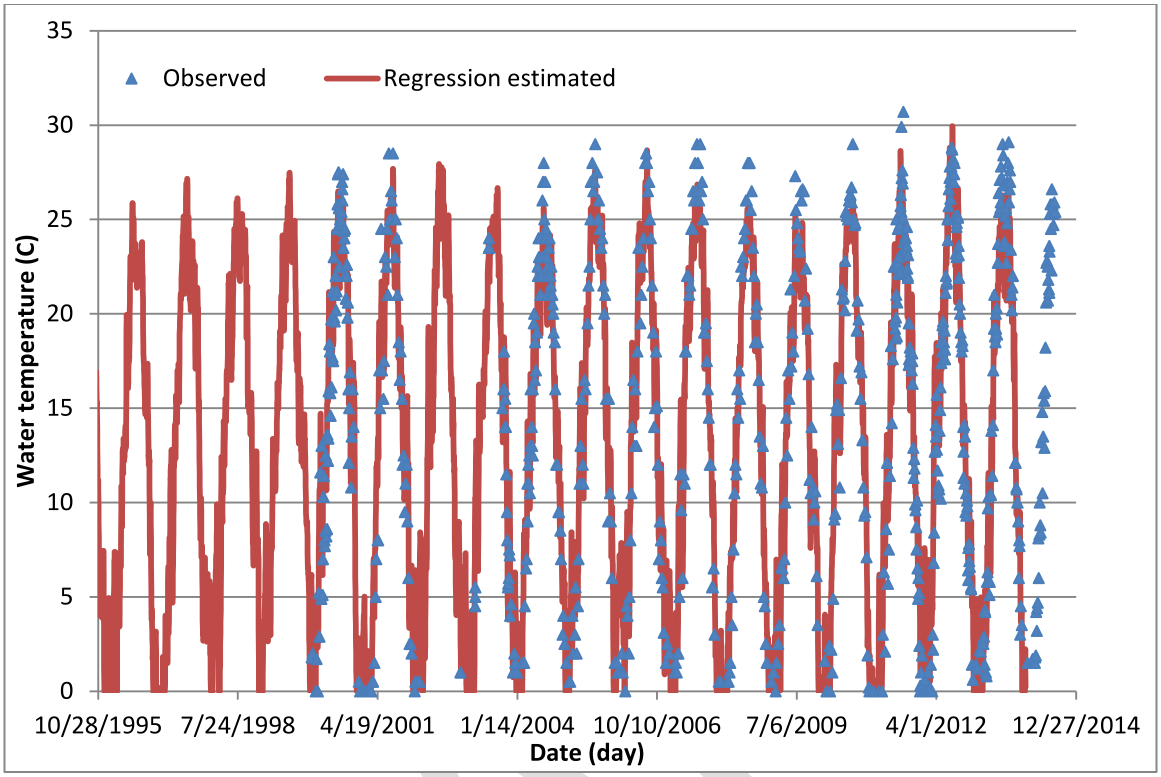


Figure 58. Regression computed versus observed water temperature at BC9

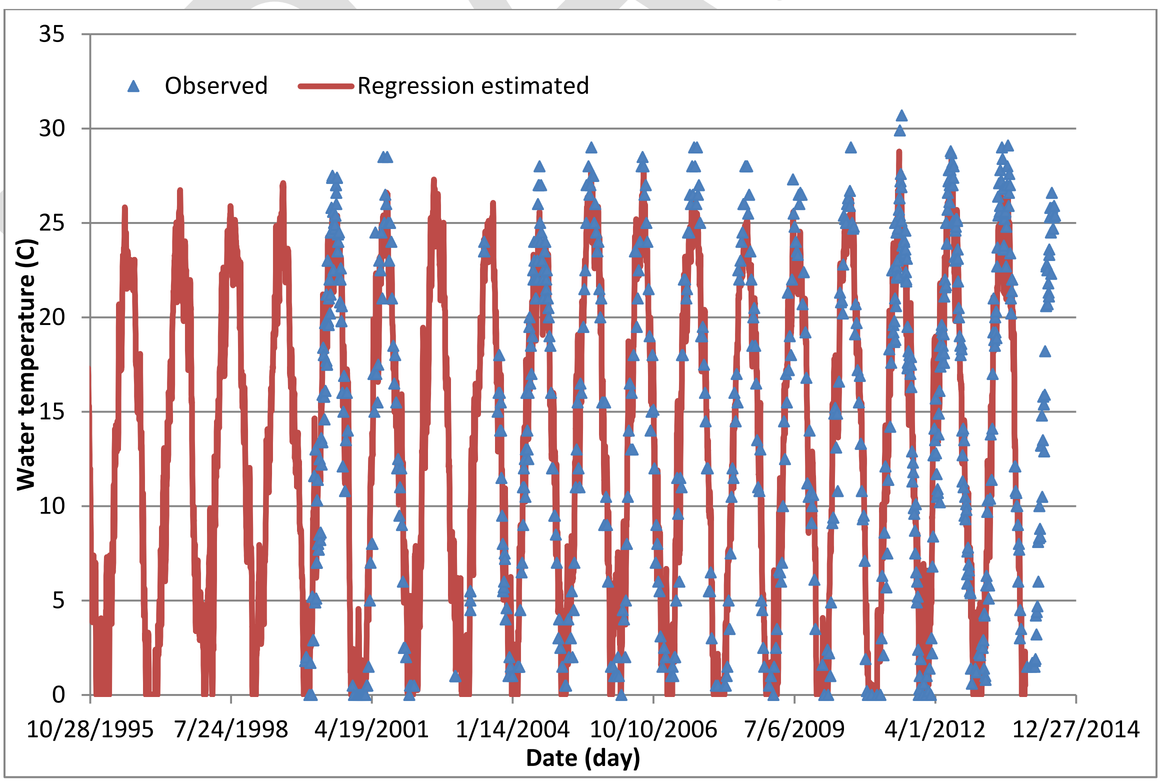


Figure 59. Regression computed versus observed water temperature at BC10

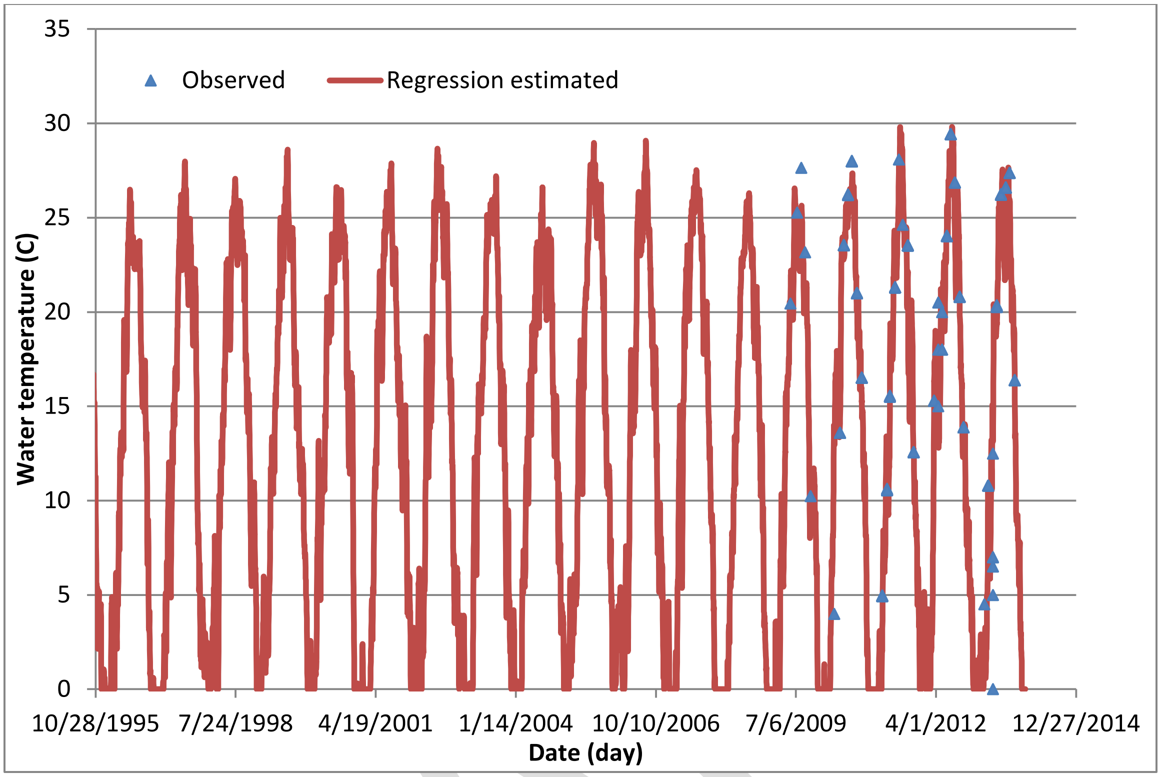


Figure 60. Regression computed versus observed water temperature at BC11

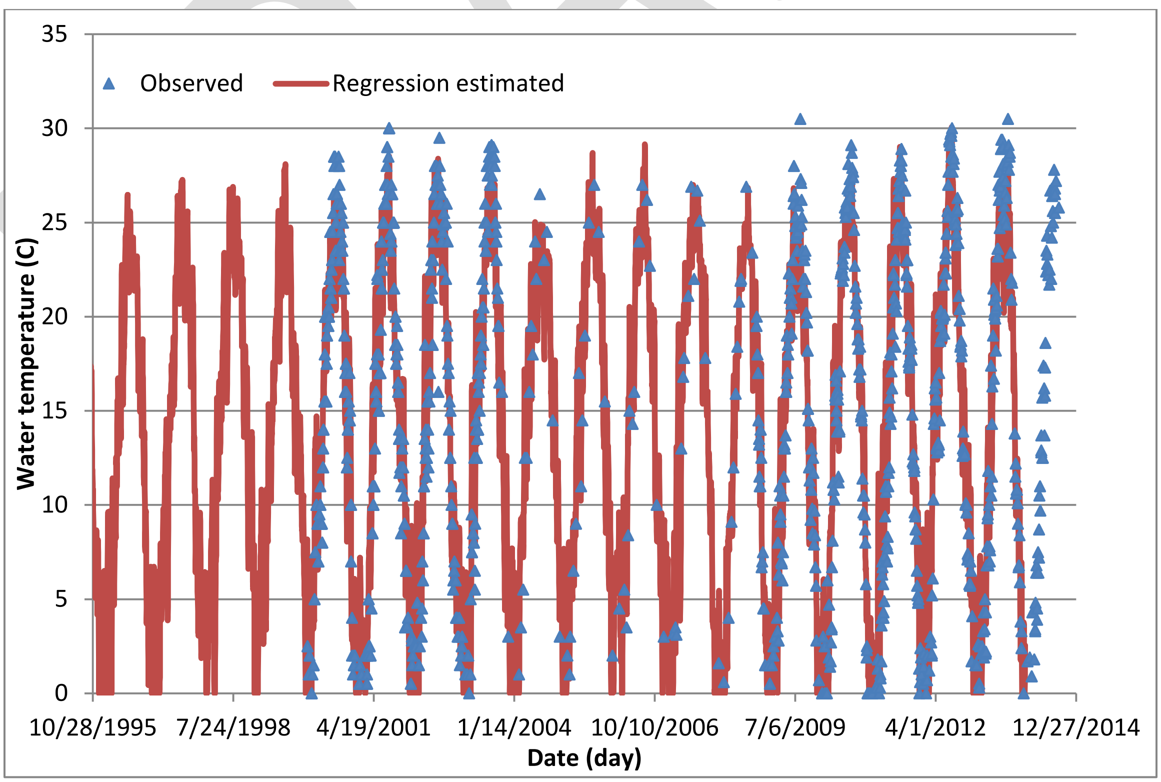


Figure 61. Regression computed versus observed water temperature at BC12

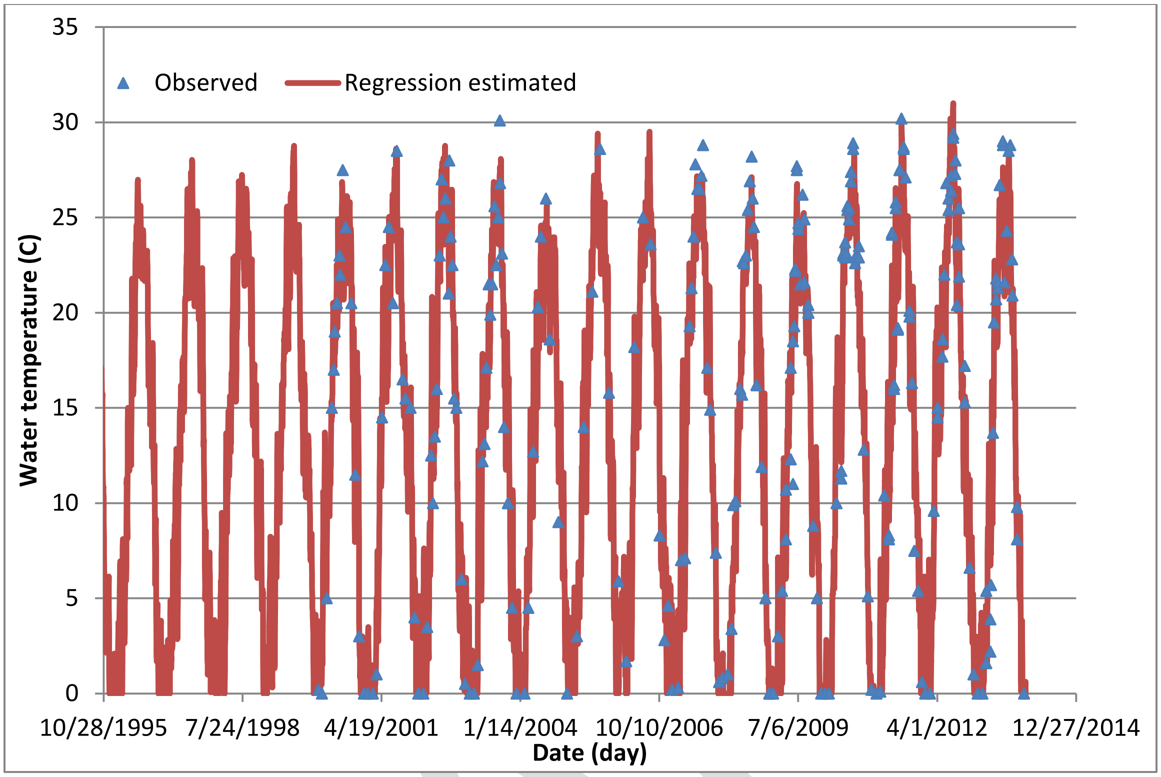


Figure 62. Regression computed versus observed water temperature at BC13

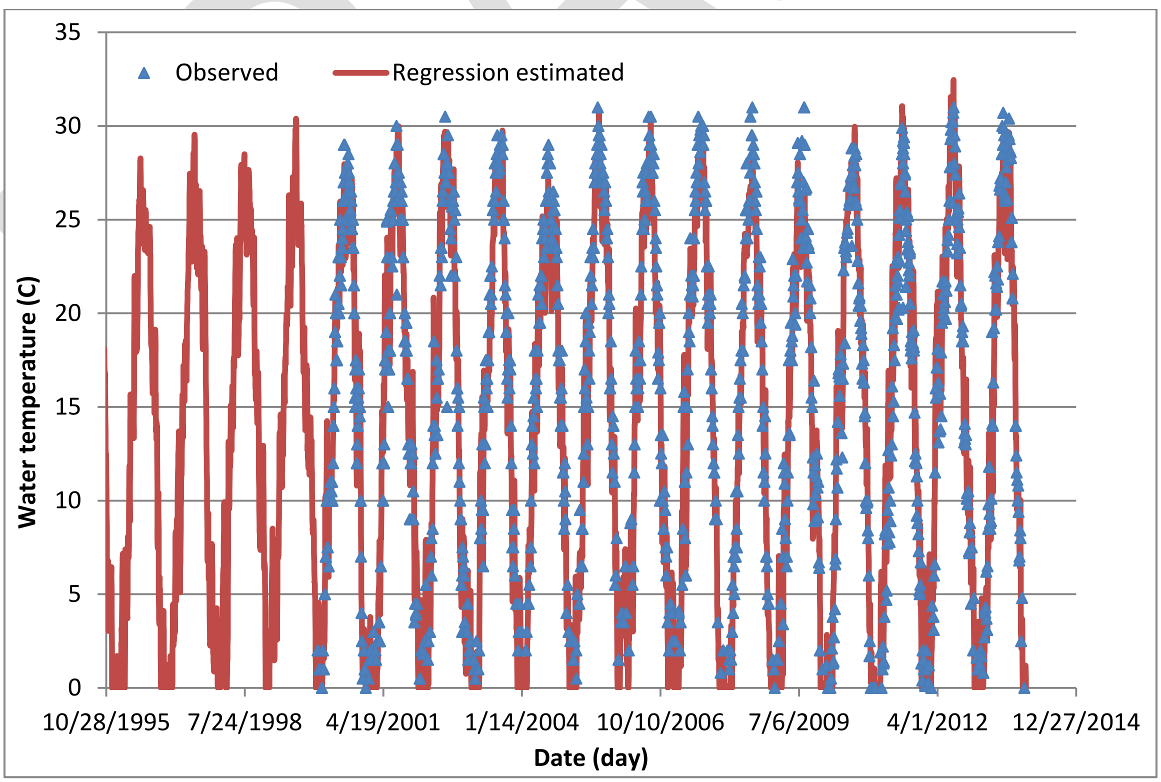


Figure 63. Regression computed versus observed water temperature at BC14

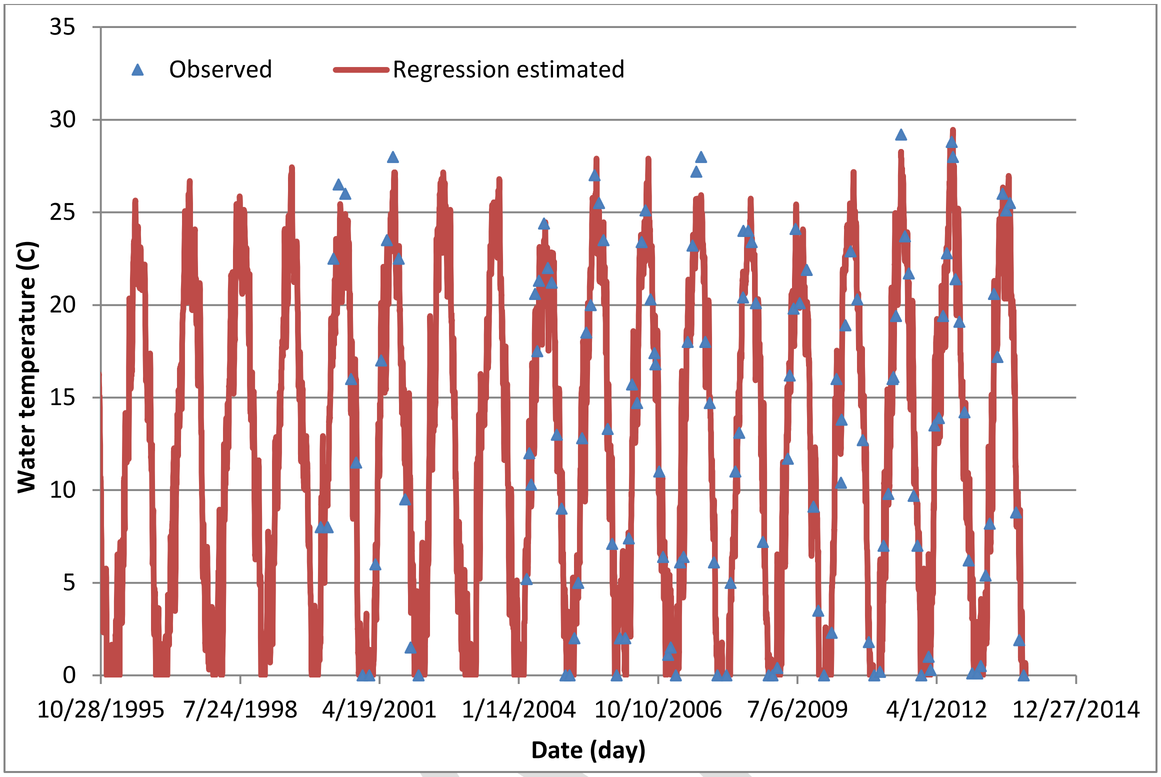


Figure 64. Regression computed versus observed water temperature at BC15

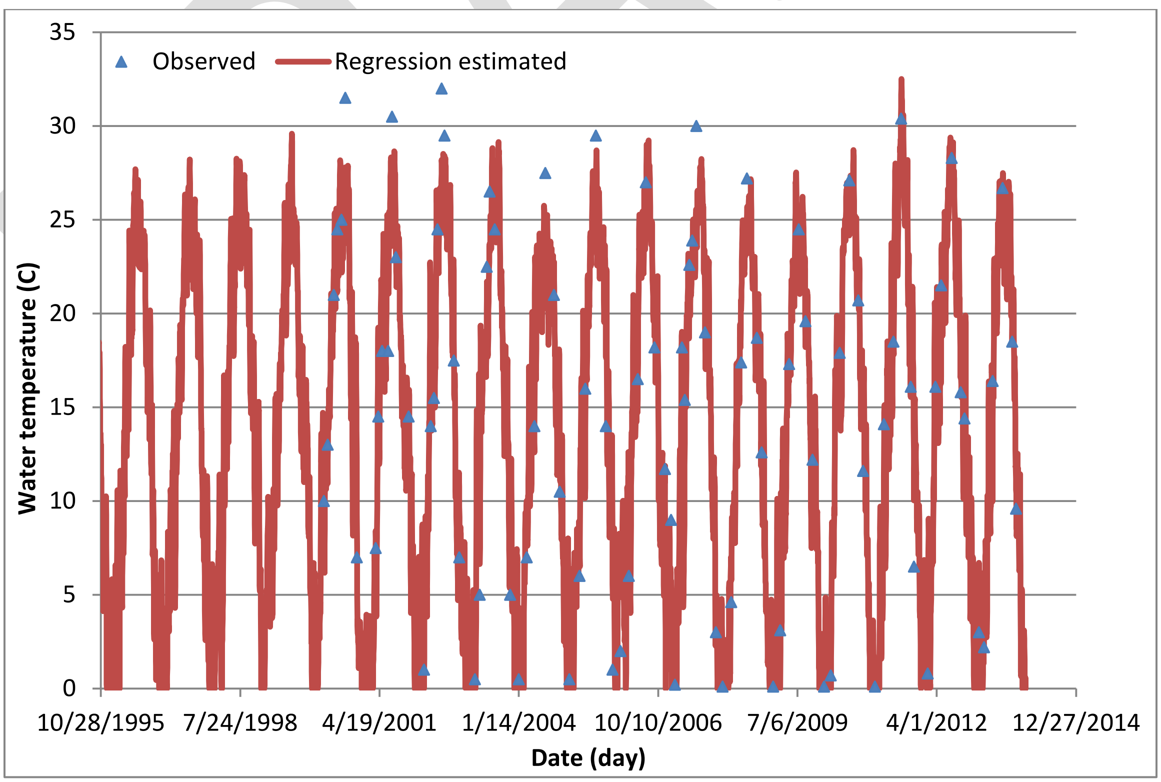
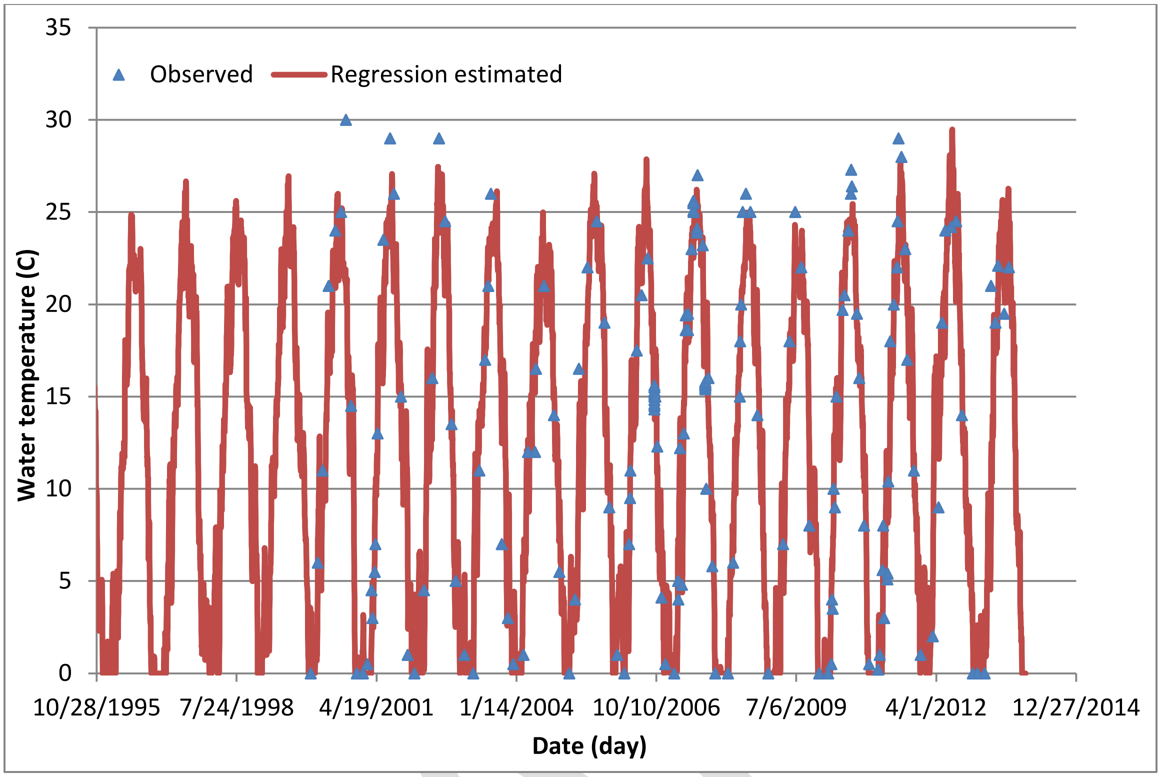


Figure 65. Regression computed versus observed water temperature at BC16



Appendix C. Time Series Plots of Regression Computed versus Observed Water Temperatures for the Rulo to the Mouth Reach

Figure 66 to Figure 92 present time series plots of regression computed and observed water temperatures for the Rulo to the Mouth reach HEC-RAS model.

Figure 66. Regression computed versus observed water temperature at BC1

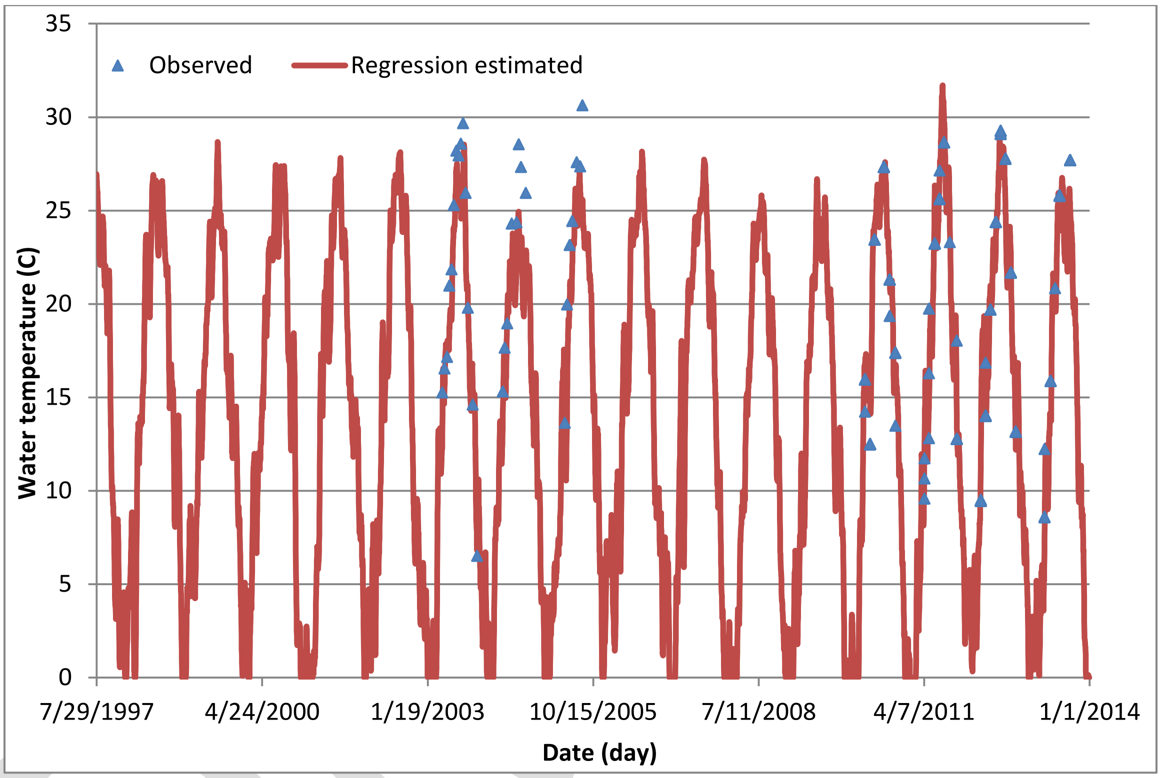


Figure 67. Regression computed versus observed water temperature at BC2

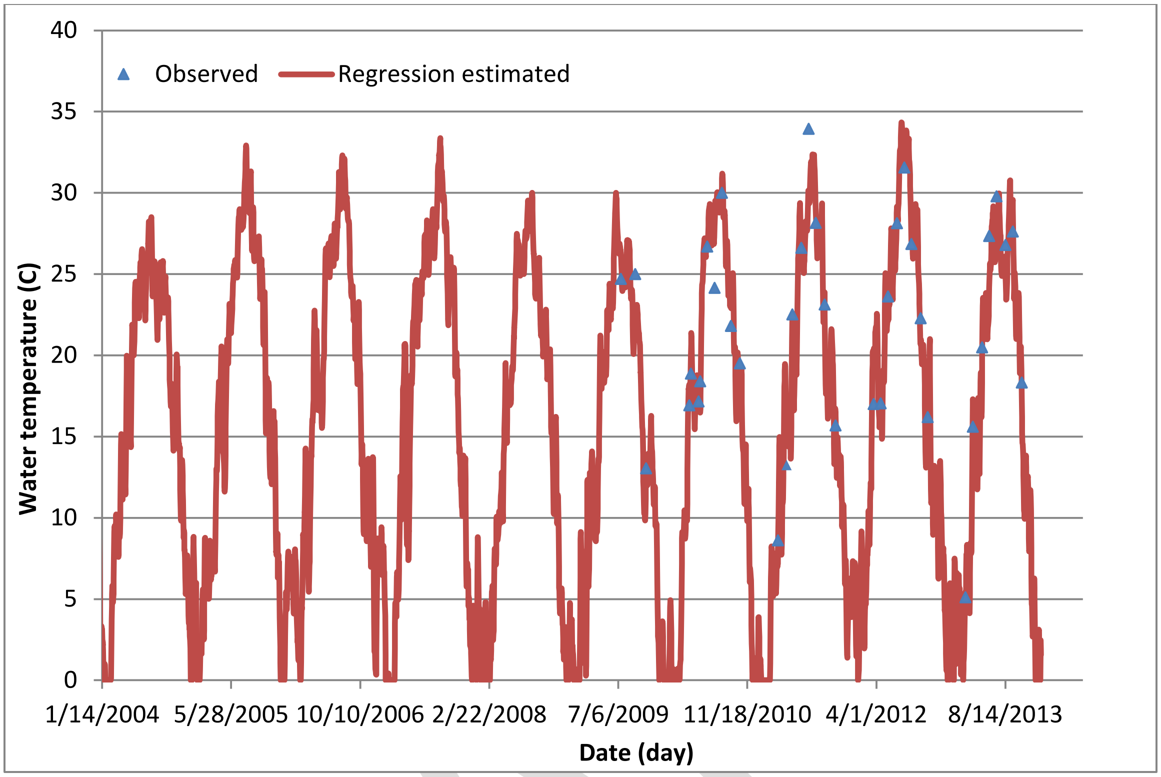


Figure 68. Regression computed versus observed water temperature at BC3

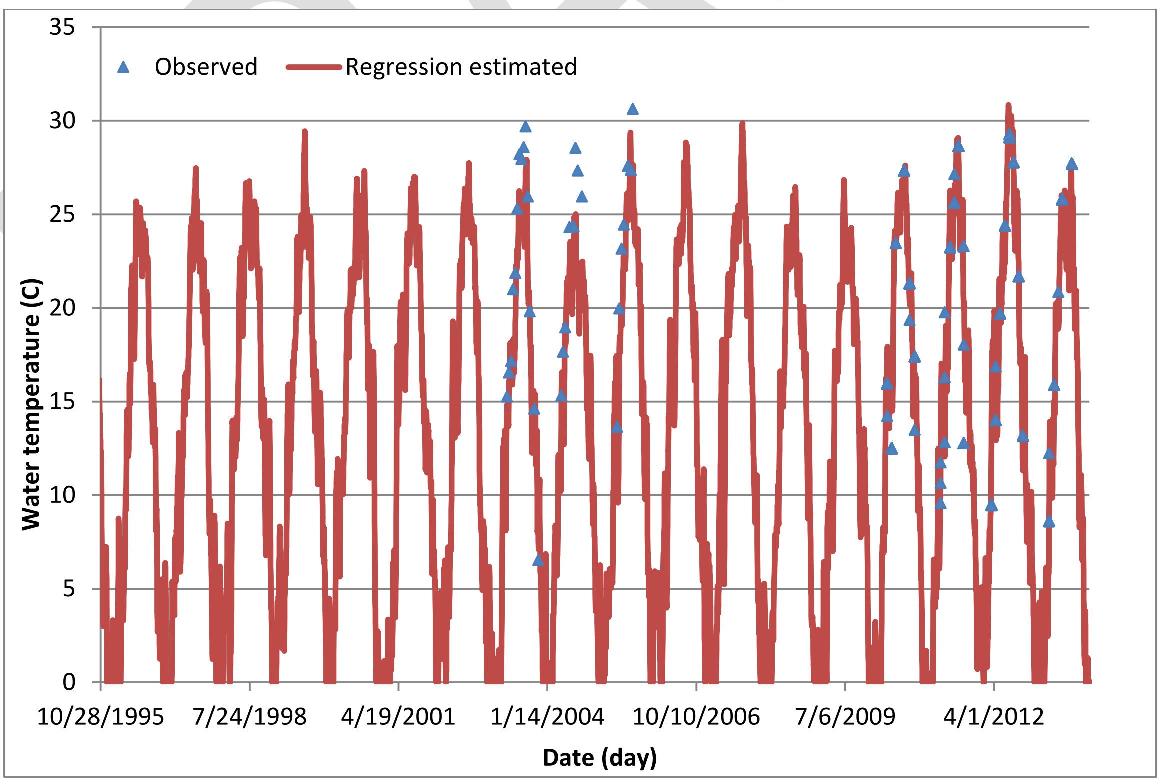


Figure 69. Regression computed versus observed water temperature at BC4

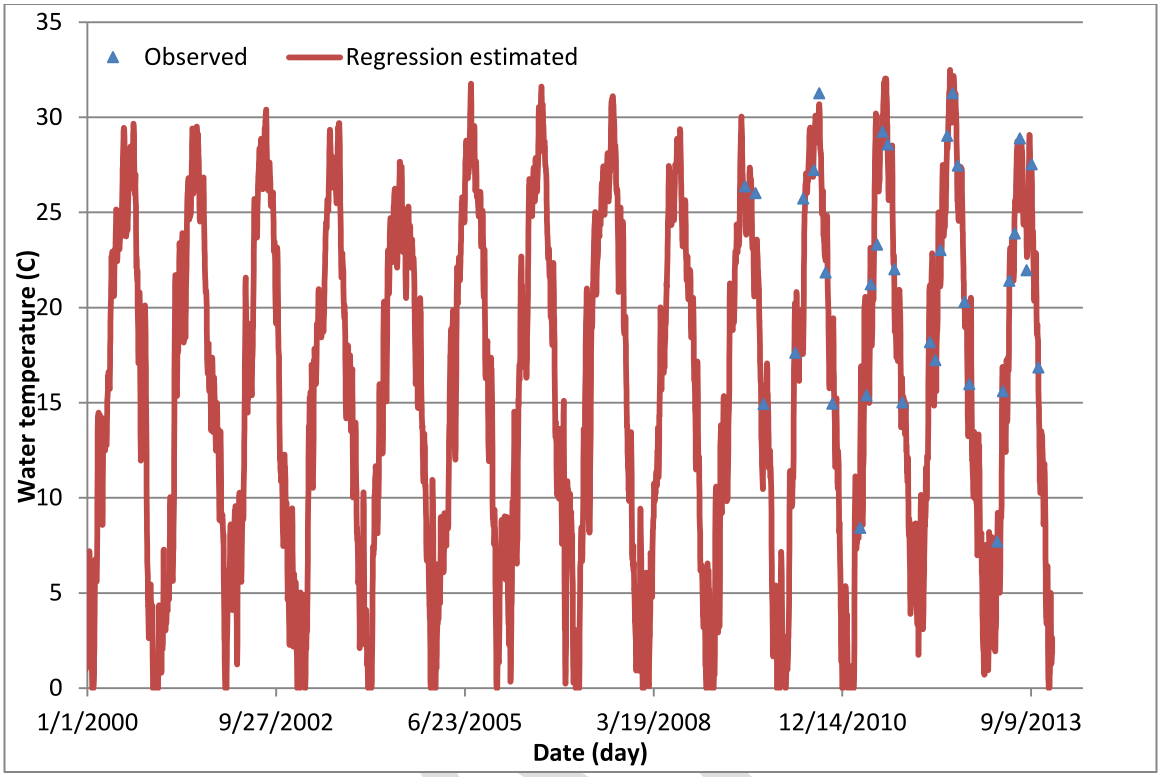


Figure 70. Regression computed versus observed water temperature at BC5

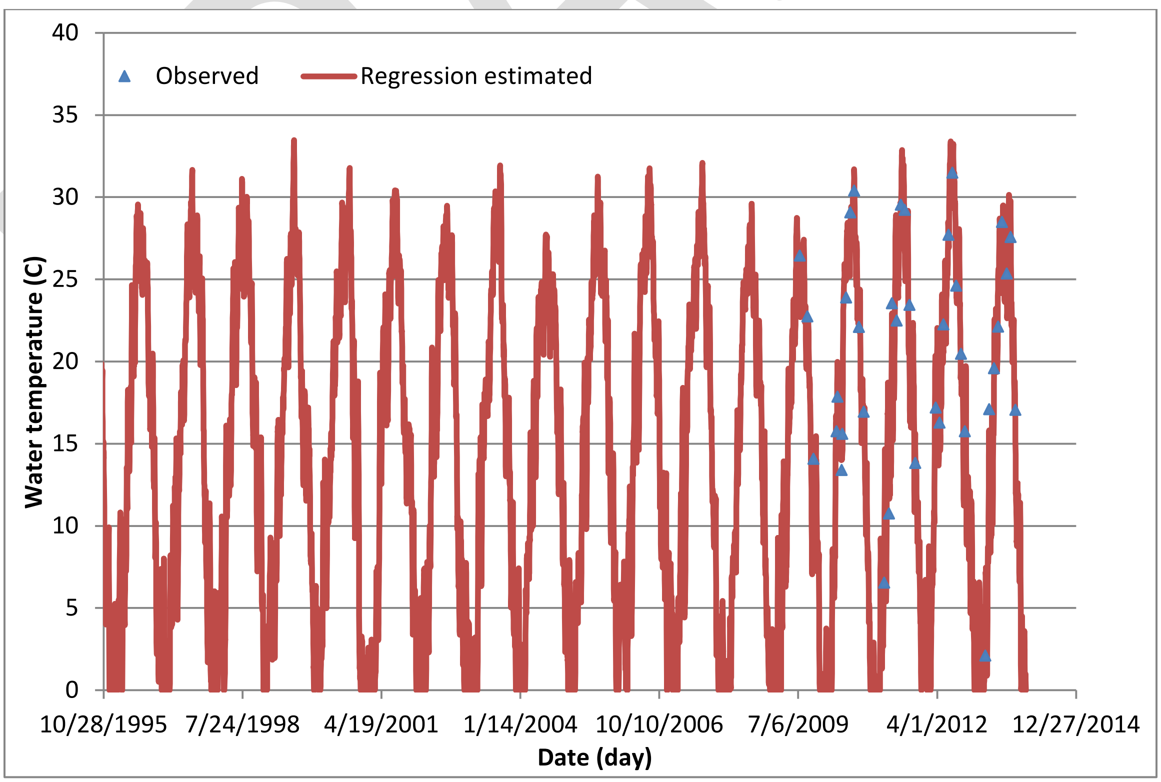


Figure 71. Regression computed versus observed water temperature at BC6

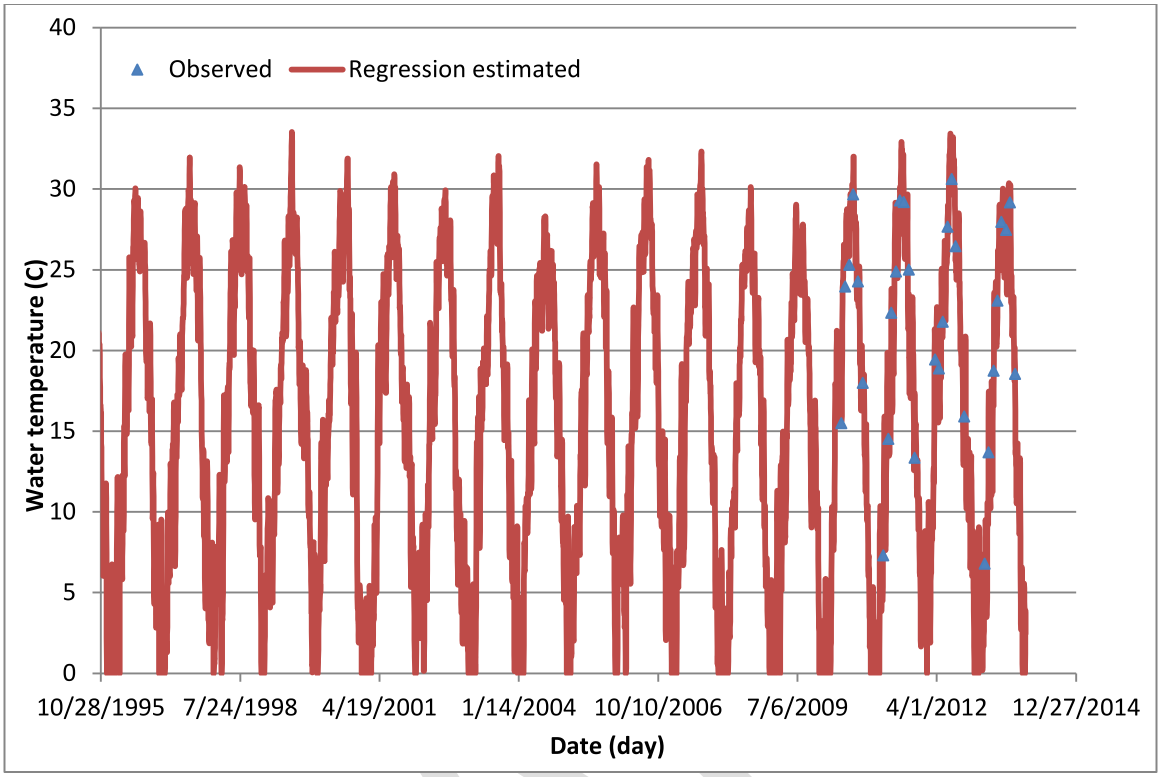


Figure 72. Regression computed versus observed water temperature at BC7

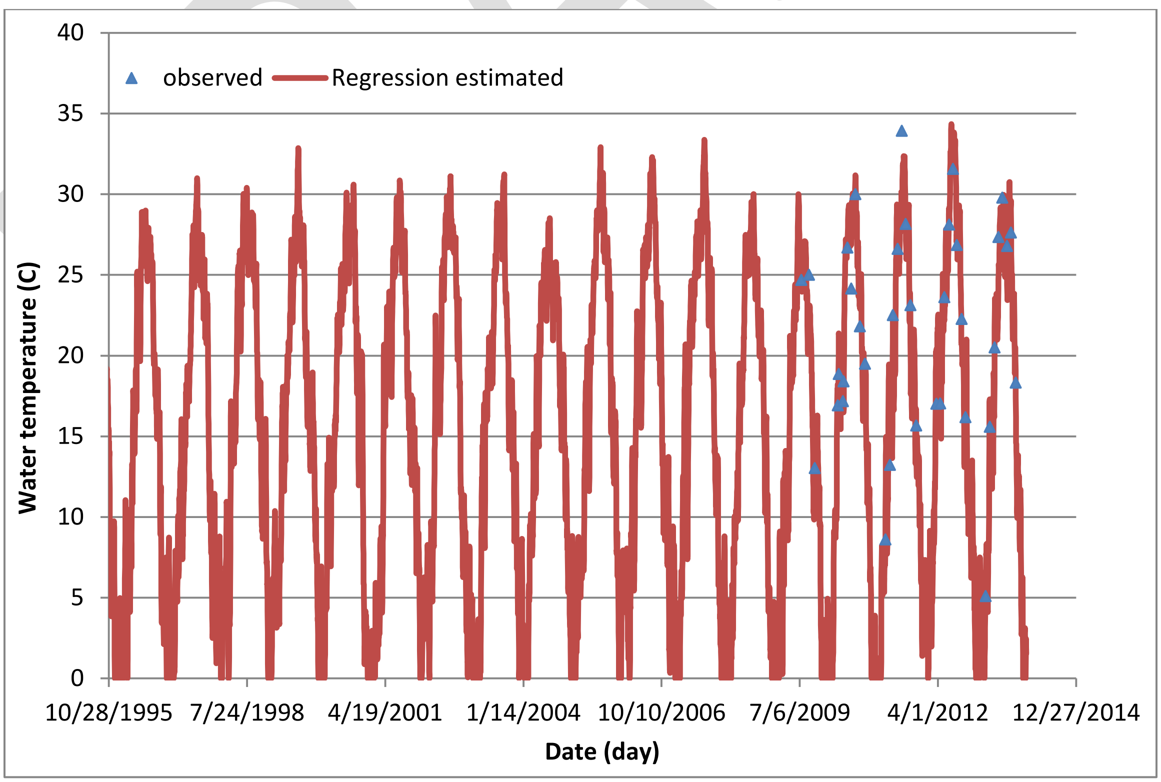
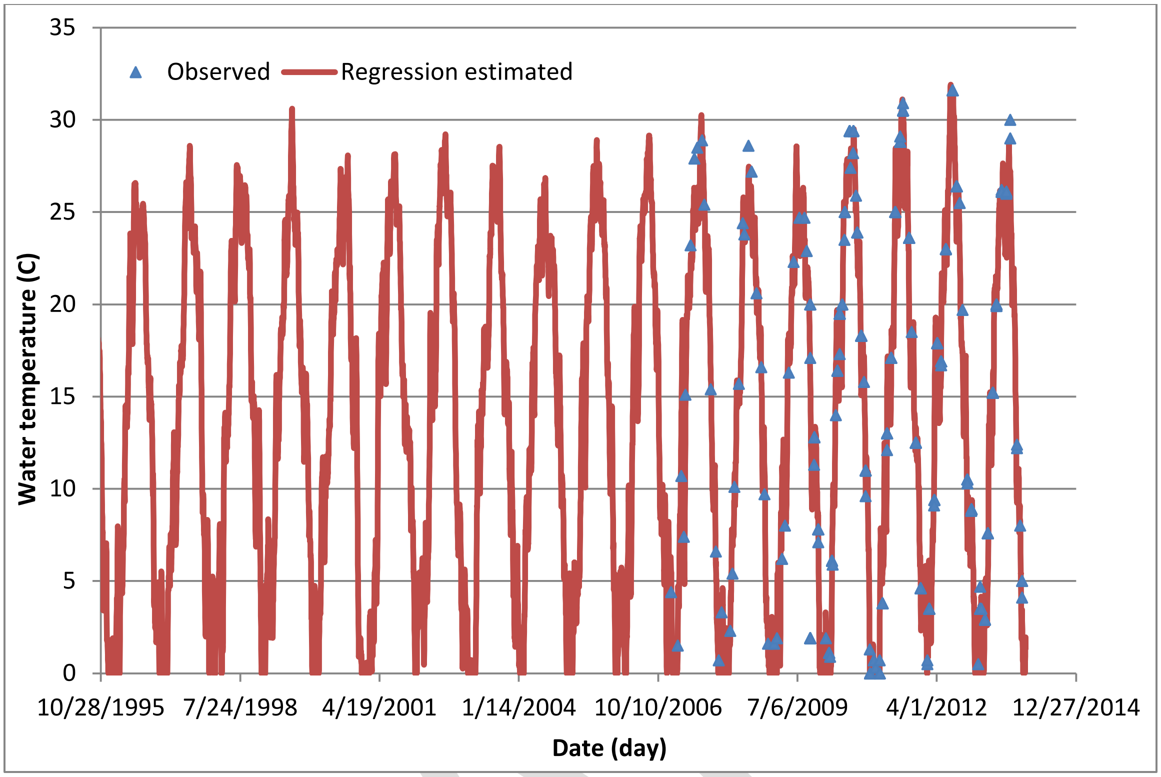


Figure 73. Regression computed versus observed water temperature at BC8



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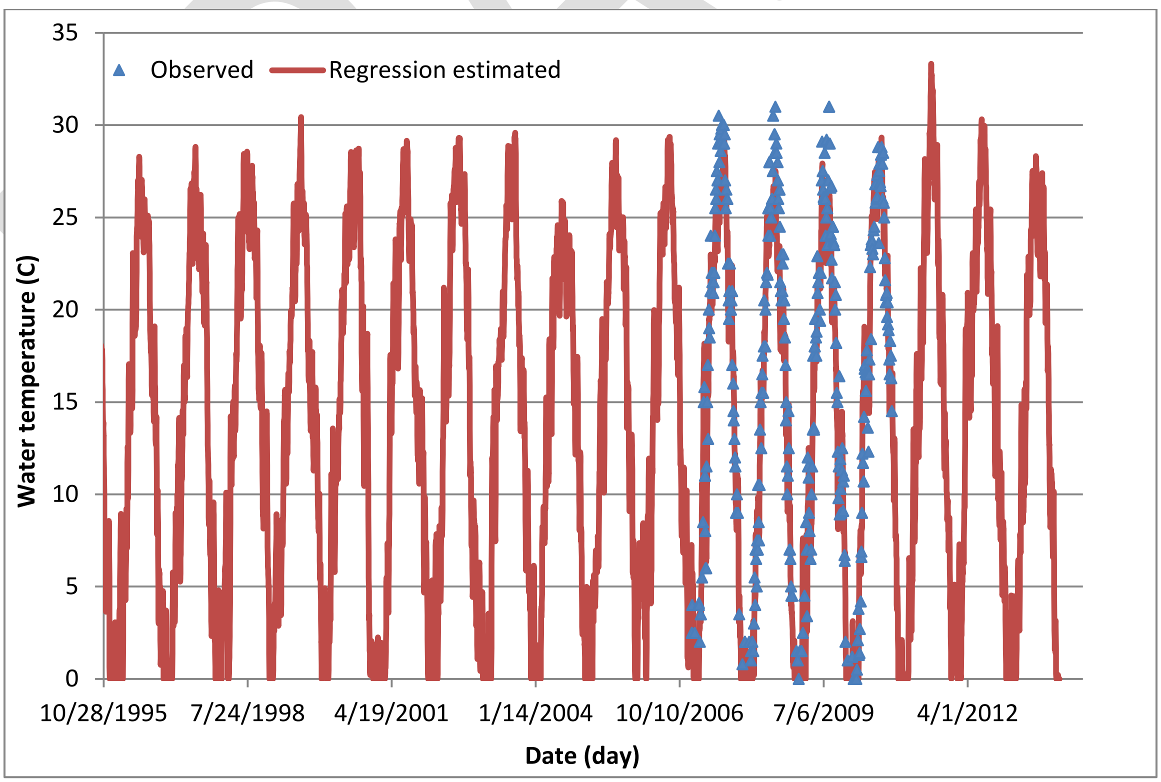

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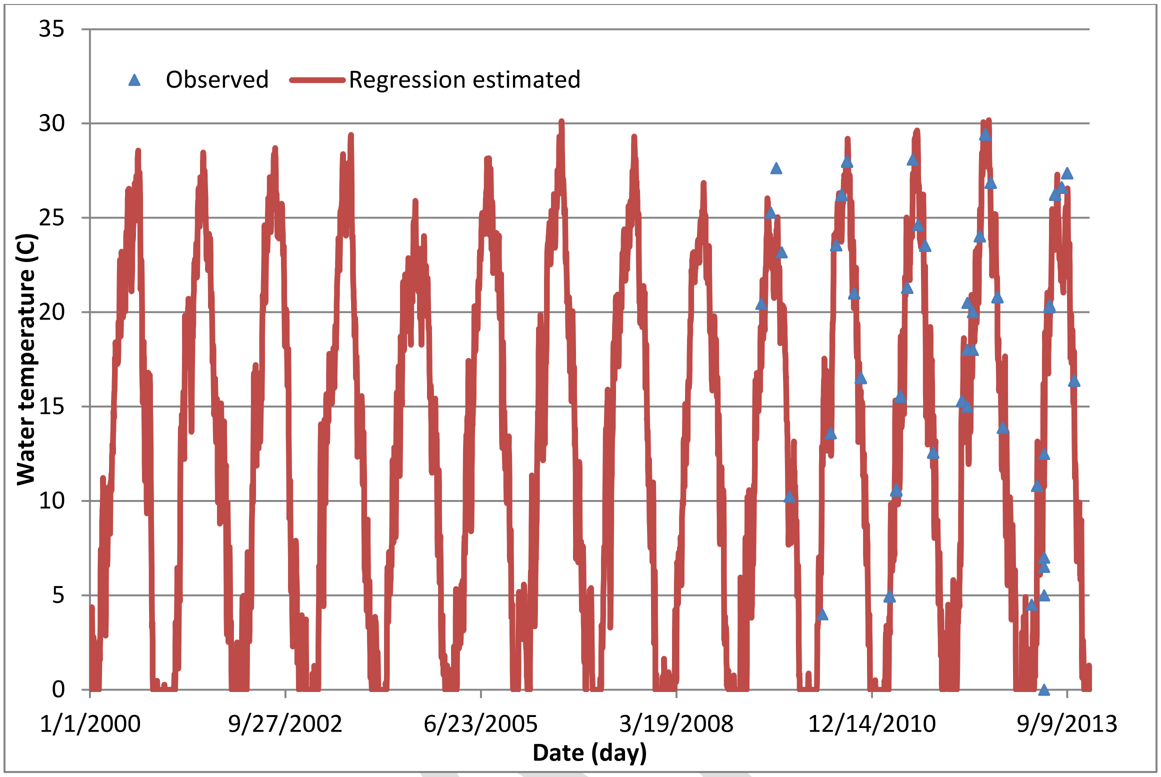

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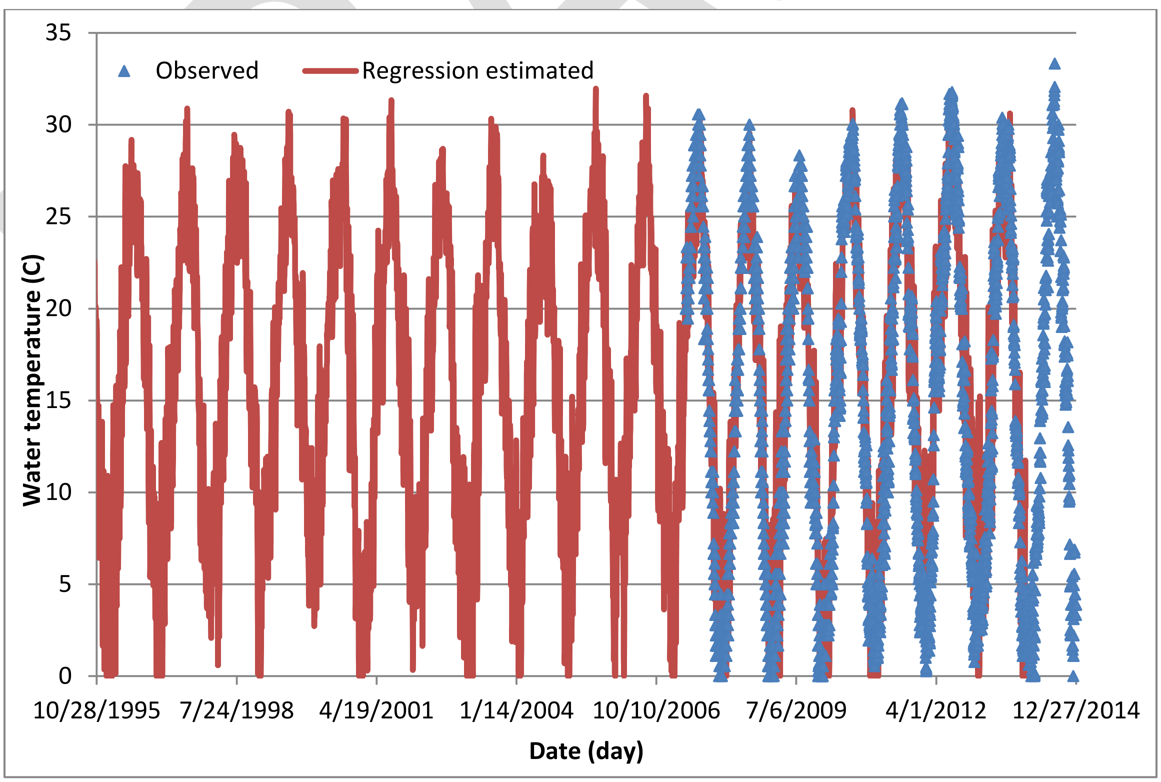

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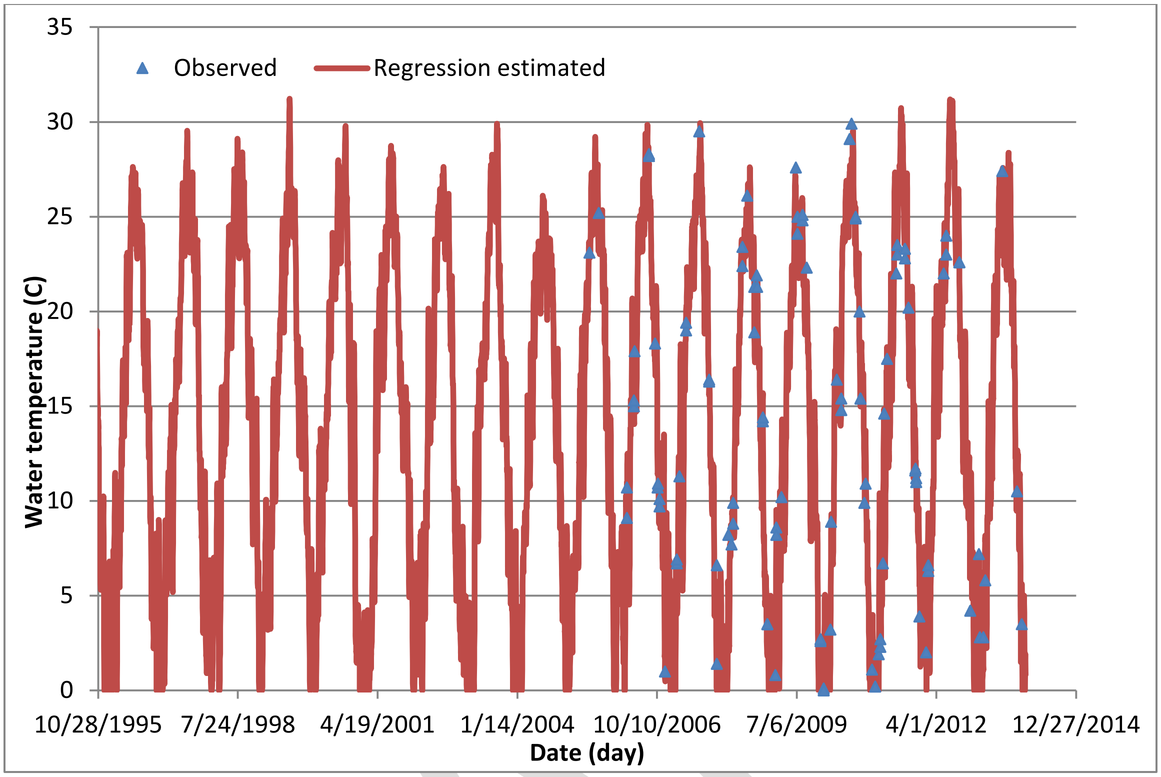

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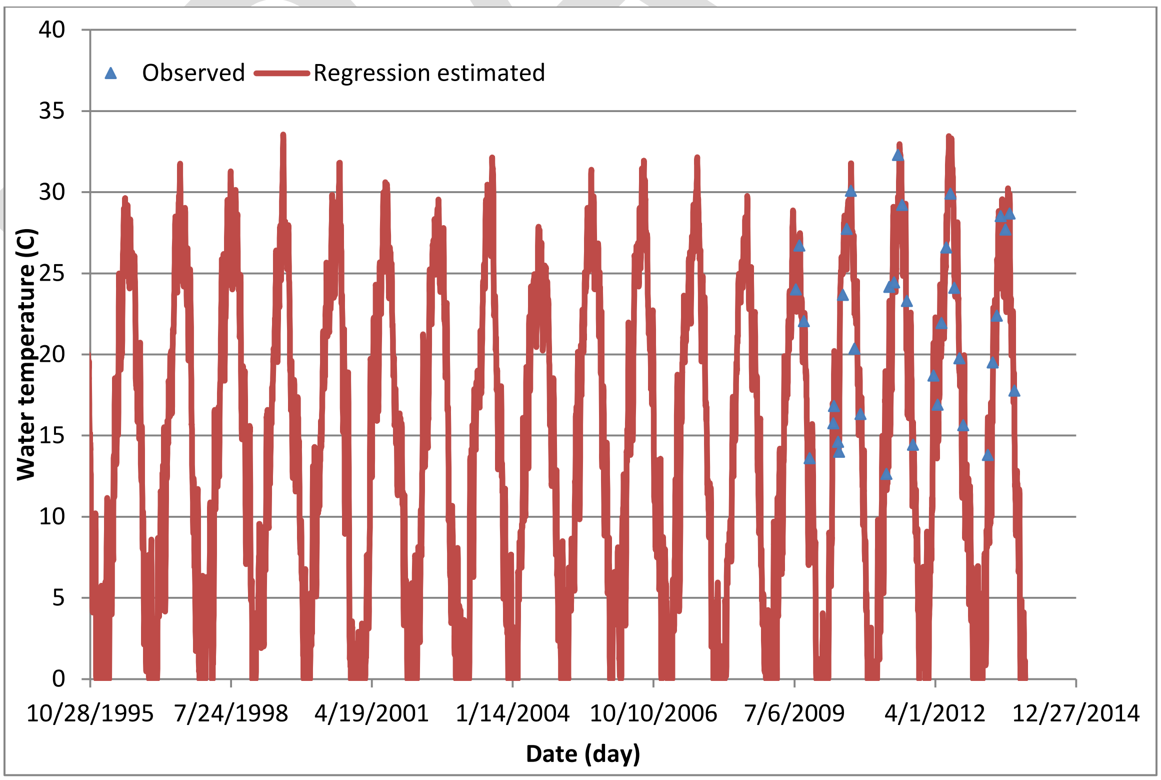

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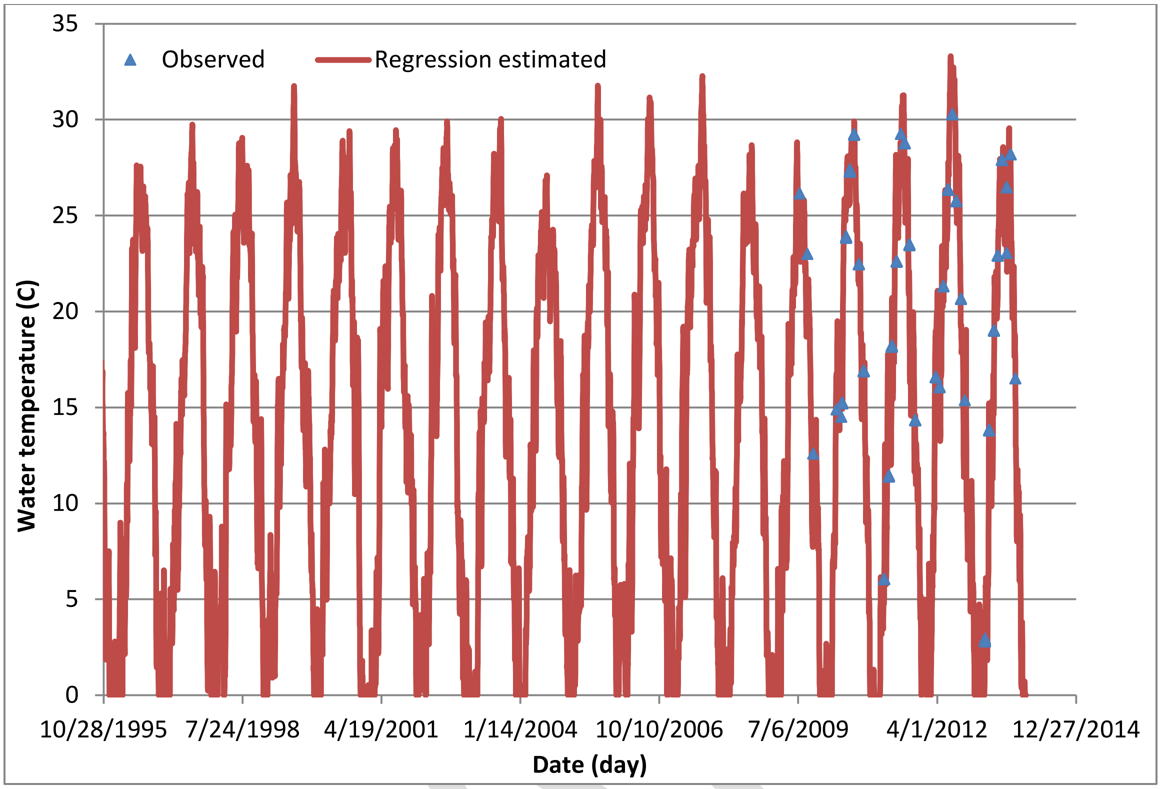

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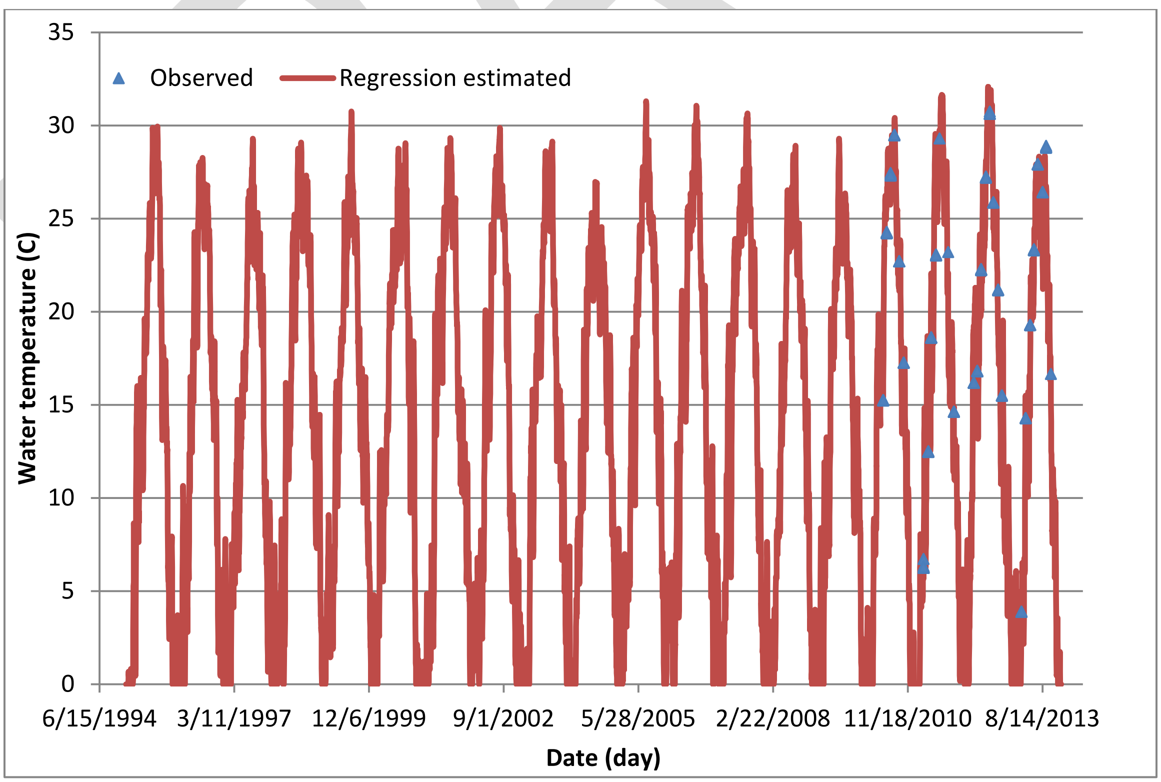

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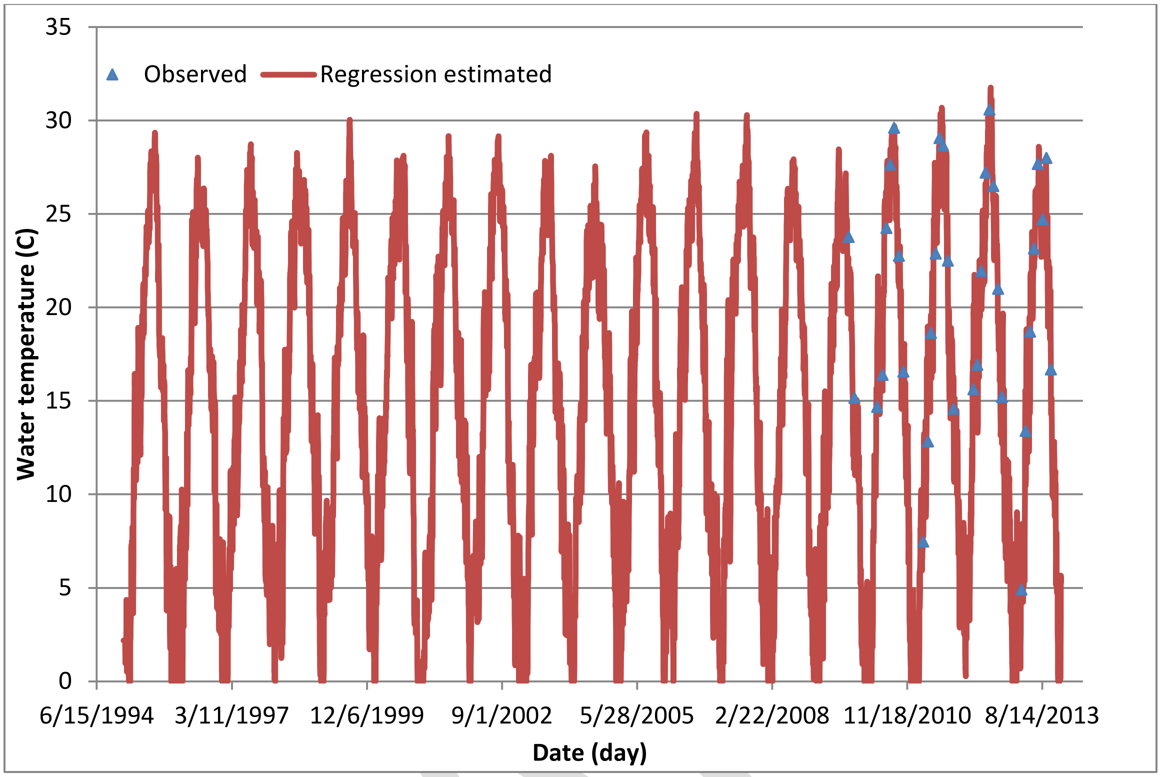

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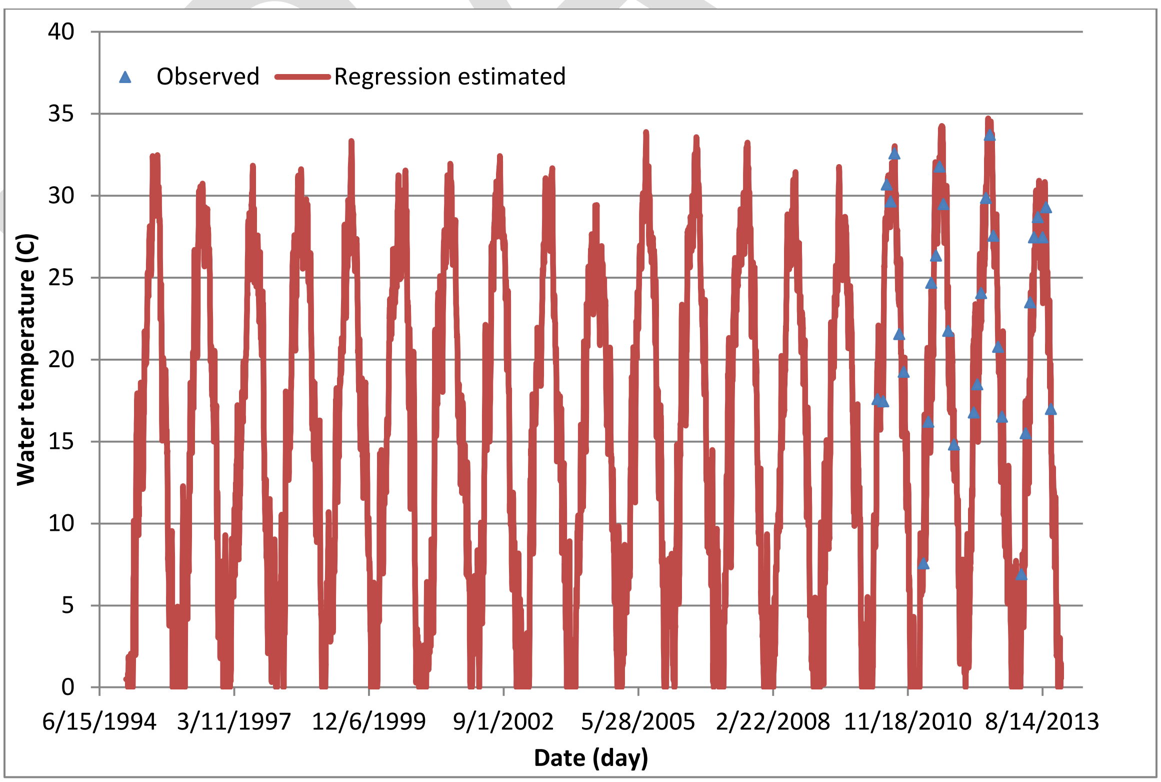

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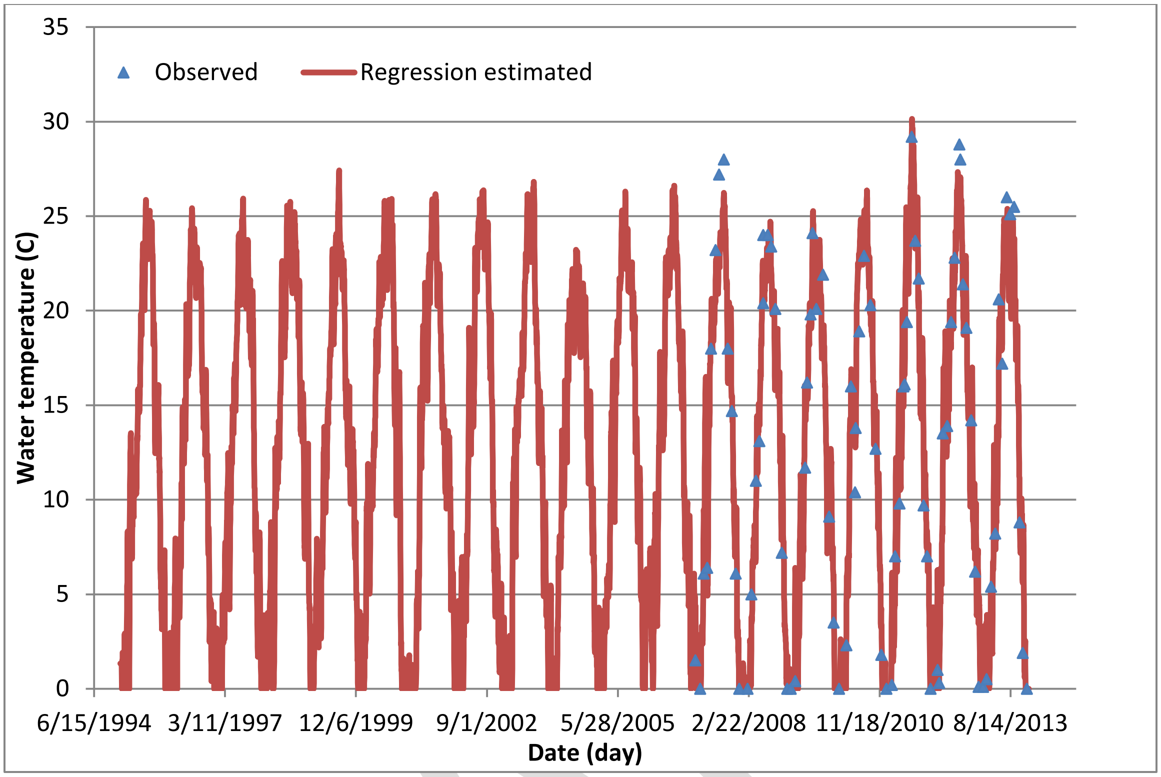

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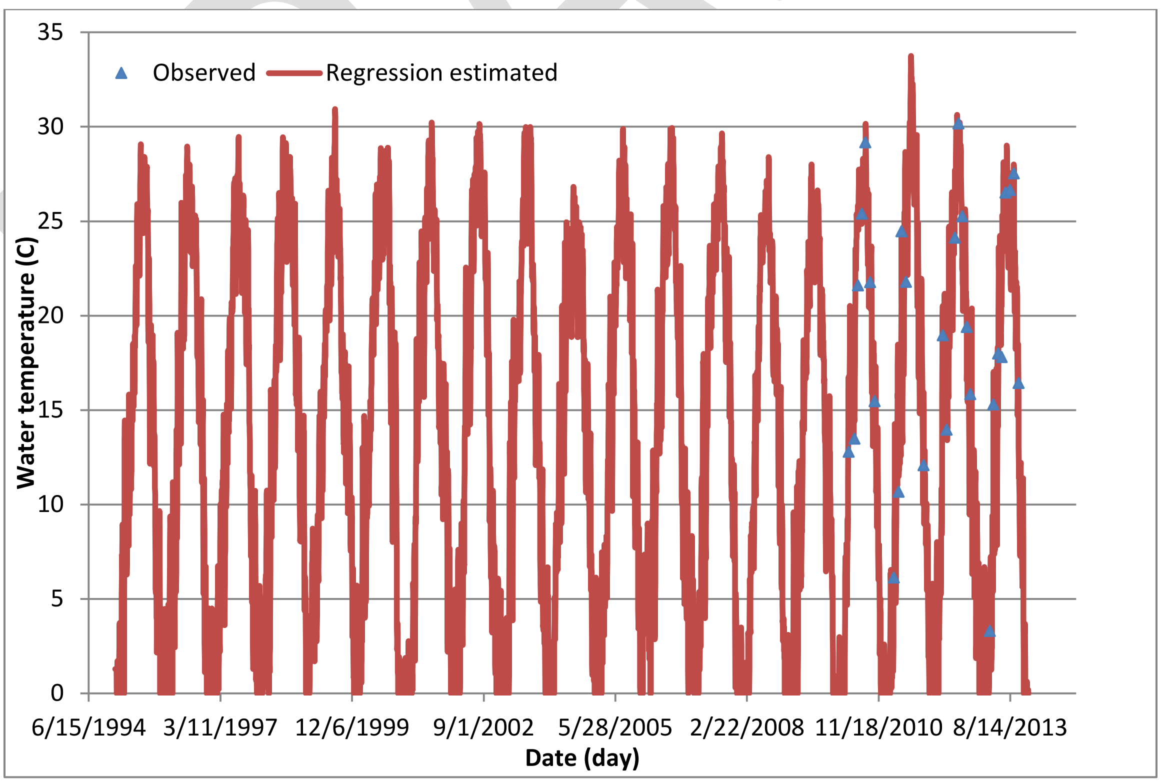

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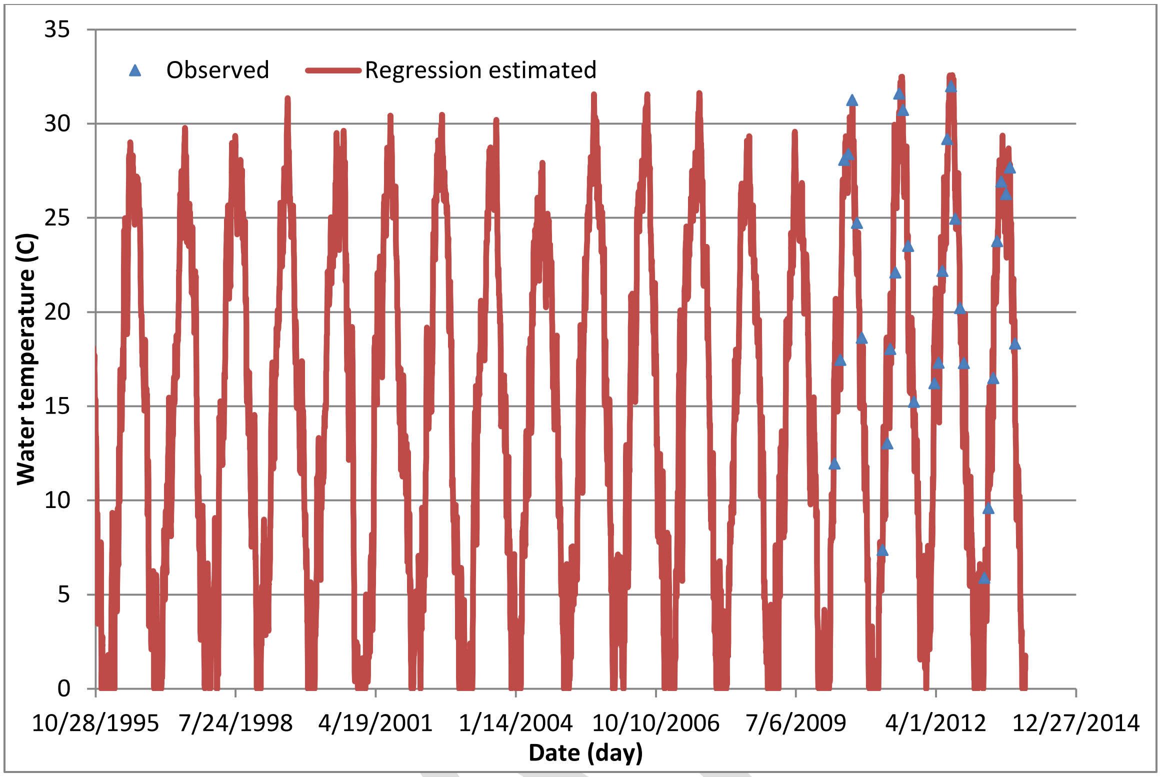

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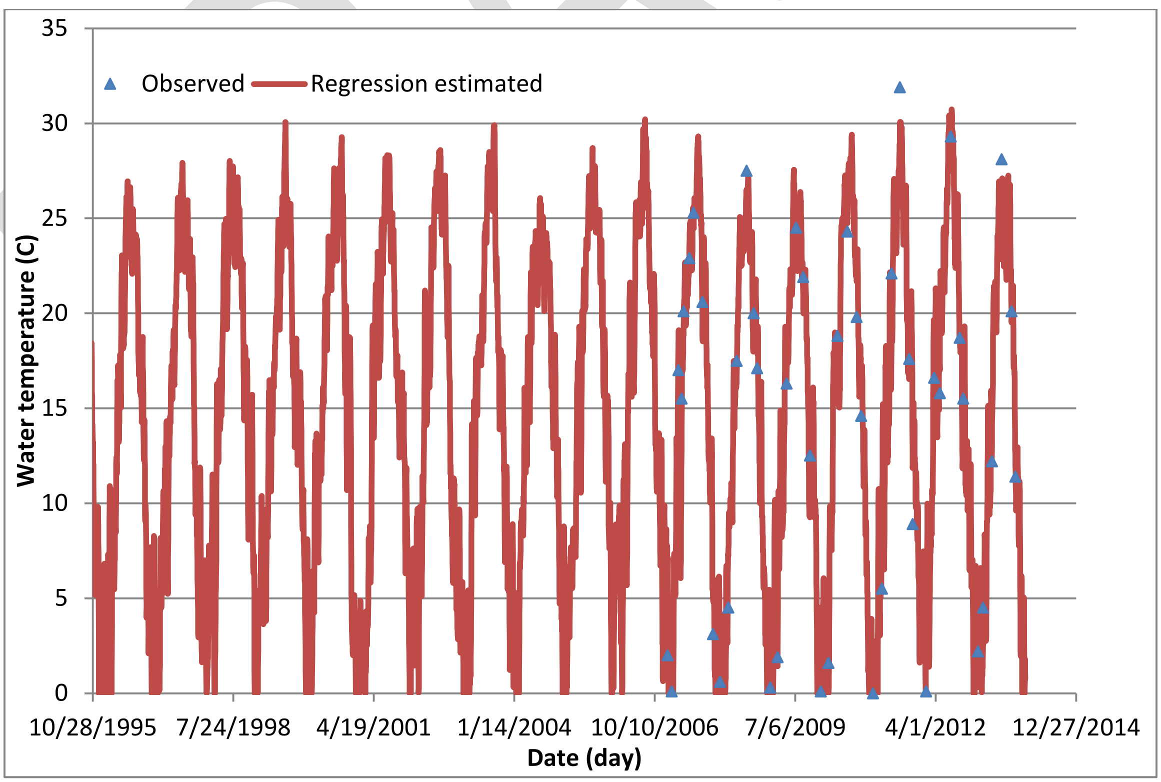

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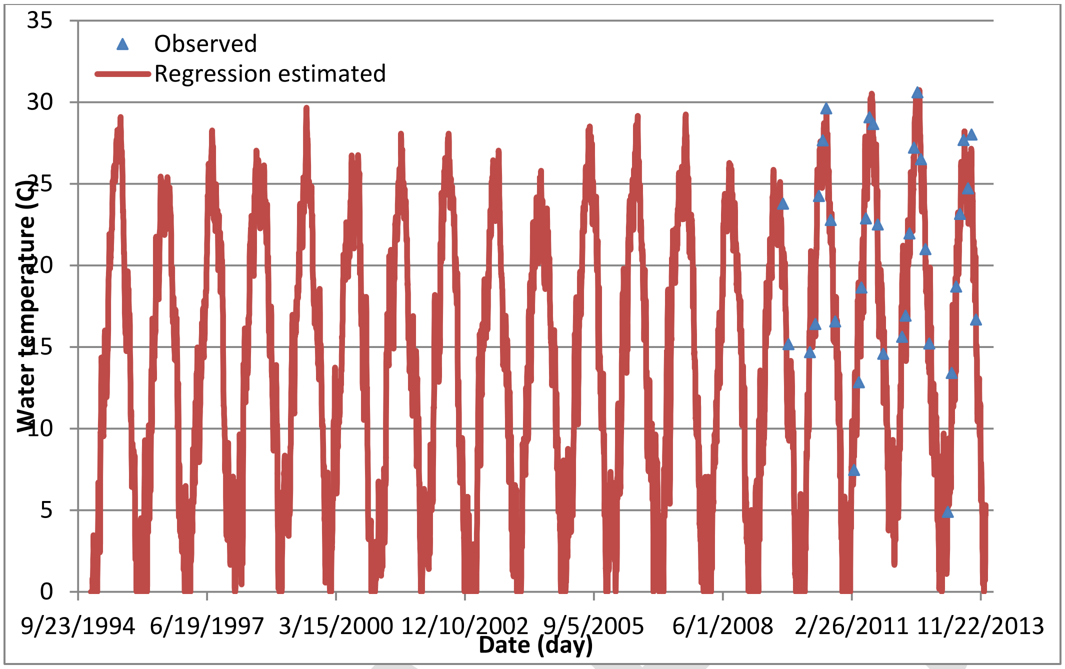

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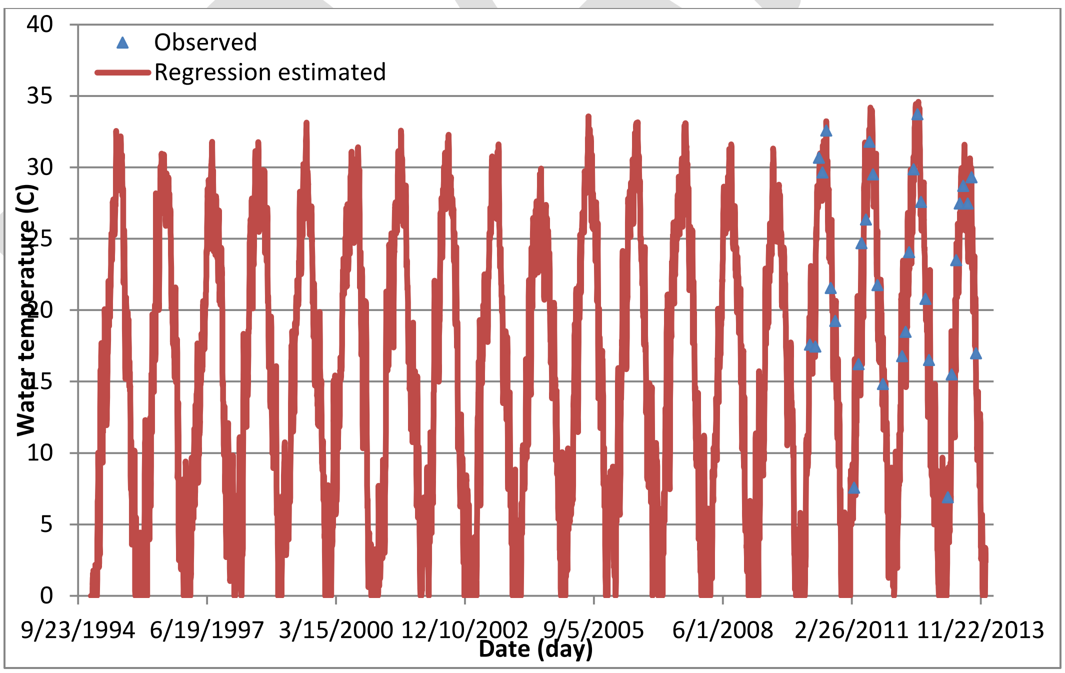

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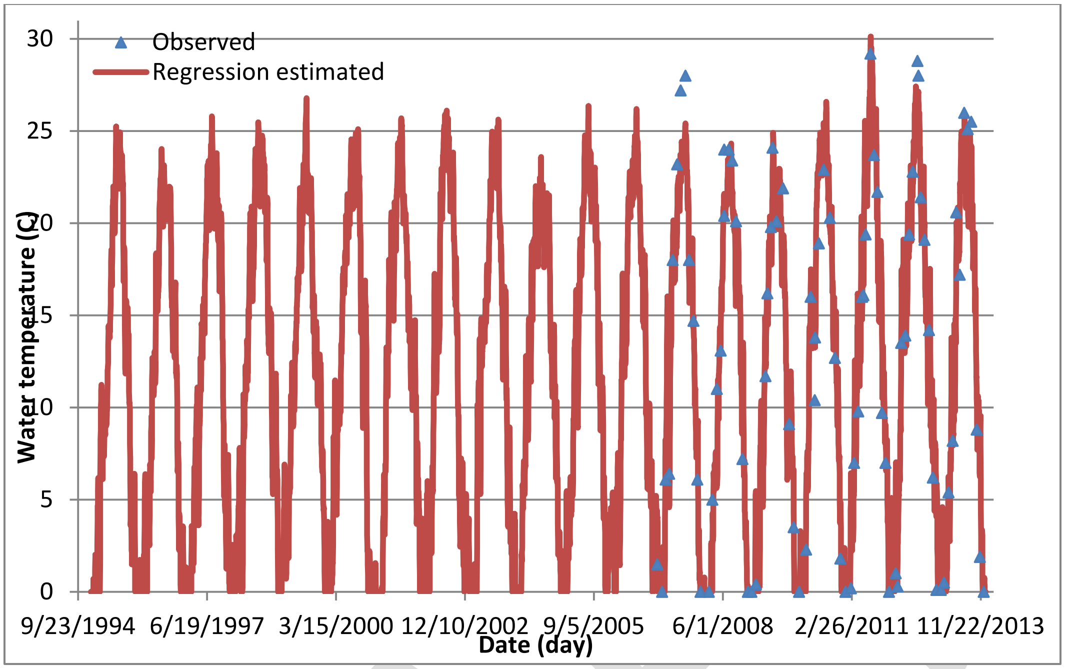

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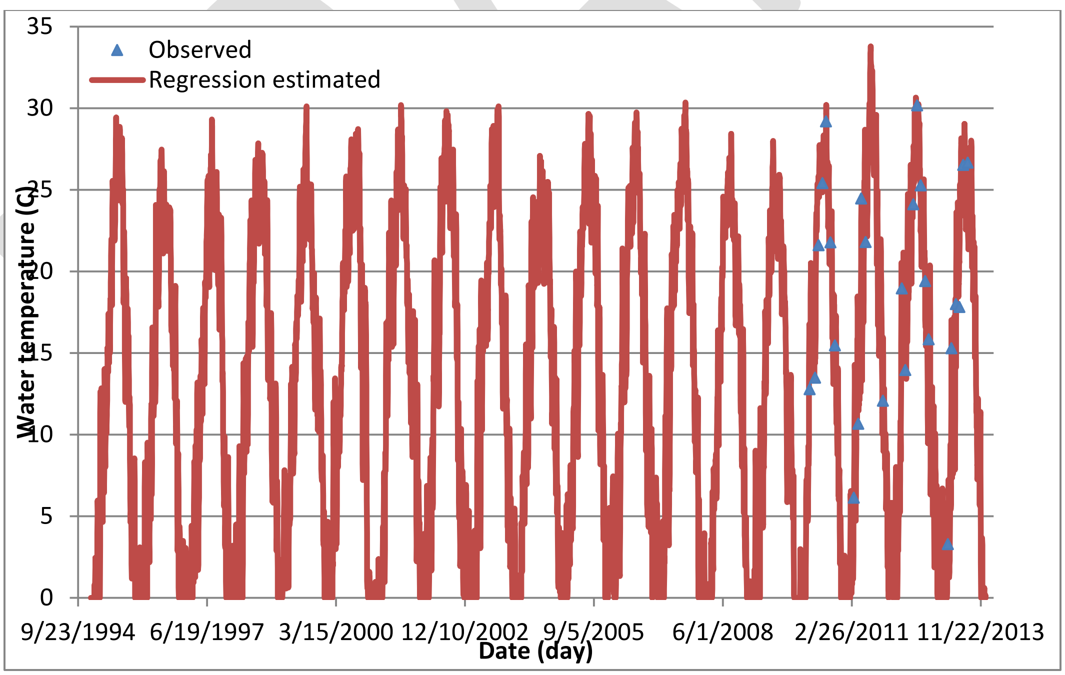

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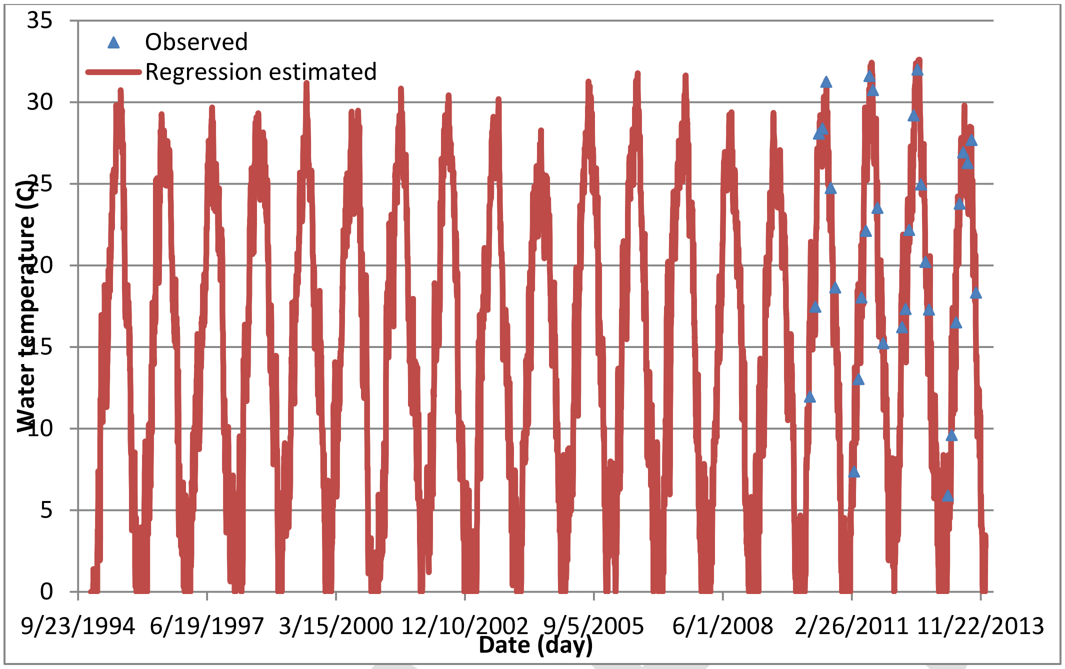

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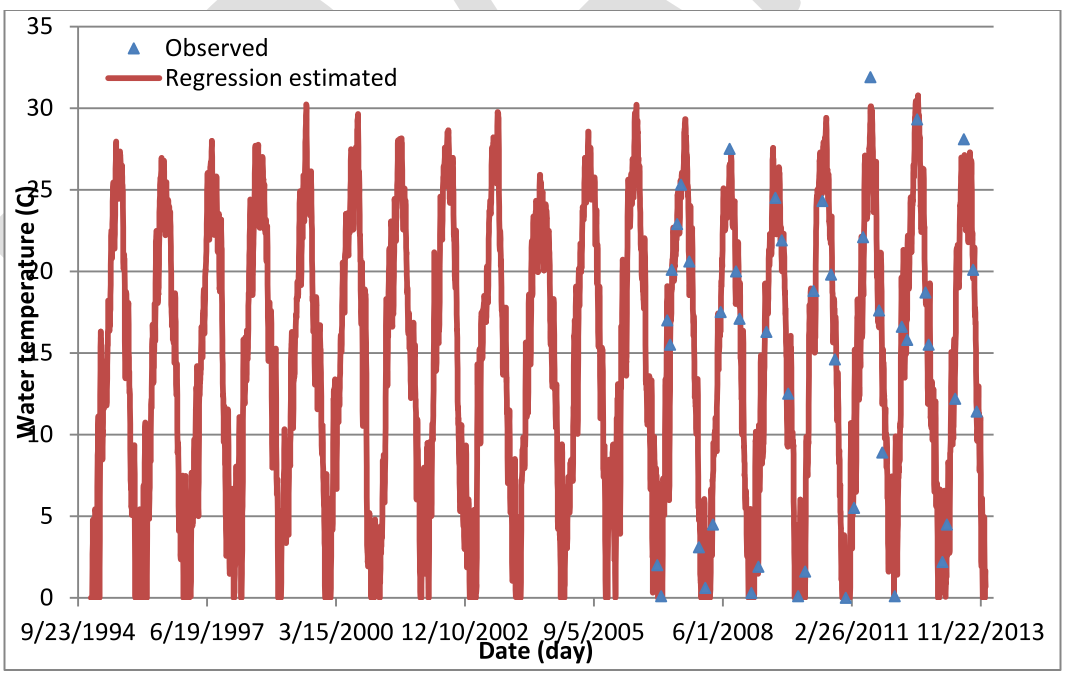

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14. ABSTRACT

This report describes the HEC-RAS water temperature model development and calibration 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. The water temperature model results conducted for the baseline and management alternative scenarios are presented along the Missouri River. The sources of model uncertainty are discussed in the report. The HEC-RAS hydraulic models for five Missouri River reaches were developed and calibrated by USACE Omaha and Kansas City Districts. These models were further expanded to simulate the water temperature along the Missouri River. The HEC-RAS water temperature models were set up and preliminarily calibrated with limited observed data to simulate current conditions of water temperature along the Missouri River, with the intention of running management scenarios to compare alternatives in support of developing the Missouri River recovery management plans and environmental impact statement.

15. SUBJECT TERMS

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Missouri River
Management plans
Environmental impact statement

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