Modeling Water Temperature in Nemote Creek

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4/3/2014	3.0	Addressed U.S. EPA comments
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Acronyms and Abbreviations

AME	absolute mean error
EPA	U.S. Environmental Protection Agency
DEQ	Montana Department of Environmental Quality
QUAL2K	River and Stream Water Quality Model
REL	relative error
TMDL	total maximum daily load
USGS	U.S. Geological Survey (U.S. Department of the Interior)
WRCC	Western Regional Climate Center

Units of Measure

°F	degrees Fahrenheit
cfs	cubic feet per second
g/cm^3	grams per cubic centimeter
MSL	mean sea level
RM	river mile

Executive Summary

Nemote Creek was identified by the Montana Department of Environmental Quality (DEQ) as being impaired due to elevated water temperatures. The causes of impairment are attributed to dredge mining and flow alterations from water diversions (DEQ 2012). The U.S. Environmental Protection Agency contracted with Tetra Tech to develop a QUAL2K water quality model to investigate the relationship between flow, shade, and in-stream water temperature.

Field studies were carried out in 2011 to support water quality model development for the project. A QUAL2K water quality model was then developed for Nemote Creek to evaluate management practices suitable for meeting state temperature standards. The QUAL2K model was constructed, in part, using field collected data from the summer of 2011. Shadev3.0 models were also developed to assess shade conditions using previously collected field data. The calibrated and validated QUAL2K model met previously designated acceptance criteria. Once developed, various water temperature responses were evaluated for a range of potential watershed management activities. Four scenarios were considered:

- **Scenario 1:** Baseline condition (i.e., critical low-flow and critical weather).
- **Scenario 2:** Baseline with a 15 percent reduction of water withdrawals.
- **Scenario 3:** Baseline with improved riparian vegetation by applying the shading from the reference segment (river miles 1.2 to 2.3) to two segments with anthropogenically diminished shade (river miles 0.4 to 0.5 and 2.3 to 5.1).
- **Scenario 4:** An improved flow and shade scenario with improved shade based upon a reference segment and a 15 percent reduction of water withdrawals (i.e., the combination of scenarios 2 and 3).

In comparison to the baseline condition (scenario 1), results ranged from little to no change in water temperature (scenario 2) to considerable temperature reductions (scenarios 3 and 4). The improved flow and shade scenario (scenario 4), which combined the potential benefits associated with a 15 percent reduction in water withdrawals (scenario 2) with improved shading along two segments with anthropogenically diminished shade (scenario 3) to represent application of conservation practices, resulted in overall reductions along the lower five miles of the stream that ranged from 0.8° F to 8.6° F. Generally, small changes in shade or inflow had minimal effects on water temperature while large increases in shade had a considerable effect on water temperature.

1 Introduction

Tetra Tech, Inc. is under contract with the U.S. Environmental Protection Agency (EPA) to set up, calibrate, and run a temperature model (QUAL2K) for Nemote Creek in support of future total maximum daily load (TMDL) development by the Montana Department of Environmental Quality (DEQ). Background information is provided in the following section (**Section 2**). A summary of model set up, calibration, and validation is provided in **Section 3** and a series of model scenarios and results are presented in **Section 4**.

2 Background

This section presents background information to support QUAL2K model development.

2.1 Problem Statement

Nemote Creek (MT76M002_160) is west of the Rocky Mountains in western Montana and is part of the Middle Clark Fork Tributaries TMDL Planning Area and the Lower Clark Fork 8-digit HUC (17010204). The impaired segment is 10.38 miles long and extends from the headwaters of Nemote Creek to its mouth on the Clark Fork River (DEQ 2012) (**Figure 1**).

Nemote Creek has a B-1 use class and is in partial support of its Aquatic Life and Primary Contact Recreation designated uses (DEQ 2012). Six potential causes of impairment are identified in the assessment record (DEQ 2012), including water temperature, the subject of this memorandum. According to DEQ's assessment record (DEQ 2012), the potential sources of the water temperature impairment are dredge mining and flow alterations from water diversions. "Nemote Creek is a FWP *Dewatering Concern Area*. There is periodic dewatering from river miles 0.0 to 2.0 and chronic dewatering from river mile 2.0 to 6.0" (DEQ 2012, p. 17; zero denoting the most upstream location). During a field assessment, DEQ (2012, p. 17) found that the water temperatures were optimal at a site in the headwaters, which is forested, and were "3° [Celsius] above the upper incipient lethal temperature for westslope cutthroat trout" at a site in the lower reach that was dominated by ranches and hayfields. Nemote Creek runs dry and is limited to interstitial flow in multiple locations in the lower reaches of the segment.

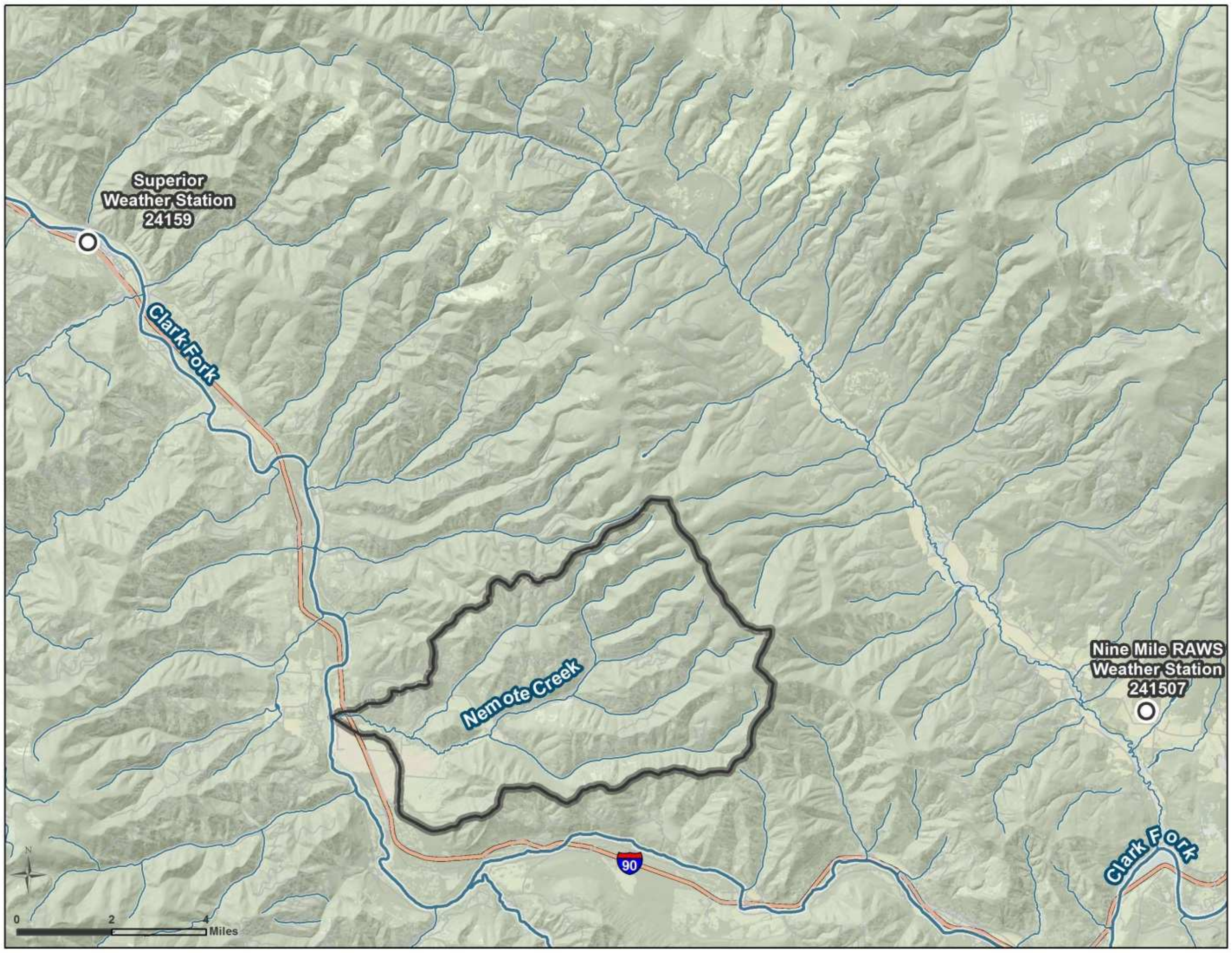


Figure 1. Nemote Creek watershed.

2.2 Montana Temperature Standard

For a waterbody with a use classification of B-1, the following temperature criteria apply:[1]

> A 1° F maximum increase above naturally occurring water temperature is allowed within the range of 32° F to 66° F; within the naturally occurring[2] range of 66° F to 66.5° F, no discharge is allowed [that] will cause the water temperature to exceed 67° F; and where the naturally occurring water temperature is 66.5° F or greater, the maximum allowable increase in water temperature is 0.5° F. A 2° F per-hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55° F. A 2° F maximum decrease below naturally occurring water temperature is allowed within the range of 55° F to 32° F.

The model results will ultimately be compared to these criteria.

2.3 Project History

Tetra Tech was contracted by EPA in February 2011 to develop the QUAL2K temperature model. Temperature and flow data were collected in Nemote Creek in 2011 by Atkins (Helena, MT; under contract with Tetra Tech). A field team from Atkins collected data on July 12-13 and September 14-15, 2011 to characterize flow and shade in support of the modeling effort.

2.4 Factors Potentially Influencing Stream Temperature

Stream temperature regimes are influenced by processes that are external to the stream as well as processes that occur within the stream and its associated riparian zone (Poole et al. 2001). Examples of factors external to the stream that can affect in-stream water temperatures include: topographic shade, land use/land cover (e.g., vegetation and the shading it provides, impervious surfaces), solar angle, meteorological conditions (e.g., precipitation, air temperature, cloud cover, relative humidity), groundwater exchange and temperature, and tributary inflow temperatures and volumes. The shape of the channel can also affect the temperature—wide shallow channels are more easily heated and cooled than deep, narrow channels. The amount of water in the stream is another factor influencing stream temperature regimes. Streams that carry large amounts of water resist heating and cooling, whereas temperature in small streams (or reduced flows) can be changed more easily.

The following additional factors that may have an influence on stream temperatures in Nemote Creek were evaluated prior to model development and are discussed in detail in **Appendix A**:

[1] ARM 17.30.623(e).

[2] ARM 17.30.602(17): "Naturally occurring" means conditions or material present from runoff or percolation over which man has no control or from developed land where all reasonable land, soil and water conservation practices have been applied. Conditions resulting from the reasonable operation of dams in existence as of July 1, 1971, are natural.

- Local/regional climate
- Land ownership
- Land use
- Riparian vegetation
- Shade
- Hydrology
- Point sources

2.5 Observed Stream Temperatures

EPA (and their consultants Tetra Tech and Atkins, as described above) collected stream temperature data using in-stream loggers at eight locations in the Nemote Creek watershed. The dataset is presented and discussed in the following sections.

2.5.1 Available Temperature Data

In 2011, Atkins deployed continuous temperature data loggers at six locations in Nemote Creek (sites NMTC-T3, NMTC-T4, NMTC-T6, NMTC-T7, NMTC-T9, and NMTC-T10) and at two tributary locations (NMTC-T5 and NMTC-T8) (**Figure 2)**. Data loggers recorded temperatures every one-half hour for approximately two months between July 12-13 and September 14-15. Instantaneous temperatures were also monitored by Atkins and DEQ (**Appendix A**).

Atkins and Tetra Tech identified periods of partial and full exposure to ambient air at the following three loggers: NMTC-T3, NMTC-T5, and NMTC-T6. Based upon Atkins field notes and photographs, the following general conclusions can be drawn:

- **NMTC-T3:** Atkins reported that logger NMTC-T3 in Nemote Creek was exposed to air (in culvert) at retrieval. Site photographs at logger retrieval show logger NMTC-T3 to be partially submerged and partially exposed to ambient air in a wet, shallow, flowing channel. Thus, it is assumed that the logger was partially exposed to ambient air while in a shallow flowing channel during the latter portion of the summer season.
- **NMTC-T5:** Atkins reported that there was a spike in daily maximum temperature at logger NMTC-T5 in South Fork Nemote Creek from July 25, 2011 through August 15, 2011 and from August 21, 2011 to August 30, 2011. Atkins also reported that the logger was retrieved from a dry stream channel. Site photographs at retrieval show logger NMTC-T5 to be fully submerged in an isolated pool. The photographs show no surficial flow in the stream channel. Thus, it is assumed that the logger was fully submerged in an isolated pool within a dry channel without surficial flow during the latter portion of the summer season.
- **NMTC-T6:** Atkins reported that (1) from August 20, 2011 to September 2, 2011 logger NMTC-T6 in Nemote Creekmay have been in pooled water, (2) from September 3, 2011 to September 14, 2001 it was likely in a dry channel, and (3) logger NMTC-T6 was retrieved from a dry channel. Site photographs at retrieval show logger NMTC-T6 fully exposed to ambient air in a dry channel. Thus, it is assumed that the logger was partially or fully exposed to ambient air during much of the summer season.

Footnotes on the figures and tables in this section identify which data were used to develop the figures and tables.

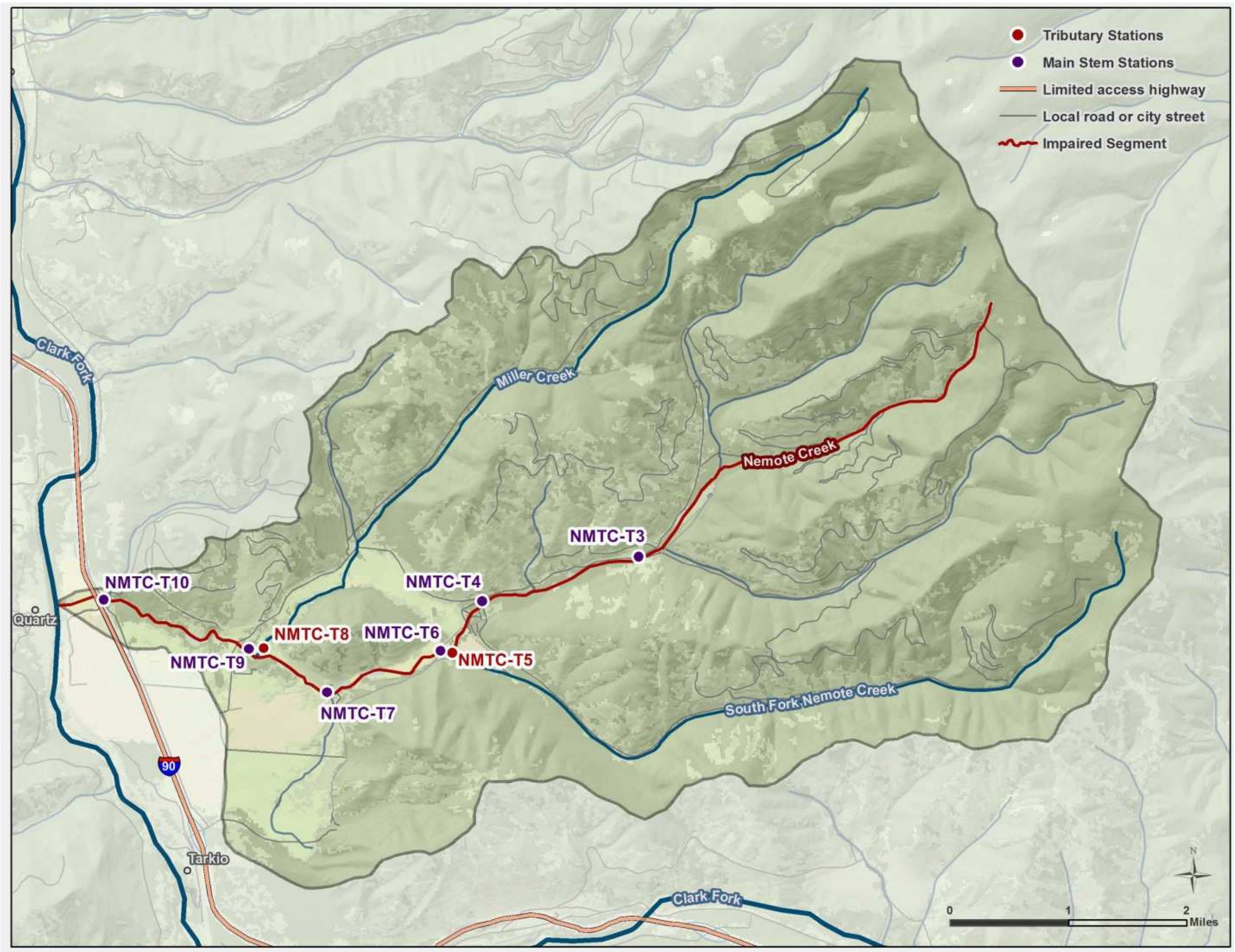
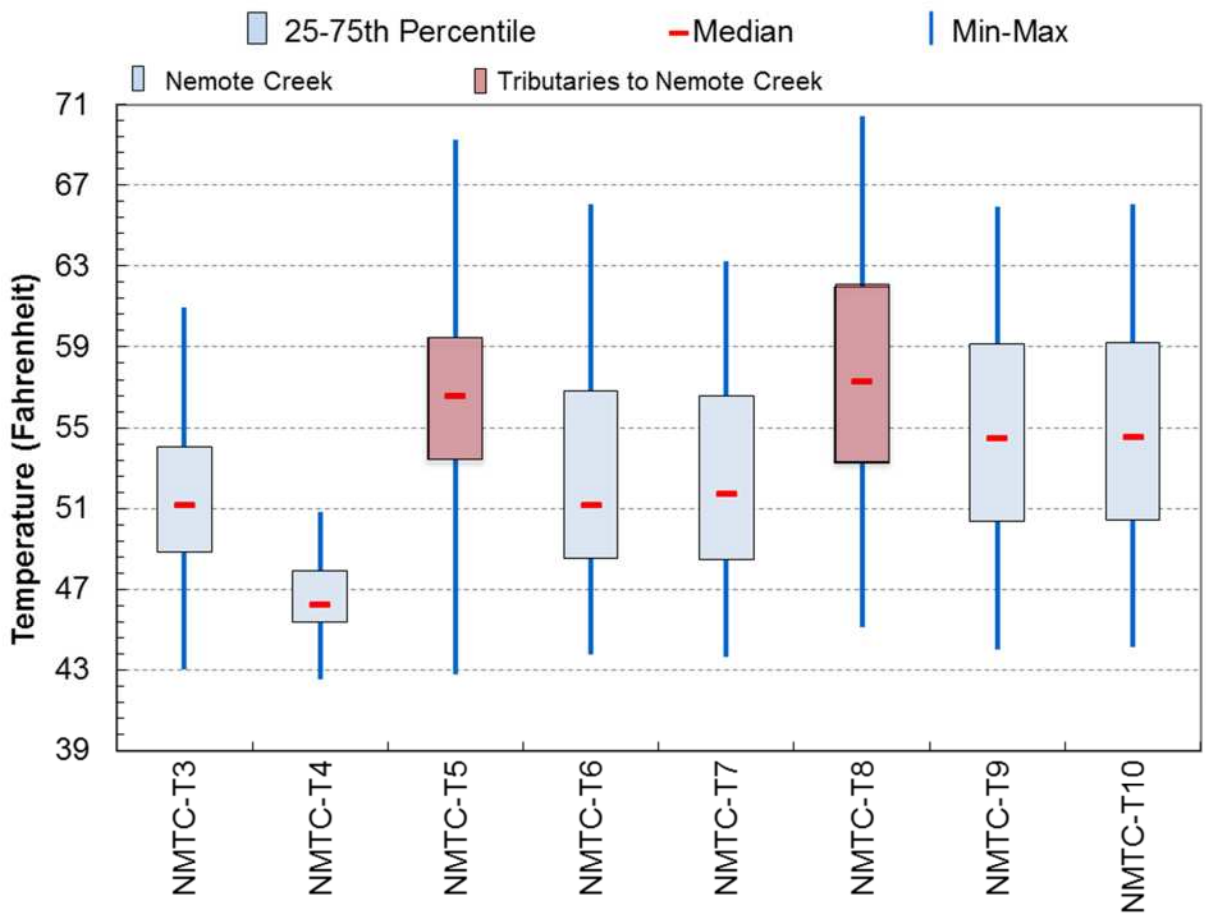


Figure 2. Temperature loggers in the Nemote Creek watershed.

2.5.2 Temperature Data Analysis

No temperatures trends within Nemote Creek are readily apparent, as can be seen in **Figure 3**. There is a considerable temperature decrease between the two uppermost sites (NMTC-T3 and NMTC-T4). There is one unnamed tributary that joins with Nemote Creek between these two sites. Further downstream, South Fork Nemote Creek is relatively warm (median value of 56.8° F), and the median temperature of the main stem increases from 46.3° F to 51.1° F after it joins. The middle section of the stream (corresponding to sites NMTC-T6 and NMTC-T7) appear to be relatively stable. Similar to South Fork Nemote Creek, the warmer waters of Miller Creek (median value of 57.3° F) may be associated with an increasing main stem temperature (rising from 51.7° F to 54.5° F between NMTC-T7 and NMTC-T9). Seasonal maximum temperatures vary more than the seasonal median temperatures, decreasing between each consecutive pair of main stem sites, but generally increasing downstream. The highest temperature recorded was from Miller Creek, at 70.9° F, considerably higher than the maximum main stem temperature of 66.1° F.



Notes

Logger NMTC-T3 in Nemote Creek was exposed to ambient air while in a shallow flowing channel during the latter portion of the summer season. All data for the period of record were included in this figure.

Logger NMTC-T5 in South Fork Nemote Creek was fully submerged in an isolated pool within a dry channel without surficial flow during the latter portion of the summer season. All data for the period of record were included in this figure.

Logger NMTC-T6 in Nemote Creek was partially or fully exposed to ambient air during much of the summer season. Data presented in this figure were limited to the subset of temperatures from July 13, 2011 through August 19, 2011.

Figure 3. Box-and-whisker plots of temperature data, July 12-13, 2011 to September 14-15, 2011.

Daily maximum recorded temperatures in Nemote Creek are summarized in **Table 1** and shown in **Figure 4.** In 2011, the warmest temperatures occurred at different times during the summer; three sites experienced the warmest daily maximum temperatures on July 18, 2011. The warmest weeks varied from early-July through mid-August.

Daily maximum recorded temperatures in Nemote Creek are summarized in **Table 1** and shown in **Figure 4**. In 2011, the warmest in-stream temperatures in Nemote Creek were generally detected on July 18 and August 27. The warmest weeks were generally the last week of July/first week of August and the last week of August. Generally, loggers in the upper segments of Nemote Creek detected cooler temperatures and smaller diurnal ranges than loggers in the middle and lower segments of Nemote Creek (**Figure 5**).

Table 1. Maximum and maximum weekly maximum temperatures in Nemote Creek, 2011

Temperature logger site	Maximum temperatures [a]		Maximum weekly maximum temperature [b]	
	Temperature (°F)	Date	Temperature (°F)	Date
NMTC-T3[c]	61.0	Aug 27	59.7	Aug 24-30
NMTC-T4	50.8	Aug 27	50.5	Aug 21-27
NMTC-T5[d]	69.3	Aug 25	66.9	August 23-29
NMTC-T6[e]	66.1	Aug 3	64.3	Jul 28 - Aug 3
NMTC-T7	63.2	July 18	61.6	Jul 28 - Aug 3
NMTC-T8[f]	70.4	July 31	68.8	Jul 29 - Aug 4
NMTC-T9	65.9	July 18	64.6	Aug 22-28
NMTC-T10	65.7	July 18	63.9	Jul 29 - Aug 4

Notes

a. Maximum temperature is the maximum of recorded one-half hourly temperatures.

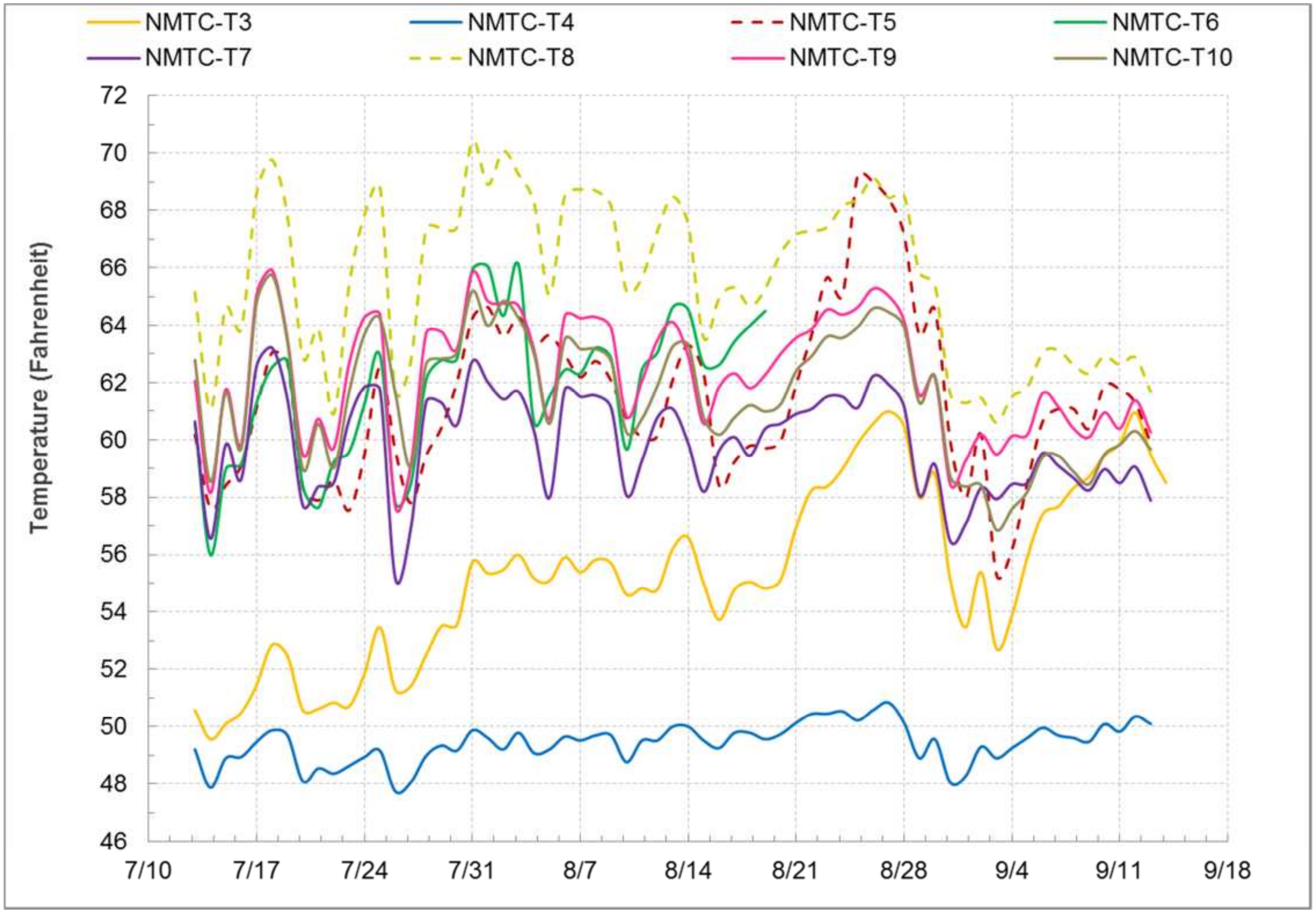
b. Maximum weekly maximum temperature is the mean of daily maximum water temperatures measured over the warmest consecutive seven-day period.

c. Logger NMTC-T3 in Nemote Creek was exposed to ambient air while in a shallow flowing channel during the latter portion of the summer season. All data for the period of record were included in this table.

d. Logger NMTC-T5 in South Fork Nemote Creek was fully submerged in an isolated pool within a dry channel without surficial flow during the latter portion of the summer season. All data for the period of record were included in this table.

e. Logger NMTC-T6 in Nemote Creek was partially or fully exposed to ambient air during much of the summer season. Data presented in this figure were limited to the subset of temperatures from July 13, 2011 through August 19, 2011.

f. Site is located on Miller Creek, a tributary to Nemote Creek.



Notes

Logger NMTC-T3 in Nemote Creek was exposed to ambient air while in a shallow flowing channel during the latter portion of the summer season. All data for the period of record were included in this figure.

Logger NMTC-T5 in South Fork Nemote Creek was fully submerged in an isolated pool within a dry channel without surficial flow during the latter portion of the summer season. All data for the period of record were included in this figure.

Logger NMTC-T6 in Nemote Creek was partially or fully exposed to ambient air during much of the summer season. Data presented in this figure were limited to the subset of temperatures from July 13, 2011 through August 19, 2011.

Figure 4. Daily maximum temperatures along Nemote Creek, July 12-13 to September 14-15, 2011.

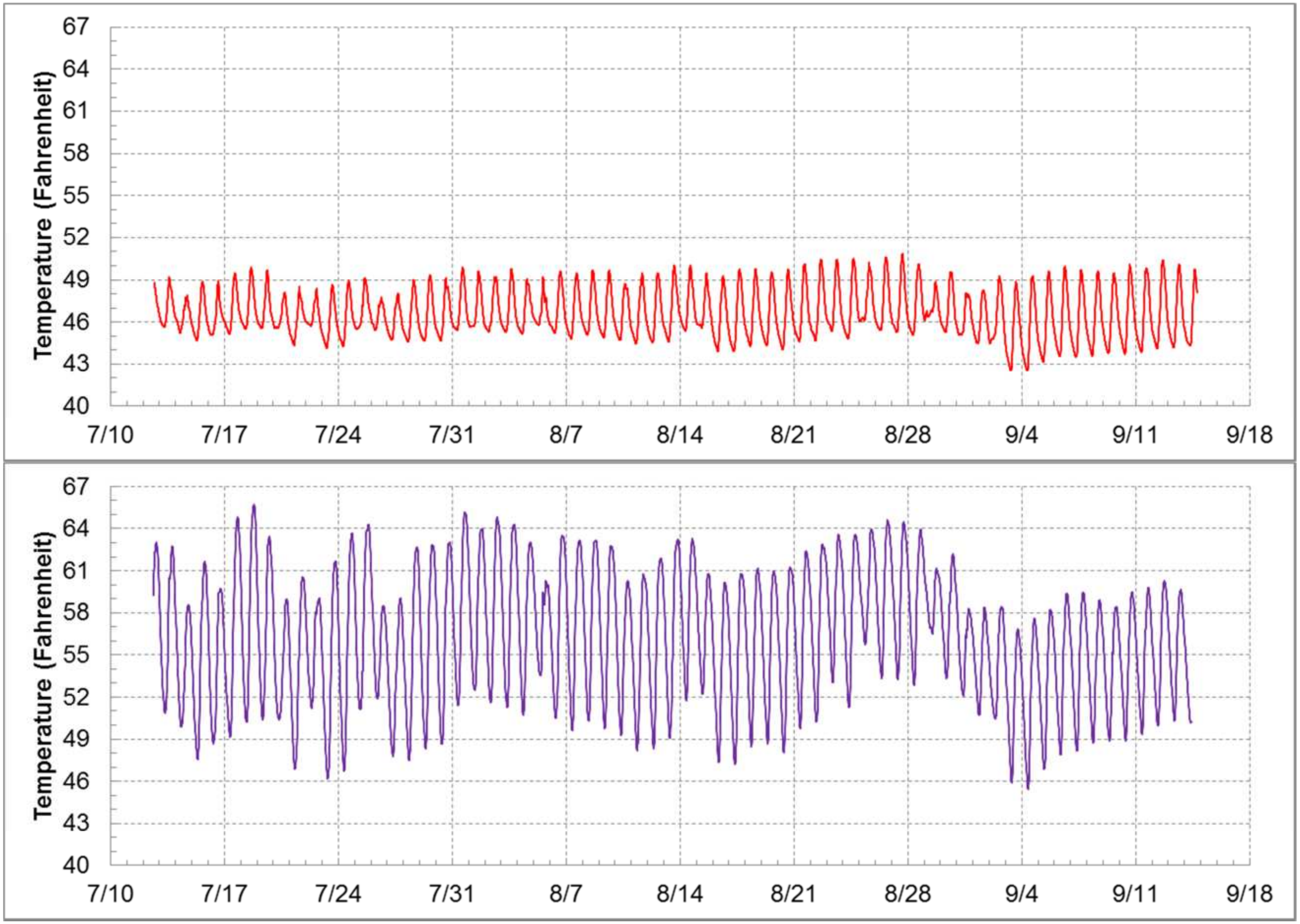


Figure 5. Continuous temperature at logger NMTC-T4 (top) and NMTC-T10 (bottom), July 13 to September 15, 2011.

3 QUAL2K Model Development

EPA and DEQ selected the QUAL2K model to simulate temperatures in Nemote Creek. QUAL2K is supported by EPA and has been used extensively for TMDL development and point source permitting across the country. The QUAL2K model is suitable for simulating water temperatures of small rivers and creeks. It is a one-dimensional uniform flow model with the assumption of a completely mixed system for each computational cell. QUAL2K assumes that the major pollutant transport mechanisms, advection and dispersion, are significant only along the longitudinal direction of flow. The heat budget and temperature are simulated as a function of meteorology on a diel time scale. Heat and mass inputs though point and nonpoint sources are also simulated. The model allows for multiple waste discharges, water withdrawals, nonpoint source loading, tributary flows, and incremental inflows and outflows. QUAL2K also simulates in-stream temperatures via a heat balance that accounts "for heat transfers from adjacent elements, loads, withdrawals, the atmosphere, and the sediments" (Chapra et al. 2008, p. 19).

The current release of QUAL2K is version 2.11b8 (January 2009). The model is publicly available at http://www.epa.gov/athens/wwqtsc/html/QUAL2K.html. Additional information regarding QUAL2K is presented in the *Quality Assurance Project Plan for Montana TMDL Support: Temperature Modeling* (Tetra Tech 2012).

The following sections describe the process that was used to setup, calibrate, and validate the QUAL2K models for Nemote Creek.

3.1 Model Framework

The QUAL2K model (Chapra et al. 2008) was selected for modeling Nemote Creek. The modeling domain included the stream at logger NMTC-T3 down to the confluence with the Clark Fork River just below NMTC-T10 (refer back to **Figure 2** for a map of the Nemote Creek watershed with logger locations).

Data were specifically collected to support the QUAL2K model for the Nemote Creek. Flow, shade, and continuous temperature were acquired during July 12 to September 15, 2011. In addition flow and temperature data were also collected at two major tributaries to Nemote Creek.

3.2 Model Configuration and Setup

Model configuration involved setting up the model computational grid and setting initial conditions, boundary conditions, and hydraulic and light and heat parameters. All inputs were longitudinally referenced, allowing spatial and continuous inputs to apply to certain zones or specific stream segments. This section describes the configuration and key components of the model.

3.2.1 Modeling Time Period

The calibration and validation steady-state model periods were July 14, 2011 and September 13, 2011. These dates were selected since they had the most complete datasets that could be used for model setup and calibration/validation.

Calibration Period: The calibration period was July 14, 2011, which is associated with logger deployment flow monitoring; flow was monitored at all Atkins logger sites on Nemote Creek and its major tributaries on July 12 and 13, 2011. The first full day of temperature data for all the EPA loggers was July 14, 2011. Flows monitored on July 12-13 were assumed to be representative of flow conditions on July 14, 2011 as no precipitation was recorded July 12-14, 2011. In addition July 14, 2011 also represented critical hot summer period conditions.

Validation Period: The validation period was September 13, 2011 which was associated with logger retrieval; flow was monitored and the Atkins loggers were retrieved on September 14-15, 2012. The last full day of temperature data for all EPA loggers was September 13, 2011. Flows monitored on September 14-15, 2011 were assumed to be representative of flow conditions on September 13, 2011 as no precipitation was recorded September 13-15, 2011.

3.2.2 Segmentation

Segmentation refers to discretization of a waterbody into smaller computational units (e.g., reaches and elements). Segmentation into reaches allows for representation of stretches of the stream that have constant hydraulic characteristics (e.g. slope, bottom width). Each reach is further divided into elements that are the fundamental computational units in QUAL2K. The Nemote Creek main stem was segmented into 38 reaches with lengths 984 feet (0.30 kilometer). The reach lengths were sufficient to incorporate any point inputs to the waterbody. Two major tributaries were represented through boundary condition designation (see **Section 3.2.4** for a discussion of boundary conditions and **Appendix A** for a discussion of the shade model).

3.2.3 Streamflow and Hydraulics

The flow rates were estimated through flow mass balance calculations at the loggers where flows were monitored. The rating curve method was used to relate the depth and the velocity to the flow rate in a reach. This method requires specification of the empirical coefficients and exponents based on numerous measurements of depths, velocities, and flows. Due to the limited amount of field data, coefficients of the rating curve were treated to be the calibration parameters against the observed depths and velocities.

Typical exponents for velocity (0.43) and depth (0.45) are described in the QUAL2K manual (Chapra et al. 2008). Exponents were also calculated for three nearby USGS gages (**Table 2**) of similar size to Nemote Creek, which is 37 square miles. In the Nemote Creek QUAL2K model, exponents were set to the averages calculated from the three USGS gages: 0.55 for velocity and 0.32 for depth.

Table 2. Calculated exponents for nearby USGS gages

Gage ID	Gage name	Drainage area (square miles)	Exponents	
			Velocity	Depth
12388400	Revais Creek below West Fork near Dixon, MT	24	0.58	0.27
12387450	Valley Creek near Arlee, MT	16	0.54	0.38
12377150	Mission Creek above reservoir near St. Ignatius, MT	12	0.52	0.30

3.2.4 Boundary Conditions

Boundary conditions represent external contributions to the waterbody being modeled. A flow and temperature input file was configured for inputs to Nemote Creek. Boundary conditions were specified at the upstream terminus of Nemote Creek model domain (i.e., logger NMTC-T3), for each of the two major tributaries' confluences with Nemote Creek, and for diffuse sources along the creek. These are further discussed in the following sections.

3.2.4.1 Headwater (Upstream) Boundary

QUAL2K requires specification of the headwater flow and temperature. Headwater flow (July 12, 2011) and diurnal temperature (July 14, 2011) at the upstream boundary were specified using observed data from the in-stream logger at site NMTC-T3 for the calibration period. A flow of 5.83 cubic feet per second (cfs) was specified for the calibration period. Note that flow for July 14, 2013 was not available and observed flow from July 12, 2011 was used.

Headwater flow (September 13, 2011; 0.19 cfs) and diurnal temperature (September 15, 2011) at the upstream boundary were specified for the boundary conditions based on the data available at site NMTC-T1 for the validation period too. **Figure 6** shows the headwater temperatures specified in the model.

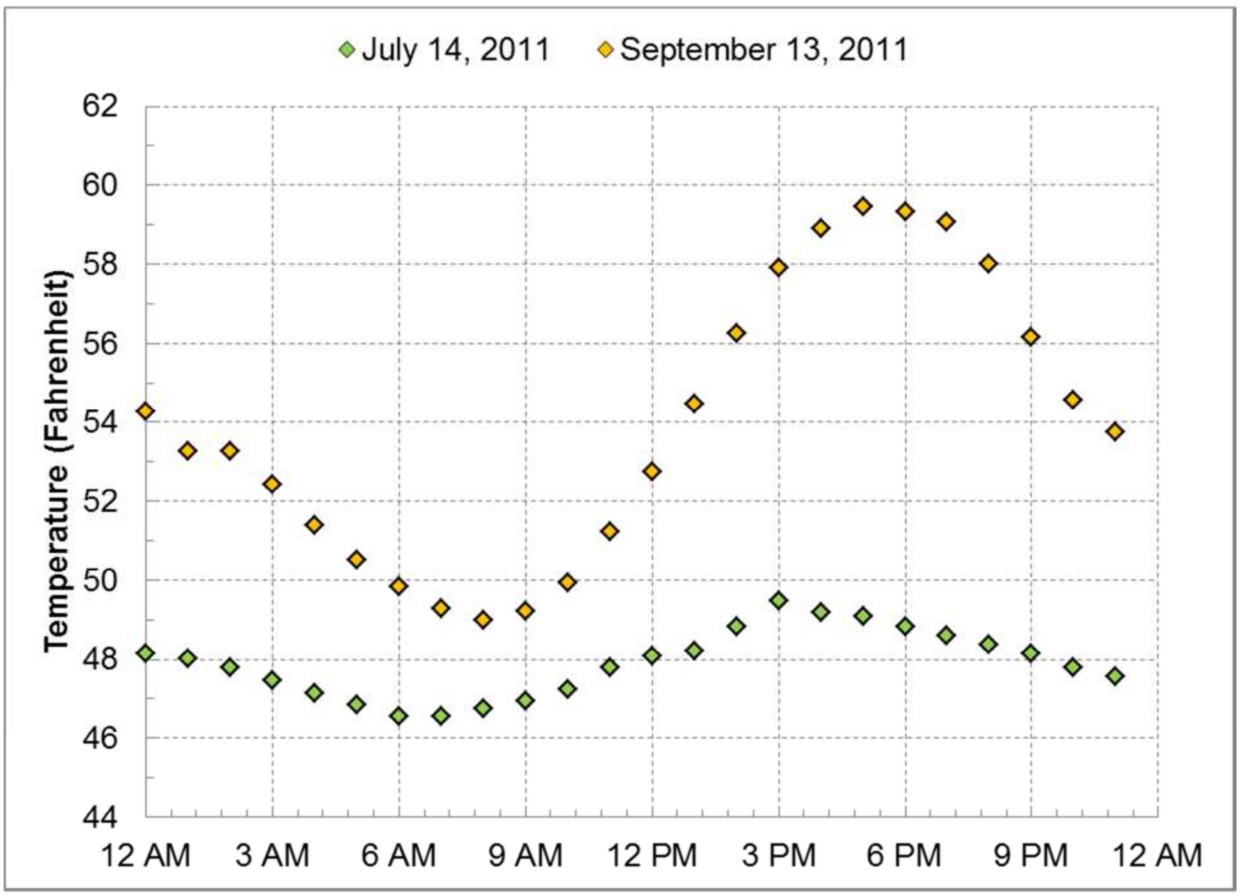


Figure 6. Diurnal temperature at the headwaters input to Nemote Creek.

3.2.4.2 Tributary Inputs

There are many small tributaries in the watershed; however, monitoring data were available for only two major tributaries feeding into Nemote Creek – South Fork Nemote Creek (NMTC-T5) and Miller Creek (NMTC-T6) (refer back to **Figure 2** for a map of the logger locations). **Table 3** and **Table 4** show the flow and temperature assigned to the tributaries in the model.

In addition to tributary inputs, irrigation withdrawals from Nemote Creek were also identified (see **Appendix A** for a discussion of these withdrawals) and assigned in the model; additional withdrawals in the watershed (e.g., groundwater) were excluded from the model as they were outside of the model domain. Information on withdrawal rates or whether withdrawal is occurring during the calibration and validation dates was not readily available. Net irrigation requirements to irrigate the fields were queried from the Montana Natural Resource Information System for the months of July and September, which were 5.5 and 2.6 inches per month, respectively. A maximum daily flow rate was estimated using the net irrigation requirements and the maximum area irrigated (a total of 312 acres[3]). It was calculated that up to 2.33 cfs and 1.10 cfs may be withdrawn from Nemote Creek on a daily basis in the months of July and September. Most of the irrigation withdrawals were used in the model (rows identified as *irrigation withdrawal* in **Table 3** and **Table 4)**, where irrigation withdrawals sum to 2.24 cfs on July 14, 2011 and to 0.78 cfs on September 13, 2011. One irrigation withdrawal is upstream of logger NMTC-T3 and thus outside of the model domain. Additionally, many irrigation withdrawals were set to zero during the simulation of September 13, 2011 because there was insufficient water in Nemote Creek to fulfill the water rights. More information on the irrigation withdrawals can be found in **Appendix A**.

[3] The 312 acres of irrigated land was calculated using the "places of use" data associated with the "points of diversion" data available from the Natural Resources Information System (http://nris.mt.gov/gis/gisdatalib/gisDataList.aspx).

Table 3. QUAL2K model flow and temperature inputs to Nemote Creek - Tributaries and withdrawal for the calibration period (July 14, 2011)

Description	Location (RM)	Point sources [a] Abstraction (cfs)	Point sources [a] Inflow (cfs)	Temperature [b] Daily mean (°F)	Temperature [b] ½ daily range (°F)	Temperature [b] Time of maximum (hour)
irrigation withdrawal	6.24	0.27	--	--	--	--
irrigation withdrawal	6.16	0	--	--	--	--
irrigation withdrawal	5.69	0	--	--	--	--
irrigation withdrawal	5.21	0.15	--	--	--	--
irrigation withdrawal	5.06	0.15	--	--	--	--
irrigation withdrawal	4.76	0.15	--	--	--	--
South Fork Nemote Creek	4.37	--	1.53	55.8	2.2	5:30 PM
irrigation withdrawal	4.37	0.15	--	--	--	--
Miller Creek	2.00	--	2.03	55.7	5.1	5:30 PM
irrigation withdrawal	1.99	0.05	--	--	--	--
irrigation withdrawal	1.04	0.22	--	--	--	--
irrigation withdrawal	0.89	0.22	--	--	--	--
irrigation withdrawal	0.52	0	--	--	--	--
irrigation withdrawal	0.31	0.82	--	--	--	--
irrigation withdrawal	0.26	0.06	--	--	--	--
irrigation withdrawal	0.19	0	--	--	--	--

Notes

°F = degrees Fahrenheit; cfs = cubic feet per second; RM = river mile.

a. Point sources are simulated at specific points (versus diffuse sources that are simulated uniformly along a segment). Each point source can be an abstraction or an inflow.

b. The daily mean temperature, one-half of the daily range of temperatures across the model period, and time of the maximum hourly temperature are only applicable to point source inflows.

Table 4. QUAL2K model flow and temperature inputs to Nemote Creek - Tributaries and withdrawal for the validation period (September 13, 2011)

Description	Location (RM)	Point sources [a] Abstraction (cfs)	Point sources [a] Inflow (cfs)	Temperature [b] Daily mean (°F)	Temperature [b] ½ daily range (°F)	Temperature [b] Time of maximum (hour)
irrigation withdrawal	6.24	0.13	--	--	--	--
irrigation withdrawal	6.16	0	--	--	--	--
irrigation withdrawal	5.69	0	--	--	--	--
[model outflow] [c]	5.26	0.92	--	--	--	--
irrigation withdrawal	5.21	0	--	--	--	--
irrigation withdrawal	5.06	0	--	--	--	--
irrigation withdrawal	4.76	0	--	--	--	--
South Fork Nemote Creek	4.37	--	0	--	--	--
irrigation withdrawal	4.37	0	--	--	--	--
[model inflow] [c]	3.48	--	1.91	52.2	5.5	5:00 PM
Miller Creek	2.00	--	0.54	56.4	5.5	7:00 PM
irrigation withdrawal	1.99	0.03	--	--	--	--
irrigation withdrawal	1.04	0.10	--	--	--	--
irrigation withdrawal	0.89	0.10	--	--	--	--
irrigation withdrawal	0.52	0	--	--	--	--
irrigation withdrawal	0.31	0	--	--	--	--
irrigation withdrawal	0.26	0.39	--	--	--	--
irrigation withdrawal	0.19	0.03	--	--	--	--

Notes
°F = degrees Fahrenheit; cfs = cubic feet per second; RM = river mile.
a. Point sources are simulated at specific points (versus diffuse sources that are simulated uniformly along a segment). Each point source can be an abstraction or an inflow.
b. The daily mean temperature, one-half of the daily range of temperatures across the model period, and time of the maximum hourly temperature are only applicable to point source inflows.
c. The dry segment of Nemote Creek was simulated by removing and then returning the flow via artificial groundwater point sources.
d. The diurnal conditions of NMTC-T7 were used to calculate the artificial groundwater inflow at the bottom of the dry segment.

3.2.4.3 Diffuse Sources

Groundwater and other sources of water not accounted as point sources can be specified along the length of the waterbody using the *Diffuse Sources* worksheet in the QUAL2K model. A flow balance was constructed using the observed flows along Nemote Creek and the observed tributary flows, and the amount of diffuse flow along Nemote Creek was calculated for the days when flow was available on July 12-13, 2011 and September 14-15, 2011 (**Table 5**).

The diffuse inflow temperature (49.5° F) was calculated as the average of groundwater wells' temperatures from the Groundwater Information Center (range: 46.0° F to 54.9° F). The same groundwater inflow temperature was used for the calibration and validation.

Table 5. QUAL2K model flow and temperature inputs to Nemote Creek - Diffuse sources

Description	Location [a]		Diffuse Abstraction	Diffuse Inflow	
	Upstream (RM)	Downstream (RM)	(cfs)	Inflow (cfs)	Temp (°F)
August 11, 2012					
From NMTC-T3 to NMTC-T4	6.99	5.37	--	1.82	49.5
From NMTC-T4 to NMTC-T6	5.37	4.73	2.84	--	--
From NMTC-T6 to NMTC-T7	4.73	3.39	--	5.26	49.5
From NMTC-T7 to NMTC-T9	3.39	2.39	--	1.14	49.5
From NMTC-T9 to NMTC-T10	2.39	0.48	0.77	--	--
From NMTC-T10 to mouth	0.47	0.00	--	0.88	49.5
September 20, 2012					
From NMTC-T3 to NMTC-T4	6.99	5.37	--	0.88	49.5
From NMTC-T4 to NMTC-T6 [b]	5.37	4.73	--	--	--
From NMTC-T6 to NMTC-T7	4.73	3.39	--	--	--
From NMTC-T7 to NMTC-T9	3.39	2.39	--	0.58	49.5
From NMTC-T9 to NMTC-T10	2.39	0.48	1.20	--	--
From NMTC-T10 to mouth	0.47	0.00	--	0.42	49.5

Notes
°F = degrees Fahrenheit; cfs = cubic feet per second; RM = river mile.
a. Upstream and downstream termini of segments.
b. Nemote Creek ran dry in a segment between NMTC-T4 and NMTC-T7; no diffuse flow was simulated along this segment.

3.2.5 Meteorological Data

The surface boundary conditions are determined by the meteorological conditions in QUAL2K. The QUAL2K model requires hourly meteorological input for the following parameters: air temperature, dew point temperature, wind speed, and cloud cover. The Nine Mile RAWS is in near proximity to Nemote Creek (**Appendix A**). The Nine Mile RAWS records hourly air temperature, dew point temperature, wind speed and solar radiation, whereas the Superior, Montana weather station (24159 in **Appendix A**) only records hourly air temperature data. The Nine Mile RAWS hourly observed meteorological data were used to develop the QUAL2K model after appropriate unit conversions.

The wind speed measurements at the Nine Mile RAWS were measured at 20 feet (6.10 meters) above the ground. QUAL2K requires that the wind speed be at a height of 7 meters. The wind speed measurements ($U_{w,z}$ in meter/second) taken at a height of 6.10 meters (z_w in meters) were converted to equivalent conditions at a height of z = 7 meters (the appropriate height for input to the evaporative heat loss equation), using the exponential wind law equation suggested in the QUAL2K user's manual:

$$U_w = U_{wz}\left(\frac{z}{z_w}\right)^{0.15}$$

3.2.6 Shade Data

The QUAL2K model allows for spatial and temporal specification of shade, which is the fraction of potential solar radiation that is blocked by topography and vegetation. A shade model was developed and calibrated for the Nemote Creek watershed. The calibrated shade model was first run to simulate shade estimates for July 14, 2011 to simulate hourly shade every 30 meters (the resolution of the shade model) along Nemote Creek. Reach-averaged integrated hourly effective shade results were then computed and were then input into each reach within the QUAL2K model. The overall average daytime shade on July 14, 2011 (75 percent) was less than that predicted on September 13, 2011 (79 percent). A more detailed discussion on the shade modeling can be found under **Appendix A**.

3.3 Model Evaluation Criteria

The goodness of fit for the simulated temperature using the QUAL2K model was summarized using the absolute mean error (AME) and relative error (REL) as a measure of the deviation of model-predicted temperature values from the measured values. These model performance measures were calculated as follows:

$$AME = \frac{1}{N}\sum_{n=1}^{n} |P_n - O_n|$$

$$\mathrm{REL} = \frac{\sum_{n=1}^{n} |P_n - O_n|}{\sum_{n=1}^{n} O_n}$$

These performance measures are detailed later in the section in evaluation of the model calibration and validation.

3.4 Model Calibration and Validation

The time periods selected for calibration and validation were July 14, 2011 and September 13, 2011, respectively. These dates were selected as they had the most comprehensive dataset available for modeling and corresponded to the synoptic study done for Nemote Creek, which included collecting flow, temperature, and shade information.

Flow, depth, velocity and temperature data were available at six locations along the main stem of Nemote Creek. **Table 6** shows the monitoring sites used for calibration and validation.

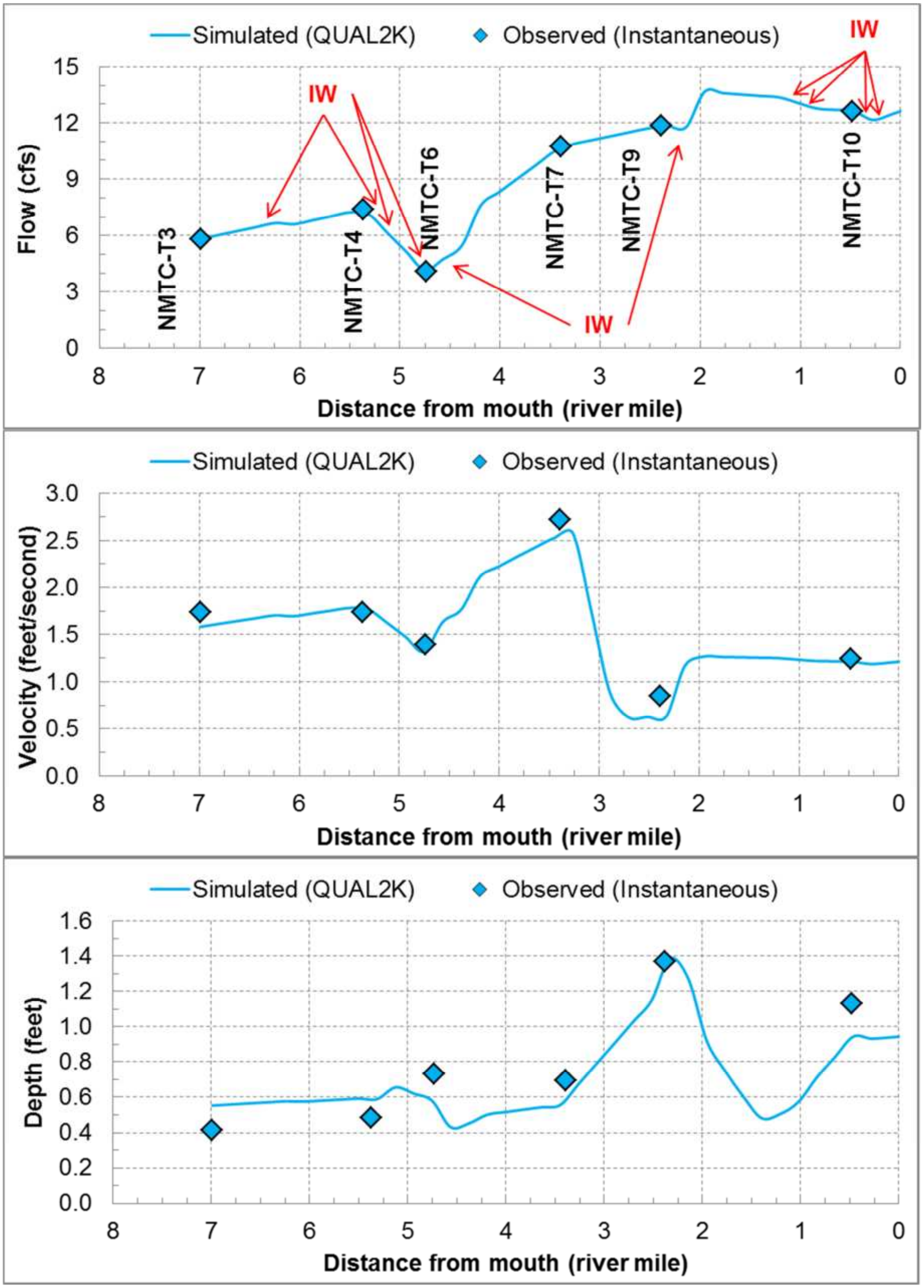
Table 6. Temperature calibration and validation locations

Site name	Distance (RM)	Available Data	Source
NMTC-T3	6.99	Flow, depth, velocity, and temperature	EPA
NMTC-T4	5.37	Flow, depth, velocity and temperature	EPA
NMTC-T6	4.73	Flow, depth, velocity and temperature	EPA
NMTC-T7	3.39	Flow, depth, velocity, and temperature	EPA
NMTC-T9	2.39	Flow, depth, velocity, and temperature	EPA
NMTC-T10	0.47	Flow, depth, velocity, and temperature	EPA

Note: EPA = U.S. Environmental Protection Agency and its contractors; RM = river mile.

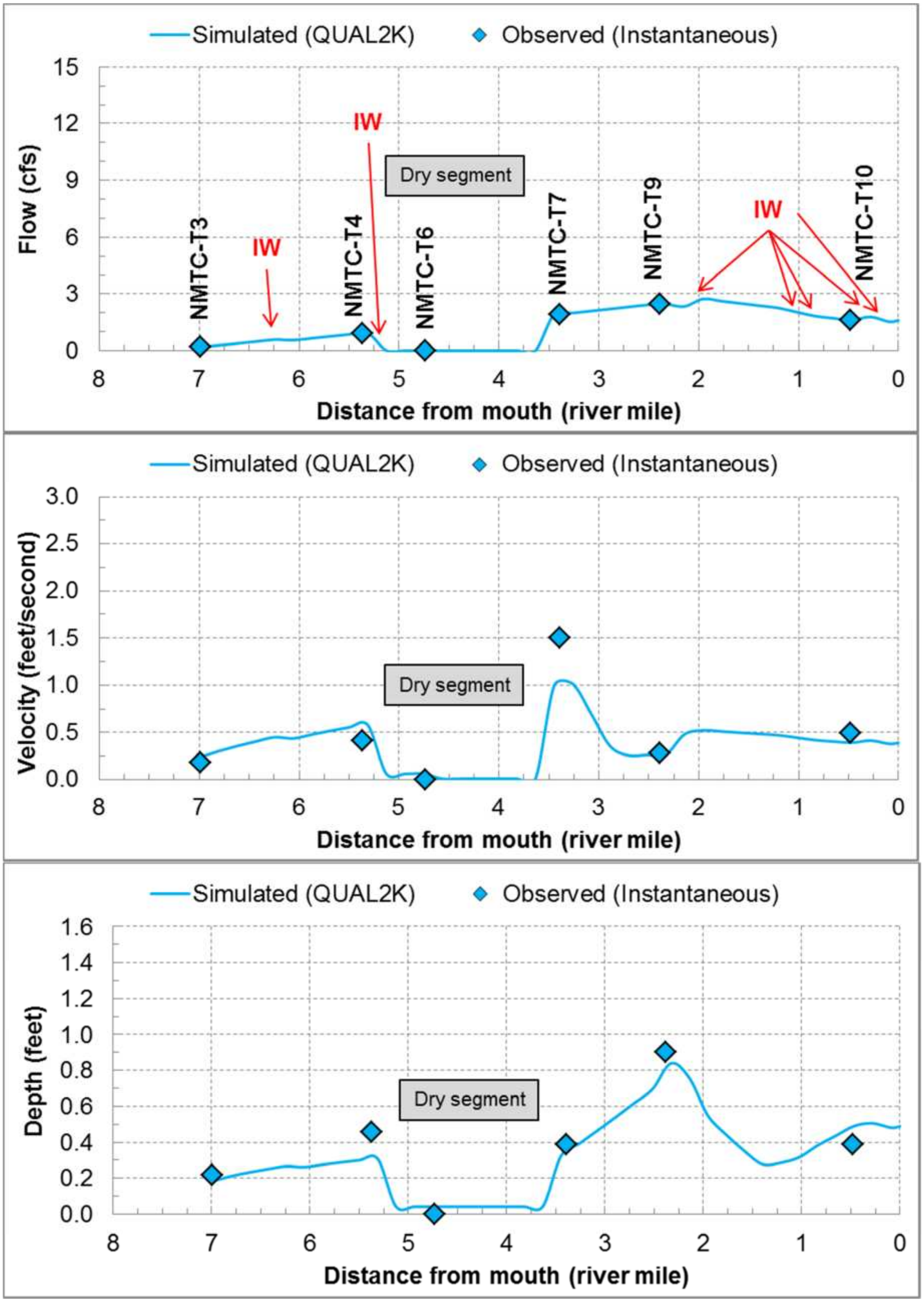
The first step for calibration was adjusting the flow balance and calibrating the system hydraulics. A flow balance was first constructed for the calibration and validation dates. This involved accounting for all the flow in the system. Observed flows along Nemote Creek, tributary flows, and withdrawals were used to estimate the amount of diffuse flow along the system.

After the mass balance of the flow rates, the modeled velocity and depth were simulated using the previously described rating curve method. To summarize, the exponents of the rating curve for the depth and the velocity were set to be 0.32 and 0.55 respectively. While the exponents were not varied during the model calibration, the rating curve coefficients were modified and evaluated against the observed data. After identifying the most suitable coefficients for each segment using the calibration data for July 14, 2011, the selected coefficients were evaluated with the validation data for September 13, 2011. The model results indicated a reasonable model simulation capability (**Figure 7** and **Figure 8**).



Note: IW = irrigation withdrawal.

Figure 7. Observed and simulated flow, velocity, and depth on July 14, 2011 (calibration).



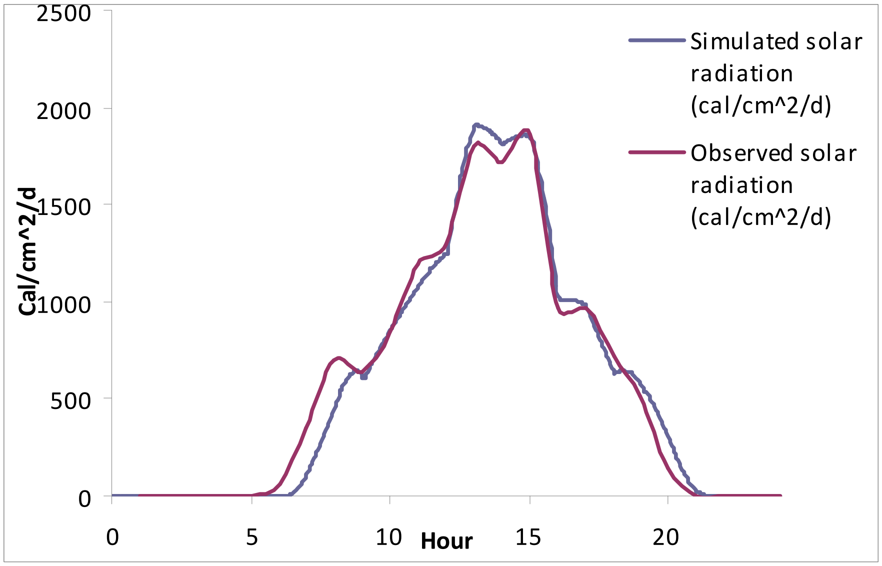
Note: IW = irrigation withdrawal.

Figure 8. Observed and predicted flow, velocity, and depth on September 13, 2011 (validation).

Once the system hydraulics were established, the model was then calibrated for water temperature. Temperature calibration included calibrating the model by adjusting the light and heat parameters with available data. A discussion of the solar radiation model and calibration along with other heat related inputs that were selected is presented below.

Hourly solar radiation is an important factor that affects stream temperature. The QUAL2K model does not allow for input of solar radiation. Instead the model calculates short wave solar radiation using an atmospheric attenuation model. For the Nemote Creek QUAL2K model, the Ryan-Stolzenbach model was used to calculate the solar radiation. The calculated solar radiation values (without stream shade) for the calibration and validation date were compared with observed solar radiation measurements at the Nine Mile RAWS. **Figure 9** shows the observed and predicted solar radiation for the calibration and validation. No cloud cover data were available and the observed solar radiation during calibration showed some influence due to cloud cover throughout most of the day on July 14, 2011. The cloud cover was adjusted to more closely mimic observed solar radiation during calibration on July 14, 2011. During the validation period, cloud cover was assumed to be minimal and set to zero[4] on September 13, 2011. The Ryan-Stolzenbach atmospheric transmission coefficient (default 0.80) was also adjusted to 0.85 (July 14, 2011) and 0.82 (September 13, 2011) to reflect the atmospheric conditions represented through the short wave solar radiation.

[4] However, cloud cover was set to 100 percent in model segment from loggers NMTC-T4 to NMTC-T6). Between these loggers, Nemote Creek runs dry. The cloud cover was set to 100 percent to insure that the solar radiation did not affect the temperature of the tiny flow volume in the dry segment, which was essentially a tiny interstitial or subsurface flow.



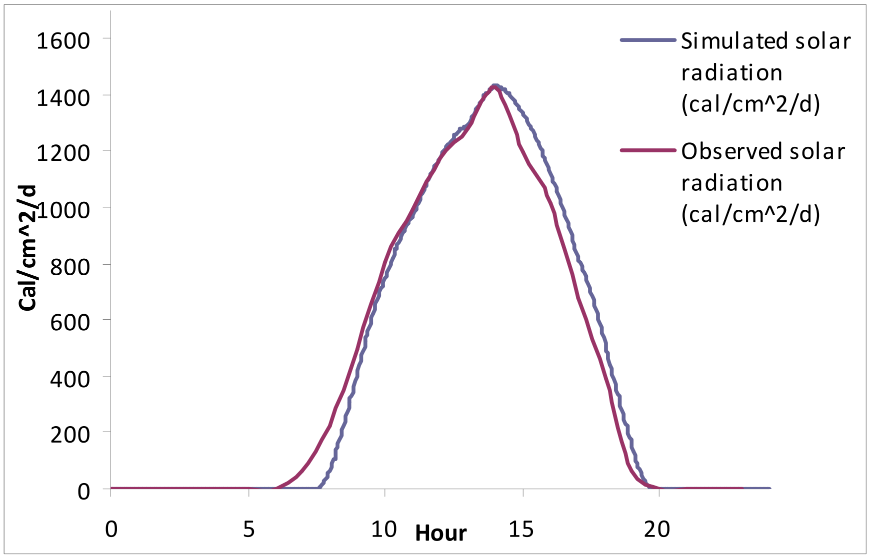


Figure 9. Observed and predicted solar radiation on July 14, 2011 (calibration; chart on top) and September 13, 2011 (validation; chart on bottom).

The longwave solar radiation model and the evaporation and air conduction/convections models were kept at the default QUAL2K settings. The solar radiation settings are shown in **Table 7**.

Table 7. Solar radiation settings

Parameter	Value
Solar Shortwave Radiation Model	
Atmospheric attenuation model for solar	Ryan-Stolzenbach
Ryan-Stolzenbach solar parameter (used if Ryan-Stolzenbach solar model is selected)	
Atmospheric transmission coefficient [a]	0.85 | 0.82
Downwelling atmospheric longwave infrared radiation	
Atmospheric longwave emissivity model	Brutsaert
Evaporation and air convection/conduction	
Wind speed function for evaporation and air convection/conduction	Adams 2

Note: a. The range of atmospheric transmission coefficients is 0.70 to 0.91 and the QUAL2K model default is 0.80 (Chapra et al. 2008).

The sediment heat parameters were also evaluated for calibration. In particular the sediment thermal thickness, sediment thermal diffusivity, and sediment density were adjusted during calibration. The sediment thermal thickness was slightly increased from the default value of 10 cm to 15 cm, and the sediment heat capacity of all component materials of the stream was set to 0.4 calories per gram °C, which is the QUAL2K default (Chapra et al. 2008). The sediment thermal diffusivity was set to a value of 0.0118 square centimeters per second (Chapra et al. 2008). This was consistent with the stream photographs that indicated a predominant rocky substrate along the main channel.

The sediment density was set to 2.2 grams per cubic centimeter (g/cm^3). Surficial geology data from Montana Bureau of Mines and Geology (1955) indicated that the type of rock within the watershed was mainly argillite and quartzite. Based on the field photographs, the surface layer of the stream substrate was estimated to be mainly gravel (including pebbles, cobbles, and some small boulders) and appeared to contain larger sand grain size particles. The densities of argillite (1.82 g/cm^3) and quartzite (2.60 g/cm^3) were averaged to estimate the sediment density.

Calibration was followed by validation. The validation provides a test of the calibrated model parameters under a different set of conditions. Only those variables that changed with time were changed during validation to confirm the hydraulic variables. This included headwater and tributary in-stream temperatures, air and dew point temperatures, wind speed, cloud cover, solar radiation, and shade. All other inputs were based on observed data in July 14, 2011. Groundwater temperatures, for which there were no direct observed data, were unchanged since they are not expected to vary greatly.

Figure 10 and **Figure 11** show the calibration and validation results along Nemote Creek. The temperature calibration and validation statistics of the average, maximum, and minimum temperatures are shown in **Table 8** and **Table 9**, respectively.

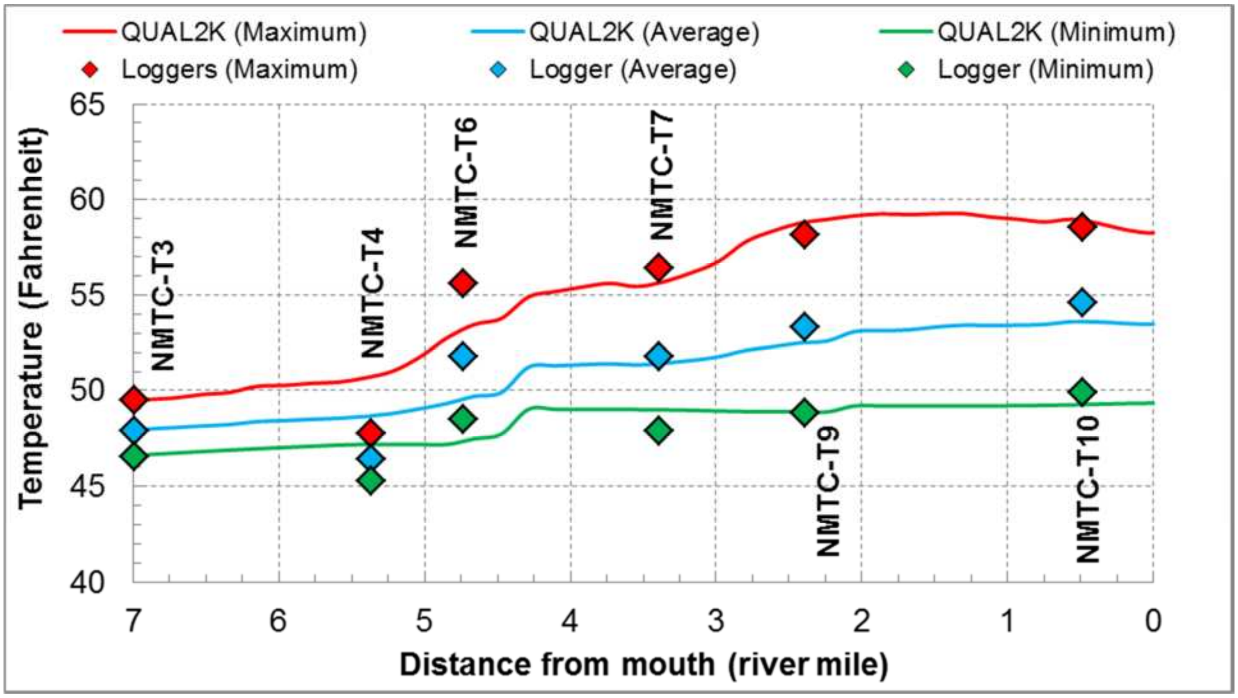
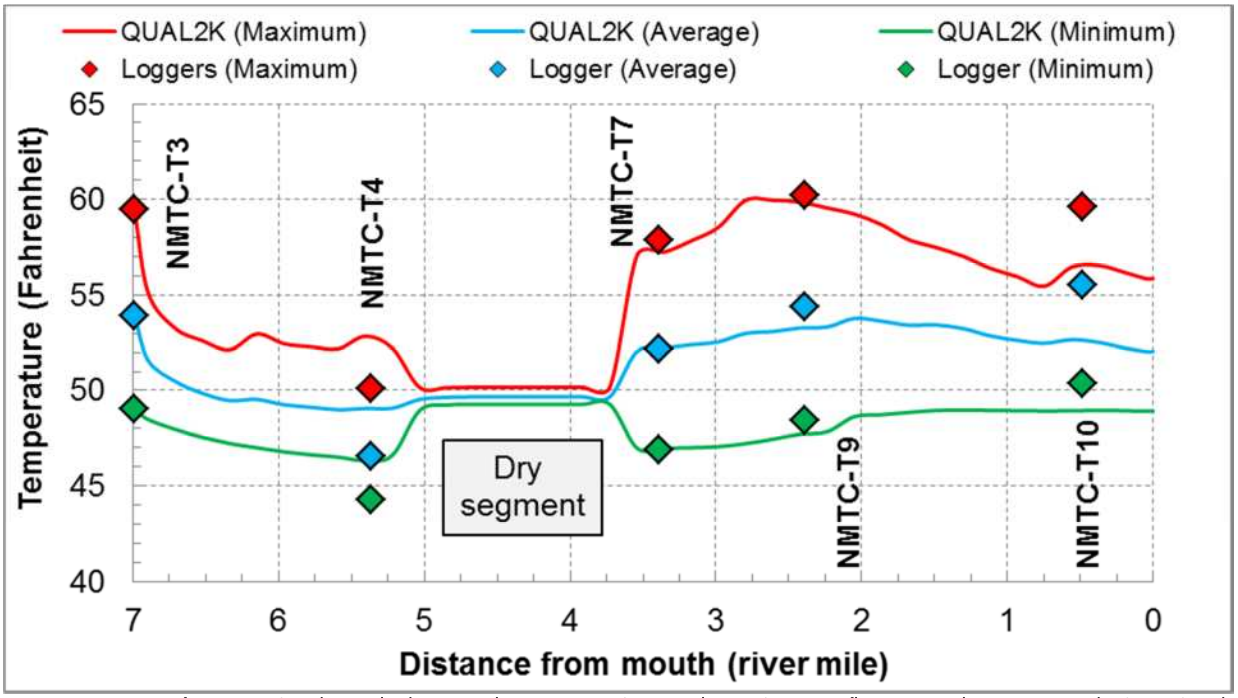


Figure 10. Longitudinal profile of the temperature calibration (July 14, 2011).



Note: A segment of Nemote Creek ran dry between loggers NMTC-T4 and NMTC-T7. As flow cannot be set to zero in QUAL2K, the segment was simulated with a tiny flow volume.

Figure 11. Longitudinal profile of the temperature validation (September 13, 2011).

Table 8. Calibration statistics of observed versus predicted water temperatures

Site name	RM	Average daily temperature		Maximum daily temperature		Minimum daily temperature	
		AME (°F)	REL (%)	AME (°F)	REL (%)	AME (°F)	REL (%)
NMTC-T3	6.99	--	--	--	--	--	--
NMTC-T4	5.37	2.22	4.8%	2.89	6.1%	1.96	4.3%
NMTC-T6	4.73	2.42	4.7%	2.82	5.1%	1.30	2.7%
NMTC-T7	3.39	0.31	0.6%	0.68	1.2%	1.13	2.4%
NMTC-T9	2.39	0.79	1.5%	0.64	1.1%	0.09	0.2%
NMTC-T10	0.47	0.96	1.8%	0.43	0.7%	0.63	1.3%
Overall Calibration		**1.34**	**2.6%**	**1.49**	**2.7%**	**1.02**	**2.1%**

Note: AME = absolute mean error; km = river kilometer; REL = relative error.

Table 9. Validation statistics of observed versus predicted water temperatures

Site name	RM	Average daily temperature		Maximum daily temperature		Minimum daily temperature	
		AME (°F)	RE (%)	AME (°F)	REL (%)	AME (°F)	REL (%)
NMTC-T3	6.99	--	--	--	--	--	--
NMTC-T4	5.37	2.49	5.3%	2.78	5.6%	2.09	4.7%
NMTC-T6 [a]	4.73	--	--	--	--	--	--
NMTC-T7	3.39	0.06	0.1%	0.65	1.1%	0.09	0.2%
NMTC-T9	2.39	1.13	2.1%	0.35	0.6%	0.72	1.5%
NMTC-T10	0.47	2.82	5.1%	3.18	5.3%	1.43	2.8%
Overall Validation		**1.63**	**3.1%**	**1.74**	**3.1%**	**1.08**	**2.3%**

Notes
AME = absolute mean error; km = river kilometer; REL = relative error.
a. Nemote Creek ran dry along a segment between loggers NMTC-T4 and NMTC-T7. Logger NMTC-T6 was fully exposed to ambient air in a dry channel on September 13, 2011.

In general, the model was able to capture the observed temperature range. All the simulated minimum, maximum, and mean temperatures were contained within relatively small errors. The overall calibration results showed an overall 2.7 percent relative error with an AME of 1.49° F for the maximum temperatures. The overall validation results for the maximum temperatures were similar to the calibration statistics with an overall 3.1 percent relative error and an AME of 1.74° F.

Both the calibration and the validation model indicated an over-predication at logger NMTC-T4. The selected rating curve coefficients and exponents at the location simulated the observed depth and velocity reasonably well. However, it is possible that a combination of localized shading and potential colder diffuse inflow could affect the in-stream temperature at logger NMTC-T4; thus, the logger temperature may represent very localized conditions.

The calibration model indicated an under-prediction at logger NMTC-T6. Similar to the other loggers, the selected rating curve coefficients and exponents simulated depth and velocity reasonably well at loggers NMTC-T6. This under-prediction could be due to a number of reasons, including: (1) the fact that no diffuse inflows were simulated based upon the results of the flow mass balance, (2) the effects of localized shading, or (3) a slight over-prediction of stream depth.

The validation model indicated an under-prediction at logger NMTC-T10. Similar to the other loggers, the selected rating curve coefficients and exponents simulated depth and velocity reasonably well at logger NMTC-T10. Model sensitivity to groundwater temperature in the segment between loggers NMTC-T9 and NMTC-T10 was evaluated by increasing the diffuse inflow temperatures that represent groundwater inflow; however, the sensitivity analysis did not result in significantly warmer simulated temperatures at logger NMTC-T10. Model sensitivity to the rating curve coefficients in this segment were also evaluated by simulating a shallower depth. While this sensitivity analysis did simulate warmer temperatures at logger NMTC-T10, the results were not significantly warmer than the original calibration results. Thus, no modifications were made to the final model calibration.

3.5 Model Sensitivity

Sensitivity analysis measures the relative importance of parameters, such as shade and water withdrawals, on model response. Model sensitivity was generally evaluated by making changes to shade[5] and water use[6] (i.e., the key thermal mechanisms [Tetra Tech 2012]) in separate model runs and evaluating the model response. Model sensitivity analyses with similar QUAL2K models for streams in western Montana (Fortine, Wolf, and McGregor creeks) suggest that the QUAL2K models developed with the data typically available for the Montana temperature projects are not very sensitive to changes in water use but are sensitive to changes in shade. The sensitivity of water withdrawals and shade were explored with the Nemote Creek QUAL2K model during model development and the results were consistent with previous Montana streams QUAL2K projects.

[5] To assess model sensitivity to shade, all vegetation was converted to high density trees (with the exception of roads and hydrophytic shrubs) to represent the maximum potential shade.

[6] To assess model sensitivity to water withdrawals, the point source abstractions representing the withdrawals were removed and the existing condition model was run to represent the maximum achievable change in water temperatures from changes in water use.

4 Model Scenarios and Results

The Nemote Creek QUAL2K model was used to evaluate in-stream temperature response associated with multiple scenarios. **Table 10** summarizes the alterations to input parameters for each model scenario. The following sections present a discussion of the modifications to the QUAL2K models and the results for each scenario.

Table 10. QUAL2K model scenarios for Nemote Creek

Scenario [a]		Description	Rationale
Baseline Scenario			
1	Existing Condition	Existing shade and irrigation practices under critical low-flow[b] and critical weather	The baseline model simulation from which to construct the other scenarios and compare the results against.
Water Use Scenario			
2	15 % reduction in withdrawals	Reduce existing withdrawals by 15 percent	Represent application of conservation practices for agricultural and domestic water use.
Shade Scenario			
3	50-foot Buffer	Set the shading levels along two segments[c] with anthropogenically reduced shade to the shading levels along the reference segment[d].	Represent application of conservation practices for riparian vegetation.
Improved Flow and Shade			
4	Improved flow and shade	Existing conditions with 15% reduction in withdrawals (scenario 2) and increased shading (scenario 3).	Represent application of conservation practices for water withdrawals and riparian vegetation.

Notes

a. Scenarios were developed in accordance with concurrence from the EPA task order manager Lisa Kusnierz to Tetra Tech's project manager Ron Steg on January 14, 2014 during a conference call with EPA, DEQ, and Tetra Tech staff.

b. The critical low-flow is based upon on the 25th percentile of daily average flow across for water years 1957-2012 at the nearby USGS gage 12413875 (St. Joe's River at Red Ives Ranger Station, ID).

c. The two segments with anthropogenically reduced shade are: (1) between river miles 2.3 and 5.1 (i.e., between loggers NMTC-T4 and NMTC-T9), and (2) between river miles 0.4 and 0.5.

d. The reference segment is between river miles 1.2 and 2.3, which is from logger NMTC-T9 downstream to a location that is just upstream of logger NMTC-T10.

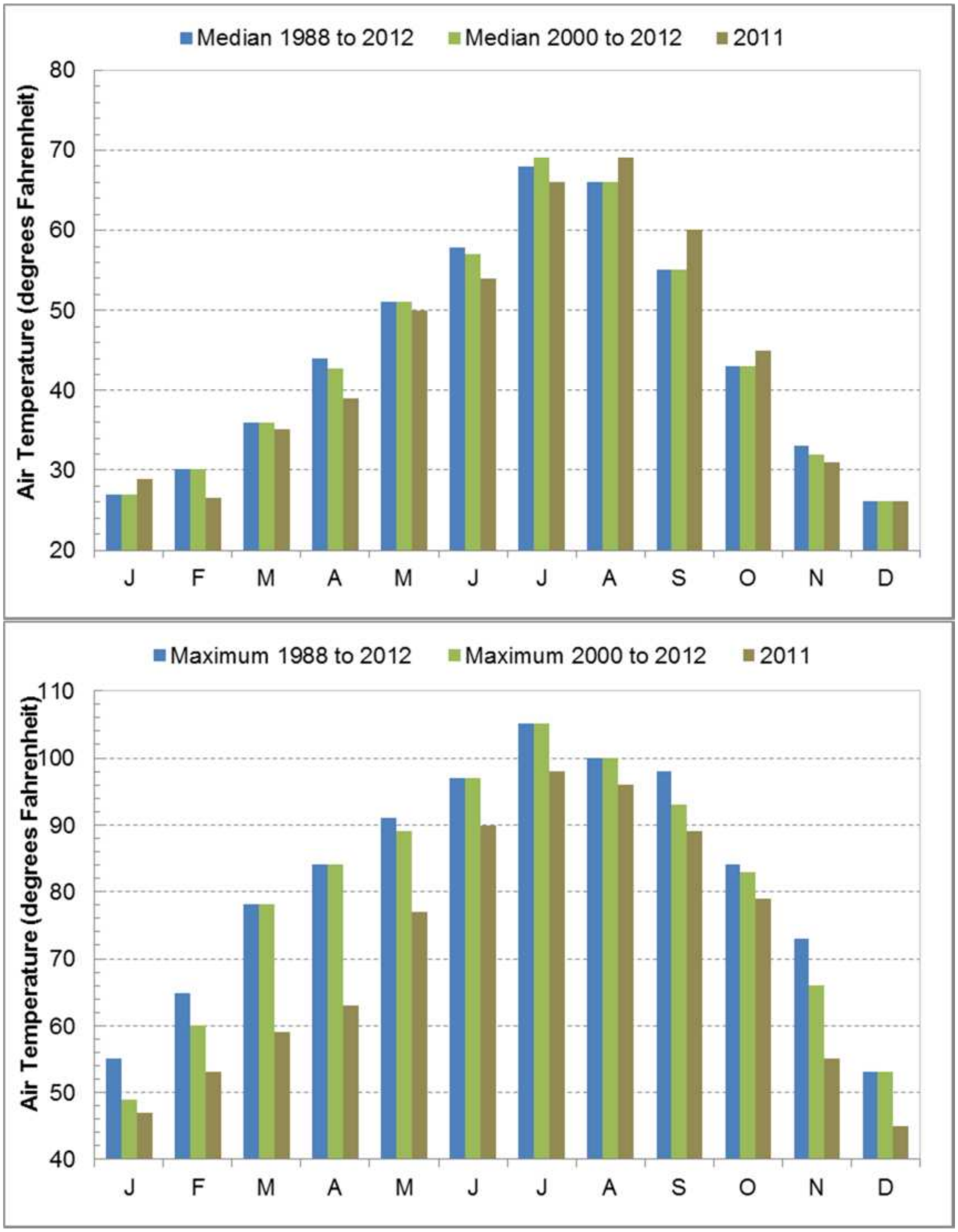
4.1 Baseline Scenario

The baseline model (scenario 1) serves as the model simulation from which to construct the other scenarios and compare the results against. The baseline scenario was run using the critical low-flow and critical weather on the calibration date.

4.1.1 Weather Data

The Nine Mile RAWS has hourly data available for the period from August 2000 through December 2012. Since the weather data extends only for a period of twelve years, a nearby station with long-term meteorological data (Missoula International Airport [1988-2012]) was queried to confirm if the years from 2000 to 2012 were (1) not anomalously warm or cold and (2) similar to the overall historical normal. Additionally, comparisons with the year 2011 (during which the QUAL2K model calibration and validation periods occur) were made to ensure that 2012 was not an anomalous year. The long-term monthly median and maximum air temperatures for the period from 2000 to 2012 and for the year 2011 were estimated to be similar to the overall period from 1988 through 2012 (**Figure 12**)[7]. While the monthly maximum air temperatures in the summer of 2011 were cooler than the monthly long-term maximum of monthly maximum air temperatures of the years 1988-2012, they were warmer than the monthly long-term median of monthly maximum air temperatures of the years 1988-2012 (**Figure 12**). Therefore, since neither the period from 2000 through 2012 nor the summer of 2011 was substantially anomalous, it is appropriate to use the Nine Miles RAWS data for QUAL2K modeling.

[7] Hourly average air temperatures were obtained for the Missoula International Airport (KMSO). Monthly maximum air temperatures were calculated for each month from January 1988 through December 2012 using the hourly average air temperatures. Monthly long-term medians and maximums were calculated from the 25 years of monthly maximums of hourly average air temperatures.



Note: Hourly average air temperatures were obtained for the Missoula International Airport (KMSO). Monthly maximum air temperatures were calculated for each month from January 1988 through December 2012 using the hourly average air temperatures. Monthly long-term medians and maximums were calculated from the 25 years of monthly maximums of hourly average air temperatures.

Figure 12. Long-term median (chart on top) and maximum (chart on bottom) of monthly air temperature at Missoula.

4.1.2 Critical Weather

The critical weather conditions were estimated based upon meteorological data collected at the Nine Miles RAWS. After the Nine Mile RAWS data were compiled, the data were used estimate the critical weather conditions through the following steps: .

1. The averaging duration for the critical weather condition was estimated. The travel time of the Nemote Creek QUAL2K model was just over one day. Therefore, the averaging duration is 2 days.
2. The 2-day moving averages of daily maximum temperatures were calculated for every day in July from 2001 through 2013 at the Nine Mile RAWS.
3. The maximum of 2-day rolling averages of daily maximum temperatures was selected for each July from 2001 through 2013. This step yielded 13 July-maximums of 2-day rolling averages of daily maximum temperatures.
4. The 2-day period that corresponded to the median of the 13 July-maximums of 2-day rolling averages of daily maximum temperatures (98.5° F) was selected as the critical temperature period. This step yielded a 2-day period (July 16-17).
5. The hourly air temperature, dew point temperature, and wind speed from July 16-17, 2011 were compiled from the Nine Mile RAWS. The data were averaged by hour to yield a single day's input to the Nemote Creek QUAL2K model (e.g., 55° F at 12 AM on July 16th was averaged with 57° F at 12 AM on July 17th to yield 57° F for the 12am input to the Nemote Creek QUAL2K model).
6. The cloud cover in the Nemote Creek QUAL2K model was set to zero to represent clear sky conditions.

4.1.3 Critical Low Flow

The summer season critical low flow was selected as the 25th percentile of mean-daily flow. Continuous flow data are not available for Nemote Creek. Therefore, daily average flow data from water years 1957 through 2012 monitored as USGS gage 12413875 (St. Joe's River at Red Ives Ranger Station, ID) were used along with instantaneous discharge measurements from Nemote Creek to estimate the 25th percentile flow in Nemote Creek.Refer to **Appendix A, Section A-6** for a discussion of flow at USGS gage 12413875.

Daily average flow on July 14, 2011 at gage 12413875 was 1,140 cfs, and the 25th percentile of July 14ths from water years 1957 through 2012 is 220 cfs (**Appendix A, Section A-6**). To achieve the 25th percentile of July 14ths (220 cfs), the July 14,2011 flow (1,140 cfs) would need to be reduced by 81 percent. This percent reduction, calculated for USGS gage 12413875, was then applied to all flow inputs to the Nemote Creek QUAL2K calibration model for July 14, 2011 to develop the baseline scenario with critical weather and critical low-flow . For example, the headwaters boundary condition for the calibration (i.e., existing condition) of 5.83 cfs was reduced to 1.09 cfs for the baseline (i.e, critical low flow condition).

4.1.4 Baseline Scenario Results

The modeled water temperature using the critical low-flow and critical weather conditions is shown below in **Figure 13**.

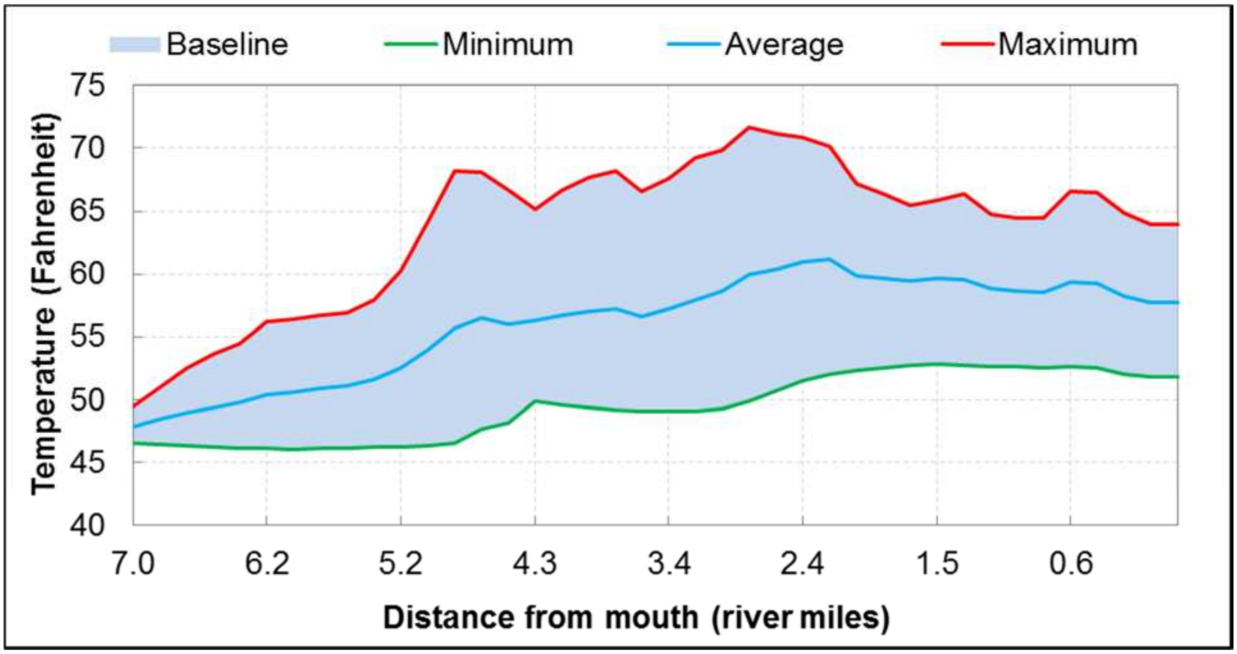


Figure 13. Simulated water temperature for the baseline condition.

4.2 Water Use Scenario

Irrigation (or other water withdrawals) depletes the volume of water in the stream and reduces in-stream volumetric heat capacity. Theoretically the reduced stream water volume heats up more quickly, and to a higher temperature, given the same amount of thermal input. A single water use scenario was modeled to evaluate the potential benefits associated with application of water use best management practices (scenario 2).

In this scenario, the abstractions representing the withdrawals (see **Appendix A** for the withdrawals) in the QUAL2K model are reduced by 15 percent (NRCS 1997). The water previously withdrawn is now allowed to flow down Nemote Creek. This scenario is intended to represent application of conservation practices relative to water use.

Water temperatures in Nemote Creek for this scenario generally had little effect (**Figure 14**). Changes in the maximum daily water temperatures, as compared to the baseline condition (scenario 1), ranged from a 0.53° F decrease to a 0.42° F increase. Decreases greater than 0.2° F were limited to river miles 2.62 to 2.80 and 4.47 to 5.52; increases greater than 0.1° F were limited to river mile 0.19 to the mouth. The difference in water temperature only once exceeded 0.5° F, signifying minimal sensitivity and conditions that are similar to the baseline condition.

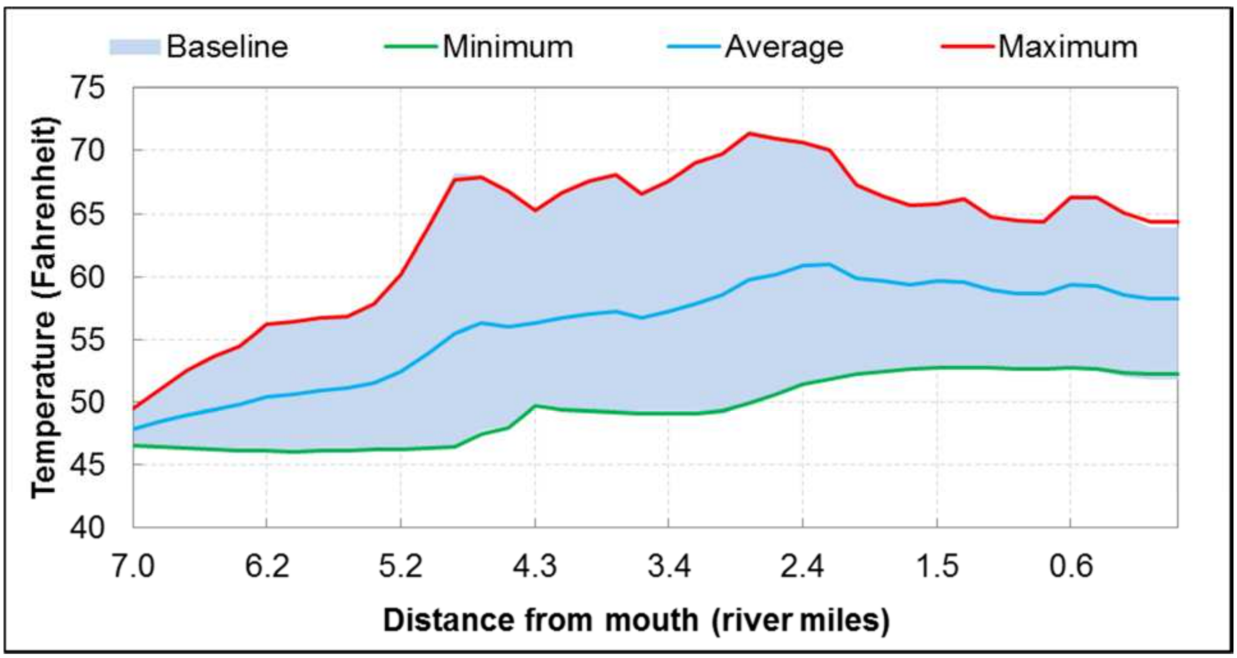


Figure 14. Simulated water temperatures for the baseline (scenario 1) and 15-percent withdrawal reduction (scenario 2).

4.3 Shade Scenarios

The riparian plant community blocks incoming solar radiation, which directly reduces the heat load to the stream. A single shade scenario was modeled to evaluate the potential benefits associated with increased shade along Nemote Creek.

The segments of Nemote Creek from river miles 0.4 to 0.5 and 2.3 to 5.1 exhibit low shading due to anthropogenic activities along the riparian corridor (**Figure 15**). For this scenario, the shading in these two segments was increased to reflect the average daily shade in a reference reach (i.e., a segment of Nemote Creek between rivermiles 1.2 to 2.3 with minimal anthropogenic influence). The riparian corridor along the two segments with anthropogenically diminished shade can be reasonably improved to yield similar shading levels associated with riparian vegetation in the reference reach (**Table 11**).

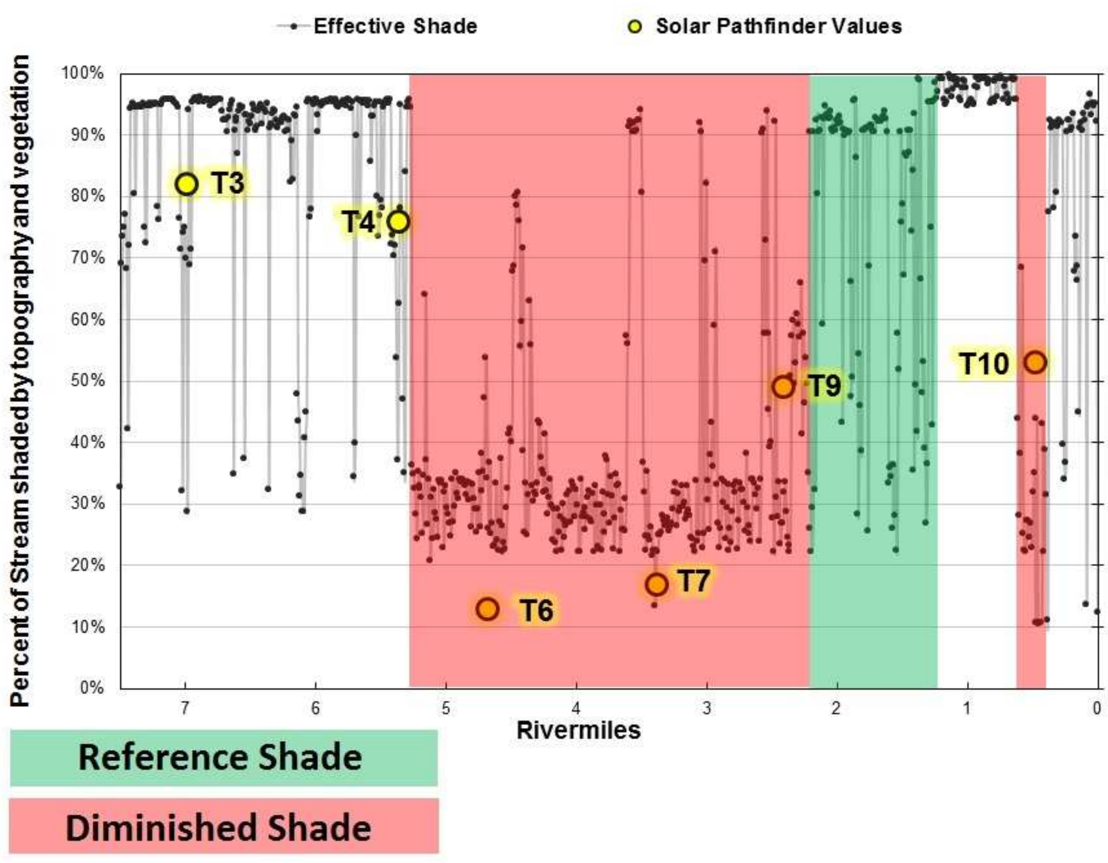


Figure 15. Effective shading along Nemote Creek for the baseline condition showing the segments with anthropogenically diminished shade and reference quality shade.

Table 11. Average daily shade inputs per model segment

Segment	Baseline condition (scenario 1)	Improved shade (scenario 3)
NMTC-T3 to NMTC-T4	88%	88%
NMTC-T4 to NMTC-T6	50%	70%
NMTC-T6 to NMTC-T7	49%	77%
NMTC-T7 to NMTC-T9	46%	77%
NMTC-T9 to NMTC-T10	77%	78%
NMTC-T10 to mouth	74%	80%

Note: For each segment, the effective shade per hour was averaged across 15 meter intervals for each hour from 5:00 am through 9:59 pm (yielding average effective shade per hour per model segment) and then averaged across daylight hours (yielding average effective shade per day per model segment).

The water temperatures for Nemote Creek in this scenario decrease throughout the two segments that were assigned increased shading (**Figure 16**). A maximum change in the maximum daily water temperature of 8.5° F from the baseline condition was observed at river mile 2.80. The difference in the daily maximum water temperature between the existing condition and maximum potential shade scenario was always greater than 0.5° from river mile 5.03 to the mouth.

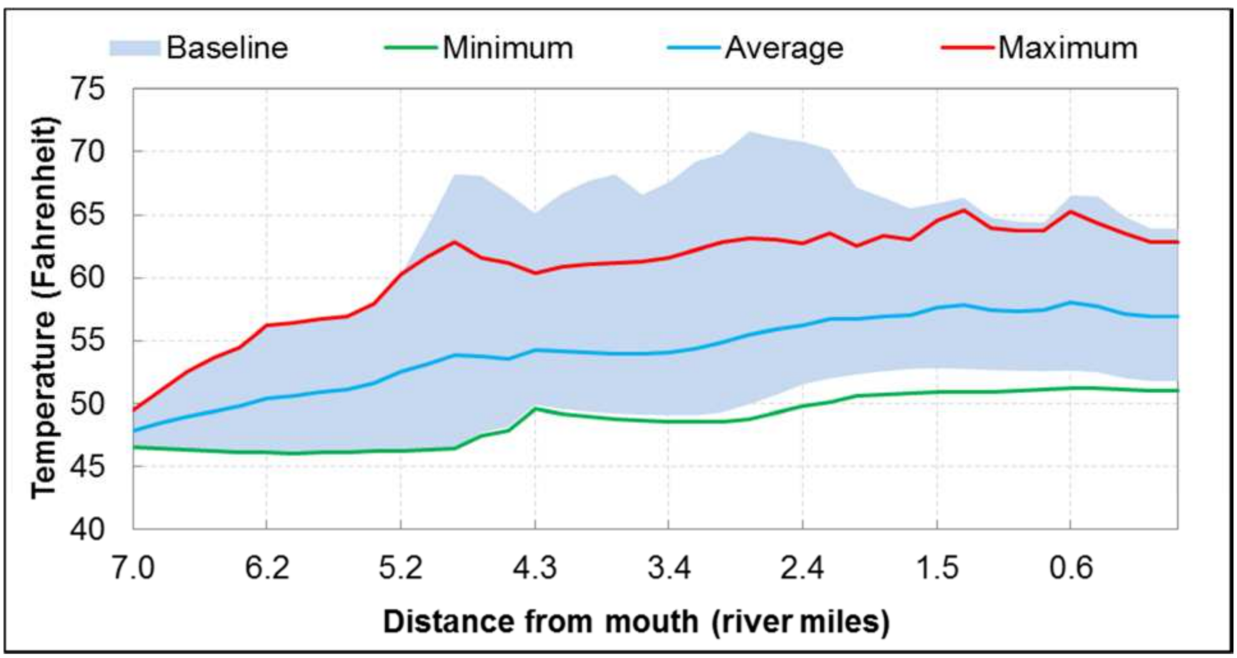


Figure 16. Simulated water temperatures for the baseline condition (scenario 1) and shade with the improved shade condition (scenario 3).

4.4 Improved Flow and Shade Scenario

The improved flow and shade scenario (scenario 4) combines the potential benefits associated with a 15 percent reduction in water withdrawals (scenario 2) with improved shading along two segments with anthropogenically diminished shade (scenario 3).

The water temperatures for Nemote Creek in this scenario decreased from rivermile 5.97 downstream to the mouth (**Figure 17** and **Figure 18**). A maximum change in the maximum daily water temperature of 8.6° F from the existing condition was observed at river mile 8.6. The results are similar to shade scenario (scenario 3) since the water use scenario (scenario 2) showed negligible sensitivity to a 15 percent reduction in the withdrawals except in two short segments. The difference in the daily maximum water temperature between the existing condition and maximum potential shade scenario was greater than 0.5° F for this scenario for 5.03 of 6.99 miles (72 percent). As with the other scenarios, no changes in water temperatures were simulated from the headwaters boundary condition downstream to river mile 6.15.

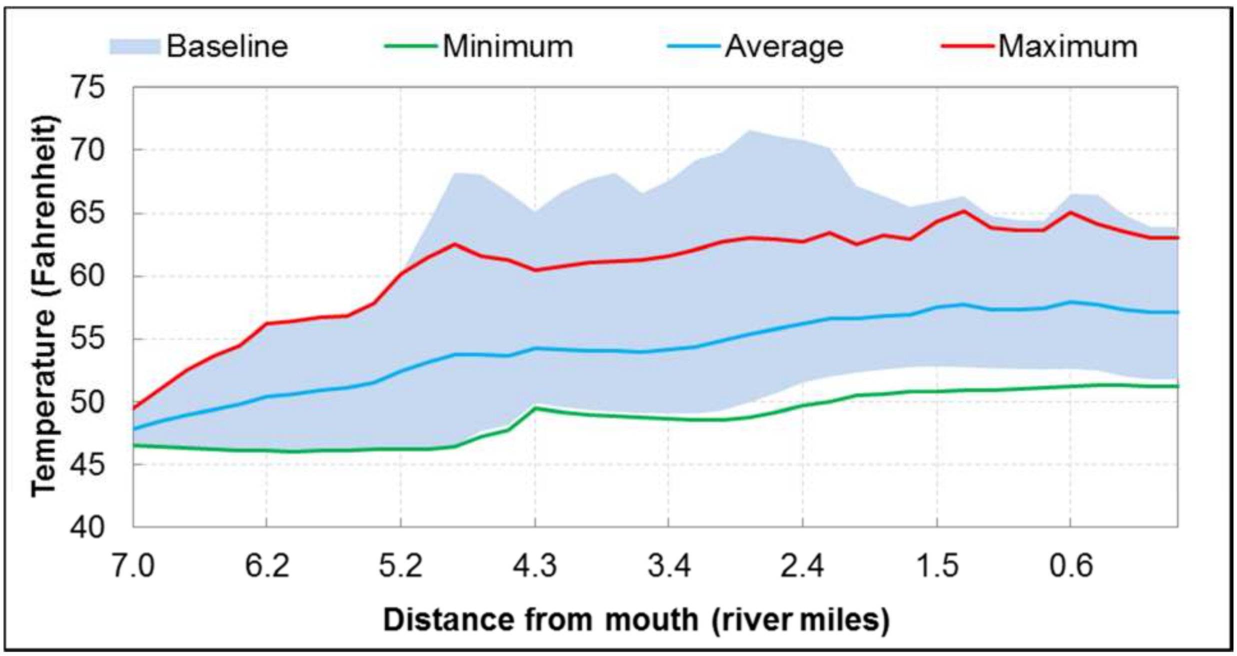


Figure 17. Simulated water temperature for the baseline condition (scenario 1) and the improved flow and shade scenario (scenario 4).

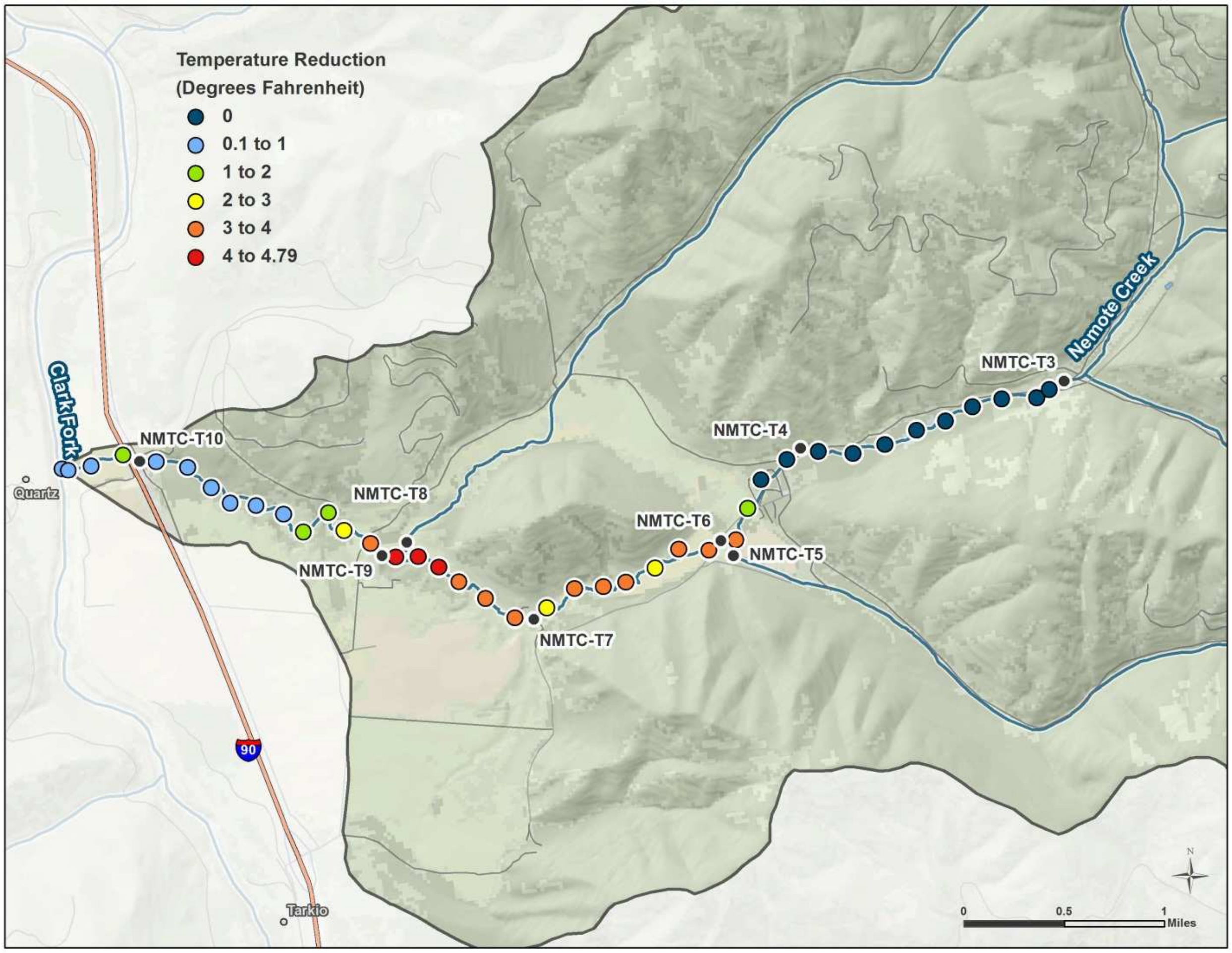


Figure 18. In-stream temperature difference from the baseline condition (scenario 1) to the improved flow and shade scenario (scenario 4).

5 Assumptions and Uncertainty

As with any model, the QUAL2K model is subject to uncertainty. The major sources of model uncertainty include the mathematical formulation, input and boundary conditions data uncertainty, calibration data uncertainty, and parameter specification (Tetra Tech 2012). As discussed in the quality assurance project plan (Tetra Tech 2012), the QUAL2K model code has a long history of testing and application, so outright errors in the coding of the temperature model are unlikely. The Shade Model has also been widely used so a similar sentiment exists. A potentially significant amount of the overall prediction uncertainty is due to uncertainty in the observed data used for model setup, calibration, and validation, and assumptions used in the scenario analysis itself.

5.1 Uncertainty with Model Development

With respect to input data (including instantaneous flow, continuous temperature, channel geometry, hourly weather, spatial data or other secondary data), weather and spatial data were obtained from other government agencies and were found to be in reasonable ranges, and are therefore assumed to be accurate. Uncertainty was minimized for the use of other these data following procedures described in the quality assurance project plant (Tetra Tech 2012).

In addition, assumptions regarding how these data are used during model development contain uncertainty. The following key assumptions were used during Nemote Creek QUAL2K model development:

- Nemote Creek can be divided into distinct segments, each considered homogeneous for shade, flow, and channel geometry characteristics. Monitoring sites at discrete locations were selected to be representative of segments of Nemote Creek.
- Spatial variability of velocity and depth (e.g. stream meander and hyporheic flow paths) are represented through exponents and coefficients of the selected rating curves for each segment.
- Weather conditions at the Nine Mile RAWS are representative of local weather conditions along Nemote Creek.
- Shade Model results are representative of riparian shading along segments of Nemote Creek. Shade Model development relied upon the following three estimations of riparian vegetation characteristics:
  - Riparian vegetation communities were identified from visual interpretation of aerial imagery.
  - Tree height and percent overhang were estimated from other similar studies conducted outside of the Nemote Creek watershed.
  - Vegetation density was estimated using the National Land Cover Dataset (Multi-Resolution Land Characteristics Consortium 2001) and best professional judgment.

  Shade Model results were corroborated with field measured Solar Pathfinder™ results and were found to be reasonable. The average absolute mean error is 7 percent. (i.e., the average error from the Shade Model output and Solar Pathfinder™ measurements was 7 percent daily average shade).

- All of the cropland associated with water rights is fully irrigated. No field measurements of irrigation withdrawals or returns were available.
- Simulated diffuse flow rates are representative of groundwater inflow/outflow, irrigation diversion, irrigation return flow, and other sources of inflow and outflow not explicitly modeled. Diffuse flow rates were estimated using flow mass balance equations for each model reach.
- Shallow groundwater temperature is approximately 49.5° F (as the model was calibrated and validated), which was derived from monitored groundwater temperatures in nearby wells.

5.2 Uncertainty with Scenario Development

The increased shade scenario (scenario 3) assumes that the shade from vegetation along the reference segment is achievable in the segments with anthropogenically diminished shade. The increased shade scenario (scenario 3) represents the feasible temperature benefit that could be achieved over a time period long enough to allow vegetation to mature (tens of years). Therefore, temperature improvements in the short term are likely to be less than those identified in the scenario 3 results. Natural events such as flood and fire may also alter the maximum potential for the riparian vegetation or shift the time needed to achieve the maximum potential. This condition may not be achievable for all areas due to the coarse scaled used to identify the current and potential shade conditions and the fact that even natural systems tend to have spatial patchiness of tree canopy cover.

6 Model Use and Limitations

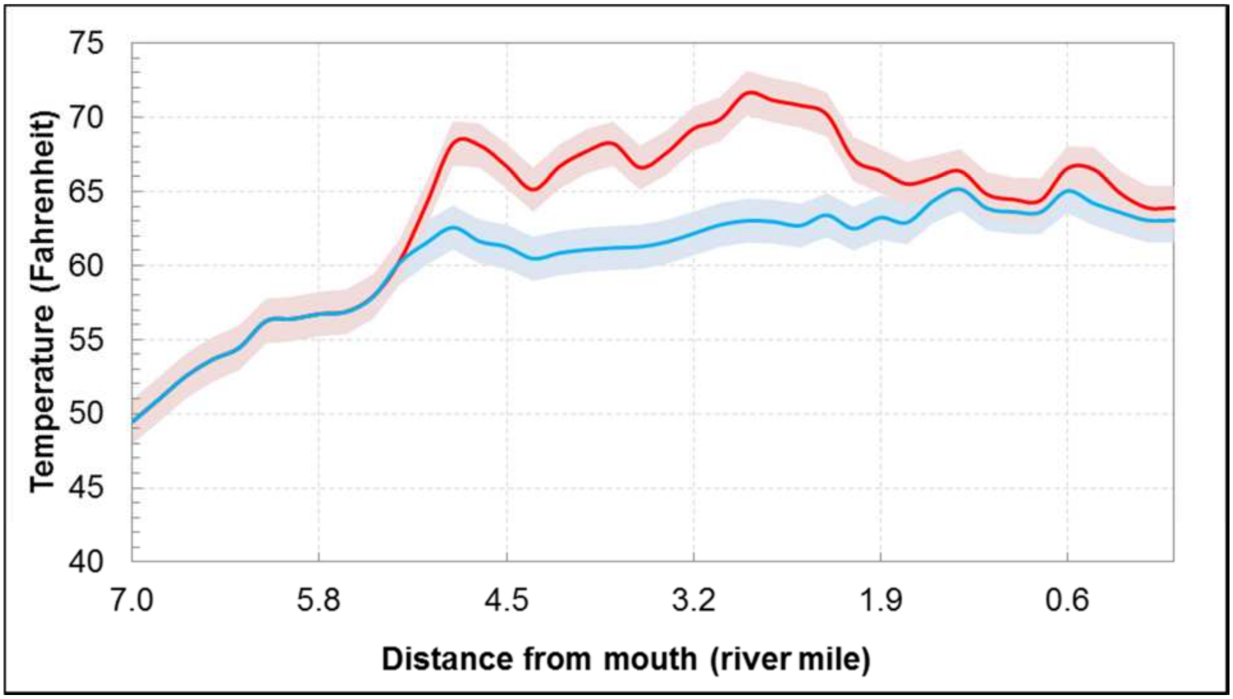
The model is only valid for summertime, low flow conditions and should not be used to evaluate high flow or other conditions. As described above, steps were taken to minimize uncertainty as much as possible. Despite the uncertainty, the model adequately addresses the primary questions:

1. What is the sensitivity of in-stream temperature to the following thermal mechanisms and stressors: shade, irrigation withdrawal and return?
2. What levels of reductions in controllable stressors are needed to achieve temperature standards?

The first question can be answered using the calibrated and validated QUAL2K model for Nemote Creek. As previously discussed, Nemote Creek is sensitive to shade but not flow.

The second question can be answered using the baseline condition QUAL2K model and the scenarios developed to assess shade. In this instance, increasing riparian shading will decrease in-stream temperatures significantly (>8.6°F for maximum); however, there is uncertainty in the magnitude of temperature reduction as estimates are contingent on what was considered to be reference shade (>90 percent shading). While a “good” model calibration was achieved, the overall Absolute Mean Error (AME) for the maximum daily temperature was 1.5° F with increasing uncertainty in the uppermost portions of the model.

Figure 19 graphically summarizes the comparison between the baseline condition and improved flow and shade scenario. Based on these results, and the fact that Montana’s temperature standard as applied to Nemote Creek is limited to an increase of 1° F, it is clear that impacts are occurring to the stream and that the mechanism to address these temperature concerns will be the mitigation of stream shade through plantings or riparian enhancement. Continued monitoring should be done in conjunction with these activities to ensure that they are of benefit, in particular given that model results are uncertain as described previously.



Note: The existing condition (scenario 1) is the red line and the improved flow and shade scenario (scenario 4) is the blue line. The shaded areas are plus or minus the average AME (1.5° F).

Figure 19. Simulated daily maximum water temperatures from the baseline condition (red; scenario 1) and improved flow and shade scenario (blue; scenario 4).

7 Conclusions

The scenarios resulted in a range of no change in water temperatures to reductions as much as 8.6° F. Some of the reductions in water temperatures were localized and others affected nearly the entire reach.

A flow scenario representing irrigation efficiency was evaluated and the locations that showed the greatest potential for improvement were localized to areas just downstream of the existing withdrawals. The 15-percent reductions in water use did not result in any appreciable reduction to the temperature with the exception of the segment from river mile 4.47 to 5.03 (0.53° F reduction).

The shade scenario showed great extent and impact (reduction) to water temperatures from river mile 5.03 to the mouth. This scenario that represents potential shade improvements showed reductions of 0.6° F or more from river mile 5.03 to the mouth and reductions of2.6° F or more from river miles 1.68 to 4.10.

The improved flow and shade scenario combined the potential benefits associated with a 15 percent reduction in water withdrawals (scenario 2) with improved shade along segments with anthropogenically diminished shade (scenario 3) to represent application of land, soil, and water conservation practices relative to the temperature impairment. The model results show that the reductions for the improve flow and shade scenario (scenario 4)are mostly from the shade increase (scenario 3) (**Table 12**). The potential shade improvements showed reductions of 0.8° F or more from river mile 1.49 to the mouth and reductions of 2.6° F or more from river miles 1.49 to 5.03 (**Figure 20**). The temperature decreases in these segments were driven by increases in shade (**Figure 21**).

Table 12. In-stream temperature difference from the baseline scenario

Scenario ID	Scenario name	Daily maximum			Daily average		
		Range of change [a]	Average change [b]	Median change [c]	Range of change [a]	Average change [b]	Median change [c]
2	Water Use	-0.53 to +0.42	-0.05	-0.06	-0.22 to +0.45	-0.01	-0.01
3	Shade	-4.77 to 0	-1.83	-1.72	-8.53 to 0	-3.14	-2.15
4	Improved Flow and Shade	-4.84 to 0	-1.84	-1.80	-8.62 to 0	-3.20	-2.30

Notes

Results are reported in degrees Fahrenheit. Negative values represent scenario results that were cooler than the Baseline scenario while positive values represent scenario results that were warmer than the baseline scenario.

a. The range of temperature changes along Nemote Creek as compared with the baseline scenario.

b. The distance-weighted average temperature change along Nemote Creek as compared with the baseline scenario.

c. The distance-weighted median temperature change along Nemote Creek as compared with the baseline scenario.

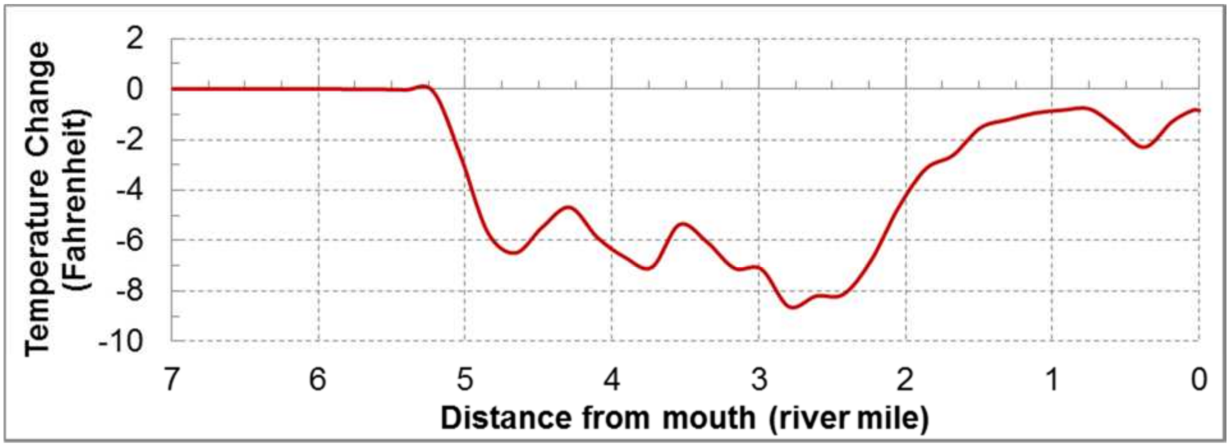


Figure 20. Simulated water temperature reduction from the baseline condition (scenario 1) to the improved flow and shade scenario (scenario 4).

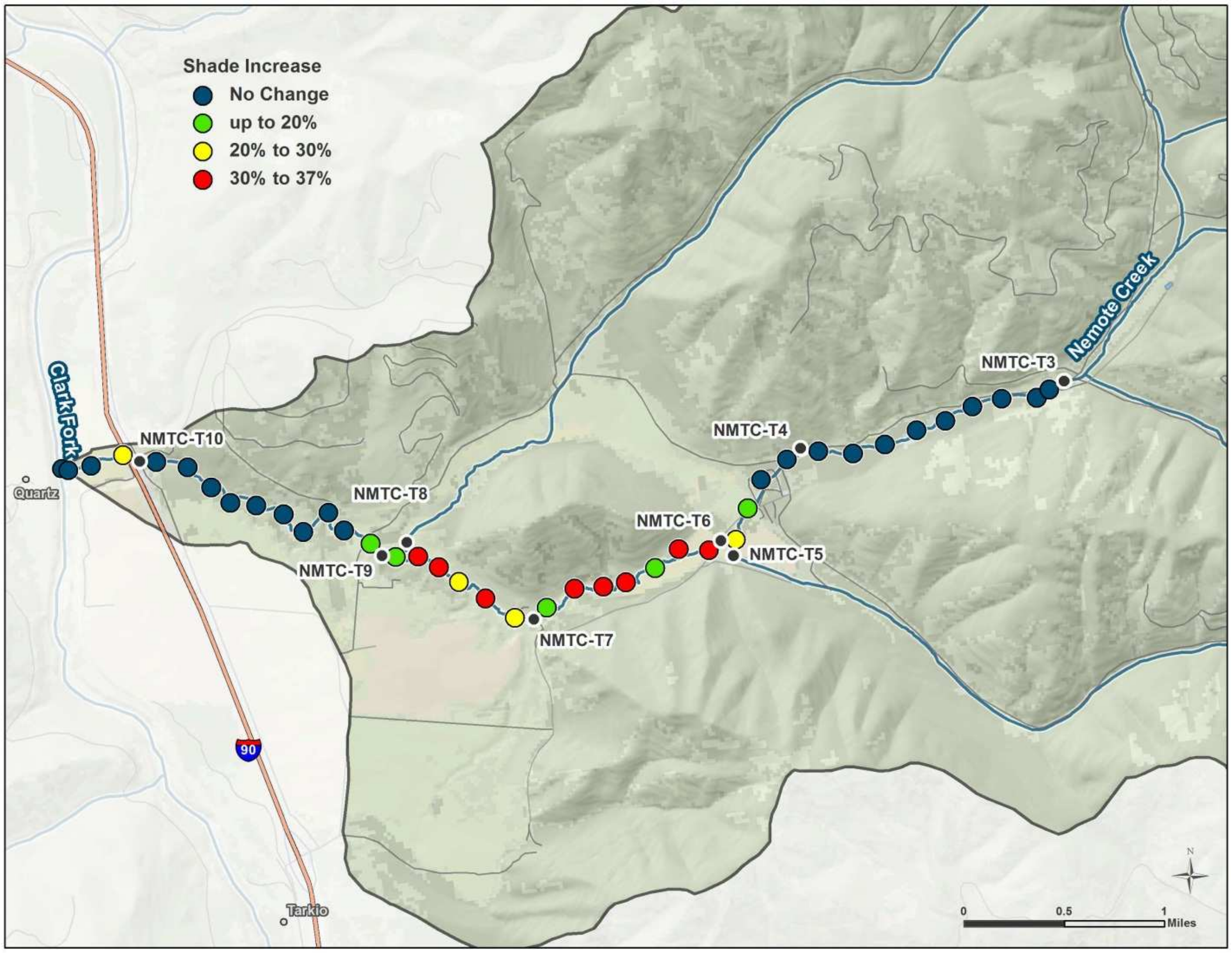


Figure 21. Shade deficit of the existing condition (scenario 1) from the improved flow and shade scenario (scenario 4).

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