ATTACHMENT A - MODELING WATER TEMPERATURE IN MILL CREEK

Modeling Water Temperature in Mill Creek

Prepared for:

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Version

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6/2/2014	1.0	First full draft to agencies for initial review
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6/18/2014	1.2	DEQ modeler comments
6/23/2014	2.0	DEQ & EPA comments addressed; final report

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Acronyms and Abbreviations

AME	absolute mean error
EPA	U.S. Environmental Protection Agency
DEQ	Montana Department of Environmental Quality
MPDES	Montana Pollutant Discharge Elimination System
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)

Units of Measure

°F	degrees Fahrenheit
cfs	cubic feet per second
cm^2/s	square centimeter per second
g/cm^3	grams per cubic centimeter
MSL	mean sea level
RM	river mile

Executive Summary

Mill Creek was identified by the Montana Department of Environmental Quality (DEQ) as being impaired due to elevated water temperatures. The cause of the impairment was attributed to loss of riparian habitat and site clearance (land development or redevelopment) (DEQ 2013). The U.S. Environmental Protection Agency (EPA) 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 2013 to support water quality model development for the project. A QUAL2K water-quality model was then developed for Mill 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 2013. Shade v3.0 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., synthetic flow and weather conditions to represent August).
- **Scenario 2:** Baseline with a 15 percent reduction of water withdrawals.
- **Scenario 3:** Baseline with improved riparian vegetation in certain segments based upon reference segments.
- **Scenario 4:** An improved flow and shade scenario that combines the potential benefits associated with a 15 percent reduction in water withdrawals with improved shading along certain segments.

In comparison to scenario 1, results ranged from minimal change in water temperature (scenario 3) to considerable reductions (scenarios 2 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 to certain segments based upon reference segments (scenario 3) to represent application of conservation practices, resulted in overall reductions along the entire reach that ranged from no effect to 10° F. Generally, small changes in shade or inflow had minimal effects on water temperature while large increases in shade or decreases in irrigation withdrawals 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, validate, and conduct scenario analysis with a temperature model (QUAL2K) for Mill Creek in support of 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 and calibration 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

Mill Creek is in western Montana and is part of the Bitterroot TMDL Planning Area. The Mill Creek watershed is in the Bitterroot 8-digit HUC (17010205). The impaired segment is 8.72 miles long and extends from the Selway-Bitterroot boundary to the mouth on Fred Burr Creek (DEQ 2013) (**Figure 1**).

Mill Creek has a B-1 use class. The impaired segment is not supporting its Aquatic Life and Primary Contact Recreation designated uses (DEQ 2013). Three potential causes of impairment are identified in the assessment record, including water temperature (DEQ-2013). The potential sources of the water temperature impairment are: loss of riparian habitat and site clearance (land development or redevelopment) (DEQ 2013).

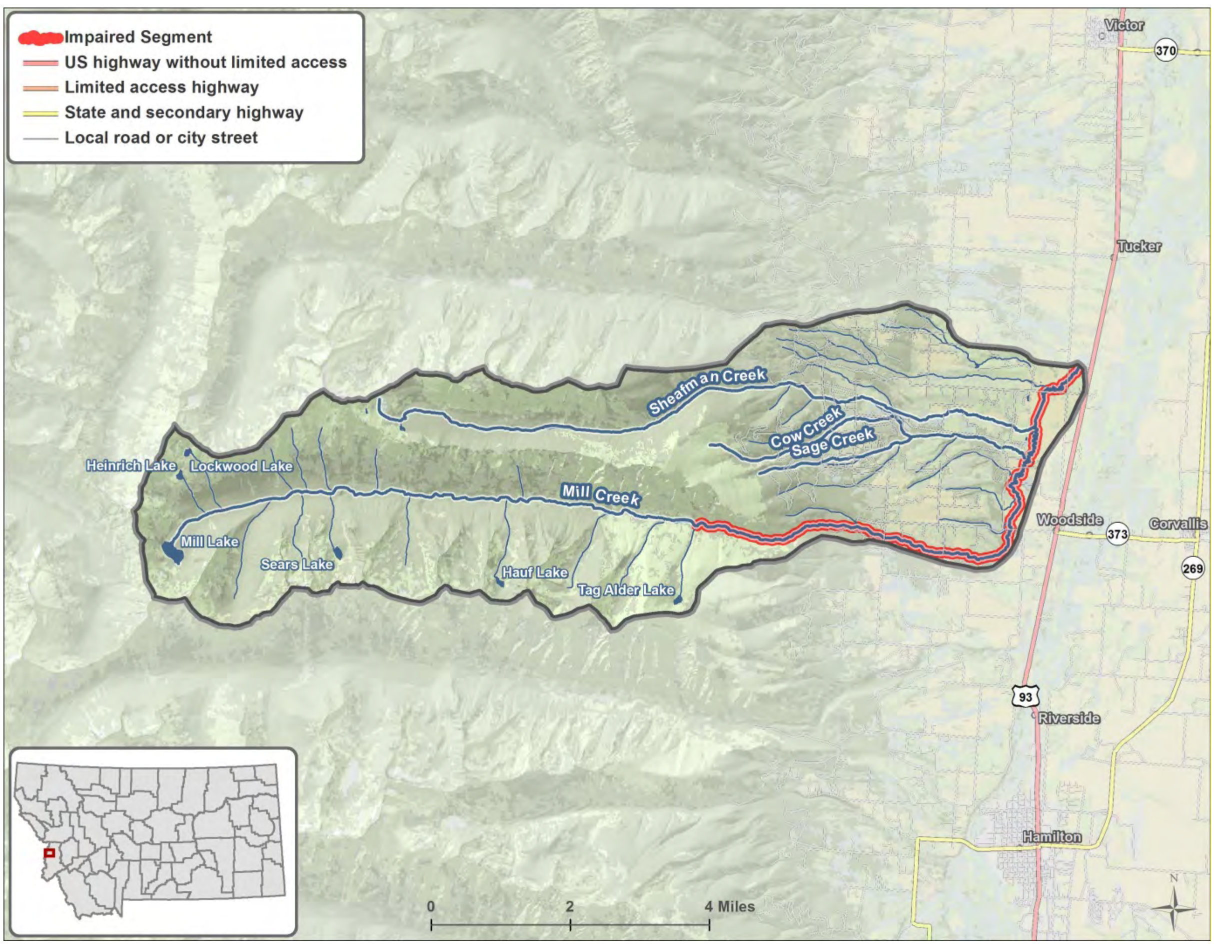


Figure 1. Mill Creek watershed.

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 May 2013 to develop the QUAL2K temperature model using the data and information that was collected in the summer of 2013. Temperature and flow data were collected in Mill Creek in 2013 by Tetra Tech. A field team from Tetra Tech collected data on July 26-27, 2013, August 12-13, 2013, September 9, 2013 and September 12, 2013 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, irrigation return flows, and tributary inflow temperatures and volumes. The shape of the channel can also affect 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 factors that may have an influence on stream temperatures in Mill Creek were evaluated prior to model development and are further discussed in **Appendix A**:

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

[1] ARM 17.30.623(e).
[2] "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.

- Point sources

2.5 Observed Stream Temperatures

Tetra Tech collected stream temperature data using in-stream loggers at multiple locations in the Mill Creek watershed. These data are presented and summarized in the following sections.

2.5.1 Available Temperature Data

In 2013, Tetra Tech collected continuous temperature data at six sites along Mill Creek and at one tributary site (Sheafman Creek) in support of this modeling effort (**Figure 2**). Data loggers recorded temperatures every one-half hour for two months between June 26-27 and September 9, 2013. In 2007, Montana DEQ collected continuous temperature data at two locations on Mill Creek (sites C05MILLC01 and C05MILLC02). Tetra Tech also collected instantaneous temperatures from Mill Creek (**Appendix A**). Temperatures varied spatially and temporally; generally, the warmest instantaneous temperatures were detected in July. Additionally, Montana DEQ recorded an instantaneous temperature of 76.5° F on July 12, 2007, at the C05MILLC01 station.

Tetra Tech identified a period of time at the logger on Sheafman Creek (SC-TT1) when the logger was likely exposed to ambient air: July 13 through September 12, 2013. These data were excluded from analyses and model development.

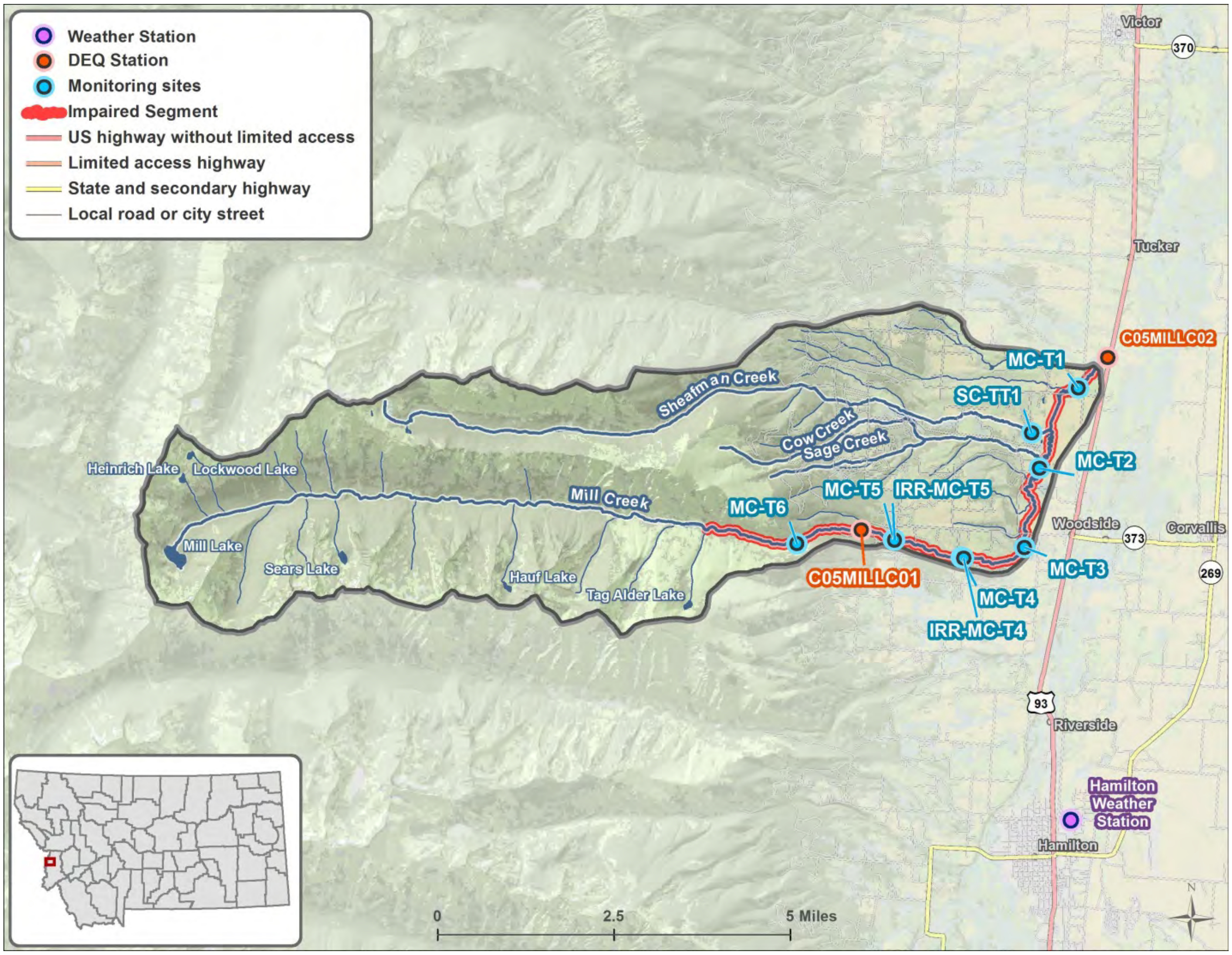
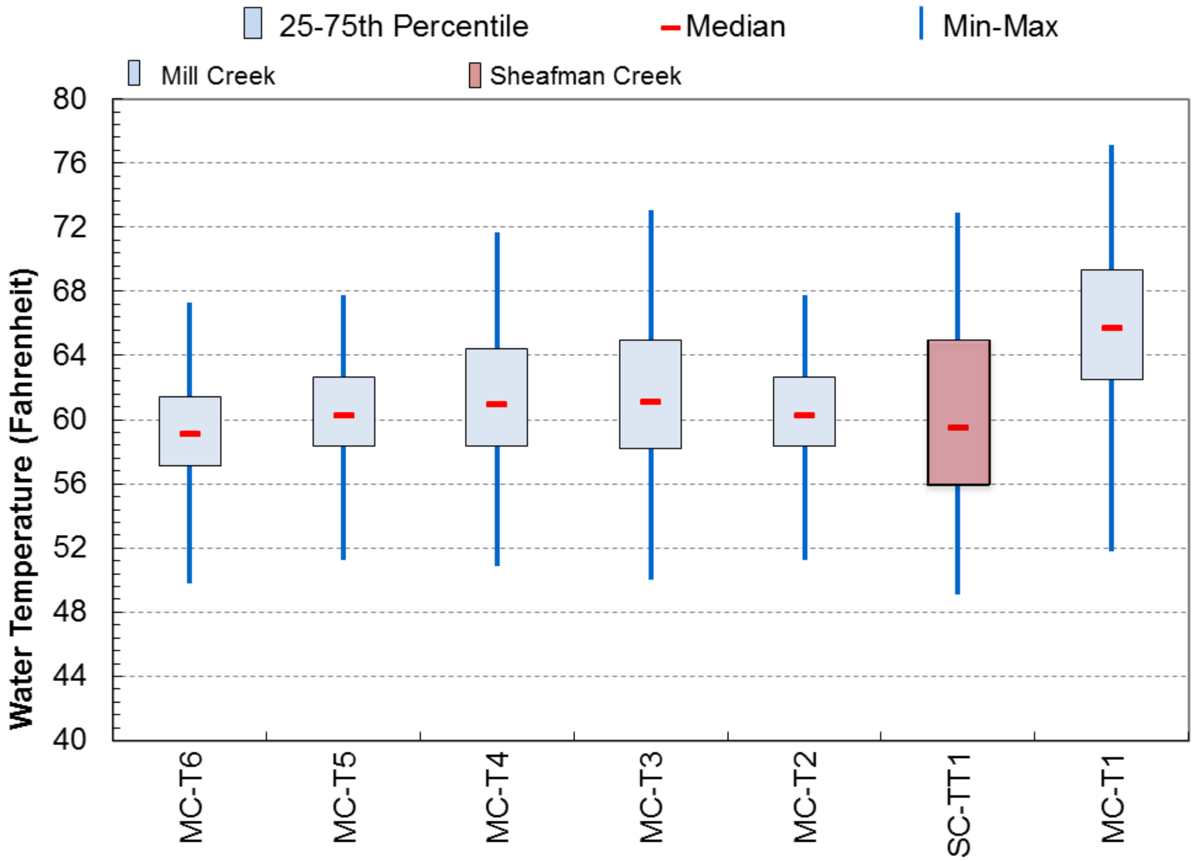


Figure 2. Temperature loggers in the Mill Creek watershed.

2.5.2 Temperature Data Analysis

Stream temperatures in Mill Creek generally increase from its source downstream to its mouth. A summary of the continuous temperature data collected by Tetra Tech is provided in (**Figure 3**)**.** Median temperatures in Mill Creek ranged from approximately 59° F to approximately 66° F in 2013 (**Figure 3**) and from approximately 55.4° F to approximately 57.2° F in 2007.



Note: Logger SC-TT1 may have been exposed to ambient air from July 13, 2013 through September 12, 2013. The data presented in this figure are limited to a subset of the monitored temperatures from June 27, 2013 through July 12, 2013.

Figure 3. Box-and-whisker plots of summer 2013 Tetra Tech continuous temperature data.

Maximum daily temperatures in Mill Creek ranged from approximately 67.3° F to 77.1° F in July of 2013 (**Table 1** and **Figure 4**). The highest maximum temperatures were recorded near the mouth at MC-T1. In 2013, the warmest temperatures were detected on July 18 and July 23-26. Similarly, in 2007, the maximum daily temperatures at sites C05MILLC01 and C05MILLC02 were 68.4° and 70.9° F (respectively) and occurred on July 18 (**Table 2** and **Figure 5**). The warmest weeks were generally the third and fourth weeks of July. As shown in **Figure 6**, the diurnal variation in Mill Creek in the upper watershed (as shown with MC-T6) is often only two-thirds of the diurnal variation in the lower watershed (as shown with MC-T1).

Table 1. Maximum and maximum weekly maximum temperatures in Mill Creek, 2013

Temperature logger site	Maximum temperatures [a]		Maximum weekly maximum temperature [b]	
	Temperature (°F)	Date	Temperature (°F)	Date
MC-6 (upper segment)	67.3	July 23	66.6	July 20-26
MC-5	67.8	July 24	67.3	July 20-26
MC-4	71.7	July 26	71.2	July 20-26
MC-3	73.0	July 18	72.2	July 17-23
MC-2	70.0	July 18	68.6	July 15-21
MC-1 (mouth)	77.1	July 18	76.4	July 18-24

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.

Table 2. Maximum and maximum weekly maximum temperatures in Mill Creek, 2007

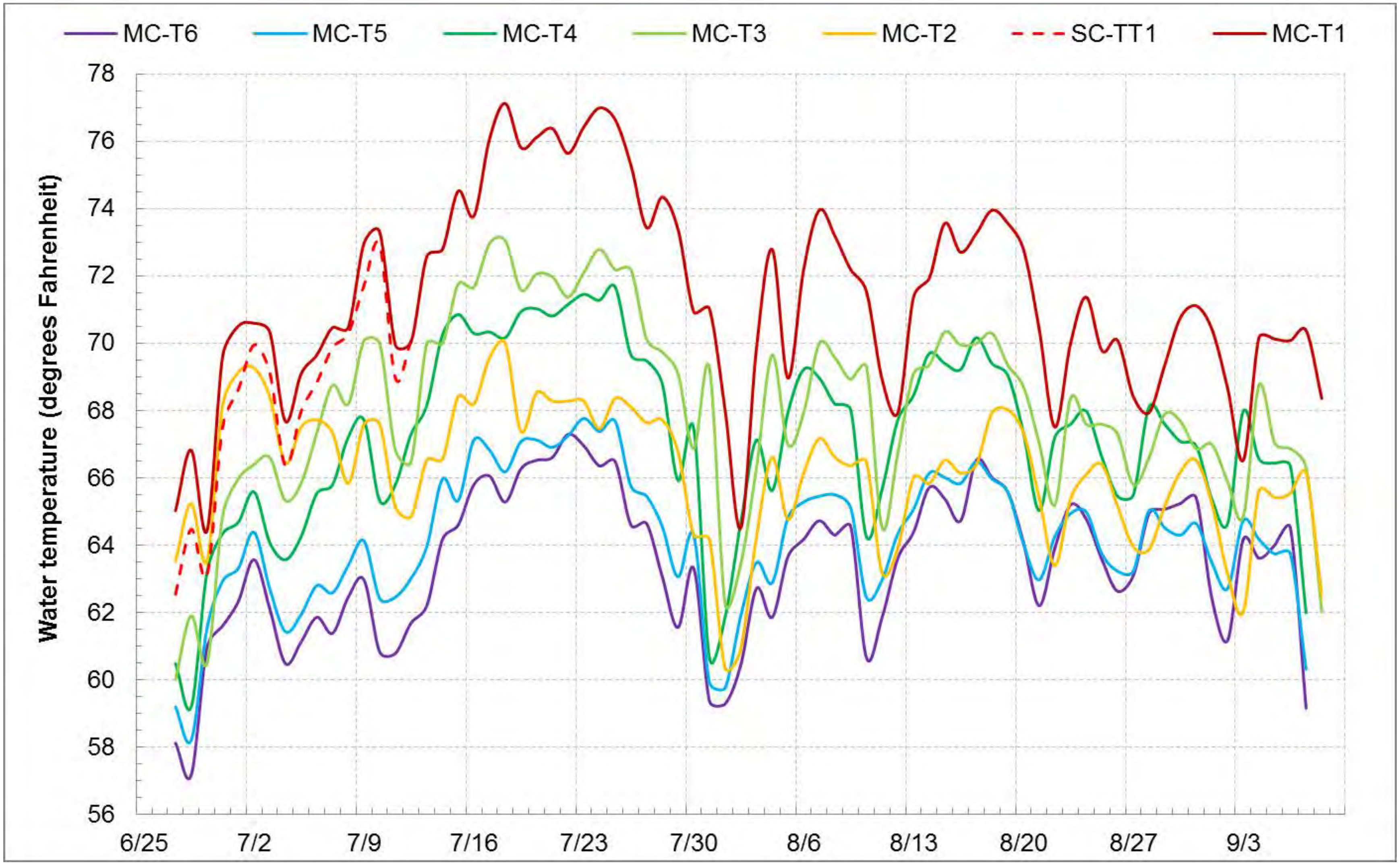
Temperature logger site	Maximum temperatures [a]		Maximum weekly maximum temperature [b]	
	Temperature (°F)	Date	Temperature (°F)	Date
C05MILLC01	68.4	July 18	67.6	July 14-20
C05MILLC02	70.9	July 18	69.5	July 16-22

Notes

Only data from July 13, 2007 through August 9, 2007 were used to assess the maximum and maximum weekly maximum temperatures.

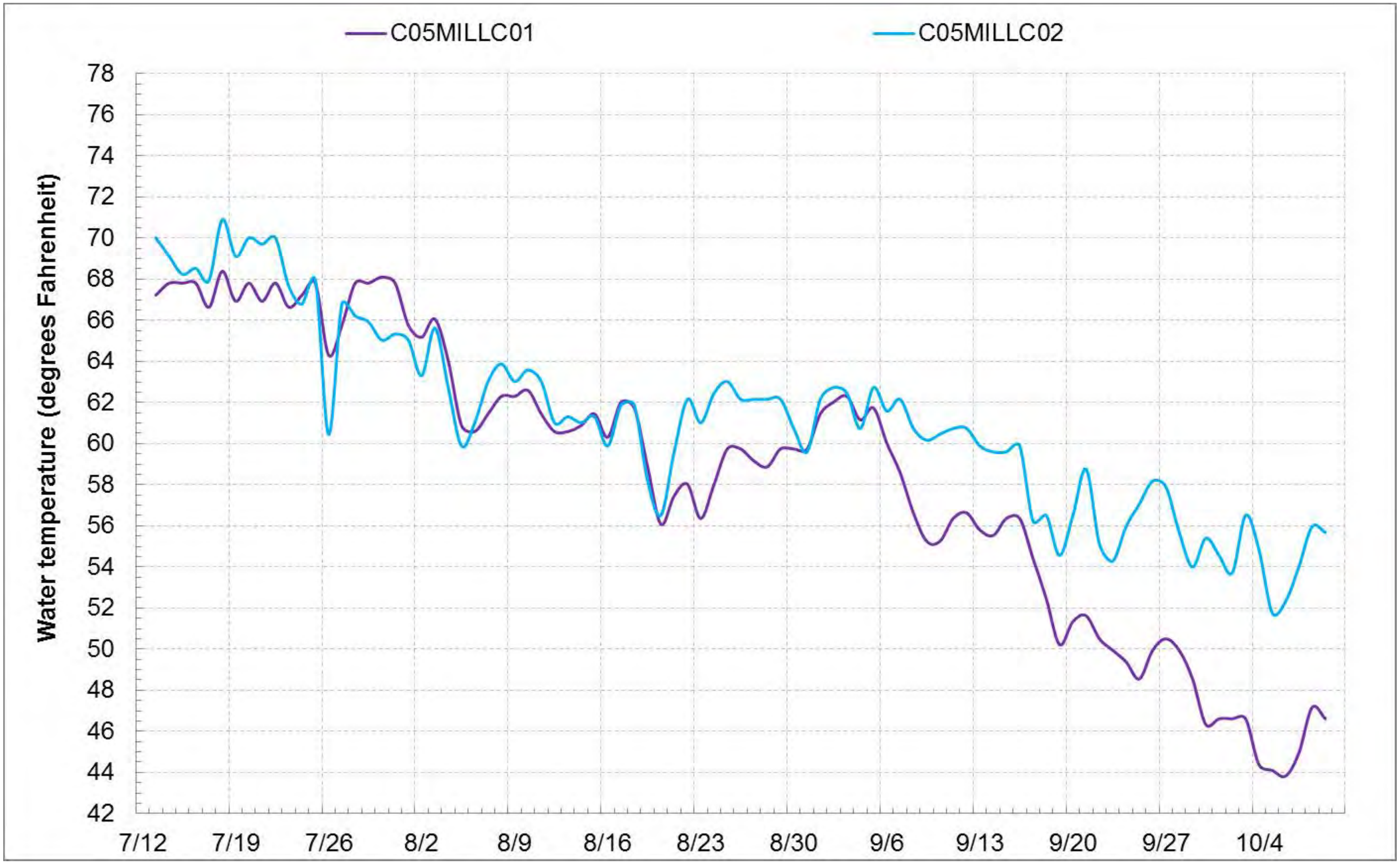
a. Maximum temperature is the maximum of recorded one-half hourly temperatures.

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



Note: Logger SC-TT1 may have been exposed to ambient air from July 13, 2013 through September 12, 2013. The data presented in this figure are limited to a subset of the monitored temperatures from June 27, 2013 through July 12, 2013.

Figure 4. Daily maximum temperatures, Mill Creek and a tributary (dashed line), June 26-27 to September 9, 2013.



Note: Data from both loggers from July 11-12, 2007 and October 10-25, 2007 were excluded. Data from these time periods were significantly warmer than from July 13, 2007 - October 9, 2007.

Figure 5. Daily maximum temperatures in Mill Creek (2007).

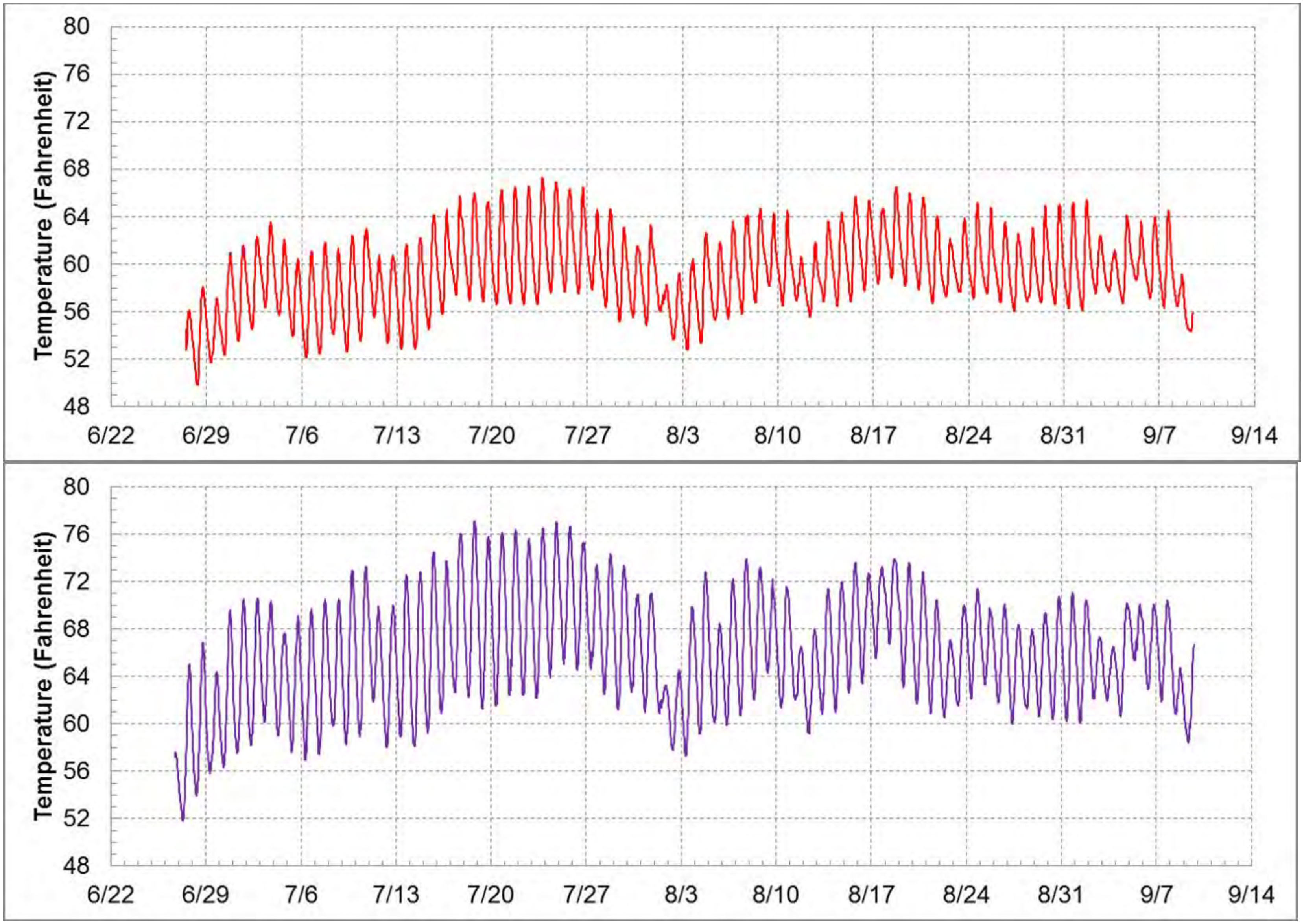


Figure 6. Continuous temperature at logger MC-T6 (top) in upper Mill Creek and logger MC-T1 (bottom) in lower Mill Creek, June 26-27 to September 9, 2013.

3 QUAL2K Model Development

EPA and DEQ selected the QUAL2K model to simulate temperatures in Mill 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 water temperatures in 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 through 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 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 and http://qual2k.com/. Additional information regarding QUAL2K is presented in the *Quality Assurance Project Plan for Montana TMDL Support: Temperature Modeling* (Tetra Tech 2012).

The following describes the process that was used to setup, calibrate, and validate the QUAL2K models for Mill Creek.

3.1 Model Framework

The QUAL2K model (Chapra et al. 2008) was selected for modeling Mill Creek. The modeling domain was limited to the main stem below MC-T6, which is approximately RM 8.46, to the mouth on Fred Burr Creek (refer back to **Figure 2** for a map of the Mill Creek watershed).

Data were specifically collected to support the QUAL2K model for the Mill Creek. Flow, shade, and continuous temperature were acquired during June, August, and September 2013. In addition, flow and temperature data were collected at a major tributary to Mill 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 June 28, 2013 and September 8, 2013, respectively. These dates were selected since they had the most complete datasets that could be used for model setup, calibration, and validation. Flow and logger temperature data were available for most sites on those dates and weather data were also available for those dates.

Calibration Period: The calibration period was June 28, 2013 and was selected due to the availability of flow and temperature data (**Appendix A**). Flow was monitored at the loggers on June 26-27, 2013. The first full day of temperature data for all the loggers was June 28, 2013. Flows monitored on June 26-27 were assumed to be representative of flow conditions on June 28, 2013 as no precipitation was recorded July 26-28, 2013[3].

Validation Period: The validation period was September 8, 2013 and was selected due to the availability of flow and temperature data (**Appendix A**). Flow was monitored at the loggers on September 9, 2013. The last full day of temperature data for all the loggers was September 8, 2013. Flows monitored on September 9, 2013 were assumed to be representative of flow conditions on September 8, 2013 as no precipitation was recorded September 8-9, 2014.

3.2.2 Segmentation

Segmentation refers to discretization of a waterbody into smaller computational units (e.g., reaches and elements). Reaches in QUAL2K have constant hydraulic characteristics (e.g. slope, bottom width) and each reach is further divided into elements that are the fundamental computational units in QUAL2K. The Mill Creek mainstem was segmented into reach lengths of 0.19 mile (300 meters), which were sufficient to incorporate any point inputs to the waterbody and to maintain Courant stability. In addition since shading is applied at the reach level this allowed for better representation of the spatial variability observed in the Shade Model results along Mill Creek (see **Appendix A** for shade modeling discussion). One major tributary, Sheafman Creek, was represented through boundary condition designation (see **Section 3.2.4** for a discussion of boundary conditions). Refer back to **Figure 2** for a map that shows the Mill Creek mainstem and its tributaries.

3.2.3 Streamflow and Hydraulics

The flow rates were estimated through flow mass balance (continuity) calculations at the loggers and other sites 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 two nearby U.S. Geological Survey (USGS) gages of similar size to Mill Creek, which is 40.0 square miles (**Table 3)**. The exponents were set to the averages calculated from the three USGS gages: 0.40 for velocity and 0.33 for depth.

Table 3. Calculated exponents for nearby USGS gages

Gage ID	Gage name	Drainage area (square miles)	Exponents	
			Velocity	Depth
12327100	Fred Burr Creek near Philipsburg, MT	15.70	0.47	0.38
13305700	Dahlonega Creek at Gibbonsville, ID	32.00	0.34	0.28

[3] Precipitation data reported for June 28, 2013 at the Smith Creek RAWS were erroneous. Weather data were also retrieved from National Weather Service station 243885, which is 6.7 miles south of the mouth of Mill Creek, to verify that no precipitation occurred at or just before the selected calibration period.

3.2.4 Boundary Conditions

Boundary conditions represent external contributions to the waterbody being modeled. A flow and temperature input file was therefore configured for inputs to Mill Creek. Boundary conditions were specified at the upstream terminus of Mill Creek (at logger MC-T6), for the Sheafman Creek confluence with Mill 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. Diurnal temperatures (June 28, 2013 for calibration and September 8, 2013 for validation) at the upstream boundary were specified using observed data from the in-stream logger at site MC-T6. A flow of 88.4 cubic feet per second (cfs) was specified for the calibration period and 9.82 cfs was specified for the validation period. **Figure 7** shows the headwater temperatures specified in the model.

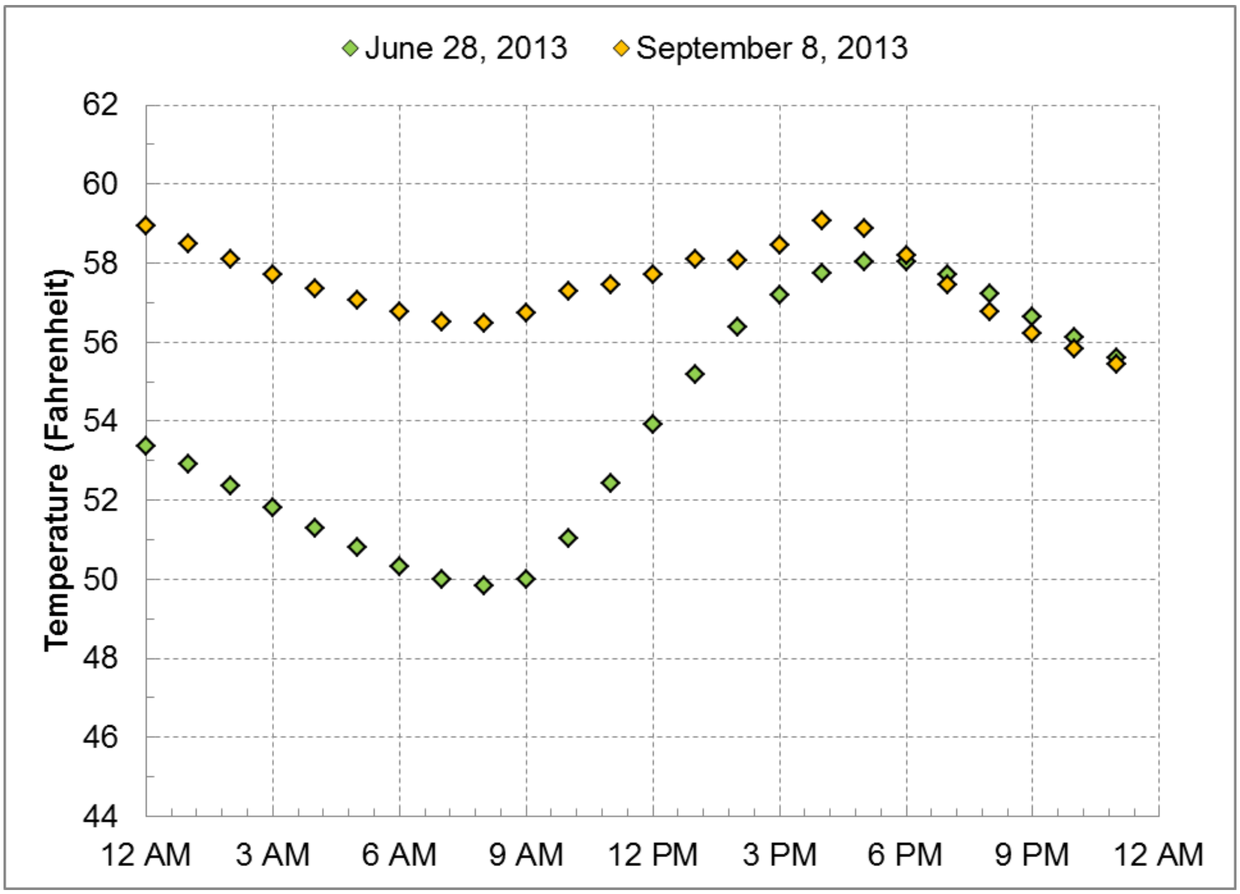


Figure 7. Diurnal temperature at the headwaters to Mill Creek.

3.2.4.2 Tributary and Irrigation Inputs

There are many small tributaries in the watershed; however, monitoring data were available for only one major tributary – Sheafman Creek (**Figure 2**). **Table 4** shows the flow and temperature assigned to Sheafman Creek.

In addition to tributary inputs, irrigation withdrawals from Mill Creek were also identified[4] (see **Appendix A** for a discussion of these withdrawals) and assigned in the model. A total of 22.4 cfs was withdrawn from Mill Creek on June 28, 2013, while 5.00 cfs was withdrawn on September 9, 2013. These withdrawals were used in the model (rows identified as *irrigation withdrawal* in **Table 4**). More information on the irrigation withdrawal can be found in **Appendix A**.

Table 4. QUAL2K model flow and temperature inputs to Mill Creek - Tributary and irrigation withdrawals

		Point sources [a]		Temperature [b]		
Description	Location (RM)	Abstraction (cfs)	Inflow (cfs)	Daily mean (°F)	½ daily range (°F)	Time of maximum (hour)
June 28, 2013						
irrigation withdrawal	8.03	2.00	--	--	--	--
irrigation withdrawal	8.01	1.95	--	--	--	--
irrigation withdrawal	7.92	4.60	--	--	--	--
irrigation withdrawal	7.72	2.25	--	--	--	--
irrigation withdrawal	6.92	4.25	--	--	--	--
irrigation withdrawal	6.69	4.25	--	--	--	--
irrigation withdrawal	6.25	1.38	--	--	--	--
irrigation withdrawal	5.87	1.75	--	--	--	--
Sheafman Creek	1.91	--	10.47	54.0	6.6	5:00 PM
September 8, 2013						
irrigation withdrawal	8.03	--	--	--	--	--
irrigation withdrawal	8.01	--	--	--	--	--
irrigation withdrawal	7.92	1.00	--	--	--	--
irrigation withdrawal	7.72	1.00	--	--	--	--
irrigation withdrawal	6.92	2.25	--	--	--	--
irrigation withdrawal	6.69	--	--	--	--	--
irrigation withdrawal	6.25	0.75	--	--	--	--
irrigation withdrawal	5.87	--	--	--	--	--
Sheafman Creek [c]	1.91	--	--	--	--	--

Notes
°F = degrees Fahrenheit; cfs = cubic feet per second; RM = river mile.
a. Points sources represent abstractions (i.e., withdrawals) or inflows. 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. Sheafman Creek ran dry and was not simulated during the validation period.

3.2.4.3 Diffuse Sources

Groundwater, irrigation return flows, and other sources of water not accounted for in the tributaries 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 Mill Creek and its tributary. The amount of diffuse flow along Mill Creek was calculated for June 28, 2013 and September 8, 2013.

[4] Jordan Tollefson (TMDL Planner, DEQ) identified 13 ditches that withdrawal water from Mill Creek for irrigation purposes, based on personal communications with Sandy Schlotterbeck and David Allen of the Mill Creek Irrigation District on February 5th, 10th, and 13th, 2014.

The initial diffuse flow temperature was selected as the maximum reported groundwater temperature (range: 44.1° F to 60.3° F) from nearby wells, which was further evaluated during calibration. A diffuse inflow temperature of 59.0° F was selected to account for potentially warmer, open channel irrigation return flows. The final flow and water temperature assignment are shown below in **Table 5**.

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

Segment	Location [a] Upstream (RM)	Downstream (RM)	Diffuse Abstraction (cfs)	Diffuse Inflow Inflow (cfs)	Temp (°F)
June 28, 2013					
MC-T6 to MC-T5	8.46	6.84	--	1.93	59.0
MC-T5 to MC-T4	6.83	5.71	20.01	--	--
MC-T4 to MC-T3	5.70	4.60	4.11	--	--
MC-T3 to MC-T2	4.60	2.85	--	6.96	59.0
MC-T2 to Sheafman Creek	2.84	1.92	--	8.29	59.0
Sheafman Creek to MC-T1	1.91	0.54	--	--	--
MC-T1 to mouth	0.53	0.00	--	--	--
September 8, 2013					
MC-T6 to MC-T5	8.46	6.84	3.99	--	
MC-T5 to MC-T4	6.83	5.71	--	0.63	59.0
MC-T4 to MC-T3	5.70	4.60	1.36	--	
MC-T3 to MC-T2	4.60	2.85	--	3.55	59.0
MC-T2 to Sheafman Creek	2.84	1.92	2.83	--	
Sheafman Creek to MC-T1	1.91	0.54	--	1.41	59.0
MC-T1 to mouth	0.53	0.00	--	--	

Notes
°F = degrees Fahrenheit; cfs = cubic feet per second; RM = river mile.
a. Upstream and downstream termini of segments.

3.2.5 Meteorological Data

Forcing functions for heat flux calculations 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. One of the nearest weather stations in the vicinity of the Mill Creek watershed is the Smith Creek RAWS (National Weather Service ID 242912), which is 7.3 miles to the north of the mouth of Mill Creek at an elevation of 5,560 feet above mean sea level. The other nearby weather station is in Hamilton (National Weather Service ID 243885); however, its dataset does not include hourly data for the pertinent weather parameters. Since the Smith Creek RAWS has a complete hourly dataset, the RAWS was used to develop the QUAL2K model (refer to Appendix A for more discussion of these two weather stations).

The Smith Creek RAWS records hourly air temperature, dew point temperature, wind speed and solar radiation. Therefore, the Smith Creek RAWS hourly observed meteorological data were used to develop the QUAL2K model after appropriate unit conversions.

The wind speed measurements at the Smith Creek 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 meters per 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 (Chapra et al. 2008):

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

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 Mill Creek. The calibrated Shade Model was first run to simulate shade estimates for June 28, 2013 to simulate hourly shade every 49 feet (15 meters, the resolution of the Shade Model) along Mill Creek. Reach-averaged integrated hourly effective shade results were then computed at every 0.19 mile (300 meters; i.e., each reach). The reach-averaged results were then input into each reach within the QUAL2K model. 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.

3.4 Model Calibration and Validation

The time periods selected for calibration and validation were June 28, 2013 and September 8, 2013; the travel times were 6 hours and three days, respectively. These dates were selected as they had the most comprehensive datasets available for modeling and corresponded to the synoptic study done for Mill Creek, which included collecting flow, temperature, and shade.

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

Table 6. Temperature calibration locations

Site name	Distance (river mile)	Available Data	Source
MC-6	8.47	Flow, depth, velocity, and temperature	Tetra Tech
MC-5	6.84	Flow, depth, velocity and temperature	Tetra Tech
MC-4	5.71	Flow, depth, velocity and temperature	Tetra Tech
MC-3	4.60	Flow, depth, velocity, and temperature	Tetra Tech
MC-2	2.85	Flow, depth, velocity, and temperature	Tetra Tech
MC-1	0.56	Flow, depth, velocity, and temperature	Tetra Tech

The first step for calibration was adjusting the flow balance and calibrating the system hydraulics. A flow balance was constructed for the calibration date. This involved accounting for all the flow in the system. Observed flows along Mill Creek, Sheafman Creek, 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 0.33 and 0.40 respectively. While the exponents were not varied during the model calibration, the rating curve coefficients were modified and evaluated against the observed data. The model results indicated a reasonable model representation. The calibrated coefficients were deemed appropriate since they were based upon observed data and yielded reasonable fits of velocity and depth. The model results indicated a reasonable model simulation as shown in **Figure 8** and **Figure 9**.

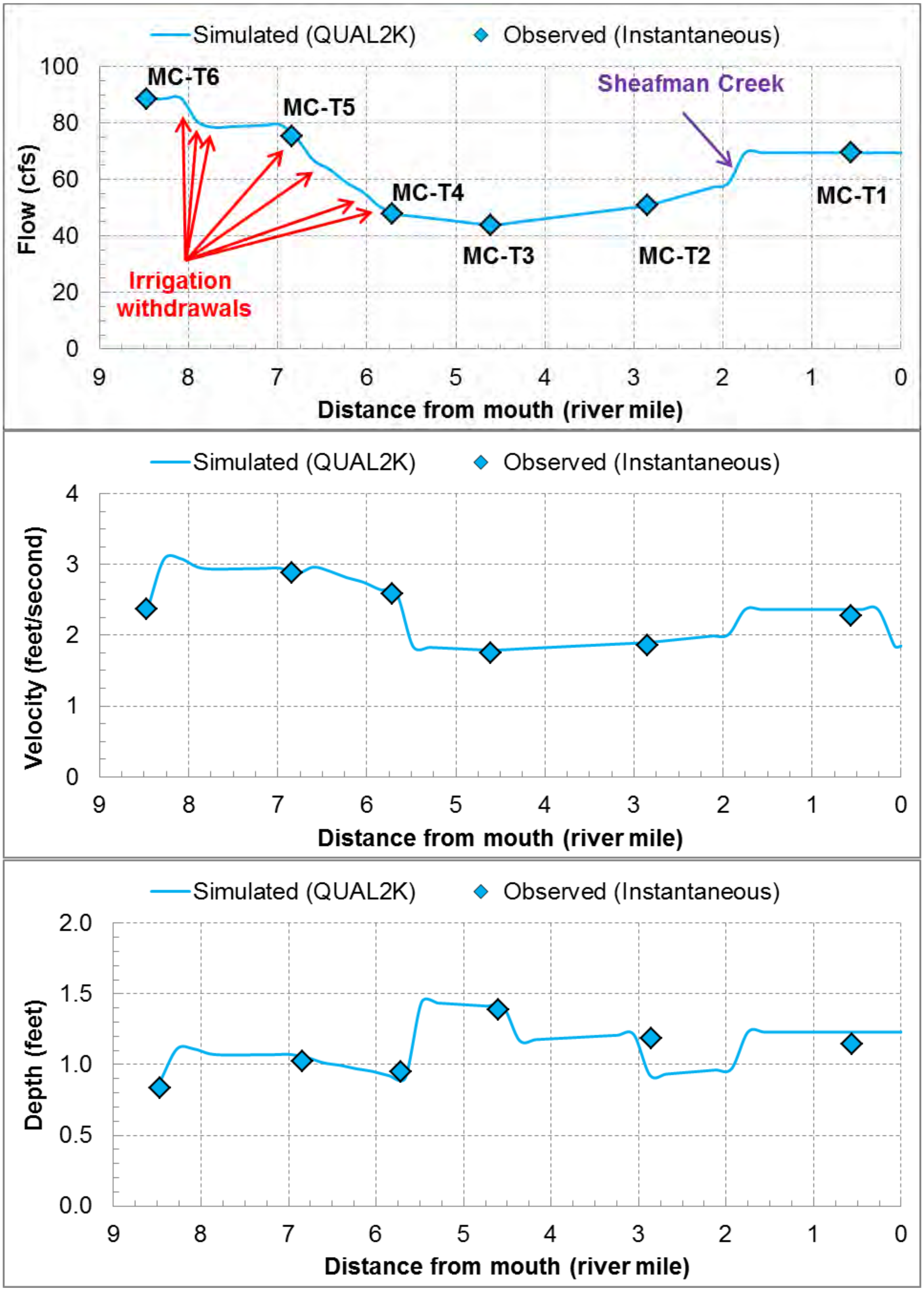


Figure 8. Observed and predicted flow, velocity, and depth on June 28, 2013 (calibration).

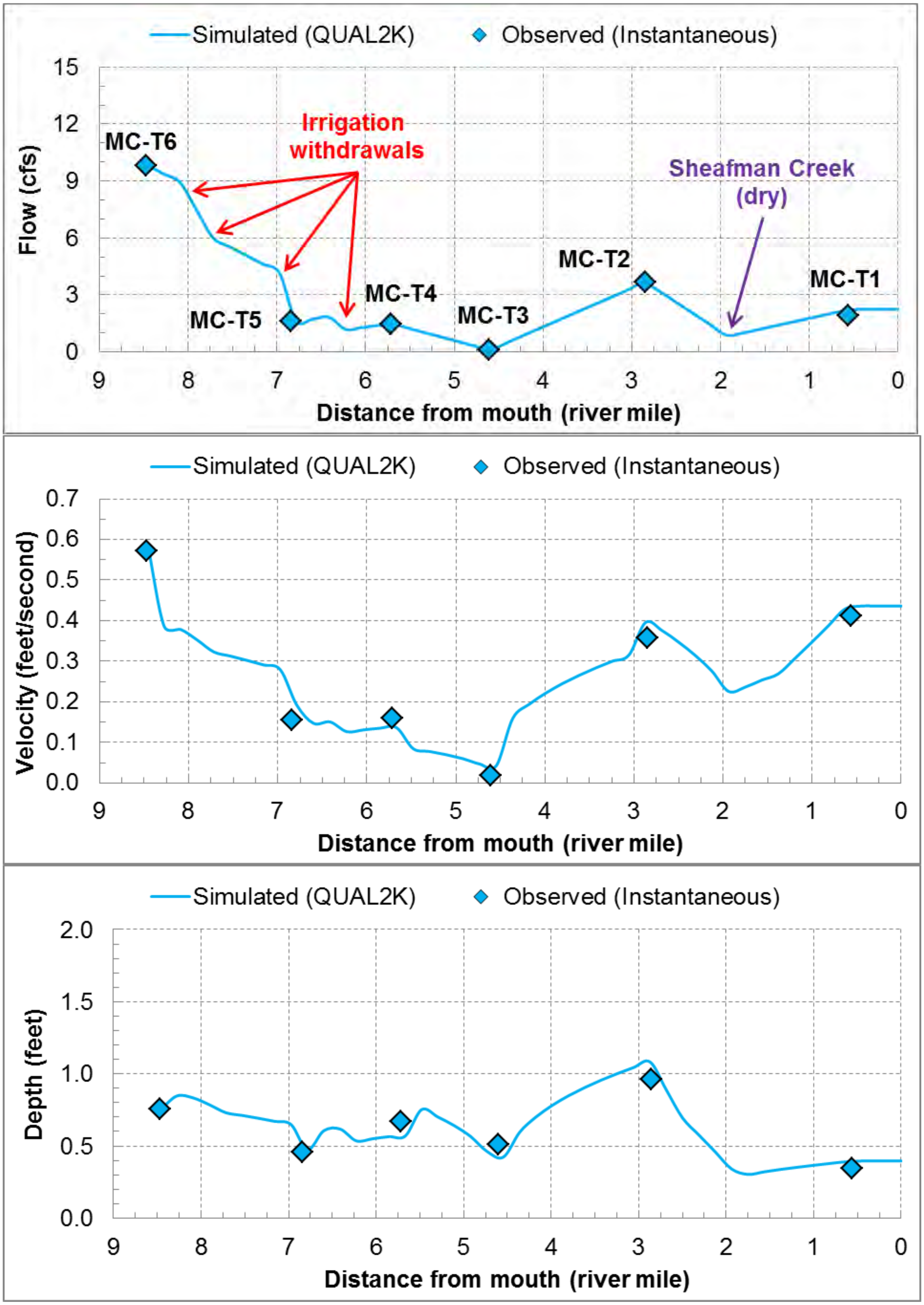


Figure 9. Observed and predicted flow, velocity, and depth on September 8, 2013 (validation).

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 Mill Creek, the Ryan-Stolzenbach model was used to calculate the solar radiation. The calculated solar radiation values (without stream shade) for the calibration and validation were compared with observed solar radiation measurements at the Smith Creek RAWS. **Figure 10** shows the observed and predicted solar radiation for the calibration. The Ryan-Stolzenbach atmospheric transmission coefficient was set at 0.90 for the calibration to reflect the atmospheric conditions (i.e., cloudy) to minimize the deviation between the observed and modeled short wave solar radiation.

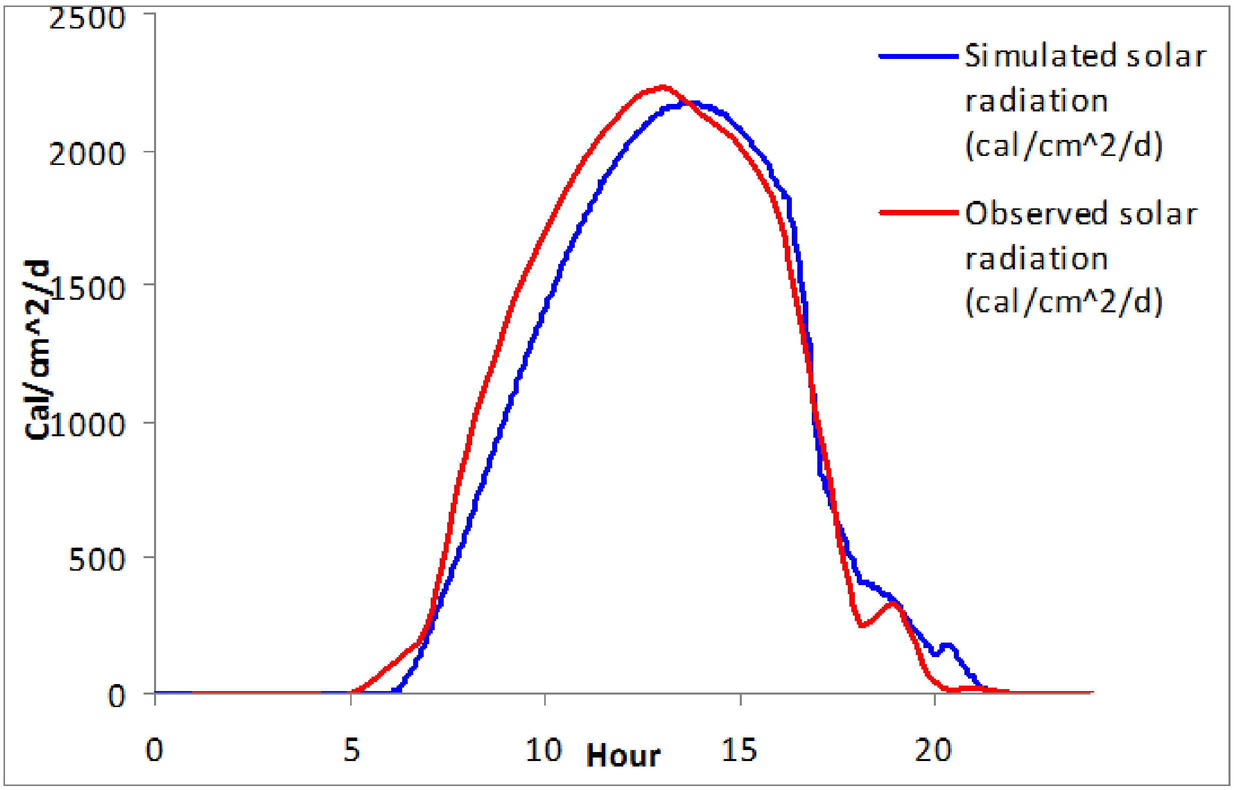


Figure 10. Observed and predicted solar radiation on June 28, 2013 (calibration).

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]	0.90
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 increased from the default value of 10 cm to 20 cm, and the sediment heat capacity of all component materials of the stream was set to 0.4 calories per gram per degree Celsius, which is the QUAL2K default (Chapra et al. 2008).

The sediment density was set to 2.04 grams per cubic centimeter (g/cm^3). Based on the field photographs, the surface layer of the stream substrate was estimated to be composed of 80 percent rock gravel and 20 percent of silt and clay. The following calculation was conducted:

$$\begin{aligned}\text{sediment density} &= (\text{ratio} * \text{density})_{\text{gravel}} + (\text{ratio} * \text{density})_{\text{silt and clay}} \\ &= (0.80 * 2.00\ g/cm^3) + (0.20 * 2.20\ g/cm^3) \\ &= 2.04\ g/cm^3\end{aligned}$$

where 2.00 g/cm^3 is the density of gravel and 2.20 g/cm^3 is typical of clay and silt densities.

The sediment thermal diffusivity was set to a value of 0.0112 square centimeters per second (cm^2/s; Chapra et al. 2008). The following calculation was conducted:

$$\begin{aligned}\text{thermal diffusivity} &= (\text{ratio} * \text{thermal diffusivity})_{\text{rock+gravel}} + (\text{ratio} * \text{thermal diffusivity})_{\text{sand}} \\ &\quad + (\text{ratio} * \text{thermal diffusivity})_{\text{silt}} \\ &= (0.80 * 0.0118\ cm^2/s) + (0.11 * 0.0079\ cm^2/s) + (0.09 * 0.0098\ cm^2/s) \\ &= 0.0112\ cm^2/s\end{aligned}$$

where 0.118 cm^2/s is the thermal diffusivity of rock, 0.0079 cm^2/s is the thermal diffusivity of sand, and 0.0098 cm^2/s is the thermal diffusivity of clay, which is assumed to be representative of silt.

These adjustments helped in improving the minimum temperatures simulated.

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. The atmospheric transmission coefficient was changed from 0.90 in the calibration, which represents cloudy conditions, to 0.70 in the validation, which represents clear conditions for much of the day. All other inputs were based on observed data June 28, 2014. Groundwater temperatures, for which there were no direct observed data, were unchanged since they are not expected to vary greatly. **Figure 11** and **Figure 12** show the calibration and validation results along Mill Creek. The temperature calibration and validation statistics of the average, maximum, and minimum temperatures are shown in **Table 8** and **Table 9**, respectively.

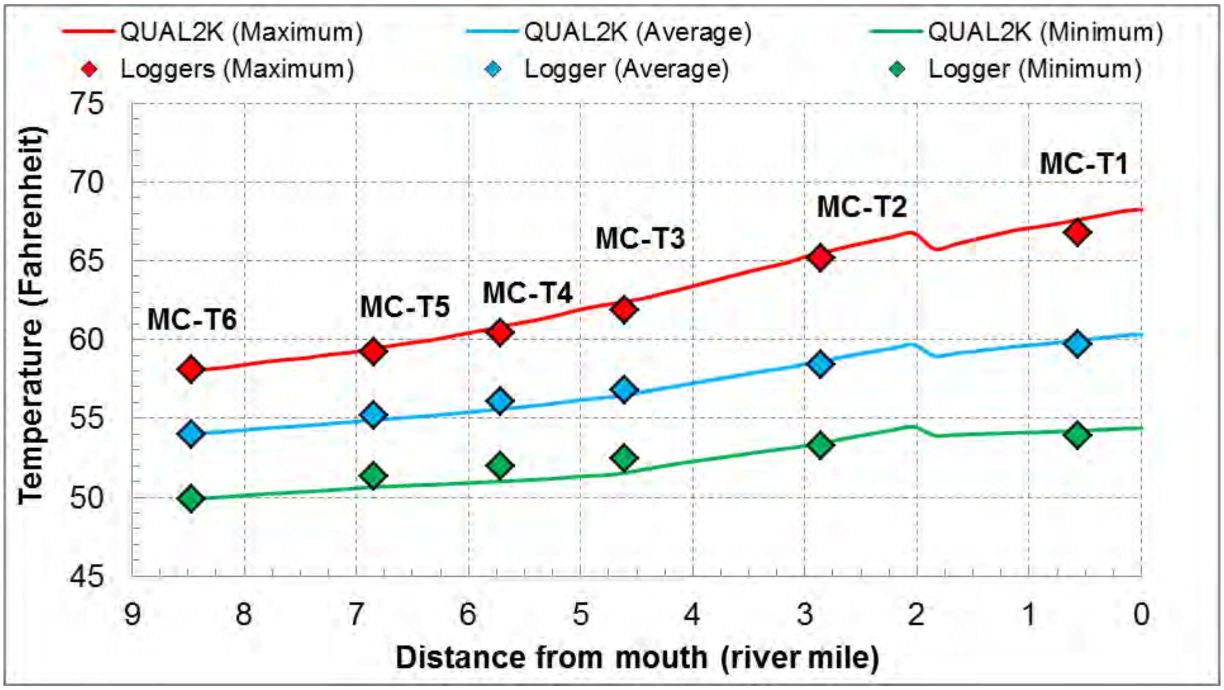


Figure 11. Longitudinal profile of the temperature calibration (June 28, 2013).

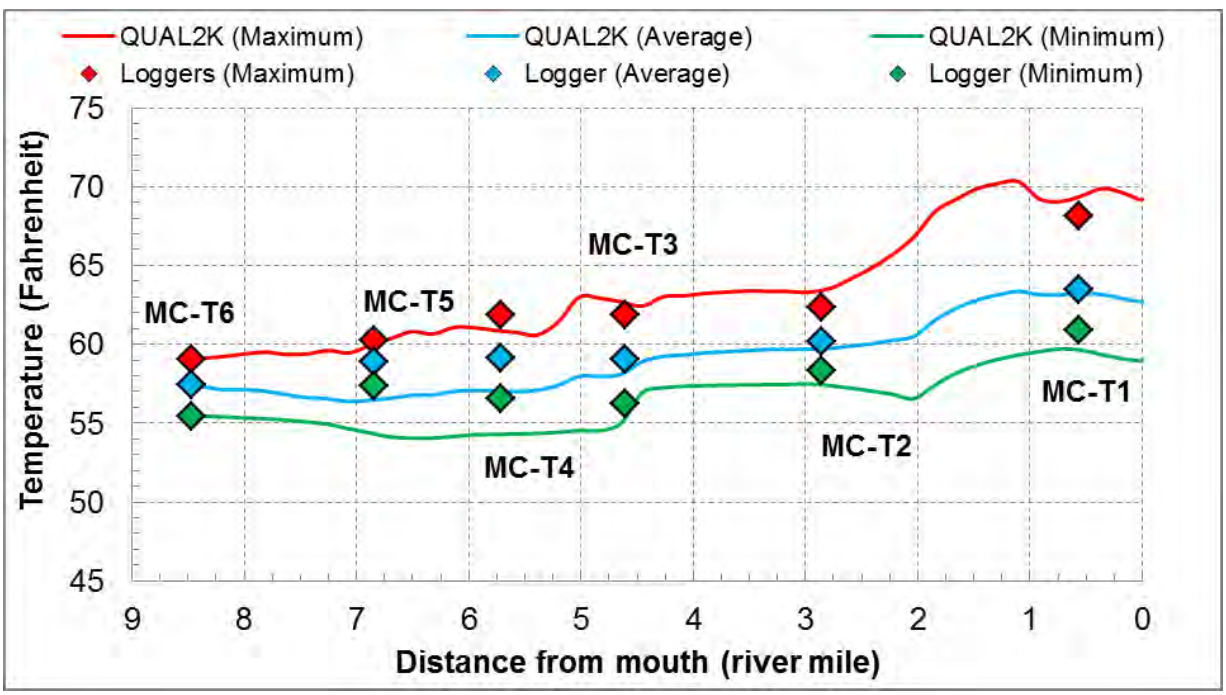


Figure 12. Longitudinal profile of the temperature validation (September 8, 2013).

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 (%)
MC-T6	8.47	--	--	--	--	--	--
MC-T5	6.84	0.30	0.5%	0.23	0.4%	0.71	1.4%
MC-T4	5.71	0.52	0.9%	0.33	0.5%	1.02	2.0%
MC-T3	4.60	0.35	0.6%	0.52	0.8%	0.92	1.8%
MC-T2	2.85	0.29	0.5%	0.49	0.7%	0.28	0.5%
MC-T1	0.56	5.46	9.1%	0.90	1.3%	0.29	0.5%
Overall Calibration		**1.38**	**2.4%**	**0.49**	**0.8%**	**0.64**	1.2%

Note: AME = absolute mean error; REL = relative error; RM = river mile.

Table 9. Validation 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 (%)
MC-T6	8.47	--	--	--	--	--	--
MC-T5	6.84	2.41	4.1%	0.29	0.5%	2.98	5.2%
MC-T4	5.71	2.05	3.5%	0.94	1.5%	2.26	4.0%
MC-T3	4.60	0.97	1.6%	0.85	1.4%	1.19	2.1%
MC-T2	2.85	0.09	0.2%	1.22	2.0%	0.95	1.6%
MC-T1	0.56	0.27	0.4%	1.25	1.8%	1.23	2.0%
Overall Validation		**1.16**	**1.9%**	**0.91**	**1.4%**	**1.72**	**3.0%**

Note: AME = absolute mean error; REL = relative error; RM = river mile.

Based on the calibration results, the model is able to simulate the flow, depth, and velocity and the minimum, mean, and maximum temperatures reasonably well. The model over-predicts the minimum, mean, and maximum temperature at all loggers though the AMEs of the maximums (range: 0.23° F to 0.90° F) are considerably smaller than the AMEs of the averages (range: 0.29° F to 5.46° F) and the minimums (range: 0.28° F to 1.02° F) (**Table 8**). The overall calibration results showed an overall 0.8 percent relative error with an AME of 0.49° F for the maximum temperatures; thus, the model simulation is good.

The model results for the validation are similar to those of the calibration. The model often over-predicts the minimum and mean temperatures and often under-predicts the maximum temperatures (**Table 9**). However, the AMEs of the maximums (range: 0.29° F to 1.25° F) are considerably smaller than the AMEs of the averages (range: 0.09° F to 2.41° F) and the minimums (range: 0.95° F to 2.98° F). The overall validation results showed an overall 1.4 percent relative error with an AME of 0.91° F for the maximum temperatures.

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 sometimes not sensitive to changes in water use but are sensitive to changes in shade. This is however stream/rivers specific, thus the sensitivity of water withdrawals and shade were explored with the Mill Creek QUAL2K model during model development and the results were generally 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 Mill Creek QUAL2K model was used to evaluate in-stream temperature response associated with multiple management scenarios. **Table 10** summarizes the alterations for each model scenario. The following subsections present discussions of the modifications to the QUAL2K models and the results for each scenario.

Table 10. QUAL2K model scenarios for Mill Creek

Scenario [a]		Description	Rationale
Baseline Scenario			
1	Existing Condition	Summer shade (August 12, 2013) and irrigation practices (average of August 12-13, 2013) under low-flows[b] and summer weather conditions (August 15,2013)	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	Shade increased to reference levels	Increased shading along two segments: (1) from RMs 7.5 to 4.5 to be equivalent to MC-T3, and (2) from RM 4.5 to the mouth to be equivalent to MC-T2.	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 increase to reference levels (scenario 3).	Represent application of conservation practices for water withdrawals and riparian vegetation.

Notes

a. Scenarios were developed in accordance with electronic correspondence from the DEQ project manager Jordan Tollefson to Tetra Tech's project manager Ron Steg on April 15-29, 2014.

b. Flows from the calibration model, which were field-monitored on June 26-27, 2013, were reduced 79 percent to represent August flow conditions, based in part upon field measured flows on June 26-27, 2013 and August 12-13, 2013 and flow relationships at a surrogate USGS gage (12342500 West Fork Bitterroot River, near Connor, MT).

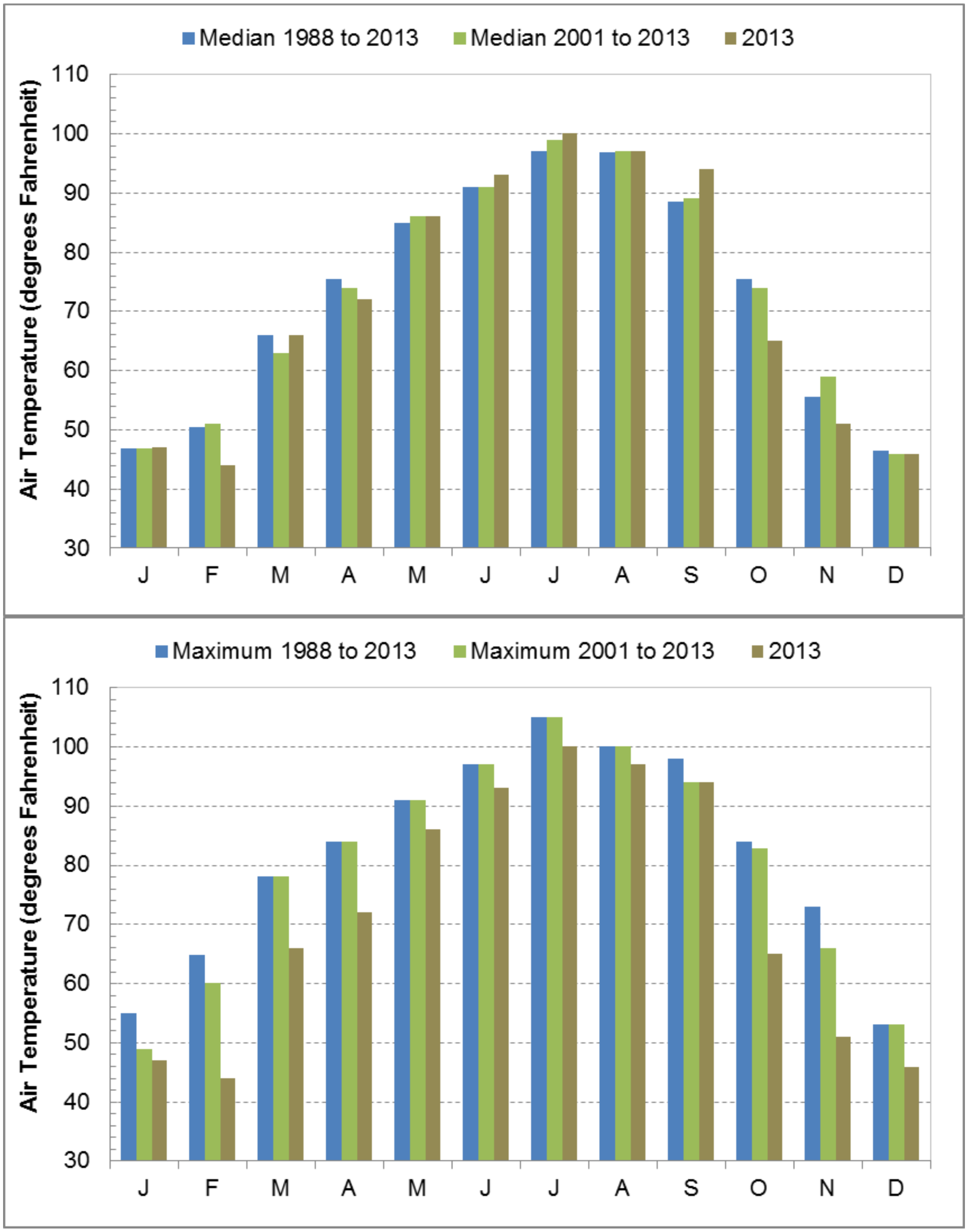
4.1 Baseline Scenario

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 flow and weather conditions from August 12-15, 2013 to create a synthetic August condition.

4.1.1.1 Weather Data

The Smith Creek RAWS has hourly data available for the period from February 2001 through May 2014. Since the weather data extends only for a period of 14 years, a nearby station with long-term meteorological data (Missoula International Airport [1988-2013]) was queried to confirm if the years from 2001 to 2013 were (1) not anomalously warm or cold and (2) similar to the overall historical normal. Additionally, comparisons with the year 2013 (during which the QUAL2K model calibration period occurs) were made to ensure that 2013 was not an anomalous year. The long-term monthly median and maximum air temperatures for the period from 2001 to 2013 and for the year 2013 were estimated to be similar to the overall period from 1988 through 2013 (**Figure 13**)[7]. While the monthly maximum air temperatures in the summer of 2013 were cooler than the monthly long-term maximum of monthly maximum air temperatures of the years 1988-2013, they were warmer in some months as compared with the monthly long-term median of monthly maximum air temperatures of the years 1988-2013 (**Figure 13**). Therefore, since neither the period from 2001 through 2013 nor the summer of 2013 was substantially anomalous, it is appropriate to use the Smith Creek 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 2013 using the hourly average air temperatures. Monthly long-term medians and maximums were calculated from the 26 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 2013 using the hourly average air temperatures. Monthly long-term medians and maximums were calculated from the 26 years of monthly maximums of hourly average air temperatures.

Figure 13. Long-term median (chart on top) and maximum (chart on bottom) of monthly maximum air temperature at Missoula.

4.1.1.2 Synthetic August Weather

Weather conditions from August 15, 2013 were used for the baseline model. While the mid-season flows were monitored on August 12-13, 2014, the solar radiation from these days indicated considerable cloud cover. To simulate a more typical sunny August day, the solar radiation from August 15, 2013 was selected as the most representative sunny day in mid-August, though there were some clouds in the evening. All QUAL2K model inputs for weather were selected from the Smith Creek RAWS for August 15, 2013.

4.1.1.3 Synthetic Low-Flow

No continuous flow datasets are available in the Mill Creek watershed. The closest continuously recording USGS gage in a watershed of similar size is gage 12353650 (West Fork Bitterroot River at USGS gage 12353650; water years 1941-2013). Daily average flows for the surrogate gage on the days that instantaneous flow data were collected from Mill Creek are presented in **Section A-6** of **Appendix A**.

The Mill Creek model was calibrated to June 28, 2013, which was representative of spring high-flows. Therefore, the flow condition for the calibration model was not used and a synthetic August low-flow condition was developed. Since the input of monitored flows on August 12-13, 2013 would require a re-calibration of the hydrology, all flow inflows and outflows were reduced by 79 percent to preserve the water balance developed during model calibration. This 79 percent reduction factor was based upon a comparison of monitored flows from June 26-27, 2013 and August 12-13, 2013. The 79 percent reductions were applied to tributary and headwaters boundary conditions inflows and groundwater inflow/outflows.

4.1.1.4 Irrigation Withdrawals

The August 12-13 irrigation withdrawals provided by DEQ were used to develop the baseline condition. Refer to Section A-8 of Appendix A for a discussion of irrigation withdrawal data. The baseline was developed using August because considerably less water is diverted for irrigation in September.

4.1.1.5 Baseline Scenario Results

The modeled water temperatures for the baseline scenario are shown below in **Figure 14**. The simulated maximum temperatures ranged from 58.0° F to 81.7° F. Simulated maximum daily temperatures exceeded 80 F from the mouth upstream to river mile 0.17, from river miles 2.59 to 3.52 (segments upstream of logger MC-T2), and from river miles 4.64 to 4.83 (just upstream of logger MC-T3). The warmest temperature (81.7° F) occurred at river mile 2.96, just upstream of logger MC-T2).

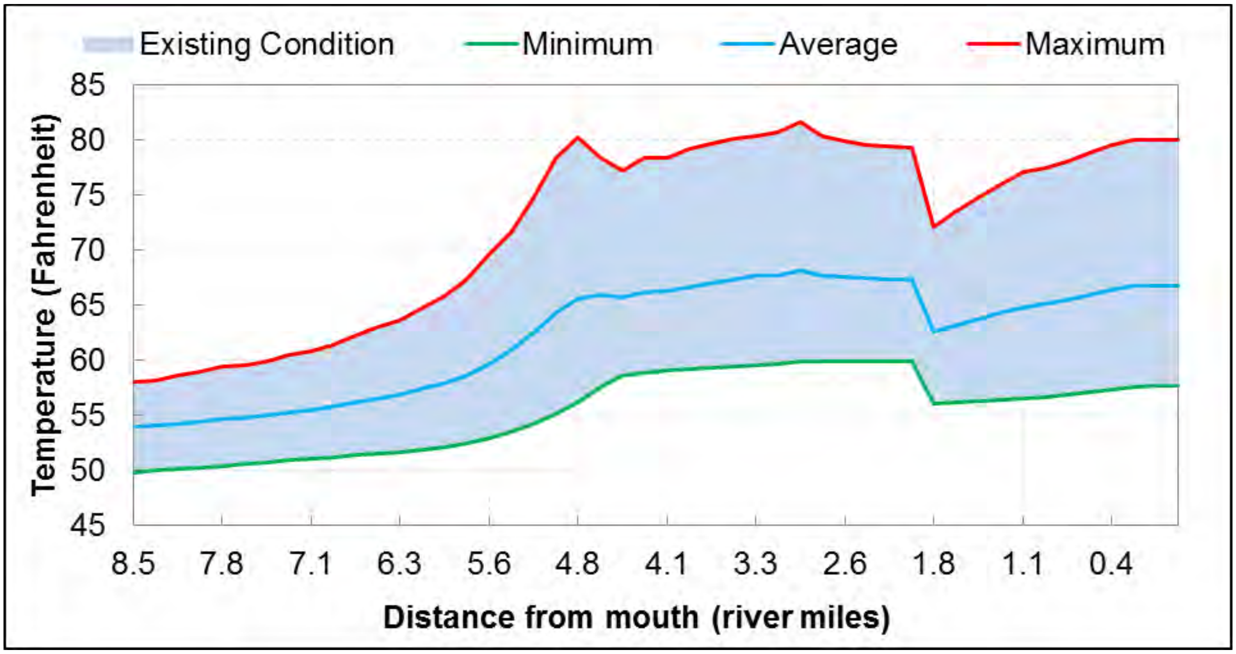


Figure 14. Simulated water temperature for baseline condition (August 15, 2013).

4.2 Water Use Scenario

Irrigation (or other water withdrawals) deplete the volume of water in the stream and reduce in-stream volumetric heat capacity. Theoretically the reduced stream water volume heats up more quickly (and also cools more quickly), 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 point sources abstractions representing the withdrawals (see **Appendix A** and **Table 4** for the withdrawals) in the QUAL2K model are reduced by 15 percent (NRCS 1997). The water previously withdrawn (2.07 cfs) is now allowed to flow down Mill Creek; flow in Mill Creek was 2.52 cfs at logger MC-T1, near the mouth, on August 13, 2013. This scenario is intended to represent application of conservation practices relative to water use.

The water temperatures under this scenario generally exhibited decreases along the middle segments of Mill Creek that reflect the locations of the irrigation withdrawals (**Figure 15**). The maximum change in the maximum daily water temperature is representative of the worst case conditions. A maximum change in the maximum daily water temperature of 8.1° F from the existing condition was observed at RM 4.8. Cooler temperatures at RM 4.8 may be due to the upstream irrigation withdrawals' reductions that allowed for more water in Mill Creek.

The changes in maximum daily temperatures from the water use scenario, as compared to the baseline, ranged from 8.1° F cooler to 0.7° F warmer with an average of 0.7° F cooler. The temperature difference of the daily maximums was 0.5° F or greater for about three-fifths of the stream.

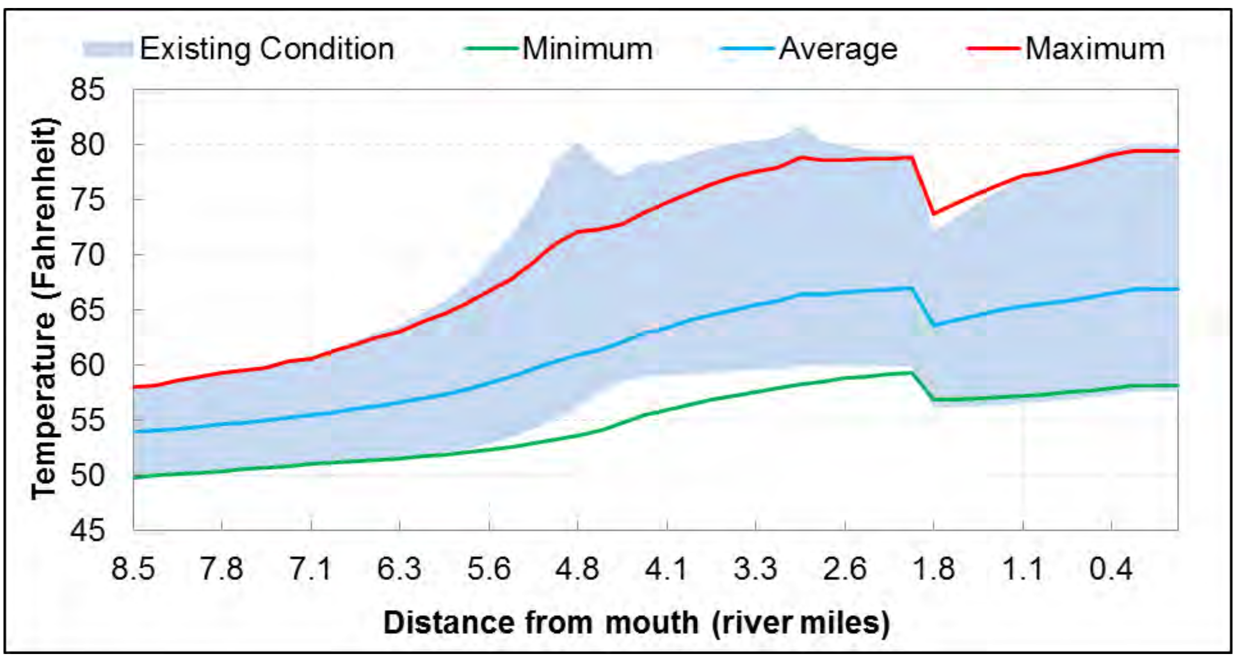


Figure 15. Simulated water temperatures for the baseline (scenario 1) and 15-percent withdrawal reduction (scenario 2).

4.3 Shade Scenario

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 certain segments of Mill Creek.

An evaluation of shading using the Solar Pathfinder™ measurements, Shade model results, GIS, and aerial imagery and incorporating DEQ's input resulted in the following conclusions:

1. Vegetation along Mill Creek above RM 7.5 (i.e., above logger MC-T6) is likely at potential and there is very little opportunity to improve shade. Therefore, the segments upstream of logger MC-T6 will not be altered for the shade scenario.
2. Vegetation communities along Mill Creek from RMs 7.5 to 4.5 (i.e., just upstream of logger MC-T5 to logger MC-T3) are dominated by mixed coniferous/deciduous forest and are impacted by encroachment from residential developments and agriculture. There is opportunity to convert some of the encroached areas to mixed coniferous/deciduous trees. Therefore, shade along this segment will be improved to a reference condition, which is conservatively defined as the segment at logger MC-T3 that is forested and at potential.
3. Downstream of RM 4.5 (i.e., from logger MC-T3 to the mouth), Mill Creek flows through predominantly low-density residential lands. There is opportunity to improve the vegetation communities in these areas. Therefore, shade along this segment will be improved to a reference condition, which is conservatively defined as the segment at logger MC-T2 that is composed of shrubs in a 50-foot to 100-foot buffer, when the existing average daily effective shade of a given segment is less than 50 percent.

The Mill Creek QUAL2K model was re-run using the altered shade inputs, based upon the findings presented above (**Table 11**); refer to **Appendix B** for additional information regarding the shade scenario. This scenario is intended to represent application of conservation practices relative to shade although it is important to note that even in natural forested conditions, there are still openings in the canopy and some areas without vegetation. Hence this is likely an upper limit to what plausibly could occur from vegetation management practices.

Table 11. Average daily shade inputs per model segment

Segment	Existing condition (scenario 1)	Shade (scenario 3)
MC-T6 to MC-T5	68%	69%
MC-T5 to MC-T4	61%	61%
MC-T4 to MC-T3	52%	59%
MC-T3 to MC-T2	39%	47%
MC-T2 to Sheafman Creek	36%	46%
Sheafman Creek to MC-T1	39%	48%
MC-T1 to mouth	53%	55%

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).

Water temperatures in Mill Creek downstream of logger MC-T4 decreased (**Figure 16**). A maximum change in the maximum daily water temperature of 3.7° F from the baseline was observed at RM 4.8. Shading increased between RMs 4.73 to 4.92, which had lower levels of shading that segments immediately upstream and downstream of this segment. The larger change (to cooler temperatures) at RM 4.8 was likely do to the increased shading. The difference in the daily maximum water temperature between the baseline and shade scenario was greater than 0.5° F from RM 5.2 to the mouth. It is important to note the caveats previously stated: that this is likely the largest improvement that could be observed through vegetation management practices.

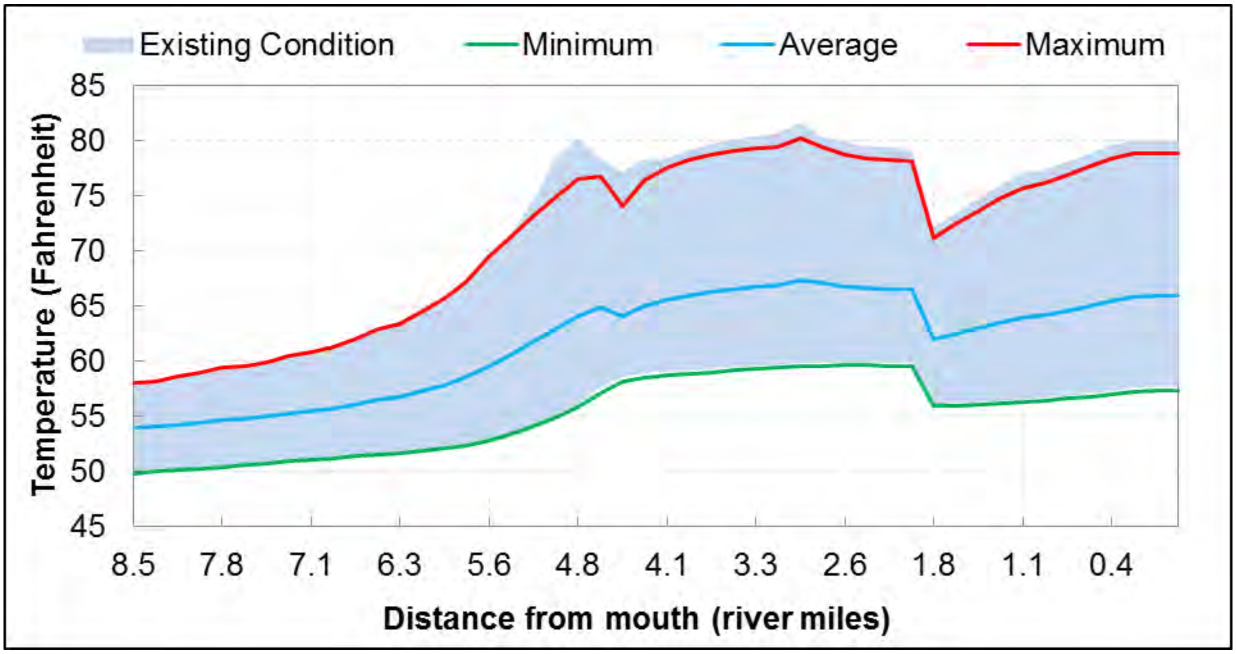


Figure 16. Simulated water temperatures for the baseline (scenario 1) and increased shade (scenario 3).

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 increases shade to reference levels along certain segments (scenario 3).

Simulated maximum daily temperatures ranged from 58.0° to 65.5° from rivermiles 8.5 to 5.6 and ranged from 66.7° to 78.8° from rivermiles 5.6 to the mouth. As per the temperature standard discussed in **Section 2.2**, anthropogenic activities may increase the in-stream temperatures by 1.0° F for the segment from rivermiles 8.5 to 5.6 and by 0.5° F for the segment from rivermile 5.6 to the mouth.

In this scenario, water temperatures in Mill Creek decrease throughout much of the system (**Figure 17** and **Figure 18**). A maximum change in the maximum daily water temperature of 10.3° F from the baseline was observed at RM 4.8. The changes in maximum daily temperatures from the improved flow and shade scenario, as compared to the baseline, ranged from 10.3° F cooler to 0.5° F warmer with an average of 2.5° F cooler. The difference in the daily maximum water temperature between the baseline and the improved flow and shade scenario was greater than 1.0° F in most simulated segments of Mill Creek, which confirms that Mill Creek is impaired by elevated in-stream water temperatures.

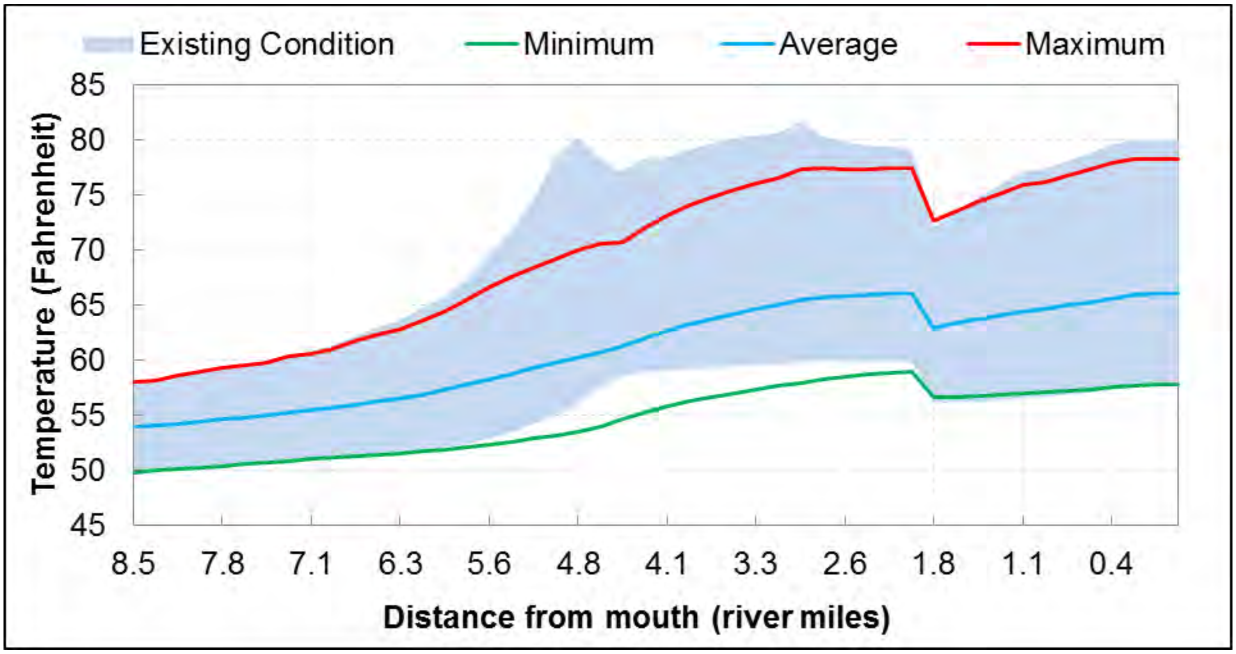


Figure 17. Simulated water temperature for the baseline (scenario 1) and the improved flow and shade scenario (scenario 4).

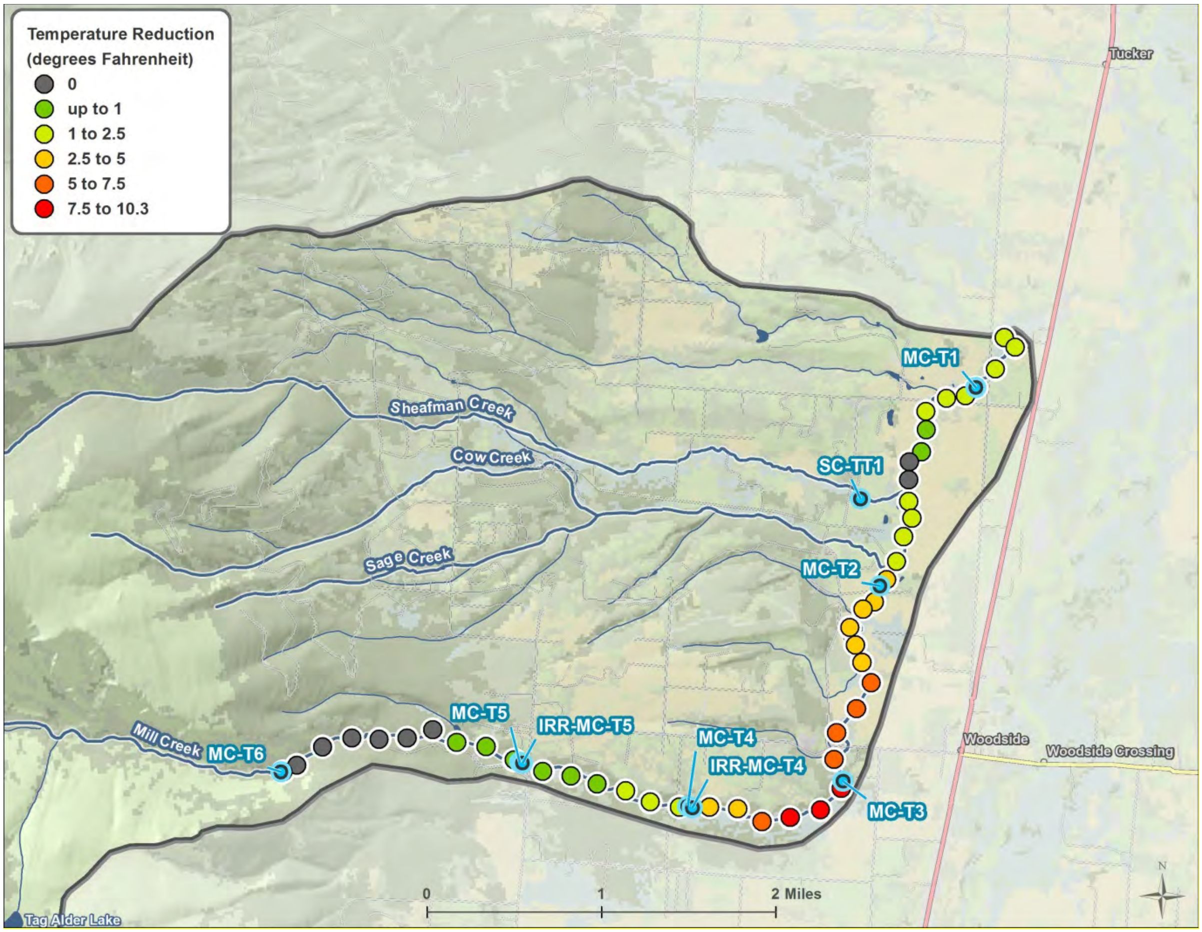


Figure 18. In-stream temperature difference from the baseline (scenario 1) to the improved flow and shade scenario (scenario 4).

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 Mill Creek QUAL2K model development:

- Mill 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 Mill 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 Smith Creek RAWS are representative of local weather conditions along Mill Creek.
- Shade Model results are representative of riparian shading along segments of Mill 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 Mill 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 8 percent. (i.e., the average error from the Shade Model output and Solar Pathfinder™ measurements was 5 percent daily average shade).

- 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.

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

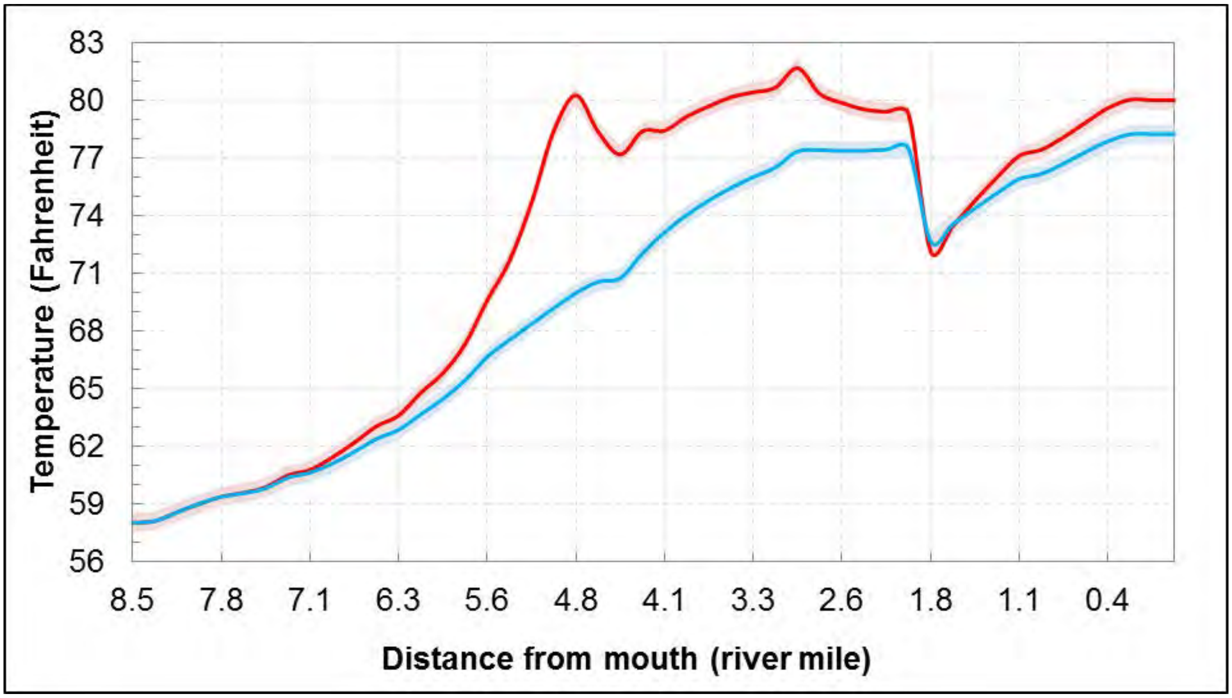
The model is only valid for summertime, warm-weather conditions and should not be used to evaluate high flow or other conditions. As described above, steps were taken to minimize uncertainty as much as possible. Despite the uncertainty, the model adequately addresses the primary questions:

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 Mill Creek. As previously discussed, Mill Creek is sensitive to shade and flow.

The second question can be answered using the calibrated QUAL2K model and the scenarios developed to assess water use and shade. In this instance, increasing riparian shading will decrease in-stream temperatures significantly (>3°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. Additionally, decreasing water diverted for irrigation will decrease in-stream temperatures significantly (>8°F for maximum). While a "good" model calibration was achieved, the overall Absolute Mean Error (AME) for the maximum daily temperature was 0.5° F.

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 Mill 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 and reduction of irrigation withdrawals to allow more water to flow down the stream. 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 baseline (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 (0.5° F).

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

7 Conclusions

The scenarios resulted in water temperatures reductions as much as 10.3° F.

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 resulted in appreciable reductions to the temperature in the middle segments of Mill Creek. The largest reductions (range: 4.5° F to 8.1° F) occurred from RMs 4.1 to 5.2.

The improved shade scenario showed smaller temperature reductions than the water use scenario; however, the improved shade scenario showed reductions along more length of stream than the water use scenario. Reductions of 0.5° F occurred from RM 5.2 to the mouth.

The improved flow and shade scenario that combined the potential benefits associated with a 15 percent reduction in water withdrawals (scenario 2) with increased shading based upon reference levels (scenario 3) to represent application of conservation practices relative to the temperature impairment was also simulated. This scenario resulted in overall reductions along the most of the stream, which ranged from <0.1° F to 10.3° F (Table 12), except for the segment from RMs 1.7 to 1.9. The scenario shows that reductions in water temperatures are achievable throughout the stream, but reductions of 0.5° F are achievable from RMs 6.5 to 6.1 and reductions of 1.0 F are achievable from RM 6.1 to the mouth (except from RMs1.3 to 1.9); refer back to **Figure 18** for a map of potential temperature reductions. The greatest potential improvement (i.e., reduction) occurs between RMs 2.8 and 5.4 (4.1° F to 10.3° F improvement) (**Figure 21**). Above logger MC-T6 (about RM 8.5), the vegetation communities are at potential and no shade improvements were simulated. Efforts should be spent on re-vegetation in these areas most amenable to this type of restoration activity in the lower reaches of Mill Creek.

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	-8.1 to +1.6	-1.6	-0.6	-3.8 to +0.7	-0.7	-0.1
3	Shade	-3.7 to 0	-0.9	-1.1	-0.4 to 0	-0.2	-0.2
4	Improved Flow and Shade	-10.3 to +0.5	-2.5	-1.8	-3.9 to +0.5	-0.8	-0.1

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 Mill Creek as compared with the baseline scenario.

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

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

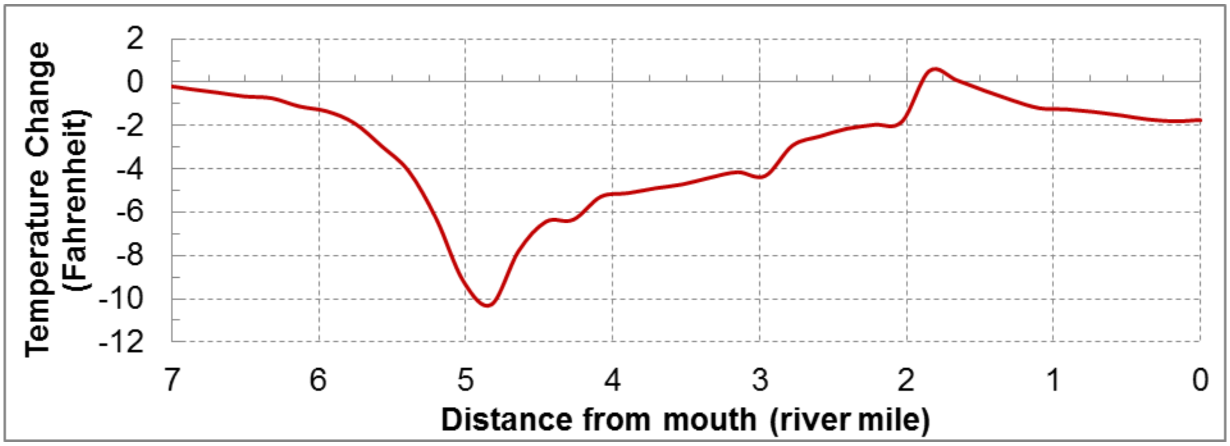


Figure 20. Simulated water temperature reduction from the existing condition (scenario 1) to the improved flow and shade scenario (scenario 4).

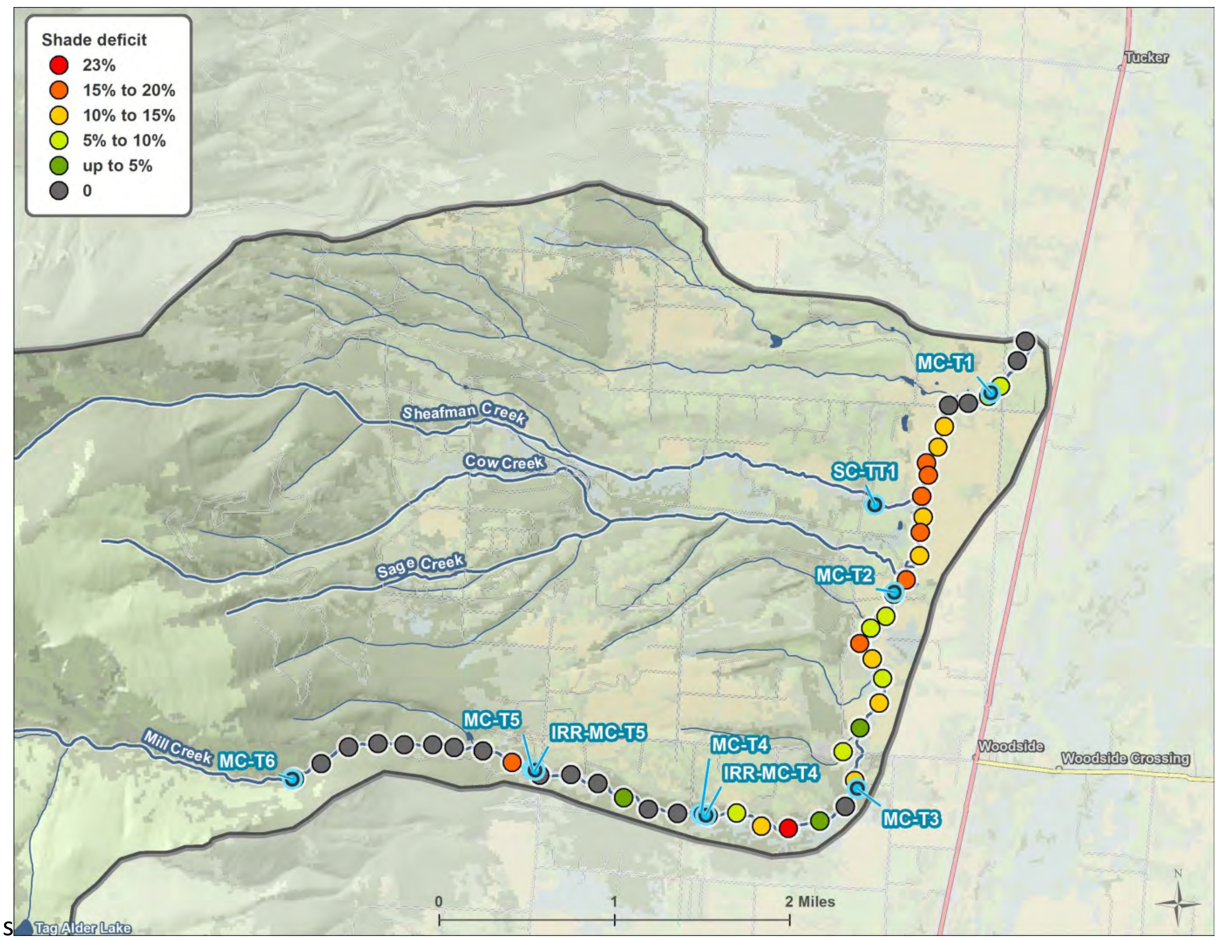


Figure 21. Shade deficit of the existing condition (scenario 1) from the improved flow and shade scenario (scenario 4).

8 References

Chapra, S.C., 1997. Surface water quality modeling. McGraw-Hill Companies, Inc.

Chapra, S., G. Pelletier, and H. Tao. 2008. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.11: Documentation and User's Manual. Tufts University, Civil and Environmental Engineering Department, Medford, MA.

Chow, V.T., D.R. Maidment, and L.W. Mays, 1988. Applied Hydrology. McGraw-Hill, New York. 592 pp.

DEQ (Montana Department of Environmental Quality). 2013. Water Quality Assessment Database. Montana Department of Environmental Quality, Clean Water Act Information Center. <http://cwaic.mt.gov/query.aspx>. Accessed June 5, 2013.

Multi-Resolution Land Characteristics Consortium. 2006. *National Land Cover Dataset 2006*. <http://www.mrlc.gov/nlcd2006.php>. Accessed June 28, 2012.

NRCS (Natural Resources Conservation Service). 1997. National Engineering Handbook Irrigation Guide, Part 652. United States Department of Agriculture, Natural Resources Conservation Service. Washington, D.C.

Poole, G.C., Risley, J. and M. Hicks. 2001. Issue Paper 3 – Spatial and Temporal Patterns of Stream Temperature (Revised). United States Environmental Protection Agency. EPA-910-D-01-003.

Tetra Tech. 2012. *Quality Assurance Project Plan for Montana TMDL Support: Temperature Modeling*. QAPP 303 Revision 0, March 28, 2012. Prepared for the U.S. Environmental Protection Agency, by Tetra Tech, Inc., Cleveland, OH.

Appendix A.

Factors Potentially Influencing Stream Temperature

in Mill Creek

Contents

Tables

Figures

A-1. Introduction

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 factors that may have an influence on stream temperatures in Mill Creek are discussed below:

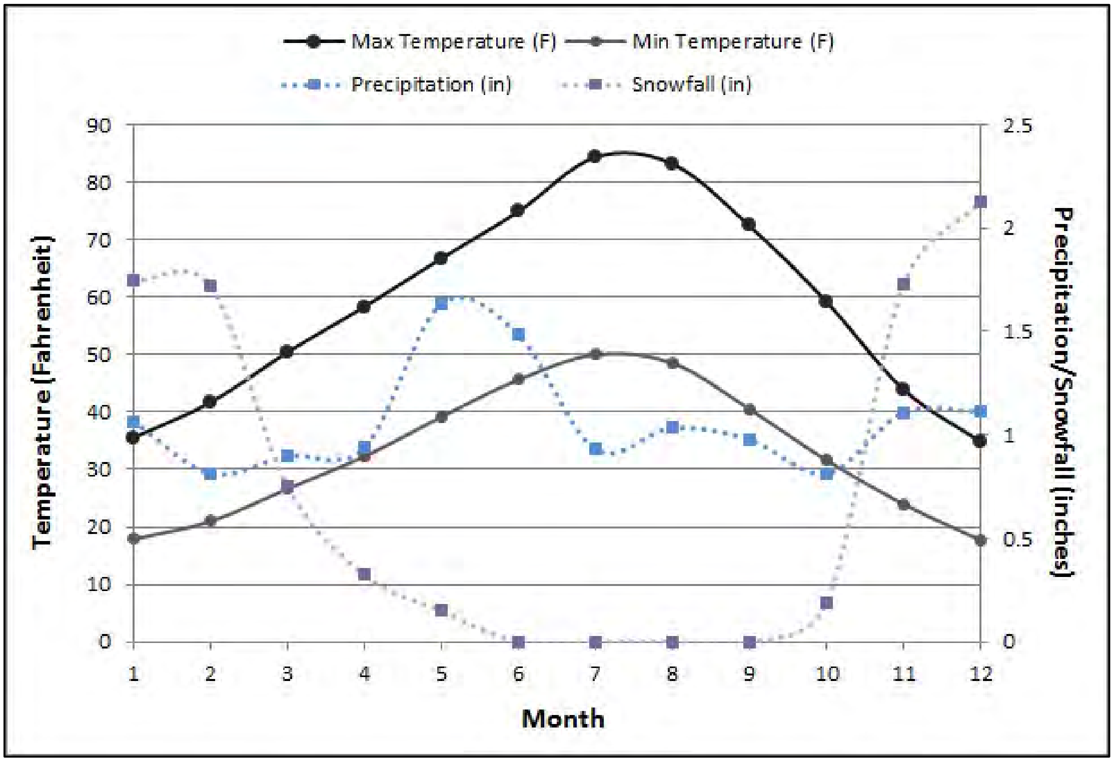
- Local/regional climate
- Land ownership
- Land use
- Riparian vegetation
- Shade
- Hydrology
- Point sources

A-2. Climate

The nearest weather station to the Mill Creek watershed is located in the city of Hamilton, Montana, 6.7 miles to the south of the mouth of Mill Creek. (National Weather Service station 243885). Average annual precipitation is 12.8 inches with the greatest amounts falling in May and June (**Figure A-2**; National Climate Data Center 2012). Average maximum temperatures occur in July and August and are 84.3° F and 83.1° F, respectively.

It should be noted that the Hamilton weather station is located at an elevation of 3,593 feet above MSL, compared to Mill Creek that ranges in elevation from approximately 3,400 to 8,800 feet above MSL.

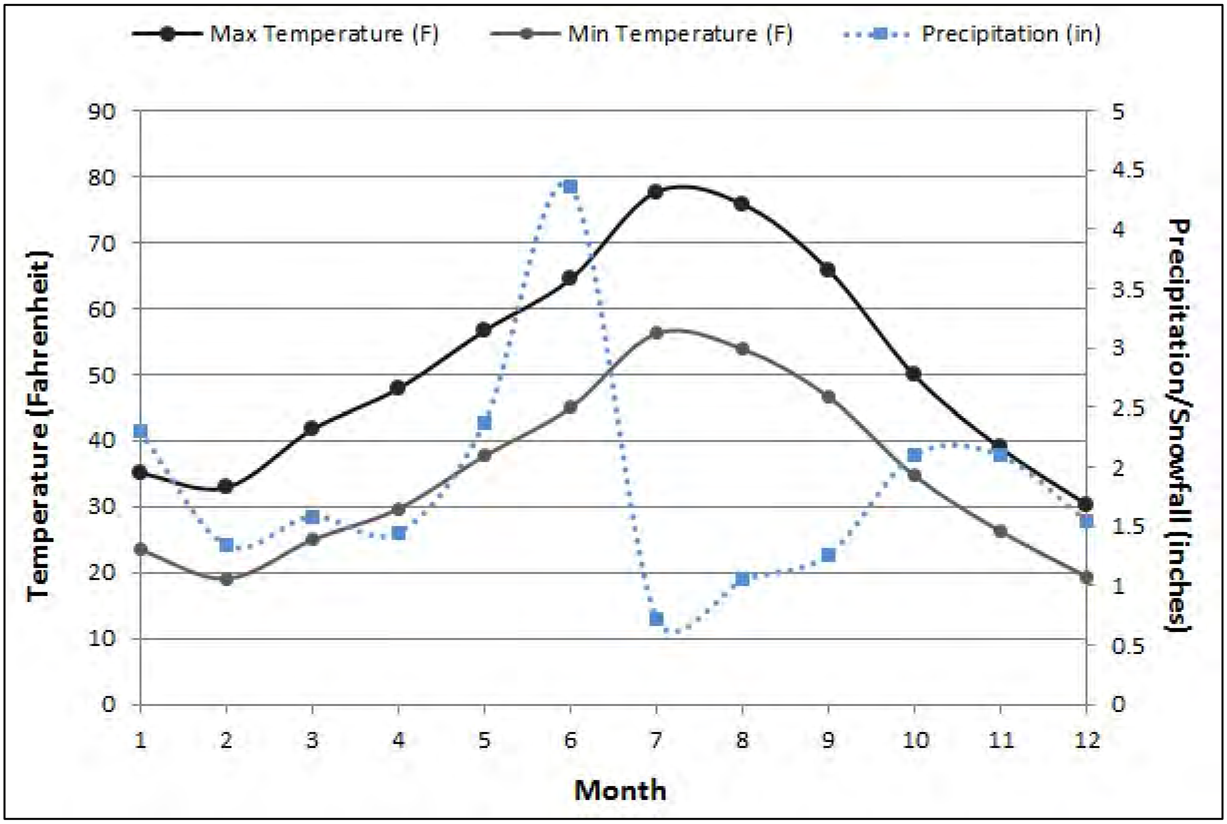
Figure A-1. Mill Creek watershed.



Source: GHCN-D Monthly Summaries from 1970 to 2012 at Station 243885 (National Climactic Data Center 2013).

Figure A-2. Monthly average temperatures and precipitation at Hamilton, Montana.

The Hamilton station only has hourly air temperature data and does not have additional hourly datasets necessary for QUAL2K modeling. The Smith Creek RAWS records hourly air temperature, dew point temperature, wind speed and solar radiation and these data were used to develop the QUAL2K model. The Smith Creek RAWS is located 7.3 miles to the north of the mouth of Mill Creek at an elevation of 5,650 feet above MSL, compared to Mill Creek that ranges in elevation from approximately 3,400 to 8,800 feet above MSL.

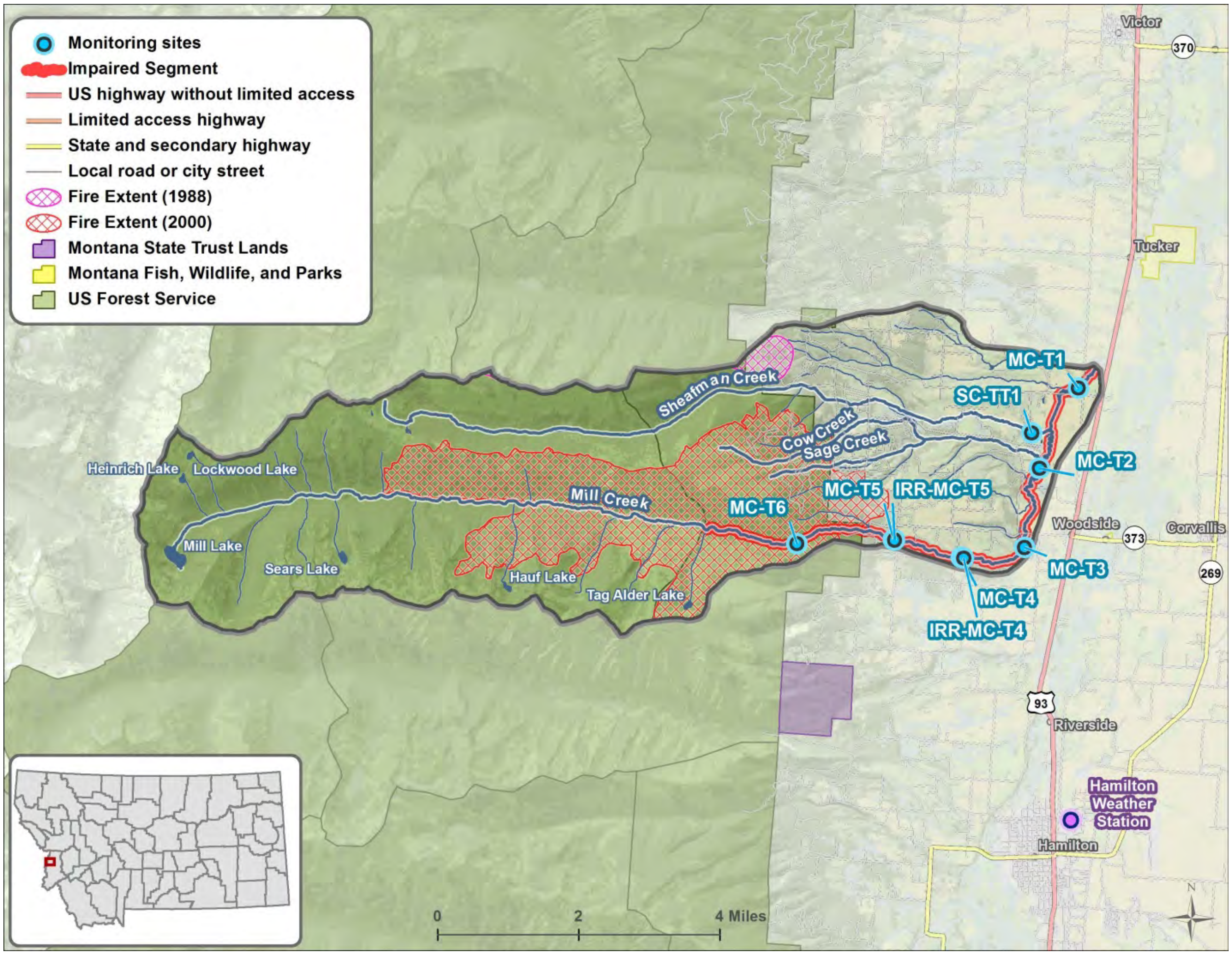


Source: RAWS weather data from 2001 to 2013 at Smith Creek station (Western Regional Climate Center, 2014).

Figure A-3. Monthly average temperatures and precipitation at Smith Creek RAWS.

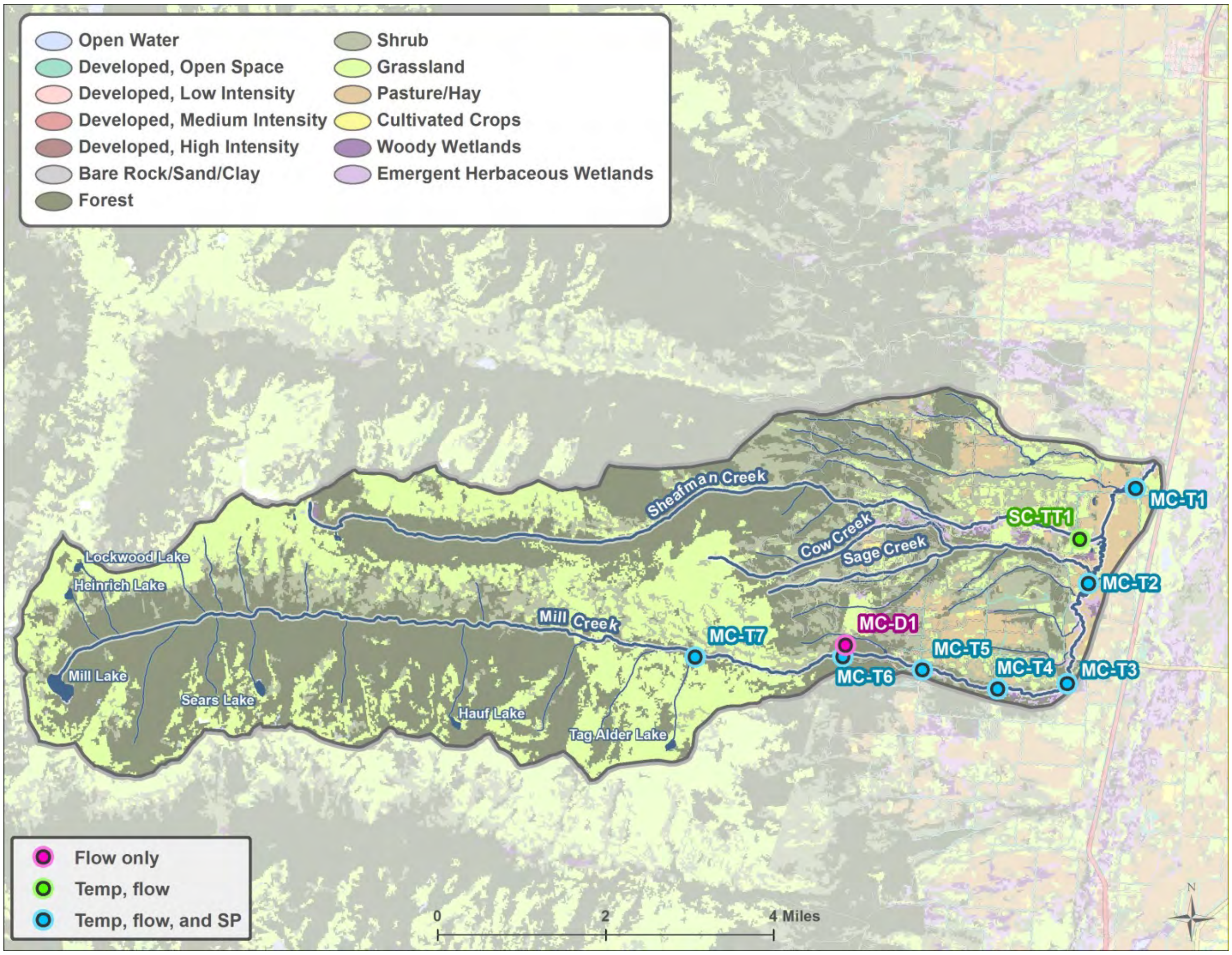
A-3. Land Ownership and Land Use

The upper two-thirds of the Mill Creek watershed is owned by the U.S. Forest Service and is predominantly forested (**Figure A-4** and **Figure A-5**). Two fires occurred in recent history within the watershed (U.S. Forest Service 2008). The earliest, in 1988, covered 240 acres, or approximately 1% of the watershed (**Figure A-4**). More recently, in 2000, a fire covering 6,551 acres (26% of the area) occurred in the middle section of the watershed (**Figure A-4**). The lower reaches of the watershed are privately held and transition into a mosaic of small acerage agricultural lands and low density residential.



Source of land ownership: NRIS 2012.

Figure A-4. Land ownership in the Mill Creek watershed.



Source of land cover: 2006 National Land Cover Dataset (MRLC, 2006).

Figure A-5. Land cover and land use in the Mill Creek watershed.

A-4. Existing Riparian Vegetation

A comprehensive inventory and assessment of the current riparian vegetation communities adjacent to Mill Creek was not conducted as part of this project. Riparian vegetation communities, however, were qualitatively assessed, and the height and density of the dominant vegetation were measured at the six shade monitoring sites in August 2013. A summary of the observed characteristics of the vegetation communities is provided in **Table A-1**.

The impaired reach of Mill Creek is 8.7 miles in length. The upper 2.5 miles flow through the Bitterroot National Forest in an area that was burned in 2000. The riparian corridor in this area, however, is largely un-impacted by the fire and dominated by conifer forest with an alder understory. This vegetation appears to be at its natural potential.

Downstream, Mill Creek flows out of the mountains and onto private property until discharging into the Bitterroot River. Mixed coniferous/deciduous forests and shrub communities are more common in the riparian corridor in this lower reach. Throughout much of its length in this lower reach, the riparian corridor has been encroached upon, to varying degrees, by agricultural and residential land uses. Sites MC-T1 and MC-T5 (refer to **Figure A-8** for site locations) are examples of areas not meeting their potential due to encroachment by residential and agricultural activities. Where undisturbed buffers have been maintained (e.g., sites MC-T2, MC-T3, and MC-T4), the vegetation appears to be largely at potential.

Table A-1. Observed characteristics of the Mill Creek riparian vegetation community

Station ID	Site Name	Dominant Vegetation	Vegetation at potential?	Average Vegetative Density (percent shade)[a]	Dominant Vegetation Height (feet)[a]	Dominant Vegetation Overhang (feet)[a]	Description
MC-T1	Mill Creek near mouth	Shrub	N	62	17.5	7	This site is located in a rural residential area. An approximate 25 ft. band of shrubs (willow, alder, and dogwood) borders the stream at this location, with mowed lawns or agricultural fields adjacent on the landward side.
MC-T2	Mill Creek near Shadow Mountain Road	Shrub	Y	92	17.5	1.5	Wetland shrub dominated riparian corridor (willows and alders) with an occasional cottonwood. Point bars dominated by reed canary grass.
MC-T3	Mill Creek near Dutch Hill Rd	Tree (mixed decid/conifer)	Y	***75***	63	3.5	Forested site dominated by cottonwood and pine.
MC-T4	Mill Creek near Pheasant Run Rd	Tree (mixed decid/conifer)	Y	84	62		Mixed deciduous/coniferous vegetation community (cottonwood, aspen, pine, spruce).
MC-T5	Mill Creek near Bowman Rd	Tree (mixed decid/conifer)	N	***25-75***	46	10	The right bank is dominated by cottonwood and alder. The left bank has been partially cleared with occasional pine/spruce remaining.
MC-T6	Mill Creek headwaters	Tree (conifer)	Y	75	80		This site is located on the edge of a burned area. The riparian corridor, however, has been largely unaffected and is dominated by pine/spruce with an occasional cottonwood with an alder dominated understory.

Notes
Bold/italicized blue values are based on visual estimate (no measurements available).
a: Average of field measurements.

Vegetation communities between the shade monitoring sites were visually characterized based on aerial imagery (GoogleEarth™ 2013) with qualitative field verification conducted during temperature logger deployment and retrieval. Observed vegetative communities within 150 feet of the stream centerline were classified as trees, shrubs, herbaceous. Areas without vegetation, such as bare earth or roads, were also identified. Trees were further divided into the following classes based on percent canopy cover derived from the 2001 National Land Cover Dataset (**Figure A-6**):

- High density (75 to 100 percent cover)
- Medium density (51 to 74 percent cover)
- Low density (25 to 50 percent cover)
- Sparse density (less than 24 percent cover)

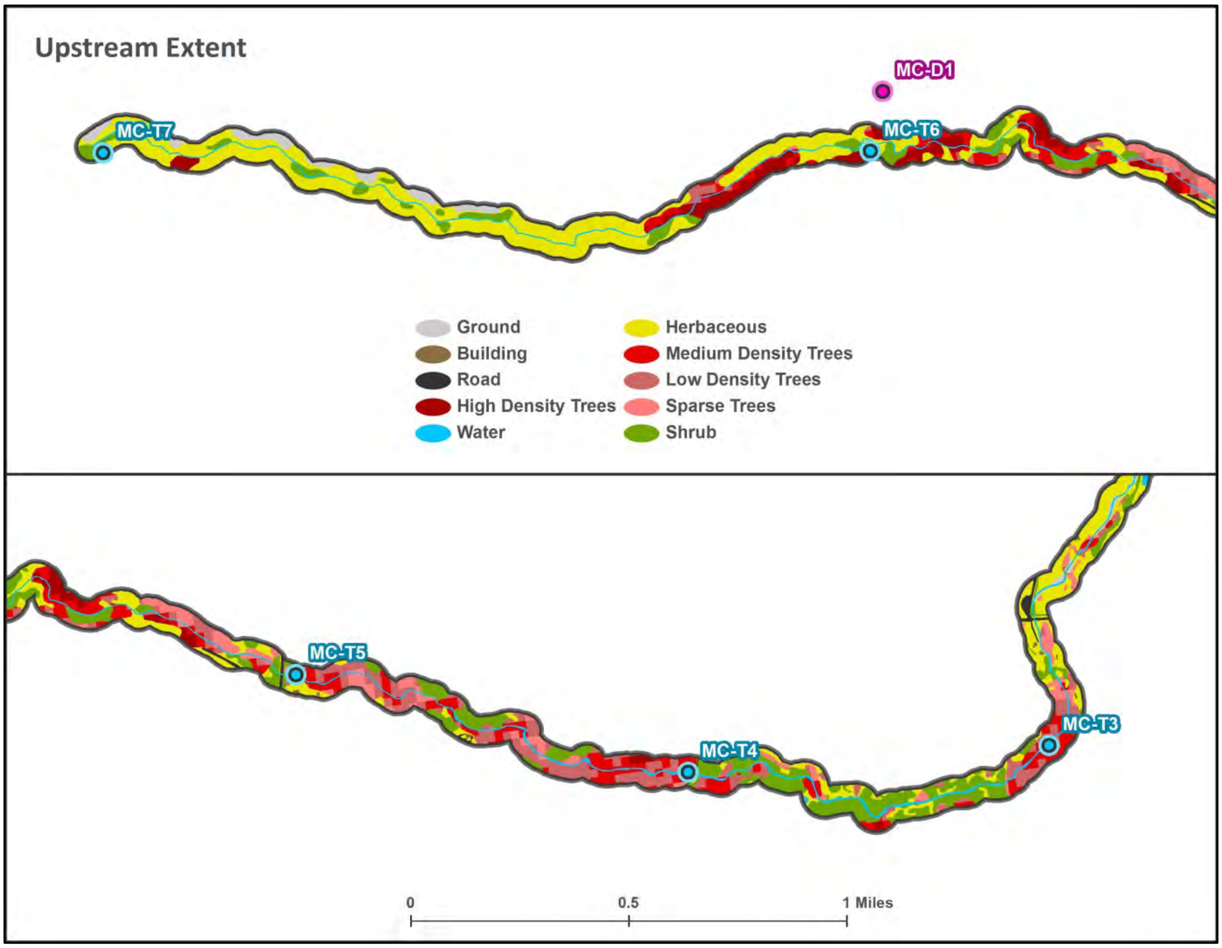


Figure A-6. Vegetation mapping example for Mill Creek in the upper reaches.

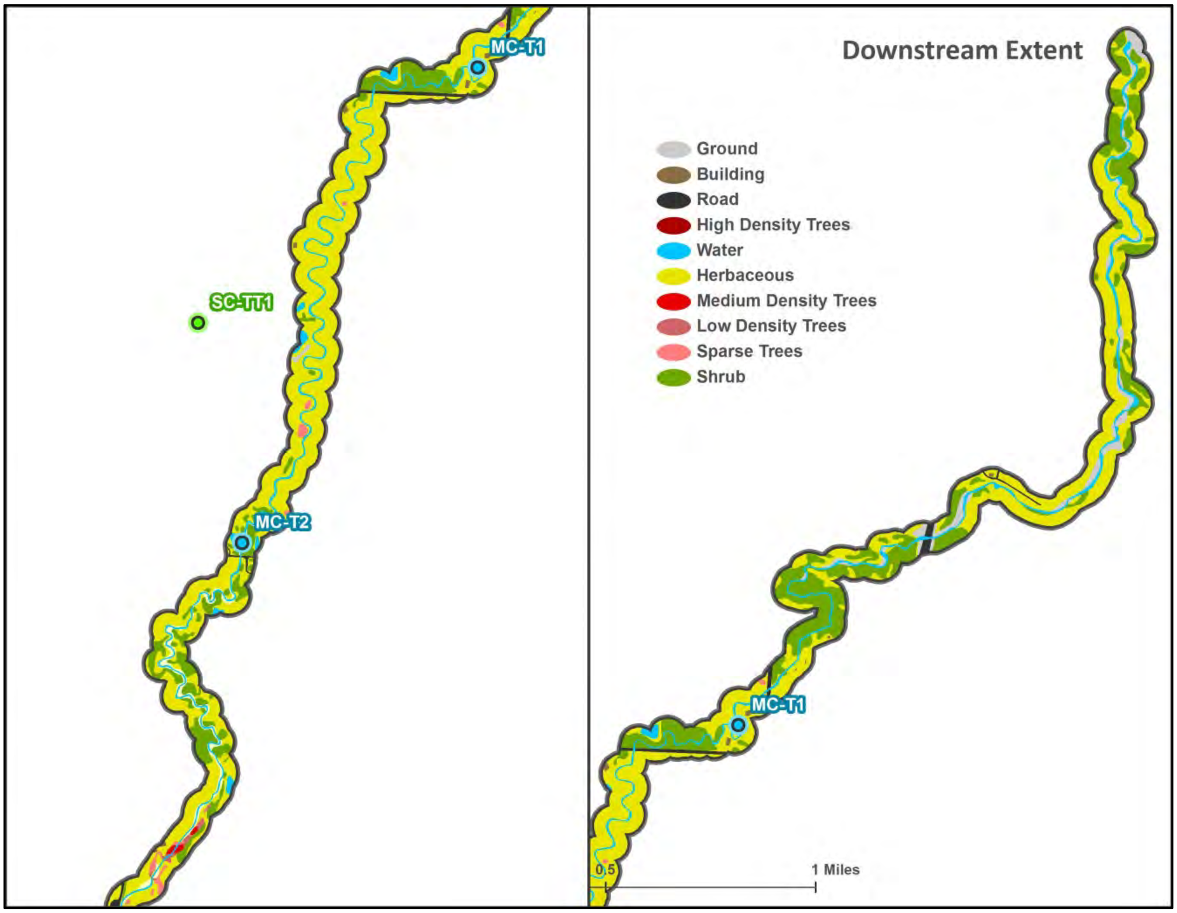


Figure A-7. Vegetation mapping example for Mill Creek in the lower reaches.

Herbaceous vegetation (47 percent) is the most common cover type along Mill Creek, followed by shrubs and trees (**Table A-2**).

Table A-2. Land cover types in the Mill Creek riparian zone

Land cover type	Area (acres)	Relative area (percent)
Buildings	0.9	0.2%
Bare ground	18.0	4.0%
Herbaceous	213.4	47.0%
Roads	5.2	1.2%
Shrub	98.3	21.7%
Sparse trees	14.8	3.2%
Low density trees	28.7	6.3%
Medium density trees	28.0	6.2%
High density trees	13.8	3.0%
Water	32.9	7.2%

A-5. Shade

Shade is one of several factors that control in-stream water temperatures. Shade is defined as the fraction of potential solar radiation that is blocked by topography and vegetation.

A-5.1. *Measured Shade*

Under contract with EPA, Tetra Tech collected shade characterization data on August 12 & 13, 2013 at six monitoring locations along Mill Creek using a Solar Pathfinder™ (**Figure A-8**). Hourly shade estimates based on the Solar Pathfinder™ measurements are presented in **Attachment A**. The data are summarized in **Table A-3**.

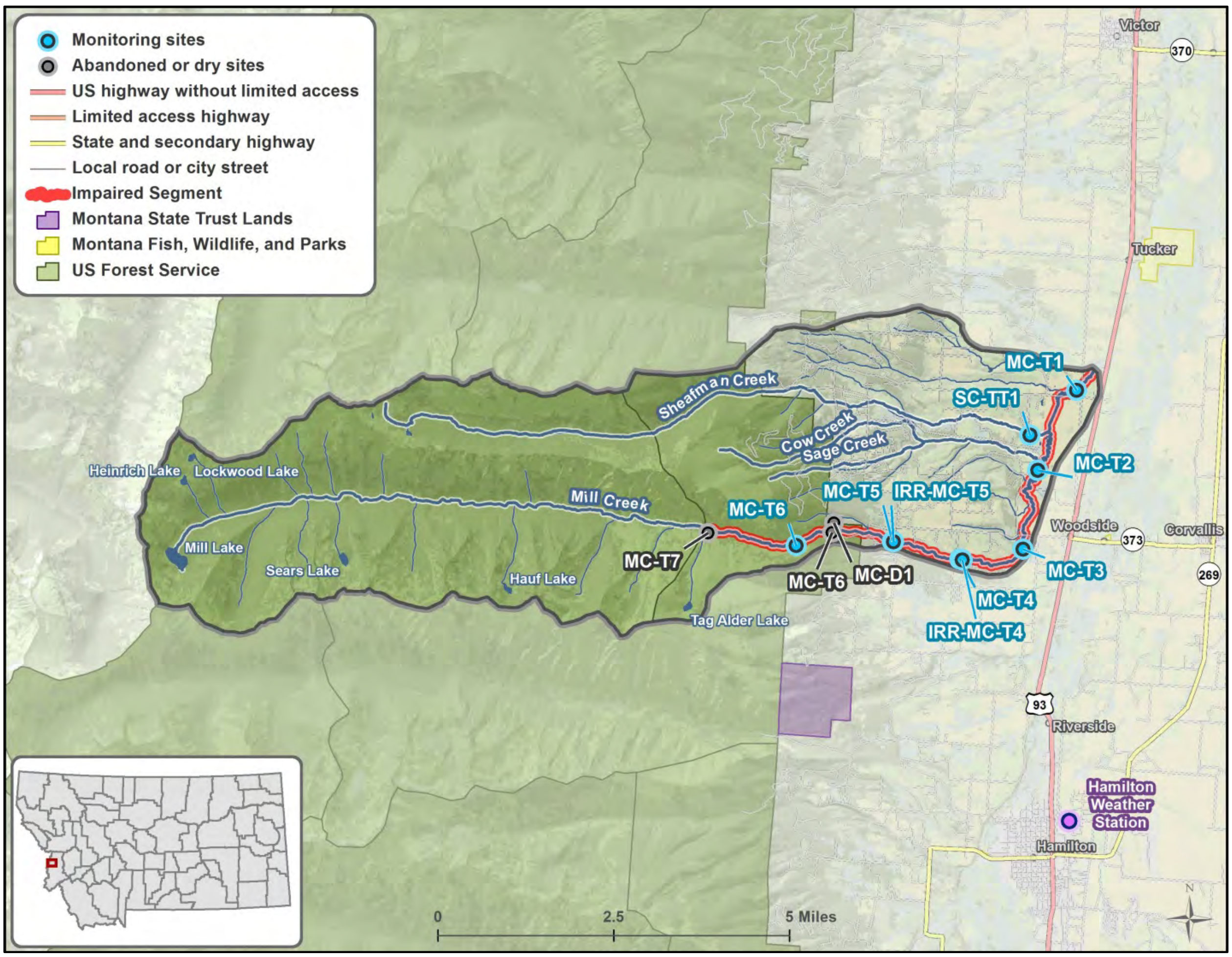


Figure A-8. EPA flow, shade, and continuous temperature monitoring locations.

Table A-3. Average shade per reach from Solar Pathfinder™ measurements

Site ID	Average daily shade (averaged across daylight hours)
MC-T6	82.8%
MC-T5	82.6%
MC-T4	61.4%
MC-T3	82.1%
MC-T2	50.6%
MC-T1	43.8%

Note: Sites are listed as headwaters to mouth from top to bottom.

A-5.2. *Shade Modeling*

An analysis of aerial imagery and field reconnaissance showed that shading along Mill Creek was highly variable. Therefore, shade was also evaluated using the spreadsheet Shadev3.0.xls. Shade version 3.0 is a riparian vegetation and topography model that computes the hourly effective shade for a single day (Washing State Department of Ecology 2008). Shade is an Excel/Visual Basic for Applications program. The model uses the latitude and longitude, day of year, aspect and gradient (the direction and slope of the stream), solar path, buffer width, canopy cover, and vegetation height to compute hourly, dawn-to-dusk shade. The model input variables include channel orientation, wetted width, bankfull width, channel incision, topography, and canopy cover. Bankfull width in the shade calculations is defined as the near-stream disturbance zone (NSDZ), which is the distance between the edge of the first vegetation zone on the left and right bank.

Available Data

The application of the Shade Model to Mill Creek relied upon the vegetation data and analysis described in **Section A-4**, aerial imagery from GoogleEarth™ (2013), tree canopy density information (MRLC 2001), and a digital elevation model (U.S. Geological Survey [USGS] 2014).

GIS Pre-Processing

TTools version 3.0 is an ArcView extension to translate spatial data into Shade Model inputs (Oregon Department of Environmental Quality 2001). TTools was used to estimate the following values: elevation, aspect, gradient, distance from the stream center to the left bank, and topographic shade. Elevation was calculated using a 10 meter (33 foot) digital elevation model (DEM) and a stream centerline file digitized from aerial imagery in GoogleEarth™. Aspect was calculated to the nearest degree using TTools with the stream centerline file.

Wetted width was estimated by digitizing both the right and left banks from aerial imagery in GoogleEarth™. TTools then calculates wetted width based on the distance between the stream centerline and the left and right banks. Topographic shade was calculated using TTools with the stream centerline file and a DEM.

Riparian Input

The Shade Model requires the description of riparian vegetation: a unique vegetation code, height, density, and overhang (OH). The vegetation input values for the Shade Model are listed in (**Table A-4**).

Table A-4. Vegetation input values for the Shade Model

Attribute	Value	Basis
Trees		
Height	19.2 meters (63 feet)	Average of field-measured values (see **Table A-1**)
Density	Variable	2006 NLCD.
Overhang	1.9 meters (6.3 feet)	Estimated as 10% of height (Stuart 2012).
Shrubs		
Height	5.3 meters (17.5 feet)	Average of field-measured values (see **Table A-1**)
Density	77%	Average of field-measured values
Overhang	0.5 meter (1.8 feet)	Estimated as 25% of height (Shumar and de Varona 2009)
Herbaceous		
Height	1 meter (3.3 feet)	Estimated
Density	100%	
Overhang	0 meters	

Shade Input

The Shade Model inputs are riparian zones, reach length, channel incision, elevation, aspect, wetted width, near-stream disturbance zone width, distance from the bank to the center of the stream, and topographic shade. Input for the riparian zone is presented above in **Table A-4**. The Shade Model requires reach lengths be an equal interval. A uniform reach length interval of 30 meters (98 feet) was used. Channel incision was estimated from an examination of field photos. Incision is the vertical drop from the bankfull edge to the water surface, and was estimated at 0.3 meter (1 foot). The remaining variables were computed as part of the GIS pre-processing described above.

Shade Model Results

The current longitudinal effective shade profile generated from the Shade Model and the Solar Pathfinder™ measurements are presented in **Figure A-9**.

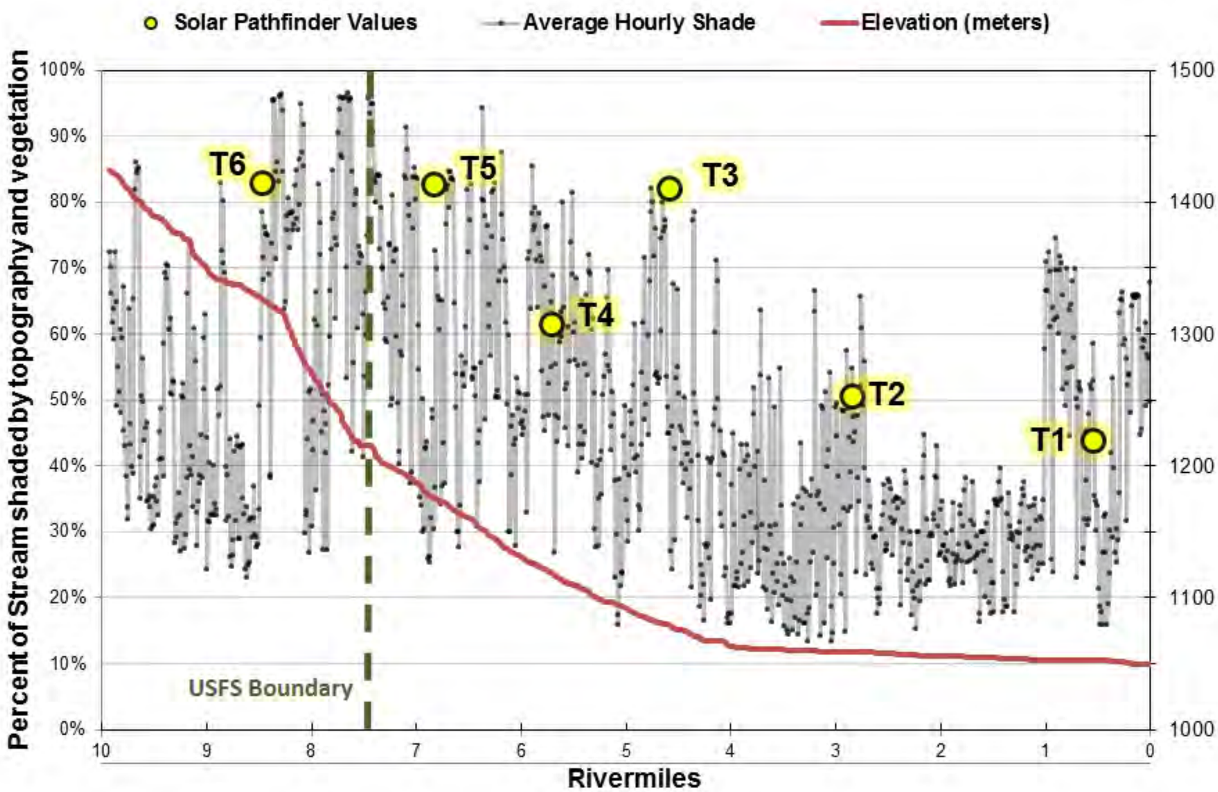


Figure A-9. Longitudinal estimates of observed and simulated effective shade along Mill Creek.

The goodness of fit for the Shade Model was summarized using the mean error (ME), average absolute mean error (AME), and root mean square error (RMSE) as a measure of the deviation of model-predicted shade values from the measured values. These model performance measures were calculated as follows:

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

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

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{n} (P_n - O_n)^2}$$

where

P = model predicted values
O = observed values
n = number of samples

Model error statistics are provided in **Table A-5** and suggest a good fit between observed and predicted average effective shade values. The average absolute mean error is 5 percent. (i.e., the average error from the Shade Model output and Solar Pathfinder™ measurements was 5 percent daily average shade; see **Table A-5**).

Table A-5. Shade model error statistics

Error Statistic	Formula	Result	Units
Mean Error (ME)	$(1/N)*\Sigma(P_n-O_n)$	-3%	percent of percent shade
Average Absolute Mean Error (AME)	$(1/N)*\Sigma\vert(P_n-O_n)\vert$	5%	percent shade
Root Mean Square Error (RMSE)	$[(1/N)*\Sigma(P_n-O_n)^2]^{1/2}$	6%	percent of percent shade

A-6. Stream Temperatures

In 2013, Tetra Tech collected continuous temperature data at six locations in Mill Creek and at one tributary. Data loggers recorded temperatures every one-half hour for approximately two months between June 26-27 and September 9, 2013. In 2007, Montana DEQ collected continuous temperature data at two locations on Mill Creek.

Instantaneous temperatures were also monitored by Tetra Tech in June, August, and September 2013(**Table A-6**). Additionally, Montana DEQ recorded an instantaneous temperature of 76.5° F on July 12, 2007, at the C05MILLC01 station.

Table A-6. EPA instantaneous water temperature measurements (°F), summer 2013

Date	MC-T1	SC-TT1	MC-T2	MC-T3	MC-T4	MC-T5	MC-T6
June 26, 2013	56.4	54.4	55.9	54.2	--	---	-
June 27, 2013	--	--	--	--	50.3	50.7	51.2
August 13, 2013[a]	--	Dry	--	--	--	--	--
September 9, 2013	66.7	Dry	59.5	66.0	57.9	62.3	59.5

Notes
Temperatures were originally reported in degrees Celsius and were converted to degrees Fahrenheit as displayed in this table.
a. Temperature data rejected due to quality control issues with the temperature probe calibration.

A-7. Hydrology

No active USGS continuously recording gages are located on Mill Creek. EPA collected instantaneous flow measurements in 2013, during temperature data logger deployment and retrieval, as well as during mid-season site visit (**Table A-7**). DEQ monitored flow on July 12, 2007 at site C05MILL01 (9.8 cfs). Locations of the flow measurements are shown in **Figure A-10**. A portion of Mill Creek, approximately 0.25 miles downstream from logger MC-T3 was observed to be dry during an August 12, 2013 site reconnaissance visit. Flow resumed upstream from logger MC-T2.

Table A-7: EPA instantaneous flow measurements (cfs) on Mill Creek in support of modeling

Date	FLUME @ MC –T6A	FLUME @ MC –T6B	MC –T6	MC –T5	MC –T4	MC –T3	SC –TT1 [a]	MC-T2	MC-T1
June 26-27, 2013	--	--	88.4	75.28	47.89	43.79	10.47	50.74	69.50
August 12-13, 2013	4.13	2.68	16.30	3.09	2.28	0.22	0	5.35	2.31
September 9, 2013	--	--	9.83	1.60	1.48	0.11	0	3.66	1.94

Note: a. Site is on Sheafman Creek that is a tributary of Mill Creek.

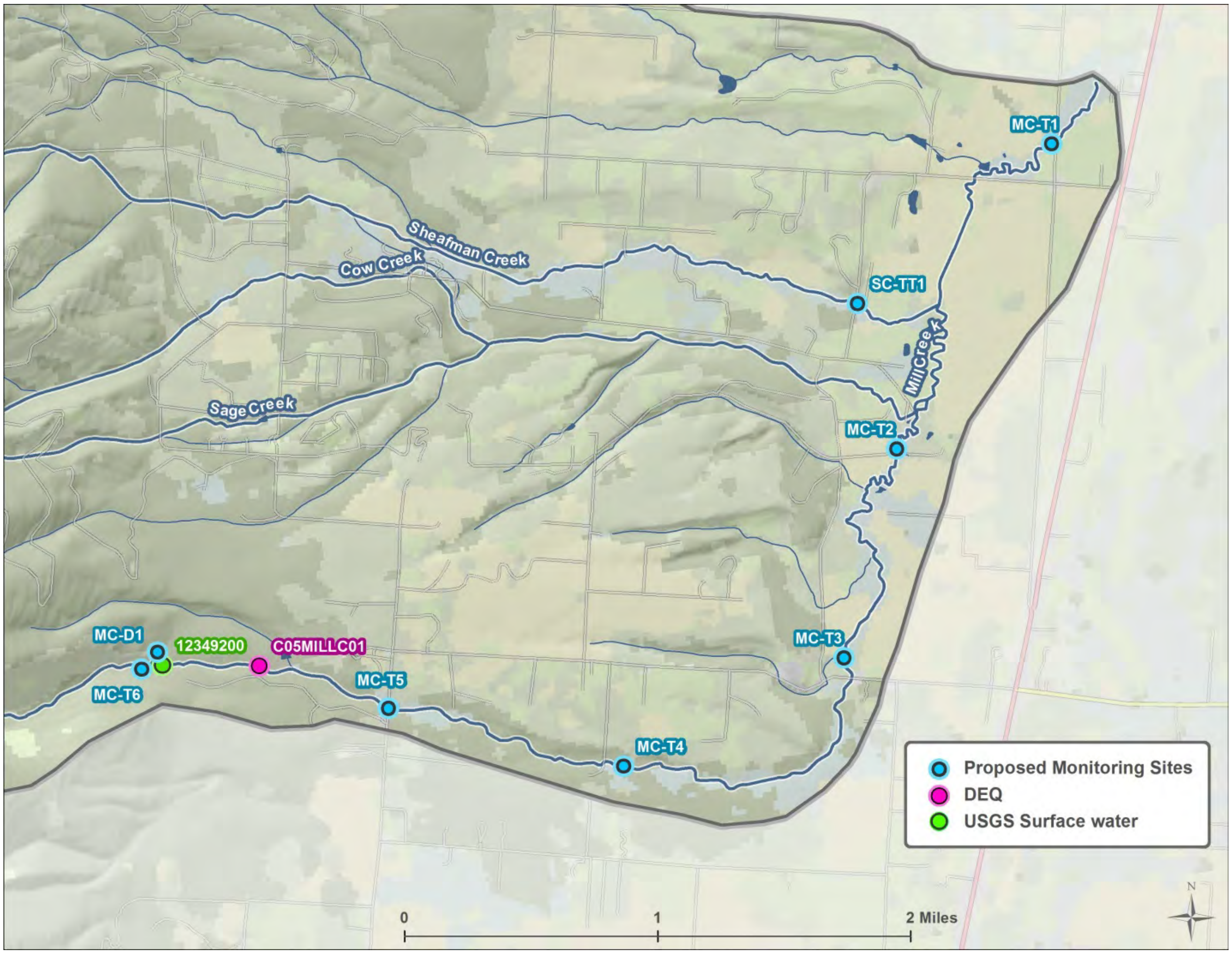
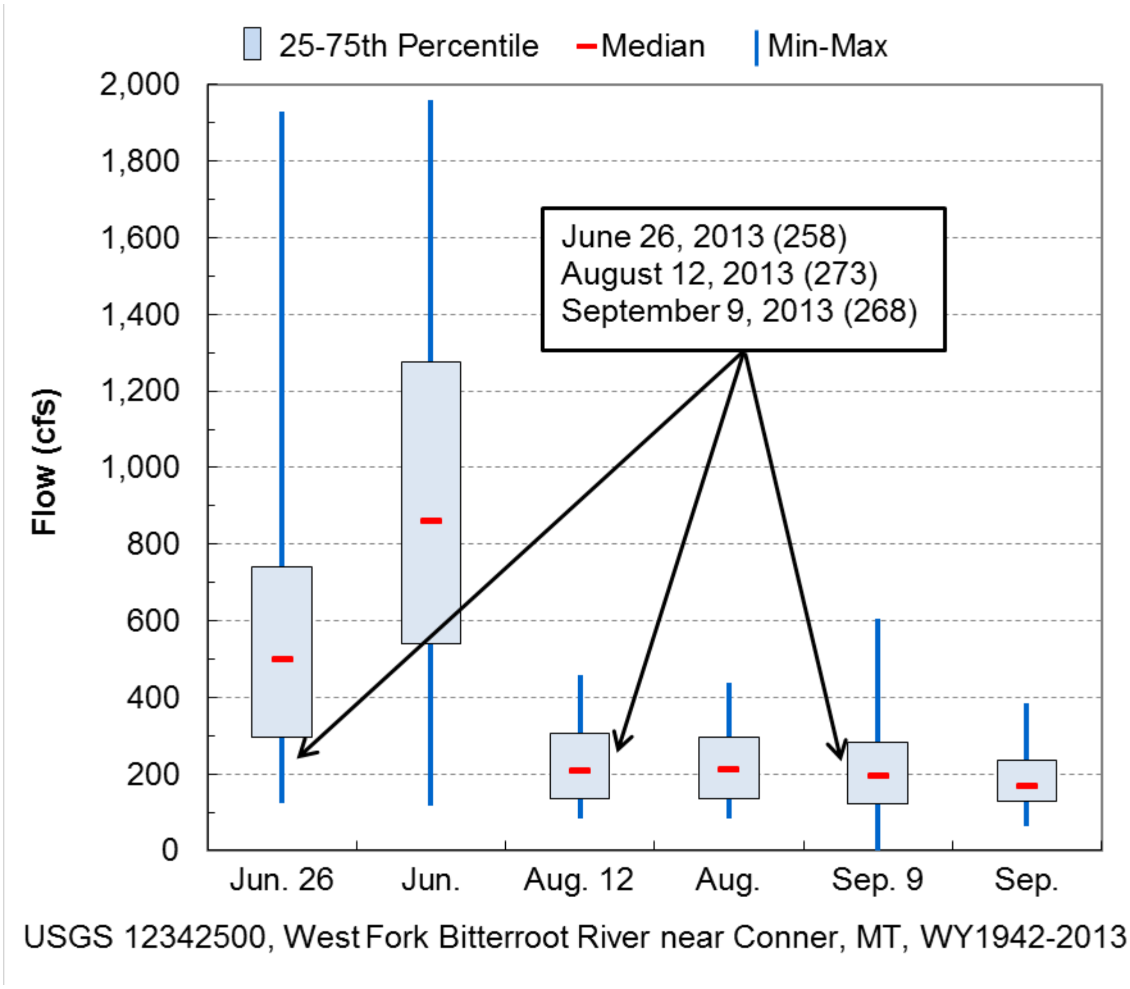


Figure A-10. Flow monitoring locations in the Mill Creek watershed.

Continuous flow data monitored on the West Fork Bitterroot River at USGS gage 12342500 were evaluated with instantaneous discharge data from Mill Creek to assess the hydrologic conditions of Mill Creek during the summer of 2013. USGS gage 12342500 was used as a surrogate to represent regional hydrologic conditions. Statistics were calculated for the average daily flows (per year) for the month of June and for June 26th from water years 1941 through 2013 at the gage (**Figure A-11**).

The flow at gage 12353650 on June 26, 2013 (the calibration date for the QUAL2K model) was 258 cfs, which is near the 25th percentile of flows on June 26th across the period of record. At gage 12353650, flow on June 26 was similar to flows on August 12 and September 9 (**Figure A-11**).



Note: "June" represents the daily average flow for the month of June per year (i.e., the average of 30 daily average flows). Similarly, August and September represent the daily average flow for the moths of August and September per year.

Figure A-11. Average daily flows for the months of June, August, and September and for June 26, 2013, August 12, 2013, and September 9, 2013 at USGS gage 12342500(West Fork Bitterroot River).

A-8. Flow Modification

There are 13 ditches actively withdrawing water from Mill Creek for irrigation purposes[1]. Of these, nine ditches were withdrawing water during the study period (**Figure A-12**). It is estimated that between approximately 5 and 24 cfs are withdrawn from Mill Creek during the study period (**Table A-8**).

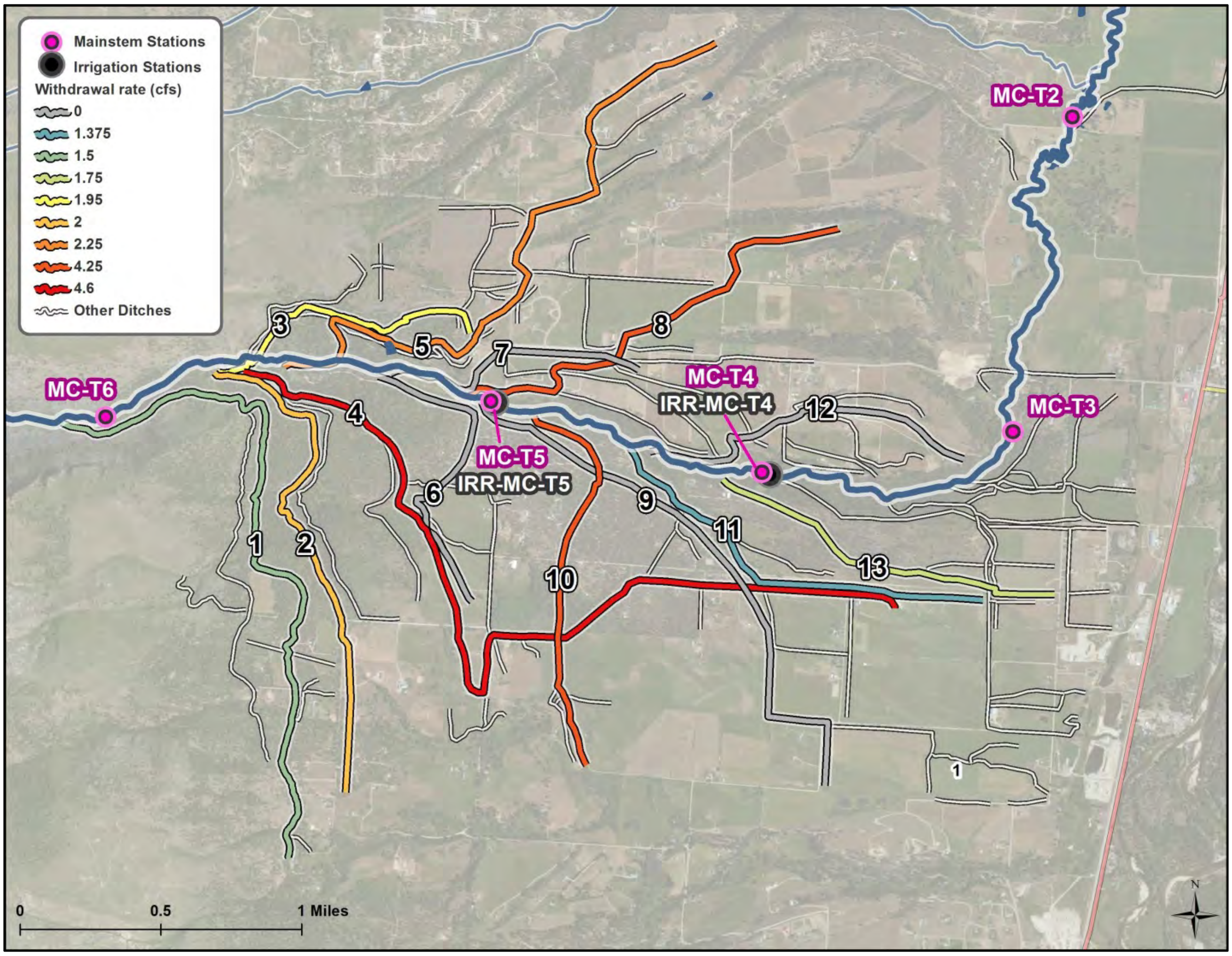


Figure A-12. Ditches actively withdrawing water from Mill Creek on June 26 and 27, 2013.

[1] According to Jordan Tollefson (TMDL Planner, DEQ), based on personal communications with Sandy Schlotterbeck and David Allen of the Mill Creek Irrigation District on February 5th, 10th, and 13th, 2014.

Table A-8. Summary of irrigation diversions from Mill Creek

Ditch ID	Daily flow rate (cfs)			
	June 26/27	August 12	August 13	September 9
1	1.50	1.25	1.25	0
2	2.00	0	2.25	0
3	1.95	0	2.60	0
4	4.60	3.76	4.08	1.00
5	2.25	2.40	2.43	1.00
6	--	--	--	--
7	--	--	--	--
8	4.25	4.08	3.60	2.25
9	--	--	--	--
10	4.25	0	0	0
11	1.38	0.75	0.75	0.75
12	--	--	--	--
13	1.75	0.43	0.43	0
Total Withdrawal	***23.93***	***12.66***	***17.38***	***5.00***

Note: Values originally provided in Miner's Inches and converted to cfs.

A-9. Point Sources

There are no permitted discharges in the Mill Creek watershed.

Three abandoned mines are present in the Mill Creek watershed, all situated near the U.S. Forest Service boundary. Mill Creek Mine, a former titanium, iron, thorium, and zirconium producer, was near Mill Creek. Ore Finder Group Mine, an expired prospect mine, was near Fred Burr Creek. Sheafman Creek Mine, another titanium, iron, thorium, and zirconium producer, was near Sheafman Creek.

The mines are not expected to have an influence on stream temperature and are not considered further.

A-10. References

DEQ (Montana Department of Environmental Quality). 2012. Water Quality Assessment Database. Montana Department of Environmental Quality, Clean Water Act Information Center. <http://cwaic.mt.gov/query.aspx>. Accessed March 16, 2012.

GoogleEarth™ 2013. Aerial imagery of Mill Creek and surrounding area. dated November 20, 2011 <http://www.google.com/earth/index.html>. Accessed May 29, 2013.

MRLC (Multi-Resolution Land Characteristics Consortium). 2001. *National Land Cover Dataset 2001*. <http://www.mrlc.gov/nlcd2006.php>. Accessed June 28, 2012.

MRLC (Multi-Resolution Land Characteristics Consortium). 2006. *National Land Cover Dataset 2006*. <http://www.mrlc.gov/nlcd2006.php>. Accessed June 28, 2012.

National Climatic Data Center. 2013. *Monthly Summaries GHCND.* <http://www.ncdc.noaa.gov/land-based-station-data/find-station>. Accessed June 18, 2013.

Natural Resources Conservation Service. 2003. *Irrigation Water Requirements.* < <http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/irrigation/?cid=stelprdb1044890>. Accessed February 6, 2013.

NRIS (Natural Resources Information System). 2012. *GIS Data List.* <http://nris.mt.gov/gis/gisdatalib/gisDataList.aspx>. Accessed June 28, 2012.

Oregon Department of Environmental Quality. 2001. TTools 3.0 Users Manual. Oregon Department of Environmental Quality.

Oregon Department of Environmental Quality. 2009. TTools version 7.5.6 (TTools 756.mxd in TTools756.zip) in *Water Quality: Total Maximum Daily Loads (TMDLs) Program: Analysis Tools and Modeling Review* at <http://www.deq.state.or.us/wq/tmdls/tools.htm>. Downloaded July 1, 2011.

Poole, G.C., Risley, J. and M. Hicks. 2001. Issue Paper 3 – Spatial and Temporal Patterns of Stream Temperature (Revised). United States Environmental Protection Agency. EPA-910-D-01-003.

Shumar, M. and J. de Varona. 2009. The Potential Natural Vegetation (PNV) Temperature Total Maximum Daily Load (TMDL) Procedures Manual. Idaho Department of Environmental Quality. State Technical Services Office. Boise, ID.

Stuart, T. 2012. Asotin Creek Temperature Straight-to-Implementation Vegetation Study. Washington State Department of Ecology. Eastern Regional Office. Spokane, WA.

U.S. Forest Service. 2008. *Fire History in the Bitterroot National Forest.* <http://www.fs.usda.gov/detailfull/bitterroot/landmanagement/gis/?cid=stelprdb5157563&width=full>. Accessed February 4, 2014.

USGS (United States Geological Survey). 2014. *National Elevation Dataset*. <http://ned.usgs.gov>. Accessed January 20, 2014.

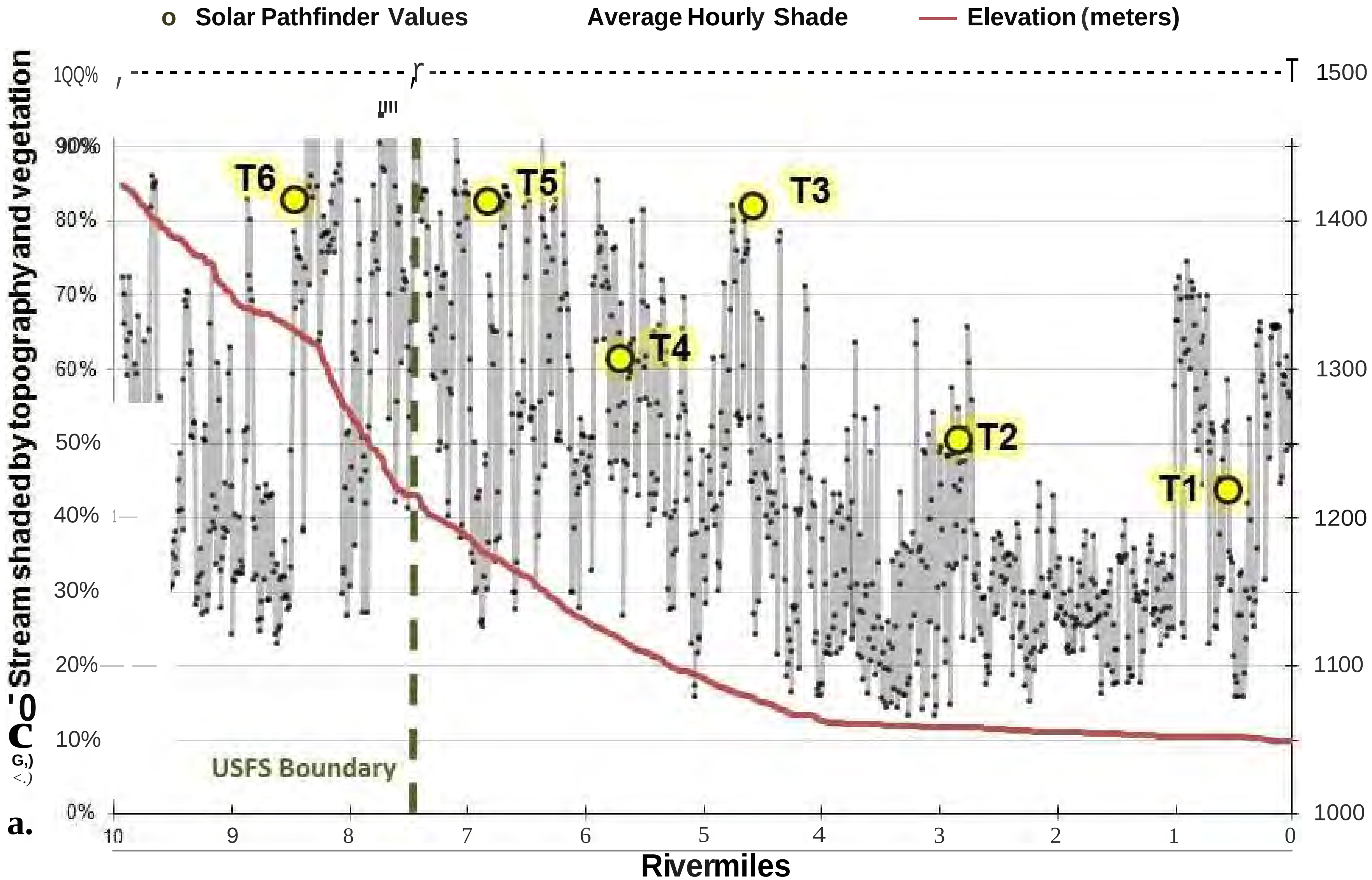
Washington State Department of Ecology. 2007. *Shade* (shade_ver31b02.xls in shade.zip) in *Models for Total Maximum Daily Load Studies* at <http://www.ecy.wa.gov/programs/eap/models.html>. Downloaded November 29, 2011.

Washington State Department of Ecology. 2008. *tTools for ArcGIS (*tTools for ArcGIS 9.x (Build 7.5.3).mxd in tTools_for_ArcGIS.zip) in *Models for Total Maximum Daily Load Studies* at <http://www.ecy.wa.gov/programs/eap/models.html>. Downloaded November 29, 2011.

Western Regoinal Climate Center. 2013. *Monthly Summary Time Series.* <http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?mtMSMI>. Accessed February 12, 2014.

Appendix B.

Vegetation and Shade Analysis for Scenario Development



This reach (RM 0 to "4.S) is relatively low gradient and flows through the Bitterroot Valley bottom. Irrigated agriculture mixed with low density residential land uses predominant. Much of this reach is not meeting its shade potential due to encroachment by these land uses ("yellow" area downstream of MC-T2 shown below). However, based on site reconnaissance in 2013, the vegetation at Site MC-T2 is at potential and will be used as a reference condition for this reach. Vegetation in the vicinity of MC-T2 consists of a SO to 100 foot buffer of shrubs (see below) and average daily effective shade is approximately SO%. In the improved shade scenario, areas less than SO% shade will be increased to that level. Areas already exceeding SO% shade will not be modified.

From RM 10 down to approximately RM 7.S, Mill Creek flows through the Bitterroot National Forest. In spite of the fact that a fire occurred in the area in 2000, vegetation in this area is considered at potential.

From RM 7.S down to approximately RM 4.S, Mill Creek flows through the Bitterroot National Forest. In spite of the fact that a fire occurred in the area in 2000, vegetation in this area is considered at potential. Between RM 9.S and RM 6.S, Mill Creek flows through an area transitional from the mountains (dominated by coniferous forest) down to the valley. Much of this reach is dominated by mixed coniferous/deciduous forest with some encroachment by residential and agricultural land uses. Site MC-T3 (a forested site dominated by mixed coniferous/deciduous vegetation) was considered at potential based on site reconnaissance and will be used as a reference condition for this reach in the improved shade scenario.