Modeling Water Temperature in Petty Creek

Prepared for:

U.S. Environmental Protection Agency, Region 8
Montana Operations Office
10 West 15th Street, Suite 3200
Helena, MT 59626

Prepared by:

Tetra Tech, Inc.
P.O. Box 11895
Jackson, WY 83002

December 26, 2013

Version

Report date	Version number	Description
11/15/2013	1.0	First full draft to agencies for initial review
12/4/2013	1.1	Corrected Table 10, added sensitivity statement, added elevation-correction text, standardized to American units (cfs, °F, RM).
12/13/2013	2.0	Added text for hydraulic calibration/validation at PTTYC-T4 (Section 3.4), revised long-term weather discussion (Section 4.1), revised scenario 3 text (Section 5.0), updated references (Section 8.0), updated Appendix A, and corrected minor editorial errors.
12/26/2013	3.0	Addressed editorial comments

Note: Lisa Kusnierz (EPA) provided comments on 11/27/2013 and 12/19/2013 and Eric Sivers (DEQ) provided comments on 12/6/2013.

Contents

Tables

Figures

Acronyms and Abbreviations

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

Units of Measure

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

Executive Summary

Petty Creek was identified by the Montana Department of Environmental Quality (DEQ) as being impaired due to elevated water temperatures. According to DEQ's assessment record (DEQ 2012), the potential sources of the water temperature impairment are agricultural activities, including stream dewatering and channelization (DEQ 2012). The U.S. Environmental Protection Agency contracted with Tetra Tech to develop a QUAL2K water quality model to investigate the relationship between flow, shade, and in-stream water temperature in Petty Creek.

Field studies were carried out in 2012 to support water quality model development for the project. A QUAL2K water quality model was then developed for Petty 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 2012. Field data and observations showed that segments of Petty Creek and two of its tributaries (Madison and Reservoir creeks) ran dry. Thus, water withdrawals have considerable impact upon the Petty Creek watershed.

Shadev3.0 models were also developed to assess shade conditions using previously collected field data to calibrate the shade model. The calibrated and validated QUAL2K model met previously designated acceptance criteria. Users of the QUAL2K model results should consider that the model was calibrated when flow was continuous throughout Petty Creek; however, segments of Petty Creek and its tributaries ran dry in the late summer and early fall of 2012.Once developed, various water temperature responses were evaluated for a range of potential watershed management activities. Four scenarios were evaluated:

- **Scenario 1:** Existing condition (i.e., the calibrated model)
- **Scenario 2:** Existing conditions with a 15 percent reduction of water withdrawals
- **Scenario 3:** Existing condition with improved riparian vegetation in a 50-foot buffer
- **Scenario 4:** An improved flow and shade scenario that combines the potential benefits associated with a 15 percent reduction in water withdrawals with a 50-foot vegetated buffer.

In comparison to scenario 1, results ranged from almost no change in water temperatures (scenario 2) to considerable reductions (scenario 3). 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 a 50-foot vegetated buffer (scenario 3) to represent application of conservation practices, resulted in overall reductions along the entire reach that ranged from 0.3° F to 3.8° F. Generally, small changes in shade or inflow had minimal effects on water temperatures while large increases in shade had a considerable effect on water temperatures.

1 Introduction

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

2 Background

This section presents background information to support QUAL2K model development.

2.1 Problem Statement

Petty Creek is in the Rocky Mountains of western Montana and is part of the Middle Clark Fork Tributaries TMDL Planning Area. The Petty Creek watershed is in the Lower Clark Fork subbasin (hydrologic unit code 17010204). The impaired segment is 12.2 miles long and extends from the confluence of the South and East Forks of Petty Creek to the mouth (DEQ 2012) (**Figure 1**).

Petty Creek has a B-1 use class. The 12.2 mile segment is not supporting its Aquatic Life and Primary Contact Recreation designated uses (DEQ 2012). Five potential causes of impairment are identified in the assessment record, including elevated water temperature, the subject of this memorandum (DEQ 2012). According to the assessment record, the potentials source of the water temperature impairment are agricultural activities, including stream dewatering and channelization (DEQ 2012).

West Fork Petty Creek (MT76M002_100) is also impaired from its headwaters to its mouth on Petty Creek. The creek is impaired for five causes, excluding in-stream water temperatures, with potential sources of impairment from forest roads (construction and use) and silviculture harvesting.

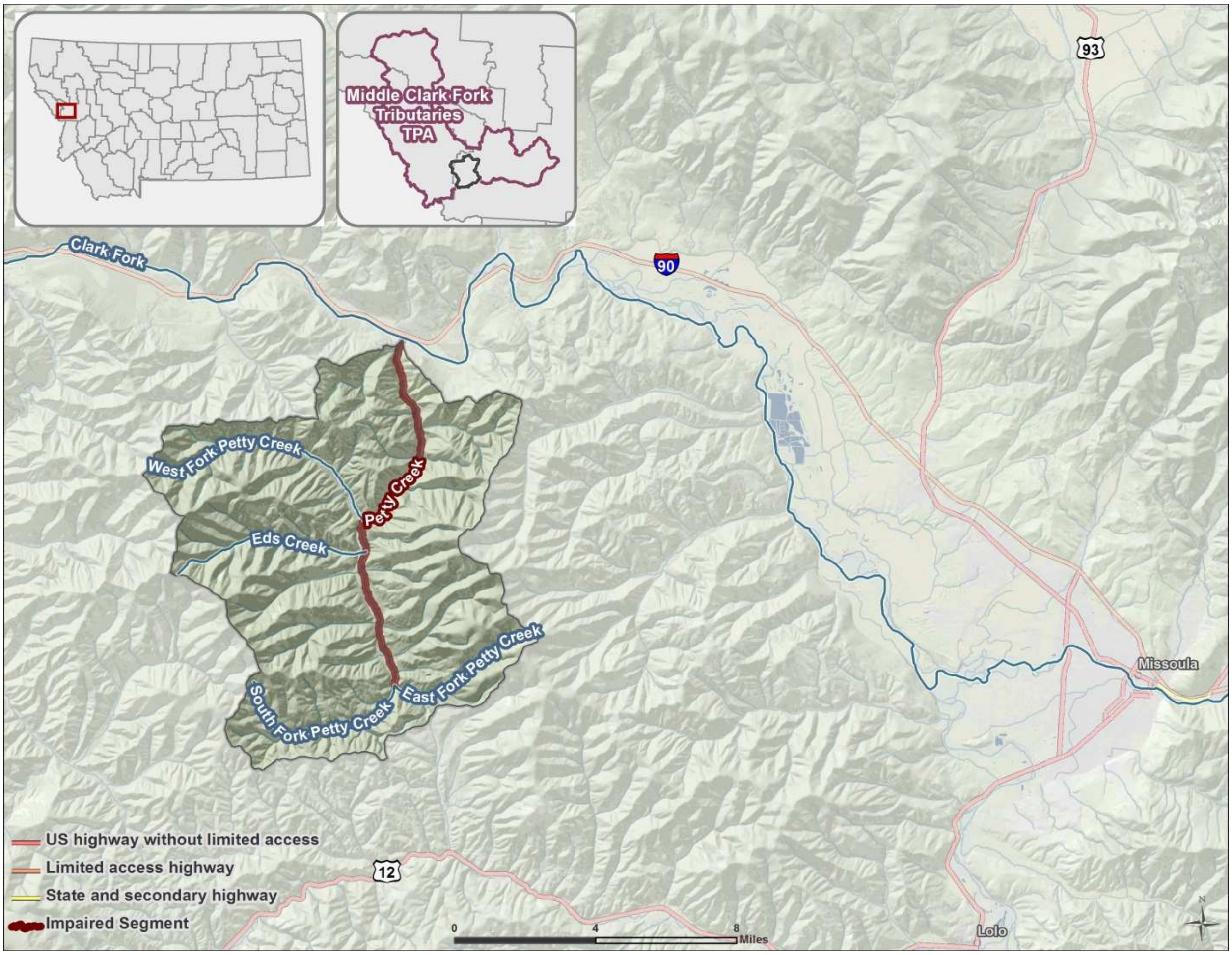


Figure 1. Petty Creek watershed.

2.2 Montana Temperature Standard

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

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

The model results will ultimately be compared to these criteria.

2.3 Project History

Tetra Tech was contracted by EPA in February 2012 to develop the QUAL2K temperature model. Temperature and flow data were collected in Petty Creek in 2012 by Atkins (Helena, MT; under contract with Tetra Tech). A field team from Atkins collected data on June 27-28, July 31-August 1, and October 11, 2012 to characterize channel geometry, flow, and shade in support of the modeling effort.

2.4 Factors Potentially Influencing Stream Temperature

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

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

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

[1] ARM 17.30.623(e).
[2] ARM 17.30.602(17): "Naturally occurring" means conditions or material present from runoff or percolation over which man has no control or from developed land where all reasonable land, soil and water conservation practices have been applied. Conditions resulting from the reasonable operation of dams in existence as of July 1, 1971, are natural.

2.5 Observed Stream Temperatures

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

2.5.1 Available Temperature Data

In 2012, Atkins collected continuous temperature data at six locations in Petty Creek (sites PTTYC-T1, PTTYC -T2, PTTYC -T3, PTTYC -T4, PTTYC -T5, and PTTYC -T6) and at five tributary locations (EDS on Ed's Creek, JHNS on John's Creek, MDSN on Madison Gulch, PRINT on Printers Creek, and RSVR on Reservoir Creek) (**Figure 2)**. An additional logger was deployed on West Fork Petty Creek, but was lost due to nearby bridge construction. Data loggers recorded temperatures every one-half hour for approximately three months between June 27 and October 11. Instantaneous temperatures were also monitored by Atkins and DEQ (refer to **Appendix A** for these data).

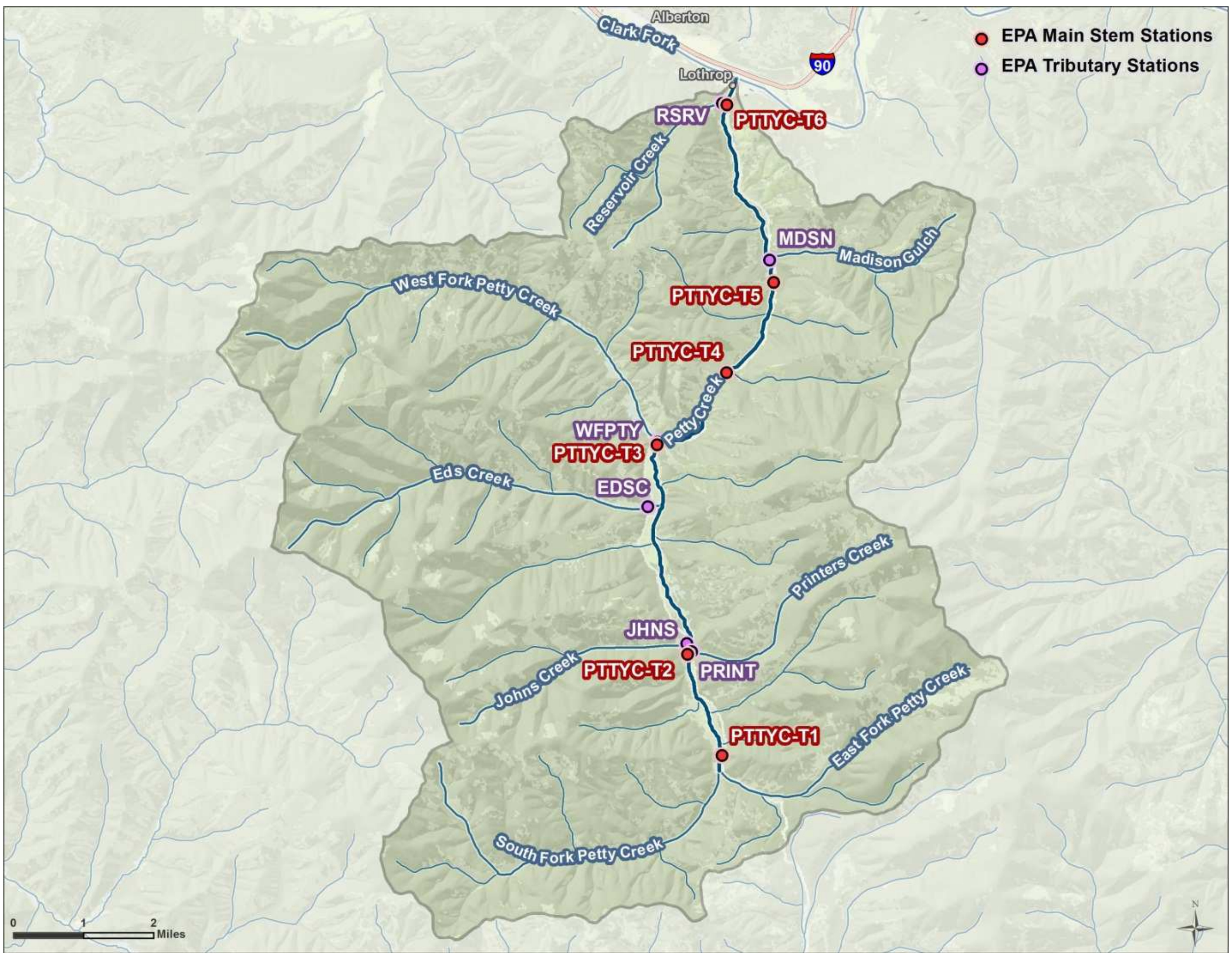


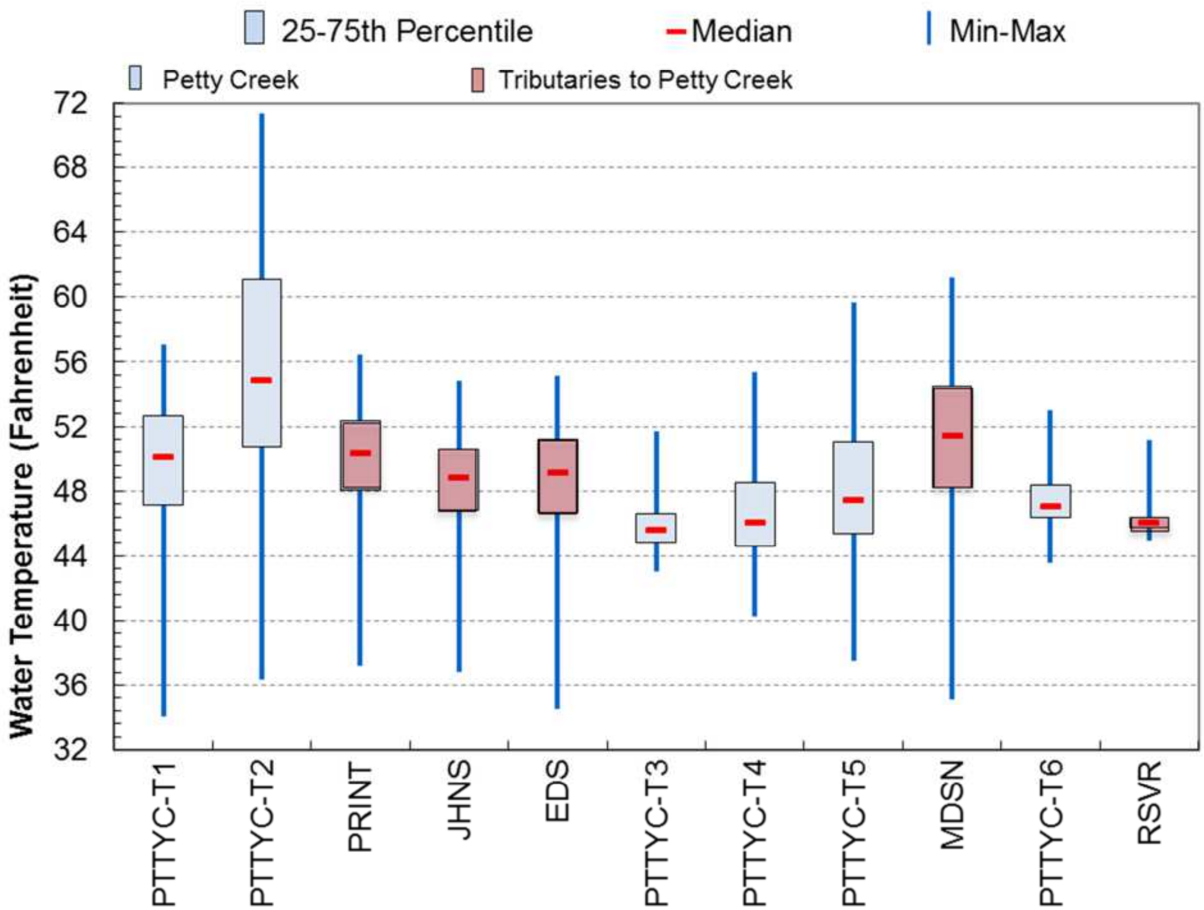
Figure 2. Temperature loggers in the Petty Creek watershed.

2.5.2 Temperature Data Analysis

By mid-July and August, a segment of Petty Creek between John's Creek and Ed's Creek ran dry, until surface flow began again near Bruce Creek (known locally as Gus Creek). By October, Petty Creek ran dry in the segment with logger PTTYC-T2 (**Figure 3**), upstream of the confluence with West Fork Petty Creek, and between logger PTTYC-T5 and PTTYC-T6. Segments of Madison and Reservoir creeks were also dry channels by October. Interviewed landowners also reported other segments of Petty Creek typically run dry each year.

Figure 3. Petty Creek at logger PTTYC-T2 on October 11, 2012.

Median temperatures in Petty Creek ranged from approximately 45° F to approximately 55° F with no apparent, consistent spatial trend from headwaters to mouth (**Figure 4**). Maximum daily temperatures in Petty Creek ranged from approximately 51° F to approximately 71° F. The highest maximum temperatures were recorded at PTTYC-T2; however, elevated temperatures may be due to partial exposure to ambient air. It appears that Printer's, John's, and Ed's creeks may have cooling influences on Petty Creek.



Notes

Atkins reported that logger PTTYC-T2 was partially exposed to ambient air on July 30, 2012, and Atkins repositioned the logger such that it was fully submerged. Atkins also reported the logger to be fully exposed to ambient air in a dry channel on October 11, 2012. Logger PTTYC-T2 was probably exposed to ambient air from about September 10, 2012 through October 11, 2012, when the channel was observed to be dry. The data presented in this figure are limited to a subset of the monitored temperatures from June 28, 2012 through September 9, 2012. The logger was partially exposed to ambient air during one or more days within this time period.

Atkins reported that logger MDSN was probably exposed to ambient air from July 30, 2012 to August 30, 2012. During this time period, water in Madison Creek was diverted during road construction and culvert replacement. The data presented in this figure are limited to a subset of the monitored temperatures from June 28, 2012 through July 29, 2012 and August 30, 2012 through October 11, 2012.

Atkins reported that logger RSVR was observed to be partially exposed to ambient air on August 1, 2012 and on October 11, 2012. Data from the full period of record are displayed in this figure.

Figure 4. Box-and-whisker plots of temperature data, June 27 2012 to October 11, 2012.

Daily maximum recorded temperatures in Petty Creek are summarized in **Table 1** and shown in **Figure 5**. In 2012, the warmest temperatures were detected on June 28, several days in July, and August 9. The warmest weeks varied from early-July through mid-August. As shown in **Figure 6**, the diurnal variation in Petty Creek is less in the upper watershed (as shown with PTTYC-T1) than the lower watershed (as shown with PTTYC-T5).

Table 1. Maximum and maximum weekly maximum temperatures in Petty Creek, 2012

Temperature logger site	Maximum temperatures [a]		Maximum weekly maximum temperature [b]	
	Temperature (°F)	Date	Temperature (°F)	Date
PTTYC-T1	57.1	July 28	56.2	July 17-23
PTTYC-T2[c]	71.4	August 9	69.3	August 7-13
PRINT	56.5	August 9	55.8	August 8-14
JHNS	54.9	August 9	54.3	August 8-14
EDS	55.2	July 28	54.3	July 16-22
PTTYC-T3	51.7	June 28	50.8	July 2-8
PTTYC-T4	55.4	July 8	54.3	July 6-12
PTTYC-T5	59.7	July 18	58.4	July 16-22
MDSN[d]	61.2	July 18	60.1	July 16-22
PTTYC-T6	53.0	July 8	52.2	July 6-12
RSVR[e]	51.1	July 31	50.1	July 26 - August 1

Notes

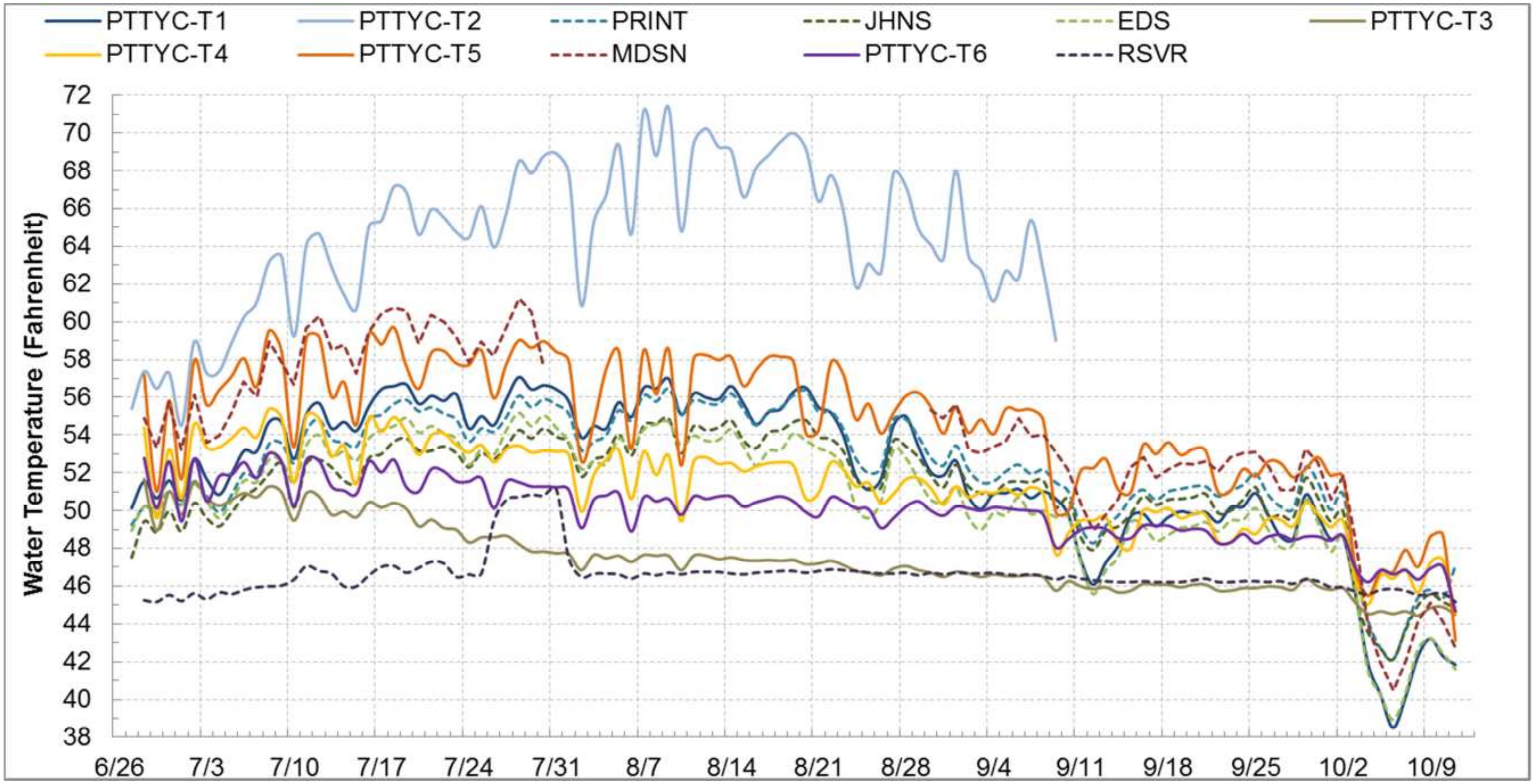
a. Maximum temperature is the maximum of recorded one-half hourly temperatures.

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

c. Atkins reported that logger PTTYC-T2 was partially exposed to ambient air on July 30, 2012, and Atkins repositioned the logger such that it was fully submerged. Atkins also reported the logger to be fully exposed to ambient air in a dry channel on October 11, 2012. Logger PTTYC-T2 was probably exposed to ambient air from about September 10, 2012 through October 11, 2012, when the channel was observed to be dry. The data presented in this table are limited to a subset of the monitored temperatures from June 28, 2012 through September 9, 2012. The logger was partially exposed to ambient air during one or more days within this time period.

d. Atkins reported that logger MDSN was probably exposed to ambient air from July 30, 2012 to August 30, 2012. During this time period, water in Madison Creek was diverted during road construction and culvert replacement. The data summarized in this table are limited to a subset of the monitored temperatures from June 28, 2012 through July 29, 2012 and August 30, 2012 through October 11, 2012.

e. Atkins reported that logger RSVR was observed to be partially exposed to ambient air on August 1, 2012 and on October 11, 2012. Data from the full period of record are summarized in this table.



Notes

Atkins reported that logger PTTYC-T2 was partially exposed to ambient air on July 30, 2012, and Atkins re-positioned the logger such that it was fully submerged. Atkins also reported the logger to be fully exposed to ambient air in a dry channel on October 11, 2012. Logger PTTYC-T2 was probably exposed to ambient air from about September 10, 2012 through October 11, 2012, when the channel was observed to be dry. The data presented in this figure are limited to a subset of the monitored temperatures from June 28, 2012 through September 9, 2012. The logger was partially exposed to ambient air during one or more days within this time period.

Atkins reported that logger MDSN was probably exposed to ambient air from July 30, 2012 to August 30, 2012. During this time period, water in Madison Creek was diverted during road construction and culvert replacement. The data presented in this figure are limited to a subset of the monitored temperatures from June 28, 2012 through July 29, 2012 and August 30, 2012 through October 11, 2012.

Atkins reported that logger RSVR was observed to be partially exposed to ambient air on August 1, 2012 and on October 11, 2012. Data from the full period of record are displayed in this figure.

Figure 5. Daily maximum temperatures along Petty Creek, June 27 to October 11, 2012.

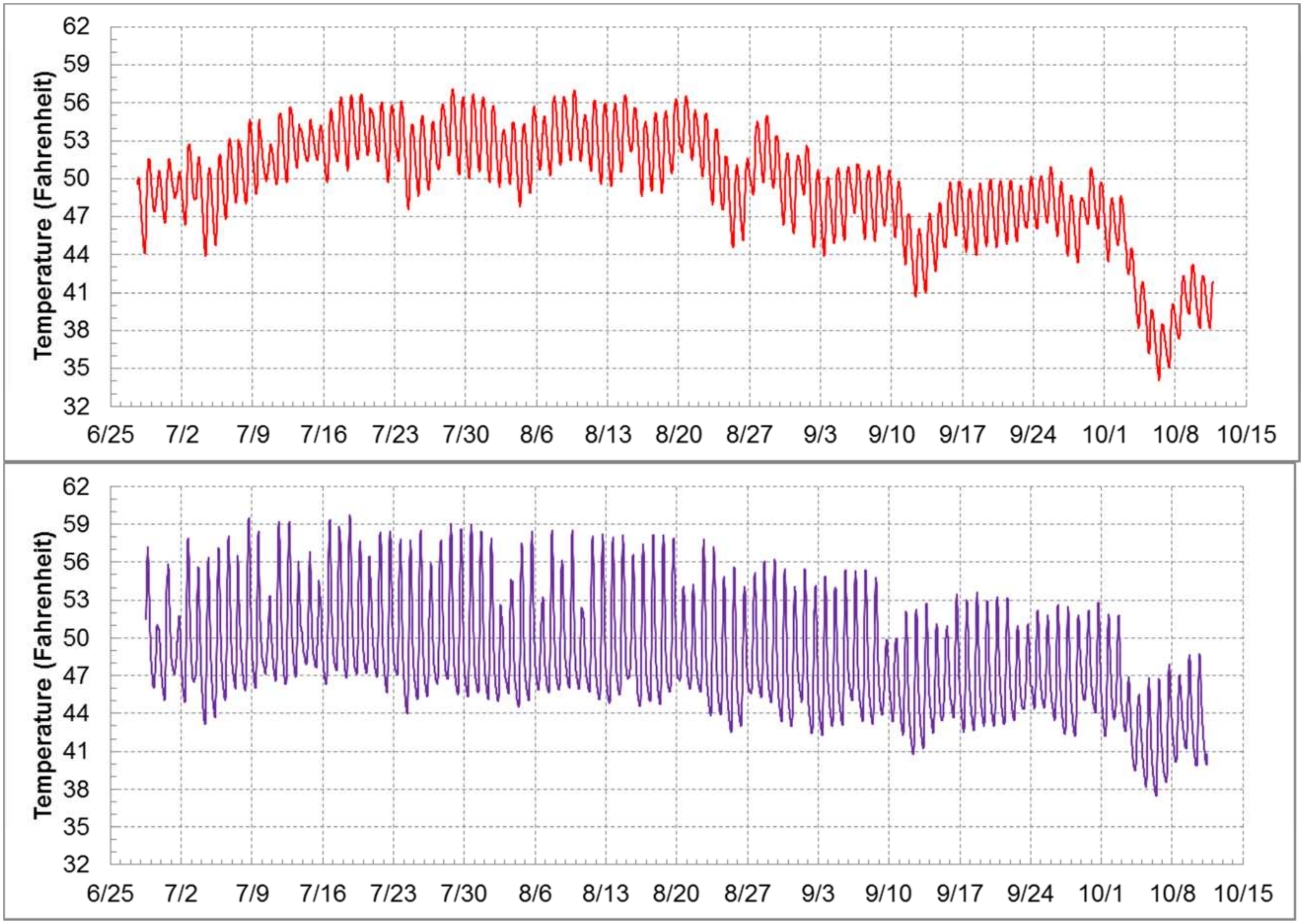


Figure 6. Continuous temperature at loggers PTTYC-T1 (top) and PTTYC-T5 (bottom), July 14 to September 13, 2011.

3 QUAL2K Model Development

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

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

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

3.1 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 Model Framework

The QUAL2K model (Chapra et al. 2008) was selected for modeling Petty Creek. The modeling domain included the stream at the confluence of East Fork Petty Creek and South Fork Petty Creek at PTTYC-T1 down to the confluence with Clark Fork just below PTTYC-T6 (refer back to **Figure 2** for a map of the Petty Creek watershed with logger locations).

Data were specifically collected to support the QUAL2K model for the Petty Creek. Flow, shade, and continuous temperature were acquired during June 27-28, July 30-August 1, and October 11, 2012. In addition flow and temperature data were also collected at five major tributaries to Petty Creek.

3.2.1 Modeling Time Period

The calibration and validation steady-state model periods were June 29, 2012 and July 30, 2012. These dates were selected since they had the most complete datasets that could be used for model setup and calibration/validation. Flow and logger temperature data were available for most sites on both dates and weather data was also available for both dates.

Calibration Period: The calibration period was June 29, 2012, which was associated with logger deployment monitoring; flow was monitored June 27 or 28, 2012 at all logger sites on Petty Creek and its six major tributaries. As loggers were deployed on June 27 or 28, 2012, the first date with a complete 24-hour temperature record at all loggers was June 29, 2012. Precipitation data were evaluated and no precipitation occurred during the calibration period or the preceding days; thus, hydrologic conditions on June 27 or 28, 2012 were assumed to be representative of flow conditions on June 29, 2012.

Validation Period: The validation period was July 30, 2012, which is associated with the mid-season flow monitoring at the loggers on July 30, July 31, and August 1, 2012. Flow data monitored on July 31 and August 1, 2012 were assumed to be representative of flow conditions on July 30, 2012 because precipitation data from these days were evaluated, similar to the evaluation with the calibration period. Flow was not monitored at Madison Gulch because the water was diverted during road construction and culvert replacement.

3.2.2 Segmentation

Segmentation refers to discretization of a waterbody into smaller computational units (e.g., reaches and elements). Segmentation into reaches allows for representation of stretches of the stream that have constant hydraulic characteristics (e.g. slope, bottom width). Each reach is further divided into elements that are the fundamental computational units in QUAL2K. The Petty Creek main stem was segmented into eight reaches with lengths ranging from 0.47 miles to 2.85 miles. Element lengths were 820.21 feet (0.25 kilometer). An element size of 820.21 feet was sufficient to incorporate any point inputs to the waterbody. Six major tributaries were represented through boundary condition designation (see **Section 3.2.4** for a discussion of boundary conditions and **Appendix A** for a discussion of the shade model). **Figure 7** shows the Petty Creek mainstem and its tributaries.

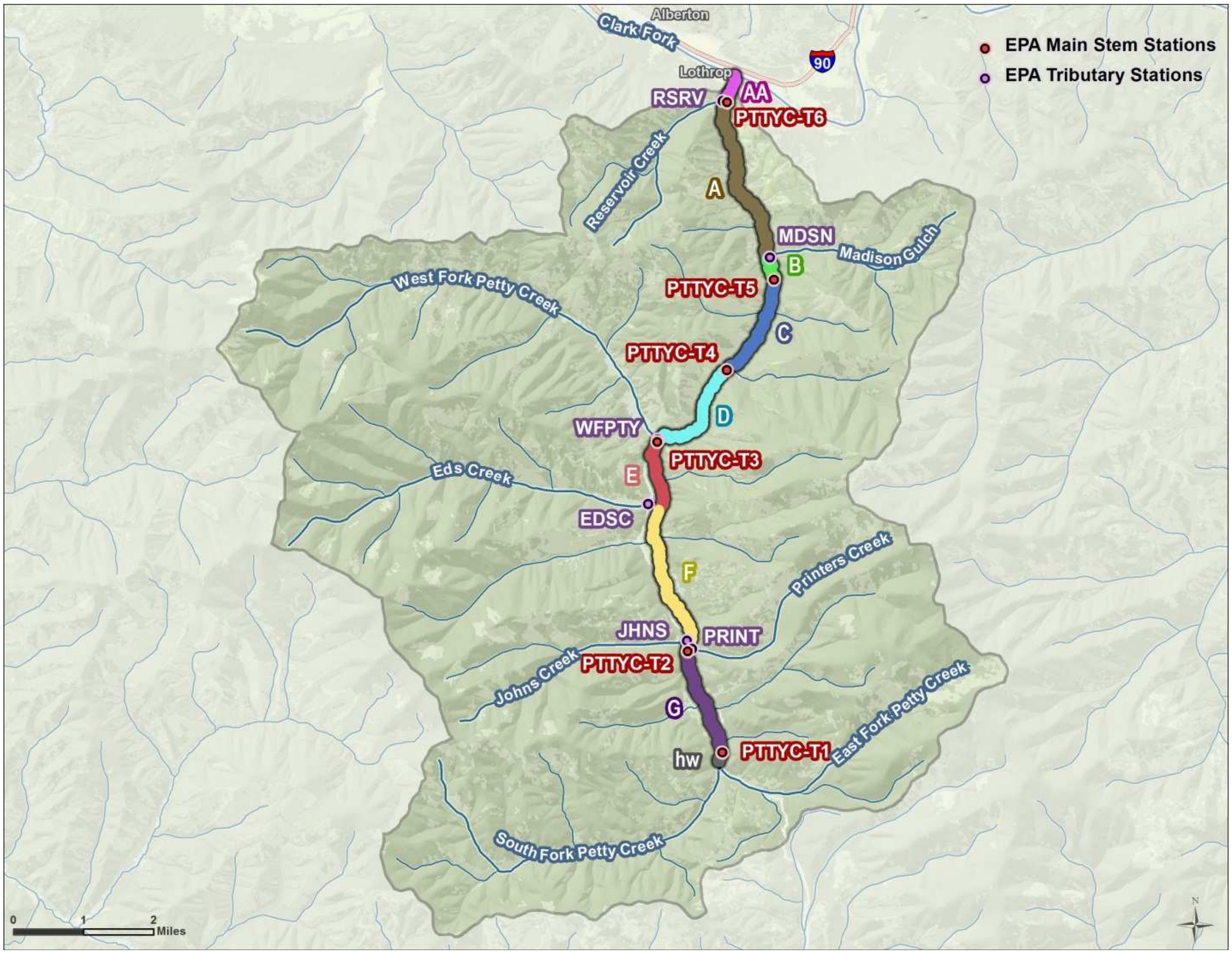


Figure 7. Petty Creek model segments.

3.2.3 Streamflow and Hydraulics

The flow rates were estimated through flow mass balance 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 three nearby U.S. Geological Survey (USGS) gages (**Table 2**) of similar size to Petty Creek, which is 82 square miles. The exponents were set to the averages calculated from the three USGS gages: 0.43 for velocity and 0.40 for depth.

Table 2. Calculated exponents for nearby USGS gages

Gage ID	Gage name	Drainage area (square miles)	Exponents	
			Velocity	Depth
12325500	Flint Creek near Southern Cross, MT	53	0.45	0.34
12332000	Middle Fork Rock Creek near Philipsburg, MT	123	0.28	0.50
12381400	South Fork Jocko River near Arlee, MT	56	0.55	0.36

3.2.4 Boundary Conditions

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

3.2.4.1 Headwater (Upstream) Boundary

QUAL2K requires specification of the headwater flow and temperature. Headwater flow (June 27, 2012) and diurnal temperature (June 29, 2012) at the upstream boundary were specified using observed data from the in-stream logger at site PTTYC-T1 for the calibration period. A flow of 8.44 cubic feet per second (cfs) was specified for the calibration period; note that flow for June 29, 2012 was not available and observed flow from June 27, 2012 was used.

Headwater flow (July 30, 2012) and diurnal temperature (July 30, 2012) at the upstream boundary were specified for the boundary conditions based on the data available at site PTTYC-T1 for the validation period. A flow of 3.89 cfs was specified for the validation period. **Figure 8** shows the headwater temperatures specified in the model.

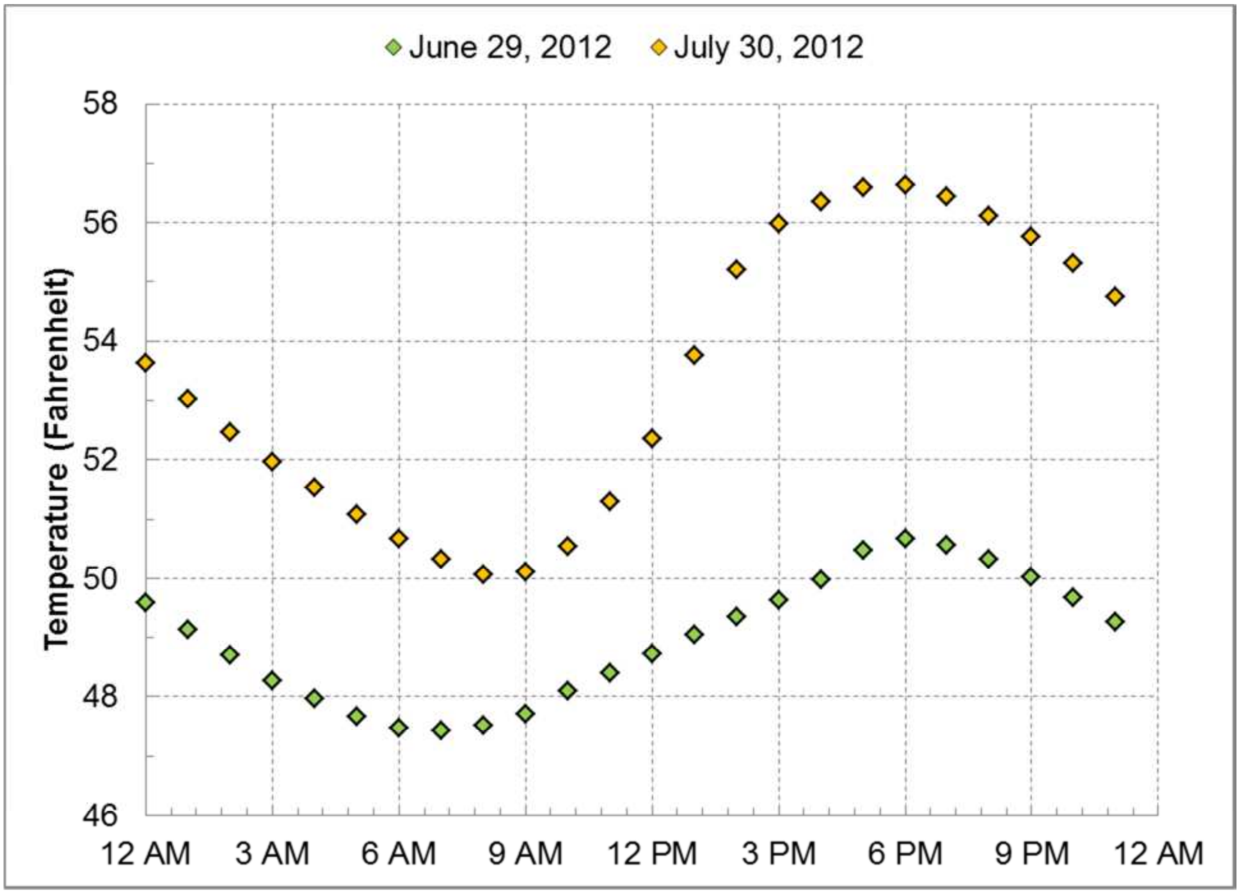


Figure 8. Diurnal temperature at the headwaters input to Petty Creek.

3.2.4.2 Tributary Inputs

There are many small tributaries in the watershed; however, monitoring data were available for only five of six major tributaries feeding into Petty Creek – Printer's Creek (PRINT), Ed's Creek (EDS), John's Creek (JHNS), Madison Gulch (MDSN), and Reservoir Creek (RSVR). The logger in West Fork Petty Creek was lost due to road construction. **Table 3** shows the flow and temperature assigned to the tributaries in the model (refer back to **Figure 2** for a map of the logger locations).

In addition to tributary inputs, irrigation withdrawals from Petty Creek was also identified (see **Appendix A** for a discussion of these withdrawals) and assigned in the model; additional withdrawals in the watershed (e.g., groundwater) were excluded from the model as they were outside of the model domain. Information on withdrawal rates or whether withdrawal is occurring during the calibration and validation dates was not readily available. Net irrigation requirements to irrigate the fields were queried from the Montana Natural Resource Information System for the months of June and July, which were 3.9 and 5.5 inches per month, respectively. A maximum daily flow rate was estimated using the net irrigation requirements and the maximum area irrigated (a total of 482 acres). It was calculated that up to 6.00 cfs may be withdrawn from Petty Creek on a daily basis in the month of July. These calculated withdrawals were used in the model (rows identified as *irrigation withdrawal* in **Table 3**). More information on the irrigation withdrawals can be found in **Appendix A**.

Table 3. QUAL2K model flow and temperature inputs to Petty Creek - Tributaries and withdrawal for the calibration period, June 29, 2012

Description	Location (RM)	Point sources [a]		Temperature [b]		
		Abstraction (cfs)	Inflow (cfs)	Daily mean (°F)	½ daily range (°F)	Time of maximum (hour)
irrigation withdrawal	12.82	0.32	--	--	--	--
irrigation withdrawal	12.76	0.081	--	--	--	--
irrigation withdrawal	11.84	0.17	--	--	--	--
Printer Creek	10.94	--	1.25	48.3	1.51	6:00 PM
lawn and garden withdrawal	10.85	0.21	--	--	--	--
John's Creek	10.84	--	1.65	47.0	1.57	6:00 PM
irrigation withdrawal	9.19	0.89	--	--	--	--
irrigation withdrawal	8.85	1.30	--	--	--	--
Ed's Creek	8.40	--	4.44	48.1	1.60	4:00 PM
irrigation withdrawal	7.77	0.060	--	--	--	--
West Fork Petty Creek [c]	7.27	--	4.32	46.1	1.60	4:00 PM
irrigation withdrawal	6.97	0.011	--	--	--	--
irrigation withdrawal	6.93	0.011	--	--	--	--
irrigation withdrawal	6.69	0.088	--	--	--	--
Madison Gulch	3.33	--	0.34	51.4	1.96	6:00 PM
irrigation withdrawal	1.15	0.081	--	--	--	--
irrigation withdrawal	0.69	2.52	--	--	--	--
irrigation withdrawal	0.56	0.071	--	--	--	--
Reservoir Creek	0.42	--	0.29	45.0	0.11	2:00 PM
irrigation withdrawal	0.40	0.039	--	--	--	--
irrigation withdrawal	0.29	0.021	--	--	--	--
irrigation withdrawal	0.21	0.021	--	--	--	--

Notes

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

a. Points sources represent abstractions (i.e., withdrawals) or inflows. Each point source can be an abstraction or an inflow.

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

c. The logger on West Fork Petty Creek was lost during road construction. The temperature inputs shown in this table were derived from the continuous temperature data monitored at Ed's Creek (logger EDS) that were modified by using the difference between instantaneous temperature measurements collected on West Fork Petty Creek and Ed's Creek.

Table 4. QUAL2K model flow and temperature inputs to Petty Creek - Tributaries and withdrawal for the validation period, July 30, 2012

Description	Location (RM)	Point sources [a]		Temperature [b]		
		Abstraction (cfs)	Inflow (cfs)	Daily mean (°F)	½ daily range (°F)	Time of maximum (hour)
irrigation withdrawal	12.82	0.32	--	--	--	--
irrigation withdrawal	12.76	0.081	--	--	--	--
irrigation withdrawal	11.84	0.17	--	--	--	--
Printer Creek	10.94	--	0.68	52.73	3.08	5:00 pm
lawn and garden withdrawal	10.85	0 [c]	--	--	--	--
John's Creek	10.84	--	0.86	50.86	3.19	4:00 pm
irrigation withdrawal	9.19	0 [c]	--	--	--	--
irrigation withdrawal	8.85	0 [c]	--	--	--	--
Ed's Creek	8.40	--	1.93	51.89	3.23	4:00 pm
irrigation withdrawal	7.77	0.060	--	--	--	--
West Fork Petty Creek [d]	7.27	--	1.57	56.0	3.23	5:00 pm
irrigation withdrawal	6.97	0.011	--	--	--	--
irrigation withdrawal	6.93	0.011	--	--	--	--
irrigation withdrawal	6.69	0.088	--	--	--	--
Madison Gulch [e]	3.33	--	0.19 [f]	56.78	3.83	6:00 pm
irrigation withdrawal	1.15	0.081	--	--	--	--
irrigation withdrawal	0.69	2.52	--	--	--	--
irrigation withdrawal	0.56	0.071	--	--	--	--
Reservoir Creek	0.42	--	0.28	46.82	2.43	5:00 pm
irrigation withdrawal	0.40	0.039	--	--	--	--
irrigation withdrawal	0.29	0.021	--	--	--	--
irrigation withdrawal	0.21	0.021	--	--	--	--

Notes

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

a. Points sources represent abstractions (i.e., withdrawals) or inflows. Each point source can be an abstraction or an inflow.

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

c. Since Petty Creek ran dry from John's Creek to Ed's Creek, irrigation withdrawals on this segment were set to zero.

d. The logger in West Fork Petty Creek was lost during road construction. The temperature inputs shown in this table were derived from the continuous temperature data monitored at Ed's Creek (logger EDS) that were modified by using the difference between instantaneous temperature measurements collected on West Fork Petty Creek and Ed's Creek.

e. The logger in Madison Gulch (MDSN) was exposed to ambient air when water was diverted during road construction and culvert replacement from July 30, 2012 to August 30, 2012. Data from July 30, 2012, prior to flow diversion, were compared with data from previous days and no significant differences were identified. Temperature data from July 29, 2012 were used to develop the tributary boundary condition.

f. Flow in Madison Gulch (MDSN) was diverted during road construction and culvert replacement from July 30, 2012 to August 30, 2012 and Atkins did not monitor flow on July 30, 2012. Flow was estimated using a mass balance. The results were compared with the flow Atkins monitored during logger retrieval on October 11, 2012 and found to be reasonable.

3.2.4.3 Diffuse Sources

Groundwater 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 Petty Creek and the observed tributary flows, and the amount of diffuse flow along Petty Creek was calculated for the days when flow was available on June 27 and 28, 2012 and July 31 through August 1, 2012.

A multi-step process was used to evaluate diffuse temperatures using multiple methods and datasets:

- The mean annual air temperature for the preceding year was 46.4° F
- Groundwater wells' temperatures from the Groundwater Information Center ranged from 43.7° F to 50.0° F
- The regression methodology[3] from Yoshitake et al. (2002) resulted in 50.5° F

The initial diffuse flow temperature was selected as the minimum reported groundwater well temperature (43.7° F), which was further evaluated during calibration. The initial diffuse source water temperature (43.7° F) was retained during calibration and was kept the same for the validation period. The final flow and water temperature assignment are shown below in **Table 5**.

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

Segment description	Location [a] Upstream (RM)	Location [a] Downstream (RM)	Diffuse Abstraction (cfs)	Diffuse Inflow: Inflow (cfs)	Diffuse Inflow: Temp (°F)
June 29, 2012					
G: PTTYC-T1 to PTTYC-T2	12.825	10.989	--	1.65	43.7
F: PTTYC-T2 to Ed's Creek	10.989	8.398	4.5	--	--
E: Ed's Creek to PTTYC-T3	8.398	7.289	--	27.01	43.7
D: PTTYC-T3 to PTTYC-T4	7.289	5.480	3.52	--	--
C: PTTYC-T4 to PTTYC-T5	5.480	3.784	8.43	--	--
B: PTTYC-T5 to Madison Gulch	3.784	3.318	--	0.86	43.7
A: Madison Gulch to PTTYC-T6	3.318	0.466	--	10.55	43.7
AA: PTTYC-T6 to mouth	0.466	0.000	--	0.25	43.7
July 30, 2012					
G: PTTYC-T1 to PTTYC-T2	12.825	10.989	1.77	--	--
F: PTTYC-T2 to Ed's Creek	10.989	8.398	3.00	--	--
E: Ed's Creek to PTTYC-T3	8.398	7.289	--	14.83	43.7
D: PTTYC-T3 to PTTYC-T4	7.289	5.480	0.88	--	--
C: PTTYC-T4 to PTTYC-T5	5.480	3.784	6.00	--	--
B: PTTYC-T5 to Madison Gulch	3.784	3.318	--	7.63	43.7
A: Madison Gulch to PTTYC-T6	3.318	0.466	--	9.89	43.7
AA: PTTYC-T6 to mouth	0.466	0.000	--	2.83	43.7

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

[3] The Yoshitake et al. (2002) regression methodology is calculated as 3.7° C added to the quantity of 0.83 multiplied by the mean annual air temperature.

Groundwater seepages were observed in the field near PTTYC-T3 and between PTTYC-T5 and PTTYC-T6. The flow volumes and colder groundwater temperatures were accounted for in model segments E, B, and A, as shown in **Table 5.**

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. The Nine Mile RAWS is in closest proximity to Petty Creek (**Appendix A**) and records hourly air temperature, dew point temperature, wind speed and solar radiation, whereas the Superior, Montana weather station (246580 in **Appendix A**) only records hourly air temperature data. The Nine Mile RAWS hourly observed meteorological data were used to develop the QUAL2K model after appropriate unit conversions and adjustments (as discussed below).

Air temperature and dew point temperature data from the Nine Mile RAWS were adjusted using the moist air adiabatic lapse rate (-0.00656 degrees Celsius per meter) to account for the elevation difference between the RAWS and the individual model segments.

The wind speed measurements at the Nine Mile RAWS were measured at 20 feet (6.10 meters) above the ground. QUAL2K requires that the wind speed be at a height of 7 meters. The wind speed measurements ($U_{w,z}$ in 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:

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

3.2.6 Shade Data

The QUAL2K model allows for spatial and temporal specification of shade, which is the fraction of potential solar radiation that is blocked by topography and vegetation. A shade model was developed and calibrated for the Petty Creek watershed. The calibrated shade model was first run to simulate shade estimates for June 29 and July 30, 2012 to simulate hourly shade every 30 meters (the resolution of the shade model) along Petty Creek. Reach-averaged integrated hourly effective shade results were then computed and were then input into each reach within the QUAL2K model. The overall average daytime shade on June 29, 2012 (55 percent) was less than that predicted on July 30, 2012 (62 percent). A more detailed discussion on the shade modeling can be found under **Appendix A**.

3.3 Model Evaluation Criteria

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

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

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

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

3.4 Model Calibration and Validation

The time periods selected for calibration and validation were June 29, 2012 and July 30, 2012, respectively. These dates were selected as they had the most comprehensive dataset available for modeling and corresponded to the synoptic study done for Petty Creek, which included collecting flow, temperature, shade, and channel geometry information.

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

Table 6. Temperature calibration and validation locations

Site name	Distance (RM)	Available Data	Source
PTTYC-T1	12.8	Flow, depth, velocity, and temperature	EPA
PTTYC-T2	11.0	Flow, depth, velocity, and temperature	EPA
PTTYC-T3	7.3	Flow, depth, velocity, and temperature	EPA
PTTYC-T4	5.5	Flow, depth, velocity, and temperature	EPA
PTTYC-T5	3.8	Flow, depth, velocity, and temperature	EPA
PTTYC-T6	0.5	Flow, depth, velocity, and temperature	EPA

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

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

After the mass balance of the flow rates, the modeled velocity and depth were simulated using the previously described rating curve method. While the exponents were not varied during the model calibration, the rating curve coefficients were modified and evaluated against the observed data. After identifying the most suitable coefficients for each segment using the calibration data for June 29, 2012, the selected coefficients were evaluated with the validation data for July 30, 2012[4]. The model results indicated a reasonable model representation (**Figure 9** and **Figure 10**).

[4] During the validation, the coefficients were modified for segment F because Petty Creek ran dry in this segment during the validation period. The coefficients were not modified for the other segments during the validation.

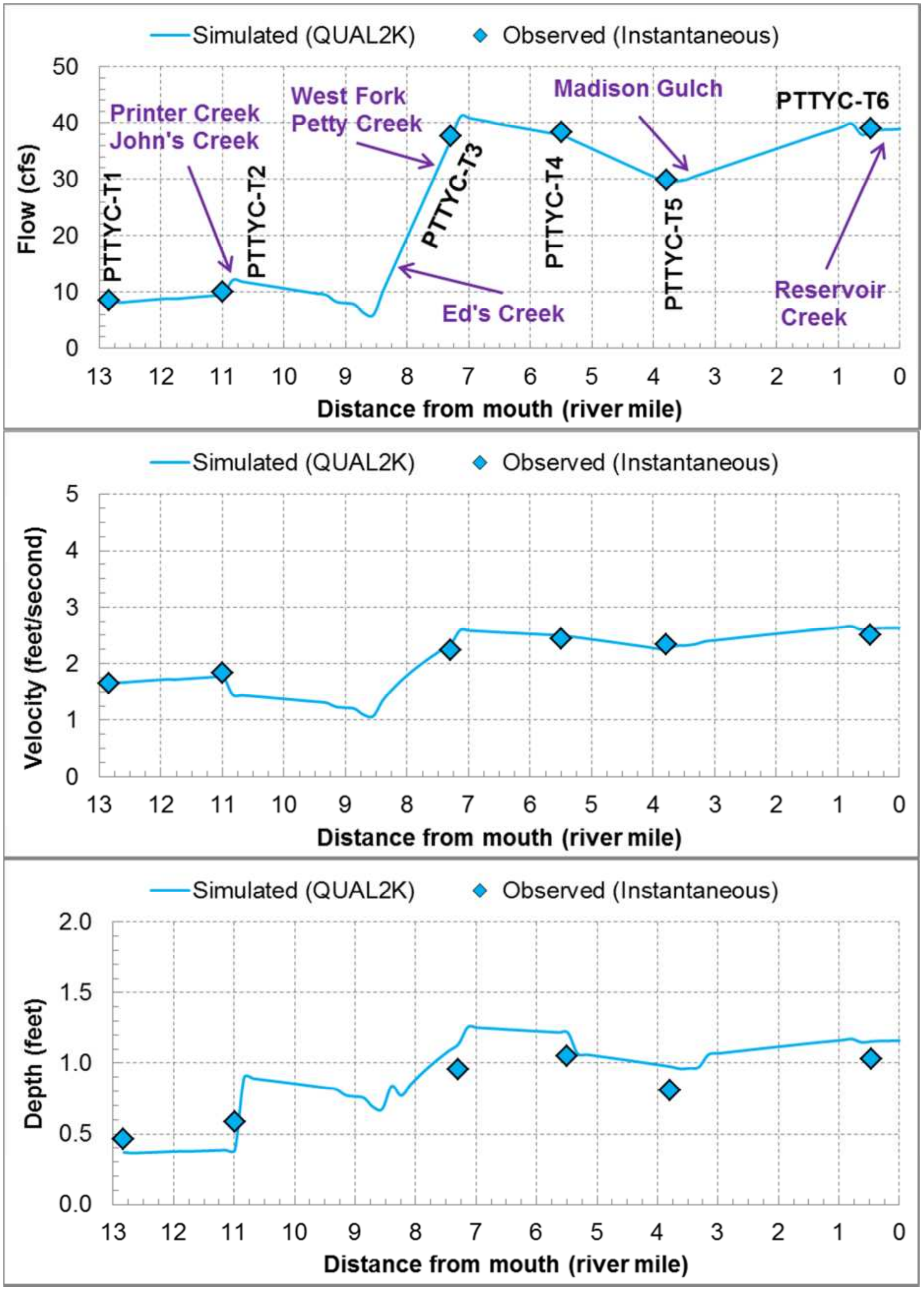


Figure 9. Observed and simulated flow, velocity, and depth on June 29, 2012 (calibration).

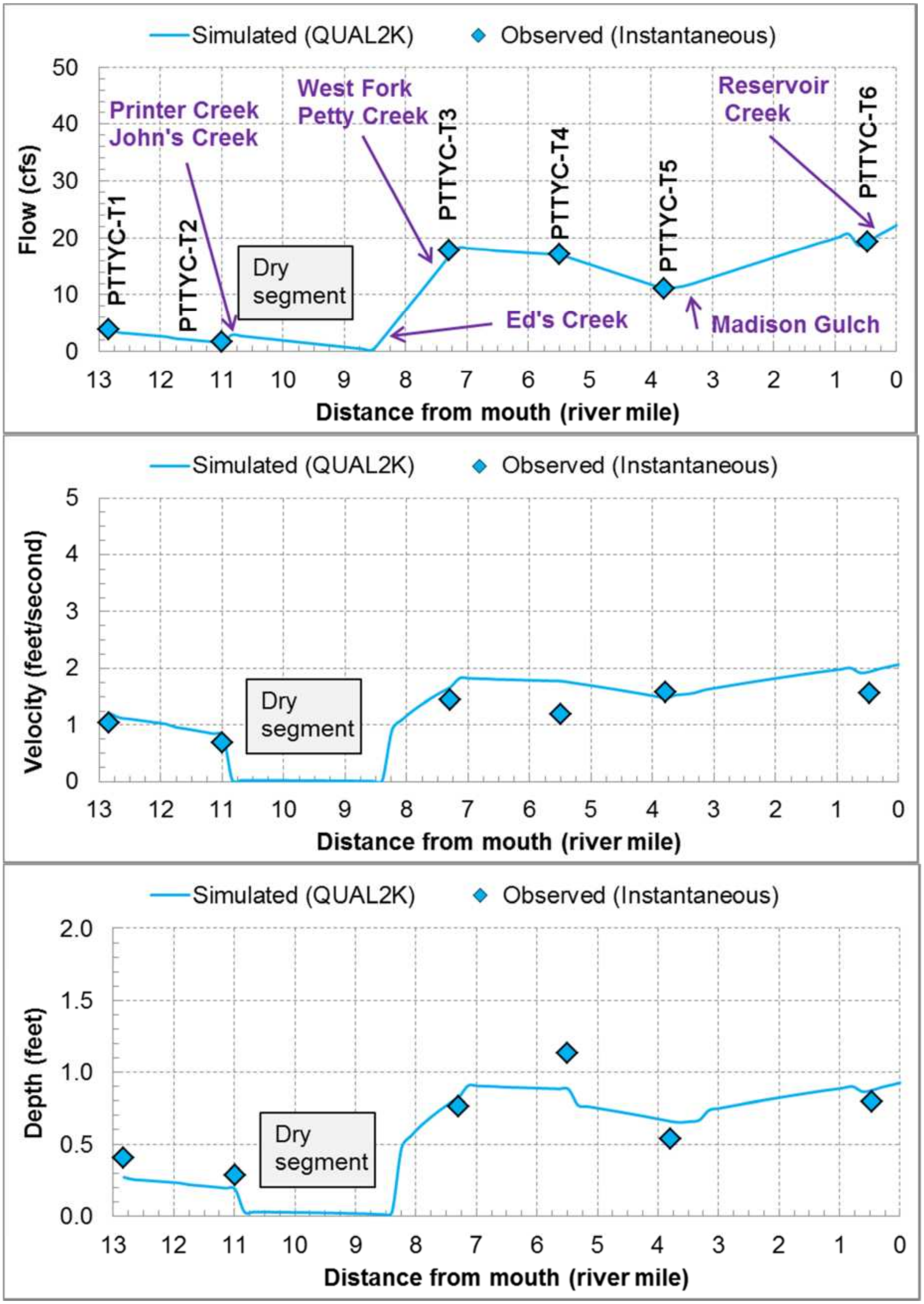


Figure 10. Observed and predicted flow, velocity, and depth on July 30, 2012 (validation).

As shown in **Figure 10**, the QUAL2K model simulated a faster in-stream velocity and shallower depth at PTTYC-T4 than was observed. The depth and velocity coefficients (see **Section 3.2.3** for a discussion of the rating curve methodology to simulate hydraulic conditions) were varied in an attempt to better simulate observed depth and velocity during the validation period. However, adjustments to the coefficients to better simulate hydraulics at PTTYC-T4 during the validation period resulted in a offsetting the simulation of hydraulics at PTTYC-T4 during the calibration period; additionally, the adjustment did not positively affect the simulated temperatures below PTTYC-T4 in either the calibration or validation period. Therefore, the depth and velocity coefficients from the calibration were retained.

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 Petty 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 Nine Mile RAWS. **Figure 11** shows the observed and predicted solar radiation for the calibration and validation. No cloud cover data were available and the observed solar radiation during calibration showed some influence due to cloud cover throughout most of the day on June 29, 2012. The cloud cover was adjusted to more closely mimic observed solar radiation during calibration on June 29, 2012. During the validation period, cloud cover was assumed to be minimal and set to zero[5] on July 30, 2012. The Ryan-Stolzenbach atmospheric transmission coefficient (default 0.80) was also adjusted to 0.85 (June 29, 2012) and 0.82 (July 30, 2012) to reflect the atmospheric conditions to minimize the deviation between the observed and modeled short wave solar radiation.

[5] However, cloud cover was set to 100 percent in model segment F (from PTTYC-T2 to Ed's Creek). Between John's Creek and Ed's Creek, Petty Creek runs dry (i.e., segment F, see **Figure 7**). As flow cannot be set to zero in QUAL2K, a very small 0.35 cfs flow volume was simulated in segment F and the cloud cover was set to 100 percent to insure that the solar radiation did not affect the temperature.

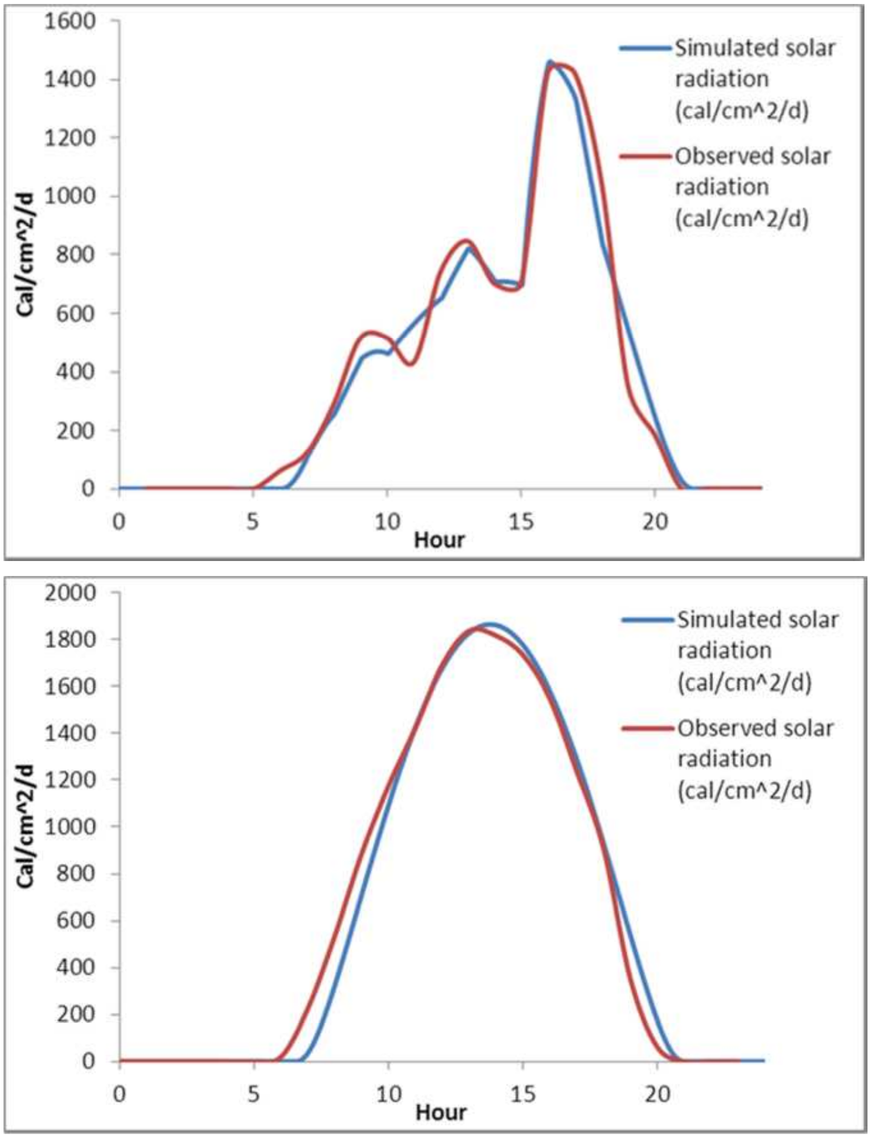


Figure 11. Observed and predicted solar radiation on June 29, 2012 (calibration; chart on top) and July 30, 2012 (validation; chart on bottom).

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

Table 7. Solar radiation settings

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

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 17 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 thermal diffusivity was set to a value of 0.0118 square centimeters per second (Chapra et al. 2008). This was consistent with the stream photos that indicated a predominant rocky substrate along the main channel.

The sediment density was set to 2.25 grams per cubic centimeter (g/cm^3). A review of Soil Survey Geographic Database (SSURGO) data indicated that most of the soil proximal to the stream was sand and silt soil types. Geology data from Montana Bureau of Mines and Geology indicated that the type of rock geology within the watershed was mainly limestone and sandstone. Based on the field photographs, the surface layer of the stream substrate was estimated to be composed of 65 percent of sandstone and limestone rock and 35 percent of sand and silt with silt to be higher percentage based on SSURGO data. The following calculation was conducted:

$$
\begin{aligned}
\text{sediment density} &= (\text{ratio of rock} * \text{rock density}) + (\text{ratio of soil} * \text{soil density}) \\
&= (0.65 * 2.65\ \text{g/cm}^3) + (0.35 * 1.52\ \text{g/cm}^3) \\
&= 2.25\ \text{g/cm}^3
\end{aligned}
$$

where 2.65 g/cm^3 is the average of the typical sandstone (2.6 g/cm^3) and limestone (2.7 g/cm^3) densities and 1.52 g/cm^3 is typical of clay and silt densities.

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. Variables that changed with time included headwater and tributary in-stream temperatures, air and dew point temperatures, wind speed, cloud cover, solar radiation, and shade. All other inputs were based on observed data in July 30, 2012. Groundwater temperatures, for which there were no direct observed data, were unchanged since they are not expected to change significantly between June 29 and July 30.

Figure 12 and **Figure 13** show the calibration and validation results along Petty Creek. The temperature calibration and validation statistics of the average, maximum, and minimum temperatures are shown in **Table 8** and **Table 9**, respectively.

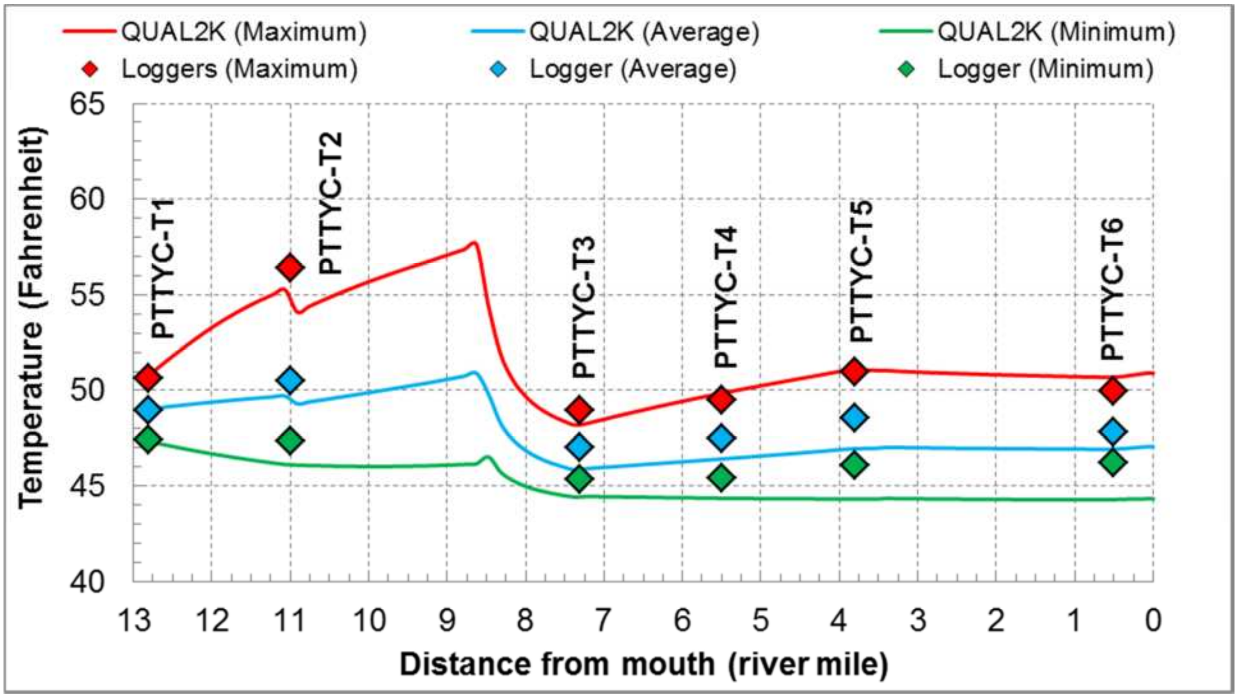
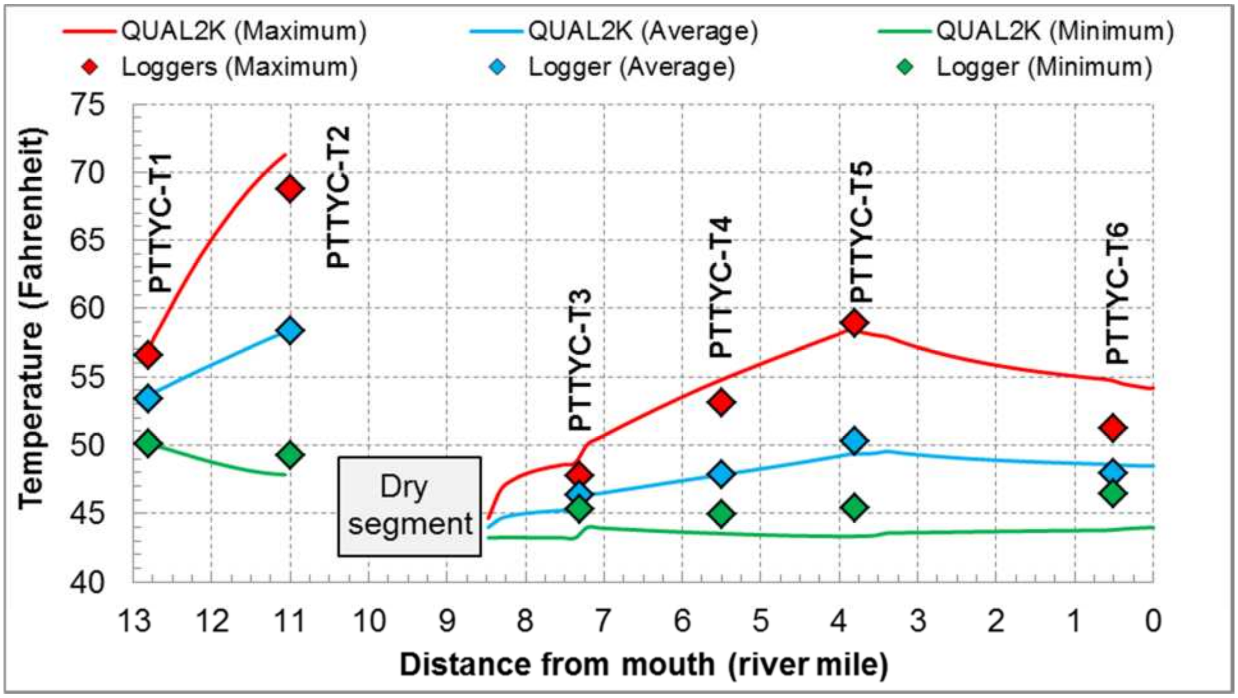


Figure 12. Longitudinal profile of the temperature calibration (June 29, 2012).



Note: Petty Creek ran dry in segment F. As flow cannot be set to zero in QUAL2K, the segment was simulated with a tiny flow volume. Since the flow was assumed to be interstitial or subsurface, the cloud cover was set to 100 percent. Essentially, segment F was forced to simulate water temperatures near 6.5° C (43.7° F) to represent a groundwater seepage observed in the field at the lower terminus of this segment.

Figure 13. Longitudinal profile of the temperature validation (July 30, 2012).

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 (%)
PTTYC-T1	12.8	--	--	--	--	--	--
PTTYC-T2	11.0	0.80	1.6%	1.14	2.0%	1.25	2.6%
PTTYC-T3	7.3	1.18	2.5%	0.75	1.5%	0.94	2.1%
PTTYC-T4	5.5	1.08	2.3%	0.30	0.6%	1.04	2.3%
PTTYC-T5	3.8	1.58	3.3%	0.15	0.3%	1.74	3.8%
PTTYC-T6	0.5	0.90	1.9%	0.73	1.5%	1.96	4.2%
Overall Calibration		**1.11**	**2.3%**	**0.61**	**1.2%**	**1.39**	**3.0%**

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 (%)
PTTYC-T1	12.8	--	--	--	--	--	--
PTTYC-T2	11.0	0.05	0.1%	2.50	3.6%	1.38	2.8%
PTTYC-T3	7.3	1.04	2.2%	0.92	1.9%	2.07	4.6%
PTTYC-T4	5.5	0.08	0.2%	1.57	3.0%	1.41	3.1%
PTTYC-T7	3.8	0.93	1.9%	0.48	0.8%	2.04	4.5%
PTTYC-T8	0.5	0.62	1.3%	3.52	6.9%	2.66	5.7%
Overall Validation		**0.55**	**1.1%**	**1.80**	**3.2%**	**1.91**	**4.1%**

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

In general, the model was able to capture the observed temperature range and longitudinal profile. All the simulated minimum, maximum, and mean temperatures were contained within relatively small errors. The overall calibration results showed an overall 1.2 percent relative error with an AME of 0.6° F for the maximum temperatures. The overall validation results for the maximum temperatures were similar to the calibration statistics with an overall 3.2 percent relative error and an AME of 1.8° F.

The Petty Creek model shows a reasonable agreement with the observed in-stream temperature data during the model calibration and the validation periods. As previously described, the data and the model results indicated that there was large seep inflow occurring nearby PTTYC-T3. The seep's low temperature appeared to control the diurnal temperature pattern after the PTTYC-T3 location for the calibration period of June 29, 2012. The validation period also confirmed the seep setting the trend of the diurnal temperature pattern for the segments. The validation diurnal ranges of the temperature were larger compared with the calibration ranges mainly due to less cloud coverage for the validation date.

In both the calibration and validation periods, the QUAL2K model shows the converging temperature trend around the mouth of Petty Creek. The observed temperature indicated a smaller range of the diurnal temperature. During calibration, the model velocity and depth were reviewed and the rating curve coefficients adjusted to better represent observed velocity and depth; the adjustments helped better represent the diurnal pattern. Additional model parameters were also adjusted to match the converging trends; however the model could not simulate the similar converging diurnal trends at the mouth of the Petty Creek.

4 Model Scenarios and Results

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

Table 10. QUAL2K model scenarios for Petty Creek

Scenario [a]		Description	Rationale
Existing Condition Scenario			
1	Existing Condition	Existing shade and irrigation practices under field-measured flows (define the flow relative to nearby gages as low, **high**, average)[b]	The baseline model simulation from which to construct the other scenarios and compare the results against.
Water Use Scenario			
2	15 % reduction in withdrawals	Reduce existing withdrawals by 15 percent	Represent application of conservation practices for agricultural and domestic water use.
Shade Scenario			
3	50-foot buffer	River miles 0 - 7: Transform all vegetation communities, with the exception of hydrophytic shrubs, roads, and railroads to **medium density trees** within 50 feet of the stream banks. Existing conditions vegetation to be retained beyond the 50-foot buffer. River miles 7 – Headwaters Boundary: Transform all herbaceous communities to **shrubs** within 50 feet of stream banks. Existing conditions to be retained beyond the 50-foot buffer.	Represent application of conservation practices for riparian vegetation.
Water Use and Shade Scenario			
4	Improved Flow and Shade	Existing conditions with 15% reduction in withdrawals (scenario 2) and 50-foot buffer (scenario 3).	Represent application of conservation practices for water withdrawals and riparian vegetation.

Notes

a. Scenarios were developed in accordance with electronic correspondence from Eric Sivers (DEQ) to Tetra Tech's project manager Ron Steg on September 9, 2013 and comments provided by Lisa Kusnierz (EPA) on September 26, 2013 in *Modeling Water Temperature in Wolf Creek*.

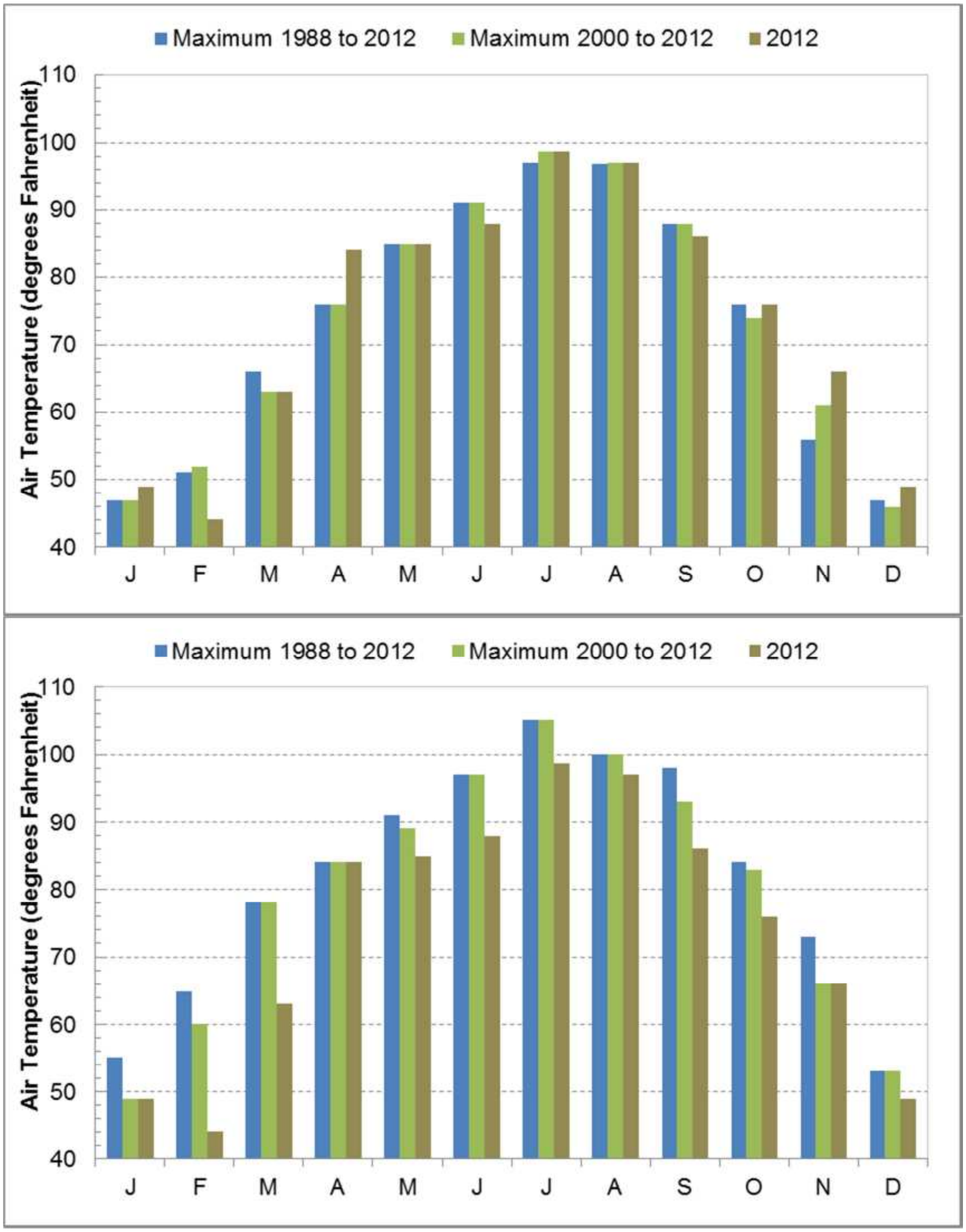
b. Based on an analysis of discharge records from a nearby USGS gage, flows in Petty Creek during the calibration timeframe were likely above average.

4.1 Existing Condition Scenario

The existing conditions model (scenario 1) serves as the baseline model simulation from which to construct the other scenarios and compare the results against. The existing condition scenario was run using the observed discharge in Petty Creek (on the calibration date). The daily average flow on June 29, 2012 at USGS gage 12381400 (South Jocko River near Arlee, MT; water years 1983-2012) was high (86th percentile) as compared to the daily average flows on all June 29ths on record. The daily average flow for June 2012 at USGS gage 12381400 was also high (83rd percentile) as compared to the daily average flow for all Junes on record (see **Appendix A, Section A-6**).

The Nine Mile RAWS has hourly data available for the period from August 2000 through December 2012. Since the weather data extends only for a period of twelve years, a nearby station with long-term meteorological data (Missoula International Airport [1988-2012]) was queried to confirm if the years from 2000 to 2012 were (1) not anomalously warm or cold and (2) similar to the overall historical normal. Additionally, comparisons with the year 2012 (during which the QUAL2K model calibration and validation periods occur) were made to ensure that 2012 was not an anomalous year. The long-term monthly median and maximum air temperatures for the period from 2000 to 2012 and for the year 2012 were estimated to be similar to the overall period from 1988 through 2012 (**Figure 14**)6. While the monthly maximum air temperatures in the summer of 2012 were cooler than the monthly long-term maximum of monthly maximum air temperatures of the years 1988-2012, they were similar to the monthly long-term median of monthly maximum air temperatures of the years 1988-2012 (**Figure 14**). Therefore, since neither the period from 2000 through 2012 nor the summer of 2012 was anomalous, it is appropriate to use the Nine Miles RAWS data for QUAL2K modeling.

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



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

Figure 14. Long-term median (chart on top) and maximum (chart on bottom) of monthly air temperature at Missoula.

The Nine Mile RAWS data were then used to simulate existing meteorological conditions during the calibration period. The travel time in Petty Creek was 0.4 days. The modeled water temperature using the existing flow and meteorological data is shown below in **Figure 16**.

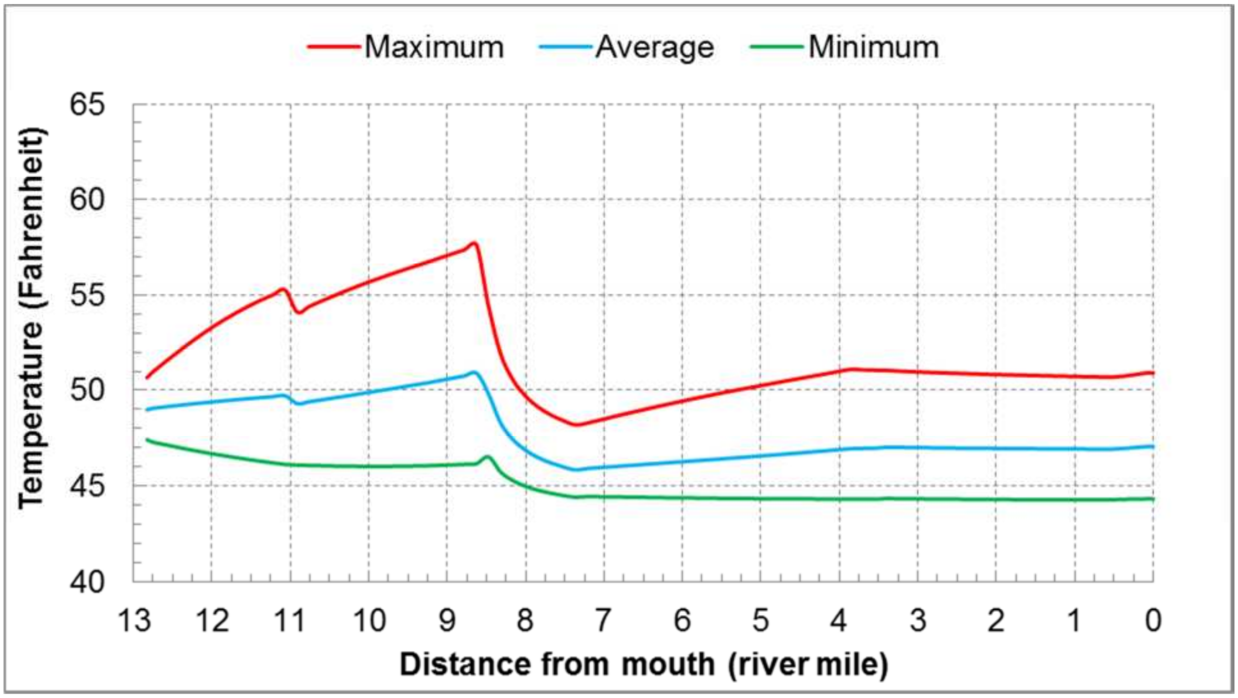


Figure 15. Simulated water temperature for existing condition.

4.2 Water Use Scenario

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

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

Water temperatures in Petty Creek for this scenario generally changed very little (**Figure 16**). Changes in the maximum daily water temperatures, as compared to the existing condition (scenario 1), ranged from a 0.04° F decrease to a 0.13° F increase. The difference in water temperature was always less than 0.5° F, signifying minimal sensitivity and conditions that are similar to the existing condition.

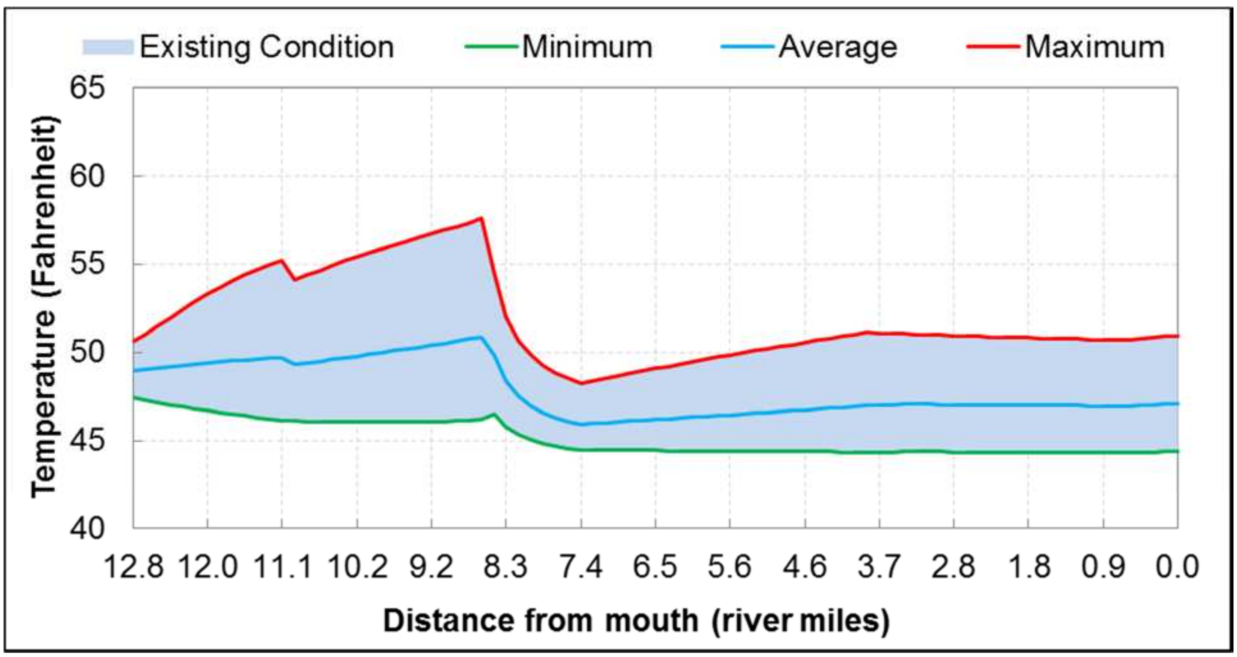


Figure 16. Simulated water temperatures for the existing condition (scenario 1) and 15-percent withdrawal reduction (scenario 2).

4.3 Shade Scenarios

The riparian plant community blocks incoming solar radiation, which directly reduces the heat load to the stream. A single shade scenario was modeled to evaluate the potential benefits associated with increased shade within a 50-foot buffer along Petty Creek.

The 50-foot buffer scenario consists of the existing condition scenario with a 50-foot buffer along the stream channel where vegetation is allowed to grow naturally. All vegetation communities (with the exception of areas with hydrophytic shrubs and roads) from river mile 7.0 to the mouth are transformed to medium density trees within 50 feet of the stream banks. From river mile 7.0 and upstream, all herbaceous communities are transformed to shrubs within 50 feet of the stream banks. Beyond 50 feet, existing condition vegetation remains. The Shade Model was re-run using this vegetation configuration (**Figure 17** and **Table 11**).

The 50-foot buffer was selected to be generally consistent with Montana's Streamside Management Zone Law, which limits clear cutting within 50 feet of the ordinary high water mark in order to provide large woody debris, stream shading, water filtering effects, and to protect stream channels and banks. This scenario is intended to represent application of *all reasonable land, soil and water conservation practices* relative to shade. The technical basis for this scenario is provided in **Appendix A** in **Section A-4**.

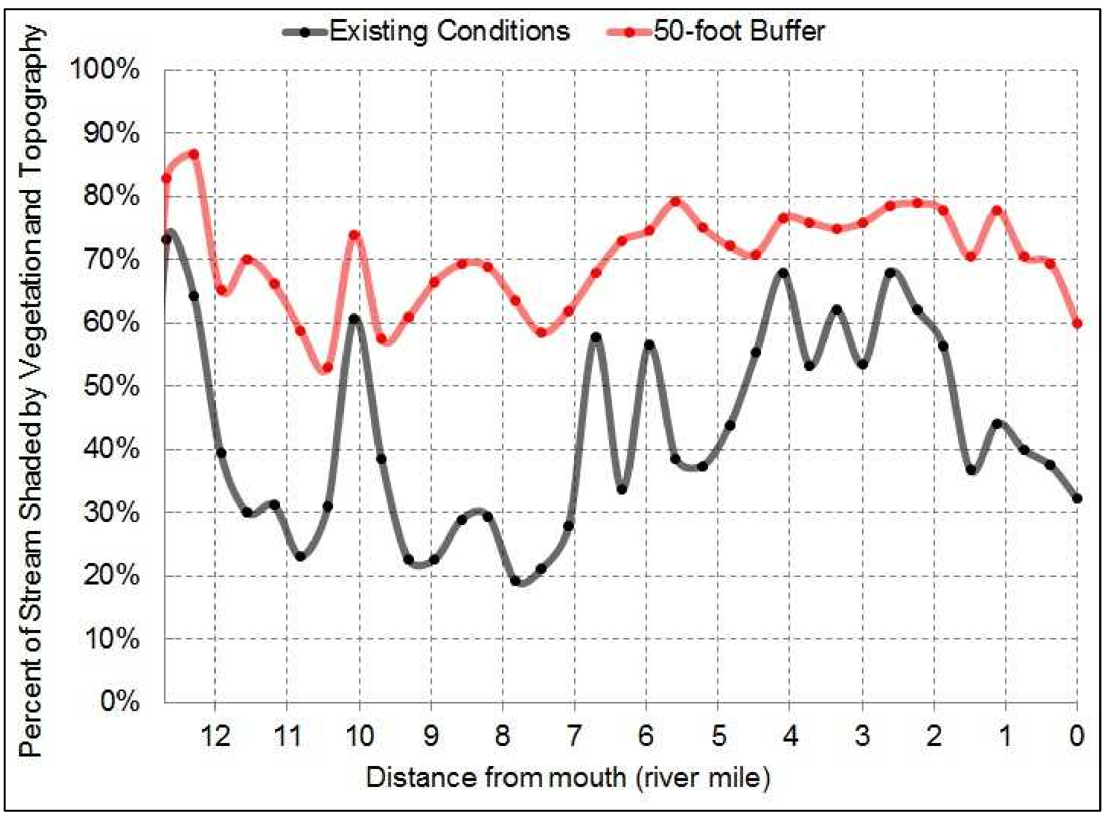


Figure 17. Effective shading along Petty Creek for the existing condition and 50 foot buffer shade scenario.

Table 11. Average daily shade inputs per model segment

Segment	Existing condition (scenario 1)	50-foot buffer (scenario 3)
G	54%	80%
F	47%	74%
E	38%	74%
D	59%	80%
C	66%	81%
B	72%	83%
A	63%	82%
AA	43%	69%

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 the daylight hours (yielding average effective shade per day per model segment).

The water temperatures for Petty Creek in this scenario decrease throughout the system (**Figure 18**). A maximum change in the maximum daily water temperature of 3.8° F from the existing condition was observed at river mile 8.6. The difference in the daily maximum water temperature between the existing condition and maximum potential shade scenario was always greater than 0.5° F (excluding the 0.1 mile just below the headwaters boundary condition).

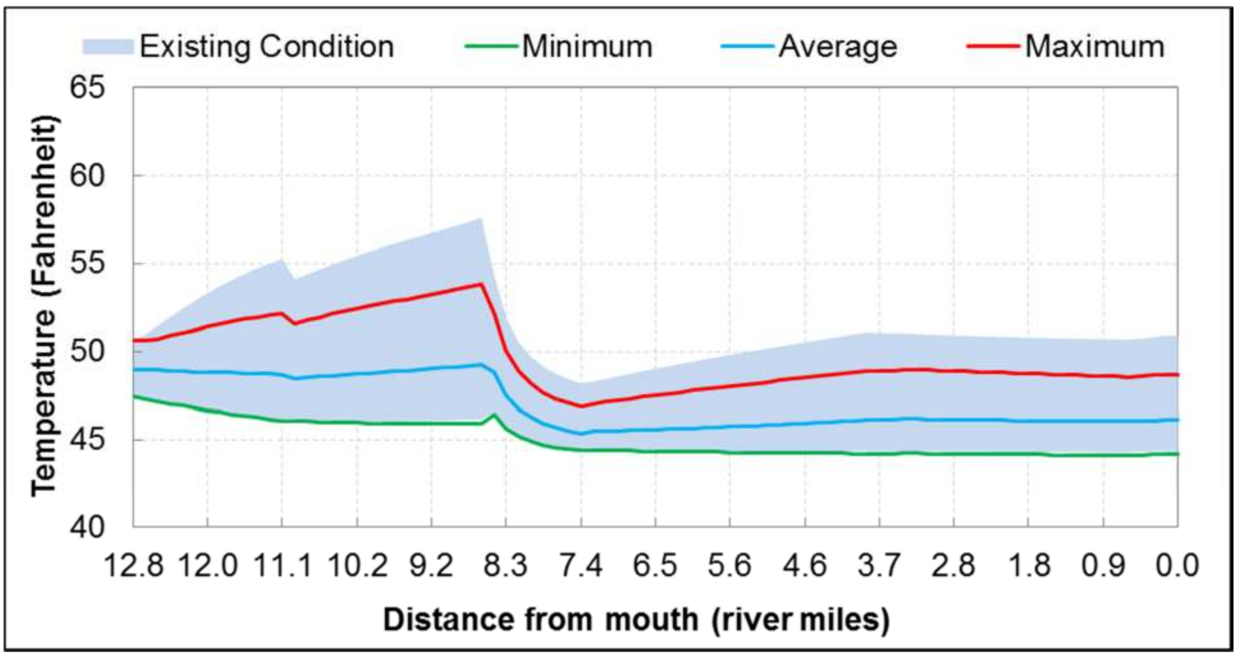


Figure 18. Simulated water temperatures for the existing condition (scenario 1) and shade with a 50 foot buffer (scenario 3).

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 a 50-foot vegetated buffer (scenario 3).

The water temperatures for Petty Creek in this scenario decrease throughout the system (**Figure 19** and **Figure 20**). A maximum change in the maximum daily water temperature of 3.8° F from the existing condition was observed at river mile 8.6. The results are similar to shade scenario (scenario 3) since the water use scenario (scenario 2) showed negligible sensitivity to a 15 percent reduction in the withdrawals. The difference in the daily maximum water temperature between the existing condition and maximum potential shade scenario was always greater than 0.5° F for this scenario (excluding the 0.1 mile just below the headwaters boundary condition)..

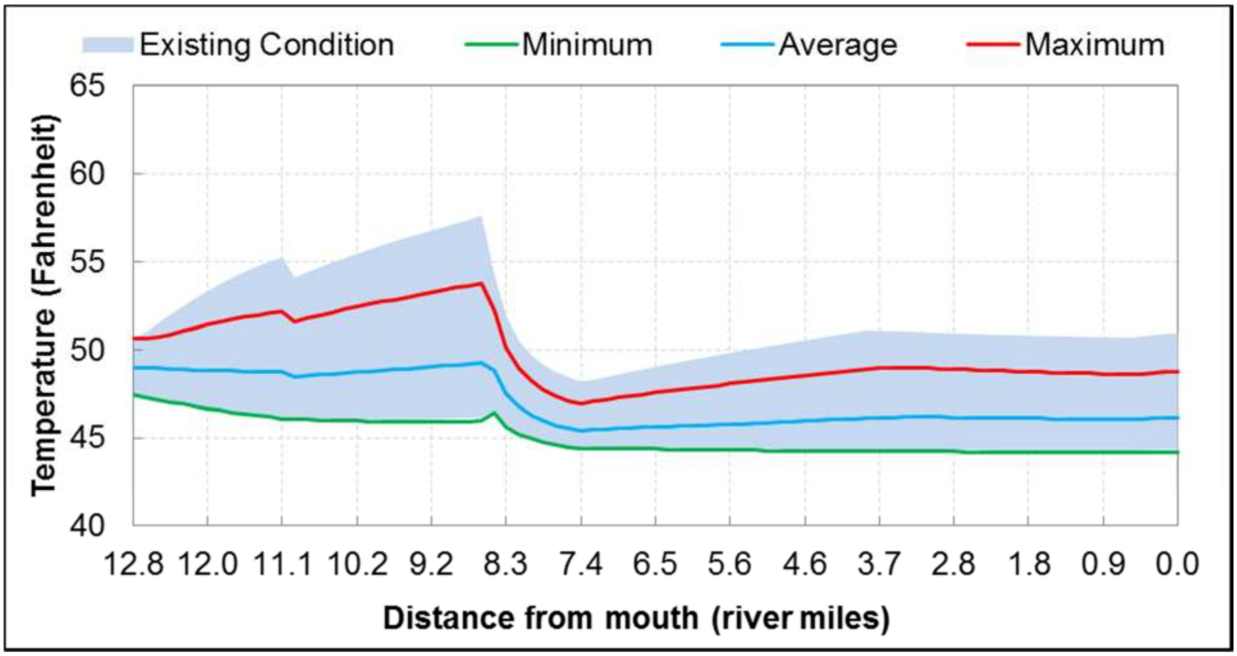


Figure 19. Simulated water temperature for the critical existing condition (scenario 1) and the improved flow and shade scenario (scenario 4).

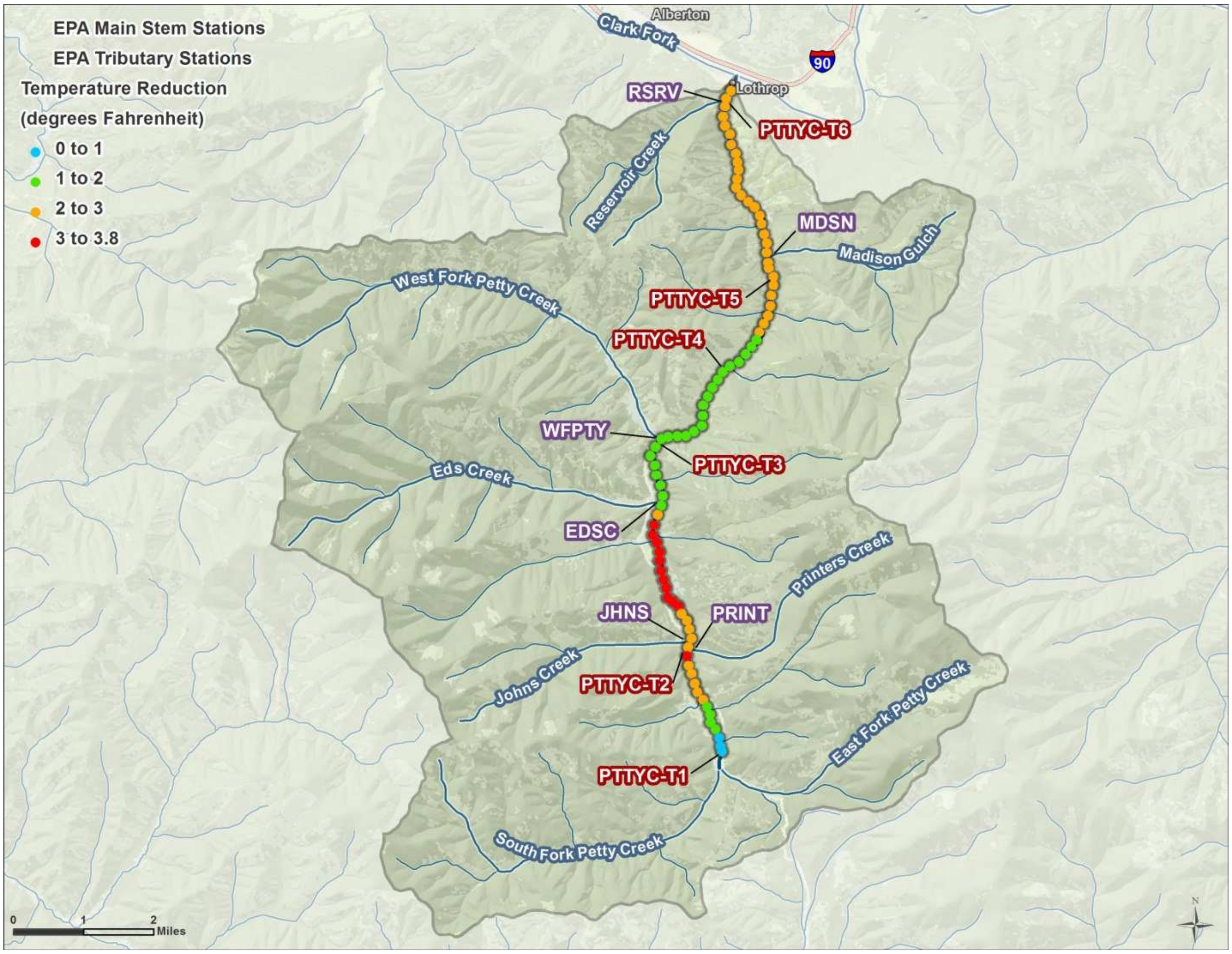


Figure 20. In-stream temperature difference from the existing condition (scenario 1) to the improved flow and shade scenario (scenario 4).

5 Assumptions and Uncertainty

As with any model, the QUAL2K model is subject to uncertainty. The major sources of model uncertainty include the mathematical formulation, input and boundary conditions data uncertainty, calibration data uncertainty, and parameter specification (Tetra Tech 2012). As discussed in the quality assurance project plan (Tetra Tech 2012), the QUAL2K model code has a long history of testing and application, so outright errors in the coding of the temperature model is 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.

The secondary data used during model setup included instantaneous flow, continuous temperature, channel geometry, hourly weather, and spatial data. Weather and spatial data were obtained from other government agencies, were found to be in reasonable ranges, and are assumed to be accurate. Uncertainty was minimized for the use of other secondary data following procedures described in the quality assurance project plan (Tetra Tech 2012).

In addition to uncertainty associated with secondary datasets, assumptions regarding how the secondary data are used during model development contain uncertainty. The following key assumptions were used during model development:

- Petty 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 Petty Creek.
- Spatial variability of velocity and depth (e.g. stream meander and hyporheic flow paths) are represented through exponents and coefficients of the selected rating curves for each segment.
- Weather conditions at the Nine Mile RAWS, which were elevation-corrected, are representative of local weather conditions along Petty Creek.
- Shade Model results are representative of riparian shading along segments of Petty 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 Petty Creek watershed.
    - Vegetation density was estimated using the National Land Cover Dataset (Multi-Resolution Land Characteristics Consortium 2006) and best professional judgment.

  Shade Model results were corroborated with field measured Solar Pathfinder™ results and were found to be reasonable. The average absolute mean error is 7 percent. (i.e., the average error from the Shade Model output and Solar Pathfinder™ measurements was 7 percent daily average shade).
- All of the cropland associated with water rights is fully irrigated. No field measurements of irrigation withdrawals or returns were available.
- Simulated diffuse flow rates are representative of groundwater inflow/outflow, irrigation diversion, irrigation return flow, and other sources of inflow and outflow not explicitly modeled. Diffuse flow rates were estimated using flow mass balance equations for each model reach.

- Shallow groundwater temperature is approximately 43.7° C (as the model was calibrated and validated), which were derived, in part, from monitored groundwater temperatures in nearby wells and the average of mean daily air temperatures from the preceding year. Groundwater temperatures can be roughly estimated by mean annual air temperature (Bartholow 1989), but they are ultimately a calibration parameter.

Sensitivity analysis is the most widely applied approach for evaluating parameter uncertainty for complex simulation models. Although a formal sensitivity analysis was not conducted for Petty Creek, based on the results of scenarios 2 and 3, it appears that Petty Creek is more sensitive to changes in shade than water volume.

The increased shade scenario (scenario 3) assumes that the system potential vegetation for the riparian area within 50 feet of the stream bank is (1) shrubs for the headwaters downstream to river mile 7 and (2) medium density trees from river mile 7 downstream to the mouth (with the exception of areas currently dominated by hydrophytic shrubs or areas such as roads or railroads that no longer have the potential to support vegetation). The increased shade scenario (scenario 3) represents the maximum 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.

6 Model Use and Limitations

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

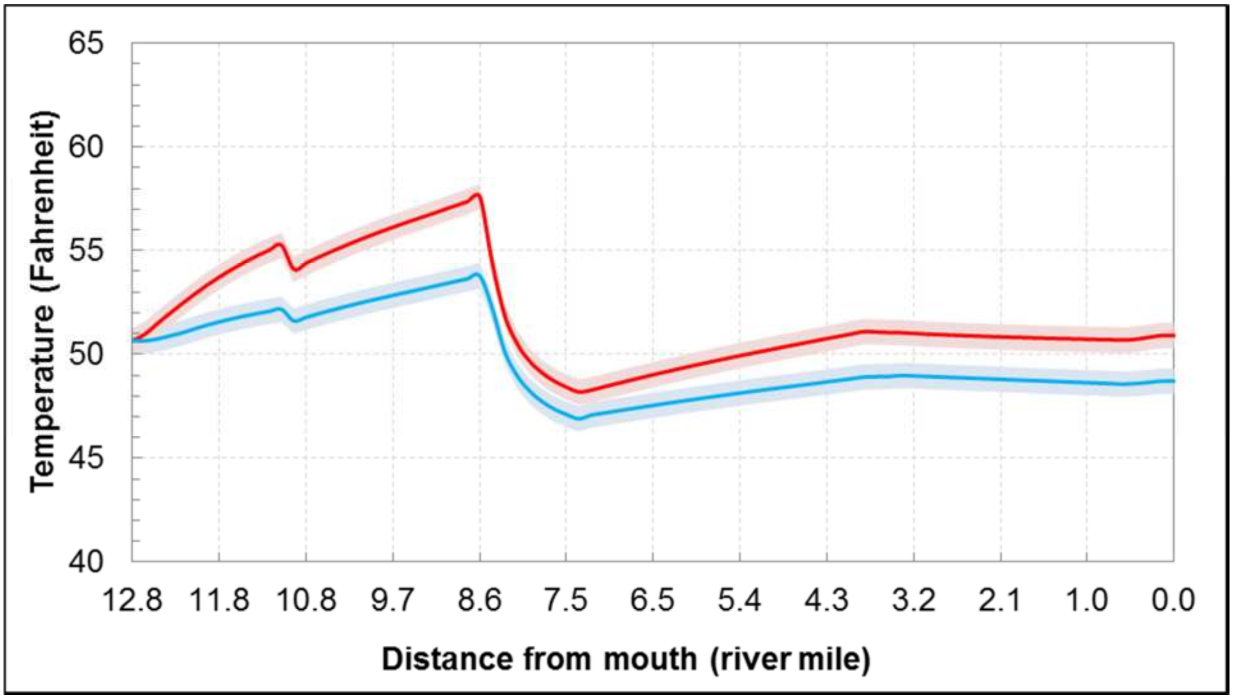
1. What is the sensitivity of instream temperature to the following thermal mechanisms and stressors: shade, irrigation withdrawal and return?
2. What levels of reductions in controllable stressors are needed to achieve temperature standards?

The first principal study question can be answered using the calibrated and validated QUAL2K model for Petty Creek. As previously discussed, Petty Creek is sensitive to shade.

The second principal study questions can be answered using the calibrated QUAL2K model and the scenarios developed to assess shade. Increasing riparian shading will decrease in-stream temperatures; however, there is uncertainty in the magnitude of temperature reduction necessary to achieve the temperature standard caused by uncertainty in the Shade Model results and QUAL2K model results. While a “good” model calibration was achieved, the overall Absolute Mean Error (AME) for the maximum daily temperature was 0.6° F.

Montana’s temperature standard as applied to Petty Creek is limited to an increase of 1° F. The model results, therefore, should be used with caution relative to the second primary question. However, in spite of the uncertainty, the magnitude of difference between the maximum daily temperatures under the naturally occurring and existing conditions scenarios is greater than the AME for most of the length of Petty Creek (**Figure 21**). This suggests that, on average[7], a reduction of 2.1°F (range: 0.3° F to 3.8° F) is necessary to achieve the temperature standard in Petty Creek.

[7] Spatial average of the QUAL2K output at each element along the entire length of Petty Creek.



Note: The existing condition (scenario 1) is the red line and the improved flow and shade scenario (scenario 4) is the blue line. The shaded areas are plus or minus the average AME (0.6° F).

Figure 21. Simulated daily maximum water temperatures from the existing condition (red; scenario 1) and the improved flow and shade scenario (blue; scenario 4).

7 Conclusions

The scenarios resulted in a range of no change in water temperatures to reductions as much as 3.8° F. Some of the reductions in water temperatures were localized and others affected nearly the entire reach.

A flow scenario representing irrigation efficiency was evaluated and the locations that showed the greatest potential for improvement were localized to areas just downstream of the existing withdrawals. The 15-percent reductions in water use did not result in any appreciable reduction to the temperature, with a maximum change of less than 0.1° F.

The shade scenario showed the greatest extent and impact (reduction) to water temperatures along the entire reach. The 50-foot buffer scenario that represents potential shade improvements showed reductions in temperature ranging from 0.3 ° F to 3.8° F.

The improved flow and shade scenario that combined the potential benefits associated with a 15 percent reduction in water withdrawals (scenario 2) with a 50-foot vegetated buffer (scenario 3) to represent application of conservation practices was also simulated. This scenario resulted in overall reductions along the entire reach which ranged from 0.3 ° F to 3.8 ° F. The scenario shows that significant reductions in water temperatures are achievable throughout the reach (**Figure 20**). The areas with the greatest changes demonstrate the most sensitive areas. The greatest potential improvement (i.e., reduction) occurs near river mile 8.6 (almost a 4° F improvement) with several other areas upstream and downstream along the system also showing sensitivity to shade (**Figure 23**). Hence efforts should largely be spent on re-vegetation in those areas most amenable to this type of restoration activity.

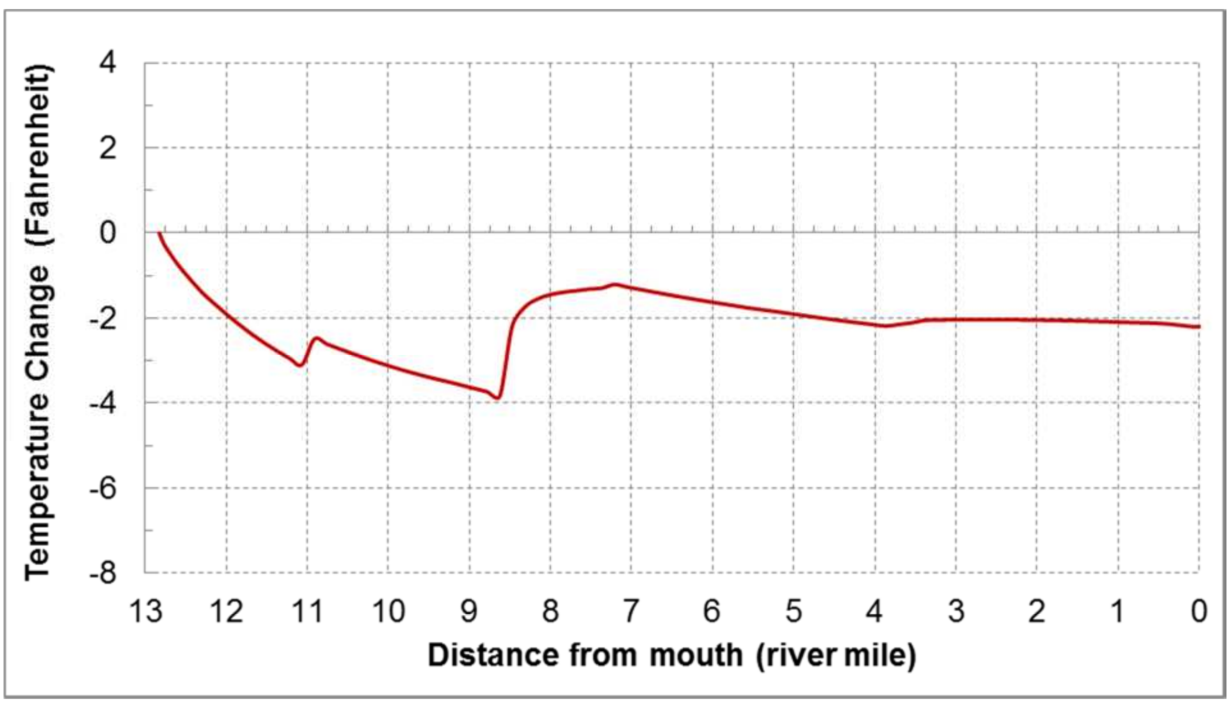


Figure 22. Simulated water temperature reduction from the existing condition (scenario 1) to the improved flow and shade scenario (scenario 4).

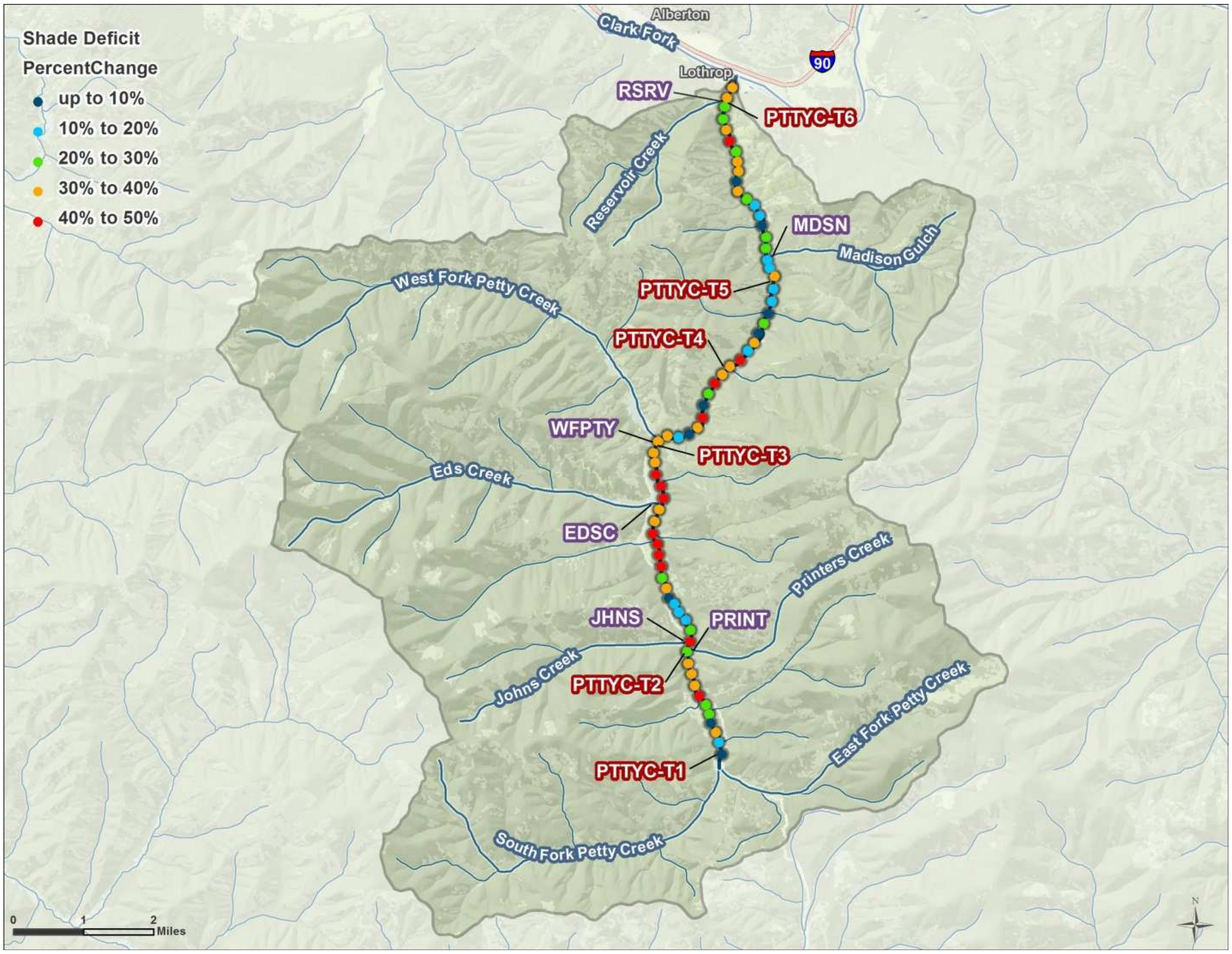


Figure 23. Shade deficit of the existing condition (scenario 1) from the improved flow and shade scenario (scenario 4).

8 References

Bartholow, J.M., 1989. Stream temperature investigations: field and analytic methods. Instream Flow Information Paper No. 13. U.S. Fish and Wildlife Service Biological Report 89(17). 139 pp.

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.

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.

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 1, June 29, 2012. Prepared for the U.S. Environmental Protection Agency, by Tetra Tech, Inc., Cleveland, OH.

Appendix A.

Factors Potentially Influencing Stream Temperature

in Petty 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 Petty 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 Petty Creek watershed is 20 miles to the northwest in the city of Superior, Montana (National Weather Service station 24159) at 2,700 feet above mean sea level (MSL). A Remote Automatic Weather Station (RAWS) is 9 miles away in Nine-Mile, Montana (National Weather Service station ID 241507, **Figure A-1**) at 3,300 feet above MSL. Petty Creek ranges in elevation from approximately 2,950 to 3,900 feet above MSL.

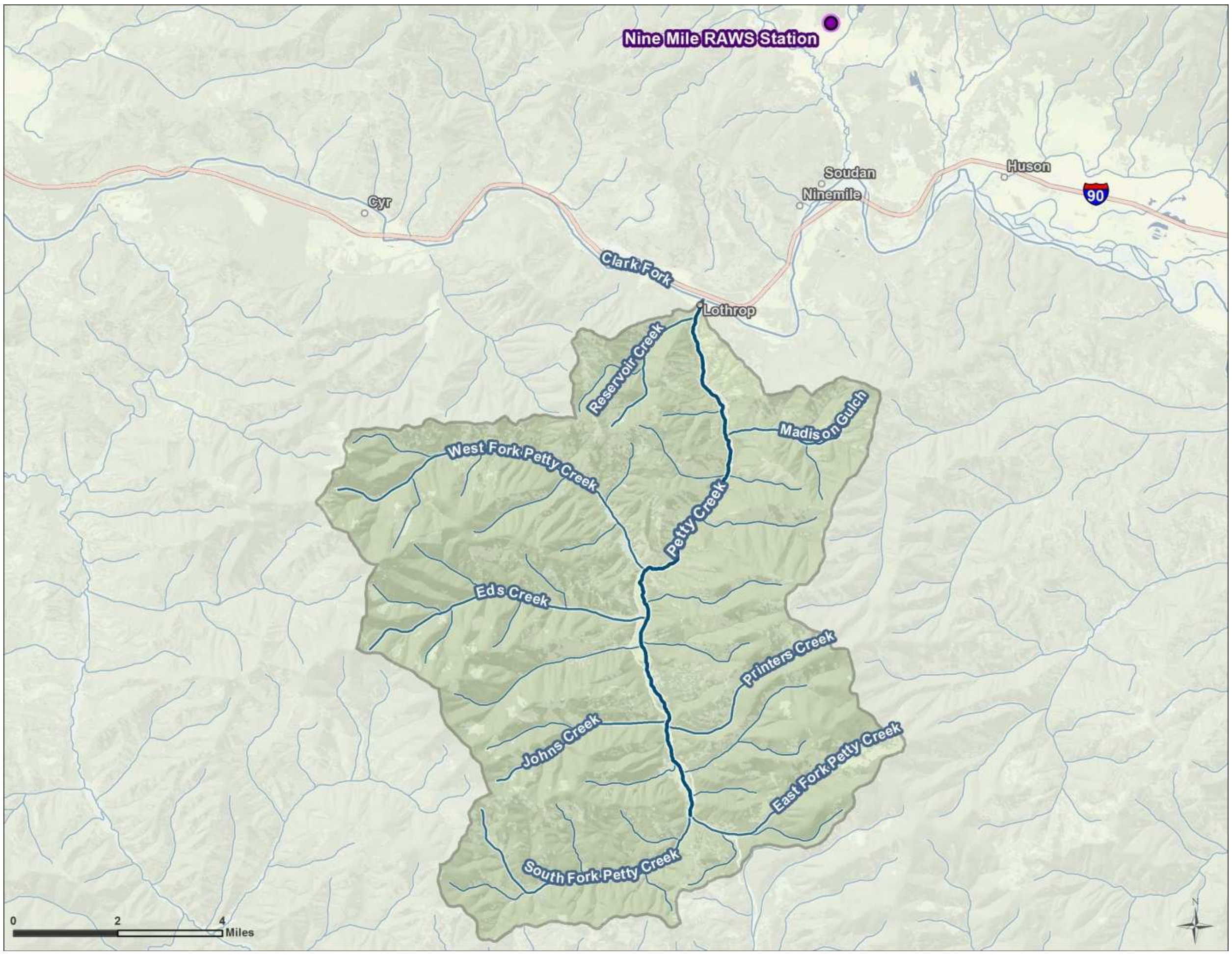
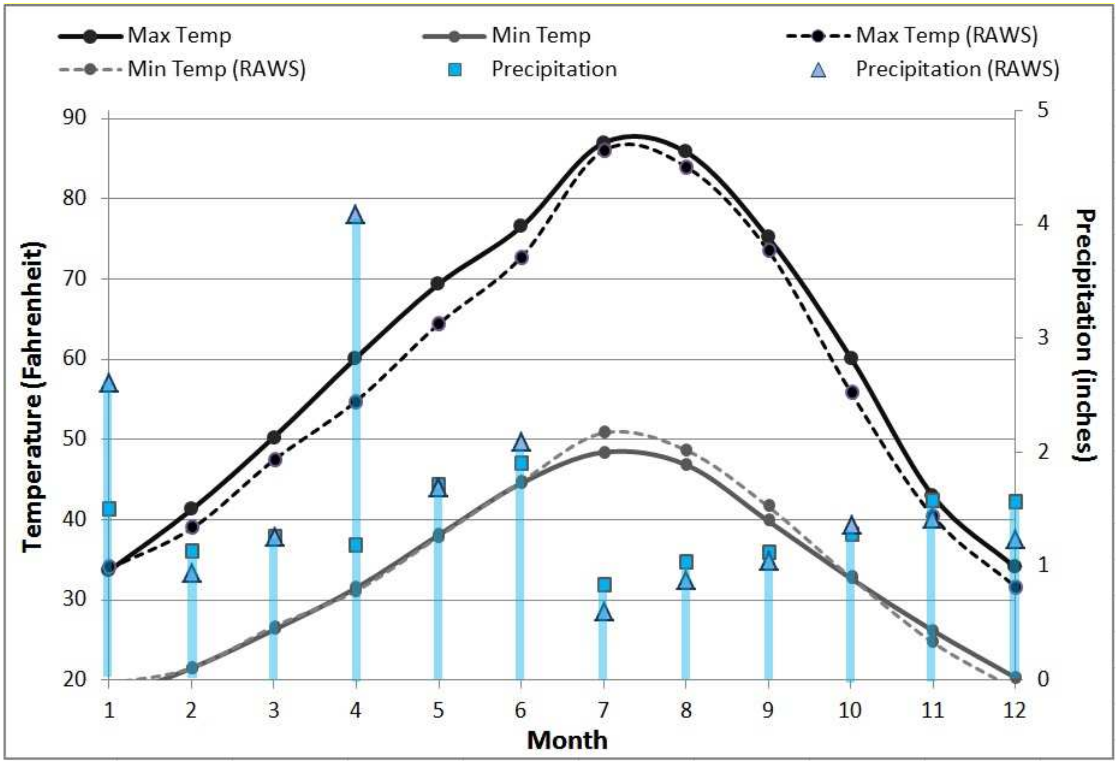


Figure A-1. Petty Creek watershed.

Average annual precipitation at station 24159 is 16.1 inches with a relatively even distribution throughout the year (**Figure A-2**; National Climatic Data Center 2013). Average maximum temperatures occur in July and August and are 87.0° F and 85.9° F, respectively. The available data at Nine Mile RAWS only date back to 2000, but the station records weather data hourly whereas station 24159 only records weather data daily. Thus, Nine-Mile RAWS hourly temperature data were used to develop the QUAL2K inputs. The Nine-Mile RAWS data are also summarized in **Figure A-2**.



Source: GHCN-D Monthly Summaries from 1914 to 2013 at NWS station 24159, in Superior, Montana (NCDC 2013).

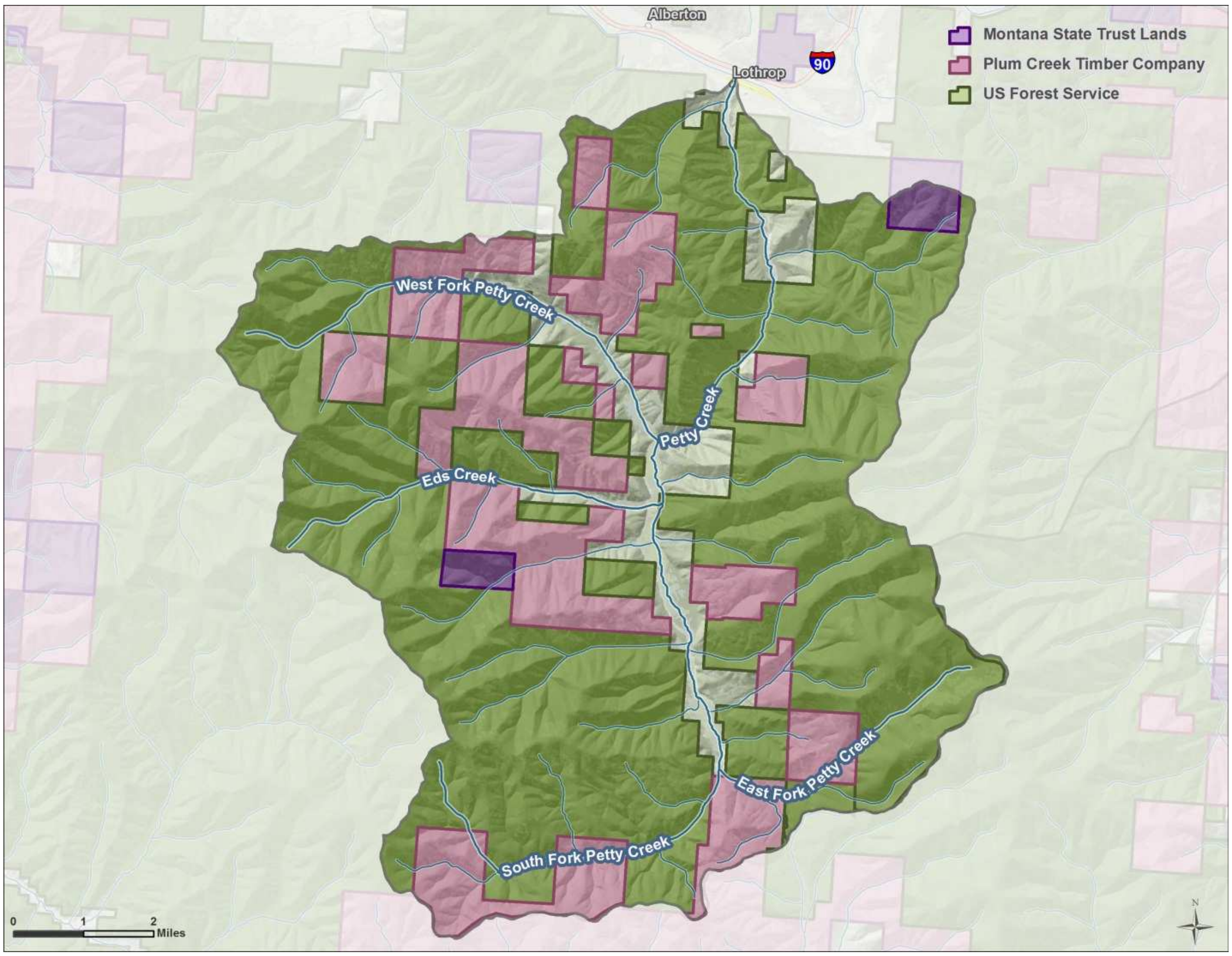
Figure A-2. Monthly average temperatures and precipitation at Superior, Montana.

As previously discussed, the Superior station only has hourly air temperature data and does not have additional hourly datasets necessary for QUAL2K modeling. The Nine MIle RAWS records hourly air temperature, dew point temperature, wind speed and solar radiation and these data were used to develop the QUAL2K model.

A-3. Land Ownership and Land Use

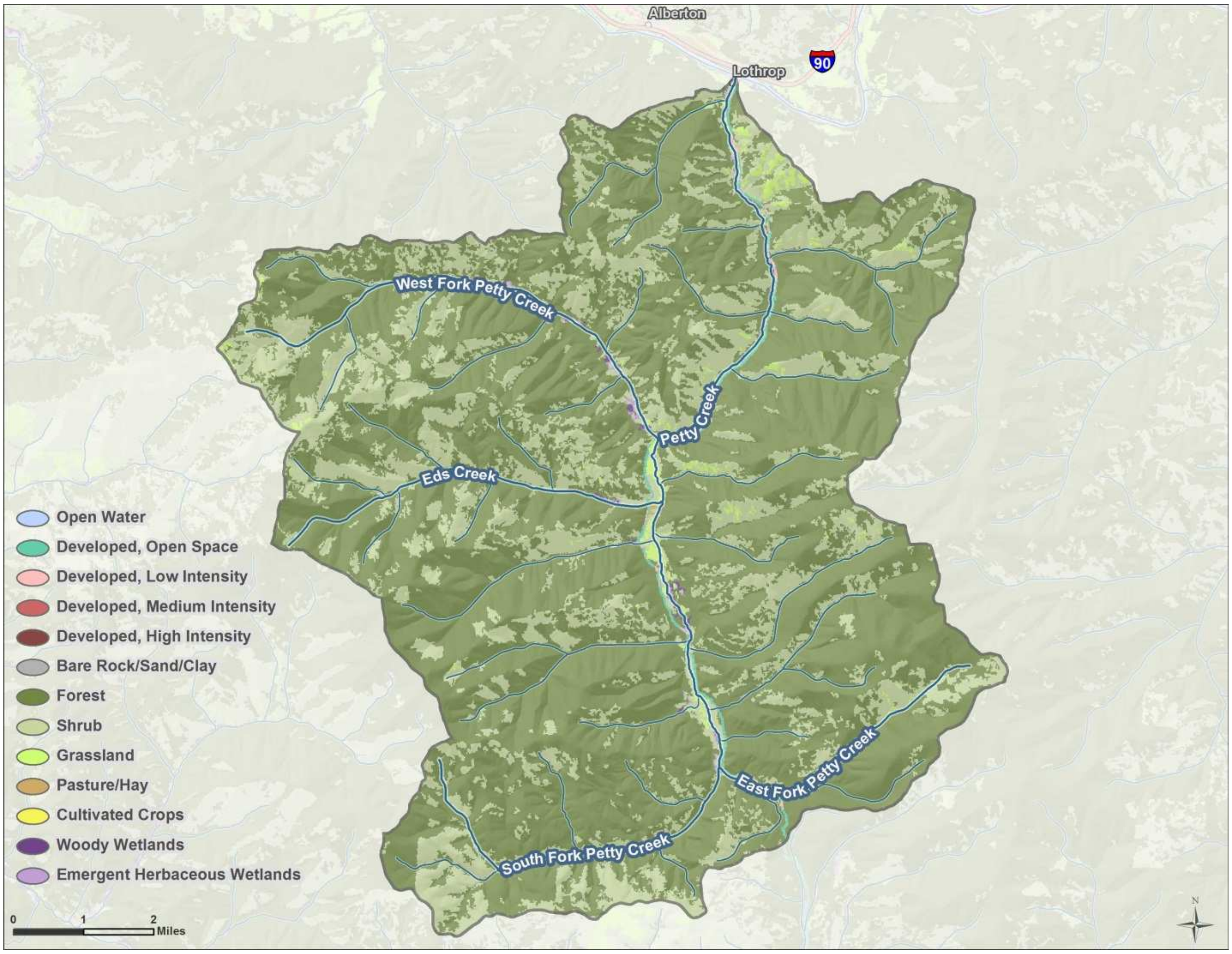
Petty Creek is in the Rocky Mountains of western Montana and is part of the Middle Clark Fork Tributaries TMDL Planning Area. The Petty Creek watershed is in the Lower Clark Fork subbasin (hydrologic unit code 17010204). The impaired segment is 12.2 miles long and extends from the confluence of the South and East Forks of Petty Creek to the mouth (DEQ 2012).

Private ownership accounts for 9 percent of the land ownership in the the Petty Creek watershed, primarily in the valleys. The Plum Creek Timber Company manages 22 percent of the area, the U.S. Forest Service manages 67 percent; the remainder is owned by the state in trust lands (**Figure A-3**). The landscape is predominantly forested, with patches of mature forest interspersed with selective harvests and clearcuts at various stages of regrowth (**Figure A-4** and **Figure A-5**).



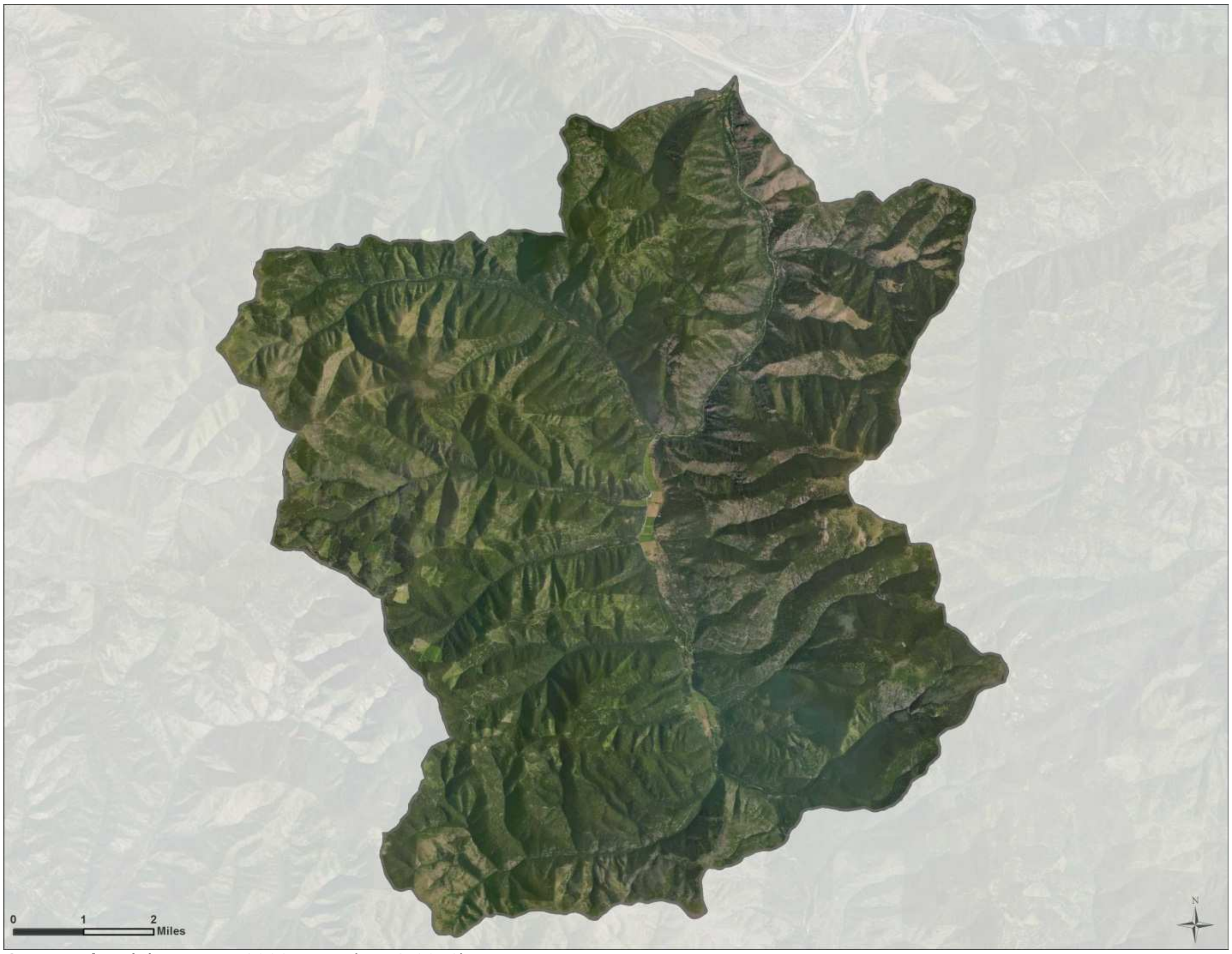
Source of land ownership: NRIS 2012.

Figure A-3. Land ownership in the Petty Creek watershed.



Source of land cover: 2006 National Land Cover Dataset (Multi-Resolution Land Characteristics Consortium 2006).

Figure A-4. Land cover and land use in the Petty Creek watershed.



Source of aerial Imagery: 2009 NAIP (NRIS 2012).

Figure A-5. Aerial imagery of the Petty Creek watershed.

A-4. Existing Riparian Vegetation

Vegetation communities between the shade monitoring sites were visually characterized based on aerial imagery (Google Earth™ 2013). 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 (NLCD) (**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)

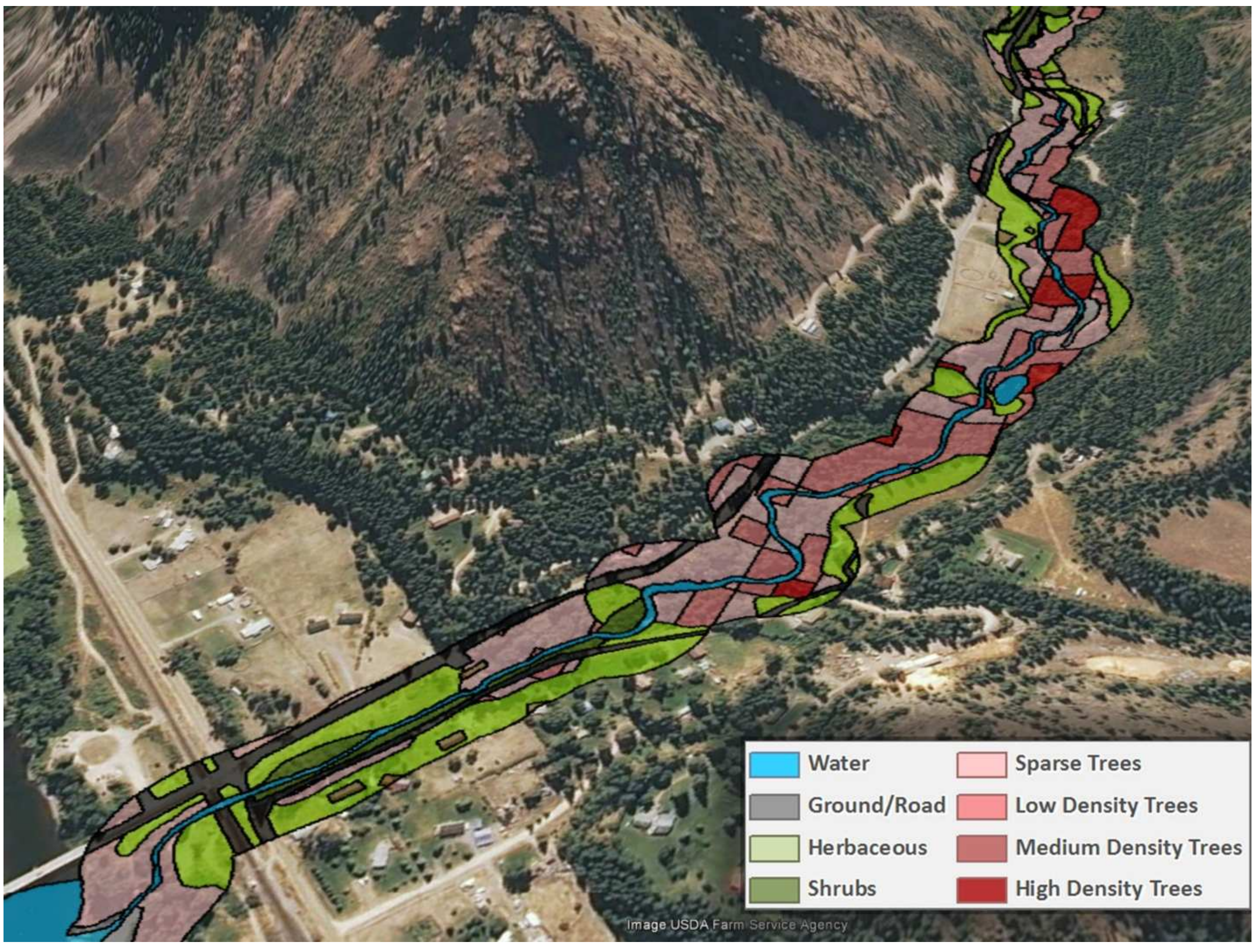


Figure A-6. Vegetation mapping example for Petty Creek.

Herbaceous vegetation and sparse trees are the most common cover types along Petty Creek, followed by shrubs and low density trees (**Table A-1**). High and medium density trees, roads, and bare ground compose only a small percentage of the riparian area.

Table A-1. Land cover types in the Petty Creek riparian zone

Land cover type	Area (acres)	Relative area (percent)
Bare ground	5.3	1.2%
Herbaceous	203.7	44.5%
Roads	22.5	4.9%
Shrub	59.0	12.9%
Sparse trees	76.0	16.6%
Low density trees	43.5	9.5%
Medium density trees	39.4	8.6%
High density trees	8.5	1.9%

From the confluence of the South and East forks, Petty Creek flows through a fairly broad agricultural valley down to the confluence with West Fork Petty Creek. Based on a review of aerial photography, hay fields dominate much of the valley bottom and it does not appear that the riparian vegetation in this area is at potential. In many areas it appears that the natural riparian vegetation has been removed along one or both banks. Downstream from the confluence with the West Fork, the valley narrows and the stream is closely paralleled by Petty Creek Road. In some areas, the road has encroached upon the riparian corridor.

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*

EPA and Tetra Tech collected shade characterization data between July 30 and August 1, 2012, at ten monitoring locations along Petty Creek using a Solar Pathfinder™ (**Figure A-7**). Shade estimates based on the Solar Pathfinder™ measurements are presented in **Attachment A**. The data are summarized in **Table A-2**.

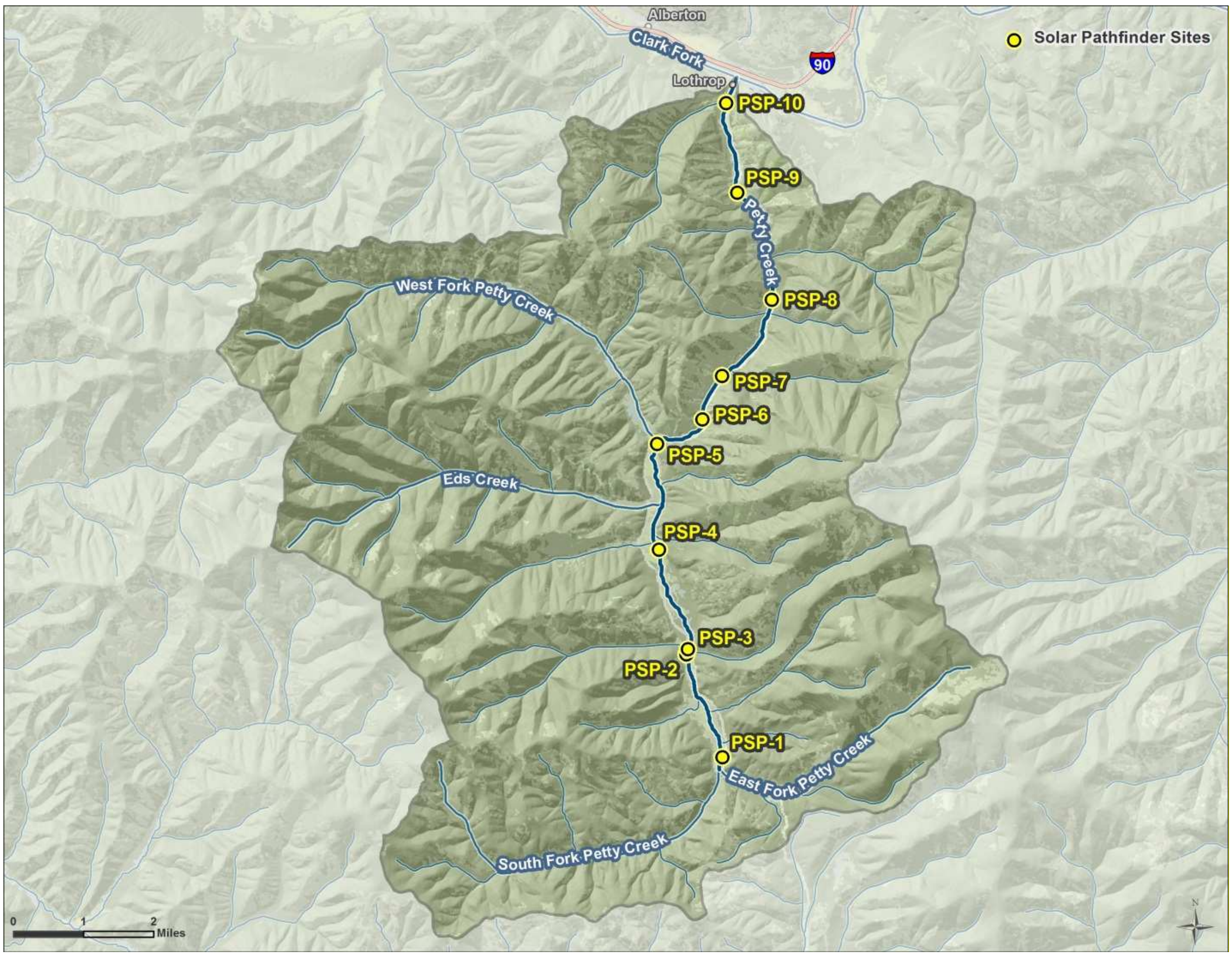


Figure A-7. Solar Pathfinder™ monitoring locations.

Table A-2. Average shade per reach from Solar Pathfinder™ measurements

Site ID	Average daily shade (averaged across daylight hours)
PSP-1	86%
PSP-2	23%
PSP-3	14%
PSP-4	4%
PSP-5	2%
PSP-6	42%
PSP-7	20%
PSP-8	49%
PSP-9	55%
PSP-10	49%

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 Petty 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 2007). 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 Petty Creek relied upon field data collected during a 2012 field study and the interpretation of these data. The results of the study included: tree/shrub height, overhang, wetted channel width, and bankfull width.

GIS Pre-Processing

TTools for ArcGIS is a project to translate spatial data into Shade Model inputs (Oregon Department of Environmental Quality 2001, 2009). 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™(2013). Aspect was calculated to the nearest degree using TTools with the stream centerline file.

Although the field study report provided an estimate of the wetted width, an assessment along the entire stream was obtained by digitizing both the right and left banks from aerial imagery in GoogleEarth™ (2013). 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 results in the field study report and the above described vegetation mapping were used to develop a riparian description table (**Table A-3**). Vegetation descriptions used the average value for tree/shrub height and overhang from field observation.

Table A-3. Vegetation input values for the Shade Model

Attribute	Value	Basis
Trees		
Height	23 meters (75 feet)	In the absence of site-specific data, this value was based on work conducted in Wolf and Fortine creeks.
Density	Variable	2006 NLCD.
Overhang	2.3 meters (7.5 feet)	Estimated as 10% of height (Stuart 2012).
Shrubs		
Height	4.0 meters (13 feet)	In the absence of site-specific data, this value was based on work conducted in Wolf and Fortine creeks.
Density	90%	Ocular estimate based on aerial imagery.
Overhang	1.0 meter (3.3 feet)	Estimated as 25% of height (Shumar and de Varona 2009)
Herbaceous		
Height	0.5 meter (1.6 feet)	Estimated from field photographs
Density	100%	Estimated from field photographs
Overhang	0 meters	Estimated from field photographs

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-3**. The Shade Model requires reach lengths be an equal interval. The reaches in the field study report were not at an equal interval and were very widely spaced. A uniform reach length interval of 15 meters (49 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^{TM} measurements are presented in **Figure A-8**.

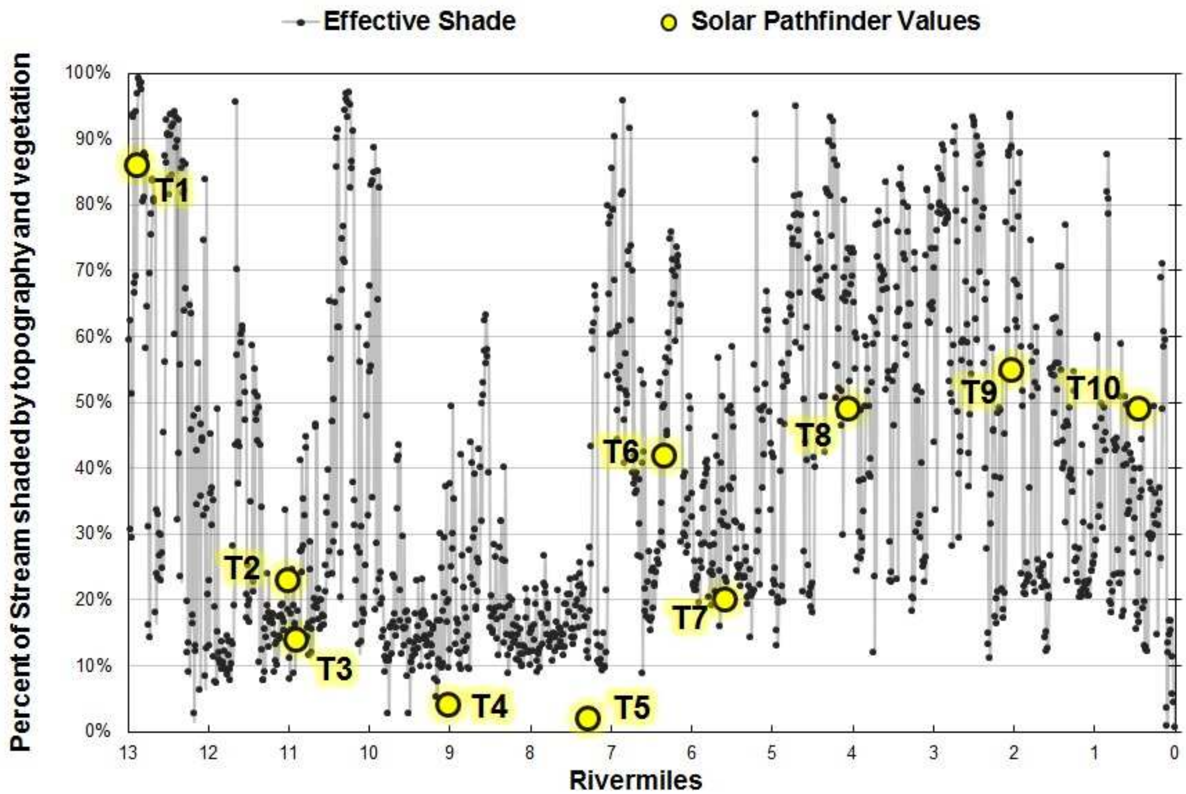


Figure A-8. Longitudinal estimates of observed and simulated effective shade along Petty Creek.

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-4** and suggest a good fit between observed and predicted average effective shade values. The average absolute mean error is 7 percent. (i.e., the average error from the Shade Model output and Solar Pathfinder™ measurements was 7 percent daily average shade; see **Table A-4**).

Table A-4. Shade model error statistics

Error Statistic	Formula	Result	Units
Mean Error (ME)	$(1/N)*\Sigma(P_n-O_n)$	5%	percent of percent shade
Average Absolute Mean Error (AME)	$(1/N)*\Sigma\|(P_n-O_n)\|$	7%	percent shade
Root Mean Square Error (RMSE)	$[(1/N)*\Sigma(P_n-O_n)^2]^{1/2}$	8%	percent of percent shade

A-6. Stream Temperatures

In 2012, Atkins collected continuous temperature data at six locations in Petty Creek (sites PTTYC-T1, PTTYC -T2, PTTYC -T3, PTTYC -T4, PTTYC -T5, and PTTYC -T6) and at five tributary locations (EDS on Ed's Creek, JHNS on John's Creek, MDSN on Madison Gulch, PRINT on Printers Creek, and RSVR on Reservoir Creek). An additional logger was deployed on West Fork Petty Creek, but was lost due to nearby bridge construction. Data loggers recorded temperatures every one-half hour for approximately three months between June 27 and October 11. Instantaneous temperatures were also monitored by Atkins and DEQ (**Table A-5** and **Table A-6**).

Table A-5. Atkins instantaneous water temperature measurements (°F), summer 2012

Date	PTTYC-T1	PTTYC-T2	PRINT[a]	JHNS[b]	EDSC[c]	WFPTY[d]	PTTYC-T3	PTTYC-T4	MDSN[e]	PTTYC-T6	RSRV[f]
June 27-28, 2012	49.5	55.4	49.5	47.8	49.1	45.5	44.8	46.9	50.9	52.2	45.0
July 30-Aug 1, 2012	50.5	62.6	52.5	54.1	55.0	59.2	47.8	52.7	--	47.1	46.6
October 10, 2012	42.3	--	45.5	45.0	42.3	40.8	45.1	45.5	40.1	44.6	45.0

Notes
a. Site is on Printer's Creek, a tributary to Petty Creek.
b. Site is on John's Creek, a tributary to Petty Creek.
c. Site is on Ed's Creek, a tributary to Petty Creek.
d. Site is on West Fork Petty Creek, a tributary to Petty Creek.
e. Site is on Madison Gulch, a tributary to Petty Creek.
f. Site is on Reservoir Creek, a tributary to Petty Creek.

Table A-6. DEQ instantaneous water temperature measurements (°F)

Date	C04PETYC07	C04PRNTC01[a]	C04PETYC06	C04PETYC05	C04PYWFC02[b]	C04PETYC04	C04PETYC03	C04PETYC02	C04PETYC01
August 13, 2004	--	--	--	--	57.2	--	--	--	--
September 11, 2006	--	50.2	--	--	--	--	--	--	--
August 8-9, 2011	52.0	--	57.9	55.8	54.7	46.9	45.9	47.7	48.2
September 7-12, 2011	49.3	--	53.6	--	48.2	45.3	55.6	--	48.9
June 28, 2012	--	--	--	--	45.5	--	50.4	--	--
July 5, 2012	--	--	--	--	48.0	--	--	--	--
July 30-31, 2012	--	--	--	--	59.2	--	58.1	--	--
October 11, 2012	--	--	--	--	40.8	--	41.5	--	--

Notes
a. Site is located on Printer's Creek, a tributary to Petty Creek.
b. Site is located on West Fork Petty Creek, a tributary to Petty Creek.

A-7. Hydrology

No active U.S. Geological Survey continuously recording gages are located on Petty Creek. The closest such gage is gage 12353000, located 12 miles away on the Clark Fork River below Missoula, MT. The closest continuously recording gage on a small stream similar to Petty Creek is gage 12381400, located 40 miles away on the South Fork Jocko River[1].

Atkins (under subcontract from Tetra Tech) collected instantaneous flow measurements in 2012, during temperature data logger deployment and retrieval and during a mid-season site visit (**Table A-7** and **Attachment B**). Flow data were collected by DEQ in support of other water quality studies in 2004, 2011, and 2012 (**Table A-8**). Locations of the flow measurements are shown in **Figure A-9**.

Table A-7: Instantaneous flow measurements (cfs) on Petty Creek in support of modeling

Date	PTTYC-T1	PTTYC-T2	PRINT[a]	JHNS[b]	EDSC[c]	WFPTY[d]	PTTYC-T3	PTTYC-T4	MDSN[e]	PTTYC-T6	RSRV[f]
June 27-28, 2012	8.44	10.1	1.25	1.65	4.44	4.32	37.68	38.37	0.34	39.02	0.29
July 30-Aug 1, 2012	3.89	1.73	0.68	0.86	1.93	1.57	17.81	17.09	--[g]	19.23	0.28
October 11, 2012	2.03	0	0.32	0.35	1.6	0.79	11.09	9.91	0.2	9.51	0.25

Notes
a. Site is located on Printer's Creek, a tributary to Petty Creek.
b. Site is located on John's Creek, a tributary to Petty Creek.
c. Site is located on Ed's Creek, a tributary to Petty Creek.
d. Site is located on West Fork Petty Creek, a tributary to Petty Creek.
e. Site is located on Madison Gulch, a tributary to Petty Creek.
f. Site is located on Reservoir Creek, a tributary to Petty Creek.
g. Road construction at site with new box culvert being added prevented access to site.

[1] Gage 12381400 on the South Fork Jocko River near Arlee, MT drains 56 square miles.

Table A-8: Instantaneous flow measurements (cfs) on Petty Creek in support of other studies

Date	C04PETYC07	C04PETYC06	C04PETYC05	C04PYWFC02[a]	C04PETYC04	C04PETYC03	C04PETYC02	C04PETYC01
Aug 13, 2004	--	--	--	1.82	--	--	--	--
Aug 8-9, 2011	3.35	6.53	2.65	2.86	28.37	17.26	8.77	41.51
Sept 7-12,2011	2.58	1.19	0	1.2	16.86	7.05	0	28.83
June 28, 2012	--	--	--	4.32	--	29.94	--	--
July 5, 2012	--	--	--	4.12	--	--	--	--
July 30-31, 2012	--	--	--	1.57	--	11.06	--	--
October 11, 2012	--	--	--	0.79	--	5.37	--	--

Note: a. Site is located on West Fork Petty Creek, a tributary to Petty Creek.

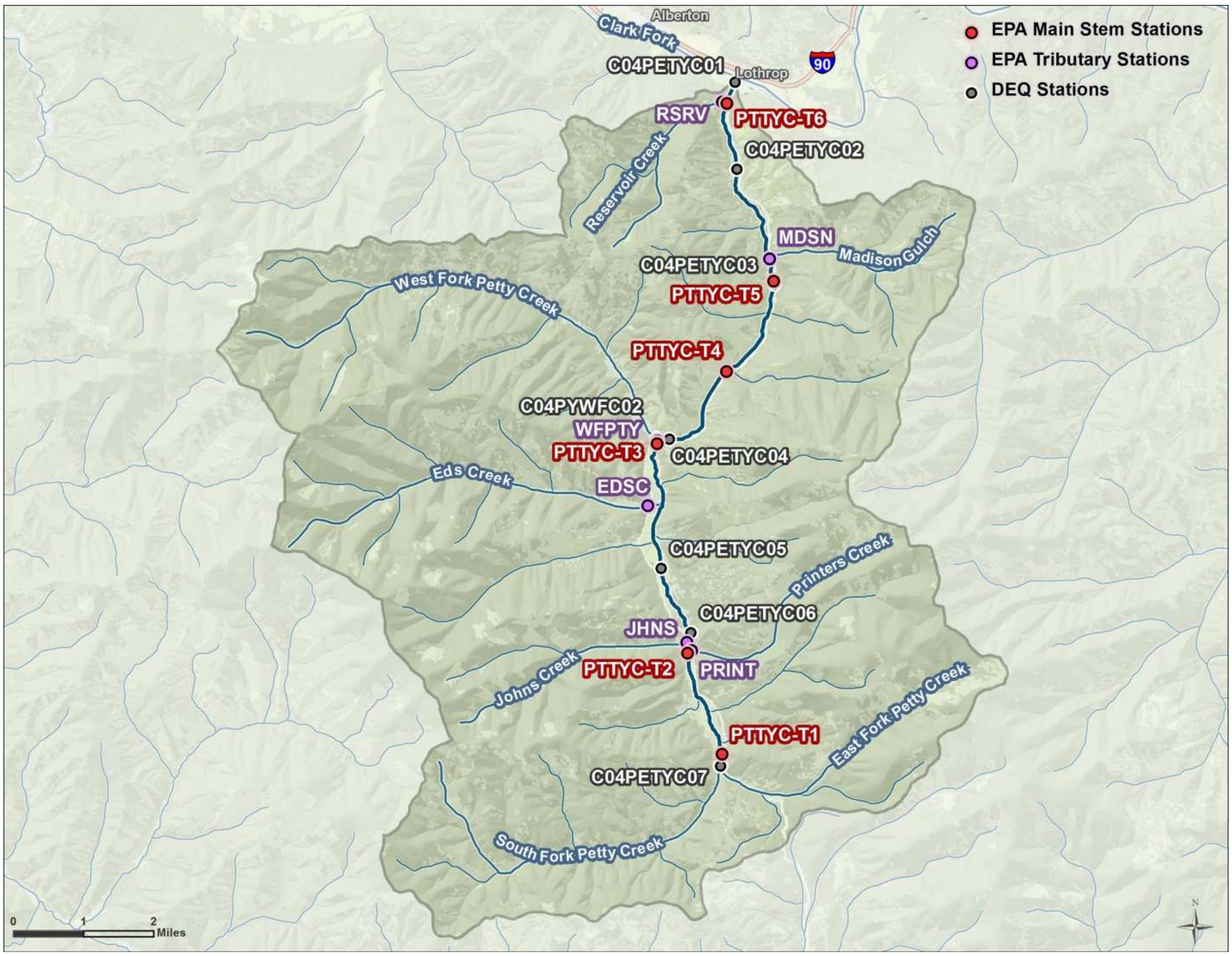
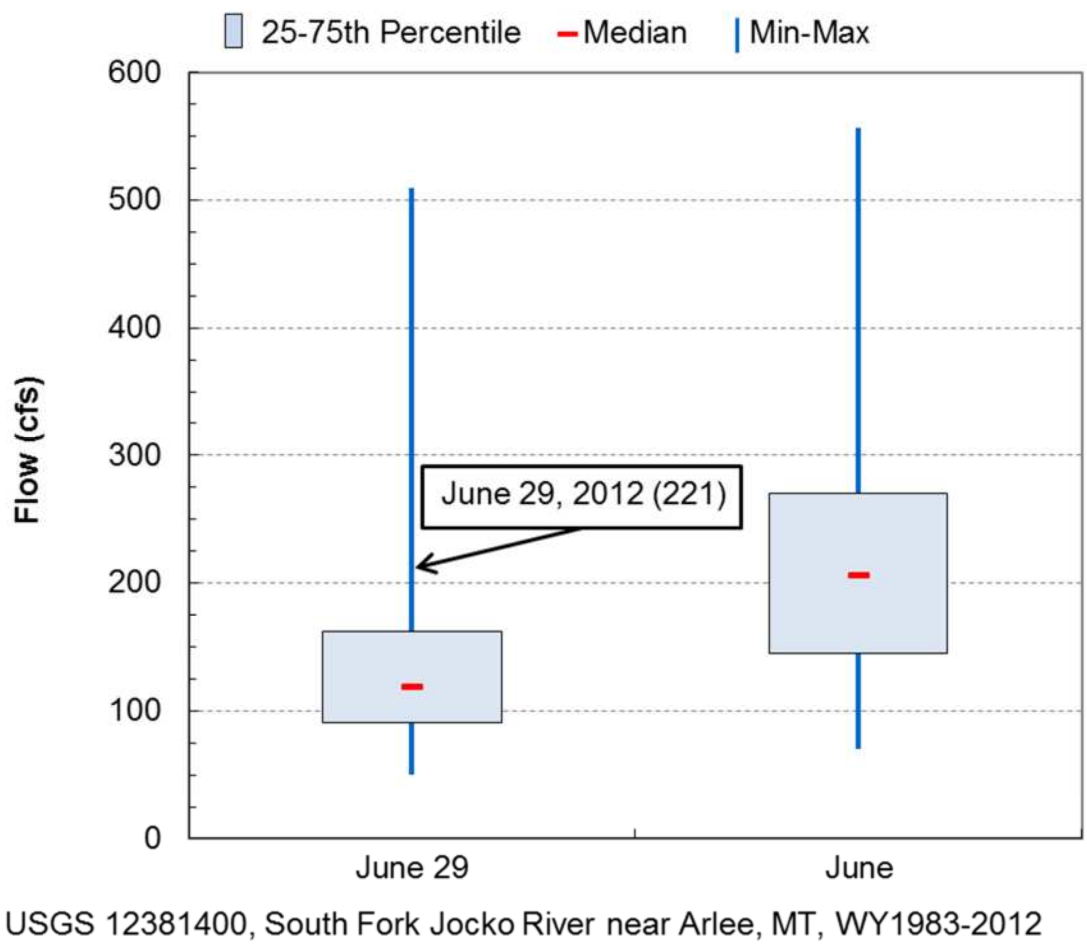


Figure A-9. Flow monitoring locations in the Petty Creek watershed.

All available data were used to evaluate the water balance in Petty Creek and to develop a pre-modeling understanding of the hydrology. However, the 2012 data will be relied upon for model inputs and hydrologic calibration. It should be noted that, compared to the historic period of record at the nearest continuous recording USGS gage on a waterbody of similar size to Petty Creek (i.e., USGS 12381400, South Fork Jocko River near Arlee, MT), flows on June 29, 2012 were above the average of 20 years of records (**Figure A-10**).

Statics were calculated for the average daily flows (per year) for the month of June and for June 29th from water years 1983 through 2012 at the gage (**Figure A-10**). The flow at gage 12381400 on June 29, 2012 (the calibration date for the QUAL2K model) was 221 cfs, which is the 86th percentile of flows on July 16th across the period of record. Additionally, June of 2012 was the 83rd percentile of Junes across the period of record (i.e., June 2012 was wetter than a typical June).



Note: "June" represents the daily average flow for the month of June per year (i.e., the average of 30 daily average flows)

Figure A-10. Flow analysis with USGS gage 12381400 (South Fork Jocko River near Arlee, MT).

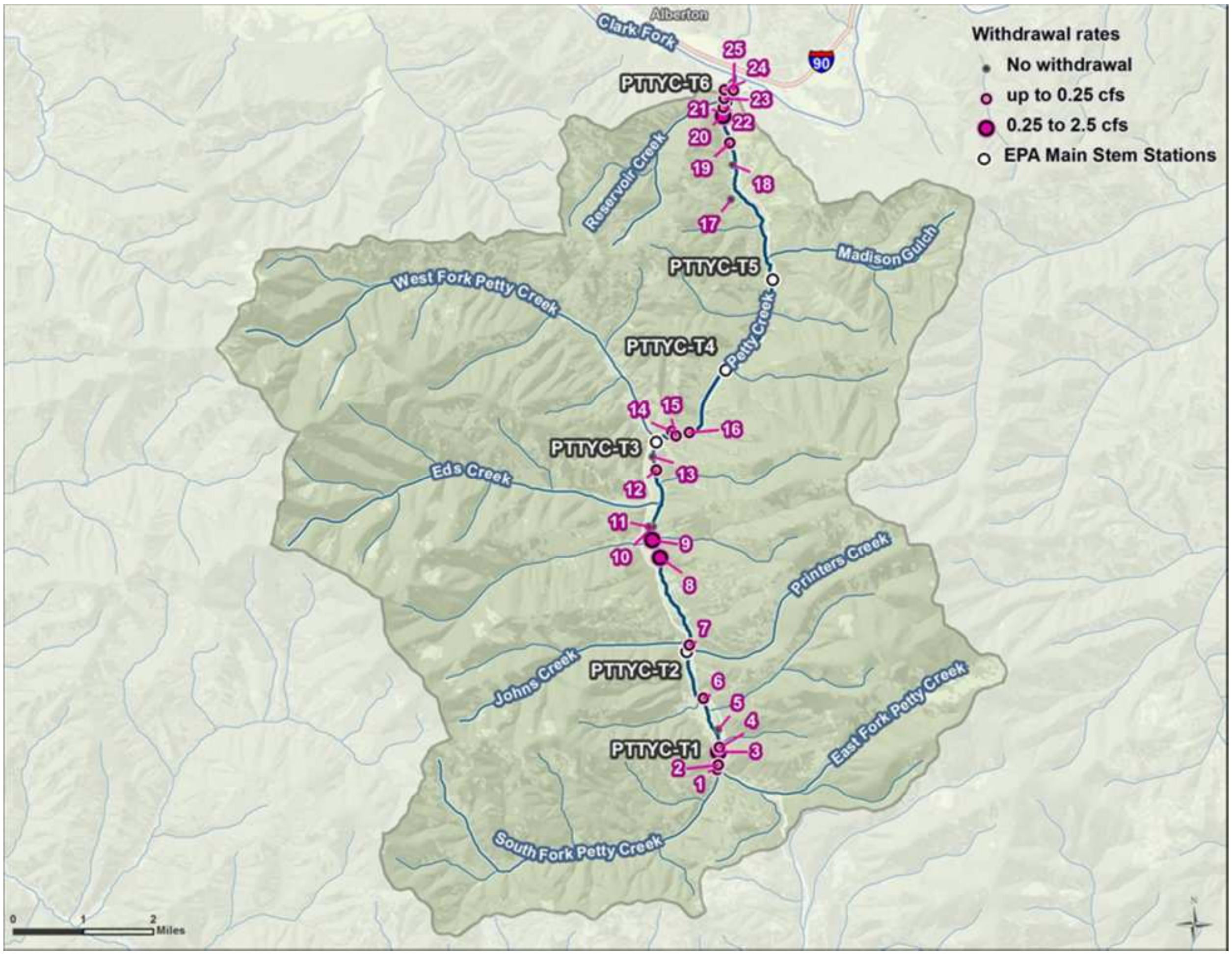
A-8. Flow Modification

Based on review of aerial photographs and online water rights data (ftp://nris.mt.gov/dnrc), there are surface and groundwater diversions in the Petty Creek watershed that support localized irrigation (**Figure A-11**). “Points of diversion” and “places of use” spatial data were obtained from the Montana Natural Resource Information System (NRIS 2012). A total of 42 “places of use” were found, which represent individual water usage allotments, such as a total annual volume required for a specific acreage of land. These “places of use” corresponded to 38 “points of diversion”, which represent individual water right permit numbers associated with the physical stream diversions. These “points of diversion” further correspond to 25 distinct locations along Petty Creek (**Figure A-11**). Diversions from groundwater or tributaries to Petty Creek were not considered during QUAL2K modeling as QUAL2K simulated one-dimensional flow along the Petty Creek mainstem.

Where individual locations corresponded to multiple permits, the estimated withdrawal rates were summed. Where individual permits were associated with multiple locations, an equal distribution of the permitted rate was assumed across sites. The withdrawal volume applied for irrigation was estimated using the Irrigation Water Requirements (IWR) program developed by the USDA to estimate crop requirements (NRCS 2003). This method assumes application over the maximum acres reported at a constant rate across a 24-hour period during the months of June, July, and October.

The withdrawal for industrial purposes (#20 in **Figure A-11**) is assumed to be at the maximum permitted withdrawal rate. Withdrawals directly from Petty Creek for livestock are considered negligible. The instream fisheries (#17 and #18 in **Figure A-11**) are a water reservation, with no withdrawal, held by the U.S. Forest Service.

It is estimated that a maximum of 6.01 cfs may be withdrawn from Petty Creek during the month of July (**Table A-9**).



Source of "points of diversion" data: NRIS 2012.

Figure A-11. Surface and groundwater diversions in the Petty Creek watershed.

Table A-9. Points of diversion from Petty Creek

Map ID	Purpose	Irrigation type	Means of withdrawal	Est. daily flow rate (cfs)		
				June	July	October
1	Irrigation	Flood	Headgate	0.16	0.22	0.01
2	Irrigation	Flood	Headgate	0.06	0.08	0.00
3	Irrigation	Flood	Headgate	0.23	0.32	0.02
4	Irrigation	Flood	Livestock *	0.06	0.08	0.00
5	Stock		Livestock *	0.00	0.00	0.00
6	Irrigation	Flood	Headgate	0.12	0.17	0.01
7	Lawn and Garden		Headgate	0.01	0.02	0.00
8	Irrigation	Flood	Dike	0.64	0.89	0.04
9	Irrigation	Flood	Dike	0.93	1.30	0.06
10	Stock		Livestock *	0.00	0.00	0.00
11	Stock		Livestock *	0.00	0.00	0.00
12	Irrigation	Sprinkler	Livestock *	0.04	0.06	0.00
13	Stock		Livestock *	0.00	0.00	0.00
14	Irrigation	Sprinkler	Headgate	0.01	0.01	0.00
15	Irrigation	Sprinkler	Pump	0.01	0.01	0.00
16	Irrigation	Sprinkler	Pump & Headgate	0.06	0.09	0.00
17	Instream Fishery		Instream	0	0	0.
18	Instream Fishery		Instream	0	0	0
19	Irrigation	Sprinkler	Pump	0.06	0.08	0.00
20	Industrial & Irrigation		Pipeline & Headgate	2.51	2.52	2.50
21	Terminated			--	--	--
22	Irrigation		Pump	0.05	0.07	0.00
23	Irrigation	Sprinkler	Pump	0.03	0.04	0.00
24	Lawn and Garden & Irrigation		Pump	0.01	0.02	0.00
25	Lawn and Garden & Irrigation	Sprinkler	Pump	0.01	0.02	0.00
			Total Withdrawal	**4.99**	**6.01**	**2.67**

Source: NRIS 2012.
Note: * = livestock direct from source.

A-9. Point Sources

Any facility that discharges to Petty Creek or its tributaries must be permitted through DEQ's Montana Pollution Discharge Elimination System. A search of U.S. EPA's Enforcement and Compliance Online database (http://www.epa-echo.gov/echo/index.html) did not identify any facilities in the Petty Creek watershed.

An evaluation of abandoned mines data from NRIS (2012) showed that three abandoned mines are in the Petty Creek watershed. White Cap Prospect, Coppersmith, and Petty Creek Placer are near the confluence of Ed's Creek with Petty Creek.

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 Lynch Creek and surrounding area. <http://www.google.com/earth/index.html>. Accessed June 18, 2013.

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.

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.

Attachment A.

Atkins Solar Pathfinder^{TM} Data

GIS Station ID	Field ID	GIS riparian description	field riparian description	field calculated % shade
PTTYC-T1	PSP-1	dense	dense coniferous	86
PTTYC-T2	PSP-2	moderate	moderate mixed riparian	23
SP-F1	PSP-3	low	low mixed riparian	14
SP-04-02	PSP-4	low	low mixed riparian	4
PTTYC-T3	PSP-5	low	low mixed riparian	2
SP-F2	PSP-6	moderate	moderate mixed riparian	42
PTTYC-T4	PSP-7	moderate	moderate mixed riparian	20
PTTYC-T5	PSP-8	dense	dense mixed riparian	49
SP-08-01	PSP-9	dense	dense mixed riparian	55
PTTYC-T6	PSP-10	dense	dense mixed riparian	49

field riparian description	mean % shade
dense coniferous	86
dense mixed riparian	51
moderate mixed riparian	28
low mixed riparian	7

mixed riparian includes both conifers and cottonwoods in the overstory and woody shrubs in the understory

Attachment B.

Atkins Field Measurements Data

Field Data - EPA Task Order 19 Petty Creek Temperature Assessment													7/1/2012
Station ID	**Site Name**	**Logger ID**	**Date**	**Time**	**Ta (°F)**	**Tw (°C)**	**pH**	**EC (µS/cm)**	**Flow (cfs)**	**Comments**	**Latitude**	**Longitude**	**Riparian Observation**
PTTYC-T1	Petty Creek downstream of the confluence of the East Fork Petty Creek and South Fork Petty Creek	9790520	06/27/12	14:15	67	9.7	7.51	113.5	8.44	Bill Creek 0.7 miles downstream estimated flow = 1 cfs	46.85237	-114.43820	conifers with understory shrubs
PTTYC-T2	Petty Creek upstream of Printers Creek and Johns Creek	9790461	06/27/12	15:30	68	13.0	7.83	104.3	10.10	temperature increased 3.3°C in the ~1.6 miles between PTTYC-T1 and PTTYC-T2 as stream flows through open meadows	46.87312	-114.45092	open meadow with moderate conifers
PRINT	Printers Creek near mouth	9790465	06/27/12	16:30	70	9.7	7.74	95.9	1.25		46.87359	-114.44929	
JHNS	Johns Creek near mouth	9790483	06/27/12	17:30	70	8.8	8.31	199.9	1.65		46.87471	-114.45093	
EDSC	Eds Creek near mouth	9790458	06/27/12	18:30	70	9.5	8.38	243.0	4.44	landowner reports stream flows year-round	46.90273	-114.46576	
WFPTY	West Fork Petty Creek near mouth	9790460	06/28/12	10:00	41	7.5	8.18	132.7	4.32		46.91710	-114.46428	
									21.76	only other named stream between PTTYC-T2 and PTTYC-T3 is Bruce Creek, so mostly groundwater upwelling? Due to change in geology as stream enters the canyon?			
PTTYC-T3	Petty Creek downstream of West Fork Petty Creek	9790495	06/28/12	9:00	41	7.1	7.66	186.6	37.68	~5.2 miles between PTTYC-T2 and PTTYC-T3, landowner reports that from here downstream 1.5 miles is the only "consistent" (perennial) flow	46.91702	-114.46046	low riparian
PTTYC-T4	Petty Creek upstream of Spring Gulch	9790464	06/28/12	11:00	41	8.9	8.51	188.9	38.37		46.93095	-114.44562	moderate riparian with mix of cottonwoods and conifers
PTTYC-T5	Petty Creek upstream of Madison Gulch	9790472	06/28/12	12:15	53	10.2	8.60	186.0	29.94	PTTYC-T5 ~0.6 miles upstream of Madison Gulch	46.94710	-114.43207	dense riparian with mix of cottonwoods and conifers
MDSN	Madison Gulch near mouth	9790462	06/28/12	13:15	53	10.5	8.06	167.5	0.34		46.95526	-114.43350	
PTTYC-T6	Petty Creek upstream of Reservoir Creek	9790463	06/28/12	14:15	63	11.2	8.12	190.0	39.02	landowner reported that Petty Creek goes dry ~1 mile upstream at the brick house but is always flowing at this site	46.98678	-114.44952	dense riparian with mix of cottonwoods and conifers
PTTYC-T6	duplicate	9790459	06/28/12	14:15	63	11.2							
RSVR	Reservoir Creek at mouth	9790457	06/28/12	15:30	63	7.4	7.51	214.0	0.29	stream goes subsurface and reappears as a spring in which the data logger is located	46.98673	-114.44971	

Petty Creek goes dry ~1.5 miles upstream of PTTYC-T3 and ~1.5 miles downstream of PTTYC-T2 based on 2011 NAIP
…also somewhere between PTTYC-T4 and PTTYC-T6 based on landowner accounts…

Field Data - EPA Task Order 19 Petty Creek Temperature Assessment										8/2/12
Station ID	Site Name	Logger ID	Date	Time	Ta (°F)	Tw (°C)	pH	EC (µS/cm)	Flow (cfs)	Comments
PTTYC-T1	Petty Creek downstream of the confluence of the East Fork Petty Creek and South Fork Petty Creek	9790520	07/30/12	9:30		10.3	7.49	149.0	3.89	
PTTYC-T2	Petty Creek upstream of Printers Creek and Johns Creek	9790461	07/30/12	12:45		17.0	8.21	136.6	1.73	
PRINT	Printers Creek near mouth	9790465	07/30/12	11:45		11.4	7.85	123.9	0.68	
JHNS	Johns Creek near mouth	9790483	07/30/12	14:30		12.3	8.28	197.0	0.86	
EDSC	Eds Creek near mouth	9790458	07/30/12	16:00		12.8	8.39	244.0	1.93	Petty Creek goes dry between Johns Creek and Eds Creek, with flow starting again at Bruce Creek (called 'Gus' Creek by the locals)
WFPTY	West Fork Petty Creek near mouth	9790460	07/30/12	16:45		15.1	8.13	161.6	1.57	
									3.50	Eds+West Petty (also should include Bruce/'Gus' for a total of approximately 5 cfs)
PTTYC-T3	Petty Creek downstream of West Fork Petty Creek	9790495	07/30/12	17:30		8.8	7.51	185.0	17.81	large spring just upstream of this site increases flow and affects water temperature, with spring flow estimated to contribute at least 12 cfs
PTTYC-T4	Petty Creek upstream of Spring Gulch	9790464	07/31/12	13:30		11.5	8.59	182.0	17.09	
PTTYC-T5	Petty Creek upstream of Madison Gulch	9790472	07/31/12	15:00		14.5	8.74	178.0	11.06	downwelling between T4 and T5?
MDSN	Madison Gulch near mouth	9790462								road construction at site with new box culvert being added prevented access during mid-summer monitoring event
PTTYC-T6	Petty Creek upstream of Reservoir Creek	9790463	08/01/12	10:00		8.4	8.00	195.0	19.23	upwelling between T5 and T6?
PTTYC-T6	duplicate	9790459	08/01/12	10:00		8.4				
RSVR	Reservoir Creek at mouth	9790457	08/01/12	11:15		8.1	7.41	203.0	0.28	spring

Field Data - EPA Task Order 19 Petty Creek Temperature Assessment										10/15/12
Station ID	**Site Name**	**Logger ID**	**Date**	**Time**	**Ta (°F)**	**Tw (°C)**	**pH**	**EC (µS/cm)**	**Flow (cfs)**	**Comments**
PTTYC-T1	Petty Creek downstream of the confluence of the East Fork Petty Creek and South Fork Petty Creek	9790520	10/11/12	17:15	~60	5.7	8.01	172.9	2.03	
PTTYC-T2	Petty Creek upstream of Printers Creek and Johns Creek	9790461	10/11/12	15:45	~60					DRY CHANNEL
PRINT	Printers Creek near mouth	9790465	10/11/12	16:30	~60	7.5	7.98	136.8	0.32	short flowing section of Petty Creek due to water inputs from Printers Creek and Johns Creek
JHNS	Johns Creek near mouth	9790483	10/11/12	16:00	~60	7.4	8.31	213.0	0.35	
EDSC	Eds Creek near mouth	9790458	10/11/12	15:00	~55	5.7	8.30	262.0	1.60	
WFPTY	West Fork Petty Creek near mouth	9790460	10/11/12	14:15	~55	4.9	8.08	180.9	0.79	LOGGER NOT RETRIEVED…lost during bridge construction
PTTYC-T3	Petty Creek downstream of West Fork Petty Creek	9790495	10/11/12	13:30	~55	7.3	7.45	191.0	11.09	from the road, Petty Creek appears to be dry upstream of West Fork Petty Creek
PTTYC-T4	Petty Creek upstream of Spring Gulch	9790464	10/11/12	12:30	~50	7.5	8.23	189.0	9.91	
PTTYC-T5	Petty Creek upstream of Madison Gulch	9790472	10/11/12	11:45	~45	5.3	8.36	189.0	5.37	Petty Creek dry between T5 and T6 with flow extending from T5 downstream past Madison Gulch
MDSN	Madison Gulch near mouth	9790462	10/11/12	11:00	~40	4.5	8.10	198.0	0.20	data logger placed back into channel on 8/30 following disturbance during bridge construction
PTTYC-T6	Petty Creek upstream of Reservoir Creek	9790463	10/11/12	9:30	~40	7.0	7.85	200.0	9.51	
PTTYC-T6	duplicate	9790459	10/11/12	9:30	~40	7.0				
RSVR	Reservoir Creek at mouth	9790457	10/11/12	10:00	~40	7.4	7.43	208.0	0.25	Reservoir Creek dry, data collected in a spring along Petty Creek where the Reservoir Creek watershed enters