ATTACHMENT D – MODELING WATER TEMPERATURE IN LYNCH CREEK

Modeling Water Temperature in Lynch Creek

Prepared for:

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Acronyms and Abbreviations

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

Units of Measure

°F	degrees Fahrenheit
cfs	cubic feet per second
MSL	mean sea level
RM	rivermile

Executive Summary

Lynch Creek was identified by the Montana Department of Environmental Quality (DEQ) as being impaired due to elevated water temperatures. The cause of the impairment was attributed to grazing in riparian or shoreline zones and irrigated crop production (DEQ 2012). The U.S. Environmental Protection Agency (EPA) contracted with Tetra Tech to develop a QUAL2K water quality model to investigate the relationship between flow, shade, and in-stream water temperature.

Field studies were carried out in 2012 to support water quality model development for the project. A QUAL2K water quality model was then developed for Lynch 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. Shadev3.0 models were also developed to assess shade conditions using previously collected field data. The calibrated and validated QUAL2K model met previously designated acceptance criteria. Once developed, various water temperature responses were evaluated for a range of potential watershed management activities. Four scenarios were considered:

- **Scenario 1:** 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 temperature (scenario 2) to considerable reductions (scenarios 3 and 4). The improved flow and shade scenario (scenario 4), which combined the potential benefits associated with a 15 percent reduction in water withdrawals (scenario 2) with a 50-foot vegetated buffer (scenario 3) to represent application of conservation practices, resulted in overall reductions along the entire reach that ranged from 0.1° F to 13.5° F. Generally, small changes in shade or inflow had minimal effects on water temperature while large increases in shade had a considerable effect on water temperature.

1 Introduction

Tetra Tech, Inc. is under contract with the U.S. Environmental Protection Agency (EPA) to set up, calibrate, and conduct scenario analysis with a temperature model (QUAL2K) for Lynch 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

Lynch Creek (MT76N003_010) is in northwest Montana within the Northern Rockies ecoregion and is located in the Middle Clark Fork Tributaries TMDL Planning Area and the Thompson TMDL Project Area. The impaired segment is 13.3 miles long and is a tributary to the Clark Fork (**Figure 1**).

Lynch Creek has a B-1 use class. The entire 13.3 mile creek is not supporting its Aquatic Life and Primary Contact Recreation designated uses (DEQ 2012). Six potential causes of impairment are identified in the assessment record, including water temperature (DEQ 2012). The potential sources of the water temperature impairment are: grazing in riparian or shoreline zones and irrigated crop production.

The lower reaches of Lynch Creek were straightened and there is limited woody vegetation (i.e., a lack of shading) in the riparian corridor, as the lower reaches are dominated by hay production and cattle grazing (DEQ 2012). The upper reach has more diverse vegetation but the stream is intermittent and limited by a streamside road. Elevated water temperatures were monitored and found to be a significant problem due to dewatering from over-allocation of water rights (DEQ 2012).

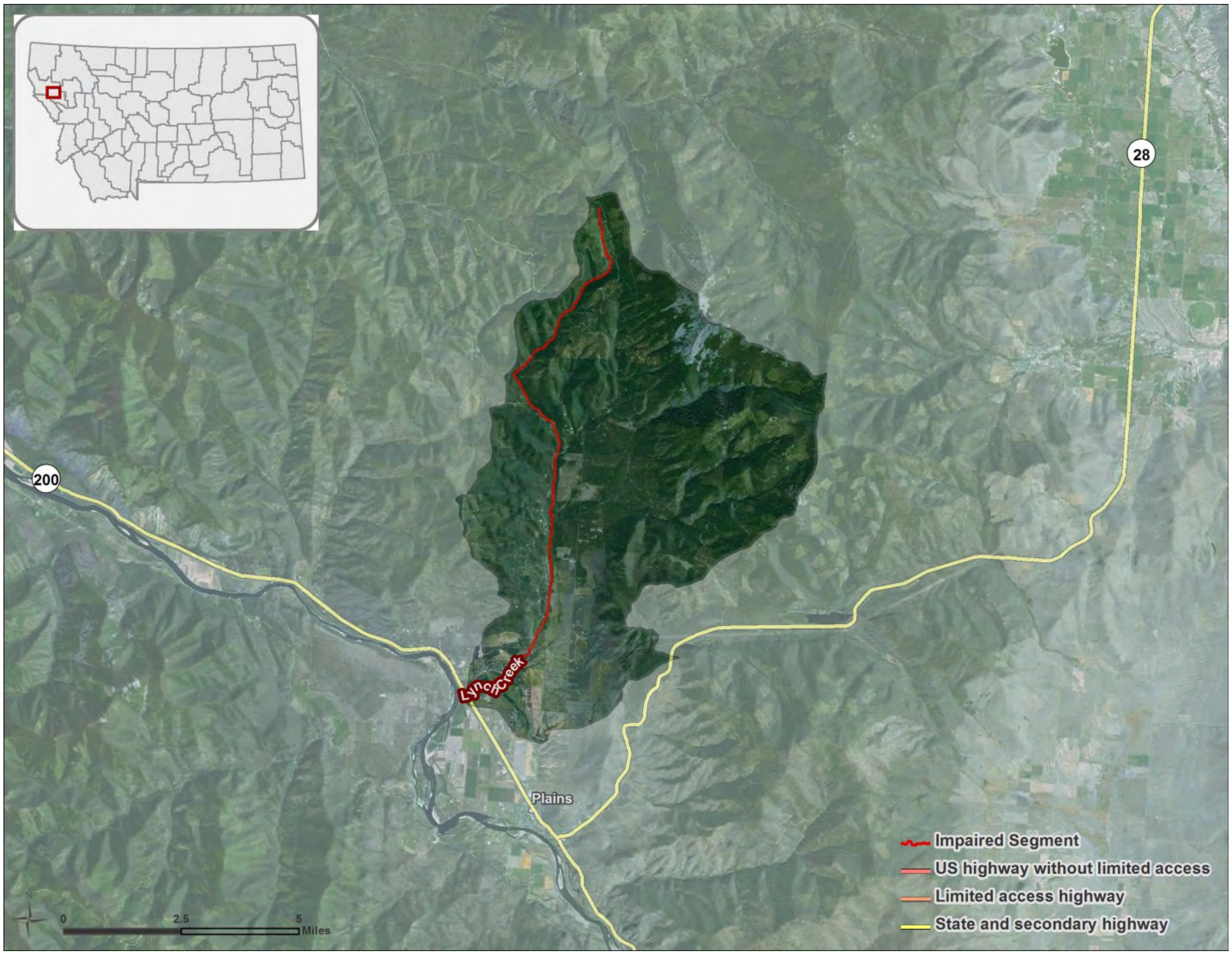

Figure 1. Lynch Creek watershed.

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 using the data and information that was to be collected in the summer of 2012. Temperature and flow data were collected in Lynch Creek in 2012 by Atkins (Helena, MT; under contract with Tetra Tech) and by EPA and Tetra Tech. A field team from Atkins collected data on June 27-28, July 12-13, August 11, and September 20, 2012 to characterize channel geometry, flow, and shade in support of the modeling effort. A second field team from EPA and Tetra Tech collected data on September 12 and 13, 2012 to characterize channel geometry and shade, also in support of the modeling effort.

2.4 Factors Potentially Influencing Stream Temperature

Stream temperature regimes are influenced by processes that are external to the stream as well as processes that occur within the stream and its associated riparian zone (Poole et al. 2001). Examples of factors external to the stream that can affect in-stream water temperatures include: topographic shade, land use/land cover (e.g., vegetation and the shading it provides, impervious surfaces), solar angle, meteorological conditions (e.g., precipitation, air temperature, cloud cover, relative humidity), groundwater exchange and temperature, irrigation return flows, and tributary inflow temperatures and volumes. The shape of the channel can also affect 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 Lynch Creek were evaluated prior to model development and are further discussed in **Appendix A**:

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

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[1] ARM 17.30.623(e).

[2] "Naturally occurring" means conditions or material present from runoff or percolation over which man has no control or from developed land where all reasonable land, soil and water conservation practices have been applied.

- Hydrology
- Point sources

2.5 Observed Stream Temperatures

EPA (and their consultants Tetra Tech and Atkins as described above) collected stream temperature data using in-stream loggers at multiple locations in the Lynch Creek watershed. Their datasets are presented in the following sections

2.5.1 Available Temperature Data

In 2012, Atkins collected continuous temperature data at six locations in Lynch Creek (sites LYNHC-T1, LYNHC-T2, LYNHC-T3, LYNHC-T5, LYNHC-T6, and LYNHC-T7) and at two tributary locations (CEDRC on Cedar Creek, and CLRKC on Clark Creek) (**Figure 2**). Data loggers recorded temperatures every one-half hour for approximately two months between June 28 and September 20, 2012.

EPA, DEQ, and other entities also collected instantaneous temperatures from Lynch Creek and some of its tributaries. Temperatures varied spatially and temporally; generally, the warmest instantaneous temperatures were detected in August.

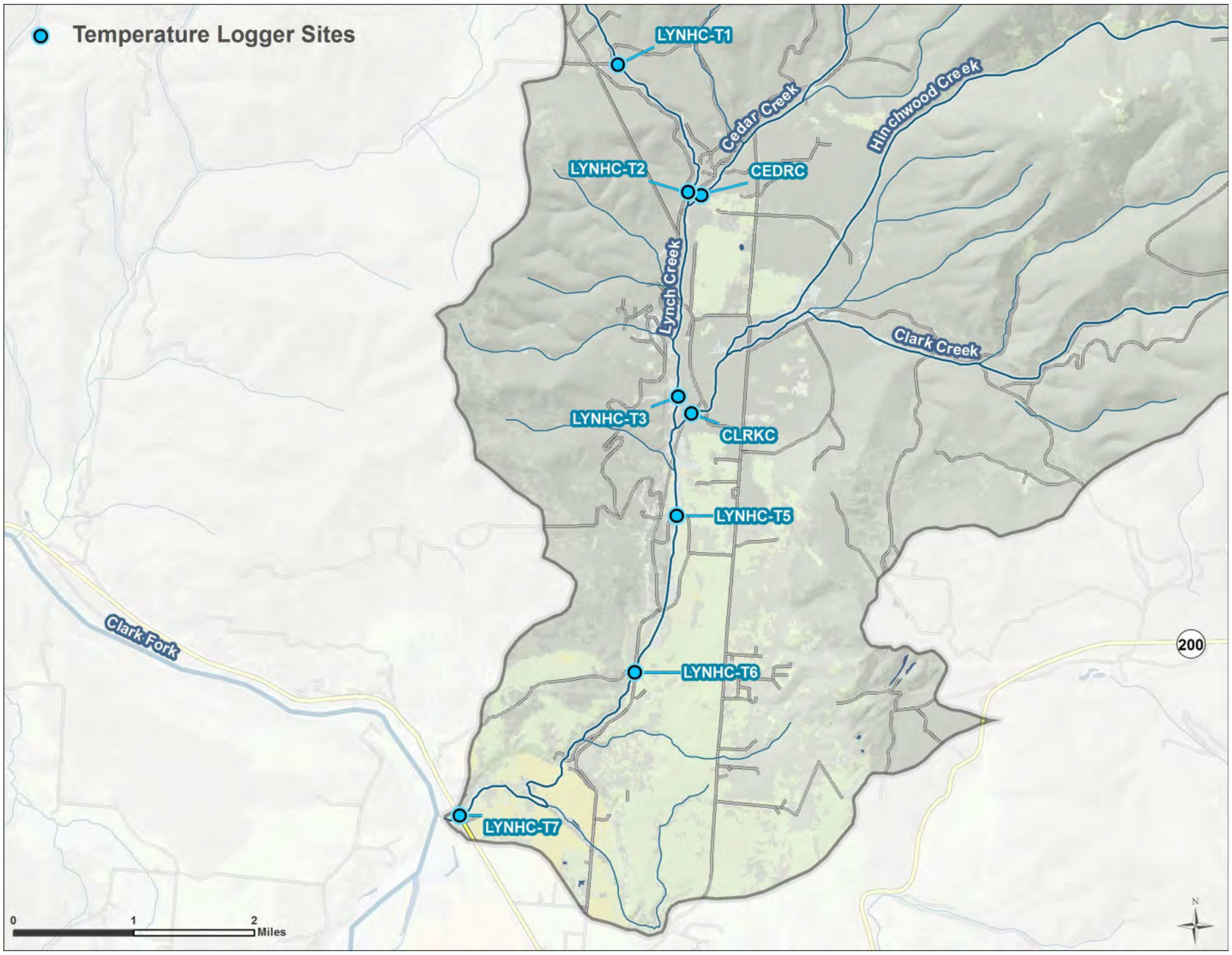
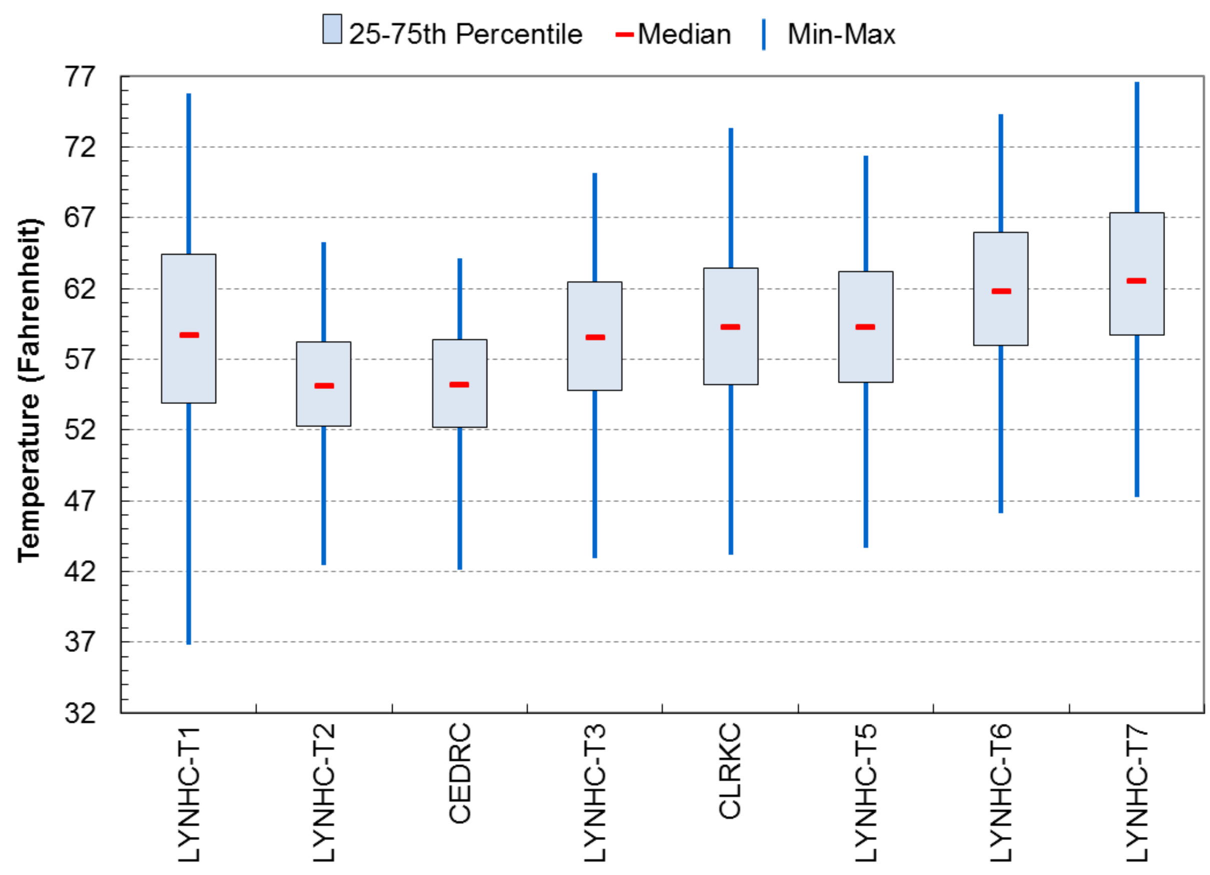


Figure 2. Temperature loggers in the Lynch Creek watershed.

2.5.2 Temperature Data Analysis

Stream temperatures in Lynch Creek along the segment from loggers LYNHC-T2 through LYNHC-T5 generally increase downstream to its mouth. A summary of the continuous temperature data collected by EPA is provided in **Figure 3**. Median temperatures in Lynch Creek ranged from approximately 55° F to approximately 62° F with no apparent, consistent spatial trend from headwaters to mouth. While Cedar Creek was cooler than lower Lynch Creek, it appears that Clark Creek (CLRKC) may have a slight warming influence on Lynch Creek.



Note: Atkins observed logger LYNHC-T1 to be in isolated pools on August 11, 2012 and September 20, 2012; no surface water flow was observed that connected the pools. Atkins reported that Lynch Creek at logger LYNHC-T1 was likely a dry channel from August 20, 2012 to September 8, 2012. Data from this time period are excluded from this figure.

Figure 3. Box-and-whisker plots of summer 2012 EPA continuous temperature data.

Maximum daily temperatures in Lynch Creek ranged from approximately 50° F to approximately 77° F (**Figure 4**). The highest maximum daily temperature was recorded at LYNHC-T7 on July 18, 2012. Lynch Creek near logger LYNHC-T1 was a series of isolated pools on August 11, 2012 and September 20, 2012 and no surface water flow between pools was observed. Daily maximum recorded temperatures in Lynch Creek are summarized in **Table 1** and shown in **Figure 4**. In 2012, the warmest temperatures were detected on July 18 and July 31. The warmest weeks varied from July 16/17 through July 22/23 or August 7 through August 13. As shown in **Figure 5**, the diurnal variation in Lynch Creek is smaller in the upper watershed (as shown with LYNHC-T2) than the lower watershed (as shown with LYNHC-T5).

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

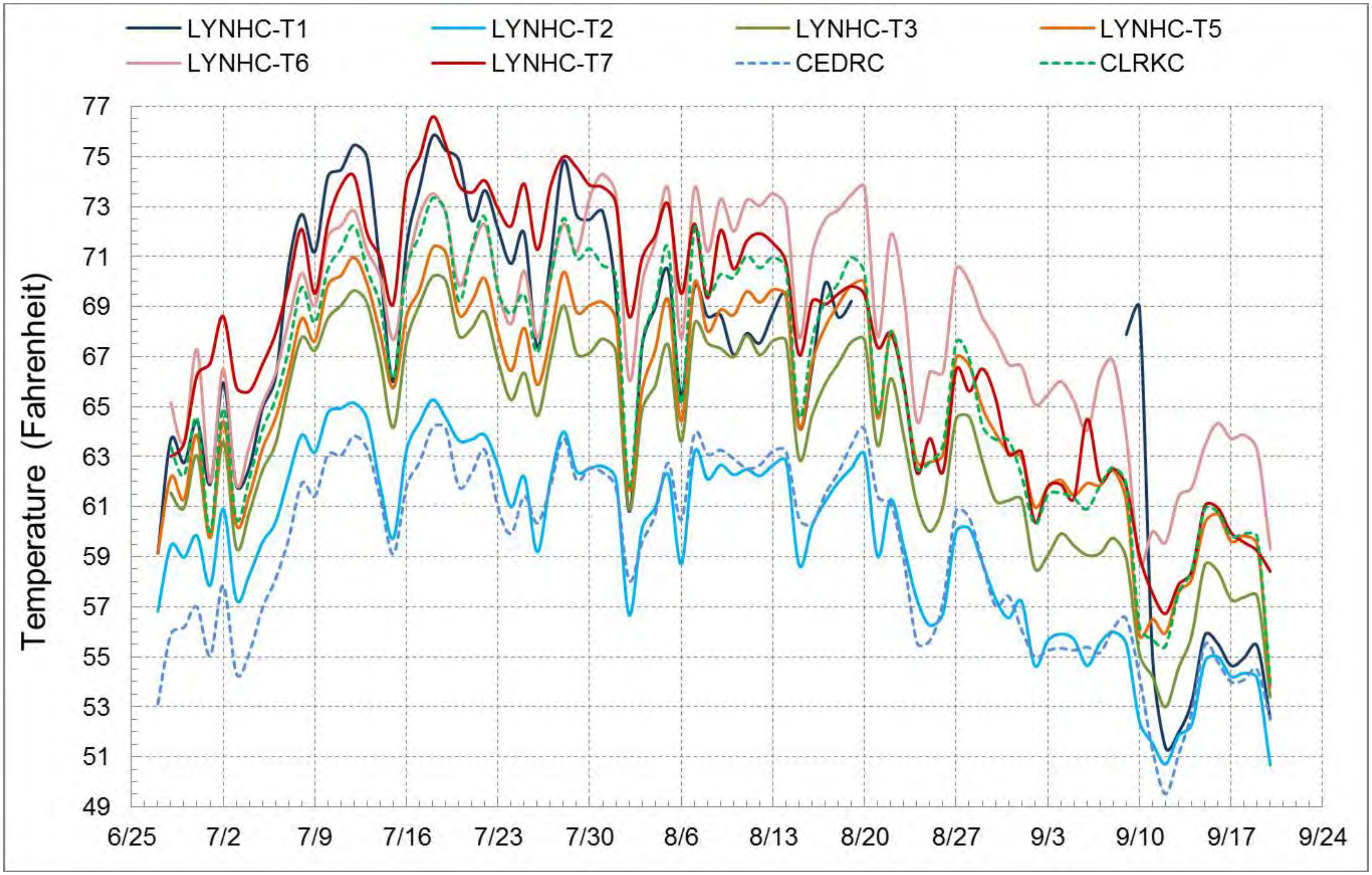
Temperature logger site	Maximum temperatures [a]		Maximum weekly maximum temperature [b]	
	Temperature (°F)	Date	Temperature (°F)	Date
LYNHC-T1 [c]	75.8	July 18	74.0	July 17-23
LYNHC-T2	65.3	July 18	64.1	July 16-22
LYNHC-T3	70.2	July 18	68.8	July 16-22
LYNHC-T5	71.4	July 18	69.8	July 16-22
LYNHC-T6	74.3	July 31	72.9	August 7-13
LYNHC-T7	76.6	July 18	74.6	July 16-22

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 observed logger LYNHC-T1 to be in isolated pools on August 11, 2012 and September 20, 2012; no surface water flow was observed that connected the pools. Atkins reported that Lynch Creek at logger LYNHC-T1 was likely a dry channel from August 20, 2012 to September 8, 2012. Data from this time period are excluded from this table.



Note: Atkins observed logger LYNHC-T1 to be in isolated pools on August 11, 2012 and September 20, 2012; no surface water flow was observed that connected the pools. Atkins reported that Lynch Creek at logger LYNHC-T1 was likely a dry channel from August 20, 2012 to September 8, 2012. Data from this time period are excluded from this figure.

Figure 4. Daily maximum temperatures, Lynch Creek and tributaries, June 27-28 to September 20, 2012.

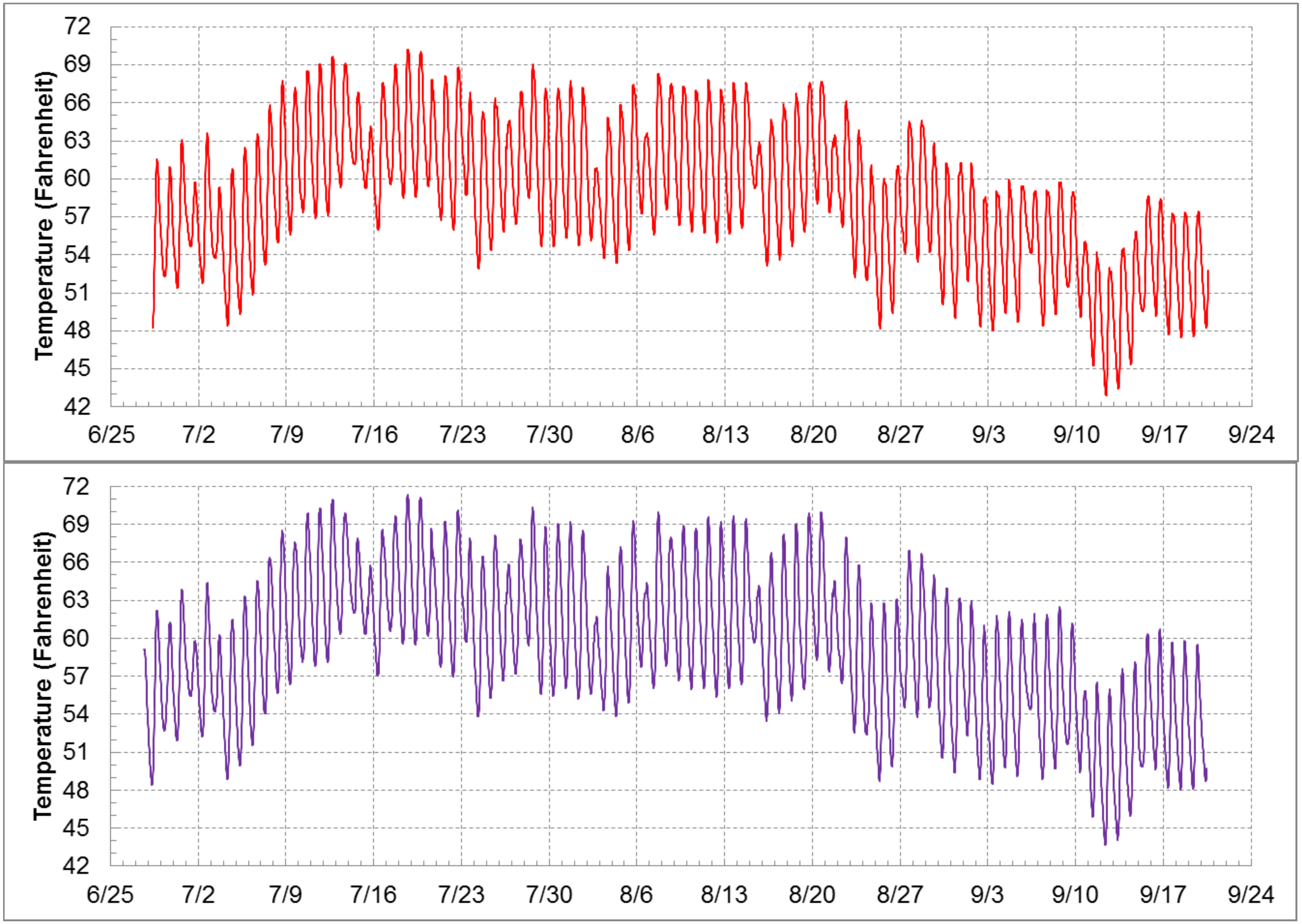


Figure 5. Continuous temperature at loggers LYNHC-T2 (top) and LYNHC-T5 (bottom), June 27 to September 20, 2012.

3 QUAL2K Model Development

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

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

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

3.1 Model Framework

The QUAL2K model (Chapra et al. 2008) was selected for modeling Lynch Creek. The modeling domain included the entire 13.3 mile reach of Lynch Creek (refer back to **Figure 2** for a map of the Lynch Creek watershed).

Data were specifically collected to support the QUAL2K model for the Lynch Creek. Flow, shade, and continuous temperature were acquired during August and September 2012. In addition flow and temperature data were also collected at major tributaries to Lynch Creek. To support model development, channel geometry was also measured at each of the flow and temperature monitoring locations along Lynch Creek.

3.2 Model Configuration and Setup

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

3.2.1 Modeling Time Period

The calibration and validation steady-state model periods were August 11, 2012 and September 20, 2012, respectively. 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 August 11, 2012, which is the mid-season flow monitoring; flow was monitored at all Atkins logger sites on Lynch Creek and its major tributaries on August 11, 2012 except for LYNHC-T1, which was in an isolated pool. In addition August 11, 2012 also represented critical hot summer period conditions.

Validation Period: The validation period was September 20, 2012 which was associated with logger retrieval; flow was monitored and the Atkins loggers were retrieved on September 20, 2012. Similar to the calibration period, logger LYNHC-T1 was in an isolated pool and flow was not monitored. The last full day of temperature data for all EPA loggers was September 19, 2012. Temperature data monitored on September 19, 2012 was assumed to be representative of temperature conditions on September 20, 2012.

3.2.2 Segmentation

Segmentation refers to discretization of a waterbody into smaller computational units (e.g., reaches and elements). Reaches in QUAL2K have constant hydraulic characteristics (e.g. slope, bottom width) and each reach is further divided into elements that are the fundamental computational units in QUAL2K. The Lynch Creek main stem was segmented into reach lengths of 0.37 mile (600 meters), with an element size of 0.06 mile (100 meters) within each reach (i.e., six elements per reach). An element size of 0.06 mile was sufficient to incorporate any point inputs to the waterbody and to maintain courant stability. In addition since shading is applied at the reach level this allowed for better representation of the spatial variability observed in the Shade Model results along Lynch Creek (see **Appendix A** for shade modeling discussion). Two major tributaries were represented through boundary condition designation (see **Section 3.2.4** for a discussion of boundary conditions). **Figure 6** shows the Lynch Creek mainstem and its tributaries.

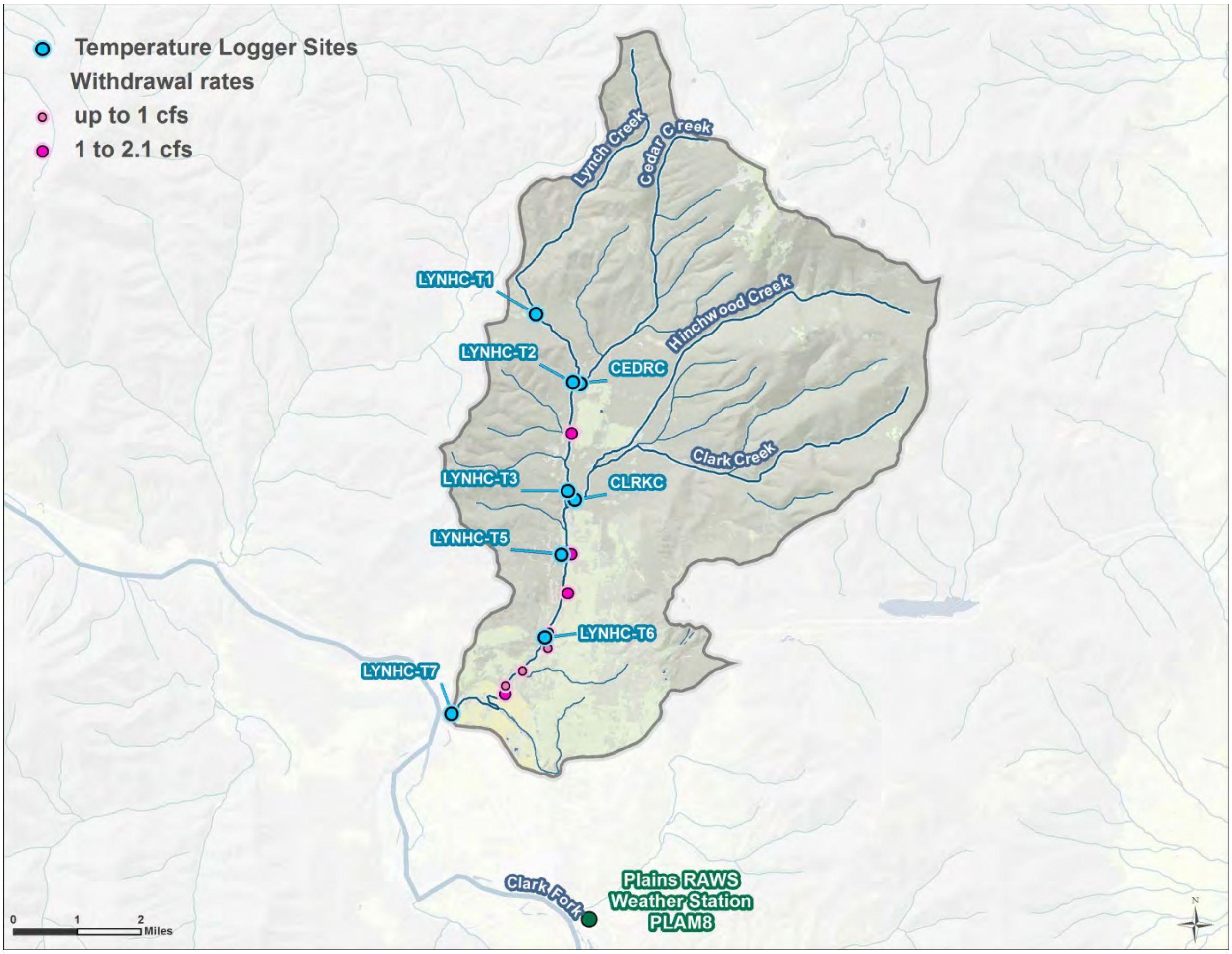


Figure 6. Lynch Creek logger locations, RAWS, and irrigation withdrawals.

3.2.3 Streamflow and Hydraulics

System hydraulics were specified using the Manning formula method. This method requires specification of the bottom width, side slope, channel slope, and Manning roughness coefficient (i.e., Manning *n* value) for each reach segment. These geometric and physical characteristics of Lynch Creek were estimated based on the cross-section survey conducted during 2012. The bottom width and side slopes were first estimated from the channel cross-section data at each of the six logger locations. Intermediate widths and side slopes were defined using linear interpolation based on longitudinal distance travelled between end points, with minor adjustments at certain locations during calibration. Channel slope information was calculated based on the centerline elevations sampled during shade modeling (calculated every 49 feet [15 meters] along a 33 foot digital elevation model [10 meter DEM] from the National Elevation Dataset). For each QUAL2K reach an elevation was assigned based on the centerline elevations sampled during Shade modeling. The elevation data were then used to calculate the slope between two end points. Channel slopes were typically around 2.59 percent (median) and ranged from 0.04 percent to 13.66 percent. Due to the variation and uncertainty in slopes, the Manning roughness coefficients varied significantly along the stream path. **Figure 7** shows the channel elevations and slopes assigned in the QUAL2K model.

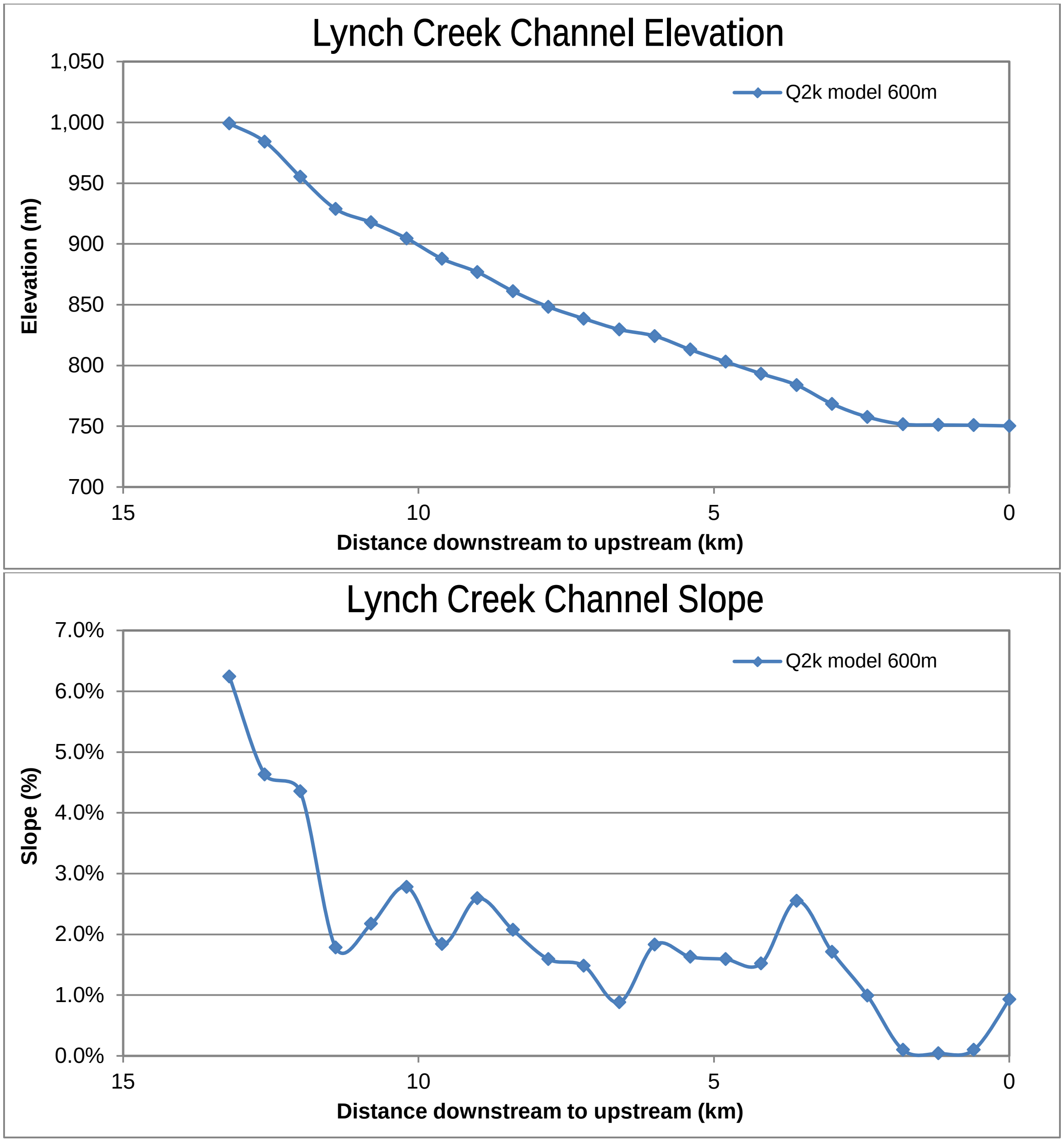


Figure 7. Lynch Creek channel elevation and slope representations.

3.2.4 Boundary Conditions

Boundary conditions represent external contributions to the waterbody being modeled. A flow and temperature input file was therefore configured for inputs to Lynch Creek. Boundary conditions were specified at the upstream terminus of Lynch Creek, for each of the major tributaries' confluences with Lynch Creek, and for diffuse sources along the creek. These are further discussed in the following sections.

3.2.4.1 Headwater (Upstream) Boundary

QUAL2K requires specification of the headwater flow and temperature. Diurnal temperatures (August 11, 2012) at the upstream boundary were specified using observed data from the in-stream logger at site LYNHC-T1 for the calibration period. No flow was specified for the calibration period as the stream was dry on this date. A dry channel was also observed on Lynch Creek at LYNHC-T1 on September 20, 2012. However, since the model requires specification of a headwater flow a very small flow of 0.001 cfs was input. The model is not sensitive to the temperature (due to the very small negligible flow that was specified) and has no impact on the model results. **Figure 8** shows the headwater temperatures specified in the model.

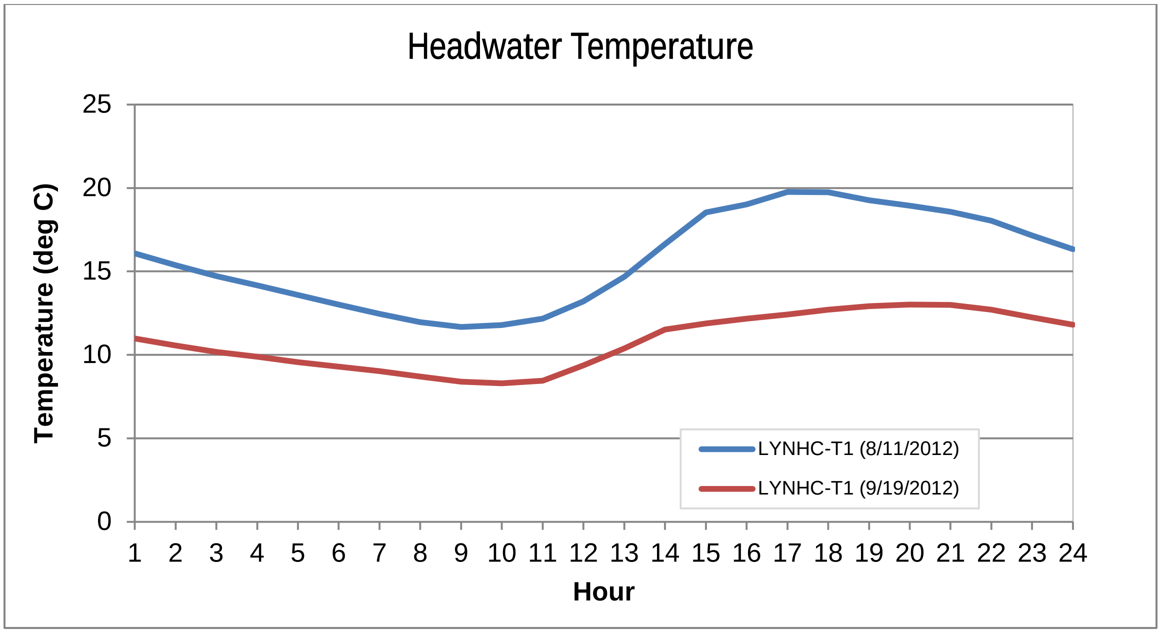


Figure 8. Diurnal temperature at the headwaters to Lynch Creek.

3.2.4.2 Tributary Inputs

There are many small tributaries in the watershed; however, monitoring data were available for only two major tributaries feeding into Lynch Creek – Cedar Creek and Clark Creek (**Figure 6**). **Table 2** shows the flow and temperature assigned to the tributaries in the model. Flows during the validation period were observed on September 20, 2012 and were used in conjunction with temperatures observed on September 19, 2012, which was the closest day of full temperature data available.

In addition to tributary inputs, irrigation withdrawals from Lynch Creek were also identified (see **Appendix A** for a discussion of these withdrawals) and assigned in the model. 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 August and September. A maximum daily flow rate was estimated using the net irrigation requirements and the maximum area irrigated (1,294 acres). It was calculated that up to 6.50 cfs and 4.14 cfs may be withdrawn from Lynch Creek on a daily basis during August and September, respectively. These calculated withdrawals were used in the model (rows identified as *irrigation withdrawal* in **Table 2**). More information on the irrigation withdrawal can be found in **Appendix A**.

Table 2. QUAL2K model flow and temperature inputs to Lynch Creek - Tributaries and withdrawal

		Diffuse sources [a]		Temperature [b]		
Description	Location (RM)	Abstraction (cfs)	Inflow (cfs)	Daily mean (°F)	½ daily range (°F)	Time of maximum (hour)
August 11, 2012						
Cedar Creek (CEDRC)	6.84	--	0.49	58.3	4.2	7:30 PM
irrigation withdrawal	6.13	0.94	--	--	--	--
Clark Creek (CLRKC)	5.01	--	0.74	62.6	7.5	5:00 PM
irrigation withdrawal	4.16	1.25	--	--	--	--
irrigation withdrawal	3.55	1.25	--	--	--	--
irrigation withdrawal	2.91	0.53	--	--	--	--
irrigation withdrawal	2.67	0.32	--	--	--	--
irrigation withdrawal	2.16	0.35	--	--	--	--
irrigation withdrawal	1.78	0.021	--	--	--	--
irrigation withdrawal	1.49	1.85	--	--	--	--
September 20, 2012						
Cedar Creek (CEDRC)	6.84	--	0.33	58.8	3.7	7:30 PM
irrigation withdrawal	6.13	0.52	--	--	--	--
Clark Creek (CLRKC)	5.01	--	0.57	53.5	5.7	5:00 PM
irrigation withdrawal	4.16	1.12	--	--	--	--
irrigation withdrawal	3.55	0.68	--	--	--	--
irrigation withdrawal	2.91	0.29	--	--	--	--
irrigation withdrawal	2.67	0.17	--	--	--	--
irrigation withdrawal	2.16	0.33	--	--	--	--
irrigation withdrawal	1.78	0.011	--	--	--	--
irrigation withdrawal	1.49	1.02	--	--	--	--

Notes

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

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

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

3.2.4.3 Diffuse Sources

Groundwater, irrigation return flows, and other sources of water not accounted for in the tributaries can be specified along the length of the waterbody using the Diffuse Sources worksheet in the QUAL2K model. A flow balance was constructed using the observed flows along Lynch Creek and its tributaries The amount of diffuse flow along Lynch Creek was calculated for the days when flow was available on August 11, 2012 and September 20, 2012.

Temperature assignment for the diffuse sources was done using the average water temperature of the preceding four months (June, July, August, and September), which was 62.6° F. This value was used as an estimate for diffuse sources water temperature that was dominated by surficial irrigation return flows, which was then further refined during calibration and validation. Based on an aerial photograph review and a review of available irrigation information, it appears that there are significant surficial irrigation return flows (i.e., open channels exposed to sunlight and ambient air temperatures) that impact the diffuse flow temperatures. The final diffuse source water temperatures were varied for the calibration and validation period to better match recorded data (64.4° C and 60.8° F respectively). The final flow and water temperature assignment are shown in **Table 3**.

Table 3. QUAL2K model flow and temperature inputs to Lynch Creek - Diffuse sources

Description	Location [a] Upstream (RM)	Downstream (RM)	Diffuse Abstraction (cfs)	Diffuse Inflow Inflow (cfs)	Temp (°F)
August 11, 2012					
From LYNHC-T1 to LYNHC-T2	8.35	6.87	--	0.27	64.4
From LYNHC-T2 to LYNHC-T3	6.87	5.33	--	0.81	64.4
From LYNHC-T3 to LYNHC-T5	5.33	4.19	--	0.29	64.4
From LYNHC-T5 to LYNHC-T6	4.19	2.67	--	2.59	64.4
From LYNHC-T6 to *irrigation withdrawal* [b]	2.67	1.64	--	1.50	64.4
From *irrigation withdrawal* [b] to LYNHC-T7	1.64	0.26	--	0.58	64.4
September 20, 2012					
From LYNHC-T1 to LYNHC-T2	8.35	6.87	--	0.25	60.8
From LYNHC-T2 to LYNHC-T3	6.87	5.33	--	0.44	60.8
From LYNHC-T3 to LYNHC-T5	5.33	4.19	--	0.61	60.8
From LYNHC-T5 to LYNHC-T6	4.19	2.67	--	1.45	60.8
From LYNHC-T6 to *irrigation withdrawal* [b]	2.67	1.64	--	0.69	60.8
From *irrigation withdrawal* [b] to LYNHC-T7	1.64	0.26	--	0.25	60.8

Notes
°F = degrees Fahrenheit; cfs = cubic feet per second; RM = river mile.
a. Upstream and downstream termini of segments.
b. This is the eighth irrigation withdrawal along Lynch Creek, which is at RM 1.64.

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 nearest weather station in the vicinity of the Lynch Creek watershed is the Plains RAWS (NESS ID 323F46F2), which is near the Clark Fork River a few miles downstream of the mouth of Lynch Creek, at almost the same elevation (**Figure 6**); it records hourly air temperature, dew point temperature, wind speed and solar radiation. The Plains RAWS hourly observed meteorological data were used to develop the QUAL2K model after appropriate unit conversions.

The wind speed measurements at the Plains RAWS were measured at 20 feet (6.10 meters) above the ground. QUAL2K requires that the wind speed be at a height of 7 meters. The wind speed measurements ($U_{w,z}$ in meters per second) taken at a height of 6.10 meters (z_w in meters) were converted to equivalent conditions at a height of z = 7 meters (the appropriate height for input to the evaporative heat loss equation), using the exponential wind law equation suggested in the QUAL2K user's manual (Chapra et al. 2008):

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

3.2.6 Shade Data

The QUAL2K model allows for spatial and temporal specification of shade, which is the fraction of potential solar radiation that is blocked by topography and vegetation. A Shade Model was developed and calibrated for Lynch Creek. The calibrated Shade Model was first run to simulate shade estimates for August 11, 2012 and September 20, 2012 to simulate hourly shade every 49 feet (15 meters, the resolution of the Shade Model) along Lynch Creek. Reach-averaged integrated hourly effective shade results were then computed at every 0.37 mile (600 meters; i.e., each reach). The reach-averaged results were then input into each reach within the QUAL2K model. The overall average shade on September 20, 2012 (81 percent) was greater than that predicted on August 11, 2012 (78 percent). A more detailed discussion on the shade modeling can be found under **Appendix A**.

3.3 Model Evaluation Criteria

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

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

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

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

3.4 Model Calibration and Validation

The time periods selected for calibration and validation were August 11, 2012 and September 20, 2012, respectively. These dates were selected as they had the most comprehensive dataset available for modeling and corresponded to the synoptic study done for Lynch 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 Lynch Creek. **Table 4** shows the monitoring sites used for calibration and validation.

Table 4. Temperature calibration and validation locations

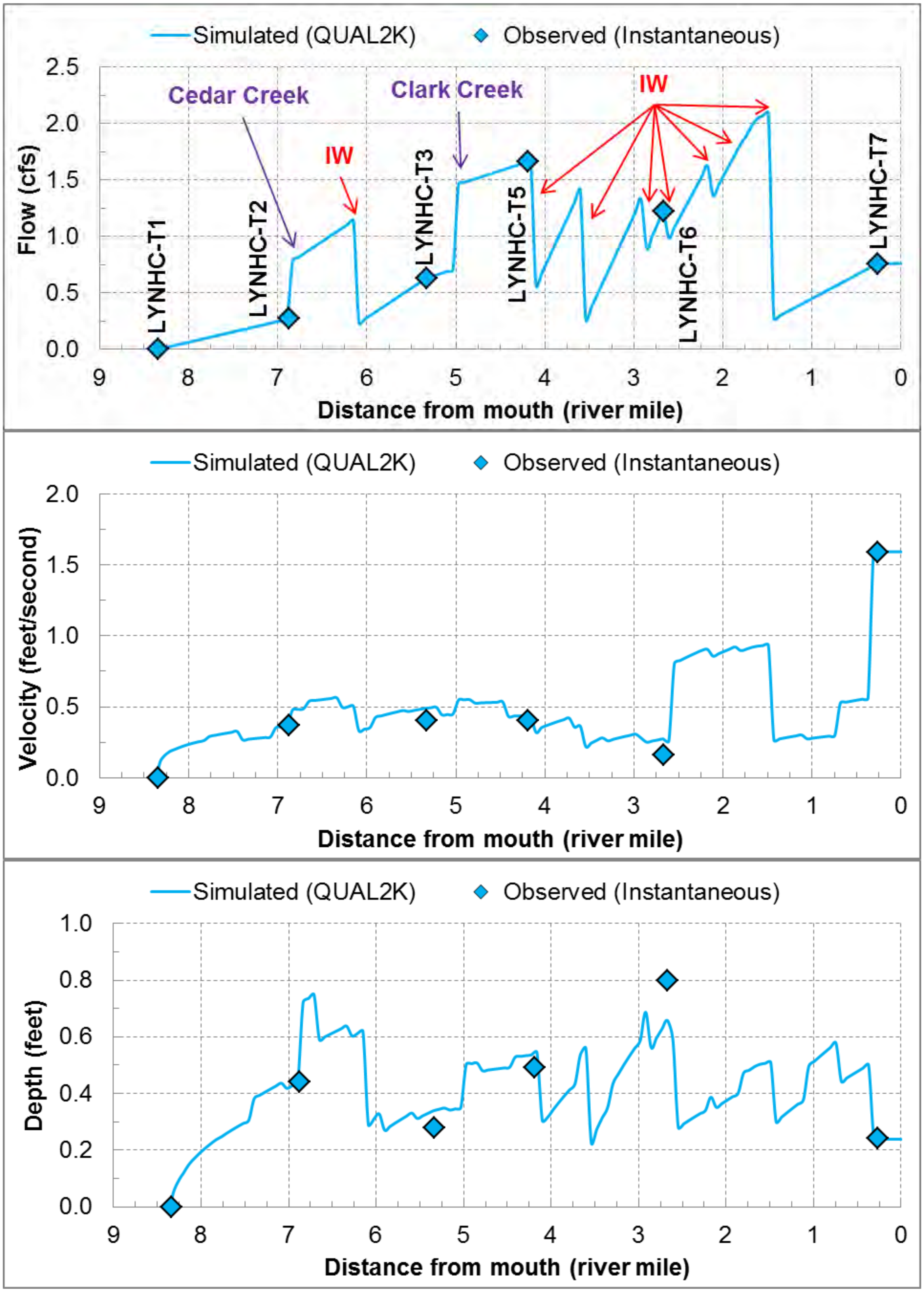
Site name	Distance (RM)	Available Data	Source
LYNHC-T1	8.35	Flow, depth, velocity, and temperature	EPA
LYNHC-T2	6.87	Flow, depth, velocity and temperature	EPA
LYNHC-T3	5.33	Flow, depth, velocity and temperature	EPA
LYNHC-T5	4.16	Flow, depth, velocity, and temperature	EPA
LYNHC-T6	2.67	Flow, depth, velocity, and temperature	EPA
LYNHC-T7	0.26	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 Lynch Creek, tributary flows, and withdrawals were used to estimate the amount of diffuse flow along the system.

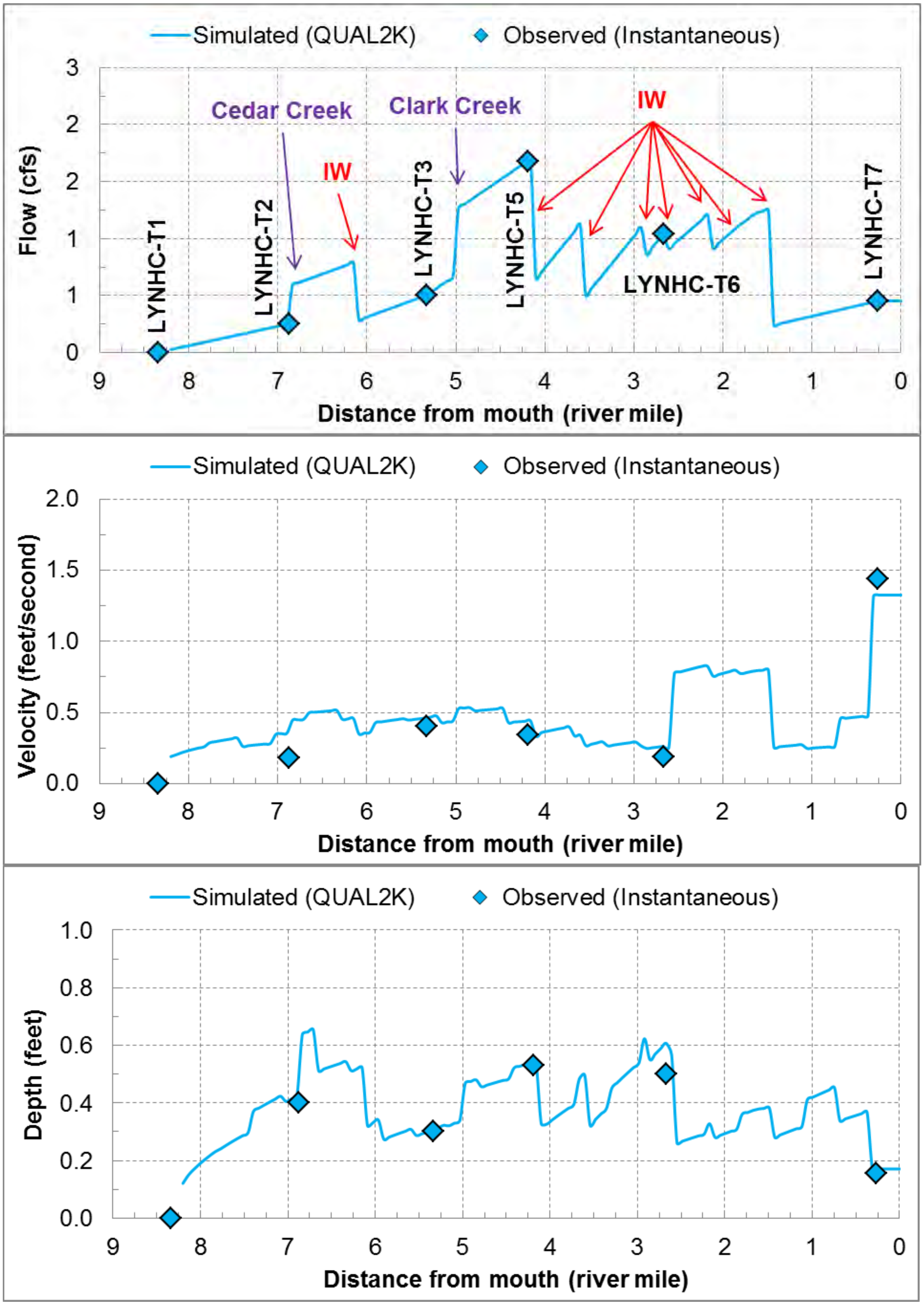
After the mass balance of the flow rates, channel roughness was adjusted to better match simulated velocities and depths to observed conditions. Since streamflow, depth, and geometry measurements were monitored at sites distributed along Lynch Creek, Manning *n* values were calculated numerically (Chapra 1997) for each model segment based on the field data. The calculated Manning roughness coefficients were further refined during calibration and validation. Final Manning roughness coefficients ranged from 0.030 to 0.400 during calibration and validation which are higher than coefficients in traditional applications. This was due to low flow conditions (i.e., more effective roughness per unit area) and large quantities of stone, pebble, and vegetation as substrate in the channel. Traditional applications with higher, bankfull flow conditions typically range from 0.025 to 0.2 for natural main channels (Chow 1988). The calibrated/validated coefficients were deemed appropriate since they were based upon observed data and yielded reasonable fits of velocity and depth, as shown in **Figure 9** and **Figure 10**.

Comparison of the observed and predicted longitudinal changes in flow, depth, and velocity for the calibration and validation period are shown below in **Figure 9** and **Figure 10**, respectively.



Note: IW indicates an irrigation withdrawal as calculated in Appendix A.

Figure 9. Observed and predicted flow, velocity, and depth on August 11, 2012 (calibration).



Note: IW indicates an irrigation withdrawal as calculated in Appendix A.

Figure 10. Observed and predicted flow, velocity, and depth on September 20, 2012 (validation).

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

Hourly solar radiation is an important factor that affects stream temperature. The QUAL2K model does not allow for input of solar radiation. Instead the model calculates short wave solar radiation using an atmospheric attenuation model. For Lynch 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 Plains RAWS. **Figure 11** shows the observed and predicted solar radiation for the calibration and validation. No cloud cover data were available and was assumed as 10 percent for the calibration and validation dates. The Ryan-Stolzenbach atmospheric transmission coefficient was set at 0.86 for the calibration and validation dates to reflect the atmospheric conditions to minimize the deviation between the observed and modeled short wave solar radiation.

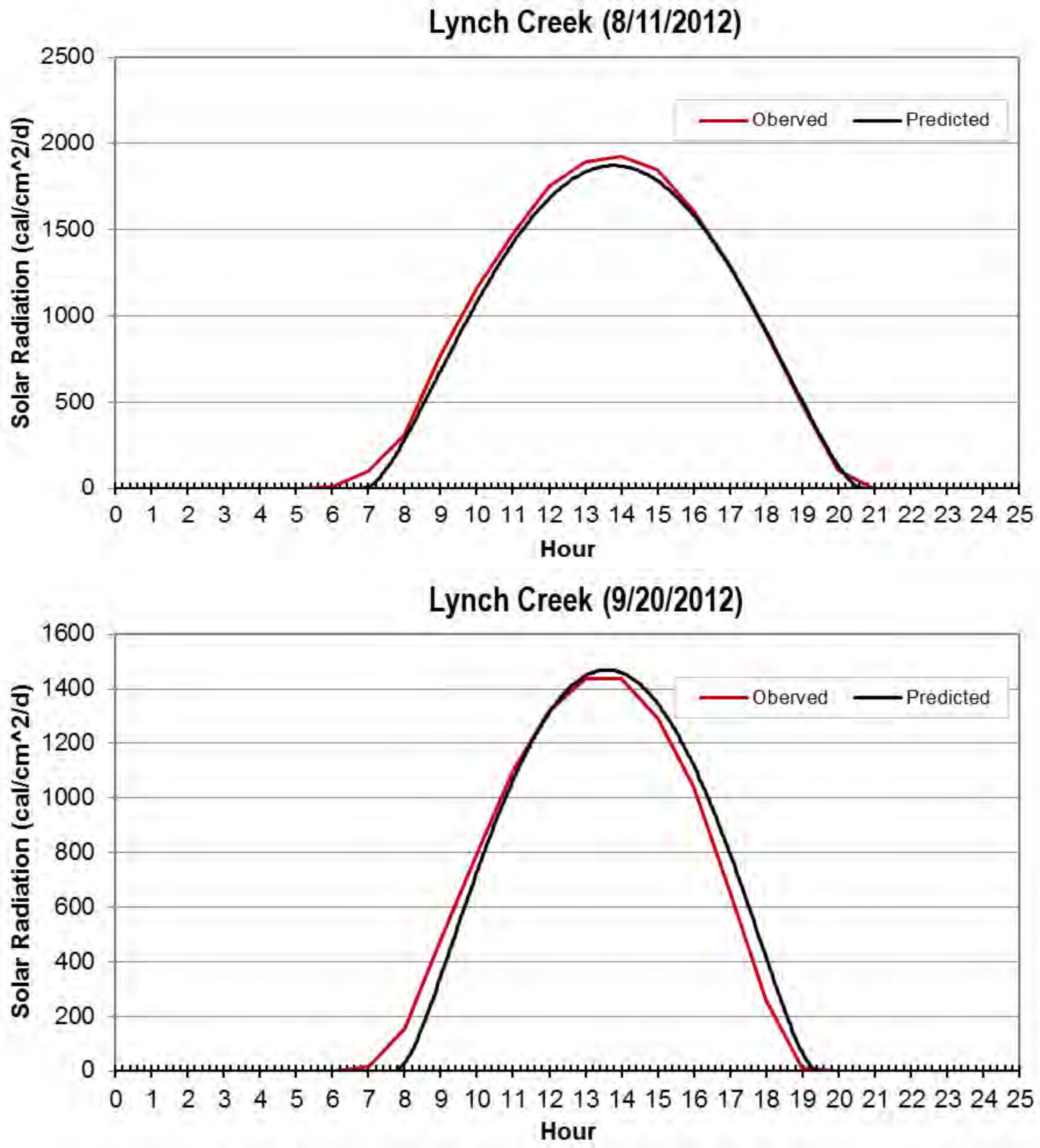


Figure 11. Observed and predicted solar radiation on August 11, 2012 and September 20, 2012 (calibration and validation).

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 5**.

Table 5. 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]	0.86
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. These parameters have an impact especially on the minimum temperatures simulated. In particular the sediment thermal thickness, sediment thermal diffusivity, and sediment heat capacity were adjusted during calibration. The sediment thermal thickness was slightly increased from the default value of 10 cm to 15 cm, and the sediment heat capacity of all component materials of the stream was also increased to 0.55 calories per gram per degree Celsius from the default value of 0.432 calories per gram per degree Celsius to better match recorded conditions. The sediment thermal diffusivity was set to a value of 0.0118 square centimeters per second (Chapra et al. 2008). This value is consistent with the stream photos that indicated a predominantly rocky substrate along the main channel. These adjustments helped in improving the minimum temperatures simulated.

Calibration was followed by validation. The validation provides a test of the calibrated model parameters under a different set of conditions. Only those variables that changed with time were changed during validation to confirm the hydraulic variables. This included headwater and tributary in-stream temperatures, diffuse source temperatures, air and dew point temperatures, wind speed, cloud cover, solar radiation, and shade. Reach properties such as slope, width, and other associated parameters were unchanged from the calibration. All other inputs were based on observed data in September 20, 2012. Irrigation return flow temperatures, for which there were no direct observed data and only an aerial imagery and irrigation record review, were changed due to the drop in measured stream temperatures.

Figure 12 and **Figure 13** show the calibration and validation results along Lynch Creek. As can be seen in the figures, the ranges of temperatures during calibration and validation are quite different. In addition, the observed temperatures during the calibration are much warmer than those during the validation in some instances over 5° F warmer. The temperature calibration and validation statistics of the average, maximum, and minimum temperatures are shown in **Table 6** and **Table 7**, respectively.

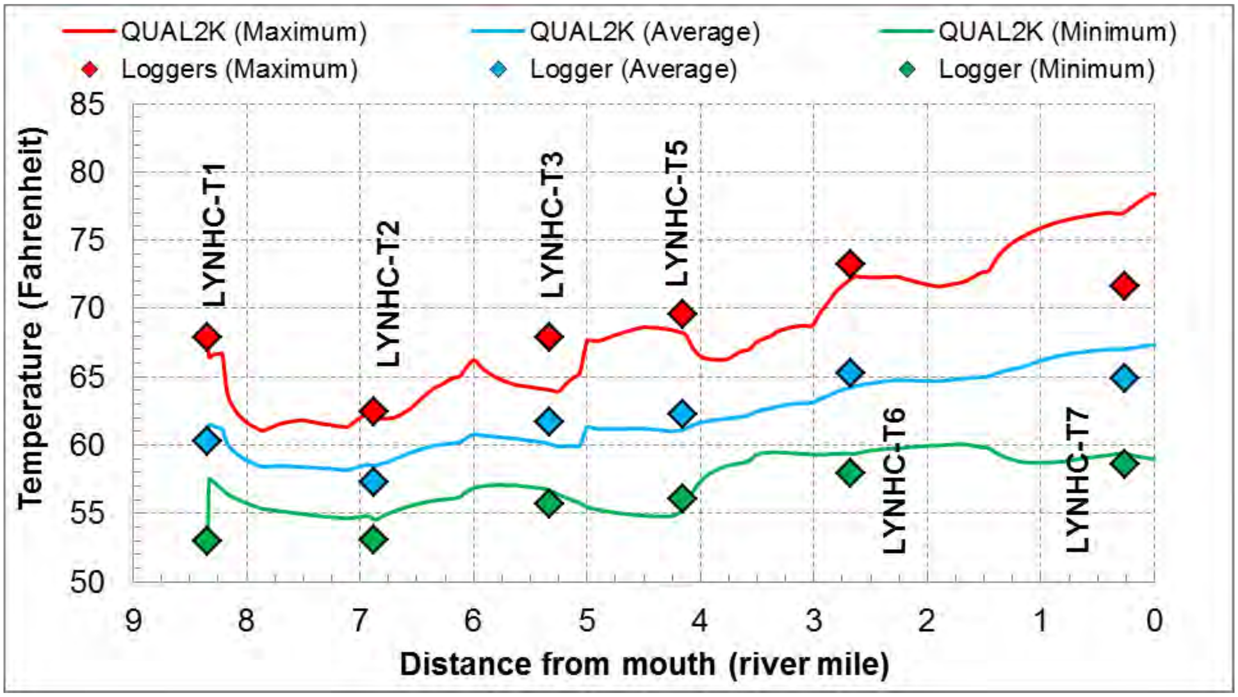


Figure 12. Longitudinal profile of the temperature calibration (August 11, 2012).

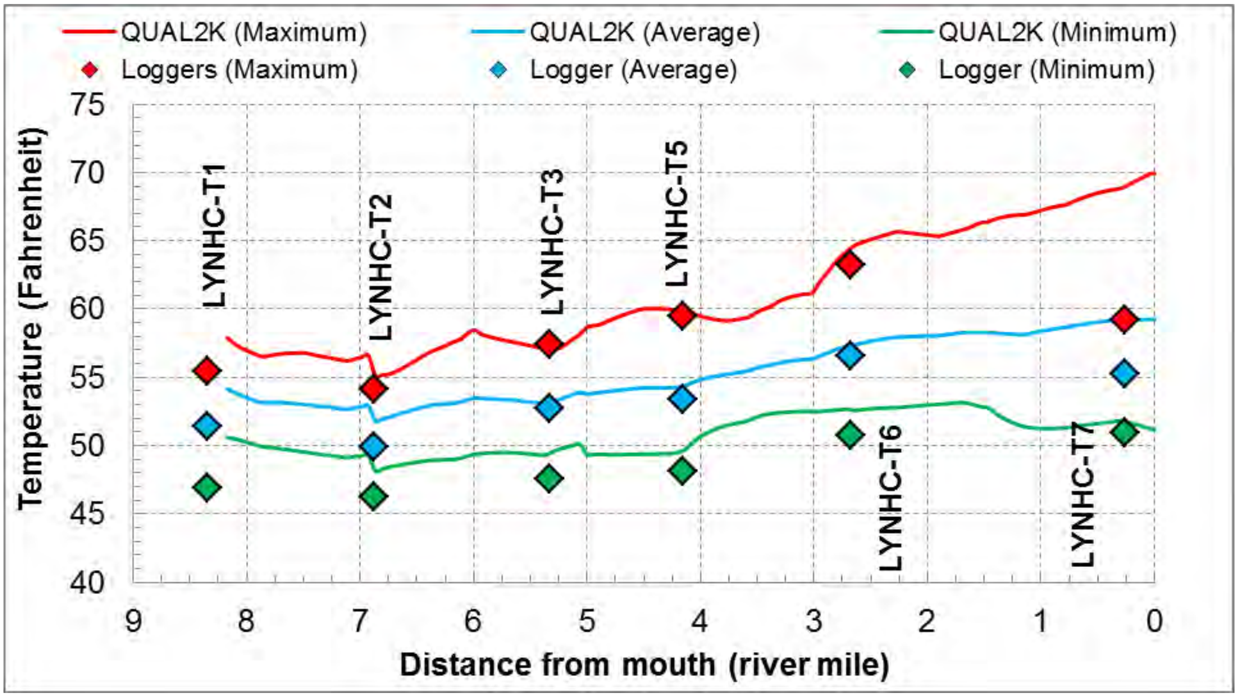


Figure 13. Longitudinal profile of the temperature validation (September 20, 2012).

Table 6. 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 (%)
LYNHC-T1	8.3	0.35	0.0%	0.01	0.5%	0.01	0.0%
LYNHC-T2	6.9	0.51	2.1%	1.22	0.8%	1.46	2.8%
LYNHC-T3	5.3	3.82	2.6%	1.63	5.6%	0.89	1.6%
LYNHC-T5	4.2	1.51	1.7%	1.04	2.2%	0.54	1.0%
LYNHC-T6	2.7	1.26	1.6%	1.05	1.7%	1.45	2.5%
LYNHC-T7	0.3	5.37	3.2%	2.10	7.5%	0.76	1.3%
Overall Calibration		**1.41**	**2.3%**	**2.49**	**3.6%**	**1.02**	**1.8%**

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

Table 7. Validation statistics of observed versus predicted water temperatures

Site name	RM	Average daily temperature		Maximum daily temperature		Minimum daily temperature	
		AME (°F)	RE (%)	AME (°F)	REL (%)	AME (°F)	REL (%)
LYNHC-T1	8.3	--	--	--	--	--	--
LYNHC-T2	6.9	1.87	3.7%	1.01	1.9%	1.86	4.0%
LYNHC-T3	5.3	0.52	1.0%	0.31	0.5%	1.91	4.0%
LYNHC-T5	4.2	1.05	2.0%	0.48	0.8%	1.65	3.4%
LYNHC-T6	2.7	0.77	1.4%	1.02	1.6%	1.91	3.8%
LYNHC-T7	0.3	3.94	7.1%	9.66	16.3%	0.89	1.7%
Overall Validation		**1.63**	**3.0%**	**2.50**	**4.3%**	**1.64**	**3.4%**

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

The model is able to simulate the minimum, mean, and maximum temperatures fairly well but does have some difficulty accurately simulating the maximum temperatures at several locations, especially at the downstream locations. The overall calibration results showed an overall 3.6 percent relative error with an AME of 2.5° F for the maximum temperatures; thus, the model simulation is good. The overall validation results for the maximum temperatures were similar to the calibration statistics with an overall 4.3 percent relative error and an AME of 2.5° F.

The model is not able to simulate the maximum temperatures well at LYNHC-T7 during both calibration and validation. Decreased withdrawals could decrease the temperatures along the stream, especially in the near vicinity downstream due to the existing low flows. During validation the model was unable to simulate the observed temperatures at LYNHC-T7 (AME = 9.7° F and REL = 16.3 percent); whereas at the same location during calibration, the model is able to capture the diurnal range (AME = 2.1° F and REL = 7.5 percent). The maximum temperature values during both calibration and validation were not captured in the model and estimated to be warmer than observed conditions. One possible explanation is that the simulated diffuse source inflow temperatures that represent warmer surficial irrigation return flow should be colder to reflect groundwater contribution. Without direct field observations and field measured flows and temperatures, it is not possible to determine what the source of inflow in this segment is.

4 Model Scenarios and Results

The Lynch Creek QUAL2K model was used to evaluate in-stream temperature response associated with multiple management scenarios. **Table 8** summarizes the alterations for each model scenario. The following subsections present discussions of the modifications to the QUAL2K models and the results for each scenario.

Table 8. QUAL2K model scenarios for Lynch Creek

Scenario [a]		Description	Rationale
Existing Condition Scenario			
1	Existing Condition	Existing shade and irrigation practices under field-measured flows[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	Transform all vegetation communities, with the exception of hydrophytic shrubs, and roads to medium density trees within 50 feet of the stream banks. Existing conditions vegetation to be retained beyond the 50-foot buffer.	Represent application of conservation practices for riparian vegetation.
Improved Flow and Shade			
4	Improved flow and shade	Existing conditions with 15% reduction in withdrawals (scenario 2) and 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 the EPA task order manager Lisa Kusnierz to Tetra Tech's project manager Ron Steg on September 10 and 12, 2013.

b. Based on an analysis of a discharge records from a nearby USGS gage, flows in Lynch Creek during the calibration timeframe were likely above the median of flows for August 11th.

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 calibrated model was used to represent the baseline flow and meteorological conditions. The daily average flow on August 11, 2012 at U.S. Geological Survey continuously recording gage 12390700 (Prospect Creek at Thompson Falls, MT; water years 1958-2012) was above the median (65th percentile) daily average flows on all August 11ths on record. The daily average flow for August 2012 at gage 12390700 similar (62nd percentile) as compared to the daily average flow for all Augusts on record (see **Appendix A, Section A-6**). Based on the fact that it is midway between the median and 75th percentile, it was a judged to be an adequate flow for which to use as the baseline scenario.

The modeled water temperature using the existing condition flow and meteorological data is shown below in **Figure 14**.

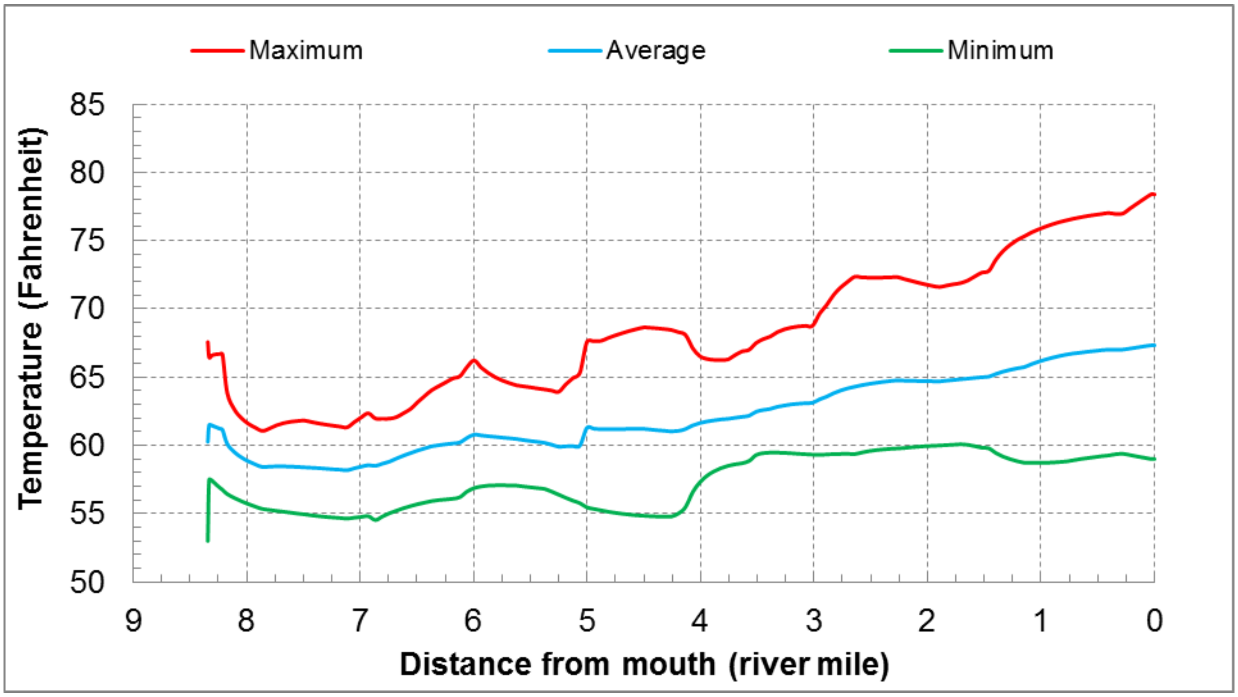


Figure 14. Simulated water temperature for existing condition (August 11. 2012).

4.2 Water Use Scenarios

Irrigation (or other water withdrawals) deplete the volume of water in the stream and reduce in-stream volumetric heat capacity. Theoretically the reduced stream water volume heats up more quickly (and also cools more quickly)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 diffuse 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 Lynch Creek. This scenario is intended to represent application of conservation practices relative to water use.

The water temperatures for Lynch Creek under this scenario exhibited a very small incremental decrease (**Figure 15**). The maximum change in the maximum daily water temperature is representative of the worst case conditions. A maximum change in the maximum daily water temperature of 2.95° F from the existing condition was observed in the segment immediately before the terminus of the creek. The temperature difference only becomes significant for the final 1.5 miles of the stream.

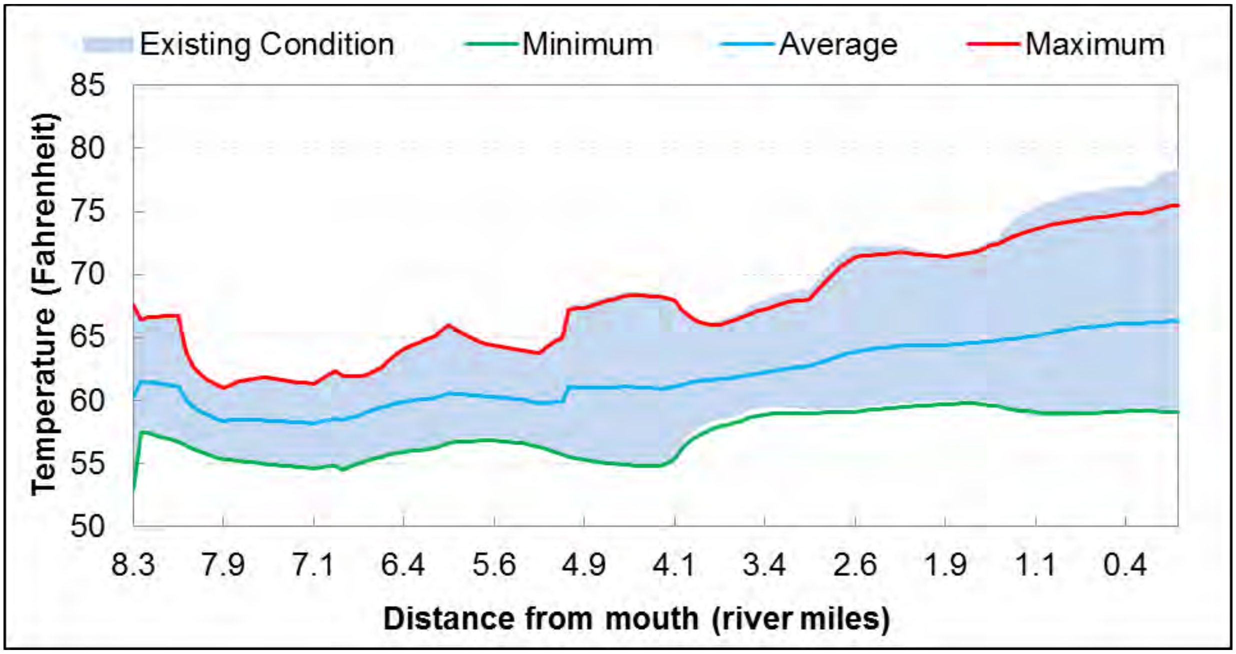


Figure 15. Simulated water temperatures for the existing condition (scenario 1) and 15-percent withdrawal reduction (scenario 2).

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 Lynch 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 hydrophytic shrubs and roads) are transformed to medium density trees 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 16** and **Table 9**).

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 conservation practices relative to shade although it is important to note that even in natural forested conditions, there are still openings in the canopy and some areas without vegetation. Hence this is likely an upper limit to what plausibly could occur from vegetation management practices. The technical basis for this scenario is provided in **Appendix A** in **Section A-4**.

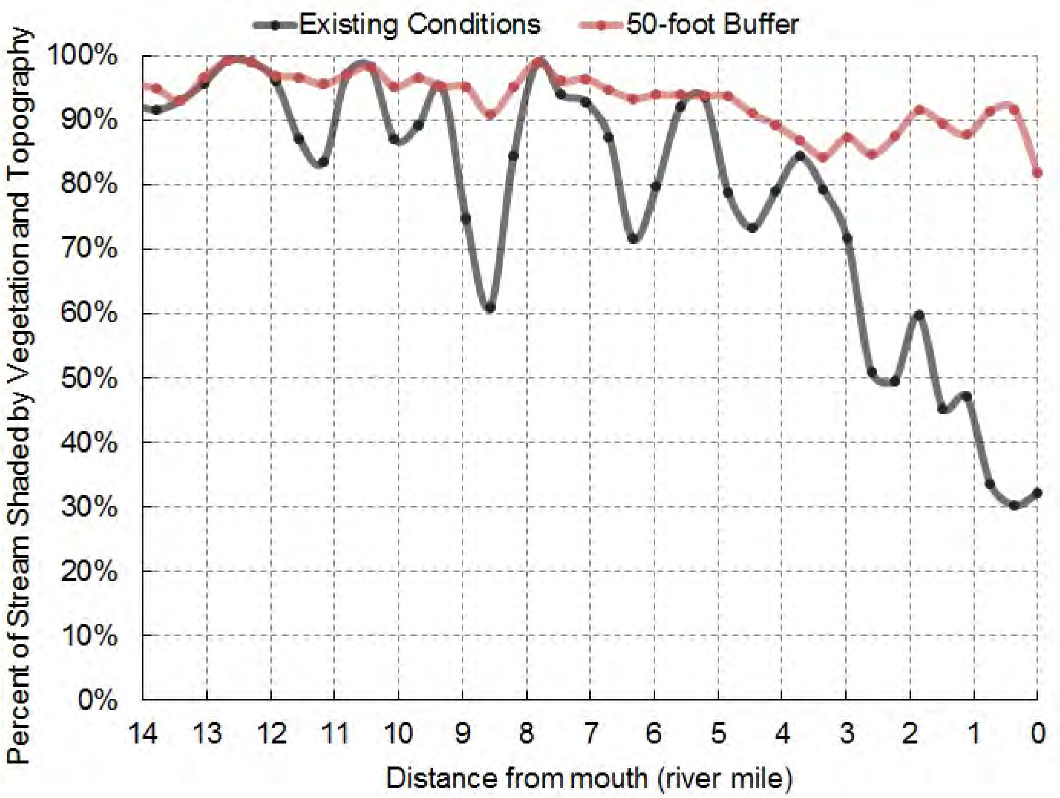


Figure 16. Effective shading along Lynch Creek for the existing condition and 50-foot buffer shade scenario.

Table 9. Average daily shade inputs per model segment

Segment	Existing condition (scenario 1)	50-foot buffer (scenario 3)
8.3 - 7.1	95%	97%
7.1 - 5.6	87%	96%
5.6 - 4.5	87%	96%
4.5 - 3.0	84%	96%
3.0 - 1.5	61%	95%
1.5 - 0.0	44%	91%

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

The water temperatures for Lynch Creek in this scenario decrease throughout the system (**Figure 17**). The upper reach of the system (i.e., approximately river kilometer 11 to 13) showed the least impact due to shade. The change in shade was minimal because this area is well vegetated. A maximum change in the maximum daily water temperature of 12.2° F from the existing condition was observed at river mile 0.1 to the mouth. The difference in the daily maximum water temperature between the existing condition and maximum potential shade scenario was almost always greater than 0.5° F. It is important to note the caveats previously stated, that this is likely the largest improvement that could be observed through vegetation management practices.

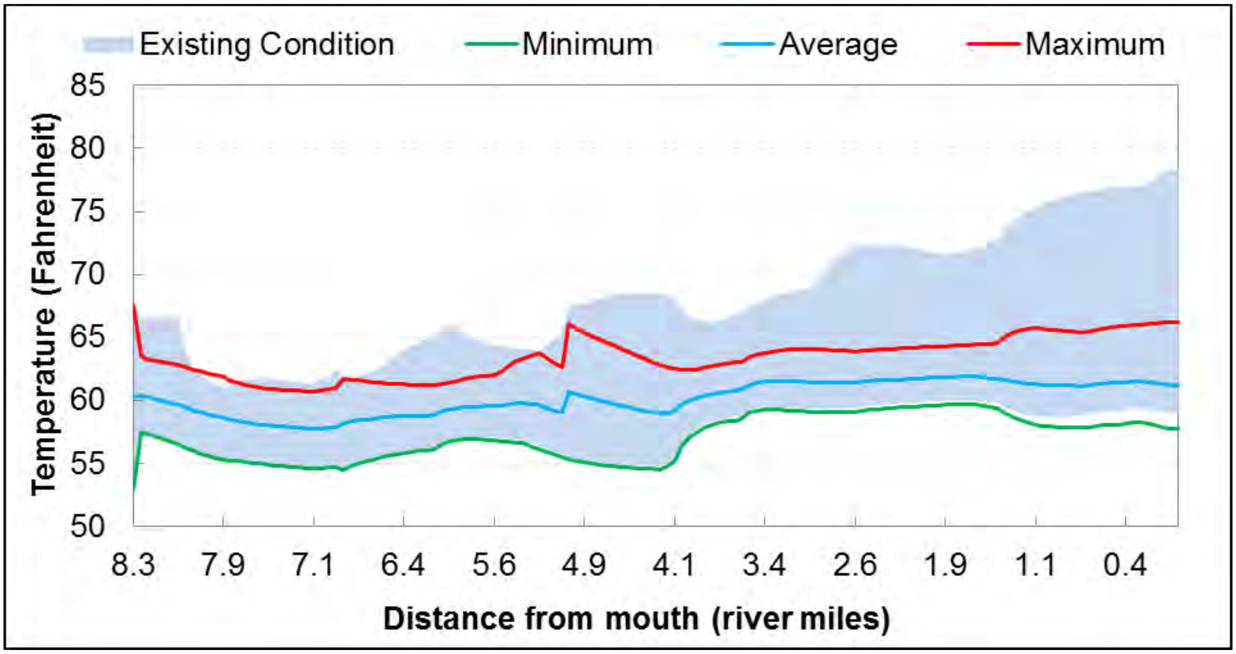


Figure 17. Simulated water temperatures for the critical existing condition (scenario 1) and shade with 50 foot buffer (scenario 3).

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 Lynch Creek in this scenario decrease throughout the system (**Figure 18** and **Figure 19**). A maximum change in the maximum daily water temperature of 13.5° F from the existing condition was observed at river mile 0.1 to the mouth. The results are similar to scenario 3 since scenario 2 showed minimal 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 almost always greater than 0.5° F for this scenario.

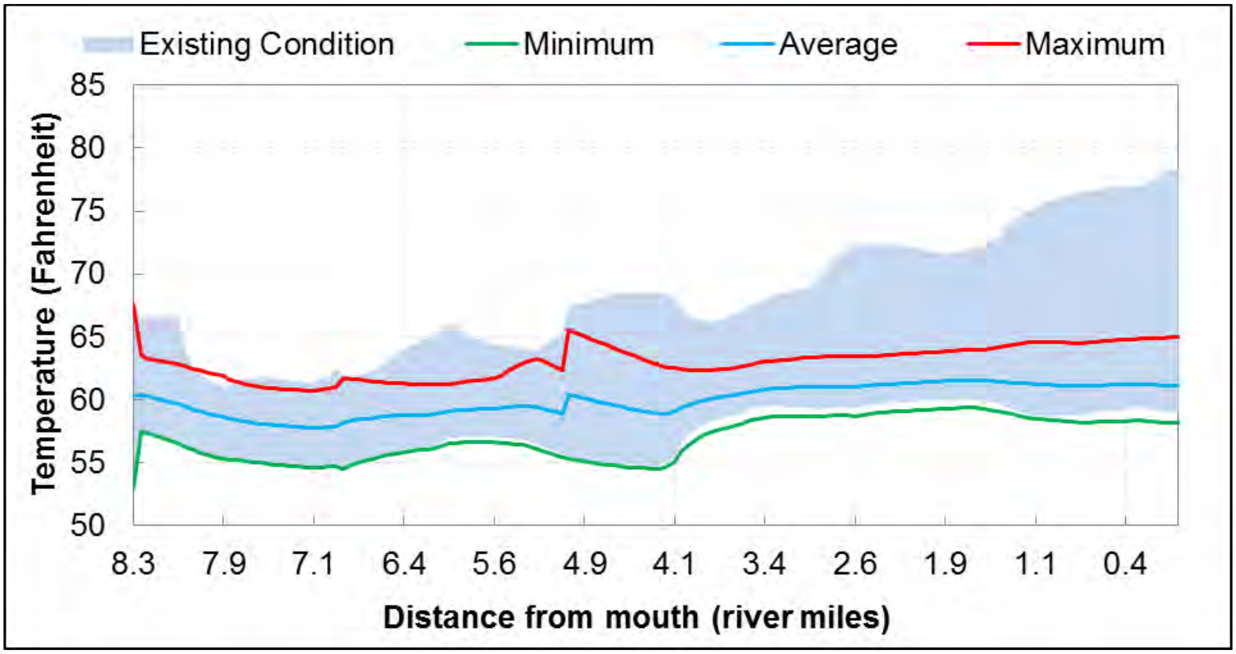


Figure 18. Simulated water temperature for the existing condition (scenario 1) and the improved flow and shade scenario (scenario 4).

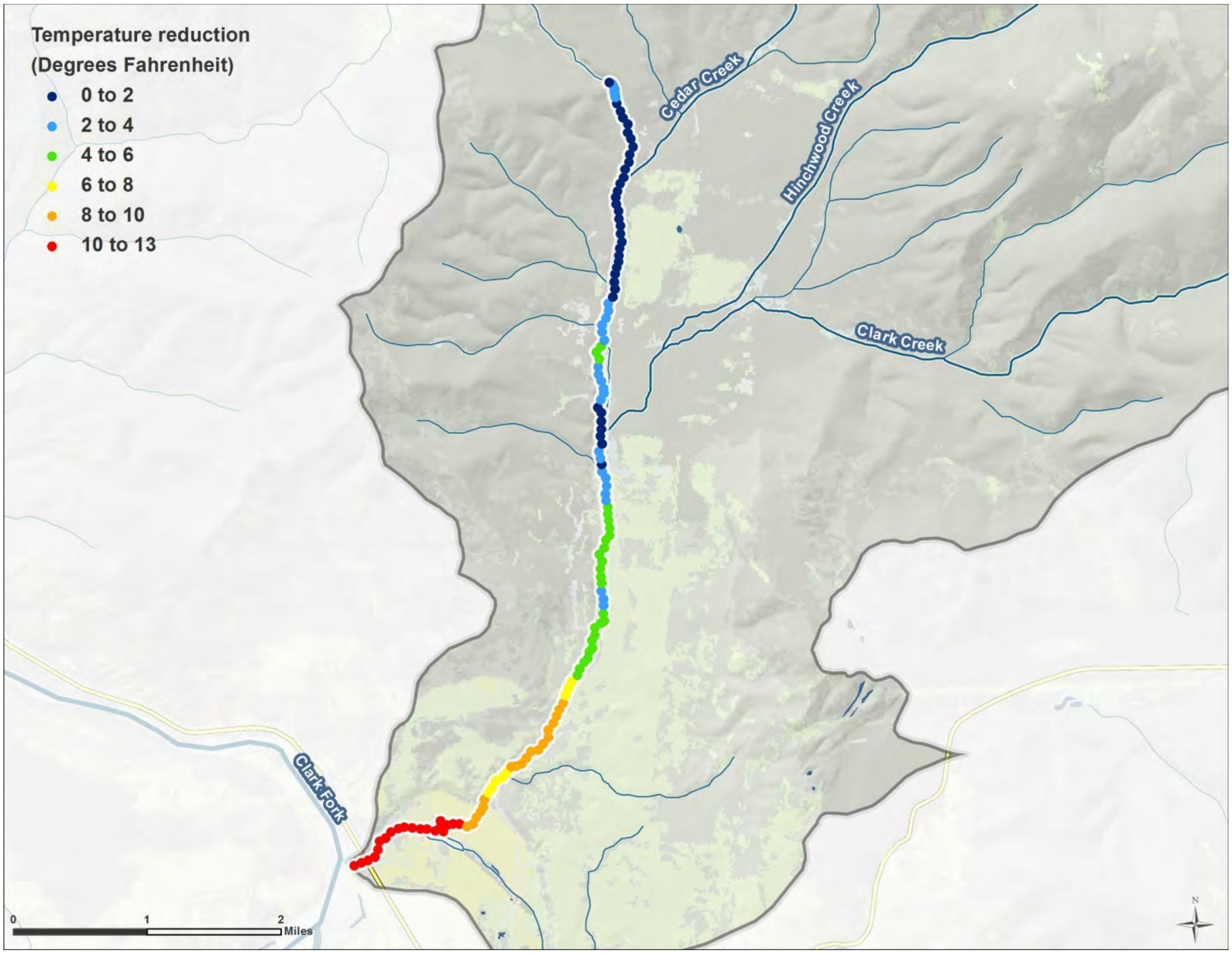


Figure 19. In-stream temperature difference from existing condition (scenario 1) to the improved flow and shade scenario (scenario 4).

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 are unlikely. The Shade Model has also been widely used so a similar sentiment exists. A potentially significant amount of the overall prediction uncertainty is due to uncertainty in the observed data used for model setup, calibration, and validation, and assumptions used in the scenario analysis itself.

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

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

- Lynch 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 Lynch Creek.
- Stream meander and hyporheic flow paths (both of which may affect depth-velocity and temperature) are inherently represented during the estimation of various parameters (e.g., stream slope, channel geometry, and Manning's roughness coefficient) for each segment.
- Weather conditions at the Plains RAWS are representative of local weather conditions along Lynch Creek.
- Shade Model results are representative of riparian shading along segments of Lynch 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 Lynch 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.

Sensitivity analysis is the most widely applied parameter uncertainty analysis approach for complex simulation models. Although sensitivity analysis is limited in its ability to evaluate nonlinear interactions among multiple parameters, model sensitivity was generally evaluated by making changes to shade and water use (i.e., the key thermal mechanisms [Tetra Tech 2012]) in separate model runs and evaluating the model response.

Model Sensitivity to Water Withdrawals and Shade

Model sensitivity to water withdrawal and shade was further evaluated by varying the amounts of water withdrawn and shade and then re-running the model. To assess model sensitivity to water withdrawals, the point source abstractions representing the withdrawals (see ***Appendix A*** *for the withdrawals) were removed and the existing condition model was run to represent the maximum achievable change in water temperatures from changes in water use. To assess model sensitivity to shade, all vegetation was converted to high density trees (with the exception of roads and hydrophytic shrubs) to represent the maximum potential shade. While not likely feasible, these conditions were run to assess model sensitivity. The results suggest that the model is not very sensitive to changes in water use but is sensitive to changes in shade.*

The increased shade scenario (scenario 3) assumes that the system potential vegetation for the riparian area within 50 feet of the stream bank is medium density trees (i.e., with the exception of areas currently dominated by hydrophytic shrubs or areas such as roads 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 scale used to identify the current and potential shade conditions and the fact that even natural systems tend to have spatial patchiness of tree canopy cover.

6 Model Use and Limitations

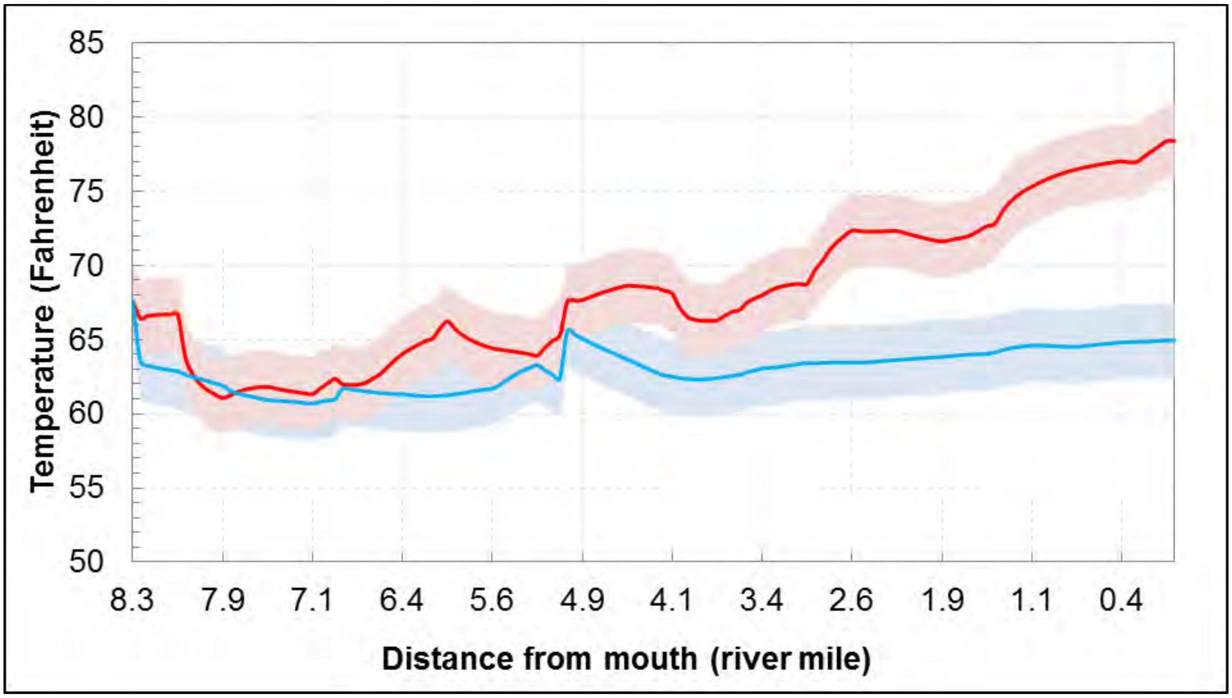
The model is only valid for summertime, low flow conditions and should not be used to evaluate high flow or other conditions. As described above, steps were taken to minimize uncertainty as much as possible. Despite the uncertainty, the model adequately addresses the primary questions:

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

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

The second question can be answered using the calibrated QUAL2K model and the scenarios developed to assess shade. In this instance, increasing riparian shading will decrease in-stream temperatures significantly (>10°F for maximum); however, there is uncertainty in the magnitude of temperature reduction as estimates are contingent on what was considered to be reference shade (>90 percent shading). While a “good” model calibration was achieved, the overall Absolute Mean Error (AME) for the maximum daily temperature was 2.5° F with increasing uncertainty in the lowermost portions of the model.

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



Note: The existing condition (scenario 1) is the red line and the improved flow and shade scenario (scenario 4) is the blue line. The shaded areas are plus or minus the average AME (2.5° F).

Figure 20. Simulated daily maximum water temperatures from the existing condition (red; scenario 1) and improved flow and shade scenario (blue; scenario 4).

7 Conclusions

The scenarios resulted in a range of almost no change in water temperatures to reductions as much as nearly 13.5° 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 exception to the lower 1.5 miles of Lynch Creek where a maximum change of 2.95° F occurs.

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 0.1° F to 12.2° 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 relative to the temperature impairment was also simulated. This scenario resulted in overall reductions along the entire reach which ranged from 0.1° F to 13.5° F. The scenario shows that reductions in water temperatures are achievable throughout the stream but significant reductions are achievable in only the lower one-third of Lynch Creek (refer back to **Figure 19** for a map of potential temperature reductions). The greatest potential improvement (i.e., reduction) occurs between river mile 0.5 and the mouth (about a 12.5° F improvement) with several other areas immediately upstream (i.e., the lower reaches of Lynch Creek) also showing sensitivity to shade (**Figure 22**). The reach between river miles 6.2 and 7.7 shows the least impact due to the presence of hydrophytic shrubs, which are considered to be at their maximum site potential. Efforts should be spent on re-vegetation in these areas most amenable to this type of restoration activity.

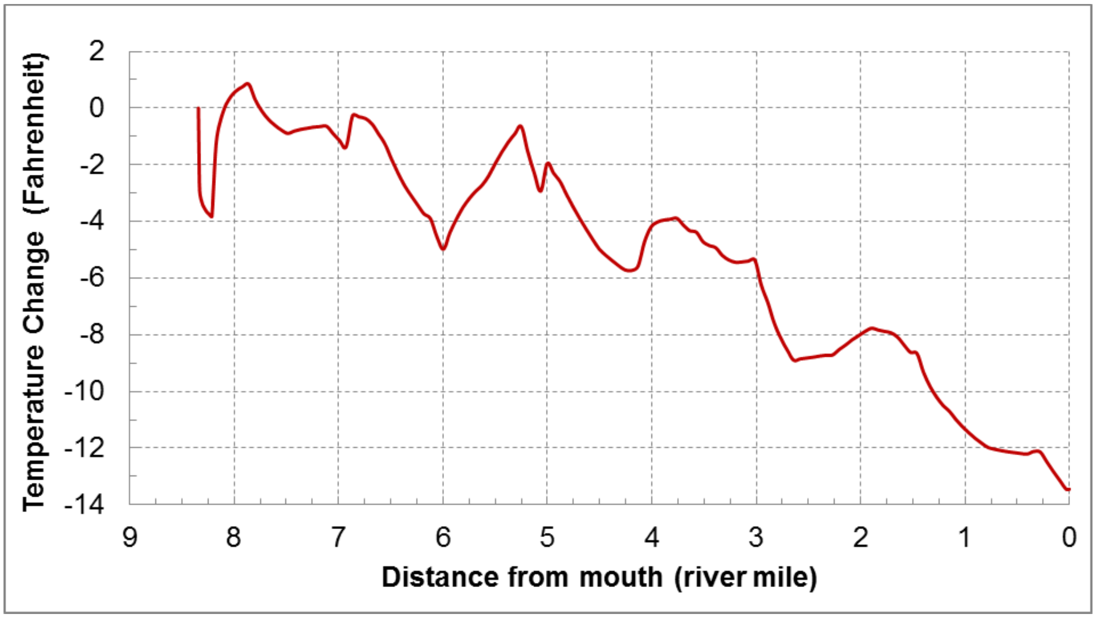


Figure 21. Simulated water temperature reduction from the existing condition (scenario 1) to the improved flow and shade scenario (scenario 4).

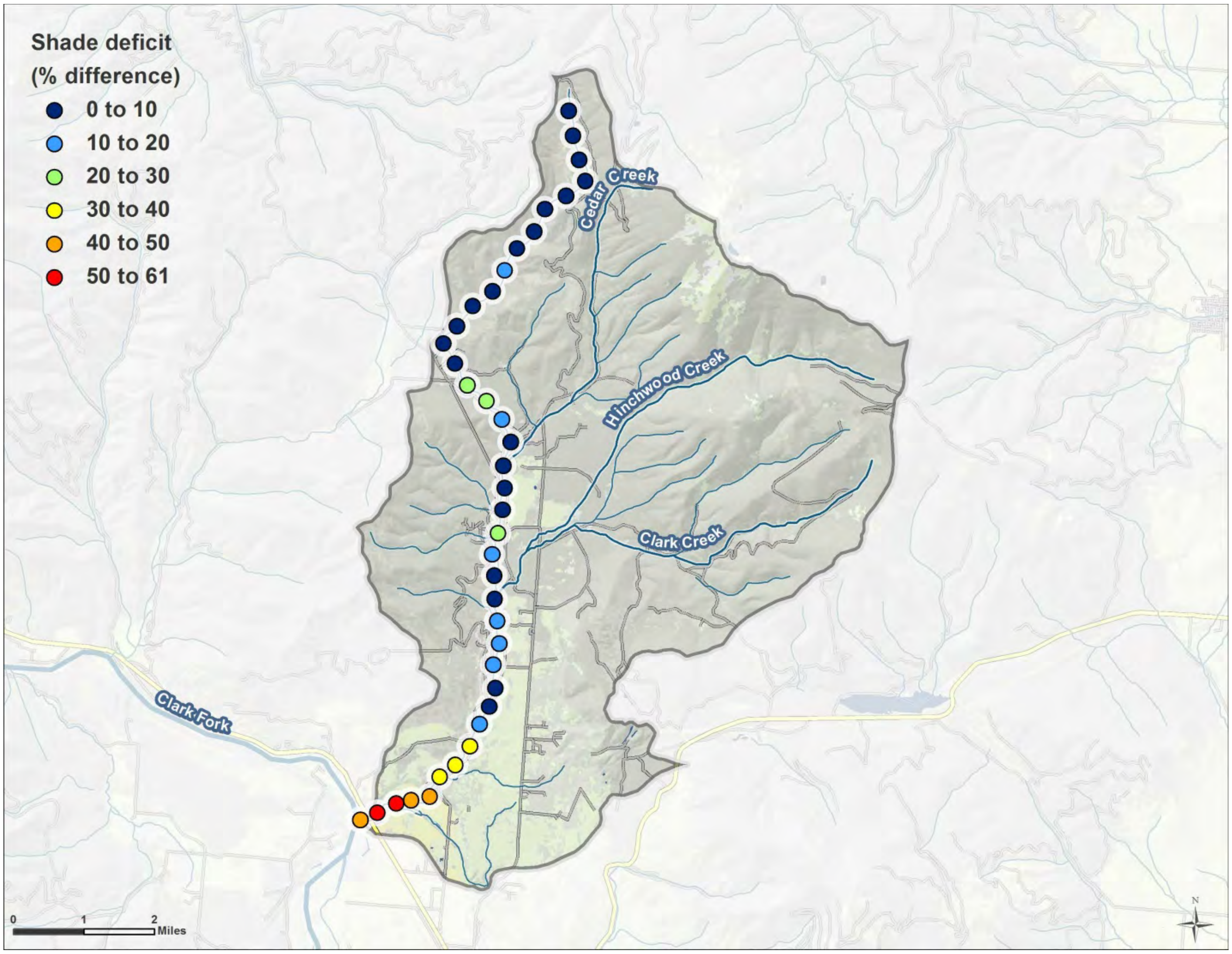


Figure 22. Shade deficit of the existing condition (scenario 1) from the improved flow and shade scenario (scenario 4).

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Appendix A.

Factors Potentially Influencing Stream Temperature in Lynch Creek

Contents

Tables

Figures

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 Lynch Creek are discussed below:

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

• Climate

The nearest weather station to the Lynch Creek watershed is 22 miles to the west in the city of Thompson Falls, Montana (National Weather Service station ID 248211) at an elevation of 2,380 feet above mean sea level (MSL). A Remote Automatic Weather Station (RAWS) is 9 miles away in Plains, Montana (National Weather Service station ID 241206, **Figure A-23**) at 2,480feet above MSL. Lynch Creek ranges in elevation from approximately 2,440 to 5,160 feet above MSL.

Average annual precipitation at station 248211is 22.4 inches, with the greatest amounts falling in November and January (**Figure A-24**; National Climatic Data Center 2013).

Average maximum temperatures occur in July and August and are 87.3° F and 87.4° F, respectively. The available data at Plains RAWS only date back to 2000, but the station records weather data hourly whereas station 248211 only records weather data daily. Thus, Plains RAWS hourly temperature data were used to develop the QUAL2K inputs. The Plains RAWS data are also summarized in **Figure A-24.**

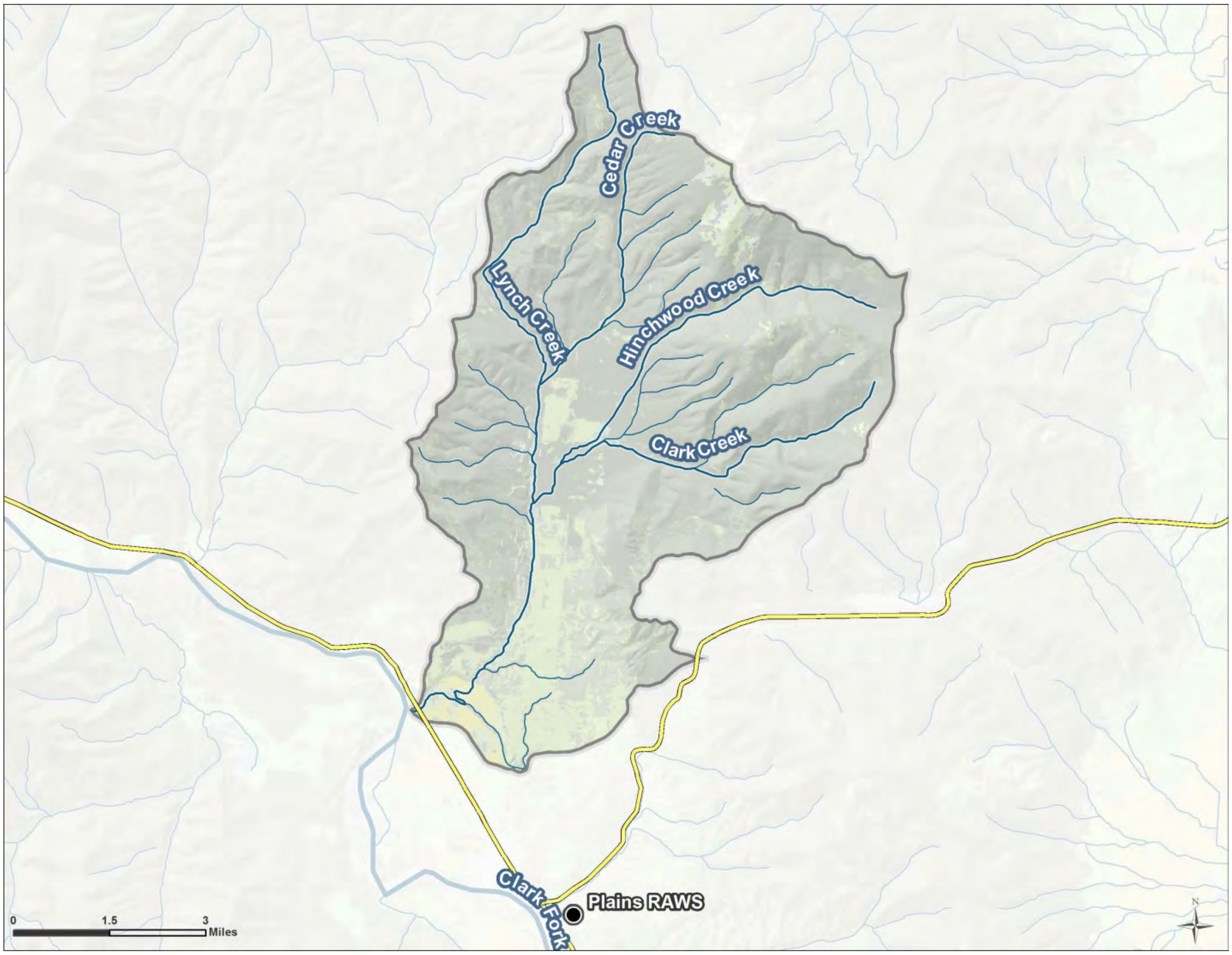
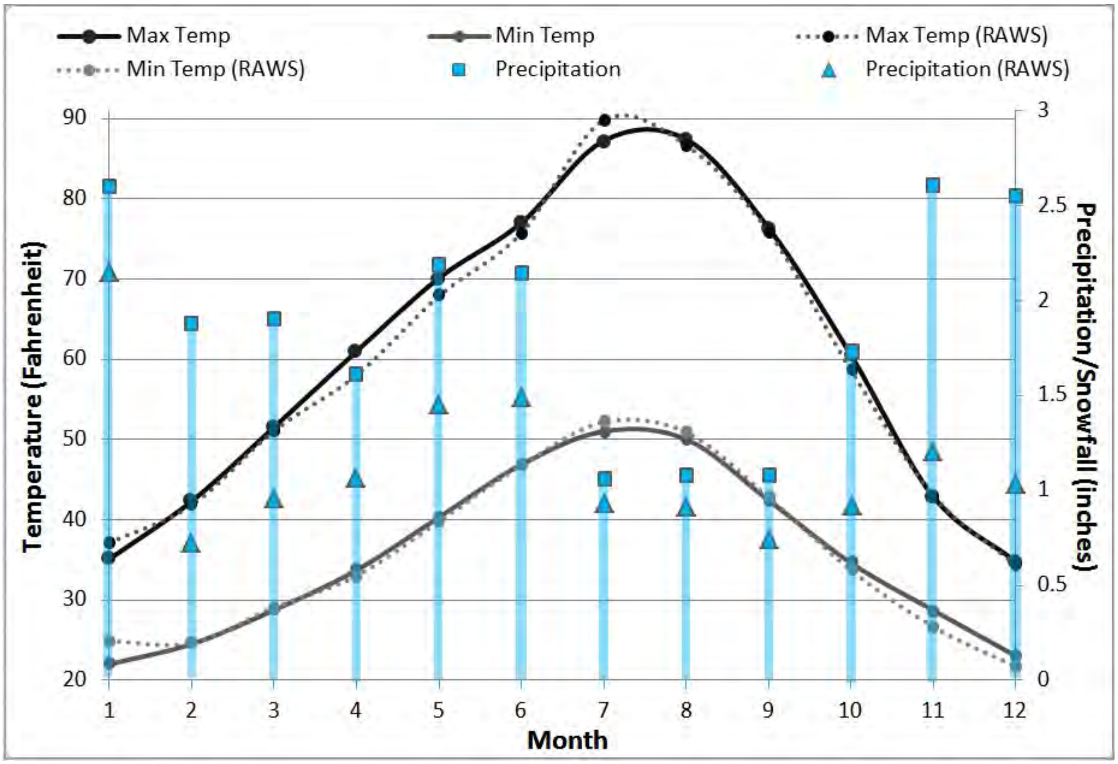


Figure A-23. Lynch Creek watershed and Plains RAWS.



Source: GHCN-D Monthly Summaries from 1970 to 2012 at Thompson Falls Power House weather station (National Climactic Data Center 2013) and from 2002 to 2013 at Plains RAWS weather station (Western Regional Climate Center 2013).

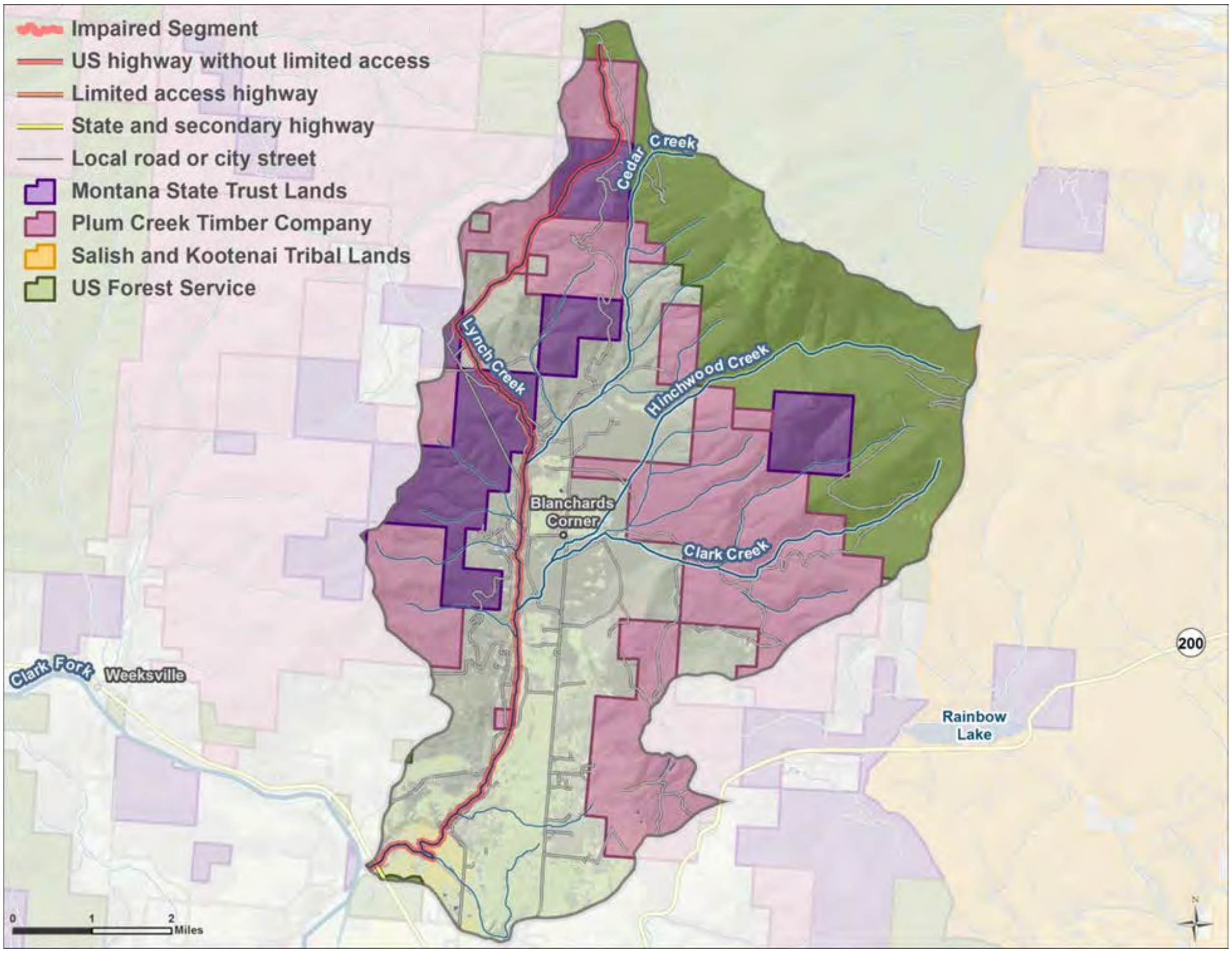
Figure A-24. Monthly average temperatures and precipitation at Thompson Falls, Montana.

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

- ## Land Ownership and Land Use

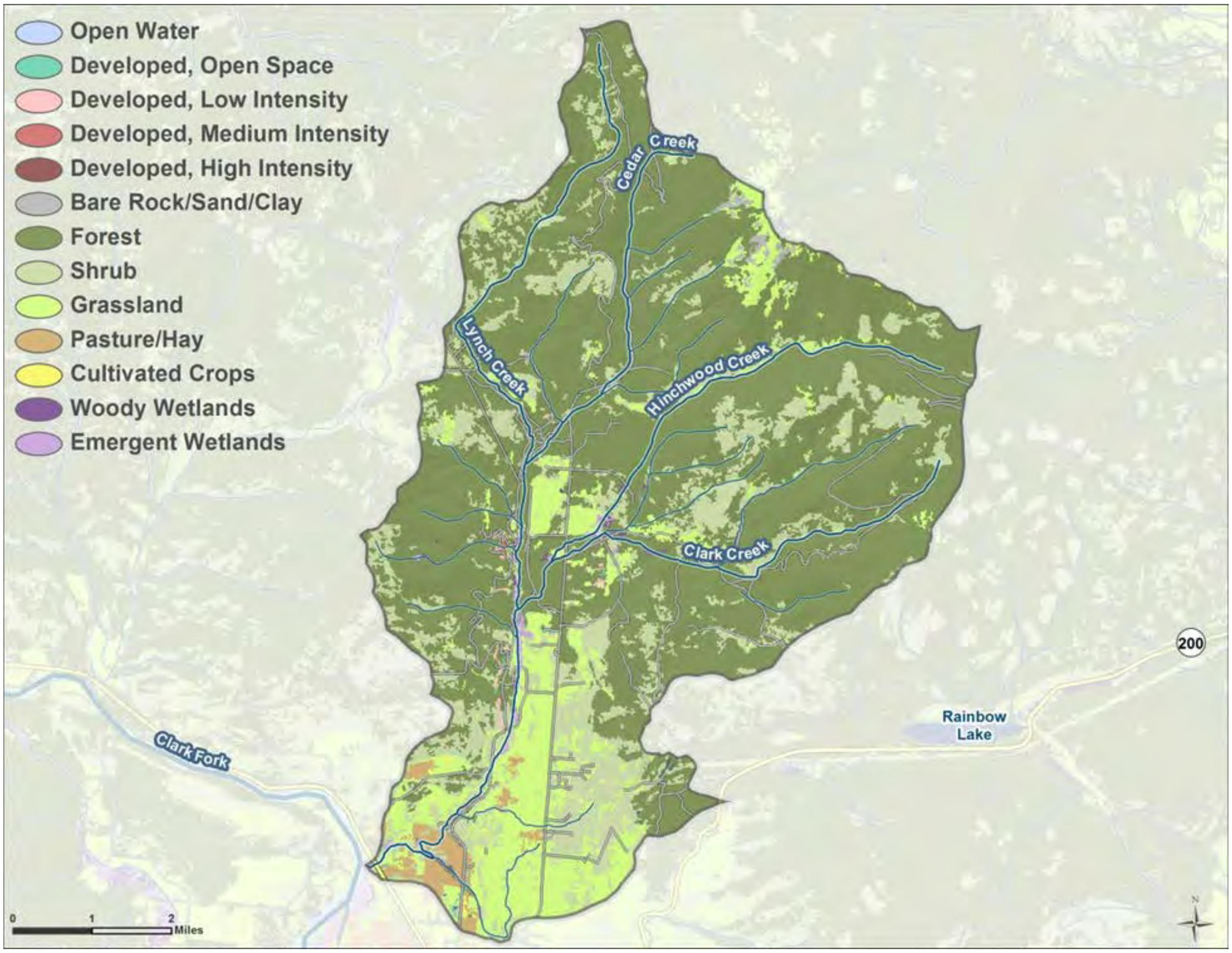
Lynch Creek is in the Rocky Mountains of western Montana and is part of the Middle Clark Fork Tributaries TMDL Planning Area. The Lynch Creek watershed is in the Lower Clark Fork subbasin (hydrologic unit code 17010213). The impaired segment is 13.3 miles long and extends from the headwaters to the mouth (DEQ 2012).

Private ownership accounts for 38 percent of the land ownership in the Lynch Creek watershed, which is primarily in the valleys. The Plum Creek Timber Company manages 28 percent of the area, the U.S. Forest Service manages another 23percent, and the remainder is owned by the state in trust lands (**Figure A-25**). The landscape is predominantly forested, with patches of mature forest interspersed with selective harvests and clearcuts at various stages of regrowth (**Figure A-26** and **Figure A-27**).



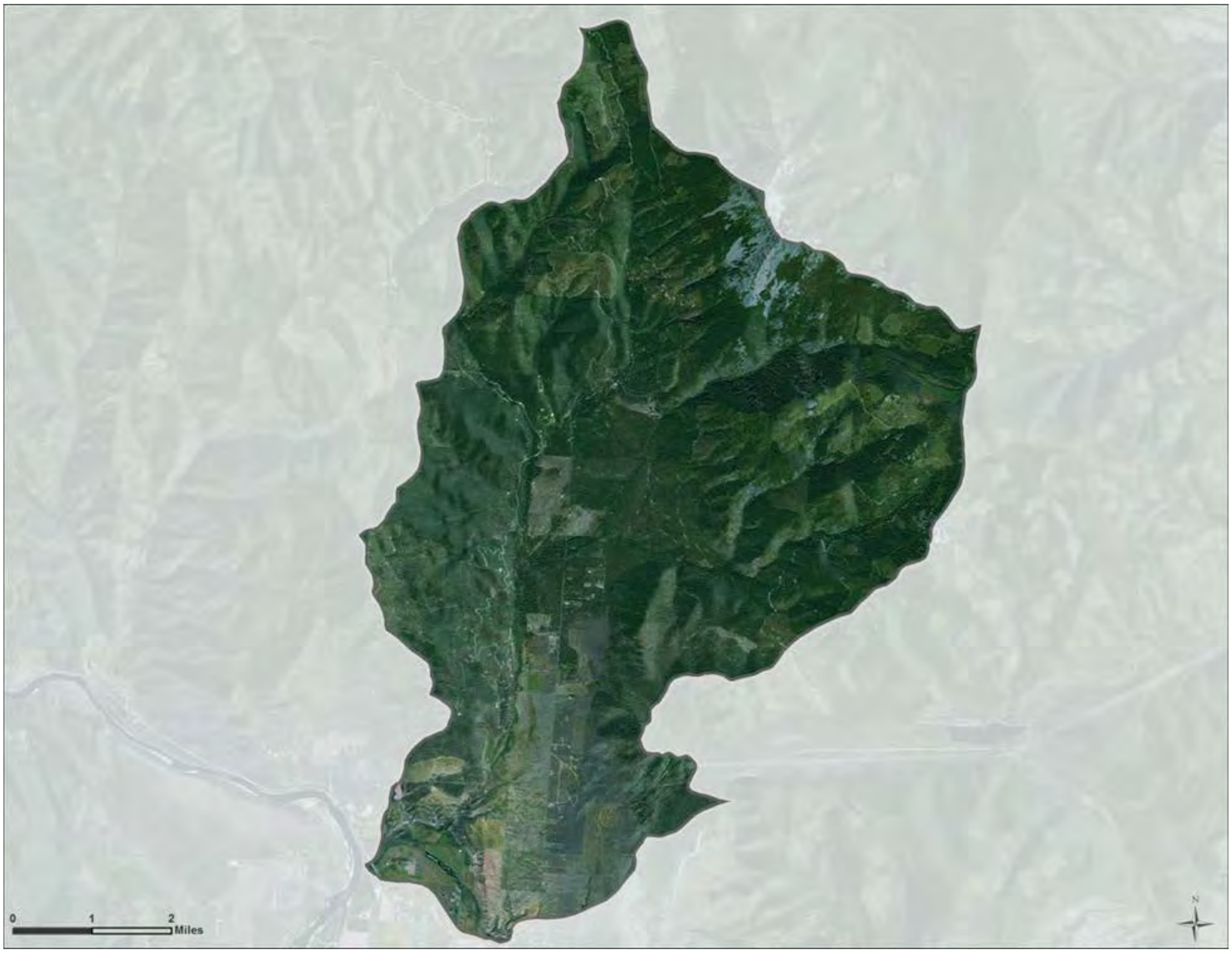
Source of land ownership: NRIS 2012.

Figure A-25. Land ownership in the Lynch Creek watershed.



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

Figure A-26. Land cover and land use in the Lynch Creek watershed.



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

Figure A-27. Aerial imagery of the Lynch Creek watershed.

• Existing Riparian Vegetation

Vegetation communities between the shade monitoring sites were visually characterized based on aerial imagery (GoogleEarth^{TM} 2013). Observed vegetative communities within 150 feet of the stream centerline were classified as trees, shrubs, or 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-28**):

- 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)

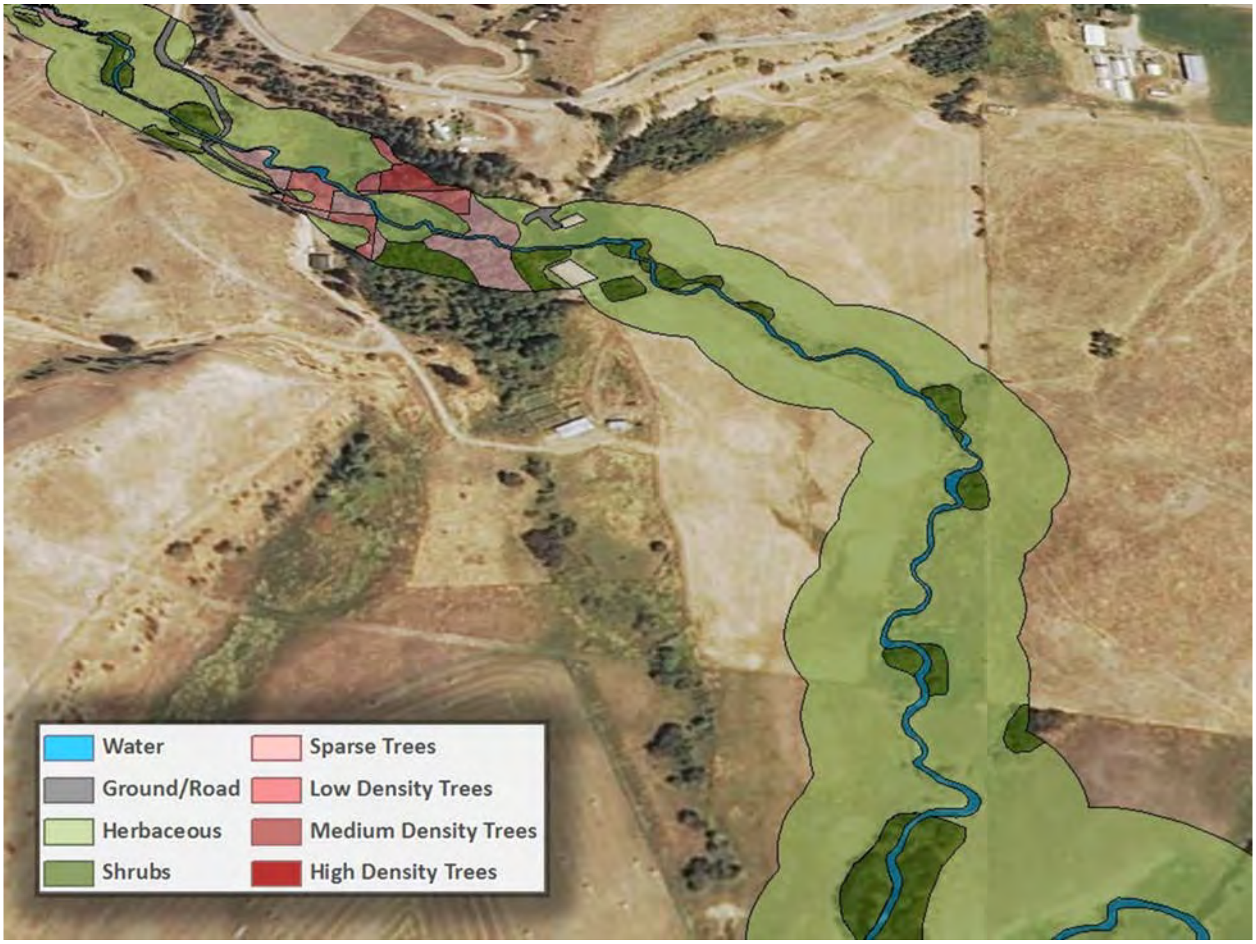


Figure A-28. Vegetation mapping example for Lynch Creek.

Herbaceous vegetation and shrubs are the most common cover types along Lynch Creek, followed by high and medium density trees (**Table A-10**). Sparse trees, roads, and bare ground compose only a small percentage of the riparian area.

Table A-10. Land cover types in the Lynch Creek riparian zone

Land cover type	Area (acres)	Relative area (percent)
Bare ground	1.3	0.3%
Herbaceous	130.5	25.5%
Roads	9.3	1.8%
Shrub	117.1	22.9%
Sparse trees	19.0	3.7%
Low density trees	47.0	9.2%
Medium density trees	96.5	18.9%
High density trees	90.5	17.7%

• 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.

o Measured Shade

EPA and Tetra Tech collected shade characterization data on September 10, 2012, at seven monitoring locations along Lynch Creek using a Solar Pathfinder^{TM} (**Figure A-29**). Shade estimates based on the Solar Pathfinder^{TM} measurements are presented in **Attachment A**. The data are summarized in **Table A-11**.

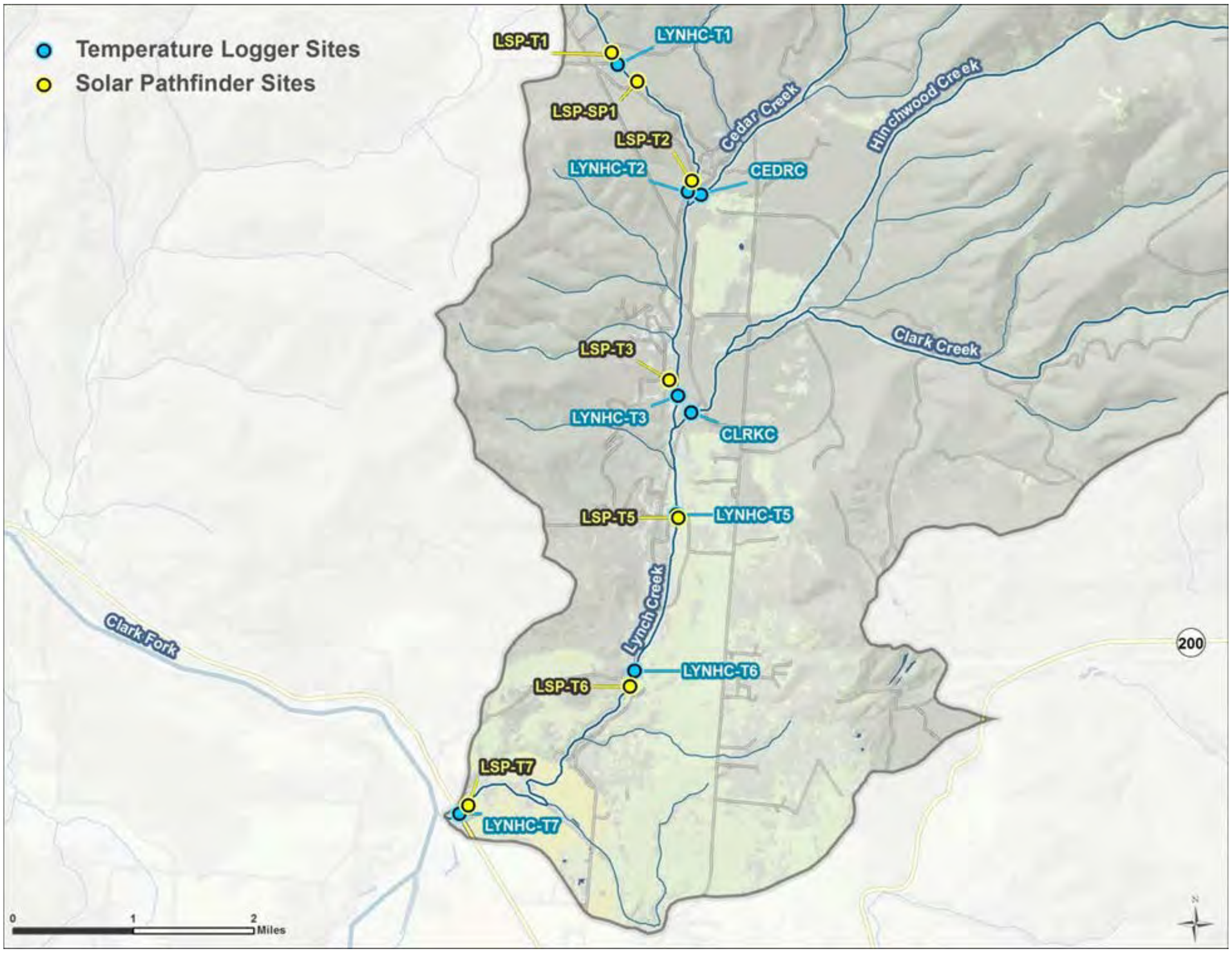


Figure A-29. Solar Pathfinder^{TM} monitoring locations.

Table A-11. Average shade per reach from Solar Pathfinder™ measurements

Site ID	Average daily shade (averaged across daylight hours)
LSP-T1	51%
LSP-SP1	34%
LSP-T2	96%
LSP-T3	83%
LSP-T5	75%
LSP-T6	74%
LSP-T7	39%

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

o Shade Modeling

An analysis of aerial imagery and field reconnaissance showed that shading along Lynch 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 (Washington 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 Lynch 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-12**). Vegetation descriptions used the average value for tree/shrub height and overhang from field observation.

Table A-12. Vegetation input values for the Shade Model

ribute	Value	Basis
es		
ght	meters (75 feet)	he absence of site-specific data, this value was based on work conducted in Wolf and Fortine creeks.
nsity	iable	6 NLCD.
erhang	meters (7.5 feet)	mated as 10% of height (Stuart 2012).
ubs		
ght	meters (13 feet)	he absence of site-specific data, this value was based on work conducted in Wolf and Fortine creeks.
nsity	%	ular estimate based on aerial imagery.
erhang	meter (3.3 feet)	imated as 25% of height (Shumar and de Varona 2009)
rbaceous		
ght	meter (1.6 feet)	imated from field photographs
nsity	%	imated from field photographs
erhang	eters	imated 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-12**. 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 49 feet (15 meters) 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 1 foot (0.3 meter). 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-30**.

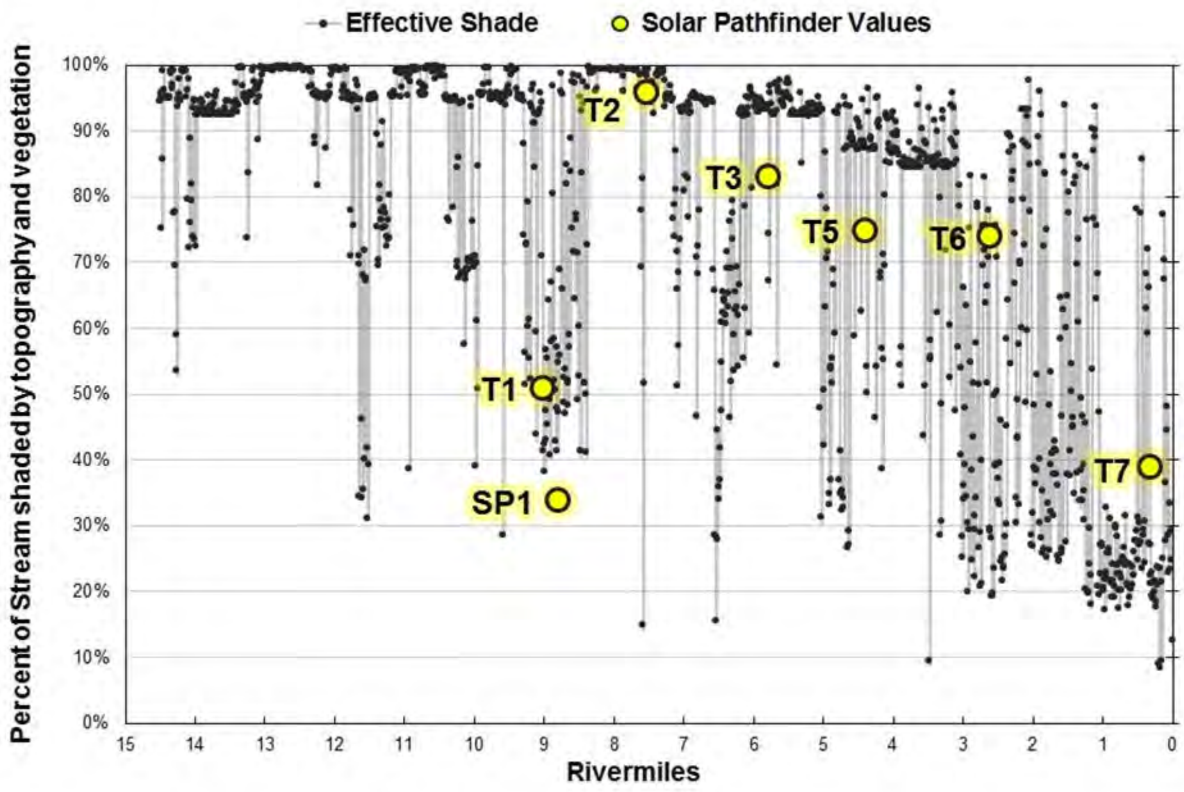


Figure A-30. Longitudinal estimates of observed and simulated effective shade along Lynch Creek.

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-13** 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^{TM} measurements was 7 percent daily average shade; see **Table A-13**).

Table A-13. Shade model error statistics

Error Statistic	Formula	Result	Units
Mean Error (ME)	$(1/N)*\Sigma(P_n-O_n)$	<1%	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

• Stream Temperatures

In 2012, Atkins collected continuous temperature data at six locations in Lynch Creek (sites LYNHC-T1, LYNHC -T2, LYNHC -T3, LYNHC -T5, LYNHC -T6, and LYNHC -T7) and at two tributary locations (CEDRC on Cedar Creek and CLRKC on Clark Creek). Data loggers recorded temperatures every one-half hour for approximately three months between June 27 and September 20. Instantaneous temperatures were also monitored by Atkins and DEQ (**Table A-14** and **Table A-15**) in Lynch Creek and by USGS at nearby wells (**Table A-16**).

Table A-14. EPA instantaneous temperature measurements (°F)

Date	LYNHC-T1	LYNHC-T2	CEDRC [a]	LYNHC-T3	CLRKC [b]	LYNCH-T5	LYNCH-T6	LYNCH-T7
June 27 & 28, 2012	55.7	55.9	51.8	48.4	49.3	60.0	56.4	56.0
August 11, 2012	67.8	61.0	58.7	67.6	67.7	69.5	72.7	70.3
September 20, 2012	49.8	48.1	48.9	53.5	52.4	55.6	60.9	58.6

Notes

a. Site is located on Cedar Creek, a tributary to Lynch Creek.
b. Site is located on Clark Creek, a tributary to Lynch Creek.

Table A-15. DEQ instantaneous temperature measurements (°F) in support of other water quality studies

Date	C13LYNCC08	C13LYNCC11	C13LYNCC07	C13LYNCC06	C13LYNCC05	C13CEDRC01 [a]	C13LYNCC20	C13LYNCC04	C13LYNCC09	C13LYNCC10	C13LYNCC03	C13LYNCC30	C13LYNCC01
Sept 7, 2004	--	--	--	--	--	--	60.4	--	--	--	--	57.8	--
Aug 11-12, 2009	--	--	--	--	--	61.7	62.4	--	--	67.6	--	--	--
Sept 9-10, 2009	--	--	--	--	--	47.5	54.3	--	--	59.2	--	--	58.1
July 26-27, 2011	52.2	--	57.6	59.7	55.0	--	--	57.2	--	--	59.0	--	59.9
Aug 25, 2011	--	--	--	--	57.4	--	--	--	70.3	--	--	--	--
Sept 3-5, 2011	50.4	--	46.8	59.5	50.7	--	--	48.9	--	--	64.6	--	57.4
July 3, 2012	--	52.0	54.0	56.3	53.6	--	--	--	--	--	--	--	--

Note: a. Site is located on Cedar Creek, a tributary to Lynch Creek.

Table A-16. USGS instantaneous groundwater temperature measurements (°F) in support of other water quality studies

Date	472940114532401	472950114533601
September 1, 1992	52.0	52.3

• Hydrology

No active U.S. Geological Survey continuously recording gages are located on Lynch Creek. The closest such gage is 12389000 and it is on the Clark Fork River in nearby Plains, MT. The closest continuously recording gage on a small stream similar to Lynch Creek is gage 12390700, located 30 miles away on Prospect Creek[3].

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-17** and **Attachment B**). Flow data were collected by DEQ in support of other water quality studies in 2004, 2011, and 2012 (**Table A-18**). Locations of the flow measurements are shown in **Figure A-31**.

Table A-17: Instantaneous flow measurements (cfs) on Lynch Creek in support of modeling

Date	LYNHC-T1	LYNHC-T2	CEDRC [a]	LYNHC-T3	CLRKC [b]	LYNCH-T5	LYNCH-T6	LYNCH-T7
June 27 & 28, 2012	0.37	0.72	2.25	3.87	1.98	10.69	12.46	--[c]
August 11, 2012	--[c]	0.27	0.49	0.64	0.74	1.66	1.22	0.76
September 20, 2012	--[c]	0.25	0.33	0.5	0.57	1.68	1.04	0.45

Notes
a. Site is located on Cedar Creek, a tributary to Lynch Creek.
b. Site is located on Clark Creek, a tributary to Lynch Creek.
c. Blank entries indicate standing water.

Table A-18: DEQ instantaneous flow measurements (cfs) on Lynch Creek in support of other studies

Date	C13LYNCC08	C13LYNCC11	C13LYNCC07	C13LYNCC06	C13LYNCC05	C13LYNCC20	C13LYNCC04	C13LYNCC03	C13LYNCC30	C13LYNCC01
September 7, 2004	--	--	--	--	--	3.8	--	--	0.43	--
September 3-5, 2011	0.07	--	0.07	0.07	0.28	--	0.43	0.97	--	0.72
July 26-27, 2012	0.29	--	0.37	0.42	0.76	--	5.76	5.14	--	5.53
July 3, 2012	--	0.26	0.4	0.45	0.68	--	--	--	--	--

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[3] Gage 12390700 on Prospect Creek at Thompson Falls, MT drains 182 square miles.

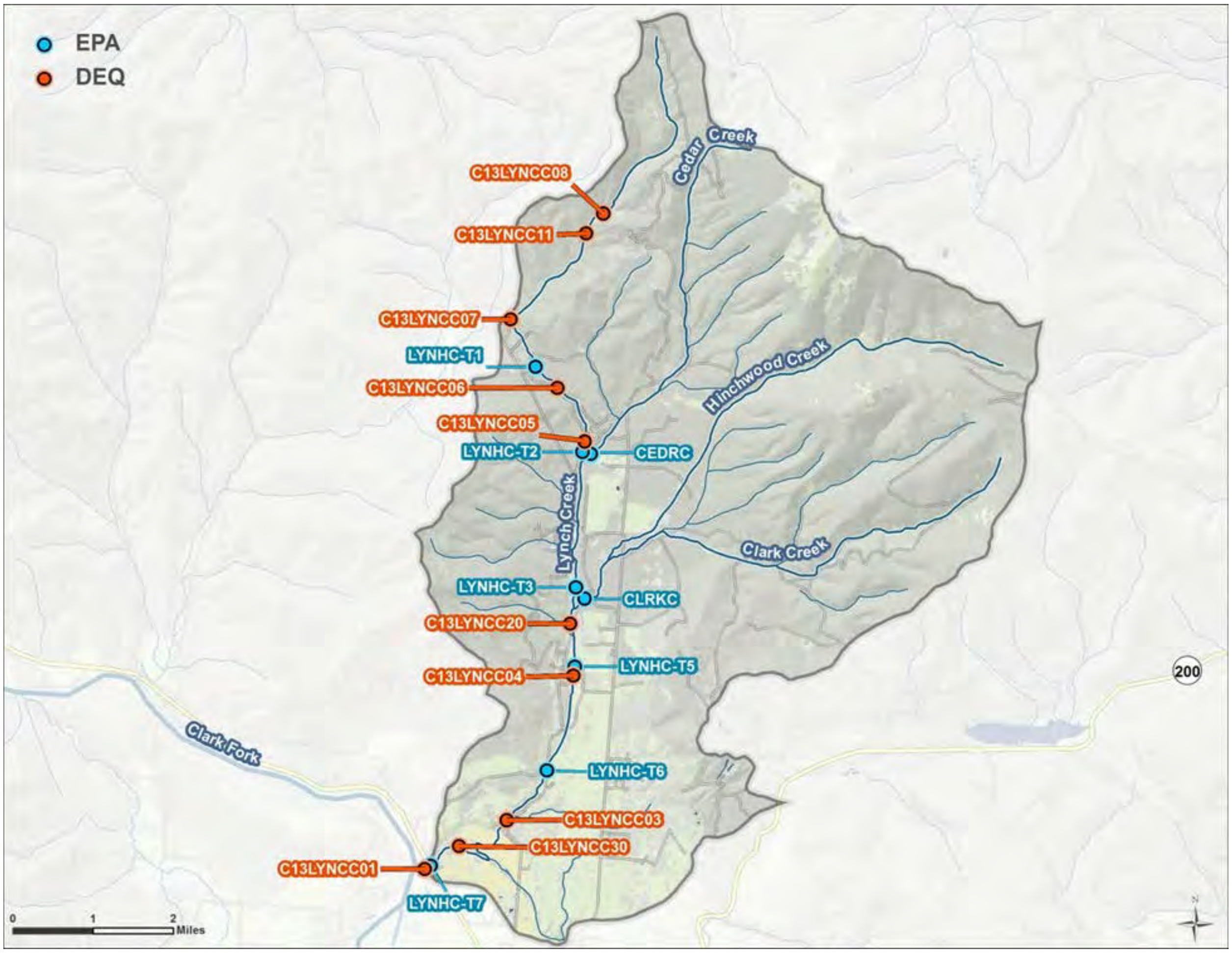
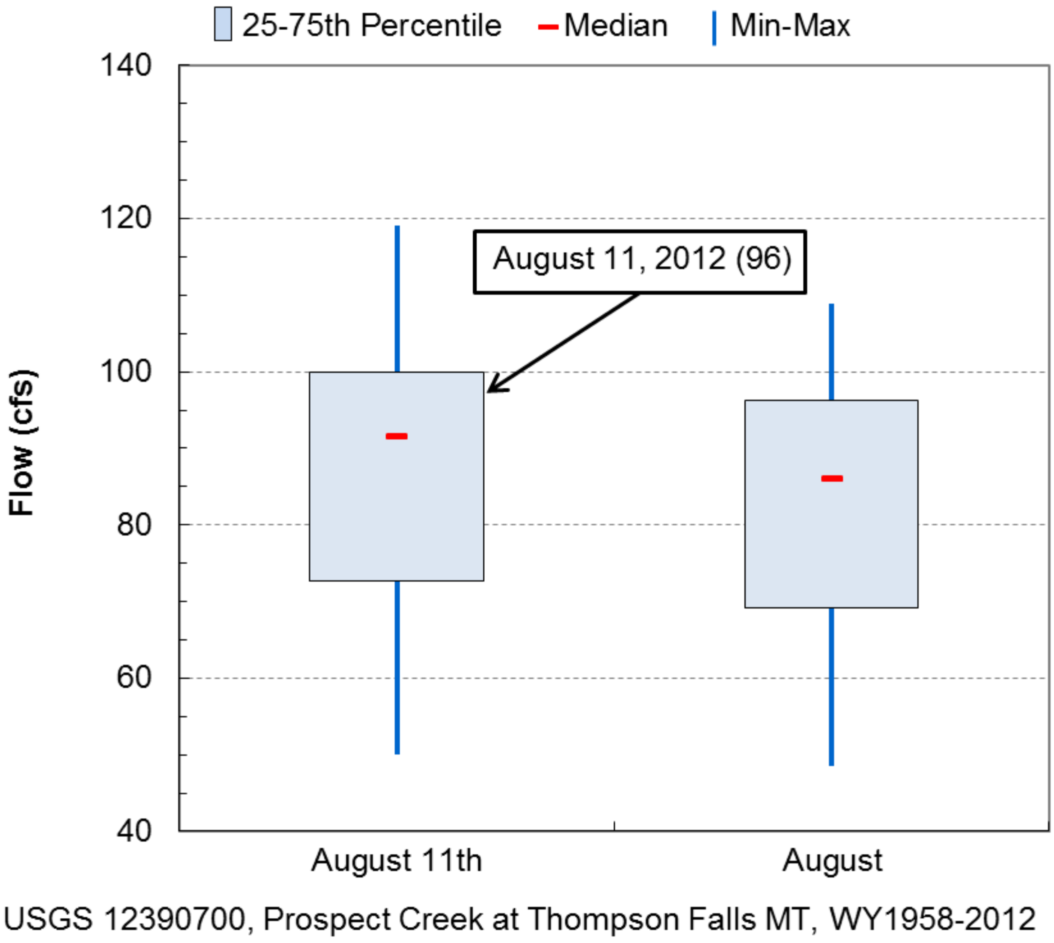


Figure A-31. Flow monitoring locations in the Lynch Creek watershed.

All available data were used to evaluate the water balance in Lynch 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 Lynch Creek (i.e., USGS 12390700, Prospect Creek at Thompson Falls, MT), flows on August 11, 2012 were above the average of 54 years of records (**Figure A-32**).

Statics were calculated for the average daily flows (per year) for the month of August and for August 11th from water years 1958 through 2012 at the gage (**Figure A-32**). The flow at gage 12390700 on August 11, 2012 (the calibration date for the QUAL2K model) was 96 cfs, which is the 65th percentile of flows on August 11th across the period of record. Additionally, August of 2012 was the 62nd percentile of Augusts across the period of record (i.e., August 2012 was wetter than a typical August).



Note: "August" represents the daily average flow for the month of August per year (i.e., the average of 31 daily average flows)

Figure A-32. Flow analysis with USGS gage 12390700 (Prospect Creek at Thompson Falls, MT).

• 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 Lynch Creek watershed that support localized irrigation (**Figure A-33**). "Points of diversion" and "places of use" spatial data were obtained from the Montana Natural Resource Information System (NRIS 2012). A total of 28 "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 16 "points of diversion", which represent individual water right permit numbers associated with the physical stream diversions. These "points of diversion" further correspond to nine distinct locations along Lynch Creek (**Figure A-33**). Diversions from groundwater or tributaries to Lynch Creek were not considered during QUAL2K modeling as QUAL2K simulated one-dimensional flow along the Lynch 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 (Natural Resources Conservation Service 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 volume for the purpose of watering livestock directly from the stream is usually considered negligible. However, water right 76N 214612 00 (#7 in **Figure A-33**) is permitted to use a headgate to supply water to 150 cattle[4]. The headgate diverts water from Lynch Creek to Lansing Slough, a reservoir covering approximately 30 acres. The withdrawal rate from Lynch Creek required to maintain the water level in Lansing Slough was calculated by combining the losses due to evaporation[5] and cattle consumption[6]. Evaporation accounts for 0.29 cfs, while the cattle consume 0.003 cfs. Thus, the water right contributes approximately 0.3 cfs to the withdrawal rate at # 7.

It is estimated that a maximum of 7.26 cfs may be withdrawn from Lynch Creek during the month of July (**Table A-19**).

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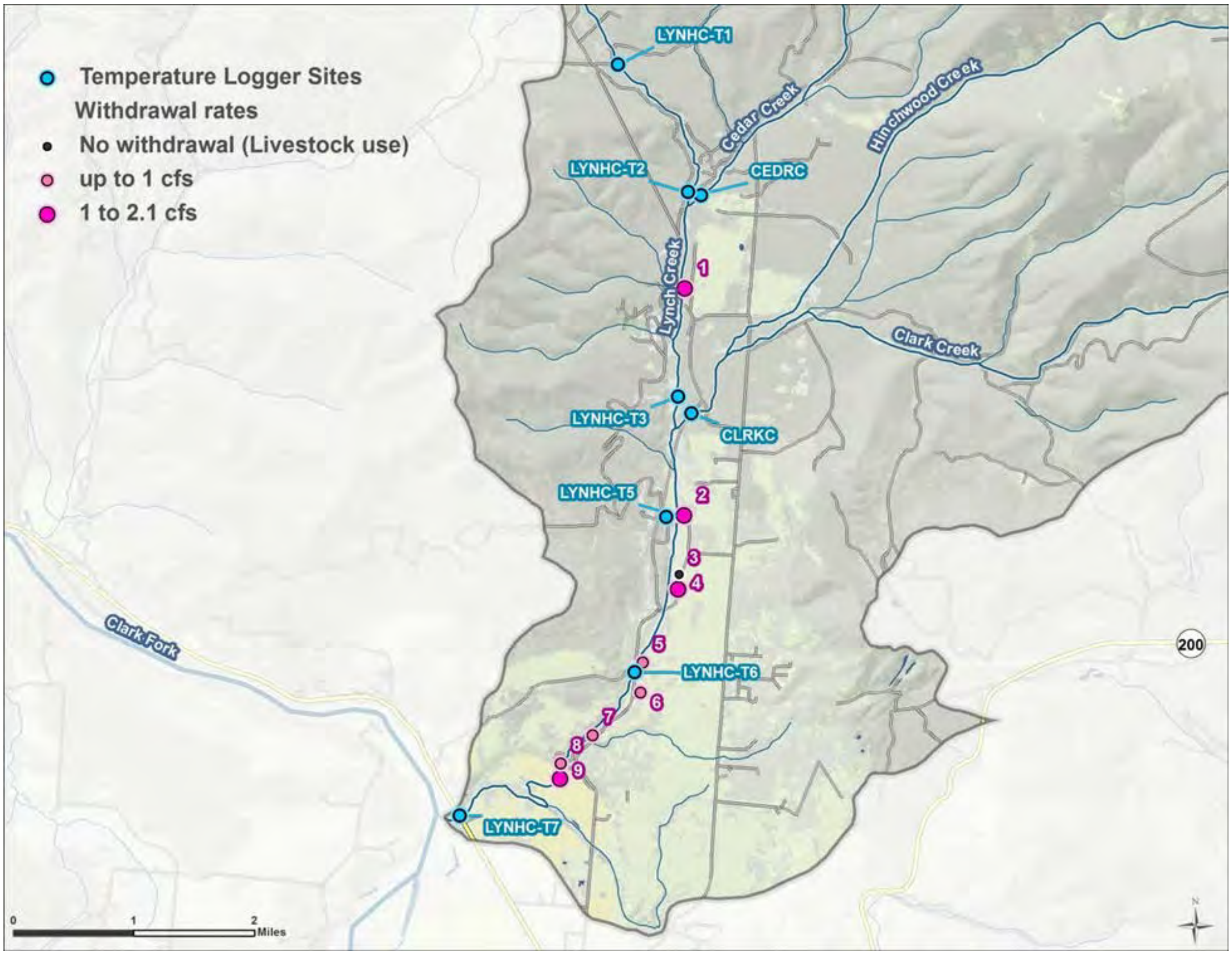
4 http://nris.mt.gov/dnrc/waterrights/default.aspx.
5 http://www.wrcc.dri.edu/htmlfiles/westevap.final.html.
6 http://www.uaex.edu/Other_Areas/publications/PDF/FSA-3021.pdf.



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

Figure A-33. Surface and groundwater diversions in the Lynch Creek watershed.

Table A-19. Points of diversion from Lynch Creek

Map ID	Purpose	Irrigation type	Means of withdrawal	Estimated daily flow rate in July (cfs)	Estimated daily flow rate in September (cfs)
1	Irrigation	Flood	Headgate	1.06	0.52
2	Irrigation	Flood	Headgate	1.40	1.12
3	Livestock	--	--	--	--
4	Irrigation	Flood	Headgate	1.40	0.68
5	Irrigation	Sprinkler	Pump	0.59	0.29
6	Irrigation	--	Pump	0.36	0.17
7	Irrigation	Sprinkler/Flood	Pump/Headgate with Ditch/Pipeline	0.35	0.33
8	Irrigation	Sprinkler/Flood	Dam/Pump	0.03	0.01
9	Irrigation	Sprinkler	Headgate/Pump	2.08	1.02
			Total Withdrawal	**7.26**	

Source: NRIS 2012.

• Point Sources

Any facility that discharges to Lynch 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 Lynch Creek watershed.

An evaluation of abandoned mines data from NRIS (2012) showed that there are not any known abandoned mines in the Lynch Creek watershed.

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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.

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