LOWER GRANDE RONDE SUBBASINS TMDLS
APPENDIX A: STREAM TEMPERATURE ANALYSIS

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TABLE OF CONTENTS

FIGURES

TABLES

A1. INTRODUCTION

This appendix provides information about the temperature and shade assessment for the Lower Grande Ronde Subbasins. The assessment was completed to support the Total Maximum Daily Load (TMDL) and implement the Oregon water quality standard for temperature. The specific required components of the TMDL are provided in **Chapter 2** of the TMDL document. This appendix provides additional background information about stream heating processes, the methodology and data used for temperature TMDL development, and stream simulation results.

The lands within the Lower Grande Ronde Subbasins occupy 2,982 square miles in northeastern Oregon. This area includes three 4th field hydrologic unit subbasins: Wallowa River Subbasin (17060105), Imnaha River Subbasin (17060102), and the Lower Grande Ronde Subbasin (17060106). While the stream temperature TMDL considers all surface waters within the Lower Grande Ronde Subbasins, the TMDL analysis largely focuses on the Wallowa River where both stream temperature modeling and site specific shade analyses were completed. Generalized effective shade curves were developed to cover the rest of the waterbodies in the Subbasins where site specific simulations were not performed.

A1.1 Overview of Temperature and Stream Heating Processes

Parameters that affect stream temperature can be grouped as near stream vegetation and land cover, channel morphology, and hydrology (**Figure A-1**). Many of these stream parameters are interrelated (i.e., the condition of one may impact one or more of the other parameters). These parameters affect stream heat transfer processes and stream mass transfer processes to varying degrees. The analytical techniques employed to develop this temperature TMDL are designed to include all of the parameters, along with latitude, elevation, humidity, air temperature and wind speed.

Many parameters exhibit considerable spatial variability. For example, channel width measurements can vary greatly over small stream lengths. Some parameters can have a diurnal and seasonal temporal component as well as spatial variability. The current analytical approach developed for this stream temperature assessment relies on ground level and remotely sensed spatial data. Techniques employed in this effort are statistical and deterministic modeling of hydrologic and thermal processes.

A1.1.1 Stream Heating Processes

Stream temperature is an expression of heat energy per unit volume, which in turn is an indication of the rate of heat exchange between a stream and its environment. The heat transfer processes that control stream temperature include solar radiation, long wave radiation, convection, evaporation and bed conduction (Wunderlich 1972; Jobson and Keefer 1979, Beschta and Weatherred 1984, Sinokrot and Stefan 1993, Boyd 1996, Johnson 2004). With the exception of solar radiation, which only delivers heat energy, these processes are capable of both introducing and removing heat from a stream. **Figure A-2** displays the stream heat transfer processes, along with mass transfer, that are considered in this analysis.

When a stream surface is exposed to midday solar radiation, large quantities of heat will be delivered to the stream system (Brown 1969, Beschta et al. 1987). Some of the incoming solar radiation will reflect off the stream surface, depending on the elevation of the sun. All solar radiation outside the visible spectrum (0.36μ to 0.76μ) is absorbed in the first meter below the stream surface and only visible light penetrates to greater depths (Wunderlich 1972). Sellers (1965) reported that 50% of solar energy passing through the stream surface is absorbed in the first 10 cm of the water column. Removal of riparian vegetation, and the shade it provides, contributes to elevated stream temperatures (Rishel et al. 1982, Brown 1983, Beschta et al. 1987, Johnson and Jones 2000, Johnson, 2004). Channel widening can similarly increase the solar radiation load. The principal source of heat energy delivered to the water column is solar energy striking the stream surface directly (Brown 1970). Exposure to direct solar radiation will often cause a

dramatic increase in stream temperatures. The ability of riparian vegetation to shade the stream throughout the day depends on vegetation height, width, density and position relative to the stream, as well as stream aspect.

Figure A-1. Factors that affect stream temperature
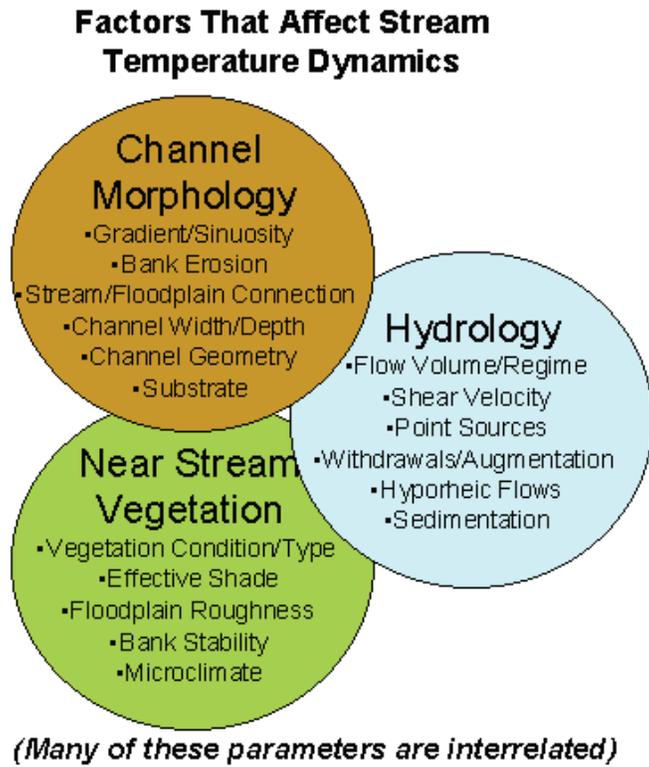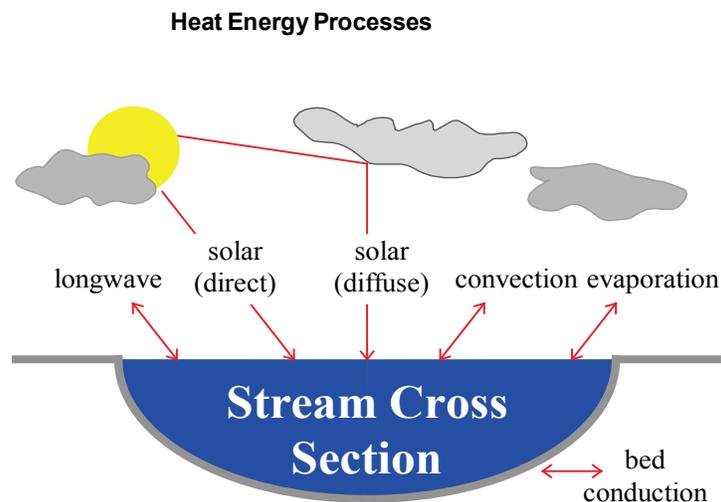

Figure A-2. Heat transfer processes

Both the atmosphere and vegetation along stream banks emit long wave radiation that can heat the stream surface. Water is nearly opaque to long wave radiation and complete absorption of all wavelengths greater than 1.2μ occurs in the first 5 cm below the surface (Wunderlich 1972). Long wave radiation has a cooling influence when emitted from the stream surface. The net transfer of heat via long wave radiation usually balances so that the amount of heat entering is similar to the rate of heat leaving the stream (Beschta and Weatherred 1984, Boyd 1996).

Evaporation occurs in response to internal energy of the stream (molecular motion) that randomly expels water molecules into the overlying air mass. Evaporation is the most effective method of dissipating heat from a given volume of water (Parker and Krenkel 1969). As stream temperatures increase, so does the rate of evaporation. Air movement (wind) and low vapor pressures increase the rate of evaporation and accelerate stream cooling (Harbeck and Meyers 1970).

Convection transfers heat between the stream and the air via molecular and turbulent conduction (Beschta and Weatherred 1984). Heat is transferred in the direction of decreasing temperature. Air can have a warming influence on the stream when the stream is cooler, or vice versa. The amount of convective heat transfer between the stream and air is low (Parker and Krenkel 1969, Brown 1983). Nevertheless, this should not be interpreted to mean that air temperatures do not affect stream temperature.

Depending on streambed composition, shallow streams (less than 20 cm) may allow solar radiation to warm the streambed (Brown 1969). Large cobble (> 25 cm diameter) dominated streambeds in shallow streams may store and conduct heat as long as the bed is warmer than the stream. Bed conduction may cause maximum stream temperatures to occur later in the day, possibly into the evening hours.

The instantaneous heat transfer rate experienced by the stream is the summation of the individual processes:

$$\Phi_{Total} = \Phi_{Solar} + \Phi_{Longwave} + \Phi_{Evaporation} + \Phi_{Convection} + \Phi_{Conduction}.$$

Solar Radiation (Φ_{Solar}) is a function of the solar angle, solar azimuth, atmosphere, topography, location and riparian vegetation. Simulation is based on methodologies developed by Ibqal (1983) and Beschta and Weatherred (1984). *Longwave Radiation* ($\Phi_{Longwave}$) is derived by the Stefan-Boltzmann Law and is a function of the emissivity of the body, the Stefan-Boltzmann constant and the temperature of the body (Wunderlich, 1972). *Evaporation* ($\Phi_{Evaporation}$) relies on a Dalton-type equation that utilizes an exchange coefficient, the latent heat of vaporization, wind speed, saturation vapor pressure and vapor pressure (Wunderlich, 1972). *Convection* ($\Phi_{Convection}$) is a function of the Bowen Ratio and terms include atmospheric pressure, and water and air temperatures. *Bed Conduction* ($\Phi_{Conduction}$) simulates the theoretical relationship ($\Phi_{Conduction} = K \cdot dT_b / dz$), where calculations are a function of thermal conductivity of the bed (K) and the temperature gradient of the bed (dT$_b$/dz) (Sinokrot and Stefan 1993). Bed conduction is solved with empirical equations developed by Beschta and Weatherred (1984).

The primary source of heat energy is solar radiation, both diffuse and direct. Secondary sources of heat energy include long-wave radiation from the atmosphere and streamside vegetation, streambed conduction and in some cases, groundwater exchange at the water-stream bed interface. Several processes dissipate heat energy at the air-water interface, namely: evaporation, convection and back radiation. Heat energy is acquired by the stream system when the flux of heat energy entering the stream is greater than the flux of heat energy leaving. The net energy flux provides the rate at which energy is gained or lost per unit area and is represented as the instantaneous summation of all heat energy components.

A1.1.2 The Dynamics of Shade

Stream surface shade is a function of several landscape and stream geometric relationships. Some of the factors that influence shade are listed in **Table A-1**. Geometric relationships important for

understanding the mechanics of shade are displayed in **Figure A-3**. In the Northern Hemisphere, the earth tilts on its axis toward the sun during summertime months allowing longer day length and higher solar altitude, both of which are functions of solar declination (i.e., a measure of the earth's tilt toward the sun). Geographic position (i.e., latitude and longitude) fixes the stream to a position on the globe, while aspect provides the stream/riparian orientation. Riparian height, width and density describe the physical barriers between the stream and sun that can attenuate and scatter incoming solar radiation (produce shade). The solar position has a vertical component (altitude) and a horizontal component (azimuth) that are both functions of time/date (solar declination) and the earth's rotation (i.e., hour angle). While the interaction of these shade variables may seem complex, the math that describes them is relatively straightforward geometry, much of which was developed decades ago by the solar energy industry.

Solar altitude and solar azimuth are two measurements of the sun's position. When a stream's orientation, geographic position, riparian condition and solar position are known, shading characteristics can be simulated.

Table A-1. Factors that influence stream surface shade

Description	Measure
Season/Time	Date/Time
Stream Characteristics	Aspect, Near-Stream Disturbance Zone Width
Geographic Position	Latitude, Longitude
Vegetative Characteristics	Buffer Height, Buffer Width, Buffer Density
Solar Position	Solar Altitude, Solar Azimuth

Figure A-3. Geometric relationships that affect stream surface shade
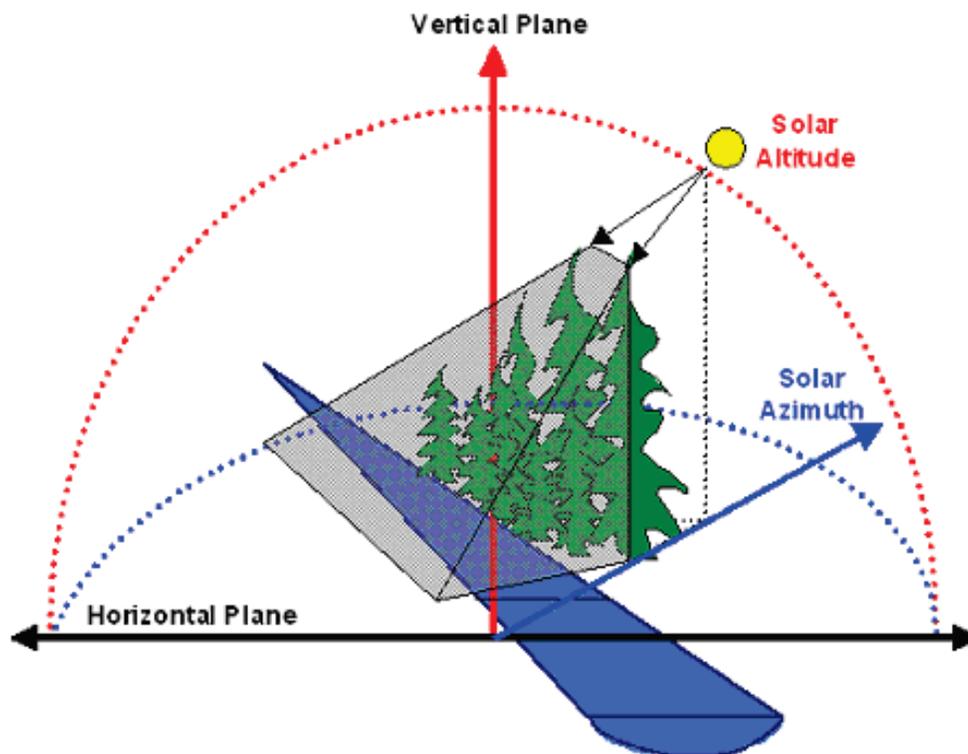
Percent effective shade is perhaps the most straightforward stream parameter to monitor and calculate and is easily translated into quantifiable water quality management and geometric relationships that affect stream surface shade recovery objectives. **Figure A-4** demonstrates how effective shade is monitored and calculated. Using solar tables or mathematical simulations, the *potential daily solar load* can be quantified. The *measured solar load (current conditions)* at the stream surface can easily be measured with a Solar Pathfinder[©] or estimated using mathematical shade simulation computer programs (Boyd 1996, Park 1993).

Figure A-4. **Effective shade – defined**

Solar₁ – Potential Daily Solar Radiation Load
(Adjusted for Solar Altitude and Solar Azimuth)

Solar₂

Effective Shade Defined:

$$Effective\ Shade = \frac{(Solar_1 - Solar_2)}{Solar_1}$$
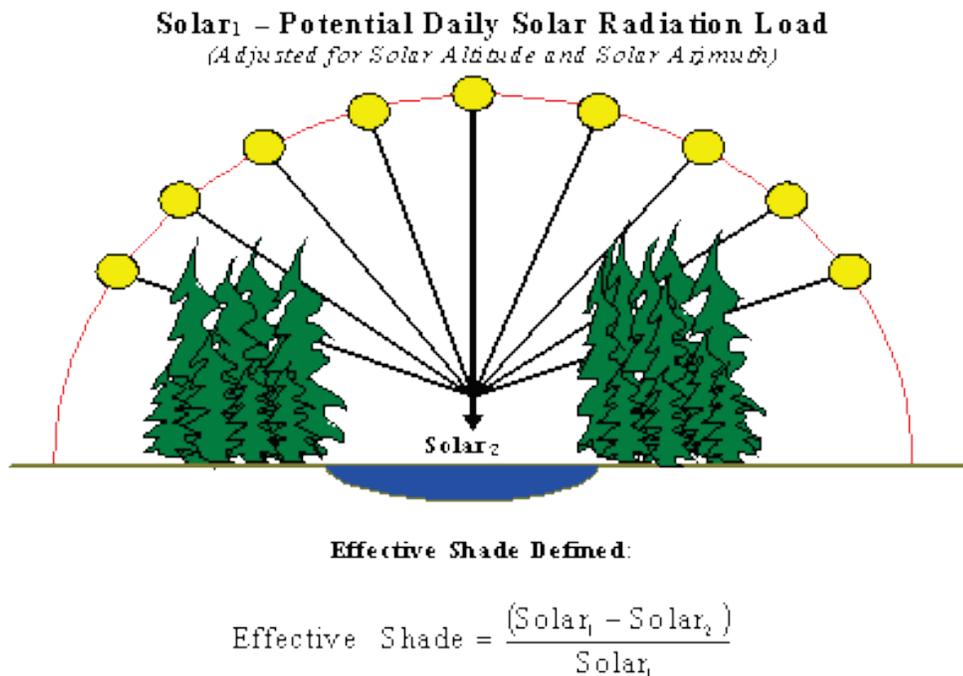
Where,

$Solar_1$: Potential Daily Solar Radiation Load
$Solar_2$: Measured Daily Solar Radiation Load at Stream Surface

A1.1.3 Limitation of Stream Temperature TMDL Approach

The purpose of stream temperature modeling is to: (1) determine temperatures for various scenarios including natural thermal potential (NTP), (2) assess heat loading for the purpose of TMDL allocations, (3) compute readily measurable surrogates for the allocations, and (4) better understand heat controls at the local and subbasin scale. Heat Source, version 7.0 (Boyd and Kasper 2003) was the model used for TMDL development in the Lower Grande Ronde Subbasins. The data used in the models and the simulation results are presented in the remainder of this appendix. Limitations of the data and simulation methodology are mentioned in subsequent sections, however, DEQ feels that it is important to acknowledge some of the limitations to this analytical effort up front. The limitations include the following:

1. The scale of this effort is large with obvious challenges in capturing spatial variability in stream and landscape data. Available spatial data sets for land cover and channel morphology are coarse, while derived data sets are limited to aerial photo resolution and human error.

    *   Riparian vegetation was mapped from Digital Orthophoto Quads (DOQs) and USFS GIS vegetation data and placed within general height categories. For example, trees identified as

"Large Conifers" were assigned a single height of 93.7 feet throughout the Lower Grande Ronde Subbasins, when in reality, "Large Conifer" heights ranged between 70 and 120 feet.   It is not feasible to assign actual heights to each tree mapped using DOQs. These general height categories became Heat Source inputs and are one source of modeling imprecision. Similarly, riparian vegetation densities were also estimated for different vegetation categories, with a single density associated with each category. In the real world, vegetation densities are variable and this variability is not accounted for in the simulations.

- Heat Source breaks the stream into 50-meter segments. Inputs (vegetation, channel morphology, etc.) are averaged for each 50-meter segment, which means that the simulation may not account for some of the real world variability. For example, isolated pools or riffles within a 50 meter reach will not be included as unique features.
- Stream elevations and gradients were sampled and calculated from 10-meter digital elevation models (DEMs). DEMs have a certain level of imprecision associated with them and may be a source of uncertainty in the simulation results.

2. Current analytical methods fail to capture some upland, atmospheric and hydrologic processes. At a landscape scale, these exclusions can lead to errors in analytical outputs.

- Methods are not currently available to simulate riparian microclimates at a landscape scale. Regardless, recent studies (Anderson et. al. 2007 and Rykken et. al. 2007) indicate that forested microclimates play an important, yet variable, role in moderating air temperature, humidity fluctuations and wind speeds.
- Existing air temperature and relative humidity data were used from various weather stations in the Subbasins. This data, however, may not capture natural variations in air temperature and relative humidity along the stream. For example, temperatures may change as the landscape changes over short distances along the stream. These are similar to the microclimates created by vegetation cover.
- The actual position of the sun within the sky can only be calculated with an uncertainty of 10-15%. The sun's position is important when determining a stream's effective shade. Solar position is another source of modeling imprecision.
- Sinuosity change is typically not simulated, because the selected simulation methods are spatially explicit.
- Heat Source always assumes that the wetted stream is flowing directly down the center of the active channel, and effective shade calculations are based upon that assumption. In reality, a stream migrates all over the active channel. This is another source of modeling imprecision.

3. Quantification techniques for estimating potential subsurface inflows/returns and behavior within substrate are not employed in this analysis. Groundwater exchanges and hyporheic flows are difficult to measure and may not always be accounted for within stream temperature modeling.

4. Current analysis is focused on a defined critical condition – a three-week period during a single summer. This time period is intended to represent a critical condition for aquatic life when stream flows are low, radiant heating rates are high and ambient conditions are warm. However, there are several other important time periods where fewer data are available and the analysis is less explicit. For example, spawning periods have not received treatment comparable to that of the seasonal maximum stream temperature.

5. Land use patterns vary through the drainage from heavily impacted areas to areas with little human impacts. However, it is extremely difficult to find large areas without some level of either current or past human impacts. The development of Natural Thermal Potential (NTP) conditions that estimate stream conditions when human influences are minimized is statistically derived and based on stated assumptions within this document. Limitations to stated assumptions are presented where appropriate. It should be acknowledged that as better information is developed these assumptions will be refined.

- In some cases, there is not scientific consensus related to riparian, channel morphology and hydrologic potential conditions. This is especially true when confronted with highly disturbed sites, meadows and marshes, and potential hyporheic/subsurface flows.
- "Natural" flows were included in the NTP simulation. Estimates were used to create the existing flow mass balance, and withdrawals were estimated for the current condition, based on thermal infrared aerial data, the OWRD points of diversion database, and instream flow measurements. "Natural" flows are estimates based on removing the assumed anthropogenic impacts on the current flow regimes.
- Stream velocities and depths were calculated by Heat Source for the "natural" flow conditions based on measured channel dimensions and substrate composition. These estimated velocities and depths for the "natural" flows may have some error associated with them since they have not been verified through field measurements.
- Natural stream conditions may have had more groundwater connection, wetland areas, and hyporheic interactions prior to anthropogenic disturbances. These conditions are not included in the NTP scenario. Stream restoration may increase groundwater connectivity which could reduce the NTP temperatures.
- Increased channel complexity and more coarse woody debris are not accounted for in the NTP simulation. Including these factors may result in cooler NTP temperatures.

While these assumptions outline potential areas of weakness in the methodology used in the stream temperature analysis, DEQ has undertaken a comprehensive approach. All important stream parameters that can be accurately quantified are included in the analysis. In the context of understanding of stream temperature dynamics, these areas of limitations should be the focus for future studies.

A2. AVAILABLE DATA

A2.1 Ground Level and Remote Sensing Data

Stream temperature, flow, and stream habitat surveys have been collected by the following local stakeholders:

- Oregon Department of Environmental Quality (DEQ)
- U.S. National Forest (USFS)
- Oregon Department of Fish and Wildlife (ODFW)
- Wallowa County Soil and Water Conservation District (SWCD)
- Nez Perce Tribe
- Oregon Water Resources Department (OWRD)

The data collection methods include both ground level measurements and remote sensing. Most of the data used in this modeling effort was collected during the summers of 1999 and 2000, although much of the ground level data has been collected other years as well. The remote sensing data (thermal infrared) was collected in 1999. The data used in this assessment is available from DEQ upon request. Much of the temperature data is also available through the DEQ website in the LASAR database (http://www.deq.state.or.us/lab/lasar.htm).

A2.1.1 Stream Temperature Data

Two types of stream temperature data were collected in 1999 and 2000:

- Continuous instream monitoring data
- Thermal infrared (TIR) data

It should be noted that not all of the data collected in 1999 and 2000 and presented in this section was used in the TMDL simulations described in this Appendix. A summary of the TIR and continuous temperature data collected throughout the Subbasins is summarized in this section. Only the Wallowa River temperature data (and data at the mouths of tributaries) was used in the TMDL temperature simulations.

Continuous Data

Continuous temperature data were collected at a number of locations using thermistors[1] and data from these devices were routinely checked for accuracy. Continuous temperature data were collected in 1999 and/or 2000 at eighty-one sites (**Figure A-5**).

In this TMDL analysis, the continuous data was used to: calibrate stream emissivity for the TIR; calibrate stream statistics and assess the temporal component of stream temperature; and calibrate temperature simulations.

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[1] Thermistors are small electronic devices that are used to record stream temperature at one location for a specified period of time, usually spanning several summertime months.

Figure A-5. Continuous stream temperature measurement locations in 1999 and 2000
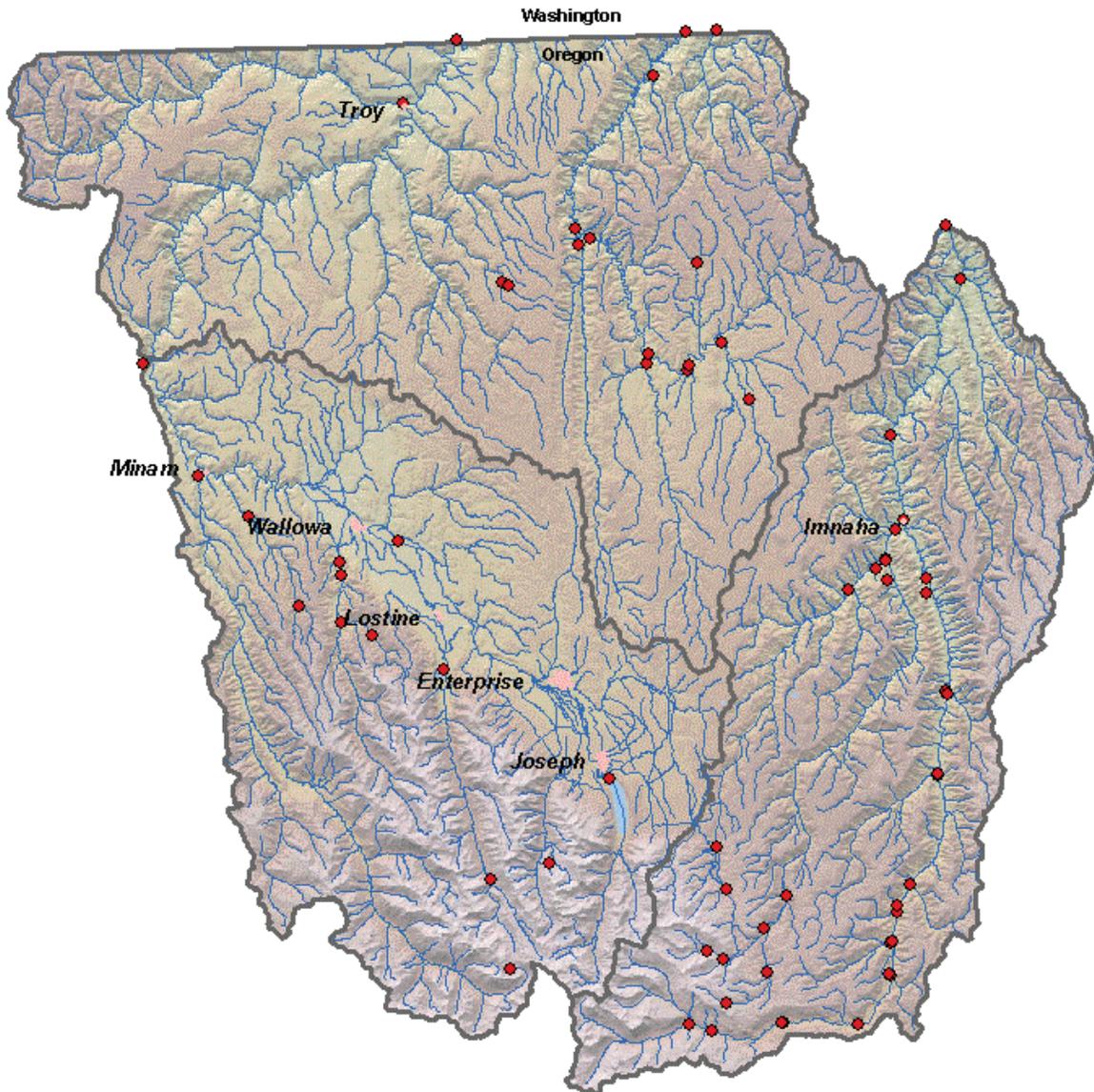
TIR Data

Thermal imagery data measures the temperature of the outermost portions of the bodies/objects in the image (i.e., ground, riparian vegetation, stream). The bodies of interest are opaque to longer wavelengths and there is little, if any, penetration of the bodies.

TIR data was remotely sensed from a sensor mounted on a helicopter that collected digital data directly from the sensor to an on-board computer at a rate that insured the imagery maintained a continuous image overlap of at least 40%. The TIR detected emitted radiation at wavelengths from 8-12 microns (long-wave) and recorded the level of emitted radiation as a digital image across the full 12-bit dynamic range of the sensor. Each image pixel contained a measured value that was directly converted to a temperature. Each thermal image has a spatial resolution of less than one-half meter/pixel. Visible video

sensor captured the same field-of-view as the TIR sensor. GPS time was encoded on the recorded video as a means to correlate visible video images with the TIR images during post-processing.

Data collection was timed to capture maximum daily stream temperatures, which typically occur between 14:00 and 18:00 hours. The helicopter was flown longitudinally over the center of the stream channel with the sensors in a vertical (or near vertical) position. In general, the flight altitude was selected so that the stream channel occupied approximately 20-40% of the image frame. A minimum altitude of approximately 300 meters was used both for maneuverability and for safety reasons. If the stream split into two channels that could not be covered in the sensor's field of view, the survey was conducted over the larger of the two channels.

Instream thermistors were distributed in each subbasin prior to the survey to ground truth (i.e., verify the accuracy) the radiant temperatures measured by the TIR. TIR data can be viewed as GIS point coverages or TIR imagery.

Direct observation of spatial temperature patterns and thermal gradients is a powerful application of TIR derived stream temperature data. Thermally significant areas can be identified in a longitudinal stream temperature profile and related directly to specific sources (i.e., water withdrawal, tributary confluence, land cover patterns, etc.). Areas with stream water mixing with subsurface flows (i.e., hyporheic and inflows) are apparent, and often dramatic, in TIR data. Thermal changes captured with TIR data can be quantified as a specific change in stream temperature or a stream temperature gradient that results in a temperature change over a specified distance.

DEQ contracted with Watershed Sciences, Inc. to collect TIR data in the Lower Grande Ronde and Wallowa River Subbasins during 1999. TIR data was not collected in the Imnaha River Subbasin. The TIR-derived temperatures for each stream are shown in **Figure A-6**. In this TMDL analysis, the TIR data for the Wallowa River were used to: measure surface temperatures; develop longitudinal temperature profiles; develop flow mass balances; map/identify significant thermal features; indicate subsurface hydrology, groundwater inflow and/or springs; and validate simulated stream temperatures.

Figure A-7 displays the measured TIR profiles for each of the streams sampled in the Lower Grande Ronde and Wallowa River Subbasins (note: tributary/spring temperatures are from TIR imagery). **Figures A-8** through **A-16** depict TIR longitudinal graphic profiles and digital video imagery for selected areas of interest.

It is important to note that thermal stratification can be identified in TIR imagery and by comparison with the instream temperatures loggers. In unstratified streams, temperature measurements from bottom-anchored thermistors and TIR should be the same, within the range of measurement uncertainty. In the case of the Lower Grande Ronde Subbasins TIR flights, no stream reaches were identifiably stratified. The streams where TIR data was collected were fully mixed.

Figure A-6. River sampled TIR temperatures on the Lostine River, Bear Creek, Minam River, Wallowa River, Lower Grande Ronde River, Chesnimnus Creek, and Joseph Creek
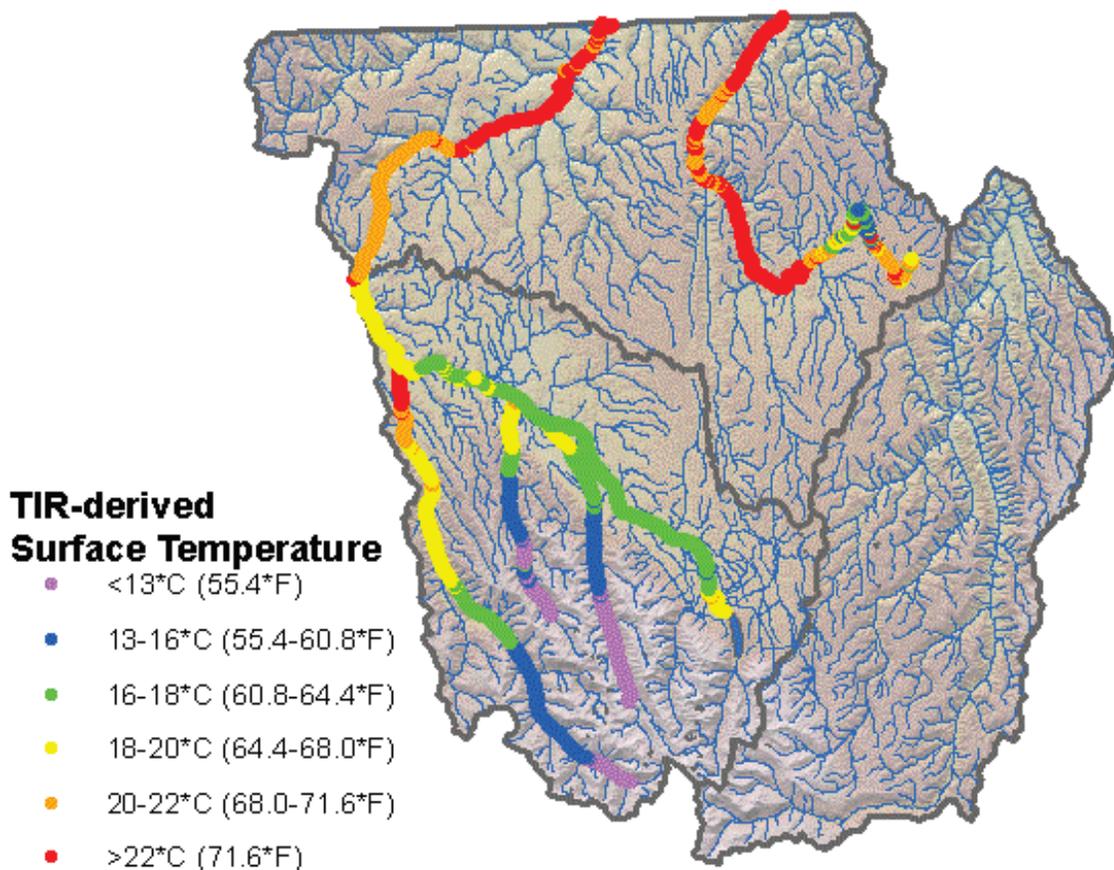
Figure A-7. Measured stream temperature longitudinal profiles
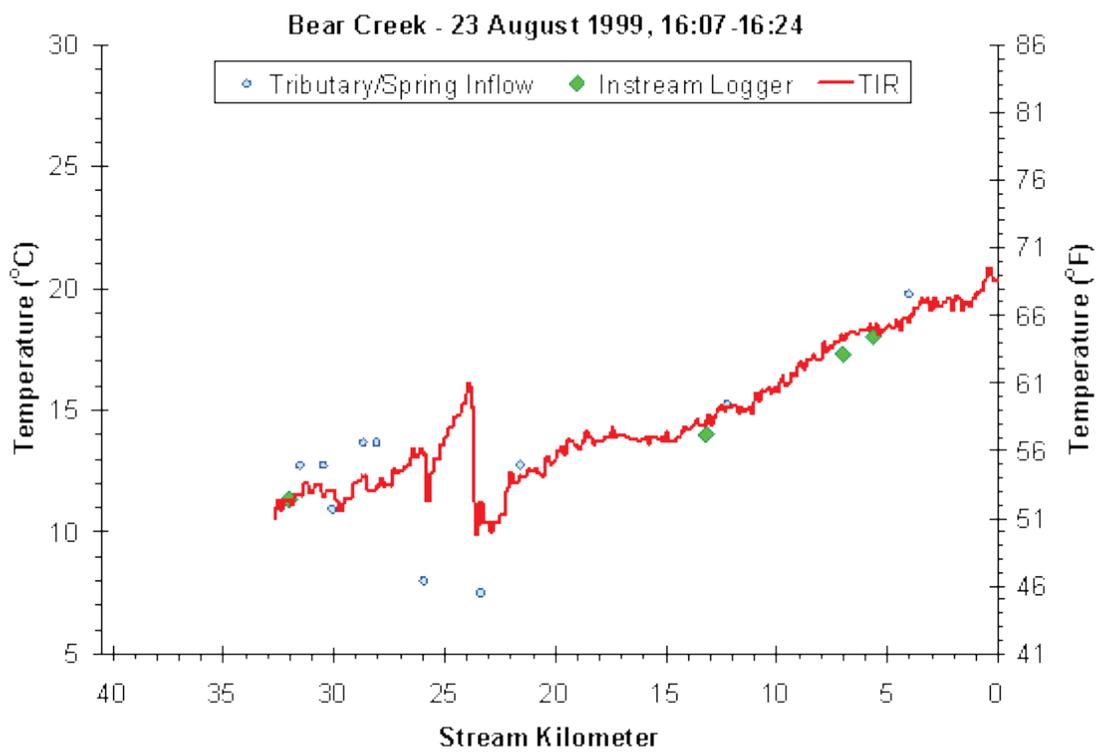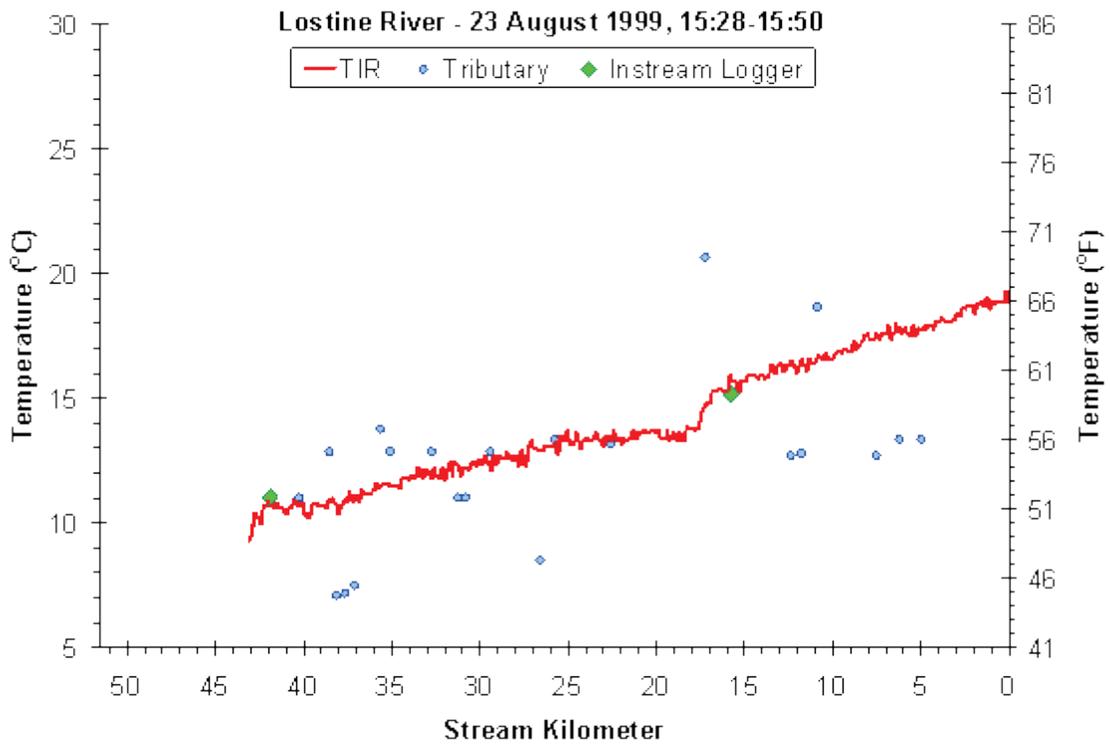
Figure A-7 (continued). Measured stream temperature longitudinal profiles

Figure A-7 (continued). Measured stream temperature longitudinal profiles

Lower Grande Ronde River - 19 August 1999, 15:00-15:39

Chesnimnus Creek - 22 August 1999, 15:14-15:37
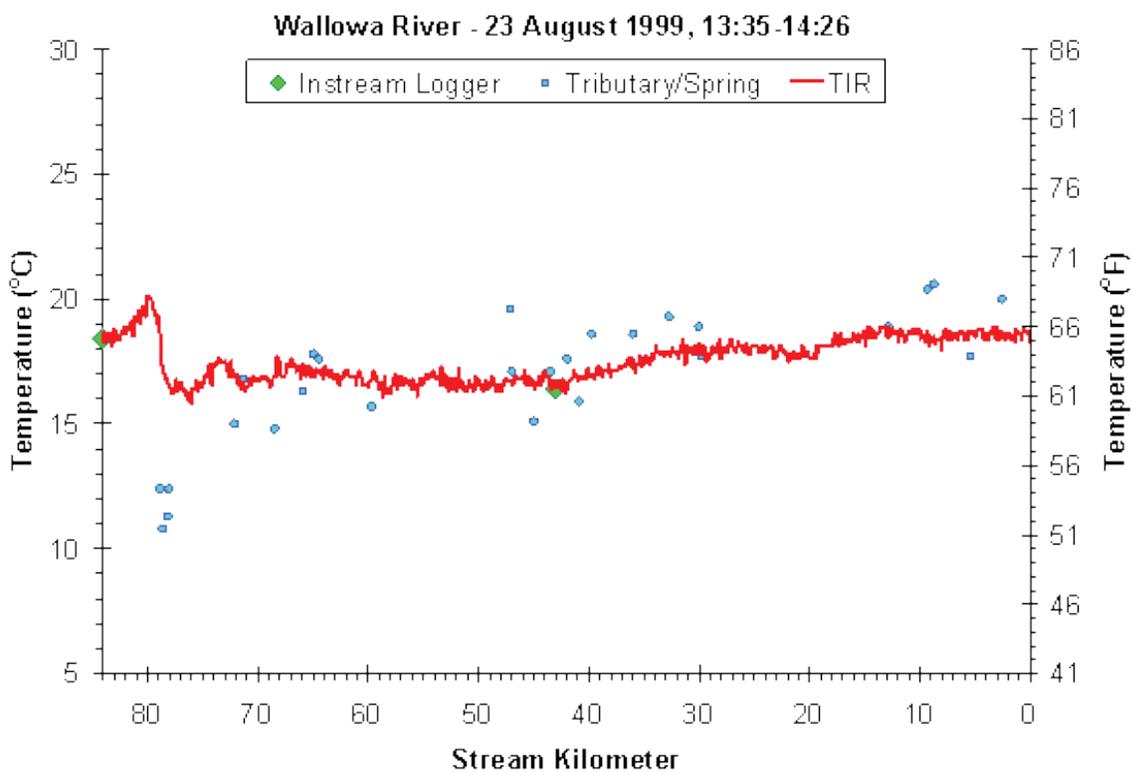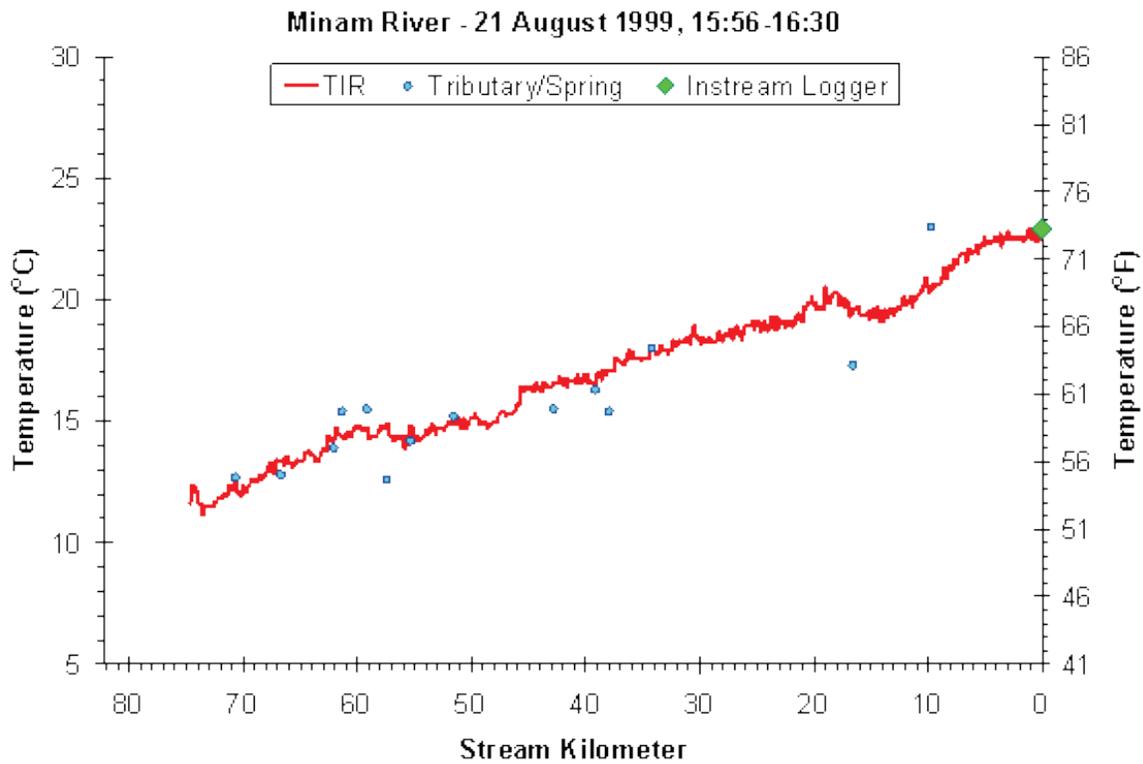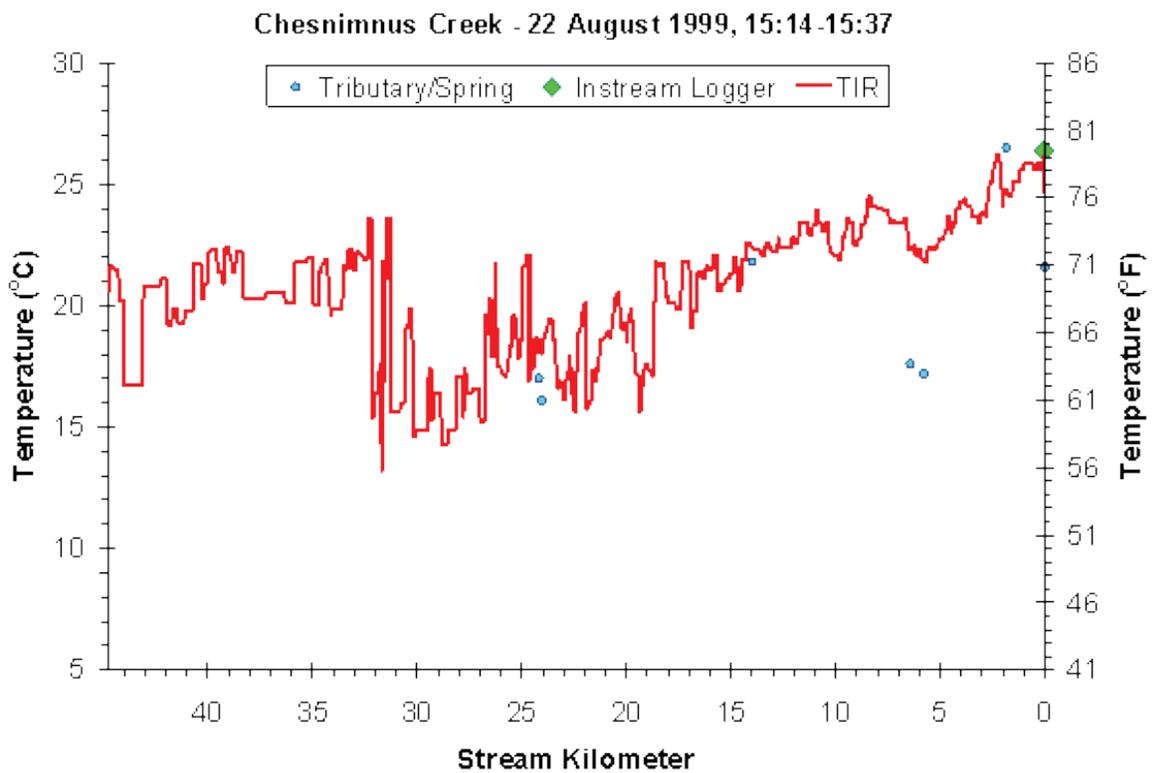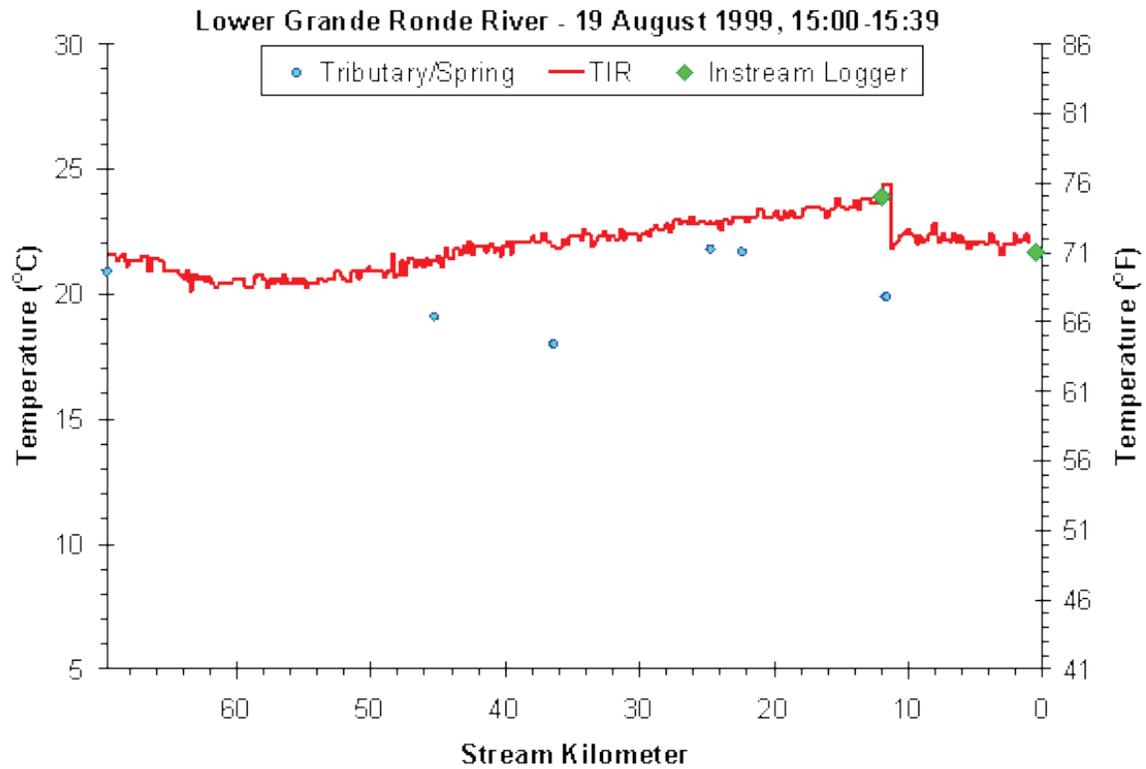
Figure A-7 (continued). Measured stream temperature longitudinal profiles
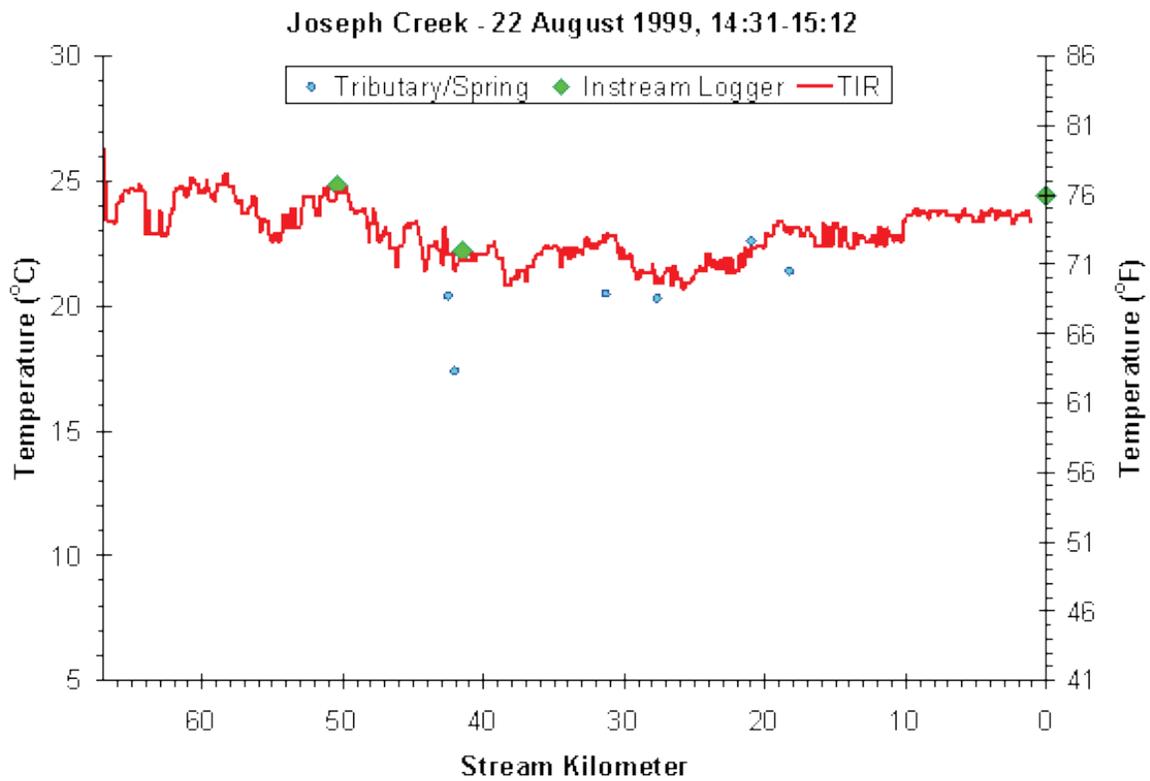
Figure A-8. Chesnimnus Creek at Butte Creek confluence
Chesnimnus Creek is flowing from the top of the image to the bottom, and Butte Creek confluence is just downstream the bridge

Temperature Scale (°F)
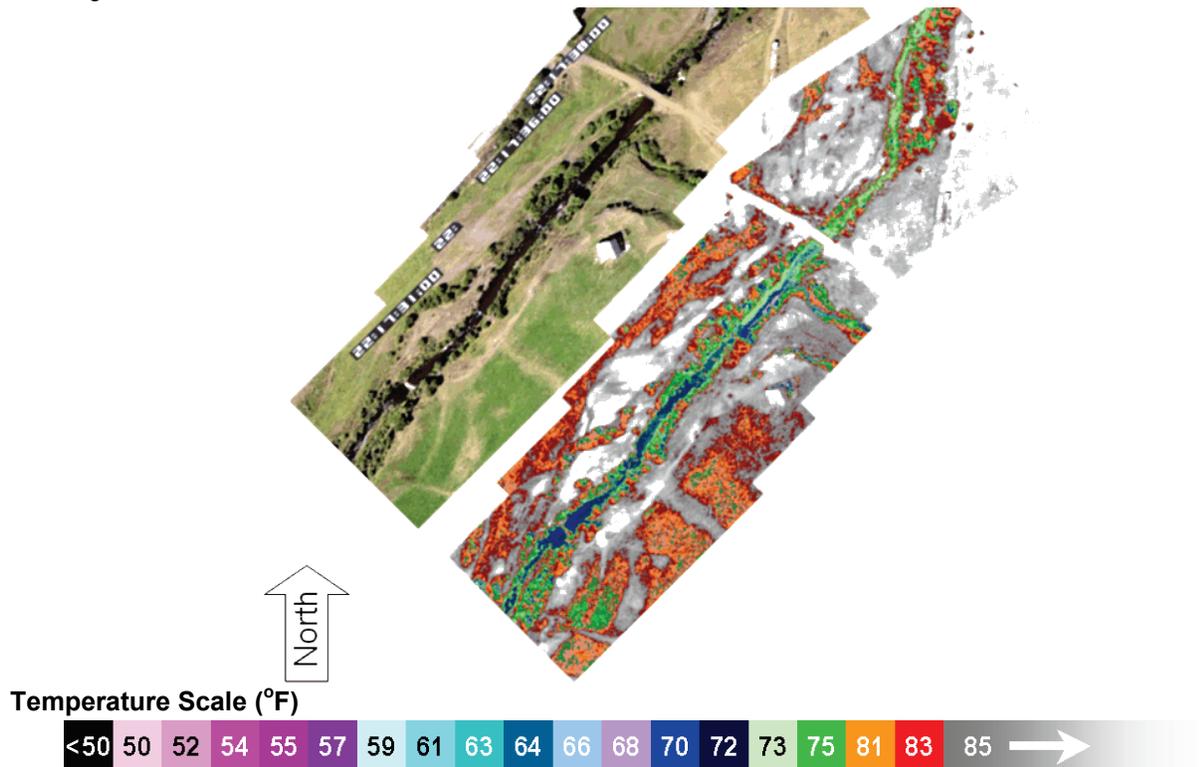
Figure A-9. Lostine River at inflow from Lostine Reservoir

The Lostine River (~57°F) is flowing from the bottom of the image to the top, while reservoir water (~70°F) is returning to the stream from the left side of the image
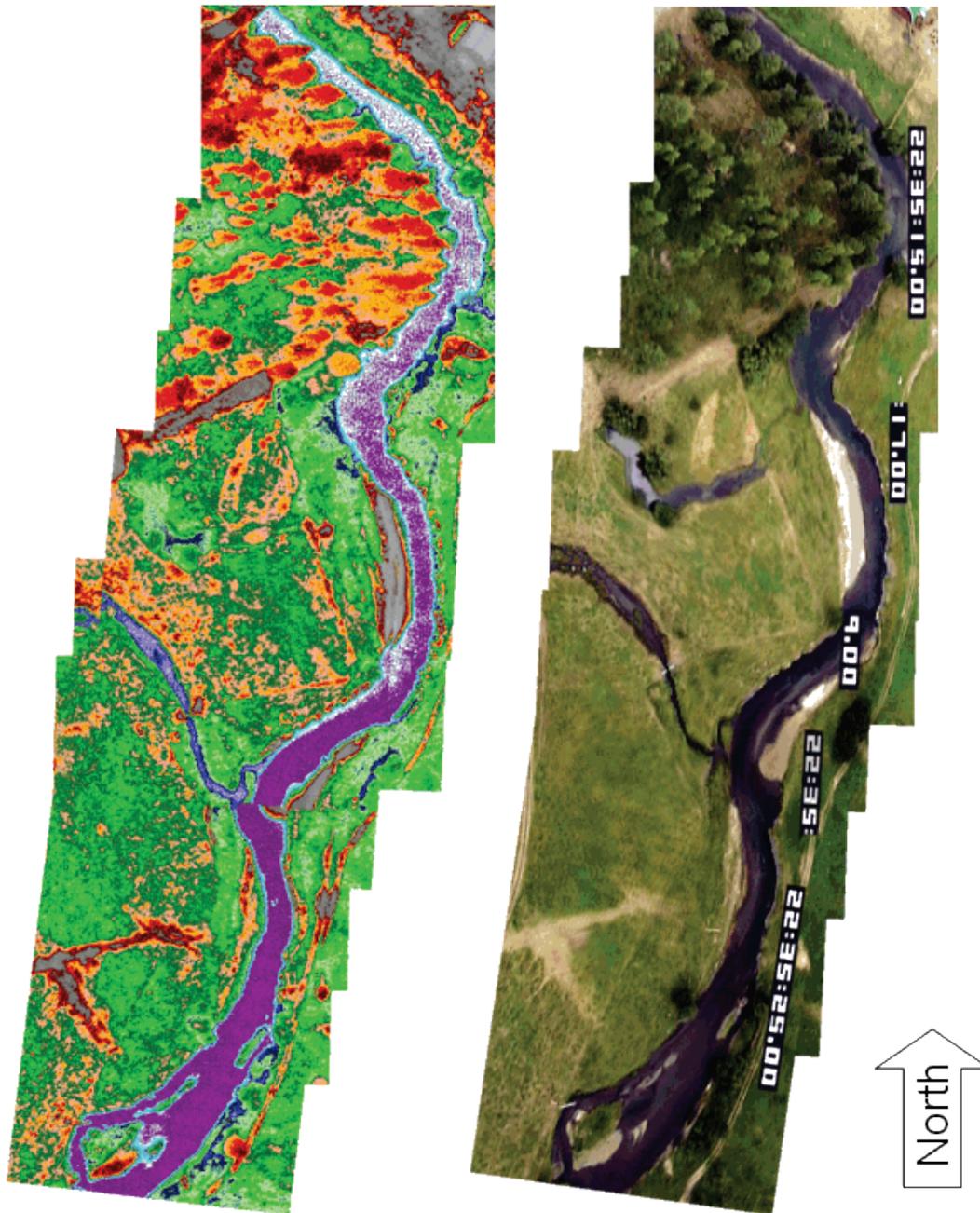
Temperature Scale (°F)

Figure A-10. Lostine River Diversions
The Lostine River is flowing from the bottom of the image to the top. There are instream structures and diversion ditches visible in the day video and TIR images.
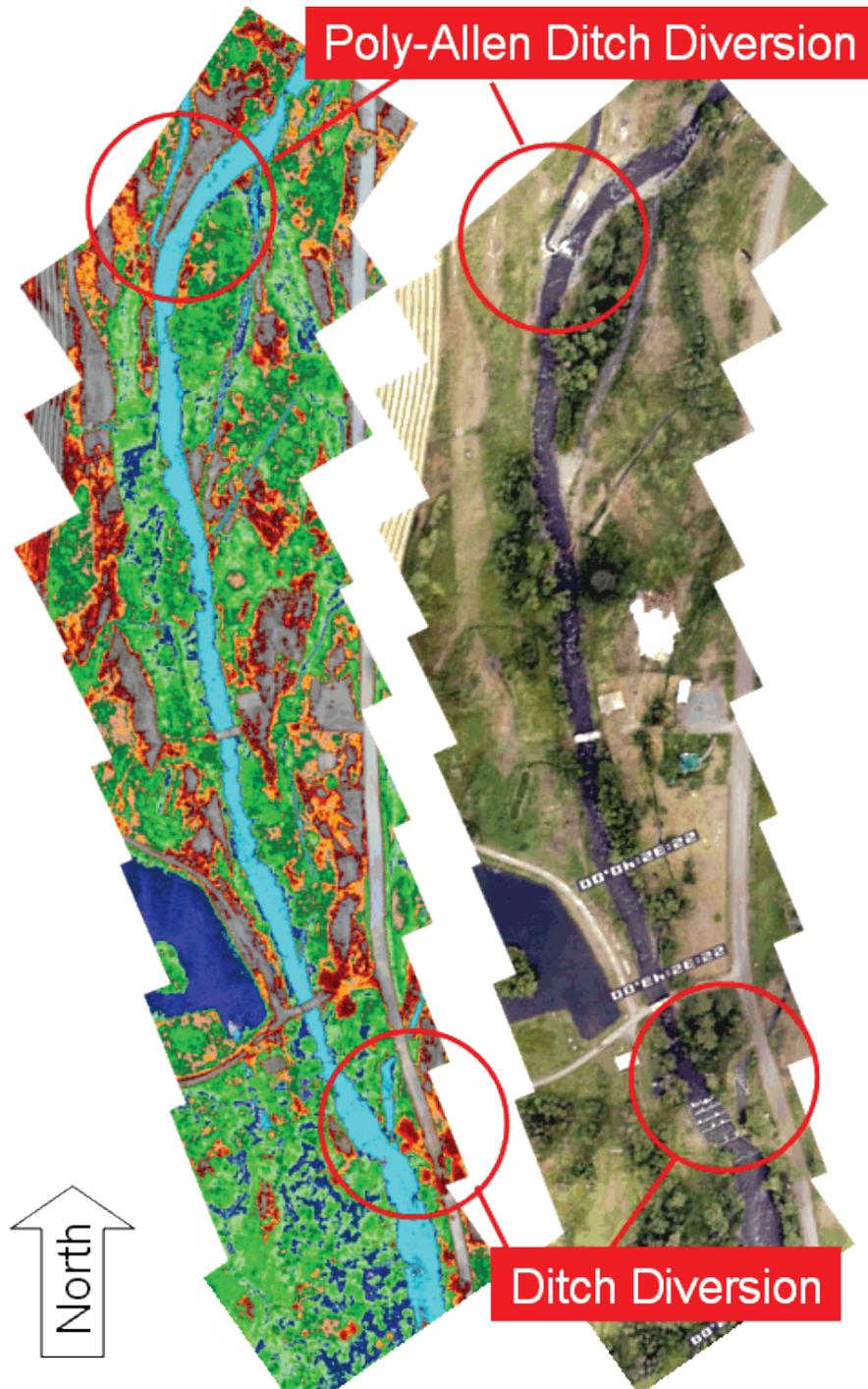
Temperature Scale (°F)

Figure A-11. Bear Creek at river mile 14.1, near Dobbin Creek.

This stretch of river has a complex channel system with cool side channels and springs. Note how the temperature changes from about 61°F to the low 50's as a spring and cool side channel waters mix with the mainstem.

Temperature Scale (°F)

| <50 | 50 | 52 | 54 | 55 | 57 | 59 | 61 | 63 | 64 | 66 | 68 | 70 | 72 | 73 | 75 | 81 | 83 | 85 |
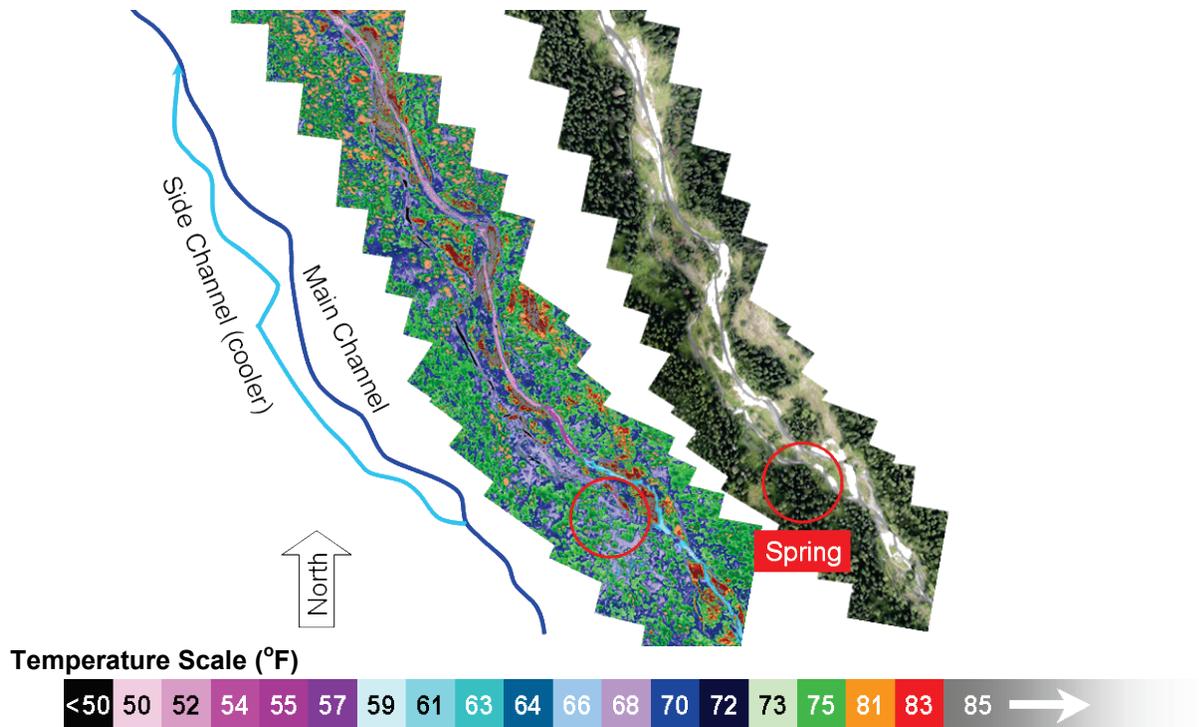
Figure A-12. Grande Ronde River at Wenaha River confluence

The Grande Ronde River (~74°F) is flowing up from the bottom to the right of the image, while the Wenaha River (~68°F) is entering at the north side of the bend.

Temperature Scale (°F)

| <50 | 50 | 52 | 54 | 55 | 57 | 59 | 61 | 63 | 64 | 66 | 68 | 70 | 72 | 73 | 75 | 81 | 83 | 85 |

Figure A-13. Wallowa River at Cross Country Ditch diversion

The Wallowa River is flowing from the bottom to the top of the image, while the diversion for the Cross Country Ditch is visible on the left side.
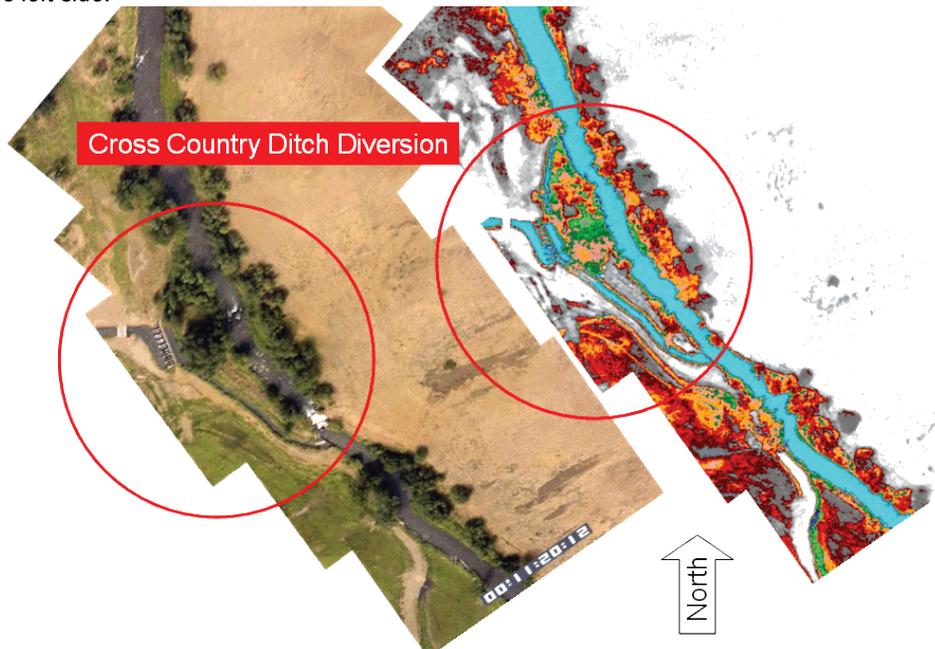
Temperature Scale (°F)

Figure A-14. Wallowa River at mouth/Grande Ronde River confluence

The Wallowa River is flowing from the bottom right of the image, while the Grande Ronde River is flowing from the bottom left to the top of the image.
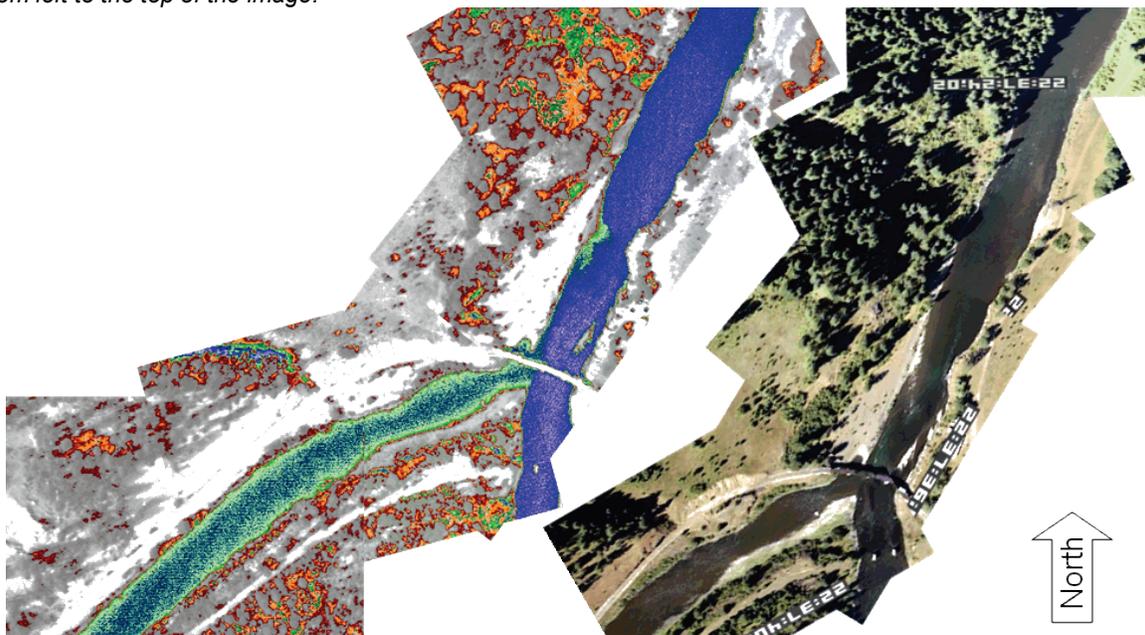
Temperature Scale (°F)

Figure A-15. Wallowa River at Lostine River confluence

The Wallowa River is flowing from the left to the right of the image, while the Lostine River is entering form the bottom of the image. A temperature gradient is visible for a short distance downstream of the confluence, before completely mixing at the bend.
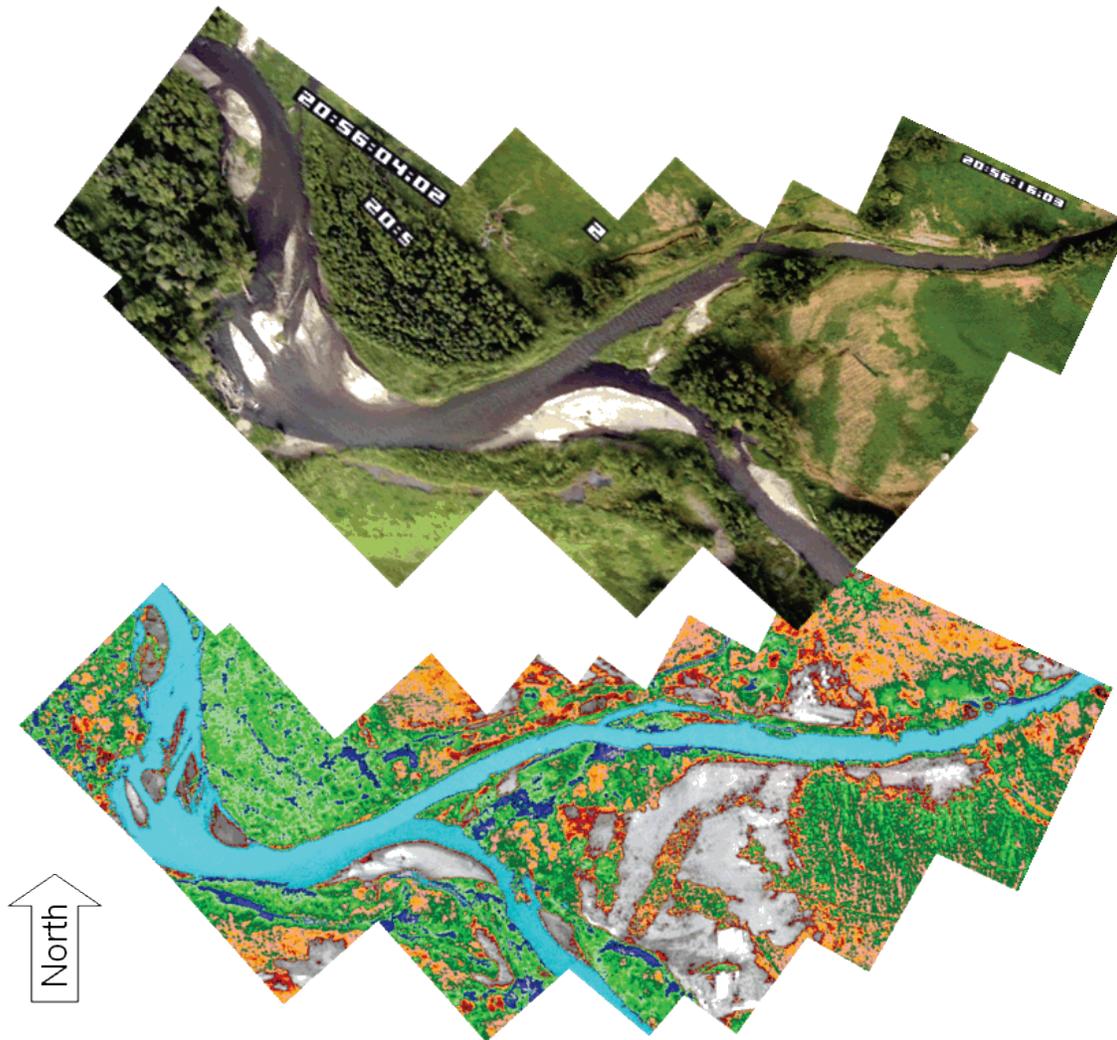
Temperature Scale (°F)

Figure A-16. Wallowa River at Minam River confluence

The Wallowa River (~64°F) is flowing from the bottom to the top of the image, while the Minam River (~68°F) is entering on the left. The thermal gradient is apparent the entire length of the image (~1/4 mile). Complete mixing occurs after the bend seen at the top of this image.

Temperature Scale (°F)

<50	50	52	54	55	57	59	61	63	64	66	68	70	72	73	75	81	83	85 →
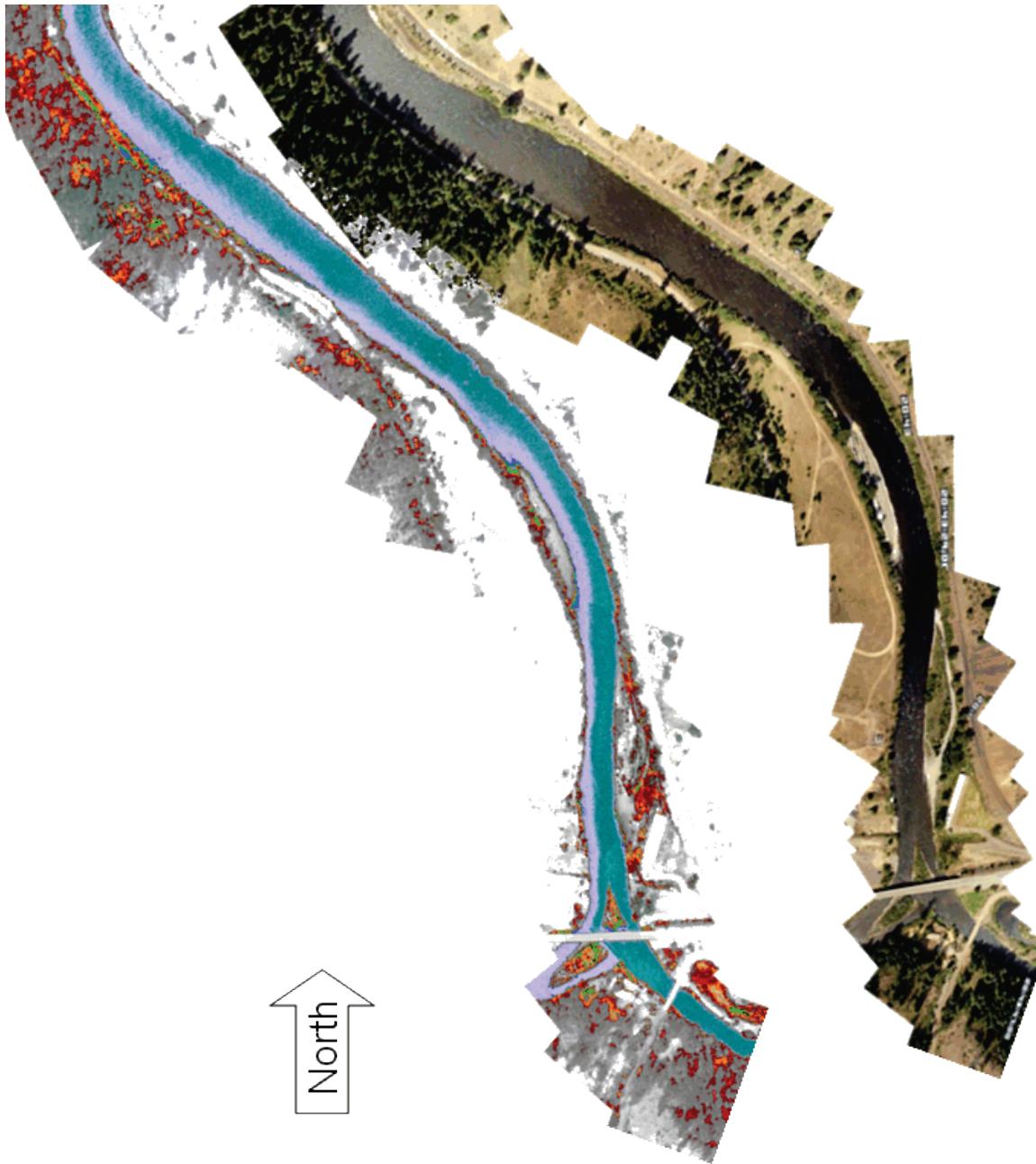
A2.1.2 Flow Volume – Gage Data and Instream Measurements

Flow volume data was collected at several sites during the critical stream temperature period in late August of 1999 and 2000 by DEQ (**Figure A-17**). Where applicable, these instream measurements were used to develop flow mass balances for the Wallowa River temperature model. In addition to flow rate data, wetted width, depth and velocity measurements were also made at these sites. This data were used to corroborate the simulated stream hydraulics. Data from one USGS gage and OWRD gages was also used in the analysis.

Figure A-17. Flow measurement locations (August, 1999 and 2000).
DEQ collected instream measurements during this period.
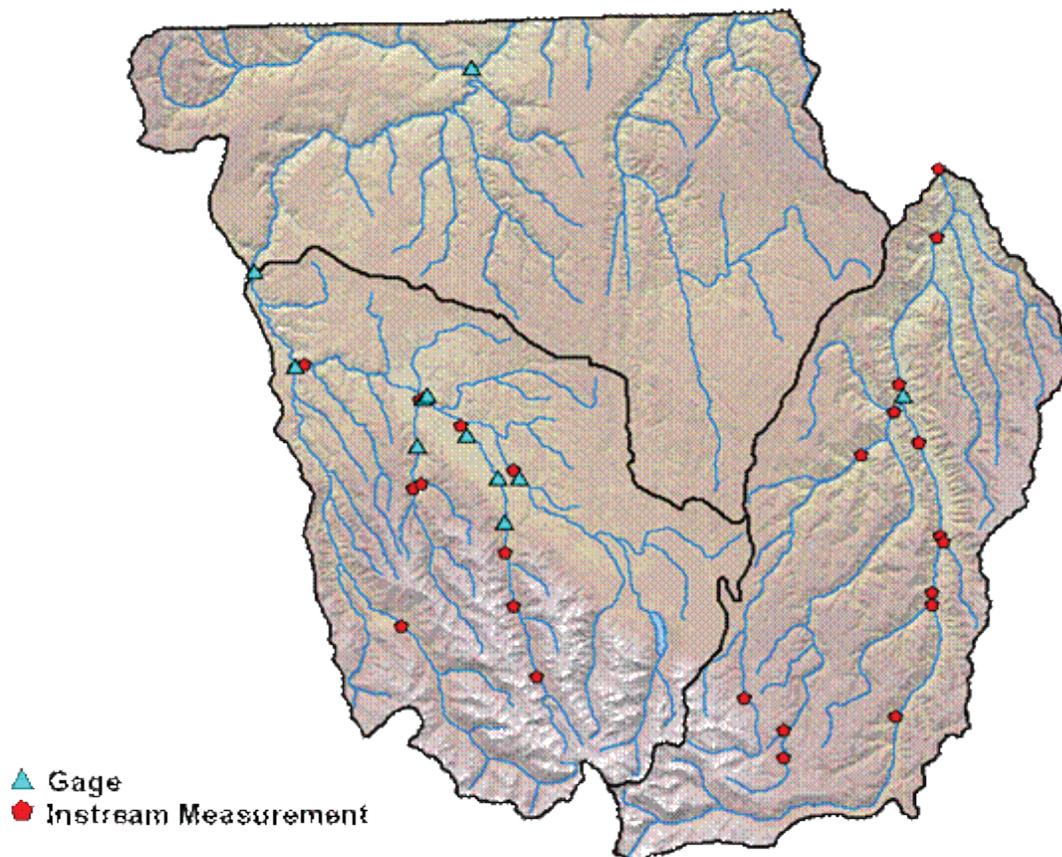
A2.1.3 Stream Habitat Surveys

During the summers of 1999 and 2000, Oregon DEQ collected ground-level habitat data at several locations in the Lower Grande Ronde Subbasins, focusing on the Wallowa River and Imnaha River Subbasins. Stream survey data focused on near stream vegetation classification and measurements, channel morphology measurements, and stream shade measurements.

ODFW has also collected stream habitat data (ODFW 1999). Their data sets also focus on channel morphology, near stream land cover, and stream shade measurements. **Figure A-18** displays the DEQ and ODFW stream survey locations.

Figure A-18. Ground level stream habitat survey sites
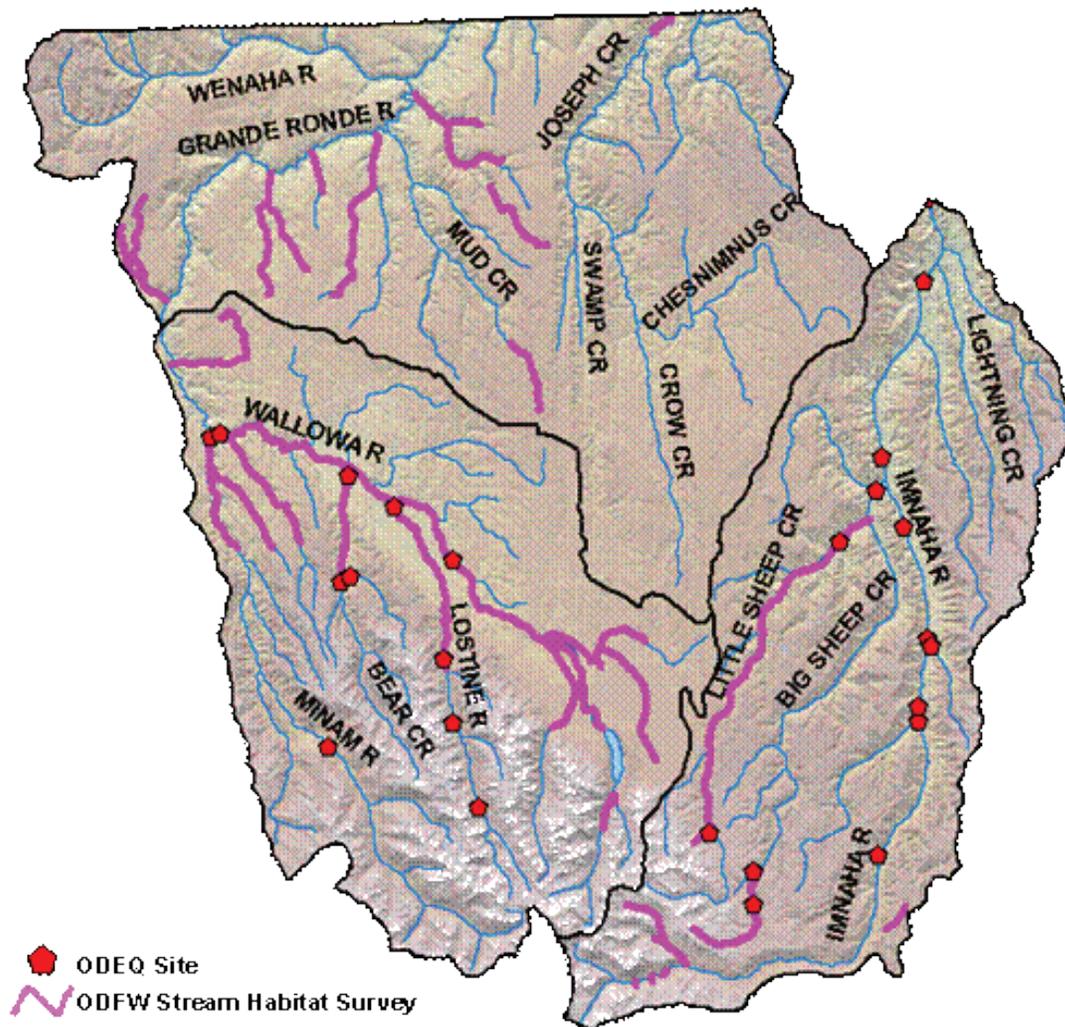
A2.2 GIS Data

This stream temperature TMDL relies extensively on GIS data. Water quality issues in the Lower Grande Ronde Subbasins are interrelated, complex and spread over hundreds of square miles. The TMDL analysis strives to capture these complexities using the highest resolution data available.   The GIS data used to develop this TMDL are listed below in **Table A-2** and further described below.

Table A-2. Spatial data and application

Spatial Data	Application
10-Meter Digital Elevation Models (DEM)	Measure stream elevation and gradient Measure valley shape and landform Measure topographic shade angles
Aerial Imagery – Digital Orthophoto Quads	Map near stream vegetation Map stream position and channel edges Map channel morphology and aspect Map road, developments, and other structures
Water Rights Information System (WRIS) and Points of Diversion (POD) Data	Map locations and estimate quantities of water withdrawals

A2.2.1 10-Meter Digital Elevation Model (DEM)

Digital Elevation Model (DEM) data files are representations of cartographic information in a raster form. DEMs consist of a sampled array of elevations for a number of ground positions at regularly spaced intervals. The U.S. Geological Survey, as part of the National Mapping Program, produces these digital cartographic/geographic data files. Ten-meter DEM grid elevation data is rounded to the nearest meter for ten-meter pixels (vertical resolution is approximately one meter in flat terrain).

A2.2.2 Aerial Imagery – Digital Orthophoto Quads

A digital orthophoto quad (DOQ) is a digital image of an aerial photograph in which camera distortion has been removed. In addition, DOQs are projected in map coordinates combining the image characteristics of a photograph with the geometric qualities of a map. The digital orthophotos used in this report were black-and-white with one-meter pixels covering a USGS quarter quadrangle. The images were collected in May through July of 1994, 1995 and 1996, and were provided through the Natural Resources Conservation Service National Cartography and Geospatial Center. Color DOQ imagery (NAIP, 2005) became available in 2007, but were not used in this TMDL because the modeling work had already been completed.

A2.2.3 WRIS and POD Data – Water Withdrawal Mapping

Flow is diverted throughout the Lower Grande Ronde Subbasins during the summer for irrigation purposes. The Oregon Water Resources Department (OWRD) maintains the Water Rights Information System (WRIS). WRIS is a database used to monitor information related to water rights. A separate database tracks points of diversions (POD). These two databases were linked by DEQ to map the locations of diversions, rates of water use and types of water use in the Lower Grande Ronde Subbasins (**Figure A-19**). Consumptive use was estimated using these data and incorporated in developing mass balance flow profiles for the Wallowa River. There are over 1,000 permitted water rights in the Subbasins.

Figure A-19. Mapped points of diversion in Lower Grande Ronde Subbasins derived from the WRIS and POD databases (OWRD data, DEQ database programming and mapping)
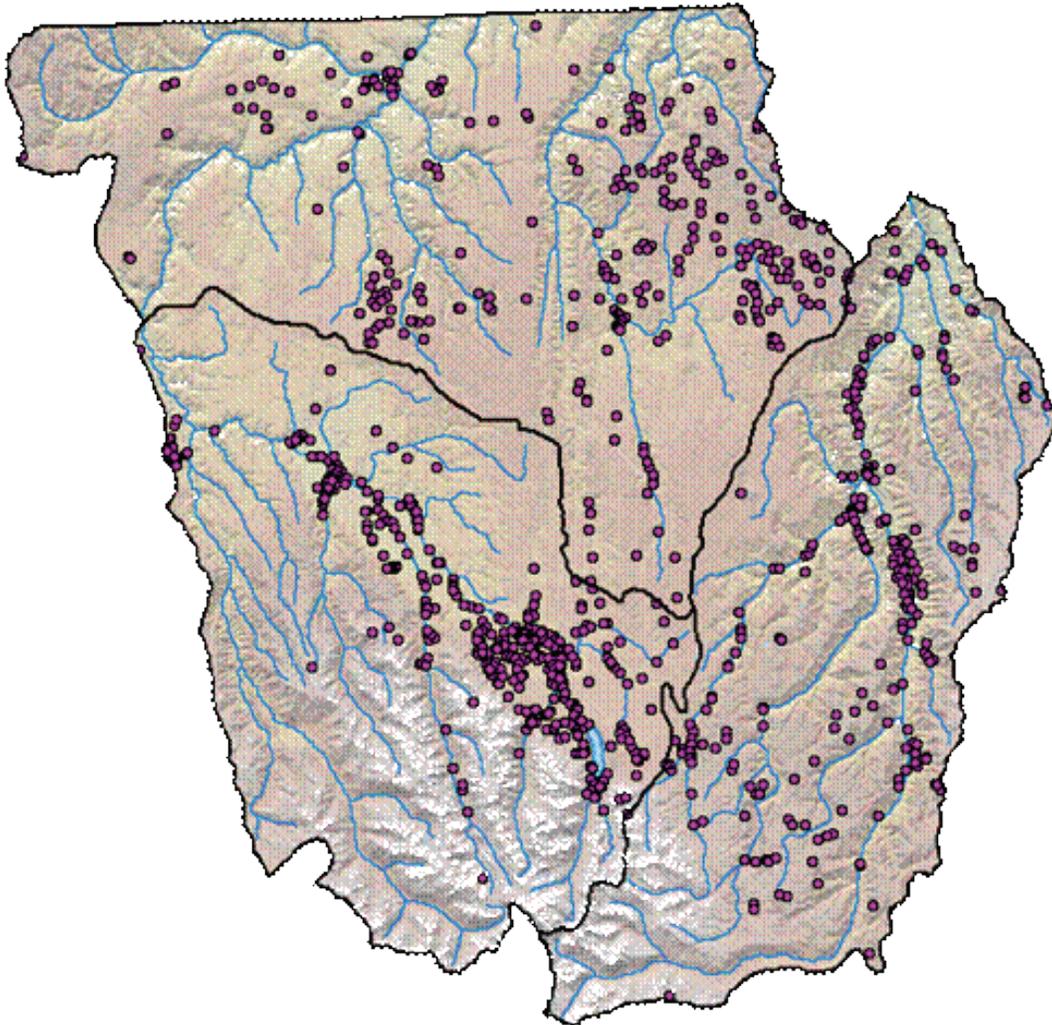
A2.3 Derived Data and Sampled Parameters

Sampling numeric GIS data sets for several landscape parameters and performing simple calculations was done to derive spatial data for several stream parameters for the Wallowa River. Sampling density was user-defined and generally matched any GIS data resolution and accuracy. The sampled parameters used in the stream temperature/shade analysis were:

- Stream Position and Aspect
- Stream Elevation and Gradient
- Maximum Topographic Shade Angles (East, South, West)
- Channel Width
- TIR Temperature Data Associations
- Near Stream Vegetation

Most of these parameters were derived using TTools Version 7 (Boyd and Kasper 2003). TTools is a set of ArcView GIS tools that are designed to automatically sample spatial data sets and assemble an input database for Heat Source modeling (both shade and temperature modeling). The methodologies used

for deriving this data in the Lower Grande Ronde Subbbasins Temperature TMDL analysis are described below.

In addition to these derived landscape parameters, stream flows were derived using a mass balance method. Stream flow measurements were taken at a limited number of locations as described in **Section A2.1.2**. The mass balance method was used to calculate stream flows in areas where field measurements were not collected.

A2.3.1 Stream Position and Aspect

Stream position was assessed by digitizing the stream centerline for each modeled stream. This polyline was segmented into 50-meter reaches (separated by nodes). The latitude/longitude and aspect (downstream direction) were calculated at each node. An aspect of zero would by north, 90 (east), 180 (south), and 270 (west).

A2.3.2 Stream Elevation and Gradient

Stream elevation was sampled from the 10-meter DEM at each of the segmented TTools nodes. Gradients were calculated from the elevation of the stream node and the distance between nodes.

A2.3.3 Topographic Shade Angle

The maximum topographic shade angles to the west, south and east were measured using the 10-meter DEM at each of the segmented nodes. The topographic angle represents the vertical angle to the highest topographic feature as measured from a flat horizon. The sampling routine extended 10.0 kilometers (6.2 miles) in each direction.

A2.3.4 Channel Width Assessment

Channel width is an important component in stream heat transfer and mass transfer processes. Effective shade, stream surface area, wetted perimeter, stream depth and stream hydraulics are all highly sensitive to channel width. Accurate measurement of channel width across the stream network, coupled with other derived data, allows a comprehensive analytical methodology for assessing channel morphology. The steps listed below were used for determining channel widths in the TMDL analysis.

Step 1. Using the DOQs, the right and left banks (looking in the downstream direction) of the Wallowa River were digitized (**Figure A-20** shows an example of the digitization process). All digitized line work was completed at a 1:5,000 map scale or less. These channel boundaries establish the channel width, which is defined for purposes of the TMDL, as the width between shade-producing near-stream vegetation.

Step 2. The distance between each of the digitized banks (perpendicular to the stream aspect) was then measured at each of the segmented TTools nodes.

Figure A-20. Digitized channel centerline (stream data nodes), right bank, and left bank
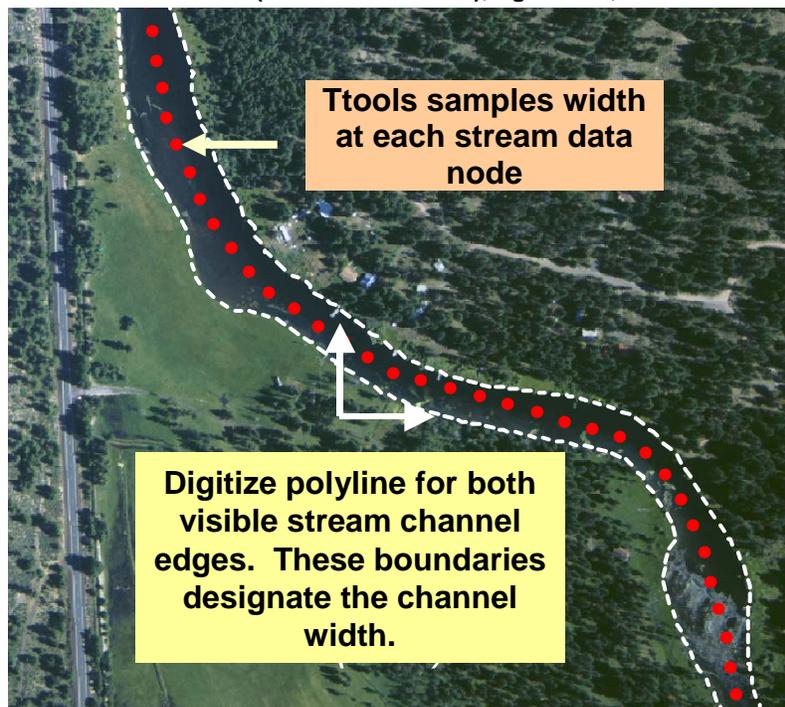
A2.3.5 Near Stream Vegetation

The role of near stream vegetation in maintaining a healthy stream condition and water quality is well documented and accepted in scientific literature ((Barton et al. 1985, Beschta et al. 1987, Coleman and Kupfer 1996, Karr and Schlosser 1978, Malanson 1993, Osborne and Wiley 1988, Roth et al. 1996, Steedman 1988, Zelt et al. 1995). The list of important impacts that near stream vegetation has upon the stream and the surrounding environment is long and warrants listing.

- Near stream vegetation plays an important role in regulating radiant heat in stream thermodynamic regimes.

- Channel morphology is often highly influenced by vegetation type and condition by affecting flood plain and instream roughness, contributing coarse woody debris, and influencing sedimentation, stream substrate compositions and stream bank stability.

- Near stream vegetation creates a thermal microclimate that generally maintains cooler air temperatures, higher relative humidity and lower wind speeds along stream corridors.

- Riparian and instream nutrient cycles are affected by near stream vegetation.

With the recognition that near stream vegetation is an important parameter in influencing water quality, DEQ made the development of vegetation data sets in the Lower Grande Ronde Subbasins a high priority.

A2.3.5.1 Current Condition Vegetation

Variable vegetation conditions in the Lower Grande Ronde Subbasins require a higher resolution mapping than is currently available with existing GIS data sources.   DEQ used GIS to digitally map and identify near stream vegetation along the Wallowa River below Wallowa Lake as described below (**Steps 1** through **3**) and as illustrated in **Figure A-21**. More detailed information can be found in *Analytical Methods for Dynamic Open Channel Heat and Mass Transfer: Methodology for Heat Source Model*

Version 7.0 (Boyd and Kasper 2003), which can be downloaded from the DEQ website. (http://www.deq.state.or.us/wq/TMDLs/tools.htm).

Step 1. DEQ created vegetation polygons using the DOQs. Using the digitized stream channel, vegetation was mapped 100 meters (300 feet) from each channel edge. Within this zone, polygons were drawn to capture visually alike vegetation features. All digitized line work was completed at a 1:5,000 map scale or less.

Step 2. Basic vegetation types were categorized and assigned to individual polygons. Vegetation types were classified as deciduous, coniferous, grass, barren, and other general descriptions. **Table A-3** summarizes the numeric codes and descriptions used to uniquely identify each of the digitized land cover polygons. Height values and densities were estimated based on field measurements taken during the habitat surveys, as well information gained from USFS vegetation data for the Wallowa-Whitman National Forest (described further below).

Step 3. Automated sampling was conducted on the classified vegetation spatial data set in two-dimensions using TTools. At each node along the stream centerline, the vegetation polygons were sampled. The polygons were sampled in a radial pattern, using a 15-meter outwards step, out to 60 meters from the stream centerline. This sampling rate resulted in 928 measurements of vegetation per every mile of stream.

USFS Vegetation Data. The USFS maintains a GIS coverage of existing vegetation for the Wallowa-Whitman National Forest (USFS 2001) that was used to assist in classification of existing vegetation. The USFS vegetation coverage consists of thousands of polygons, each with a unique vegetation type, density, and diameter at breast height (DBH) range. The USFS vegetation coverage was classified based on aerial photograph analysis and ground level data collection. Tree growth curves (Wallowa Valley Ranger District Cruise Statistics) were used to translate USFS diameter at breast height classes to tree height values (**Table A-4**).

The USFS vegetation coverage was then spatially analyzed to determine average existing height values for the different forest types along riparian areas throughout the Lower Grande Ronde Subbasins. As can be seen in **Figure A-22**, the majority of "large" trees fell within 70 to 120 feet, while the majority of "small" trees were between 10 and 60 feet. These two ranges were then separately analyzed to determine an average height value for large and small conifer stands (i.e., the DEQ-digitized vegetation). It was determined that the spatial average USFS stand height was 93.7 feet for the larger trees, and 32.2 feet for the smaller trees. These values were then applied to the DEQ vegetation classifications (**Table A-3**).

Figure A-21. Steps for digitizing and classifying vegetation

Example of polygon mapping of vegetation from aerial color imagery

(At this point only the line work is complete And no data is associated with the polygons.)
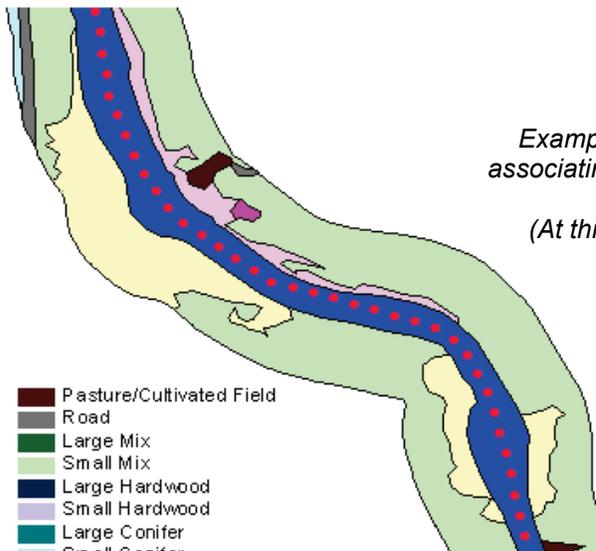
Example of classification of vegetation polygons, associating a vegetation type to each of the polygons.

(At this point a vegetation type numeric code is associated with each polygon.)

Pasture/Cultivated Field
Road
Large Mix
Small Mix
Large Hardwood
Small Hardwood
Large Conifer
Small Conifer
Shrubs - Upland
Shrubs - Wetland
Grasses - Upland
Grasses - Wetland
Water
Developed - Residential;
25% Distribution of Shrubs
75% Distribution of Shrubs

Land Cover and DEM sampling (green dots)

TTools radial sampling pattern for vegetation (sampling interval is user defined). Sampling occurs for every stream data node at four user-defined intervals every 45 degrees from north (north is not sampled since the sun does not shine from that direction in the northern hemisphere). A database of vegetation type is created for each stream data node.
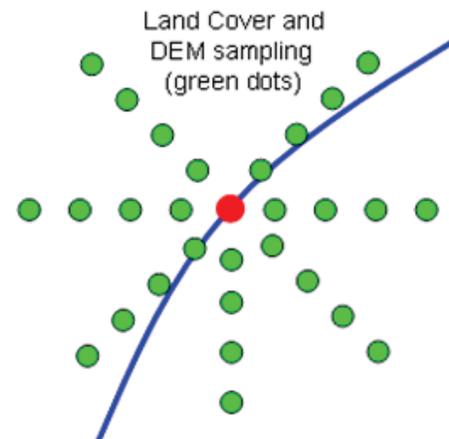
Table A-3. Summary of existing vegetation classifications

Code	Land Cover Description	Height (feet)	Density
301	Water	0	0%
302	Pasture/Cultivated Agriculture	3	90%
303	Tree Farm	15	65%
304	Barren – Rock	0	0%
305	Barren – Bank	0	0%
308	Barren – Clearcut	0	0%
309	Barren – Soil	0	0%
310	Steep/rocky/non-vegetated natural	0	0%
400	Road	0	0%
401	Forest Road	0	0%
402	Railroad	0	0%
500	Large Mixed Conifer-Hardwood	81.9	65%
501	Small Mixed Conifer-Hardwood	24.9	65%
550	Large Mixed Conifer-Hardwood	81.9	25%
551	Small Mixed Conifer-Hardwood	24.9	25%
555	Large Mixed Conifer-Hardwood	81.9	10%
600	Large Hardwood	70	65%
601	Small Hardwood	24.9	65%
650	Large Hardwood	70	25%
651	Small Hardwood	24.9	25%
655	Large Hardwood	70	10%
700	Large Conifer	93.7	65%
701	Small Conifer	32.2	65%
750	Large Conifer	93.7	25%
751	Small Conifer	32.2	25%
755	Large Conifer	93.7	10%
800	Upland Shrubs	5	65%
850	Upland Shrubs	5	25%
801	Wetland Shrubs	10	65%
851	Wetland Shrubs	10	25%
900	Grass - upland	3	90%
3011	Active River Channel	0	0%
3248	Developed - House-sized Structures	20	100%
3249	Developed - Industrial Sized Structures	30	100%
3252	Dam or Weir	0	0%
3255	Canal	0	0%
3256	Dike	0	0%
3300	Hatchery	0	0%
3400	Sewage Pond	0	0%
3025	Tree Farm	15	65%
3257	Canal	0	0%

Table A-4. Wallowa Valley Ranger District local DBH/height chart

Cruise Statistics Derived From 4 Sales			
(Note: Cruise statistics derived from "thinning from below" prescription (intermediate and suppressed component). Residual stocking of similar size classes consist of codominant and dominant trees and would reflect consistently greater heights.)			
	Tree Height (Feet)		
DBH	**Ponderosa**	**Douglas Fir**	**Grand Fir**
5	32	32	33
6	38	37	39
8	46	49	50
10	52	55	55
12	56	58	60
14	62	66	67
16	69	70	73
18	76	80	82
20	85	89	91

Figure A-22. USFS average vegetation coverage height ranges for riparian areas in the Lower Grande Ronde Subbasins
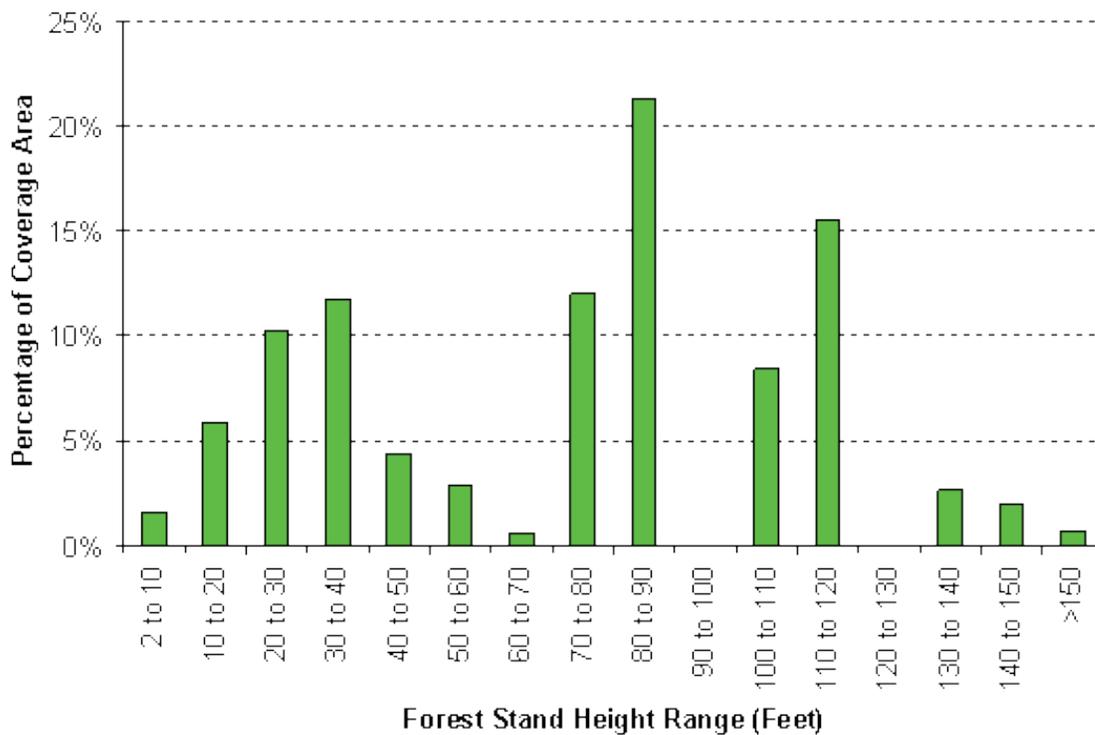
A2.3.5.2 System Potential Vegetation

System potential vegetation refers to the vegetation which can grow and reproduce on a site given the natural plant biology, site elevation, soil characteristics, and climate. Potential near stream vegetation is essentially the mature species composition, height, and density of vegetation that would occur in the absence of human disturbances. Potential near stream vegetation does not include considerations for resource management, human use or other legacy human disturbance. Natural disturbance regimes (i.e., fire, disease, wind-throw, etc.) are also not accounted for in this definition. It is assumed that despite natural disturbance, potential near stream vegetation types (as defined) will survive and recover from a natural disturbance event. That said, DEQ views natural disturbance as an essential part of a dynamic ecosystem and does therefore not expect continuous attainment of shade targets representing un-disturbed conditions. This is further articulated in water quality standard rules and in **Chapter Two**.

Since near stream vegetation is a controlling factor in stream temperature regimes, the condition and health of vegetation is considered a primary parameter in the TMDL. System potential vegetation is a key condition targeted in the TMDL. DEQ worked with members of the Wallowa County TMDL Committee to determine system potential near stream vegetation for the areas covered by the Lower Grande Ronde Subbasins TMDL (**Table A-5**). Through simple assumptions regarding land cover succession and by examining land cover types adjacent to major anthropogenic disturbance areas (i.e., clearcuts, roads, cultivated fields, etc., it was possible to develop a rule set that could be used to estimate *natural potential vegetation* conditions. For example, small conifers were assumed to have the potential to become large conifers. The methodology for applying potential vegetation in the temperature model for the Wallowa River was based on the following general rules:

Rules for Developing System Potential Near Stream Vegetation

1. Barren areas that could grow vegetation (i.e., clearcut areas, embankments, forest roads, etc.) were assigned the nearest adjacent non-developed vegetation type.

2. Developed areas that could grow vegetation were assigned the nearest adjacent vegetation type.

3. Pastures, cultivated fields and lawn vegetation types were assigned the mixed deciduous component, unless completely surrounded by a different forest type.

4. Instream and channel structures (i.e., dikes, canals, etc.) that could grow vegetation were assigned the nearest adjacent vegetation type.

5. Water and barren rock cannot grow vegetation and were not changed.

6. Steep and rocky slopes where soil conditions and/or aspect prohibit tree growth were left unchanged.

7. The conifer vegetation type was assumed to grow to undisturbed potential height and density.

8. The hardwood vegetation type was assumed to grow to undisturbed potential height and density.

9. The mixed conifer/hardwood vegetation type was assumed to grow to undisturbed potential height and density.

Using the rules described above, automated near stream vegetation sampling (**Steps 1-3** in **Section A2.3.5.1**) was repeated to determine the natural system potential condition for each stream reach. Potential tree heights were determined based on local expertise and are consistent with regional plant guide literature (Johnson and Simon 1987, Johnson 1998). Potential near stream vegetation conditions were used in stream temperature modeling scenarios for the Wallowa River to target Natural Thermal Potential (NTP) conditions, quantify the impacts of nonpoint source solar radiation loads, and ultimately to develop nonpoint source load allocations for the TMDL.

The potential near stream vegetation communities identified in **Table A-5** were also used in developing the generalized effective shade curves used to set load allocations for all other streams in the Lower Grande Ronde Subbasins (other than the Wallowa River).

Table A-5. Potential Vegetation Communities (Wallowa County TMDL Committee, 2003)

Potential Vegetation Communities with Dominant Species Composition	Average Mature Tree Height feet (meters)	Average Shade Producing Height feet (meters)
Mixed Conifer above 6000 feet: Lodgepole Pine & alpine fir	65-75 (19.8-22.9)	45-55 (13.7-16.8)
Old Growth Conifer: Ponderosa Pine & Douglas fir	120 (36.6)	120 (36.6)
Wallowa River valley bottom: Englemann Spruce	120 (36.6)	100 (30.5)
Cottonwood Galleries	80-90 (24.4–27.4)	80-90 (24.4–27.4)
Valley Bottom Mixed Deciduous: Alder, Willow, Cottonwood Hawthorne, Snowberry, Dogwood Currents, Mock Orange, Rose	25 (7.6)	25 (7.6)
Mixed Conifer: Ponderosa Pine, Douglass Fir, Larch	100-105 (30.5–32.0)	80-85 (24.4–25.9)
Mixed Deciduous <2000 feet elevation: Where alders are dominant, increase heights to as much as 35 ft (Lower Grande Ronde River, Lower Imanha River, Lower Joseph Creek)	30-35 (9.1-10.7)	30-35 (9.1-10.7)

A2.3.6 Mass Balance Analysis

Where available, TIR sampled stream temperature data can be used to develop a mass balance for stream flow using minimal ground level data collection points. Simply identifying mass transfer areas is an important step in quantifying heat transfer within a stream network. The TIR temperature data was used to identify mass transfer areas occurring in the Wallowa River. **Figure A-23** displays the longitudinal flow mass balance derived from measured flows, OWRD points of diversion data, and TIR temperature data. The "potential flow" shown on the chart assumes that there are no withdrawals, diversions, or returns.

All stream temperature changes that result from mass transfer processes (i.e., tributary confluence, point source discharge, groundwater inflow, etc.) can be described mathematically using the following relationship:

$$T_{mix} = \frac{(Q_{up} \cdot T_{up}) + (Q_{in} \cdot T_{in})}{(Q_{mix})} = \frac{(Q_{up} \cdot T_{up}) + (Q_{in} \cdot T_{in})}{(Q_{up} + Q_{in})}$$

where,
Q_{up}: Stream flow rate upstream from mass transfer process
Q_{in}: Inflow volume or flow rate
Q_{mix}: Resulting volume or flow rate from mass transfer process (Q_{up} + Q_{in})
T_{up}: Stream temperature directly upstream from mass transfer process
T_{in}: Temperature of inflow
T_{mix}: Resulting stream temperature from mass transfer process assuming complete mix

All water temperatures (i.e., T_{up}, T_{in} and T_{mix}) are apparent in the TIR sampled stream temperature data. Provided that at least one instream flow rate is known the other flow rates can be calculated.

Water volume losses are often visible in TIR imagery since diversions and water withdrawals usually contrast with the surrounding thermal signature of landscape features. Highly managed stream flow regimes can become complicated where multiple diversions and return flows mix or where flow diversions and returns are unmapped and undocumented. In such cases it becomes important to establish the direction of flow (i.e., influent or effluent). With the precision afforded by TIR sampled stream temperatures, effluent flows are generally indicated when temperatures are the same (because of the low probability of an inflow with precisely the same temperature as the receiving stream). Temperature differences indicate that the flow is influent. This holds true even when observed temperature differences are very small. The rate of water loss from diversions or withdrawals cannot be easily calculated. Oregon DEQ estimates water withdrawal flow rates from the water right information maintained by OWRD.

Discussion of Assumptions and Limitations for Mass Balance Methodology

1. **Small mass transfer processes are not accounted**. A limitation of the methodology is that only mass transfer processes with measured ground level flow rates or those that cause a quantifiable change in stream temperature with the receiving waters (i.e., identified by TIR data) can be analyzed and included in the mass balance. For example, a tributary with an unknown flow rate that cause small temperature changes (i.e., less than $\pm 0.5^o$F) to the receiving stream cannot be accurately included. *This assumption can lead to an under estimate of influent mass transfer processes.*
2. **Limited ground level flow data limit the accuracy of derived mass balances**. Errors in the calculations of mass transfer can become cumulative and propagate in the methodology since validation can only be performed at sites with known flow rates. *These mass balance profiles should be considered estimates of a steady state flow condition*.
3. **Water withdrawals are not directly quantified**. Instead, water right data is obtained from the POD and WRIS OWRD databases. An assumption is made that these water rights are being used if water availability permits. *This assumption can lead to an over estimate of water withdrawals.*
4. **Water withdrawals are assumed to occur only at OWRD mapped points of diversion sites.** There may have been additional diversions occurring throughout the stream network. *This assumption can lead to an underestimate of water withdrawals and an under estimate of potential flow rates.*
5. **It is not possible to determine the amount of return flows derived from ground water withdrawals relative to those derived from instream withdrawals.** Some of the irrigated water comes from ground water sources. Therefore, one should assume that portions of the return flows are derived from ground water sources. Return flows can occur over long distances from irrigation application and generally occur at focal points down gradient from multiple irrigation applications. It is not possible to estimate the portion of irrigation return flow that was pumped from ground water rights. In the potential flow condition all return flows are removed from the mass balances. *This assumption can lead to an under estimate of potential flow rates.*
6. **Return flows may deliver water that is diverted from another watershed.** In some cases, irrigation canals transport diverted water to application areas in another drainage. This is especially common in low gradient meadows, cultivated fields and drained wetlands used for agriculture production. The result is that accounting for a tributary flow in the potential flow condition is extremely difficult. DEQ is unable to track return flows to withdrawal origins between drainage areas. *When return flows are removed in the potential flow condition this assumption can lead to an under estimate of potential tributary flow rates.*

Figure A-23. Longitudinal flow mass balance for the Wallowa River
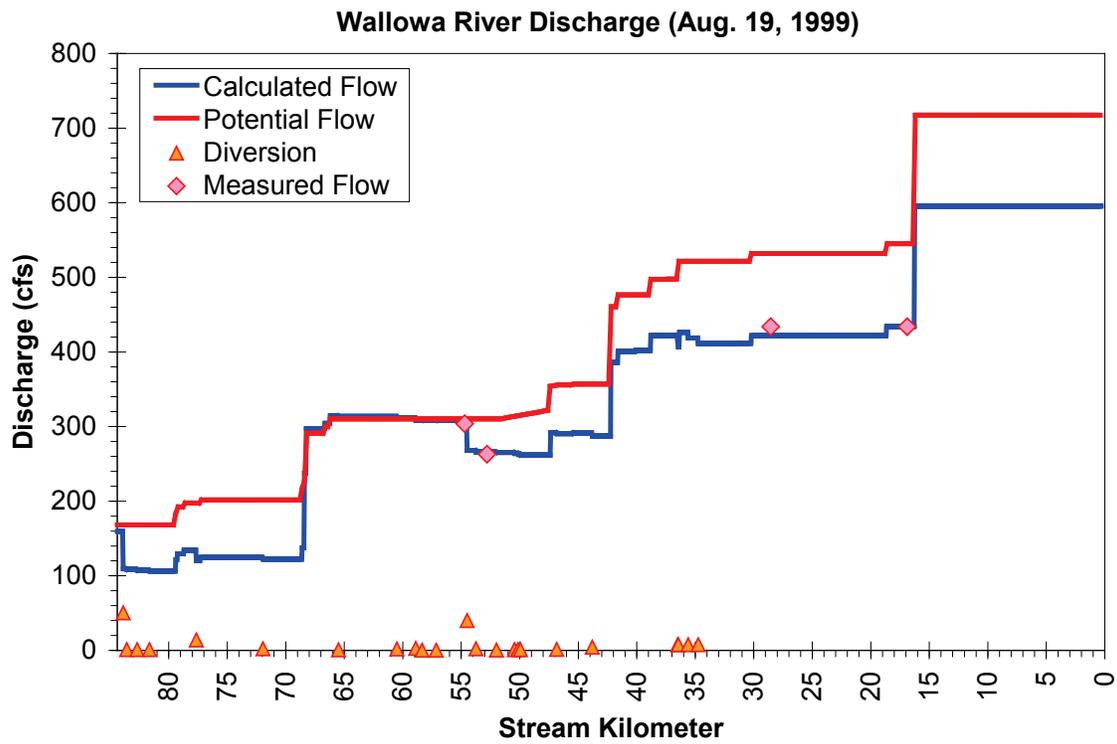
A3. SIMULATIONS

The data sources described in the previous Chapter were used to set up site-specific Heat Source models for temperature and effective shade for the Wallowa River. All solar radiation loads are the clear sky received loads that account for Julian time, elevation, atmospheric attenuation and scattering, stream aspect, topographic shading, near stream vegetation, stream surface reflection, water column absorption and stream bed absorption. An overview of stream heat transfer processes is provided in **Section A1.1**.

Model Used

- Heat Source, version 7.0[2]

Simulation Extent

- Wallowa Lake outlet to the mouth (84.4 miles or 135.8 kilometers)

Simulation Period

- August 14 – September 2, 1999

Simulation Resolution

- Time step: one minute
- Input distance step: 50 meters
- Output distance step: 100 meters

A3.1 Overview of Modeling Purpose, Valid Applications & Limitations

An overview of the different components of the models is provided in **Sections A3.1.1** – **A3.1.4** below, including modeling purpose, valid applications and limitations for each type of analysis.

A3.1.1 Near Stream Vegetation Analysis

Modeling Purpose
- Quantify existing near stream vegetation types and physical attributes.
- Develop a methodology to estimate potential conditions for near stream vegetation.
- Establish threshold near stream vegetation type and physical attributes for the stream network, below which vegetation conditions are considered to deviate from a potential condition.
- Develop near stream vegetation input parameters for the Effective Shade Analysis (**Section A3.1.2**).

Valid Applications
- Estimate current condition near stream vegetation type and physical attributes.
- Estimate potential condition near stream vegetation type and physical attributes.
- Identify site-specific deviations of current near stream vegetation conditions from threshold potential conditions.

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[2] *Heat Source* documentation "*Analytical Methods for Dynamic Open Channel Heat and Mass Transfer: Methodology for Heat Source Model Version 7.0*" (Boyd and Kasper, 2003) is available on-line at http://www.deq.state.or.us/wq/TMDLs/tools.htm.

Limitations
- Methodology is based on ground level and GIS data such as vegetation surveys and digitized polygons from DOQs. Each data source has accuracy considerations.
- Associations used for vegetation classification are assigned median values to describe physical attributes, and in some cases, this methodology significantly underestimates landscape variability.

A3.1.2 Effective Shade Analysis

Modeling Purpose
- Simulate current condition effective shade levels over stream network.
- Simulate potential condition effective shade levels based on channel width and vegetation types and physical attributes over stream network.
- Calculate solar heat flux associated with both current condition and potential condition effective shade levels.
- Establish threshold effective shade values for the stream network, below which current conditions are considered to deviate from a potential condition.
- Provide vegetation type specific shade curves that allow target development where site-specific targets are not completed (i.e., establish relationships between effective shade and channel width, for a specified aspect and vegetative condition).
- Develop shade and heat flux parameters for use in the Stream Temperature Analysis (**Section A3.1.4**).

Valid Applications
- Estimate current condition effective shade and heat flux over the stream network.
- Estimate potential condition effective shade and heat flux over the stream network.
- Identify site-specific deviations of current effective shade conditions from threshold potential conditions.

Limitations
- Limitations for input parameters apply (i.e., near stream vegetation type and physical attributes).
- The period of simulation is valid for effective shade values that occur in late August.
- Assumed channel widths where they were not measurable from aerial photographs may reduce accuracy of the effective shade simulation.

A3.1.3 Hydrology Analysis

Modeling Purpose
- Map and quantify surface and subsurface flow inputs and withdrawal outputs.
- Develop a mass balance for the stream network by quantifying existing instream flow volume.
- Quantify average velocity and average stream depth as a function of flow volume, stream gradient, average channel width and channel roughness.
- Develop a potential mass balance that estimates flow volumes when withdrawals and artificial surface returns are removed.
- Develop hydrology input parameters for use in the Stream Temperature Analysis (**Section A3.1.4**).

Valid Applications
- Estimate current condition flow volume, velocity and stream depth.
- Estimate natural potential condition flow volume, velocity and stream depth.
- Identify site specific deviations of current mass balance from the threshold potential mass balance.

Limitations
- Small mass transfer processes are not accounted.
- Limited ground level flow data limit the accuracy of derived mass balances.
- Water withdrawals are not directly quantified
- Water withdrawals are assumed to occur only at OWRD mapped points of diversion.
- Return flows are oversimplified.
- It is not possible to determine the amount of return flows derived from ground water withdrawals relative to those derived from instream withdrawals.
- Return flows may deliver water that is diverted from another watershed.
- Inter-annual variations are not simulated.
- Intra-annual variations are not simulated.

A3.1.4 Stream Temperature Analysis

Modeling Purpose
- Analyze current condition stream temperature over stream network during low flow/warm season.
- Analyze natural potential condition stream temperature based on potential vegetation types and physical attributes and flow volume over stream network.
- Establish threshold stream temperature values for the stream network, above which current conditions are considered to deviate from a natural potential condition.
- Evaluate temperature differences between conditions with and without anthropogenic warming.
- Provide riparian condition and temperature goals that are protective of beneficial uses.
- Provide a robust methodology for stream heating and temperature analysis, provided data and analytical constraints.

Valid Applications
- Estimate critical condition stream temperatures over the stream network.
- Estimate natural potential critical condition stream temperatures over the stream network.
- Identify site-specific deviations of current stream temperatures from natural potential conditions.
- Analyze the sensitivity of single or multiple parameters on stream temperature regimes.
- Identify stream temperature distributions during low flow/warm season.

Limitations
- Limitations for input parameters apply (i.e., channel morphology, near stream vegetation type and physical attributes and hydrology).
- Accuracy of the methodology is limited to validation statistics of results.
- Stream temperature results are limited to the Wallowa River. Application of the stream temperature output to other streams within or outside of the Subbasins is not valid.
- The period of simulation is valid for stream temperature values that occur in mid to late August.

- Inter-annual variations are not simulated.
- Intra-annual variations are not simulated.

A3.2 Effective Shade Analysis

Effective shade can be thought of as the amount of daily solar radiation directed toward the stream that is blocked by features such as topography and vegetation. Factors that influence stream surface effective shade and are incorporated into the simulation methodology include the following:

Season/Time: Date/Time
Stream Morphology: Aspect, Channel Width, Incision
Geographic Position: Latitude, Longitude, Topography
Land Cover: Near Stream Vegetation Height, Width, Density
**Solar Position:** Solar Altitude, Solar Azimuth

A3.2.1 Site-Specific Effective Shade Simulations

Site-specific effective shade and heat flux simulations were performed for the Wallowa River. Three different effective shade scenarios were simulated, as shown in **Table A-6**. Once the current condition effective shade model was calibrated, a potential near stream vegetation scenario was simulated. Natural site potential vegetation was estimated as described in **Section A2.3.5**. The amount of shade provided by topographic features was also determined. This scenario provided the lower end of the *Natural Disturbance Range*, indicating the amount of shade that the stream would receive if topography was the only shade-producing feature (i.e. in the absence of vegetation).   The results of the simulations are shown in **Figure A-24**.

Table A-6. Site-specific effective shade simulations

Scenario 1:	Current Condition: This simulation establishes current effective shade by modeling the vegetation and anthropogenic landcover that was present at the time of the DOQ was produced (1994/1995).
Scenario 2: (TMDL Loading Capacity)	System Potential Vegetation: The simulation establishes effective shade that would be possible under natural conditions.
Scenario 3:	Topographic Shade: The scenario establishes the effective shade from natural topography by removing all vegetation and anthropogenic landcover such as houses and buildings.

Figure A-24. Effective shade – Current Condition and System Potential during late August

Wallowa River
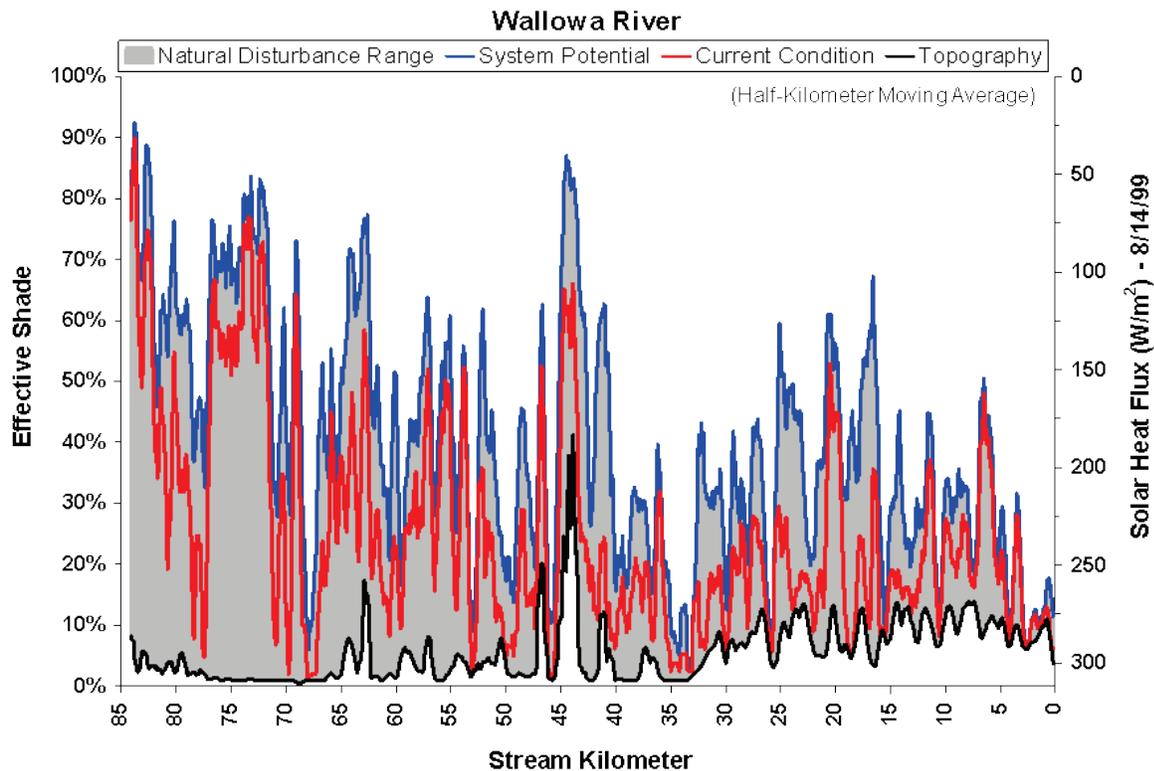
A3.2.2 Generalized Effective Shade Curves

Generalized effective shade curves were developed for streams where site-specific effective shade simulations were not completed. The effective shade curves account for latitude, critical summertime period (August), elevation and stream aspect and display effective shade levels for potential vegetation communities as a function of channel width. Stream aspect is based on coordinate directions, such as North-South, East-West, and Northeast-Northwest**.**

The potential vegetation communities and the associated height and density were determined by the Wallowa County TMDL Committee as shown in **Table A-5**. The results of the shade curve development are shown in **Figure 2-8** in the TMDL document. An example is shown here in **Figure A-25**. Refer to **Section 2.9.2** in the TMDL document for additional discussion of the use of the curves.

Figure A-25. Generalized warm-season system potential effective shade curve for the Old Growth Conifer Community in the Lower Grande Ronde Subbasins (North-South, East-West, and Northeast-Northwest refer to stream aspect.)
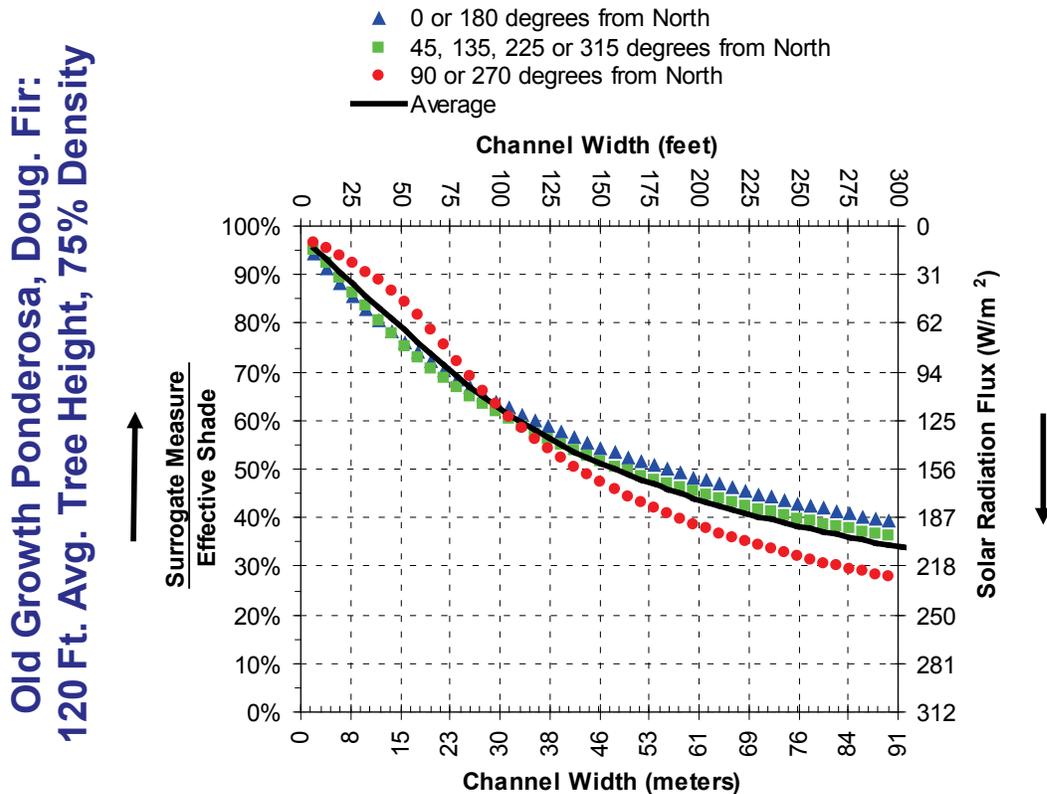
A3.3 Total Daily Solar Heat Load Analysis

Solar heat is established as a primary pollutant in stream heating processes. The total daily solar heat load is the cumulative (entire stream surface area) solar heat received by a stream over one day during the critical period (i.e., July/August period). For the purposes of this analytical effort, the total solar heat load (H_{solar} in the equation below) is the longitudinal sum of the products of the daily solar heat flux and surface area of exposure for each stream reach (i.e., for each stream data node every 50 meters).

$$H_{solar} = \Sigma(\Phi_{solar} * A_y) = \Sigma\ (\Phi_{solar} * W_{wetted} * dx)$$

Background (NTP) levels of solar heat estimate the portion of the total daily solar heat load that occurs when anthropogenic nonpoint sources of heat are minimized.   The total daily solar load is calculated for both the current condition (H_{solar}) and the potential condition ($H_{Solar}^{Background}$). The anthropogenic nonpoint source total daily solar load is the difference between the existing total daily solar load and the background total daily solar load (see equation below).

$$H_{solar}^{NPS} = H_{solar} - H_{Solar}^{Background}$$

where,

A_y:	Stream surface area unique to each stream segment (m^2)
dx:	Stream segment length and distance step in the methodology (m)
Φ_{solar}:	Solar heat flux unique to each stream segment (MW m^{-2})
H_{solar}:	Total daily solar heat load delivered to the stream (MW)
H_{solar}^{NPS} :	Portion of the total daily solar heat load delivered to the stream that originates from anthropogenic nonpoint sources of pollution (MW)
$H_{Solar}^{Background}$:	Portion of the total daily solar heat load delivered to the stream that originates from solar input not affected by human activities (MW)
W_{wetted}:	Wetted width unique to each stream segment (m)

The total daily heat load analysis was done for the Wallowa River. Of the total daily heat loading that occurs during the summertime critical condition, 85% is attributed to natural background sources and 15% is from anthropogenic nonpoint sources.

A3.4 Stream Temperature Simulations

Stream temperature modeling was done on the Wallowa River. Site specific shade modeling was done as described in **Section A3.2**. In addition to effective shade and flux, hydraulic parameters and stream temperature were simulated every 100 meters longitudinally as well. Simulations were completed for a 20-day period (August 14-September 2, 1999). Prediction time steps were limited by stability considerations for the finite difference solution method. Simulation periods represent the critical summertime period. The limitations and assumptions for each of the different analysis included in Heat Source are described in **Sections A3.1.1-A3.1.4**.

A3.4.1 Model Validation - Simulation Accuracy

For the purposes of this analytical effort, validation refers to the statistical comparison of measured and simulated data. Standard error statistics were calculated for TIR derived spatial temperature data sets and instream measured temporal temperature data sets (**Table A-7**). Each measurement of temperature is discrete and was used to assess model accuracy. Simulation outputs are only accurate to levels that exceed the validation statistics. A statistically significant simulated result is one that produces a temperature change greater than validation statistics listed in **Table A-7**.

Stream temperatures derived from TIR data offer an extremely robust validation data set for spatial stream temperature simulation tools. Since the TIR temperature data is continuous, the number of simulated temperatures available for model validation is limited to model resolution. With TIR temperature data, the spatial scalability for any given methodology is unlimited by validation data. This represents a significant improvement over previous data sources.

Spatial and temporal data is stratified in the validation to test for biases in the simulation methodology. Since TIR temperature data sets are robust spatially, there is a possibility that the simulation could be calibrated to the specific time when TIR data was obtained, yet perform poorly for other periods of the day. However, validation statistics demonstrate that this is not the case. **Figure A-26** displays the measured TIR temperatures versus the simulated temperatures.

Table A-7. Stream temperature simulation validation

	Validation Statistic	Wallowa River Model Performance
Temporal Instream Data	Samples (n)	240
	Standard Error (°C)	0.5
Spatial TIR Derived Data	Samples (n)	845
	Standard Error (°C)	0.4

Figure A-26. Stream temperature simulation calibration
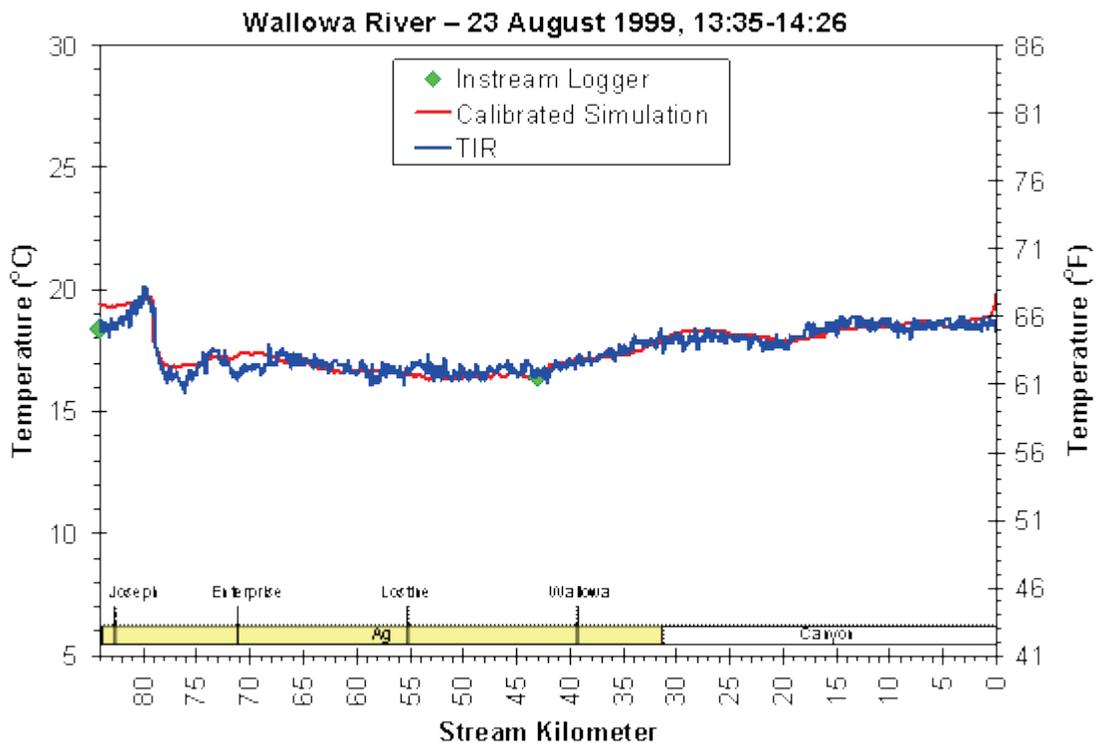
A3.4.2 Simulated Scenarios

Once the current condition stream temperature model was calibrated for the Wallowa River, three different scenarios were then simulated by changing one or more stream input parameters and then re-running the model over the 20-day simulation period (**Table A-8**). The simulated scenarios focused largely on estimated natural potential conditions for vegetation and derived flow mass balances. Combinations of these potential conditions were also simulated to investigate the cumulative thermal effect of attaining defined conditions.

Table A-8. Summary of simulated scenarios

Current Condition	Current Condition (August 1999)
Potential Veg	System Potential Near Stream Vegetation Current Flows
Potential Veg/Tribs	System Potential Near Stream Vegetation Reduced Tributary Temperatures[3] Current Flows
Potential Veg/Tribs/Flow (Natural Thermal Potential)	System Potential Near Stream Vegetation Reduced Tributary Temperatures Natural Flows (no water withdrawals)

Figure A-27 compares the results of the four simulations with results displayed for the day the TIR data was collected.   The top graph shows the simulated temperatures for each scenario that would have been observed at the time the TIR data was collected. The bottom graph compares the diurnal temperature range observed on that day under current condition and natural thermal potential conditions. Model output was also available for every hour of the 20-day simulation period. This enabled calculation of the moving seven-day average of the daily maximums (7DADM), providing for comparison of simulated natural condition and biologically-based temperature standard criteria, which is based on the 7DADM statistic. The results of this analysis are provided in **Section 2.13** of the main TMDL document.

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[3] If tributary temperatures exceeded the numeric criteria, then temperatures were set to approximate the temperature of other cooler temperatures in the Subbasin under this scenario. Tributaries that currently were below the numeric criteria were left at their current temperature.

Figure A-27. Wallowa River temperature simulation results

Wallowa River – 23 August 1999, 13:35-14:26

Diurnal Temperature Range - Wallowa River – 23 August 1999
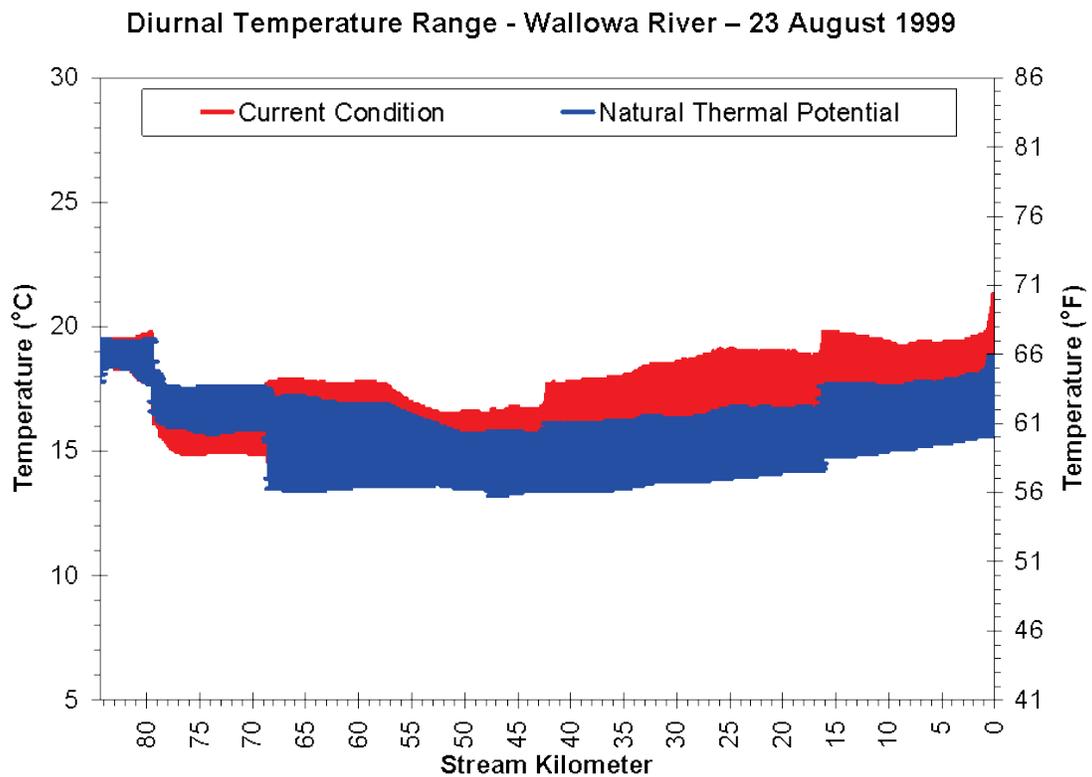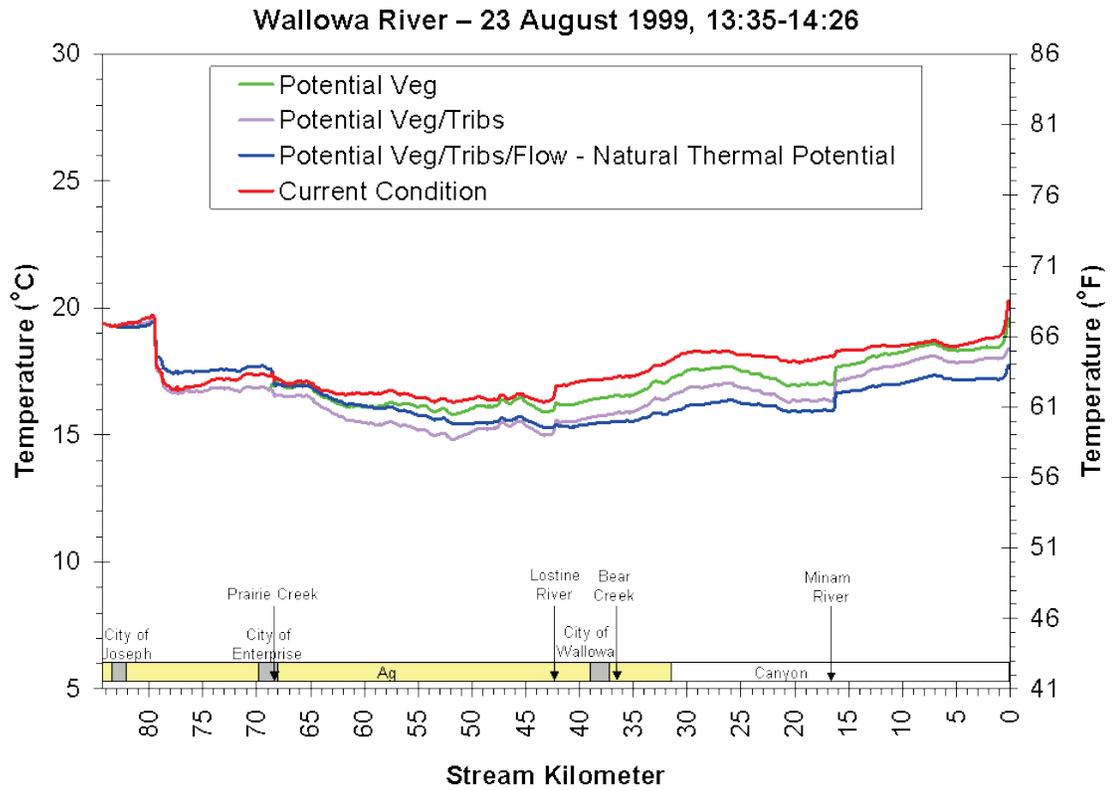
A4. REFERENCES

Anderson, P.D., D.J. Larson, and S.S. Chan, 2007. Riparian Buffer and Density Management Influences on Microclimate of Young Headwater Forests of Western Oregon. *Forest Science 53*(2) 254-269.

Barton, D.R., W.D. Taylor, and R.M. Biette. 1985. Dimensions of Riparian Buffer Strips Required to Maintain Trout Habitat in Southern Ontario Streams. *North American Journal of Fisheries Management* 5:364-378.

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream temperature and aquatic habitat: Fisheries and forestry interactions. Pages 191-232 in E. O. Salo and T. W. Cundy, eds. *Streamside management: Forestry and fishery interactions*. University of Washington, Institute of Forest Resources, Seattle, USA.

Beschta, R.L. and J. Weatherred. 1984. A computer model for predicting stream temperatures resulting from the management of streamside vegetation. USDA Forest Service. WSDG-AD-00009.

Boyd, M.S. 1996. Heat Source: stream temperature prediction. Master's Thesis. Departments of Civil and Bioresource Engineering, Oregon State University, Corvallis, Oregon.

Boyd, M. and B. Kasper. 2003. Analytical Methods for Dynamic Open Channel Heat and Mass Transfer: Methodology for Heat Source Model Version 7.0. http://www.deq.state.or.us/wq/TMDLs/tools.htm.

Brown, G.W. 1969. Predicting temperatures of small streams. *Water Resour. Res.* 5(1):68-75.

Brown, G.W. 1970. Predicting the effects of clearcutting on stream temperature. *Journal of Soil and Water Conservation.* 25:11-13.

Brown, G.W. 1983. Chapter III, Water Temperature. Forestry and Water Quality. Oregon State University Bookstore. Pp. 47-57.

Coleman, D.S. and Kupfer, J.A. 1996. Riparian Water Quality Buffers: Estimates of Effectiveness and Minimum Width in an Agricultural Landscape. *Southeastern Geographer* 36:113-127.

Harbeck, G.E. and J.S. Meyers. 1970. Present day evaporation measurement techniques. *J. Hydraulic Division*. A.S.C.E., Prceed. Paper 7388.

Ibqal, M. 1983. An Introduction to Solar Radiation. Academic Press. New York. 213 pp.

Jobson, H.E. and T.N. Keefer. 1979. Modeling highly transient flow, mass and heat transfer in the Chattahoochee River near Atlanta, Georgia. Geological Survey Professional Paper 1136. U.S. Gov. Printing Office, Washington D.C.

Johnson, C. G., and S. A. Simon. 1987. Plant Associations of the Wallowa-Snake Province, Wallowa-Whitman National Forest. USDA Forest Service Pacific Northwest Region. Publication: R6-ECOL-TP-255A-86.

Johnson, C.G. 1998. Conmon Plants of the Inland Pacific Northwest. USDA Forest Service Pacific Northwest Region. Publication: R6-NR-ECOL-TP-04-98.

Johnson, S.L. 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. *Canadian Journal of Fisheries and Aquatic Sciences,* 61:30-39*.*

Johnson, S.L. and J.A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. *Canadian Journal of Fisheries and Aquatic Sciences,* 57(Suppl. 2):30-39.

Karr, J.R. and Schlosser, I.J. 1978. Water Resources and the Land-Water Interface. *Science* 201:229-234.

Malanson, G.P. 1993. *Riparian Landscapes.* Cambridge University Press, Cambridge, New York, 296 pp.

National Agriculture Imagery Program. 2005. http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai

Oregon Department of Fish & Wildlife. 1999. ODFW Aquatic Inventories Project Stream Habitat Distribution Coverages. Natural Production Section. Corvallis. Oregon Department of Fish & Wildlife.

Oregon Water Resources Department. 2001. Water rights information system (WRIS) and points of diversion (POD) databases. http://www.wrd.state.or.us/

Osborne, L.L. and Wiley, M.J. 1988. Empirical Relationships Between Land Use/Cover and Stream Condition in an Agricultural Watershed. *Environmental Management* 26:9-27.

Park, C. 1993. SHADOW: stream temperature management program. User's Manual, v. 2.3. USDA Forest Service. Pacfic Northwest Region.

Parker, F.L. and P.A. Krenkel. 1969. Thermal pollution: status of the art. Rep. 3. Department of Environmental and Resource Engineering, Vanderbilt University, Nashville, TN.

Rishel, G.B., Lynch, J.A. and E.S. Corbett. 1982. Seasonal stream temperature changes following forest harvesting. *J. Environ. Qual.* 11:112-116.

Roth, N.E., Allan, J.D and Erikson, D.L. 1996. Landscape Influences on Stream Biotic Integrity Assessed at Multiple Spatial Scales. *Landscape Ecology* 11:141-156.

Rykken, J.J., S.S. Chan, and A.R. Moldenke. 2007. Headwater Riparian Microclimate Patterns under Alternative Forest Management Treatments. *Forest Science* 53(2) 270-280.

Sellers, W.D. 1965. Physical Climatology. University of Chicago Press. Chicago, IL. 272 pp.

Sinokrot, B.A. and H.G. Stefan. 1993. Stream temperature dynamics: measurement and modeling. *Water Resour. Res.* 29(7):2299-2312.

Steedman, R.J. 1988. Modification and Assessment of an Index of Biotic Integrity to Quantify Stream Quality in Southern Ontario. *Canadian Journal of Fisheries and Aquatic Sciences* 45:492-501.

United States Forest Service. 2001. Wallowa-Whitman National Forest Existing Vegetation GIS Coverage. http://www.reo.gov/waw/.

Wunderlich, T.E. 1972. Heat and mass transfer between a water surface and the atmosphere. Water Resources Research Laboratory, Tennessee Valley Authority. Report No. 14, Norris Tennessee. Pp 4.20.

Zelt, R.B., Brown, J.F. and Kelley, M.S. 1995. Validation of National Land-cover Characteristics Data for Regional Water Quality Assessment. *Geocarto International* 10:69-80.