CHAPTER 4. TEMPERATURE

Key Points:

- This chapter presents an analysis of the factors that affect stream temperatures in the Scott River and its tributaries.

- Regional Board Staff identified five factors influenced by human activities in the Scott River watershed that have affected, or have a potential to affect stream temperatures. The five factors are: stream shade, stream flow via surface diversion, stream flow via changes in groundwater accretion, channel geometry, and microclimate.

- Regional Water Board staff investigated the effects of human activities using a stream temperature model. Stream temperature model applications were developed for the Scott River, South Fork Scott River, East Fork Scott River, and portions of Houston and Cabin Meadows creeks.

- The analysis of factors affecting the temperature of the Scott River and its tributaries indicate that human activities have resulted in significant increases in temperature in many areas of the watershed, small to modest increases in other areas of the watershed, and that removal of vegetation could cause temperature increases in the future.

- The mainstem Scott River has been drastically altered over the past 170 years. During that time the following changes have occurred:
  - The beaver population has been dramatically reduced.
  - The river has been straightened and levees have been built.
  - Flows have been diverted.
  - The extent and quality of riparian forests has been drastically reduced.
  - A number of periods of increased sediment loads have occurred.

- The primary human-caused factor affecting stream temperatures in the Scott River watershed is increased solar radiation resulting from reductions of shade provided by riparian vegetation.

- Groundwater inflows are also a primary driver of stream temperatures in Scott Valley. The temperature of the Scott River is affected by groundwater in two ways.

Key Points, continued:

First, groundwater accretion directly affects stream temperature by direct addition of cold water, changes in volume, and transit time. Second, the elevation of groundwater affects the ability of riparian tree species to thrive and reproduce, which indirectly affects stream temperatures by increasing exposure to solar radiation.

- Diversions of surface water lead to relatively small temperature impacts in the mainstem Scott River, but have the potential to affect temperatures in smaller tributaries, where the volume diverted is large relative to the total flow. Effects of surface diversions on stream temperatures may be significant when effects of human activities are considered cumulatively.
- Microclimate alterations have the potential to increase stream temperatures. The magnitude of such increases is small to moderate.
- This TMDL uses effective shade as a surrogate measure of solar loading.
- Current and potential effective shade estimates were developed at the watershed-scale using a computer model. The results of the modeling exercise provide an estimate of the loading capacity of the watershed, and were used to develop load allocations at the watershed level. The results should not be used to define load allocations at the site-specific level.
- The temperature TMDL for the Scott River watershed is the adjusted potential effective shade conditions for the date of the summer solstice, as expressed in Figure 4.34 and Table 4.10.
- Further study is required to better understand the interaction of groundwater and surface water.
- Stream temperature conditions are expected to benefit from actions taken to reduce sediment loads.

4.1 INTRODUCTION

This chapter presents the supporting technical analysis for the Scott River Temperature TMDL. The analysis investigates the factors that determine stream temperature conditions in the Scott River and its tributaries. The analysis was developed using the best available information.

The objective of this analysis is to evaluate and quantify the impacts of human activities on the temperature of the Scott River and its tributaries, and to provide an understanding of stream heating processes so that sources of the impairment can be effectively addressed. Specifically, the analysis addresses the following questions: "Have water temperatures been altered by human activities?", and "Have water temperatures been increased more than 5^{o} F?" These questions must be answered to evaluate current conditions in relation to the Water Quality Objective for Temperature (see Table 2.1).

Please note that all figures and tables for this chapter are located towards the end of this Staff Report.

4.1.1 Temperature Sources: Stream Heating Processes

Water temperature is a measure of the total heat energy contained in a volume of water. Stream temperature is the product of a complex interaction of heat exchange processes. These processes include heat gain from direct solar (short –wave) radiation, both gain and loss of heat through long-wave radiation, convection, conduction, and advection, and heat loss from evaporation (Brown, 1980; Beschta et al., 1987; Johnson, 2004; Sinokrot and Stefan, 1993; Theurer et al., 1984).

- Net direct solar radiation reaching a stream surface is the difference between incoming radiation and reflected radiation, reduced by the fraction of radiation that is blocked by topography and stream bank vegetation (Sinokrot and Stefan, 1993). At a given location, incoming solar radiation is a function of position of the sun, which in turn is determined by latitude, day of the year, and time of day. During the summer months, when solar radiation levels are highest and streamflows are low, shade from streamside forests and vegetation can be a significant control on direct solar radiation reaching streams (Beschta et al., 1987). At a workshop convened by the State of Oregon's Independent Multidisciplinary Science Team, 21 scientists reached consensus that solar radiation is the principal energy source that causes stream heating (Independent Multidisciplinary Science Team, 2000).

- Heat exchange via long-wave radiation at a stream surface is a function of the difference between air temperature and water surface temperature (Sinokrot and Stefan, 1993;

ODEQ, 2000). Long-wave radiation emitted from the water surface can cool streams at night. Likewise, long-wave radiation emitted from the atmosphere and surrounding environment can warm a stream during the day. During the course of a 24-hour period, heat leaving and heat entering a stream via long-wave radiation generally balance (Beschta, 1997; ODEQ, 2000).

- Evaporative heat losses are a function of the vapor pressure gradient above the stream surface and wind conditions (Sinokrot and Stefan, 1993). Evaporation tends to dissipate energy from water and thus tends to lower temperatures. The rate of evaporation increases with increasing stream temperature. Air movement (wind) and low vapor pressures (dry air) increase the rate of evaporation and accelerate stream cooling (ODEQ, 2000).

- Convection describes heat transferred between the air and water via molecular and turbulent motion. Heat is transferred from areas of warmer temperature to areas of cooler temperature. The amount of heat transferred by this mechanism is generally considered low (Brown, 1980; Sinokrot and Stefan, 1993).

- Conduction is the means of heat transfer between the stream and its bed. In shallow streams, solar radiation may be able to warm the streambed (Brown, 1980). Bedrock or cobbles on the streambed may store heat and conduct heat back to the water if the bed is warmer than the water (ODEQ, 2000). Likewise, water can lose or gain heat as it passes through subsurface sediments during intra-gravel flow through gravel bars and meanders. Bed conduction is a function of the thermal conductivity of the bed and the temperature gradient within the bed (Sinokrot and Stefan, 1993). A streambed that has absorbed radiant energy during the day will conduct that energy back to the stream at night.

- Advection is heat transfer through the lateral movement of water as stream flow or groundwater. Advection accounts for heat added to a stream by tributaries or groundwater. This process may warm or cool a stream depending on whether a tributary or groundwater entering the stream is warmer or cooler than the stream.

Each of the heat fluxes discussed above can be represented by mathematical equations. By adding the values of the fluxes for a particular location, the net of the heat fluxes associated with all of these processes can be calculated (Theurer et al., 1984; Sinokrot and Stefan 1993). The net heat flux represents the change in the water body’s heat storage. The net change in storage may be positive, leading to higher stream temperatures, negative, leading to lower stream temperatures, or zero such that stream temperature does not change.

Of the processes described above, solar radiation is most often the dominant heat exchange process. In some cases and locations advection has a great effect on stream temperatures by diluting heat loads via mixing of colder water. Although the dominance of solar radiation is well accepted (Johnson, 2004; Johnson, 2003; Sinokrot and Stefan 1993; Theurer et al., 1984), some studies have indicated that air temperatures are the prime determinant of stream temperatures. These studies have based their conclusions on correlation rather than causation (Johnson, 2003). Air and water temperatures are generally well correlated, however correlation does not imply causation. Heat budgets developed to track heat exchange consistently demonstrate that solar radiation is the dominant source of heat energy in stream systems (Johnson, 2004; ODEQ, 2002; Sinokrot and Stefan, 1993). Stream temperature modeling conducted as part of this analysis (described below), confirms that solar radiation is the dominant heat exchange process in the Scott River watershed (Figures 4.1A-D). The analysis also demonstrates that heat exchange from air to water via convection is a minor component of the heat budget.

The conclusion that solar radiation is the dominant source of stream temperature increases is supported by studies that have demonstrated both temperature increases following removal of shade-producing vegetation, and temperature decreases in response to riparian planting. Johnson and Jones (2000) documented temperature increases following shade reductions by timber harvesting and debris flows, followed by temperature reductions as riparian vegetation became re-established. Shade loss caused by debris flows and high waters of the flood of 1997 led to temperature increases in some Klamath National Forest streams (de la Fuente and Elder, 1998). Riparian restoration efforts by the Coos Watershed Association reduced the MWAT of Willanch Creek by 2.8 ^{o}C (6.9 ^{o}F) over a six-year period (Coos Watershed Association, undated). Miner and Godwin (2003) reported similar successes following riparian planting efforts.

4.1.2 Stream Heating Processes Affected by Human Activities in the Scott River Watershed

Regional Water Board staff identified five factors influenced by human activities in the Scott River watershed have affected, or have a potential to affect stream temperatures. The five factors are:

- Stream shade
- Stream flow via changes in groundwater accretion
- Stream flow via surface diversion
- Channel geometry
- Microclimate

4.1.2.1 Stream Shade

Direct solar radiation is the primary factor influencing stream temperatures in summer months. The energy added to a stream from solar radiation far outweighs the energy lost or gained from evaporation or convection (Beschta and others, 1987; Sinokrot and Stefan 1993; Johnson, 2004). Because shade limits the amount of direct solar radiation reaching the water, it provides a direct control on the amount of heat energy the water receives.

Shade is created by vegetation and topography; however, vegetation typically provides more shade than topography. The shade provided to a water body by vegetation, especially riparian vegetation, has a dramatic, beneficial effect on stream temperatures. The removal of vegetation decreases shade, which increases solar radiation levels, which, in turn, increases stream temperatures. Additionally, the removal of vegetation increases ambient air temperatures, can result in bank erosion, and can result in changes to the channel geometry to a wider and shallower stream channel, all of which also increase water temperatures.

4.1.2.2 Groundwater

Ground water accretion affects temperatures in a number of ways. Most importantly, groundwater accretion provides a stream with a cold source of water that dilutes the thermal energy in the stream (advection). This dilution increases a stream's capacity to assimilate heat. Additionally, groundwater accretion increases the volume of water, which increases the thermal mass and velocity of the water. Thermal mass refers to the ability of a body to resist changes in temperature. Basically, more water heats or cools slower than less water. Increases in velocity reduce the time required to travel a given distance, and thus reduces the time heating and cooling processes can act on the water. These principles are true for any stream, however because the Scott River gains so much of its volume from groundwater accretion in most years (see discussion in section 4.3.1.7), the processes that groundwater accretion influences are particularly effective at limiting stream temperatures.

Water use in Scott Valley is intense. The major human uses of the water are irrigation of alfalfa and other hay crops, irrigation of pasture, watering of livestock, and domestic needs. The great demand for water resulted in the adjudication of water rights in 1980. Unfortunately, the adjudication does not establish minimum instream flows for aquatic life. The US Forest Service does have a junior water right for instream fisheries and recreation flows downstream of Scott Valley, but the requirements are rarely met.

The Scott River Adjudication was the first in California to recognize the linkage between groundwater and surface water. In fact, new legislation was required (resulting in water code section 2500.5) to allow ground water resources to be included in the adjudication.

Unfortunately, the adjudication only recognized a narrow zone of the aquifer as being interconnected with surface water. The interconnected zone is defined in the adjudication as follows (Superior Court of Siskiyou County, 1980):

> Interconnected ground water means all ground water so closely and freely connected with the surface flow of the Scott River that any extraction of such ground water causes a reduction in the surface flow in the Scott River prior to the end of a current irrigation season.

The aquifer characteristics and groundwater-surface water dynamics of Scott Valley are poorly understood. The degree to which water use affects groundwater accretion cannot be determined from the available information. The analysis is complicated by the fact that, while groundwater pumping undoubtedly contributes to a drawn down aquifer, irrigation and leaky ditches must also contribute some amount of recharge.

The Scott River Adjudication allows for irrigators to switch from surface water to interconnected ground water, provided that any new wells are located at least 500 feet from the Scott River, or at the most distant point from the river on the land that overlies the area of interconnected groundwater, whichever is less. The only restriction placed on the use of interconnected groundwater is that the water pumped shall be used for irrigation of crops overlying the "Scott River ground water basin" in amounts reasonable for the acreage irrigated. The adjudication does not address groundwater use outside the interconnected zone.

A human-related factor not related to water use that has negatively affected the water table is the incision of the river channel. In 1938, the US Army Corps of Engineers constructed levees, and straightened and channelized the Scott River throughout the middle part of Scott Valley. Many landowners have subsequently rip-rapped the river banks, which has kept the river channelized. Additionally, the removal of a diversion dam in the mid 1980s resulted in a knick-point that has since migrated upstream and further lowered the channel bed. One effect of these channel changes is that with the stream channel lower, the water table drops faster and further during the dry season. Consequently, the aquifer is unable to store as much water compared to the un-incised channel condition. In essence, the river acts as a drain, and the channel incision makes it a more effective drain. A second effect is that the river does not flood as frequently, which reduces groundwater recharge.

There are a number of issues related to drawdown of the Scott Valley aquifer that do or may affect water quality and stream habitat:

1. Dewatered Channel. This is the most severe impact related to drawdown of the Scott Valley aquifer. In dry years the water table is lower than the bottom of the river channel and

consequently the river water percolates into the aquifer to the point that there is no continuous flow. The Scott River went dry for long stretches in 1924, 1977, 1991, 1994, 2001, 2002, and 2004. Pumping groundwater can contribute to drawdown of the aquifer. However, the river would likely go dry in severe droughts, even without pumping. (Channel dewatering can also be affected by channel aggradation as a result of increased sediment loads.)

2. Temperature Impacts. In normal water years the river is a gaining system. The ground water that enters the Scott River is relatively cold (approximately 58 ^{o}F) and has a cooling effect on the river. The temperature modeling results indicate that the amount of groundwater entering the Scott River has a profound effect on its temperature.

3. Migration Impacts. The depletion of groundwater also affects the ability of adult salmonids to access reaches of the river and tributaries they use for spawning during the fall of dry years. Adult chinook salmon often begin their migration prior to the beginning of the rainy season and before the end of the irrigation season. In dry years, river flows do no rebound even after irrigation ceases. During those dry years, there are insufficient flows to allow the fish to pass some stretches of the river in the canyon downstream of Scott Valley. The Scott River Watershed Council has identified fall flows as a limiting factor affecting salmonids in the Scott River watershed.

4. Riparian Impacts. The rapid lowering of the Scott Valley water table may interrupt the natural succession of riparian tree species and hinder the success of riparian planting projects. Basically, the issue is whether trees can grow roots fast enough to keep up with the drop in water table elevation. Riparian shade is critical for maintenance of natural stream temperatures.

The available data pertaining to ground water conditions in the Scott River mostly consist of a few reports that characterize the aquifer and subsurface sediments in broad terms. The only readily available data that provide a glimpse of recent groundwater conditions are water table measurements at five wells in Scott Valley. Analysis of these data shows that in general drawdown is greater in dry years. The water table measurements for one of the wells are presented in Figure 4.2.

4.1.2.3 Surface Water

Surface water diversions affect stream-heating processes by reducing advection, reducing thermal mass, and increasing travel time. The diversion of water often has a similar but opposite affect of that of groundwater accretion.

4.1.2.4 Channel Geometry

The geometry of a stream channel affects stream temperature processes in a number of ways, at multiple scales. The primary changes in channel geometry that affect stream heating processes are changes in width-to-depth ratios, sinuosity, and streambed complexity (e.g. side channels, deep pools, topographic relief). All of the stream heating processes described in section 4.1.1 are affected by channel geometry to some degree.

A stream's width-to-depth ratio influences stream heating processes by determining the relative proportion of the wetted perimeter in contact with the atmosphere versus the streambed. Water in contact with the streambed exchanges heat via conduction. Conductive heat exchange has a moderating influence, reducing daily temperature fluctuations. Water in contact with the atmosphere exchanges heat via evaporation, convection, solar radiation, and long-wave radiation. Heat exchange from solar radiation far outweighs heat exchange from evaporation, convection, and long-wave radiation, unless the stream is significantly shaded. The net effect of changes in width-to-depth ratios is that streams that are wider and shallower heat and cool faster than streams that are narrower and deeper.

The sinuosity (degree of meandering) of a stream channel can influence stream heating processes in alluvial areas by affecting the amount of intra-gravel flow (hyporheic exchange). In sinuous stream channels, a portion of the water flowing in the channel will pass through the sediments and short-circuit the meanders. The water that passes through the sediments loses heat to the earth through conduction, and re-enters the stream channel cooler than before.

The complexity of the streambed can also influence stream heating processes by affecting the amount of intra-gravel flow, and can lead to the existence of pockets of cold water through stratification of deep pools and hyporheic-fed side channels. Stream channels with greater complexity have deeper pools, more prominent riffles, and back-watered side-channels. The difference in elevation between a pool and riffle determines the amount of water passing through the riffle gravels. Thus, streams with prominent pool-riffle morphology exchange more heat via conduction than flat, simplified stream channels.

4.1.2.5 Microclimate

Microclimate is a phenomenon that results from the separation of air masses. In well-vegetated riparian areas, the mass of air directly over the stream is often effectively separated from the overlying air mass by vegetation, which limits the flow and mixing of air. This separation of air masses can lead to significant differences in air temperature, relative humidity, and wind speed between the near stream air and the overlying air. Removal of riparian vegetation can lead to increased air temperatures, decreased relative humidities, and increased wind speeds.

Air temperature, relative humidity, and wind speed both affect convection and evaporation processes. During warm periods convection typically warms a stream, whereas evaporation cools a stream. The amount of heat exchange that results from convection and evaporation depends on all three microclimate factors. Increased air temperature typically increases the rate of convective and evaporative heat exchange. Decreased relative humidity increases the rate of evaporative heat exchange, but decreases the rate of convective heat exchange. Increased wind speeds increase both evaporation and convection by transporting heat and water vapor away from the stream. It is possible that changes in vegetation inside and/or outside of the riparian area can result in microclimate changes that significantly influence stream temperatures.

4.2 METHODS

4.2.1 Sources of Information

Information used in the development of the temperature analysis came from a variety of sources. Much of the information used in the analysis was developed specifically for the analysis, either by Regional Water Board staff or by entities under contract.

Much of the data used in the development of the temperature model applications was collected during the summers of 2003 and 2004 by Regional Water Board staff. These data included:

- Eighty-nine flow measurements at thirty-two sites,
- Forty-three water temperature records,
- Thirty-four meteorological records,
- Bankfull geometry measurements at twenty sites,
- One hundred fifteen effective shade measurements.

Other supporting data and analysis were developed by the Information Center for the Environment (ICE) at UC Davis, under contract to the Regional Water Board. The analysis and data included a shade model developed for the Scott River watershed, and a Thermal Infrared Radiometry (TIR) survey by Watershed Sciences, LLC, funded through the same contract.

Regional Water Board staff coordinated temperature monitoring activities with the Siskiyou RCD and the USFS. These agencies collected and provided temperature data at thirty sites in the summer of 2003, in addition to a large amount of temperature data from previous years.

Other primary data used in the temperature analysis included habitat typing data provided by the Siskiyou RCD and US Fish and Wildlife Service, flow data obtained from the USGS and

California Department of Water Resources (CDWR), and meteorology data obtained from CDWR.

4.2.2 Approach and Model Selection

The approach used to evaluate and quantify the impacts of human activities in the Scott River and its tributaries relies on the use of computer simulation models. Stream heating processes are inherently complex and non-linear. The degree to which one factor can impact stream temperature is dependent on the state of the other factors involved, and vice versa, thus it is difficult or nearly impossible to quantify the impacts of a single factor without tools that can take into account all the factors at once and evaluate the non-linear relationships involved.

Many computer simulation models have been developed to approximate solutions to the non-linear differential equations that govern stream-heating processes. However, not all stream temperature models are suited for evaluating the particular factors that human activities affect in the Scott River watershed.

To evaluate the five factors identified, Regional Water Board staff selected the Heat Source temperature model. Heat Source is a computer model designed to simulate dynamic mass and heat transfer in streams and rivers. The model is designed to make use of high-resolution spatial data, as well as field measurements. Heat Source calculates a thermal budget at every calculation node along the stream length, and for each time step. The distance between calculation nodes and length of time steps are user-defined. In this analysis, the distance between calculation intervals was 100 meters (328 feet) in all simulations, and the length of time steps varied between one and five minutes. The Heat Source model reports results for every hour of the simulated period. For further information regarding Heat Source, refer to "Analytical Methods for Dynamic Open Channel Heat and Mass Transfer: Methodology for Heat Source Model Version 7.0" (Boyd and Kasper, 2003). The Heat Source documentation is available at http://www.deq.state.or.us/wq/TMDLs/WQAnalTools.htmHeat Source.

The Heat Source model was chosen because it was designed to evaluate the five identified factors (and others) for the purpose of evaluating the effects of human activities. Also, the Heat Source model represents the state of the art in temperature models, has been peer-reviewed, and uses the same approach used to develop temperature TMDLs throughout the Pacific Northwest. Additionally, the Heat Source model has a well described methodology, was designed to make use of high-resolution data, and makes use of a commonly available software platform (Microsoft Excel) that makes it more broadly accessible and user-friendly for other potential users. Other temperature models, such as SNTEMP, Qual2E, and the TVA model, were considered but rejected because none of them simulate the complexity of stream heating processes as well as Heat Source. Also the other models considered have a cumbersome user interface in comparison to Heat Source.

Heat Source requires compilation of a great amount of spatial data. The Oregon Department of Environmental Quality developed the TTools to automate sampling and derivation of spatial data for use in the Heat Source temperature model. Regional Water Board staff also made use of the TTools ArcView extension to organize land cover data and measure channel widths, elevations, and spatial coordinates. TTools also calculates channel gradient, stream aspect, and the angle to the topographic and vegetation horizons. TTools and its calculation methods are described in detail in the Heat Source documentation (Boyd and Kasper, 2003). The parameters required by Heat Source are presented in Table 4.1.

Finally, the RipTopo model (described in Appendix A) was used to evaluate current and potential shade conditions in areas of the Scott River watershed where the Heat Source model was not applied. The RipTopo model uses the same general approach to estimating stream shade as the Shade-a-lator shade model, which is included with the Heat Source model package.

4.2.3 Collection and Use of Stream Temperature and Meteorology Data

Stream temperature and meteorology data were used to develop and calibrate computer simulation models of the selected river stream segments. Stream temperature and meteorology data from multiple sources were used in the source analysis. Regional Water Board staff and contractors, US Forest Service staff, and Siskiyou Resource Conservation District staff collected stream temperature data used in the analysis. Regional Water Board staff collected meteorology data at many locations. Data from the Callahan and Quartz Hill weather stations were also used.

Stream temperature data were specifically used to define boundary conditions and evaluate the accuracy of the models. Data describing air temperature, relative humidity, and wind speed also were used to define local weather conditions required as input to the model. Meteorology from the nearest or most appropriate source was used when site-specific data was unavailable (see Table 4.2).

4.2.4 Collection and Use of Infrared Imagery

The Regional Water Board funded a thermal infrared remote radiometry (TIR) survey of the Scott River and select tributaries (Watershed Sciences, 2004) in support of this study. On July 25 & 26, 2003, Watershed Sciences, LLC conducted aerial TIR surveys of the Scott River, East Fork Scott River, South Fork Scott River, Shackleford Creek, and the lower reaches of Kidder Creek. The imagery was collected using side-by-side video and infrared cameras. The survey yielded temperature measurements of approximately half-meter resolution, in images that captured an area approximately 140 m – 193 m (459ft - 635ft) on the ground, depending on flight altitude. The accuracy of TIR data was better than +/- 0.5^{o}C (0.9^{o}F), based on temperatures measured at the time of the flight. Watershed Sciences subsequently processed the thermal information into longitudinal profiles, a GIS database, and other data products. A complete description of Watershed Sciences' methods, measurement accuracy, and findings are available in their 2004 report (Appendix B).

The survey yielded a tremendous amount of information related to the temperature dynamics of the areas surveyed, as well as high-resolution color imagery. Regional Water Board staff used the thermal data to identify areas of groundwater accretion (the influx of groundwater to a stream), identify springs and seeps, identify stream diversions, calculate tributary flows, and validate the temperature models.

Areas of groundwater accretion are identified in the longitudinal temperature profiles as areas showing cooling or reduced rates of warming. Some examples of this are the pronounced cooling at the downstream end of Scott Valley, and the dip in temperature downstream of Young's dam. Springs and seeps are identifiable in the infrared imagery by their thermal contrast and, in some cases, cold water plumes. For model input, unmeasured tributary flows were often calculated using the mass balance equations shown below.

$$Q_{\text{upstream}} \times T_{\text{upstream}} + Q_{\text{tributary}} \times T_{\text{tributary}} = Q_{\text{downstream}} \times T_{\text{downstream}}$$
$$Q_{\text{upstream}} + Q_{\text{tributary}} = Q_{\text{downstream}}$$

(Q denotes flow and T denotes temperature.)

Given that the downstream flow is equal to the sum of the tributary and upstream flows, and the three temperatures are known from the infrared imagery, only one flow is required to solve for the remaining two values.

4.2.5 Rectification and Use of Color Imagery

Regional Water Board staff used the color imagery collected by Watershed Sciences, LLC to develop a spatial database of stream and riparian attributes. The color images captured during the TIR survey were merged into mosaics, which were then georeferenced, and rectified (aligned with digital maps) using digital orthophoto quads for reference. These rectified images were used to digitize the stream center, wetted widths, and riparian land cover extending 300 feet from the stream. The digitized stream and riparian features were then used to develop information for use in the Heat Source model using the TTools ArcView extension. Examples of rectified imagery are presented in Figures 4.3A –4.3D.

4.2.6 Mapping and Classification of Land Cover

Mapping included digitization of the stream center, stream banks, and land cover up to 300 feet on both sides of the stream. The land cover was digitized to capture visually like land cover types. Land cover types include: seventeen types of native vegetation, pasture, roads, structures, open water, and gravel bars. Vegetation characterizations included type (conifers, deciduous, and mixed), height, and density. Each land cover type was assigned a numeric code describing the species, density, and height of vegetation. Water board staff relied on low-level oblique aerial photos, and species and height measurements collected by staff during field surveys, during the assignment of the numeric codes. Vegetation densities where estimated from the aerial images. Examples of classified land cover are presented in Figures 4.3A –4.3D.

4.2.7 Collection and Use of Flow Data

Regional Water Board staff made 89 flow measurements at 32 sites as part of the data collection for this project. The majority of flow measurements were made using standard velocity-area methods using a tape and velocimeter, however in some cases flows were measured at culverts using a bucket and stopwatch or calculated from the geometry of the culvert and hydraulic principles. Regional Water Board staff also relied on stream gage data provided by USGS and CDWR. The flow data were used to estimate boundary condition flows and estimate rates of ground water accretion using standard mass balance techniques. Measured and estimated flows are presented in Table 4.3

4.2.8 Estimation of Stream Diversions

The Heat Source temperature model accounts for thermal effects of flow diversions. The amount of water diverted at Young's dam was estimated based on information provided by the Scott Valley Irrigation District. Stream diversions were estimated based on the adjudicated water rights associated with a given diversion. Diversions in the East Fork Scott River were estimated based on comparison of upstream and downstream conditions and professional judgment.

4.2.9 Measurement and Estimation of Channel Geometry and Morphology

Regional Water Board staff measured bankfull channel dimensions at twenty locations. These data were collected using a laser rangefinder and digital clinometer. The bankfull cross-sectional areas and widths were plotted against the drainage area for each site to develop relationships of bankfull cross-sectional area to drainage area (Figure 4.4), and bankfull width to drainage area (Figure 4.5). Bankfull channel measurements were used to estimate the channel widths as part of the RipTopo shade modeling (described in Appendix A), and to estimate the potential channel width of the modeled streams.

Modeled stream widths were developed in two ways. Wetted widths corresponding to current conditions were digitized and measured using the rectified color imagery and mapped channel dimensions. Widths were sampled at 100 meter intervals, based on the digitized wetted channel margins, using the TTools ArcView extension. Potential widths were developed as described in section 4.2.10, below.

Dominant particle sizes were estimated from staff observations and limited channel typing information. The information describing dominant particle sizes is used in the Heat Source computational scheme to calculate streambed heat conduction and hyporheic exchange.

4.2.10 Development of Potential Condition Scenarios

Regional Water Board staff have developed depictions of potential shade, flow, and channel geometry for use in evaluating potential stream temperature conditions.

4.2.10.1 Shade

Potential shade estimates were developed through the use of two models. The first model, RipTopo (discussed in Kennedy et al., 2005; attached), was used to estimate current and potential shade conditions in streams throughout the watershed. The second model, Heat Source, was used to evaluate potential shade conditions in the mainstem Scott River, South Fork Scott River, East Fork Scott River, and Cabin Meadows/Houston Creek modeling scenarios. RipTopo evaluates potential shade conditions by calculating a shade value based on mature tree heights of the tree species present, and estimates of channel width based on drainage area. Potential shade conditions in the mainstem Scott River, South Fork Scott River, and East Fork Scott River are based on both the mature height of the tree species historically present, as well as the potential width of the channel. Potential shade estimates developed for the Cabin Meadows/Houston Creek scenarios are based on the assumption that current and potential channel widths are the same.

Regional Water Board staff reviewed aerial photos of relatively undisturbed areas taken in 1944 to evaluate whether predicted potential shade conditions are reasonable. The 1944 aerial photos generally show dense vegetation growing along streams. In many cases the vegetation obscures the streams, providing high levels of shade. Based on these and similar observations of mature vegetation encountered during field surveys, Regional Water Board staff feel that the 1944 aerial photos provide validation of the potential shade conditions predicted by the shade models. It is worth noting that many of the upland areas appear more open than current forest conditions, however.

4.2.10.2 Flow

Potential flow conditions were estimated based on full natural flow, with no diversions. Because of the uncertainty regarding potential groundwater accretion rates, Regional Water Board staff evaluated groundwater accretion at a range of values to understand the magnitude of the effects of groundwater on stream temperatures.

4.2.10.3 Width

Potential channel widths were developed using the bankfull relationships described in Section 4.2.9 and a typical width-to-depth ratio for a C-type stream (24) (Rosgen, 1996). Regional Water Board staff assumed:

- The top width of the potential low flow channel of the Scott River would be half the bankfull width, based on a comparison of the wetted widths measured from imagery captured on July 25th and 26th, 2003, to the bankfull widths predicted by the relationship of bankfull width to drainage area (Figure 4.5).
- The potential channel dimensions of the Scott River upstream of the Scott River canyon correspond to a “C” type channel. The Scott River is currently an “F” type channel in this reach (Quigley, 2003).
- The wetted channel widths of July 25th and 26th, 2003, are representative of the top widths of the low-flow channel.
- The low-flow channel width-to-depth ratios are similar to the bankfull width-to-depth ratios.

4.2.10.4 Sinuosity

A hypothetical depiction of the Scott River was developed to represent the river as it was prior to the straightening that occurred in 1938 (SRWC, 2004). The hypothetical stream channel was developed from Fay Lane to Fort Jones. The purpose of the exercise was to evaluate the effects of channel straightening on stream temperatures. Regional Water Board staff used orthophotos to identify remnants of the channel that existed prior to the straightening. In some areas the former channel was easily identified, but in other areas the former channel was not apparent or many former channels were evident. Consequently, much of the channel was developed based on the judgment of Regional Water Board staff. Although the resulting channel alignment and sinuosity does not precisely depict the historic stream channel, the analysis has value because it defines the magnitude of temperature change that could be expected from a more sinuous channel. The increased sinuosity of the hypothetical channel resulted in an increase in channel length from 31.7 kilometers to 34.4 kilometers.

4.2.10.5 Combined Factors

Regional Water Board staff evaluated the combined effects of individual factors affected by human activities on Scott River temperatures. The magnitudes of stream temperature change related to the individual factors affected by human activities (shade, groundwater accretion, surface diversions, channel geometry) were initially analyzed separately to distinguish the importance of each of the factors. However, it is important to understand how the interactions of the individual factors affect stream temperatures. Regional Water Board staff developed three scenarios to evaluate the interaction of individual factors, and to evaluate the expected benefits of the combination of potential restoration measures under various conditions.

The first scenario is meant to define the temperature regime of the Scott River when all potential conditions are met. The scenario assumes a riparian forest of cottonwood, potential channel widths, potential sinuosity, and no diversions. Rates of groundwater accretion were left as estimated for the July 28 – August 1, 2003 time period due to the uncertainty of potential accretion rates.

The second scenario is meant to define the temperature regime of the Scott River when potential vegetation conditions are achieved and rates of groundwater accretion are increased. The scenario assumes a riparian forest of cottonwood with groundwater accretion rates set as 150% of the rates estimated for the July28 – August 1, 2003 time period. Channel widths, sinuosity, and diversions were left as currently depicted.

The third scenario is meant to define the temperature regime of the Scott River in a dry year when potential vegetation conditions are achieved but groundwater accretion is reduced to 25% of the rates estimated for the July28 – August 1, 2003 time period. The purpose of this scenario is to evaluate whether the water quality standard for temperature could be met solely by the achievement of potential vegetation conditions in dry years.

4.3 MODEL APPLICATIONS

Stream temperature models were developed for the mainstem Scott River, the South Fork Scott River, the East Fork Scott River, and Houston and Cabin Meadows creeks. The details pertaining to the development of individual model applications are presented below.

4.3.1 Scott River Mainstem

The Heat Source temperature model was used to simulate the stream temperatures of the Scott River from Fay Lane (RM 50.2) to the mouth of the river, as shown in Figure 4.6. The tailings reach of the river was mapped but was not included in this model application. The tailings reach was not included because the river goes dry for a large stretch of the tailings reach as river water infiltrates into the subsurface, and the infiltrated river water re-emerges in multiple locations that have not been characterized.

4.3.1.1 Boundary Conditions

The boundary condition locations of the Scott River temperature model are listed in Table 4.2 and shown in Figure 4.6. The upstream boundary is at Fay Lane (RM 50.2). The flow at Fay Lane were estimated based on one or more flow measurements at Fay Lane during each simulation period, with daily flow values adjusted based on the relationship between the flows measured at Fay Lane and the summation of the East and South Fork gage flows. Hourly temperature data collected at the site were used to define temperatures at the upstream boundary.

Boundary conditions were defined for twelve tributaries, as shown in Table 4.2 and shown in Figure 4.6. Flows were estimated based on measurements, comparisons with other nearby streams, and TIR data. Seven of the twelve tributaries had temperature data for the modeled time periods Table 4.2. The temperature of Boulder Creek was estimated to be 1.5 ^{o}C less than the temperature of Canyon Creek, based on comparison of summer temperature data collected in the two creeks from 1995 through 1997. The other tributaries (McCarthy, Big Ferry, Mill, and Franklin Creeks) were characterized using the unaltered temperature records of nearby streams. Given the small magnitude of the tributary flows relative to the mainstem, the model results are insensitive to the temperatures of these tributaries.

4.3.1.2 Channel Geometry and Substrate Representation

The channel geometry and substrate of the Scott River were characterized based on channel mapping, habitat typing data, cross sections, channel type, and observations made by Regional Water Board staff.

The channel widths were developed based on the mapped wetted widths of the river on July 25, 2003, the date of the FLIR survey. The wetted widths were then sampled at 100-meter intervals and recorded in a database using the TTools ArcView 3.2 extension. The decision to map wetted channel widths rather than widths of the near-stream disturbance zone, as described in the Heat Source documentation, was based on the assumption that the wetted widths would provide a better representation of the channel when modeled as a trapezoidal channel. The morphology of the Scott River is generally such that a low-flow channel exists within the larger bankfull channel during the summer months.

The width-to-depth ratios were assigned based on typical ratios for the respective Rosgen channel types (Rosgen, 1996). The river channel in Scott Valley was treated as an “F” type channel and assigned a width-to-depth ratio of 28. The river channel in the canyon area (downstream of the valley) was treated as a “B” type channel and assigned a width-to-depth ratio of 17. Regional Water Board staff assigned Rosgen channel types based on habitat typing surveys conducted by the Siskiyou RCD (2003).

The dominant particle size and embeddedness values, used in the Heat Source model to calculate bed conduction and hyporheic exchange, are based on observations made by Regional Water Board staff and limited substrate information reported in habitat typing data collected by the SRCD and USFWS in the valley and canyon reaches, respectively. The bed particle size and embeddedness values are presented in Figure 4.7.

Stream gradients were calculated for each node based on a 10-meter digital elevation model (DEM) using TTools. A full description of the methodology employed by TTools for the gradient calculation can be found in the Heat Source documentation (Boyd and Kasper, 2003). Stream gradients are presented in Figure 4.8.

The Manning’s “n” channel roughness coefficients were the parameters used to calibrate the model. These values were initially approximated based on the values reported in USGS Water Supply Paper 1849 (Barnes, 1967). The values were then adjusted so that width, depths and velocities were similar to measured and observed values, and the amplitude of the calculated diurnal change in stream temperature were similar to the measured values. The final values of Manning’s “n” are presented in Figure 4.9.

4.3.1.3 Flow Simulation

Regional Water Board staff developed estimates of tributary inputs, groundwater accretion, and surface water diversions as part of the model development. The hydrologic depiction of the Scott River was developed using a mass balance approach. The methods used to define the flows at tributaries and upstream boundary are described in the boundary conditions section, above.

The groundwater accretion estimates were developed based on measured flows at ten locations distributed throughout the modeled reaches. The change in flow rate between measured points, after subtracting tributary inputs and adding diversion withdrawals, was attributed to groundwater accretion. The measured and estimated flows are presented in Table 4.3; modeled stream flows are presented in Figure 4.10. The estimated rates of groundwater accretion are presented in Figure 4.11. Groundwater accretion was estimated and assigned to two locations, both near the mouth of Canyon Creek, based on TIR data and field observations of fisheries biologists (S. Maurer, personnel communication, 9-23-04, described by McFadin, 2006). In some cases the distribution of the groundwater accretion was estimated based on temperature trends observed in the TIR-derived longitudinal temperature profile.

Surface water diversions were estimated for the Scott Valley Irrigation District (SVID) and Farmer's Ditch diversions. The SVID has a water right that allows for 42 cfs to be diverted from the river. However, the river was flowing less than 42 cfs in both of the modeled time periods. The SVID diversion was estimated as 90% of the flow of the Scott River, based on information provided by the SVID. The Farmer's Ditch diversion is upstream of the reach modeled, but was estimated to account for changes in flow that would occur at the upstream boundary as a result of reduced diversions. The Farmer's Ditch diversion was estimated as the difference between the flow measured at Callahan and the estimated flow at Fay Lane.

The flow routing was modeled using the Muskingum-Cunge method, with a storage factor of 0.2.

4.3.1.4 Shade Simulation

Regional Water Board staff developed estimates of current and potential stream shade as part of the model development. The shade estimates were developed using the Shade-a-lator shade model, which is included with the Heat Source model package, and the TTools pre-processor. The inputs to the Shade-a-lator model are the mapped land cover and associated height and density estimates, and the 10-meter DEM. The Shade-a-lator model calculates shade from both vegetation and topography. A full description of the Shade-a-lator methodology is provided in the Heat Source documentation (Boyd and Kasper, 2003).

The estimates of current shade are based on current near-stream vegetation. The estimated current and potential effective shade values are presented in Figure 4.12. A comparison of measured and modeled shade values is presented in Table 4.4.

The potential near-stream vegetation depiction in the canyon reaches was developed based on the distribution and type of current vegetation. The potential vegetation was represented as the mature height of the current vegetation, with open areas represented as the mature condition of the vegetation surrounding them.

In the Scott Valley, historical changes in the near-stream vegetation distribution have been extreme, thus the current vegetation mapping was not useful for depicting potential vegetation. The potential near-stream vegetation depictions in the Scott Valley reaches were developed based on historical photos, vestigial trees, literature, and an assessment of potential Scott River watershed riparian conditions (Appendix A). The available historical photos, taken in the early 1900s, show a continuous riparian forest bordering the Scott River. In most of the photos the trees appear to be Black Cottonwood, although a photo of the river near Fort Jones indicates the river was bordered by a shorter species, most likely willows. Given the uncertainty, Regional Water Board staff modeled shade for a range of potential vegetation conditions. Regional Water Board staff developed a depiction of potential vegetation conditions that represents the potential riparian tree species height, density, and distribution, based on information contained in the assessment of potential Scott River watershed riparian conditions prepared by UC Davis ICE (Appendix A), and Lytle and Merritt (2004).

4.3.1.5 Meteorological Data

Meteorological conditions were characterized using air temperature data from six sites, relative humidity data from five sites, and wind speed data from three sites, as shown in Table 4.2. These data were distributed along the length of the modeled reaches, as shown in Table 4.5. Solar radiation intensity data from the Quartz Hill weather station was used to estimate cloud cover.

4.3.1.6 Model Calibration and Validation

The first application of the model was developed to represent the stream temperature conditions for the August 27 – September 10, 2003 time period. This time period was chosen because it was the time period with the most complete input and calibration data, and relatively constant flows. Although the Heat Source model represents dynamic mass and heat transfer, the groundwater accretion is represented as a constant, which necessitated a period of relatively constant flow. The model performance for the August 27 – September 10, 2003 time period is detailed in Table 4.6A. Charts of measured and modeled stream temperatures are presented in Appendix C.

The model was calibrated by adjusting values of Manning’s n. Manning’s n (channel roughness) is routinely determined by solving for the coefficient when all the other hydraulic variables (wetted dimensions, slope, and flow) are known. Because it is not subject to direct measurement (i.e. channel roughness can’t be measured, rather the effects of channel roughness are measured), and because it affects both wetted dimensions and travel time, it is a logical calibration parameter. In this analysis, the flows and wetted widths were known and some information describing velocities and depths was available, though they were not measured comprehensively. The remaining hydraulic variables, width-to-depth ratio and Manning’s n, were the only missing variables required to describe the hydrodynamics of the river. Regional Water Board staff used the estimates of width-to-depth ratios suggested in the model documentation for the given channel types, for lack of better data. The remaining variable, Manning’s n, was first approximated using best professional judgment so that initial model runs could be generated, then the variable was adjusted so that the modeled hydraulic conditions approached the measured hydraulic conditions. Although better results may have been possible by also adjusting the width-to-depth ratios, Regional Water Board staff decided to limit the subjectiveness of the calibration by limiting the calibration to only one parameter.

Once the calibration of the August 27 – September 10 model was complete, a second application of the model was developed for another time period. The second time period was chosen because it coincides with the date of many of the MWATs at sites in the Scott River and it is a relatively constant flow period between two spikes in the season's hydrograph. The model performance for the July 28 – August 1, 2003 time period is detailed in Table 4.6B.

There are differences in input values between the model applications representing the two time periods that go beyond the differences in observed conditions. Adjustments to input values were necessary because of data availability and changes in conditions between modeling periods. The first of these adjustments was in the number of calibration/validation data sets available. The July 28 – August 1 time period coincides with 17 data sets, whereas the August 27 – September 10 time period coincides with 20. Sixteen of the calibration/validation data sets were common to both time periods.

The second difference between the model representations of the two time periods was in the number of tributaries represented. The July 28 – August 1 time period simulates 12 tributaries, whereas the August 27 – September 10 time period simulates 10. The two tributaries, Big Ferry and Franklin Gulch creeks, were not included in the later time period because they had fallen below 1 cfs, an amount considered negligible when the river is flowing at 60 cfs.

The comparison of measured and simulated temperatures indicates that, on average, the model under-predicts temperatures from approximately Fay Lane to Fort Jones, over-predicts temperatures from Fort Jones to the USGS gage, and under-predicts again in the canyon. Upstream of Fort Jones the model results are out of phase with the measured temperatures by about two hours, with the simulated temperatures lagging the measured temperatures. The model results are in phase with the measured temperatures in the area near and below Fort Jones. The model is generally in phase with measured temperatures in the reach between Meamber Bridge and Jones Beach, but the model consistently predicts higher temperatures. Below Canyon Creek, the model results are generally in phase with measured temperatures, but the range of diurnal variation is higher in the simulated temperatures.

The model is out of phase with measured temperatures most likely because of differences between actual and simulated travel times. A discrepancy in travel times could be explained by any of the following factors:

1. Groundwater accretion was assumed to be evenly distributed between sites where flows were measured, which is not likely to be the case in reality.
2. The channel roughness coefficients (Manning's n) are mostly constant in the simulation. In reality the channel roughness would be expected to vary from reach to reach.
3. The width-to-depth ratios are mostly constant in the simulation. In reality the width-to-depth ratio varies from reach to reach.

The reason for the consistent bias at Meamber Creek and the USGS gage is most likely due to uncertainty in the magnitude and extent of groundwater accretion, which is known to be significant in the lowest part of the valley. The differences in measured and simulated temperatures below Canyon Creek may be due to differences between actual and modeled width-to-depth ratios, channel roughness, and Canyon Creek flows. The temperature of the Scott River in the lower canyon reaches is sensitive to the temperature and flow rate of Canyon Creek.

Despite the errors described above, Regional Water Board staff believe the model performance is adequate for evaluating the relative roles of management-related factors. This assessment is supported by the following facts:

1. The model predicts the same trends as seen in the measured temperature data during a wide range of weather, flow, and solar conditions.
2. The mean absolute error for the validation period ranged from 0.5 to 2.4 ^{o}C (0.9 to 4.3 ^{o}F), and averaged 1.1 ^{o}C (2.0 ^{o}F). Average bias of the daily average error for the validation period ranged from –1.9 to 2.1 ^{o}C (3.4 to 3.8 ^{o}F), and averaged -0.2 ^{o}C (-0.36 ^{o}F). The measures of error are similar to results of other stream temperature modeling efforts (Deas et al., 2003; Watercourse Engineering, 2003; ODEQ, 2002).
3. The performance of the model is similar in both time periods, which indicates the model performed consistently.

4.3.1.7 Results and Discussion

Groundwater Flow Scenarios

Regional Water Board staff evaluated the effects of groundwater accretion on Scott River temperatures. The Scott River Adjudication (Superior Court for Siskiyou County, 1980) recognizes the interconnection of groundwater and surface waters. Groundwater is the source of much of the irrigation water used in Scott Valley. Given the interconnectedness of groundwater and surface water, and the prevalent use of groundwater for irrigation, evaluating the effects of groundwater accretion on stream temperatures in the Scott River is necessary for evaluating impacts of management on stream temperature. Unfortunately, the Scott Valley groundwater resource has not been well studied. It is not possible to evaluate the degree to which ground water pumping has affected the rate of groundwater accretion at this time. It is possible, however, to evaluate the degree to which the rate of groundwater accretion affects stream temperatures.

To evaluate the degree to which the rate of groundwater accretion affects Scott River temperatures, Regional Water Board staff simulated Scott River temperatures with varying rates of groundwater accretion. The groundwater accretion rates measured in August of 2003 were used as a baseline condition. Regional Water Board staff varied groundwater accretion from 0% to 200% of the baseline condition in 25% increments. The resulting longitudinal profiles of temperature modeling results quantifying effects of groundwater accretion are shown in Figure 4.13.

The results illustrated in Figure 4.13 indicate that as groundwater accretion is reduced, both the rate of heating and cooling and maximum temperatures of the Scott River increase dramatically. As groundwater accretion decreases, the temperature of the river becomes more responsive to shade and cold tributaries. These results can be explained by the fact that groundwater enters the river at a cold temperature (57-67 ^{o}F), as well as the fact that a reduced rate of groundwater accretion results in a reduction of river flow. As flow volume increases, the rate of heating and cooling decreases. Simply put, more water takes longer to heat. It is logical then that because the majority of Scott River summer flow originates from groundwater, the rate of groundwater accretion greatly affects the total volume of the river, and thus, its rate of heating and cooling.

The results indicate that the temperature of the Scott River is very sensitive to the amount of groundwater entering the river. Given that groundwater is the source of the majority of the water that flows out of Scott Valley, this is not a surprising result. For instance, on August 27, 2003, the flow at Fay Lane was approximately 11 cfs, while at the same time the flow at Jones Beach was 34 cfs. Regional Water Board staff have estimated that tributary flows accounted for 2 cfs, while the rate of surface diversion was 17 cfs. This results in approximately 38 cfs discharged from the Scott Valley aquifer on that day. Although the amount of groundwater entering the river varies over the course of the season, flow measurements indicate that groundwater contributed the majority of the Scott River's flow at the downstream end of Scott Valley throughout the post-snow melt summer season. These conclusions are supported by the Scott River flow measurements reported in the State Water Resource Control Board's Report on Water Supply and Use of Water, Scott River Stream System (SWRCB, 1974).

Vegetation Scenarios

Regional Water Board Staff evaluated the effects of solar radiation (energy from the sun) on Scott River temperatures. Studies have confirmed that solar radiation is the single most important factor affecting water temperatures in rivers and streams (see discussion, page 4-2).

The two most common factors that affect the amount of solar radiation reaching a stream are shading by topography (mountains and canyons walls) and vegetation. The stream shade analysis takes into account both factors, and uses effective shade as an inverse surrogate for solar radiation. Effective shade is a measure of the percentage of direct beam solar radiation attenuated and scattered before reaching the ground or stream surface, and takes into account the differences in solar intensity that occur throughout a day.

Given the importance of shade in determining stream temperatures, and the fact that riparian vegetation provides shade, evaluating the effects of riparian vegetation on stream temperatures in the Scott River is necessary for evaluating impacts of management on the Scott River. Regional Water Board staff simulated the effects of riparian vegetation on stream temperatures by evaluating the degree of shading and resulting stream temperatures for a range of potential Scott Valley vegetation conditions. Vegetation conditions in the canyon reach of the river were modeled as the mature height of existing vegetation, except in the no vegetation scenario. The simulated potential riparian vegetation depictions are: no vegetation, willows, cottonwoods, ponderosa pines, and a depiction of potential vegetation conditions that represents the potential riparian tree species height, density, and distribution, based on information contained in the assessment of potential Scott River watershed riparian conditions prepared by UC Davis ICE. The average land cover heights depicted in the potential vegetation scenario for the Scott River mainstem are presented in Figures 4.14A and 4.14B for the left and right banks, respectively.

Figure 4.15 presents the longitudinal profiles of temperature modeling results, which quantify the effects of riparian vegetation on Scott River temperatures. The results indicate that riparian vegetation has great potential for reducing the temperature of the Scott River. All vegetation simulations indicate reductions in stream temperature, with the greatest reductions associated with the tallest vegetation. Table 4.7 presents current and potential 5-day average temperatures at monitored sites along the Scott River. The data indicate that some reaches of the Scott River mainstem would meet the non-core juvenile rearing temperature criteria presented in Table 2.8, given potential vegetation conditions. Although the criteria in Table 2.8 are based on 7-day averages, the values reported in Table 4.7 are comparable to these criteria since the five days modeled (July 28 –August 1, 2003) were the five days of 2003 in which water temperatures were the highest. In addition, these data and the stream temperature differences resulting from current and potential vegetation presented in Figure 4.16 clearly show that current stream conditions are not in compliance with the prohibition against temperature increases greater than 5 ^{o}F, stated in the Water Quality Objective for Temperature.

Surface Water Scenarios

Regional Water Board Staff evaluated the effects of surface water diversions on temperatures in the Scott River watershed. Simulations depicting stream temperatures that result from a range of stream diversion magnitudes were developed for the modeled reaches. The resulting longitudinal profiles of temperature modeling results, which quantify effects of changes in surface water diversions, are presented in Figure 4.17.

The results of the surface diversion analysis indicate that reduction of surface diversions from the Scott River would result in modest temperature decreases, relative to the groundwater and vegetation scenarios. However, it is important to consider the effects of surface water diversions when evaluating the cumulative impacts of human activities on stream temperatures.

Channel Geometry Scenarios

Regional Water Board Staff evaluated the effects that changes in stream channel width and sinuosity have on temperatures of the Scott River. Simulations depicting stream temperatures resulting from a range of channel widths were developed for the modeled reaches.

Figure 4.18 presents longitudinal profiles of temperature modeling results quantifying effects of changes in stream geometry. These results indicate that a reduction in channel widths alone would result in moderate reductions in the temperature of the Scott River. The analysis of the effects of channel straightening on temperatures of the Scott River indicates that the reductions in stream temperature associated with a more sinuous stream channel would not be significant. However, it is important to consider the effects of changes in channel geometry when evaluating the cumulative impacts of human activities on stream temperatures.

Combined Scenarios

Regional Water Board staff evaluated the combined effects of individual impacts of various factors affected by human activities on Scott River temperatures. The longitudinal profiles of temperature modeling results quantifying effects of combined scenarios are presented in Figure 4.19. The results of the combined impacts analysis indicate that much of the Scott River could provide summer habitat for juvenile salmonids in at least some years, and some reaches of the Scott River could provide summer habitat for juvenile salmonids even in drier years, if mature riparian vegetation were present. Additionally, the results clearly demonstrate that water quality standards are not being met.

The analysis clearly shows that mature riparian vegetation in and of itself does not prevent stream heating such that the water quality standard for temperature is met. Without improvements in other factors, such as water use and channel geometry, the beneficial uses of the Scott River will continue to be adversely affected by human activities, and thus the Scott River will not meet the water quality standard for temperature.

Discussion

Of the factors affected by human activities, two of the factors stand out as the most important:

- Shading by riparian vegetation, and
- Groundwater accretion.

These two factors affect stream temperatures differently.

Shade limits the amount of solar radiation reaching the water, and thus provides a direct control on the amount of thermal energy the water receives. The reduction in solar radiation results in a lower equilibrium temperature during the hottest parts of the day (which is why a container placed in direct sunlight will be a higher temperature then an identical container placed in shade).

Ground water accretion affects temperatures in a number of ways. Most importantly, groundwater accretion provides a stream with a cold source of water that dilutes the thermal energy in the stream. This dilution increases a stream’s capacity to assimilate heat. Additionally, groundwater accretion increases the volume of water, which increases the thermal mass and velocity of the water. Thermal mass refers to the ability of a body to resist changes in temperature. Basically, more water heats or cools slower than less water. Increases in velocity reduce the time required to travel a given distance, and thus reduces the time heating and cooling processes can act on the water. These principles are true for any stream, however because the Scott River gains so much of its volume from groundwater accretion in most years (see discussion in section 4.3.1.7), the processes that groundwater accretion influences are particularly effective at limiting stream temperatures.

Although shade and groundwater accretion are the two factors that appear to be the most significant, the other factors (surface water diversions and channel geometry) are not trivial and should be considered when evaluating the cumulative impacts of human activities. Diversions of surface water affect stream-heating processes in much the same way that groundwater accretion does. Diversion of surface water reduces the velocities and thermal mass of a river, which ultimately causes it to heat faster.

Changes in channel geometry affect stream temperatures in multiple ways. Increases in channel widths result in a shallower stream for a given flow condition, which results in more of the water being accessible to solar radiation. Conversely, narrower channels have less of their surface exposed to solar radiation.

4.3.2 South Fork Scott River

4.3.2.1 Boundary Conditions

The boundary condition locations of the South Fork Scott River temperature model are listed in Table 4.2 and shown in Figure 4.6. The upstream boundary is just upstream of the road 40N21Y bridge (RM 5.1). The upstream boundary flows were based on the South Fork at Callahan preliminary gage record and a relationship between the gage record and measured flows (Figure 4.20 presents the relationship of flow at the South Fork Scott River gage to measured flows at the upper model boundary). Hourly temperature data collected at the site were used to define temperatures at the upstream boundary.

Boundary conditions were defined for two tributaries, as shown in Table 4.2 and shown in Figure 4.6. Tributary flows were estimated based on FLIR data (calibration period) and preliminary South Fork gage flow data (validation period). Daily flow values were adjusted based on the change in the South Fork gage record. Temperature data was not available for either of the tributaries. The tributaries were characterized using the temperature data from the upstream boundary.

4.3.2.2 Channel Geometry and Substrate Representation

The channel geometry and substrate of the South Fork Scott River was characterized based on channel type, channel mapping, and observations made by Regional Water Board staff.

The channel widths were developed based on the mapped wetted widths of the river on July 26, 2003, the date of the FLIR survey. The wetted widths were then sampled at 100-meter intervals and recorded in a database using the TTOOLs ArcView 3.2 extension. The decision to map wetted channel widths rather than widths of the near-stream disturbance zone, as described in the Heat Source documentation, was based on the assumption that the wetted widths would provide a better representation of the channel when modeled as a trapezoidal channel. The morphology of the South Fork Scott River is generally such that a low-flow channel exists within the larger bankfull channel during the summer months.

The width-to-depth ratio of the South Fork Scott River stream channel was assigned a value of 24, based on the Rosgen channel type (Rosgen, 1996; Boyd and Kasper, 2003). The entire South Fork Scott river channel was treated as a “C” type channel.

The substrate and embeddedness values assigned to the South Fork Scott River were assigned using best professional judgment. The substrate size was assigned a single value of 96 millimeters for the entire reach, based on observations made by Regional Water Board staff. The embeddedness was assigned a value of zero. Regional Water Board staff have found that the model results are not sensitive to either of these parameters.

Stream gradients were calculated for each node based on a 10-meter digital elevation model (DEM) using TTOOLs. A full description of the methodology employed by TTOOLs for the gradient calculation can be found in the Heat Source documentation (Boyd and Kasper, 2003). Stream gradients are presented in Figure 4.21.

The Manning's "n" channel roughness coefficients was assigned a single value of 0.04 for the entire reach. These values were based on the values reported in USGS Water Supply Paper 1849 (Barnes, 1967). Unlike the mainstem Scott River model application, the South Fork Scott River model required no adjustment of the channel roughness coefficient for calibration.

4.3.2.3 Flow Simulation

Regional Water Board staff developed estimates of tributary inputs and surface water diversions as part of the model development. The hydrologic depiction of the South Fork Scott River was developed using a mass balance approach. The methods used to define the flows at tributaries and upstream boundary is described in the boundary conditions section, above. Groundwater accretion into the South Fork Scott River was assumed to be negligible, based on the confined channel morphology. Two surface water diversions were estimated based on the water rights information. The flow routing was modeled using the Muskingum-Cunge method, with a storage factor of 0.2 (Boyd and Kasper, 2003).

4.3.2.4 Shade Simulation

Regional Water Board staff developed estimates of current and potential stream shade as part of the South Fork Scott River model development. The shade estimates were developed using the Shade-a-lator shade model, which is included with the Heat Source model package, and the TTOOLs pre-processor. The inputs to the Shade-a-lator model are the mapped land cover and associated height and density estimates, and the 10-meter DEM. The Shade-a-lator model calculates shade from both vegetation and topography. A full description of the Shade-a-lator methodology is provided in the Heat Source documentation (Boyd and Kasper, 2003).

Potential shade estimates were developed based on depictions of potential near-stream vegetation. The estimates of current shade are based on current near-stream vegetation. The estimated current and potential effective shade values are presented in Figure 4.22.

The potential near-stream vegetation depiction in the South Fork Scott River was developed based on the distribution and type of current vegetation. The potential vegetation was represented as the mature height of the current vegetation, with open areas represented as the mature condition of the vegetation surrounding them.

4.3.2.5 Meteorological Data

Meteorological conditions were characterized using air temperature data and relative humidity data from two sites, as shown in Table 4.2. Data from the Callahan weather station was used to characterize wind speed. Solar radiation intensity data from the Quartz Hill weather station was used to estimate cloud cover.

4.3.2.6 Model Calibration and Validation

The first application of the model was developed to represent the stream temperature conditions for the July 26 – July 31, 2003 time period. This time period was chosen because it was the time period with the most complete input data, and because it was the time period when the water was the warmest. The model performance for the July 26 – July 31, 2003 time period is detailed in Table 4.8.

Once the calibration of the July 26– July 31, 2003 model was complete, a second application of the model was developed for the August 28 – September 10, 2003 time period. The second time period was chosen because it is late enough in the season that flows and shade were substantially different from the first time period. Unfortunately, there was no tributary flow data corresponding to the second time period. The tributary flows were estimated based on the change in flow between the time periods at the South Fork Scott River gage. The estimated flows are less reliable than those estimated from FLIR data in the first time period. The mean absolute error for the validation period ranged was 1.0 ^{o}C (1.8 ^{o}F). Average bias of the daily average error for the validation period was –1.0 ^{o}C (-1.8 ^{o}F). The model performance for both time periods is presented in Table 4.8 and Appendix C. The measures of error are similar to results of other stream temperature modeling efforts conducted in the basin (Deas et al., 2003; PacifiCorp, 2003; ODEQ, 2002), including those that have been developed as part of adopted TMDLs.

4.3.2.7 Results and Discussion

Vegetation Scenarios

The results of the riparian vegetation analysis, presented in Figure 4.23, show that small (<0.5 ^{o}C) differences in temperature would result from the achievement of potential riparian vegetation conditions in the modeled reach of the South Fork Scott River. These results suggest that riparian vegetation in the modeled reach of the South Fork Scott River is already near the

potential condition, as modeled. Other factors that may explain the similarities are the moderating influence of Boulder Creek and a relatively short travel time.
Surface Water Scenarios

The results of the surface diversion analysis, presented in Figure 4.23, indicate that diversions from the South Fork Scott River result in minimal temperature increases. The minor difference in model temperatures reflect the fact that the amount of water diverted from the South Fork is small relative to the total flow.

Discussion

The results of the analysis indicate that the modeled reach of the South Fork Scott River is near potential conditions, and the impact of surface diversions on stream temperatures is minor when conditions are as they were in the summer of 2003. It is possible that surface diversions could have more of an effect on stream temperatures in dry years when flows are lower. The impact of surface diversions on stream temperatures would increase as flows in the South Fork Scott River decreased.

4.3.3 East Fork Scott River

4.3.3.1 Boundary Conditions

The boundary condition locations of the East Fork Scott River temperature model are listed in Table 4.2 and shown in Figure 4.6. The upstream boundary is just downstream of Houston Creek (RM 14.0). The flow values were based on the East Fork at Callahan preliminary gage record and a relationship between the gage record and measured flows at the upstream model boundary (Figure 4.24). Hourly temperature data collected at the site were used to define temperatures at the upstream boundary.

Boundary conditions were defined for five tributaries, as shown in Table 4.2 and Figure 4.6. Flows were estimated based on FLIR data and preliminary East Fork gage flow data. Daily flow values were adjusted based on the change in the East Fork gage record. Temperature data was not available for any of the tributaries. The tributaries were characterized using the temperature data from a site on Rail Creek. The Rail Creek data was adjusted based on the difference between the FLIR measurement of the tributary and the Rail Creek record. Regional Water Board staff assumed that the difference between the FLIR-derived tributary measurements and the temperature of Rail Creek at the time of the measurement (4:00 pm) represented a reasonable approximation of the daily maximum temperatures difference at the sites. The differences ranged from 1.4 to 4.0 ^{o}C. Synthetic temperature records were then constructed for the five tributaries such that the absolute difference in maximum and minimum stream temperatures was equal to the difference between the FLIR-derived temperature and the temperature of Rail Creek.

4.3.3.2 Channel Geometry and Substrate Representation

The channel geometry and substrate of the East Fork Scott River was characterized based on channel type, channel mapping, and observations made by Regional Water Board staff.

The channel widths were developed based on the mapped wetted widths of the river on July 25, 2003, the date of the FLIR survey. The wetted widths were then sampled at 100-meter intervals and recorded in a database using the TTOOLs ArcView 3.2 extension. The decision to map wetted channel widths rather than widths of the near-stream disturbance zone, as described in the Heat Source documentation, was based on the assumption that the wetted widths would provide a better representation of the channel when modeled as a trapezoidal channel. The morphology of the East Fork Scott River is generally such that a low-flow channel exists within the larger bankfull channel during the summer months.

The width-to-depth ratio of the East Fork Scott River stream channel was assigned a value of 40, based on the professional judgment and observations of Regional Water Board staff, who noted that the East Fork Scott River was very wide and shallow in comparison to other streams.

The substrate and embeddedness values assigned to the East Fork Scott River were assigned using best professional judgment. The substrate size was assigned a single value of 64 millimeters for the entire reach, based on observations made by Regional Water Board staff. The embeddedness was assigned a value of 0. Regional Water Board staff have found that the model results are not sensitive to either of these parameters.

Stream gradients were calculated for each node based on a 10-meter digital elevation model (DEM) using TTOOLs. A full description of the methodology employed by TTOOLs for the gradient calculation can be found in the Heat Source documentation (Boyd and Kasper, 2003). Stream gradients are presented in Figure 4.25.

The Manning’s “n” channel roughness coefficients were assigned a single value of 0.06 for the entire reach. These values were based on the values reported in USGS Water Supply Paper 1849 (Barnes, 1967). Unlike the mainstem Scott River model application, the East Fork Scott River model required no adjustment of the channel roughness coefficient for calibration.

4.3.3.3 Flow Simulation

Regional Water Board staff developed estimates of tributary inputs and surface water diversions as part of the model development. The hydrologic depiction of the East Fork Scott River was

developed using a mass balance approach. The methods used to define the flows at tributaries and upstream boundary are described in the boundary conditions section, above.
Stream flows in the East Fork Scott River are complex. Thermal infrared imagery of the East Fork shows at least thirteen springs scattered along the length of the East Fork of the Scott River, eight of which were represented in the model application (the five remaining springs were identifiable, but deemed negligible). The spring flow rates were estimated using the FLIR data and mass balance techniques described in Section 2.3. The estimated flows ranged from 0.2 – 1.1 cfs. The temperatures of the springs were assigned the accretion temperature calculated by the model. The modeled stream flows of the East Fork Scott River are presented in Figure 4.26.

The East Fork Scott River hydrology reflects the intense irrigation practiced in the basin, in addition to the natural hydrologic complexity. Ten irrigation diversions were accounted for in the model application. Additionally, a number of sites were identified where tailwater (irrigation runoff) was re-entering the river. Water rights information was not helpful for defining diversion amounts because the water rights exceeded the estimated flow of the river. Instead, Regional Water Board staff estimated the rate of diversion by comparing the wetted dimensions of the channel upstream and downstream of the diversion, by estimating the efficiency of gravel dams, and by best professional judgment. Tailwater return flows were not accounted for in the model due to lack of data.

Groundwater accretion was used as a calibration parameter in this analysis. Accretion values were adjusted to ensure the simulated stream did not become dewatered, and to match the trends seen in the infrared data. The modeled groundwater accretion values are shown in Figure 4.27.

The flow routing was modeled using the Muskingum-Cunge method, with a storage factor of 0.2 (Boyd and Kasper, 2003).

4.3.3.4 Shade Simulation

Regional Water Board staff developed estimates of current and potential stream shade as part of the East Fork Scott River model development. The shade estimates were developed using the Shade-a-lator shade model, which is included with the Heat Source model package, and the TTOOLs pre-processor. The inputs to the Shade-a-lator model are the mapped land cover and associated height and density estimates, and the 10-meter DEM. The Shade-a-lator model calculates shade from both vegetation and topography. A full description of the Shade-a-lator methodology is provided in the Heat Source documentation (Boyd and Kasper, 2003).

Potential shade estimates were developed based on depictions of potential near-stream vegetation. The estimates of current shade are based on current near-stream vegetation. The estimated current and potential effective shade values are presented in Figure 4.28. In areas where the natural vegetation type is intact the potential vegetation was represented as the mature height of the current vegetation, with open areas represented as the mature condition of the vegetation surrounding them. In areas that have been converted to pasture, such as the areas upstream of Masterson road, the potential vegetation was simulated as mature Black Cottonwood, based on vestigial stands in the area.

4.3.3.5 Meteorological Data

Meteorological conditions were characterized using air temperature data and relative humidity data from two sites, as shown in Table 4.2. Data from the Callahan weather station was used to characterize wind speed. Solar radiation intensity data from the Quartz Hill weather station was used to estimate cloud cover.

4.3.3.6 Model Calibration and Validation

The East Fork model application was developed to represent the stream temperature conditions for the July 25 – July 31, 2003 time period. This time period was chosen because it was the time period that coincides with the infrared data, and because it was the warmest time period. The infrared data and associated imagery were relied on extensively during the model development and calibration process, due to a lack of on-the-ground data. Because of the complex hydrology of the East Fork Scott River and the paucity of data, a model application was not developed for another time period. The model performance for the July 25– July 31, 2003 time period is detailed in Table 4.9.

The results of the model calibration indicate that the model simulates the trends seen in the infrared and instream data. The error statistics presented in Table 4.9 indicate the model underestimates temperatures at both sites, with site two being underestimated considerably more than site one. The shade estimates that the Shade-a-lator model calculated for the reach between Masterson Road and Highway 3 are relatively high. Regional Water Board were denied access to this reach of the river, and the available oblique aerial photos only cover a small portion of the reach. Given that, the vegetation classification has greater uncertainty. Given the uncertainty associated with the vegetation mapping and the estimated flows and temperatures of the lower tributaries (Mule, Grouse, and Big Mill Creeks) and their great influences on downstream temperatures, it is not surprising that the model has less accuracy at Callahan site two.

4.3.3.7 Results and Discussion

Vegetation Scenarios

The longitudinal profiles of temperature modeling results quantifying effects of vegetation are presented in Figure 4.29. The results of the vegetation analysis indicate that the East Fork Scott River has great potential for reduced temperatures. These results indicate that the restoration of potential vegetation conditions could result in a decrease of daily maximum temperatures in the range of 2-6 ^{o}C, and suggest that current stream conditions may not be in compliance with the 5 ^{o}F limit on increased stream temperatures stated in the Water Quality Objective for Temperature. If temperatures were to decrease by 2-6 ^{o}C, much of the East Fork Scott River would improve substantially, and possibly achieve temperature conditions suitable for salmonid migration. The presence of springs also suggests that there is potential for thermal refugia with temperatures suitable for rearing.

Surface Water Scenarios

The longitudinal profiles of temperature modeling results quantifying effects of stream diversions are presented in Figure 4.29. The results indicate that diversions from the East Fork Scott River result in minimal temperature increases. The minor difference in modeled temperatures may reflect that the East Fork Scott River reaches equilibrium quickly regardless of whether the flows are unimpaired.

Discussion

The East Fork Scott River analysis indicates that temperature conditions could improve substantially if riparian areas were restored to their potential conditions. Although the modeling analysis of the East Fork Scott River presents a macro-scale depiction of temperature conditions, the analysis is not able to adequately evaluate the increase in cold water refugia that would accompany the increase in riparian vegetation near the thirteen springs identified in the TIR data. It is likely that an increase in shade would increase the volume of cold water habitat currently created by the springs.

This analysis does not quantify the effects of changes in tributary temperatures on temperatures of the East Fork Scott River. However, it is clear that tributaries such as Crater, Houston, Grouse, and Big Mill Creeks significantly influence the temperature of the East Fork Scott River. Restoration of potential vegetation conditions in these tributaries may provide additional temperature reductions in the East Fork Scott River.

The East Fork Scott River analysis was developed with much less instream data than the other analyses presented. A lack of data describing the flow rates of diversions, tailwater returns, tributaries and springs has resulted in more uncertainty in the model results. However, although there is more uncertainty associated with the East Fork Scott River model applications, the results are consistent with the findings of the other modeling exercises presented in this report.

4.3.4 Houston/Cabin Meadows Creeks

Regional Water Board staff developed an application of the Heat Source model that encompasses the reach of Houston Creek from its mouth at the East Fork Scott River to Cabin Meadows Creek (1.6 miles), then up Cabin Meadows Creek to the 41N03 road crossing, 2.2 miles upstream of Houston Creek. The approach used to develop the Houston/Cabin Meadows model application differed from the approach used to develop the other model applications due to the resolution of the available imagery.

4.3.4.1 Boundary Conditions

The boundary condition locations of the Houston/Cabin Meadows model application are listed in Table 4.2 and shown in Figure 4.6. The upstream boundary is just downstream of the 41N04 road crossing. The flow values were based on measurements made by Regional Water Board staff. Hourly temperature data collected at the site were used to define temperatures at the upstream boundary.

Boundary conditions were defined for two tributaries (upper Houston and Little Houston Creeks), as shown in Table 4.2 and Figure 4.6. Flows were estimated using the mass balance equations described in Section 2.3.6, based on estimates of upstream flows and temperature data from upstream, downstream, and within the tributaries.

4.3.4.2 Channel Geometry and Substrate Representation

The channel geometry and substrate of the modeled reaches of Houston and Cabin Meadows Creeks were characterized based on channel type, and measurements and observations made by Regional Water Board staff.

The upper half kilometer (RM 4.4 - 4.7) of Cabin Meadows Creek stream channel was represented as a B-type channel, with a width-to-depth ratio of 17. From RM 4.4 to RM 2.1, the channel was represented as an A-type channel, with a width-to-depth ratio of 8. Downstream of RM 2.1 the Cabin Meadows and Houston Creek channels were represented as a B-type channel, with a width-to-depth ratio of 17. These representations of the stream channels were based on gradient and field estimates of the wetted widths and depths.

The Manning's "n" channel roughness coefficients were assigned a value of 0.04 in the B-type channel reaches from RM 4.4 to RM 4.7, 0.2 in the A-type reaches (RM 4.4 to RM 2.1), 0.06 from R 2.1 to RM 1.1 and 0.04 downstream of RM 1.1. The values were assigned based on model performance, gradient, and observations of morphological characteristics.

The wetted channel widths were developed based on the relationship of bankfull width to drainage area described in Section 4.2.9. The approximation of channel widths assumed that wetted channel widths were half the bankfull width, based of field measurements.

The substrate and embeddedness values assigned to the modeled reaches of Houston and Cabin Meadows Creeks were assigned using best professional judgment. The substrate size was assigned a single value of 64 millimeters for the all reaches, based on observations made by Regional Water Board staff. The embeddedness was assigned a value of 0. Regional Water Board staff have found that the model results are not sensitive to either of these parameters.

Stream gradients were calculated for each node based on a 10-meter digital elevation model (DEM) using TTOOLs. A full description of the methodology employed by TTOOLs for the gradient calculation can be found in the Heat Source documentation (Boyd and Kasper, 2003). Stream gradients are presented in Figure 4.30.

4.3.4.3 Flow Simulation

Regional Water Board staff developed estimates of tributary inputs using a mass balance approach. The methods used to define the flows at tributaries and upstream boundary is described in the boundary conditions section, above. Groundwater accretion was approximated for only the upper 0.5 km (0.3 mi) of stream channel, the only reach in an alluvial setting.

4.3.4.4 Shade Simulation

Regional Water Board staff developed estimates of current and potential stream shade for the modeled reaches of Houston and Cabin Meadows Creeks. The shade estimates were developed using the Shade-a-lator shade model, which is included with the Heat Source model package, and the TTOOLs pre-processor. The inputs to the Shade-a-lator model are the mapped land cover and associated height and density estimates, and the 10-meter DEM.

High-resolution imagery was unavailable for the modeled reaches of Houston and Cabin Meadows Creek. Instead, the landcover mapping of the modeled reaches was developed based on digital orthophotos. Because the mapping is based on lower-resolution imagery, the uncertainty of the mapped landcover attributes is greater than in the other model applications.

The density of coniferous trees (primarily Pine and Cedar) in the modeled reaches of Houston and Cabin Meadows Creeks is less than the tree density of coniferous reaches (primarily Douglas Fir) in the other model applications, such as the canyon area of the mainstem Scott River and South Fork Scott River. The difference in tree density is reflective of the drier conditions found in the eastern areas of the watershed. The vegetation density was reduced from 60% to 25% in the higher density coniferous areas and from 30% to 10% in the lower density coniferous areas. These values were determined by comparison of modeled shade results with measured shade values.

4.3.4.5 Meteorological Data

Meteorological conditions were characterized using air temperature data and relative humidity data from five sites, as shown in Table 4.2. Wind speed data collected at the bottom end of the modeled reach was used to characterize wind speed for the entire modeled reach. Solar radiation intensity data from the Quartz Hill weather station was used to estimate cloud cover.

4.3.4.6 Model Calibration and Validation

The Houston/Cabin Meadows model application was developed to represent the stream temperature conditions for the August 2 – August 3, 2004 time period. This time period was chosen because of data availability. These are the only two days of data available for this reach.

The model performance is summarized in Table 4.10 and Appendix C. The results demonstrate that the model accurately predicts temperatures on both an hourly and daily basis. The measures of error are similar or better than results of other stream temperature modeling efforts conducted in the basin (Deas et al., 2003; PacifiCorp, 2003; ODEQ, 2002), including those that have been developed as part of adopted TMDLs. However, the model has not been validated with data from an independent time period.

4.3.4.7 Results and Discussion

Vegetation Scenarios

Regional Water Board staff did not develop a depiction of potential vegetation conditions for the Houston / Cabin Meadows model application. Staff did not prepare such an analysis because the resolution of the available imagery is not sufficient to depict a meaningful representation of current and potential vegetation. Regional Water Board staff traversed a significant portion of the modeled reaches (~ 25-35% of the total length). While traversing these reaches, staff observed large tree stumps near the banks of the creek in many of the reaches, and other reaches that appeared undisturbed. Many of the tree stumps were in locations where standing trees would have provided significant shade. Unfortunately, due to the resolution of the imagery, the distinction between the more and less disturbed areas was difficult or impossible to discern in the 1993 orthophotos.

Surface Water Scenarios

Regional Water Board staff evaluated the effects of stream diversions in the Houston / Cabin Meadows Creek stream system. There are currently no stream diversions in Houston or Cabin Meadows Creek. However, stream diversions were evaluated because other similar streams do have diversions, which can be inferred to have similar temperature impacts as those evaluated in this exercise. Regional Water Board staff simulated the effects of stream diversions by parameterizing the flow at the upstream boundary, in 25% increments. Longitudinal profiles of temperature modeling results quantifying effects of surface water flow are presented in Figure 4.31. The results of the surface diversion analysis indicate that diversions of water from small streams can lead to significant temperature increases. . The results presented in Figure 4.31 indicate that, given a 75% reduction in flow, an increase in temperature of 3 ^{o}C (5.4 ^{o}F) would occur 4.8 kilometers downstream of the simulated diversion. An increase of 3 ^{o}C clearly violates the water quality objective for temperature. A stream with less ambient stream shade would be expected to have more extreme temperature increases. Also, without the cool flows of Houston Creek, the reduction in surface flows would result in greater temperature increases downstream.

Evaluation of Forest Practice Rules Effects on Temperatures

Regional Water Board staff developed hypothetical scenarios in order to evaluate the effectiveness of the California Forest Practice Rules' (FPRs) measures for protecting stream temperatures. The analysis evaluated the effects of changes in both shade and microclimate conditions.

Because the pattern of vegetation in the Houston Creek watershed is relatively sparse, potential vegetation conditions are likely to result in less canopy cover than the minimum canopy retention specified in the FPRs. Also, the more sparse vegetation pattern may not result in a significant microclimate. Because of these considerations, Regional Water Board staff developed hypothetical depictions of mature forest conditions that would be expected in a high-density Douglas Fir-dominated environment, which typically has near-stream microclimates. This approach is meant to evaluate the adequacy of the FPRs in a worst-case scenario. Microclimate changes and/or reductions of riparian shade from timber harvest activities are not an issue in all harvest plans.

Regional Water Board staff developed hypothetical depictions of alterations to near-stream microclimate that could occur as a result of near-stream vegetation removal. The depictions were developed based on the magnitude of microclimate changes as reported in the literature (Bartholow, 2000; Brosofske, 1997; Chen et al., 1993; Chen et al., 1999; Dong et al., 1998;

Ledwith, 1996). Because of the variability reported in the literature, a range of microclimate alterations was evaluated.

Four depictions of meteorological conditions were developed as part of the analysis of microclimate effects on temperature. The depictions were developed by multiplying the measured wind speed and relative humidity data by a constant, and increasing air temperature by adding a constant. The constants used to develop the microclimate analysis are presented in Table 4.11. The depictions and the measured meteorological data,

The Houston Creek watershed naturally has a low vegetation density, which has been further reduced by timber harvesting. The meteorological data collected at the five sites monitored in 2004 (listed in Table 4.2) do not provide a good representation of the meteorological conditions associated with forest-stream microclimates in a more dense forest setting (e.g. Douglas Fir). Accordingly, a depiction of riparian microclimate was developed using the measured meteorological data.

The four depictions are meant to provide a range of possible microclimate alteration. The approach used to parameterize changes in microclimate assumes a constant shift. In reality, increases of air temperatures and wind speeds, and decreases of relative humidity resulting from reductions of riparian vegetation are greater in the mid-day than in the morning and evening. Given the approximate nature of the simulation of microclimate alteration, the results of the microclimate analysis should be interpreted accordingly.

Regional Water Board staff evaluated the temperature effects of riparian buffer requirements for both the standard rules, as well as the "Threatened and Impaired" (T&I) rules. The T&I rules apply to watercourses in planning watersheds where threatened species are present. Watercourses in the Scott River could fall under either of the rule sets, depending on whether the watercourse is in a planning watershed upstream of a barrier to salmonid migration.

The FPR stream canopy requirements for T&I waterbodies differ for class I and class II streams. For class I streams, defined as streams with fish always or seasonally present or streams that provide water for domestic use, foresters are required to retain at least 85 percent stream canopy within 75 feet of the stream, with 65 percent retained in the next 75 feet. Additionally, 25 percent of the existing overstory must be composed of conifer species and the 10 largest diameter conifers along any 330-foot stretch of stream must be retained. For class II streams, defined as streams providing aquatic habitat for nonfish aquatic species, foresters are required to retain 50 percent of the total canopy, with retention of 25 percent of the existing overstory conifer (Ch. 14 CA Code of Regulations, Section 916, available online at: http://www.fire.ca.gov/ResourceManagement/pdf/2005FPRulebook.pdf#page2).

The standard FPR stream canopy requirements allow for riparian canopies to be reduced to 50% for class I and class II streams, with the residual overstory canopy consisting of at least 25% of existing overstory conifers. The width of the canopy is required to be 75 feet to 150 feet for class I streams, and 50 feet to 100 feet for class II streams, depending on the slope of the ground.

The results of the analysis of the T&I rules indicate that a reduction from 95% to 85% canopy would not significantly affect stream temperatures of Houston / Cabin Meadows Creek. However, the results indicate temperature increases of approximately 0.5 ^{o}C may occur when combined with microclimate effects. Diurnal temperature modeling results quantifying effects of CA Forest Practice Rules' threatened and impaired riparian buffer requirements and potential microclimate effects are presented in Figure 4.32.

The results of the analysis of the standard FPR riparian canopy requirements indicate that a reduction from 95% to 50% canopy would significantly affect stream temperatures of Houston / Cabin Meadows Creek. The modeling results indicate temperatures would increase from 0.5 ^{o}C to 1.5 ^{o}C. When microclimate effects are taken into account temperatures may increase an additional 0.5 ^{o}C. Diurnal temperature modeling results quantifying effects of CA Forest Practice Rules' standard riparian buffer requirements and potential microclimate effects are presented in Figure 4.33.

The California Forest Practice Rules allow for reduction of stream canopy, as much as 50 percent in some cases. Although stream canopy and effective shade are different measures of riparian characteristics, effective shade is dependent on stream canopy, thus large reductions of stream canopy result in large reductions in effective shade in many cases. The Basin Plan's water quality objective for temperature states that temperatures of intrastate waters shall not be altered unless it can be shown that such an alteration does not impact beneficial uses. Our analysis of factors affecting stream temperatures has determined that reductions of stream shade cause increases in stream temperature. Therefore, the California Forest Practice Rules do not ensure that water quality objectives set in the Basin Plan will be met.

4.3.5 Conclusions of Model Applications

The analysis of factors affecting the temperature of the Scott River and its tributaries indicate that human activities have resulted in significant increases in temperature in many areas of the watershed, small to modest increases in other areas of the watershed, and that removal of vegetation could cause temperature increases in the future. The primary factor affecting stream temperatures is increased solar radiation resulting from reductions of shade provided by riparian vegetation. Groundwater accretion is also a primary factor affecting stream temperatures in Scott Valley. Diversions of surface water lead to relatively small temperature impacts in the Scott River, but add to the cumulative impacts of human activities and have the potential to significantly affect temperatures in smaller tributaries, where the volume diverted is large relative to the total flow.

The analysis of the effects that alteration of near-stream microclimates have on stream temperatures, while crude, indicates that microclimate alterations have potential to increase stream temperatures. The analysis results indicate that the magnitude of such increases is moderate. However, microclimate impacts may be more significant in some situations, and add to cumulative impacts of human activities.

4.4 TEMPERATURE TMDL AND ALLOCATIONS

This section presents the temperature TMDL and load allocations. The starting point for the analysis is the equation that describes the Total Maximum Daily Load or loading capacity:

$$\text{TMDL} = \Sigma\text{WLAs} + \Sigma\text{LAs} + \text{Natural Background}$$

where Σ = the sum, WLAs = waste load allocations, and LAs = load allocations. Waste load allocations are contributions of a pollutant from point sources while load allocations are contributions from management-related non-point sources.

Figure 4.34 shows the adjusted potential shade and current shade aggregated into cumulative frequency curves for the entire set of stream reaches included in the shade analysis. These curves are analogous to curves such as grain size distribution curves that show the percent of the grain size sample that is finer than a given grain diameter. In this case, the curves show the percent of the stream length in the watershed that is shadier than a given shade value. For instance, currently 50% of the stream length in the watershed has an effective shade index greater than 3.6, whereas the 50% of the stream length in the watershed is estimated to have an adjusted potential effective shade index greater than 6.3. Figure 4.35 presents the same information in a different format. Table 4.12 presents in tabular form the same information as Figures 4.34 and 4.35. The estimated adjusted potential shade conditions expressed in Table 4.12 constitute the temperature TMDL for the Scott River watershed.

4.4.1 Development of Pollutant Load Capacity and Surrogate Measures

Under the TMDL framework, and in this document, identification of the ‘loading capacity’ is a required step. The loading capacity represents the total loading of a pollutant that a water body can assimilate and still meet water quality objectives so as to protect beneficial uses. The water quality objective of concern is the temperature objective, which states that natural receiving water temperatures must be met. The loading capacity provides a reference for calculating the amount of pollutant reduction needed to bring a water body into compliance with standards.

This temperature TMDL is focused on the heat loads that arise from changes in streamside vegetation. Other controllable factors possibly influenced by human activities have been identified (i.e, changes in stream flow, microclimates, and channel geometry), but are not included in the TMDL at this time, due to a lack of information. However, these issues are addressed in the implementation actions described in Chapter 5. Regional Water Board staff expect that channel geometry issues will be resolved through reductions in sediment loads that result from implementation of the sediment TMDL. Temperature impacts that result from changes in microclimates will be addressed in the forthcoming Wetland and Riparian Protection Policy, currently under development. The lack of information related to groundwater and surface water interaction and water use is addressed in the implementation plan. Therefore, this temperature TMDL is based on heat loads that arise from changes in streamside vegetation. The temperature TMDL may require revision as hydrologic information becomes available.

To use the loading capacity that focuses on heat loads that arise from changes streamside vegetation, and to be able to compare it to current conditions, a surrogate measure of loading capacity is proposed. It is possible to relate heat load to effective shade (that shade resulting from topography and vegetation that reduces the heat load reaching a stream) and to relate effective shade to temperature conditions. Effective shade can be readily measured in the field and also can be calculated using mathematical equations. EPA regulations (40 CFR §130.2(i)) allow for the use of other appropriate measures (surrogate measures) to allocate loads for conditions "when the impairment is tied to a pollutant for which a numeric criterion is not possible…" (USEPA, 1998c).

For this temperature TMDL, the loading capacity is expressed as effective shade on the summer solstice. Effective shade is an inverse surrogate for solar radiant energy load. The percentage of effective shade represents a percentage reduction of the possible radiant energy load reaching the streams of the watershed during critical temperature periods. Effective shade is evaluated at summer solstice because it is the date at when the sun is highest in the sky and solar radiation loading is the greatest. The annual maximum stream temperature conditions generally occur about four to five weeks after the solstice.

In this analysis, natural effective shade is estimated as potential effective shade (based on fully mature trees growing along the bankfull channel of the streams) reduced by 10 percent to account for natural disturbances such as fire, windthrow, and earth movements that would reduce the actual riparian area vegetation below the site potential. This modified condition is referred to in this document as adjusted potential effective shade, and is the desired condition that meets the water quality objective for temperature and the TMDL.

There are no point sources of temperature within the Scott River watershed, thus the WLA is zero. Therefore, the TMDL loading capacity is equal to adjusted potential effective shade conditions and the associated solar loading. The TMDL equation becomes:

TMDL = Loading Capacity = Adjusted Potential Effective Shade

The loading capacity estimate uses a GIS model developed as part of the Scott River Temperature TMDL analysis (and described in Kennedy et al., 2005; attached) to approximate shade provided by potential vegetation conditions throughout the watershed. The GIS model also was used to estimate current effective shade conditions. These results were used to calculate adjusted potential effective shade. The difference between current and adjusted potential effective shade is the amount of effective shade increase and reduced solar loading that is required to restore beneficial uses.

4.4.2 Load Allocations

In accordance with EPA regulations, the TMDL (i.e., loading capacity) for a water body is to be allocated among the various sources of the targeted pollutant, with a margin of safety. The sum of the load allocations for individual locations in the watershed is equivalent to the loading capacity for the watershed as a whole. Allocations for point sources are known as wasteload allocations. Those for non-point sources are known as load allocations. There are no known point sources of heat into the Scott River and its tributaries.

The TMDL for temperature for the Scott River and its tributaries is distributed among the non-point sources of heat in the watershed, with a margin of safety. In this case, with the non-point sources being sunlight at the various streamside locations in the watershed, and with effective shade being used as a surrogate for solar energy, the establishment of load allocations equates to the identification of the effective shade requirement for any specific streamside location.

Site-specific potential shade is set as the legally required load allocation for the Scott River Temperature TMDL. The load allocations for this TMDL are the shade provided by topography and potential vegetation conditions at a site with an allowance for natural disturbances such as floods, wind throw, disease, landslides, and fire, and is approximated as adjusted potential shade conditions as described in Section 4.4.1. The results of the shade modeling exercises provide an approximation of potential effective shade conditions at the watershed scale. The adjusted potential effective shade conditions for the East Fork Scott River, South Fork Scott River, and mainstem Scott River were calculated from Shade-a-lator model results. Adjusted potential effective shade conditions for the rest of the stream reaches were calculated from the RipTopo model results. The results should not be used to define load allocations at the site-specific level.

The extent of streams in the Scott River watershed that have the potential to support the COLD beneficial use during the critical time periods was developed based on the perennial designation in the "srfish" stream database, and best professional judgment. The adjusted potential shade estimates are presented as an index, with values ranging from 0 (no shade) to 10 (complete shade). The distribution of adjusted potential shade index values, presented in Figure 4.36, is the TMDL load allocation.

4.5 SYNTHESIS

Based on the insights gained from this analysis, Regional Water Board staff have developed the following opinions and judgments related to stream temperatures of the Scott River and its tributaries.

4.5.1 Mainstem Scott River

The mainstem Scott River has been drastically altered over the past 170 years. During that time the following changes have occurred:

- The beaver population has been dramatically reduced,
- the river has been straightened and levied,
- flows have been diverted,
- the extent and quality of riparian forests has been drastically reduced,
- a number of periods of increased sediment loads have occurred.

All of the historic changes mentioned above have affected the temperature regime. Despite these changes, the mainstem Scott River is an important cold water resource that has great potential to contribute to the recovery of salmonid species.

Efforts to actively restore cold water habitats and reduce stream temperatures should proceed in a manner that takes into account the current hydrological setting. Efforts to re-establish riparian vegetation should begin in areas of high groundwater accretion, where the water table is within reach of the trees' roots. Areas of high groundwater accretion are:

- Downstream of the dredger tailings to approximately Etna Creek.
- From the valley/canyon transition upstream to approximately one-half mile upstream of the Quartz Valley Road bridge.
- Downstream of Kidder Creek an unknown distance (the TIR data indicates groundwater accretion, but accretion was not confirmed with flow measurements).

Efforts to re-establish riparian vegetation outside these areas may be limited by the rate at which the water table elevation drops during the growing season. These areas may not recover until changes in water use and management have occurred.

Efforts to restore floodplain processes in the dredger tailing reach downstream of Callahan should also take into account the great ability for this reach to exchange heat with the alluvial substrate. Thermal infrared data clearly demonstrate the pronounced cooling that occurs in this reach via hyporheic processes. A restoration design that includes side channels and other avenues for hyporheic exchange could create significant thermal refugia. In the intervening period, significant increases in cold water habitat volume could be created by enhancement of the west side channel.

The temperature of the Scott River is affected by groundwater in two ways. First, groundwater accretion directly affects stream temperature by direct addition of cold water, changes in volume, and transit time, as described in section 4.3.1.7. Second, the elevation of groundwater affects the ability of riparian tree species to thrive and reproduce, which indirectly affects stream temperatures by increasing exposure to solar radiation.

The degree to which water use affects the elevation of groundwater is unknown. Although groundwater pumping must affect water table elevations, percolation of irrigated water and leaky conveyance ditches must also partially offset pumping effects. A better understanding of groundwater dynamics is needed for future management of Scott Valley water resources. It may be that the aquifers of Scott Valley represent an opportunity to store more water for all uses. The interaction of groundwater elevation, riparian vegetation, and stream temperatures is clearly an area deserving more study.

4.5.2 Scott River Tributaries

Riparian shade is the most important factor affecting the temperatures of tributaries to the Scott River. The current riparian conditions of Scott River tributaries vary widely, due to differences in past and current management practices. In some areas the vegetation is at or near potential conditions, while in other tributaries riparian vegetation has been nearly eliminated.

Management of riparian areas in timber production zones has greatly improved in recent decades, although room for improvement still exists. The current Forest Practice Rules are not protective of stream temperatures in many situations. In addition, the assessment of the effects of timber activities on stream temperatures during the timber harvest planning process could be improved so that a project’s potential for altering stream temperatures could be more reliably evaluated.

Efforts to actively restore cold water habitats and reduce stream temperatures in Scott River tributaries should make use of the results of the shade modeling developed as part of this analysis. The shade modeling results can be used to identify areas that are well below potential conditions. When considered together with other pertinent factors, the RipTopo results could be used to develop a prioritized list of riparian restoration sites.

Debris flows related to road fills, stream crossings, and other management features are another factor affecting stream temperatures that is related to forest management activities. Debris flows often drastically reduce riparian shade for great distances downstream of the initial failure. Management-related debris flows that occurred during the flood of 1997 resulted in tremendous changes to riparian areas throughout the Klamath National Forest, including areas of the Scott River watershed (de la Fuente and Elder, 1998). In the Scott River watershed debris flows devastated riparian areas in Tompkins, Kelsey, and Houston Creeks. Efforts to abate the discharge of sediment will positively affect stream temperatures by reducing the risk of future debris flows.

Cattle grazing practices are an ongoing factor related to increased stream temperatures in some Scott River tributaries, particularly but not only in the eastern half of the watershed. In these areas, unrestricted grazing of riparian areas has resulted in a reduction of the density, succession, and vigor of riparian vegetation. Although past and current management in these areas has had a negative effect on riparian vegetation, management approaches have been developed that use grazing as a tool for managing riparian areas in a way that benefits the riparian vegetation, while increasing the available forage. These management approaches take into account the environmental requirements of the particular riparian species, as well as the behavior of cattle and sheep. Outreach efforts that promote these types of management approaches should be supported and encouraged.

4.6 RECOMMENDATIONS FOR ADDITIONAL STUDY AND FUTURE ACTION

- Reduce uncertainty of vegetation mapping in the East Fork Scott River between Masterson Road and Highway 3.
- Reduce uncertainty of vegetation mapping in the Houston / Cabin Meadows Creek model application.
- Complete the mainstem Scott River model development all the way to the East and South Forks.
- Work with stakeholders to develop and implement a Scott Valley groundwater study.
- Work with stakeholders to develop a list of high priority sites for riparian restoration, based on the Rip Topo results.
- Participate in the development and negotiation of Habitat Conservation Plans to ensure long-term planning efforts conform with water quality standards.
- Develop a strategy for addressing issues related to grazing in riparian areas.

- Support riparian grazing workshops where local range managers and other experts can exchange information on the latest techniques for managing riparian areas in rangelands.
- Work with agencies involved in flood response to identify areas of overlapping regulatory authority and develop coordination protocols.

4.7 MARGINS OF SAFETY AND SEASONAL VARIATION

The Clean Water Act Section 303(d) and the associated regulations at 40 CFR §130.7 require that TMDLs include a margin of safety that takes into account any lack of knowledge concerning the relationship between the pollutant loads and the desired receiving water quality. The margin of safety is often implicitly incorporated into conservative assumptions used in calculating loading capacities, waste load allocations, and load allocations (USEPA, 1991). The margin of safety may also be incorporated explicitly as a separate component in the TMDL equation. For this TMDL analysis, conservative assumptions were made that account for uncertainties in the analysis.

- This report analyzes temperature and sediment separately. Some improvements in stream temperature that may result from reduced sedimentation are not calculated explicitly. Reduced sediment loads could be expected to lead to increased frequency and depth of pools and to reduced wetted channel width/depth ratios. These changes tend to result in lower stream temperatures overall and in more lower temperature pool habitat. These changes are not accounted for in the analysis and provide a margin of safety.

- While the potential shade conditions used to calculate the loading capacity assume that the occurrence of potential vegetation at a site extends to the bankfull channel width, the effective shade curves can be applied to either current channel widths or to projected bankfull widths. Application of the curves to current channel conditions does not account for channel narrowing that may occur as a result of reduced sediment loads. These effects constitute a margin of safety.

- Changes in streamside vegetation toward larger, mature trees will increase the potential for contributions of large woody debris to the streams. Increases in large woody debris benefit stream temperatures and associated cool water habitat by increasing channel complexity, including the number and depth of pools. These changes were not accounted for in the analysis and provide a margin of safety.

With respect to seasonal variations in stream temperatures, the analysis takes the most extreme heating conditions as measured by the 7-day running average of temperatures as constituting a limiting condition for salmonid survival with respect to temperature. Additionally, the analysis evaluated thermal processes during the time of year when the streams are the hottest.