2.0 ANALYSIS OF TEMPERATURE

This section of the document presents an overview of temperature dynamics, drawing on the findings of temperature TMDL analyses and the body of scientific literature relevant to the topic of stream temperature. The discussion has undergone scientific peer review, as required by law. The three reviewers concurred with the scientific assumptions, assertions, and conclusions that this Policy reflects, although each had suggestions for strengthening the discussion. The discussion below reflects suggestions made by the reviewers. The peer reviewers' specific comments and Regional Water Board staff's response can be found in Appendix A of this document.

2.1 Identification of Drivers of Elevated Water Temperature

The sensitivity and response of stream temperatures to factors that drive them have been evaluated in temperature TMDL analyses completed in the North Coast Region. Figure 2.1 presents an example of such sensitivity analyses. Similar reach-scale sensitivity analyses were developed for the Mattole, Salmon, and Upper Lost River TMDLs. These sensitivity analyses were conducted using reach-scale temperature models and data representing site-specific conditions, represented as average values for the reach. The model calculates the temperature that results at the downstream end of the modeled reach based on the reach averaged inputs. The sensitivity of stream temperatures to driving factors over multiple reaches was also evaluated in both the Scott and Shasta River temperature analyses using deterministic temperature models that simulated temperature dynamics over many miles (NCRWQCB 2005, NCRWQCB 2006).

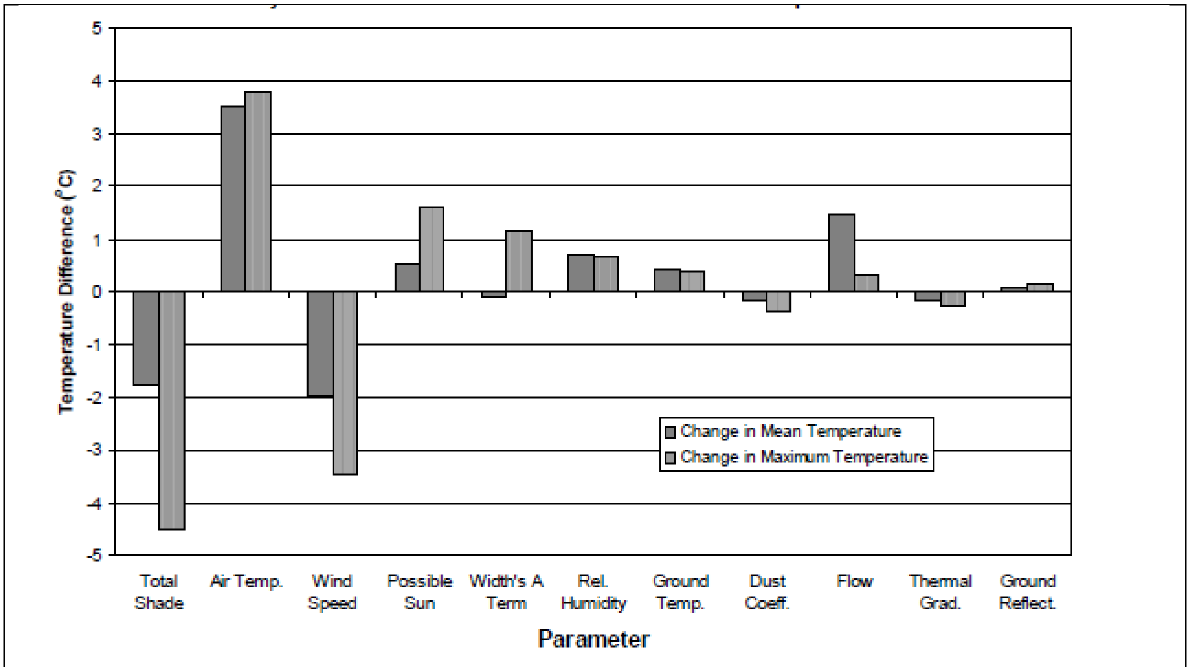

Figure 2.1: Results of a sensitivity analysis from the Navarro River temperature TMDL ranking temperature drivers (Source: NCRWQCB 2000)

The investigation of elevated stream temperatures in north coast streams points to a limited number of stream temperature factors that are directly affected by management activities. Figure 2.1 presents the results of an analysis examining the sensitivity of stream temperatures to the various factors acting to drive water temperature dynamics in the Navarro River watershed (NCRWQCB 2000). Of the factors that determine stream temperatures, shade and flow can be most directly affected by management activities. Air temperature, relative humidity, wind speed, ground temperature, width-to-depth ratio, channel roughness, and ground reflectivity can be indirectly affected by management activities, but generally do not cause temperature alteration of the same magnitude in response to changes in the values over the range that management actions most often create.

It should be noted that substantial changes in width-to-depth ratios and channel roughness can result in substantial temperature changes. Increased width-to-depth ratios primarily affect temperature through increased exposed surface area, which increases solar exposure. Increased channel roughness results in a deeper wetted channel, which often decreases width-to-depth ratios, thereby reducing solar exposure. Streams with greater depths are less sensitive to changes in temperature drivers than shallower streams (Herb and Stefan 2010). Increased channel roughness can also reduce the time of travel through a reach, which may have a cooling or warming effect depending on the characteristics of the reach.

2.2 Interaction of Temperature Drivers

Sensitivity analyses such as those mentioned above evaluate the significance of changes in individual temperature drivers well. Evaluating the interaction of multiple drivers is more complex; however their interaction can be more easily understood when considered in the context of equilibrium temperature.

A stream is considered in equilibrium with its surroundings when the sum of the heat fluxes equals zero (i.e., heat inputs and outputs are balanced) (Bogan et al. 2003, Mohseni et al. 2002). Essentially, the equilibrium temperature is the temperature a stream (or any body of water) will reach if given enough time to come into balance with its surroundings. A simple example of this concept is a glass of cold water placed in a warm room: given enough time, the water will reach the temperature of the room, and that temperature is the equilibrium temperature. Headwater stream temperatures reflect the temperature of their sources, such as snow melt, groundwater, or lakes. As water travels downstream, its temperature changes in response to its surroundings, trending toward the local equilibrium temperature.

The strongest driver of equilibrium temperature is air temperature, while shading, wind sheltering, and groundwater inputs are the greatest modifiers of the relationship of air temperature to equilibrium temperature (Bogan et al. 2003, Morrill et al. 2005, Mohseni et al. 2002). These facts are represented in the sensitivity analysis results shown in Figure 2.1. The model used to generate Figure 2.1, SSTEMP, calculates daily average water temperatures based in part on equilibrium temperatures. It is not surprising then, that the simulated reach, which is low in the Navarro system in a reach with little groundwater inputs, is calculated to be most sensitive to air temperature, shade, and wind speed. Despite the sensitivity of equilibrium temperature to air temperature and wind speed, solar radiation (which is represented in Figure 2.1 by total shade and possible sun) has been demonstrated to result in heat fluxes an order of magnitude higher than those associated with air temperature and wind speed (i.e., convection and evaporation), which explains why shade is so important for stream temperature control (Johnson 2004).

The equilibrium temperature is not constant, just as air temperature is not constant. While all stream reaches approach the equilibrium, many stream reaches do not reach the highest daily equilibrium temperature of the day before the equilibrium temperature drops as the air temperatures drop in the late afternoon and evening. Factors other than air temperature, such as shade, depth, flow, and groundwater inputs, determine how quickly a stream reaches the equilibrium temperature, and what that equilibrium temperature is in that reach (Mohseni et al. 2002, Bogan et al. 2004, Herb and Stefan 2010).

To summarize the discussion above:

1. Streams reflect the temperature of their sources (e.g., groundwater, snow melt, or lake temperatures) near their headwaters.
2. An equilibrium temperature exists that represents the temperature a stream will eventually reach, given the external temperature drivers don't change and enough time has passed.
3. Streams that are above or below the equilibrium temperature trend toward that equilibrium temperature.
4. Increasing shade, depth, flow, or groundwater inputs will slow the rate at which streams approach equilibrium.
5. Increasing solar radiation, or reducing flow and/or depth will increase the rate at which streams approach equilibrium.

Given the temperature dynamics described above, the ways in which the drivers of temperature interact becomes clearer. Air temperature determines equilibrium temperatures, and thus how hot a stream can be, while shade and flow determine how quickly a stream approaches the equilibrium, and thus how hot a stream actually becomes. A reduction in flow requires an increase in shade in order to maintain the same temperatures and vice versa. Also, increases in air temperature will result in increased water temperatures, with the magnitude of the increase dampened by higher shade and flow levels.

The water temperature dynamics described above have implications for the future, given the fact that global temperatures are increasing (Wu et al. 2012, Bartholow 2005). Climate is outside the control of the Regional Water Board. However, the factors that can lessen the impacts of climate change - shade, flow, and depth (to the degree that sediment loads and channel alterations affect stream depth) - can be managed. Given the forecasted changes in global climate, the protection of shade and flows and control of sediment loads becomes even more important for the protection of beneficial uses into the future.

Another practical implication of the discussion above relates to the preservation and restoration of shade. Preservation of shade is most important in stream reaches with temperatures far below the equilibrium temperature because they are the reaches the most susceptible to rapid heating. Newton's Law of Cooling states that the rate of temperature change is proportional to the difference in temperature, which is the difference between the stream temperature and equilibrium in these situations. Conversely, restoration of shade in reaches of stream that regularly reach or come near equilibrium temperatures is not likely to result in significant temperature changes until upstream reaches are addressed, and in some cases, such as wide high-order streams, the increased shade may only have a negligible effect, regardless, as described in more detail in section 2.3, below.

2.3 Additional Considerations

It is important to note that solar radiation loads are not always the primary controllable driver of elevated water temperatures in most waterways in the North Coast Region. For instance, some situations exist where vegetation is ineffective at increasing effective shade. High-order streams are often too wide relative to the height of vegetation to provide levels of shade that have a substantial temperature effect. The Klamath and Eel River Temperature TMDLs recognize this phenomenon and do not assign riparian shade load allocations for the mainstems. However, in these cases the shade provided by riparian vegetation may still be important for the maintenance of thermal refugia. In summary, increased solar radiation loads are likely to be the primary controllable driver of elevated water temperatures in most waterways in the North Coast Region, but aren't always.

In addition to the benefits of shade, riparian vegetation provides many other water quality benefits besides those associated with temperature, such as bank stability, nutrient and sediment filtering, and large woody debris recruitment (see section 5.2.2 for further discussion). These benefits are additional considerations that should be evaluated when the Regional Water Board evaluates projects that involve alterations to riparian vegetation, in addition to shade.

Another important consideration regarding temperature dynamics and compliance with temperature objectives involves scale, from both spatial and temporal perspectives. The intrastate water quality objective for temperature states "at no time or place" shall the temperature be increased by more than 5°F above natural receiving water temperature (see section 3.0). Some have questioned if there is a minimum scale of consideration that should be applied to the assessment of this objective. The objective doesn't explicitly state there are minimum dimensions that should be considered, however, the objective references adverse impacts to beneficial uses as the ultimate criteria. From a practical perspective then, the spatial scale of consideration is that which is relevant to the beneficial uses in question.

Staff have witnessed distressed juvenile steelhead gathered in high densities within a small volume of water colder than its surroundings as a result of hyporheic exchange through a gravel bar. In that case, the relevant spatial scale was small, yet the biological importance appeared to be very high.

Other issues of spatial and temporal scales involve the rate of physical and biological processes. One of the time scales most relevant to the recovery of temperature in previously impacted stream systems of the north coast is the rate of tree growth. In places where recovery of temperatures is dependent on the restoration of riparian shade, recovery occurs as fast as trees grow. Similarly, the impacts of large sediment pulses on stream morphology can persist for many decades. An example of this is the Eel River system where large volumes of sediment delivered in the 1955 and 1964 floods still remain in the active channel (USEPA 2007).

2.4 Temperature TMDL Analyses

A necessary step in the development of Total Maximum Daily Loads is the interpretation of water quality objectives. The intrastate water quality objective for temperature is the only temperature objective applicable to all of the TMDLs developed, and thus has been the focus of temperature TMDL development in the North Coast Region. The temperature TMDL analyses have consistently found that the shade provided by riparian vegetation has a dramatic beneficial effect on stream temperatures, and that achieving the intrastate water quality objective for temperature requires riparian shade consistent with natural conditions. This concept is the basis of TMDL load allocations prescribed in every north coast temperature TMDL. Similarly, north coast temperature TMDLs have also identified the alteration of channel geometry caused by elevated sediment loads as a factor that must be controlled in order to meet the intrastate water quality objective for temperature. Load allocations for sediment are absent from many north coast temperature TMDLs due to the fact that sediment TMDLs were developed concurrently for the same waterbodies. In those cases, the control of elevated sediment loads was identified in the temperature TMDL margins of safety. Additionally, some north coast temperature TMDLs have identified the role of hydrologic alteration as a causative factor that must be addressed in order to meet the intrastate water quality objective for temperature.

The technical approach to developing load allocations meeting the water quality objectives for temperature in north coast temperature TMDLs has varied among the 13 temperature source analyses, based on the situations present. However, the 13 temperature TMDL analyses share common elements. All of the temperature TMDLs have made use of temperature models to investigate temperature dynamics using locally derived data. Most temperature TMDLs also have made use of shade models that predict the incidence of shade on stream segments. Table 2.1 summarizes information pertaining to the development of the 13 temperature TMDLs completed in the North Coast Region to date.

2.4.1 Shade Analyses

Shade models have been used in the development of north coast temperature TMDLs to quantify the difference between current and potential stream shade conditions on both a watershed and reach scale. The products of the watershed-scale shade models - spatial databases of current and potential shade condition approximations - were used as the basis of TMDL load allocations (loads that meet the intrastate water quality objective for temperature). The watershed-scale shade models used in the development of north coast temperature TMDLs are simplified applications of the approach presented by Chen and others (1998a & 1998b), who developed the approach for the Upper Grand Ronde River (Oregon) Temperature TMDL.

The shade models used to determine north coast temperature TMDLs determine whether sunlight reaches a given segment of stream based on the location of the stream channel, the surrounding topography, attributes of the surrounding vegetation, and the path of the sun in the sky. The models calculate shade using readily available data describing ground elevations, stream hydrography, and vegetation present on the landscape (Boyd and Kasper 2003, Kennedy et al. 2005, Tetra Tech 2002). Information describing bankfull channel dimensions and the relationship of tree diameter to tree height was also collected and incorporated into the spatially explicit shade models.

The shade models used in the development of north coast temperature TMDLs provide a relative index of shade values in a spatially explicit manner. The models calculate the incidence of sunlight on a stream channel for each hour of the day, by determining whether sunlight is blocked by topography or vegetation at a given site and time of day. The daily score is the sum of the hourly scores, weighted by the relative magnitude of the solar load for each hour of the day.

The determination of whether sunlight is blocked by riparian vegetation is partly based on the assumed height of the vegetation, which in turn is based on relationships of diameter-at-breast-height (dbh) to tree height for the species of vegetation present. Information describing the species of vegetation at a given site is based on remotely sensed data describing vegetation distributions. Current vegetation heights were approximated based on the dbh of the species present in each grid cell, whereas the potential vegetation heights were based on the assumed mature height for the same species. The remotely sensed data used for these analyses include the Timber Task Force Klamath Province habitat database developed as part of the Klamath Region Vegetation Mapping Project and the CALVEG database developed by the USFS.

TMDL Assessment	South Fork Eel River	Navarro River	Mattole River	North Fork Eel River	Middle Fork Eel River	Upper Main Eel River	Middle Main Eel River	Lower Main Eel River	Upper Lost River	Salmon River	Scott River	Shasta River	Klamath River
Year	1999	1999	2001	2002	2003	2004	2005	2007	2004	2005	2005	2006	2009
Temperature Model	BasinTemp	SSTEMP	SSTEMP	Q2ESHADE	Q2ESHADE	Q2ESHADE	Q2ESHADE	Q2ESHADE	SSTEMP	SSTEMP	Heat Source	TVA	RMA-2, RMA-11, CE-QUAL-W2
Shade Model	Topquad	RipTopo	RipTopo	Q2ESHADE	Q2ESHADE	Q2ESHADE	Q2ESHADE	Q2ESHADE	n/a	SSTEMP	Heat Source	n/a	n/a
Vegetation Data Source	Klamath Bioregional Mapping Project	Klamath Bioregional Mapping Project	Calveg	Calveg	Calveg	Calveg	Calveg	Calveg	measured values	measured values	Calveg	measured values	n/a
Factors Identified	Shade, Sediment	Shade, Sediment, Flow	Shade, Sediment	Shade, Sediment	Shade, Sediment	Shade, Sediment	Shade, Sediment	Shade, Sediment	Delisted	Shade, Sediment	Shade, Sediment, Flow	Shade, Flow, Ag Return Flows	Shade, Sediment, Impoundments
Concurrent Sediment TMDL?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No
Lead agency (development)	USEPA	NCRWQCB	NCRWQCB	USEPA	USEPA	USEPA	USEPA	USEPA	NCRWQCB	NCRWQCB	NCRWQCB	NCRWQCB	NCRWQCB, ODEQ, USEPA

Table 2.1: Summary of North Coast Temperature TMDL development information

The first temperature TMDL developed in the North Coast Region was the South Fork Eel River Temperature TMDL (USEPA 1999). The temperature source analysis was conducted by Stillwater Sciences under contract to the USEPA and utilized a temperature model called the Stillwater Sciences Temperature Model, which in turn relied on a geographic information system (GIS) based method to calculate solar radiation reductions resulting from riparian vegetation and topography (Stillwater Sciences 1999). The solar radiation loads were then incorporated into a one-dimensional heat balance model (ibid). Figure 2.2 presents a graphical representation of the stream shade modeling approach.

The results of the South Fork Eel River temperature TMDL analysis demonstrated the importance of the shade provided by riparian vegetation for achievement of the intrastate water quality objective for temperature.

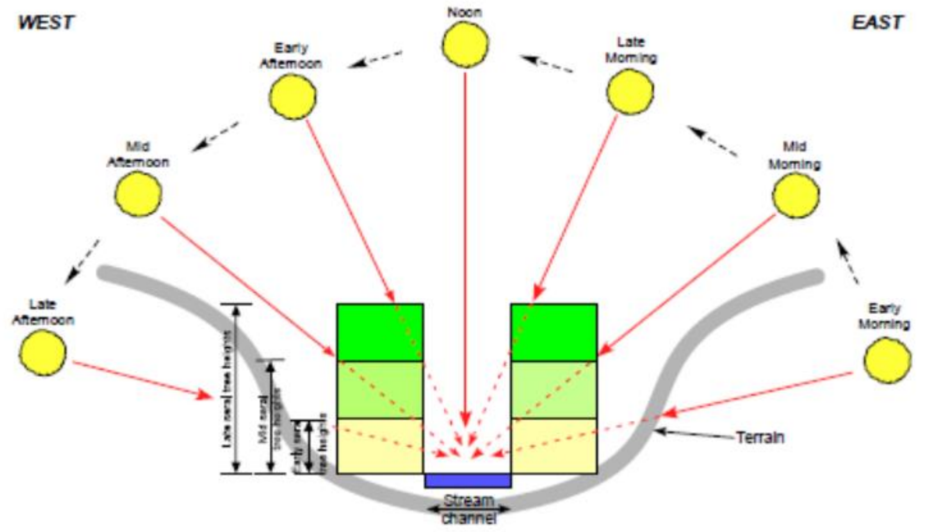

Figure 2.2: conceptual representation of riparian shade model. (Allen 2008)

The second temperature TMDL developed in the North Coast Region was the Navarro River Temperature TMDL (Navarro TMDL; USEPA 2000). The Navarro River temperature source analysis also identified the importance of shade provided by riparian vegetation for protection of stream temperatures. The Navarro River temperature source analysis was conducted by the NCRWQCB with assistance from the UC Davis Information Center for the Environment. The temperature source analysis utilized a riparian shade model called RipTopo, a GIS-based model much like the model developed by Stillwater Sciences for the South Fork Eel River Temperature TMDL (Kennedy et al. 2005). The Navarro TMDL also relied on the use of the USGS stream reach temperature model SSTEMP as a screening tool, as discussed above. The TMDL load allocations were set at the effective shade levels that represent potential vegetation conditions, based on the screening analysis conclusions. The RipTopo shade modeling results were the basis of the TMDL load allocations (NCRWQCB 2000, USEPA 2000).

The RipTopo model was later used for the Mattole River Temperature TMDL (NCRWQCB 2002, USEPA 2002a) and the Scott River Temperature TMDL (NCRWQCB 2005) in the same manner (defining TMDL load allocations) as in the Navarro TMDL. However, the Mattole River Temperature TMDL source analysis also estimated current and potential temperatures in nine tributary and three mainstem reaches using the SSTEMP model (NCRWQCB 2002), while the Scott River Temperature TMDL made use of the Heat Source temperature model to calculate stream shade and temperature approximations for the Scott River mainstem and three tributaries (Boyd and Kasper 2003, NCRWQCB 2005). The more sophisticated modeling approach was employed for the Scott River Temperature TMDL due to the more complex hydrology (i.e., effects of surface diversions, groundwater-surface water dynamics) present in that watershed. The Mattole River and Scott River temperature TMDLs also assigned temperature load allocations at levels corresponding to shade conditions representing potential vegetation conditions (USEPA 2003a, NCRWQCB 2005).

Five of the six of the Eel River basin temperature TMDL source analyses were developed by Tetra Tech, Inc., under contract to the USEPA (USEPA 2002b, USEPA 2003a, USEPA 2004, USEPA 2005, USEPA 2007). Tetra Tech developed a modeling system called Q2ESHADE for use in the temperature TMDL process (Tetra Tech 2002). The Q2ESHADE model combines the USEPA-supported QUAL2E hydrodynamic and water quality model with a shade modeling routine called SHADE, a GIS-based model formulated based on the model developed by Chen et al. (1998a) and applied to the Upper Grande Ronde River watershed (Chen et al. 1998b). The Q2ESHADE modeling system calculates hourly shade-attenuated solar radiation at various locations based on riparian vegetation characteristics and topographic relief, and utilizes these solar radiation loads to predict in-stream temperatures throughout a stream network (Tetra Tech 2002). The six temperature TMDLs developed in the Eel River basin assigned temperature load allocations at levels corresponding to shade conditions representing potential vegetation conditions based on the results of the modeling analysis (USEPA 2002b, USEPA 2003a, USEPA 2004, USEPA 2005, USEPA 2007).

The Klamath River temperature TMDL analysis also evaluated the impacts of shade on tributary temperatures. The Klamath tributary analysis relied on principles of stream thermal dynamics supported by scientific literature and the analyses and conclusions of previous temperature TMDLs, particularly those developed for the Salmon, Scott, and Shasta River, and assigned load allocation for effective shade at levels corresponding to shade conditions representing potential vegetation conditions accordingly (NCRWQCB 2010).

2.4.2 Hydrologic Analyses

The evaluation of temperature impacts associated with changes in hydrology was a major focus of both the Shasta River Temperature TMDL (Shasta TMDL) and Klamath River Temperature TMDL (Klamath TMDL). The Shasta TMDL analysis evaluated the effects of stream diversions, irrigation tailwater return flows, impoundments, and riparian vegetation on temperatures of the Shasta River. The analysis of impacts relied on an application of the Tennessee Valley Authority's River Modeling System (TVA-RMS) temperature model originally developed for the Shasta Valley Resource Conservation District's Shasta River Flow and Temperature Modeling Project (Deas et al. 2003, Deas 2005). The shade values depicting current vegetation conditions and represented in the model were based on riparian vegetation inventories and measurements conducted by UC Davis, Watercourse Engineering, and Regional Water Board staff. Potential solar transmittance values representing potential vegetation conditions were developed by Regional Water Board staff, with consideration of existing vegetation, channel geometry, and soil conditions (NCRWQCB 2006). The effects of tailwater return flows and stream diversions were also evaluated using the TVA-RMS model. Temperature load allocations corresponding to potential shade conditions, increased cold water flows of 45 ft^3/s, and zero thermal loading from tailwater returns were assigned based on the modeling exercise.

The Klamath TMDL analysis evaluated the effects of flow alteration and impoundments using a package of riverine hydrodynamic and water quality models (RMA-2 and RMA-11, respectively), coupled with a reservoir model (CE Qual-W2). The Klamath TMDL analysis evaluated the temperature impacts of altered tributary flows, altered mainstem flows, point sources, and reservoir operations on mainstem Klamath River temperatures. The analysis evaluated the effects of current and historic tributary flows on the temperature of the Klamath mainstem and determined that the tributary flows are too small to substantially alter the temperature of the much larger Klamath River in either the current or historic situation. The impacts of reduced flows from Upper Klamath Lake, the origin of the Klamath River, were also evaluated and found to have no appreciable effect on temperatures at the California-Oregon border.

The Upper Main Eel River Temperature TMDL and Middle Main Eel River Temperature TMDL also included an explicit evaluation of temperature effects associated with the Potter Valley Project, a Pacific Gas and Electric project that alters hydrologic conditions in the Eel River (USEPA 2004, USEPA 2005). That analysis determined that the impacts of the flow alteration were not impacting beneficial uses because the flows during the summer months under the 2004 FERC/NMFS flow schedule are of the same magnitude as unimpaired flows. EPA found that the current FERC/NMFS summer flow schedule likely results in stream temperatures cooler or nearly equal to the possible natural stream temperatures, and thus the FERC/NMFS flow schedule is projected to attain water quality standards.

The Scott River temperature TMDL source analysis explicitly evaluated the stream temperature impacts of reduced groundwater accretion. Regional Water Board staff used the Heat Source model to evaluate changes in stream temperature associated with both increases and decreases in the magnitude of groundwater accretion values based on measured flows and mass balances. The results of the analysis showed that the temperatures of the Scott River, which is primarily a groundwater dominated stream from July-September, are driven in part by the amount of groundwater entering the river as diffuse accretion.

2.4.3 Microclimate

Air temperature, wind speed, and relative humidity interact with one another to create microclimates associated with riparian corridors, and thus can affect stream temperatures. However, while these conditions are demonstrated to be factors indirectly affected by human activities, the information describing the magnitude of effects of human activities on microclimates indicate changes are relatively small and difficult to quantify (Bartholow 2000, Brosofske 1997, Chen et al. 1993, Chen et al. 1999, Dong et al. 1998, Ledwith 1996). Additionally, the types of changes in air temperature, wind speed, and relative humidity anticipated to arise from disturbance of riparian areas do not all act to increase stream temperatures. For instance, decreased relative humidity and increased wind speed, a likely result of riparian zone disturbances, act in concert to remove heat from a stream surface by increasing evaporation (Moore et al. 2005). Conversely, increased air temperatures that may result from riparian disturbances act to increase stream temperatures.

The magnitude of stream temperature impacts associated with changes in microclimate was explicitly evaluated in the Scott River TMDL analysis. In that TMDL analysis, a modeling exercise was conducted that evaluated the change in stream temperature resulting from a combination of changes in air temperature, relative humidity, and wind speed of magnitudes reported in the literature. The micro climate changes were represented in three scenarios that span the range of changes reported in the literature. The analysis results, presented in Figure 2.3, indicate that the magnitude of temperature alteration would be small, on the order of 0.5 ^{o}C or less, whereas the temperature alteration associated with changes in vegetative shade could result in changes of up to 1.5 ^{o}C over the same reach.

The impacts of elevated sediment loads are another factor identified as having the potential to elevate water temperatures. Elevated sediment loads, while not directly addressed in the sensitivity analysis presented in Figure 2.1, indirectly impact many of the factors evaluated by the sensitivity analysis. For instance, elevated sediment loads can result in increased channel widths. 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 incidence. Conversely, narrower channels have less of their surface exposed to solar radiation. Elevated sediment loads can also lead to the removal of vegetation that shades a watercourse, as well as fill in deep pools that may thermally stratify in low flow conditions.

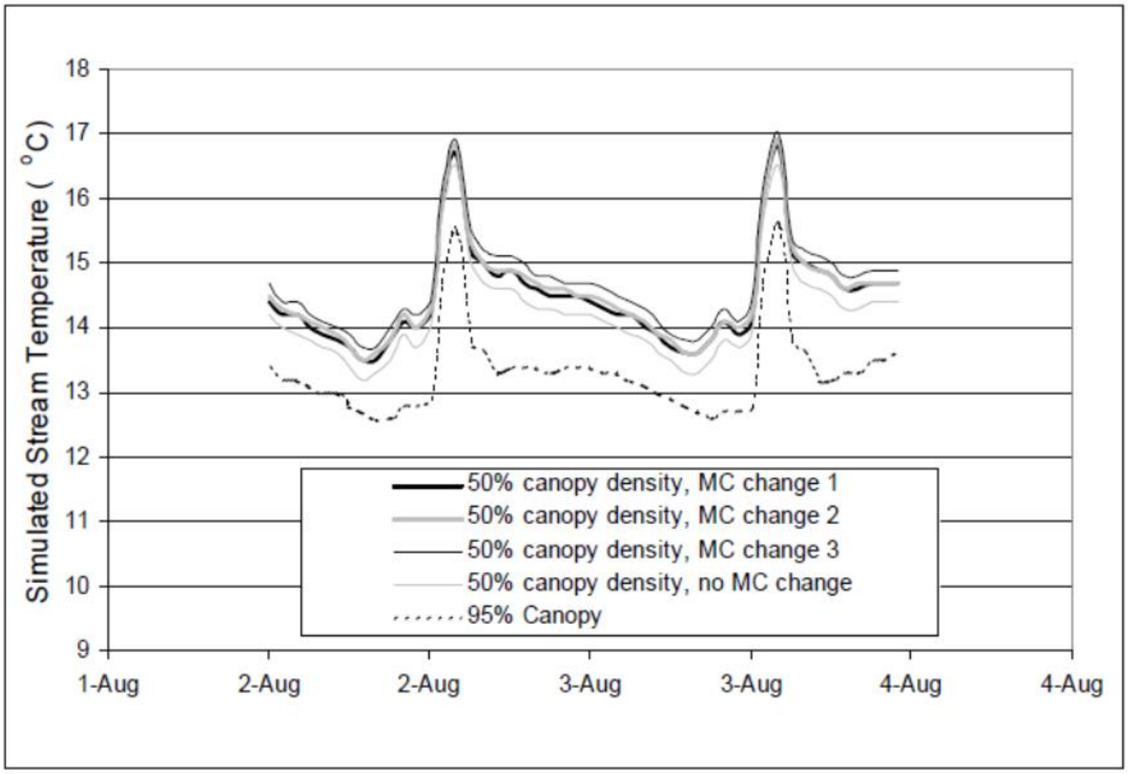

Figure 2.3: Temperature modeling analysis results showing theoretical impacts of microclimate relative to impacts of canopy removal (Source: NCRWQCB 2005). Note that "MC" stands for microclimate.

Based on the analyses described above and the available literature, the implementation strategies developed to achieve TMDLs and the intrastate water quality objective for temperature have focused on a common set of pollutant discharges and controllable factors that have the potential to elevate water temperatures. These controllable factors and discharges are shade, flow, and sediment load.