CHAPTER 3. TEMPERATURE SOURCE AND LINKAGE ANALYSIS

3.1 Introduction

This chapter identifies the sources (or factors) that affect the temperature of the Shasta River and its tributaries and establishes a linkage between these sources (or factors) and stream temperature. First, the general stream heating processes applicable to any surface waterbody are described in the following section. The contributions from the identified sources (or factors) affecting Shasta River watershed temperatures are quantified in Chapter 6.

3.1.1 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, collectively referred to as heat fluxes, are applicable to all surface waterbodies and include heat gain from direct solar (short-wave) radiation, both gain and loss of heat through long-wave radiation, convection, conduction, advection, and heat loss from evaporation (Beschta et al. 1987; Brown 1980; 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 stream flows 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 (Oregon Department of Environmental Quality [ODEQ] 2000; Sinokrot and Stefan 1993). 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 (Sinokrot and Stefan 1993; Theurer et al. 1984). 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 2003; Johnson 2004; 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).

The conclusion that solar radiation is a major source of stream temperature increases is supported by studies demonstrating 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. In another study, 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 (located in Oregon) 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.

3.2 Sources of Information

Much of the data and information used in the development of the temperature TMDL were collected during the summers of 2002, 2003, and 2004 by Regional Water Board staff, with assistance from the U.S. Geological Survey and Watershed Sciences, LLC. These data included:

- Stream and tailwater temperature monitoring data:
- Thermal infrared remote radiometry (TIR) survey of the Shasta River and select tributaries;
- Existing flow and temperature modeling of the Shasta River developed for the SVRCD; and
- Text books and scientific literature.

3.3 Stream Heating Processes Affected by Human Activities in the Shasta River Watershed

Regional Water Board staff identified factors affecting stream temperatures of the Shasta River watershed. Human activities have affected, or have a potential to affect, each of these factors. The factors include:

- Stream shade;
- Tailwater return flows;
- Flow and surface water diversions;
- Groundwater accretion / spring inflow; and
- Lake Shastina and minor channel impoundments.

Following a discussion on the collection and use of infrared imagery in developing the temperature TMDL, the Shasta River stream heating factors are evaluated.

3.3.1 Collection and Use of Infrared Imagery

The North Coast Water Board funded a thermal infrared remote radiometry (TIR) survey of the Shasta River and select tributaries (Watershed Sciences, LLC 2004) in support of this study. On July 26 and 27, 2003, Watershed Sciences, LLC conducted aerial TIR surveys of the Shasta River from the mouth to Dwinnell Dam, Little Shasta River, Parks

Creek, and Big Springs Creek. The imagery was collected using side-by-side video and infrared cameras. The survey yielded temperature measurements of approximately ½ meter-square pixel 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 instream temperatures directly 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 is available in their 2004 report (Appendix B, *Aerial Surveys using Thermal Infrared and Color Videography: Scott River and Shasta River Sub-Basins*).

The longitudinal temperature profile of the Shasta River from the TIR survey shows that the river is thermally complex, with reaches of pronounced heating and cooling, as well as reaches with stable temperatures (Figure 3.1). The results also provide insight into factors likely to have an influence on Shasta River temperatures.

The following sections discuss the effects of stream shade, tailwater return flows, surface water diversions, and groundwater accretion / spring inflow on stream temperature, and present TIR imagery and associated data that provide supporting evidence.

3.3.2 Shade

Direct solar radiation is a significant 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 et al. 1987; Johnson 2004; Sinokrot and Stefan 1993). 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. In addition to ridges, topographic shade includes channel banks. In small streams with deep, incised channels the shade created by the channel banks can comprise a significant portion of the total shade on the channel.

Topographic shade is minimal to non-existent in the Shasta Valley, but is more prominent in the Shasta canyon reach (Figure 1.4). The average percentage of the sky (180 degrees, horizon to horizon, regardless of aspect) that is in view from the Shasta River stream channel is 95%. USGS made this calculation using the computer program SKYVIEW, which calculates topographic shading and blocking ridges around each pixel in a 30-meter digital elevation model (Flint and Flint 2005, Table 1).

The shade provided to a water body by riparian vegetation has a dramatic, beneficial effect on stream temperatures by blocking solar radiation, reducing wind speed, altering the microclimate above the water surface (i.e. air temperature and relative humidity), and reflecting long-wave radiation. 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.

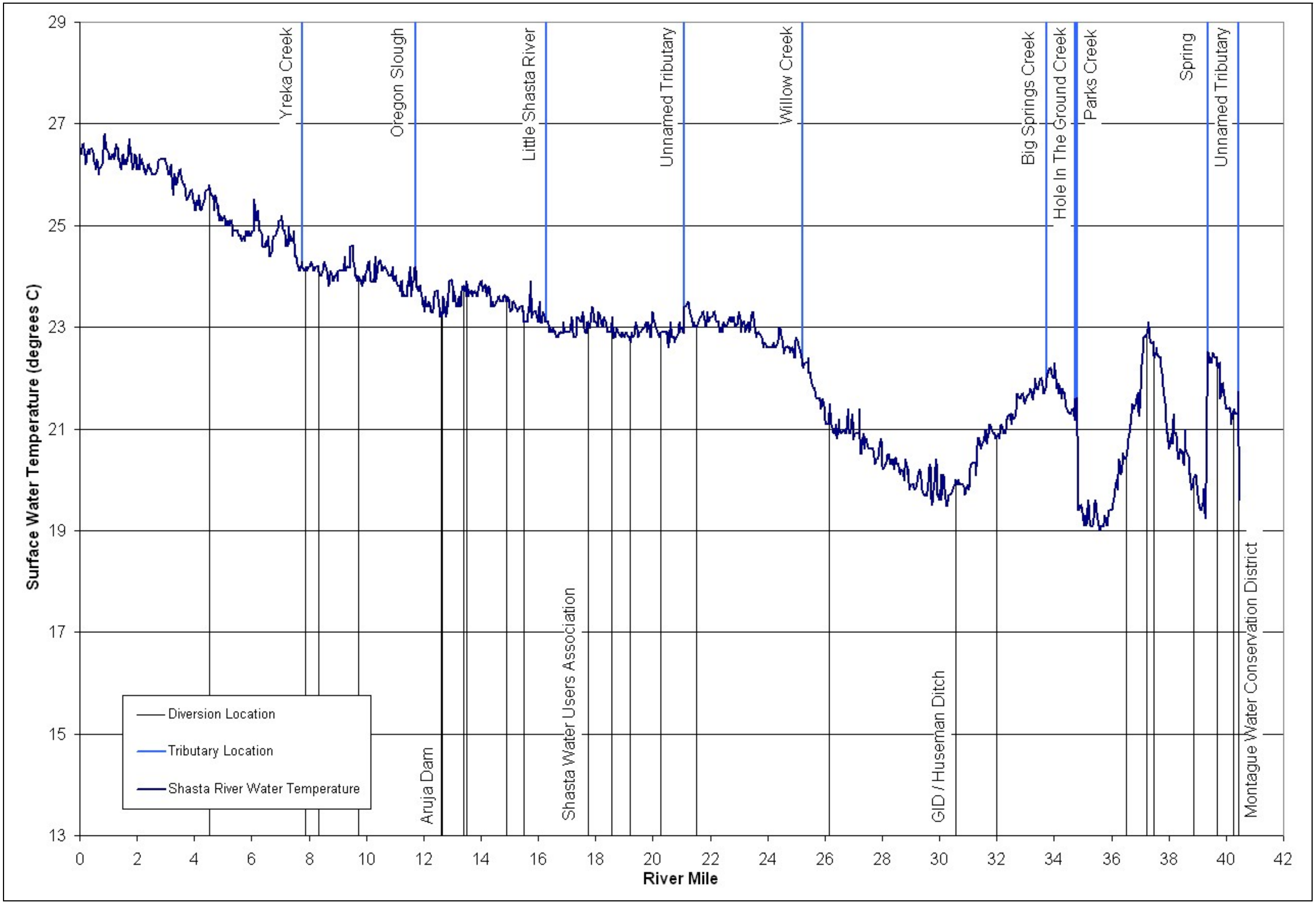


Figure 3.1: Shasta River longitudinal surface water temperature profile, and locations of tributaries and diversions, July 26, 2003

Figure 3.2 presents TIR data from the 2003 survey and is an example of the cooling effect of riparian vegetation on Shasta River temperatures. At RM 37.3 the riparian vegetation noticeably changes from sparsely vegetated to densely vegetated. In some areas the river is difficult to see because the vegetation is so thick (Figure 3.2). This change in riparian condition coincided with a 4-degree drop in temperature. Based on a review of the TIR data, there are no indications of springs or groundwater accretion in this reach, though either may be present. In contrast, Figure 3.3 presents an example of a sparsely vegetated reach of the Shasta River, where stream temperatures remain elevated and fairly constant.

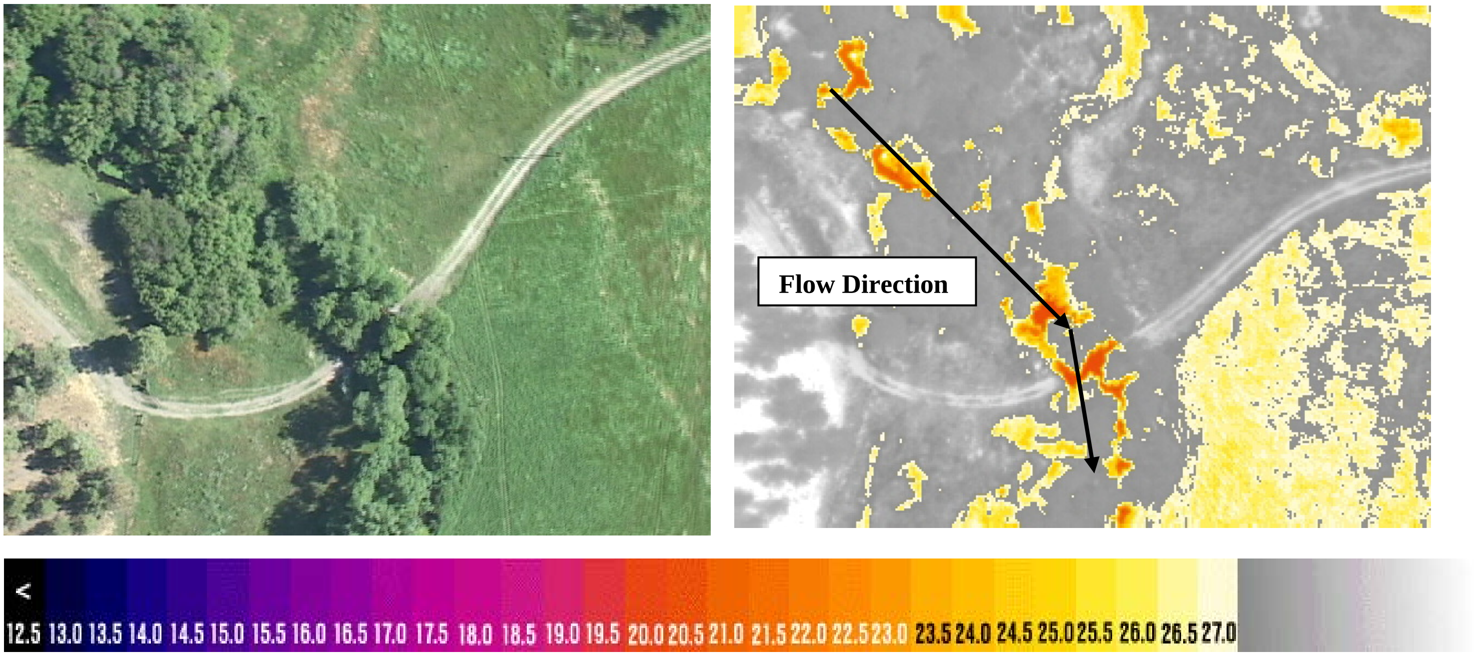


Figure 3.2: Example of dense riparian vegetation in the RM 37.3 – 34.1 cooling reach, RM 36.4
Source: Watershed Sciences 2004

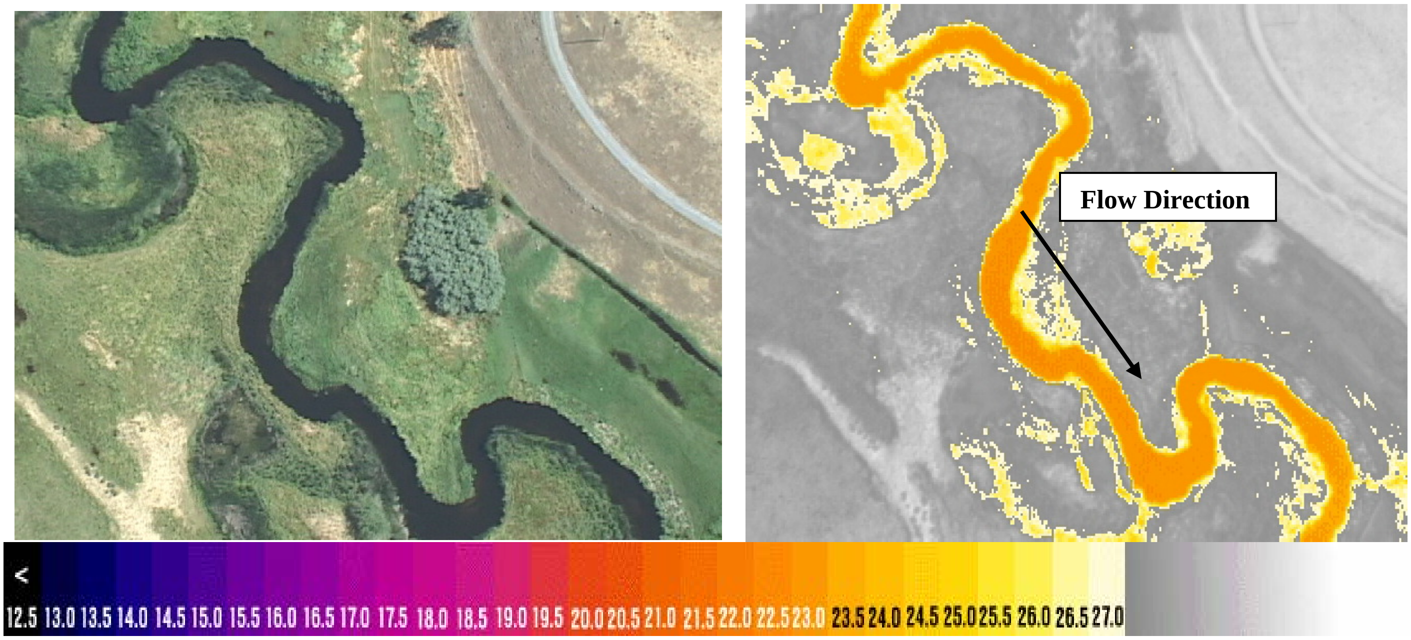


Figure 3.3: Example of sparse riparian vegetation, RM 24.2
Source: Watershed Sciences 2004

In 2003 a flow and temperature model of the Shasta River was developed for the Shasta Valley Resource Conservation District with funding from the California Department of Fish and Game (Deas et al. 2003). The Tennessee Valley Authority's River Modeling System (RMS), a one-dimensional hydrodynamic and water quality model, was used. The purpose of the project was to investigate the effects of management actions on stream temperature (Deas et al. 2003).

The project used the RMS model as a tool to assess the role of riparian shade on stream temperature, among other factors. Figure 3.4 presents model results of stream temperature sensitivity to transmittance. These model simulations were run for August 28, 2001 meteorological conditions with a flow of 50 cubic feet per second (cfs). Transmittance of 100% means no solar blockage (i.e. no shade), and transmittance of 10% means solar radiation is reduced by 90%. As seen in Figure 3.4, no shading produces an average daily temperature at the mouth of 19.2 ^{o}C. Reducing solar radiation by 15, 50, and 90% translated to an average cooling of the system at the mouth of about 1.5, 3.0, and 4.0 ^{o}C, respectively (Deas et al. 2003).

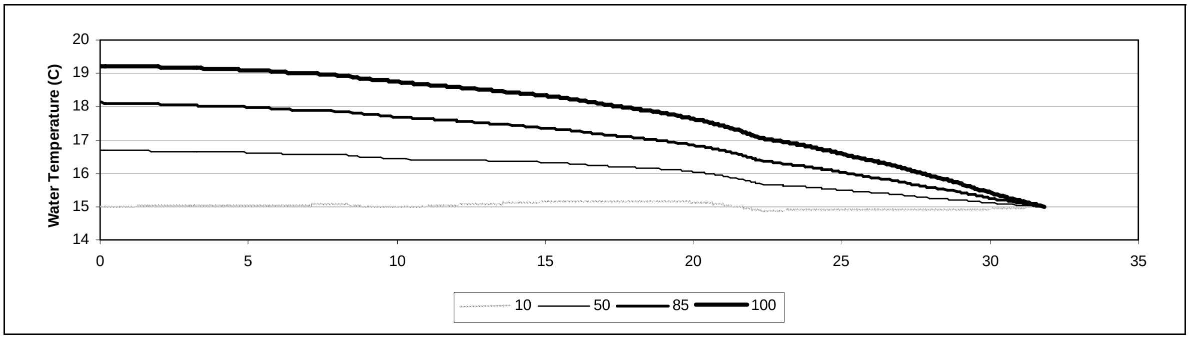


Figure 3.4: Longitudinal profile of average daily temperature for August 28, 2001 meteorological conditions for 50 cfs test case with varying transmittance (10%, 50%, 85%, 100%)
Source: Deas et al. 2003

Deas and others (2003) also evaluated the effects of riparian shading on stream temperature on a reach-by-reach basis. In these simulations shade associated with existing riparian vegetation was applied to the entire river, and then shade from mature trees (parameterized as 22 feet tall trees on each bank, based on field monitoring of Shasta River riparian tree heights) was added to each of five reaches of the modeled river, one reach at a time. The reaches are numbered 1 to 5 from downstream to upstream. The results of the August 2001 simulations are presented for select river locations in Figure 3.5. The largest reduction in daily maximum temperature was nearly 3 ^{o}C at the mouth associated with mature shade-producing riparian trees in the canyon reach.

Finally, the effects on stream temperature associated with alternate riparian vegetation restoration schemes were simulated by Deas and others (2003). When 7 foot tall bulrushes, with a transmittance value of 90%, were added to all reaches currently devoid of riparian vegetation, maximum temperature at the Mouth was reduced by nearly 1 ^{o}C compared to the baseline condition. When all reaches currently devoid of riparian vegetation were colonized by 22 foot high trees, with a transmittance of 10%, maximum temperature at the mouth was reduced by 7 ^{o}C, and the overall mean daily increase from

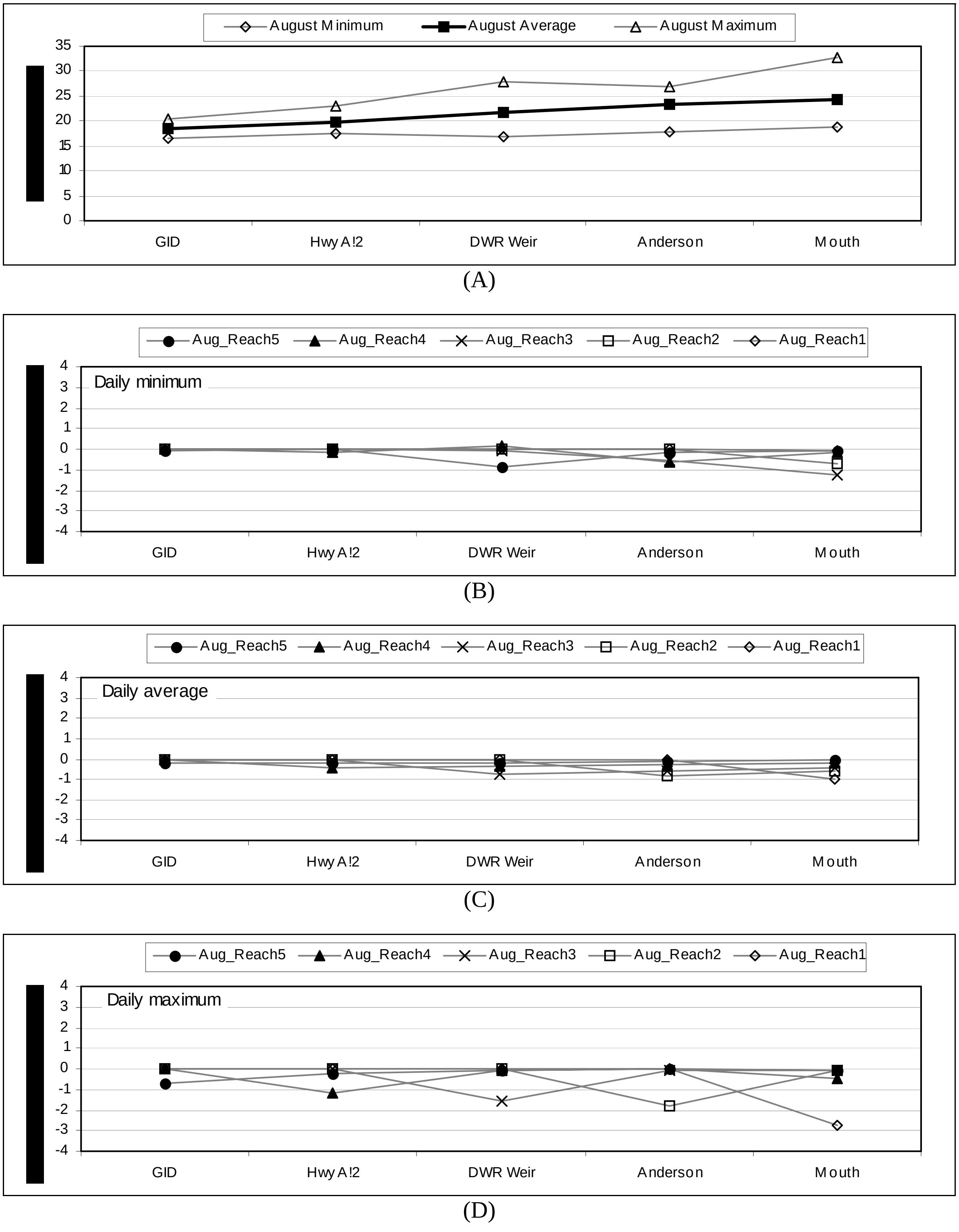


Figure 3.5: Reach by reach shading results for August. Deviations from (A) August base-case condition in (B) daily minima, (C) daily average, and (D) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.

Source: Deas et al. 2003

the top of the model reach (RM 31.8) to the mouth was less than 1 ^{o}C.

These model results indicate that reductions in solar loading associated with increases in riparian shading cause a cooling of stream temperatures in the Shasta River. While maximum temperature reductions of up to 7 ^{o}C may be possible under a condition of mature riparian tree coverage on the Shasta River, even modest improvements caused by bulrush colonization could produce a noticeable reduction in stream temperature.

Based on these model results and the Shasta River TIR survey, Regional Water Board staff identified shade as an important factor affecting stream temperatures of the Shasta River and its tributaries.

3.3.3 Tailwater Return Flows

Flood irrigation is the common irrigation practice in the Shasta Valley. When irrigation water is applied to a field in this manner, it generally flows across the field as a thin sheet or in shallow rivulets, and is prone to heating during daylight hours and cooling at night in response to air temperature. Regional Water Board staff deployed temperature monitoring devices at several locations with irrigation return flows. Upon review of the monitoring results, it was very difficult to determine when the temperature monitoring probes were exposed to irrigation return flow versus when they were exposed to the air, indicating that the temperature of the tailwater return flows were generally at equilibrium with the air temperature.

The July 26 and 27, 2003 TIR imagery shows a number of examples of locations where tailwater return flows caused an increase in Shasta River stream temperatures. The most significant example of this is on Big Springs Creek, where a tailwater return flow was 9.2 ^{o}C warmer than the creek and caused a plume of hot water that extended for hundreds of meters (Figure 3.6). Based on this information, Regional Water Board staff determined that irrigation return flows can have a significant effect on the temperature of the Shasta River and its tributaries.

3.3.4 Flow and Surface Water Diversions

Surface water diversions decrease the volume of water in the stream and thereby decrease a stream's capacity to assimilate heat. When water is removed from a stream the thermal mass and velocity of the water are decreased. Thermal mass refers to the ability of a body to resist changes in temperature. Basically, less water heats or cools faster than more water. Decreases in velocity increase the time required to travel a given distance and thus increase the time heating and cooling processes can act on the water. These principles are true for any stream.

Locations of surface water diversions from the Shasta River are identified on the longitudinal temperature profile of the Shasta River in Figure 3.1. Several of these diversions coincide with an increase in the rate of heating of the river, most notably at RM 26.2. The longitudinal temperature profile of the Shasta River is from the TIR survey conducted on July 26, 2003, and all diversions identified on Figure 3.1 may not have been diverting on this date.

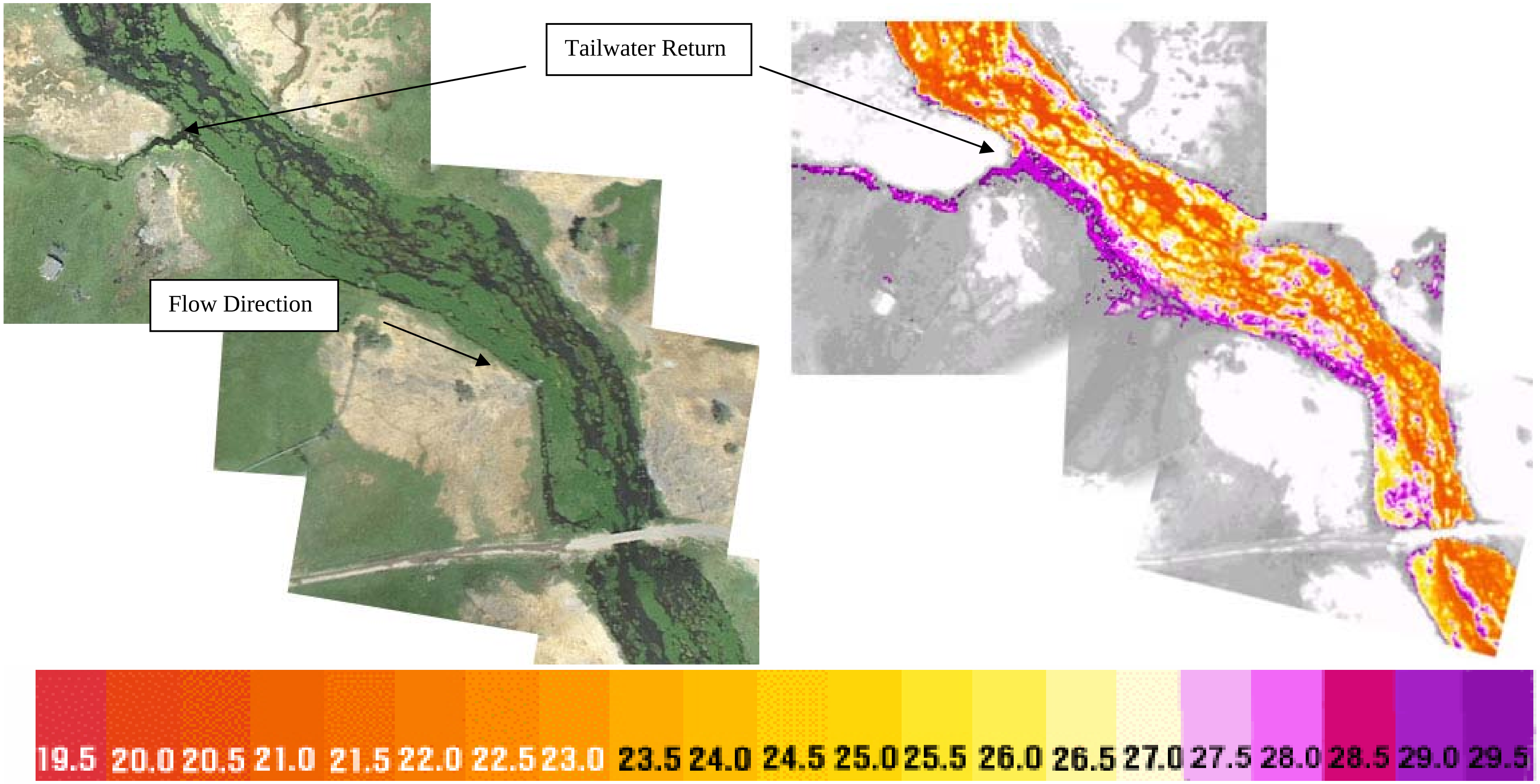


Figure 3.6 Tailwater return, Big Springs Creek
Source: Watershed Science 2004

As demonstrated in the TIR survey report (Appendix B), stream warming occurs in Parks Creek and the Little Shasta River, and portions of these tributaries completely dry up, most likely due to surface water diversion. Potential thermal refugia are lost when the mouth of a tributary that has cold water sources, such as Parks Creek, dries up.

The Shasta River flow and temperature modeling by Deas and others (2003) evaluated the effect of flow on stream temperature. Sensitivity of stream temperature to flow was modeled using 10, 50, and 100 cfs for August 28, 2001 meteorological conditions. The simulations assumed no shading. Daily average temperatures over this range of flows are shown in Figure 3.7.

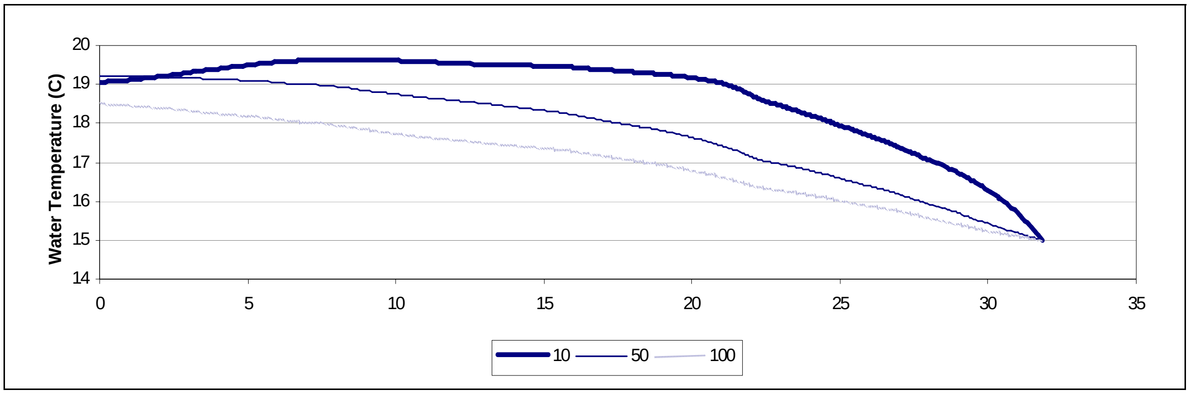
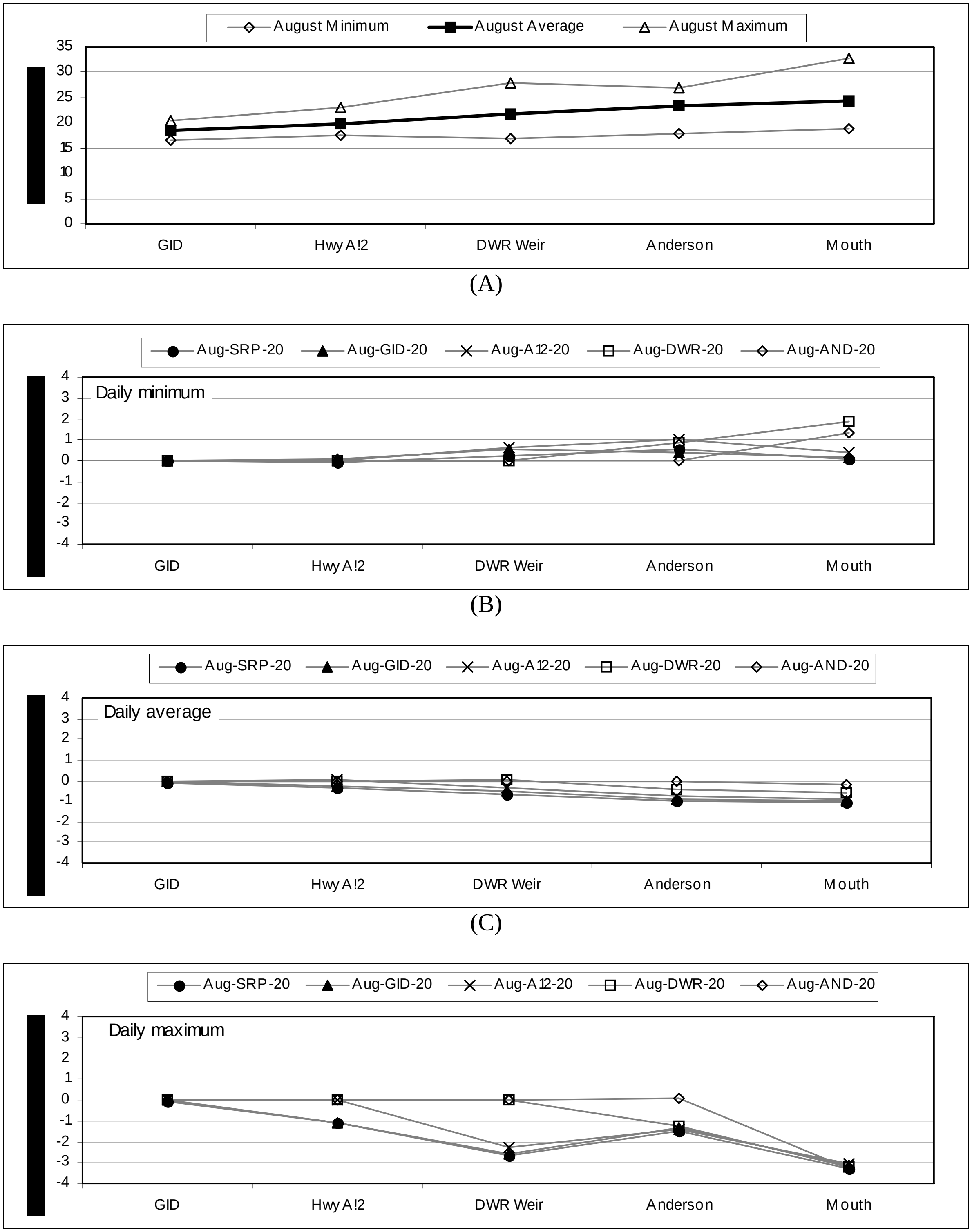


Figure 3.7: Longitudinal profile of average daily temperature by river mile for August 28, 2001 meteorological conditions for 10, 50, 100 cfs
Source: Deas et al. 2003

To further assess the impact of flow regime on water temperature in the Shasta River, Deas and others (2003) simulated adding water to the river base flow at the beginning of each of the five river reaches in a stepwise fashion. For example, one simulation added 20 cfs to the most upstream reach. The next simulation removed the added 20 cfs from the upstream reach and placed an additional 20 cfs at the beginning of the next reach, and so on. The temperature of the added flow for each simulation was the same as that of the baseline flow. Simulation results of adding 20 cfs in each reach in August are presented in Figure 3.8. The simulation results indicate that the farther upstream the water is added, the more miles of river experience a decrease in water temperature, corresponding with the baseline temperature of these flows.

In summary, the addition of 20 cfs reduces the maximum temperatures in the middle and lower reaches by 2 to 3 ^{o}C and increases daily minimum temperatures by up to 2 ^{o}C. It is important to note, however, that the increases in the daily minimum temperatures were associated only with 20 cfs flow increases from locations in the lower valley where baseline temperatures are warmer than at more upstream reach locations. Based on these modeling results and the TIR information, Regional Water Board staff identified flow as an important factor affecting temperatures of the Shasta River and its tributaries.

An important indirect effect of flow on stream temperature is related to soil moisture levels. Generally, soil moisture levels in the riparian zone of streams decrease with decreasing flow.



(A)

(B)

(C)

(D)

Figure 3.8: Flow regime results for 20 cfs inflows in August. Deviations from (A) August base-case condition in (B) daily minima, (C) daily average, and (D) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.
Source: Deas et al. (2003)

Soil moisture limitation is an important limiting factor for riparian vegetation establishment and growth (Kennedy et al. 2005, p 17). As surface water levels drop in a stream, the roots of riparian vegetation may not get the amount of water needed to survive. Soil moisture stress is a common cause of failure of riparian restoration efforts. This relationship between summer flow and riparian condition is important. If inadequate soil moisture levels limit or prevent riparian vegetation growth, then the opportunity for stream temperature improvements due to increase in riparian shade cannot be realized

3.3.5 Groundwater Accretion / Spring Inflows

Ground water accretion and spring inflows affect stream temperatures in a number of ways. Most importantly, groundwater accretion and spring inflows provide a stream with a cold source of water that cools the stream (advection). The effect of groundwater and spring inflows on Shasta River and tributary temperatures has not been well documented. Regional Water Board monitoring of selected springs within the Shasta River basin, however, shows that the average temperatures of spring flows range from 9 ^oC to 12 ^oC, temperatures significantly lower than the average Shasta River temperature (NCRWQCB 2004b, see Appendix C_e).

The TIR survey identified a number of springs that caused cooling of stream temperatures, including springs on Parks Creek, Big Springs Creek, and the Shasta River. Figure 3.9 provides an example of a significant cold water source, most likely a spring, which dropped the stream temperature 3.2 ^oC to 19.3 ^oC. Based on the above referenced monitoring data and the TIR survey results, Regional Water Board staff identified groundwater accretion and spring inflows as important factors lowering temperatures of the Shasta River and its tributaries.

3.3.6 Lake Shastina and Minor Impoundments

Information on the effect of Lake Shastina and minor Shasta River impoundments is synthesized from Vignola and Deas (2005) and Deas (2005a). In addition to Dwinnell Dam, the largest impoundment on the Shasta River, there are several smaller impoundments – often termed "flashboard" dams – that are used to raise the water level in the river to provide for diversion (either direct or pumping) primarily for agricultural use. Impoundments can alter the thermal regime of a river system. Differences in heat loading due to impoundments can occur because of an increase in water surface area, providing a larger surface area over which energy transfer can occur. Larger air-water interface provides additional area for solar radiation to enter the system; however, the larger surface area also allows increased fetch (allowing more wind mixing) and potentially improved cooling due to evaporation. Probably a more important characteristic of the impoundment is the increased thermal mass, which leads to moderation of the diurnal temperature signal.

Finally, impoundments generally increase river width and limit the ability of riparian shading to reduce incoming solar radiation. Similarly, the effect of topographic shading due to stream banks or bluffs is reduced when the river width is increased due to an impoundment. There are not sufficient stream temperature data within and downstream of the existing flashboard dams on the Shasta River to evaluate their effect on stream temperature. However, Regional Water Board staff suspect they cause heating of surface waters behind the impoundments, and this heating may be expressed a short distance downstream of the impoundments.

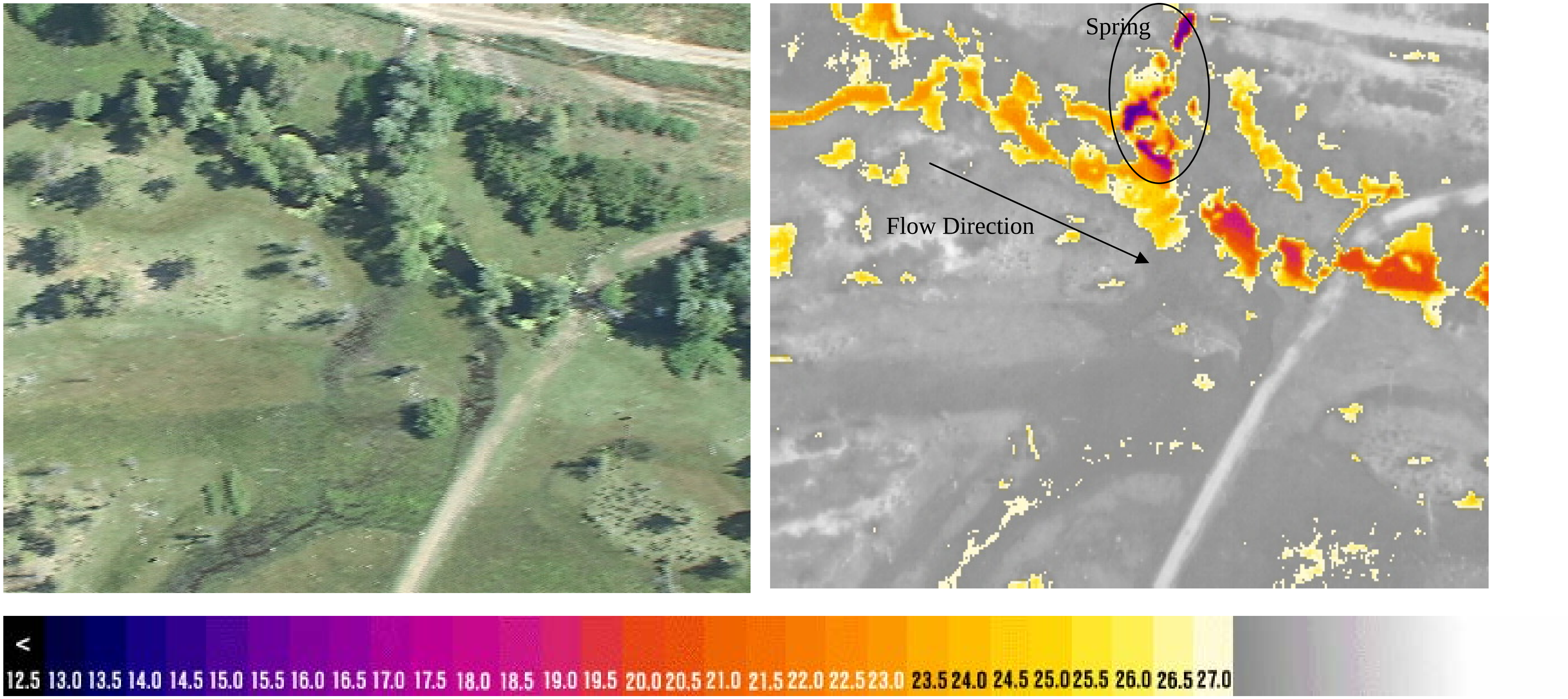


Figure 3.9: Spring entering from top of images cools the Shasta River 3.2 °C, tailwater return flow enters the river from the bottom of the picture, RM 39.0
Source: Watershed Sciences 2004

The water temperatures within Lake Shastina are summarized in Section 2.3.4. Figure 3.10 illustrates water temperatures of Shasta River inflows to Lake Shastina, surface water temperatures in Lake Shastina near the dam, and temperatures in the Shasta River below Lake Shastina for the period fall 2000 through fall 2001. As shown in Figure 3.10 the temperatures of the Shasta River above Lake Shastina are roughly similar to the surface water temperatures of Lake Shastina near the dam. Lake Shastina near the dam exhibits slightly warmer surface water temperatures in the spring of 1998. Most notably, the Shasta River below Lake Shastina is generally cooler than Lake Shastina surface water temperatures and the river temperature upstream of Lake Shastina during summer months. This is most likely due to the fact that the outflow from Lake Shastina comes from the bottom of the reservoir, where water is cooler in summer months (see Figure 2.6). The discontinuity in the water temperature trace of the Shasta River below Lake Shastina from October through November most likely represents turnover. The temperature of the Shasta River below Lake Shastina is similar to upstream locations from late fall through mid-spring when the reservoir is de-stratified. Based on this information, Regional Water Board staff identified the presence of Dwinnell Dam as an important factor affecting stream temperatures in Lake Shastina and in the Shasta River downstream of the dam.

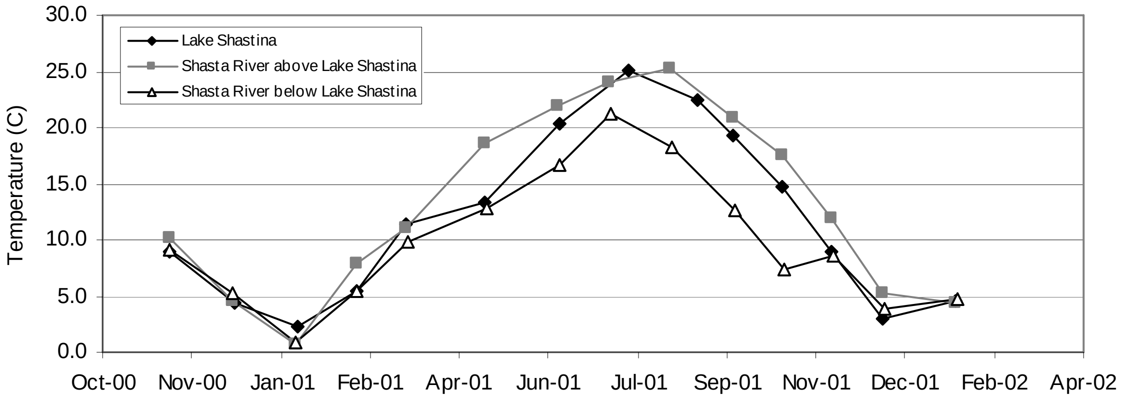


Figure 3.10: A comparison of surface water temperatures in the Shasta River above Lake Shastina, the surface water temperature of Lake Shastina near the dam, and in the Shasta River below Lake Shastina.
Source: Vignola and Deas 2005