SHASTA RIVER FLOW AND TEMPERATURE MODELING PROJECT

Sponsored by the
Shasta Valley Resource Conservations District
with funding from the
California Department of Fish and Game

Watercourse Engineering, Inc.
1732 Jefferson St.
Napa, CA 94559
April, 2003

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Prepared by
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Executive Summary

The Shasta River basin, located in central Siskiyou County, is 800 square miles with a mean annual unimpaired runoff of approximately 162,300 acre-feet. The river originates in the Scott Mountains in the vicinity of Mt. Eddy and flows north and north-westward for roughly seventy miles before discharging into the Klamath River. Numerous accretions from tributaries, springs, and agricultural diversion and return flows contribute to a complex flow regime both seasonally and over the river length. The river is impounded by Dwinnell Dam at river mile 36.4.

Historically the Shasta River supported fall and spring-run chinook salmon, coho salmon and steelhead trout. According to annual spawning counts at the Shasta River weir, the 1931 run of over 80,000 chinook salmon had dropped to 553 fish in 1990 (DFG, 1991). The Department of Water Resources (DWR, 2001) has identified physical barriers (dams, weirs), flow alterations due to water management practices, and water quality issues such as temperature and contaminant concentration as potential problems associated with the ability of salmon to spawn in this basin. The DFG and the United States Fish and Wildlife Service have determined that flow and temperature are the critical water quality parameters for restoration of this system (DWR, 2001).

This modeling project, undertaken through the Great Northern Corporation with funding provided by the Klamath River Basin Fisheries Task Force and California Department of Fish and Game, is the second component of a two-part study to investigate the effects of management actions on these critical water quality parameters. The first part of this study included extensive efforts to collect the necessary field observations of flow, temperature, riparian vegetation, and other data to support analysis and modeling. Data collection was funded by the Klamath River Basin Fisheries Task Force, and administered by USFWS. Cost sharing between USFWS and DFG made this study possible.

The TVA hydrodynamic and water quality model ADYN and RQUAL were selected for the project. RQUAL was used to simulate temperature and was modified to accommodate spatially diverse riparian vegetation location, height and shade providing characteristics. As noted above, extensive field monitoring efforts were completed to support the modeling effort.

Critical components of the study include model implementation and testing: formulating input data, model parameters, and testing the sensitivity of model results to various input parameters and data values. The sensitivity analysis is a useful introduction to several model variables that are altered in the model application section of the report. Model calibration and validation was completed over week-long periods using multiple locations along the river.

Model application was completed to assess several alternative conditions, including the thermal impacts of variable flow rates, pulse flow operations, tailwater return management, and various riparian vegetation shading conditions. Several hundred simulations were completed to define these scenarios completely. Results are presented in graphical and tabular form. The principal findings of the studies are identified below.

- Advection, the physical transport of thermal energy downstream is an important consideration in the Shasta River. The transport of water from upstream

- Additional volume of water generally translates to a reduction in the diurnal range in temperatures, i.e., lower daily maximum and higher daily minimum temperatures. Mean daily temperature may show some reduction over longer reaches of river due to increased flows, especially if upstream sources are cooler.

- Identifying the reach or reaches with the largest heat gain (e.g. °C per mile) provides insight into the locations where the greatest opportunity for decreasing mean daily temperature through increased flow exists.

- Pulse flows affect the water temperature through increase stream volume and reduction in transit time. The model effectively routed these transient flow conditions through the system. However, the thermal benefit is uncertain, primarily due to a lack of biological data relating changes in thermal regime to outmigrating salmonids

- Water temperature conditions should be monitored prior to and during the pulse flow to ensure water temperature conditions are conducive to the operation. For example if releases from Lake Shastina are inordinately warm, it may be more beneficial to not use that water in the pulse operation.

- Sequential pulse flow operations and simultaneous pulse flow operations showed modest differences in thermal regime. There are probably more pressing issues associated with the pulse flow than timing of diversions are shut down, such as meteorological conditions at the time of the pulse, the available flow, the time that all diversions are shut down in the simultaneous operation (morning better than evening), and ramping flows up and down in a manner that is beneficial to the objective of encouraging juvenile fish to move out.

- The amount, distribution, location, and temperature of return flow can impact the thermal regime of the river. The impacts for a single reach may be modest. The impacts of a system wide program were not analyzed.
- Riparian vegetation shading can potentially reduce minimum, mean, and particularly maximum daily, temperatures over the distance of a single reach (five to seven miles).
- Where water temperatures were closer to equilibrium conditions (e.g., away from

cool spring inflow influences) riparian vegetation had a more noticeable affect. This does not discount the importance of riparian vegetation in cool water areas.

- In general, the reduction in water temperature from a restored riparian vegetation condition does not persist more than several miles downstream (applicable to conditions where downstream reaches are not restored).
- Time of year and solar altitude play a role in ability of riparian vegetation to reduce incoming solar radiation, thus affecting the thermal regime of the river.
- Riparian restoration efforts are long-term management approaches to moderating and/or reducing river temperatures. Model simulations can assist decision makers in management approaches to address potential spatial distribution of restoration, how long it may take to reach maturity and provide temperature control benefits, and what thermal relief intermediate conditions may provide.
- Herbaceous riparian vegetation (e.g., bulrush) can provide sufficient shade to affect water temperature if present in sufficient quantity (density and distribution) along the river bank.
- Riparian vegetation on small river systems such as the Shasta River plays an important role in reducing mean daily temperatures (as well as maximum and minimum). Further studies should be completed to determine the trade-off between flow volume, riparian shading, and return flow management for various reaches of the Shasta River to identify a "most favorable" combination of management actions to meet desired objectives.

The developed models, as well as supporting data, have provided constructive insight into flow, temperature, and riparian vegetation shading inter-relationships. Not only have potential effects been identified, but the potential magnitude of temperature changes associated with various management strategies have been identified for locations specific to the Shasta River. The principal recommendation is to build upon the findings herein and apply the model to a broader set of alternatives – possibly combinations of certain management strategies identified herein. Additional recommendations were identified and are outlined below.

- Identify funding sources to support additional collection of field data to refine the geometric representation of the flow and temperature models. Seek to collect data system wide.
- Complete a pilot study, for a representative reach or area to identify the various modes at which water may enter the river (e.g., groundwater, diffuse surface flow, localized inflow), quantity of inflow, and temperature associated with each type of source. These data can then be entered into the flow and temperature model to assess potential impacts of managing these various sources.
- Conduct a field study to quantify the role of bed conduction in the heat budget.

Identify several locations based primarily on substrate to conduct the tests. Use the results to test/calibrate the bed conduction logic included in the model, and complete a battery of tests to determine the potential role of bed conduction in the Shasta River.

- Conduct a riparian vegetation survey that includes woody vegetation, as well as herbaceous. Identify plant species, as well as conditions that provide additional benefit or dis-benefit to shading potential (e.g., narrow or wide river width, high banks (local topographic shading) or low banks.). Use this data to update, as necessary, the riparian vegetation within the model

- Using solar radiation equipment similar to that used in Abbott and Deas (2003), carry out measurements adjacent to the Shasta River at several locations. Alternatively, use a digital elevation model to approximate shade reduction potential.

- Using a portable meteorological station and conduct field studies at the various locations within the Shasta Valley over several weeks. Use the NOAA station at the Montague Grenada Airport and the CDF station at Brazie Ranch as controls.

- Add and maintain a seasonal flow monitoring station at Anderson Grade, Highway A-12, and a location upstream of A-12 to collect daily flow information to support modeling and other management activities.

- Add and maintain additional temperature monitoring locations, principally in the accretion reaches upstream of A-12. Hourly data would be necessary to support modeling and other management activities.

- Complete a test using the model to quantify numerical dispersion, if any. Document the findings and append to the modeling report.

Acknowledgements

This project was sponsored by the Shasta Valley Resources Conservation District and funded through a grant from the California Department of Fish and Game. Great Northern Corporation managed the project funding. This project is one component of a two part study. The field work to support the flow and temperature modeling effort addressed herein was funded through a separate grant provided by the Klamath River Basin Fisheries Task Force and administered by the United States Fish and Wildlife Service. This cooperative effort was paramount to the success of the project and we wish to acknowledge those staff at both the California Department of Fish and Game and United States Fish and Wildlife Service who made such arrangements possible.

Our most sincere acknowledgements go to the landowners who provided access to the river for field surveys and data collection. We also would like to thank all those who attended and participated in public meetings and workshops. There are a few people whom we wish to specifically acknowledge for their support and participation.

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Mark Gilpin	California Department of Fish and Game
Dave Webb	CRMP Coordinator
Dan Drake	University of California Extension
Jerry Boles and staff	California Department of Water Resources

As well as many others, without whom this project would not have been feasible.

Preface

This document summarizes the flow and temperature modeling component of a two year study on the Shasta River that was funded through a grant from the California Department of Fish and Game. During this period field data was collected (funded separately through a Klamath Basin Fisheries Task Force grant), and a model was selected, modified to represent riparian shading, and applied. Because the results of any study have the potential to shape local water resources management practices, the authors have attempted to complete the work in a responsible and professional fashion with sufficient documentation to clearly present assumptions, decision, sources of information, and other pertinent information.

As such, this document has sections that are fairly technical. This information is placed early in the report because, although potentially wearisome reading for some, it forms the basis for all model applications. Outlined herein are the contents of the report with some guidance to the reader, if he or she pleases, to read selected portions of the report that are deemed of most interest.

Chapter 1 provides a brief background to the project objective, namely, to formulate a flow and temperature model and employ that tool to ascertain flow and temperature relationships to aid in the management of the Shasta River anadromous fishes. Included in this chapter is a brief discussion of thermal criteria for anadromous fish, a summary of basin characteristics, and the potential for riparian vegetation to reduce water temperature through direct reduction in incoming solar radiation (i.e., shade).

Chapter 2 presents the intricacies of the selected model, a discussion of the heat budget used to represent the exchange of thermal energy between the atmosphere and the water body, and a detailed description of the modifications completed to effectively represent riparian vegetation shading in the numerical model. This chapter, and the model user guide, can be used strictly as a reference for those readers seeking details of the model function, and can be skipped with little loss by those interested principally in model results.

Chapter 3 is a brief outline of the fieldwork performed to support the modeling effort. This work, funded by the Klamath Basin Fisheries Task Force, is presented in a separate report and the reader is referred to Abbott and Deas (2003) for a detailed description of the tasks and results.

Chapter 4 describes the process of model implementation and testing, essentially summarizing the data needs, model parameters, and sensitivity of model results to various input parameters and data. Review of this chapter will provide the reader with an appreciation of the steps and stages of modeling. The sensitivity analysis is a useful introduction to several model variables that are altered in the model application section of the report (Chapter 5). This chapter can also be treated as a reference section for those interested primarily in model results.

Chapter 5 includes of two main topics: model calibration and validation; and model application. Model calibration and validation results are useful in assessing model performance and uncertainty – two criteria that are valuable when interpreting simulation results. The model application section presents the findings of several studies completed with the model, including the thermal impacts of variable flow rates, pulse flow operations, tailwater return management, and various riparian vegetation shading conditions. Conclusions and findings of each study are presented within the body of this chapter. This portion of the report will be of most interest for those readers interested primarily in model results.

Chapter 6 includes recommendations that were borne out of this study, and Chapter 7 includes a list of references. Several appendices are included addressing model modification, model processors, and a summary of files used for the model application.

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List of Abbreviations

ADYN	Hydrodynamic component of RMS
BZR	Brazie Ranch Weather Station
CF	Vegetative Continuity Factor
CFS	Cubic Feet per Second
CRS	Shading subroutine in RMS
DFG	California Department of Fish and Game
DLG	Digital Line Graph
DWR	California Department of Water Resources
EBH	Effective Barrier height
EPA	Environmental Protection Agency
GID	Grenada Irrigation District Pumps
ICE	Information Center for the Environment
MAE	Mean Absolute Error
NHD	National Hydrography Dataset
PT	Pressure Transducer
RM	River Mile
RMS	River Modeling System
RQUAL	Water Quality component of RMS
SHSOL	Shade modeling parameter
SRP	Shasta Above Parks Creek
SWA	Shasta Water Users Association
Tr	Transmittance
TVA	Tennessee Valley Authority
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

1.0 Background

The California Department of Fish and Game (DFG) and the United States Fish and Wildlife Service (USFWS) have determined that flow and temperature are the critical water quality parameters for restoration of Shasta River salmon runs (DWR, 2001). This report describes results of flow and temperature modeling on the Shasta River, CA. This modeling project, undertaken through the Great Northern Corporation with funding provided by the Klamath River Basin Fisheries Task Force and DFG, is the second component of a two-part study to investigate the effects of management actions on these critical water quality parameters. The first part of this study included extensive efforts to collect the necessary field observations of flow, temperature, riparian vegetation, and other data to support analysis and modeling. Data collection was funded by the Klamath River Basin Fisheries Task Force, and administered by USFWS. Cost sharing between USFWS and DFG made this study possible.

1.1 Statement of Problem

The California Department of Fish and Game has determined that the Shasta River (Figure 1-1) is the most important spawning nursery area for chinook salmon in the Upper Klamath basin (DWR, 2001). Historically the Shasta supported fall and spring-run chinook salmon, coho salmon and steelhead trout. According to annual spawning counts at the Shasta River weir, the 1931 run of over 80,000 chinook salmon had dropped to 553 fish in 1990 (DFG, 1991). The Department of Water Resources (DWR) has identified physical barriers (dams, weirs), flow alterations due to water management practices, and water quality issues such as temperature and contaminant concentration as potential problems associated with the ability of salmon to spawn in this basin. The DFG and the United States Fish and Wildlife Service have determined that flow and temperature are the critical water quality parameters for restoration of this system (DWR, 2001).

Concern for fish habitat, water temperature and flow has prompted a number of studies in the Shasta River basin. The California Department of Fish and Game (DFG, 1995; DFG, 1996) and the United States Fish and Wildlife Service (USFWS, 1992) have carried out studies to assess the current fish habitat and associated needs. Flow and water temperature studies have been performed by the California Department of Water Resources (DWR, 1964; DWR, 1985). The Department of Civil and Environmental Engineering Modeling Group at the University of California, Davis (CEEMG) conducted a data inventory in 1997. In addition, Deas *et al.* (1996) conducted a woody riparian vegetation inventory. Preliminary modeling of flow and temperature was explored by the CEEMG (1998). These studies provide a basis for continuing work in the Shasta River basin.

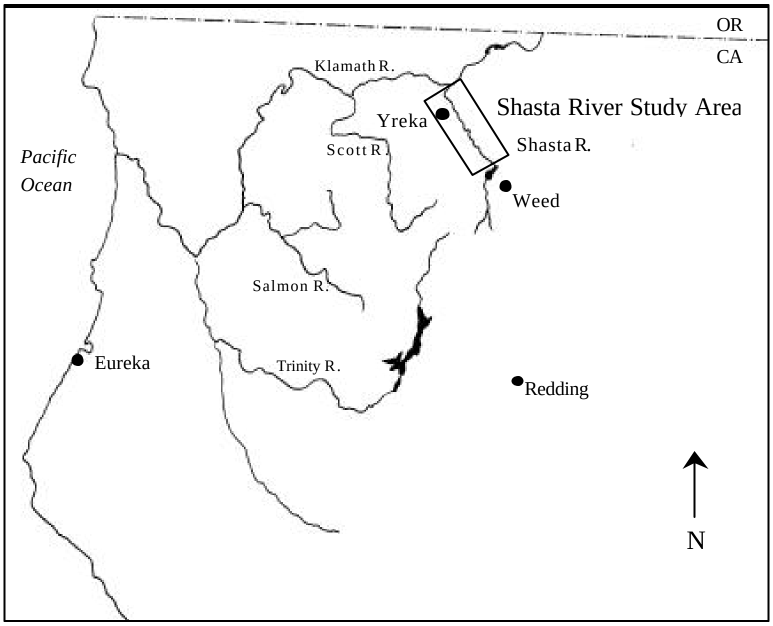


Figure 1-1 Location of the Shasta River

Water temperatures in sections of the 32-mile study reach of the Shasta River, which extends from four miles below Dwinnell Reservoir to the confluence with the Klamath River, are documented to occasionally exceed temperatures lethal to the three species of cold-water fish present in the basin (USFWS, 1992; Piper *et al*., 1983). The Shasta River basin is 800 square miles with a mean annual unimpaired runoff of approximately 162,300 acre-feet. The Shasta River receives numerous accretions from tributaries, springs, and agricultural return flows while losing water to several dams and irrigation diversions. For small streams, such as the Shasta River, riparian shading can play an important role in water temperature response through the direct reduction of incoming solar radiation. Thus, riparian restoration is a potentially useful tool to aid in control of stream temperature. The factors that make small streams sensitive to riparian shading include relatively shallow depths, low flows, and the ability of the tree canopy to shade significant portions of the stream. Riparian revegetation is not the only viable alternative to reduce stream temperatures. Flow also plays a vital role in the heating capacity of the system. Thus, two main options available to lower stream temperatures in the Shasta River are (a) to increase flow and (b) increase riparian vegetation. The focus of this study is to compare the effect of current riparian vegetation on stream temperature with the effect of riparian vegetation under various restoration scenarios.

1.2 Temperature and Anadromous Fisheries

Temperature is a critical parameter for fish survival because it controls the rates of many biological, physical, and chemical processes including active heart rate, metabolic rate, growth rate, swimming speed, feeding rate and efficiency of food conversion (Brett, 1971; Elliot, 1981). Temperatures adequate for fish survival vary with species and life stage. Temperature response for various life stages of chinook salmon, coho salmon, and steelhead trout are briefly outlined herein.

Chinook salmon eggs can survive temperatures between 1.7°C and 16.7°C, with highest survival rates between 4 and 12°C. Juvenile chinook salmon grow at temperatures from 8-24°C, under otherwise optimal conditions. Maximum growth rates occur between 13.2 and 20°C. Although chinook salmon exhibit high growth rates at temperatures approaching 19°C, lower temperatures are required to adapt to life in saltwater. Those salmon which smolt at temperatures above 16°C display reduced saltwater survival. Water temperature generally becomes lethal to Central Valley chinook salmon at chronic temperatures of approximately 25°C, although temperatures as high as 29°C can be tolerated for short periods of time. It is important to note that chinook begin to experience serious chronic effects at temperatures below their lethal limits. In addition, at higher temperatures salmon have increased risk of predations and are more sensitive to other water quality parameters and pathogens. (Myrick *et al.*, 2001)

Preferred temperatures for coho salmon eggs are between 4.4°C and 13.4°C. Juvenile coho salmon prefer temperatures between 11.8 and 14.6°C. However, coho can survive temperatures up to approximately 25°C (Hassler, 1987). Temperatures ranging from 7.2 to 16.7°C are required for coho out migration. The upper lethal limit for out migration of coho is also approximately 25°C (Birk, 1996).

Steelhead trout eggs can survive temperatures between 2 and 15°C, with highest survival rates between 7 and 10°C. Juvenile steelhead experience significant mortality at chronic temperatures of greater than 25°C, although temperatures as high as 29.6°C can be tolerated for short periods of time. Juvenile steelhead grow at temperatures from =6.9°C to at least 22.5°C, under otherwise optimal conditions. The highest growth rates reported for Central Valley steelhead occur at 19°C, however higher temperatures have not been tested. As with chinook salmon lower temperatures are required to become adapted to life in salt water. Steelhead smolt at temperatures between 6.5 and 11.3°C. (Myrick *et al.*, 2001)

In summary, chinook and coho salmon and steelhead trout survival rates exhibit a temperature dependence that varies with life stage. Eggs for these species show the highest survival rates at temperatures between approximately 4 and 13°C. Juveniles show maximum growth rates at warmer temperatures between 15 and 19°C for chinook and steelhead, and cooler water temperatures of about 11.8 to 14.6°C for coho. All three species require cooler temperatures for transition into salt water (10-17°C for chinook, 7-17°C for coho, and 6-10°C for steelhead). All three species experience increased mortality rates at chronic temperatures above 25°C. (Myrick *et al.* 2001; Hassler, 1987; Birk, 1996)

1.3 Functions of Riparian Vegetation

Riparian vegetation plays an important role in stream geomorphology and biology, and potentially water quality. Riparian vegetation acts as a cohesive agent to resist erosion from both precipitation and the stream itself. Biologically, vegetation provides habitat for various species, including insects that in turn provide food for juveniles. Trees are specifically vital to fish survival because they supply woody debris to the river that accumulate in log jams used as hiding places from predators in addition to providing a range of velocities acceptable to juveniles. A well-developed riparian zone can also assist in controlling water temperatures.

Riparian vegetation can affect stream temperature by altering the heat flux in several ways. Vegetation can affect the heat flux by reducing wind speed, altering the microclimate above the water surface (i.e. air temperature and relative humidity), and reflecting long-wave radiation (CEEMG, 2001). If the forest canopy covers a significant portion of the stream, perhaps its greatest effects are absorbing, filtering and reflecting solar radiation. Brown (1970) noted that incoming solar radiation may account for close to 95% of the heat input during midday in the summer. Under non-shaded conditions solar radiation has more of an influence on water temperature than air temperature, thus being the dominant source of heat input into the stream. In addition, Bartholow (1989) described two other (less effective) ways through which riparian vegetation affects stream temperature. First, vegetation reduces the amount of the water's back radiation at night, tending to moderate the minimum stream temperatures. Second, the vegetation produces its own long wave (thermal) radiation, which also tends to raise minimum temperatures at night.

For this study it is assumed that the largest impact riparian vegetation has on stream temperature of the Shasta River is through the filtering of incoming solar radiation. This research focuses on that primary role.

1.4 Summary of Vegetation Effects on Water Temperature

The aforementioned researchers and others have helped to provide a basis for understanding the effects of riparian vegetation on stream temperature through modification of existing temperature models to account for riparian vegetation. The USFWS adapted the model SNTEMP to include shading. Their modeling shows that streams are sensitive to shading when flows are low, the width-to-depth ratio is large, wind speed is low, and solar radiation is high. La Marche, *et al.* (1997) altered the stream temperature model STRTEMP to model vegetative effects on two reaches of the Dechutes River. They discovered that stream orientation and the width of a strip of buffer vegetation were key to maximizing shading effects. Chen, *et al.* (1997) modified a comprehensive hydrologic model, HSPF, to incorporate shading. In modeling of the Upper Grande Ronde watershed they determined that riparian vegetation was the only critical factor that could be managed to reduce stream temperature. Lowney (2001) adapted the finite-element water quality model RMA-10 to model several vegetative characteristics and their effects on the temperature of the Sacramento River. She found that, of all vegetative characteristics, shading had the largest effect on water temperature. She also concluded that riparian shading had a negligible effect on rivers the size of the Sacramento River. Based on the above findings, the Shasta River appears to present the ideal conditions for maximum use of vegetation to control river temperature. The Shasta River is a small system that experiences low summer flows with very high solar radiation fluxes.

1.5 Study Area

The Shasta River, located in central Siskiyou County, Northern California, originates in the Scott Mountains in the vicinity of Mt. Eddy and flows north and north-westward for roughly seventy miles before discharging into the Klamath River. The river is fed by glacial melting and precipitation runoff from Mount Shasta that is delivered to the river by groundwater flows and springs. The river is impounded by Dwinnell Dam at river mile 36.4. Due to minimal flows (J. Whelan, pers. comm.) and difficulty in gaining access to the upper river, the study area extends from approximately river mile 32 to the confluence with the Klamath River. Figure 1-2 depicts the Shasta River as derived from the National Hydrography Dataset. The upstream end of the study reach is referred to as Shasta River above Parks (SRP). The Shasta River flowing downstream from SRP is joined by several small tributaries including Parks Creek, Willow Creek, Little Shasta River, and Yreka Creek and a large tributary, Big Springs, that is spring fed. Many of the system's smaller tributaries are dry in the summer. During the irrigation season from April to October there are several agricultural diversions along the river. Although most diversions are associated with individual landowners, the larger diversions include the Grenada Irrigation District (GID) and the Shasta Water Users Association (SWA). Agricultural return flow varies along the system and enters the river in a variety of forms: as flow in defined channels, diffuse overland flow, and subsurface flow. The Shasta River is relatively steep at its headwaters with an average slope from Dwinnell Reservoir (RM 36.4) to SRP (RM 31.8) of 0.008, or about 40 feet per mile. Between SRP and where Interstate 5 crosses the river (RM 8.3) the average slope is approximately 0.002, or about 10 feet per mile. This allows the river to develop a complex set of meanders. For the last eight miles the river runs through a canyon with a steeper slope of 0.01, or about 50 feet per mile. Figure 1-3 illustrates the profile of the river with elevations taken from 1:24,000-scale United States Geological Survey (USGS) maps.

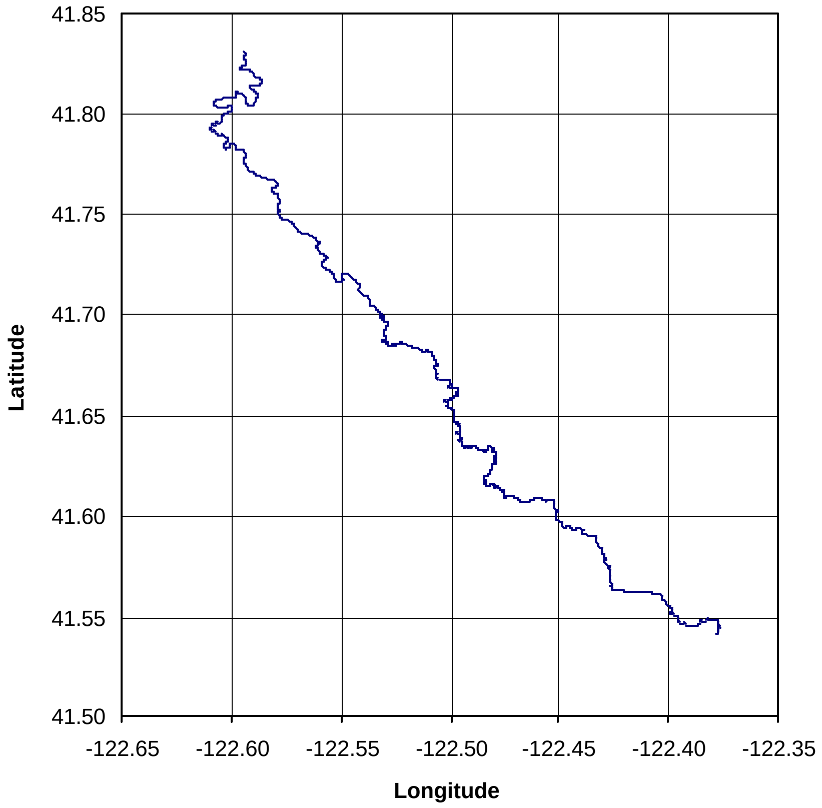


Figure 1-2 Shasta River as derived from the National Hydrography Dataset

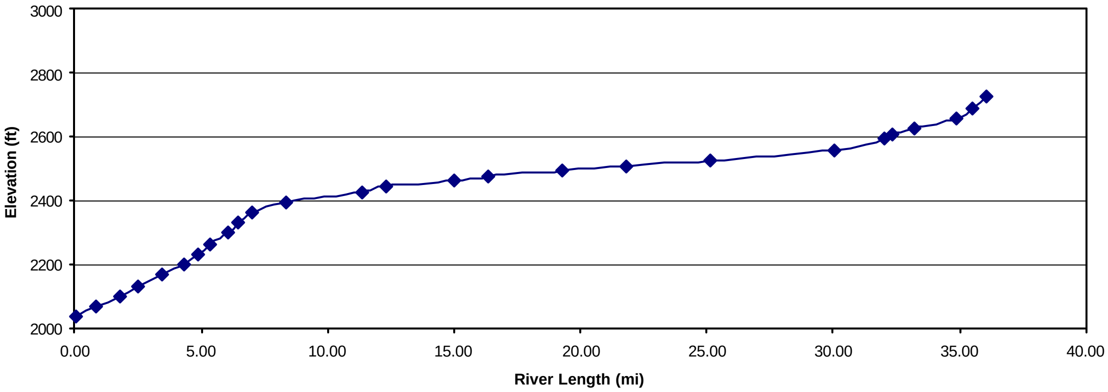


Figure 1-3 Shasta River longitudinal profile

2.0 Modeling Approach

To quantify the influence of riparian vegetation on Shasta River water temperatures, it was necessary to simulate flow, temperature, and riparian shade. This chapter addresses the choice of an appropriate model, the mathematical formulations in the model, the theoretical considerations in modeling temperature and a discussion of modifications made to the model for this particular application.

2.1 Model Choice

After a review of the models available in the public domain, the Tennessee Valley Authority's (TVA) River Modeling System (RMS), a one-dimensional hydrodynamic and water quality model, was chosen to model the Shasta River. This model was chosen because it is readily available, contains basic shading logic, allows for modeling at an hourly time step, and is supported by TVA. RMS has two components, the hydrodynamic model, ADYN, and the water quality model, RQUAL. These components may be used independently or in sequence. This section includes a discussion of the formulations of each model component. Information discussed below about model formulation was found in the RMS User's Manual (Hauser, 1995).

2.1.1 The Hydrodynamic Component: ADYN

ADYN solves the one-dimensional unsteady flow equations for conservation of mass and momentum using either a four-point implicit finite difference scheme with weighted spatial derivatives or a McCormack explicit scheme. The four-point implicit finite difference scheme was chosen for this application because the irregularity of the channel geometry rendered the explicit scheme inadequate. ADYN can model interactions with dynamic tributaries at channel junctions, multiple tributary systems with multiple internal boundary conditions along each system, and the effects of distributed or point lateral inflows. For this application the Shasta River will be modeled as one continuous reach with several distributed dynamic lateral inflows.

2.1.2 The Water Quality Component: RQUAL

RQUAL uses the geometry, velocities and depths from the hydrodynamic model in the calculation of water quality variables. RQUAL can be used to study several water quality parameters. However, this application employs only the temperature modeling capability. RQUAL offers three options of numerical schemes used to solve the one-dimensional transport equation: a four-point-implicit finite difference scheme with weighted spatial derivatives, a McCormack explicit scheme, or a Holly-Preissman scheme. Preliminary model testing found negligible difference in results between the four-point-implicit and Holly-Preissman schemes when applied to the Shasta River. The four-point implicit scheme was chosen for use in this application. In the coding of RQUAL, dispersion is neglected because the model was designed for application in highly river systems where transport is the dominant factor. Numerical dispersion serves to account for the lack of an explicit dispersion term (Hauser, pers. comm.).

The heat budget (outlined in Section 2.2) used in RQUAL includes logic for bed heat exchange and riparian shading. Bed conduction logic was not used in this modeling study. Existing shading logic was not entirely sufficient to represent the dynamics of the Shasta River, so modifications were made. These modifications are discussed in Section 2.3 of this report. In addition, a specific piece of shading logic that lowers dry bulb temperature in shade was not implemented.

It should be noted that RQUAL does not model shading by large-scale topographic features (e.g. hills, canyons, etc.). If this type of shading is considered to have a significant effect on water temperature, then modifications need to be made to the model to account for it. For the Shasta River the only potential for topographic shading of this type occurs between the Mouth and RM 7, where the Shasta enters a canyon below Anderson Grade. For this modeling effort the effect of topographic shading was not considered.

2.2 Heat Budget

Temperature models fall into two general classes: empirical models relating observations of stream temperature to stream properties (such as discharge, channel geometry, and streamside vegetation characteristics) and/or meteorological conditions, and models that represent the physical processes of heat exchange by means of the energy (or heat) budget. Although simple and generally convenient to use, empirical models are limited to assessing conditions within the range of data used to construct the relationship and do not provide detailed information about the effects of certain factors on stream temperature. These factors may include variations in discharge; changes in the location, size, and extent of vegetative cover; cumulative effects of upstream disturbances in riparian areas, and stream orientation effects on incoming solar radiation (La Marche, *et al.*, 1997). Brown (1969) noted that one of the most effective process-based techniques for predicting river temperatures and temperature changes is the heat budget approach. The water quality component of the TVA model (RQUAL) uses the heat budget approach that quantifies pertinent factors by formulations based on physical processes.

The heat budget approach quantifies the net exchange of heat at the air-water interface. TVA has extended the approach to also include heat exchange at the water-bed interface. This net change may be expressed as the sum of the major sources and sinks of thermal energy or the sum of the heat fluxes.

TVA Heat Budget Formulation

$$Q_n = \frac{Q_{ns} + Q_{na} + Q_{bed} - Q_b - Q_e - Q_c}{D}$$

where:

Q_n = the net heat flux (representing the rate of heat released from or added to storage in a particular volume) (kcal/m^{3}s)
Q_{ns} = net solar (short-wave) radiation flux adjusted for shade (kcal/m^{2}s)
Q_{na} = net atmospheric (long-wave) radiation flux (kcal/m^{2}s)
Q_{bed} = net flux of heat at the water- channel bed interface (kcal/m^{2}s)
Q_b = net flux of back (long-wave) radiation from water surface (kcal/m^{2}s)
Q_e = evaporative (latent or convective) heat flux (kcal/m^{2}s)
Q_c = conductive (sensible) heat flux (kcal/m^{2}s)
D = mean depth (m)

2.2.1 Net Solar (Short-wave) Radiation Flux

The net short-wave radiation flux (Q_{sn}) is that portion of the total short-wave solar radiation that reaches the water surface. This term represents that portion of the short-wave radiation that is not scattered, intercepted, or reflected by the atmosphere, clouds or vegetation on its way to the water surface. Hence, this term largely depends on the local altitude of the sun, cloud cover, vegetation cover, and an atmospheric turbidity factor. Some models calculate this value based on a theoretical value of solar radiation and the above-mentioned parameters. RMS represents incoming solar radiation (Q_s) as an input in the meteorology input file that is then adjusted in the model to account for the vegetation cover by shading factor (R_s).

$Q_{ns} = Q_s * R_{s.}$

where:
Q_s = incoming solar radiation (an input parameter for the model)
$R_{s.}$ = shade factor, a fraction (0.0-1.0) of solar radiation that reaches the water surface

2.2.1.1 Computation of the Shade Factor (R_s)

The shade factor, R_s, depends on size and proximity of trees and banks, solar azimuth, river aspect, and the percent of solar radiation that penetrates the vegetation canopy (here referred to as vegetative transmittance, SHSOL).

There are three steps that must be taken before directly computing R_s:

1) Calculate the solar altitude (S_a)
2) Calculate the length of the shadow parallel to the azimuth of the sun (AZS)
3) Calculate the length of the shadow normal to the bank of the river

Solar altitude, S_a, is the angle between the sun and the observer's horizon (see Figure 2-1). S_a is a function of the latitude of the river, the declination of the sun, and the time of day (hour angle of the sun). S_a is calculated by the following equation (TVA 1972):

$$S_a = Sin^{-1}\left(Sin f Sin d + Cos f Cos d Cos t\right)$$

where:

S_a = solar altitude (radians)
f = latitude of the river (radians)
d = declination of the sun (radians)
t = local hour angle of the sun (radians)

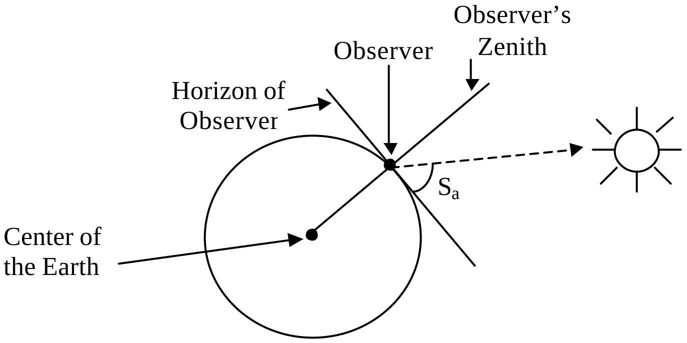


Figure 2-1 Diagram of the solar altitude

The declination of the sun is the angle between the earth's equator and the sun. It is dependent upon the time of year represented as Julian days. The declination is calculated by the following equation (TVA, 1972) where JD is the Julian day (1-365):

$$d = 23.45\left(\frac{2p}{360}\right)Cos\left(2p\,\frac{(172 - JD)}{365}\right)$$

The hour angle is the time of day, expressed in radians. The local hour angle, or the fraction of 2p that the earth has turned after local solar noon (CEEMG 2001), is calculated in RQUAL by the following equation. (Note: This formulation is appropriate for western longitudes.)

$$t = \left(180 + l - t_m - \left(360 \cdot \frac{hr}{24}\right)\right)\left(\frac{2p}{360}\right)$$

where:

l = longitude of the river (degrees)
t_m = local time zone meridian (degrees)

hr = hour of the day

Next the azimuth of the sun AZS (radians) must be determined to calculate the direction of the shadow cast by the vegetation. AZS is a function of declination, solar altitude, and the latitude of the river. This is done by the following equation which yields a value for AZ that varies from 0° to 180°. (Note: The azimuth of the sun is measured clockwise from north when the sun is east of the local meridian, and counter-clockwise from north when the sun is west of the local meridian.)

$$AZS = Cos^{-1}\left(\frac{Sin d - Sin S_a Sin f}{Cos S_a Cos f}\right)$$

where:

AZS = solar azimuth
S_a = solar altitude (radians)
f = latitude of the river (radians)
d = declination of the sun (radians)

The length of the shadow (X) cast by the effective barrier (e.g. vegetation) that is parallel to the azimuth of the sun (AZS) can be found by geometry as shown in Figure 2-2.

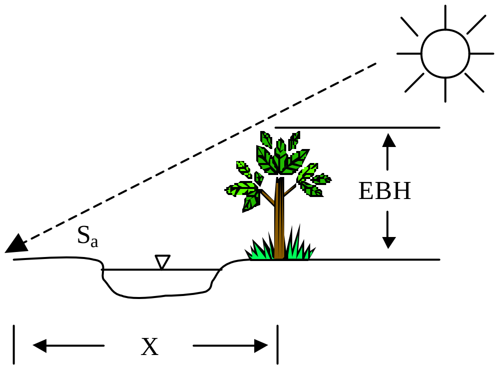


Figure 2-2 Diagram depicting the variables for calculating X, the length of the shadow parallel to the azimuth of the sun

$$X = \frac{EBH}{\tan(S_a)}$$

where:

EBH = effective barrier height (meters)
X = length of shadow parallel to the azimuth of the sun (meters)

Using geometry X_n, the length of the shadow normal to the stream aspect, can be calculated as shown in Figure 2-3.

$$X_n = X(\sin(AZS-AZ))$$

where:

X_n = length of the shadow normal to the stream aspect
X = length of the shadow cast by the effective barrier
AZS = azimuth of the sun
AZ = stream aspect

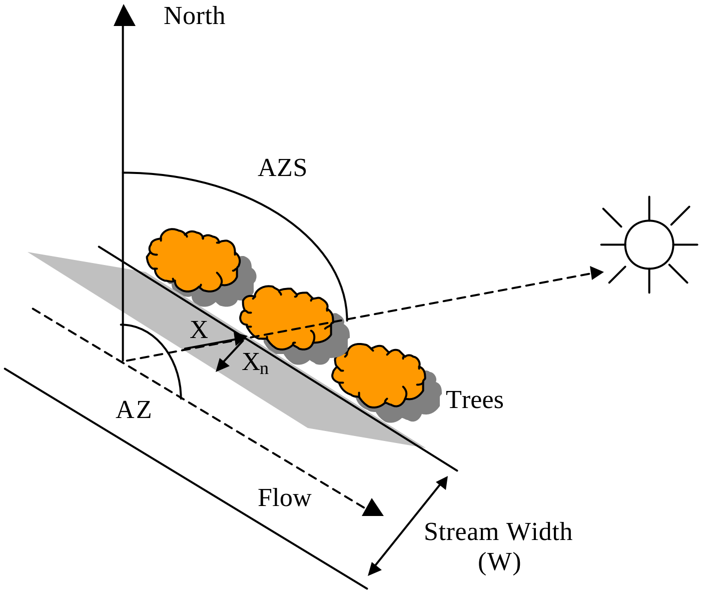


Figure 2-3 Diagram depicting the variables for calculating X_n

There are three possible shading conditions: shade free, partially shaded, and fully shaded. Once the length of the shadow normal to the stream bank is determined, R_s can be calculated by the following equations according to the appropriate scenario:

<u>No Shade</u>

$(X_n = B \text{ or } \cos ß = 0.01)$: $R_s = R_{sm}$

<u>Partial Shade</u>

$(B < X_n = W+B)$: $R_s = R_{sm} (W+B-X_n)/W + SHSOL(X_n-B)/W$

Full Shade

(W+B < X_n or S_a = 1.5 or hr < TFOG): R_s = SHSOL

where:

R_{sm} = the shade free absorption coefficient
X_n = shadow length normal to stream bank (m)
SHSOL = vegetative transmittance (0 = SHSOL = 1, 0 = no light gets through)
ß = angle between the sun and normal to the stream axis (radians)
S_a = solar altitude (radians)
TFOG = time of fog lift (hours)
B = bank width or vegetative setback (m)
W = channel width (m)

The shade free absorption coefficient (R_{sm}) is a factor that accounts for the reflectivity of the water surface given no shading by streamside vegetation. R_{sm} represents the fraction of solar radiation not reflected by the shade-free water surface. The formulation of this factor as found in RQUAL is taken from Anderson (1954):

$$R_{sm} = 1 - (a / (180 * S_a/p)^b$$

where:

R_{sm} = shade free absorption coefficient
a, b = coefficients depending on cloud cover
S_a = solar altitude

and coefficients “a” and “b” are selected based on specific cloud cover conditions, C, as follows:

C	a	b
<0.05	1.18	0.77
0.05-0.5	2.20	0.97
0.5-0.95	0.95	0.75
>0.95	0.35	0.45

2.2.2 Net Atmospheric Radiation

The net atmospheric long-wave radiation flux (Q_{na}) originates from the atmosphere when clouds, dust, and other particles re-radiates short-wave radiation intercepted from the sun. This term depends on air temperature and cloud cover. The equation used to calculate Q_{na} is in a form derived from Swinbank (1963) with a value of 0.03 for the reflectivity of the water surface (R_L).

$$Q_{na} = 1.23\times10^{-16}\left(T_a + 273\right)^6\left(1 + 0.17C^2\right)$$

where:
Q_{na} = net atmospheric radiation (kcal/m^{2}s)
C = cloud cover
T_a = dry bulb air temp (°C)

2.2.3 Net Back Radiation from the Water Surface

The net water surface long-wave radiation flux (Q_b) is heat radiated by the water surface. This term is mainly dependent on water temperature and is calculated using the Stefan-Boltzmann equation:

$$Q_b = es\,(T + 273)^4$$

$$= 0.736 + 0.00117T$$

where:
Q_b = net back radiation (kcal/m^{2}s)
s = Stefan-Boltzmann constant
T = water temperature (°C)
e = emissivity. The commonly assumed value for objects on the earth's surface is e = 0.97

2.2.4 Net Evaporative Heat Flux

The evaporative (latent or convective) heat flux (Q_e) occurs at the stream surface. It is the transfer of heat through the state change of surface water to vapor, or water vapor to liquid water. Hence, the important factors in convection are the latent heat of vaporization, wind speed, the temperature gradient between air and water (usually expressed in the form of vapor pressures at the surface and in the atmosphere). In the RMS formulation if the saturation vapor pressure at the water surface is less than the pressure in the air, then the net evaporative heat loss is assumed to be zero. Hence, in RMS this term cannot be used to model condensation in addition to evaporation.

If $e_s > e_a$

$$Q_e = rL\left(a_1 + b_1W\right)\left(e_s - e_a\right)$$

where:
? = density of water (kg/m^3)
L = latent heat of vaporization (kcal/kg) = 597-0.57 T
T = water temperature (°C)
a_1, = empirical wind coefficient (mb^{-1}m/s)
b_1 = empirical wind coefficient (mb^{-1})
W = wind speed (m/s)

e_a = saturation vapor pressure at air temp (mb)
e_s = saturation vapor pressure at water temp (mb)

Saturation vapor pressure at water temperature and air temperature are defined as:

$$e_a = 2.171 \times 10^8 \exp\left(\frac{-4157}{T_d \, 239.09} \right) \text{ and}$$

$$e_s = aj + bjT$$

where:

T_d = dewpoint temperature (°C).

2.2.5 Net Conductive Heat Flux

The sensible or conductive heat flux, Q_c, is heat flux through molecular or turbulent transfer between the air and water surface. The amount of heat gained or lost through sensible heat flux depends on the gradient of temperature between the water and air. The RMS formulation of this equation is derived using Bowen's Ratio.

$$Q_c = rL(a_1 + b_1 W)(C_B \times 10^{-3} P)(T - T_a)$$

Q_c = net conductive heat transfer (kcal/m^{2}s)
C_B = Bowen's Ratio (0.61 °C^{-1})
and ?,L, T, a_1, b_1, W, T_a as defined above.

2.2.6 Net Bed Heat Flux

The bed heat flux or bed conduction, Q_{bed}, is the net transfer of heat from the channel bed to the water. This heat flux depends on the temperature gradient between the water and the bed. (Note: This term was turned off in the calculation of the heat budget for the Shasta River simulations. See Section 2.1.2.) The RMS formulation of this process is:

$$Q_{bed} = -(Q_{nsr} + Q_{bc})$$

where:
Q_{bed} = net bed heat flux (kcal/m^{2}s)
Q_{nsr} = net solar radiation available for warming the channel bed (kcal/m^{2}s)
Q_{bc} = heat conducted from water to bed due to temperature differential (kcal/m^{2}s)

And

$$Q_{nsr} = (1 - A_b)(1 - b)\exp(-h(D - 0.6))Q_{ns}$$

where:

Q_{nsr} = net solar radiation available for warming the channel bed (kcal/m^{2}s)
A_b = albedo of bed material
ß = fraction of solar radiation absorbed in surface 0.6m of water
? = extinction coefficient in water (1/m)
D = mean depth of water (m)
Q_{ns} = net short-wave solar radiation corrected for shading (kcal/m^{2}s)

$$Q_{bc} = \frac{10C_v K(T - T_{bed})/0.5L}{3600}$$

where:
Q_{bc} = heat conducted from water to bed due to temperature differential (kcal/m^{2}s)
C_v = heat storage capacity of bed material (cal/cm^3°C)
K = thermal diffusivity of bed material (cm^2/hr)
T = water temperature (°C)
T_{bed} = average temperature of the bed (°C)
L = effective bed thickness (cm).

2.3 Model Modifications

As originally formulations for calculating R_s, the shade factor in RQUAL, include the following limitations:

1) The user may enter only one value for vegetative transmittance (SHSOL) for an entire system.

2) The user may enter only one value for effective barrier (or, vegetation) height (EBH) per node.

These limitations were designed for a river system in which there is little variability of effective barrier height and continuity of vegetation. The Shasta River is fundamentally different from the rivers typically studied by the Tennessee Valley Authority (TVA), for which this model was designed. Whereas the rivers within the TVA study region run through thick forests, the Shasta River runs through reaches of sparse vegetation, where vegetation may only occur on one bank or the other. In addition, the purpose of the Shasta River modeling project is to assess the effect of riparian vegetation on stream temperature and to provide quantitative analysis of possible revegetation scenarios. In order to have the flexibility required to accurately represent the current streamside vegetation and to run various revegetation scenarios, the model required expansion of the current ability to represent the transmittance and effective barrier height. To accomplish this, the representation of SHSOL was expanded to allow for input of transmittance and EBH values for each bank. EBH was also expanded to allow for input of vegetation height on the right and left bank that could vary by location.

2.3.1 Altered Shading Logic

Several modifications were made to the model to implement the required changes:

1) Four solar output files were added to allow access to key variables in time series at each of four nodes. The key variables include EBH, SHSOL, SWS (incoming solar radiation), QNS (adjusted solar radiation), and T2 (water temperature).

2) Modifications were made to the main program and to subroutine CRS to allow the input of right and left bank parameters for EBH and SHSOL.

3) Shading logic was added in the subroutine CRS to process the new right and left bank parameters.

The solar output files currently are programmed to output information at specific nodes. This can be altered in the code by changing the node in the write statements to files 28-31 found in the main program beginning at line 940.

To make the code flexible, a flag (IRS) was added to the first line of the water quality coefficient input file that can turn on/off the new shading logic. If IRS = 1, the new shading logic is used. (See APPENDIX A for input file modifications.) The modifications made to the subroutine CRS in order to process the new right and left bank parameters are outlined below.

To determine which bank information to use, logic was include to determine which bank provides shade to the stream at sunrise. After the first bank is labeled the model switches bank information when the sun crosses the river. This is determined by comparing the aspect of the river and the azimuth of the sun. When the aspect of the river is equal to the azimuth of the sun then the sun is directly over the river and no shading occurs. To illustrate, if the stream was flowing north the aspect would be 0° (recall that stream aspect is measured clockwise from north ranging from 0°-360°), the right bank would be on the east side of the stream and the left bank would be on the west. At sunrise the east (right bank) will be shading the stream. When the sun's azimuth reaches 180° it is directly over the stream, and once the azimuth of the sun crosses the stream the west bank (or left bank) provides the shade, as shown in Figure 2-4.

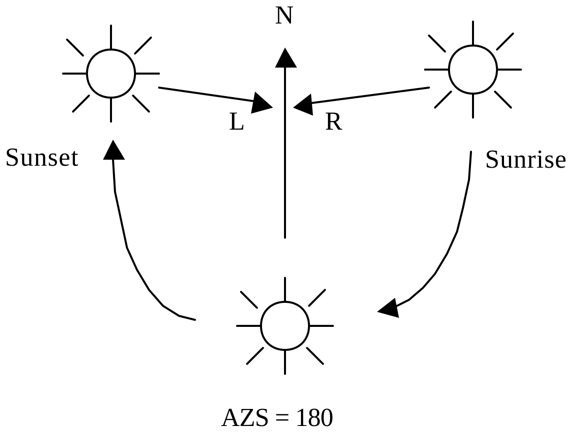


Figure 2-4 Diagram of sample stream, with aspect = 0.0

Figure 2-5 illustrates the situation if this same stream were flowing south instead of north. The aspect of the stream would be 180° and the first bank to provide shade would be the left bank.

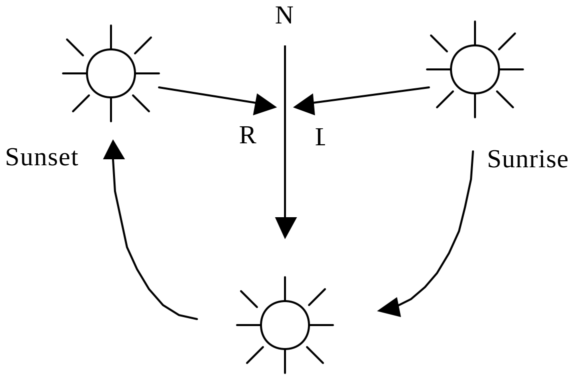


Figure 2-5 Diagram of sample stream, with aspect = 180.0

Determining which is the first bank to provide shade and then switching to use information from the opposite bank when the sun crosses the stream is accomplished by the logic described in Figure 2-6. Figure 2-6 is a flowchart of the two-bank shading logic added to RQUAL. The full listing of the modified program code can be found in Appendix B.

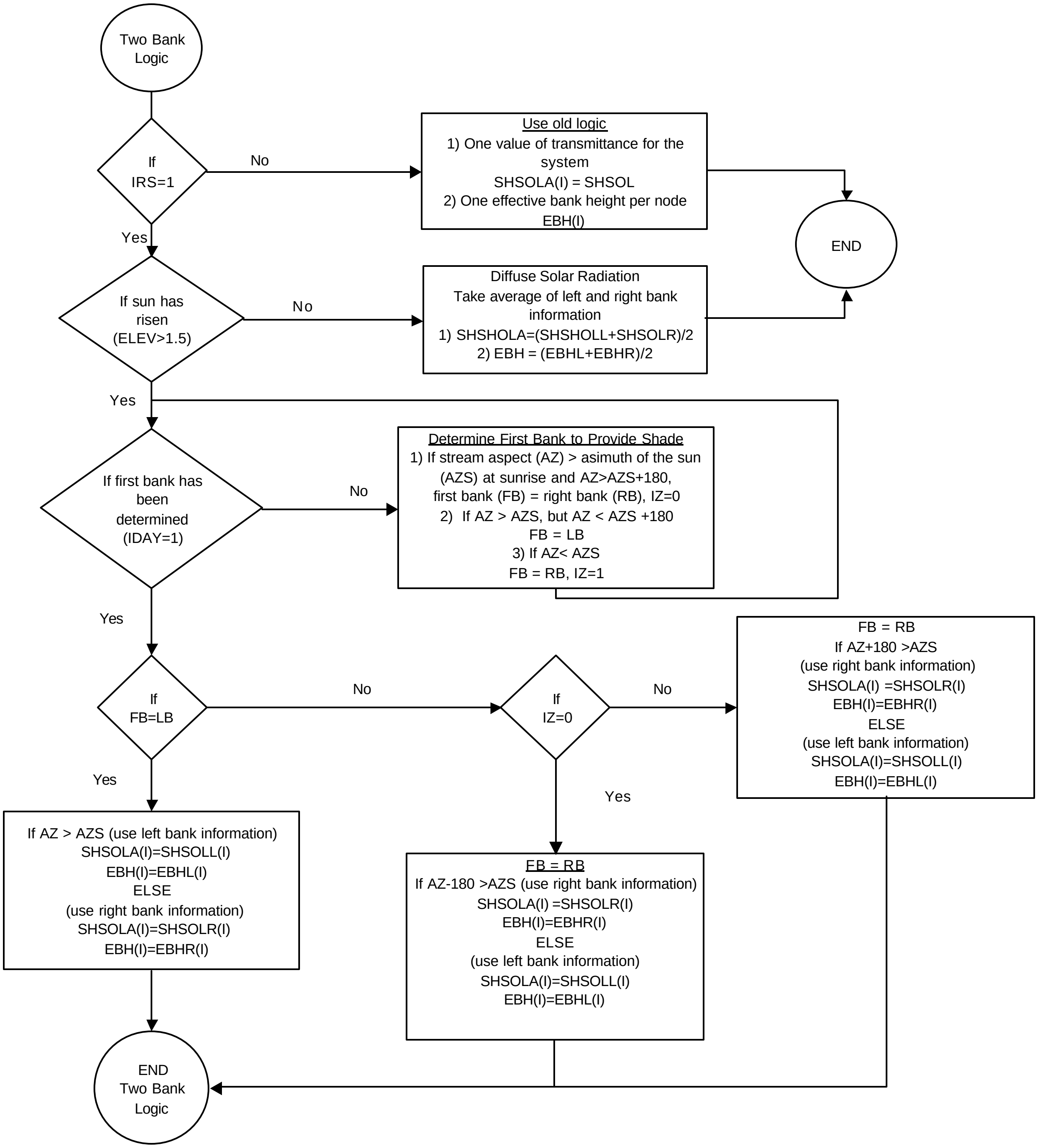


Figure 2-6 Flowchart of two-bank shading logic

Depicted in Figure 2-7 are the three scenarios to consider when assigning the first bank that provides shade to the river. Scenario One occurs when the stream aspect is less than the azimuth of the sun. Scenario Two occurs when the stream aspect is greater than the azimuth of the sun and less than the azimuth of the sun plus 180°. Scenario Three occurs when the stream aspect is greater than the azimuth of the sun and greater than the azimuth of the sun plus 180°.

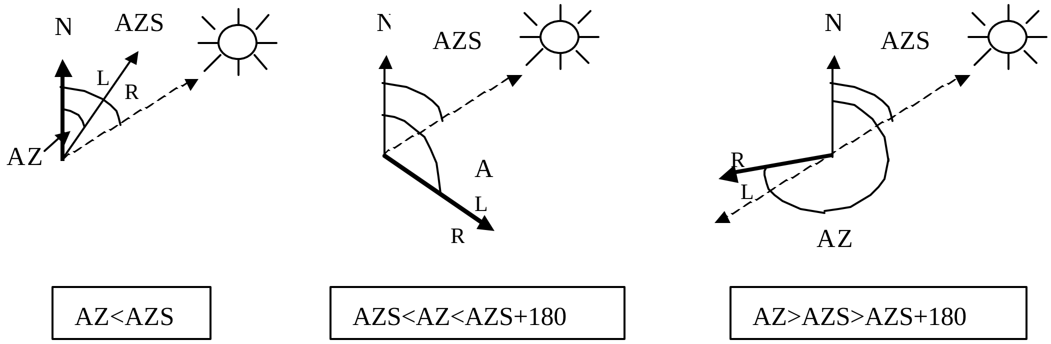


Figure 2-7 Diagram depicting three aspect scenarios of the two bank shading logic

In Scenario One the first bank to provide shade is the right bank. In Scenario Two, the first bank to provide shade is the left bank. In Scenario Three the first bank to provide shade is the right bank. After the first bank is assigned, the logic switches bank information as the sun's azimuth passes over the stream azimuth.

Before sunrise and after sunset the amount of solar radiation compared to peak daily values is negligible. Whatever solar radiation does exist at dawn and dusk is considered small. For modeling purposes SHSOL and EBH during these times is set to an average of right and left bank values. This is partially a relict of the original coding which requires a value for SHSOL and EBH during the nighttime hours. Since there is no appreciable solar radiation before sunrise or after sunset this logic does not affect simulated temperatures.

2.3.2 Testing of Modifications

The modified shading logic was tested using seven test cases. The test cases were run using a rectangular channel 2 feet deep and 100,000 feet long with flow of 100 cfs. Meteorological data from August 28, 2001 was used. Transmittance factors for all left bank nodes were set to 0.15 and all right bank nodes were set to 0.0. Effective barrier height (EBH) was set to 10 feet (3.048 m) for the left bank and 40 feet (12.192 m) for the right bank. Figure 2-8 depicts the stream aspects and compass direction for each test case, they were: 0(north), 45(northeast), 90(east), 135 (southeast), 180(south), 225 (southwest), 270 (west). Each test case was assigned a different stream aspect to test the ability of the model to use the appropriate bank information for each time step throughout a 24-hour period. It was expected that as the sun passed from one side of the stream to the other the value of SHSOL and EBH would change according to the values for the left and right bank. The model accurately assigned both variables for each time of day for each test case as shown in Table 2-1 and Table 2-2.

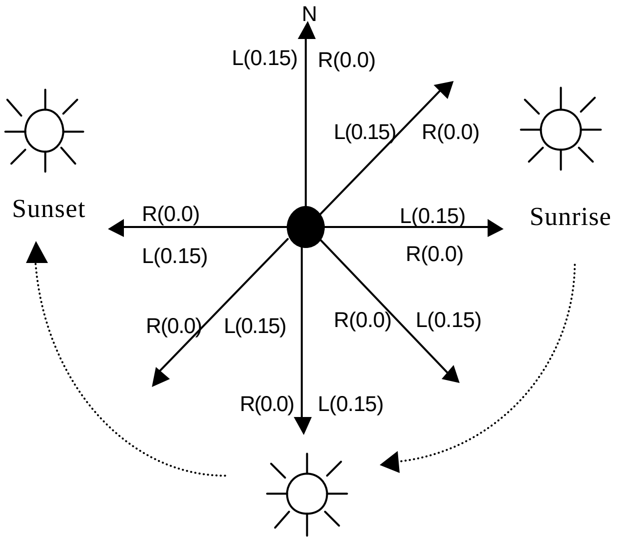


Figure 2-8 Diagram of stream aspects used in testing of two-bank shading logic

To illustrate, at 1pm (or hour 13) for the north flowing stream the transmittance switched from the right bank value of 0.0 to the left bank value of 0.15. In addition, the effective barrier height also changed from the right barrier height of 40 ft (12.192 m) to the left barrier height of 10 ft (3.048 m). Note that before sunrise and after sunset the value for SHSOL and EBH is an average of the values for right and left bank (explanation included in Section 2.3.1).

Table 2-1 Transmittance factors during the course of one day for seven test cases

SimHR	N	NE	E	SE	S	SW	W
1	0.075	0.075	0.075	0.075	0.075	0.075	0.075
2	0.075	0.075	0.075	0.075	0.075	0.075	0.075
3	0.075	0.075	0.075	0.075	0.075	0.075	0.075
4	0.075	0.075	0.075	0.075	0.075	0.075	0.075
5	0.075	0.075	0.075	0.075	0.075	0.075	0.075
6	0	0	0.15	0.15	0.15	0.15	0
7	0	0	0	0.15	0.15	0.15	0.15
8	0	0	0	0.15	0.15	0.15	0.15
9	0	0	0	0.15	0.15	0.15	0.15
10	0	0	0	0.15	0.15	0.15	0.15
11	0	0	0	0	0.15	0.15	0.15
12	0	0	0	0	0.15	0.15	0.15
13	0.15	0	0	0	0	0.15	0.15
14	0.15	0	0	0	0	0.15	0.15
15	0.15	0.15	0	0	0	0	0.15
16	0.15	0.15	0	0	0	0	0.15
17	0.15	0.15	0	0	0	0	0.15
18	0.15	0.15	0	0	0	0	0.15
19	0.075	0.075	0.075	0.075	0.075	0.075	0.075
20	0.075	0.075	0.075	0.075	0.075	0.075	0.075
21	0.075	0.075	0.075	0.075	0.075	0.075	0.075
22	0.075	0.075	0.075	0.075	0.075	0.075	0.075
23	0.075	0.075	0.075	0.075	0.075	0.075	0.075
24	0.075	0.075	0.075	0.075	0.075	0.075	0.075

Table 2-2 Effective barrier height during the course of one day for seven test cases

SimHR	N	NE	E	SE	S	SW	W
1	7.62	7.62	7.62	7.62	7.62	7.62	7.62
2	7.62	7.62	7.62	7.62	7.62	7.62	7.62
3	7.62	7.62	7.62	7.62	7.62	7.62	7.62
4	7.62	7.62	7.62	7.62	7.62	7.62	7.62
5	7.62	7.62	7.62	7.62	7.62	7.62	7.62
6	12.192	12.192	3.048	3.048	3.048	3.048	12.192
7	12.192	12.192	12.192	3.048	3.048	3.048	3.048
8	12.192	12.192	12.192	3.048	3.048	3.048	3.048
9	12.192	12.192	12.192	3.048	3.048	3.048	3.048
10	12.192	12.192	12.192	3.048	3.048	3.048	3.048
11	12.192	12.192	12.192	12.192	3.048	3.048	3.048
12	12.192	12.192	12.192	12.192	3.048	3.048	3.048
13	3.048	12.192	12.192	12.192	12.192	3.048	3.048
14	3.048	12.192	12.192	12.192	12.192	3.048	3.048
15	3.048	3.048	12.192	12.192	12.192	12.192	3.048
16	3.048	3.048	12.192	12.192	12.192	12.192	3.048
17	3.048	3.048	12.192	12.192	12.192	12.192	3.048
18	3.048	3.048	12.192	12.192	12.192	12.192	3.048
19	7.62	7.62	7.62	7.62	7.62	7.62	7.62
20	7.62	7.62	7.62	7.62	7.62	7.62	7.62
21	7.62	7.62	7.62	7.62	7.62	7.62	7.62
22	7.62	7.62	7.62	7.62	7.62	7.62	7.62
23	7.62	7.62	7.62	7.62	7.62	7.62	7.62
24	7.62	7.62	7.62	7.62	7.62	7.62	7.62

2.3.3 Limitations of the Shading Logic

There are limitations to the correct application of the shading logic in RQUAL. The two-bank shading logic should be applied to systems using an hourly or finer time step. Time steps greater than one hour could result in misapplication of bank information. There is a possibility that with large time steps the model would not be able to detect the first bank accurately. In addition, the formulation of the hour angle equation limits the use of this model to the western hemisphere.

3.0 Fieldwork

To support the flow and temperature model of the Shasta River, field programs to collect the necessary data were designed and implemented. This monitoring effort was funded through a separate grant from the Klamath Basin Fisheries Task Force and administered by the United States Fish and Wildlife Service.

Required data for modeling flow and temperature include geometric descriptions of locations and cross-sections, riparian vegetation data, flow data, water temperature data, and climatic data. Existing programs and information were reviewed to determine the availability of data and specific needs for monitoring. The individual programs are briefly outlined below. Complete details can be found in Abbott and Deas (2003, in press).

Geometry: Detailed stream cross-section geometry was largely unavailable. DFG habitat surveys were available, but provided only limited data. Additional fieldwork was carried out to further characterize the geometric stream channel representation of the river.

Riparian Vegetation: Riparian vegetation field monitoring included measurement of baseline (no shade) and reduced (shaded) incoming solar radiation conditions throughout the Shasta River twice during the 2001 field season and a survey of tree height throughout the basin. The focus of this element of the project was to quantify the effect of riparian shading on water temperature and water temperature control potential for anadromous fisheries restoration. Findings are relevant to re-vegetation projects, water temperature monitoring, water temperature modeling studies, and other restoration activities on the Shasta River as well as neighboring reaches of the main stem Klamath River and tributaries (e.g., Scott River).

Flow: A flow study was proposed to characterize the dynamic nature of the Shasta River during late spring through fall. Subtask elements included review of existing data, reevaluation of past monitoring efforts, selection of appropriate locations, development of a flow monitoring protocol, and remote gauging of flow at fifteen-minute intervals during low flow periods (seasonally). Flow monitoring sites were chosen by dividing the study reach into five approximately equal sections. The exact location of each monitoring site was governed by access (roads and land owner cooperation). Water temperature was monitored at all flow monitoring locations. These data proved invaluable in understand the flow and thermal variability of the Shasta River and were paramount to effective modeling of flow and temperature.

Temperature: Watercourse Engineering, Inc. assisted the DFG in implementing the 2001 and 2002 temperature monitoring programs. Subtask elements included review of existing data, reevaluation of past monitoring efforts, development of monitoring protocol, selection of appropriate locations, and remote gauging of temperature at hourly intervals during low flow periods (seasonally). Hourly temperature monitoring sites were chosen based on previous DFG monitoring sites and additional locations where more data was desirable as indicated by preliminary modeling. The exact location of each monitoring site was governed by access (roads and land owner cooperation).

Meteorological Data: Climatic data for the Shasta River basin was available from Brazie Ranch weather station. No additional field studies beyond the solar radiation measurements associated with quantifying riparian vegetation shading were carried out under this project.

4.0 Model Implementation and Sensitivity Testing

Model implementation is the process of gathering and formatting all necessary data for model application, selecting default model parameters and coefficients, and verifying model operation. In order to efficiently transfer the available geometric, flow, and water quality data into a format consistent with model requirements, computer programs (or, preprocessors) were constructed. One preprocessor was written for the hydrodynamic model, ADYN, and a separate preprocessor was written for the water quality model, RQUAL. A code listing for each preprocessor can be found in Appendix C.

After completion of input files, the Shasta River model was initially tested to insure it was functioning properly. Further testing provided insight into system response, the sensitivity and relationships between various modeling parameters. This section addresses sources for the modeling data and the results of model testing prior to model application.

4.1 Modeling Data

To implement the hydrodynamic and water quality models a significant amount of data was required to represent various characteristics of the system. Since temperature was the parameter of interest and highest temperatures often occur in July and August, two six-day modeling periods were selected, July 21-27 and August 17-23 of 2001. Geometric, meteorological, flow, temperature, and vegetation data were assembled for each modeling period. The following sections describe the data sources, and estimations or approximations used when data was unavailable.

4.1.1 Geometry

To characterize the geometry of the Shasta River three types of data were required: nodes with associated river aspects, bed elevations, and cross-sectional shape.

4.1.1.1 River Grid

Both the hydrodynamic and temperature models required the construction of a “grid” or “network” of nodes to represent the stream course. Bed elevation, cross section geometry, bed roughness, stream aspect, and riparian vegetation characteristics are assigned to each node. The Shasta River grid was formed with every third point of the NHD dataset (total of 1,310 points), including the first and last points, for a total of 438 nodes. Minimum node spacing was 110 feet, with maximum node spacing of 853 feet, with the higher resolution applied in the meandering reaches. In constructing the grid, NHD river mileage was preserved so that length of the entire river (not just the study section) was maintained at 36.38 miles. Because shading logic depends upon the orientation of each small river section, care was taken to preserve the north-south aspect of each node.

4.1.1.2 River Slope

The model calculated the river bed slope from the bed elevations input with the cross-sectional data. Bed elevations were estimated from USGS 1:24,000 topographical maps.

For those nodes located between the intersections of topographic contours and the river, bed elevations were linearly extrapolated between known values.

4.1.1.3 Cross Sections

Cross-sectional data were compiled from the 2001 field studies (Abbott and Deas, 2003). Cross-sections for the modeling were assembled for each of the 24 nodes corresponding to a measured cross-section and then linearly interpolated at the intermediate nodes. (NOTE: Measured data at River Mile 17.61 was not used due to an extremely wide measurement of 101 feet. This was not considered representative, i.e., it was inconsistent with upstream and downstream river reaches.) A modified trapezoidal cross-section was calculated assuming 1:1 side slopes, the maximum measured depth was assumed to occur in the middle of the section, the bottom width was approximated by the measured water surface on the day of field measurements. Bank heights were extended five feet to allow the modeling of larger flows. The maximum depth at each node was assigned the corresponding bed elevation from the 1:24,000 USGS maps. A sample cross-section is found in Figure 4-1.

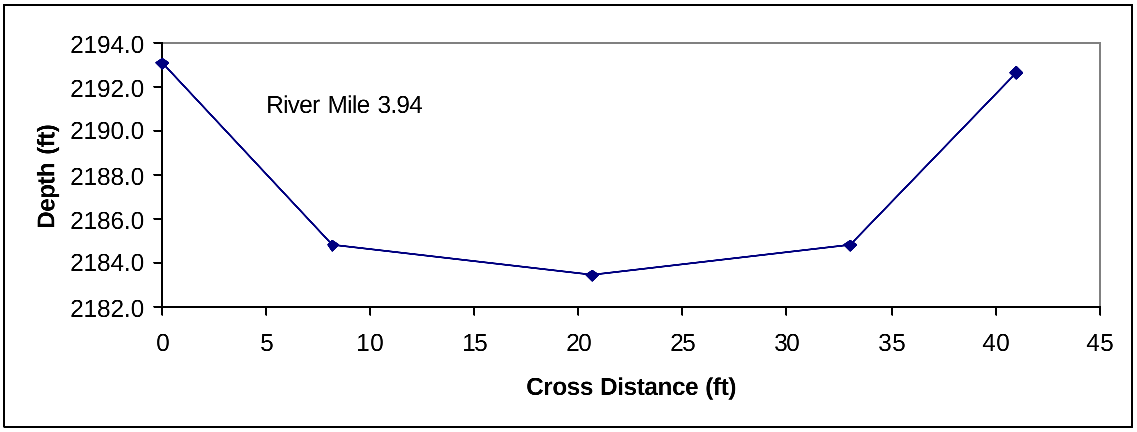


Figure 4-1 Sample cross section used for modeling river mile 3.94

4.1.2 Meteorological data

Meteorological data required to run the temperature model included cloud cover, barometric pressure (mb), dry bulb temperature (°C), wind speed (m/s), short wave solar radiation (Kcal/m^2/hr), and dew point temperature (°C). Cloud cover was assumed to be 0.0 (no cloud cover) for the simulation period, to simulate the warmest conditions and because cloud cover data was not available. Barometric pressure (P) was assumed constant (930 mb) and calculated according to the elevation (2430 ft) of the Shasta Valley (University of California Cooperative Extension, Leaflet 21372).

Hourly meteorological data was acquired from the USGS gauging site at Brazie Ranch (BZR) located to the west of the study area. The Brazie Ranch Handbar weather station is operated by California Department of Forestry. The data used from the BZR station were dry bulb air temperature (F), wind speed (mph), solar radiation (W/m^2), and relative humidity (%). The Brazie Ranch hourly data were corrected for daylight savings time by lagging the data one hour. (On the California Data Exchange Center website where the Brazie Ranch data is posted the solar radiation is listed with units of cal/cm. These units are incorrect and should be listed as W/m^2 (P. Gilbert, pers. comm.).

The dew point temperature was calculated using the relative humidity and dry bulb temperature from BZR by first converting the temperature to degrees Celsius.

$$T_c = \frac{5.0}{9.0}\left(T_f - 32.0\right)$$

Then the saturation vapor pressure (E_s) in mb was computed.

$$E_s = 6.11 \times 10.0^{\left(\frac{17.27 T_c}{237.3 T_c}\right)}$$

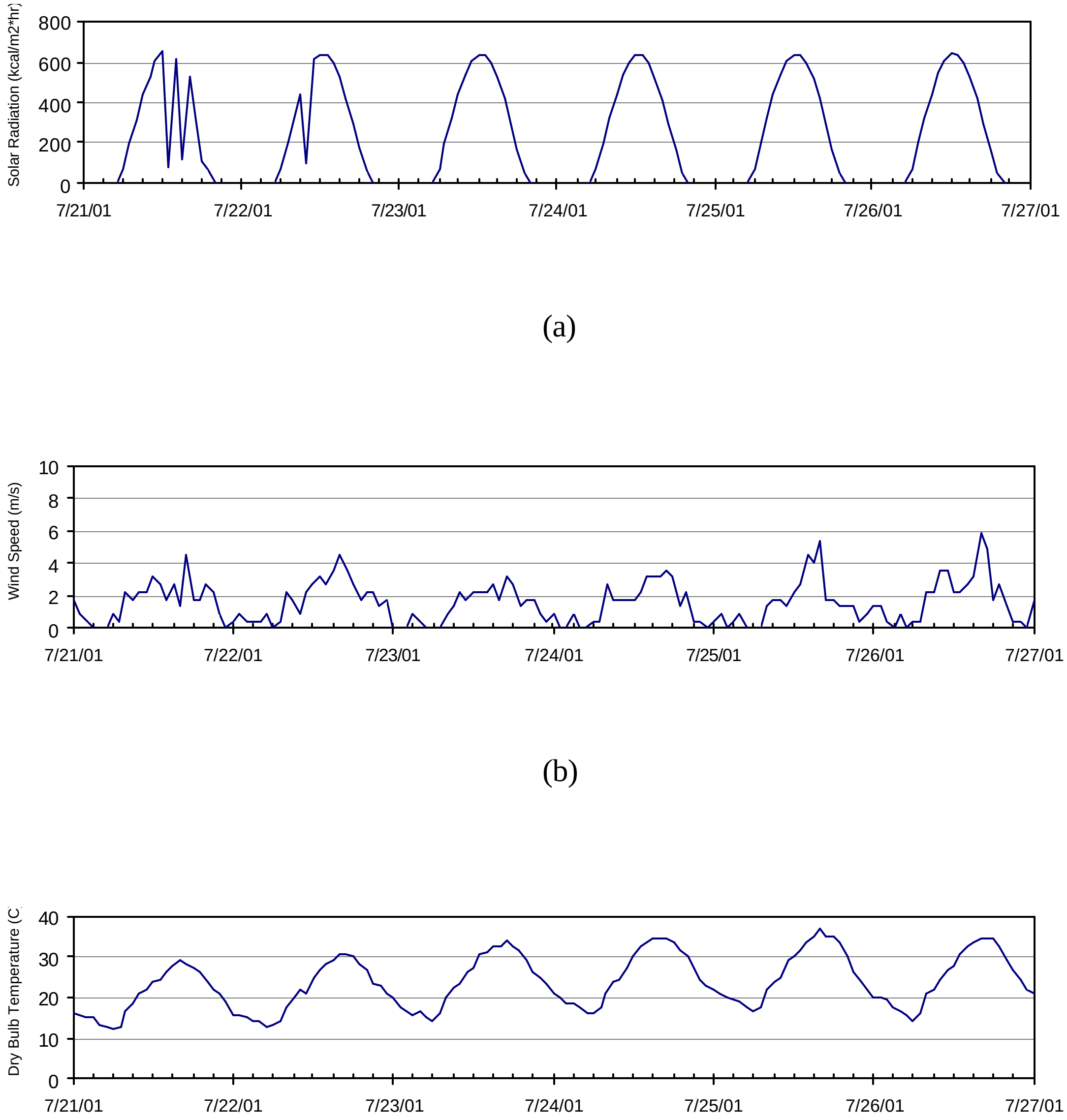
The vapor pressure (E) in mb is then computed by multiplying the relative humidity (RH, %) by the saturation vapor pressure.

$E = RH * E_s$

Finally dew point temperature (D) in ^{o}C is computed using the calculated vapor pressure (E).

$$D = \frac{\left(-430.22 + 237.7 + \ln[E]\right)}{\left(-\ln[E] + 19.08\right)}$$

Meteorological data for modeling periods 1 and 2 can be found in Figure 4-2 and Figure 4-3 respectively.

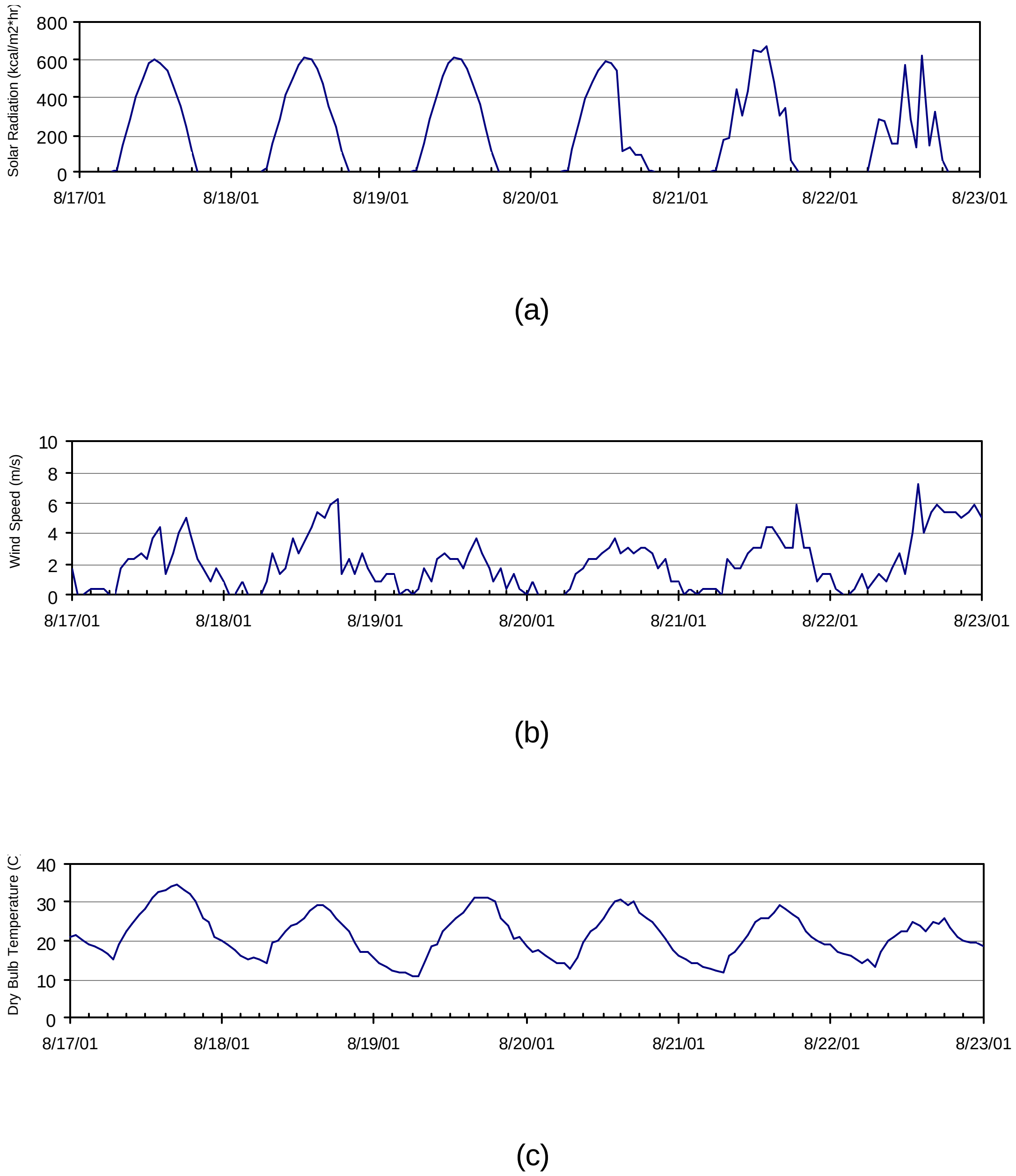


(a)

(b)

(c)

Figure 4-2 Meteorological data for July 21st to July 27th: (a) solar radiation (b) wind speed (c) dry bulb temperature



(a)

(b)

(c)

Figure 4-3 Meteorological data for Aug. 17th to Aug. 23rd: (a) solar radiation (b) wind speed (c) dry bulb temperature

4.1.3 Flow

Hourly measured flows were collected at six pressure-transducer sites in 2001 and in 2002 (Watercourse, 2001). These data were augmented with USGS gage data (RM 0.5). Hourly hydrograph at Shasta River above Parks was used as the upstream boundary condition for the hydrodynamic model. Diversions were estimated from irrigation district records, where available. Partial records were available from the Grenada Irrigation District and the Shasta Water Users Association. Parks Creek inflow was derived from the measured data. All of the above-mentioned data were used to determine the ungaged accretions (inflows) and depletions (outflows) in the system for each of the five study segments using a water balance approach.

4.1.3.1 Water Balance

The Shasta River has many ungaged diversions, spring flows, return flows and tributaries that may be described together as accretions and depletions. Because a particular reach can experience an accretion in one time period and a depletion during a subsequent time period, these ungaged flows are identified as “net accretion/depletion.” To determine accretions and depletions for each of the five study segments, a water balance approach was employed moving upstream to downstream.

Net accretions/depletions (net A/D) were assigned based on field survey, available records, and aerial photographs. The major accretion in Reach 5 was assigned to the location of Big Springs Creek. Based on flow records and aerial photographs of the channel this accretion is quite sizeable; however, the exact magnitude is unknown. Hence, this accretion was based on a water balance including Shasta River above Parks and Parks Creek measured inflows and measured flow at GID, taking into account the GID diversion. Diversions at the Grenada Irrigation District pumps were estimated from the irrigation records and include Huseman Ditch flows. Since the differences in flow between GID and A12 are small, and since little is known about this reach, net A/D for the GID-A12 reach was applied just above A12.

Between A12 and DWR, diversion by the Shasta Water Users Association was based on DWR water master records. There are accretions distributed along the reach, likely due to various return flows (e.g. Huseman Ditch, as well as others). Therefore, the net A/D was distributed uniformly throughout the entire reach. A water balance between A12 and DWR Weir, taking into account the SWA depletion, was used to determine the magnitude of net A/D of Reach 3.

Little information was available about A/D in Reach 2, so net A/D was assigned just above Anderson Grade. No accretion/depletion was calculated for Reach 1. The values of these net accretions/depletions are different for each modeling period, and vary by hour. Locations, methods of determination, and magnitudes of the accretions/depletions for each reach and modeling period are shown in Table 4-1 and Table 4-2.

Table 4-1 Location and method of determining flows

Reach	Location	River Mile	Method of determination
Upstream BC	Shasta above Parks	31.8	measured
5	Parks Creek	31.0	measured
	Net A/D: Big Springs Creek	29.9	calculated by water balance
	Diversion: GID	26.9	estimated from records
4	Net A/D: A12	21.9	calculated by water balance
3	Diversion: SWUA	16.8	estimated from records
	Net A/D: DWR	14.72–21.89*	calculated by water balance
2	Net A/D: Anderson Grade	7.9	calculated by water balance
1	N/A	N/A	N/A

* distributed throughout reach

Table 4-2 Average, minimum, and maximum values of lateral inflows (cfs)

Location	7-21 to 7-27-01			8-17 to 8-23-01		
	avg	min	max	avg	min	max
Parks Creek	5	4	8	2	2	3
Accretion: Big Springs Creek	66	61	72	59	55	63
Diversion: GID	-20	-20	-20	-10	-10	-10
Net A/D: A12	1	-4	7	-3	-7	2
Diversion: SWUA	-42	-42	-42	-42	-42	-42
Net A/D: DWR	9	1	15	11	4	54
Net A/D: Anderson Grade	-3	-16	7	0	-13	14

4.1.4 Water Temperature

Hourly water temperature data from 2001 field studies (Watercourse, 2001) were used to describe boundary conditions and for model calibration/validation. Inflow water temperatures for Shasta River above Parks and Parks Creek were taken from reported values. Water temperatures at Big Springs were assumed equal to water temperatures reported at GID. Water temperatures for all other accretions and depletions were assumed to be equal to the local temperature of the Shasta River.

4.1.5 Riparian Vegetation Representation

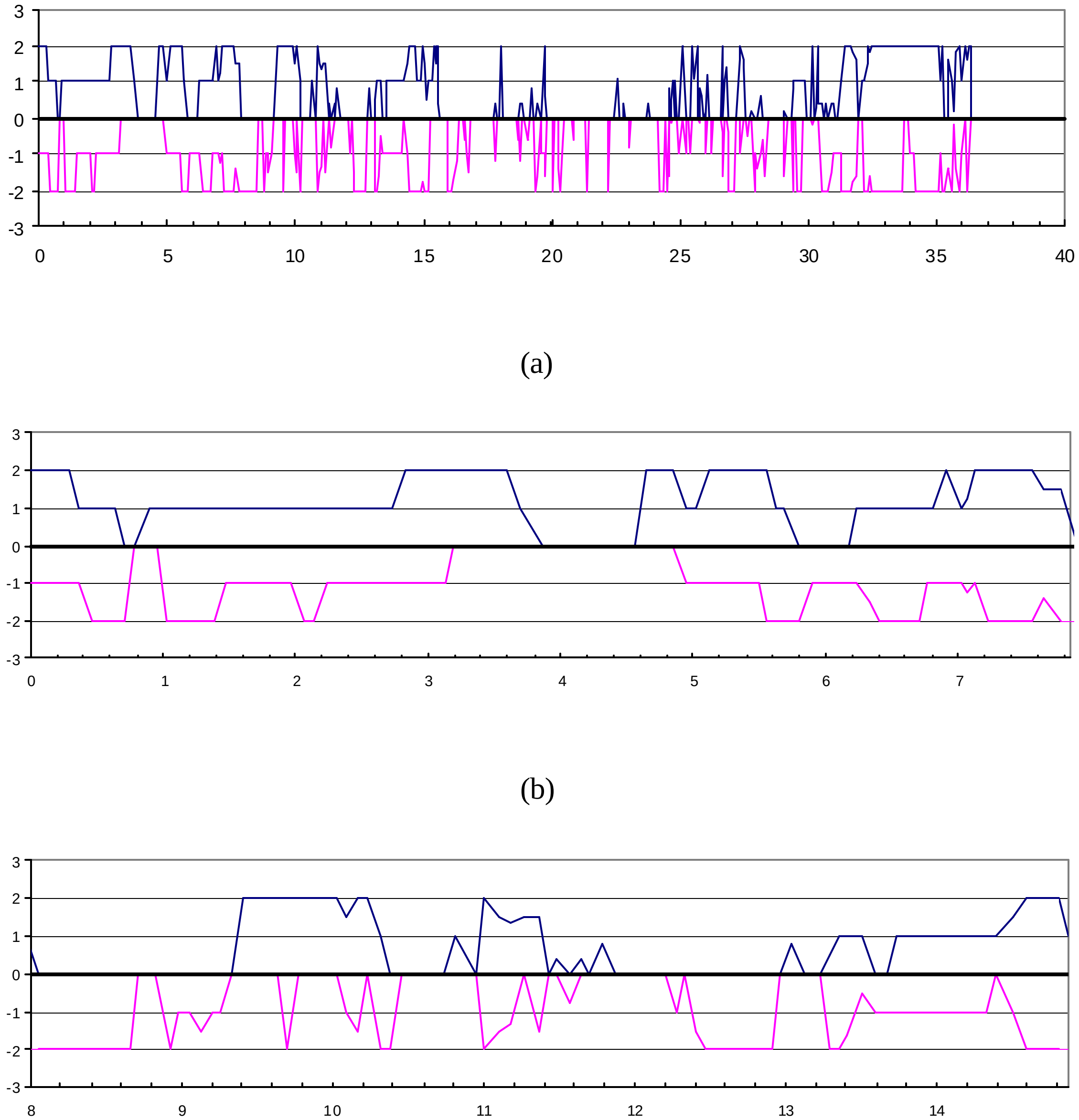
Data required to characterize riparian vegetation in the model include setback (bank width), effective barrier height, and net transmittance at each node (SHSOL). Due to the close proximity of the vegetation (where present) to the Shasta River, setback was assumed to be zero along the entire system. Because existing data do not describe riparian vegetation in detail, effective barrier (vegetation) height was estimated to be homogeneous throughout the basin and was modeled using results from the 2001 fieldwork. Tree height in the basin was estimated to be 22 feet, the average height of the majority of trees measured. Simulations tested the sensitivity of this parameter (see Section 4.2). Net transmittance is a function of the continuity, location, and density of vegetation at any particular node. These values were quantified during fieldwork completed in 1996 as cited in Shasta River Woody Riparian Vegetation (Deas, *et al.* 1996). In that study, every location was assigned a density classification, called a continuity factor (CF). Because the canopy along the Shasta River is not uniform, net transmittance at any node was estimated from weighted average of adjacent continuity factors.

Each continuity factor has an associated transmittance value. Where the CF=0 (i.e. no vegetation present) incoming solar radiation is not reduced and transmittance = 100%. Where CF=2, vegetation is continuous and transmittance is 10% (i.e. solar radiation is reduced by 90%). The transmittance value of 10% is an average value of "good" shading taken from the 2001 fieldwork (Abbott and Deas, 2003). Where CF=1, there are less than two trees per 100 feet. In these sparsely shaded areas, it was assumed that the average width-to-height ratio of a tree was 2/3, so that the width of a 22-foot high tree was 15 feet. Hence, the amount of shading over 100 feet of river classified CF=1 would be 15%, leading to an estimated transmittance of 85%. Where a node is adjacent to areas with different continuity factors, a weighted average was used to determine the net transmittance value (SHSOL) for the model. A summary of the transmittance values associated with each continuity factor is given in Table 4-3.

Table 4-3 Transmittance classification system

Description	Continuity Factor	Transmittance Value
No trees	0	100%
Less than 2 trees per 100 feet	1	85%
Greater than 2 trees per 100 feet	2	10%

Continuity factors for right and left banks along the entire system are shown in Figure 4-4 (a). Values for the right bank are positive numbers (on the top), while left bank values are indicated by negative numbers (on the bottom). Continuity factors for each reach, ordered from the Mouth moving upstream are depicted in Figure 4-4 (b) through (f).

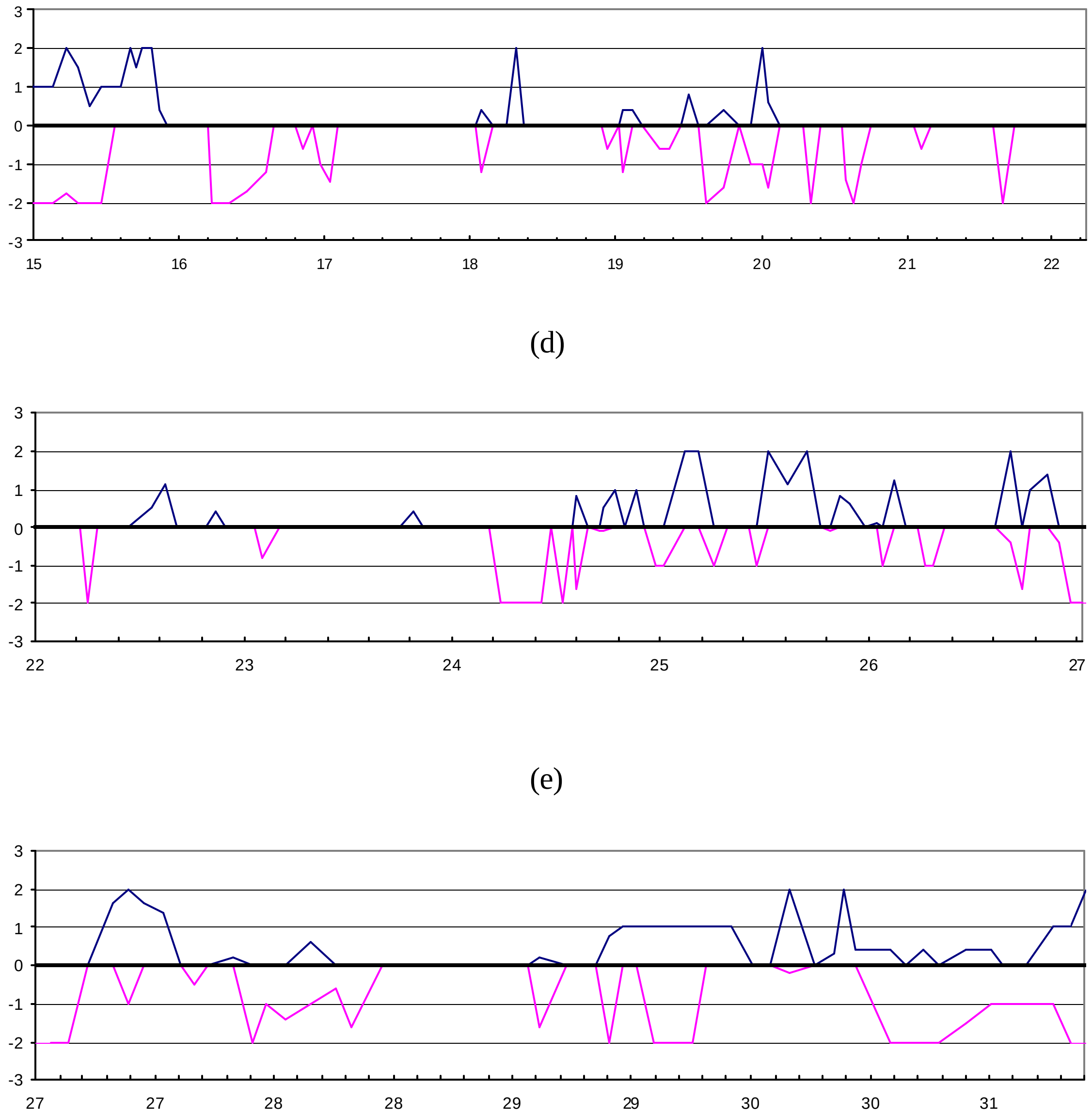


(a)

(b)

(c)

Figure 4-4 Vegetative continuity factors of the Shasta River (a) Mouth to Dwinnell Reservoir (b) Mouth to Anderson Grade (c) Anderson Grade to DWR Weir. Right bank values are positive and left bank values are negative.



(d)

(e)

(f)

Figure 4.4 cont. Vegetative continuity factors of the Shasta River (d) DWR Weir to Highway A12 (e) Highway A12 to GID (f) GID to Shasta Above Parks. Right bank values are positive and left bank values are negative.

4.1.6 Model Parameters

There are certain parameters in both the hydrodynamic and water quality components of the RMS components that were set before calibration and used throughout the modeling process. The four-point implicit scheme with an hourly time step was employed in each component. The section lists other parameters specific to each RMS component.

The flow model, ADYN, required selection of Manning's n, contraction/expansion coefficients, and numerical controls. Manning's n was set to 0.045 for each node. This value of Manning's n was chosen based on previous flow and temperature modeling of the Shasta River (CEEMG, 1998). The transition between each node was considered to be gradual so that the contraction coefficient = 0.1 and the expansion coefficient = 0.3. (Transition loss in the model is computed as the product of this coefficient and the difference in velocity head between the nodes (Hauser, 1995).) The flow model required tolerances for convergence of the Newton-Raphson iterations. The tolerance for flow = 0.005 cfs, tolerance for elevation = 0.005 feet. The weighting factor on spatial derivatives in ADYN was set to 0.55. Parameters specifications for ADYN are listed in Table 4-4.

Table 4-4 Parameters specified in flow model ADYN

Parameter	Specified value
Manning's n	0.045
Contraction coefficient	0.1
Expansion coefficient	0.3
Newton-Raphson convergence	
Flow:	0.005 cfs
Elevation:	0.005 feet
Weighting factor for spatial derivatives	0.55

The water quality component (RQUAL) required specification of river latitude/longitude, time of fog lift, wind coefficients, and numerical controls. River latitude was set to 41.875, longitude = 122.630. Since fog was not found to be a persistent condition on the Shasta River, time of fog lift was set to 6 am. The wind coefficients were initially set at: AA = 3.0E-09, BB = 1.4E-09. These coefficients were later used for calibration. The weighting factor on spatial derivatives in RQUAL was set to 0.5. Parameters specifications for ADYN are listed in Table 4-5.

Table 4-5 Parameters specified in water quality model RQUAL

Parameter		Specified value
River latitude		41.875
River longitude		122.630
Time of fog lift		6 am
Wind coefficients		
	AA:	3.0E-09
	BB:	1.4E-09
Weighting factor for spatial derivatives		0.5

4.2 Sensitivity Testing

Sensitivity testing involved making several trial simulations while varying certain parameters to ensure that the model was working properly and to assess the system response to each parameter.

4.2.1 ADYN: Flow Sensitivity Testing

Trial simulations made using the hydrodynamic model were used to check geometry file data and to compute system transit times at the following steady-state flows: 2 cfs, 5 cfs, 10 cfs, 50 cfs, 100 cfs, 150 cfs, and 200 cfs. Average velocities were captured at each node for each flow and averaged by study segment to compute travel times through each study segment. Table 4-6 contains the computed transit times. (Recall that reaches are numbered from downstream to upstream).

Table 4-6 Comparison of Shasta River transit times in hours for each study segment

Reach	Length (mi)	2 cfs	5 cfs	10 cfs	50 cfs	100 cfs	150 cfs	200 cfs
1	7.9	10.8	8.6	7.4	4.9	3.9	3.4	3.1
2	6.9	14.0	11.2	9.5	6.3	5.1	4.5	4.0
3	7.2	18.1	14.6	12.4	8.3	6.7	5.8	5.2
4	5.0	13.1	10.5	8.8	5.8	4.5	3.9	3.6
5	4.8	10.4	8.5	7.1	4.6	3.7	3.2	2.9
Total Time (hrs)		66.4	53.3	45.2	29.8	23.9	20.8	18.8
Total Time (days)		2.8	2.2	1.9	1.2	1.0	0.9	0.8

During the steady-state test runs, water surface elevation was determined and maximum water depth was calculated. Simulated maximum water depths at 10 cfs, 50 cfs, and 100 cfs are depicted in Figure 4-5. When flow was increased from 10 to 50 cfs, maximum water depth increased on average by about 1 foot. When the flow was increased from 50 to 100 cfs, maximum water depth increased on average 0.6 feet.

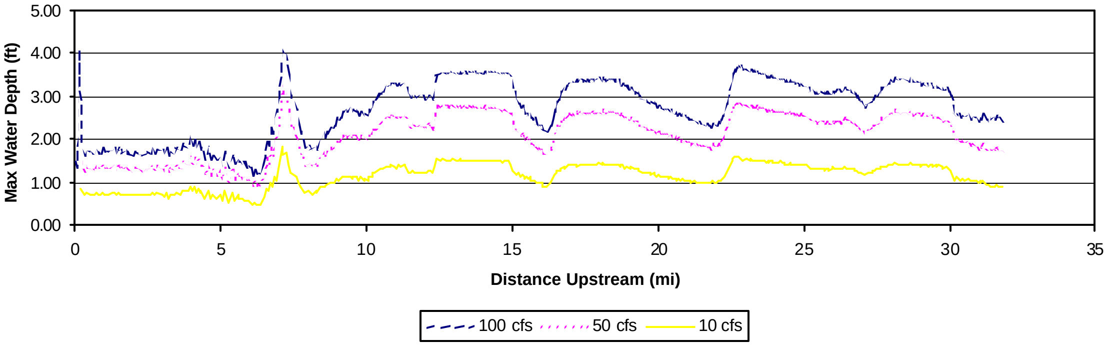


Figure 4-5 Steady-state test cases: maximum water depth

4.2.2 RQUAL: Temperature Sensitivity Testing

Using the water quality model and the Shasta River geometry file, simulations were made to test the sensitivity of the temperature response to three parameters: flow, tree height, and transmittance. Flow during these simulations was steady-state with no accretions or depletions, the upstream boundary had a constant temperature of 15°C, and meteorological data from August 28, 2001 was used.

4.2.2.1 Temperature Sensitivity to Flow

Sensitivity to flow was tested using 10 cfs, 50 cfs, and 100 cfs. The flow simulations contained no shading. Daily average temperature at each node over this range of flows is depicted in Figure 4-6.

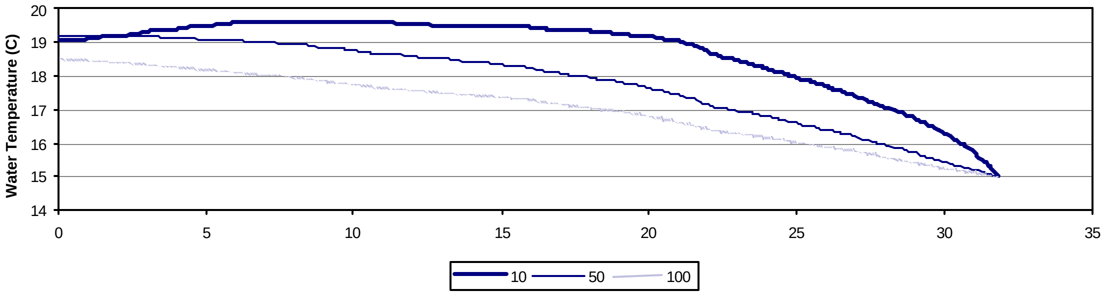


Figure 4-6 Longitudinal profile of average daily temperature by river mile for August 28, 2001 meteorological conditions for 10, 50, 100 cfs.

Notice that the flow-temperature relationship is not linear. The river warms approximately 0.7°C at the Mouth (RM 0.0) when the flow is reduced by 50% (100 cfs to 50 cfs). However, when the flow is reduced again by 80% (to 10 cfs), the river warms a maximum of 1.5°C in upper reaches and there is no net effect at the Mouth. The lack of a net effect at the Mouth is likely due to the water temperatures approaching an equilibrium with the meteorological conditions. Table 4.4 contains the average maximum and minimum daily temperatures for each of the three flow cases. This non-linear relationship illustrates that as flow increases, water temperature decreases at a slower rate. Whereas increasing flow from 10 to 50 cfs reduces the maximum daily temperature averaged over all reaches by 5°C, adding another 50 cfs only reduces the average maximum daily temperature by approximately 1.5°C.

Table 4-7 Average, maximum, and minimum temperatures for 10cfs, 50cfs, 100cfs test cases

Flow (cfs)	Average Minimum Daily Temperature (°C)	Average Maximum Daily Temperature (°C)	Avg Max – Avg Min (°C)
10	11.1	24.6	13.5
50	12.8	21.3	8.5
100	13.4	19.7	6.3

4.2.2.2 Temperature Sensitivity to Transmittance

To test the temperature response to transmittance, simulations were made over a range of flows (10 cfs, 50 cfs, 100 cfs) and transmittance factors (10%, 50%, 85%, 100%). For these simulations it was assumed that the river was fully shaded and that the trees were 22 feet in height. The effects of transmittance during flows of 50 cfs are presented in Figure 4-7. Recall that a transmittance factor of 10% translates to only 10% of the solar radiation being available for heating the river, whereas a transmittance factor of 100% represents no shading.

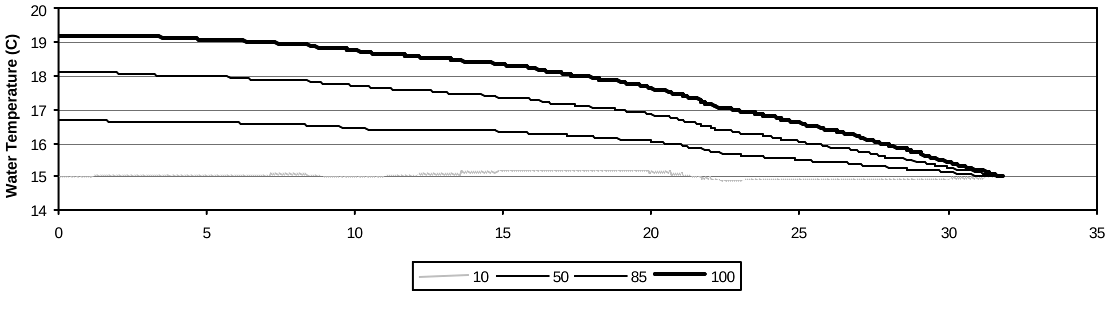


Figure 4-7 Longitudinal profile of average daily temperature for August 28, 2001 meteorological conditions for 50 cfs test case with varying transmittance (10%, 50%, 85%, 100%)

As seen in Figure 4-7, no shading produces an average daily temperature at the Mouth (RM 0.0) of 19.2°C. Reducing solar radiation by 15% translates to an average cooling of the system at the Mouth of about 1.5°C. If solar radiation is reduced to 50%, the average daily temperature is reduced by approximately 3.0°C. Finally, if solar radiation is reduced by 90%, average daily temperature is reduced by approximately 4.0°C. This last scenario implies that if the river were fully shaded and all shade has a transmittance factor of 10%, then there would be no net heating of the river through the study reach. The fieldwork supports an average transmittance factor of 10%, but recall that this simulated condition requires that the river be flowing through a “tunnel” of trees. Notice that this relationship is also non-linear (i.e. tripling the reduction in solar radiation resulted in a doubling of the reduction in average daily temperature at the Mouth).

4.2.2.3 Temperature Sensitivity to Tree Height

Sensitivity to tree height was tested using the 50 cfs test case and the average values of tree height found during the field season. Two tree heights were tested, the average tree height for Sandbar Willow (22 feet), and the average tree height for Arroyo Willow (38 feet). Temperature sensitivity to tree heights under two conditions (a) with a transmittance of 50% and (b) with a transmittance of 85% is illustrated in Figure 4-8. The average daily temperature at the Mouth in case (a) is reduced by 0.7°C when the tree height is increased to 38 feet. However, if the transmittance is increased to 85% then there is no noticeable difference in the average daily temperatures along the river due to tree height. It appears that the model is not as sensitive to variation in tree height as it is to flow and transmittance.

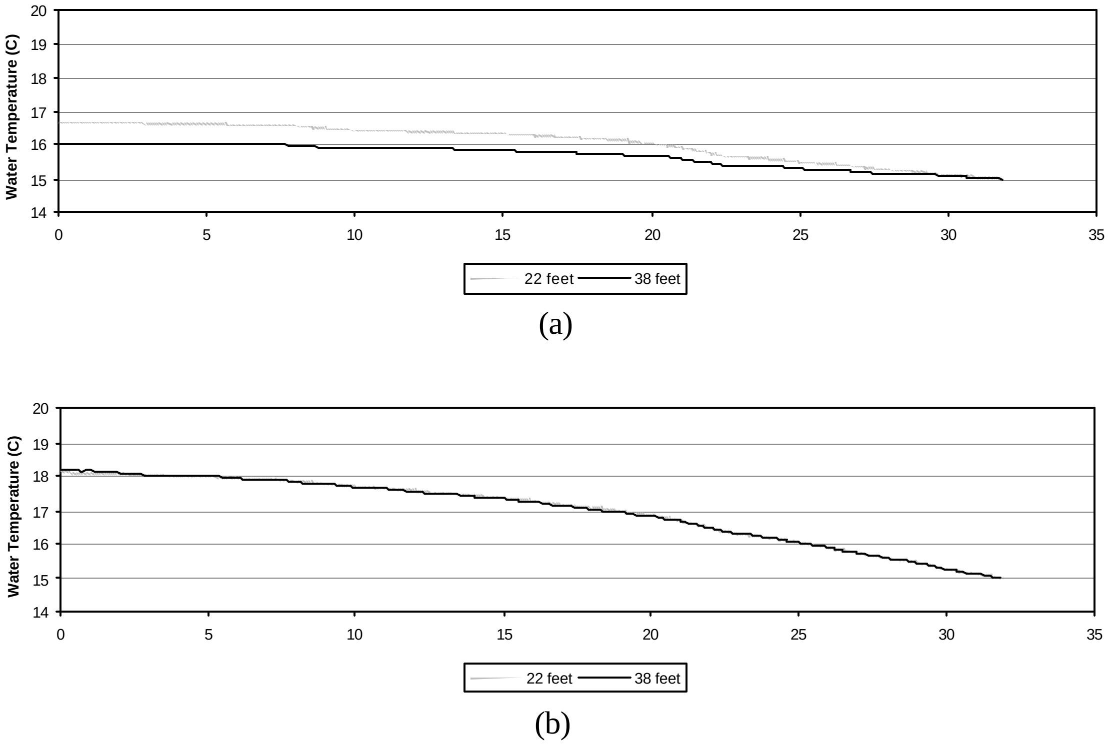
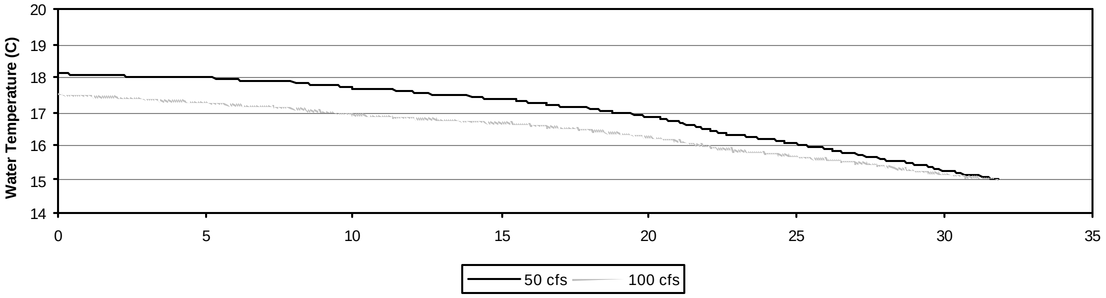


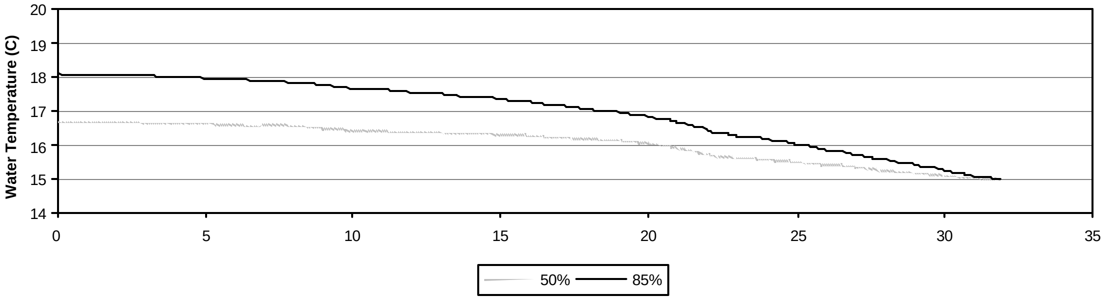
Figure 4-8 Longitudinal profile of average daily temperature for August 28, 2001 meteorological conditions for 50 cfs test case with varying tree height, (a) tr=50% (b) tr=85%

4.2.2.4 Temperature Sensitivity to Flow vs. Transmittance

The two main identified options available to lower temperature on the Shasta River are to (a) increase the flow and/or (b) increase the riparian vegetation. It is worthwhile, therefore, to compare the effects of increased flow and transmittance on water temperature. Since summer flows in the Shasta are closest to the 50 cfs test case and the majority of trees measured in the Shasta averaged 22 feet, these two parameters were used as the base case. In addition, there is currently modest riparian shading on the Shasta River; hence 85% transmittance will be used as in this base case. These simulations compare the impact of increasing flow 100%, and increasing the vegetation so that there is 50% transmittance along the entire river. Figure 4-9 (a) shows that an increase in flow reduces average daily water temperature by approximately 0.6°C at the Mouth, whereas Figure 4-9 (b) shows that an increase in vegetation reduces average daily water temperature by about 1.4°C at the Mouth. The simulated increase in vegetation has over twice the effect of the increase in flow.



(a)



(b)

Figure 4-9 Longitudinal profile of average daily temperature for August 28, 2001 meteorological conditions flow vs. transmittance sensitivity (a) flow increased from 50cfs to 100cfs (b) transmittance decreased from 85% to 50%

5.0 Model Application

Following model testing, calibration/validation and model application were completed. The model was calibrated using the field observations of flow and temperature and meteorological data from August 17th to August 23rd, 2001. Following this calibration the model was validated using the field observations and meteorological data from July 21st to July 27th, 2001. This section addresses the processes of calibration and validation, quantifying the errors of those processes, and using the model results to provide insight into various management scenarios.

5.1 Boundary and Initial Conditions

Model application required specification of boundary and initial conditions for both flow and temperature. The upstream boundary condition for flow was represented by the hourly hydrograph of Shasta River above Parks. The downstream boundary condition was calculated by the model using the Manning equation within the RQUAL model. Nine initial conditions were assigned along the system after each lateral inflow/outflow and at the Mouth using a flow and an elevation. There were seven lateral inflows/outflows as shown in Table 4.1. The upstream boundary condition for temperature was represented by the hourly temperatures measured at Shasta above Parks. The nine initial condition temperatures were specified according to the temperatures of the closest field location where observed data was available.

5.2 Flow Verification

This project included a hydrodynamic representation of the river to effectively model velocity, depth, and surface area; variables that were used in the temperature model to calculate the transport and fate of heat energy. The hydrodynamic representation was achieved by a system water balance as described in section 4.1.3. This section contains the results of the flow simulation for the calibration and validation periods. The figures contain graphs of simulated versus measured flow for all measured sites ordered upstream to downstream.

5.2.1 Calibration Period

Figure 5-1 to Figure 5-5 contain graphs of simulated versus measured flow for the calibration period, August 17th to August 23rd. All flow simulations were within 3 cfs of measured flows with two exceptions. The first exception was the short duration event observed in the DWR Weir hydrograph on August 18th. This event was apparently due to the Shasta River Water Users diversion being shut down for a period of time. It was difficult to simulate this peak because the accretion in this reach was assumed to be distributed over the entire reach. The second exception was at the Mouth. No correction was made for flow between Anderson Grade and the Mouth due to the limited information concerning accretions and depletions for this reach.

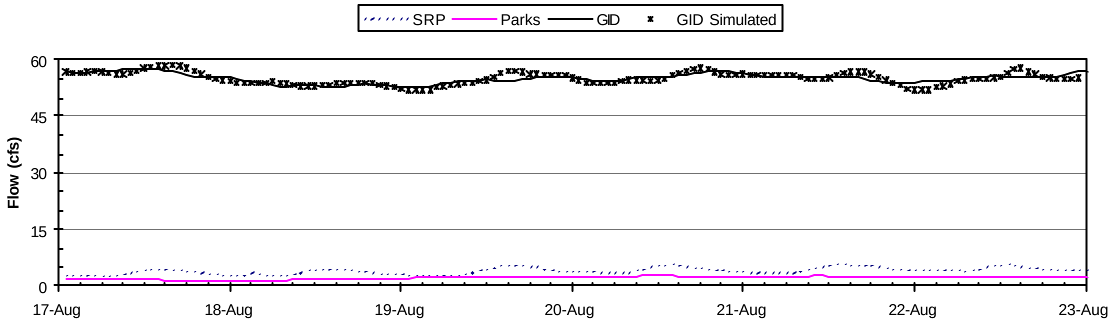


Figure 5-1 Measured vs. simulated flow for GID, Aug 17-Aug 23, 2001

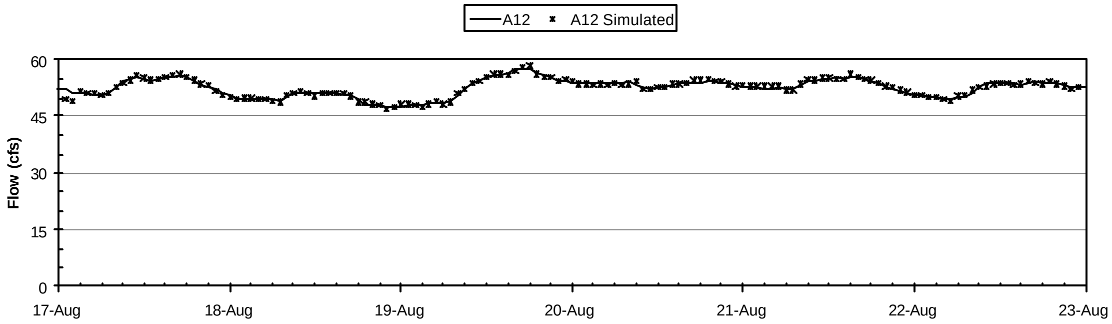


Figure 5-2 Measured vs. simulated flow for A12, Aug 17-Aug 23, 2001

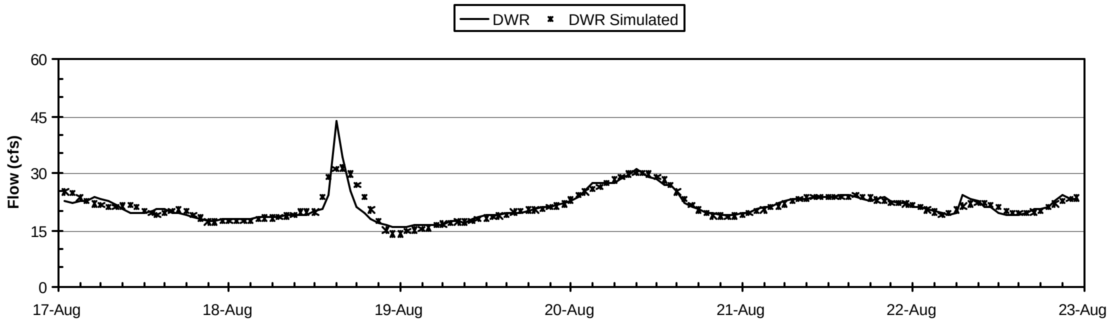


Figure 5-3 Measured vs. simulated flow for DWR Weir, Aug 17-Aug 23, 2001

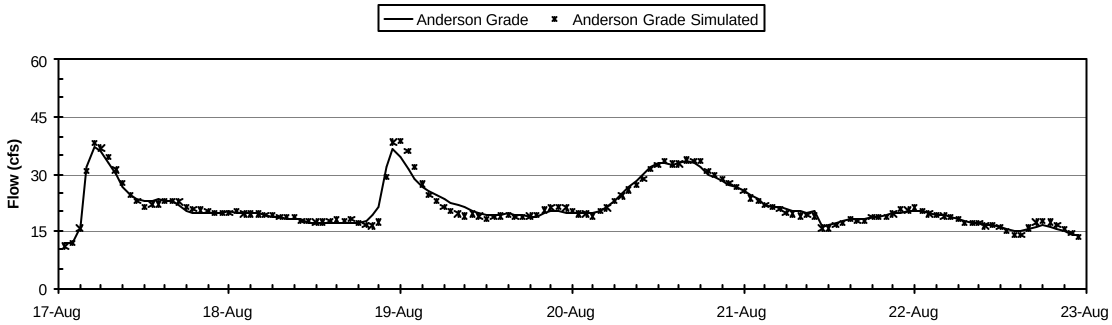


Figure 5-4 Measured vs. simulated flow for Anderson Grade, Aug 17-Aug 23, 2001

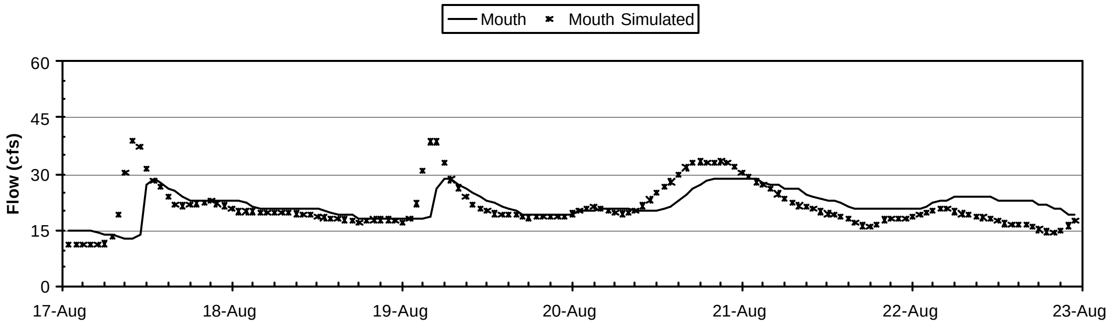


Figure 5-5 Measured vs. simulated flow for Mouth, Aug 17-Aug 23, 2001

5.2.2 Validation Period

Figure 5-6 to Figure 5-10 contain graphs of simulated versus measured flow for the validation period, July 21st to July 27th. All flows are within 3 cfs of the measured value with the exception of the flows at the Mouth. As with the calibration period, no correction was made for flows at the Mouth due to lack of data in that reach.

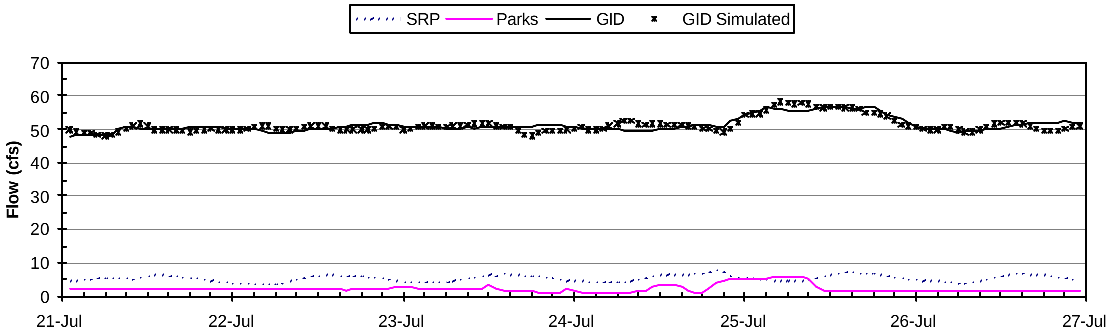


Figure 5-6 Measured vs. simulated flow for GID, July 21-July 27, 2001

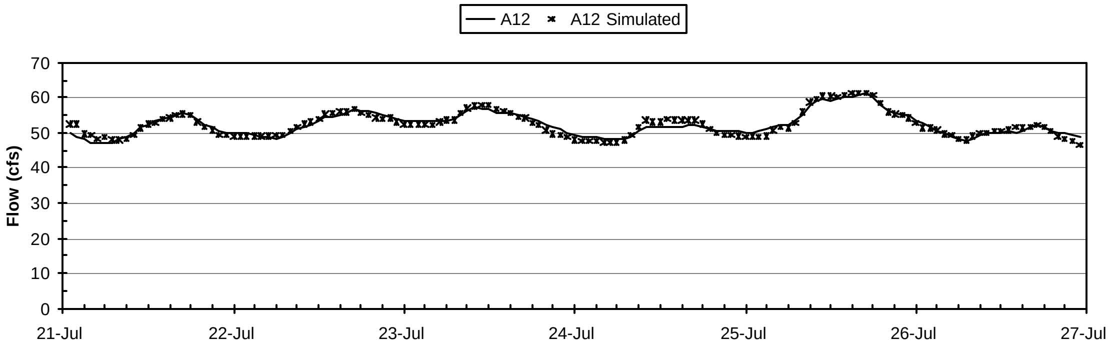


Figure 5-7 Measured vs. simulated flow for A12, July 21-July 27, 2001

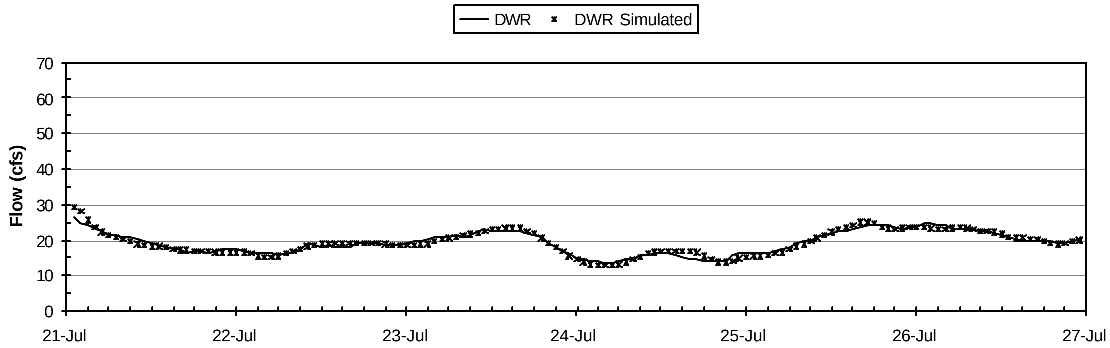


Figure 5-8 Measured vs. simulated flow for DWR Weir, July 21-July 27, 2001

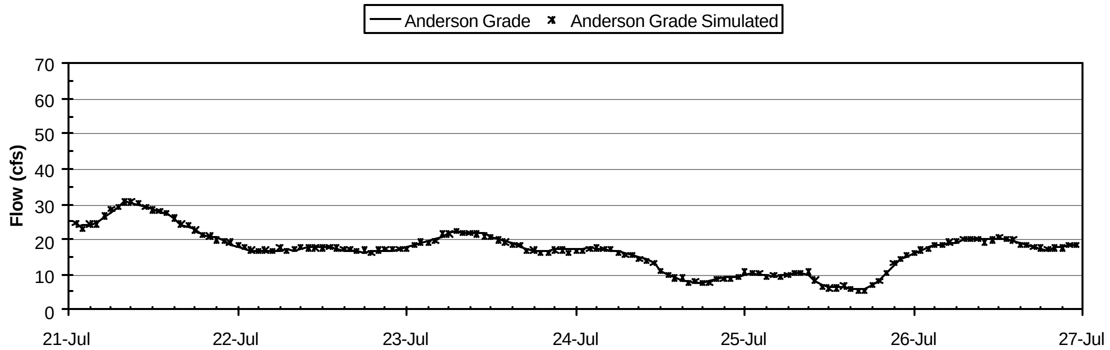


Figure 5-9 Measured vs. simulated flow for Anderson Grade, July 21-July 27, 2001

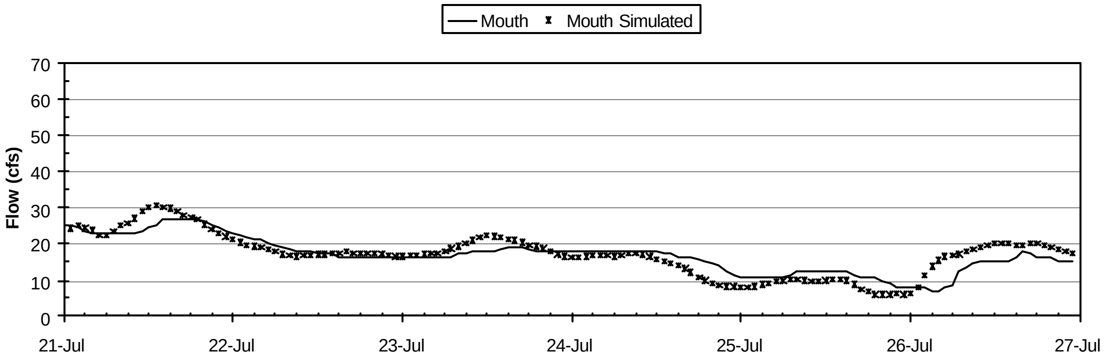


Figure 5-10 Measured vs. simulated flow for Mouth, July 21-July 27, 2001

5.3 Temperature Calibration

After verification of the flows was completed an initial temperature simulation was made with no temperatures assigned to the lateral inflows. It was evident from this first run that a diurnal temperature cycle needed to be applied to Parks Creek and the Big Springs accretion. The measured temperatures at Parks Creek were applied to the Parks Creek lateral inflow, and because measured temperatures were unavailable at Big Springs, the measured temperatures at GID were applied to the Big Springs accretion. Calibration continued by adjusting the evaporation coefficients AA and BB, refining the placement of accretions/depletions, and adjusting boundary condition temperatures. The final coefficients were AA = 0.1E-09 and BB = 1.4E-09. These are consistent with the range of default values given in the RMS User's Manual (Hauser, 1995). Simulated versus measured temperatures can be found in Figure 5-11 to Figure 5-16.

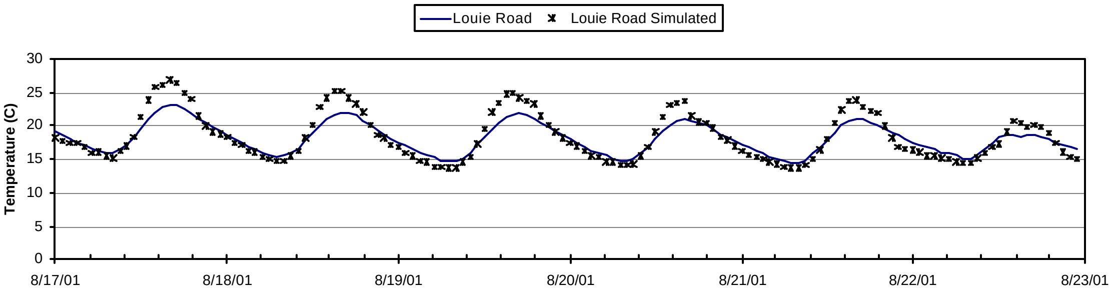


Figure 5-11 Measured vs. simulated temperature for Louie Rd., Aug 17-23, 2001

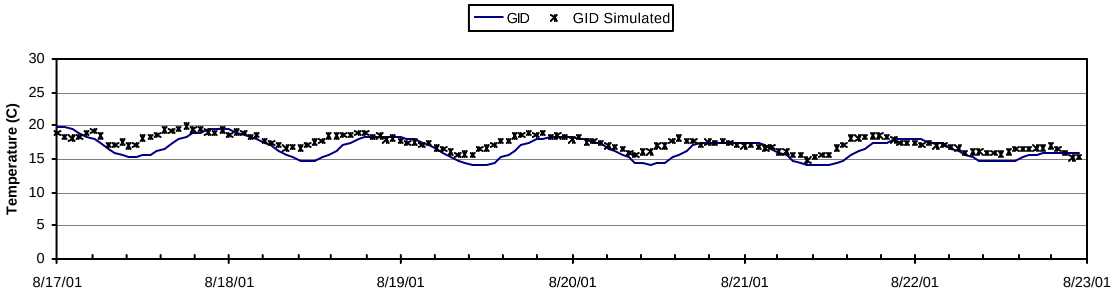


Figure 5-12 Measured vs. simulated temperature for GID, Aug 17-23, 2001

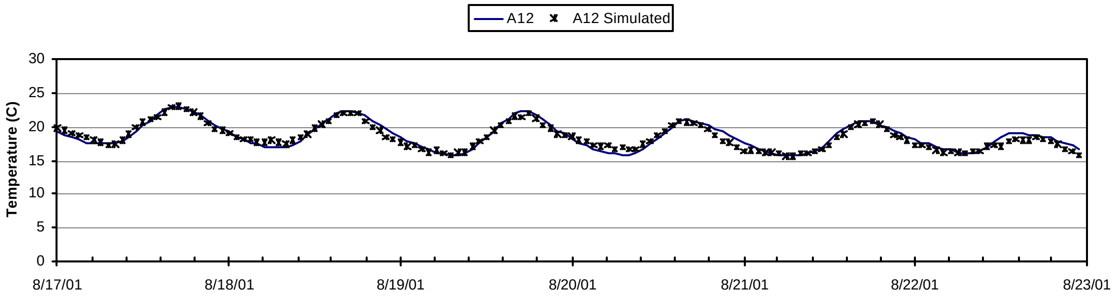


Figure 5-13 Measured vs. simulated temperature for A12, Aug 17-23, 2001

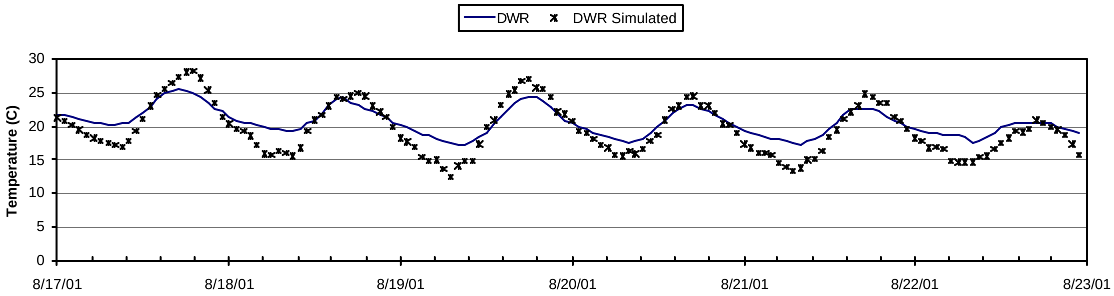


Figure 5-14 Measured vs. simulated temperature for DWR Weir, Aug 17-23, 2001

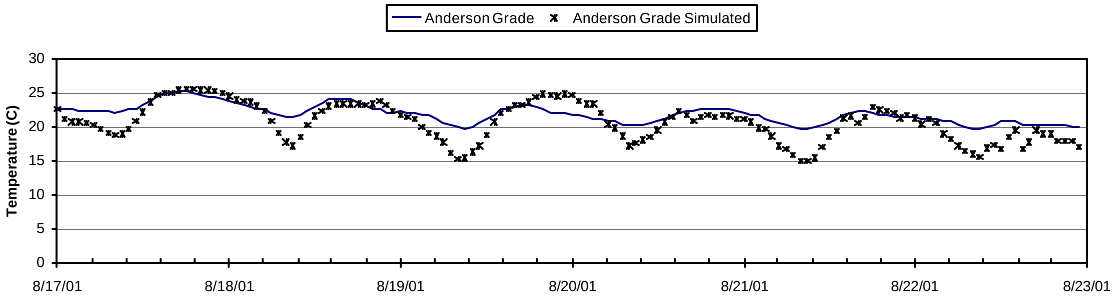


Figure 5-15 Measured vs. simulated temperature for Anderson Gr, Aug 17-23, 2001

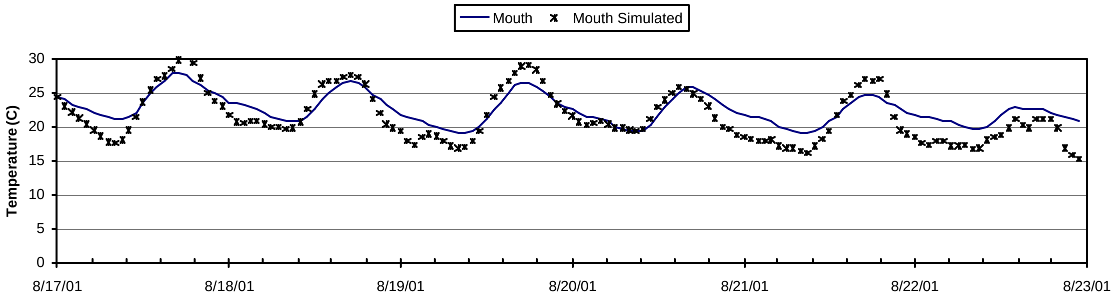


Figure 5-16 Measured vs. simulated temperature for Mouth, Aug 17-23, 2001

The water temperature regime of small rivers can be highly sensitive to meteorological conditions. The Shasta River, with highly variable flows, but generally small volumes, exhibits such behavior. This was evident during the final day of simulation, August 22nd, at Louie Road, DWR, Anderson Grade, and the Mouth. On this day at approximately 2:00 p.m. there was a disturbance in the solar radiation curve (Figure 4-3) that caused a drop in mid-day solar radiation of approximately 400 W/m^2. This was likely due to transient cloud cover. This disturbance was reflected in the temperature plots by a drop in simulated temperature at approximately the same time (see Figure 5-11 to Figure 5-16). This illustrated the model's sensitivity to meteorological conditions at low flows. However, when flows were larger, such as at GID or A12, the model was less sensitive to meteorological data.

Table 5-1 contains the error analysis of this temperature calibration. At GID (Figure 5-112) the mean absolute error (MAE) was 1.0°C. The simulated values consistently over-predict the measured values. This bias was possibly due to model sensitivity at low flows, uncertain placement and quantity of the reach A/D, assumed river geometry, and estimates on location and quality of riparian vegetation.

Table 5-1 Error analysis of the temperature calibration (°C)

Location	Average Bias	Maximum Bias	Minimum Bias	Mean Absolute Error
GID	-0.8	1.4	-3.0	1.0
A12	0.1	1.5	-1.1	0.5
DWR Weir	1.0	5.0	-3.4	1.7
Anderson Grade	1.2	4.8	-2.9	1.7
Mouth	1.1	5.5	-2.7	1.9

GID (Figure 5-12) had a MAE of about 1°C. The simulated temperature signal was out of phase with the measured signal by about 2 hours. This is most likely due to approximating Big Springs inflow temperatures with water temperatures from GID. A further confounding factor may be the accretion location and quantity. It is possible that more flow was coming into the system downstream or upstream of Big Springs, and that the Big Springs accretion was actually smaller. At A12 (Figure 5-13), the MAE was less than 0.5°C. This reach generally experienced high flows and relatively modest lateral inflows. The peaks were well positioned at DWR weir (Figure 5-14), however a there was a craggy temperature trace. Just above DWR Weir vegetation becomes more frequent. Several simulations with and without vegetation were completed to identify the source of the cragginess. It appears that the signal was due to the shading logic, or the riparian vegetation shading representation. The exact component, or interaction of components, was not identified.

The MAE at DWR Weir was approximately 1.7°C. This was likely due to placement and quantity of the a/d in this reach. To better understand this reach it would be necessary to have a gage upstream and downstream of the SWA diversion. The variation of the temperature signal at DWR was perpetuated downstream and affected the temperature trace at Anderson Grade (Figure 5-15). The simulated signal at Anderson Grade, however, did recreate the flat peaks that distinguished the measured signal. The low troughs may be partially due to the geometric approximation, an under estimation of the flow, unknown A/D location and temperature, and estimated riparian shading conditions. Further characterization of the flow conditions between DWR Weir and Anderson Grade, particularly below Yreka Creek, could lead to improved simulations in this reach. The signal at the Mouth (Figure 5-16) had the highest mean absolute error of 1.9°C. This was expected considering that a water balance was not computed between Anderson Grade and the Mouth (see Figure 5-5).

5.4 Temperature Validation

Validation is the process of applying the parameters set during calibration to an independent time period. Figure 5-17 through Figure 5-22 show the validated versus measured temperatures for each site. Similar trends appeared in the validation that were present in the calibration. Statistical analysis of validation can be found in Table 5-2.

Table 5-2 Error analysis of the temperature validation (°C)

Location	Average Bias	Maximum Bias	Minimum Bias	Mean Absolute Error
GID	-1.1	0.5	-3.3	1.1
A12	-0.2	1.9	-1.6	0.7
DWR Weir	-0.1	4.7	-5.0	1.9
Anderson Grade	-0.9	4.0	-6.5	1.9
Mouth	3.8	6.4	0.1	3.8

The phase of the temperature signal at GID (Figure 5-18) matched observed data well – about 1 hour out of phase with the measured data. This was an hour less than the calibration simulation. The MAE at GID was 1.1°C; 0.1°C more than in calibration. A12 (Figure 5-19) was the site with the lowest MAE. However, the MAE in validation was 0.7°C, 0.2°C greater than in August.

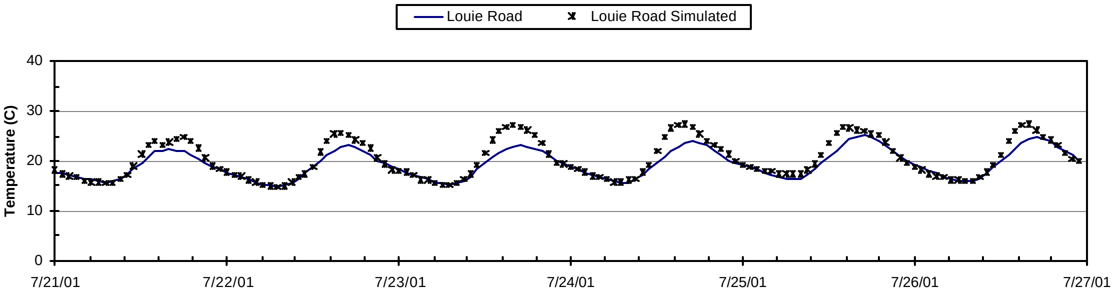


Figure 5-17 Measured vs. simulated temperature for Louie Road, July 21-27, 2001

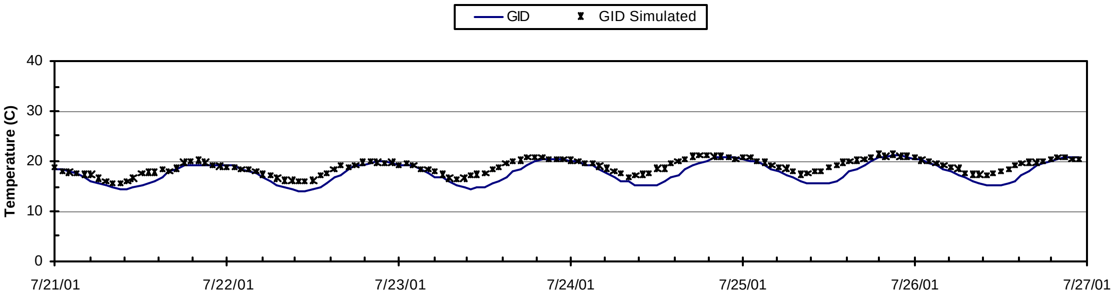


Figure 5-18 Measured vs. simulated temperature for GID, July 21-27, 2001

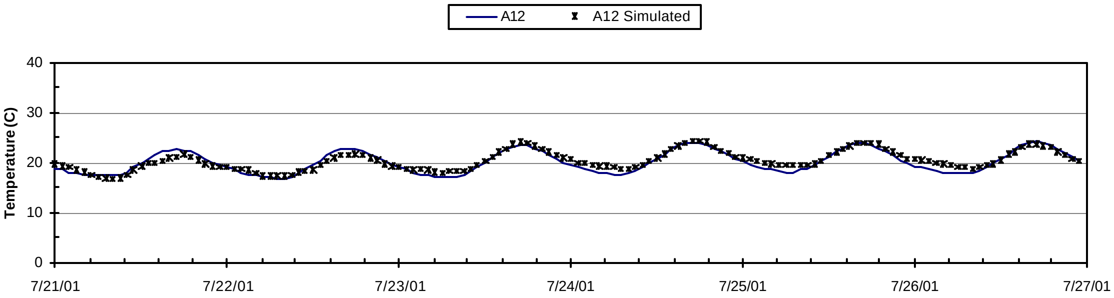


Figure 5-19 Measured vs. simulated temperature for A12, July 21-27, 2001

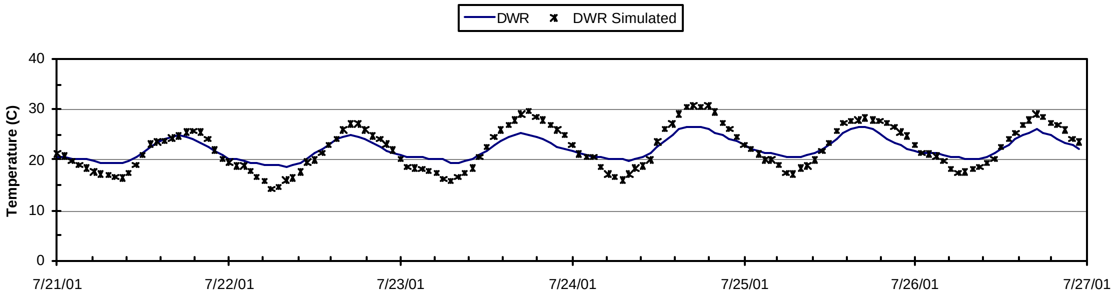


Figure 5-20 Measured vs. simulated temperature for DWR Weir, July 21-27, 2001

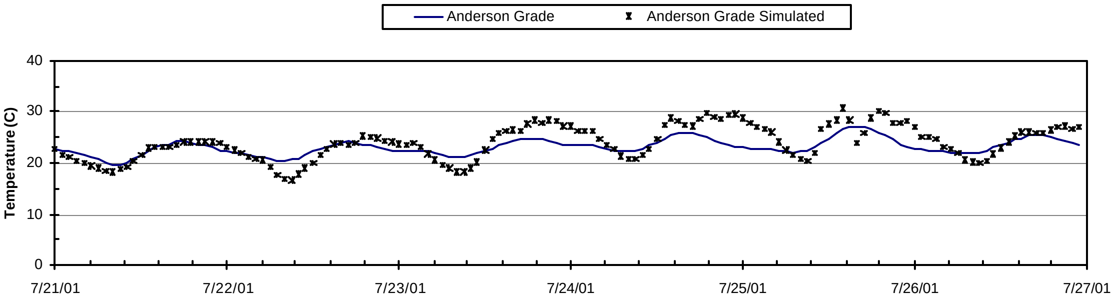


Figure 5-21 Measured vs. simulated temperature for Anderson Gr, July 21-27, 2001

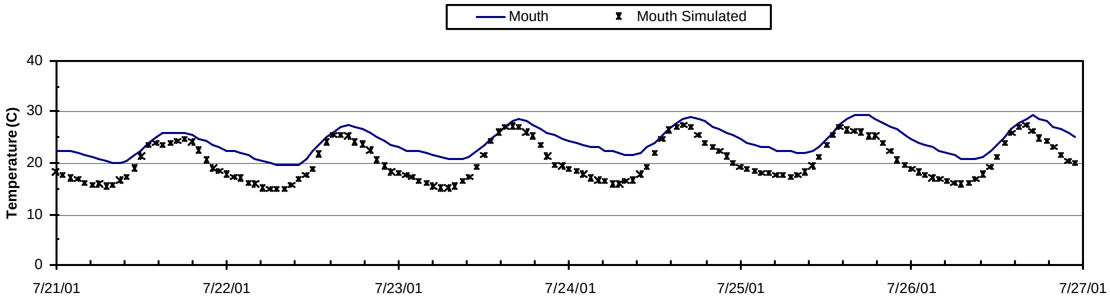


Figure 5-22 Measured vs. simulated temperature for Mouth, July 21-27, 2001

DWR Weir did not appear as craggy as in calibration and phase was well represented, but persisted in over-predicting the peaks and under-predicting the troughs with a MAE of 1.9°C, 0.2°C greater than calibration. Anderson Grade was particularly sensitive to the meteorological data on July 25^{th}, and although the daytime lows were underpredicted, the moderated diurnal signal is evident in the simulated values. The MAE was the same as DWR Weir: 1.9°C. Again, the site at the Mouth experienced the largest deviation. However, whereas at upstream locations where the model deviations were predominately associated with amplitude, the simulated temperatures at the Mouth were systematically lower than observed data (Figure 5-22).

It was evident that the conditions that existed in calibration persisted in validation, illustrating that the model performed consistently.

5.5 Model Application

Several management scenarios were investigated with the calibrated and validated temperature model. Based on input from local stakeholders, four formal management schemes were identified to assess the potential impact on the river thermal regime.

1. Effects of modified flow regime
2. Impacts of pulse flows
3. Effects of tailwater management schemes
4. Variable riparian shading conditions

In addition, two other analyses were completed regarding variable riparian vegetation conditions along Shasta River reaches. These analyses follow riparian shading conditions study identified in item 4, listed above. Several of the studies presented in this report were completed over several months. Attempts have been made to keep performance metrics and results consistent; however, there is some variation in format.

5.5.1 Management Alternatives Study

Details and findings of the management alternatives investigated with the Shasta River Flow and Water Quality Model (SRWQM) are presented below. Basic assumptions on flow, water temperature and meteorological conditions are presented as well, followed by results for each alternative.

Scenarios associated with each alternative were based upon existing geometry, meteorology and water flows for June, August, and September 2001 and 2002. Because a complete set of inflow temperatures was not available for 2002, inflow temperatures from 2001 were employed for these studies. As a result, conditions do not necessarily represent particular historic periods as much as general conditions for spring, summer, and fall on the Shasta River. Where records of inflow temperatures were completely missing (e.g. tailwater inflows or accretion-depletions) water was assumed to enter the river at local river temperatures. As in calibration-validation, inflow temperatures for Big Springs area accretions, a significant source of water on the upper river, were assumed to be equal to those measured at Grenada Irrigation district (GID). Inflow at the headwaters of the model, Shasta River above Parks (SRP) was assumed to be 60 percent of the flow measured at Louie Road, with Parks Creek contributing 40 percent of the flow.

Boundary conditions for these investigations consisted of hourly-averaged meteorological and flow data repeated daily for seven days to minimize the effects of daily changes. Meteorological and flow were derived from reported data for the weeks of 6/14-20/2002, 8/6-12/2002, and 9/24-31/2002. Actual observed hourly water temperatures for the same weeks in year 2001 were used. Base-case simulations assumed existing shade conditions. All results, except for those from the Pulse flow study, were evaluated on the last day of simulation (Day 7). The same reaches identified earlier in this report were employed for these studies, namely: Shasta River above Parks (SRP) to Grenada Irrigation District

(GID), GID to Hwy A12 (A12), A12 to DWR Weir (DWR), DWR to Anderson Grade Road (AND), and AND to river's mouth (MOU).

5.5.2 Flow Regime Study

The relationship between flow and temperature is a well-established phenomenon in surface water systems. However, the particular impact of specific flow regimes on the water temperatures in the Shasta River is not straightforward. It has been proposed that increasing base flow in the Shasta River may potentially decrease the water temperature so as to affect the habitat for cold-water fish. The goal of this alternative was to determine the effect of altering the amount of flow in the Shasta River by adding base flow to the river at different locations at different times of the year and examining the impact on the thermal regime.

To assess the impact of flow regime on water temperature in the Shasta River additional water was added to the river base flow at rates of 10 and 20 cfs at the beginning of each study reach (SRP, GID, A12, DWR, and AND). For example, the one simulation included a 10 cfs inflow at GID. The next simulation required the removal of the 10 cfs inflow at GID and placing it at A-12, and so on for subsequent simulations. The inflow temperature for each reach was assumed equal to the river temperature at the inflow location. Thus, ten simulations were completed for each of three study period: June, August, and September. Results are compared to base-case simulations of river temperatures for each of the three study periods by examining (plotting) the deviation or temperature change compared to the baseline case. Base flow conditions are listed in Table 5-3.

Table 5-3 Average weekly base inflow boundary conditions for the flow regime alternative analysis periods

		Average Base Flow (cfs)	
Location	June	August	September
SRP	16.1	17.9	11.7
PKS	10.7	12.0	7.8
Big Springs	63.1	52.2	72.5
GID	-21.4	-25.0	-23.5
A12	-1.6	7.7	13.5
SWUA	-42.0	-42.0	-42.0
DWR	-2.6	-6.5	-11.1
AND	6.4	-0.3	1.2

June

June conditions suggest that the addition of 10 cfs had minimal impact on overall thermal regime, as represented by deviations in the daily maximum, mean, and minimum temperatures at the identified locations. Deviations from the base case were less than 1°C for all summary statistics (Figure 5-23). The addition of 20 cfs had a larger impact, especially on the middle and lower reaches where such inflows formed a larger proportion of the base flow. Minimum temperature dropped by up to 1.5°C, while maximum temperatures were reduced to a lesser extent in the reach between Hwy A-12 and the mouth (Figure 5-24). Certain results are counter-intuitive. For example, because the addition of water to the various reaches directly adds volume and reduces transit time, it is expected that the diurnal maximum and minimum temperature range may be reduced. However, under steady flow conditions the advective transport of thermal energy can produce aberrant temperature signals due to inflows of different quantities and temperatures. These conditions directly affect the maximum and minimum temperature values in the river at different locations. In June, where the river base line condition illustrates a decline in mean daily temperature from upstream to downstream, the addition of water at the local river temperature, results in an addition of water that is (over the daily cycle) warmer than downstream reaches. The result is a slight positive deviation for all runs from the baseline condition (for comparison, see discussion for August, below).

August

Simulation results from August suggest that as base flow drops, smaller volumes of water can have a larger impact during warm periods. The 10 cfs flow reduces maximum temperatures in the middle and lower reaches by 1°C-2°C and increased minimum temperatures by about 1°C (Figure 5-25). The 20 cfs flow reduces maximum temperatures in the middle and lower reaches by 2°C-3°C and increased minimum temperatures by about 2°C (Figure 5-26).

Mean daily temperatures show a maximum decrease of little over 0.5°C and 1.0°C for the 10 cfs and 20 cfs cases, respectively. The farther upstream the water is added, the more miles of river experience a decrease in water temperature. The largest impact occurs within the reach that illustrates the largest heat gain, which in this case is the A-12 to DWR reach. Water added at extreme downstream locations (e.g., DWR Weir, Anderson grade) do not provide the same level of benefit either in length of river affected or overall magnitude of mean daily temperature decrease. Because August conditions indicate the river is heating from upstream to downstream, the addition of water at the local river temperature, results in an addition of water that is (over the daily cycle) cooler than downstream reaches. This is the converse condition for June.

September

Simulation results from September suggest that additional water (added at local river temperature) has a modest impact if meteorological conditions produce cooler water temperatures, even when base flow is low. Meteorological conditions in September, namely solar energy considerations, are markedly different from June and August. The result is shorter days and lower solar altitude, and thus lower solar energy input to the river system. In August the simulated water temperatures ranged from roughly 17°C to

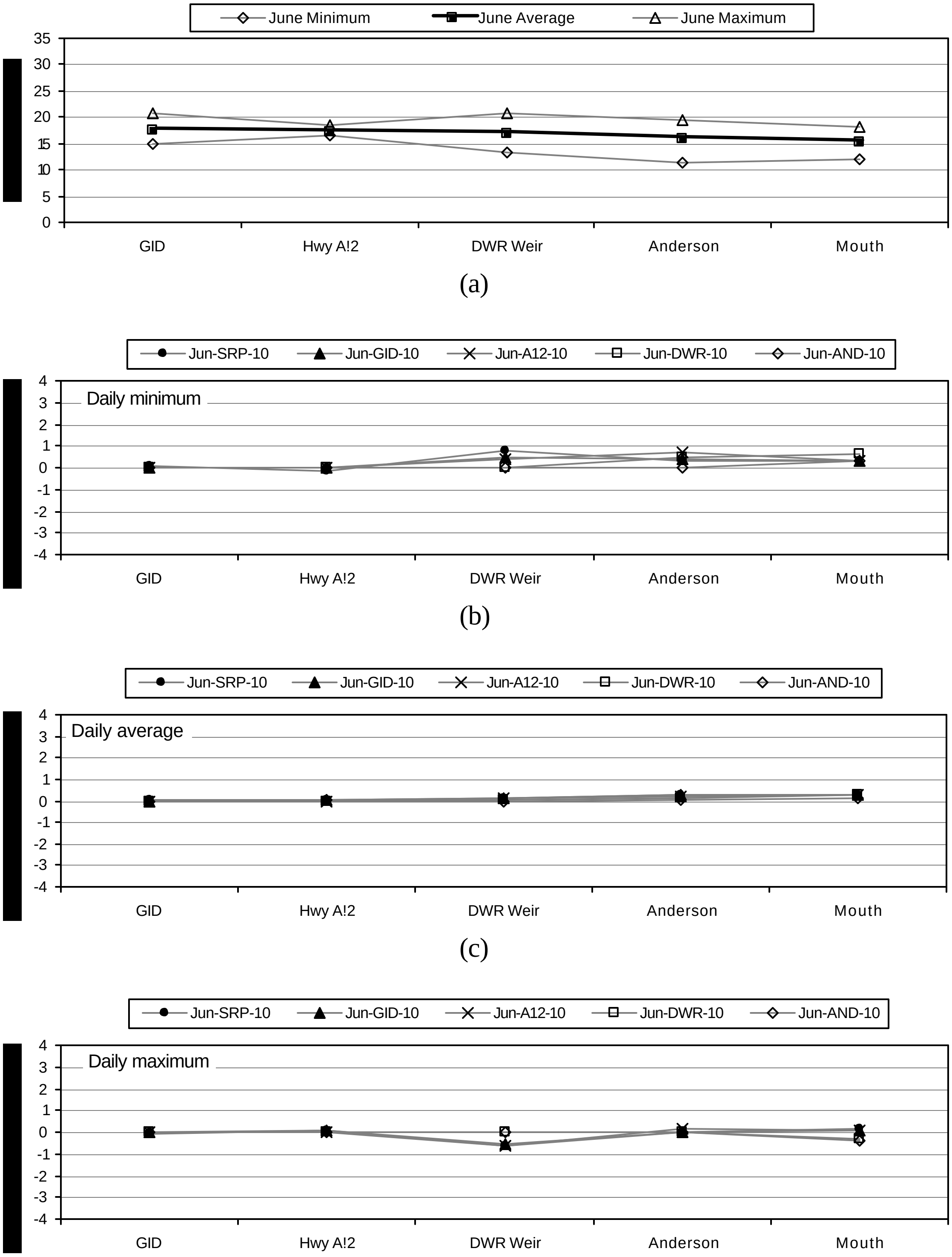
30°C, while in September the range is roughly 10°C to 20°C (Figure 5-27and Figure 5-28). Examination of the baseline condition shows the mean daily temperature from GID to the Mouth is almost constant at about 14°C to 15°C. These conditions are somewhat similar to June.

Summary

These three periods illustrate a wide range of conditions and suggest several important findings:

- Advection, the physical transport of thermal energy is an important consideration in the Shasta River. The transport of water from upstream locations to downstream locations affects downstream water temperature.
- When the river is generally warming in the downstream direction, additional volumes input at upstream locations reduce mean daily water temperatures over a both the length of river and in overall magnitude. The converse is true of the river is warmer in upstream reaches.
- Additional volume of water generally translates to a reduction in the diurnal range in temperatures, i.e., lower daily maximum and higher daily minimum temperatures.
- Identifying the reach or reaches with the largest heat gain (e.g. °C per mile) provides insight into the locations where the greatest opportunity for decreasing mean daily temperature through increased flow exists.

It is critical to recall that the three representative periods examined do not represent all possible conditions. Meteorology and hydrology of the Shasta River basin are highly variable annually, seasonally, and even over a few days. Short duration, severe meteorological conditions (heat waves) can occur from early-May through September.



(a)

(b)

(c)

(d)

Figure 5-23 Flow Regime Study results for 10 cfs inflows in June. Deviations from (a) June 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.

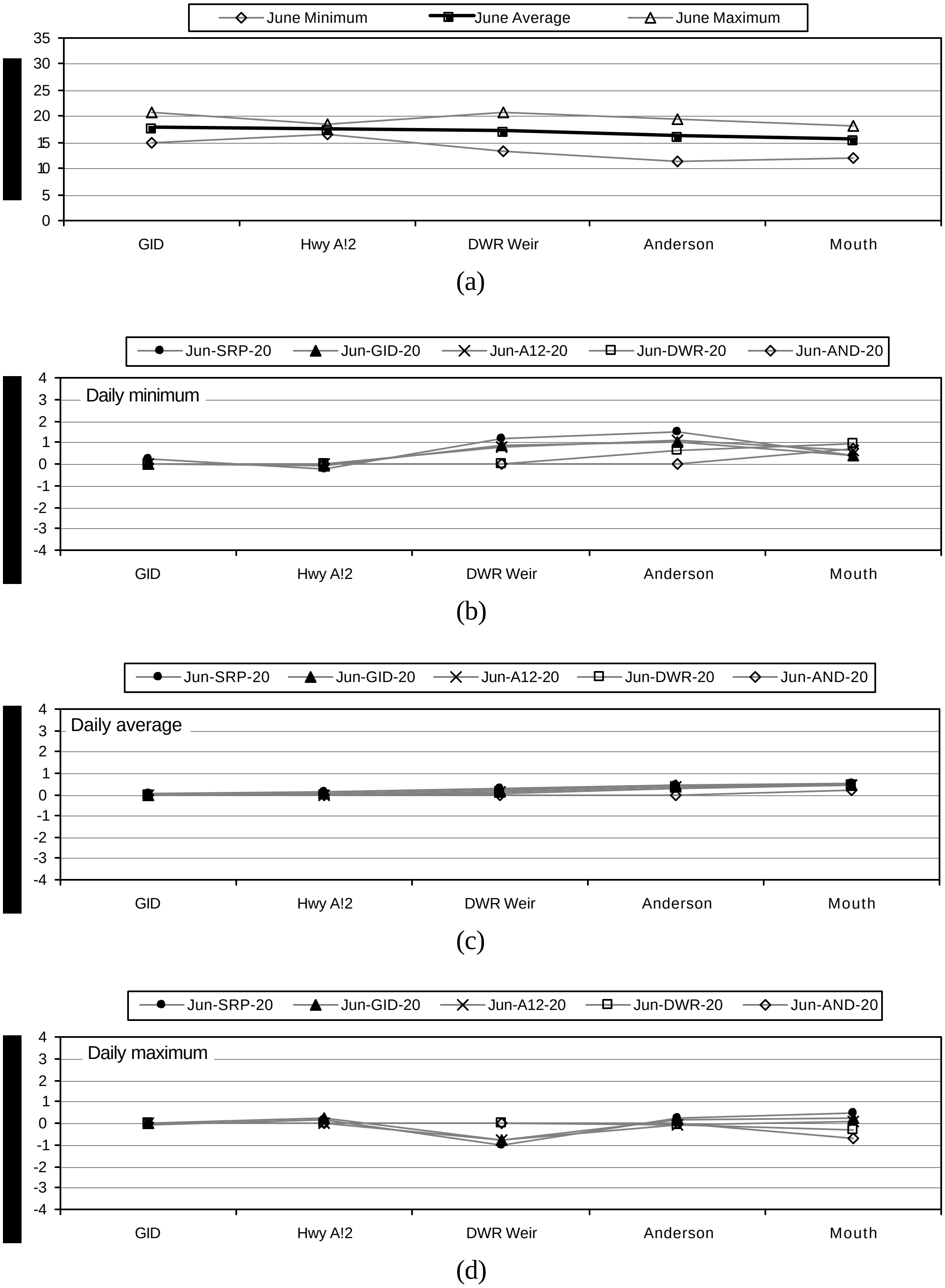


Figure 5-24 Flow Regime Study results for 20 cfs inflows in June. Deviations from (a) June base-case condition in (b) daily minima, (c) daily average, and (d) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.

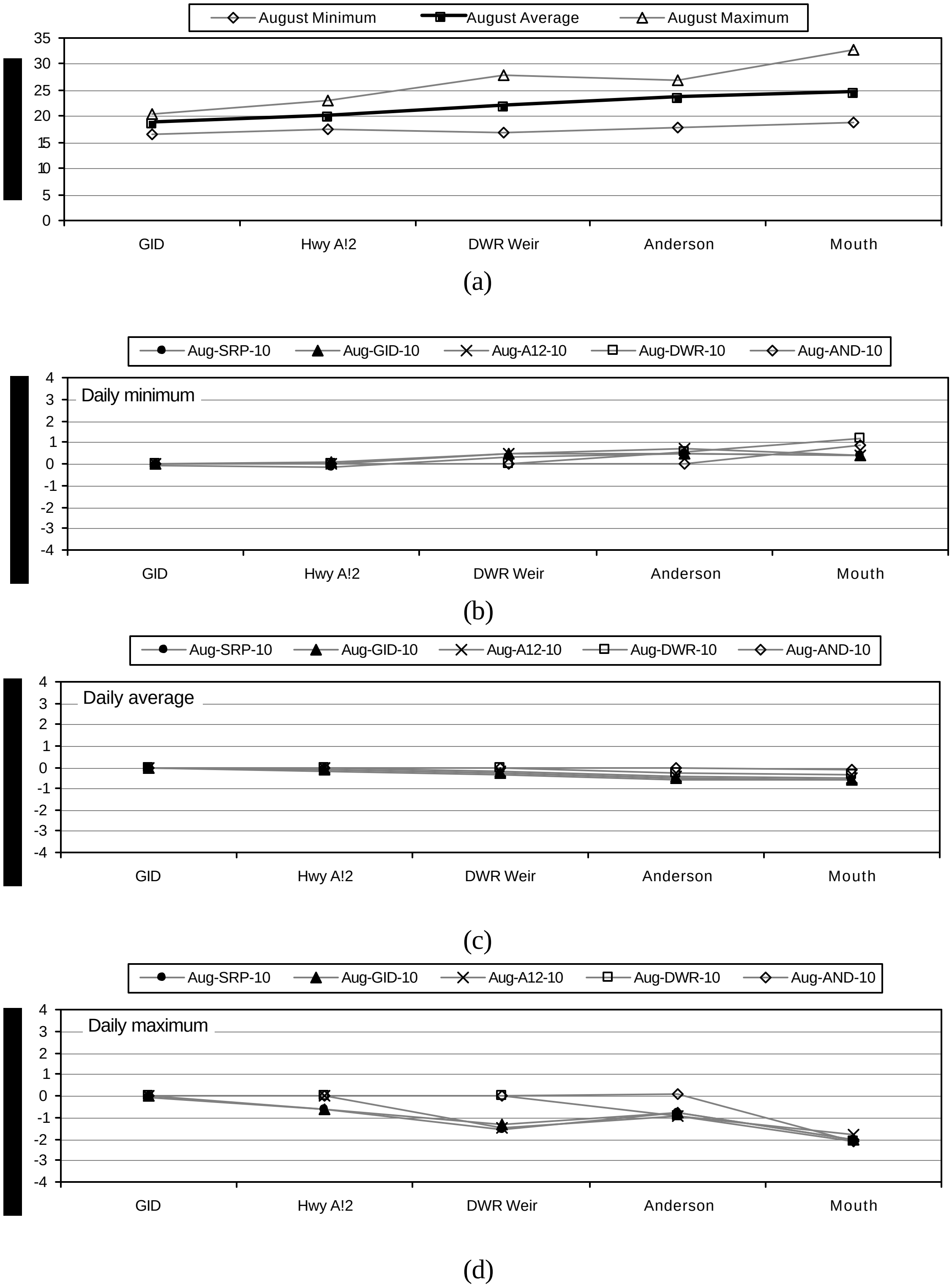
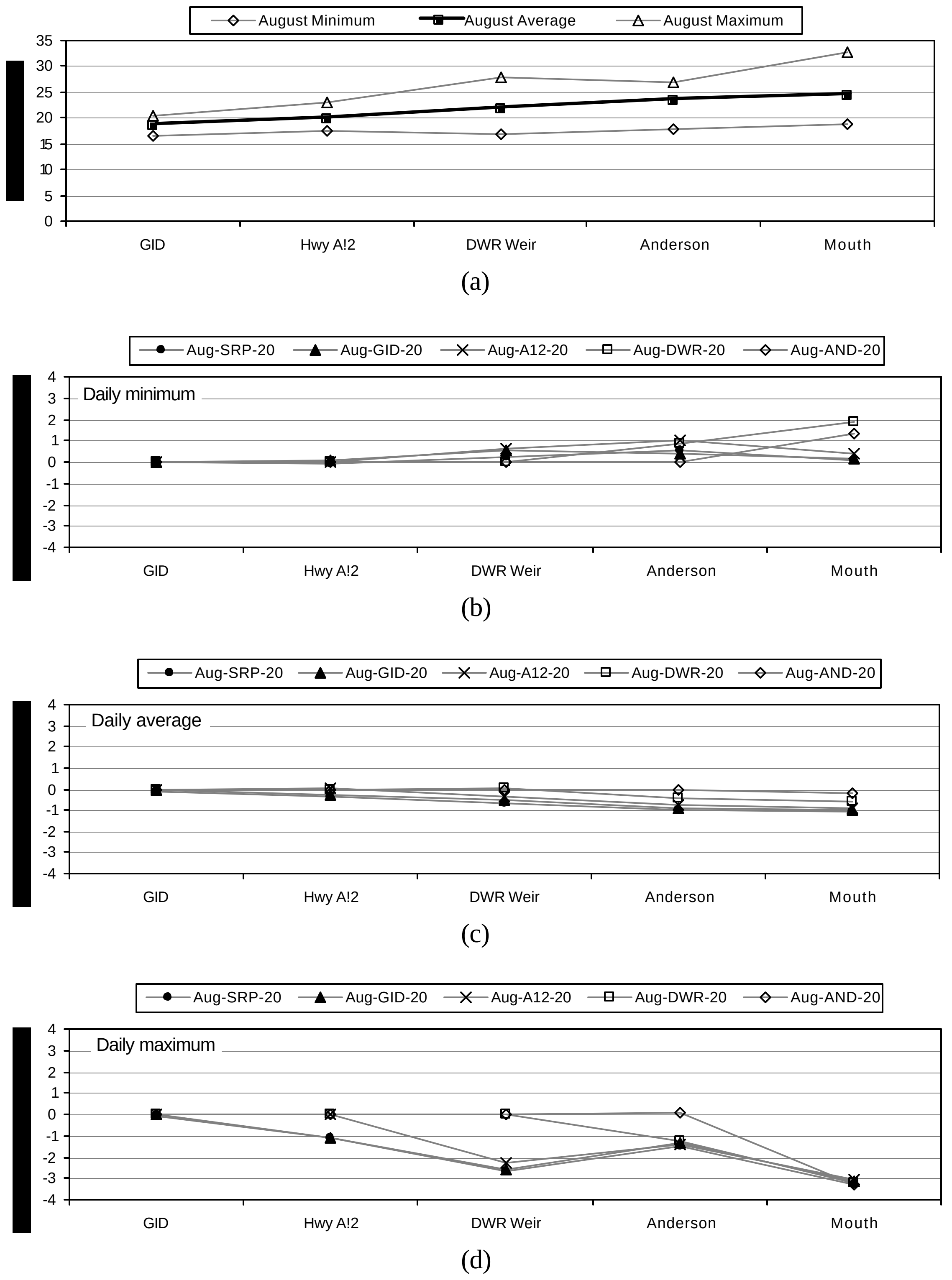


Figure 5-25 Flow Regime Study results for 10 cfs inflows in August. Deviations from (a) August base-case condition in (b) daily minima, (c) daily average, and (d) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.



(a)

(b)

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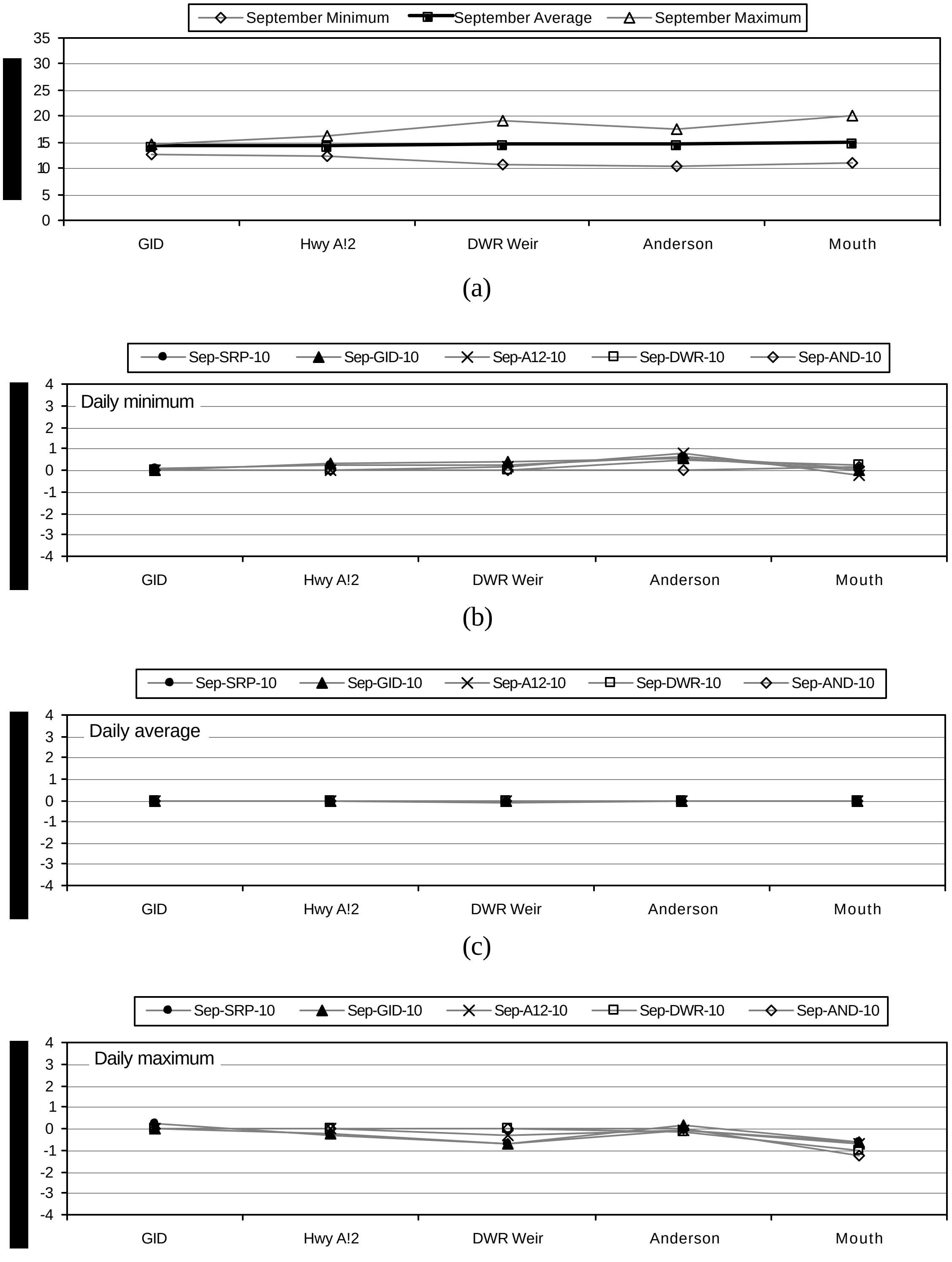
Figure 5-26 Flow Regime Study results for 20 cfs inflows in August. Deviations from (a) August base-case condition in (b) daily minima, (c) daily average, and (d) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.



(a)

(b)

(c)

(d)

Figure 5-27 Flow Regime Study results for 10 cfs inflows in September. Deviations from (a) September 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.

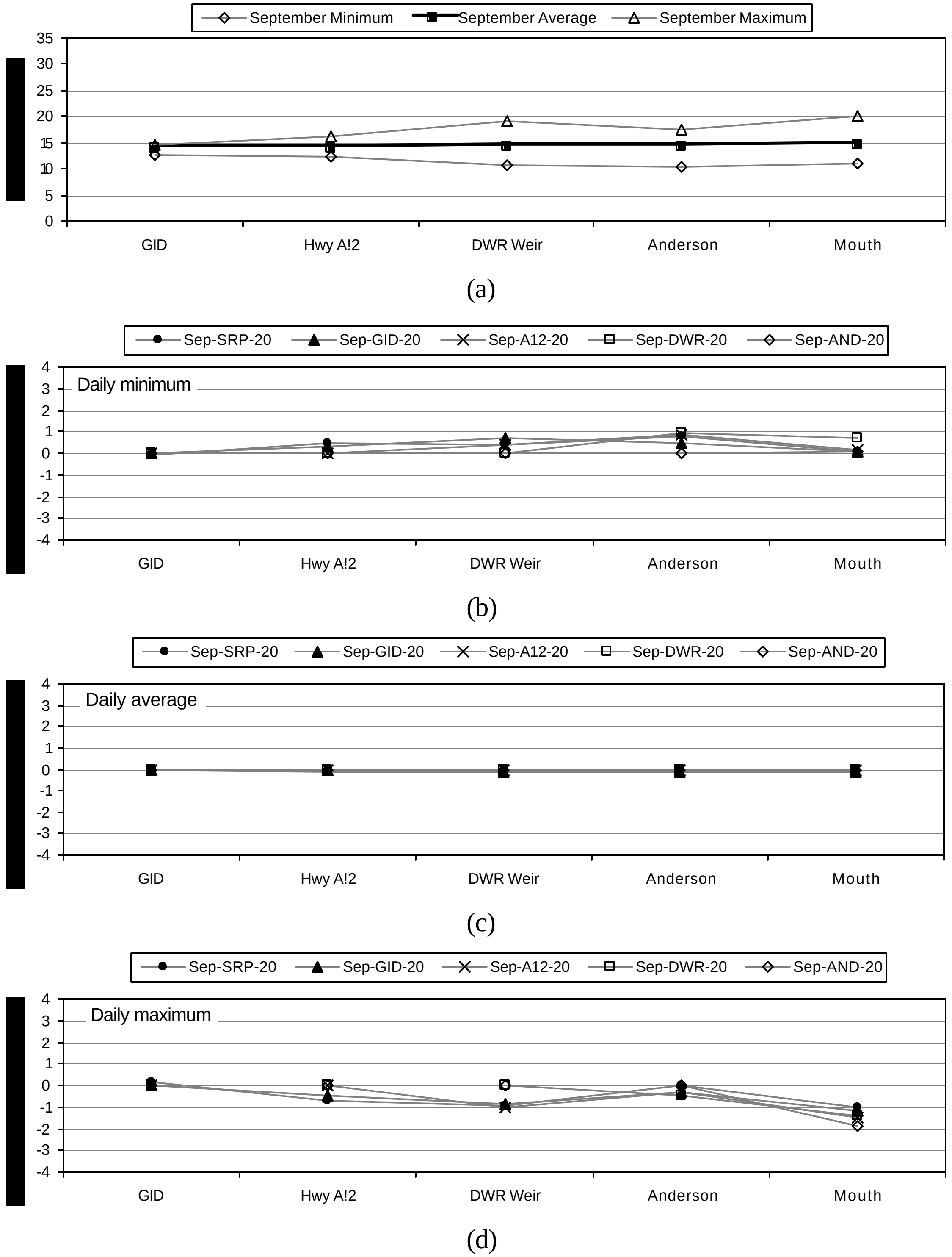


Figure 5-28 Flow Regime Study results for 20 cfs inflows in September. Deviations from (a) September base-case condition in (b) daily minima, (c) daily average, and (d) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.

5.5.3 Pulse Flow

As noted in the flow regime study, above, there is a relationship between flow and temperature in surface water systems. The purpose of this scenario is to assess this relationship for a special pulse flow operation that is often carried out in the spring period (May/June) to assist outmigrating juvenile salmonids. Simulating this highly dynamic process is intended to assess flow and temperature during that pulse.

The dynamic flow regime from a week in early June was used to determined accretions and depletions in the system. The pulse flow was be simulated by adding water at the quantity and locations specified below in two scenarios. The first scenario represents a "sequential" pulse flow where flows were added (i.e., diversions terminated) in sequential order as the pulse travels down stream. The pulse flow was continued for 48 hours at any given location. For the sequential scenario the pulse was presumed to start at Dwinnell Dam at 3 a.m., and was estimated to arrive at Shasta above Parks (RM 31.8) five hours later. The model was used to route the pulse flow from Shasta above Parks to each identified site (see below). The second scenario represents a "simultaneous" operation where all users shut down at 7 p.m. on the first day and stay off line for 48 hours, then resume (no specific ramping of diversion rates will be applied).

- Montague Irrigation District - 10 cfs (to be applied at Shasta above Parks)[1]
- Grenada Irrigation District and Huseman Ditch – 50 cfs
- Novy Dam – 3 cfs (combined with Grenada Irrigation District and Huseman Ditch)
- Shasta Water Association, and other users – 50 cfs (applied at SWA)
- Highway 3 – 12 cfs
- Yreka-Ager Road – 3 cfs

The schedule for both the sequential and simultaneous pulse flows are provided in Table 5-4. The travel times, mean reach velocity, and arrival times of the pulse as derived from the hydrodynamic model are provided for the sequential and simultaneous pulse flows in Table 5-5 and Table 5-6. Not, travel time through the system is on the order of one day.

Table 5-4 Actual Inflow Schedule

Location	Flow (cfs)	Reach Travel time (hrs)	Inflows applied at hour: “Successive”	“Simultaneous”
SRP	10	5.0	8 (day 1 8:00)	19 (day 1 19:00)
GID	53	4.0	12 (day 1 12:00)	19 (day 1 19:00)
SWUA	50	9.0	21 (day 1 21:00)	19 (day 1 19:00)
HWY3	12	3.0	24 (day 2 0:00)	19 (day 1 19:00)
AGER	3	1.0	25 (day 2 1:00)	19 (day 1 19:00)
All diversions reinstated 48 hours after terminated				

Table 5-5 Sequential pulse flow data

Reach	Upstream Inflow Location	Location	Begin (RM)	End (RM)	Length (mi)	Mean Vel (ft/s)	Travel time (hr)	Pulse Arrival (hr)
-	Dwinnell	SRP	36.4	31.8	4.6	1.5	4.5	7.5
1	SRP	GID	31.8	26.9	4.9	1.6	4.4	11.9
2	GID	A12	26.9	21.9	5.0	1.8	4.1	16.0
3	A12	DWR	21.9	14.7	7.2	1.7	6.0	22.0
4	DWR	AND	14.7	7.9	6.8	2.2	4.5	26.5
5	AND	MOU	7.9	0.0	7.9	3.5	3.3	29.8

Dwinnell – release from the Montague Water Conservation District Canal
SRP – Shasta River above Parks
GID – Grenada Irrigation District
A12 – Highway A-12
DWR – DWR Water Master weir at Montague Grenada Road
AND – Anderson Grade
MOU – Mouth of the Shasta River
SWUA – Shasta Water Users Association

Table 5-6 Simultaneous pulse flow data

Reach	Upstream Inflow Location	Location	Begin (RM)	End (RM)	Length (mi)	Mean Velocity (ft/s)	Travel time (hr)	Pulse Arrival (hr)
-	Dwinnell	SRP	36.4	31.8	4.6	1.50	4.5	23.5
1	SRP	GID	31.8	26.9	4.9	1.64	4.4	23.4
2	GID	A12	26.9	21.9	5.0	1.69	4.4	23.4
-	SWUA	DWR	16.8	14.7	2.1	2.08	1.5	20.5
-	HWY3	AND	12.3	7.9	4.4	2.55	2.5	21.5
-	HWY3	MOU	12.3	0.0	12.3	3.15	5.7	24.7

Dwinnell – release from the Montague Water Conservation District Canal
SRP – Shasta River above Parks
GID – Grenada Irrigation District
A12 – Highway A-12
DWR – DWR Water Master weir at Montague Grenada Road
AND – Anderson Grade
MOU – Mouth of the Shasta River
SWUA – Shasta Water Users Association

Figure 5-29 illustrates longitudinal profiles of water temperature for pre-pulse flow conditions, as well as representative day one and day two conditions for the sequential and simultaneous pulse flows. Distance upstream represents miles from the Shasta River mouth. Prior to the pulse flow, all scenarios are coincident, which is to be expected. After one day, the impacts of pulse flow operations are evident between river miles 10 and 25. After two days the changes in thermal regime are between 1°C and 2°C throughout much of the middle and lower river reaches. The results indicate that the increased flow have reduced transit times and increased river volume.

The implications of these conditions are more clearly illustrated in time series of temperatures at SRP, GID, A12, DWR, AND, and MOU locations. Examining Figure 5-30 it is apparent that the peak daily temperature occurs earlier once the pulse flow has started (both sequential and simultaneous). Recall from Figure 5-23(a) that the river for the June period is warmer at upstream locations than downstream. Thus, not only does the peak occur earlier due to increased mean stream velocity, but in several cases the peak temperature is equal to or higher than the base condition. Reiterating the aforementioned point, this occurs because upstream conditions are warmer than downstream conditions. The conditions at DWR for baseline conditions suggest that this is one of the warmest locations on the river for the selected base line conditions with water temperatures peaking out at hour 40 at nearly 21°C. The larger volumes associated with the pulse flows result in a more moderated diurnal range at this location.

Generally there are only modest differences between the sequential and simultaneous pulse flow operations. Results at DWR and MOU suggest that the sequential scenario maintains lower minimum temperatures at certain times of the operation. After the pulse flow operations are terminated, conditions tend to return to baseline temperatures.

Summary

These two pulse flow operations suggest:

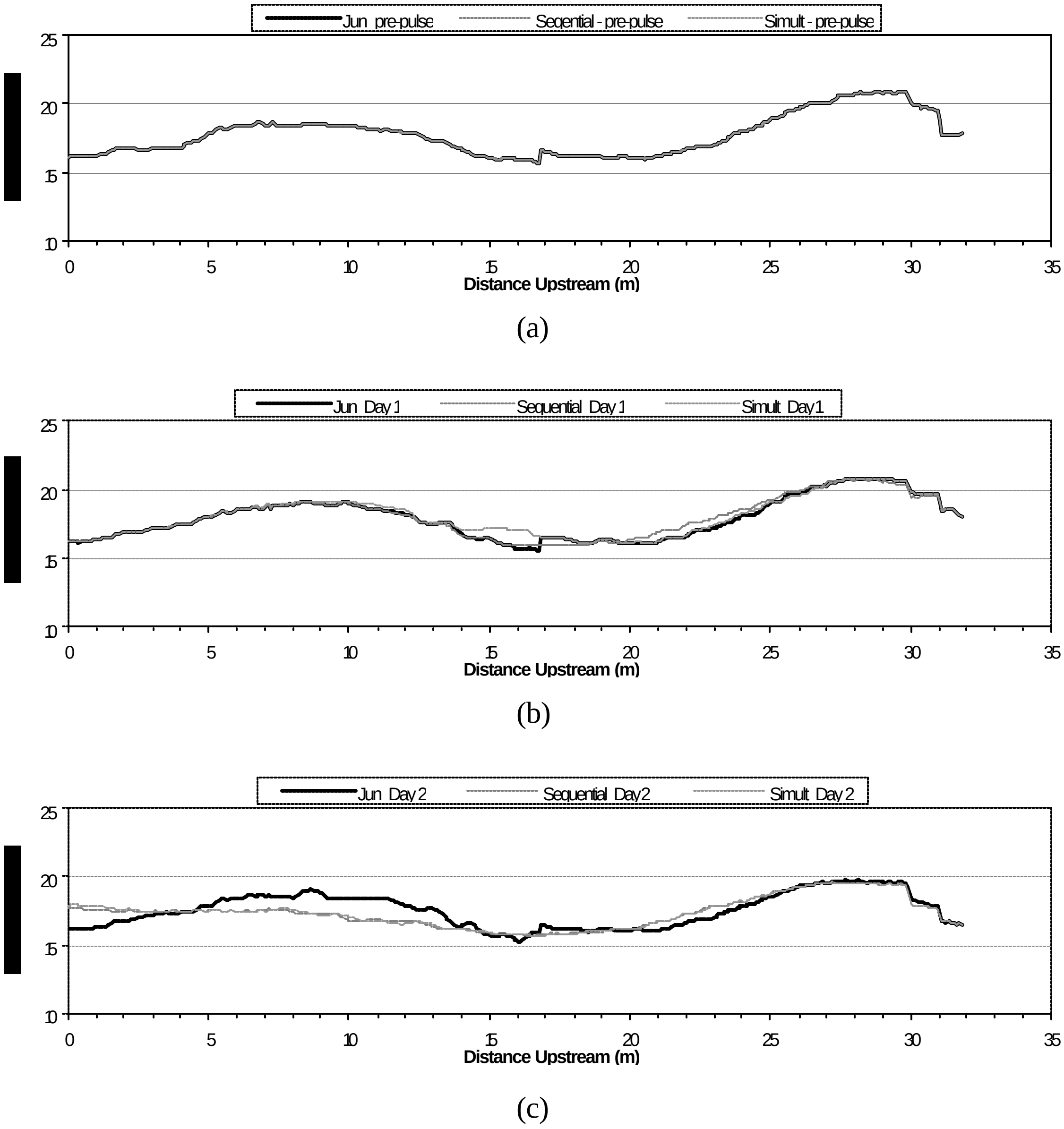
- As with the flow regime study, advection, the physical transport of thermal energy is an important consideration in the Shasta River in pulse flow operations. The transport of water from upstream locations to downstream locations affects downstream water temperature.

- Because the pulse flow traverses the river system in roughly one day, timing the commencement of the pulse flow operation should be examined in further detail. For example, it may yield more beneficial conditions for the simultaneously pulse flow operations if diversions were terminated at 7:00 a.m., when water temperatures are near minimum values than at 7:00 p.m. when water temperatures are still elevated above the mean daily values.

- Water temperature conditions should be monitored prior to and during the pulse flow. Temperature of release waters from Dwinnell (Montague Water Conservation District Canal) and in-river temperatures at intermediate locations should be determined prior to the pulse to ensure that desired water temperature conditions exist within the system. If upstream conditions are warmer than downstream, there is potential to heat the river (mean daily temperature). If upstream conditions are cooler, there is potential to cool the river with pulse flow operations.

- Further explore biological impacts on juvenile salmonids of shifting the peak daily temperature to earlier in the diurnal cycle, e.g., does shifting the diurnal signal promote, deter, or have no effect on outmigration.

- Additional conditions should be analyzed to examine the potential range of spring time, pulse flow conditions (flow, water temperature, and meteorological conditions). Variable meteorological conditions and magnitude and timing of pulse flows would lend additional insight into potential management actions.



(a)

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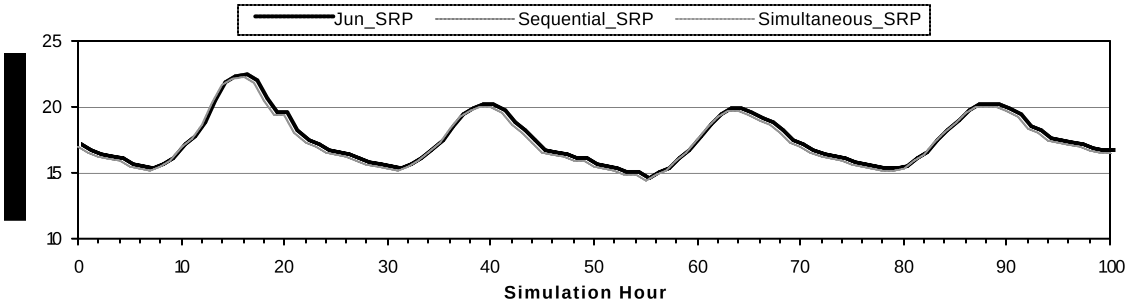
Figure 5-29 Longitudinal river temperature for June baseline, sequential, and simultaneous pulse flows: (a) pre-pulse, and representative (b) day 1 and (c) day 2 conditions.



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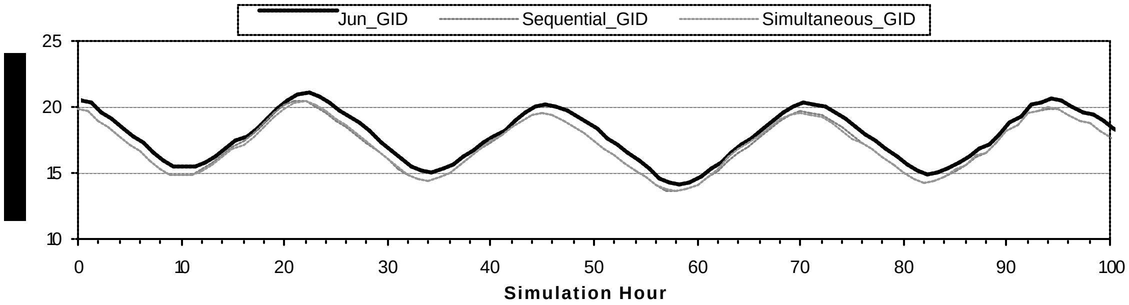

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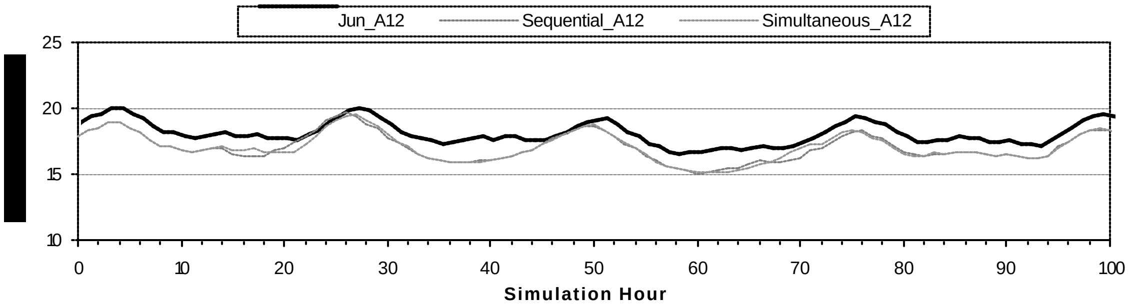

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Figure 5-30 Time series from day 1 through 4 of the baseline, sequential, and simultaneous pulse flows for (a) SRP, (b) GID, (c) A12, (d) DWR, (e) AND, and (e) MOU locations. Continued on next page.

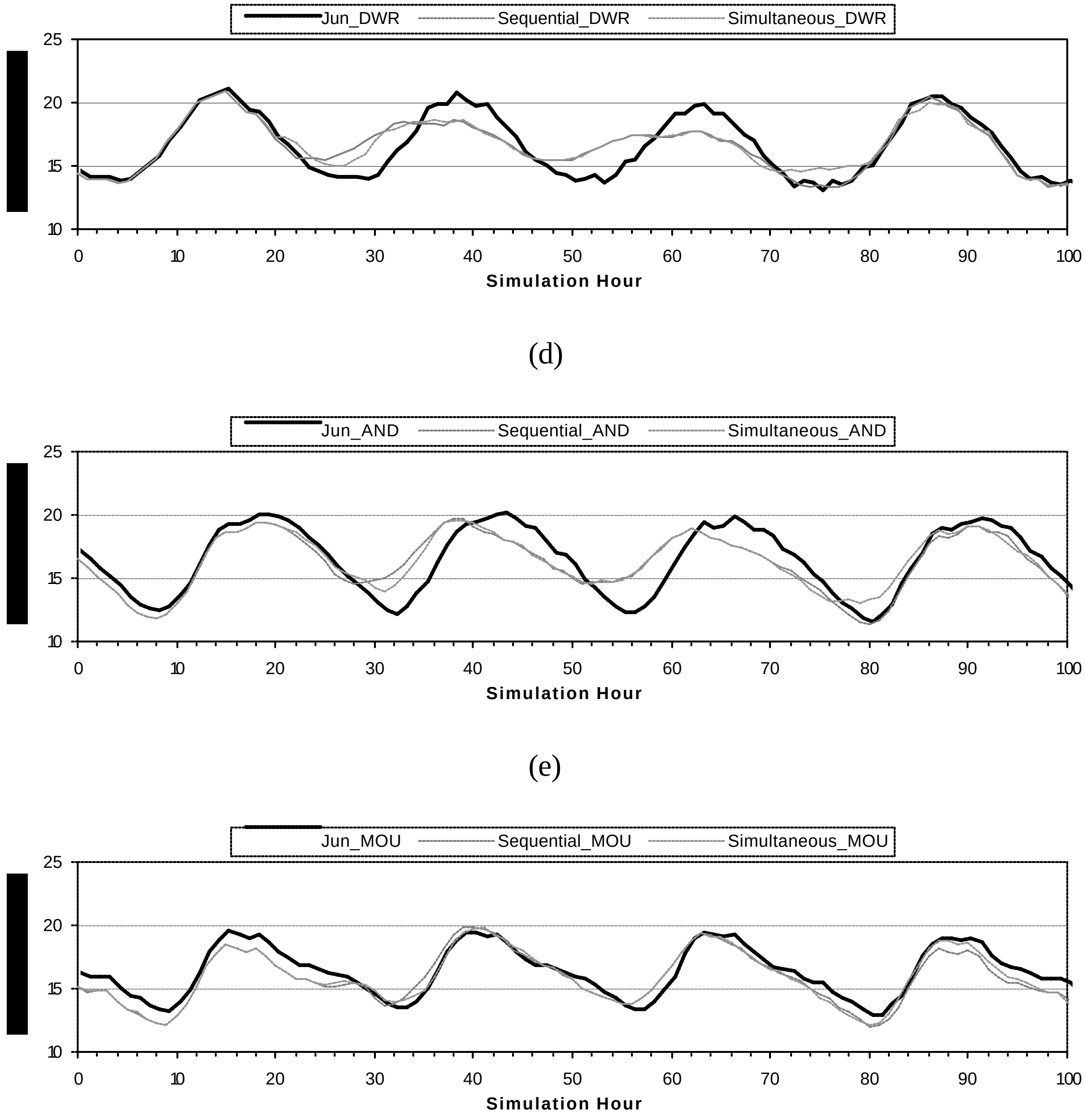

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Figure 5-30, continued. Time series from day 1 through 4 of the baseline, sequential, and simultaneous pulse flows for (a) SRP, (b) GID, (c) A12, (d) DWR, (e) AND, and (e) MOU locations.

5.5.4 Tailwater return

The tailwater return study was designed to investigate the effects that distribution of tailwater returns might have on the temperature regime of the Shasta River. In this study, water was added to Reach 3 (DWR Weir to Anderson Grade Road) under a variety of different conditions. In the 32 simulations for this study, point source returns at the top of the reach are compared to returns of equal volume distributed over the entire reach. Comparisons between these two return flow distributions were made for two different tailwater inflows (5 and 10 cfs) at two times of year (June and September) with two upstream inflows (20 and 50 cfs at SRP) at two upstream inflow temperatures (15°C and 20°C at SRP). Returns flows were assumed to enter the river at local water temperature. All other inflows and diversions were eliminated from the model.

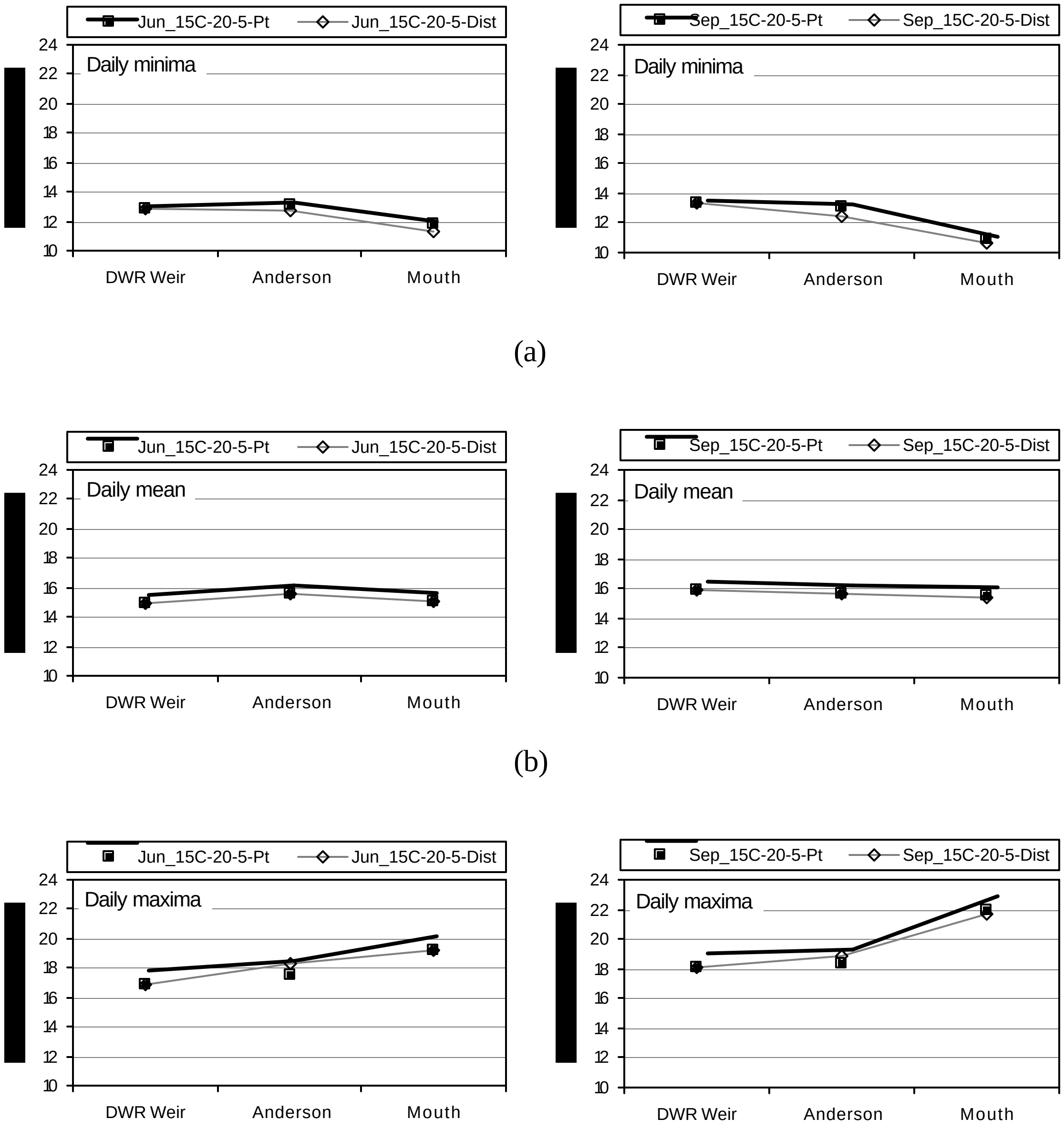
Results of this study are presented only from DWR to MOU locations and are shown in the following Figure 5-31 through Figure 5-38. Distribution of return flows resulted in lower downstream water temperatures than resulted from point inflow. Generally, the difference in mean daily temperatures was negligible. The difference in maximum and minimum water temperatures was small, always less than 1°C. For all simulations the mean difference between temperatures associated with point and distributed inflows of equal magnitude was 0.32°C (CV=0.90). The greatest differences occurred when headwater flow was 20 cfs and tailwater flow was 10 cfs, regardless of time-of-year or headwater temperature. Under these conditions, flows distributed over the reach produced an average drop in temperature of about 0.5°C at Anderson Grade Road and about 0.8°C at the river mouth. In this study, time-of-year made little difference (probably because meteorological conditions were similar in June and September). Not surprisingly, the scenario least affected by a change in inflow distribution was that in which high flows of 50 cfs were imposed on the upstream boundary at SRP.

Summary

The distributed return flow provided conditions of smaller in-river volume for the entire reach between DWR and AND, resulting in maximum and minimum river temperatures that were higher and lower, respectively, than the case where the discharge was a point source at the tope of the reach. These findings suggest:

- That distribution and location of return flow can impact the thermal regime of the river.
- The temperature of the return flow could potentially play an important role in the management of tailwater.

Further, carefully crafted studies that identify actual conditions along the Shasta River should be tested to explore the potential range of responses that could realistically be expected with tailwater control projects.



(a)

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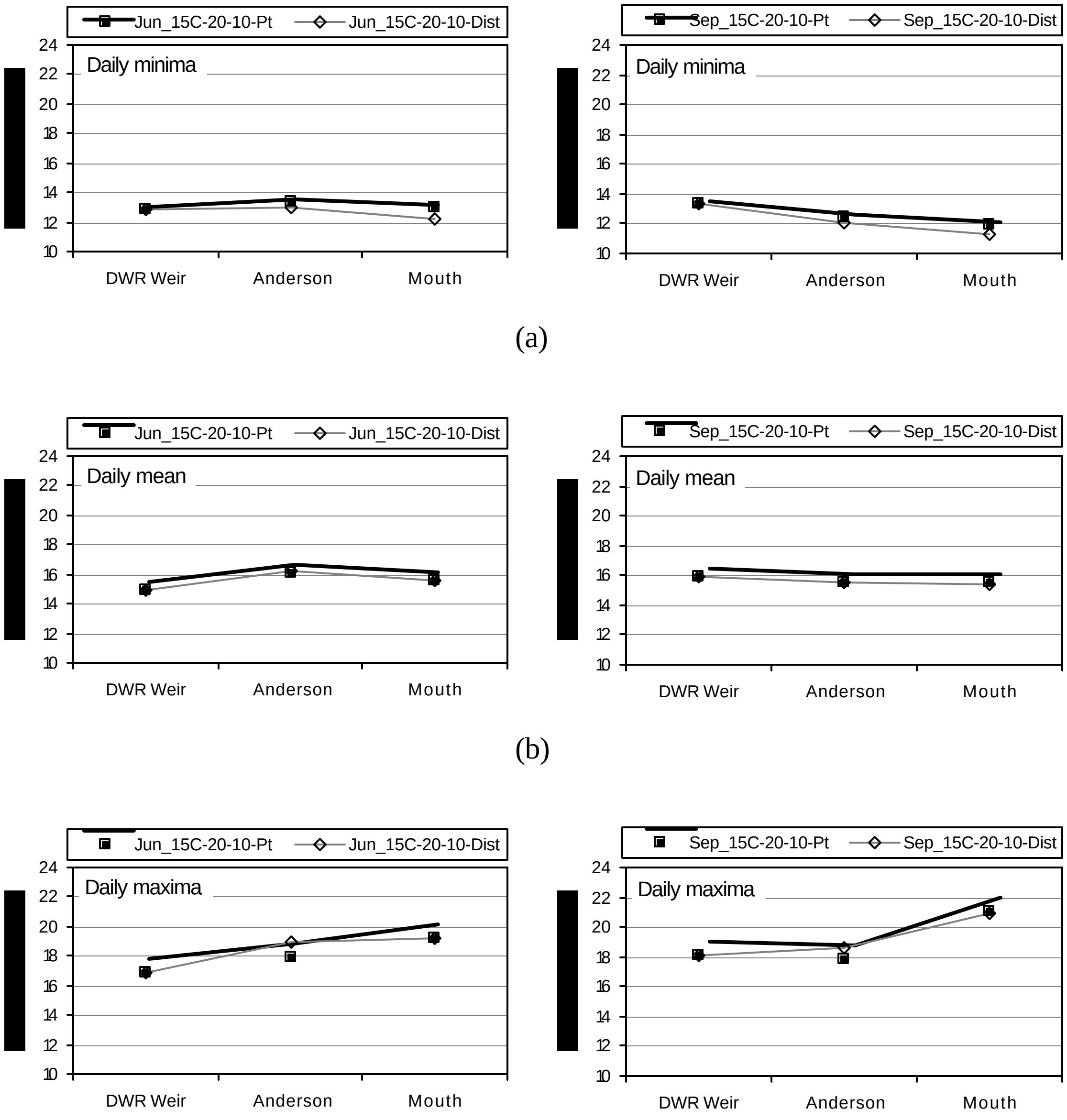
Figure 5-31 Tailwater Return Study 15°C-20-5 results for June and September. Upstream boundary condition of 15°C and 20 cfs at SRP, tailwater return flow of 5 cfs. Simulated (a) daily minimum, (b) daily average, and (c) daily maximum water temperature at DWR Weir, Anderson Grade Road, and the mouth of the Shasta River comparing point and distributed discharge of tailwater. Simulations designated by "month_upstream water temperature-upstream inflow-tailwater flow" (e.g. Sep_15C-20-5).



(a)

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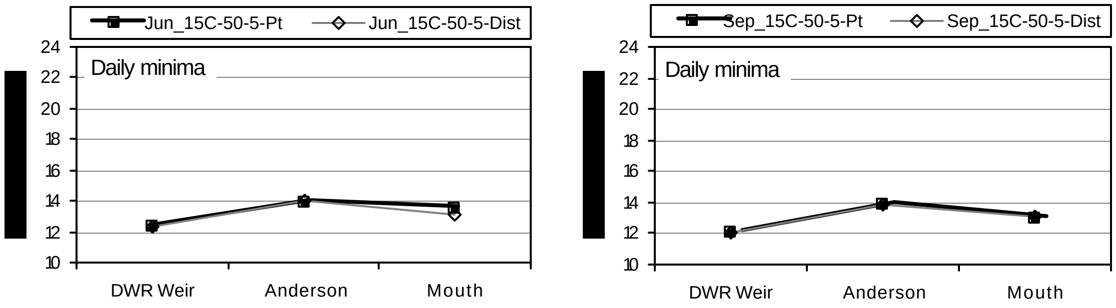
Figure 5-32 Tailwater Return Study 15°C-20-10 results for June and September. Upstream boundary condition of 15°C and 20 cfs at SRP, tailwater return flow of 10 cfs. Simulated (a) daily minimum, (b) daily average, and (c) daily maximum water temperature at DWR Weir, Anderson Grade Road, and the mouth of the Shasta River comparing point and distributed discharge of tailwater. Simulations designated by "month_upstream water temperature-upstream inflow-tailwater flow" (e.g. Sep_15C-20-10).



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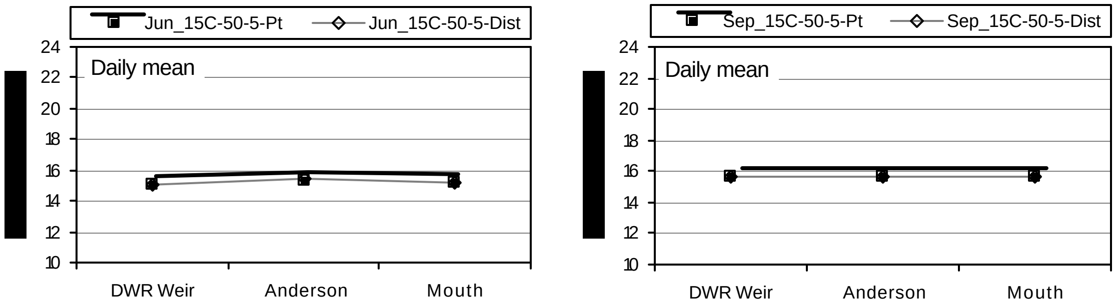

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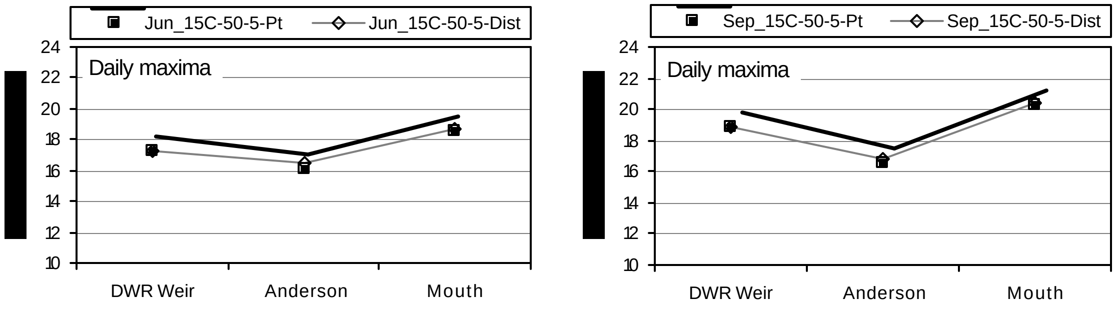
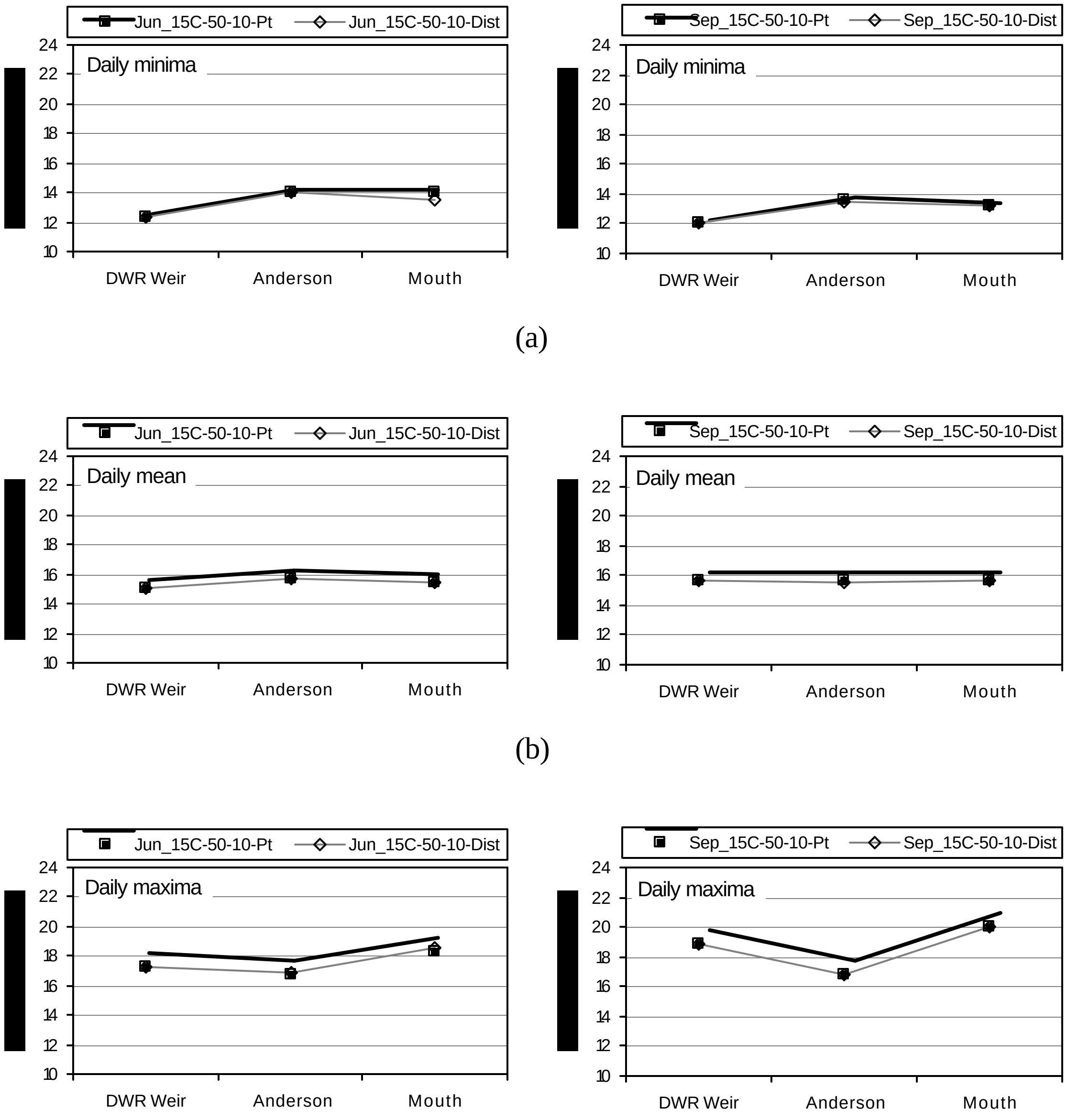


(c)

Figure 5-33 Tailwater Return Study 15°C-50-5 results for June and September. Upstream boundary condition of 15°C and 50 cfs at SRP, tailwater return flow of 5 cfs. Simulated (a) daily minimum, (b) daily average, and (c) daily maximum water temperature at DWR Weir, Anderson Grade Road, and the mouth of the Shasta River comparing point and distributed discharge of tailwater. Simulations designated by "month_upstream water temperature-upstream inflow-tailwater flow" (e.g. Sep_15C-50-5).



(a)

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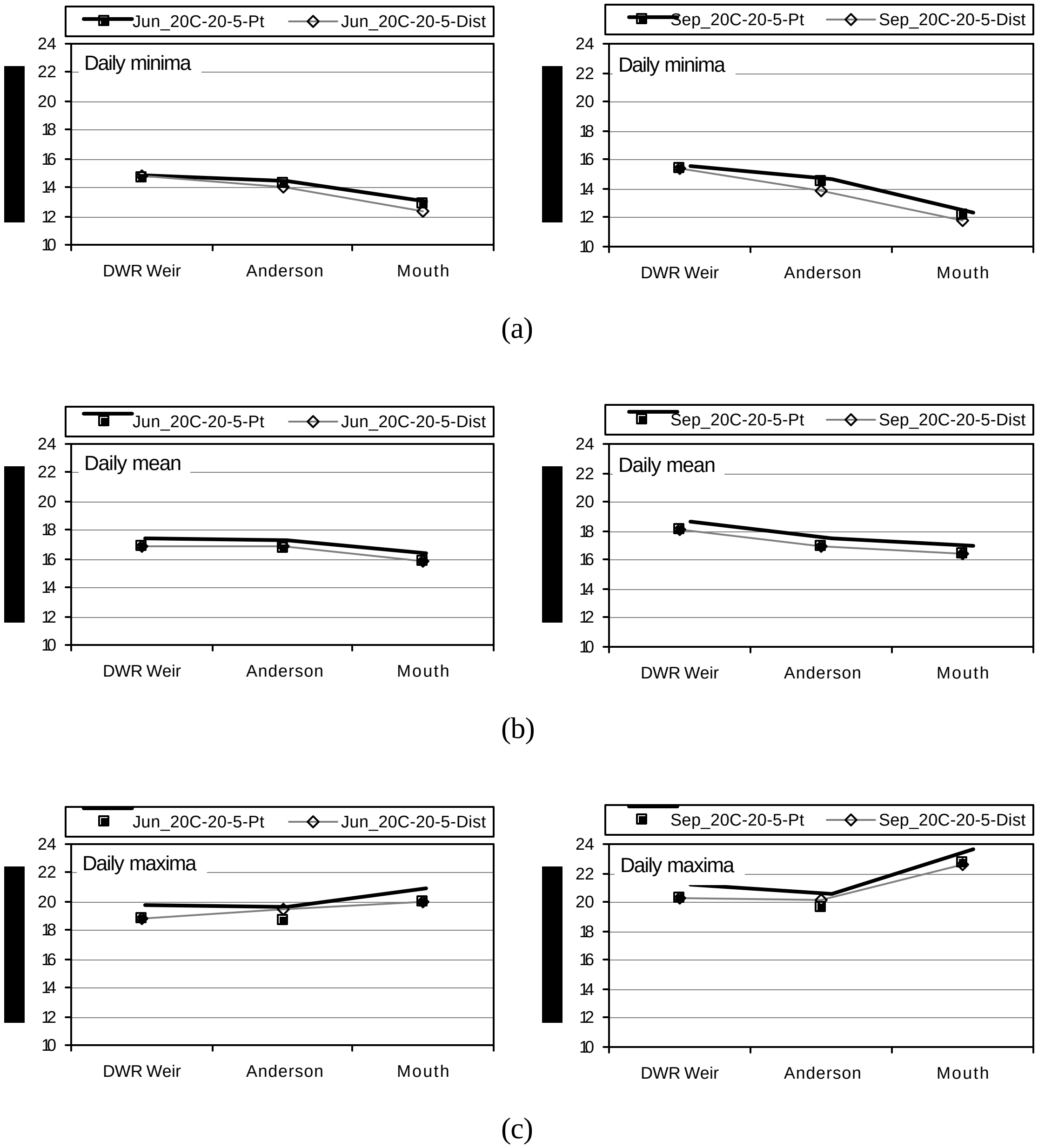
Figure 5-34 Tailwater Return Study 15°C-50-10 results for June and September. Upstream boundary condition of 15°C and 50 cfs at SRP, tailwater return flow of 10 cfs. Simulated (a) daily minimum, (b) daily average, and (c) daily maximum water temperature at DWR Weir, Anderson Grade Road, and the mouth of the Shasta River comparing point and distributed discharge of tailwater. Simulations designated by “month_upstream water temperature-upstream inflow-tailwater flow” (e.g. Sep_15C-50-10).



(a)

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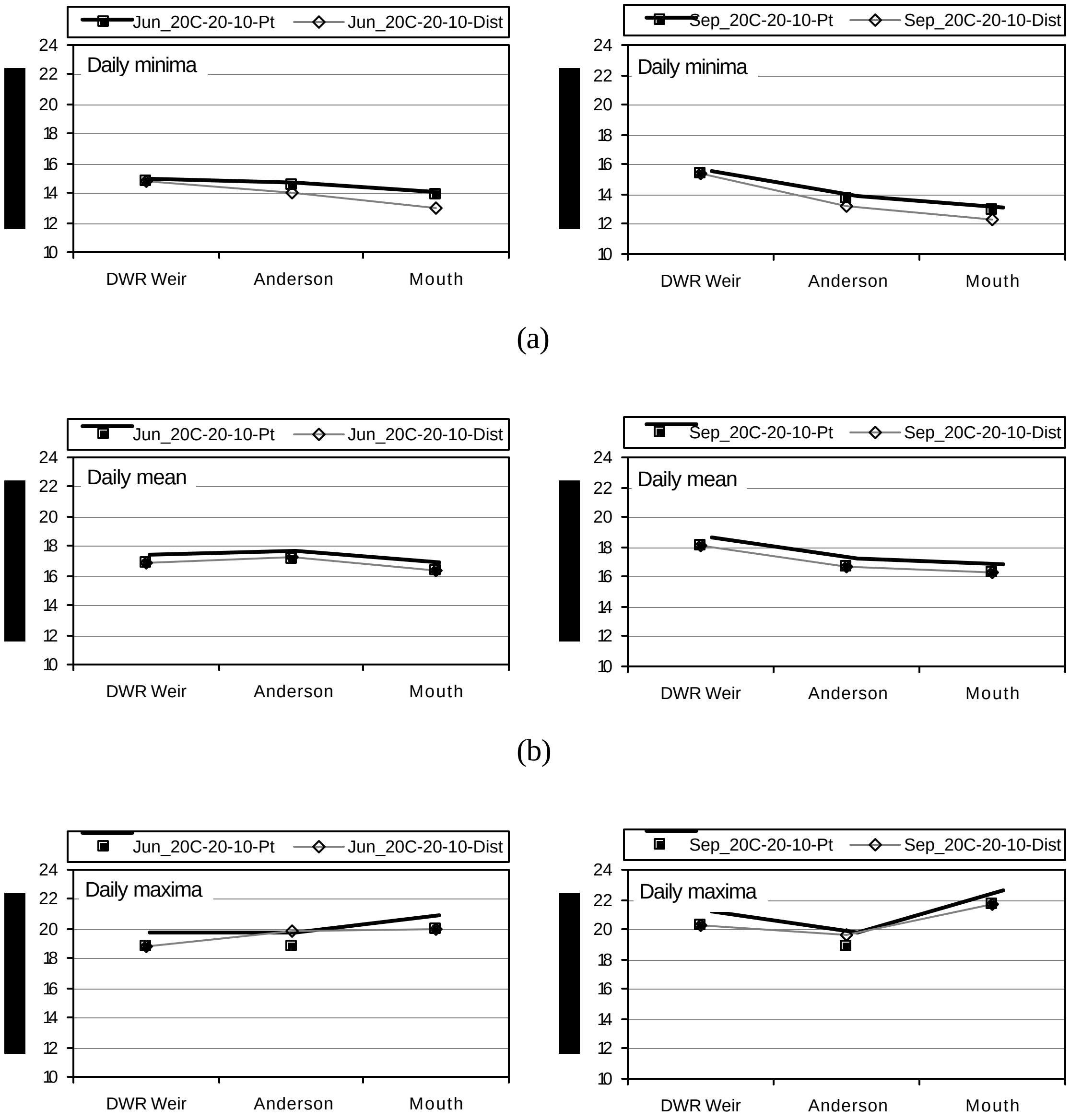
Figure 5-35 Tailwater Return Study 20°C-20-5 results for June and September. Upstream boundary condition of 20°C and 20 cfs at SRP, tailwater return flow of 5 cfs. Simulated (a) daily minimum, (b) daily average, and (c) daily maximum water temperature at DWR Weir, Anderson Grade Road, and the mouth of the Shasta River comparing point and distributed discharge of tailwater. Simulations designated by "month_upstream water temperature-upstream inflow-tailwater flow" (e.g. Sep_20C-20-5).



(a)

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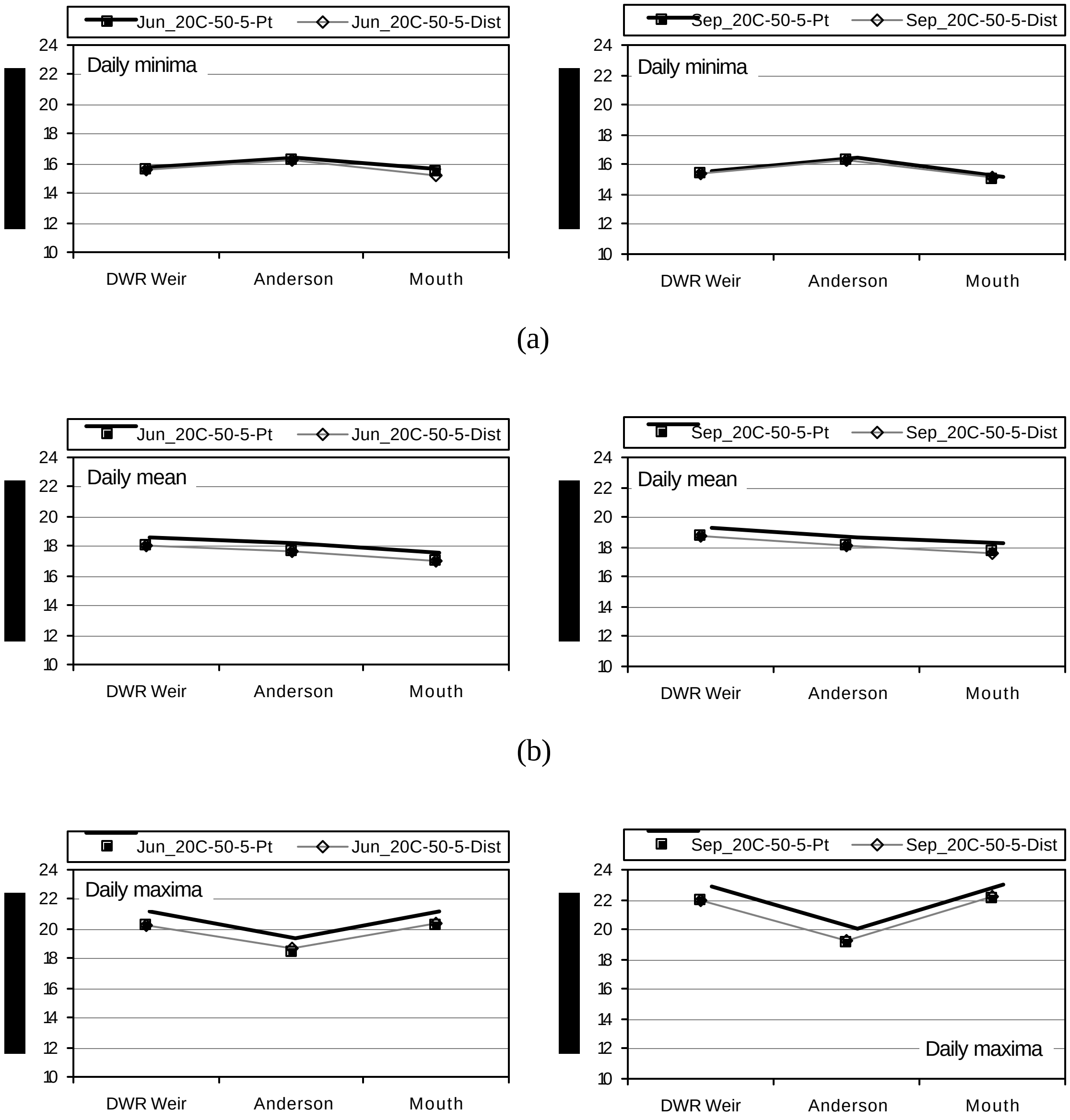
Figure 5-36 Tailwater Return Study 20°C-20-10 results for June and September. Upstream boundary condition of 20°C and 20 cfs at SRP, tailwater return flow of 5 cfs. Simulated (a) daily minimum, (b) daily average, and (c) daily maximum water temperature at DWR Weir, Anderson Grade Road, and the mouth of the Shasta River comparing point and distributed discharge of tailwater. Simulations designated by “month_upstream water temperature-upstream inflow-tailwater flow” (e.g. Sep_20C-20-10).



(a)

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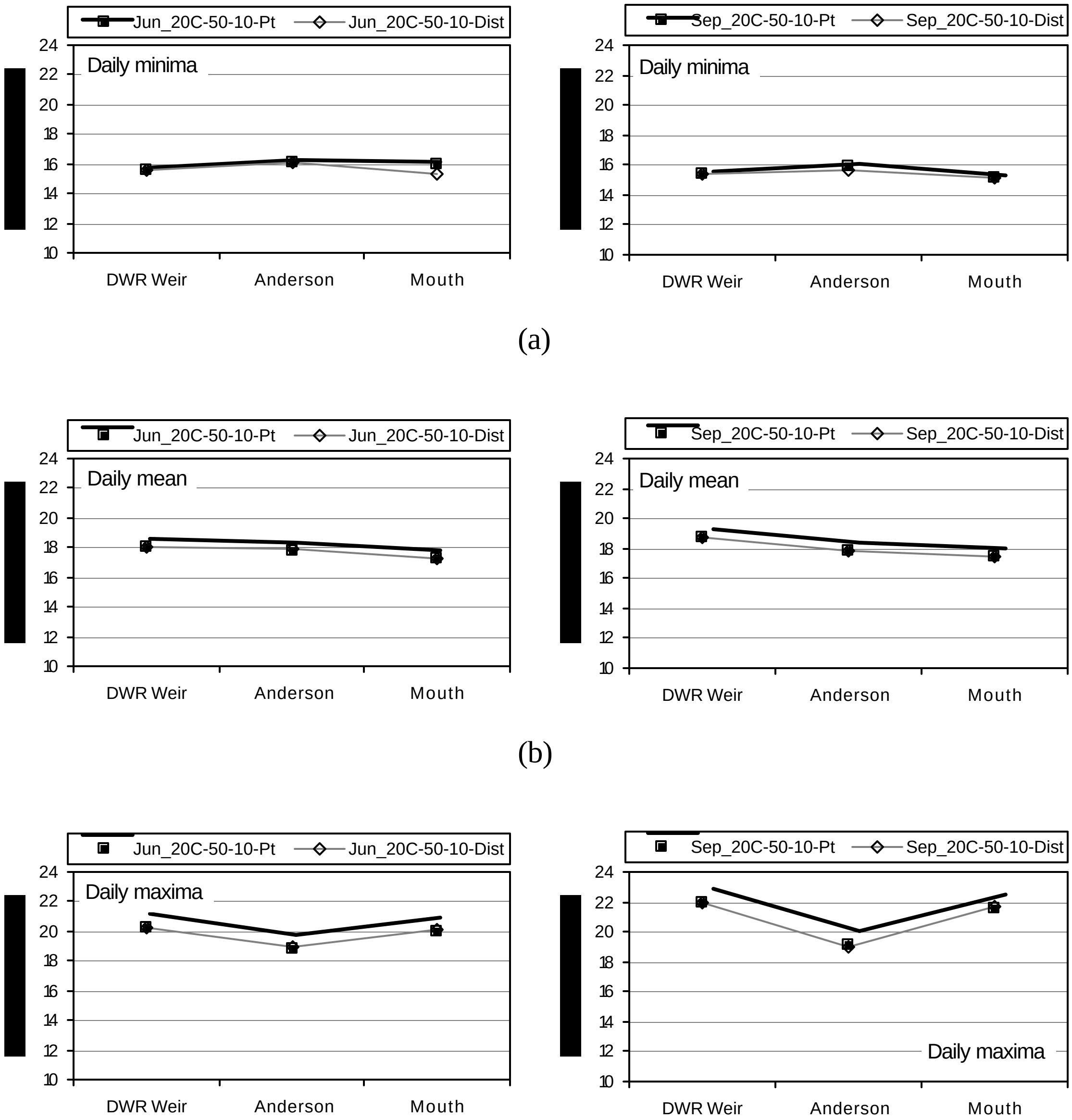
Figure 5-37 Tailwater Return Study 20°C-50-5 results for June and September. Upstream boundary condition of 20°C and 50 cfs at SRP, tailwater return flow of 5 cfs. Simulated (a) daily minimum, (b) daily average, and (c) daily maximum water temperature at DWR Weir, Anderson Grade Road, and the mouth of the Shasta River comparing point and distributed discharge of tailwater. Simulations designated by "month_upstream water temperature-upstream inflow-tailwater flow" (e.g. Sep_20C-50-5).



(a)

(b)

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Figure 5-38 Tailwater Return Study 20°C-50-10 results for June and September. Upstream boundary condition of 20°C and 50 cfs at SRP, tailwater return flow of 5 cfs. Simulated (a) daily minimum, (b) daily average, and (c) daily maximum water temperature at DWR Weir, Anderson Grade Road, and the mouth of the Shasta River comparing point and distributed discharge of tailwater. Simulations designated by "month_upstream water temperature-upstream inflow-tailwater flow" (e.g. Sep_20C-50-10).

5.5.5 Shading Reach-by-Reach

The shading reach-by-reach alternative was designed to determine the effects of re-vegetation on the temperature regime of the Shasta River on a reach-by-reach basis during different times of the year. In this study, shade associated with existing riparian vegetation was applied to the entire river to determine the base-case condition for the time of year. Then, shading from mature trees was added to each reach of the river in turn. Only one reach was shaded with the re-vegetated growth at a time. Re-vegetated shade was represented by barrier heights of 22 feet on each bank of the river. Results are compared to base-case simulations of river temperatures for each of the three study periods.

Results of this study are shown in the following Figure 5-39 through Figure 5-41. As in the presentation of flow regime study results, results of each simulation are presented as deviations from the base-case. Base-case simulations were the same as those used in the flow regime study. Generally, shading always decreased all downstream temperatures. But the effects on mean daily temperatures were generally modest (mean= -0.29°C, CV=-0.75). As with added inflow, the effect of increased shading was most dramatic on maximum river temperatures. Maximum temperatures were reduced in downstream reaches as a result of shading in upstream reaches, but the effect was only significant in the first two reaches downstream from where additional riparian shading was provided. Reduction in maximum temperatures were most noticeable (i.e. >0.5°C) in August. Shading of Reach 5 (the most downstream reach) in August resulting in a lowering of water temperature at the mouth of 2.7°C. Shading also generally dropped minimum temperatures downstream, but this effect was only noticeable in August and September. Interestingly, the largest drop in minimum temperature (-1.2°C) occurred at the mouth when Reach 3 was shaded in August. This result is presumed to be associated with the analysis assumptions of steady flow boundary condition, temperature boundary conditions, stable meteorological conditions, and advective properties of the system.

June

The impact of shading individual reaches had little impact on maximum, mean, or minimum temperatures. This is probably due to the moderate water temperature conditions in the river during the selected week of study. As note in the flow regime alternative, mean daily river temperatures were fairly cool, between 15°C and 17°C and the river was cooling in the downstream direction. Additional shading under such circumstances would provide little additional benefit.

August

August conditions in the river were somewhat different than June. The river was significantly warmer and the system was typically gaining heat in the downstream directions. In upstream reaches where accretions from spring flow maintains cooler water temperatures (e.g., above A12), the addition of riparian vegetation provided only modest benefit locally and did not measurably improve conditions far downstream.

However, in downstream reaches where mean daily water temperatures rose from 20°C at A12 to 25°C at MOU (and were closer to equilibrium temperature), riparian shading had a larger impact, but again, somewhat local. Careful examination of the daily mean and maximum temperature change show that while riparian vegetation provided relief within and immediately downstream of the shaded reach, water temperatures quickly rose back to baseline levels over the distance of the next reach or two.

September

Although the thermal regime of the Shasta River in September was similar to June, the response of the river system to shading was more marked. Maximum, mean, and minimum water temperatures all illustrated reductions to shading. The main difference was probably due to the time of year and concomitant reduced solar altitude and shorter day length. The lower solar altitude would result in more efficient shading of the stream by riparian vegetation compared to the June period wherein the solar altitude and day length were nearly at the annual maximum. Further, in late September the shortening day length results in a lower equilibrium temperature for the river than that which occurred in June. Reaches experiencing water temperatures near equilibrium temperature benefited from riparian vegetation shading more than reaches where water temperatures were lower. This is most clearly seen in the figure presenting deviations from maximum daily water temperatures.

Summary

Reach by reach riparian vegetation restoration simulations illustrated insight into the thermal characteristics of the Shasta River and how conditions vary along its length, including:

- Riparian vegetation shading can potentially reduce mean, and particularly maximum daily, temperatures over the distance of a single reach (five to seven miles).
- Where water temperatures were closer to equilibrium conditions (e.g., away from cool spring inflow influences) riparian vegetation had a more noticeable affect. This does not discount the importance of riparian vegetation in cool water areas.
- In general, the reduction in water temperature from a restored condition does not persist more than a reach or two downstream.
- Time of year and solar altitude play a role in ability of riparian vegetation to reduce incoming solar radiation, thus affecting the thermal regime of the river.

One important factor in this analysis is the distribution of riparian vegetation in the base line condition. The reader is encouraged to review previous sections of this report, as well as to refer to the USFWS (Abbott and Deas, 2003) report to become familiar with longitudinal variation in vegetation. Certain reaches have appreciably more vegetation than others. The addition of shade providing vegetation to reaches where there is very little existing vegetation can produce a different thermal response than when additional vegetation is added to reaches that have more appreciable quantities.

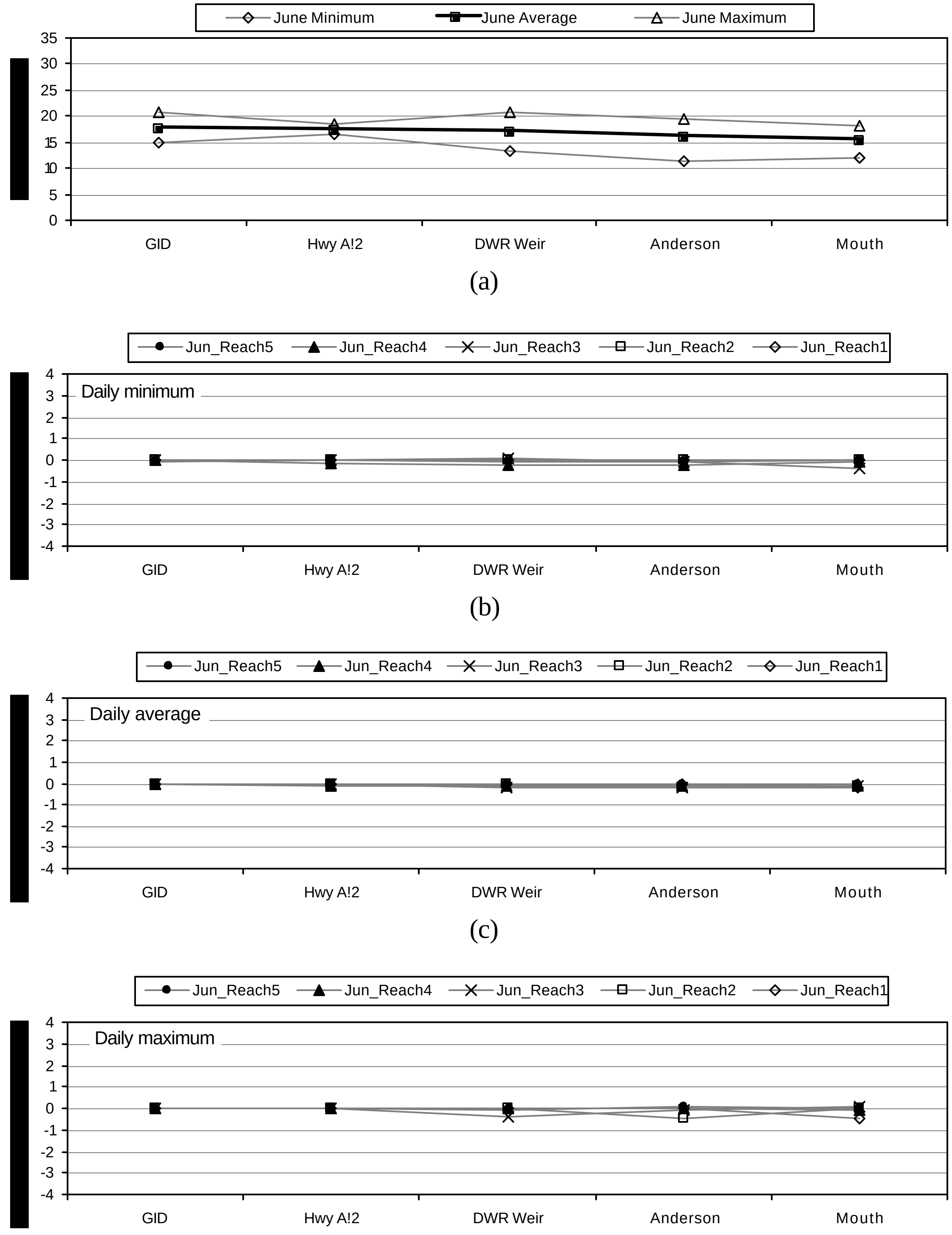

Figure 5-39 Shadinge Study results for June. Deviations from (a) June base-case condition in (b) daily minima, (c) daily average, and (d) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.

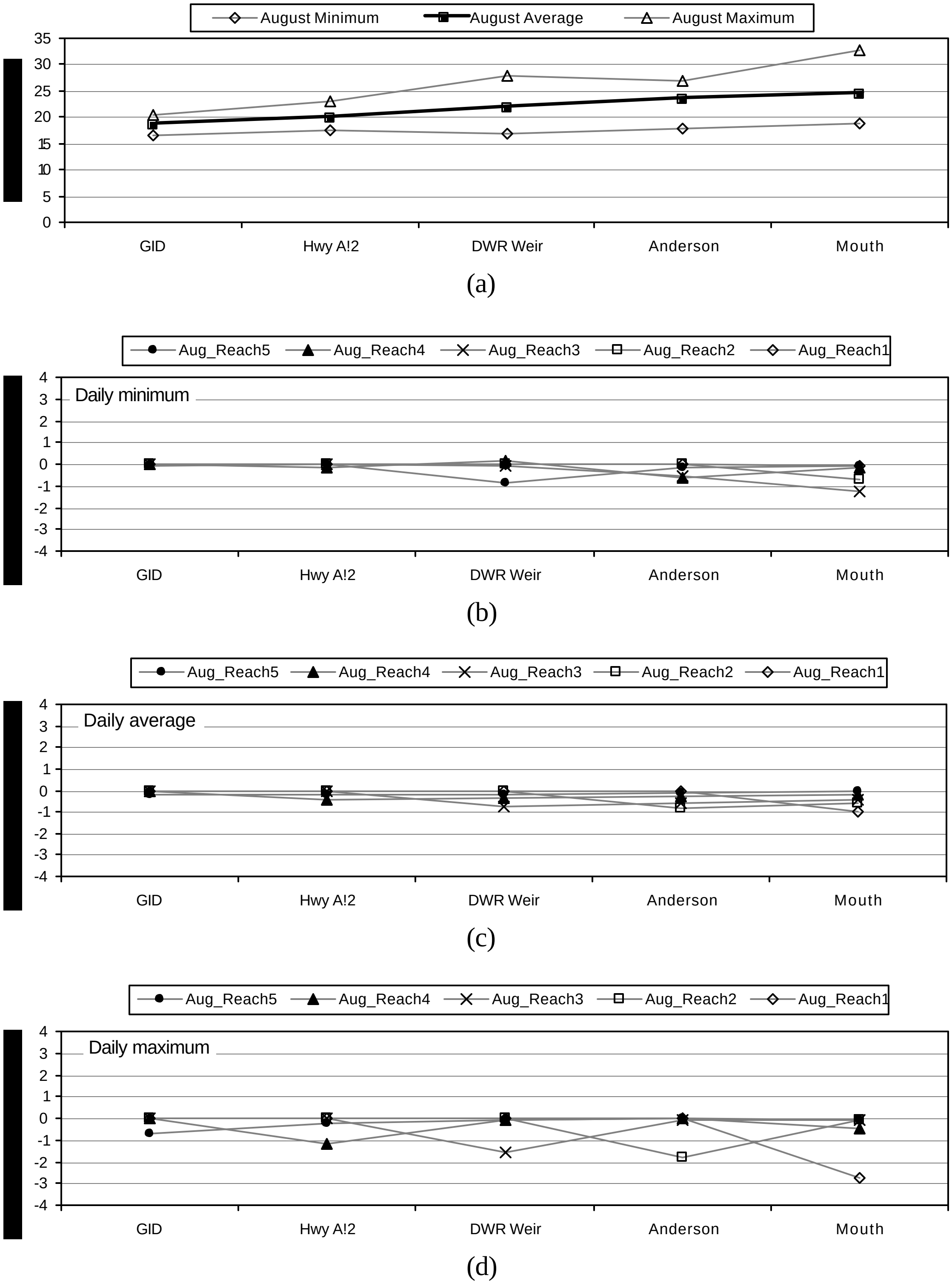

Figure 5-40 Shadinge Study results for August. Deviations from (a) August base-case condition in (b) daily minima, (c) daily average, and (d) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.

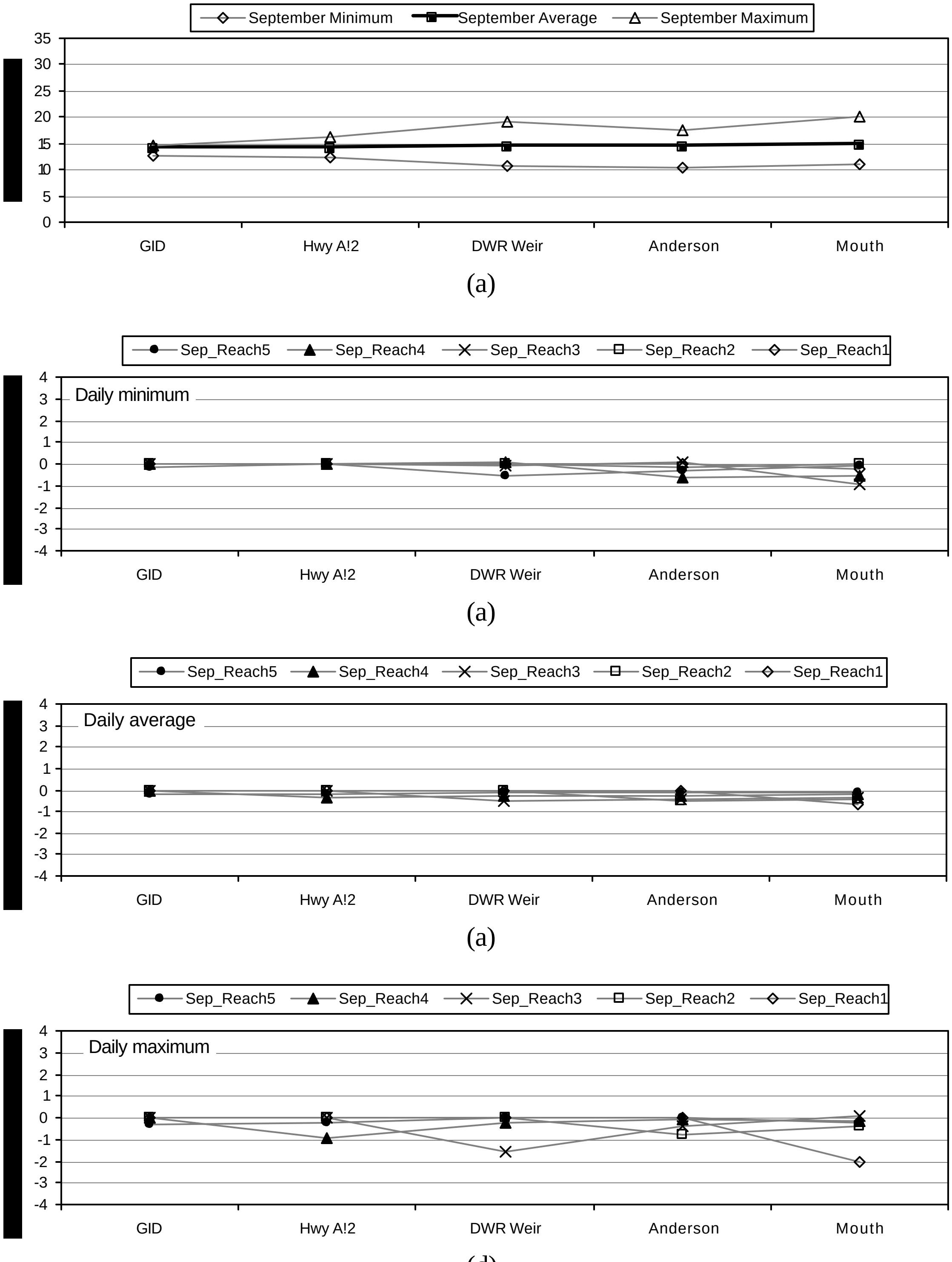

Figure 5-41 Shadinge Study results for September. Deviations from (a) September base-case condition in (b) daily minima, (c) daily average, and (d) daily maxima of simulated water temperature at GID, Hwy 12, DWR Weir, Anderson Grade Road, and the mouth of the Shasta River.

5.5.6 Additional Riparian Vegetation Management Analyses

Additional riparian vegetation management analyses had been completed during the life of the project. Although they were not formally part of the management alternatives developed above, the analysis did benefit from stakeholder involvement (both development and review). These studies augment the previously presented alternatives, providing additional information and insight into potential system response to riparian vegetation in the Shasta River basin.

5.5.6.1 Spatial and Temporal Riparian Vegetation Management Analysis

An initial modeling effort was completed early in the project to ascertain potential impacts of riparian vegetation on water temperatures in the Shasta River. Two concepts were addressed in these initial studies:

- The impact riparian vegetation shading conditions have on water temperature as riparian vegetation shading conditions change through time during potential restoration periods (temporal)
- The impact riparian vegetation shading conditions have on water temperature depending on location of riparian vegetation shading restoration efforts (spatial)

To determine the effect of various riparian vegetation scenarios on the Shasta River the data of the August 17th to August 23rd, 2001 period was used. Six day average maximum, mean, and minimum data were used to assess response. Each study will be discussed below.

Impact of Temporal Variation in Riparian Revegetation Restoration on Water Temperature

The concept of exploring temporal variation in riparian revegetation restoration efforts is borne out of the natural succession of vegetation types that would occur over a period of many years. With either active or passive measures, initially restoration would include colonization by wetland species such as sedges, grasses and rushes (e.g., bulrush). Ideally, these species would stabilize bank areas and after time give way to species such as willows, cottonwoods, and other woody riparian vegetation that could provide significant shading potential.

To provide insight on thermal conditions at the beginning, intermediate, and end point of a widespread riparian vegetation restoration effort, three simulations were completed to illustrate the current conditions, an intermediate point in time, and a final restored condition.

Current Condition

The current condition included riparian vegetation currently existing on the Shasta River.

Figure 5-42 is a plot of the longitudinal profile of river of 6-day average, minimum, and maximum simulated temperatures for the August 17th to 23rd simulation. From SRP to the Mouth there was an average temperature gain of approximately 4.4°C. The mean temperature at the Mouth was approximately 21.4°C, with a maximum temperature of about 30.0°C. The river is generally heating from upstream to downstream locations for this typical mid-summer flow and thermal regime. However, field observations and simulations of the Shasta River flow and water temperature suggest a complex relationship between flow and temperature along the system. The sharp decrease in temperature range at about RM 30 was likely due to the imposition of cool water accretions in the Big Springs Creek region. This increase in flow decreases transit time in downstream reaches and increases thermal mass – leading not only to maintenance of overall mean temperature, but a smaller diurnal range as well. The modest but abrupt increase in diurnal temperature range at approximately RM 17, was probably due to the decrease in flow and depths due to diversion.

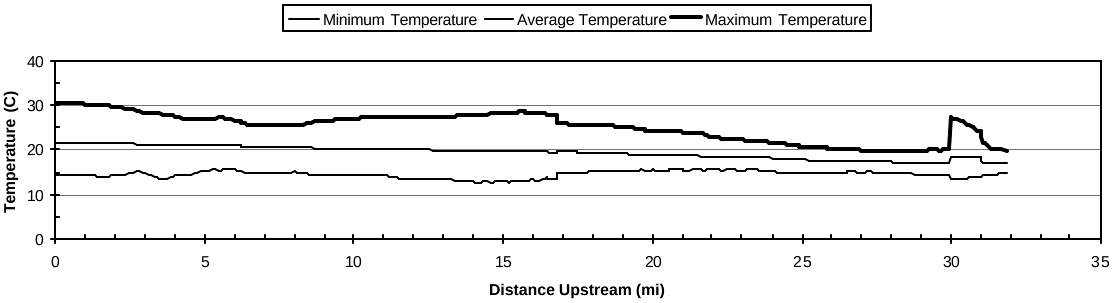

Figure 5-42 Simulated average, minimum, and maximum temperature at each node, Aug 17-Aug 23, 2001: current condition

Intermediate Restoration Potential

To represent an intermediate level of riparian vegetation restoration, it was assumed that bulrush would colonize areas currently devoid of woody riparian vegetation (existing vegetation was presumed to stay in place) over a period of several years. Based on field measurements (Abbott and Deas, 2003), bulrush could raise the maximum effective vegetation height to about 10 feet in the places where there is currently no vegetation. However, field measurements of both height and solar radiation identify that only 2/3 of the height of bulrush is effective at shading. Thus, an effective vegetation height of seven feet was applied. A vegetation transmittance value of 10 percent (vegetation reduces incoming solar radiation by 90 percent). Results of the simulation are shown in Figure 5-43.

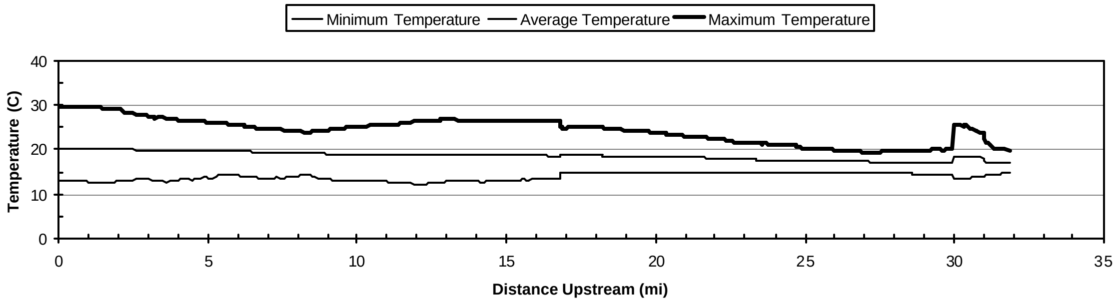

Figure 5-43 Simulated average, minimum, and maximum temperature at each node: Intermediate restoration potential

Results of this simulation suggest a total heat gain of about 3.2°C from SRP to the Mouth. The mean temperature at the Mouth is approximately 20.2°C, or about 1°C cooler than without bulrush providing shade. The maximum temperature at the Mouth is decreased from 30.2°C to 29.4°C, slightly less than a degree. It may not be feasible to attain complete colonization of all bank areas with bulrush; however even this very modest increase in shade – 7 foot high vegetation – produces a noticeable reduction water temperature. This finding suggests that herbaceous riparian vegetation should not be overlooked as a potential measure to reduce incoming solar radiation.

Mature Woody Riparian Vegetation

If riparian vegetation restoration were to occur throughout the study area it would likely be 10 to 20 years or more years before the trees were grown to full height and foliage. A simulation was completed wherein all areas currently devoid of vegetation were colonized by 22 foot high trees and a transmittance of 10 percent. Results of this simulation, shown in Figure 5-44, suggest that the overall mean daily temperature increase from SRP to the Mouth would be less than 1°C. The mean temperature at the Mouth is just over 17.0°C, with the maximum daily temperature at about 24.2°C. This simulation utilizes an extreme level of restoration that probably never have occurred naturally on the system, i.e., an optimal condition from SRP to the mouth that is probably not feasible (This point was addressed specifically in the incremental riparian vegetation shading shading analysis, below). Nonetheless, it does illustrate the potential of riparian vegetation to moderate and maintain water temperatures at lower levels than under current conditions.

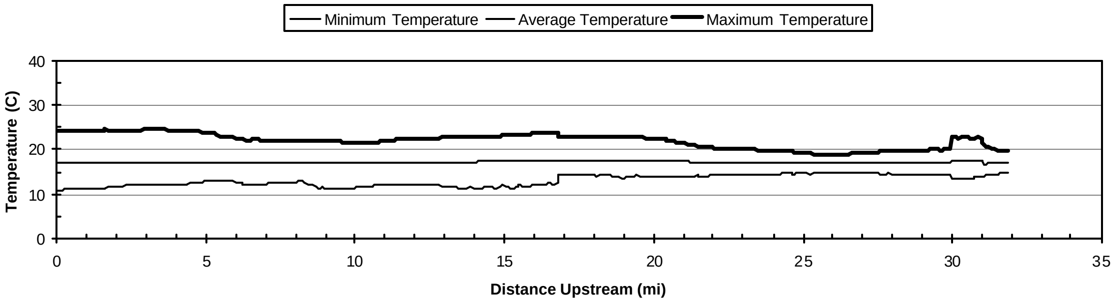

Figure 5-44 Simulated average, minimum, and maximum temperature at each node: fully shaded scenario (fully restored)

Impact of Spatial Variation in Riparian Revegetation Restoration on Water Temperature

It is likely that riparian vegetation restoration efforts would proceed in phases. To assess general response of river temperatures to different spatial patterns of riparian shading, two simulations were completed by essentially partitioning the restoration to roughly half of the river:

1) Upper River Restoration: full riparian vegetation restoration between RM 34 (SRP) and RM 17, with existing conditions from RM 17 to RM 0 (Mouth)

2) Lower River Restoration: existing conditions from RM 34 to RM 17, with full riparian vegetation restoration between RM 17 and RM 0

Tree height for full riparian vegetation restoration was assumed to be 22 feet with a transmittance of 10 percent. Figure 5-45 illustrates the longitudinal profile of river temperatures (maximum, average, and minimum) for the upper river restoration condition. Between RM 34 and RM 17 the reduction in solar radiation due to riparian vegetation shading resulted in retention of cool water down to RM 17, as well as moderated the diurnal range. Below RM 17 the river begins to increase in mean daily temperature. The diurnal range increases, but this is probably a combination of not only reduced riparian vegetation (back to the base case level), but also the result of the SWA diversion around RM 16.8 and the associated reduction in base flow. Compared with the base condition, the average temperature at the Mouth decreased from 21.4°C to 20.8°C, approximately 0.6°C, while the maximum temperature at the Mouth dropped from 31.2°C to 30.2°C, roughly 1.0°C.

Figure 5-46 illustrates the longitudinal profile of river temperatures for the lower river restoration condition. Between RM 17 and RM 0 the reduction in solar radiation due to riparian vegetation shading resulted in retention of cool water down to the Mouth, as well as moderated the diurnal range. Compared with the base condition, the average temperature at the Mouth decreased from 21.4°C to 19.7°C, approximately 1.5°C, while the maximum temperature at the Mouth dropped from 30.2°C to 28.3°C, roughly 2°C.

In sum, the upper river shading condition provided relief primarily to the upper river and immediate downstream reaches, but had only modest impact at the mouth. The lower river shading condition provided no reduction in temperatures above RM 17, but contributed more directly to reduction in average daily and maximum water temperatures at the mouth. Note, unlike volume changes addressed above in the flow regime studies, riparian shading served to potentially moderate diurnal range as well as reduce minimum daily temperatures. Additional flow volume generally reduced diurnal range through a reduction in daily maximum and increase in daily minimum, but had only modest affects on mean temperature.

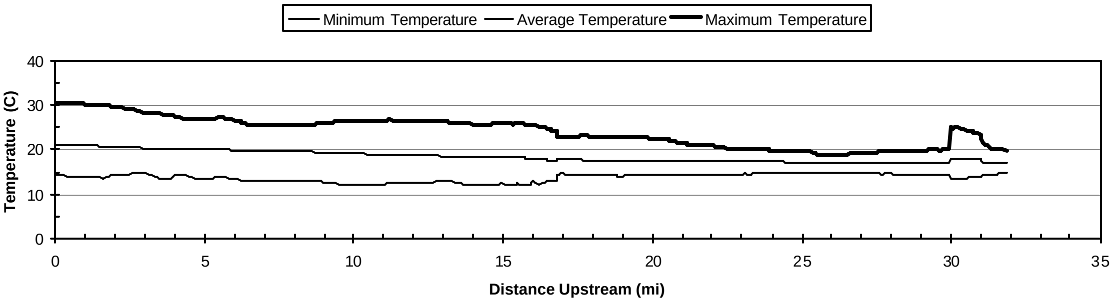

Figure 5-45 Simulated average, minimum, and maximum temperature: full riparian vegetation restoration between RM 34 and RM 17, with existing conditions from RM 17 to RM 0

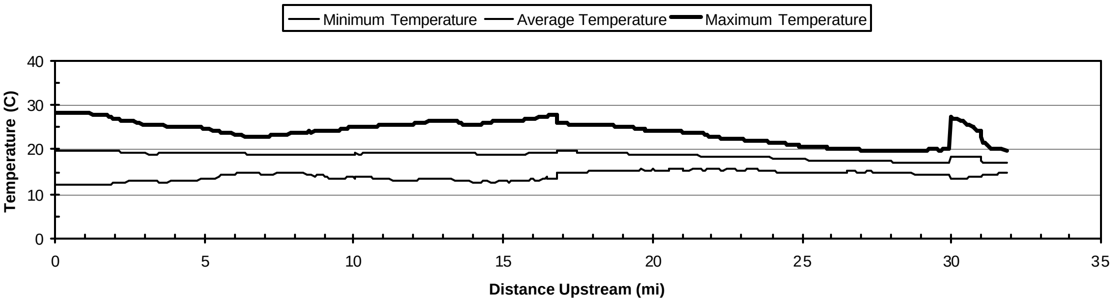

Figure 5-46 Simulated average, minimum, and maximum temperature at each node: downstream of SWA (RM 16.8) shaded

Summary

Riparian vegetation restoration does not produce short term results in terms of reduction in incoming solar radiation because it takes years for such efforts to return benefits. However, this analysis wherein existing conditions, intermediate and complete riparian restoration conditions were studies suggests that benefits may begin to manifest themselves well before mature woody riparian conditions are achieved. Table 5-7 presents mean and maximum temperatures and temperature gain from the upstream boundary (SRP) and at ten mile increments to the Mouth for all model simulations.

Table 5-7. Comparison of revegetation scenarios (all temperatures based on 6-day average, all values in °C)

Scenario	Location											
	Mouth			RM 10			RM 20			SRP		
	Mean	Max	Gain[a]	Mean	Max	Gain[a]	Mean	Max	Gain[a]	Mean	Max	Gain[a]
Base	21.4	31.2	4.4	20.2	27.3	3.2	18.9	24.6	1.9	17.0	19.9	0.0
Bulrush	20.2	29.4	3.2	19.0	25.4	2.0	18.4	23.6	1.4	17.0	19.9	0.0
Full Shade	17.1	24.2	0.1	17.1	22.4	0.1	17.1	22.2	0.1	17.0	19.9	0.0
Upper River	20.8	30.2	3.8	19.1	26.4	2.1	17.1	22.2	0.1	17.0	19.9	0.0
Lower River	19.7	28.3	2.7	19.0	25.1	2.0	18.9	24.6	1.9	17.0	19.9	0.0

[a] Gain is over the entire river reach from SRP to Mouth

Several points were illustrated through the spatial and temporal riparian vegetation management simulations, including:

- Riparian restoration efforts are long-term management approaches to moderating and/or reducing river temperatures. Model simulations can assist decision makers in management approaches to address potential spatial distribution of restoration, how long it may take to reach maturity and provide temperature control benefits, and what thermal relief intermediate conditions may provide.
- Herbaceous riparian vegetation (e.g., bulrush) can provide sufficient shade to affect water temperature if present in sufficient quantity (density and distribution) along the river bank.
- The lower river riparian restoration conditions showed a larger impact locally than the upper river riparian restoration conditions – probably because lower river reaches were closer to equilibrium temperature than cooler (spring influenced), upper river reaches.
- Riparian vegetation on small river systems such as the Shasta River plays an important role in reducing mean daily temperatures (as well as maximum and minimum). Further studies should be completed to determine the trade-off between flow volume and riparian shading to identify a “most favorable” combination of management actions to meet desired objectives.

5.5.6.2 Incremental Riparian Vegetation Shading Analysis

Introduction

During the project period a suite of model runs was completed to quantify the possible effects of incremental shading (i.e. reduction of incoming solar radiation due to woody riparian vegetation) on the thermal regime of the Shasta River. This section outlines the assumptions and results of this modeling analysis for increasing riparian shading in 0.5 mile increments along the river for a range of inflow quantities and water temperatures. These results were intended to provide insight into how much riparian vegetation may be necessary, in miles along the bank, to have an affect on stream temperatures.

Approach

To determine possible effects of incremental shading on the thermal regime of the Shasta River the following model assumptions were adopted:

1. Existing geometric representation of the Shasta River was used. (Specifically, the five-mile section used in this modeling exercise initiated at the upstream boundary (RM 31.8, Shasta above Parks) and extended five miles downstream to RM 26.8, just below the Grenada Irrigation District Pumps. This section was chosen as an illustration, however, the modeling exercise can be replicated anywhere in the system.)

2. The model parameters determined during the 2001 calibration of the Shasta River model were used.

3. For ease of interpretation steady-state flow regimes were chosen for this modeling exercise. This is used as an illustration and can be replicated with various flow regimes. The two steady-state flow regimes that were chosen for this modeling exercise were: 20 cfs, 50 cfs. These were chosen based on the range of potential flows during the summer of 2001. Running the model for two flow scenarios provided greater insight into system response in connection with the relationship between flow and temperature.

4. Two constant upstream inflow temperatures were applied to each flow regime: 15°C, 20°C. During the summer of 2001 typical inflow temperatures (based on observed temperatures at the model boundary at RM 31.8, Shasta above Parks Creek) ranged from 15°C to 23°C. Running the model with two upstream inflow temperatures provided greater insight into system thermal response.

5. Conservative vegetation parameters were chosen to simulate a modest level of revegetation. These values were determined based on input from local constituency representatives including CRMP staff, U.C. Extension, and California Department of Fish and Game.

   a. Tree height was chosen to be 22 feet (the average height of a Sandbar Willow based on summer 2001 fieldwork, the smallest measured species, refer to Abbott and Deas (2003) for the details of this field work).
   b. Transmittance was assumed to be approximately 50%. This value is calculated based on following assumptions:
      i. Vegetation consisted of 3 trees per 100 feet, where the width of a single tree canopy was approximately 2/3 of the total tree height. (These assumptions yielded approximately 50 feet of potential shade producing vegetation per 100 feet of river.)
      ii. Vegetation was equally distributed on the left and right bank (i.e., 3 trees per 100 feet of river on each bank).
      iii. From measured field data the vegetative transmittance of solar radiation was assigned a valued of 10% for shaded areas (i.e., 90% of the solar radiation was blocked by the vegetation).
      iv. Using a weighted average the overall transmittance of a reach with continuous vegetation was calculated.

6. Twenty-four hours of meteorological data from August 28, 2001 was used.
7. The effects of vegetative shading were simulated in 0.5-mile increments up to a total reach length of 5 miles.

Model Simulations and Results

Four model simulations were conducted: two at a flow regime of 20 cfs, and two at 50 cfs. The first simulation of each flow regime was assigned upstream inflow temperature of 15°C, whereas the second simulation of each flow regime was assigned an upstream inflow temperature of 20°C. Table 5-8 contains a list of the model simulations, associated conditions, and corresponding data tables in this document. For each simulation vegetative shading, as outlined above, was applied to the system in increments of 0.5 miles starting at the upstream boundary (RM 31.8) and continuing downstream for 5 miles. For each simulation the average daily water temperatures and the maximum daily water temperatures were determined from simulated hourly data. Each simulation is represented by four tables:

- Average Daily Water Temperatures
- Maximum Daily Water Temperatures
- Reduction in Average Daily Water Temperatures
- Reduction in Maximum Daily Water Temperatures.

A more detailed description of these tables will be presented after the discussion of the summary presented in Table 5-9.

Table 5-8 Summary of model simulation flows, upstream inflow temperatures, and associated data tables

Simulation	Flow (cfs)	Upstream Inflow Temperature (C)	Data Tables for Each Simulation
1	20	15	Table 5-10 to Table 5-13
2	20	20	Table 5-14 to Table 5-17
3	50	15	Table 5-18 to Table 5-21
4	50	20	Table 5-22 to Table 5-25

A summary of key findings of the model simulations has been tabulated (Table 5-9) from results presented in

to Table 5-25. This summary table contains the daily-average total heating (°C), as well as the daily average rates of heating (degrees Celsius per mile) for each simulation with (a) no shading and (b) with shading over the 5-mile river reach. When discussing the data found in Table 5-9 comparative analysis is used, hence the analysis focuses on relative differences, not absolute values.

Table 5-9 Total heating (°C) over 5 miles of the daily-average simulated water temperatures for the with shade and without shade cases and rates of heating for the daily-average simulated water temperatures (°C/mi) for the with shade and without shade cases

Simulation	Daily avg. total heating over 5 mi °C, (max T_W)						Daily Avg. Heating per mi (°C/mi)		
	W/O Shade			With Shade			W/O Shade	With Shade	?
	T_{RM5}	T_{RM0}	?	T_{RM5}	T_{RM0}	?			
1	17.6 (24.)	15.0 (15.0)	2.6 (9.0)	16.2 (20.9)	15.0 (15.0)	1.2 (4.9)	0.5	0.2	0.3
2	21.3 (27.0)	20.0 (20.0)	1.3 (7.0)	20.2 (24.1)	20.0 (20.)	0.2 (4.1)	0.3	0.0	0.3
3	16.5 (20.5)	15.0 (15.0)	1.5 (5.5)	15.8 (19.0)	15.0 (15.)	0.8 (4.0)	0.3	0.2	0.1
4	20.6 (24.8)	20.0 (20.0)	0.6 (4.8)	20.0 (23.4)	20.0 (20.0)	0.0 (3.4)	0.1	0.0	0.1

T_{RM5} = Water temperature five miles downstream from the upstream boundary
T_{RM0} = Water temperature at the upstream boundary
? = The change or difference between the two water temperatures or rates

Simulation 1: flow = 20 cfs, upstream inflow temperature = 15°C

For Simulation 1, as shown in Table 5-9, without shade the average daily temperature five miles downstream heated approximately 2.6°C, whereas with shade that same point heated 1.2 °C. The rate of heating over five miles of river without shade is approximately 0.5°C per mile. When shade was applied over the 5-mile reach, the rate of heating decreases to approximately 0.2°C per mile.

Simulation 2: flow = 20 cfs, upstream inflow temperature = 20°C

For Simulation 2, as shown in Table 5-9, without shade the average daily temperature five miles downstream heated approximately 1.3°C, whereas with shade that same point heated 0.2 °C. The rate of heating over five miles of river without shade was approximately 0.3°C per mile. When shade was applied over the 5-mile reach, the rate of heating decreased to less than a tenth of a degree Celsius per mile.

At the higher upstream inflow temperature the river did not heat as quickly as Simulation 1 due to the inflow temperature being closer to the equilibrium temperature* of the stream. (Rates of heating decrease as inflow temperatures approach equilibrium temperatures.) The difference in daily average heating rate with and without shading was similar for both upstream inflow temperatures: a reduction of 0.3°C/mile for Simulation 1, and 0.3°C/mile for Simulation 2.

Simulation 3: flow = 50 cfs, upstream inflow temperature = 15°C

The daily average heating rates for Simulations 3 & 4 are less than Simulations 1 & 2. This is due to the increased thermal mass and shorter transit time. (The transit time through the modeled section of river at 20 cfs is roughly 7 hours, while the transit time at 50 cfs is roughly 5 hours.) For Simulation 3, as shown in Table 5-9, without shade the average daily temperature five miles downstream heated approximately 1.5°C, whereas with shade that same point heated 0.8 °C. The rate of heating over five miles of river without shade was approximately 0.3°C per mile. When shade was applied to the 5-mile reach the rate of heating decreased to approximately 0.2°C per mile.

Simulation 4: flow = 50 cfs, upstream inflow temperature = 20°C

As shown in Table 5-9, Simulation 4, as with Simulation 2, did not heat as quickly as the simulations with lower inflow temperatures due to the close proximity to the equilibrium temperature of the river. Without shade the average daily temperature five miles downstream heated approximately 0.6°C, whereas with shade that same point did not

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* Equilibrium Temperature: water temperature at which the rate of heat leaving the fluid is exactly equal to the rate of heat entering the fluid. For these simulations equilibrium temperature is between about 22°C-24°C.

experience any net heating. The rate of heating over five miles of river without shade was approximately 0.1°C per mile. When shade was applied to the 5-mile reach there was no net heating of the river at the point.

As with Simulations 1 & 2, the rate reduction caused by shading was similar for both upstream inflow temperatures: a reduction of 0.1°C/mile for Simulation 3, and 0.1°C/mile for Simulation 4.

Findings

1. Under the "without shade" scenario the lower flow rate simulations (20 cfs) experienced higher heating rates than the higher flow rate simulations (50 cfs) due to decreased thermal mass and longer transit time through the reach.
2. Under the "with shade" scenario the lower flow rate simulations (20 cfs) experienced heating rates equal to that of the higher flow rate simulations (50 cfs) due to decreased incoming solar radiation.
3. For the assumptions stated in this study, simulations with upstream inflow temperatures far from equilibrium temperature (e.g. 15°C) experienced higher daily average rates of heating than those simulations with upstream inflow temperatures close to equilibrium temperature (e.g. 20°C).
4. For the assumptions stated in this study, under the "without shade" scenario flow has a pronounced effect on the average daily rates of heating. However, under the "with shade" scenario the effect of flow is not appreciable. Suggesting that the upstream inflow temperatures play a larger role in determining the average daily rates of heating when incoming solar radiation is appreciably reduced, i.e., shading in place.

Whereas the above findings provide valuable insight into the relationships between flow, solar radiation as altered by vegetative shading, and water temperature in the Shasta River this is only a brief illustration of how the Shasta River Flow and Water Temperature model can be used. The same exercise can be conducted on different reaches of the system, with different steady-state or dynamic flow regimes and various shading scenarios.

Data Tables and Interpretation

This section contains four data tables for each of the four simulations. The first two tables for each simulation represent the daily average and daily maximum water temperatures throughout the 5-mile reach. Moving from top to bottom the table rows present water temperature at 0.5-mile increments in the downstream direction for various longitudinal shading in increments of 0.5 mi, 1.0 mi, 1.5 mi, etc. (columns). Although these tables provide the necessary information to assess the impacts of vegetative shading it is easier to identify effects by comparing each simulation with the "no shade" scenario. The second two tables of each simulation present this information in a similar format for daily average and daily maximum temperatures, respectively. The diagonal entries (shown in bold) illustrate the extent of temperature reduction at 0.5-mile increments downstream. All temperatures are reported in °C. A brief discussion is presented for each set of tables.

Simulation 1: Flow = 20 cfs, Upstream Inflow Temperature = 15°C

Figure 5-12 suggests that under the assumed shading conditions, riparian vegetation would contribute on the order of about 0.3°C reduction in water temperatures per mile when compared with a "no shade" scenario for a steady state flow of 20 cfs and an upstream inflow temperature of about 15°C. Figure 5-13 indicates that maximum daily water temperatures were also reduced under the assumed shading conditions for a total reduction over 5 miles of about 3.1°C.

Simulation 2: Flow = 20 cfs, Upstream Inflow Temperature = 20°C

Table 5-16 illustrates that for an upstream inflow temperature of 20°C at a flow of 20 cfs for every mile of shading the water temperature was reduced by approximately 0.3°C, for a total reduction of 1.1°C at 5 miles of shading. As expected shading does not have as large an impact on warmer water temperatures because the temperature is closer to equilibrium temperature, thereby producing a slower rate of heating. Table 5-17 illustrates that the maximum daily water temperatures were also reduced under the assumed conditions for a total reduction over 5 miles of about 2.9°C.

Simulation 3: Flow = 50 cfs, Upstream Inflow Temperature = 15°C

Shading had less of an impact for the larger flow regime of 50 cfs. Table 5-20 illustrates that for an upstream inflow temperature of 15°C at a flow of 50 cfs for every mile of shading the water temperature was reduced by approximately 0.1°C for a total reduction of 0.7°C with 5 miles of shading. Table 5-21 indicates that the maximum daily water temperatures were also reduced under the conditions for a total reduction over 5 miles of about 1.5°C.

Simulation 4: Flow = 50 cfs, Upstream Inflow Temperature = 20°C

Similar to Simulation 3, for every mile of shading the water temperature was reduced by 0.1°C for a total reduction over 5 miles of 0.6 °C (see Table 5-24). As in Simulation 3, the maximum daily water temperatures were also reduced under the assumed conditions for a total reduction over 5 miles of about 1.5°C (see Table 5-25).

Table 5-10 Average daily simulated water temperatures for 20 cfs steady-state flow with a constant upstream boundary condition of 15°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
	0.5	15.3	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
	1.0	15.6	15.4	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
	1.5	15.8	15.7	15.5	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4
	2.0	16.1	16.0	15.8	15.7	15.5	15.5	15.5	15.5	15.5	15.5	15.5
	2.5	16.4	16.2	16.1	15.9	15.7	15.6	15.6	15.6	15.6	15.6	15.6
	3.0	16.6	16.5	16.4	16.2	16.1	15.9	15.7	15.7	15.7	15.7	15.7
	3.5	16.9	16.7	16.6	16.5	16.3	16.2	16.0	15.8	15.8	15.8	15.8
	4.0	17.1	17.0	16.8	16.7	16.6	16.4	16.2	16.1	15.9	15.9	15.9
	4.5	17.3	17.2	17.1	17.0	16.8	16.7	16.5	16.4	16.2	16.1	16.1
	5.0	17.6	17.5	17.4	17.3	17.1	17.0	16.8	16.7	16.6	16.4	16.2

Table 5-11 Maximum daily simulated water temperatures for 20 cfs steady-state flow with a constant upstream boundary condition of 15°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
	0.5	16.1	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9
	1.0	17.3	17.1	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
	1.5	18.2	17.9	17.7	17.4	17.4	17.4	17.4	17.4	17.4	17.4	17.4
	2.0	19.3	19.1	18.8	18.6	18.1	18.1	18.1	18.1	18.1	18.1	18.1
	2.5	20.2	20.0	19.8	19.6	19.1	18.7	18.7	18.7	18.7	18.7	18.7
	3.0	21.2	21.0	20.8	20.6	20.1	19.7	19.0	19.0	19.0	19.0	19.0
	3.5	22.0	21.7	21.6	21.4	21.0	20.6	19.9	19.4	19.4	19.4	19.4
	4.0	22.7	22.4	22.2	22.0	21.6	21.3	20.8	20.4	19.9	19.9	19.9
	4.5	23.4	23.1	22.9	22.6	22.3	22.0	21.8	21.4	20.9	20.5	20.5
	5.0	24.0	23.7	23.5	23.3	23.0	22.7	22.5	22.4	21.9	21.4	20.9

Table 5-12 Reduction in average daily simulated water temperatures for 20 cfs steady-state flow with a constant upstream boundary condition of 15°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.5		**0.2**	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	1.0			**0.3**	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	1.5				**0.5**	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	2.0					**0.6**	0.6	0.6	0.6	0.6	0.6	0.6
	2.5						**0.8**	0.8	0.8	0.8	0.8	0.8
	3.0							**0.9**	0.9	0.9	0.9	0.9
	3.5								**1.0**	1.0	1.0	1.0
	4.0									**1.2**	1.2	1.2
	4.5										**1.3**	1.3
	5.0											**1.4**

Table 5-13 Reduction in maximum daily simulated water temperatures for 20 cfs steady-state flow with a steady upstream boundary condition of 15°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.5		**0.2**	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	1.0			**0.5**	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	1.5				**0.7**	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	2.0					**1.2**	1.2	1.2	1.2	1.2	1.2	1.2
	2.5						**1.6**	1.6	1.6	1.6	1.6	1.6
	3.0							**2.2**	2.2	2.2	2.2	2.2
	3.5								**2.6**	2.6	2.6	2.6
	4.0									**2.9**	2.9	2.9
	4.5										**2.9**	2.9
	5.0											**3.1**

Table 5-14 Average daily simulated water temperatures for 20 cfs steady-state flow with a constant upstream boundary condition of 20°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	0.5	20.2	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	1.0	20.3	20.2	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1
	1.5	20.5	20.3	20.2	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1
	2.0	20.6	20.5	20.4	20.3	20.1	20.1	20.1	20.1	20.1	20.1	20.1
	2.5	20.7	20.6	20.5	20.4	20.2	20.1	20.1	20.1	20.1	20.1	20.1
	3.0	20.9	20.8	20.6	20.6	20.4	20.3	20.1	20.1	20.1	20.1	20.1
	3.5	21.0	20.9	20.8	20.7	20.5	20.4	20.3	20.2	20.2	20.2	20.2
	4.0	21.1	21.0	20.9	20.8	20.7	20.5	20.4	20.3	20.1	20.1	20.1
	4.5	21.2	21.1	21.0	20.9	20.8	20.7	20.6	20.5	20.3	20.2	20.2
	5.0	21.3	21.2	21.1	21.1	20.9	20.8	20.7	20.6	20.5	20.3	20.2

Table 5-15 Maximum daily simulated water temperatures for 20 cfs steady-state flow with a constant upstream boundary condition of 20°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	0.5	20.9	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7
	1.0	21.9	21.7	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4
	1.5	22.6	22.4	22.2	21.9	21.9	21.9	21.9	21.9	21.9	21.9	21.9
	2.0	23.5	23.3	23.1	22.9	22.4	22.4	22.4	22.4	22.4	22.4	22.4
	2.5	24.3	24.0	23.9	23.7	23.2	22.8	22.8	22.8	22.8	22.8	22.8
	3.0	25.0	24.8	24.6	24.4	23.9	23.5	22.9	22.9	22.9	22.9	22.9
	3.5	25.6	25.4	25.2	25.0	24.6	24.2	23.6	23.2	23.2	23.2	23.2
	4.0	26.2	25.9	25.7	25.5	25.1	24.8	24.3	24.0	23.5	23.5	23.5
	4.5	26.6	26.4	26.2	26.0	25.7	25.3	25.1	24.8	24.3	24.0	24.0
	5.0	27.0	26.8	26.6	26.5	26.2	25.9	25.7	25.5	25.1	24.6	24.1

Table 5-16 Reduction in average daily simulated water temperatures for 20 cfs steady-state flow with a constant upstream boundary condition of 20°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.5		**0.1**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1.0			**0.3**	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	1.5				**0.4**	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	2.0					**0.5**	0.5	0.5	0.5	0.5	0.5	0.5
	2.5						**0.6**	0.6	0.6	0.6	0.6	0.6
	3.0							**0.7**	0.7	0.7	0.7	0.7
	3.5								**0.8**	0.8	0.8	0.8
	4.0									**0.9**	0.9	0.9
	4.5										**1.0**	1.0
	5.0											**1.1**

Table 5-17 Reduction in maximum daily simulated water temperatures for 20 cfs steady-state flow with a steady upstream boundary condition of 20°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	0.5mi	1mi	1.5mi	2mi	2.5mi	3mi	3.5mi	4mi	4.5mi	5mi
Distance Downstream (mi)	0.0	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.5		**0.2**	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	1.0			**0.5**	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	1.5				**0.7**	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	2.0					**1.2**	1.2	1.2	1.2	1.2	1.2	1.2
	2.5						**1.6**	1.6	1.6	1.6	1.6	1.6
	3.0							**2.1**	2.1	2.1	2.1	2.1
	3.5								**2.5**	2.5	2.5	2.5
	4.0									**2.7**	2.7	2.7
	4.5										**2.7**	2.7
	5.0											**2.9**

Table 5-18 Average daily simulated water temperatures for 50 cfs steady-state flow with a constant upstream boundary condition of 15°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
	0.5	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
	1.0	15.3	15.2	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
	1.5	15.4	15.3	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
	2.0	15.5	15.5	15.4	15.3	15.2	15.2	15.2	15.2	15.2	15.2	15.2
	2.5	15.7	15.6	15.5	15.5	15.4	15.3	15.3	15.3	15.3	15.3	15.3
	3.0	15.9	15.8	15.7	15.7	15.6	15.5	15.4	15.4	15.4	15.4	15.4
	3.5	16.0	15.9	15.9	15.8	15.7	15.7	15.6	15.5	15.5	15.5	15.5
	4.0	16.2	16.1	16.0	16.0	15.9	15.8	15.7	15.7	15.6	15.6	15.6
	4.5	16.3	16.3	16.2	16.2	16.1	16.0	15.9	15.8	15.8	15.7	15.7
	5.0	16.5	16.4	16.4	16.3	16.3	16.2	16.1	16.0	15.9	15.9	15.8

Table 5-19 Maximum daily simulated water temperatures for 50 cfs steady-state flow with a constant upstream boundary condition of 15°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	0.5mi	1mi	1.5mi	2mi	2.5mi	3mi	3.5mi	4mi	4.5mi	5mi
Distance Downstream (mi)	0.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
	0.5	15.5	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4
	1.0	16.0	15.9	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8	15.8
	1.5	16.4	16.3	16.2	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
	2.0	17.0	16.9	16.8	16.7	16.5	16.5	16.5	16.5	16.5	16.5	16.5
	2.5	17.6	17.5	17.4	17.3	17.1	16.9	16.9	16.9	16.9	16.9	16.9
	3.0	18.3	18.2	18.1	18.1	17.9	17.7	17.4	17.4	17.4	17.4	17.4
	3.5	18.8	18.7	18.6	18.5	18.3	18.2	18.0	17.8	17.8	17.8	17.8
	4.0	19.3	19.2	19.2	19.1	18.9	18.8	18.6	18.4	18.2	18.2	18.2
	4.5	19.9	19.8	19.7	19.7	19.5	19.4	19.2	19.0	18.8	18.6	18.6
	5.0	20.5	20.4	20.3	20.2	20.1	19.9	19.8	19.7	19.5	19.3	19.0

Table 5-20 Reduction in average daily simulated water temperatures for 50 cfs steady-state flow with a constant upstream boundary condition of 15°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.5		**0.1**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1.0			**0.1**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1.5				**0.2**	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	2.0					**0.3**	0.3	0.3	0.3	0.3	0.3	0.3
	2.5						**0.4**	0.4	0.4	0.4	0.4	0.4
	3.0							**0.4**	0.4	0.4	0.4	0.4
	3.5								**0.5**	0.5	0.5	0.5
	4.0									**0.6**	0.6	0.6
	4.5										**0.7**	0.7
	5.0											**0.7**

Table 5-21 Reduction in maximum daily simulated water temperatures for 50 cfs steady-state flow with a steady upstream boundary condition of 15°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.5		**0.1**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1.0			**0.2**	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	1.5				**0.3**	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	2.0					**0.4**	0.4	0.4	0.4	0.4	0.4	0.4
	2.5						**0.6**	0.6	0.6	0.6	0.6	0.6
	3.0							**0.9**	0.9	0.9	0.9	0.9
	3.5								**1.0**	1.0	1.0	1.0
	4.0									**1.2**	1.2	1.2
	4.5										**1.4**	1.4
	5.0											**1.5**

Table 5-22 Average daily simulated water temperatures for 50 cfs steady-state flow with a constant upstream boundary condition of 20°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	0.5	20.1	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	1.0	20.1	20.1	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	1.5	20.2	20.1	20.1	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	2.0	20.2	20.2	20.1	20.1	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	2.5	20.3	20.3	20.2	20.1	20.1	20.0	20.0	20.0	20.0	20.0	20.0
	3.0	20.4	20.3	20.3	20.2	20.2	20.1	20.0	20.0	20.0	20.0	20.0
	3.5	20.4	20.4	20.3	20.3	20.2	20.2	20.1	20.0	20.0	20.0	20.0
	4.0	20.5	20.5	20.4	20.4	20.3	20.2	20.2	20.1	20.0	20.0	20.0
	4.5	20.6	20.5	20.5	20.4	20.4	20.3	20.2	20.2	20.1	20.0	20.0
	5.0	20.6	20.6	20.5	20.5	20.4	20.4	20.3	20.3	20.2	20.1	20.0

Table 5-23 Maximum daily simulated water temperatures for 50 cfs steady-state flow with a constant upstream boundary condition of 20°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
	0.5	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9
	1.0	21.1	21.0	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9	20.9
	1.5	21.4	21.3	21.1	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
	2.0	21.8	21.7	21.7	21.6	21.4	21.4	21.4	21.4	21.4	21.4	21.4
	2.5	22.3	22.3	22.2	22.1	21.8	21.7	21.7	21.7	21.7	21.7	21.7
	3.0	22.9	22.8	22.7	22.6	22.3	22.2	22.0	22.0	22.0	22.0	22.0
	3.5	23.3	23.2	23.1	23.0	22.8	22.7	22.6	22.5	22.5	22.5	22.5
	4.0	23.8	23.7	23.6	23.5	23.3	23.2	23.1	22.9	22.7	22.7	22.7
	4.5	24.2	24.1	24.0	23.9	23.8	23.6	23.5	23.4	23.2	23.0	23.0
	5.0	24.8	24.7	24.6	24.5	24.4	24.2	24.2	24.0	23.8	23.6	23.4

Table 5-24 Reduction in average daily simulated water temperatures for 50 cfs steady-state flow with a constant upstream boundary condition of 20°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.5		**0.1**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1.0			**0.1**	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1.5				**0.2**	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	2.0					**0.2**	0.2	0.2	0.2	0.2	0.2	0.2
	2.5						**0.3**	0.3	0.3	0.3	0.3	0.3
	3.0							**0.4**	0.4	0.4	0.4	0.4
	3.5								**0.4**	0.4	0.4	0.4
	4.0									**0.5**	0.5	0.5
	4.5										**0.5**	0.5
	5.0											**0.6**

Table 5-25 Reduction in maximum daily simulated water temperatures for 50 cfs steady-state flow with a steady upstream boundary condition of 20°C with shade applied in 0.5 mile increments, Aug. 28, 2001 meteorological conditions

		Distance vegetative shading extends downstream										
		No Shade	**0.5mi**	**1mi**	**1.5mi**	**2mi**	**2.5mi**	**3mi**	**3.5mi**	**4mi**	**4.5mi**	**5mi**
Distance Downstream (mi)	**0.0**	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.5		**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1.0			**0.2**	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	1.5				**0.4**	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	2.0					**0.4**	0.4	0.4	0.4	0.4	0.4	0.4
	2.5						**0.7**	0.7	0.7	0.7	0.7	0.7
	3.0							**0.9**	0.9	0.9	0.9	0.9
	3.5								**0.8**	0.8	0.8	0.8
	4.0									**1.1**	1.1	1.1
	4.5										**1.2**	1.2
	5.0											**1.5**

6.0 Findings and Recommendations

6.1 Findings

Through the implementation and application of a set of flow and temperature models several relationships between flow, variable flow patterns, tail water return distribution and riparian vegetation shading conditions. The principal findings are identified below.

- Advection, the physical transport of thermal energy downstream is an important consideration in the Shasta River. The transport of water from upstream

- Additional volume of water generally translates to a reduction in the diurnal range in temperatures, i.e., lower daily maximum and higher daily minimum temperatures. Mean daily temperature may show some reduction over longer reaches of river due to increased flows, especially if upstream sources are cooler.

- Identifying the reach or reaches with the largest heat gain (e.g. °C per mile) provides insight into the locations where the greatest opportunity for decreasing mean daily temperature through increased flow exists.

- Pulse flows affect the water temperature through increase stream volume and reduction in transit time. The model effectively routed these transient flow conditions through the system. However, the thermal benefit is uncertain, primarily due to a lack of biological data relating changes in thermal regime to outmigrating salmonids

- Water temperature conditions should be monitored prior to and during the pulse flow to ensure water temperature conditions are conducive to the operation. For example if releases from Dwinnell Dam (Lake Shastina) are inordinately warm, it may be more beneficial to not use that water in the pulse operation.

- Sequential pulse flow operations and simultaneous pulse flow operations showed modest differences in thermal regime. There are probably more pressing issues associated with the pulse flow than timing of diversions are shut down, such as meteorological conditions at the time of the pulse, the available flow, the time that all diversions are shut down in the simultaneous operation (morning better than evening), and ramping flows up and down in a manner that is beneficial to the objective of encouraging juvenile fish to move out.

- The amount, distribution, location, and temperature of return flow can impact the thermal regime of the river. The impacts for a single reach may be modest. The impacts of a system wide program were not analyzed.
- Riparian vegetation shading can potentially reduce minimum, mean, and particularly maximum daily, temperatures over the distance of a single reach (five to seven miles).
- Where water temperatures were closer to equilibrium conditions (e.g., away from

cool spring inflow influences) riparian vegetation had a more noticeable affect. This does not discount the importance of riparian vegetation in cool water areas.

- In general, the reduction in water temperature from a restored riparian vegetation condition does not persist more than several miles downstream (applicable to conditions where downstream reaches are not restored).
- Time of year and solar altitude play a role in ability of riparian vegetation to reduce incoming solar radiation, thus affecting the thermal regime of the river.
- Riparian restoration efforts are long-term management approaches to moderating and/or reducing river temperatures. Model simulations can assist decision makers in management approaches to address potential spatial distribution of restoration, how long it may take to reach maturity and provide temperature control benefits, and what thermal relief intermediate conditions may provide.
- Herbaceous riparian vegetation (e.g., bulrush) can provide sufficient shade to affect water temperature if present in sufficient quantity (density and distribution) along the river bank.
- Riparian vegetation on small river systems such as the Shasta River plays an important role in reducing mean daily temperatures (as well as maximum and minimum). Further studies should be completed to determine the trade-off between flow volume, riparian shading, and return flow management for various reaches of the Shasta River to identify a “most favorable” combination of management actions to meet desired objectives.

6.2 Recommendations

The developed models, as well as supporting data, have provided constructive insight into flow, temperature, and riparian vegetation shading inter-relationships. Not only have potential effects been identified, but the potential magnitude of temperature changes associated with various management strategies have been identified for locations specific to the Shasta River. The principal recommendation is to build upon the findings herein and apply the model to a broader set of alternatives – possibly combinations of certain management strategies identified herein.

Although further application of the models is the principal recommendation, additional recommendations were identified. As with most investigative studies, an appreciable amount of information and knowledge was gained during the project. This information and knowledge provided a new perspective on many aspects of the Shasta River system, and specific items were recognized as beyond the scope of the current work but worthy of further consideration. These items form the recommendations outlined below.

- River geometric data, principally cross section data, could be improved for the Shasta River flow and temperature model. Although field measurements were made to secure the information, a more comprehensive effort would provide more detailed representation in certain reaches.
  Recommendation: identify funding sources to support additional collection of

field data to refine the geometric representation of the flow and temperature models. Seek to collect data system wide.

- Accretions and depletions were estimated on a reach-by-reach basis using flow data from seasonal gages placed at the top and bottom of each reach. This proved to be useful, but certain reaches include several outflows (e.g., diversions) and/or inflows (e.g., return flows, springs, tributaries). System inflows are distributed non-uniformly along the river. Further, they experience variable flow rates magnitude and timing) and enter at various temperatures. Currently, the details of such inflows and outflows are not well characterized, but potentially play a critical role in the long-term management of the Shasta River.
  Recommendation: Complete a pilot study, for a representative reach or area to identify the various modes at which water may enter the river (e.g., groundwater, diffuse surface flow, localized inflow), quantity of inflow, and temperature associated with each type of source. These data can then be entered into the flow and temperature model to assess potential impacts of managing these various sources.

- Bed conduction in small, shallow rivers may play a role in the thermal regime of the system.
  Recommendation: Conduct a field study to quantify the role of bed conduction in the heat budget. Identify several locations based primarily on substrate to conduct the tests. Use the results to test/calibrate the bed conduction logic included in the model, and complete a battery of tests to determine the potential role of bed conduction in the Shasta River.

- Woody riparian vegetation was characterized in 1997 for a significant portion of the system using aerial photographs combined with site visits. Herbaceous riparian vegetation was not identified.
  Recommendation: Conduct a riparian vegetation survey that includes woody vegetation, as well as herbaceous. Identify plant species, as well as conditions that provide additional benefit or dis-benefit to shading potential (e.g., narrow or wide river width, high banks (local topographic shading) or low banks.). Use this data to update, as necessary, the riparian vegetation within the model

- Topographic shading may be a factor for the canyon reach of the Shasta River.
  Recommendation: Using solar radiation equipment similar to that used in Abbott and Deas (2003), carry out measurements adjacent to the Shasta River at several locations. Alternatively, use a digital elevation model to approximate shade reduction potential.

- The Shasta River in the study area changes in elevation of about 800 feet in the study area and flows through riparian corridors, open fields, and steep bedrock canyons. Meteorological conditions may vary throughout the reach.
  Recommendation: Using a portable meteorological station and conduct field studies at the various locations within the Shasta Valley over several weeks. Use

the NOAA station at the Montague Grenada Airport and the CDF station at Brazie Ranch as controls.

- There are two gages currently on the system: the DWR station at Montague Grenada Road, and the USGS station near the mouth. Two stations are insufficient to characterize the complexity of the Shasta River system. There are certain reaches of the system where flow data is underrepresented. Either flow data are unavailable or long-term records necessary to capture the natural variability of the system are unavailable. To effectively and efficiently manage water resources in the basin additional flow data is necessary.
  Recommendation: Add and maintain a seasonal flow monitoring station at Anderson Grade, Highway A-12, and a location upstream of A-12 to collect daily flow information to support modeling and other management activities.

- The current temperature monitoring program carried out by California Department of Fish and Game effectively covers a large portion of the Shasta River basin downstream of Dwinnell Dam. There are certain reaches of the system where temperature data is underrepresented. Either temperature data are unavailable or long-term records necessary to capture the natural variability of the system are unavailable. To effectively and efficiently manage water resources in the basin additional temperature data is necessary.
  Recommendation: Add and maintain additional temperature monitoring locations, principally in the accretion reaches upstream of A-12. Hourly data would be necessary to support modeling and other management activities.

- In the coding of TVA's RQUAL (water temperature model), dispersion is neglected. The numerical approximations used in solving the governing equations of transport probably introduce some level of numerical dispersion into the solution. (Numerical dispersion is a function of the mathematical approximation used in the solution of the governing equations, and has no relation to dispersive properties of the actual, physical system.)
  Recommendation: Complete a test using the model to quantify numerical dispersion, if any. Document the findings and append to the modeling report.

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Peter Gilbert	Remote Automatic Weather Station Program, RAWS

Appendix A: Modified Input Files

One input file was modified and one input file was added to allow for the new shading logic. This appendix contains the modifications and the format for the new file.

A.1 Water Quality Coefficients (name.ric)

The first line (record) of the water quality coefficient input file was modified.

Original Input File (record number 1)

PRT,IPLT,THET,TSI,I02R,PLT,ROUTE,TDC,PDCX
(F8.0,I5,2F8.0,I5,F8.0,4X,A1,2F8.0)

Modified Input File (record number 1)

PRT,IPLT,THET,TSI,I02R,PLT,ROUTE,TDC,PDCX,IRS
(F8.0,I5,2F8.0,I5,F8.0,4X,A1,2F8.0,I5)

If IRS=0, RQUAL will run as originally constituted. If IRS=1, a shade data (shade.ris) input file is required. In addition, EBH and SHSOL should be left out of the .ric file.

A.2 Shade Data (shade.ris)

The shade data input file (shade.ris) must be named ‘shade.ris’ and be located in the same directory as RQUAL. The format of ‘shade.ris’ is (8X,4F8.0) where the first column may be used as an identifier with the node or river mile. The following four columns contain left effective barrier height, right effective barrier height, left bank transmittance factor, and right bank transmittance factor respectively.

Sample Input File (shade.ris)

```
Head       10.0   40.00    0.15     0.0  EBHL,EBHR,SHSOLL,SHSOLR
    2      10.0   40.00    0.15     0.0
    3      10.0   40.00    0.15     0.0
    4      10.0   40.00    0.15     0.0
    5      10.0   40.00    0.15     0.0
Mouth      10.0   40.00    0.15     0.0
```

Appendix B: Modified Program Code

Modifications were made in the main program, the subroutine CRS, in the commonblock RA which exists in the MAIN program and in subroutines CRS, BEDFLX, BEDFL2, INTEGR, TEMPDK, BODDK, NODDK, OXYDK, MROUTE, H-P, and in the commonblock CR which exists in the main program and in subroutine CRS. The original program code is in normal print, the modifications made for this application are in bold print. The dashed lines indicate that parts of the code have been deleted that were not of interest in these changes.

```
$debug
      PROGRAM RQUAL
C Modified version agpa 09/10/01
------------------------------------------------------------------------
      REAL N1,N2,NOD1,NOD2,NDK1,NDK2,NP1,NP2,NINIT,NK20,NODR,K1,K2
      CHARACTER*1 ROUTE
C
c agpa 9/17/01 modified EBH to accommodate both banks
c COMMON/CR/ EBH(500),AZ(500),BW(500),PHI,ALON,TZM,TFOG
c      COMMON/CR/ EBH(500),AZ(500),BW(500),PHI,ALON,TZM,TFOG,EBHL(500),
c     XEBHR(500),IEBH

c agpa 9/18/01 take out IEBH, no longer needed
c only one control variable will be used to turn on new shading logic
c if IRS=1 then the user inputs EBHL,EBHR and SHSOLL,SHSOLR
       COMMON/CR/ EBH(500),AZ(500),BW(500),PHI,ALON,TZM,TFOG,EBHL(500),
     XEBHR(500)

      COMMON/HYD/DX(499),Q1(500),Q2(500),H1(500),H2(500),
     X           A1(500),A2(500),E1(500),E2(500),W1(500),W2(500),
     X           K1(500),K2(500),DT,THET,TSI,
     X           QL1(499),QL2(499),QLAT1(44),QLAT2(44)
      COMMON/HYDNC/NC(500),ICONST,WFAC,WLEN,pdc,pdcx
c agpa 9/13/01 added IRS COMMON/RA/EXCO,HMAC,AA,BB,NXSEC,THR,THB,BK20,THS,SK20(500),
c     XTHN,NK20,THPR,IK2EQ,BS20,BETW,XL,XL2,DIF,CV,BEDALB,SHSOL,SHDBT

      COMMON/RA/EXCO,HMAC,AA,BB,NXSEC,THR,THB,BK20,THS,SK20(500),
     XTHN,NK20,THPR,IK2EQ,BS20,BETW,XL,XL2,DIF,CV,BEDALB,SHSOL,SHDBT,
     XIRS,SHSOLL(500),SHSOLR(500),SHSOLA(500),IDAY,JOLD
      COMMON/PHOT/PMAX(500),RESP(500),O2KM
C
      COMMON/PROCES/PHOTO(500),RESPR(500),REAR(500),NODR(500),BODR(500),
     XSODR(500),RETYP(500),TQS(500),TRS(500),TQA(500),TQB(500),TQE(500)
      COMMON/PROCS2/TBC(500),TBC2(500),TQC(500),IPROC
      COMMON/WQ/O1(500),O2(500),T1(500),T2(500),B1(500),B2(500),
     XOM(500),QM(500),N1(500),N2(500)
      COMMON/UWEIR/NEVQ,EVQ(20,2)
      COMMON/BDFX/TBED(500),TBED2(500)
      COMMON/LAT/NL,NLW,NLS(44,2),LSEC(11),INDS(11)
C
      COMMON/JUK/ RMI(500),CHB(500),RML(11),RMIND(11),
     X          RS1(500),RS2(500),ALPHX(500),IC(500),ICCH(500),
     X          TDK1(500),TDK2(500),TP1(500),TP2(500),
     X          BDK1(500),BDK2(500),BP1(500),BP2(500)
      COMMON/JUK1/RDBT1(500),RDBT2(500)
      COMMON/JUK2/ ODK1(500),ODK2(500),OP1(500),OP2(500),
     X           NDK1(500),NDK2(500),NP1(500),NP2(500)
      COMMON/JUK3/ WLT1(11),WLT2(11),WLO1(11),WLO2(11),
     X          WLB1(11),WLB2(11),WT1(499),WT2(499),
     X          WB1(499),WB2(499),WO1(499),WO2(499),
```

```
     X          WLN1(11),WLN2(11),WN1(499),WN2(499)
      COMMON/JUK4/ WTL2(11),WBL2(11),WOL2(11),WNL2(11)
C agpa 09/10/01 QNSO(I) added to output solar radiation in main program
c      DIMENSION JFIRST(4),NX(4),MCJ(3),NQLH(4),IDTSAVE(4)
       DIMENSION JFIRST(4),NX(4),MCJ(3),NQLH(4),IDTSAVE(4),QNSO(500)
      DATA IDTSAVE/4*0/,ipr/0/
-----------------------------------------------------------------------

C agpa 09/10/01 Added an output files for solar radiation and shade factor
C Four outfiles, one for each of four nodes. Output is a time series
C  OPEN SOLAR RADIATION OUTPUT FILE Solar.out
       OPEN(28,FILE='Solar1.out ',STATUS='unknown')
       WRITE(28,'(/A)')' ***********************************************'
      WRITE(28,'(A)') ' *  Solar Radiation Output for RQUAL           *'
      WRITE(28,'(A)') ' * SIM Hr = simulation hour,RMI = River Mile   *'
       WRITE(28,'(A)') ' * SHSOL = shade reduction factor,             *'
       WRITE(28,'(A)') ' * EBH = effective bank height,                *'
       WRITE(28,'(A)') ' * RS = shade reduction, QNS = reduced solar   *'
       WRITE(28,'(A)') ' * SWS = incoming solar (kcal/m2-s)            *'
      WRITE(28,'(A)') ' ***********************************************'
       WRITE(28,799)'SimHR','RMI','SHSOL','EBH','RS','QNS','SWS','Temp'
       WRITE(28,799) 'hr','mi','','m','','kcal/m2-s','kcal/m2-s','C'
       OPEN(29,FILE='Solar3.out ',STATUS='unknown')
       WRITE(29,'(/A)')' ***********************************************'
      WRITE(29,'(A)') ' *  Solar Radiation Output for RQUAL           *'
       WRITE(29,'(A)') ' * SIM Hr = simulation hour,RMI = River Mile   *'
       WRITE(29,'(A)') ' * SHSOL = shade reduction factor,             *'
       WRITE(29,'(A)') ' * EBH = effective bank height,                *'
       WRITE(29,'(A)') ' * RS = shade reduction, QNS = reduced solar   *'
       WRITE(29,'(A)') ' * SWS = incoming solar (kcal/m2-s)            *'
       WRITE(29,'(A)') ' ***********************************************'
       WRITE(29,799)'SimHR','RMI','SHSOL','EBH','RS','QNS','SWS','Temp'
       WRITE(29,799) 'hr','mi','','m','','kcal/m2-s','kcal/m2-s','C'
       OPEN(30,FILE='Solar5.out ',STATUS='unknown')
       WRITE(30,'(/A)')' ***********************************************'
      WRITE(30,'(A)') ' *  Solar Radiation Output for RQUAL           *'
      WRITE(30,'(A)') ' * SIM Hr = simulation hour,RMI = River Mile   *'
       WRITE(30,'(A)') ' * SHSOL = shade reduction factor,             *'
       WRITE(30,'(A)') ' * EBH = effective bank height,                *'
       WRITE(30,'(A)') ' * RS = shade reduction, QNS = reduced solar   *'
       WRITE(30,'(A)') ' * SWS = incoming solar (kcal/m2-s)            *'
      WRITE(30,'(A)') ' ***********************************************'
       WRITE(30,799)'SimHR','RMI','SHSOL','EBH','RS','QNS','SWS','Temp'
       WRITE(30,799) 'hr','mi','','m','','kcal/m2-s','kcal/m2-s','C'
       OPEN(31,FILE='Solar11.out ',STATUS='unknown')
       WRITE(31,'(/A)')' ***********************************************'
      WRITE(31,'(A)') ' *  Solar Radiation Output for RQUAL           *'
      WRITE(31,'(A)') ' * SIM Hr = simulation hour,RMI = River Mile   *'
       WRITE(31,'(A)') ' * SHSOL = shade reduction factor,             *'
       WRITE(31,'(A)') ' * EBH = effective bank height,                *'
       WRITE(31,'(A)') ' * RS = shade reduction, QNS = reduced solar   *'
       WRITE(31,'(A)') ' * SWS = incoming solar (kcal/m2-s)            *'
      WRITE(31,'(A)') ' ***********************************************'
       WRITE(31,799)'SimHR','RMI','SHSOL','EBH','RS','QNS','SWS','Temp'
       WRITE(31,799) 'hr','mi','','m','','kcal/m2-s','kcal/m2-s','C'
  799  FORMAT(8A10)
-------------------------------------------------------------------------------

c agpa 9/13/01 added new variable IRS to added SHSOL on both banks
c      READ(5,1011)PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE,pdc,pdcx
c      WRITE(60,'(A)') ' PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE='
c      WRITE(60,2013)PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE

c agpa 9/17/01 added new variable IEBH as flag to turn on ability to enter l/r bank ebh
c agpa 9/18/01 went back to one control variable (IRS)
       READ(5,1011)PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE,pdc,pdcx,IRS
      WRITE(60,'(A)') ' PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE,IRS='
      WRITE(60,2013)PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE,IRS
```

```
c agpa 9/18/01 took out IEBH, and reverted back to one control variable for new logic
(IRS)
c      READ(5,1011)PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE,pdc,pdcx,IRS,IEBH
c      WRITE(60,'(A)') ' PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE,IRS,IEBH='
c      WRITE(60,2013)PRT,IPLT,THET,TSI,IPROC,PLT,ROUTE,IRS,IEBH

      IF(PLT.EQ.0.0)PLT=PRT
C
      IF(PRT.GE.DTHR)GO TO 3
      WRITE(60,'(A)') ' PRT,DTHR='
      WRITE(60,3232)PRT,DTHR
 3232 FORMAT(/' ERROR...PRT<DT  PRT=',F6.3,' DT=',F6.3)
      GO TO 9999
    3 CONTINUE
      IF(PLT.GE.DTHR)GO TO 4
      WRITE(60,'(A)') ' PRT,DTHR='
      WRITE(60,3332)PLT,DTHR
 3332 FORMAT(/' ERROR...PLT<DT  PLT=',F6.3,' DT=',F6.3)
      GO TO 9999
    4 CONTINUE
C
C
      IF(THET.EQ.0.0)THET=0.5
      IF(TSI.EQ.0.0)TSI=1.0
c agpa 9/13/01 2013 FORMAT(F8.4,I5,2F8.2,I5,F8.2,4X,A1)
c agpa 9/13/01 1011 FORMAT(F8.0,I5,2F8.0,I5,F8.0,4X,A1,2f8.0)
 2013 FORMAT(F8.4,I5,2F8.2,I5,F8.2,4X,A1,I5)
 1011 FORMAT(F8.0,I5,2F8.0,I5,F8.0,4X,A1,2f8.0,I5)
c apga 9/18/01 2013 FORMAT(F8.4,I5,2F8.2,I5,F8.2,4X,A1,2I5)
c agpa 9/18/01 1011 FORMAT(F8.0,I5,2F8.0,I5,F8.0,4X,A1,2f8.0,2I5)

      READ(5,1001)(ALPHX(J),J=1,NXSEC)
      WRITE(60,7211)NXSEC,(ALPHX(J),J=1,5)
 7211 FORMAT(I5,5F8.2)
C
C  READ SHADING FACTOR DATA
C     PHI=LATITUDE,DECIMAL DEG
C     ALON=LONGITUDE, DECIMAL DEG
C     TZM=TIME ZONE MERIDIAN, DEG (TZM CHANGES EVERY 15 DEGREES
C          WEST OF 0 DEGREES AT GREENWICH.  WE ARE IN TIME ZONE
C           MERIDIAN AREA 75 , WHICH APPLIES TO AREA BETWEEN
C           LONGITUDES 75 AND 90)
      READ(5,1001) PHI,ALON,TZM,TFOG
      IF(TFOG.EQ.0.0) TFOG=10.
C
C  COMPUTE TIME ZONE MERIDIAN FROM LONGITUDE (I.E., IGNORE INPUT TZM)
      MTZ=IFIX(ALON)/15
       TZM=15.*FLOAT(MTZ)
      WRITE(60,'(A)') ' PHI,ALON,TZM,TFOG='
      WRITE(60,2011) PHI,ALON,TZM,TFOG
      READ(5,1001) (AZ(I),I=1,NXSEC)
      WRITE(60,2011) (AZ(I),I=1,NXSEC)
      READ(5,1001) (BW(I),I=1,NXSEC)
      WRITE(60,2011) (BW(I),I=1,NXSEC)
c      READ(5,1001) (EBH(I),I=1,NXSEC)
c      WRITE(60,2011) (EBH(I),I=1,NXSEC)

c agpa 9/17/01 flag turns on logic to read in EBH for l/r banks
c       IF (IEBH.eq.0) THEN
c         READ(5,1001) (EBH(I),I=1,NXSEC)
c         WRITE(60,2011) (EBH(I),I=1,NXSEC)
c       ELSE IF (IEBH.eq.1) THEN
c          READ(5,1001) (EBHL(I),I=1,NXSEC)
c         WRITE(60,2011) (EBHL(I),I=1,NXSEC)
c          READ(5,1001) (EBHR(I),I=1,NXSEC)
c         WRITE(60,2011) (EBHR(I),I=1,NXSEC)
c       ENDIF

C agpa 9/13/01 READ SHSOL FOR LEFT AND RIGHT BANK IF IRS=1, ELSE CONTINUE
```

```
c      IF (IRS .EQ. 1) THEN
c       READ(5,1001) (SHSOLL(I),I=1,NXSEC)
c      WRITE(60,'(A)') 'SHSOLL = '
c       WRITE(60,2011) (SHSOLL(I),I=1,NXSEC)
c       READ(5,1001) (SHSOLR(I),I=1,NXSEC)
c       WRITE(60,'(A)') 'SHSOLR = '
c      WRITE(60,2011) (SHSOLR(I),I=1,NXSEC)
c       ENDIF

c agpa 9/18/01 new input format for two bank shading input
c flag, IRS now opens a separate input file Unit=4
      IF (IRS.eq.0) THEN
         READ(5,1001) (EBH(I),I=1,NXSEC)
        WRITE(60,2011) (EBH(I),I=1,NXSEC)
       ELSE IF (IRS.eq.1) THEN
         OPEN(4,FILE='shade.ris',STATUS='OLD')
         WRITE (60,'(5A8)') 'RMI','EBHL','EBHR','SHSOLL','SHSOLR'
         WRITE (60,'(5A8)') '','ft','ft','',''
         DO J=1,NXSEC
           READ(4,'(8X,9F8.0)') EBHL(J),EBHR(J),SHSOLL(J),SHSOLR(J)
           WRITE(60,'(5F8.2)') RMI(J),EBHL(J),EBHR(J),SHSOLL(J),SHSOLR(J)
         ENDDO
       ENDIF


C
C  CHANGE BW,EBH UNITS FROM FT TO METERS
c      DO 12 J=1,NXSEC
c       BW(J)=0.3048*BW(J)
c        EBH(J)=0.3048*EBH(J)
c agpa 9/18/01 if IRS = 1 need to convert l/r bank
       DO 12 J=1,NXSEC
         IF (IRS.eq.1) THEN
          BW(J)=0.3048*BW(J)
          EBHL(J)=0.3048*EBHL(J)
           EBHR(J)=0.3048*EBHR(J)
         ELSE IF (IRS.eq.0) THEN
           BW(J)=0.3048*BW(J)
          EBH(J)=0.3048*EBH(J)
         ENDIF
   12 CONTINUE
C
 1012 FORMAT(/(5F12.0))
C
C  READ WIND COEFFICIENTS AND THERMAL PROPERTIES OF CHANNEL BED
C   EVAP=(AA+BB*WIND)*(ES-EA)
C     WHERE AA=M/(S MB)
C           BB=1/MB
C           ES,EA = MB
C   XL = THICKNESS OF UPPER BED (CM)
C   XL2 = THICKNESS OF LOWER BED (CM)
C   DIF = THERMAL DIFFUSIVITY OF BED (SQ CM/HR)
C   CV = HEAT STORAGE CAPACITY OF BED (CAL/ CU CM  DEG C)

c agpa 9/13/01 commented out to add l/r bank shade logic
c      READ(5,1001)AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHSOL,SHDBT
C  SET DEFAULTS
c      WRITE(60,'(A)') ' AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHSOL,SHDBT='
c      WRITE(60,2011) AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHSOL,SHDBT
c      IF(SHSOL.EQ.0.0) SHSOL=0.2
c      IF(SHDBT.GT.1.0) SHDBT=1.0

c agpa 9/13/01 added to include IRS=1 for l/r bank shading
       IF (IRS.EQ.0) THEN
         READ(5,1001)AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHSOL,SHDBT
C  SET DEFAULTS
        WRITE(60,'(A)') ' AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHSOL,SHDBT='
        WRITE(60,2011) AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHSOL,SHDBT
c agpa 9/18/01 turn off default for shsol        IF(SHSOL.EQ.0.0) SHSOL=0.2
```

```
        IF(SHDBT.GT.1.0) SHDBT=1.0
       ELSE IF (IRS.EQ.1) THEN
         READ(5,1001)AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHDBT
        WRITE(60,'(A)') ' AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHDBT='
        WRITE(60,2011) AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHDBT
       ENDIF
--------------------------------------------------------------------------------
C
C  COMPUTE INITIAL SHADING FACTORS
c agpa 9/14/01 set flags for new shading logic
c IDAY=0 sets the flag for first time through the new shading logic
C JOLD = julian date of previous time step, initialized at 999
      IDAY=0
       JOLD=999
      CALL CRS(HOURJ,W1,RS1,RDBT1,CLD1)
C
C  INITIALIZE HEAT SOURCE, SINK TERMS
C     WRITE(60,3335)
C3335 FORMAT('  CALLING TEMPDK')
c agpa 9/10/01 added QNSO to pass solar radiation term back to main
c  114 CALL TEMPDK(A1,W1,CLD1,DBT1,DPT1,APR1,WND1,SWS1,RS1,RDBT1,
c     XT1,TDK1,TP1)
  114 CALL TEMPDK(A1,W1,CLD1,DBT1,DPT1,APR1,WND1,SWS1,RS1,RDBT1,
     XT1,TDK1,TP1,QNSO)
C     CALL BEDC(IDT,T1)
      CALL BEDFL2(T1,A1,W1,DTHR)
--------------------------------------------------------------------------------
C  BIG TIME LOOP FOR EACH DT
C
      SIMHR=0.0
    5 IDT=IDT+1
      HOURJ=HOURJ+DT/3600.
C     SIMHR=HOURJ-BHOURJ
      SIMHR=SIMHR+DT/3600.
C      WRITE(*,2789) SIMHR
C 2789 FORMAT('    BEGINNING SIMULATION HOUR',F8.3)
--------------------------------------------------------------------------------
C  COMPUTE SHADING FACTORS
      CALL CRS(HOURJ,W2,RS2,RDBT2,CL2)
C      WRITE(8,3001)IDT,(RS2(J),J=1,NXSEC)
C3001 FORMAT(I5/(10F8.2))
C
C  SUM HEAT SOURCES,SINKS AND LINEARIZE SOURCE TERM
C     WRITE(60,3335)

c agpa 9/10/01 added QNSO to pass SWS adjusted for shading back to main program
c      CALL TEMPDK(A2,W2,CL2,DB2,DP2,AP2,WI2,SW2,RS2,
c       2RDBT2,T1,TDK2,TP2)
      CALL TEMPDK(A2,W2,CL2,DB2,DP2,AP2,WI2,SW2,RS2,
       2RDBT2,T1,TDK2,TP2,QNSO)

c agpa 09/10/01 added output to output file solar.out
C  Output solar time series at 4 nodes
C  OUTPUT TO SOLAR1.OUT-SOLAR4.out SHSOL,EBH,RS,SWS

c       WRITE(28,899)SIMHR,RMI(1),SHSOL,EBH(1),RS2(1),QNSO(1),SW2/3600.
c       WRITE(29,899)SIMHR,RMI(3),SHSOL,EBH(3),RS2(3),QNSO(3),SW2/3600.
c       WRITE(30,899)SIMHR,RMI(5),SHSOL,EBH(5),RS2(5),QNSO(5),SW2/3600.
c       WRITE(31,899)SIMHR,RMI(7),SHSOL,EBH(7),RS2(7),QNSO(7),SW2/3600.
c  899  FORMAT (7F8.3)

C  COMPUTE TEMPERATURES FOR NEW DT (INTEGRATE)
C     WRITE(60,3339)
C3339 FORMAT('  CALLING TEMP')
      ICONST=1
      IF(ROUTE.eq.'I') CALL INTEGR(TDK1,TP1,WT1,TDK2,TP2,WT2,T1,T2)
      IF(ROUTE.eq.'E')
     >  CALL MROUTE(TDK1,TP1,WT1,TDK2,TP2,WT2,T1,T2,IDTSAVE(ICONST))
      IF(ROUTE.eq.'H')
```

```
     >  CALL HPINTG(TDK1,TP1,WT1,TDK2,TP2,WT2,T1,T2)

c agpa 09/11/01 added temperature to solar output file
       WRITE(28,899)SIMHR,RMI(1),SHSOLA(1),EBH(1),RS2(1),QNSO(1),
       2SW2/3600.,T2(1)
       WRITE(29,899)SIMHR,RMI(3),SHSOLA(3),EBH(3),RS2(3),QNSO(3),
       2SW2/3600.,T2(3)
       WRITE(30,899)SIMHR,RMI(5),SHSOLA(5),EBH(5),RS2(5),QNSO(5),
       2SW2/3600.,T2(5)
       WRITE(31,899)SIMHR,RMI(11),SHSOLA(11),EBH(11),RS2(11),QNSO(11),
       2SW2/3600.,T2(11)
  899  FORMAT (8F10.3)
  ------------------------------------------------------------------------------

C*************************************************************************
C
      SUBROUTINE CRS(HOURJ,W,RS,RDBT,CLD)
C
C*************************************************************************
C  SUBROUTINE FOR COMPUTING ABSORPTION COEFFICIENTS ON A RIVER
C  VARIABLE DEFINITIONS
C  RS(I)=ABSORPTION COEFFICIENT FOR NODE I
C  RDBT(I)=DRYBULB TEMPERATURE REDUCTION FRACTION FOR NODE I
C  SHSOL=FRACTION OF SOLAR ABSORBED BY WATER IN THE SHADE (FORMERLY 0.2)
C  SHDBT=FRACTION OF DBT-DPT BY WHICH DBT IS REDUCED IN THE SHADE
C  EBH(I)=TREE HEIGHT ON EFFECTIVE BARRIER HEIGHT FOR EACH SUBREACH,M
C  AZ(I)=AZIMUTH OF RIVER SUBREACH,DEGREES
C  AZS=AZIMUTH OF SUN,DEGREES
C  BW(I)=BANK WIDTH,DISTANCE FROM TREES TO WATERS EDGE, METERS
C  THE= ANGLE BETWEEN SUN AND STREAM AXIS, DEGREES
C  BET= ANGLE BETWEEN SUN AND NORMAL TO THE STREAM AXIS, DEGREES
C  ELEV=ELEVATION OF THE SUN, DEGREES
C  XN= NORMAL DISTANCE FROM TREES TO EDGE OF SHADOW, METERS
C  X=  DISTANCE FROM TREES TO SHADOW ALONG A BEAM OF LIGHT, METERS
C  DEL= DECLINATION OF THE SUN, DEGREES
C  HA=  HOUR ANGLE FROM ZENITH TO SUN, DEGREES
C  DHA= CHANGE IN HOUR ANGLE PER TIME STEP, DEGREES
C  HAD= HOUR ANGLE AT MIDNIGHT, DEGREES
C  PHI= LATITUDE OF RIVER, DEGREES
C  ALON= LONGITUDE OF RIVER, DEGREES
C  TZM= TIME ZONE MERIDIAN
C  JDAT= JULIAN DATE FOR WHICH SHADING COMPUTATIONS ARE MADE
C  DR=  DEGREE TO RADIAN CONVERSION
C
C agpa 09/13/01 four parameters added to add shading from either/both banks
C  SHSOLL(I)=transmittance factor for left bank
C  SHSOLR(I)=transmittance factor for right bank
C  SHSOLA(I)=transmittance factor used at any given timestep
C  SHSOL= transmittance factor input if there is just one number for a whole system
c  IDAY = flag indicating the first time through new shading logic each day
c          iday=0 first time through, iday=1 not first time through
c  JOLD = julian date of previous time step, initialized as 999 in main program
c  FB = first bank to be shaded that day, RB=right, LB=left
c  IZ = flag, 1=Az<AZS, 0=AZ>AZS at first timestep after ELEV>1.5
c  IRS = flag to turn on logic for both banks (irs=1)

      REAL NK20
      DIMENSION A(4),B(4),RS(500),RDBT(500),W(500)
c agpa 9/17/01 modified ebh to accomodate both banks
c      COMMON/CR/ EBH(500),AZ(500),BW(500),PHI,ALON,TZM,TFOG
c       COMMON/CR/ EBH(500),AZ(500),BW(500),PHI,ALON,TZM,TFOG,EBHL(500),
c     XEBHR(500),IEBH
c agpa 9/18/01 IEBH removed
       COMMON/CR/ EBH(500),AZ(500),BW(500),PHI,ALON,TZM,TFOG,EBHL(500),
     XEBHR(500)
c agpa 9/13/01 added IRS  COMMON/RA/EXCO,HMAC,AA,BB,NXSEC,THR,THB,BK20,THS,SK20(500),
C     XTHN,NK20,THPR,IK2EQ,BS20,BETW,XL,XL2,DIF,CV,BEDALB,SHSOL,SHDBT

       COMMON/RA/EXCO,HMAC,AA,BB,NXSEC,THR,THB,BK20,THS,SK20(500),
```

```
     XTHN,NK20,THPR,IK2EQ,BS20,BETW,XL,XL2,DIF,CV,BEDALB,SHSOL,SHDBT,
     XIRS,SHSOLL(500),SHSOLR(500),SHSOLA(500),IDAY,JOLD
c agpa 9/14/01 new local variables for both bank shading logic
      INTEGER::IZ
       CHARACTER::FB*2

      DATA A/1.18,2.20,0.95,0.35/
      DATA B/0.77,0.97,0.75,0.45/
      DR=3.14159/180.0
      HOURD=AMOD(HOURJ,24.)
      DHA=DR*(HOURD*360./24.)
      PHI=PHI*DR
      JDAT=IFIX(HOURJ)/24+1
      DEL=DR*23.45*COS(6.2832*(172.0-FLOAT(JDAT))/365.0)
      HAD=(180.0+ALON-TZM)*DR
      SDSP=SIN(DEL)*SIN(PHI)
      CDCP=COS(DEL)*COS(PHI)
      HA=HAD-DHA
      S=SDSP+CDCP*COS(HA)
      ELEV=ASIN(S)/DR
      AZS=0.0
      IF(CLD.LT.0.05)N=1
      IF(CLD.GE.0.05.AND.CLD.LT.0.5)N=2
      IF(CLD.GE.0.5.AND.CLD.LT.0.95)N=3
      IF(CLD.GE.0.95)N=4
      IF(ELEV.GT.1.5)RSM=1.0-A(N)*(1.0/ELEV**B(N))
      IF(ELEV.GT.1.5)AZS=ACOS((SIN(DEL)-SIN(ELEV*DR)*SIN(PHI))/(COS
     X(ELEV*DR)*COS(PHI)))
      IF(HA.LT.0.0)AZS=360.0*DR-AZS
C     WRITE(60,3001) HA,S,ELEV,RSM,AZS,DEL,HAD,SDSP,CDCP
C3001 FORMAT(5H STEP,9E12.4)
C
      DO 12 I=1,NXSEC

C agpa 9/14/01 setup SHSOLA array with either SHSOL, or l/r bank information
      IF (IRS.eq.0) THEN
         SHSOLA(I)=SHSOL
       ELSE IF (IRS.eq.1) THEN
        IF (JDAT.ne.JOLD) IDAY=0
         IF (ELEV.gt.1.5) THEN
          !Set first bank
           IF (IDAY.eq.0) THEN
            IF (AZ(I).gt.AZS/DR) THEN
              IF (AZ(I).gt.(AZS/DR+180.0)) THEN
                FB='RB'
                     IZ=0
              ELSE
                     FB='LB'
              ENDIF
            ELSE
              FB='RB'
              IZ=1
            ENDIF
             IDAY=1
          ENDIF
          !Fill SHSOLA(I) array with appropriate bank transmittance factor
c agpa 9/18/01 added EBHL/EBHR to the new shading logic
          IF (IDAY.eq.1) THEN
            IF (FB.eq.'LB') THEN
              IF (AZ(I).gt.AZS/DR) THEN
                SHSOLA(I)=SHSOLL(I)
                 EBH(I)=EBHL(I)
              ELSE
                SHSOLA(I)=SHSOLR(I)
                 EBH(I)=EBHR(I)
              ENDIF
            ELSE IF (FB.eq.'RB') THEN
              IF (IZ.eq.0) THEN
                IF (AZ(I)-180.0.gt.AZS/DR) THEN
```

```
                  SHSOLA(I)=SHSOLR(I)
                    EBH(I)=EBHR(I)
                ELSE
                  SHSOLA(I)=SHSOLL(I)
                    EBH(I)=EBHL(I)
                ENDIF
              ELSE IF (IZ.eq.1) THEN
                IF (AZ(I)+180.0.gt.AZS/DR) THEN
                  SHSOLA(I)=SHSOLR(I)
                    EBH(I)=EBHR(I)
                ELSE
                  SHSOLA(I)=SHSOLL(I)
                    EBH(I)=EBHL(I)
                ENDIF
              ENDIF
            ENDIF
          ENDIF
        ELSE
        !River is fully shaded before sunrise, i.e. transmittance = 0.0
c agpa 9/17/01 make shsola() before sunrise the average of shsoll/shsolr
c to represent shading influence on diffusive solar radiation
c        SHSOLA(I)=0.2
          SHSOLA(I)=(SHSOLL(I)+SHSOLR(I))/2.
c agpa 9/18/01 make EBH(I) before sunrise the average of ebhl/ebhr
          EBH(I)=(EBHL(I)+EBHR(I))/2.
          ENDIF
      ENDIF

      WI=W(I)*0.3048
      IF(ELEV.GT.1.5) GO TO 1
C     RS(I)=0.2
C  MAKE FRAC OF SOLAR ABSORBED IN SHADED AREA AN INPUT VARIABLE
c     RS(I)=SHSOL
c agpa 9/14/01 make frac of solar absorbed/transmittance an array
      RS(I)=SHSOLA(I)
C  FRAC OF DBT-DPT TO REDUCE DBT BY IN SHADED AREA (INPUT VARIABLE)
      RDBT(I)=SHDBT
      GO TO 10
    1 THE=ABS(AZS-AZ(I)*DR)
      IF(THE.GT.(180.*DR)) THE=THE-180.*DR
      BET=ABS(THE-90.0*DR)
      X=EBH(I)/TAN(ELEV*DR)
      IF(COS(BET).GT.0.01) GO TO 2
      RS(I)=RSM
      RDBT(I)=0.0
      GO TO 10
    2 XN=X*COS(BET)
      IF(XN.GE.BW(I)) GO TO 3
      RS(I)=RSM
      RDBT(I)=0.0
      GO TO 10
    3 IF(XN.LE.(BW(I)+WI)) GO TO 4
C     RS(I)=0.2
c agpa 9/14/01 RS(I)=SHSOL
      RS(I)=SHSOLA(I)
      RDBT(I)=SHDBT
      GO TO 10
C   4 RS(I)=RSM*(WI+BW(I)-XN)/WI+0.2*(XN-BW(I))/
c agpa 9/14/01    4 RS(I)=RSM*(WI+BW(I)-XN)/WI+SHSOL*(XN-BW(I))/WI
    4 RS(I)=RSM*(WI+BW(I)-XN)/WI+SHSOLA(I)*(XN-BW(I))/WI
      RDBT(I)=0.0*(WI+BW(I)-XN)/WI+SHDBT*(XN-BW(I))/WI
C     WRITE(60,3002)I,THE,BET,X,XN,W(I),RS(I)
C3002 FORMAT(5H GRID,I5,9E13.2)
C  10 IF(HOURD.LT.TFOG) RS(I)=0.2
c agpa 9/14/01   10 IF(HOURD.LT.TFOG) RS(I)=SHSOL
c NOTE: If ELEV<=1.5 then SHSOLA(I) is an average of left and right bank,
c       IF ELEV>1.5 then SHSOLA(I) is assigned as left or right bank
   10 IF(HOURD.LT.TFOG) RS(I)=SHSOLA(I)
       IF(HOURD.LT.TFOG) RDBT(I)=SHDBT
```

```
      IF(I.EQ.35)WRITE(60,3001)HOURD,HA,ELEV,RSM,AZS,THE,BET,X,XN,RS(I)
 3001 FORMAT(10F8.3)
   12 CONTINUE
      PHI=PHI/DR
C     WRITE(60,5050)JDAT,TZM,PHI,ALON
C5050 FORMAT(1H0,39X,'ABSORPTION COEFFICIENTS FOR SOLAR RADIATION',38X,
C    X       //,53X,'JULIAN DAY ',I3,2X,',TIME ZONE  ',1F4.1,' DEGREES',29X,/,
C    X       53X,'LATITUDE=',1F5.1,' LONGITUDE= ',F5.1,' DEGREES',27X,//,
C    X       ' GRID    EBH     BW  AZIMUTH ****************************',
C    X       '****HOUR**********************************************',/,
C    X       8X,'METER  METER  DEGREE',4X,'5',5X,'6',5X,'7',5X,'8',5X,'9',4X,
C    X       '10',4X,'11',4X,'12',4X,'13',4X,'14',4X,'15',4X,'16',4X,'16',4X,'17
C    X       ,4X,'18',4X,'19',3X)
C     DO 11 I=1,NXSEC
C       WRITE(60,3000)I,EBH(I),BW(I),AZ(I),RS(I)
C3000 FORMAT(' ',I4,F9.1,F7.1,F8.1,1X,15F6.3)
   11 CONTINUE
c agpa 9/14/01 save previous time step julian date for next pass
      JOLD=JDAT

      RETURN
C     DEBUG UNIT(98),SUBTRACE
END
```

Appendix C: Preprocessor Code Listings

Two preprocessors were written to expeditiously transfer the needed data from EXCEL spreadsheets to the necessary model input formats.

C.1 Preprocessor for ADYN

```
! 10/30/01
!
! Program RMSPP: A preprocessor for the ADYN input file (.aii) for RMS by TVA.
!
!       By Alida Abbott
!
! This program reads a text files created in EXCEL and saved as .prn. and merges
! the data input by the user to form a complete ADYN input file. NOTE: This file
! is designed for the Shasta River Project and modifications may need to be made
! to apply it to other uses of RMS.
!
! This preprocessor is for 1 reach and no dynamic junctions.
! This preprocessor does not prepare for node interoplation by ADYN.
!
!
!   ~File Numbers~                                   ~Hardwired Values~
! 1 Geometry Text File                                    ICG = 1
I 2 Flow Text File                                       XUNIT = 0
! 3 Lateral Inflow Text File                              NJUNC = 0
! 5 ADYN input file (.aii)                               DGEO = 50
!                                                        iMASS = 1
!                                                        PHIDEG = 0.0
!                                                         IQUAL = 1
!                                                        FNMX = 0.0
!                                                         IVRCH, IVEL = 0
!                                                         RFC = 0.0
!                                                    DDIST1, DDIST2 = 0
!                                                        PLT=DT=QUALDT
!                                                     IUSBC,IDSBC = 1
!                                                          NC(J) = 0
!                                                        QTTOL = 0.02
!                                                        QTOL = 0.005
!                                                        HTOL = 0.005
! Boundary Conditions:
```

```
! The upstream boundary is set to be a discharge hydrograph (CFS)
! The downstream boundary is set for the model to calculate using manning eq.
!The geometry text file has the following format:
!   Line 1: Title

!   Line 2: Identifiers
!   Line 3: nxsec, iseco, ixsec
!   Line 4: identifiers
!   Line 5: NX RMI d1 d2 d3 d4 d5 elev1 elev 2 elev3 elev4 elev5(r) NMN N Con Ex !
!   Line 5 format: I2,6F6.2,5F8.2,I2,3F6.3
!   Line 5 definitions:
!    NXSEC = number of uninterpolated cross-sections
!    ISECO = order of cross-sections (0=up/down, 1=down/up)
!    IXSEC = number of interpolated cross-sections
!       NX = number of coordinates in the cross-section
!       RMI = river mile
!      d1-5 = distance of the coordinates from the left bank
!   elev1-5 = corresponding elevations for each distance
!       NMN = number of mannings n's per cross-section
!         N = manning's n
!       CON = coefficient of contraction
!        EX =      coefficient of expansion
!  NOTE: You may only have one manning n per cross-section.
!        There is no limit NX, d, elev.
!
!   For the last cross-section put a negative number for Con and Ex.
!
!The lateral inflow text file has the following format:

!  Line 1: hi, nord, ifmt, isopt (just need to be separated by spaces)
!  Line 2: identifiers
!  Lines 3 and 4 are repeated for each lateral iflow (nqlh times)
!  Line 3: rmlat1, rmlat2 (seperated by spaces)
!  Line 4: date and time (14X), discharge in cfs (F10.2) repeated nord times
!-----------------------------------------------------------------------------------------------

        program RMS_PP
        implicit none

    character (80) geoname,ubcname,outname,yesno*1,title1,identifiers,
   2 name,latname,isolv*1
        integer no ,i , nns, iog, iroute, idmpqh, iplt,nxsec,iseco,ixsec,
        2 date, nord,ifmt,isopt,nqlh,j
    real rmi , frn, kce1, kce2, rmiog1,rmiog2,rmiog3,dt, prt,hi,
        2 rmlat1,rmlat2,rmic,qic,elic,theta
```

```
     real, dimension (5) :: x, elev
          real, dimension (5000) :: w, qlat

! Get file names of input files and open files

          !Ask user for file name
100       WRITE (*,*) "Enter geometry input file name:"
          READ(*,*) geoname
          WRITE(*,*) "Enter upstream boundary input file name:"
          READ(*,*) ubcname

          !Try to open files
          name = geoname
     OPEN (1, file=geoname, status='OLD', ERR=110)
          name = ubcname
     OPEN (2, file=ubcname, status='OLD',ERR=110)
          GOTO 120

          !Error handler
110       WRITE (*,*) "Error, could not open file:", name
          WRITE (*,*) "Try again? (y/n)"
          READ (*,*) yesno
          IF (yesno == "y".or. yesno == "Y") THEN
                    GOTO 100
          ELSE
                    WRITE (*,*) "RMS PreProcessor aborting."
          ENDIF

          !Got the files, ok to proceed
120       Continue

!Get output file name and open file
          WRITE (*,*) "Enter output file name"
          READ (*,*)    outname
          WRITE (*,*) "Output file name:", outname
          OPEN (5, file=outname, STATUS='unknown')

!Read input file title
          READ(1,"(A80)") title1
          WRITE(5,'(A)') title1
          READ(1,*) identifiers

!Get information from user and write line 1 for .aii
     WRITE (*,*) "Output geometry to DYNOUT?(0=no, 2=yes)"
          READ (*,*) iog
```

```
            WRITE (*,*) "Use ADYN to route (1) or just build geometry (0)?"
            READ (*,*) iroute
            WRITE (*,*) "Dump Q,H? (0=no dump, 1=dump)"
            READ (*,*) idmpqh
            WRITE (*,*) "Build plot file? (0=no, 1=yes)"
            READ (*,*) iplt
            WRITE(5,'(16I5)') 1,iog,0,iroute,1,idmpqh,iplt,1

!Get information from geo file and write line 2 for .aii
            READ(1,*) nxsec,iseco,ixsec
            WRITE (5,'(16I5)') nxsec,iseco,ixsec,0
            READ(1,*) identifiers

!Get information from user and write line 3 for .aii
      WRITE (*,*)"Enter 3 milleages for which geom table is desired:"
            READ (*,*) rmiog1, rmiog2, rmiog3
            WRITE (5,'(10F8.2)') 50.0,0.0, rmiog1,rmiog2,rmiog3,0.0,0.0

!Read information from Geo file write lines 4-10 for each cross-section
            DO
                        READ(1,"(I2,6F6.2,5F8.2,I2,3F6.3)")  no, rmi ,
            1            (x(I),I=1,no), (elev(I),I=1,no), nns, frn, kce1,kce2
                WRITE (5,"(I5,F8.2)") no, rmi
                        WRITE (5,"(10F8.2)") (elev(I), I=1,no)
                        WRITE (5,"(10F8.2)") (x(I), I=1,no)
                        WRITE (5,"(I5)") nns
                        WRITE (5,"(10F8.3)") frn
                        IF (kce1 .lt. 0 .and. kce2 .lt. 0) THEN
                         !End of Cross-sections do not write kce1 and kce2
                 GOTO 130
                ELSE
                         WRITE (5,"(10F8.2)") kce1,kce2
                ENDIF
            ENDDO

 130  CONTINUE

!Get boundary conditions and write line 12 of .aii
            WRITE (*,*) "Enter beginning date of simulation (YYMMDD)."
            WRITE (*,*) "The clock will start on hour 24 of that day."
            READ (*,*) date
            WRITE (*,*) "Enter time step and print interval (hours):"
            READ (*,*) dt, prt
      WRITE (5,'(I6,5F8.2,A40)') date,24.00,dt,prt,dt,dt,
            2"begd/begt/dt/prt/plt/qdt"
```

```
!Get upstream boundary conditions from input file and print.
!Assumed upstream boundary is a discharge hydrograph, model calculates downstream
!Write lines 13-16 of .aii
    WRITE(5,"(2I5,A40)") 1,1,"Main Channel Boundary Conditions"
        READ(2,*) hi,nord,ifmt,isopt
        WRITE(5,'(F8.2)') hi
        WRITE(5,'(3I5)') nord,ifmt,isopt
        READ(2,'(A)') identifiers
    DO i=1,nord
         READ(2,"(12X,F10.0)") w(i)
        ENDDO
        WRITE(5,'(8F10.0)') (w(i),i=1,nord)

!Get downstream boundary conditions. (For IDSBC = 1 meaning the model calculates,
! no downstream conditions are needed. If this is changed the logic may be added here.)
!IDSBC = 1, records 17-21 omitted.


!Get internal boundary conditions for special nodes. This code is setup with NC(J) = 0,
! meaning there are no internal boundary conditions. If this is changed, logic can be
added here.
!NC(J) = 0, records 22-26 omitted

!Get lateral inflows.
!Write record 27 (.aii)
        WRITE(*,*) "Enter the number of lateral inflows:"
        READ(*,*) nqlh
        WRITE(5,'(I5)') nqlh
    IF (nqlh .gt.0) THEN
200      WRITE(*,*) "Enter the lateral inflow input file name:"
         READ(*,*) latname
         OPEN (3, file=latname, status='OLD', ERR=210)
         GOTO 220

        !Error handler
210       WRITE (*,*) "Error, could not open file:", latname
          WRITE (*,*) "Try again? (y/n)"
          READ (*,*) yesno
          IF (yesno == "y".or. yesno == "Y") THEN
                GOTO 200
          ELSE
                WRITE (*,*) "RMS PreProcessor aborting."
          ENDIF
```

```
        !Got the file, ok to proceed
220     Continue
        READ (3,*) hi,nord,ifmt,isopt
        READ (3,*) identifiers
!Write records 27-29 (.aii)
        WRITE(5,'(F8.2)') hi
        WRITE(5,'(3I5)') nord,ifmt,isopt
!Read lateral inflow hydrographs from lateral inflow text file
!Write records 30-31 (.aii)
    DO i=1,nqlh
         READ(3,*) rmlat1,rmlat2
             DO j=1,nord
              READ (3,"(14X,F10.0)") qlat(j)
         ENDDO
        WRITE (5,'(2F8.2)') rmlat1,rmlat2
        WRITE (5,'(8F10.0)') (qlat(j),j=1,nord)
        ENDDO
       ELSE
        CONTINUE
       ENDIF

!Get initial conditions: assumed initial conditions entered only at downstream end
!Write records 32-34 (.aii)
       WRITE(*,*) "Enter initial condition at end node (RM,Q,Elev):"
       READ(*,*) rmic,qic,elic
       WRITE(5,'(I5)') 0
       WRITE(5,'(3F8.2)') rmic,qic,elic
       WRITE(5,'(F8.0)') -100.

!Get numerical solution control information
!Write record 35 (.aii)
    WRITE(*,*) "What type of numerical scheme? (I/E)"
       READ(*,*) isolv
       WRITE(*,*) "What value of theta for spacial derivatives? (0-1)"
       READ(*,*) theta
       WRITE(5,'(F8.3,4X,A1,3F8.3)') 0.02,isolv,theta,0.005,0.005
       WRITE (*,*) "RMSPP done."

   END
```

C.2 Preprocessor for RQUAL

```
! 12/17/01
!
! Program RMSPP2: A preprocessor for the RQUAL Water Quality Coefficients input
! file (.ric) for RMS by TVA for simulation of water temperature only in conjuction
```

```
! with two bank shading parameters.
!
!       By Alida Abbott
!
! This program reads text files created in EXCEL and saved as .prn and merges
! them data input by the user to form a complete WQC input file.
!
! The function of this program is to format the river aspect at each node and fill
! in zeros for the water quality parameters other than temperature.
!
! INPUT FILE:  The river aspect file should be in two columns, the first 15 spaces
! can be used as an identifer with river mile and node number, the second column should
! contain the river aspect.
!
! The only user inputs are the river aspects, and the initial conditions
! the following values are hardwired into this program:
!
!       PRT          Print interval in hours for output             1 hour
!       IPLT         Plot output flag (0= no plot, 1=plot)          1
!       THET         Spatial derivative weighting factor            0.5
!       TSI          model testing coeff. (dummy variable)          1.0
!       I02R         flag to caputre T and DO process rate          1.0
!       PLT          Plot file interval in hours                    1.0
!       ROUTE        Numerical scheme (I, E, H)                     I
!       PDC          Limits for H-P scheme                          0.0
!       PDCS         "              "                               0.0
!       IRS          Flag to use new shading logic         1
!       alphx(i)     not used in current model                      0.0
!       PHI          latitude of river                              41.875
!       ALON         longitude of river                             122.63
!       TZM          no longer an input, model calculations         blank
!       TFOG         time of fog lift                               6:00 am
!       BW(i)        bank width                                     0.0
!       AA           windspeed coefficient                          3.0E-09
!       BB           "                        "                     1.4E-09
!       XL,XL2       channel bed thickness (upper,lower)            10 cm, 50 cm
!       DIF          thermal diffusivity of bed (=0 turns of bed logic) 0
!       CV           bed heat storage capacity                              0.68
!       BETW         fraction of solar rad. absorbed in
!                    surface 0.6 m of water                         0.4
!       BEDALB       albedo of bed material                         0.25
!       SHDBT        fraction drybulb/dewpoint depression                   1.0
!                    by which drybulb is coller over shaded water
!       THR          temp correction coef. for reaeration                   99.0
!       THB          temp correction ceof. for BOD decay                    99.0
```

```
!       BK20        BOD deoxygenation rate                          0.0
!       THN         temp correction ceof for NOD decay              99.0
!       NK20        NOD deoxygenation rate                          0.0
!       THS         temp correction coef. for SOD                   99.0
!       EXCO        light extinction coeff                          0.0
!       HMAC                average weed height                             0.0
!       THPR        temp correction coeff for photo/resp            99.0
!       IK2EQ       reaeration equation choice                      0.0
!       BS20        BOD settling rate                               0.0
!       WFAC        factor to reduce weir aeration                  0.0
!       SFAC(i)     factor to multiply all SK20 to test sensitivty  0.0
!       PFAC(i)     factor to multiply all PMAX to test sensitivty          0.0
!       RFAC(i)     factor to multiply all RESP to test sensitivty  0.0
!-----------------------------------------------------------------------------------------------------

        program RMS_PP2
        implicit none

        character (80) aname,yesno*1,title1,outname
        integer numnodes,i,no
        real rmic,tinit,binit,ninit
        real, dimension (500) :: alphx, aspect,bw,sfac,pfac,rfac

! Get file names of input files and open files

        !Ask user for file name
100     WRITE (*,*) "Enter aspect input file name:"
        READ(*,*) aname

        !Try to open file
    OPEN (1, file=aname, status='OLD', ERR=110)
        GOTO 120

        !Error handler
110     WRITE (*,*) "Error, could not open file:", aname
        WRITE (*,*) "Try again? (y/n)"
        READ (*,*) yesno
        IF (yesno == "y".or. yesno == "Y") THEN
                GOTO 100
        ELSE
                WRITE (*,*) "RMS PreProcessor2 aborting."
        ENDIF

        !Got the files, ok to proceed
120     Continue
```

```
!Get output file name and open file
        WRITE (*,*) "Enter output file name"
        READ (*,*)    outname
        WRITE (*,*) "Output file name:", outname
        OPEN (5, file=outname, STATUS='unknown')

!Read input file title
        READ(1,"(A80)") title1


!Write record 1 for .ric (PRT,IPLT,THET,TSI,I02R,PLT,ROUTE,PDC,PDCS,IRS)
        WRITE(5,'(F8.1,I5,2F8.1,I5,F8.1,4X,A1,2F8.1,I5)') 1.0,1,0.5,1.0,1,
    21.0,'I',0.0,0.0,1

!Write record 2 for .ric
        WRITE (*,*) "Enter the number of nodes:"
        READ (*,*) numnodes
        DO I=1,numnodes
          alphx(i)=0.0
        ENDDO
        WRITE (5,"(10F8.2)") (alphx(I), I=1,numnodes)

!Write record 3 for .ric PHI,ALON,TZM,TFOG (phi=lat of river, alon=lon of river)
        WRITE (5,'(2F8.3,8X,F8.2)') 41.875,122.63,6.0

!Read information from aspect file write record 4 for .ric
        DO i=1,numnodes
          READ(1,"(15X,F8.2)")  aspect(i)
        ENDDO
        WRITE (5,"(10F8.2)") (aspect(I), I=1,numnodes)


!Write record 5 of .ric (Bank Width is considered 0.0 for the Shasta River)
        DO i=1,numnodes
          BW(i)=0.0
        ENDDO
        WRITE (5,"(10F8.2)") (bw(I), I=1,numnodes)

!Skip EBH (record 6) due to new shading logic input file.

!Write record 7 to .ric Leave out SHSOL due to new shading logic input file
!AA,BB,XL,XL2,DIF,CV,BETW,BEDALB,SHDBT  where AA,BB are windspeed
coefficients
!This line turns off the bed conduction term by setting DIV = 0.0
```

```
          WRITE(5,'(2A8,8F8.2)')'3.0E-09','1.4E-09',10.,50.,0.,0.68,0.4,1.0,
          21.0

!Write record 8 (.ric)
!THR,THB,BK20,THN,NK20,THS,EXCO,DMAC,THPR,IK2EQ
!These are the rate coefficients for water quality parameters, they must be
!entered even when only modeling temperature
          WRITE (5,'(9F8.2,I5)') 99.0,99.0,0.0,99.0,0.0,99.0,0.0,0.0,99.0,0

!Write record 9 (.ric)
!BS20,WFAC
          WRITE(5,'(3F8.0)') 0.0, 0.0


!Write record 10 (.ric) SFAC = 0.0
          DO i=1,numnodes
            SFAC(i)=0.0
          ENDDO
          WRITE (5,"(F8.1)") 0.0
     WRITE (5,"(10F8.2)") 0.0,(sfac(I), I=1,numnodes)

!Write record 11 (.ric) PFAC = 0.0
          DO i=1,numnodes
            PFAC(i)=0.0
          ENDDO
          WRITE (5,"(F8.1)") 0.0
     WRITE (5,"(10F8.2)") 0.0,(pfac(I), I=1,numnodes)

!Write record 12 (.ric) RFAC = 0.0
          DO i=1,numnodes
            RFAC(i)=0.0
          ENDDO
          WRITE (5,"(F8.1)") 0.0
     WRITE (5,"(10F8.2)") 0.0,(rfac(I), I=1,numnodes)

!Write record 13 (.ric) The initial conditions. Need to be entered at at least two nodes
!RMIC= river mile of IC, TINIT=ini temp, BINIT= ini BOD, NINIT = ini NOD
          WRITE (*,*) "Enter number of initial conditions (at least two):"
          READ (*,*) no
          DO i=1, no
            WRITE(*,*) "Enter river mile of initial condition:"
            READ (*,*) rmic
            WRITE(*,*) "Enter initial temperature in degrees c:"
            READ (*,*) tinit
            WRITE(*,*) "Enter initial BOD concentration in mg/l:"
```

```
        READ (*,*) binit
        WRITE(*,*) "Enter initial NOD concentration in mg/l:"
        READ (*,*) ninit
        WRITE (5,'(10F8.2)') rmic,tinit,binit,ninit
      ENDDO
      WRITE(5,'(F8.1)') -100.0

      WRITE (*,*) "RMSPP2 done."

END
```

Appendix D: File Listing for Management Alternatives

In simulating management alternatives, four specific management schemes were investigated: flow regime changes, pulse flows, shading reach-by-reach, and tailwater flows. In all, over 60 simulations were made for the investigation of alternative management schemes that included flow regime changes (30), pulse flows (2), shading reach-by-reach (15), and tailwater flows (16). Additionally, three (3) base-case simulations were made for comparisons. The following tables list all input files used in simulations of management alternatives.

D.1 Base Cases

Base Case

#	Period	add Q (cfs)	at	ADYN input (.aii)	Meterology	Inflow Tw	Coeffs & ICs	Shade
1	Jun	--	--	Jun.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
2	Aug	--	--	Aug.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
3	Sep	--	--	Sep.aii	1DaySep.rim	Sep.rib	Shasta.ric	ExitingShade.ris

D.2 Flow Regime

Title	Flow Regime
Abbreviation	Flow
Objective	Determine effects of altering flow regime in Shasta River by adding water from management of diversions.

Scenario 1: 10 cfs of flow added at top of each reach

#	Period	add Q (cfs)	at	ADYN input (.aii)	Meterology	Inflow Tw	Coeffs & ICs	Shade
4	Jun	10	SRP	Jun-SRP-10.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
5	Jun	10	GID	Jun-GID-10.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
6	Jun	10	A12	Jun-A12-10.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
7	Jun	10	DWR	Jun-DWR-10.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
8	Jun	10	AND	Jun-AND-10.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
9	Aug	10	SRP	Aug-SRP-10.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
10	Aug	10	GID	Aug-GID-10.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
11	Aug	10	A12	Aug-A12-10.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
12	Aug	10	DWR	Aug-DWR-10.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
13	Aug	10	AND	Aug-AND-10.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
14	Sep	10	SRP	Sep-SRP-10.aii	1DaySep.rim	Sep.rib	Shasta.ric	ExitingShade.ris
15	Sep	10	GID	Sep-GID-10.aii	1DaySep.rim	Sep.rib	Shasta.ric	ExitingShade.ris

D.2 Flow Regime, continued

Title	Flow Regime, cont.
Abbreviation	Flow
Objective	Determine effects of altering flow regime in Shasta River by adding water from management of diversions.

Scenario 2; 20 cfs of flow added at top of each reach

#	Period	add Q (cfs)	at	ADYN input (.aii)	Meterology	Inflow Tw	Coeffs & ICs	Shade
19	Jun	20	SRP	Jun-SRP-20.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
20	Jun	20	GID	Jun-GID-20.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
21	Jun	20	A12	Jun-A12-20.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
22	Jun	20	DWR	Jun-DWR-20.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
23	Jun	20	AND	Jun-AND-20.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
24	Aug	20	SRP	Aug-SRP-20.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
25	Aug	20	GID	Aug-GID-20.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
26	Aug	20	A12	Aug-A12-20.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
27	Aug	20	DWR	Aug-DWR-20.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
28	Aug	20	AND	Aug-AND-20.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
29	Sep	20	SRP	Sep-SRP-20.aii	1DaySep.rim	Sep.rib	Shasta.ric	ExitingShade.ris
30	Sep	20	GID	Sep-GID-20.aii	1DaySep.rim	Sep.rib	Shasta.ric	ExitingShade.ris

D.3 Pulse Flows

Title	Pulse Flow
Abbreviation	Pulse
Objective	Determine the effect of a pulse flow on the temperature regime of the Shasts River

Base case

#	Condition	Flow	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
1	Jun	All	All_Jun.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris

Scenario 1: Sequentially applied pulse flows

#	Condition	Flow	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
2	Sequential	All	All_Pulsed.aii	1DayJun.rim	Pulse.rib	Shasta.ric	ExitingShade.ris

Scenario 2: Simultaneously applied pulse flows

#	Condition	Flow	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
3	Simultaneous	All	All_Together.aii	1DayJun.rim	Pulse.rib	Shasta.ric	ExitingShade.ris

D.4 Shade Study

Title	Shading Reach-by-Reach
Abbreviation	Shade
Objective	Determine the effect of revegetation on the temperature regime of the Shasts River

Base Cases

#	Period	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
1	Jun	Jun.aii	1DayJun.rim	Jun.rib	Shasta.ric	ExitingShade.ris
2	Aug	Aug.aii	1DayAug.rim	Aug.rib	Shasta.ric	ExitingShade.ris
3	Sep	Sep.aii	1DaySep.rim	Sep.rib	Shasta.ric	ExitingShade.ris

Scenario 1: Shade Reach 1

#	Period	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
4	Jun	Jun.aii	1DayJun.rim	Jun.rib	Shasta.ric	Reach1.ris
5	Aug	Aug.aii	1DayAug.rim	Aug.rib	Shasta.ric	Reach1.ris
6	Sep	Sep.aii	1DaySep.rim	Sep.rib	Shasta.ric	Reach1.ris

Scenario 2: Shade Reach 2

#	Period	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
7	Jun	Jun.aii	1DayJun.rim	Jun.rib	Shasta.ric	Reach2.ris
8	Aug	Aug.aii	1DayAug.rim	Aug.rib	Shasta.ric	Reach2.ris
9	Sep	Sep.aii	1DaySep.rim	Sep.rib	Shasta.ric	Reach2.ris

Scenario 3: Shade Reach 3

#	Period	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
10	Jun	Jun.aii	1DayJun.rim	Jun.rib	Shasta.ric	Reach3.ris
11	Aug	Aug.aii	1DayAug.rim	Aug.rib	Shasta.ric	Reach3.ris
12	Sep	Sep.aii	1DaySep.rim	Sep.rib	Shasta.ric	Reach3.ris

D.4 Shade Study, continued

Title	Shading Reach-by-Reach, cont.
Abbreviation	Shade
Objective	Determine the effect of revegetation on the temperature regime of the Shasts River

Scenario 4: Shade Reach 4

#	Period	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
13	Jun	Jun.aii	1DayJun.rim	Jun.rib	Shasta.ric	Reach4.ris
14	Aug	Aug.aii	1DayAug.rim	Aug.rib	Shasta.ric	Reach4.ris
15	Sep	Sep.aii	1DaySep.rim	Sep.rib	Shasta.ric	Reach4.ris

Scenario 5: Shade Reach 5

#	Period	ADYN input	Meterology	Inflow Tw	Coeffs & ICs	Shade
16	Jun	Jun.aii	1DayJun.rim	Jun.rib	Shasta.ric	Reach5.ris
17	Aug	Aug.aii	1DayAug.rim	Aug.rib	Shasta.ric	Reach5.ris
18	Sep	Sep.aii	1DaySep.rim	Sep.rib	Shasta.ric	Reach5.ris

D.5 Tailwater Study

Title	Tailwater study
Abbreviation	Tail
Objective	Determine the effects of varying temperture and location of tailwater lateral flows on the temperature regime of the Shasts River

Scenario1: Pt inflow

#	Upstrm Q	Tailwtr Q	Pt/Dist	Upstrm Tw	Period	ADYN input (.aii)	Meterology	Inflow Tw	Coeffs & ICs	Shade
1	20	5	Pt	15	Jun	Q20-5-Pt.aii	1DayJun.rim	JunTail-15.rib	Shasta.ric	ExitingShade.ris
2	20	5	Pt	20	Jun	Q20-5-Pt.aii	1DayJun.rim	JunTail-20.rib	Shasta.ric	ExitingShade.ris
3	20	5	Pt	15	Sep	Q20-5-Pt.aii	1DaySep.rim	SepTail-15.rib	Shasta.ric	ExitingShade.ris
4	20	5	Pt	20	Sep	Q20-5-Pt.aii	1DaySep.rim	SepTail-20.rib	Shasta.ric	ExitingShade.ris
5	20	10	Pt	15	Jun	Q20-10-Pt.aii	1DayJun.rim	JunTail-15.rib	Shasta.ric	ExitingShade.ris
6	20	10	Pt	20	Jun	Q20-10-Pt.aii	1DayJun.rim	JunTail-20.rib	Shasta.ric	ExitingShade.ris
7	20	10	Pt	15	Sep	Q20-10-Pt.aii	1DaySep.rim	SepTail-15.rib	Shasta.ric	ExitingShade.ris
8	20	10	Pt	20	Sep	Q20-10-Pt.aii	1DaySep.rim	SepTail-20.rib	Shasta.ric	ExitingShade.ris
9	50	5	Pt	15	Jun	Q50-5-Pt.aii	1DayJun.rim	JunTail-15.rib	Shasta.ric	ExitingShade.ris
10	50	5	Pt	20	Jun	Q50-5-Pt.aii	1DayJun.rim	JunTail-20.rib	Shasta.ric	ExitingShade.ris
11	50	5	Pt	15	Sep	Q50-5-Pt.aii	1DaySep.rim	SepTail-15.rib	Shasta.ric	ExitingShade.ris
12	50	5	Pt	20	Sep	Q50-5-Pt.aii	1DaySep.rim	SepTail-20.rib	Shasta.ric	ExitingShade.ris
13	50	10	Pt	15	Jun	Q50-10-Pt.aii	1DayJun.rim	JunTail-15.rib	Shasta.ric	ExitingShade.ris
14	50	10	Pt	20	Jun	Q50-10-Pt.aii	1DayJun.rim	JunTail-20.rib	Shasta.ric	ExitingShade.ris
15	50	10	Pt	15	Sep	Q50-10-Pt.aii	1DaySep.rim	SepTail-15.rib	Shasta.ric	ExitingShade.ris
16	50	10	Pt	20	Sep	Q50-10-Pt.aii	1DaySep.rim	SepTail-20.rib	Shasta.ric	ExitingShade.ris

D.5 Tailwater Study, continued

Title	Tailwater study, cont.
Abbreviation	Tail
Objective	Determine the effects of varying temperture and location of tailwater lateral flows on the temperature regime of the Shasts River

Scenario2: Distributed inflow

#	Upstrm Q	Tailwtr Q	Pt/Dist	Upstrm Tw	Period	ADYN input (.aii)	Meterology	Inflow Tw	Coeffs & ICs	Shade
17	20	5	Dist	15	Jun	Q20-5-Dist.aii	1DayJun.rim	JunTail-15.rib	Shasta.ric	ExitingShade.ris
18	20	5	Dist	20	Jun	Q20-5-Dist.aii	1DayJun.rim	JunTail-20.rib	Shasta.ric	ExitingShade.ris
19	20	5	Dist	15	Sep	Q20-5-Dist.aii	1DaySep.rim	SepTail-15.rib	Shasta.ric	ExitingShade.ris
20	20	5	Dist	20	Sep	Q20-5-Dist.aii	1DaySep.rim	SepTail-20.rib	Shasta.ric	ExitingShade.ris
21	20	10	Dist	15	Jun	Q20-10-Dist.aii	1DayJun.rim	JunTail-15.rib	Shasta.ric	ExitingShade.ris
22	20	10	Dist	20	Jun	Q20-10-Dist.aii	1DayJun.rim	JunTail-20.rib	Shasta.ric	ExitingShade.ris
23	20	10	Dist	15	Sep	Q20-10-Dist.aii	1DaySep.rim	SepTail-15.rib	Shasta.ric	ExitingShade.ris
24	20	10	Dist	20	Sep	Q20-10-Dist.aii	1DaySep.rim	SepTail-20.rib	Shasta.ric	ExitingShade.ris
25	50	5	Dist	15	Jun	Q50-5-Dist.aii	1DayJun.rim	JunTail-15.rib	Shasta.ric	ExitingShade.ris
26	50	5	Dist	20	Jun	Q50-5-Dist.aii	1DayJun.rim	JunTail-20.rib	Shasta.ric	ExitingShade.ris
27	50	5	Dist	15	Sep	Q50-5-Dist.aii	1DaySep.rim	SepTail-15.rib	Shasta.ric	ExitingShade.ris
28	50	5	Dist	20	Sep	Q50-5-Dist.aii	1DaySep.rim	SepTail-20.rib	Shasta.ric	ExitingShade.ris
29	50	10	Dist	15	Jun	Q50-10-Dist.aii	1DayJun.rim	JunTail-15.rib	Shasta.ric	ExitingShade.ris
30	50	10	Dist	20	Jun	Q50-10-Dist.aii	1DayJun.rim	JunTail-20.rib	Shasta.ric	ExitingShade.ris
31	50	10	Dist	15	Sep	Q50-10-Dist.aii	1DaySep.rim	SepTail-15.rib	Shasta.ric	ExitingShade.ris
32	50	10	Dist	20	Sep	Q50-10-Dist.aii	1DaySep.rim	SepTail-20.rib	Shasta.ric	ExitingShade.ris