CHAPTER 5. ANALYTICAL APPROACH AND METHODS

5.1 Introduction

Chapters 3 and 4 identify the sources and factors affecting stream temperature and dissolved oxygen concentrations in the Shasta River watershed. This chapter outlines the analytical methods used to quantify the TMDL load allocations attributed to these sources.

The Section 303(d) listings for the Shasta River address the entire Shasta River watershed. The analysis focuses on the mainstem of the Shasta River from Dwinnell Dam to the mouth for the following reasons:

- Dissolved oxygen and temperature impairments are well documented for the mainstem (see Chapter 2), and thus are more suitable for detailed analysis.
- Sources contributing to the impairments affect both the mainstem and the tributaries.
- The mainstem analysis is based on models that describe processes affecting the listed constituents. The general conclusions reached in the mainstem analysis will apply to other similar locations in the watershed.
- For temperature conditions in tributaries, detailed analysis in other similar landscapes has identified riparian shade as a key factor influencing stream temperatures, which can be influenced by human activities. Because this general conclusion is applicable to the Shasta watershed, separate temperature analysis was not performed on tributaries.
- Actions addressing temperature and dissolved oxygen apply to the mainstem and tributaries, and thus water quality improvements predicted for the mainstem can be expected in tributaries as well.

In short, actions that lead to water quality compliance in the portion of the mainstem analyzed are also expected to lead to water quality compliance in other parts of the mainstem and in the tributaries.

5.2 Analytic Approach and Model Selection

The analytical approach used to quantify allocations to the sources and factors affecting stream temperature and dissolved oxygen concentrations in the Shasta River relies on the use of computer simulation models. The processes that determine stream temperature and dissolved oxygen concentrations are inherently complex and non-linear. The degree to which one factor can impact stream temperature or dissolved oxygen concentration is dependent on the state of numerous other factors involved. For example, as outlined in Chapters 3, the temperature of the Shasta River is dependent on the interacting effects of the headwater temperature regime, surface water diversions, shade, and the temperature and quantity of tailwater return flows and tributary inflows. Further, as outlined in Chapter 4, dissolved oxygen concentrations of the Shasta River depend on water temperature, photosynthetic and respiration rates of aquatic vegetation, sediment oxygen demand rates, consumption of oxygen via nitrification and biochemical oxygen demand, and flow. Many computer simulation water quality models have been developed to depict stream temperature and dissolved oxygen conditions and dynamics. However, not all water quality models are suited for evaluating the particular factors that affect temperature and dissolved oxygen in the Shasta River watershed.

Regional Water Board staff selected the Tennessee Valley Authority's River Modeling System (RMS) as the primary analytical tool for developing the Shasta River temperature and dissolved oxygen TMDLs. In addition, a benthic algae box model was employed to evaluate the connection between nutrient concentrations and potential primary production in the Shasta River; a process not included in the RMS model. The components of the benthic algae box model are presented in Section 5.7.

The following text on model selection for the Shasta River TMDL is from the *Technical Memorandum: TVA River Modeling System: ADYN and RQUAL-RMS Model Specifications and Background* dated August 17, 2005 (Deas 2005c). This document is included as Appendix C and contains further discussion of the models considered for use in developing the Shasta River TMDLs.

> 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 for several reasons, including, but not limited to the fact that it is readily available in the public domain, has been widely applied to both temperature and dissolved oxygen assessments, contains detailed shading logic, allows for modeling at an hourly time step, is well documented, and is supported by TVA. Further, the model was already implemented, configured, and calibrated for flow and temperature on the Shasta River system. The primary modification was the addition of the necessary water quality modeling components applied to represent dissolved oxygen conditions for TMDL assessment.

Appendix D (*Shasta River Flow, Temperature, and Dissolved Oxygen Model Calibration Technical Report*) provides a detailed summary of the RMS model set up and calibration for the Shasta River TMDLs. This chapter provides a summary of the components and application of the model, with reference to applicable sections in Appendix D.

As identified above, the Shasta River TMDL modeling effort built upon previous flow and temperature modeling of the Shasta River conducted by Watercourse Engineering for the Shasta Valley RCD. Reports on these previous modeling efforts include Deas et al. (2003) and Watercourse Engineering, Inc. (2004). Characterization of riparian vegetation conditions was based in part on Deas et al. (1997).

5.3 River Modeling System - Model Components

RMS has two components that may be used independently or in sequence: the hydrodynamic model (ADYN) and the water quality model (RQUAL). These model components are discussed below.

5.3.1 The Hydrodynamic Component: ADYN

ADYN is a one-dimensional hydrodynamic model. The following text regarding ADYN is taken from *Shasta River Temperature and Flow Modeling Project* (Deas et al. 2003), which is included as Electronic Appendix E_e and utilizes information from the RMS User's Manual (Hauser 1995 as cited by Deas et al. 2003).

> 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.

5.3.2 The Water Quality Component: RQUAL

The following text regarding RQUAL is adapted from Deas et al. (2003) and describes RQUAL for the current model application.

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. This application employs the temperature and dissolved oxygen modeling capabilities. 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 high flow and turbulent river systems where transport is the dominant factor. Numerical dispersion serves to account for the lack of an explicit dispersion term (Hauser, pers. comm. 1995 as cited by Deas et al. 2003).

The heat budget (discussed in Section 5.3.2.1 below) used in RQUAL includes logic for bed heat exchange and riparian shading. 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 Deas et al. (2003) and are identified in Section 5.5.2 below. 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 would be made to the model to account for it. For the Shasta River, the only potential for topographic shading of this type occurs in the canyon between the Mouth and RM 7. For this modeling effort the effect of topographic shading was not considered.

5.3.2.1 <u>The Temperature Component of RQUAL - Heat Budget</u>
The following discussion regarding RQUAL Heat Budget formulation is from Deas et al. (2003).

> 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)

For detailed discussion of each of the heat budget components, the reader is referred to Section 2.2.1 through 2.3.3 of Deas et al. (2003). Deas et al. (2003) is included as Electronic Appendix E_e (*Shasta River Flow and Temperature Modeling Project*) of this report.

5.3.2.2 The Dissolved Oxygen Component of RQUAL

The RQUAL model simulates dissolved oxygen conditions in response to biochemical oxygen demand (BOD), nitrogenous biochemical oxygen demand (NBOD), sediment oxygen demand (SOD), mechanical reaeration, and photosynthesis and respiration of aquatic vegetation growing on or in the bed (as periphyton or macrophytes).

The following discussion regarding RQUAL dissolved oxygen formulation is from Geisler and Watercourse Engineering, Inc. (2005), which is included as Appendix D of this report.

Dissolved oxygen, carbonaceous biochemical oxygen demand (CBOD), and nitrogenous biochemical oxygen demand (NBOD) are represented in the RQUAL model. The time varying representation of dissolved oxygen is:

$$\Sigma[\partial O/\partial t] = K_2(O_s-O)-K_dL-K_nN+(P-R-S)/D$$

Where

t = time (s)

O = dissolved oxygen concentration (mg/L)

O_s = saturation dissolved oxygen concentration (mg/l) (based on elevation and water temperature (See TVA, 2001))

K_2 = reaeration rate based on one of several methods (see TVA, 2001), temperature corrected (1/s)

K_d = CBOD deoxygenation rate, temperature corrected (1/s)

L = CBOD concentration (mg/L)

K_n = NBOD deoxygenation rate, temperature corrected (1/s)

N = NBOD concentration (mg/L)

P = Photosynthetic rate of macrophytes (gO_2/m^2-s)

R = Respiration rate of macrophytes (gO_2/m^2-s)

S = Sediment oxygen demand (gO_2/m^2-s)

D = mean depth (m)

CBOD and NBOD are both represented as first order decay:

$$\Sigma[\partial L/\partial t] = -(K_d+K_s)/L$$

and

$$\Sigma[\partial N/\partial t] = -K_nN$$

Where

K_s = CBOD settling rate (no oxygen demand exerted) (1/s)

and t, L, N, K_d, K_n are as defined previously.

Note that the units of time represented in the above equation may differ from the model's required input values. For example, although all temporal units identified above are represented in seconds, model input decay rates are 1/day.

5.4 RMS Model Set Up and Boundary Conditions

The sections in the remainder of this chapter primarily serve as a road map referencing sections in Appendix D (Geisler and Watercourse Engineering, Inc. 2005). The following section addresses the model input parameter values and boundary conditions selected for model calibration and validation.

5.4.1 Hydrodynamics

Section 3.0 in Appendix D describes the update of the ADYN geometry input file, which included extending the model from the confluence at Parks Creek upstream to Dwinnell Dam, as well as updating the hydrographic representation of the Shasta River to reflect the most current spatial information.

Section 4.0 in Appendix D describes the water balance calculation for the updated geometry of the river. In addition, hydrodynamic input locations and types are identified.

Representation of stream flows and calibration procedures are discussed in Deas and Geisler (2004), which is included as Appendix E (*Memorandum: Shasta River flow and temperature modeling implementation, testing, and calibration*) of this report.

5.4.2 Temperature

Section 5.1.1 in Appendix D presents the temperature trace associated with the headwater condition, point inputs, and distributed inputs for the calibrated/validated model. Section 5.3 in Appendix D presents the pertinent model input parameter names, description, value, and notes regarding the rationale for value selection.

5.4.3 Dissolved Oxygen

Section 5.1.2 in Appendix D presents the dissolved oxygen trace associated with the headwater condition, point inputs, and distributed inputs for the calibrated/validated model. In addition, the CBOD and NBOD boundary conditions used for model calibration/validation are identified. Section 5.3 in Appendix D presents the pertinent model input parameter names, description, value, and notes regarding the rationale for value selection. SOD rates and macrophytic photosynthetic and respiration rates are included.

5.5 RMS Model Calibration and Validation

Section 1.1 in Appendix D identifies the calibration and two validation time periods selected.

5.5.1 Flow

The principal parameter adjusted for flow calibration was Manning's roughness coefficient, n. Section 6.1 in Appendix D presents the simulated versus measured flow for several locations along the Shasta River for the calibration and validation periods. Statistics for the final calibrated flow model are also tabulated. Daily trends are well represented; however, sub-daily deviations are apparent. Because the water balance was completed on a reach level at a daily time scale, it does not represent intra-reach diversions and return flows, and does not capture intra-day variations in diversions and return flows. As a result, modeled sub-daily flows show deviations from observed sub-daily flows.

5.5.2 Temperature

Water temperature calibration consisted primarily of modifying the evaporative heat flux coefficients, AA (m^3/mb-s) and BB (m^2/mb), for the equation ψ = AA + BB*wind. The thermal diffusivity of bed material, K (cm^2/hr), was also modified, but ultimately set to the default value. Section 6.2 in Appendix D presents the process of calibration for stream temperature, and presents the simulated versus measured temperature for several locations along the Shasta River for the calibration and validation periods. Statistics of the calibration and validation runs are also tabulated. Modeled temperatures in the upper reaches and valley reaches match up well with the measured phase and amplitude of the daily temperature trace. Simulated values at the mouth are generally under-predicted, particularly for the daily minimum, and may lag in phase slightly.

5.5.3 Dissolved Oxygen

Section 6.3 in Appendix D discusses the dissolved oxygen calibration process and presents the calibration and validation results. Simulated dissolved oxygen concentrations generally matched measured values well, capturing the amplitude and phasing of the dissolved oxygen signal.

5.6 RMS Sensitivity Analysis

Section 7.0 in Appendix D discusses the parameters for which sensitivity analyses were performed. The statistics associated with each of the sensitivity analyses are presented in Section 9.0 in Appendix D.

With respect to dissolved oxygen, CBOD, and NBOD decay rates were largely insensitive (meaning they had little effect on model outputs), as was the SOD rate. The driving factor for dissolved oxygen was maximum photosynthetic and respiration rate. These values were adjusted during calibration to fit the model to measured data. Reaeration rate, a calculated term within the model, played a pivotal role, particularly in the steep canyon reach where mechanical reaeration would be expected to occur.

5.7 Benthic Algae Box Model

The water quality component of RMS does not simulate the effect of nutrient concentrations on aquatic vegetation primary productivity. Therefore, in addition to applying the RMS model for developing the Shasta River TMDLs, an algae box model was applied in order to evaluate the connection between nutrient concentrations and primary production (photosynthesis and respiration of aquatic vegetation) in the Shasta

River. The Shasta River Benthic Algae Box Model (algae model) was applied by Deas (2005b) as reported in Appendix F (*Technical Memorandum: Shasta River Algae Box Model*).

5.7.1 Algae Model Components

The algae model predicts Shasta River aquatic vegetation, termed "periphyton" by Deas (2005b), biomass based on limiting factors such as light and nutrients, as well as on respiration and mortality rates. Scouring and shading were also included. The algae model is a simplification of the dynamics of the Shasta River, but nonetheless provides valuable insights into the response of periphyton biomass to nutrient concentrations in a river like the Shasta.

The mass balance equation for iteration of the Shasta River Benthic Algae Model is presented below:

$$P_{t+\Delta t} = P_t + \Delta t\left((\mu_{\max} LF - R_b - D_b - Z_b)P_t - \frac{s\,v P_t}{d}\right) \qquad \text{(Eq 4.3)}$$

Where:

Δt	= change in time (d)
P_t	= benthic algae biomass (mg/m^2) at current time step
$P_{t+\Delta t}$	= benthic algae biomass (mg/m^2) at next time step
μ_{max}	= maximum algal growth rate (1/d)
LF	= limiting factor (unitless)
R_b	= algal respiration rate (1/d)
D_b	= algal predatory and non-predatory mortality (1/d)
Z_b	= algal grazing mortality (1/d)
s	= scouring factor (unitless)
v	= water velocity (m/d)
d	= water depth (m)

Both minimum and maximum algal biomass values were employed to represent the restrictions of the physical world for algae growth that are not represented by the respiration, mortality, grazing rates or scour factor. Therefore, if Equation 4.3 produced an amount of algae that was either larger than the set maximum or smaller than the set minimum, the model substituted the maximum or minimum, respectively. The algae model application and nutrient sensitivity analysis results are presented in Section 7.2.