TECHNICAL MEMORANDUM: TVA River Modeling System: ADYN and RQUAL – RMS Model Specifications and Background

TO: Matt St John, North Coast Regional Water Quality Control Board

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COPIES: Josh Viers, University of California, Davis

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RE: Shasta River TMDLs – Water Quality Model Selection and Specifications

DATE: August 17, 2005

1. Introduction

Assessment of water quality conditions in support of the Shasta River TMDL analysis included consideration of a modeling approach consistent with the 303(d) listed parameters – temperature and dissolved oxygen.

2. Review of Models

Previous modeling efforts on the Shasta River were limited to flow and temperature representation. Outlined herein are the existing models, as well as selected models, that could be applicable to river systems.

2.1. Existing Models

Previous modeling efforts of flow and temperature were modeled in the Shasta River were completed by U.C. Davis (1998) and Abbott (2002). The former work was completed using the RMA-2 and RMA-11 models to represent hydrodynamics and water temperature, respectively. The work by Abbott applied the Tennessee Valley Authority models (TVA) ADYN and RQUAL to represent hydrodynamics and water temperature, respectively. The ADYN shade routine was modified to accommodate river aspect and different shading attributes on river left and river right, as well as longitudinal variations. The TVA models were applied within the River Management System (RMS) framework that assists with executing the model and assessing output through a graphical user interface.

2.2. Applicable Models

2.2.1. CE-QUAL-ICM (Eutrophication model)

CE-QUAL-ICM is a water quality model historically used to assess eutrophication. ICM stands for "integrated compartment model," which is analogous to the finite volume numerical method. The model computes constituent concentrations resulting from transport and transformations in well-mixed cells that can be arranged in arbitrary one-, two-, or three-dimensional configurations.

2.2.2. CE-QUAL-RIV1

CE-QUAL-RIV1 is a one-dimensional (laterally and vertically averaged) hydrodynamic and water quality model. CE-QUAL-RIV1 consists of two parts, a hydrodynamic code (RIV1H) and a water quality code (RIV1Q). The hydrodynamic code is applied first to predict water transport and its results are written to a file, which is then read by the quality model. It can be used to predict one-dimensional hydraulic and water quality variations in streams and rivers with highly unsteady flows, although it can also be used for prediction under steady flow conditions.

RIV1H predicts flows, depths, velocities, water surface elevations, and other hydraulic characteristics. The hydrodynamic model solves the St. Venant equations as the governing flow equations using the widely accepted four-point implicit finite difference numerical scheme.

RIV1Q can predict variations in each of 12 state variables: temperature, carbonaceous biochemical oxygen demand (CBOD), organic nitrogen, ammonia nitrogen, nitrate + nitrite nitrogen, dissolved oxygen, organic phosphorus, dissolved phosphates, algae, dissolved iron, dissolved manganese, and coliform bacteria. In addition, the impacts of macrophytes can be simulated. Numerical accuracy for the advection of sharp gradients is preserved in the water quality code through the use of the explicit two-point, fourth-order accurate, Holly-Preissman scheme.

2.2.3. CE-QUAL-W2

CE-QUAL-W2 is a water quality and hydrodynamic model in 2D (longitudinal-vertical) for rivers, estuaries, lakes, reservoirs and river basin systems. W2 models basic eutrophication processes such as temperature-nutrient-algae-dissolved oxygen-organic matter and sediment relationships. Model represents, longitudinal-vertical hydrodynamics (laterally averaged) and water quality in stratified and non-stratified systems, multiple algae, epiphyton/periphyton, CBOD, and generic water quality groups, internal dynamic pipe/culvert model, hydraulic structures (weirs, spillways) algorithms including for submerged and 2-way flow over submerged hydraulic structures, dynamic shading algorithm based on topographic and vegetative cover. Recent versions allow this model to be applied to river basins, wherein both reservoir and river reaches can be represented.

2.2.4. QUAL2E/QUAL2K

QUAL2K (or Q2K) is a river and stream water quality model that is intended to represent a modernized version of the QUAL2E. It is a one-dimensional, steady-flow stream model (laterally and vertically averaged). Water temperature and quality can be modeled on a diurnal basis (i.e., sub-daily), and point and non-point loads can be represented.

2.2.5. RMA-2/RMA-11

RMA-2 and RMA-11 are a set of hydrodynamic and water quality models, respectively. RMA-2 is a two dimensional depth averaged finite element hydrodynamic numerical model (and can be applied in one-dimension with depth and laterally averaged conditions). It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two dimensional flow fields. RMA-2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analyzed.

RMA-11 is a finite element water quality model for simulation of one- two- or three-dimensional estuaries, bays, lakes and rivers. It is also capable of simulating one and two dimensional approximations to systems either separately or in combined form. It is designed to accept input of velocities and depths, either from an ASCII data file or from binary results files produced by RMA-2. Results in the form of velocities and depth from the hydrodynamic models are used in the solution of the advection diffusion constituent transport equations.

2.2.6. WASP

The Water Quality Analysis Simulation Program (WASP6) is an enhancement of the original WASP. This model helps users interpret and predict water quality responses to natural phenomena and manmade pollution for various pollution management decisions. WASP6 is a dynamic compartment-modeling program for analyzing river and stream water quality. WASP also can be linked with hydrodynamic and sediment transport models that can provide flows, depths velocities, temperature, salinity and sediment fluxes

2.2.7. Tennessee Valley Authority Models: ADYN and RQUAL

ADYN and RQUAL are a set of one-dimensional, finite difference hydrodynamic and water quality models, respectively. ADYN computes hydrodynamic attributes for, free-surface flow in open channels using the conservation of mass and momentum equations. The model can assess unsteady flow regimes in complex channels (e.g, water or wave travel times, routing, flow reversal, interaction with dynamic tributaries, multiple point or distributed inflows/outflows, variable geometry and roughness elements).

The water quality model RQUAL, solves the mass transport equation; however, the diffusion term is not incorporated in this version of RQUAL. The water quality model represents temperature, biochemical oxygen demand, nitrogenous oxygen demand, dissolved oxygen and primary production. The model includes riparian shading, but has been modified from the original form to provide more flexibility in representing variable shade quality and tree height distribution in river reaches.

2.2.8. Model Comparison

The attributes of the TVA models are compared with other identified models in the table below.

Model Attribute	TVA	QUAL2K	WASP	CE-QUAL-ICM	CE-QUAL-W2	RMA2/ RMA11	CE-RIV1
One-dimensional	1	1	1,2,3	1,2,3	2	1,2	1
Hydrodynamic Model	Yes	No	Exter.[a]	Exter.[a]	Yes	Yes	Yes
Water Quality							
- Temperature	Yes	Yes	Yes	Yes	Yes	Yes	Yes
- Dissolved Oxygen	Yes[b]	Yes	Yes	Yes	Yes	Yes	Yes
Boundary Conditions (P: Point, NP: Nonpoint)	P,NP	P, NP	P, NP	P, NP	P, NP	P, NP	P, NP
Actively Supported	Yes	Yes	Yes	Yes[c]	Yes	Yes	Yes[c]
Vertical stratification	No	No	Yes[d]	Yes[d]	Yes	No	No
Lateral variability	No	No	Yes	Yes	No[e]	Yes	No
Other pollutants[e]	limited	limited[f]	Yes	Yes	limited[f]	limited[f]	limited[f]
Wetting and drying[g]	No	No	Yes[g]	Yes[g]	No[g]	Yes	No
Pre-processor	Yes	Yes	Yes	No	Yes	Yes	No
Post-processor	Yes	Yes	Yes	No	No	Yes	No
Open source code	Yes	Yes	Yes	Yes	Yes	Yes	Yes

[a] hydrodynamic models are external.

[b] nitrogenous biochemical oxygen demand, biochemical oxygen demand, sediment oxygen demand, reaeration, and macrophyte respiration and photosynthesis are specified boundary conditions or represented processes to assess dissolved oxygen conditions. Nutrient fate and transport, algae uptake and excretion, and other sources and sinks of nutrients are not modeled processes in TVA. Mike, for my own info, what models include these processes?

[c] CE-QUAL-ICM and CE-RIV1 are supported by the U.S. Army Corps of Engineers, but at a lesser level than the more popular models listed – more on a case-by-case application than general support.

[d] requires 3-dimensional hydrodynamic modeling.

[e] branching networks and control structures can be used to represent lateral variability for certain systems.

[f] All identified models have open source codes and modifications can be made to the models to represent other constituents and processes as necessary.

[g] wetting and drying refers to the ability of the model system to drop computational elements, segments, or nodes when water levels drop (drying) and re-activates them when water levels rise (wetting). For WASP and CE-QUAL-ICM wetting and drying can be accommodated if the selected hydrodynamic model allows such simulation. CE-QUAL-W2 cannot truly "dry" but because there are multiple layers rising and falling water levels and changing channel geometry can be represented.

2.3. Model Selection

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.

3. Tennessee Valley Authority Models

3.1. Background

ADYN and RQUAL are a set of one-dimensional, finite difference hydrodynamic and water quality models, respectively. ADYN computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in open channels. ADYN solves the conservation of mass and momentum equations (St Venant equations) using one of two numerical schemes: a four point implicit finite difference scheme with weighted spatial derivatives or a McCormack explicit scheme. The model can assess unsteady flow regimes in complex channels (e.g, water or wave travel times, routing, flow reversal, interaction with dynamic tributaries, multiple point or distributed inflows/outflows, variable geometry and roughness elements).

The water quality model RQUAL, solves the mass transport equation with the same numerical scheme used in the flow model. The diffusion term is not incorporated in this version of RQUAL. The water quality model represents temperature, biochemical oxygen demand, nitrogenous oxygen demand, dissolved oxygen, sediment oxygen demand, reaeration, and primary production (photosynthesis and respiration). Details of model formulation, application, and governing equations are presented in Hauser (1995). The original model code includes riparian shading, but has been modified by Abbott (2002) to provide more flexibility in representing variable shade quality and tree height distribution in river reaches.

Both ADYN and RQUAL can be operated from within a graphical user interface – called the River Management System (RMS) – that allows the user to prepare input files and run the model. There is an additional software package called AGPM-1D, which is a post-processor for ADYN and RQUAL, allowing the user to examine the output as time series, longitudinal profiles, as well as animation features. These software packages cost less than $500.00 and are available from Loginetics Inc.

3.2. Model Meta Data

NAME: Tennessee Valley Authority River Modeling System (ADYN and RQUAL Module)

ORGANIZATION/PERSON HOLDING AND DISTRIBUTING THE MODEL:
Tennessee Valley Authority, Resources Group, Engineering Services
TVA Engineering Lab,
129 Pine Road, Norris, Tennessee, 37828
Phone: 423-632-1888
Fax: 423-632-1840

TYPE OF MODELING OR APPLICATION:

ADYN:

- River and resource hydraulics
- One-dimensional, longitudinal, unsteady flow
- Hydraulics of floods and man-made transients (e.g., hydropower releases)
- Effects of dynamic tributary systems, local inflow sources
- Assessment of wetted areas for environmental flow assessments
- Governing Equation: St. Venant Equations
- Numerical solution: (a) four point implicit finite difference, or (b) McCormack explicit scheme

RQUAL

- Water quality fate and transport
- One-dimensional, longitudinal, dynamic representation
- Waste load allocation
- Effects of location, magnitude, and timing of interventions seeking to improve water quality
- Dilution and degradation of wastes
- Effects of thermal loadings and atmospheric heat exchange on stream temperature
- Effects of natural or artificial reaeration, diurnal photosynthesis and respiration by benthic algae/macrophytes, waste loads, tributary inflows, and variable flow regimes on the dissolved oxygen regime
- Governing Equation: Mass transport equation (advection-diffusion equation with diffusion neglected)
- Numerical solution: (a) four point implicit finite difference, or (b) McCormack explicit scheme

NUMBER OF MODEL DIMENSIONS: One (laterally and depth averaged)

MODEL LIMITATIONS: When linked to “RQUAL”, does not currently model water quality in dynamic tributaries (not applied in Shasta River analysis)

MODEL MODIFICATIONS: The model was modified by Abbott (2002) to include the ability to model riparian shading based on stream aspect, as well as different shading attributes for tree height and solar radiation transmissivity that can vary for each bank.

MODEL LANGUAGE: FORTRAN

MODEL PLATFORM: PC (personal computer)

<u>INTERFACE AND PRE-/POST-PROCESSORS</u>:
The River Management System (RMS) includes an interface to display both ADYN and RQUAL output and statistics using the ADPLT and RQPLT post processor programs.

EXPERIENCE: Used extensively by the Tennessee Valley Authority

CURRENT VERSION:

- ADYN: 4.xx
- RQUAL: 4.xx

INPUT REQUIREMENTS:
ADYN:

- River geometry
- River and local tributary hydrology (water surface elevation and flow rate at boundaries)

RQUAL:

- River geometry (consistent with ADYN)
- Meteorological conditions
- River and local tributary water quality, including sediment oxygen demand and benthic algae/macrophyte photosynthesis and respiration distribution, as well as riparian shading attributes.
- Processes include:
  - Temperature
  - Dissolved oxygen
  - Nitrogenous biochemical oxygen demand
  - Biochemical oxygen demand
  - Benthic algae/Macrophyte photosynthesis and respiration
  - Sediment oxygen demand
  - Reaeration

OUTPUT (available at all nodal locations):
ADYN

- Discharge and water surface elevation
- Water velocity
- Water depth
- Wetted area
- Travel times
- Water volume
- Froude number

RQUAL

- Water temperature
- Dissolved oxygen

3.3. TVA Model Applications

3.3.1. TECHNICAL REPORTS

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