Prepared in Cooperation with the Bureau of Reclamation

Review of Klamath River Total Maximum Daily Load Models from Link River Dam to Keno Dam, Oregon

By Stewart A. Rounds and Annett B. Sullivan

Administrative Report

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Conversion Factors, Datums, and Abbreviations and Acronyms

Inch/Pound to SI

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

SI to Inch/Pound

Multiply	By	To obtain
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per second (m/s)	3.281	foot per second (ft/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32.$$

Specific conductance is given in microsiemens (micromhos) per centimeter at 25 degrees Celsius (µS/cm at 25°C).
Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).
“Elevation” refers to distance above the vertical datum. A local vertical datum (UKLVD) is used, established by the Bureau of Reclamation.
For the purpose of this report, the conversion is UKLVD – 1.78 ft = NGVD29.
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Acronyms and Abbreviations

AFA	*Aphanizomenon flos-aquae*
DO	dissolved oxygen
DOM	dissolved organic matter
EPA	U.S. Environmental Protection Agency
ESP	elevation of spillway
FERC	Federal Energy Regulatory Commission
ISS	inorganic suspended solids
LDOM	labile dissolved organic matter
LPOM	labile particulate organic matter
ODEQ	Oregon Department of Environmental Quality
OM	organic matter
RDOM	refractory dissolved organic matter
RM	river mile
RPOM	refractory particulate organic matter
SDK	sedimentary organic matter decomposition rate
SOD	sediment oxygen demand
TDS	total dissolved solids
TMDL	total maximum daily load
TSS	total suspended solids
UKL	Upper Klamath Lake
USGS	U.S. Geological Survey

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Executive Summary

To support the development of Total Maximum Daily Load (TMDL) programs for the Klamath River in south-central Oregon and northern California, flow and water-quality models were developed by Tetra Tech for the U.S. Environmental Protection Agency, the Oregon Department of Environmental Quality (ODEQ), and the California North Coast Regional Water Quality Control Board. The EFDC model was used to simulate conditions in the Klamath River estuary, the RMA-2 and RMA-11 models were used to simulate most riverine reaches, and the CE-QUAL-W2 model was used to simulate the reservoir reaches. The U.S. Geological Survey (USGS) was asked to review only the most upstream of these models of the Klamath River, from its source at Upper Klamath Lake (Link River Dam) through its first pooled reach ending at Keno Dam.

The RMA-2 and RMA-11 models were used to simulate the 1-mile Link River reach, and the CE-QUAL-W2 model was used for the 19.7-mile reach from Lake Ewauna to Keno Dam. Models representing current (2000 and 2002) and "natural" conditions were reviewed. The natural conditions model, based on year 2000, includes the removal of Keno Dam and all point-source inflows, and boundary water-quality inputs were based on a previous Upper Klamath Lake TMDL model. The model boundary data, bathymetry, source code, parameters, and results were assessed by USGS scientists in this review.

The water quality of this Klamath River reach is greatly influenced by the quality of water imported from Upper Klamath Lake (UKL). This and other model boundary datasets, including meteorological data and shade, as well as flow, temperature and water-quality inputs for upstream, tributary and other inflows, were evaluated and compared to measured datasets. Boundary temperatures for some model inputs had been set to a constant value; it seems that some seasonal variation in those inputs would result in a more accurate simulation. The total dissolved solids concentration assigned to the Klamath Straits Drain was unrealistically low (0 milligrams per liter [mg/L]). Ammonia concentrations in Link River for the year 2000 current conditions model have the opposite seasonal pattern compared to ODEQ and USGS datasets. Finally, and perhaps most importantly, the dissolved and particulate organic matter inputs from UKL do not reflect the patterns of more recent datasets. In particular, the concentration of dissolved organic matter is greatly underestimated, and the assumption that all of it is labile (rapidly degraded) is questionable.

A model must have an accurate representation of the water body's geometry to properly simulate stage, storage, travel time, heat fluxes, and many critical water-quality processes. The grid for the Lake Ewauna to Keno Dam model is approximately 12 percent longer than the mapped channel, which may have important effects on various modeled processes. Layer widths in the grid did not vary smoothly with depth, which might not matter if reservoir levels are stable. Any changes that cause reservoir levels to vary, however, may cause the simulated widths to change abruptly, which in turn can cause

significant alterations to the heat budget and other processes such as sediment oxygen demand that are tied to simulated surface area.

CE-QUAL-W2 is a widely applied and well-documented open source water-quality model that seems to be a good choice for simulating the Lake Ewauna to Keno Dam reach of the Klamath River. Tetra Tech modified parts of the CE-QUAL-W2 source code to add new capabilities for the Klamath River models, but has not applied known bug fixes that were discovered in recent years. One problematic code modification is a 20-percent reduction in solar radiation that was applied only to the Lake Ewauna to Keno Dam reach and only for the term-by-term heat budget, whereas the full-strength solar radiation flux was used elsewhere in computations of light extinction and light limitation factors for photosynthesis. This coding change has no physical basis and compromises the model's representation of the heat budget. Other code changes were made to allow a fraction of the algal population to become stressed because of low dissolved oxygen concentrations, but little or no rationale exists, in data or published research, to justify this approach. A new spillway formula was added to facilitate the computation of streamflow for the natural conditions scenario, and the light extinction computations were modified to explicitly include the effects of dissolved organic matter. Sedimentary organic matter computations also were modified; those changes have no effect with the current models, but they could produce errors if model settings were changed. Few of these changes to the CE-QUAL-W2 source code were documented in the materials provided for this review; all code changes should be well documented (in the report and internally in the code) and properly archived.

Model parameters such as decay, settling, and growth rates should be based on field sampling, experimental data, or literature values as much as possible so that the model can be confidently applied to existing conditions and hypothetical scenarios. One important change to CE-QUAL-W2 for this application was the addition of code to allow a fraction of the algae to become stressed, or "unhealthy," as a result of low dissolved oxygen conditions. Although intriguing, this process is not yet documented in the scientific literature, nor has it been shown to occur in this reach of the Klamath River. The number of additional input parameters to support this change is large, which increases the chance of obtaining a non-unique set of calibration parameters that fit the measured data. Model settings for sediment oxygen demand produced rates that were higher than values measured by USGS. Several parameters, including the ammonia nitrification rate, organic matter decay and settling rates, and a dissolved oxygen half-saturation constant, were set to different values in the two current conditions and natural conditions models, which raises questions regarding model calibration and extrapolation to unmeasured conditions.

Selected comparisons were made between simulated and measured datasets as part of this review to assess model performance. Simulated water temperatures at Miller Island and Keno showed mean absolute errors of about 1ºC, which is a good match, but CE-QUAL-W2 is capable of better performance. Dissolved oxygen prediction errors were on the order of 2 mg/L, which are large enough to raise questions as to which process(es) are not being simulated with sufficient accuracy, or which boundary conditions are incorrect. The nitrate predictions in year 2000 at Keno appear to be inconsistent with multiple years of field data at that location. Finally, as with the boundary conditions, predicted dissolved organic matter concentrations are low compared to field measurements. Because the concentrations, fractionation, and decay rates of organic matter are not accurately represented in the current conditions models, these models may not be able to simulate organic matter and associated constituents with sufficient accuracy for regulatory decisions.

The natural conditions model scenario included only three sources of inflow: Link River, Lost River Diversion Channel, and Klamath Straits Drain. All other inflows were eliminated, including rainfall and inflows used in the current conditions model to account for ungaged tributaries and groundwater. The downstream outflow past the Keno reef used a stage-discharge relation derived by the Bureau of Reclamation from pre-dam data, but the model used an incorrect datum, leading to potential errors in reservoir stage and travel time. Total dissolved solids concentrations were unrealistically set to 0 mg/L for the Lost River Diversion Channel and the Klamath Straits Drain. The inflow dissolved organic matter concentrations in this scenario were set much lower (only 0.8 mg/L) than expected for natural rivers, lakes, or wetlands. Boundary inputs for phosphate, nitrate, and ammonia also were set to near-oligotrophic and possibly unrealistic levels; regardless, such inputs represent a large extrapolation to new conditions for the model and increase the level of predictive uncertainty.

In summary, the model developers have constructed streamflow and water-quality models to simulate a river reach that has highly complex water-quality processes that are not yet fully understood, and the models have great potential to help managers and regulators better understand the system. Certain errors identified in this review, however, need to be addressed before these models can be confidently used to predict temperature or water quality in the Link River Dam to Keno Dam reach of the Klamath River.

Background

The Klamath River flows from Upper Klamath Lake in south central Oregon past a series of dams into northern California where the river eventually empties into the Pacific Ocean near the town of Klamath (**fig. 1**). As a result of a wide range of influences such as dam construction, landscape modifications, altered hydrologic conditions, population growth, and agriculture, the Klamath River does not meet certain water-quality standards as specified by the States of Oregon and California. Both States have placed the Klamath River on their list of impaired water bodies, and as required by the Federal Clean Water Act, they and the U.S. Environmental Protection Agency (EPA) are in the process of creating Total Maximum Daily Load (TMDL) programs in an attempt to bring the water quality of the river into compliance with standards. In Oregon, Klamath River TMDL issues focus on ammonia and dissolved oxygen year-round, and pH and algae (chlorophyll) during summer. In California, the TMDL issues in the Klamath River are temperature, nutrients, organic enrichment, dissolved oxygen, sedimentation, and algal toxins, depending on the specific reach.

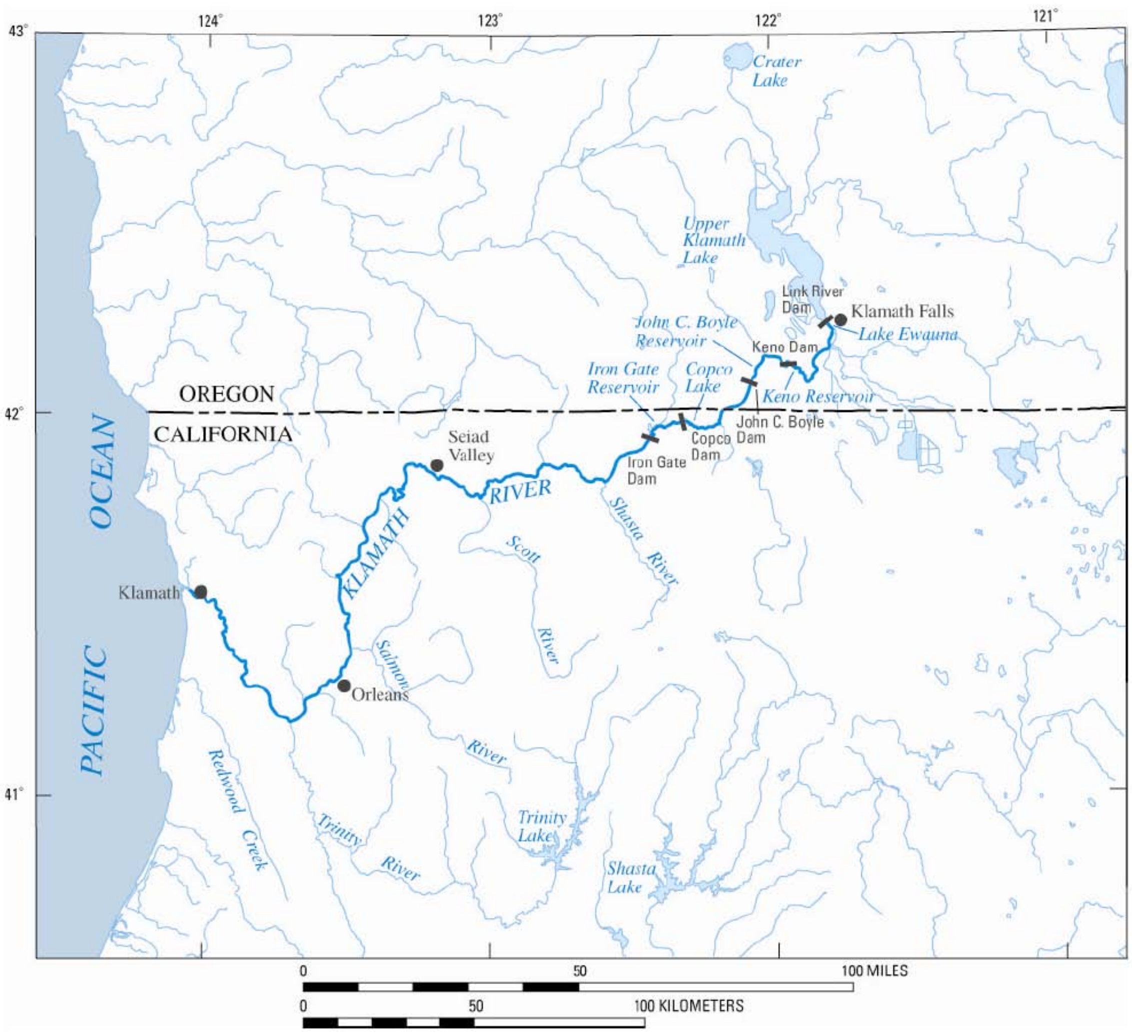

Figure 1. Map showing the Klamath River, its major tributaries, and the locations of dams on the upper river, Oregon and California. (Map from Risley and Rounds, 2006).

Water-quality models often are the tools of choice for creating or modifying TMDLs. Models are well suited for assessing the effects of altered conditions, proposed changes in management strategies, and the effects of dams, to name just a few uses. In the case of the Klamath River, water-quality models are being used to form the foundation of new TMDL programs. Most of the Klamath River models were originally developed by Dr. Michael Deas of Watercourse Engineering for the relicensing of a series of PacifiCorp dams (Watercourse Engineering, Inc., 2004). For the Lake Ewauna to Keno Dam reach of the Klamath River, Dr. Deas built upon a previous model by Dr. Scott Wells of Portland State University (CH2M-Hill and Wells, 1995). The Watercourse Engineering models have since been modified for the purpose of TMDL development by Tetra Tech under contract to the Oregon Department of Environmental Quality (ODEQ), the California North Coast Regional Water Quality Control Board, and EPA (Tetra Tech, Inc., 2008).

Models are often used in TMDL development to determine the characteristics of a historical, reference, or hypothetical condition that does not or no longer exists. For the Klamath River TMDL, a "natural conditions" scenario is being modeled to predict water quality in the river under an altered state, such as if the dams were removed and upstream water-quality conditions were improved. As the foundation of a TMDL, such model scenarios typically become the basis for regulatory actions, such as establishment of maximum point-source nutrient loads or restoration of a more natural flow, channel shape, or riparian condition.

Study Area

This model review focuses on the two most upstream models used in the Klamath River TMDL: (1) Link River and (2) Lake Ewauna to Keno Dam. The Lake Ewauna to Keno Dam reach is a reservoir-like reach that runs from Link River (the outlet of Upper Klamath Lake) to Keno Dam (**fig. 2**). The Link River Dam to Keno Dam reach is approximately 21 miles long and has an annual average flow of about 1,600 ft^3/s at the streamflow gaging station 1.4 miles downstream of Keno Dam. The Lake Ewauna to Keno Dam reach has a typical width of 100–400 meters, a typical depth of 3–6 meters, and undergoes periodic thermal stratification. The Klamath River above Keno Dam is greatly affected by water-quality conditions in Upper Klamath Lake, where large populations of blue-green algae dominate the water quality of the lake in summer (Hoilman and others, 2008). This reach of the river has been classified as having "very poor" water quality during summer, as quantified by the Oregon Water Quality Index (Mrazik, 2006). A water-quality investigation of this reach was initiated by the Bureau of Reclamation in 2006 in partnership with the U.S. Geological Survey (USGS) and Watercourse Engineering, Inc.; selected data from the study are available online (Sullivan and others, 2008, 2009).

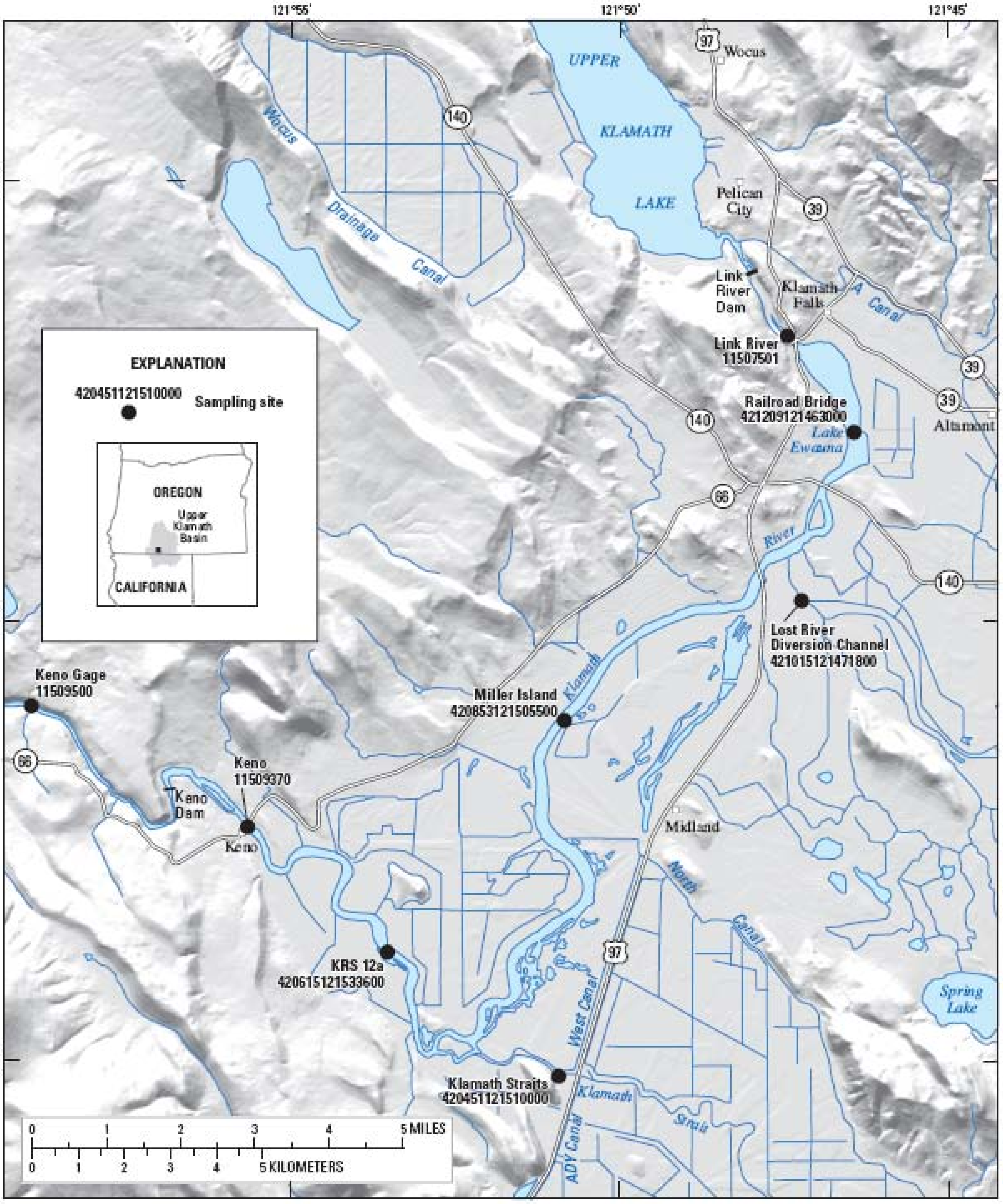

Figure 2. Map showing the Link River Dam to Keno Dam reach of the Klamath River, Oregon.

Purpose and Scope

The purpose of this report is to document a review of flow and water-quality models constructed for the 21-mile Link River Dam to Keno Dam reach of the Klamath River, just downstream of Upper Klamath Lake in Oregon (**fig. 2**). The 1-mile Link River reach was simulated with the RMA-2 and RMA-11 models (King, 2002; 2003). Output from those models provided upstream boundary conditions for a CE-QUAL-W2 model (Cole and Wells, 2002) of the 19.7-mile Lake Ewauna to Keno Dam reach; the latter model is the focus of this review. Models for this review were provided to USGS by EPA and Tetra Tech, along with a draft report documenting model development (Tetra Tech, Inc., 2008). The models reviewed included:

- Current conditions, year 2000
- Current conditions, year 2002
- Natural conditions, year 2000

The current (existing) conditions models were developed for calendar years 2000 and 2002. The natural conditions model was based on the current conditions year 2000 model, with adjustments to remove Keno Dam and point source inflows, and to set boundary inputs to median loading conditions from the 1995 Upper Klamath Lake TMDL model.

Model Review

The Link River and Lake Ewauna to Keno Dam models were used to simulate stage, flow, water temperature, and many water-quality constituents such as ammonia, nitrate, phosphate, dissolved and particulate organic matter, dissolved and suspended solids, dissolved oxygen, alkalinity, total inorganic carbon, pH, phytoplankton, and periphyton. The RMA-11 model (King, 2003) was used to simulate water quality in Link River in one dimension (along the length of the river). The laterally-averaged, two-dimensional flow and water-quality model CE-QUAL-W2 (Cole and Wells, 2002), sometimes called W2, was used to simulate the Lake Ewauna to Keno Dam reach along the length of the river and vertically, thus capturing the vertical variations that occur in stratified systems. CE-QUAL-W2 is capable of simulating the most important instream processes associated with nutrients, algae, and dissolved oxygen, as long as it is provided with good bathymetric and meteorological data, adequate boundary flow, temperature, and water-quality data, and has been well calibrated using a robust calibration dataset (Rounds and Wood, 2001; Cole and Wells, 2002; Sullivan and Rounds, 2006; Rounds, 2007; Sullivan and others, 2007).

This model review is divided into six sections along topical lines. Separate evaluations of the model boundary data, bathymetric representation, source code, parameters, results, and scenario assumptions are included in this review. Within each topical area, review comments often are separated into either “major” or “minor” technical comments in an attempt to highlight the more important findings and yet not omit other observations. Major comments include findings that could have an important effect on model predictions, although a quantitative assessment of those effects may be difficult to provide without further analysis. Minor comments are important enough to be mentioned, but probably have less of an effect on model results. Model-specific comments are focused mainly on CE-QUAL-W2 because it makes up the majority of the modeled reach and because the travel time in the Link River RMA model is short. Finally, the comments in this review are not exhaustive because time constraints limited the scope of the review.

A. Boundary Data

The RMA and CE-QUAL-W2 models require many boundary input datasets, including meteorological data as well as flow, temperature, and water-quality data for upstream inflows, all tributary and point-source inflows, and groundwater inflows. Any withdrawals, diversions, or losses to groundwater also must be characterized with a flow time series. Downstream dam releases or other boundary conditions are needed to compute outflows. Topographic relief and vegetative canopy data are used to compute how shading affects meteorological inputs.

Meteorological input data include air temperature, dew point temperature, wind speed, wind direction, cloud cover, and solar radiation. The shade inputs for the Lake Ewauna to Keno Dam model were set such that all topographic and vegetative shading was turned off. Boundary flow data included the main-stem inflow from Link River and tributary inflows from two wastewater treatment plants, Columbia Plywood, two Collins Forest Product sources, the Lost River Diversion Channel, and the Klamath Straits Drain. Rainfall was not included as a model input; instead, it was incorporated into 11 stormflow tributary inputs. Four point-source accretion inputs (miscellaneous stormwater and other flow inputs) and one distributed tributary input were used to balance the water budget and account for ungaged tributaries and groundwater. Each input of flow to the system has an associated time series of temperature and water-quality inputs.

Major Comments

A.1. **Raw boundary data.** The model input files were provided for this review, but not the measurements from which those inputs were derived. As a result, this review does not include a consistency check between the raw data and the model boundary inputs. For some inputs such as the meteorological data, other data sources were available and those data were compared to the model inputs. For many water-quality time-series inputs, comparisons were made to available data from ODEQ and USGS. Lack of access to the original raw data used by the modelers, however, imposed some limits on the scope of this review.

A.2. **Boundary temperatures.** The stormwater inflow, point-source accretion, and distributed tributary input temperatures were all set to a constant 12ºC all year long. It seems that a better approach would be to include some seasonal variation in those temperature inputs. The stormwater input is small, so it is unlikely that a constant year-round temperature would have a large effect on simulated temperatures in the Klamath River. Conversely, the point-source accretion and distributed tributary inputs make up an appreciable fraction of total inflows at certain times in 2000; therefore, inflow temperatures become important at those times. Depending on the fraction of river flow that is derived from these sources, the incurred error may be significant to the river's heat budget.

A.3. **TDS inputs.** The concentration of total dissolved solids (TDS) assigned to the Klamath Straits Drain was 0 mg/L. The TDS concentration in this tributary, however, is actually higher than in most other tributaries to the system. Field conductivity data (which can be used to estimate TDS: Hem, 1985) for the Klamath Straits Drain and for Link River in 2000 are shown in **figure 3**. An incorrect TDS concentration will affect the modeled water density, pH, and the computed concentration of carbonate species. This misassignment in TDS may not produce large errors in most of the important modeled constituent concentrations, but it should be fixed.

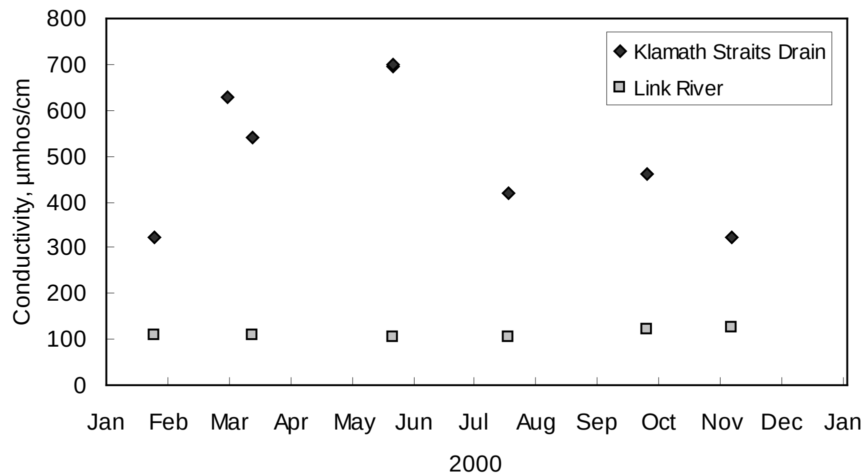

Figure 3. Graph showing field conductivity data in the Klamath Straits Drain and Link River, Oregon, during 2000. Data were collected by Oregon Department of Environmental Quality. Values in this graph are roughly equivalent to total dissolved solids concentrations of 60 to 420 mg/L.

A.4. **Ammonia inputs.** The upstream boundary condition for ammonia at Link River in the 2000 current conditions CE-QUAL-W2 model has a seasonal pattern that is different from that in measured datasets from ODEQ and USGS (**fig. 4**). The lowest ammonia concentrations in the model boundary conditions are during January through June and November through December, and the highest values are during summer (greater than 1.9 mg/L). In contrast, the measured ODEQ and USGS datasets show an opposite seasonal pattern at Link River, with the highest ammonia concentrations in winter and values generally less than 0.3 mg/L during summer.

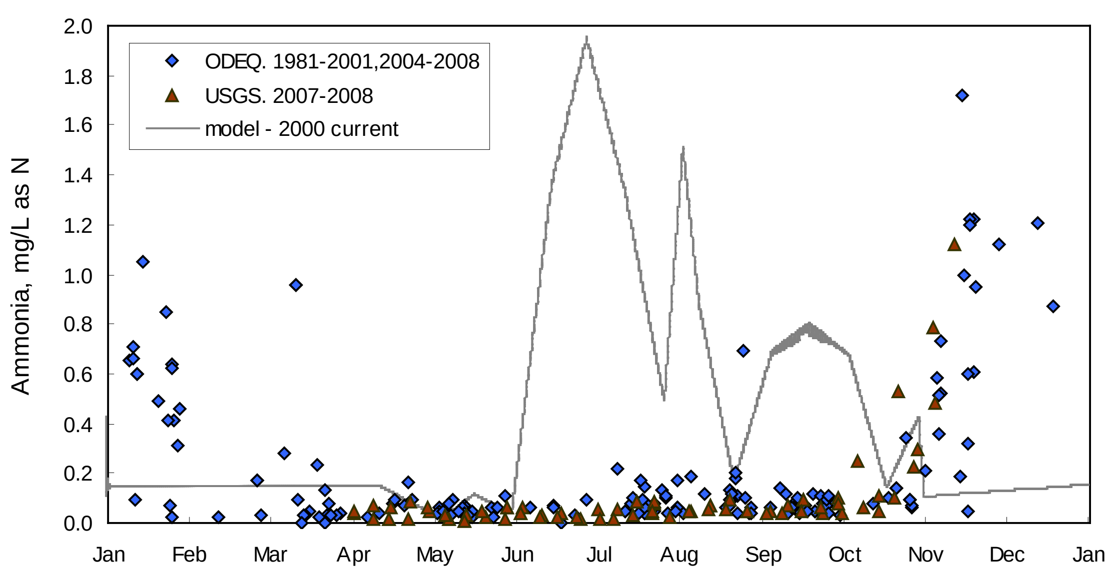

Figure 4. Graph showing year 2000 CE-QUAL-W2 model boundary condition ammonia concentrations at Link River compared to measured data from Oregon Department of Environmental Quality (ODEQ) and U.S. Geological Survey (USGS). ODEQ data were collected approximately six times a year, and data are shown only for those that were reported in units of mg/L as nitrogen. USGS data were collected weekly from April through November.

According to the draft modeling report (Tetra Tech, Inc., 2008), the ammonia inputs to the Link River RMA model were derived from data collected at Pelican Marina in Upper Klamath Lake (UKL), and the ammonia concentrations do not change much within the RMA Link River model. The poor fit to the measured ammonia concentrations at the downstream end of Link River indicates that either (1) the Pelican Marina ammonia data are not representative of the ammonia concentrations exported from UKL to Link River, or (2) the Link River model is not simulating an appropriate level of ammonia nitrification or algal uptake. Regardless of the reason, the result is that the ammonia inputs to the CE-QUAL-W2 model at the downstream end of Link River do not match the measured data.

This error in the pattern and magnitude of boundary ammonia concentrations represents a significant modeling problem, as concentrations of ammonia greater than 1.0 mg/L can affect dissolved oxygen concentrations and other instream processes in addition to the inorganic nitrogen load. In fact, this large simulated ammonia load may account for part of the underprediction of dissolved oxygen concentrations downstream (see E.2). The source of this inconsistency needs to be determined and resolved.

A.5. **Organic matter fractionation.** The CE-QUAL-W2 model defines and simulates four types of organic matter (OM): labile and refractory particulate organic matter (LPOM, RPOM), and labile and refractory dissolved organic matter (LDOM, RDOM). The labile components decompose rapidly, but the refractory components are more resistant to decomposition. At the time of model development, few direct measurements of OM concentrations were available. Input OM data had to be indirectly estimated from other data, using, for example, total phosphorus, dissolved phosphate, chlorophyll, and literature-based conversion factors. With limited information, the modelers considered all OM to be labile, and the RDOM and RPOM compartments were set to zero for the upstream boundary.

The draft modeling report (Tetra Tech, Inc., 2008) justifies the assumption that all OM was labile by attributing most organic matter from UKL to phytoplankton blooms and associated metabolism. Although phytoplankton strongly affects OM in UKL, especially particulate organic matter (POM), plankton are not the only source of OM. Wetlands in the upper areas of the watershed as well as wetlands adjacent to the lake provide dissolved organic matter (DOM) to UKL, and that OM may be more refractory than the algae-derived OM. For example, during one sampling period in May 2007, 20.3 mg/L of dissolved organic carbon was measured in the Williamson River, a major tributary to UKL, which receives drainage from the Klamath Marsh (U.S. Geological Survey, unpub. data, 2007.)

The labile OM concentrations at the boundary inputs were fractionated differently. The single-group OM output from the Link River RMA model was divided into 20 percent LDOM and 80 percent LPOM for input to the downstream CE-QUAL-W2 model. OM associated with the two wastewater treatment plants, the Lost River Diversion channel (**fig. 2**), the point-source accretions, and the distributed tributary also were divided into 20 percent LDOM and 80 percent LPOM. The Klamath Straits Drain OM, however, was set to 70 percent LDOM and 30 percent LPOM, and the Collins Forest Products, Columbia Plywood, and stormwater runoff inputs were set to 100 percent LDOM. Some model scenarios were run by Tetra Tech to determine the sensitivity of the model results to these fractions, but documentation of those results was not available for this review.

Based on more recent datasets (Sullivan and others, 2008; 2009), the OM concentrations and fractionation among groups in the Lake Ewauna to Keno Dam model are not representative of actual conditions. For example, the modeled input of DOM at the upstream boundary at Link River is lower in concentration and has a different seasonal pattern compared to the fairly consistent timing and concentrations of two years of weekly data collected at that site during 2007 and 2008 (**fig. 5**). Concentrations of the sum of modeled POM and algae appear to generally match the concentrations and seasonal patterns of measured particulate organic matter.

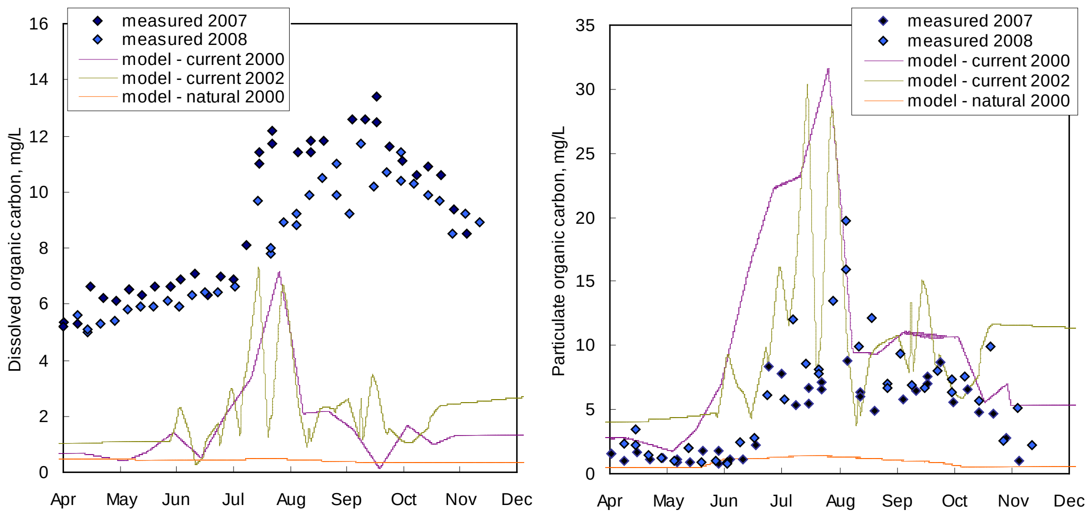

Figure 5. Graphs showing measured dissolved (left) and particulate (right) organic carbon concentrations at Link River in 2007-08, compared to boundary inputs to the Lake Ewauna model. Model LDOM was converted to dissolved organic carbon using the 0.45 organic carbon to organic matter ratio specified in the model control file. Modeled LPOM (nonliving particulate organic matter) plus modeled algae (living particulate organic matter) were converted to particulate organic carbon for comparison to measured particulate organic matter, which includes nonliving and living matter, using the 0.45 organic carbon to algae and organic matter ratio specified in the model control file.

Whatever the assumptions may have been, recent data show some significant discrepancies compared to model inputs relative to the magnitude, seasonal pattern, and distribution of OM between dissolved and particulate forms. Organic matter is a large and important input to the Klamath River from UKL that affects dissolved oxygen concentrations and nutrient loads. These model inputs need to be re-evaluated to provide a better description of water quality in the Lake Ewauna to Keno Dam reach.

Minor Comments

A.a. **Wind speed.** In the meteorological model input file for the year 2000, on day 39.292, the wind speed (22.05 m/s) is much higher than the value for the previous hour (0.82 m/s) or the subsequent hour (0.55 m/s). This and other elevated wind speeds (near days 82.5, 85.7, 96.6, 97.7, 100.8, and 103.8) in the current conditions meteorological input file were removed from the corresponding natural conditions meteorological input file. These high wind speeds may or may not have been real, but if they were deemed unreasonable to include in the natural conditions scenario, then they probably should have been removed from the current conditions scenario as well. These wind gusts affect near-surface mixing and evaporative heat losses, although the effects are transient and probably minor.

A.b. **ISS estimates.** The draft modeling report (Tetra Tech, Inc., 2008) states that the CE-QUAL-W2 inputs for inorganic suspended solids (ISS) were set to measured values of total suspended solids (TSS) for the Klamath Straits Drain, Klamath Falls wastewater treatment plant, and South

Suburban Sanitation District. This practice would overestimate the ISS concentration, because TSS includes not only inorganic particulate matter, but also organic particulate matter, which is plentiful in this system and is included separately in other model inputs. The report and input files do not indicate how ISS concentrations were set for the other model boundary inputs.

A.c. **Upstream inflow.** The draft modeling report (Tetra Tech, Inc., 2008) states that the flow in Link River that feeds into the Lake Ewauna model was determined using measured flow at the USGS streamflow-gaging station (site 11507500) minus flow from the PacifiCorp West Turbine (powerhouse) gage, which is downstream of the USGS gage. The powerhouse flow should have been added rather than subtracted from the USGS flow. This seems to be an inaccuracy in the report rather than the model. Although PacifiCorp flow data were not available, modeled flows were greater than the USGS gaged flows, so the powerhouse flows probably were added to the USGS gaged flows to create that flow boundary condition.

A.d. **Shading.** The shade inputs were used by Tetra Tech to turn off all topographic and vegetative shading in the Lake Ewauna to Keno Dam CE-QUAL-W2 model. Given the relatively flat nearby topography, the paucity of significant riparian vegetation, and the large width of the river, simulating no shade is probably a good choice. Tetra Tech made changes to the model's Fortran source code, however, to decrease the incoming solar radiation by 20 percent for this reach. The nearby topographic features and streamside vegetation are not large enough to justify a 20-percent decrease in short-wave solar radiation. This change is discussed further under comment number C.4 in the Model Source Code section of this review.

B. Bathymetric Representation

The model grid must match the river bathymetry with sufficient accuracy so that the total volume (or storage), travel time, slope, stage, and velocities can be properly simulated. Creation of a model grid requires good bathymetric data as well as attention to the requirements of the model. For example, in the case of CE-QUAL-W2, it is important to ensure that all deep pools are at least two segments long; otherwise, advective transport into and out of those pools will not be possible. Furthermore, the change in width from one segment to the next and from one layer to the next should not exceed some reasonable threshold ratio; such smooth transitions are important to ensure that the model remains stable and can properly represent the sediment contact area and surface width of the river as the stage varies.

For the Lake Ewauna to Keno Dam model, the CE-QUAL-W2 model grid has two branches. The first branch consists of 106 segments from the end of Link River (river mile [RM] 253.1) to Keno Dam (RM 233.4) (**fig. 6**). The second model branch is a short, 3-segment section to simulate a channel around an island near RM 250. All layer heights are 0.61 m (2 ft).

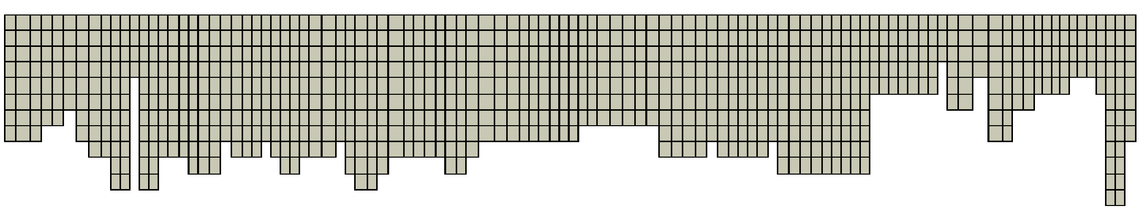

Figure 6. Schematic of the grid for the main stem (branch 1) of the Lake Ewauna to Keno Dam model. The inflow from Link River is on the right, and the outflow at Keno Dam is on the left. The bottom represents the channel bottom. The distance from left to right represents 35.7 km (22.2 mi); the maximum distance from top to bottom is 7.3 m (24 ft), and each cell is 0.61 m (2 ft) high.

Major Comments

B.1. **Reach length.** According to USGS topographic maps, the Lake Ewauna to Keno Dam reach is 19.7 miles in length, but the CE-QUAL-W2 model grid for the same reach is 22.2 miles, about 12 percent longer than the mapped channel. The length of the model grid may or may not be accurate. The model bathymetry was based on a relatively recent bathymetric survey (Watercourse Engineering, Inc., 2004). The length of the modeled reach affects the simulated storage and travel time, which in turn have a large and important effect on simulated concentrations of dissolved oxygen, algae, and all other constituents. This is a potentially important point, and the reach length needs to be verified.

B.2. **Layer widths.** The layer widths in the CE-QUAL-W2 model grid do not vary smoothly with depth. Instead, a number of layers at a given location often are assigned the same width (**fig. 7**). With water surface elevation changes, the modeled river could simulate a large change in width that would not be realistic. Such large changes affect the heat budget through the surface width; almost all of the river's heat gains and losses during the course of a day occurs at the air-water interface, and the surface width is a critical component that determines heat fluxes and the temperature of the river. The simulated width also affects all processes that occur at the sediment-water interface, such as sediment oxygen demand. The larger the surface area, the larger the effect.

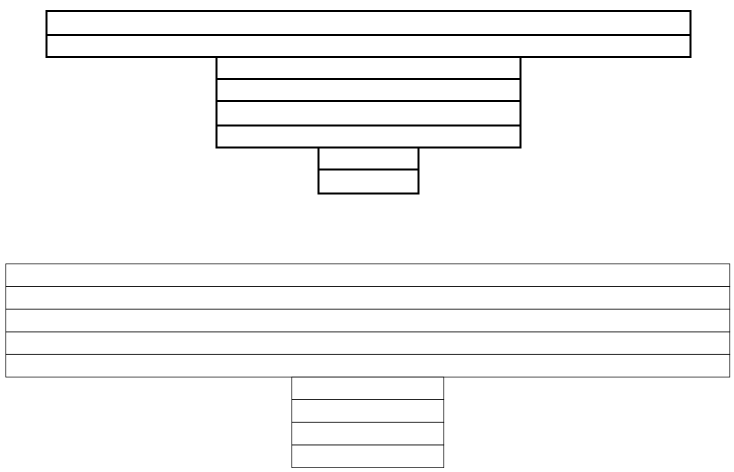

Figure 7. Typical cross sections extracted from the CE-QUAL-W2 model grid. The distance from left to right represents the distance from left bank to right bank. Each layer is 0.61 m (2 ft) high. The top cross section is segment 2 at the upstream boundary, and the bottom cross section is segment 86 at RM 237.5 near the KRS 12a sampling site (see fig. 2).

Under the current and natural condition scenarios, the river surface elevation is maintained at a fairly constant elevation, so it is possible that these cross-sectional width issues may not be important, depending on whether the water surface is near a layer interface that has large width changes. However, if different conditions were imposed that affected the water-surface elevation and the variability of that elevation in this reach, then this issue may become more important and have significant ramifications for the heat and oxygen budgets.

Minor Comment

B.a. **Shallow location.** The CE-QUAL-W2 model grid contains the expected variability in depth, but a notable shallow segment is present approximately 4 km (2.5 mi) upstream of Keno Dam (**fig. 6**). That segment is 304.8 m (1,000 ft) long, and 4.3 m (14 ft) higher than the immediately adjoining upstream and downstream segments. The presence of this shallow area in the raw bathymetric survey data was verified during this review. Shallow features such as this can be important for the modeling of thermal stratification and vertical mixing, so it is good that this feature was included in the model's bathymetric representation.

C. Model and Source Code

When the source code of a model has been modified in the course of its application, examination of that code is a critical part of a model review. Tetra Tech modified the CE-QUAL-W2 source code to add new algorithms and change how certain processes are simulated. This section reviews the CE-QUAL-W2 model in general and the code changes made for the Klamath River application in particular.

Major Comments

C.1. **Model choice.** CE-QUAL-W2 is a widely applied model with a strong record of success in simulating flow and water quality in rivers, lakes, and reservoirs around the world (Cole and Wells, 2002). This model generally is a good choice for the reservoir-like Lake Ewauna to Keno Dam reach of the Klamath River. Of some concern is the fact that CE-QUAL-W2 is not capable of simulating the recirculating current that sometimes occurs in Lake Ewauna. Most of the downstream flow in that reach occurs on the western edge because the channel is deeper near that bank. Depending on flow and wind conditions, however, upstream flow can occur along the shallower eastern side of that reach upstream of the railroad bridge. Measurements of this phenomenon on August 27 and 28, 2008, by USGS verified that this type of recirculation occurs (**fig. 8**). If this sort of recirculation occurs frequently, then the CE-QUAL-W2 model will be unable to properly represent the distribution of residence times experienced by parcels of water that traverse this reach. The median residence time may still be captured by the model, but the model will not capture some of the variability in water quality that results from shorter or longer residence times in Lake Ewauna.

Figure 8. Map showing the measured circulation pattern in Lake Ewauna just downstream of Link River, Oregon, during August 27 and 28, 2008 (U.S. Geological Survey, unpub. data). Arrows show the mean direction of flow at each measurement location (sites marked by green circles).

The residence time in this reach has an important effect on materials that settle or decompose rapidly, and on the effects of sediment oxygen demand. Despite this problem, and although a three-dimensional flow model might be better able to capture some of the more detailed circulation patterns in the Lake Ewauna area, CE-QUAL-W2 should be able to capture the most important flow and water-quality processes that occur in the Lake Ewauna to Keno Dam reach of the Klamath River.

C.2. **Code version.** Version 3.12 of CE-QUAL-W2, as released by the development team on August 15, 2003, formed the basis of the model applied to the reservoir reaches of the Klamath River for the TMDL. That version subsequently was modified by Tetra Tech to add new and customized algorithms and outputs. Version 3.12 from August 15, 2003, is a widely used and relatively bug-free version of CE-QUAL-W2. Overall, this model version is a good choice as a starting point for a W2 application.

Although version 3.12 was a good modeling framework at the time, the CE-QUAL-W2 development team has continued to improve the model over the years. The current version stands at 3.6 and has changed greatly since the release of version 3.12. Dozens of bug fixes, code improvements, and new capabilities have been added. The code used in this Klamath River application has not been modified to keep up with the developers' improvements. Where problems exist in the version 3.12 code, it is important that they be recognized and either fixed or avoided through judicious and informed use. The development team posts their updates and bug fixes with each new release, and many of those fixes can be applied by the model user to older versions of the code without undue effort.

The following list is a summary of some of the more important bugs that have been identified by the developers, but remain in the code used in this study, since the release of version 3.12.

1. The phosphorus sorption code in version 3.12 is incorrect. Several somewhat involved fixes to the code are needed, and have been applied to certain subsequent versions of the code. This problem affects the available phosphorus for algal growth, the amount that settles with particulate materials, etc. The easiest solution for the modeler is to avoid the use of phosphorus sorption and set the PARTP input parameter to zero. Although PARTP was not set to zero in the Tetra Tech models, its value was relatively small (0.001) and therefore should have little effect on the results.
2. Calculations of total phosphorus in the version 3.12 code double-count the amount of sorbed phosphorus. This should not result in a large error, given the small amount of phosphorus sorption used in the Tetra Tech model.
3. Evaporation calculations use the wrong river width if the water surface is above the KT layer of the model. The fix is simple and has been corrected in later versions of the model. For the Lake Ewauna to Keno Dam model, evaporation effects on the water budget were turned off (but ON in the heat budget), so this error is not encountered. Turning evaporation off for the water budget affects only the mass of water lost to the atmosphere through evaporation, which is a small component of the water budget in this reach, so the effect should be minimal.
4. In the pH calculations, formulations for the dependence of equilibrium constants on temperature have been updated in later versions. This will not affect the results significantly.

5. The variable WINTER is not set correctly in version 3.12, resulting in errors if ice calculations are turned on. Such calculations are turned off in the Tetra Tech model, but potential model users should be informed of this problem, or the problem should be fixed in the code.
6. An error in the LATERAL_WITHDRAWALS subroutine may set the depth of a withdrawal incorrectly. This is an easy bug to fix and has been fixed in later versions. Lateral withdrawals are used in the Lake Ewauna to Keno Dam model, and although this error may prove inconsequential, the effect has not been quantified.
7. The SEDIMENTS subroutine has changed greatly since the release of version 3.12 to correct several problems. For example, the accumulation of sedimentary organic matter from epiphytic sources counted only the contribution from the last epiphyton group. This application used a sedimentary organic matter decomposition rate of zero, however, which avoids these coding problems.

These are just a few examples, but illustrate that modelers need to be aware of bugs and shortcomings in the code, and apply the model appropriately.

C.3. **Version control and documentation.** Different versions of the model were applied to the current conditions and natural conditions scenarios. The source code reviewed for this report was from the natural conditions model. A comparison of the control files and the program sizes indicated that code differences between the current and natural conditions models probably were small, and the natural conditions code could have been applied to the current conditions model runs with just one small change to the current conditions control files. This was not done, however, and the result is that different versions of the model program (the .exe file) were used for different model runs. This is not necessary, adds complexity and is not good practice, but is easily fixed. Optimally, only one version of CE-QUAL-W2 should be applied to the various model runs, and tighter control over the model versions should be exercised in the future.

When code changes are made, those changes should be documented in the source code and in any reports so that model users know of the changes and are aware of their implications. Although some changes in model algorithms were documented in a draft report (Tetra Tech, Inc., 2008), such documentation for many of the important changes to the model code are absent. Tighter control also should be exercised over the source code versions used for these models. Apparently, the source code for the current conditions models was not archived after it was compiled, and therefore was lost when later code changes were made to the model. Such a practice is not optimal—source code should be properly archived and documented with all model versions that are used for any purpose.

C.4. **SC10 error.** Tetra Tech modified the CE-QUAL-W2 model source code to add a new variable named SC10. This variable was used to reduce the incoming short-wave solar radiation by 20 percent for the Lake Ewauna to Keno Dam model, but the change was hard-coded only for that model (models with 115 segments and 15 layers) and only if the user chose the term-by-term heat balance equations as opposed to the equilibrium temperature equations.

If a 20-percent reduction in solar radiation was desired as part of the calibration process, a static shade coefficient of 0.8 could have been imposed in the shade input file. It was not. No topographic or vegetative shading was set in the shade input file. If the solar radiation input data were known to have a positive bias of 20 percent, then those data could have been adjusted outside of the model. If the incoming solar data are accurate (and they appear to be accurate based on comparisons to other nearby data), however, then a 20-percent reduction in that input for the heat budget seems unjustified, given the lack of topographic and vegetative shading in the Lake Ewauna to Keno Dam reach of the Klamath River. If 20 percent of the incoming solar radiation was discarded in order to adequately simulate the measured water temperatures, then perhaps the surface widths in the model grid are too wide. Other items to check in the water-temperature calibration are the simulated travel times and extinction coefficients as well as simulated versus measured vertical temperature profiles.

Not only was a 20-percent loss in solar radiation hard-coded into the model, but the code changes were applied inconsistently. The reduction in short-wave solar radiation was applied only to the radiative part of the heat budget. The full amount of short-wave solar radiation flux was used in the model for layer-by-layer light extinction and for computations of available light for photosynthesis by phytoplankton and epiphyton. As a result, the heat budget for the surface layer cells is incorrect—the short-wave heat flux entering the top of the river is inconsistent with the downward moving short-wave heat flux and the light energy converted to heat within that layer.

No documentation was provided to justify this significant change in the code, but the change will affect the temperature simulations and the vertical distribution of heat in the Lake Ewauna to Keno Dam reach. Most importantly, the change severely damages the robustness of the model; even if the model matches measured temperatures under current conditions, the model algorithms to predict temperatures under other sets of conditions (other than those for which the model was calibrated) have been significantly compromised.

The only way to address this problem is to remove the changes to the code that arbitrarily reduce solar radiation by 20 percent, and then recalibrate the model for water temperature. Water temperature is an important factor that affects the rates of many other water-quality processes in the model. If recalibration of the heat budget produces significant changes in simulated water temperatures (or widths in the model grid), further recalibration of the water-quality components of the model will be needed.

C.5. **Healthy/unhealthy algae.** Code modifications were made by Tetra Tech to allow a fraction of the algae to become stressed or “unhealthy” as a result of low dissolved-oxygen conditions and thereby respond differently from healthy algae. These code changes and related issues are discussed under comment D.1 later in this review.

C.6. **Reef spillway flow.** Prior to the construction of Keno Dam in 1967, a shallow reef was present in the river where the dam was constructed. The reef was notched or removed when the dam was constructed. Agreements in place between PacifiCorp and other parties specify that the reef must be restored if Keno Dam were to be removed (Bureau of Reclamation, oral commun., 2009). Therefore, the natural conditions model scenario was set up to simulate the river without Keno Dam but with the Keno reef in place.

Bureau of Reclamation staff, using pre-dam data collected prior to 1910 (Hoyt and others, 1913), derived a quadratic stage-discharge relation for the Keno reef. CE-QUAL-W2 did not have a built-in spillway flow function that was compatible with this new stage-discharge relation, however, so Tetra Tech modified the code to implement a quadratic spillway formula. The code modifications were assessed in this review and should work properly.

C.7. **Sediments code.** In the Tetra Tech model, the coding for sedimentary organic matter decomposition was modified in several ways. Nutrient releases from this compartment were added under hypoxic conditions, in much the same way that such releases are made from the zero-order sediment oxygen demand (SOD) compartment. The release of nitrogen and phosphorus from sedimentary organic matter decomposition under oxic conditions was removed from the code, although this process does occur in the environment. The code revisions also are incomplete and sometimes incorrect because they do not include an oxygen concentration dependence for all uses of the SEDD() term, an important rate variable in the model.

Because the sedimentary organic matter decomposition rate (SDK) in the control file of these model runs was set to zero, thus zeroing out the SEDD() term, these changes in the source code are inconsequential for these applications. However, should these models be run with a non-zero SDK term, the results would not be as intended. These code modifications are incomplete and need to be corrected and updated.

Minor Comments

C.a. **Light extinction.** Tetra Tech modified the model source code to add new dissolved organic matter (DOM) terms, for both labile and refractory DOM, to the calculation of light extinction. Light extinction coefficients affect the vertical distribution of heat and light in the water column, thus affecting the vertical distribution of algae and dissolved oxygen as well. Due to the amount of DOM in the Klamath River downstream of Upper Klamath Lake, and its variation over the season, this code change appears to have been warranted. However, a light extinction coefficient of 0.05 $m^{-1}(g/m^3)^{-1}$ was added directly to the source code for the DOM components, rather than read in as an input parameter like the rest of the extinction coefficients, thus restricting flexibility for future model users. No documentation was provided to justify the use of this value for a DOM light extinction coefficient. Justification might have included laboratory or field measurements to support the selected value, or the results of model calibration and sensitivity testing. In addition, no information was provided to determine whether the baseline extinction coefficient (EXH2O) in the model was adjusted downward to account for the fact that extinction due to DOM was applied separately.

C.b. **ISC coding errors.** Tetra Tech modified the model source code in many ways to create customized outputs, compute customized quantities, perform specialized calculations, and add new algorithms. A few of these modifications have minor coding errors, which can be ignored and remain unused or should be fixed. For example, specialized code was added to the model to adjust boundary inputs of temperature and water-quality constituents through a new input variable (ISC) and several new internal variables. These adjustments are activated when ISC is set to a value greater than or equal to 2, a condition that never occurred in the set of model runs provided for this review. The new code, however, has errors associated with ISC in the TIME_VARYING_DATA subroutine that would affect the intended adjustments near the beginning of a model run.

C.c. **Compiler options.** Tetra Tech used the “CVF” or Compaq Visual Fortran version of the CE-QUAL-W2 code, and used the Compaq Visual Fortran compiler to create the program executable file from the source code. Tetra Tech used the standard “release” compiler options when compiling the program, which are:

```
/compile_only /nologo /warn:nofileopt /module:"Release/" /object:"Release/"
```

Experience has shown, however, that the following compiler options are helpful in producing faster and more accurate code for some programs:

```
/fast /nodebug /real_size:64 /warn:(argument_checking,nofileopt,unused,nousage)
```

All compiler options used when releasing compiled code should be documented.

C.d. **Source line length.** Many Fortran compilers, including the Compaq Visual Fortran compiler, have a source line length limit of 132 columns. Some modifications made by Tetra Tech resulted in source lines that exceeded the 132 column limit. It may be that the Compaq Visual Fortran compiler is somewhat forgiving about this limit and that the compiled code was unaffected by this non-adherence to convention. The CE-QUAL-W2 model development team, however, adheres to this convention, and it would be wise to do the same with all code alterations, in case a compiler is used that does not allow source line lengths greater than 132 columns.

C.e. **Flux calculations.** Changes were made in the Tetra Tech code that affect the computation of flux outputs. These values are computed for the convenience of the model user, have absolutely no effect on simulated flows, temperatures, or concentrations, and their output can be turned on or off by the user. Flux computations were turned off in the model runs that were reviewed. Should they be turned on, however, the code changes appear to introduce new errors, beyond the problems that already existed in the version 3.12 flux computation code. Model users should be aware of this problem and keep the flux outputs turned off; if user requirements dictate that these calculations be turned on, the code would first need to be fixed.

C.f. **TSR outputs.** Time series output files are missing column headings for epiphyton (a problem with the original version 3.12 code). Additionally, if ice computations are turned on, the Tetra Tech code modifications will output the phosphorus, nitrogen, and light limitation factors for algae twice. Those factors are output only for the first algae group. These problems do not affect model computations.

D. Model Parameters

A large and complex model such as CE-QUAL-W2 has dozens of important input parameters that specify critical growth rates, decomposition rates, reaeration rates, temperature functions, extinction coefficients, and more. Some of these parameters are more important than others, and many act in combination to produce a certain result. Calibration of the model involves a methodical step-by-step and constituent-by-constituent process of adjusting many of the input parameters until a desired match to calibration data is achieved. When good datasets are available, the modeler can target certain time periods and/or locations when a certain instream process is likely to be more or less important in an attempt to isolate its effect and thereby achieve a better calibration of a particular input parameter. Expected ranges may be available for some model parameters as published in the literature, and provide reasonable limits on their calibration range. When data are sparse or a particular instream process cannot be isolated in space or time, the best professional judgment of the modeler must be used to create a set of calibration parameters that is robust and reasonable.

Not all calibrated models represent a unique solution or a unique fit to the available data. It is possible that multiple sets of parameter values may achieve similar fits to the available calibration data. If that occurs, the modeler must ensure that the most dominant processes are modeled as accurately as possible in the modeled water body so that robust, or at least reasonable, extrapolations may be made when the model is used to predict the effects of altered conditions. If the calibration is more speculative or less tied to the mechanistic nature of instream processes, then any extrapolation by the model would be tenuous.

A comprehensive evaluation of all of the model parameters used by CE-QUAL-W2 was not possible within the time frame of this model review. Some key parameters that affect water quality in this reach, however, such as rates associated with algae and organic matter, were evaluated with respect to their consistency and magnitude.

Major Comments

D.1. **Algae.** Processes associated with phytoplankton are some of the most important in determining the water quality of the Klamath River in the Lake Ewauna to Keno Dam reach. In the Tetra Tech model, in an effort to simulate the spatial and temporal patterns of algae, phytoplankton were divided into two groups. This grouping was not based on any species difference or on different responses to light, nutrients, or temperature. Rather, one group was deemed “healthy” and the second group was deemed the same collection of species, but in an “unhealthy” or stressed state. The unhealthy algae were hypothesized to be stressed as a result of exposure to low dissolved oxygen concentrations. New algorithms were added to the model to allow the healthy algae to be converted to unhealthy algae at a user-defined rate upon exposure to a low dissolved-oxygen environment. Similar algorithms allow the unhealthy algae to “recover” and be converted to healthy algae at a different user-defined rate.

The user-defined rates that convert algae between the two groups were set to be functions of the simulated dissolved oxygen (DO) concentration. The calibrated model has four input parameters that determine these conversion rates for phytoplankton, and an additional four that define the conversion rates for epiphyton. The rates used in the Lake Ewauna to Keno Dam model are shown in **figure 9** as a function of DO concentration.

Tetra Tech noted in their draft modeling report (Tetra Tech, Inc., 2008) that this conversion between healthy and unhealthy algae is simply a hypothesis (although they indicate that some support for this idea is available in published research), and that more research is needed on this topic. Although this approach is intriguing and may have some value, it is clear that more research is needed. The two citations provided in the draft Tetra Tech modeling report do not, in fact, appear to support their approach. The first is a fisheries report that gives an overview of algae and water quality in Upper Klamath Lake (National Research Council, 2004), but does not show that anoxia causes poor algal health. The second study cited, by Baric and others (2003), describes an algal mortality event in a small saline lake that is a different environment than the Klamath River. Baric and others (2003) reports on a water-column mixing event that also exposed the algal community (diatoms and microflagellates, not blue-green algae) to large changes in salinity, hydrogen sulfide, temperature, and other chemical parameters, in addition to low dissolved oxygen. The observational study does not attempt to make conclusions about which factor(s) produced the elevated algal mortality. At this point, it has not been demonstrated that the decline of algal health is caused by low dissolved oxygen concentrations in the Link River Dam to Keno Dam reach.

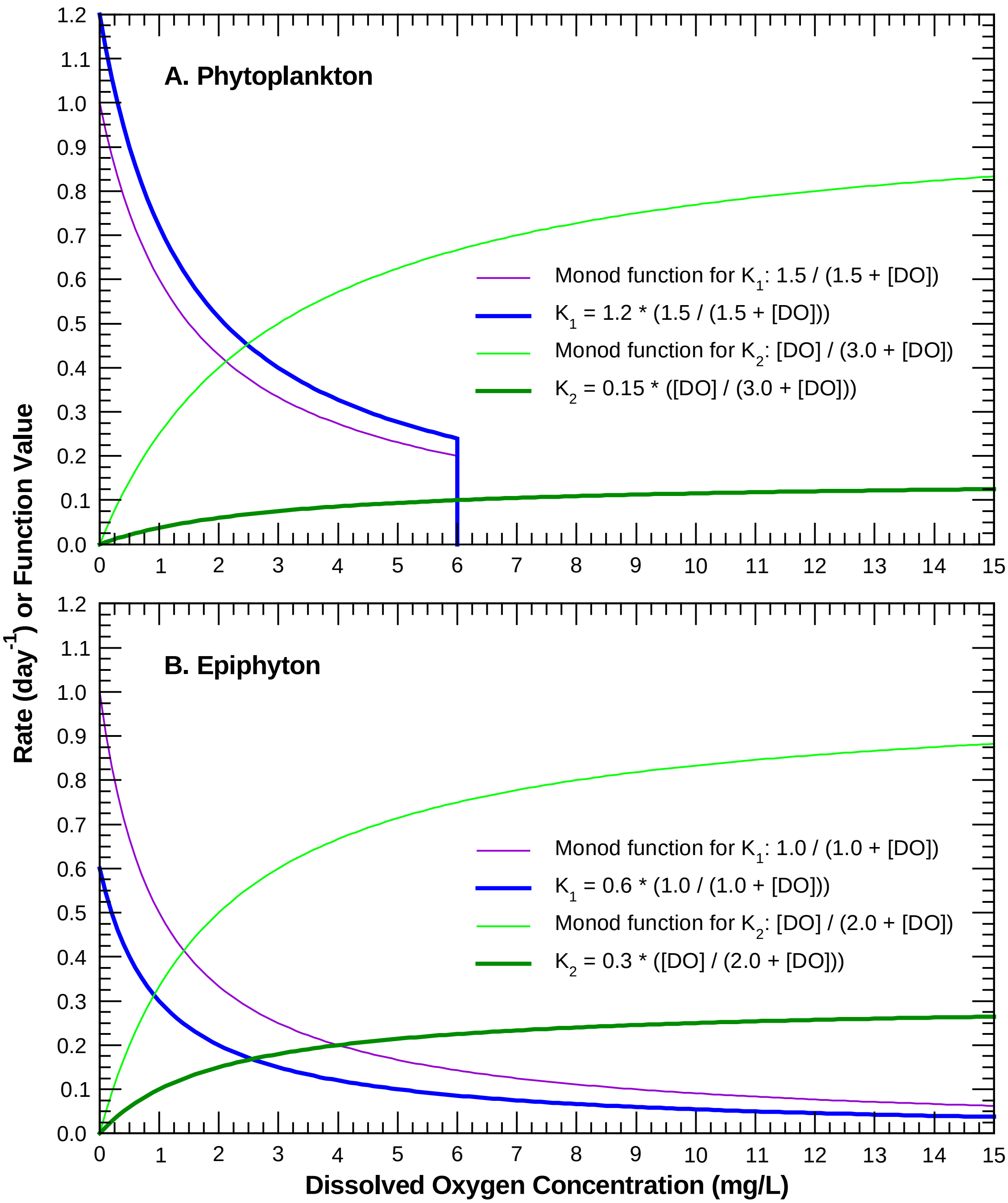

Figure 9. Graphs showing the Monod-like functions and the resulting conversion rates from “healthy” algae to “unhealthy” algae (K_1) and back (K_2) for (A) phytoplankton and (B) epiphyton as modeled by the Tetra Tech Klamath River model for Lake Ewauna to Keno Dam, Oregon. The K_1 rate for phytoplankton is zero when the dissolved oxygen concentration is greater than 6 mg/L.

Regardless of the validity of the approach, a number of questions regarding the selected parameter values are unanswered in the documentation:

- What is the basis for the chosen conversion rates between the two groups?
- Why are the rates so different for epiphyton as compared to phytoplankton?
- Why are healthy algae being converted to unhealthy algae at a significant rate (0.24/day) when the DO concentration is as high as 6 mg/L?
- What is the basis upon which that conversion is truncated to zero above 6 mg/L?
- Why was that 6 mg/L cut-off implemented for phytoplankton but not for epiphyton?
- If all of these parameter values (four for phytoplankton and four more for epiphyton) were set as the basis of a calibration process, how was that calibration process implemented? Was an optimizer used?
- What assurance does the model user have that the calibrated values offer the "best" solution?
- Does a unique solution exist, given this number of calibration parameters? It is highly likely that this solution is not a unique solution. That does not detract, by any means, from the value of a model that matches the measured data; however, it may affect the ability of the model to extrapolate to different conditions (such as natural conditions) and to offer insight into instream processes.

In addition to the rates used to convert algal biomass from one group to another, the two algae groups (healthy/unhealthy) were simulated with different growth, respiration, excretion, and mortality rates. The growth and respiration rates were set to zero for the unhealthy phytoplankton and epiphyton. The mortality rates of the unhealthy phytoplankton and epiphyton groups were set to values that are 5 or more times higher than the mortality rates of their healthy counterparts. No documentation was provided for the method used to establish these rates. Certainly if the algae are stressed, one might believe that they should have a higher mortality rate and perhaps a zero growth rate, but a zero respiration rate does not seem to be supported by either data from this site or published results from other regions.

The variable buoyancy of *Aphanizomenon flos-aquae* (AFA), often the dominant algal species in UKL that is exported to the Klamath River, makes the algae in the river even more difficult to model. The physiological processes in AFA that lead it to be buoyant under certain conditions and non-buoyant under other conditions are not yet well understood, and certainly have not been translated into usable model algorithms. At this time, CE-QUAL-W2 allows only a constant settling rate to be assigned to each simulated algae group, and although newer versions of the model allow a negative settling rate (to simulate buoyancy), algae in this Klamath River TMDL model were simulated only with positive settling rates. It may be that the algae exported to the Klamath River are not in an ideal environment for them to express such buoyancy variations; indeed, the strong settling of some algae in the Lake Ewauna to Keno Dam reach may mean that buoyancy considerations are not particularly important in this reach. The fact remains, however, that the algal communities in the Klamath River are poorly understood and the water-quality models only include algorithms that are a gross simplification of aggregate processes. It is possible that the model simulates the right patterns but for the wrong reasons. Further research into algal dynamics and processes is needed.

In summary, while Tetra Tech's approach of simulating healthy and unhealthy groups of algae seems interesting and may hold some promise for capturing some of the responses of the algal community to low DO concentrations that heretofore were not represented by CE-QUAL-W2, the additional model calibration parameters that are not tied to published research probably result in a model whose solution is not unique or robust. The uncertainty in the values of these new model parameters leads to additional uncertainty in the model predictions.

D.2. **Sediment Oxygen Demand.** The Lake Ewauna to Keno Dam model is one of four CE-QUAL-W2 models used in the Klamath TMDL to simulate a series of reservoirs on the Klamath River. Although this review focuses only on the most upstream model, it is useful to compare selected model parameters among these four models, and the sediment oxygen demand (SOD) rate provides an interesting example.

The zero-order SOD rate was set to 3.0 $g/m^2/d$ in the Lake Ewauna to Keno Dam model, 2.0 $g/m^2/d$ for the JC Boyle and Copco models, and 1.1 $g/m^2/d$ for the Iron Gate model (in downstream order). The base SOD rate is set by the user through a multiplication of the SOD values and the FSOD factor that are set in the model control file. An examination of the control files also shows that the temperature dependence functions for SOD are different for each of these reservoir models (**fig. 10**).

Measurements by Eilers and Raymond (2003) show that the SOD rate does decrease from one reservoir to the next downstream, thus providing some basis for the pattern in the modeled rates. However, measurements of SOD rates in the Lake Ewauna to Keno Dam reach by USGS in 2003 showed a range of 0.3 to 2.9 $g/m^2/d$ with a median rate of 1.8 $g/m^2/d$, as adjusted to a temperature of 20°C (n=22; Doyle and Lynch, 2005). So, although some USGS measurements of the SOD rate approach the modeled baseline value of 3.0 $g/m^2/d$ in the Lake Ewauna to Keno Dam reach, the modeled SOD rate in that reach may be too high. The temperature function used for the Lake Ewauna to Keno Dam model results in a modeled SOD rate of 2.8 $g/m^2/d$ at 20°C, which is still well higher than the USGS-measured median value adjusted to the same temperature. The temperature adjustment function used with the USGS measurements is different from those shown in **figure 10**, but the modeled rate still appears to be higher than the measured rate.

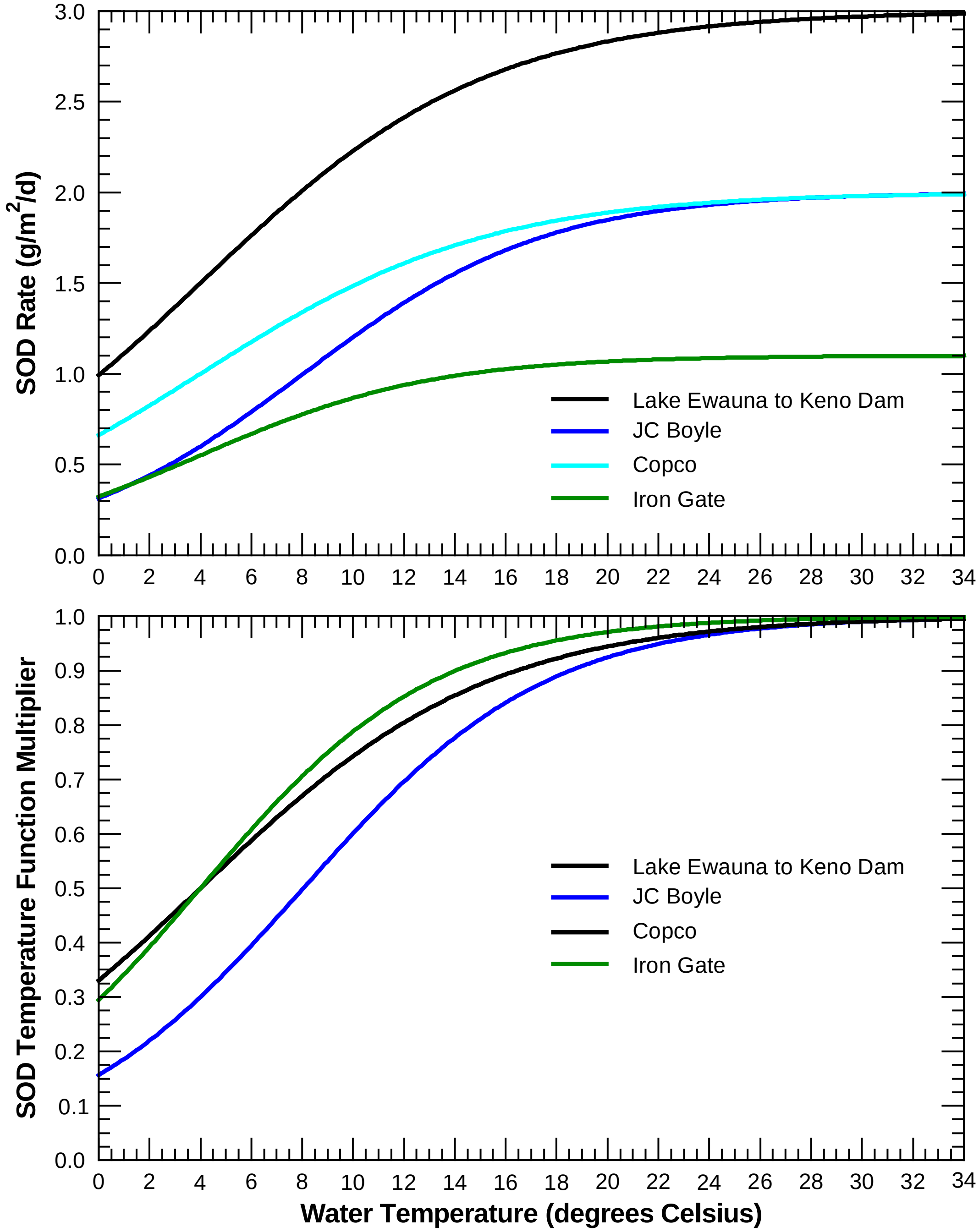

Figure 10. Graphs showing the zero-order sediment oxygen demand (SOD) rate and the SOD temperature rate multiplier function used by the Tetra Tech Klamath River reservoir models.

D.3. **2000 vs. 2002 parameter values.** A model is considered most robust when the same set of model parameters and rates is able to predict conditions for multiple years and environmental conditions where measured data are available. The Lake Ewauna to Keno Dam model was calibrated to conditions that occurred in 2000, and tested against conditions that occurred during 2002. For the 2000 and 2002 current conditions models, most of the model parameters applied to the 2 years were the same, but several differences were notable. For example, the 2002 model used an ammonia nitrification rate that was one-half that used in 2000 (**table 1**), but the basis for the difference is not documented. It seems unreasonable that the nitrification rate would change to one-half of its original value in only 2 years and that the population of nitrifying bacteria would be so different only 2 years later. The use of different parameter values in different years results in a less robust model and reduces confidence in the model's predictive ability.

Table 1. Model parameters from the CE-QUAL-W2 control file that differ between the 2000 and 2002 current conditions runs and the natural conditions scenario.

Model parameter	Parameter description	Current conditions 2000	Current conditions 2002	Natural conditions 2000
NH4DK	Ammonia nitrification rate, 1/day	0.10	0.05	0.10
O2LIM	Dissolved oxygen half-saturation constant for decomposition processes, mg/L	0.1	2.0	0.1
LDOMDK	labile DOM decay rate, 1/day	0.25	0.25	0.20
LPOMDK	labile POM decay rate, 1/day	0.25	0.25	0.20
POMS	POM settling rate, m/day	0.80	0.80	0.05

The 2002 model used a DO half-saturation constant for decomposition processes (O2LIM) that was 20 times higher than that used in the 2000 models (**table 1**). This was probably an oversight, because Tetra Tech significantly altered the use of this variable in the model source code and prior to that alteration, its value in some previous model runs for the Klamath River had been set to the value used in the 2002 model run. Still, this mistake has a significant effect on decomposition processes that occur in the river, and this inconsistency needs to be corrected. Moreover, some basis for choosing 0.1 mg/L versus 2.0 mg/L for this parameter would be useful; at this time, no such basis has been documented.

Differences also exist for some of the decomposition and settling rates used for organic matter in the 2000 current conditions and natural conditions models (**table 1**). The reason these different values were selected was not documented. If the sources and nature of organic matter truly are expected to be different under the natural conditions scenario, then it is possible that the decomposition rates might be smaller than those that occur under current conditions. However, the available data for organic matter in this system was sparse during model development, and going further to predict how decomposition rates might change in the future, without well-documented literature and/or laboratory research to back-up the new rates, is speculative. Furthermore, the very nature of particulate organic matter in the system would have to change greatly to support a decrease in the settling rate from 0.8 to 0.05 m/d. The 0.8 m/d rate for current conditions already may be biased low. Preliminary unpublished findings from recent measurements of particulate settling rates in the Lake Ewauna to Keno Dam reach of the Klamath River may show even higher settling rates (Watercourse Engineering, Inc., written commun, 2009). Further research and measurements may be necessary.

Minor Comments

D.a. **ISOURCE error.** For the Lake Ewauna to Keno Dam model, the user-supplied input values of IDAG1 and IDAG2 (or ID1 and ID2 on the ALGAL RATE input card) combined to cause the value of the ISOURCE2(2) variable in the source code to remain at its initial value of 0. With some Fortran compilers, this might have resulted in a subscript out-of-range error when values such as AKR2(ISOURCE2(2)) and HDOAG2(ISOURCE2(2)) were used, because Fortran array indices normally start at 1 rather than 0. No such run-time error was reported in this case. Perhaps these values were set to zero by the program at run-time. If so, then the correct result was obtained. It appears that IDAG2 for the first algal group should have been set to 2 rather than 1 in the control file. Setting the value of IDAG2(1) to 2 and re-running the model showed identical results, so this error in the control file did not affect the model output.

The same type of subscript problem also occurs in the code for ALG(K,I,ISOURCE2(2)). Because the ALG() array points to the C2() array, a subscript problem here might cause a subscript out-of-range error, or the compiler might set the value to zero, or an unintended value from the C2() array might be assigned to the algal concentration. This highlights the need to be careful with the IDAG1 and IDAG2 values in the control file. The same error was present in the control file for the epiphyton groups. IDEG2(1) should have been set to 2 rather than 1.

D.b. **Light extinction.** Baseline light extinction coefficients were set to 0.60/m in the Lake Ewauna to Keno Dam model and the JC Boyle model, and 0.25/m in the Copco and Iron Gate models. Watercourse Engineering has some data to show that light extinction varies considerably along the course of the river. Some documentation of these effects, if not already in place, would be useful.

D.c. **AHSN.** The nitrogen half-saturation constant for phytoplankton growth was set to 0.014 mg/L for the Lake Ewauna to Keno Dam, JC Boyle, and Iron Gate models, but was set to 0.021 mg/L for the Copco model. The reason for these differences was not documented. Note that the modeling report (Tetra Tech, Inc., 2008) states that these parameter inputs are all the same and set to 0.014 mg/L.

E. Model Results

The boundary inputs, bathymetry, parameters, and source code work together when the model is run to produce simulations of flow, water temperature, and water quality for each cell in the model grid and for each time step. Current conditions model results are compared to measured data at the same time and location as part of the model calibration process. For this review, model results were compared to measured data at Miller Island and at Keno (**fig. 2**) to assess model performance and accuracy.

Major Comments

E.1. **Calibration time period.** The Link River to Keno Dam models were calibrated to conditions that occurred during 2000 and checked with data from 2002. It has been noted that the 2002 test period was not an independent check of model performance because several model parameters were altered for the 2002 model runs. Still, an assessment of the 2002 test period is useful. Additional years of data were available for further calibration checks, but those additional data were not used.

Although all modeling studies are limited by available data and staff time, and necessary limits must be placed on the amount of effort expended, the use of data from only 1 year for model calibration can be a problem. Typically, 1 year of data is insufficient to represent the wide range of hydrologic, meteorologic, and water-quality conditions that can occur in the Klamath River. Previous work by Wood and others (2006), for example, indicates that water-quality in UKL is affected by inputs and climate conditions that vary from year to year, resulting in year-to-year variations in the water quality that enters Link River. Building a model on only 1 or 2 years of data results in a model that is less robust than if it were built on multiple years of data. Extrapolation becomes more necessary when using a model that is based upon only 1 year of calibration data, and the results, therefore, become more uncertain.

Recognizing the limitations imposed by timelines and available data, it would be appropriate, as more data become available and a better understanding of this river starts to take focus, for the modeling to be revisited in order to build a more robust predictive tool for the better management of this important river system. Staff at Watercourse Engineering, Inc., for example, have extended the modeled time frame for these models to include 4 or 5 years of data. Additional years of data, therefore, are available for testing. Note that USGS has not evaluated the Watercourse Engineering models, and this reference to that effort does not imply endorsement by the USGS.

E.2. **Error statistics.** Goodness-of-fit statistics can be useful in assessing model performance, but no such statistics were provided in the draft Tetra Tech modeling report (Tetra Tech, Inc., 2008). In order to make a performance assessment, a quantitative comparison between simulated and measured data was made in the course of this review to compute goodness-of-fit statistics for the model's predictions of water temperature and dissolved oxygen concentrations (**table 2**).

Table 2. Goodness-of-fit statistics for the Tetra Tech model of Lake Ewauna to Keno Dam, Oregon, using data from May 1 through November 1.

[Model data were compared to measurements made 1 m below the river surface. Site locations are shown in figure 2.]

Parameter	Site	Year	Mean error	Mean absolute error	Root mean squared error
Water temperature (°C)	Miller Island	2000	0.08	1.13	1.50
		2002	0.42	1.09	1.48
	Keno	2000	0.36	0.76	0.98
		2002	0.78	0.92	1.13
Dissolved oxygen (mg/L)	Miller Island	2000	-0.52	1.89	2.48
		2002	0.38	2.14	2.71
	Keno	2000	-0.67	1.61	2.08
		2002	-0.03	2.15	2.68

Previous studies indicate that a CE-QUAL-W2 model is capable of matching measured water-temperature data with a low bias (mean error) and a mean absolute error approaching 0.5°C and certainly less than 1.0°C (Sullivan and Rounds, 2005; Sullivan and others, 2007). This model comes close to that criterion for the mean absolute error at Keno, but not at Miller Island, and the model exhibits a positive bias that is larger than optimal. Moreover, this bias likely would be larger if the hard-coded 20-percent reduction in solar radiation, discussed in section C.4, were removed. As it is, the model captures the seasonal pattern in water temperature well and is adequate for framing the rates of chemical and biological reactions used by the model. These goodness-of-fit statistics indicate, however, that the model simulates water temperature with good, but not excellent, accuracy. Improvements are possible based on points made earlier in this review.

The simulation of dissolved oxygen concentrations by the model shows that large prediction errors on the order of 1.6 to 2.2 mg/L are present, although bias appears to be low most of the time, as the mean error ranges from near 0 to about -0.7 mg/L. Simulating dissolved oxygen is difficult in a system like the Klamath River where algae dominate many water-quality processes; however, it has been demonstrated that CE-QUAL-W2 can simulate dissolved oxygen concentrations with a mean absolute error of less than 1 mg/L in other aquatic systems (Rounds and Wood, 2001;

Sullivan and Rounds, 2005). Additional work is needed to identify the process(es) that are not being simulated with sufficient accuracy, or the erroneous boundary conditions that cause DO prediction errors. The performance of the model should be assessed in more detail using goodness-of-fit statistics for these and other modeled constituents, and sensitivity tests should be used to assess the importance of some of the model input parameters.

When assessing model error, two issues are paramount. First, the model errors should not be so large that they compromise the ability of the model to answer the user's questions about flow, water temperature, and water quality in the reach of interest. The user must determine how much error is acceptable and incorporate the model's uncertainty and error into their assessment of model predictions. Second, it is important to remember that goodness-of-fit statistics do not provide a complete assessment the robustness of the model algorithms. Although small errors are indicative of algorithms that are simulating the most important processes in an accurate manner, they are no guarantee that those algorithms can be extrapolated accurately to a different set of conditions. For that reason, it is important the model algorithms are based on the best science and the model is tested over as wide a range of conditions as possible.

E.3. **Nitrate calibration data.** Nitrate concentrations in the Tetra Tech calibration datasets at Miller Island and Highway 66 in 2000 show a seasonal pattern that is different from data collected by ODEQ and USGS at the same location and during the same time period. The ODEQ and USGS datasets, including the long-term 1981–2007 ODEQ dataset, show remarkably consistent low concentrations of nitrate during summer, less than 0.2 mg/L from June through early September, with higher concentrations in winter (**fig. 11**). Model output shows the opposite pattern, with low concentrations in winter and high concentrations (greater than 0.8 mg/L) during summer. The draft modeling report (Tetra Tech, Inc., 2008) also questions the validity of the nitrate calibration data, but the model apparently still was calibrated in an attempt to match that dataset. The reason for the discrepancy between the Tetra Tech and the ODEQ and USGS nitrate data should be investigated, and the model should be calibrated to the most reliable data.

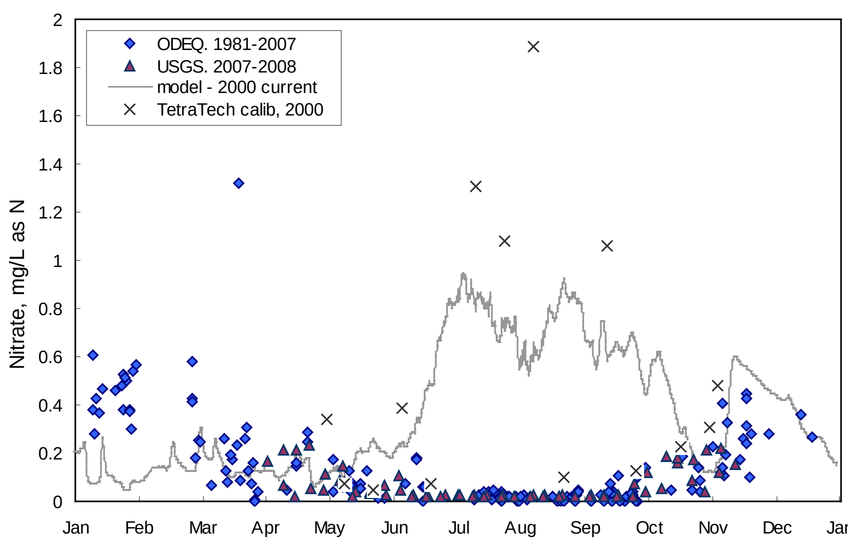

Figure 11. Graph showing comparison of year 2000 simulated nitrate concentrations to measured data from ODEQ and USGS from the Klamath River above Keno at Highway 66. ODEQ data were collected approximately six times per year, and only data reported in units of mg/L as N are plotted. USGS data were collected weekly from April to November during 2007 and 2008.

E.4. **Organic Matter**. At the time of model development, no data on dissolved and particulate organic carbon were available with which to calibrate the model. Data collected in 2007 and 2008 (**fig. 12**) at Miller Island and Keno show that the concentration and timing of seasonal cycles for dissolved organic carbon was similar between sites and years, with maximum concentrations in late summer of 12–13 mg/L. Model results for 2000 and 2002 show lower concentrations and different temporal patterns.

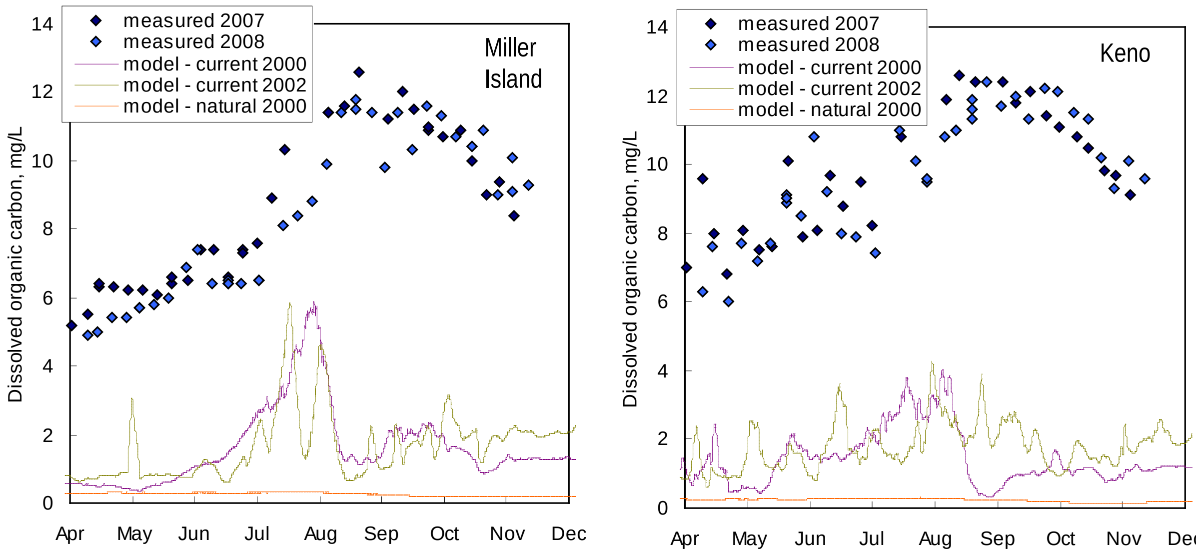

Figure 12. Graph showing measured 2007–08 dissolved organic carbon concentrations at Miller Island (left) and Keno (right) along with model output at the same locations. Modeled LDOM was converted to dissolved organic carbon using the 0.45 organic carbon to organic matter ratio specified in the model control file.

Organic matter, nutrients, algae, and dissolved oxygen are closely linked in aquatic systems, and these dependencies are included in the model code. Because the concentrations, fractionation, cycles, and decay rates of organic matter are not adequately captured in the current conditions models, it is likely that the calibrated organic matter parameters in the model, such as decay or settling rates, also are not correct. This results in less confidence in the model results for organic matter, nutrients, algae, and dissolved oxygen when the model is extrapolated to theoretical scenarios such as natural conditions.

F. Model Assumptions and the Natural Conditions Scenario

The draft Tetra Tech modeling report (Tetra Tech, Inc., 2008) includes a list of model assumptions and limitations, but the list is incomplete. This section of the model review contains a non-exhaustive list of observations made during an examination of the details of the model runs, with particular emphasis on the natural conditions scenario. Discussion of other assumptions that are built into the model parameters and source code are provided in other sections of this review.

Major Comments

F.1. **Natural condition boundary flows.** The natural conditions scenario has three sources of inflow: Link River, the Lost River Diversion Channel, and the Klamath Straits Drain. The North and Ady Canal withdrawals from the current conditions models were retained, but at slightly different flow levels. All point source, stormwater, accretion flow, and distributed tributary flows were set to zero. Although it is reasonable to remove anthropogenic inflows (such as point sources) in a natural conditions scenario, the purpose of some of these inputs was to account for natural ungaged tributaries and any groundwater inputs. Removing all of them, and having a system whose only inflows are Link River, the Lost River Diversion Channel, and the Klamath Straits Drain is overly simplistic. Furthermore, the difference in flow makes the results more difficult to compare to the current conditions scenario. Management and regulatory agencies regularly determine flow boundary conditions for natural conditions scenarios that are consistent with their needs and policies. Groundwater inflows should be retained in those scenarios to realistically simulate natural conditions.

F.2. **Keno reef flows.** Bureau of Reclamation staff, using pre-dam data collected prior to 1910 (Hoyt and others, 1913), derived a stage-discharge relation for the Klamath River at the Keno reef. Those data and the Bureau of Reclamation's quadratic fit to the data are shown in **figure 13**. The stage-discharge equation was provided to Tetra Tech, and they made code modifications to CE-QUAL-W2 to implement a new quadratic spillway flow formula to accommodate this stage-discharge relation.

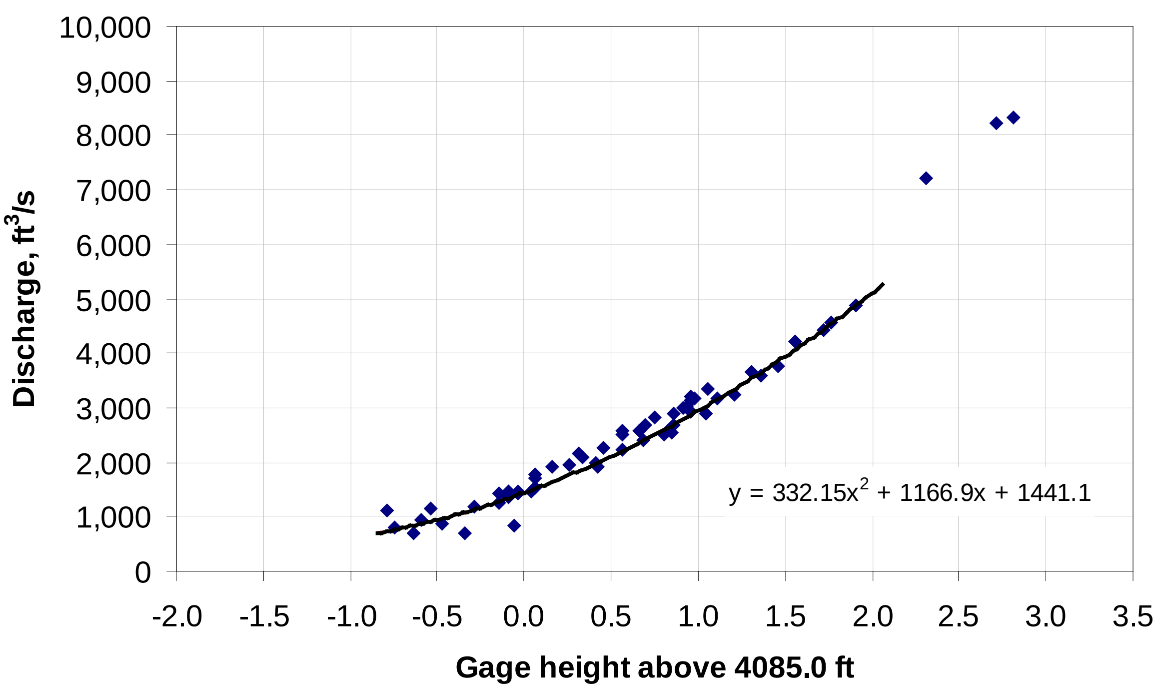

Figure 13. Graph showing stage-discharge relation generated by Bureau of Reclamation staff for the Klamath River at the Keno reef, using pre-dam data from the U.S. Geological Survey.

The natural conditions model scenario uses this new formula to calculate the flow at the Keno reef, but Tetra Tech implemented the stage-discharge relation in a slightly modified fashion. First, they had to convert the equation coefficients to metric units to be consistent with the units used by CE-QUAL-W2. Second, they translated the equation so that the stage would be relative to a datum of 4,083.0 ft rather than the datum of 4,085.0 ft used by Bureau of Reclamation, presumably so that the stage used in the model equation would always be positive. The resulting equation is

$$y = 101.239\, x^2 - 15.022\, x + 12.343,$$

where y is discharge in m^3/s and x is gage height in meters relative to a datum of 1,244.5 m (4,083.0 ft). Indeed, these three coefficients are very close to those specified in the natural conditions scenario. To preserve the functional form of the stage-discharge relation from the Bureau of Reclamation, however, the elevation of the spillway (ESP) must be set to the reference elevation of 1,244.5 m (4,083.0 ft). It was not. For some reason, the elevation of the spillway was set to 1,244.82 m (about 4,084 ft).

Simulated water surface elevations at Keno for the year 2000 show that the natural conditions levels were higher from January through March, but lower by about 0.5 m from June through December, relative to the current conditions model. Re-running the natural conditions model with a Keno reef spillway elevation of 1,244.5 m (4,083.0 ft) resulted in simulated water levels that, as expected, were about 1 ft lower (**fig. 14**).

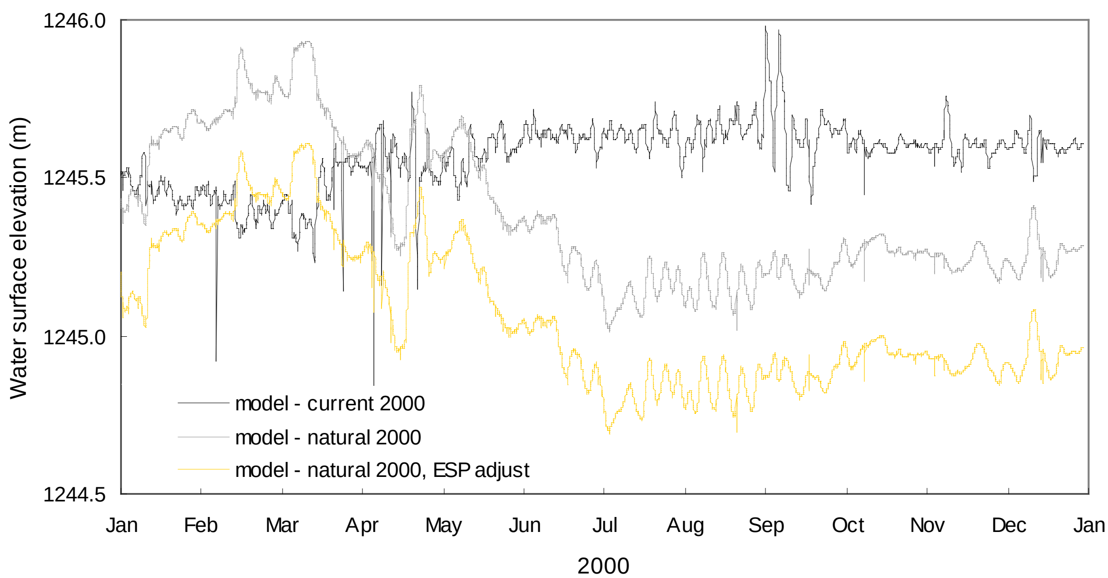

Figure 14. Graph showing water surface elevation at segment 107 (the location of Keno Dam) from the current and natural conditions model scenarios in 2000. The natural conditions model was rerun with a lower Keno reef spillway elevation to produce the “ESP adjust” results. (ESP is the model input spillway elevation.)

The Keno reef keeps the Lake Ewauna to Keno Dam reach pooled at about the same, but perhaps slightly lower, level in the absence of Keno Dam. Because the reach remains pooled, it seems appropriate to ask whether removing Keno Dam has much of an effect on the simulated residence time. CE-QUAL-W2 has the ability to track the average “age” of water that traverses its grid. When all new sources of water to the model reach are given an age of zero, and the age of all water within the grid is increased at the same rate as the elapsed simulation time, then the simulated age becomes the average time that a parcel of water has spent in the model reach. Extracting this information from the water that is discharged at the downstream boundary reveals the average residence time of the water. That average residence time is compared for the current and natural conditions scenarios for the year 2000, along with the re-run natural conditions scenario, in **figure 15**.

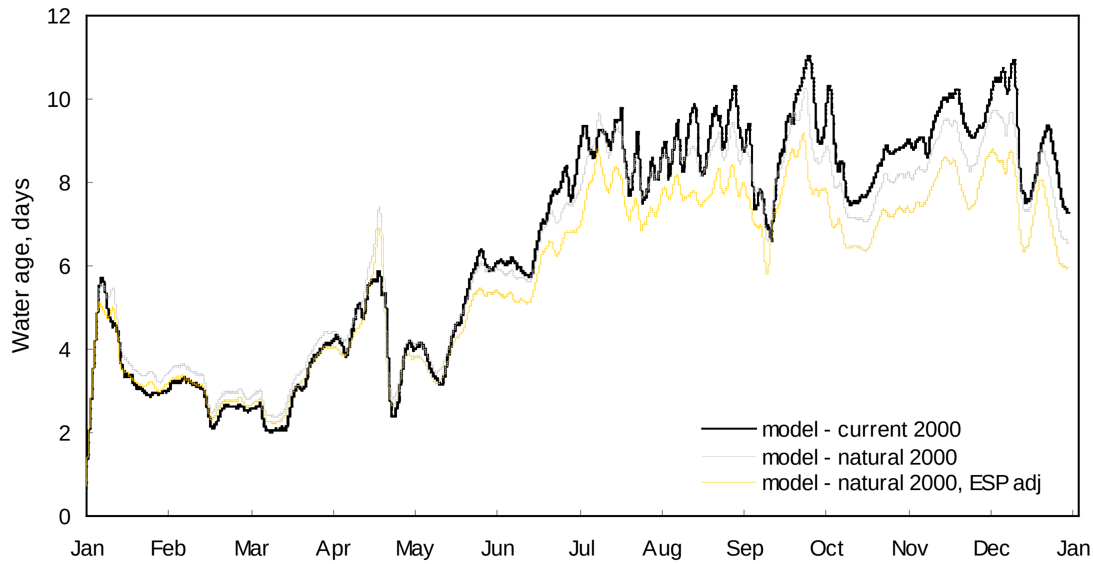

Figure 15. Graph showing average simulated residence time in the Lake Ewauna to Keno Dam model under current and natural conditions for the year 2000. The natural conditions model was rerun with a lower Keno reef spillway elevation to produce the "ESP adj" results.

The simulated residence times indicate that the current and natural conditions scenarios retain water in the Lake Ewauna to Keno Dam reach for approximately the same amount of time. The residence time is slightly shorter for the natural conditions scenario late in the year, which is consistent with the slightly lower pool level. Given that the residence times are similar, the processes of particle settling, algal growth and respiration, ammonia nitrification, and organic matter decomposition, to name just a few, will have approximately the same amount of time to exert their effects. An examination of simulated dissolved oxygen concentrations for the two natural conditions scenarios (original and rerun with a lower Keno reef spillway elevation) showed little difference at the Keno reef location. Differences in water quality between the current and natural conditions scenarios, therefore, likely are caused mainly by differences in boundary inputs rather than by removing the Keno Dam. It would be good to determine what the best Keno reef spillway elevation is for the natural conditions scenario, but the effects on residence time may not greatly affect the simulated water-quality results.

Finally, this stage-discharge relation and the accompanying code modifications were not documented by Tetra Tech in any of the materials provided for this review. Documentation for the Keno reef flow calculations needs to be included in any future model documentation.

F.3. **Natural conditions TDS.** Total dissolved solids (TDS) concentrations were set to 0 mg/L for the Lost River Diversion Channel and the Klamath Straits Drain inputs in the natural conditions scenario. Although dissolved solids may decrease under "natural" conditions, the concentration is unlikely to decrease to near 0 mg/L. Errors in TDS concentrations can lead to errors in simulated water density and pH, but should have little effect on important constituents such as dissolved oxygen, algae, nutrients, and organic matter.

F.4. **Natural conditions OM.** At the time of model calibration, few measurements of the concentration and nature of organic matter were available for the Lake Ewauna to Keno Dam reach. As a result, the way that organic matter is represented in the current conditions model does not match the data that now are available in this reach. Of particular note is the underestimation of dissolved organic matter concentrations in the current conditions model (see comments A.5 and E.4).

In the natural conditions scenario, all inflow (Link River, Lost River Diversion Channel, Klamath Straits Drain) dissolved organic matter (DOM) concentrations were decreased to concentrations less than 0.8 mg/L (0.4 mg/L as dissolved organic carbon, **figure 5**). These extremely low concentrations of DOM are unlikely in this reach of the Klamath River, given historical conditions where wetlands, which tend to be a source of refractory DOM, were plentiful (Hoyt and others, 1913). Rivers and lakes usually have concentrations of dissolved organic carbon in the range of 2 to 10 mg/L, whereas swamps, marshes, and bogs tend to have higher concentrations, from 10 to 60 mg/L (Thurman, 1985). Although DOM can be less reactive than particulate organic matter, it still contributes to the nitrogen, phosphorus, carbon, and oxygen cycles in the river and model (**fig. 16**), so any misassignments in the DOM concentration will affect these other constituents as well.

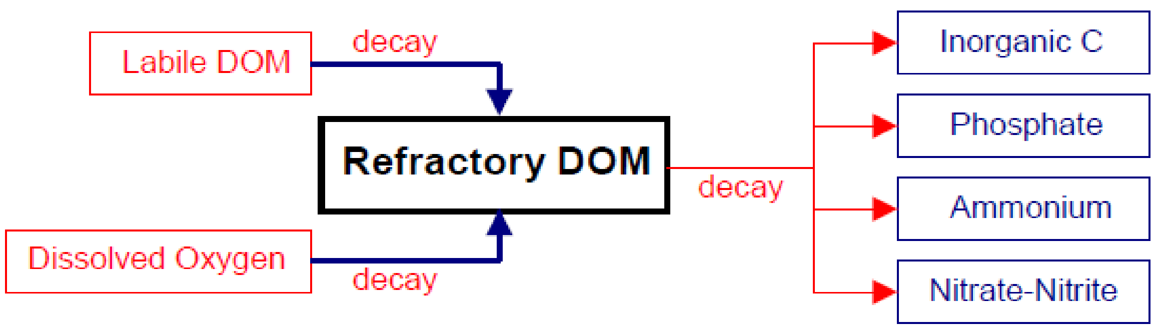

Figure 16. Diagram showing connections between refractory dissolved organic matter (DOM) and other water quality parameters in the CE-QUAL-W2 model (from Cole and Wells, 2002). Labile dissolved organic matter connections are similar, but also include sources from algal and epiphytic excretion and mortality.

The natural conditions model scenario sets much lower particular organic matter concentrations than those used in the current conditions model (see **fig. 5**). This represents a significant extrapolation from calibrated conditions, which is not a problem as long as the modeled instream processes are captured accurately. If the TMDLs for UKL are successful, however, the nature of the organic matter being delivered to Link River from UKL likely will change as the amount and type of algae change in the lake. It is difficult to know the characteristics of that organic matter in a future condition; at the least, the model predictions for the natural conditions scenario have a greater uncertainty.

F.5. **Natural conditions N and P.** The nitrogen and phosphorus upstream boundary conditions imposed for the natural conditions scenario are greatly decreased from those in the current conditions scenario (**fig. 17**). Annual average upstream boundary concentrations for the natural conditions scenario are 0.006 mg/L phosphate (as P), 0.007 mg/L nitrate (as N), and 0.068 mg/L ammonia (as N). These concentrations, though presumably set to be consistent with upstream TMDL criteria from UKL, seem rather unlikely in light of the high-phosphorus content of soils in upstream areas as well as historical data from UKL and the surrounding wetlands. The specified nitrogen and phosphorus concentrations represent conditions that probably would be classified as oligotrophic or near-oligotrophic. In contrast, paleolimnological investigations of sediment cores from UKL have reported that the lake was eutrophic and productive for the entire history embedded in those cores (hundreds of years), although recent times indicate a shift to higher nutrient and sediment inputs and new plankton species (Eilers and others, 2003; Bradbury and others, 2004). Regardless of whether these nutrient concentrations are realistic, achievable, or consistent with historical data, it is clear that these concentrations are highly uncertain. These low concentrations also are lower than most concentrations that were encountered during the model calibration process; therefore, additional uncertainty results from this extrapolation of the model.

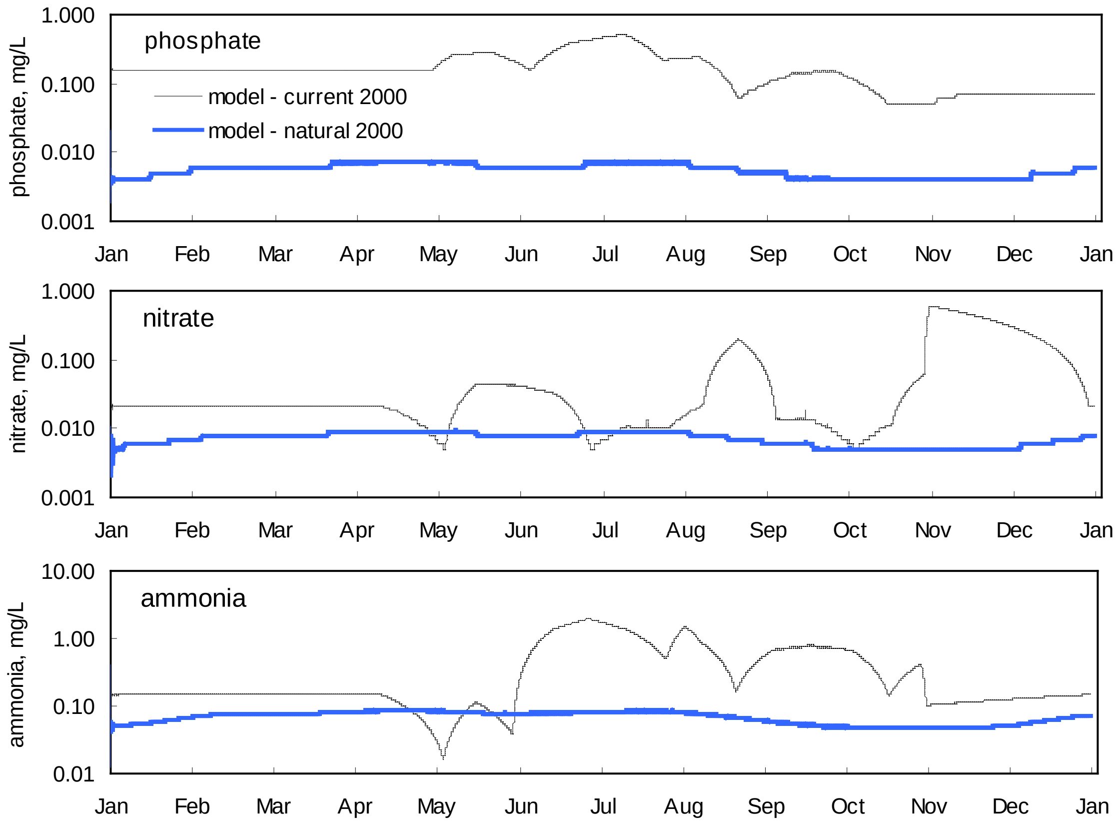

Figure 17. Graphs showing boundary input concentrations of phosphate, nitrate, and ammonia for current and natural conditions scenarios for the year 2000. Note that the graphs are on a logarithmic scale.

Minor Comment

F.a. **Natural initial conditions.** Although boundary water-quality inputs were set with nutrient concentrations that are notably lower than the current conditions inputs, initial conditions, which are set in the CE-QUAL-W2 control file, have values that are higher, closer to current condition values. For example, the initial ammonia concentration was set to 0.61 mg/L, whereas inputs from the three natural conditions inflows are mostly less than 0.1 mg/L. Similarly, initial nitrate concentrations were set to 0.21 mg/L, whereas inflow concentrations are less than 0.01 mg/L. This is not a major concern because initial conditions are quickly flushed out by inflows in this type of river model. The settings are worth noting, however, and perhaps could be decreased if further model development occurs.

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Appendix A. Qualifications of Reviewers

USGS is the Nation's largest water, earth, and biological science and civilian mapping agency. The USGS collects, monitors, analyzes, and provides scientific data and interpretations about natural resource conditions, issues, and problems. With no regulatory or resource management mission, USGS provides unbiased and impartial research and scientific information to resource managers, planners, and other customers.

A detailed model review of this type is best performed by scientists who have extensive water-quality modeling expertise, experience with the specific models under review, and knowledge of the water body being modeled. The two USGS hydrologists who performed this review meet these criteria and are currently working with the CE-QUAL-W2 model and the reach of interest of the Klamath River.

Dr. Stewart Rounds has been using CE-QUAL-W2 to model water quality in the rivers and lakes of Oregon for 17 years, including models that have formed the foundation of TMDL regulations in the Tualatin and Willamette Rivers (Rounds and Wood, 2001; Rounds, 2007). Dr. Rounds is well versed with the CE-QUAL-W2 source code and has collaborated on many occasions with the model developers on model improvements. Dr. Annett Sullivan currently leads a project designed to better understand instream water-quality processes in the Link River Dam to Keno Dam reach of the Klamath River and improve upon existing models of that reach. She has more than 7 years of experience working with CE-QUAL-W2 on river and reservoir systems in Oregon, and has published detailed USGS modeling reports using CE-QUAL-W2 on Detroit Lake, Henry Hagg Lake, and the Santiam and North Santiam River systems in Oregon (Sullivan and Rounds, 2006; Sullivan and others, 2007).

In the course of this review, USGS personnel consulted with Dr. Michael Deas of Watercourse Engineering, Inc. Dr. Deas built the Klamath River models for PacifiCorp for their FERC dam-relicensing process, and those models formed the starting point for the Tetra Tech TMDL modeling efforts on the Klamath River. Dr. Deas, therefore, is quite familiar with the models under review. Collaborations between USGS, Dr. Deas, and Bureau of Reclamation staff have led to a better understanding of the Link River to Keno Dam reach and produced a robust dataset (Sullivan and others, 2008; 2009) that can be compared to the data used in the TMDL models.