# BETTER Temperature Model of Lake Billy Chinook, Oregon

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## Abstract

The 2-D Box Exchange Transport Temperature Ecology Reservoir (BETTER) model developed by the Tennessee Valley Authority (TVA) (Bender et al. 1990) was setup and calibrated to simulate the development of temperature stratification and mixing among three branches of the Lake Billy Chinook reservoir in eastern Oregon. Application of the calibrated temperature model and the coupling of the model to a 3-D hydrodynamic model allow for the evaluation of various proposed flow modification structures on reservoir stratification and circulation. The immediate goal of the project is to identify the modification(s) most favorable to the downstream passage of juvenile salmon through the project. The ultimate goal is the restoration of anadromous fish runs to the upper tributary reaches of the Deschutes River above the project.

The calibrated temperature model successfully simulated the development of stratification and mixing patterns observed during water quality studies conducted in 1995. Simulation of four reservoir flow modification alternatives using the calibrated model and 1995 conditions indicated that the hydrothermal behavior of the reservoir could be significantly modified. Three of the simulated alternatives (surface withdrawal and two curtain alternatives) resulted in conditions that would likely be more favorable to downstream fish passage. A fourth alternative (permanent drawdown) produced stratification patterns that were very similar to the existing reservoir condition.

## Introduction

The construction of Round Butte Dam and creation of Lake Billy Chinook on the Deschutes River in Central Oregon affected the downstream migratory fish passage of juvenile salmonids. Fish passage efforts were discontinued in the late 1960's due to ineffective downstream passage. As part of the current re-licensing process Portland General Electric (PGE) is attempting to re-establish fish passage at Round Butte Dam. The passage problem has been associated with ineffective collection of downstream migrating smolts whose motion is strongly influenced by the currents encountered. Lake Billy Chinook was created by the impoundment of three major tributaries that converge near the reservoir forebay (Figure 1).

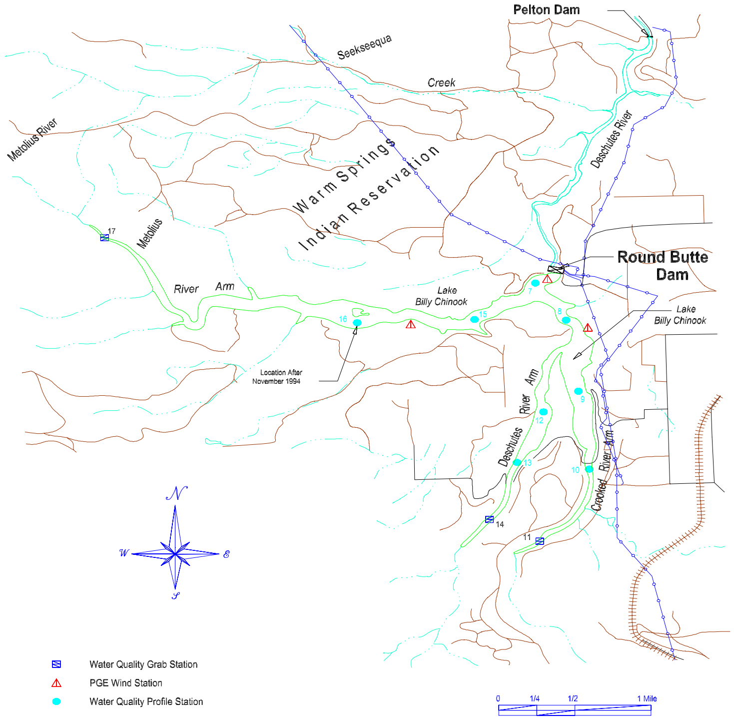

Figure 1. Site Map and Sampling Stations.

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One branch (the Crooked River) is significantly warmer throughout the year due to the influence of thermal springs. This branch tends to ride on the surface of the reservoir and bypasses the bottom outlet in the forebay. The warm Crooked River water then moves upstream on the surface of the colder branch (the Metolius River). The colder Metolius River plunges as it enters the reservoir and is withdrawn from the deep powerhouse intake located in the forebay. Salmon smolts spawned on the Crooked River tended to follow the warmer surface water away from the forebay and up the Metolius River resulting in unsuccessful downstream migration. Salmon spawned on the Metolius River encountered a front of warm upstream surface flow that also disoriented migrating smolts.

A solution to this problem may be the use of flow modification structures such that the extent of stratification observed in the lake is reduced or surface flow to the forebay is enhanced. This would be accomplished by designing structures such as curtains or surface intakes. The first step in designing structures that would improve the success of downstream salmon passage is the development and calibration of a reservoir temperature model. Such a model would predict the seasonal response of the reservoir to each structural or operational modification. Temperature predictions from this model could then provide suitable initial conditions for a 3-D hydrodynamic model that would more accurately simulate the reservoir response over shorter critical periods.

## Model Selection and Setup

The BETTER model developed by TVA (Bender et al. 1990) was selected due to its relative ease of use, reasonable computer run times for long (annual) simulations, and the availability of a post-processor to facilitate evaluation and interpretation of model output. The goal of this modeling component was to simulate the general pattern of water exchange among the three arms of the reservoir and the development of summer temperature stratification due to solar radiation and inflow water temperatures and volumes.

The BETTER model is applied in a vertical 2-D mode and assumes fully mixed conditions across the width of the reservoir. The initial setup of the model is to segment the reservoir into an array of layered volume elements or boxes. Each box has a specified volume, surface area, and a downstream conveyance area. A floating layer scheme is used in the model to allow the water surface to move in relation to the specified model geometry. This allows the model to maintain the integrity of strong gradients that develop in the surface layers. The lake was divided into three branches containing a total of 35 segments (Figure 2). The Deschutes arm was specified as the mainstem model branch and the Crooked and Metolius arms were identified as secondary branches. This segmentation provided adequate model resolution of temperature patterns observed at monitoring stations sampled from 1994 through 1996.

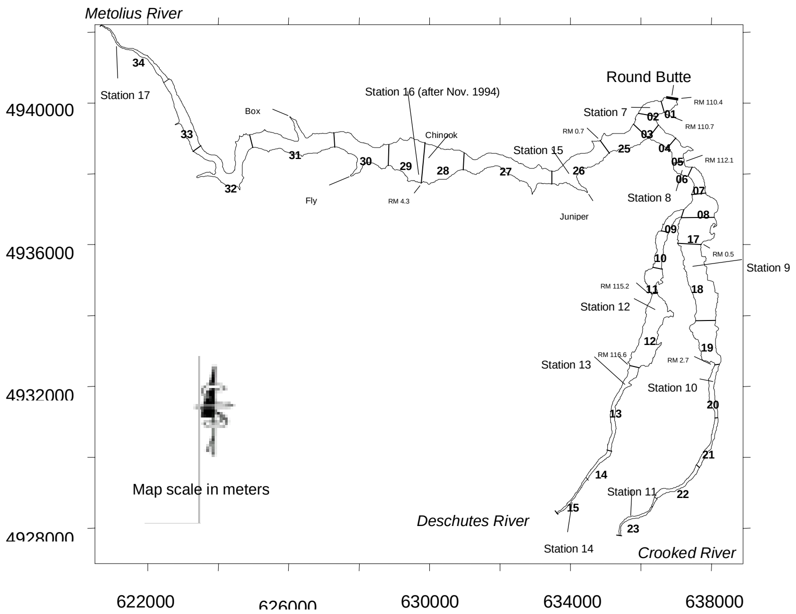
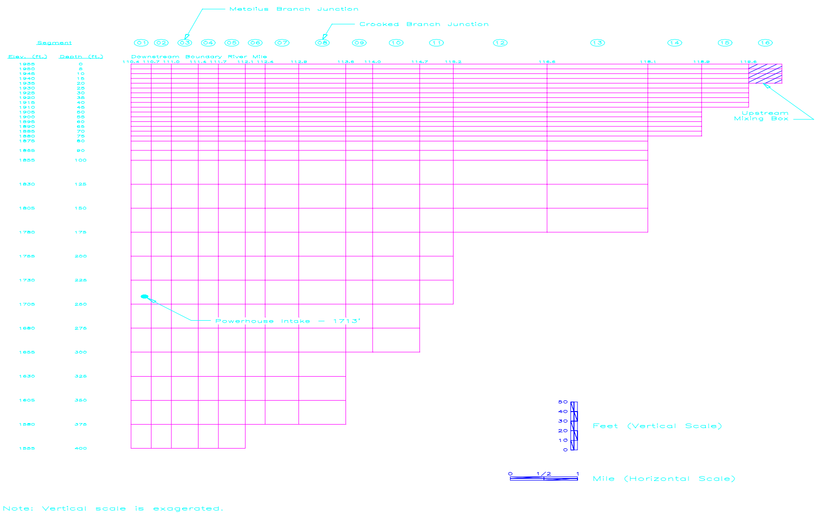


Figure 2. BETTER Model Segmentation of Lake Billy Chinook.



Note: Vertical scale is exagerated.

Figure 3. Model Geometry of the Deschutes River Branch.

The lake was also separated into 30 vertical layers beginning 10 feet above the normal maximum pool level of 1,945 feet and extending to the lake bottom at 1,545 feet. As an example, the geometry of the Deschutes branch is shown in Figure 3. Layer volumes are equivalent to the depth:volume relationship derived from the most recent bathymetry study of the lake. The first 16 layers of the model are 5 feet thick down to the 1,875-foot elevation, which is below the maximum-recorded depth of the thermocline in Lake Billy Chinook (Raymond et al. 1997). Below the 1,875-foot elevation there are two10-foot thick layers followed by 25-foot thick layers down to the bottom. Withdrawal from the reservoir occurs from the forebay at an elevation of 1,713 feet. This model geometry provides for sufficient model resolution of the vertical temperature stratification that develops in the reservoir.

Model boundary conditions include tributary temperatures, water quality, and discharge; meteorological data (dry air and dew point temperature, solar radiation, wind speed); and reservoir spillway and powerhouse discharge data. The model was setup to run on a 12-hour time step. Daily tributary discharge and hourly powerhouse withdrawal data were processed to provide 12-hour day and night averages for model input. Tributary temperatures (recorded approximately hourly) and meteorological data also required reduction to 12-hour day and night averages. Model inputs for tributary water quality were interpolated from the available measurements.

## Model Calibration

Model calibration consisted of adjusting various model coefficients and factors that control vertical and horizontal mixing, withdrawal zone thickness, and evaporative cooling. These variables include the fraction of wind energy available for mixing (WCOEF), the density deflection factor (FDFAC), the vertical mixing coefficient (DC), wind speed adjustment factor (WDFAC), evaporation adjustment factor (EVFAC), and the withdrawal zone thickness factor (QTH). With the exception of the vertical mixing coefficient, these are global model variables (i.e., a single value is applied to the entire reservoir). Different vertical mixing coefficients may be specified for each reservoir branch. These model variables were systematically adjusted until the best model fit-by-eye to the temperature profiles measured in 1995 was obtained (Figures 4 - 6).

The calibrated model is consistent with the observed vertical stratification patterns within the reservoir, particularly at the forebay Station 7 and upstream stations on the Deschutes branch of the reservoir. The model typically under-predicts the bottom temperature of the Metolius branch and over-predicts the temperature of the Crooked branch. The model fit at these locations was improved somewhat by slightly altering the forebay geometry to enhance the withdrawal of colder bottom water derived from the Metolius branch. The final calibrated model coefficients and factors are provided in Table 1.

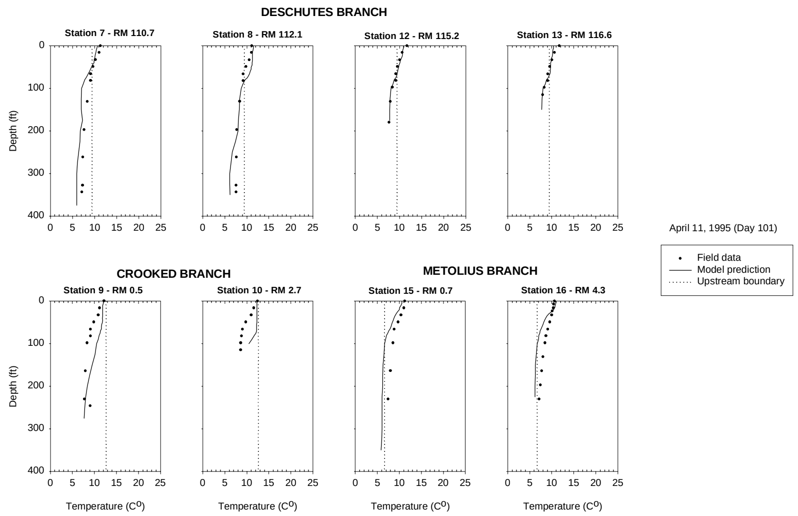


Figure 4. BETTER Model Calibration to Observed Temperature Profiles, April 1995.

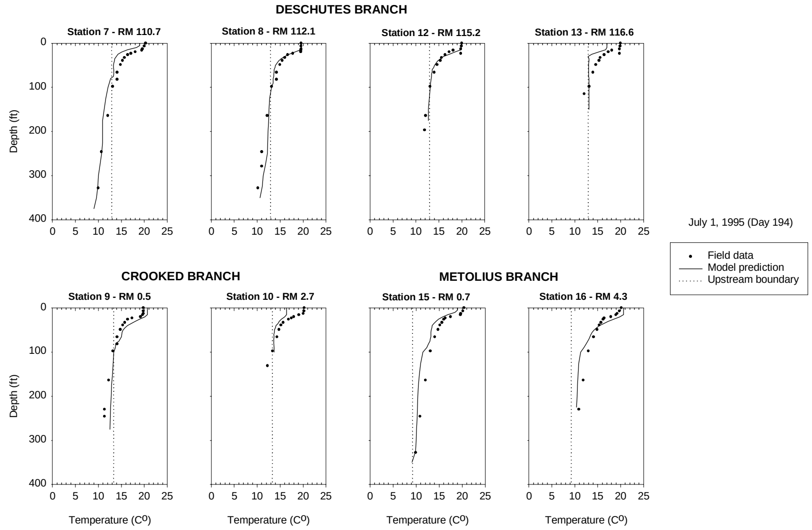


Figure 5. BETTER Model Calibration to Observed Temperature Profiles, July 1995.

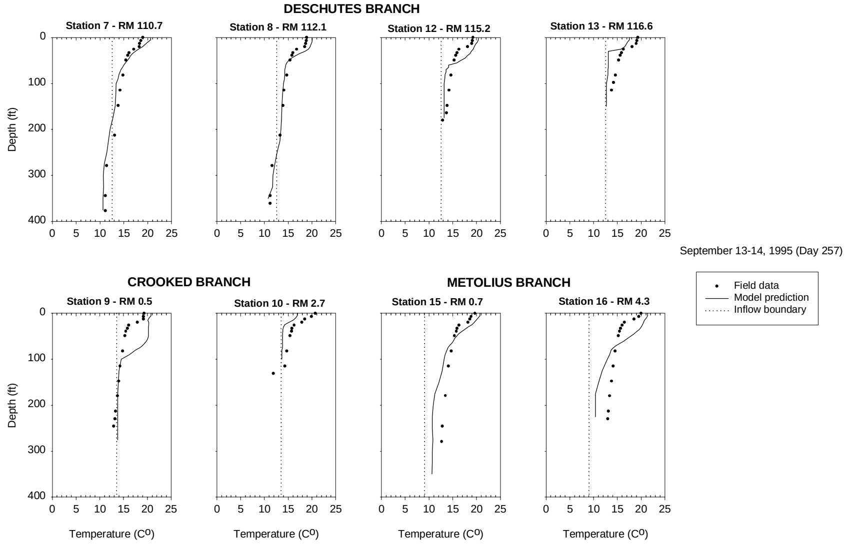


Figure 6. BETTER Model Calibration to Observed Temperature Profiles, September 1995.

**TABLE 1**
**Calibrated Model Coefficients and Factors**

| Model variable | Deschutes Branch | Crooked Branch | Metolius Branch |
|---|---|---|---|
| Mixing coefficient (DC) [Range 0.1-10] | 1 | 1 | 10 |
|  | **Calibration Value** | **Typical Range** |  |
| Wind mixing factor (WCEOF) | 0.02 | 0 - 0.1 |  |
| Density deflection factor (FDFAC) | 1 | 0.1 – 10 |  |
| Wind speed adjustment factor (WDFAC) | 1 | 0.5 – 2 |  |
| Evaporation adjustment factor (EVFAC) | 1 | 0.8 – 2 |  |
| Withdrawal zone thickness factor (QTH) | 20 | 10 – 50 |  |

The BETTER model coefficients established during calibration were well within the recommended ranges, and in general, the model behavior was very satisfactory.

## Model Application

The calibrated model was initially applied to four alternatives to evaluate the potential effectiveness of various reservoir modifications to enhance downstream fish passage. These modifications are as follows:

- **Alternative 1. Forebay Curtain:** Curtain placed in the reservoir forebay upstream of the withdrawal tower intake. Top of the curtain within 20 to 30 feet of the water surface.
- **Alternative 2. Metolius Curtain:** Curtain placed in the mouth of the Metolius branch. Top of the curtain within 20 to 30 feet of the water surface.
- **Alternative 3. Surface Withdrawal:** Surface withdrawal (at elevation 1,920 feet) from the existing intake structure.
- **Alternative 4. Reservoir Drawdown:** Permanent reservoir drawdown to an elevation of 1,865 feet.

Conceptual drawings of the preliminary modeling alternatives are shown in Figure 7.

The BETTER model-input files were modified to simulate each alternative and then run using 1995 boundary conditions. April was considered the critical month of interest from the perspective of downstream fish passage. Therefore, relative comparisons between the existing (calibrated) conditions and conditions following implementation of each alternative were made for the

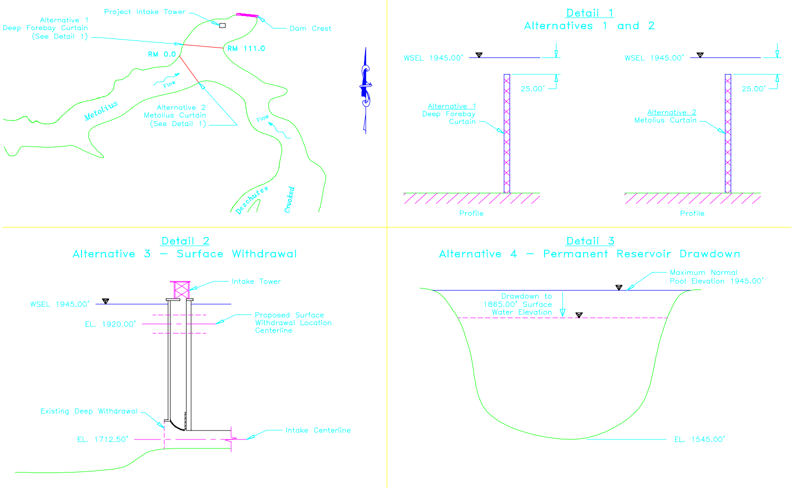
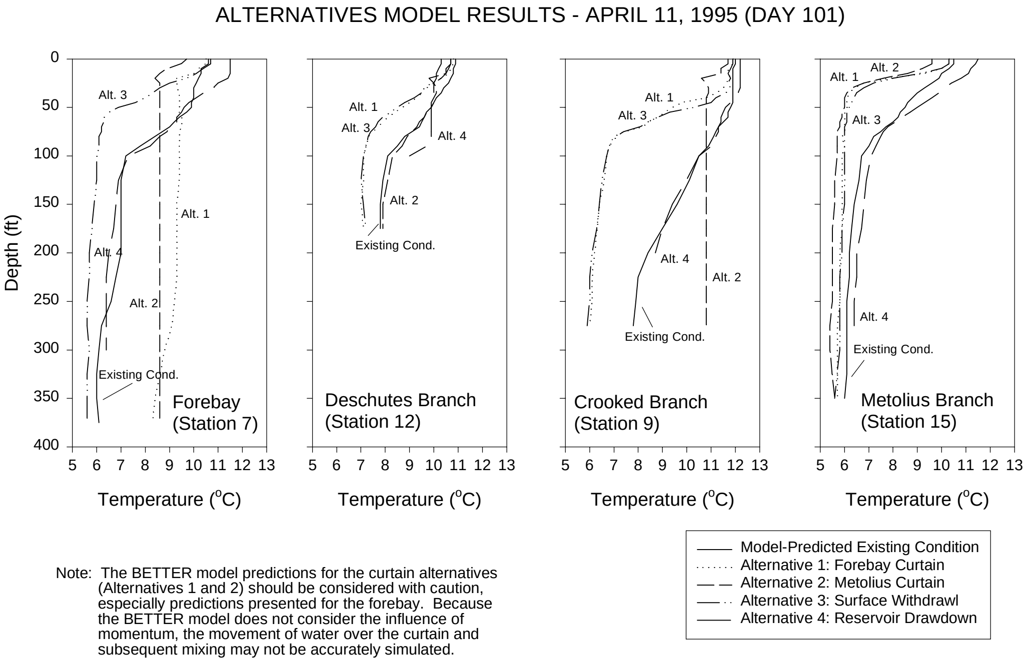


Figure 7. Conceptual Drawings of Preliminary Modeling Alternatives.

month of April. The effect of these alternatives on April reservoir stratification predicted by the temperature model compared to the modeled existing condition is shown in Figure 8.



Note: The BETTER model predictions for the curtain alternatives (Alternatives 1 and 2) should be considered with caution, especially predictions presented for the forebay. Because the BETTER model does not consider the influence of momentum, the movement of water over the curtain and subsequent mixing may not be accurately simulated.

Figure 8. BETTER Model Alternatives Results Compared to the Modeled Existing Condition, April 1995.

Alternatives 1 and 2 generally result in lower forebay temperatures in April due to enhanced mixing of surface and bottom water in the forebay downstream of the curtains (see Figure 9). Alternative 4 (Permanent Drawdown) results in forebay temperature stratification similar to vertical temperature gradients predicted by the calibrated model. Alternative 3 (Surface Withdrawal) causes an increase in forebay stratification due to the enhanced withdrawal of warmer surface waters.

Movement of warm Crooked River water up the Metolius arm was reduced to varying degrees by Alternatives 1-3 as measured by simulated dye introduced from the Crooked River. Movement of Crooked River water up the Metolius arm was enhanced in Alternative 4.

A limitation of the BETTER model is that it does not resolve the 3-D structure of flow, and momentum terms are not included in the calculations (thermal heating and heat balance between the tributaries being the focus of the BETTER model). Therefore, the results of the model were intended to provide a relative indication of the effects of these structures on reservoir temperature stratification and distribution. Because movement and mixing of water adjacent to outflow structures, including flow over curtains, would be significantly influenced by the momentum, lateral, and vertical acceleration terms; the BETTER model predictions close to the structures may be inaccurate.

## Summary and Conclusions

A predictive temperature model of Lake Billy Chinook has been developed that reproduces the temperature gradients that have been observed in the lake. The existing hydrothermal behavior in the reservoir is primarily the result of four different types of forcing: 1) temperature/density stratification, 2) wind stresses, 3) river inflows, and 4) powerhouse operations. The effect of temperature-related density stratification is the dominant forcing mechanism. The pattern and strength of reservoir circulation depends on the relationship between river inflow temperatures and reservoir water temperatures. Overall, temperature stratification is a function of reservoir surface-heating/cooling and the different river inflow volumes and temperatures.

The calibrated temperature model was modified to simulate four proposed reservoir structural modifications under 1995 flow and meteorological conditions. Relative comparisons were made for the month of April since it was the critical month of interest from the perspective of downstream fish passage.

Alternatives 1, 2, and 3 all reduced movement of Crooked River water up the Metolius arm to varying degrees in April. Alternative 4 (Permanent Drawdown), however, produced stratification patterns that were very similar to the existing reservoir condition and enhanced the movement of Crooked River water up the Metolius arm.

## References

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