Three-dimensional Modeling of Temperature Stratification and Density-driven Circulation in Lake Billy Chinook, Oregon

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Abstract

A three-dimensional (3-D) hydrodynamic model was used in conjunction with a hydrothermal mass balance model to simulate the density driven circulation in Lake Billy Chinook, Oregon. Lake Billy Chinook reservoir, created by the construction of Round Butte Dam, receives flow from three tributaries (Crooked, Deschutes, and Metolius), that have distinct temperature and flow characteristics. The velocity pattern in the lake is dominated by temperature stratification and is also affected by wind stresses. The existing flow conditions are considered ineffective for collection and passage of downstream migrating fish. The immediate goal of the project is to identify the reservoir geometry modification(s) most favorable to the downstream passage of juvenile salmon through the project.

In this paper, we present application of a 3-D hydrodynamic model to evaluate the effectiveness of various proposed flow modification structures on reservoir stratification and circulation. The hydrodynamic model is externally coupled to a long-term seasonal temperature model to provide temperature initial conditions for the hydrodynamic model. This study demonstrated the effectiveness of these models in identifying the forcing mechanisms for the lake circulation patterns and assisting the design of fish passage facilities.

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 1960s due to ineffective downstream passage after the dam was constructed in 1964. 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. The complex current patterns are attributed to reservoir stratification and mixing of inflows from three tributaries (Crooked, Deschutes, and Metolius Rivers) with distinct temperature characteristics. The Metolius River typically supplies the coldest inflow, which tends to plunges deep into the bottom layer of the reservoir and is withdrawn from the deep powerhouse intake at the forebay. The water from Crooked River is warmer throughout the year due to the influence of thermal springs. The warm Crooked water tends to travel downstream in the surface layer and moves upstream to the Metolius River.

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These distinct inflow characteristics result in a two-layer circulation system in the reservoir. The temperature stratification in the lake is mainly controlled by solar radiation and inflow temperatures. The reservoir turns over in early winter and similar inflow temperatures result in a fully mixed uniform and cold reservoir during the winter months. The reservoir becomes highly stratified in the summer. The magnitude of the temperature stratification has direct impact on the circulation patterns in the reservoir and therefore affects the downstream fish migration.

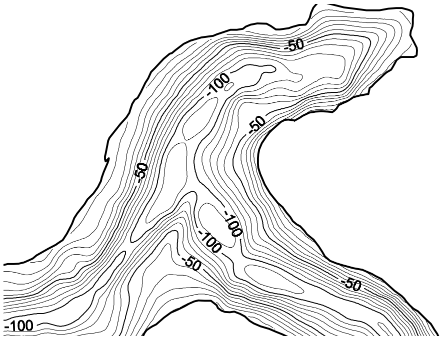
A solution to this problem may be to use flow modification structures to reduce the extent of stratification in the lake and modify flow patterns such that flow to the forebay is enhanced. This would be accomplished by designing structures such as curtains or surface intakes. The first step in designing structures to improve the success of downstream salmon passage is the development of a predictive reservoir hydrothermal and hydrodynamic model. Such a model would predict the response of the reservoir to each structural or operational modification. The 3-D numerical model used in this study was the Environmental Fluid Dynamic Code (EFDC) developed at the Virginia Institute of Marine Science (Hamrick 1992). The vertical 2-D Box Exchange Transport Temperature Ecology Reservoir (BETTER) model developed by the Tennessee Valley Authority (Bender *et al*., 1990) was used to simulate the long-term seasonal temperature distribution and provide temperature initial conditions for the hydrodynamic model. Numerical drifter experiments were also conducted using the Lagrangian particle tracking module in EFDC to investigate the over all water movement in the lake.

This paper presents the application of the hydrodynamic model of Lake Billy Chinook in support of the PGE's studies of the feasibility of fish migration enhancement in Lake Billy Chinook. Results demonstrate the model's ability to reproduce existing flow patterns and temperature. The potential effects of proposed structural modifications such as curtains, reservoir drawdown, and relocation of the intake to the reservoir surface are also presented.

Hydrodynamic Model Setup

Model Description

The numerical model used in this study was the Environmental Fluid Dynamic Code (EFDC) developed at the Virginia Institute of Marine Science (Hamrick 1992). The model is designed for the simulation of flows and transport processes in estuaries and coastal oceans, as well as reservoirs, lakes, and rivers. The model is a time domain, finite difference model. It solves the three-dimensional primitive equations of motion for turbulent flow. Three-dimensional transport equations for the turbulent intensity and length scale as well as temperature, salinity, dye tracer, and suspended sediment can also be solved simultaneously in EFDC. A second-moment turbulence closure model is solved to provide the vertical turbulent eddy viscosity in the model (Mellor and Yamada 1982). Horizontal diffusion is calculated using the Smogarinsky formula (Smogarinsky 1963). The model uses boundary-fitted curvilinear-orthogonal coordinates in the horizontal plane and a sigma-stretched coordinate system in the vertical direction. The computational scheme uses an external-internal mode splitting to solve the horizontal momentum

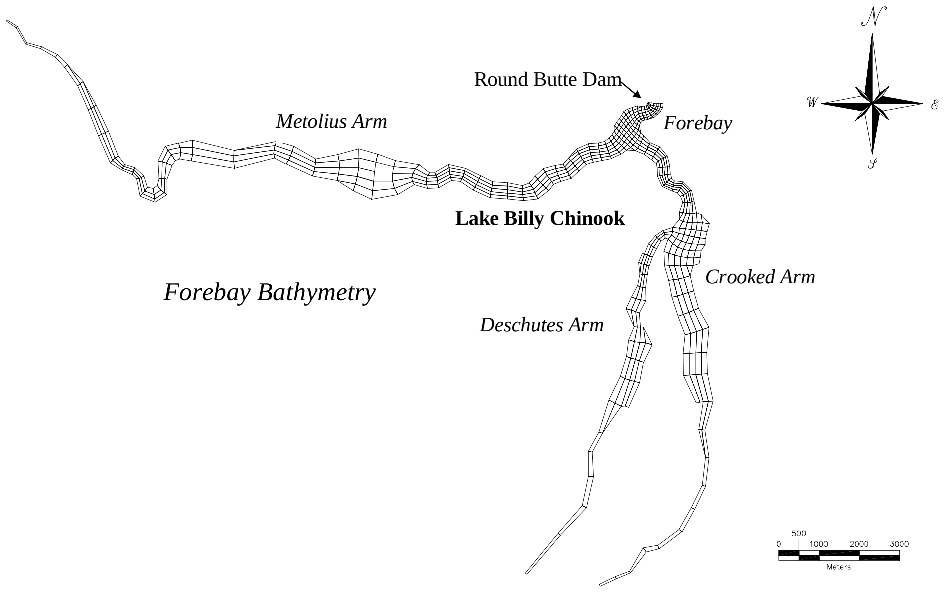


equations and the continuity equation on a staggered grid, using a combination of finite volume and finite difference techniques. For a more detailed description of EFDC, the reader is referred to Hamrick (1992) and Hamrick and Wu (1996).

Model Grid

The Lake Billy Chinook is a 561×10^6 m^3 reservoir consisting of three narrow and deep river tributaries that converge near the forebay. The lake has steep slopes and the maximum water depth is about 110m. The model grid was constructed in a horizontal curvilinear-orthogonal and vertical sigma-stretched coordinate system and contains 493 cells in the horizontal plane (Figure 1). The average grid cell size in the forebay region was about 90m by 90m.

Figure 1: Hydrodynamic Model Grid for Lake Billy Chinook



A total of 10 layers were specified in the vertical direction. Because the epiliminion is mainly confined within the upper 30 m, finer vertical layers were specified in the upper 30m of the water column to capture the sharp temperature gradient. The vertical layering scheme had an exponential distribution such that the thickness of the vertical layers increased from the surface to the bottom. The percentage of each layer in the water column is given in Table 1. (Layer 1 corresponds to the bottom layer and the water depth is normalized to 1).

Table 1: Normalized Vertical Layer Thickness Distribution for the Lake Billy Chinook Hydrodynamic Model

Layer Number	1	2	3	4	5	6	7	8	9	10
Layer Thickness	0.23	0.18	0.14	0.11	0.09	0.07	0.06	0.05	0.04	0.03

Boundary Conditions

In Lake Billy Chinook, there are no horizontal open boundary conditions. The river inflows and power intake outflow were simulated as sources and sinks in the model system. The river inflow rates and temperatures were uniformly distributed in the water column at each of the three upstream boundaries. Because the power intake is located at the bottom of the reservoir (70m bellow the surface), the power intake outflow was only specified in the bottom layer of the forebay grid cell.

Figure 2 shows the comparisons of the river inflow temperatures and the reservoir temperatures at all observed stations. Below 30m from the water surface, the reservoir temperatures at all stations are very similar in any particular season. In winter, observed temperatures indicate the reservoir is almost fully mixed vertically. Compared to the reservoir water, the Metolius River water is colder and the Crooked River water is much warmer. This pattern has a strong influence on the reservoir temperature near the river inflows to the reservoir. The Deschutes River temperature is much colder than the Crooked River temperature and is about the same as the mid-layer temperature in the reservoir.

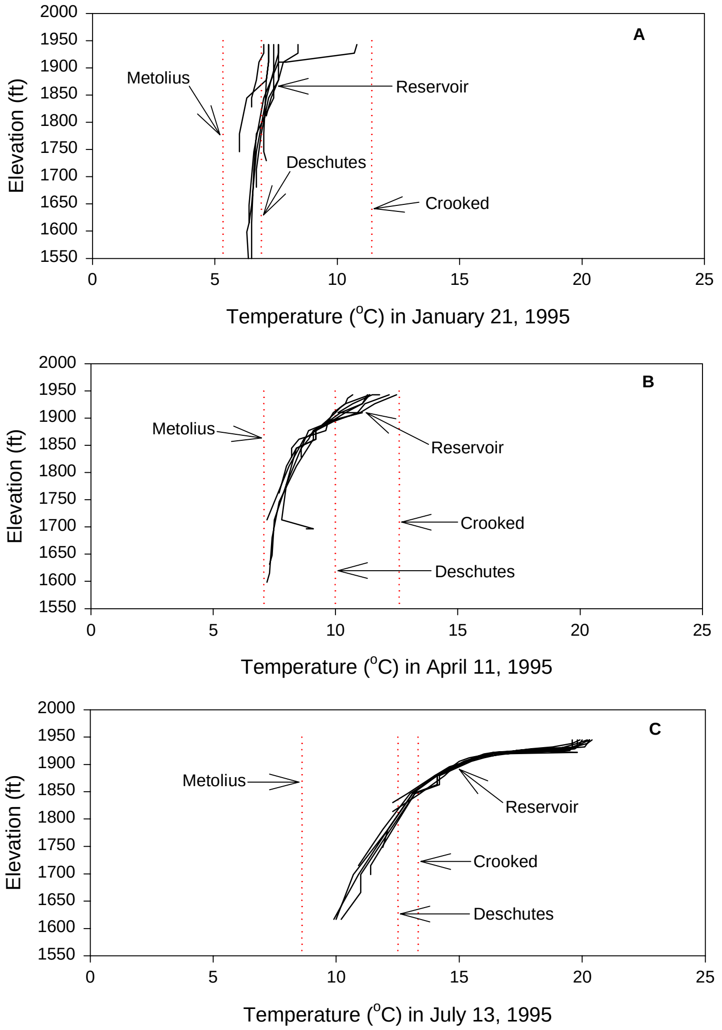


Figure 2: Reservoir Temperature Profiles in 1995

In summer, the temperature stratification in the reservoir is greatly enhanced due to the surface warming. The surface temperature in the reservoir is much warmer. The horizontal temperature distributions at all water levels in the reservoir are almost uniform. The Metolius River temperature is colder than the bottom temperature in the reservoir and the Crooked and Deschutes river temperatures are colder than the surface temperature in the reservoir. All these seasonal differences in the temperature structures result in relatively different seasonal circulation patterns in the reservoir.

Initial Conditions

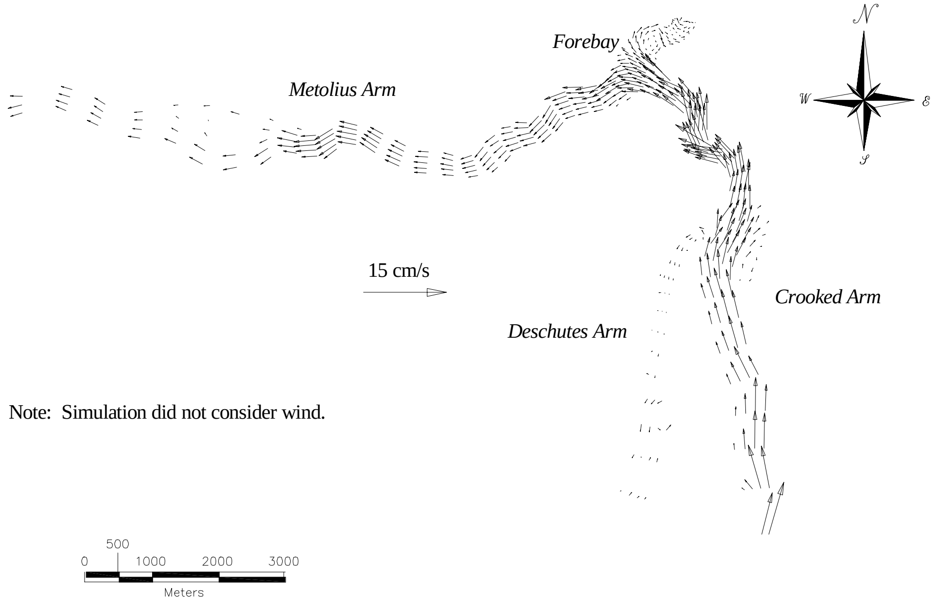
Any structural and operational changes that would alter the geometry and discharge conditions would affect the development of the stratification patterns in the lake. In order to correctly predict the hydrodynamic response of the lake the thermal behavior of the lake would also need to be correctly simulated. The computational costs associated with long period hydrodynamic model simulations with a small time step (20 seconds) are high. It is more efficient to utilize a thermal balance model to simulate the long-term temperature distribution in the reservoir separately, with a much larger time step (12-hour). The model output from the temperature therefore can be used to provide initial temperature conditions for the hydrodynamic model at any specific time. A review of temperature data in the lake showed that the temperature distribution patterns were uniform across the width of the lake arms and could be approximated with a laterally averaged, vertical, two-dimensional (2-D) representation.

The initial temperature conditions for the hydrodynamic model calculations in this study were obtained from a calibrated seasonal vertical 2-D temperature model (BETTER) that was setup specifically to operate in conjunction with the 3-D hydrodynamic model. The calibration and verification of the temperature model of Lake Billy Chinook is described elsewhere (DeGasperi, *et. al*., 1999). The temperature model was applied independent of the hydrodynamic model for all simulations for the duration of entire year. The hydrodynamic model was applied for 7-day intervals at specific periods in the year critical to salmon passage using the predicted temperatures as the initial condition.

Model Performance

Because April is an important month for downstream fish passage, April 1995 was selected as the baseline period for model calibration. The bottom roughness, background horizontal diffusion, and vertical eddy viscosity were adjusted so that the general circulation pattern and temperature profiles in the reservoir matched the observations made in the previous studies (Raymond *et al.* 1997; McCollister and Ratliff 1996; Truebe 1996). The model was run for 6 days during each simulation and the model simulation time step was 20 sec. The background horizontal diffusion and background vertical eddy viscosity were adjusted within the typical range reported in the literature such that the model could successfully produce the vertical two-layer circulation in the system. The final adjusted background horizontal diffusion, background vertical eddy viscosity and bottom roughness were 1 m^2/s, 10^{-5} m^2/s and 5 cm, respectively.

Figure 3 shows predicted velocity vectors at the surface layer of the reservoir. Figure 4 shows velocity vectors along the vertical longitudinal sections in the Metolius, Deschutes, and Crooked arms of the reservoir. These model results confirm the prevailing understanding of the two-layer behavior of this system. Crooked River water is warmer than the surface water in the reservoir while the Metolius River water is cooler than the bottom water in the reservoir. So the water from the Crooked River enters the reservoir system in the surface layer, and the water from the Metolius River enters the reservoir in the bottom layer. This results in this the observed two-layer circulation pattern. The surface water from the Crooked River moves downstream towards the forebay and continues upstream into the Metolius River.



Note: Simulation did not consider wind.

Figure 3: Surface Velocity Distribution for Existing Condition (April 1995)

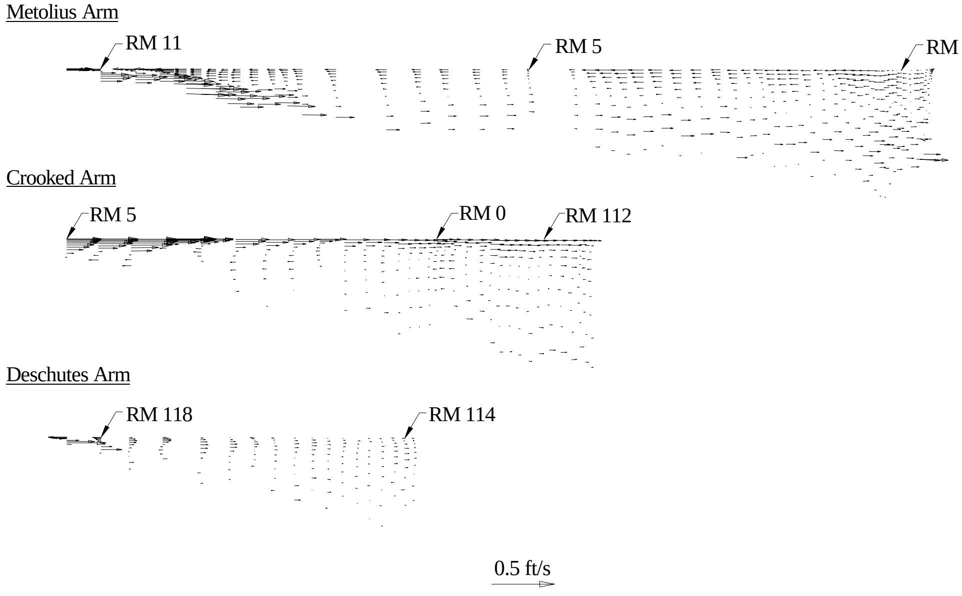


Figure 4: Velocity Distribution Along the River Arms (April 1995)

The predicted velocity magnitude in the Crooked and lower Deschutes arms was about 6 cm/s, while in the lower Metolius arm it was about 3 cm/s. In the lower Deschutes arm, surface water from Crooked River also moved upstream to the upper Deschutes arm, although the velocities were relatively small. In the forebay near Round Butte Dam, a clockwise eddy developed, which was mainly due to the geometry effect and the location of the powerhouse intake. The surface upstream flow in the Metolius arm extended upstream about 15km from the Forebay and the cold Metolius River water mainly moved downstream in the bottom layer. Due to the outflow at the powerhouse intake, relatively large bottom velocities at the location of powerhouse intake were observed. In the Crooked River, the two-layer circulation also developed from upstream. The vertical circulation in the upper Deschutes arm was slightly different from that in the Metolius and Crooked arms. There was a reduction in the velocity in the surface layer because the Deschutes River water was slightly cooler than the reservoir surface water but warmer than the reservoir bottom water in April. Therefore, water from Deschutes River entered the reservoir system in the sub-surface layer with partial Crooked River water overlaying it. It is noted that there is a significant difference between the two-layer circulation in the Metolius and Crooked arms. In the Crooked arm, the surface velocity is much stronger than that in the bottom layer, while in the Metolius arm the bottom velocity is as strong as that in the surface layer. In the Crooked River, the surface water moved downstream towards the forebay, while in the Metolius, an upstream movement of water was predicted.

Lagrangian particle tracking was also conducted to investigate how the water from the Crooked and Deschutes rivers travels through the reservoir. Fifty neutral buoyant water particles were released in the lower Deschutes arm in the entire water column. Two days of particle movement were simulated by running the model for another 2 days using the restart file outputted at the end of the 6-day model run. Figure 5 shows the particle trajectories after 2 days of simulation. As shown in the figure, most of the surface particles moved up the Metolius arm and bottom particles moved in the upstream direction of the Lower Deschutes arm. Only a small fraction of the particles traveled into the forebay.

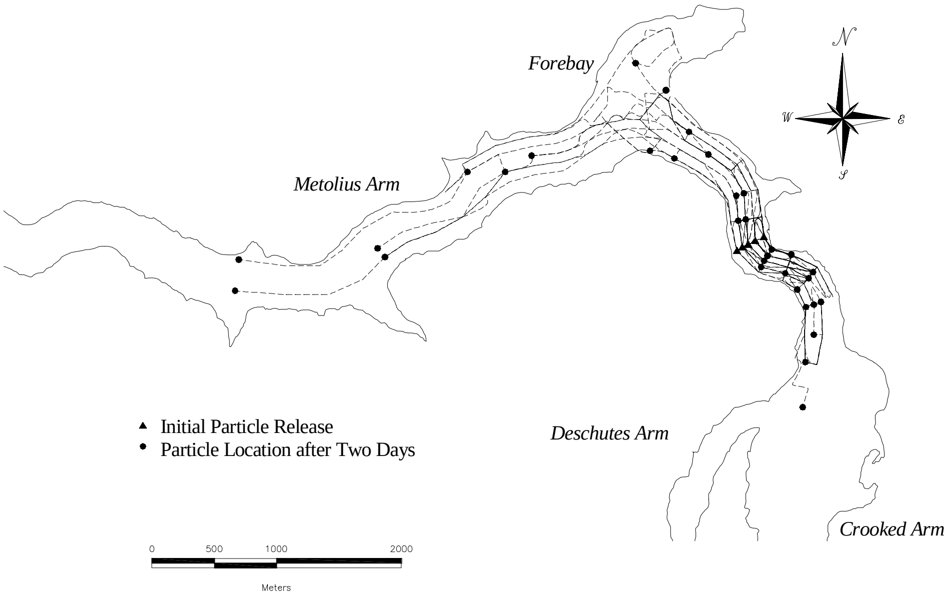


Figure 5: Particle Tracking Trajectories for Existing Conditions (April 1995)

Wind stress is an important factor in the observed circulation patterns in Lake Billy Chinook, especially in its effect on the surface current. Therefore, sensitivity of the model-predicted circulation in the lake to the effects of wind was investigated. Due to the limitation of the wind data in the study area, a designed wind pattern was generated based on statistical analysis of wind data at three wind stations (Forebay, Metolius River, and Deschutes River). At all three stations, the wind directions were mainly aligned in the directions of the reservoir arms. Based on these statistical results, a simple wind pattern given in Table 2 was used in the model to evaluate the wind effect. Wind forcing was assumed constant in the forebay, Metolius arm, and Deschutes/Crooked arms, respectively.

Table 2: Wind Data Used in the Model Sensitivity Study

	Forebay	Metolius River	Deschutes and Crooked Rivers
Wind speed (m/s)	10.0	2.5	2.5
Wind direction (degree)	270.0	247.5	225.0
Current speed without wind (m/s)	0.02	0.03	0.06
Current speed with wind (m/s)	0.08	0.08	0.11

As shown in Table 2, surface velocities in the entire lake increased and aligned in the same direction of the wind stresses. In the Metolius River, the wind-driven downstream currents were superimposed on the top of the upstream reversed flow, thus a vertical three-layer circulation was developed. In the Crooked and Deschutes arms, the surface downstream flows were strongly enhanced by the wind effect. Also, because of the strong wind in the forebay, the clockwise eddy was no longer evident, and the surface water in the forebay moved towards the Round Butte Dam.

Model Applications

As part of the current re-licensing process, PGE is attempting to re-establish fish passage at Round Butte Dam by modification of the reservoir geometry. The hydrodynamic model was applied to the proposed four alternatives to investigate the impact of the proposed reservoir modifications on the circulation patterns and provide data to aid in the selection of the best alternative for the improvement of downstream fish passage. The alternatives considered are shown in Figure 6 and are described below:

- **Alternative 1. Forebay Curtain:** Deep curtain placed in the reservoir forebay. Top of the curtain within 6 to 9 m of the water surface.
- **Alternative 2. Metolius Curtain:** Deep curtain placed in the mouth of the Metolius branch. Top of the curtain within 6 to 9 m of the water surface.
- **Alternative 3. Surface Withdrawal:** Surface withdrawal (1.5m below the water surface) **from the existing intake structure.**
- **Alternative 4. Reservoir Drawdown:** Permanent reservoir drawdown about 24 meters.

All the alternative simulations were conducted for the period of 4/11/95 to 4/17/95 and compared to the base simulation case (existing conditions in April 1995). New temperature initial conditions for each individual alternative run were obtained from independent application of the calibrated Lake Billy Chinook BETTER temperature model .

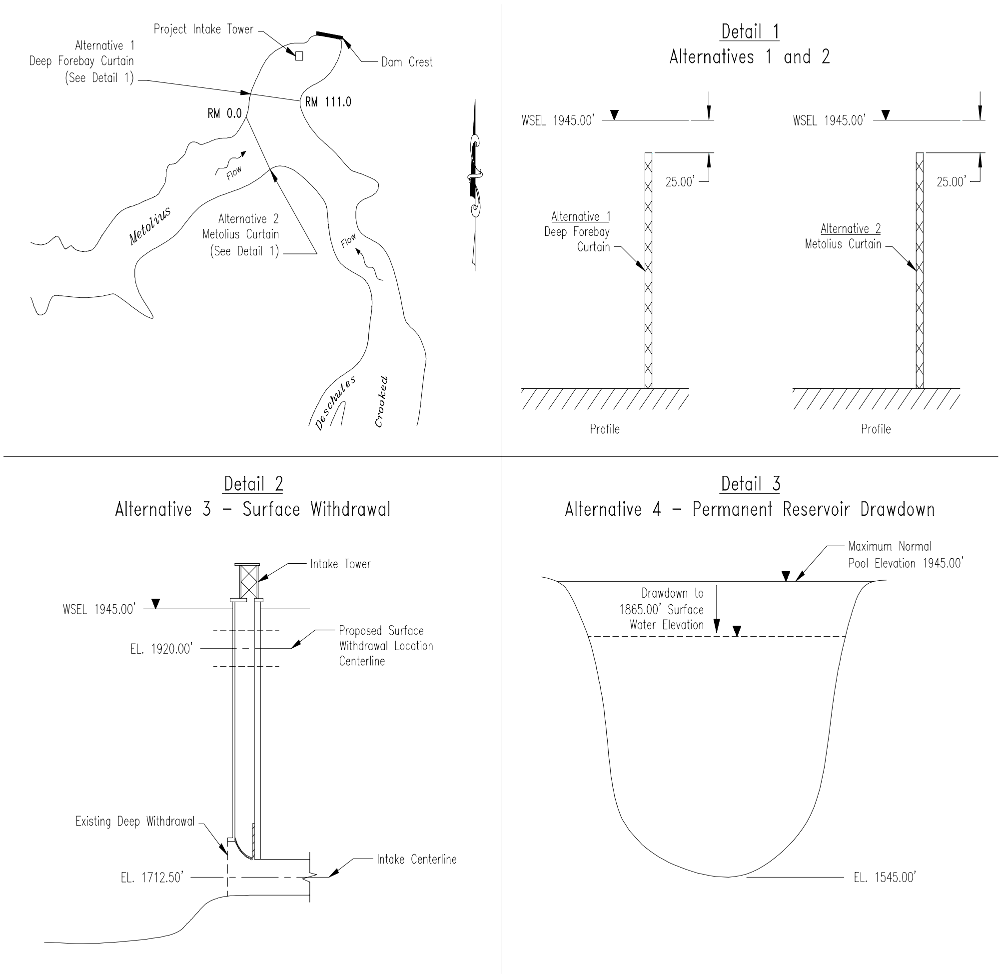


Figure 6: Proposed Four Alternatives for Reservoir Modifications

Alternative 1

To simulate Alternatives 1 and 2 with a curtain, the hydrodynamic model required some coding modifications. A thin barrier in the water column was successfully implemented in the code to simulate a curtain. The surface velocities near and behind the deep curtain in the forebay increased while the surface velocities in the lower arm of Metolius branch slowed down. However, velocity distributions in the Deschutes and Crooked arms remained almost the same compared to the existing condition. Overall two-layer circulation in all three rivers still persisted, except the surface velocities in the Metolius arm decreased. This indicated that the forebay deep curtain effectively reduced surface water movement up the Metolius arm. The particle tracking trajectories also showed that fewer water particles moved up the Metolius arm and more particles moved into the forebay.

Alternative 2

For Alternative 2, where the deep curtain was placed in the lower Metolius arm, model results indicated very different circulation patterns in the lower Metolius arm and forebay compared to the existing condition. At the center of the surface channel over the deep curtain, very strong flow from the Metolius arm to the forebay was observed. Meanwhile, in the southeastern side of the channel over the deep curtain, strong velocities up the Metolius arm were observed. A very strong horizontal velocity shear in the flow was predicted over the deep curtain. The velocity distribution along the vertical cross-section in the Metolius arm indicted that a distinct flow separation occurs at the location of the deep curtain. Similar to Alternative 1, the deep curtain in the lower Metolius arm had little effect on the circulation patterns in the Crooked and Deschutes arms. The particle tracking results showed that even though fewer particles traveled up the Metolius arm, some water particles went further upstream than in the existing condition due to the strong upstream surface velocities over the southeastern end of the deep curtain.

Alternative 3

In Alternative 3, the powerhouse intake was moved from the bottom (522m elevation) to near the surface (585m elevation). The model predicted that much more surface water from the Crooked River moved into the forebay and the surface upstream flow in the Metolius arm was reduced. Almost all the surface velocity vectors in the forebay pointed in the downstream direction because of the surface withdrawal. Compared to the existing condition, the surface downstream flows in Crooked and Deschutes arms increased slightly. Figure 7 shows results of particle tracking simulations for the surface withdrawal option. In comparison with the existing conditions (see Figure 5), particle tracking results for the surface withdrawal alternative showed that most of the surface water particles moved directly to the forebay.

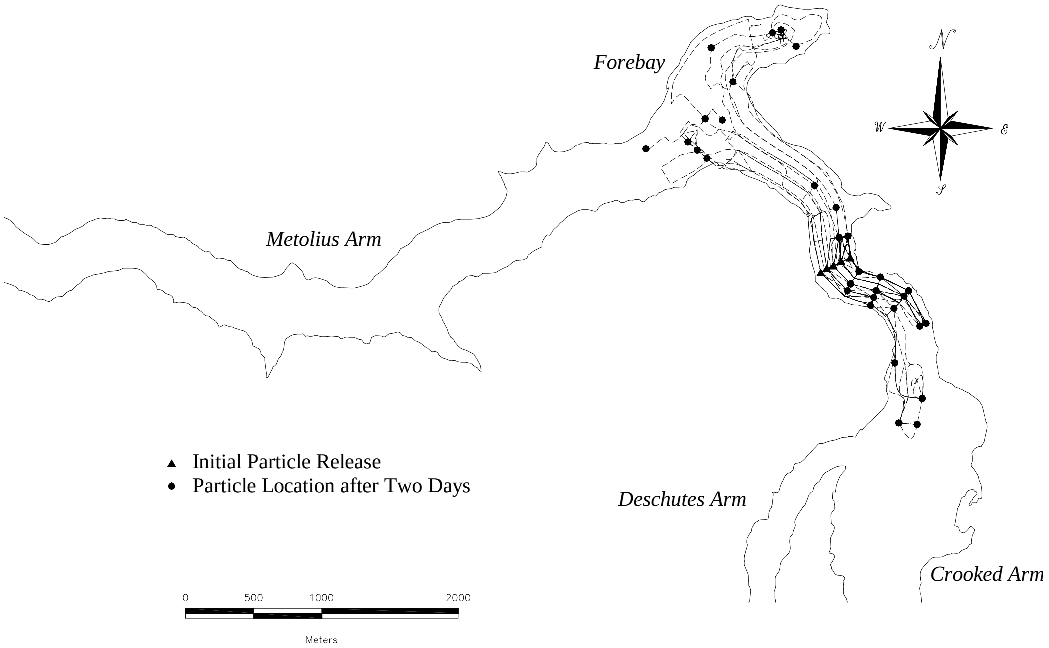


Figure 7: Particle Tracking Trajectories for Alternative 3

Alternative 4

For Alternative 4, many water grid cells for the existing condition become land cells because of the 24 meters permanent drawdown. Lowering of the reservoir also resulted in changes in the river inflow boundary locations. The new locations of the river inflow boundaries were moved farther downstream in all the tributaries. The general horizontal and vertical circulation patterns in the reservoir for alternative 4 were very similar to the existing condition, except the velocity magnitudes were increased because of the decreases of the reservoir cross-sectional area in all three branches resulting from the lower water depth. Also, surface water particles moved further upstream in the Metolius arm due to the increase in upstream surface velocities.

Discussion and Conclusions

A predictive 3-D hydrodynamic model of Lake Billy Chinook was developed to evaluate the feasibility of enhancing downstream fish passage at the Round Butte Dam. The objective of the model application was to develop an understanding of the hydrothermal behavior of the Lake Billy Chinook and to evaluate relative merits and demerits of various alternatives proposed. Each alternative affects the thermal balance of the entire reservoir. Since thermal balance and stratification in a lake are long-term processes, temperature simulations are required for an entire year. To perform these calculations with a 3-D hydrothermal model with a time step of 20 seconds is not effective for preliminary engineering analysis. In this study, the temperature modeling on an annual scale was conducted separately using a 12-hour time step. The hydrodynamic model was applied during specific months of interest over a 6-day period at a time with the initial temperature condition from the long-term temperature model. This de-coupling of temperature and hydrodynamic models allowed the models to be used cost-effectively, supporting engineering and management decision making.

The existing hydrothermal behavior in the Lake Billy Chinook is primarily the result of four different types of forcing: 1) temperature/density stratification, 2) wind stresses, 3) river inflows, and 4) power intake withdrawal. The effect of temperature-related density stratification is the dominant forcing mechanism. Stratification is a function of surface heating/cooling and different river inflow temperatures. Wind stresses are important and can result in enhanced or diminished current velocities, but wind stresses only affect the surface layer. The circulation driven by river inflows is very small due to the relatively small river inflow rates and the large lake cross-sectional areas.

For the existing condition, the hydrodynamic model results show that the two-layer circulation occurs in the Metolius River (upstream surface flow and downstream bottom flow) because the Metolius water is colder than the reservoir water all the time and plunges to the bottom of the reservoir and is withdrawn from the deep powerhouse intake. The warmer inflows from the Crooked and Deschutes Rivers ride on top of the cold Metolius River water and travel up the Metolius arm. In the Deschutes and Crooked arms of the reservoir, the pattern and strength of the vertical circulation depends on the different relationships between the river inflow temperatures and reservoir temperatures.

A screening level evaluation of four alternatives was conducted using neutrally buoyant particles as indicators of potential fish movement. The surface withdrawal, forebay curtain, and Metolius curtain alternatives appear to increase movement of water towards the forebay. Relative to existing condition, considerably higher numbers of drogues end up near the potential collector location in the forebay. Metolius curtain alternative also showed that it would effectively eliminate the undesirable upstream movement of salmonids. The permanent drawdown option resulted in increased velocities in the entire reservoir but did not change the pattern of movement of drogues relative to the existing conditions.

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Key words

Three-dimensional model, hydrodynamic, density-driven circulation, temperature, stratification, reservoir, fish passage, particle tracking, wind stress