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# The Bull Run River–Reservoir System Model

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**THE BULL RUN RIVER-RESERVOIR SYSTEM MODEL**

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**Abstract:** The Bull Run watershed is located 41.8 kilometers east of Portland, Oregon in the Mt. Hood National Forest and consists of two reservoirs supplying drinking water to over 840,000 people in the Portland metropolitan area. In March 1998 Steelhead and Spring Chinook were listed as threatened in the Lower Columbia basin under the Endangered Species Act. Historical reservoir operations during the summer released no water downstream resulting in stream temperatures exceeding the state water quality standard for salmonids. CE-QUAL-W2 Version 3 is a two-dimensional water quality and hydrodynamic model capable of modeling watersheds with interconnected rivers, reservoirs and estuaries. CE-QUAL-W2 Version 3 was used to model temperature in the reservoirs and river to investigate management strategies to meet water demand and fish habitat requirements. Management strategies evaluated included adding selective withdrawal, increasing reservoir size, constructing a new water supply reservoir, and altering selective withdrawal operations from historical patterns.

## INTRODUCTION

The Bull Run River-Reservoir system is a 264.2 km$^2$ watershed located 41.8 km east of downtown Portland as shown in Figure 1. The watershed has two reservoirs (Reservoir #1 and Reservoir #2) and serves as the primary drinking water source for the City of Portland and several surrounding communities with over 840,000 people. In March 1998 Steelhead and Spring Chinook were listed as threatened under the Endangered Species Act for the Sandy River Basin, which includes the Bull Run watershed. Historical reservoir operations have resulted in no water flowing from Reservoir #2 into the Lower Bull Run River during the summer months. Water temperatures in the Bull Run River below Reservoir #2 violated the State of Oregon's water quality standard where the seven day moving average of the daily maximum temperature must not exceed 17.8 $^oC$. A computer simulation model was developed to evaluate how to meet water supply and fish habitat objectives during the summer


**Figure 1. Bull Run Watershed System**

season by implementation of management strategies, such as adding selective withdrawal, increasing reservoir size, constructing a new water supply reservoir, and altering selective withdrawal operations from historical patterns.

A model, CE-QUAL-W2 Version 3 (Cole and Wells, 2000), was used to model the river-reservoir system. The computer model is a two dimensional, laterally averaged, hydrodynamic and water quality model. Version 3 was developed by WES and Wells (1997) and supercedes Version 2 (Cole and Buchak, 1995). The model is capable of replicating the density-stratified environment of the reservoirs as well as the sloping river channel sections. River-reservoir linkage is transparent with no need to use one model for the river sections and another for the reservoirs. The reservoir model was calibrated from January 1997 to October 1999 and the river was calibrated for the summer of 1999.

A new feature was added to CE-QUAL-W2 Version 3 to incorporate dynamic shading on streams (Annear et al. 2001). The dynamic shading algorithm incorporates vegetative shading by characterizing the vegetation density, height, and distance from the centerline of the stream. The algorithm also accounts for topographic shading by including inclination angles surrounding each model segment.

## MODEL DEVELOPMENT

### Boundary Condition Data:

#### Bathymetry

Detailed bathymetric survey data was collected for Reservoir #1 and Reservoir #2 and combined with the surrounding topography to generate the model bathymetry for each reservoir. An example of the model grid overlaid with the bathymetric contours is shown in Figure 2.

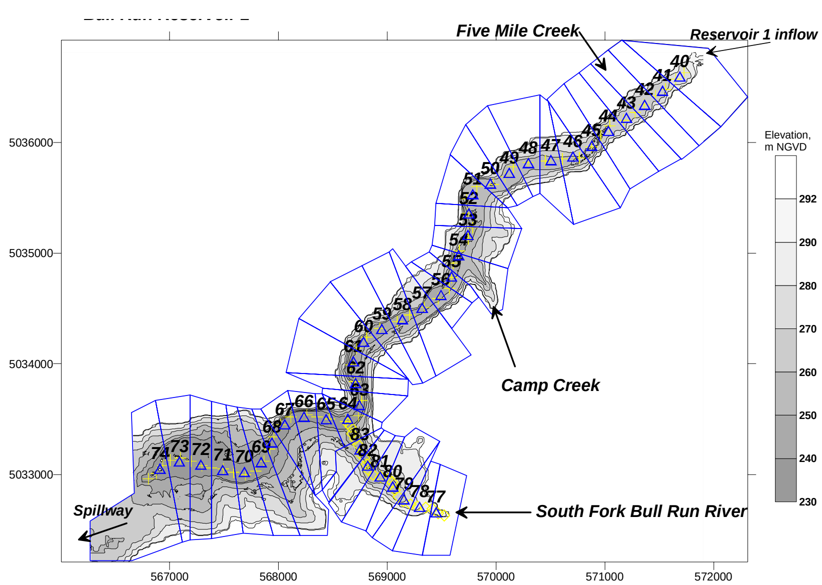


**Figure 2. Reservoir #2 Model Grid Layout**

A comparison of the model volume-elevation determined by a contour-plotting program for the Reservoir #2 bathymetry compared with data from the Water Bureau (1920s) and the CE-QUAL-W2 grid is shown in Figure 3.

The Bull Run River below Reservoir #2 is a high gradient stream to model with an average slope of 1.4%. There was little bathymetric data available for the river. A few cross sections and fish survey data provided the location of pools, riffles, and waterfalls. The information was combined with detailed topographic information of the river canyon to generate the river bathymetry. A hypothetical river model cross-section is shown in Figure 4. Figure 5 shows a layout of the grid for the Lower Bull Run River. Table 1 provides the model grid specifications.

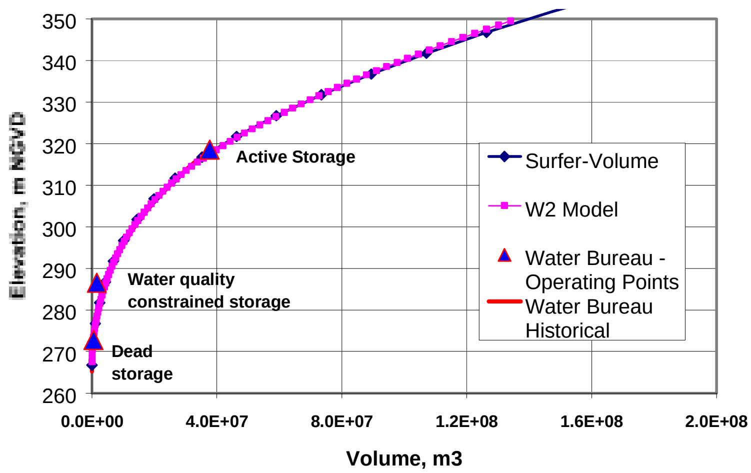


Figure 3. Volume-elevation curves for Reservoir #1 comparing model grid, SURFER, and Water Bureau historical data

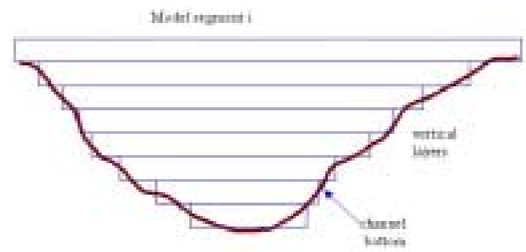

Figure 4. Hypothetical cross-sectional slice for the river grid geometry

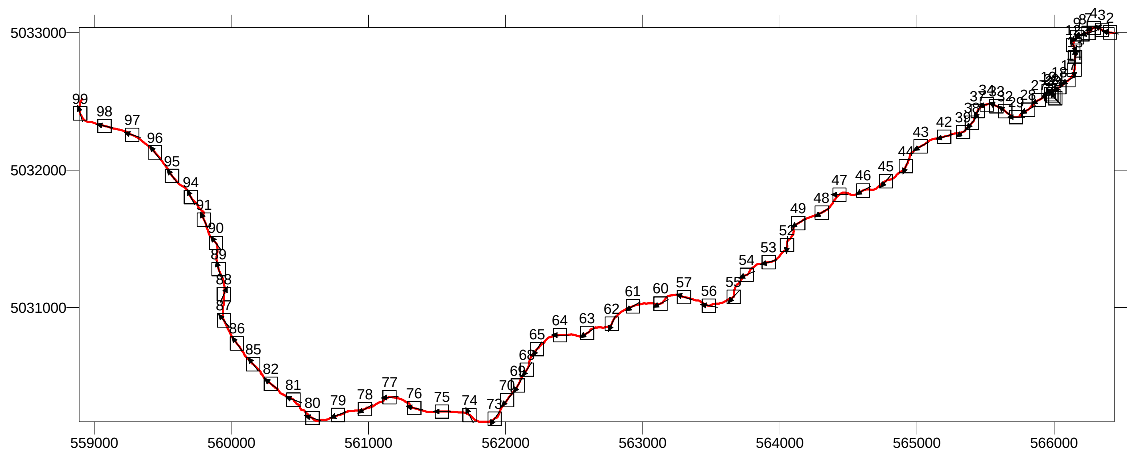


Figure 5. River grid layout

Table 1. River and reservoir grid layout specifications

| Parameter | Lower Bull Run River | Reservoir #2 | Reservoir #1 | Reservoir #3 |
|---|---|---|---|---|
| Number of branches | 15 | 2 | 2 | 6 |
| Channel slope range [-] | 0.000 to 0.022 | 0.0 | 0.0 | 0.0 |
| Segment length, Δx, range, m | 67-210 | 167-211 | 101-225 | 68-201 |
| Vertical grid Δz, m | 0.3-2 | 1 | 1 | 1 |
| IMP (number of segments) | 95 | 46 | 38 | 53 |
| KMP (number of layers) | 20 | 65 | 83 | 114 |
| ELBOT (elevation of top of lowermost vertical layer, m NGVD) | 74.2 | 228.5 | 266.5 | 498.5 |

**Inflows**
There are four large tributaries contributing flow to Reservoir #1 and Reservoir #2 and they are all gaged with measured every half hour. There are an additional five subbasins, which are smaller and have only been gaged periodically in the past. The flows in these smaller basins were correlated to the flows in the larger basins allowing a more complete record to be generated. Any remaining inflows or losses to the reservoirs were considered in the water balance calibration. There is one large tributary to the Lower Bull Run River, which was also gage with measurements every half hour. A correlation was developed between the large subbasin and one of the large tributaries contributing flow to Reservoir #2 and used to generate flows for the other small subbasins in the lower river.

**Temperature**
The same four large tributaries to the reservoirs, which had half-hourly flow measurements, also had half-hourly water temperature measurements. The five tributaries with periodic flow measurements had no water temperature data. Water temperature data from the nearest large tributaries were used for these smaller tributaries. This assumption did not have a significant influence on the thermal structure of the reservoirs due to the much smaller flows associated with these tributaries.

**Meteorological Conditions**
The meteorological conditions of the Bull Run River-Reservoir system varied across the watershed. Meteorological data required for the model include: air and dew point temperature, wind speed and direction, and cloud cover. Solar radiation measurements can also be used, if available.

Some meteorological data has been collected at Reservoir #2 on a daily basis prior to September 1998. In October 1998 a new continuously recording meteorological station was installed at Reservoir #2. Several errors were encountered after installation so reliable data were not available from the station until April 1999. Since the continuously recorded meteorological data were limited to 1999, hourly data from the Portland International Airport (PDX) were used. Although this monitoring station is located 41.8 km away, the site provided a complete data set for the calibration period of 1997 to 1999. Wind speed and direction in the Bull Run watershed did not correlate well with wind speed and direction at the PDX airport, so a time varying wind-sheltering coefficient was used during model calibration.

Another meteorological data set was from the Log Creek RAWS (US Forest Service) meteorological station high in the watershed. This site was closest to Reservoir #1 and the proposed Reservoir #3. The data consisted of wind speed and direction, air temperature, relative humidity and barometric pressure. Cloud cover data were not available at the site so cloud cover data were used from Portland International Airport. Since dew point temperature was not available at this site, the relative humidity and air temperature data were used to calculate the dew point temperature using a relationship from Singh (1992).

In June 1999 a new meteorological station was located in the Lower Bull River canyon (RM 4.9) to monitor the specific conditions in the river canyon since they are different than the data collected at Reservoir #2. The meteorological data consisted of wind speed and direction, air temperature, and relative humidity. The cloud cover data was derived from the solar radiation measured at Reservoir #2 using the equation:

$$CC = \sqrt{\frac{1 - \phi_m / \phi_{scr}}{0.65}}$$

where $\phi_{scr}$ is the clear sky short wave solar based on the latitude of the water body and $\phi_m$ is the measured short wave solar.

**Reservoir Outlet Hydraulics**

To model accurately the reservoirs, flows from Reservoir #1 to Reservoir #2, flows from Reservoir #2 to Portland, and flows to the Lower Bull Run River needed to be well characterized. Three flow pathways from Reservoir#1 to Reservoir #2 were identified; flow through the powerhouse, flow over the spillway and flow through needle values. Flow through the powerhouse used a multiple withdrawal structure with three intake elevations. There were three spillway gates located in the center of the Reservoir #1 dam structure. The reservoir full pool water level can be raised 2.9 m by closing the spillway gates. The needle valves are operated with a separate withdrawal structure with five intake elevations.

Three flow pathways were identified for sending water from Reservoir #2 to Portland or the lower river: flow through either of two intake towers and flow over a spillway. The North Intake Structure is used predominantly throughout the year by drawing water from the bottom 12 m of the reservoir and sending the water through a powerhouse and then to town or to the lower river. The South Intake Tower provides a back up intake location and also withdraws water from the reservoir bottom. The spillway is primarily used during the winter.

## CALIBRATION

**<u>Reservoirs:</u>**

### Hydrodynamics

The reservoir model calibration consisted of conducting a water balance, a water temperature profile calibration, and finally a sensitivity analysis model parameters (Annear and Wells, 2000). Reservoir #1 and Reservoir #2 were modeled as a linked system from January 2, 1997 to October 10, 1999.

The water balance of the reservoirs was designed to ensure the model was correctly reproducing the water levels in each reservoir. Model simulated water level elevations were compared

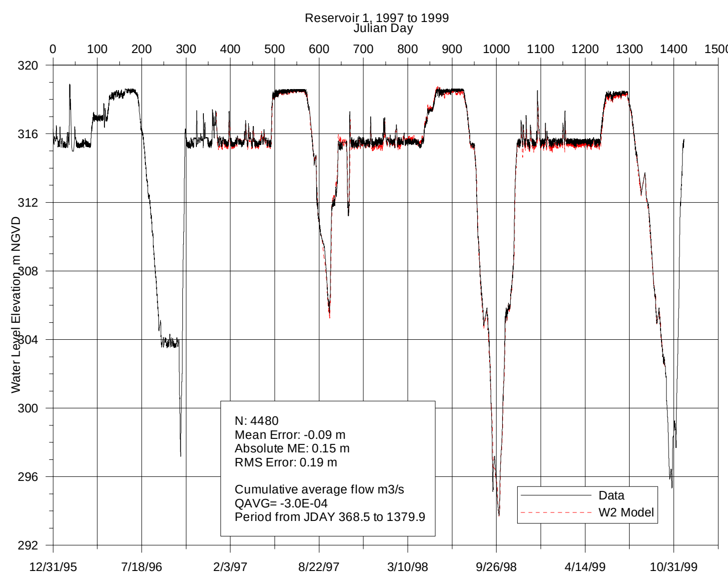


**Figure 6. Reservoir #1 water balance, January 1997 to October 1999**

with the observed water level elevations. The difference between the simulated and observed water levels and the bathymetry of the reservoirs were used to generate a times series of inflows and outflows to balance the simulated water levels with data. The water balance flows represent all inflow and outflow sources of error.

Figure 6 shows the water balance achieved for Reservoir #1. Statistics comparing the simulated and observed water level elevations show an absolute mean error (AME) of 0.15 m and root mean square error (RMS) of 0.19 m. The average water balance flow over the simulation time period was -4.6x$10^{-4}$ $m^3$/s, a small outflow from Reservoir #1. The water balance flows did not have much influence on the water balance of Reservoir #2 because the corrected flows were very small compared to typical powerhouse flows of 35 $m^3$/s. Temperatures for the water balance flows in Reservoir #1 were based on the North Fork River water temperature record.

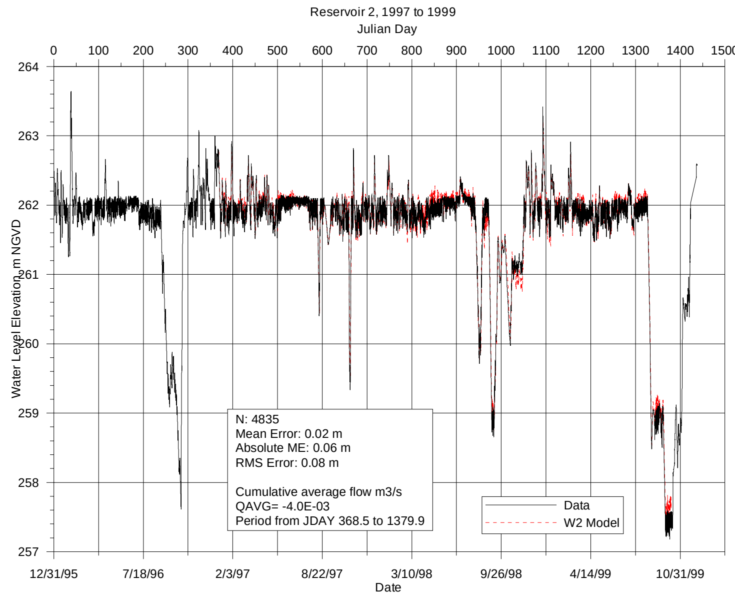


**Figure 7. Reservoir #2 water balance, January 1997 to October 1999**

A similar approach was used for Reservoir #2. Figure 7 shows the water balance for Reservoir #2. The water level model-data were an AME of 0.06 m and a RMS of 0.08 m. The average water balance flow over the simulation period was -3.1 x$10^{-4}$ $m^3$/s, small compared to average Reservoir #2 flows of 21.5 $m^3$/s. Temperatures for the water balance flows were based on the South Fork River water temperature record.

The water balance flows represent uncertainties in the model due to a lack of information or possible errors. Potential sources of error in the inflows and outflows to the two reservoirs include: groundwater, turbine flow rating curves, needle valve operation records, needle valve flow rating curves, and Howell Bunger Valve operations on Reservoir #2. Uncertainties in the reservoir bathymetry could also influence the water balance.

## Temperature

The temperature calibration involved comparing vertical temperature profile data with model predicted temperatures from 1997 to 1999 for both reservoirs. Simulated profiles were output daily and compared to field data, and statistics were calculated on differences between the model and data. Calibration simulations were made on Reservoir #1 first since the reservoir outflow temperatures would directly affect the calibration of Reservoir #2. A Hydrolab instrument was used to collect profile data in each reservoir. Adjustments were then made to model parameters and input files to achieve a better agreement between the data and simulated temperatures. Once errors in inflows and outflows were corrected an evaporation model was chosen, the only adjustment parameter was the wind-sheltering coefficient (the fraction of incident wind from the meteorological input data) for different times during the simulation. Table 2 shows the error statistics from Reservoir #1 and Reservoir #2 model calibration. Figure 8 and Figure 9 show several model-data vertical temperature profiles comparisons for Reservoir #1 and Reservoir #2.

**Table 2. Model predictions vs. vertical profile data error statistics, 1997 to 1999**

| Reservoir | Number of Profiles | Overall AME, °C | Overall RMS error, °C |
|---|---|---|---|
| Reservoir# 1 | 71 | 0.45 | 0.54 |
| Reservoir# 2 | 69 | 0.36 | 0.44 |

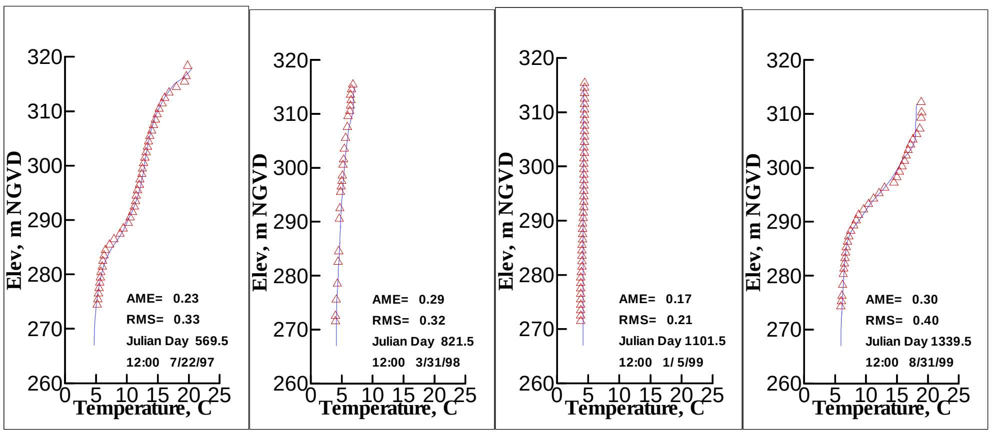


**Figure 8. Reservoir #1 model-data temperature profile comparisons, data are represented as points and the model as a line**

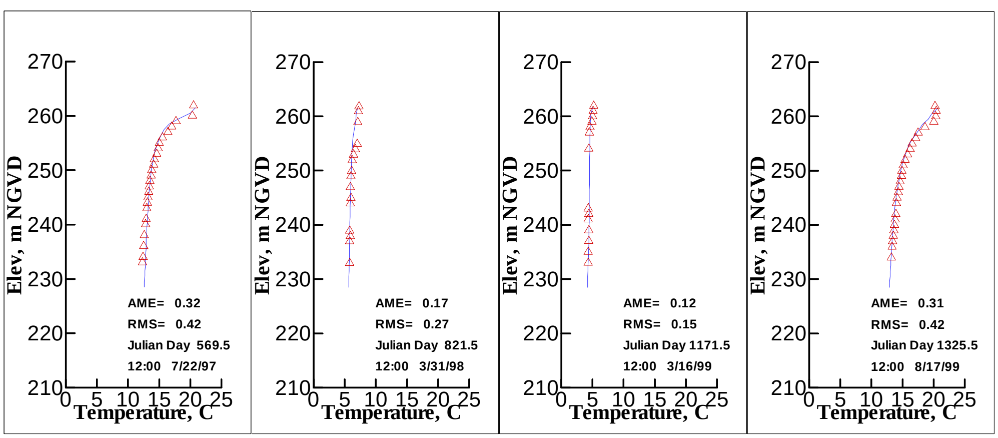


**Figure 9. Reservoir #2 model-data temperature profile comparisons, data are represented as points and the model as a line**

Predicted outflow water temperatures from Reservoir #2 were also compared with hourly temperature data. Table 3 shows the error statistics comparing the data and model results. Further work is being conducted to improve winter temperature predictions of the model. The larger errors in Table 2 compared to Table 1 are largely a result of winter temperature errors.

**Table 3. Reservoir #2 outflow model-data model error statistics**

| Reservoir #2 | Error statistics |
|---|---|
| Number of observations | 22417 |
| Mean Error °C | -0.77 |
| Absolute Mean Error °C | 0.82 |
| RMS Error °C | 0.91 |

## Lower Bull Run River:

### Hydrodynamics

The river model hydraulics was first calibrated by comparing the model predicted flows against known flows at a gage station in the Lower Bull Run River. The model was then calibrated to predict dye tracer concentrations at several locations where dye concentration data were collected for two dye studies (June and August 1999). Temperature time series plots were then examined during the same dye studies to calibrate the model for temperature.

**Table 4. Hydrodynamic error statistics at the USGS gage station, June dye study**

| Error statistics at the USGS gage station | Water Level, m | Flow, $m^3/s$ |
|---|---|---|
| N: | 480 | 480 |
| Mean Error: | -0.024 | 0.024 |
| Absolute Mean Error: | 0.084 | 0.134 |
| Root Mean Square Error: | 0.132 | 0.399 |

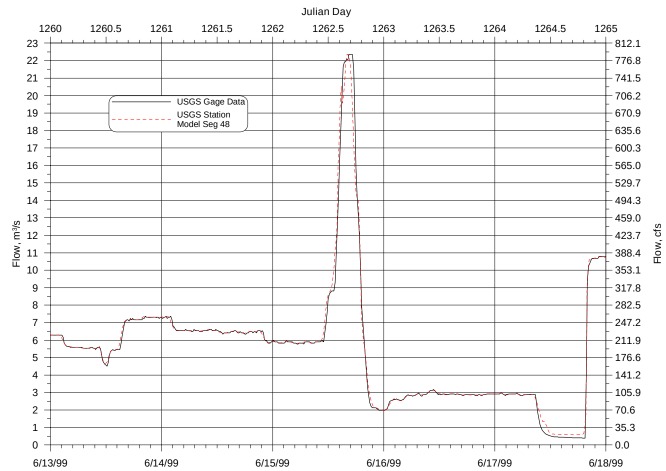


**Figure 10. USGS gage station flow data and model predictions, June Dye Study**

Inflows to the Lower Bull Run River were generated by using the gage station flow and subtracting out the subbasin inflows between the Reservoir #2 dam at river mile (RM) 6.5 and the gage station at RM 4.9. Flows lower than 0.2 $m^3/s$ were replaced with a minimum flow of 0.2 $m^3/s$ to prevent the model from drying up. Table 4 shows the water level and flow error statistics from comparing model results with data observations. Figure 10 shows the model flow prediction and gage station data at RM 4.9 during the June dye study.

The June dye study consisted of releasing a slug input of 0.5 kg of dye into the lower river. Samples of dye concentration were collected at four locations downstream. The model was then calibrated for the dye injection to the lower river by adjusting the Manning's friction factor, the slope of model branches, and the widths of the lowest layers of the model segments. These bathymetry adjustments were necessary because of poor quality and infrequent survey data for the channel dimensions. Since the Lower Bull Run River is a series

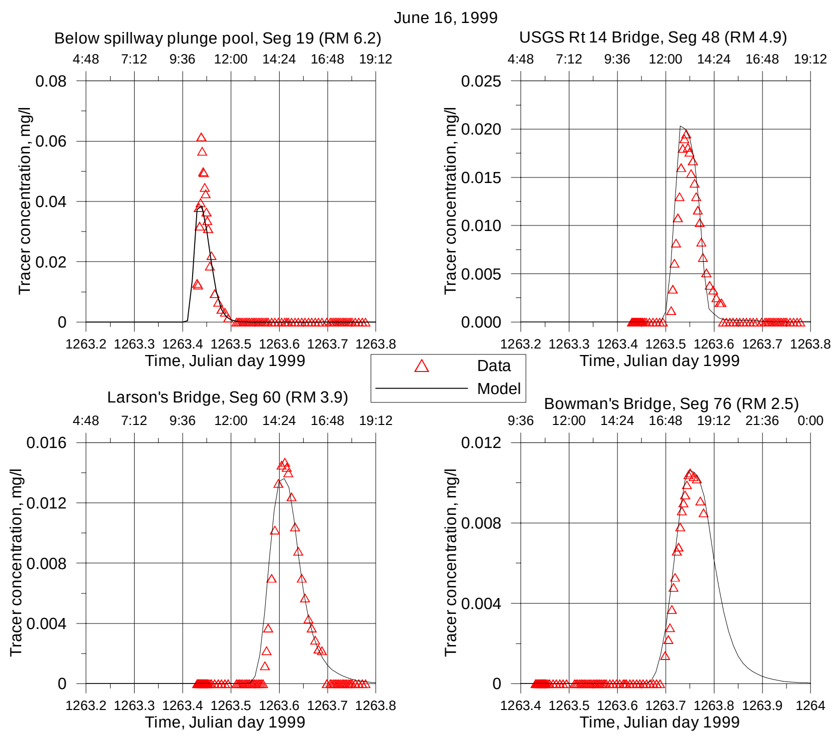


**Figure 11. June 1999 dye study tracer concentration time series**

of pools and slow moving stretches with waterfalls, the overall slope of 1.4% for the lower river was not necessarily appropriate for the W2 model. The slope adjustments were necessary to adjust the model to an “equivalent” hydraulic river section for this steep mountain stream characterized by pools, small waterfalls, and riffles. Figure 11 shows the dye concentration model results and data collected at four locations. The calibrated model matched the travel times of the dye concentration, but there was slightly too much numerical dispersion resulting in the model peak concentrations slightly under data observations. In the first plot of Figure 11 the data has a higher peak concentration than the model because the data were collected directly from the passing dye plume before it was completely mixed across the river channel.

**Temperature**

The temperature calibration consisted of comparing model predictions to data observations for a five-day period around the June 1999 dye study. The model was calibrated by making adjustments to the shade reduction factor, which reflects the variability in the vegetation density, and the fraction of short-wave solar radiation immediately re-radiated back into the water column from the river streambed. Tree top elevations and topographic inclination angles were not adjusted. There were a total of six locations where model-data comparisons were made with error statistics shown in Table 5, indicating good agreement between the model and data. Figure 12 shows the model results and data at four locations in the river.

**Table 5. Dye study temperature statistics, June 13-18, 1999**

| River Mile | Number of points | Mean Error °C | Absolute ME °C | RMS Error °C |
|---|---|---|---|---|
| 6.1 | 10 | 0.40 | 0.40 | 0.42 |
| 4.9 | 239 | 0.20 | 0.33 | 0.48 |
| 3.9 | 239 | 0.13 | 0.26 | 0.39 |
| 3.1 | 146 | 0.19 | 0.33 | 0.57 |
| 2.5 | 239 | -0.02 | 0.34 | 0.53 |
| 1.5 | 238 | 0.03 | 0.34 | 0.50 |

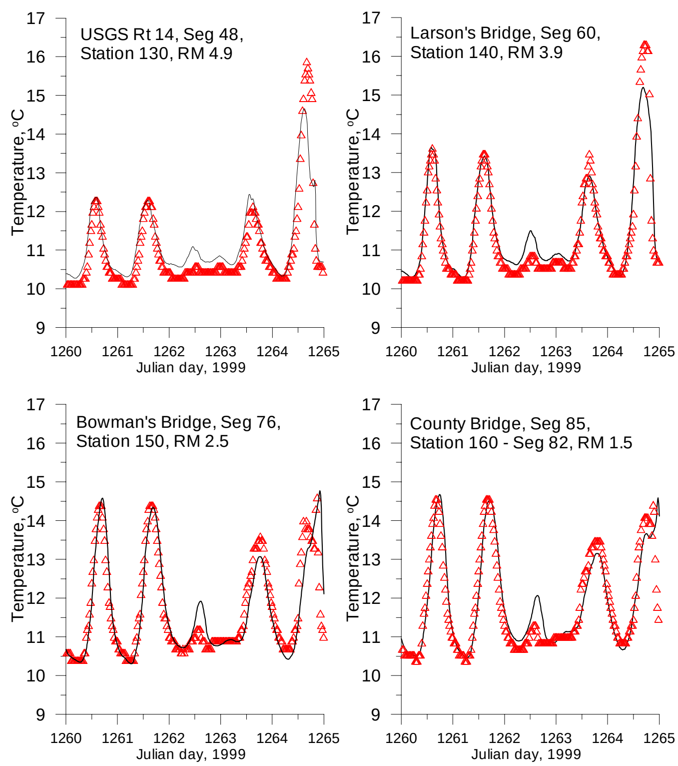


**Figure 12. June 13-18 dye study temperature time series, Julian day 1260-1265**

**Management Strategies:**

Management strategies were examined over the summer of 1998 since this represented a year when inflows to the reservoirs were normal to below normal and air temperatures were above normal, resulting in higher water demand. The reservoir model was run from January 1 through December 31, 1998.

The management strategies simulated were designed to meet a minimum in-stream flow in the lower river to support fish. Criteria for the amount of water for fish were developed by the City of Portland, Water Bureau based on the daily maximum air temperature and lower river flow rate data. The philosophy of the criteria was to increase the amount of water sent to the lower river as air temperatures increased. A minimum base flow released to the lower river from July 1 to October 31 was set at 0.28 $m^3/s$. When the daily maximum air temperature exceeded 21 $^oC$ for 4 or more days in 7, then 0.85 $m^3/s$ of water was released. When the daily maximum air temperature exceeded 24 $^oC$ for 4 or more days in 7, then 1.70 $m^3/s$ of water was released. The fish flows represented a total volume of 5 billion gallons, almost the storage capacity of Reservoir #2 (6.9 bgal).

Reservoir #2 does not have a multiple withdrawal structure. Outflows go primarily through an intake tower with a bottom withdrawal. One management strategy examined the flexibility gained by adding a multiple withdrawal structure to Reservoir #2 with three withdrawal elevations. The existing withdrawal elevations for Reservoir #1 include the three powerhouse operation elevations and two of the five needle valve operation elevations.

Several withdrawal strategies were used to hold cold water until late summer and then release it for fish. One of these strategies used an internal withdrawal elevation control based on the outgoing temperature from Reservoir #2. As the discharge water temperature exceeded 14 $^oC$, the model automatically switched the withdrawal elevation to the next lowest elevation to use colder water.

Another management strategy increased the volume of Reservoir #2 by raising the dam 3.7 m, increasing the volume from 6.9 bgal to 8.5 bgal. The larger reservoir also used a multiple withdrawal structure with elevations set for the higher dam. Several withdrawal strategies were also tested with the larger reservoir.

A proposed Reservoir #3 was added to the system and several management strategies were modeled to determine what influence it would have on temperatures in the Lower Bull Run River. Figure 13 shows the location of the proposed reservoir in the watershed. The proposed reservoir was modeled with three withdrawal elevations. Reservoir #3, at full pool elevation, was determined to have a volume of 22.5 bgal compared with the current volumes of 8.8 bgal and 6.9 bgal for Reservoir #1 and Reservoir #2, respectively.


**Figure 13. Proposed Reservoir # in the watershed**

In addition to expanding the existing water storage system to increase flexibility, the system was modeled with no dams to investigate historical water temperatures in the watershed. The model grid for Reservoir #2 and #1 were changed from a slope of 0 to slopes reflective of the general channel slope based on topography. The grid resolution at this level is very coarse and the river widths were estimated based on the original reservoir bathymetry. The model consisted of an upstream boundary condition at a gage station above Reservoir #1. Simulations were made assuming 50% and 100% shading. The assumption of 50% shading was conservative compared to the average shading in the Lower Bull Run River, which was 14% from June 18 to September 30. The average shading was computed by taking the short wave solar impinging on the water surface divided by the incident short-wave solar radiation before shading was computed for each model segment of the Lower River.

There were a total of 17 management strategies developed and tested with the reservoir model and 6 of the 17 were tested on the Lower Bull Run River on their effectiveness to meet temperature guidelines. The guideline criterion was that the 7 day-mean of the daily maximum temperature should not exceed 17.8 $^{o}$C. Temperature data in the Lower Bull Run River indicated the warmest water temperatures occurred at Larson's Bridge, RM 3.9.

The six reservoir management strategies tested in the Lower Bull Run River were adding selective withdrawal to Reservoir #2, increasing the volume of Reservoir #2, adding Reservoir #3 to the system, assuming a no-dam scenario with 50% shading in the region of Reservoir #1 and Reservoir #2, and assuming a no-dam scenario with 100% shading in the region of Reservoir #1 and Reservoir #2. These management strategies were compared against the fish flow releases during the summer of 1998 without any modifications to the Bull Run system. The Lower Bull Run River model was run from June 18$^{th}$ to September 30$^{th}$, 1998.

Statistics were developed for each simulation and are shown in Table 6. The simulation with Reservoir #3 resulted in more temperature violations than merely selective withdrawal even though the overall average temperature was lower. This occurs because (1) the selective withdrawal scheme was not optimized to account for the Reservoir #3 inflows, and (2) the additional inflows from Reservoir #3 into Reservoir #2 resulted in increased mixing in the reservoir breaking down the cold water pool, even though the average temperature was reduced.

**Table 6. Temperature statistics at Larson's Bridge for four management strategies and two no-dam strategies**

| Strategy Description | Number of 7-day temp. violations (17.8 $^{o}$C) | Mean water temp. $^{o}$C 7/1/98 -9/30/98 | Number of days >16$^{o}$C | Peak temp. $^{o}$C |
|---|---|---|---|---|
| Base case with fish flows | 38 | 15.92 | 44.0 | 20.64 |
| Selective withdrawal on Reservoir #2 | 18 | 15.63 | 35.8 | 19.50 |
| Reservoir #2 additional storage | 28 | 15.60 | 42.5 | 19.24 |
| Reservoir #3 | 30 | 15.39 | 40.7 | 18.72 |
| No dam scenario, 50% shading | 42 | 16.00 | 44.3 | 23.73 |
| No dam scenario, 100% | 32 | 14.72 | 27.2 | 23.01 |

## CONCLUSIONS

A 2-D hydrodynamic and water quality model was developed for the Bull Run system consisting of two reservoirs and the river below the reservoirs. The model incorporated flow and temperature data, the bathymetry of the system, the meteorological conditions and the reservoir operations. The calibrated river and reservoir models were within about 0.5 $^{o}$C indicating the model performed well in simulating the historical operations of the reservoir system. The system model was then used to examine six management strategies to reduce temperature violations in the Lower Bull Run River. The management strategy results show some improvements in reducing violations but there were no strategies tested which eliminated the violations. Even the no-dam scenario simulations showed that stream temperatures would have violated the State of Oregon's temperature standard.


## ACKNOWLEDGEMENTS

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