A NUMERICAL MODEL TO ASSESS DAM OPERATIONS TO MINIMIZE DOWNSTREAM TEMPERATURE

Marcela Politano. Research Engineer. IIHR Hydroscience & Engineering, The University of Iowa, USA

Ryan Laughery. Hydraulic Engineer. Department of the Army, Walla Walla District Corps of Engineers, USA

Larry Weber. IIHR Director. IIHR Hydroscience & Engineering, The University of Iowa, USA

ABSTRACT

Low river flows together with record high air temperatures had caused unprecedented elevated temperatures in the Columbia River in the summer of 2015. Warm water created lethal conditions for cold-water fish species resulting in one of the worst seasons for Snake River sockeye salmon. In this study, an unsteady three-dimensional non-hydrostatic model was used to predict the flow field and temperature dynamics in the forebay and turbine intakes of McNary Dam. The model is based on the Reynolds Average Navier Stokes equations with a Boussinesq approach. The thermal model takes into account the short and long wave radiations and heat convection at the free surface, which is function of air temperature and wind velocity.

The model was validated using temperature collected by USACE in the gatewells and at 46 stations in the McNary forebay during a warm day in the summer of 2004. After validation, the model was run with atmospheric and river conditions observed on July 9, 2015. On that day, water temperature at 5m beneath the surface was the season’s highest. The model captured well the measured temperature profiles in the forebay under this extreme condition. Possible mitigation measures to reduce temperature at the turbine intakes were evaluated with the model. Hypothetical conditions with 60% spill, spill with TSW and the inclusion of a thermal curtain were simulated. According to the model, the curtain is the best option to reduce temperature in the river downstream of the dam. Moreover, for the simulated conditions, the curtain effectively maintained gatewell temperature in the tolerance zone for migrating salmonids.

Keywords: temperature; dam operations; McNary Dam; numerical model; thermal model.
1. INTRODUCTION

The McNary project, operated by the U.S. Army Corps of Engineers (USACE) Walla Walla District, includes McNary Dam, forebay (Lake Wallula), 14 turbine units, 22 spillway bays, navigation lock and two fish ladders. Figure 1 shows a map with the location and an aerial view of the project. Each turbine unit includes three intake bays, main and intermediate piers, vertical barrier screens (VBS), extended-length bar screens (ESBS) screens, and turning vanes. Two temporary spillway weirs (TSW) were installed in spillway bays #20 and #22 to provide a less stressful downstream passage for juvenile salmon.

![Figure 1. McNary Dam. Left: location of McNary Dam in the Columbia Basin and left: aerial view of the dam](image)

Elevated river temperature increases fish metabolism and induce thermal stress in cold species fish population (Brett, 1952). Temperature recommended in the Washington State Clean Water Act for salmon is 20 °C (68 °F). The upper incipient lethal temperature (UILT) is the temperature at which death occurs within minutes. Resistance to high temperatures varies between species. The upper UILT for salmon ranges from 25 °C (77 °F) to 30 °C (86 °F). Salmon can spend several hours in streams of 23.6 °C or less without suffering mortality (“Zone of Tolerance” in Sullivan et al. 2000). In the “Zone of Resistance”, behavioral mechanisms permit fish to survive short-term extreme temperatures.

Juvenile fish mortalities associated with elevated water temperature within the fish facilities at McNary Dam were documented since the 1980s. A significant fish loss, believed to be primarily a result of high water temperature in the juvenile fish facility occurred in July 1994 (NOAA 2005). Since then warm water problems were successfully minimized by continuous
monitoring and adjusting dam operations. In 2015, low river flows from record low snowpack together with extremely high air temperature and solar radiation resulted in record high water temperature in the Columbia and Snake Rivers during mid-June to the end of July. Snake River sockeye salmon, who is listed in the Endangered Species Act (ESA) and migrates within this time period, suffered losses exceeding 95% between Bonneville and Lower Granite dams (NOAA 2016). Juveniles suffered delayed migration, but travel times were faster than those prior to TSW installation.

In this study, a numerical model was developed to simulate the temperature dynamics in the McNary forebay. Most thermal models in lakes are based on a one or two-dimensional approach (Lei and Patterson 2002, Ferrarin and Umgiesser 2005, Gooseff et al. 2005). Hydropower forebays are characterized by complex three-dimensional (3D) flow patterns as a result of dam operations and unsteady heat exchange between the atmosphere and water requiring the use of a 3D model. 3D models assuming hydrostatic pressure have been widely used over the past decade to simulate temperature dynamics (Blumberg and Mellor 1985, 1987, Beletsky and Schwab 2001, Song et al. 2004, Khangaonkar et al. 2005, among others). However, for this study, a more complex non-hydrostatic model is required since both vertical motion and vertical accelerations are important near turbine intakes.

2. ENVIRONMENTAL CONDITIONS IN 2015

Historic air temperature and solar radiation near McNary Dam are available at the U.S. Bureau of Reclamation website http://www.usbr.gov/pn/agrimet/agrimetmap/agrimap.html and the Washington State University website http://weather.wsu.edu/. Figure 2 shows the highest daily air temperature from May to September. The line shows the average in the past 32 years and the symbols temperature measured in 2015. Most of the time, air temperatures in 2015 were well above the 32 years average. From July 1st to July 10th air temperature was in average about 10 °C (5.5 °F) above average. Average air temperature on this period of time was 36.9 °C (98.4 °F). Most of the time in 2015 global daily solar radiation was also above the 32 years average (Fig. 3).
Figure 2. Maximum daily air temperature

Figure 3. Global daily solar radiation

Flowrates in McNary dam are available at the USACE website http://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/?k=mcnary. Figure 4 shows the flow used for generation and total flow out of the dam from July 1st to July 21st, 2015. Runoff volumes in the Columbia River at The Dalles from April to August, 2015 was the third lowest in 56-years due to both low snow levels in the basin and low spring precipitation (NOAA 2016).
Water temperature in the McNary forebay at different depths are available at the USACE website [http://www.nwd-wc.usace.army.mil/ftppub/water_quality/tempstrings/](http://www.nwd-wc.usace.army.mil/ftppub/water_quality/tempstrings/). Figure 5 shows the highest daily air and water temperature at 0.5 m and 5 m beneath the surface from July 1st to July 21st, 2015. On July 9 the daily average water temperature at 0.5 m from the surface was the highest of the season reaching 26.9 °C (80.4 °F).

**Figure 4.** Flowrate in McNary dam in July 2015

**Figure 5.** Water and air temperatures in July 2015
3. MODEL OVERVIEW

The numerical model includes 3300 m (2 miles) of the lake Wallula and the main features of the McNary project: turbine units, spillway, TSW, Oregon and Washington fishways, and the navigation lock (Fig. 6).

The model used in this study is based upon the commercial code ANSYS Fluent. The flow field is solved with the incompressible unsteady RANS equations using the Boussinesq approach to account for buoyancy forces due to temperature differences. The turbulence is modeled with a standard $k-\varepsilon$ model with wall functions. The fish screens were modeled as porous media of finite thickness. Equivalent screen porosities were estimated using the correlations proposed by Weber et al. (2000) for flat bar screens and perforated plates. The screen porosities were calibrated by Haque et al. (2005) using experimental data from a physical model. Uniform porosities of about 16% and 13% were used for the ESBS and VBS, respectively.

The temperature is computed from the energy conservation equation for incompressible flows. The difference between incoming and reflected measured radiation were used to adjust a quadratic sinusoidal function for the incident radiation. The radiation absorbed by the water was modeled accounting for the attenuation of solar radiation with depth given by the by the Beer’s law. The average long wave radiation measured at night (-50 W/m²) was included as a negative source term for elements contiguous to the free surface.

3.1. Computational Grid

A grid of approximately 2 million cells was created in Gambit (Fig. 6). Nearly orthogonal structured grids with cell aspect ratios smaller than 10 and expansion ratios no greater than 1.5 were used near the free surface in the forebay. Complex geometry regions near the powerhouse were meshed with unstructured grids containing only hexahedral cells. The grid was refined near all the solid boundaries, near turbine intakes where large accelerations are expected, and near the free surface where heat transfer processes occurs.
3.2. Boundary Conditions

Free surface: the free surface was modeled as a rigid-lid with a specified shear stress due to the wind using the expression proposed by Wu (1969). The conductive heat flux at the free surface was modeled as a linear function of the difference between water and air temperatures following Edinger et al. (1968).

Inlet: the flowrate out of McNary dam and hourly measured temperature profiles were specified at the upstream inflow section. The turbulent variables are assumed zero at the upstream end.

Walls and river bed: a no-slip condition and zero heat flux were imposed on all walls and at the forebay bed.

Exits: exits were defined as outflows with a specified discharge.

3.3. Numerical Method

The equations of the model were solved sequentially with the control volume based technique used by Fluent. The governing equations are non-linear and coupled, so several iterations were performed to obtain a converged solution on each time step. A first order implicit integration was employed for temporal discretization. The discrete continuity equation was enforced using the SIMPLEC pressure-velocity coupling algorithm. The pressure at the faces was obtained using the Pressure Staggering Option (PRESTO) scheme. A first-order upwind scheme was used to discretize the momentum, turbulence and temperature equations.

The radiation source, wind shear stress, heat fluxes at the free surface, and inlet temperature profiles were programmed using User Defined Functions (UDFs).
The model was run from an initial constant temperature of 22 °C in the entire domain until a periodic solution was reached.

4. MODEL VALIDATION

4.1. Field Study

Temperature measurements were obtained by USACE at 46 stations along six transects in the McNary forebay (circles in Fig. 7) and in the gatewells at 15 minute intervals during the summer of 2004. To complement this data, the Walla Walla District/OA Systems Weather Station collected air temperature, longwave radiation, incident shortwave radiation, reflected solar radiation, humidity, and wind magnitude and direction every 10 minutes.

4.2. Atmospheric and Operational Conditions

The model was run using as inputs atmospheric and operational conditions recorded on Aug. 18, 2004. On this day, atmospheric and operational conditions induced significant warming in the McNary forebay and in the central and southern turbine intake gatewells. Lines in Fig. 7 shows the water depth on Aug. 18, 2004.

![Figure 7. Temperature transects during the 2004 field study](image)

Figure 8 shows air temperature and solar radiation measured on Aug. 18, 2004. The highest air temperature and solar radiation on this day were 31.4 °C and 833 W/m², respectively. The average total river discharge during daily hours was 4381 m³/s and all turbines were operating at the same discharge level.
Figure 8. Left: air temperature and right: solar radiation on Aug. 18, 2004. Symbols: measurements and lines: adjusted functions

4.3. Measured and Predicted Temperature on Aug. 18, 2004

Figure 9 shows predicted temperature profiles and field data every six hours on Aug. 18, 2004, at eight stations (see Fig. 7 for location of stations). Good agreement was found between model predictions and measured values. On this day, wind was moderate and short wave radiation and convective heat generated an important vertical temperature gradient, with a peak between 5:00 PM to 6:00 PM. As surface water warmed, they became less dense than deeper water resulting in a stable stratification of the water column. At 6:00 PM, the difference between surface and bottom temperatures was around 4 °C. At night and in the early morning hours, the temperature at the surface decreased as heat was transferred to the atmosphere by longwave radiation and convective heat transfer by air cooler than surface water. In all stations, the model predicted the daily heating and cooling of surface water. An undisturbed region below 15 m where temperature is nearly constant was observed and also captured by the model. During the day, at most of the stations, measured temperatures range between 23.4 °C to 24.5 °C while the predictions range between 24.4 °C to 25.5 °C. Strong winds promote turbulence and mixing through surface shear and breaking waves, reducing the temperature gradient in the upper layers. In this work, wind effects were considered only through the shear stress at the free surface and the convective heat transfer coefficient and the effect of breaking waves were neglected. Note also that error in the measurements near the free surface can be large due to difficulties in data acquisition with strong vertical temperature gradient.
As observed in the field, the predicted temperature near the free surface at the southern regions (see for example T3P4) are higher than those observed in the northern stations (T3P7). The temperature around the navigation lock was about 1 to 2 °C lower than the temperature through the powerhouse. This low temperature zone is of great benefit to the Washington Fishway. On the other hand, shallow water along with the strong mixing predicted by the model raised the temperature near the Oregon Fishway.
Figure 9. Measured and simulated temperature profiles in the McNary forebay

Figure 10 on the right shows the juvenile bypass in the McNary powerhouse. Screens divert salmonids into gatewells where fish exit through orifices into a bypass channel. The figure on the left shows predicted and measured temperatures in the gatewells at 6:00 PM. A reasonable agreement between predicted and measured temperatures was found. Warm surface waters from the southern region are withdrawn into the southern intake units. End units (unit #1 and unit #14) withdraw cooler water from a less disturbed region than units located in the interior of a block of operating turbines. According to the study of Sullivan et al. (2000), on Aug. 18, 2004 salmonids traveling in the gatewells were in their “Zones of Tolerance” (northern units) or “Zones of Resistance” (central and southern units). Acute effects are unlikely to occur due to the short duration of exposures to high temperatures in the gatewells. However, as the recommended for juvenile salmonids is below 20 °C, fish population might had suffered some thermal stress during passage through the powerhouse bypass system on this day.

Figure 10. Left: temperature in the McNary gatewells and right: bypass powerhouse system. Red diamonds: field data and white circles: model results

5. TEMPERATURE ON JULY 9, 2015

5.1. Atmospheric and Operational Conditions

The model was run with atmospheric and river discharge conditions observed during July 9, 2015 to evaluate the model capability to predict the extreme temperature measured in the forebay on this day. The daily average water temperature at 5m beneath the surface was the highest of the season as a result of low river flow and high air temperature and solar radiation. The maximum air
temperature was 37.9 °C and solar radiation was 866 W/m². The effect of the wind was considered negligible in this simulation. The daily flowrate out of McNary was 3825 m³/s with 1778 m³/s used for generation.

5.2. Measured and Predicted Temperature on July 9, 2015

Figure 11 shows the observed and predicted temperature profile in the McNary forebay every 6 hours on July 9, 2015. The temperature near the free surface is about 4 °C larger than on Aug. 18, 2004 mainly due to the higher air temperature. On this day, the air temperature was higher than the water temperature at the free surface from 5:00 AM to 8:00 PM. Though the heat flux was positive until 8:00 PM, the maximum water temperature at the free surface occurred at about 6:00 PM. According to the model, the reduction of the water temperature at the free surface was induced by the heat flux from the free surface to the deeper levels, which is larger than the heat flux from the air to the water surface.

![Figure 11](image)

**Figure 11.** Left: measured and simulated temperature profiles in the McNary forebay and right: temperature contours and velocity vectors in slices passing through powerhouse units

Figure 12 shows the temperature within the gatewells (left) and temperature distribution and velocity vectors in a slice through gatewell #9 (right) at 6:00 PM. The highest temperatures are predicted in units #8 to #10. Units #1 to #4 are shut down and temperature within the corresponding gatewells is low. Though the temperature near the free surface was about 28 °C, only water at temperature of 25 °C and below was entrained into the turbine. Warmer lighter water entrained by the turbine is then transported to the fish orifice. On July, 2015 the maximum air
temperature was 6.5 °C larger than on Aug. 18, 2004. However, the predicted temperatures within the gatewells for this day were only about 0.5 °C larger. The operational conditions for these two cases were different, and therefore temperature within the gatewells are not completely comparable. However, results seems to indicate that the powerhouse operation with the northern units and lower flowrate through each unit minimized the downstream transport of warm surface water.

![Figure 12](image)

**Figure 12.** Left: temperature in the McNary gatewells and right: temperature contours and velocity vectors in a slice through gatewell 9 at 6:00 PM

6. **EFFECT OF SPILL**

6.1. **Atmospheric and Operational Conditions**

The atmospheric conditions observed on Aug. 18, 2004 were used to evaluate the effect of spill. The river flowrate of 4381 m³/s on Aug. 18, 2004 was distributed as 60% spill, Oregon and Washington fishways at 34.2 m³/s and 61.6 m³/s, and remaining discharge uniformly distributed in turbine units #1 to #5. The spill pattern was: bay #1 and bays #4 to #12 at 134 m³/s, bays #2 and #3 at 249 m³/s, and bays #13 to #19 at 110.4 m³/s.

6.2. **Temperature Distribution with Spill**

Figure 13 shows the flow field and temperature distribution in the forebay as well as close-up views of turbine unit #3 and spillway #9. Gatewells withdraw water from the southern and central forebay regions. On the other hand, water from the northern forebay region is released
almost entirely in the spillway. The spillway releases mostly warm surface water, which is expected to increase the river temperature downstream of the dam.

Figure 14 shows the temperature within the gatewells with 60% spill. Though unit discharge in the powerhouse increased by 27% respect to the non-spill condition, the temperature within the operating gatewells is slightly higher (less than 0.2 °C) than predicted on Aug. 18, 2004.

Figure 13. Temperature distribution in the McNary forebay with 60% spill at 6:00 PM

Figure 14. Temperature in the McNary gatewells with 60% spill at 6:00 PM
7. SPILL WITH TEMPORARY SPILLWAY WEIRS

7.1. Atmospheric and Operational Conditions

The atmospheric conditions and river flowrate observed on Aug. 18, 2004 were used to evaluate the effect of TSW's operating in spillbays #20 and #22 at 254 m$^3$/s each. Oregon and Washington fishways discharged 34.2 m$^3$/s and 61.6 m$^3$/s and the remaining discharge was uniformly distributed in the 14 turbine units.

7.2. Temperature Distribution and Flow Pattern with TSWs

The temperature distribution and flow pattern with TSWs operating are shown in Figure 15. The TSWs spill surface water from the northern forebay region increasing the temperature in the gatewells of units #11 to #14 by about 0.5 °C (see Figs. 10 and 14). As expected, temperature in other gatewells are practically not affected by operation of TSW’s. As it was observed on Aug. 18, 2004, the highest temperature are predicted in gatewells #4 to #6 that withdraw water from a warmer region in the forebay and are located in a region where the thermocline is disturbed by operation of the powerhouse.

Figure 15. Streamlines colored by temperature with operating TSWs at 6:00 PM
8. STRUCTURAL MITIGATION MEASURE: FOREBAY CURTAIN

8.1. Atmospheric and Operational Conditions

The flow rate and atmospheric conditions used to analyze the effect of TSWs were used to evaluate the inclusion of a thermal curtain in the forebay. Figure 16 shows the configuration of the curtain, which is located 56 m (193 ft) upstream of turbine intakes and had a depth of 10 m (35 ft).

8.2. Temperature Distribution and Flow Pattern with TSWs

Figure 16 shows streamlines colored by temperature with the thermal curtain in the forebay at 6:00 PM. There is a noticeable change in the flow pattern and temperature distribution when the curtain is included in the forebay (compare Figs. 15 and 16). The curtain blocked warm surface water from being withdrawn into the powerhouse. Upstream of the curtain the temperature at the surface increased approximately 1.3 °C respect to the condition without the curtain. The triangular shape of the curtain appears to promote recirculation of the surface water producing more uniform temperatures in the gatewells. The average temperature at the free surface downstream of the curtain was about 23 °C, which is the highest temperature within the gatewells (Fig. 14). The entrainment of warm water at the southern and northern regions caused an incremental increase of temperatures in the outer gatewells. For the simulated conditions, the curtain effectively reduced the temperature in the gatewells about 1 to 2 °C preventing fish to be in the “Resistance Zone”.

Figure 16. Streamlines colored by temperature with forebay curtain at 6:00 PM
CONCLUSIONS

In this paper, the temperature dynamics in the McNary Dam forebay and turbine intakes were numerically studied using an unsteady, non-hydrostatic three-dimensional model. The model was compared against a 24 hour data-set collected on Aug. 18, 2004. The model captured the general observed diurnal stratification periodicity and gatewell temperature were reasonably predicted. General trends such as increase in the surface water temperature in the forebay or within the gatewells with daily heating were correctly predicted. Moreover, the model was able to reproduce the period of time when the maximum temperature in the forebay and in the gatewells were reached.

The CFD model was used to quantify the impact of atmospheric, operational and structural changes on the water temperature in the forebay and intake units of McNary Dam. According to the numerical results:

1. The model reproduced well the measured temperature profiles in the forebay for an extreme atmospheric condition observed on July 9, 2015. Gatewell temperatures were below theUILT for salmon. Though air temperature on July, 2015 was 6.5 °C larger than on Aug. 18, 2004, gatewell temperatures were only about 0.5 °C larger. Numerical results seems to indicate that the powerhouse operation with the northern units minimized the transport of the warm surface water into the units resulting in less potentially damaging temperatures for salmonids migrating downstream.

2. Temperature within the southern gatewells increased about 0.2 °C when 60% of the river discharge was spilled and the northern units were closed.

3. Operating with TSWs, the temperature in the gatewells of units #11 to #14 increased by about 0.5 °C.

4. The presence of a forebay curtain upstream of the powerhouse reduced the temperature within the gatewells by 1 to 2 °C, preventing fish to be in the “Resistance Zone”.

9. REFERENCES


10. BIOGRAPHICAL SKETCH

**Dr. Marcela Politano** is a Research Engineer at IIHR-Hydrosience & Engineering, The University of Iowa. She has expertise in numerical modeling of the hydrodynamics and water quality parameters in rivers, tailraces, reservoirs and fish passage structures. Her background includes modeling of total dissolved gas, and heat and mass transfer. She holds a PhD from
Instituto Balseiro, Argentina. She has had a lead role in over thirty projects for the power industry. She regularly publishes in international journals, conferences and technical reports.

**Ryan Laughery**, P.E. is the regional technical specialist on fish passage for USACE, Northwest Division, Walla Walla District. He obtained his bachelor's degree in civil engineering from Washington State University in 2002. From 2002 to current he has primarily been involved in the design and development of fish passage structures. For the past several years he has served as technical lead for the development of physical and numerical models for the evaluation of configurations and operations of hydropower projects to improve fish survival.

**Dr. Larry Weber**, P.E. is a Professor in Civil & Environmental Engineering at the University of Iowa. He is an expert in physical modeling, river hydraulics, and computational hydraulics. For the last ten years, he has served as the Director of IIHR—Hydroscience & Engineering. Dr. Weber’s work appears in numerous journals such as the Journal of Hydraulic Engineering, Journal of Hydroinformatics, and the Journal of Hydraulic Research. He is also a member of Iowa’s Water Resources Coordinating Council.