ECOLOGICAL MODELLING 212 (2008) 408–421

available at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/ecolmodel

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A numerical study of the temperature dynamics at McNary Dam

*Marcela Politano**, *MD.M. Haque, Larry J. Weber*

IIHR-Hydroscience & Engineering, The University of Iowa, 300 South Riverside Dr., Iowa City, IA 52242, United States

ARTICLE INFO

Article history:
Received 22 February 2007
Received in revised form
10 October 2007
Accepted 23 October 2007
Published on line 20 February 2008

Keywords:
Thermal model
Temperature dynamics
Dams
Stratification

ABSTRACT

High summer water temperatures have caused increased juvenile fish stress in fish passage facilities at McNary Dam. The need to better understand the main mechanisms that generate high temperatures and result in subsequent harmful stress to downstream migrating fish motivates this study.

Most numerical studies of temperature dynamics in reservoirs are based on one- or two-dimensional models. McNary Dam forebay is characterized by complex three-dimensional flow patterns and unsteady heat exchange between the atmosphere and water. An unsteady three-dimensional non-hydrostatic model is used in this paper to predict the hydrodynamics and thermal dynamics in the forebay and turbine intakes of McNary Dam. This model is based on the Reynolds Average Navier–Stokes equations, using a Boussinesq approach, with a standard k–ε model to solve the flow field. The thermal model takes into account the short and long wave radiation and heat convection at the free surface, which is function of air temperature and wind velocity.

The predicted temperature is compared against a 24 h field data set for a warm day in 2004. Simulated and measured temperature profiles in the forebay and within the gatewells show reasonable agreement. An additional simulation studies the inclusion of a thermal curtain upstream of the turbine intakes. Numerical results indicate that the thermal curtain reduces gatewell temperatures potentially increasing survival for migratory salmonids at the dam.

1. Introduction

The Columbia River basin is the most productive source of hydropower in the United States, having a potential capacity of over 24000 MW. The Columbia and Snake Rivers are of great environmental interest, as they host the largest salmon populations in the United States. Though dams in the Columbia basin produce numerous benefits, they have also contributed to the salmon population decline. The dams have impounded most of the free flowing sections of the rivers creating a series of large, low velocity reservoirs.

A diurnal cycle of stratification is observed in some hydropower forebays from late spring to early fall. Water temperature impacts the transfer of oxygen and others dissolved gases, biological and chemical reaction rates, and plant and animal mortality. Numerous studies of temperature effects on salmon are found in literature (see, e.g. Jones, 1959; Gillet, 1991; Likongwe et al., 1996; Van Der Kraak et al., 1997; Thorpe, 2004). Warmer waters increases fish stress making them vulnerable to bacterial and fungal infection. High temperatures also cause fish to seek refuge in cool areas, sometimes delaying their migration.

* *Corresponding author*. Tel.: +1 319 335 6393; fax: +1 319 335 5238.
E-mail address: marcela-politano@uiowa.edu (M. Politano).
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doi:10.1016/j.ecolmodel.2007.10.040

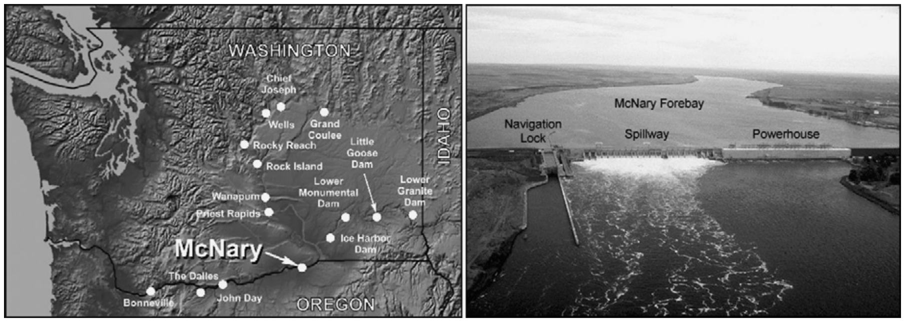

Fig. 1 – *Left*: Map of the Columbia River Basin showing the location of McNary Dam. *Right*: Primary features of McNary Dam.

McNary Dam, operated by the U.S. Army Corps of Engineers (USACE) Walla Walla District, is one of the largest hydroelectric power facilities in the Pacific Northwest influencing anadromous fish migrations for the Snake and Columbia River systems. Fig. 1 shows the location and an aerial view of McNary Dam and its forebay. In the 1980s and early 1990s, high summer water temperatures caused juvenile fish mortalities within the fish facilities at McNary Dam. At that time, warm water problems were minimized by adjusting turbine operations. However, a significant juvenile fish loss, believed to be primarily a result of high water temperatures, occurred in July 1994. There have not been any temperature related fish problems of such scale since, though concerns that fish experience harmful thermal stress during the summer persist (EPA, 2001). Over the last few decades, USACE has actively sought to improve fish survival rates. Water temperature data has been collected at various McNary Dam project locations through the years, culminating in an extensive data set collection of forebay water temperatures and meteorological data for the summer of 2004.

This paper describes a study of temperature distribution in McNary Dam forebay using a state-of-the-art Computational Fluid Dynamics (CFD) tool. The main goal is to understand the mechanisms that result in increased water temperature in the juvenile bypass system within the powerhouse and to ultimately reduce high temperature impacts on migratory salmonids. A conceptual surface barrier curtain in the forebay is evaluated as a mitigation measure to reduce thermal stresses on the fish. Temperature distribution with and without the forebay curtain are presented and discussed.

1.1. *Literature review*

Many numerical studies related to water temperature have been conducted over the years to study thermal stratification in reservoirs. Water temperature has been modeled at various levels of complexity. While numerous studies have been conducted to characterize thermal stratification in lakes and oceans, there have been fewer numerical studies of temperature dynamics in hydropower reservoirs.

An earlier experimental and analytical study of thermal stratification in lakes was presented by Dake and Harleman (1969). One-dimensional models (1D) were widely used to predict vertical temperature profiles in lakes or reservoirs. Stefan and Ford (1975), Stefan et al. (1980), and Hondzo and Stefan (1993) used a 1D vertical transport equation to predict temperature in lakes. The authors took into account net heat inputs from the atmosphere computing the heat flux from solar radiation, convection, and evaporation. The same approach was employed by Antonopoulos and Gianniou (2003) to predict seasonal temperature cycles and oxygen distribution. Condie and Webster (2001) used a coupled atmospheric boundary layer model to evaluate the level of stratification in an enclosed water body. This approach revealed daily air and water temperatures relationships, but fails when the advective term is important. A 1D vertically well-mixed model used by Kim and Chapra (1997) modeled the temperature in a shallow stream. The authors incorporated the heat flux through the channel bottom that may be significant in reservoirs with depths of 3 m or less. A similar approach was used by Gooseff et al. (2005) to quantify the potential effects of climate change on water temperature in a shallow reservoir. Note that this approach cannot predict stratification dynamics.

The use of at least a two-dimensional (2D) model is essential for the study of stratification dynamics subject to horizontal advection. 2D laterally averaged models have been applied extensively to predict water dynamics in reservoirs and rivers. Deboltsky and Neymark (1994) used a 2D model assuming hydrostatic pressure. The authors compared the temperature prediction in 1 year using different turbulent viscosity models. The stratification dynamic for lowland rivers was studied by Bormans and Webster (1998). Their 2D hydrostatic model considered the radiative, sensible, and evaporative fluxes at the free surface. The Navier–Stokes and energy equations with the Boussinesq assumption were used by Lei and Patterson (2002) for a 2D study of a sidearm reservoir subject to solar radiation. A 2D shallow water model was used by Ferrarin and Umgiesser (2005) to describe the hydrodynamic of a coastal lagoon. The authors used two additional scalar transport equations to describe the salinity and temperature in the lagoon. Their thermal model considered short and long wave radiation, heat flux by evaporation/condensation and convection process at the free surface.

In complex geometries with highly three-dimensional (3D) flows, mechanisms affecting temperature transport and mixing cannot be accurately captured by the more traditional depth or width-averaged models. Prediction of the flow field and temperature dynamics is possible through fully 3D models. 3D unsteady hydrodynamic models assuming hydrostatic flow have been widely used over the past decade. The Prince-