# Monitoring and Simulating 3-D Density Currents at the Confluence of the Snake and Clearwater Rivers

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## ABSTRACT

Summer temperatures in the Lower Snake River can be altered by releasing cold waters that originate from deep depths within Dworshak Reservoir. These cold releases are used to lower temperatures in the Clearwater River, a major tributary to the Lower Snake River, and to improve hydrodynamic and water quality conditions for migrating salmon. This project monitored the complex three-dimensional density currents at the Clearwater and Snake River confluence and the processes that led to stratification of Lower Granite Reservoir (LGR) during the late spring, summer, and fall of 2002. In addition to monitoring the LGR environment, a three-dimensional hydrodynamic and water quality model was also applied. By utilizing both field data and a numerical model, a more holistic view of the 3-D density currents was discovered than by using either method alone. During this process, it was discovered that several predictable stratification patterns would develop depending upon the discharge ratio and the thermal gradient between the two rivers. These results illustrate the complex hydrodynamic structure at the confluence of the Clearwater and Snake Rivers, which has previously been shown by fish biologists to be a difficult passage zone for migrating salmonids of various life stages.

**Keywords:** Density currents, stratification, three-dimensional CFD modeling, environmental monitoring, Snake River

## INTRODUCTION

Flow augmentation is implemented annually from Dworshak Reservoir (North Fork Clearwater River) to increase water velocities and decrease water temperatures in Lower Granite Reservoir (LGR) when juvenile fall Chinook salmon are rearing and migrating seaward. This period of summer flow augmentation also corresponds with adult fall Chinook salmon and steelhead movements into the Lower Snake River system. Historical profiles of water temperatures just

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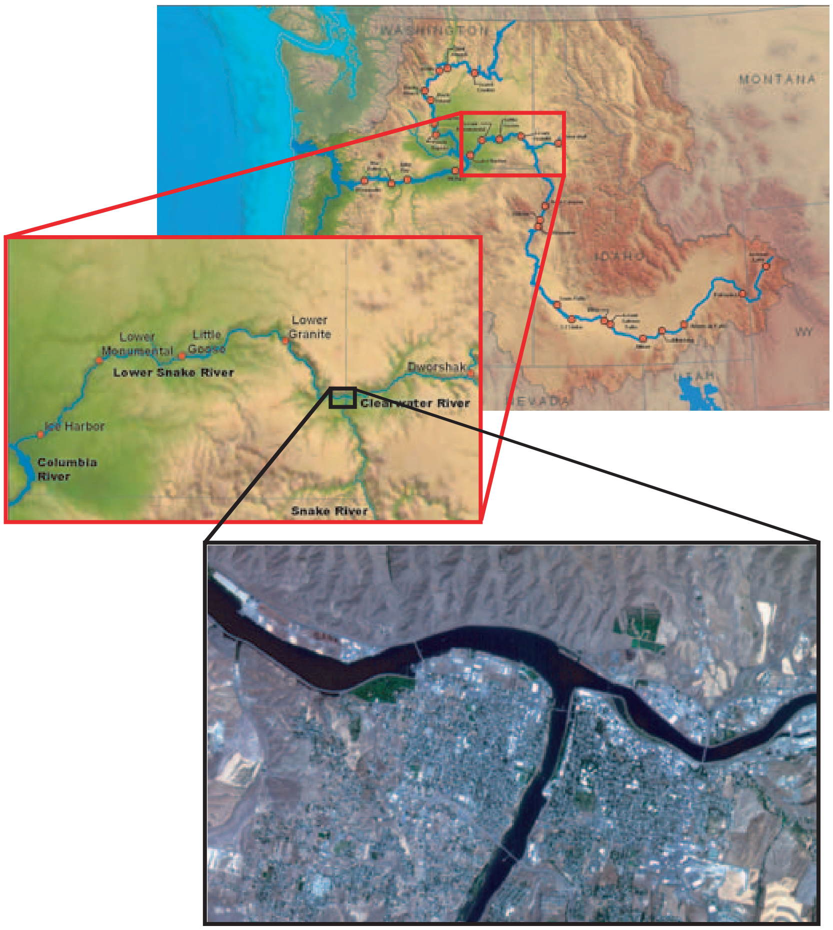



FIG. 1. Confluence of the Clearwater and Snake Rivers. Clearwater river enters from the right hand side of the figure, while the upper Snake River enters from the bottom. After the rivers meet, the general flow of the river is from right to left.

upstream of Lower Granite Dam show that the water column remains stratified through the augmentation period because releases from Dworshak Reservoir are far below equilibrium temperature. Before this study, little was known regarding the three-dimensional (3-D) water velocity and temperature variations downstream of the Snake and Clearwater River confluence and how this thermal stratification is maintained in the reservoirs downstream of the confluence.

Temperature is an important driver of many salmon life history processes. For example, temperature has been observed to affect swimming performance (Brett 1952), physiological development (Ewing et al. 1979), and disease susceptibility (Fryer and Pilcher 1974). Furthermore, sub-lethal heat stress has been shown to increase the vulnerability of fish to predation (Sylvester 1972; Coutant 1973). The precise thermal level at which lethal heat stress can occur was examined by Brett (1952) who found the upper incipient lethal temperature to be 24$^o$C for juvenile Chinook salmon, while Baker et al. (1995) reported the upper incipient lethal temperature to be 23$^o$C for hatchery-raised fall Chinook salmon in the Sacramento-San Joaquin Delta. Regardless of the exact level, temperatures in excess of 24$^o$C are routinely observed in the upper portion of the water column along the entire Lower Snake River system during summer. This suggests that temperature levels may be critical in determining the health and survival of endangered salmonids in the Lower Snake River system.

Results from this research are of use to various river managers (e.g., fisheries and hydropower) that are examining locations of concern throughout the Lower Snake River system. Information generated by this study will also help meet Action Items 141 (monitoring water temperature in the Lower Snake River during juvenile migration season) and 143 (monitoring and modeling Snake River water temperatures under various alternative release strategies) of the 2000 Biological Opinion (FCRPS 2000).

## FIELD MONITORING PROGRAM

At the start of this program, little detailed information was available regarding bathymetry, meteorology, velocity, and temperature variations downstream of the Snake and Clearwater River confluence. To close these data gaps and to collect data sufficient to calibrate and verify a three-dimensional hydrodynamic and water quality model, data were collected between June and December 2002. Bathymetry data were collected at the beginning of the program. More than 70 self-contained temperature loggers were deployed at 11 sites throughout the reservoir (see Figure 2). At each site loggers were suspended in the water column by being tethered to buoys or bridges, and collected data at 15-minute intervals between June and September 2002. Water velocity surveys using a 600 kHz RD Instruments acoustic Doppler current profiler were performed in August and September to gather 3-D water current measurements at locations covering a large portion of the reservoir. Finally, a meteorological station was deployed on Silcott Island (Chief Timothy State Park) that continually recorded atmospheric conditions and posted these data to a website in almost real time.

## VELOCITY AND THERMAL STRUCTURE

Lower Granite Reservoir (LGR) has the potential to stratify vertically, depending on inflows from the Clearwater and Snake Rivers. Releases from deep depths within Dworshak Reservoir can produce temperatures during the spring and summer months that are significantly below the equilibrium temperature of the river. Understanding and managing these cold water resources is one of the drivers for this project.

To better characterize the current structure of the reservoir, the vertical structure was broken into two modes: weak to no stratification and strong stratification.

### Weak to No Stratification Circulation

During the spring of 2002, releases from Dworshak Dam were minimal, resulting in Clearwater River discharges and temperatures that approximately equaled

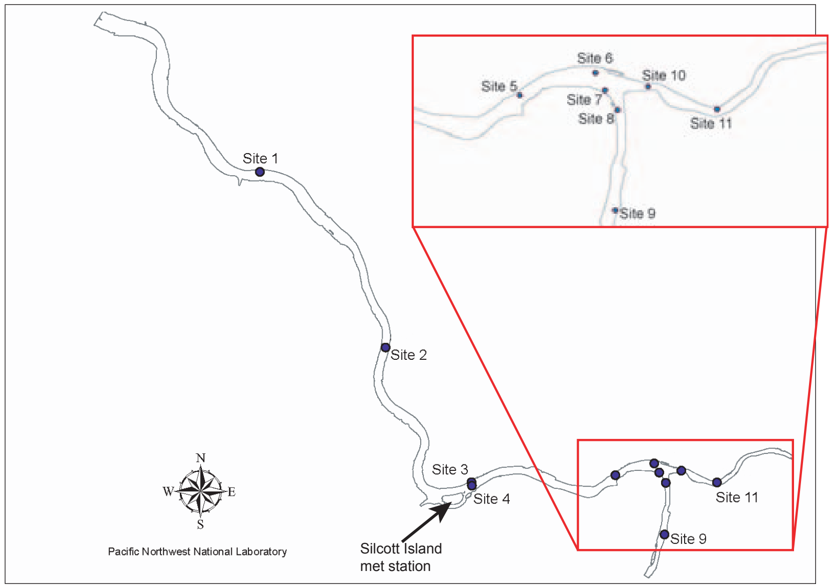



FIG. 2. Location of temperature logger strings.

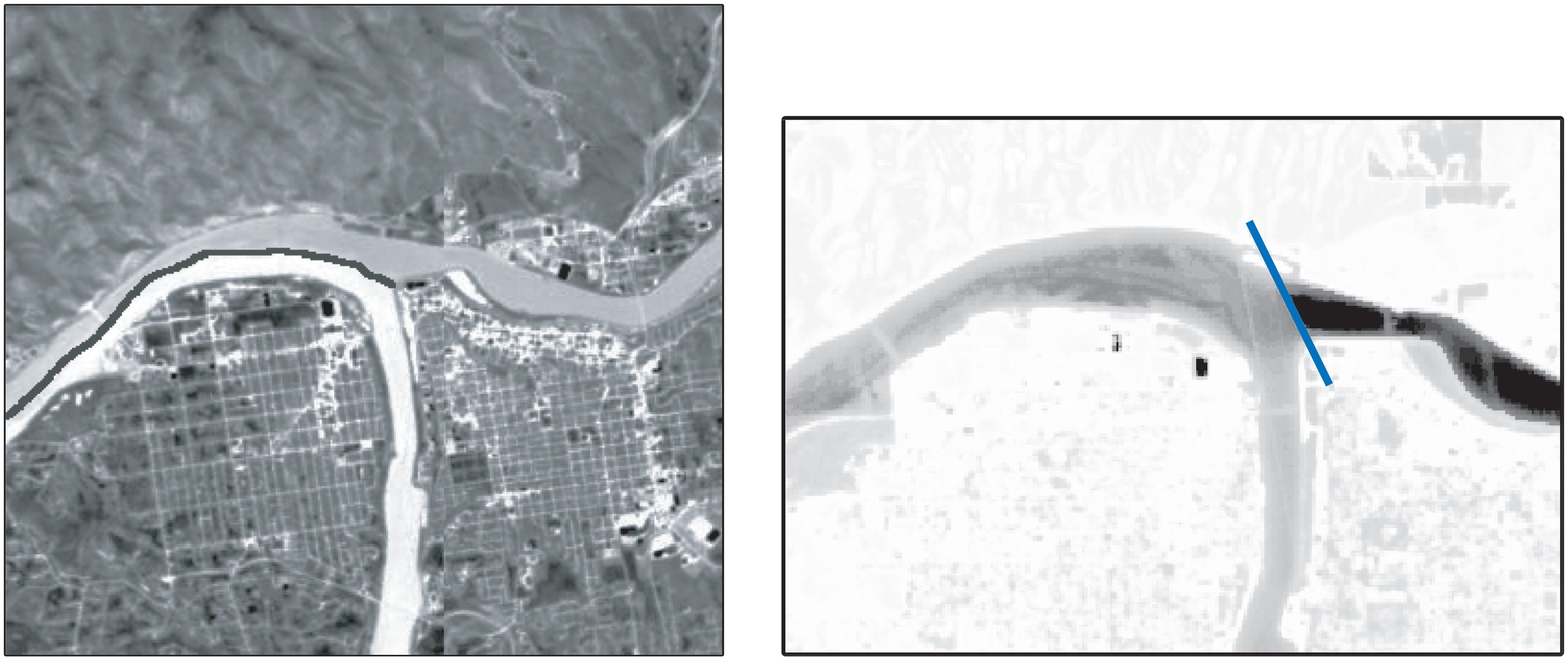
those of the Snake River near their confluence. A Multi-spectral Thermal Imager (MTI) satellite image of the confluence zone was acquired just after midnight on April 2. Composite results from three infrared bands are shown in Figure 3(a). From this image, there appears to be little mixing of the two rivers at the confluence. The two rivers meet and then flow parallel to each other for several miles downstream.

Surface temperature data at sites 8 (U.S.-12 Bridge, Snake River) and 10 (Clearwater River) loggers indicate that the Clearwater River and Snake River temperatures were 5.8 and 7.4$^o$C, respectively. Using the 1-D hydrodynamic model MASS1 (Perkins and Richmond 2001) to route flows from the nearest discharge gages, discharges at the time of satellite image acquisition were 829 $m^3/s$ for the upper Snake and 746 $m^3/s$ for the Clearwater River.

This circulation pattern was observed several times during 2002 and 2003 when the two rivers had approximately the same discharge and temperature. Under these conditions, horizontal momentum forces overcome any buoyancy forces that might cause one river to subduct under the other. Discharge from the two rivers remained separate for several miles downstream, as confirmed using specific conductivity measurements (specific conductance is approximately one order of magnitude different between the two rivers. Clearwater River specific conductance is approximately 0.02 mS/cm, while in the Snake River it is approximately 0.2 mS/cm).

**Strong Stratification Circulation**

During the late spring of 2002, releases from Dworshak Dam increased dramatically and continued through the middle of September. These cold releases produced stratification in the Snake River downstream, including Lower Granite Reservoir. Large vertical differences in temperature were observed from the



(a) 12:12 (PST) on April 4, 2002

(b) 11:03 (PST) on July 21, 2002

FIG. 3. Composite infrared MTI satellite images. April (night image) MTI bands used: J(3.5 - 4.10) $\mu m$, K(4.87-5.07 $\mu m$), and N(10.20-10.70 $\mu m$). July MTI band used: L(8.00 - 8.40 $\mu m$). Black line in the April image and blue line in the July image have been placed by hand to emphasize the separation between the two rivers.

confluence to Lower Granite Dam, more than 30 miles downstream. Stratification remained constant between June and September, with peak epilimnetic and hypolimnetic thermal differences occurring during July (Cook et al. 2003). Although the strength of vertical stratification varied from site to site, differences in excess of $10^{o}$C were commonly observed.

Figure 3(b) displays a MTI image of the confluence taken near noon on July 21. During image acquisition high precision temperature loggers (SeaBird SBE39s) were floated on the water surface within 3 centimeters of the surface. Upstream of the confluence, the Snake River temperature was approximately $23^{o}$C and the Clearwater River was approximately $13.4^{o}$C. A temperature logger placed in the center of the confluence (downstream of the plume line) recorded approximately $23^{o}$C. Discharge in the two rivers just upstream of the confluence was calculated to be 446 $m^3/s$ for the Snake and 479 $m^3/s$ for the Clearwater River.

Large differences in water temperature, and hence in water density, caused the Clearwater River flow to plunge beneath the Snake River flow at the confluence. This pattern was observed several times during 2002 and 2003. Based upon the satellite imagery and field measurements, the surface plunge line for the Clearwater River under these conditions is approximately a sharp line across the river. This plunge line has been drawn in blue on Figure 3(b), and the generally hydraulic conditions for this period are further discussed in the numerical modeling section below.

## NUMERICAL MODEL

Hydrodynamic and water quality modeling of Lower Granite Reservoir was accomplished using Flow-3D, a commercial software package that is supported though Flow Science, Inc. The model has a large user base and has been previously tested under a wide range of applications including Branford (2000), Bombardelli et al. (2001), and Savage and Johnson (2001). In addition to applying Flow-3D, PNNL has previously simulated the reservoir using both the 2-D model MASS2 (Richmond et al. 2000) and the three-dimensional model EFDC (Cook et al. 2003; Rakowski et al. 2003). Flow-3D was applied during this project because it is fully three-dimensional and does not employ the hydrostatic pressure assumption or a stretched vertical transformation.

Flow-3D uses the finite volume method to solve the three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations. The physical domain to be simulated must be decomposed into one or more Cartesian "blocks", which are composed of variable-sized hexahedral cells. For this application, the domain was discretized into four blocks (Snake above the confluence, Clearwater above the confluence, confluence zone, and downstream of the confluence) totaling approximately two million cells. Boundary conditions were specified along the six faces of each block. The upstream Snake and Clearwater Rivers block boundary conditions applied observed temperature logger data in conjunction with computed discharges, obtained from routing the nearest USGS stream gage date to the boundary using MASS1 (Perkins and Richmond 2001). The downstream block boundary condi-

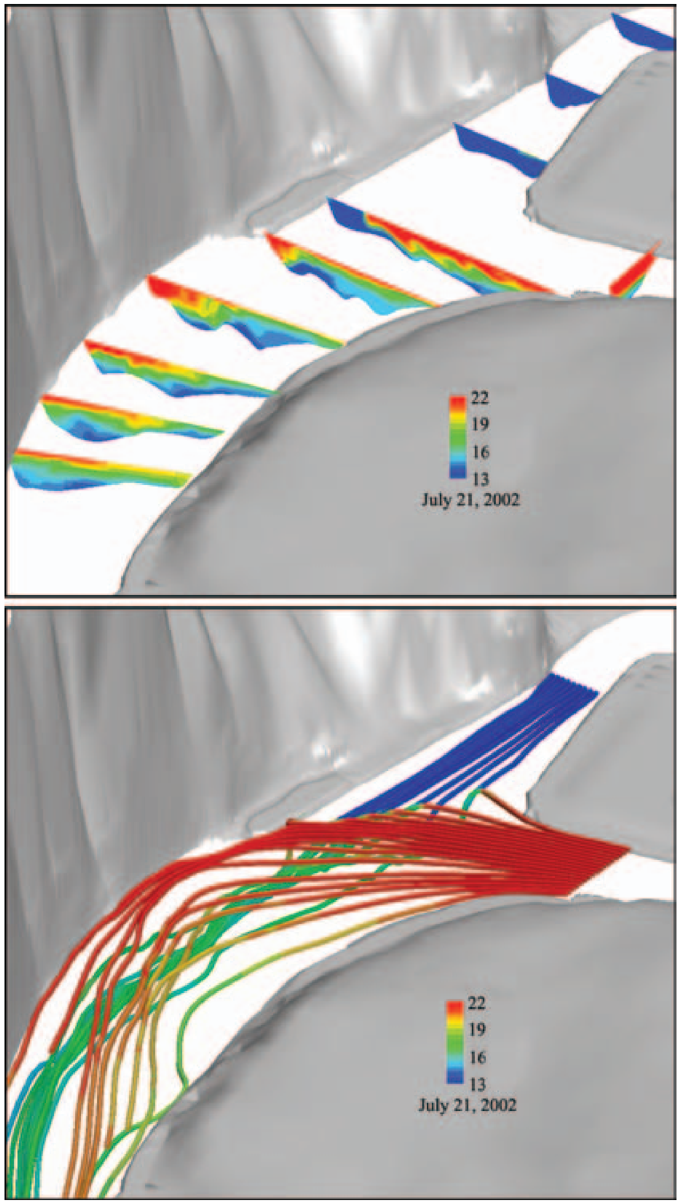



FIG. 4. CFD simulation results for 11 a.m. on July 21, 2002. Legend is water temperature in degrees Celsius.

tion was a pressure boundary with fluid height set equal to the observed tailwater at Lower Granite Dam.

CFD modeling results for July 21, 2002 at 11 a.m. (see Strong Stratification section above for discussion of river conditions at this time) are displayed in Figure 4. The upper graphic in this figure displays 2-D planes that have been placed throughout the simulated domain at various locations. Thermal CFD results match observed temperature logger data at the surface within approximately $1^{o}$C. In addition, CFD simulation results have been confirmed using the satellite image to confirm location of the surface plunge line.

The bottom graphic displays streamlines placed into both the Clearwater and Snake Rivers just upstream of the confluence. As the Clearwater River flow approaches the confluence, it subducts beneath the warmer Snake River flow. Unlike the earlier April period where the two rivers flowed parallel to each other for several miles, the warmer Snake River water extends across the entire surface of the confluence. Mixing is displayed in this bottom graphic with the intermingling and change in temperature of the Clearwater River originating streamlines. Downstream of the confluence, the majority of the Clearwater River discharge has warmed by several degrees with a corresponding decrease in Snake River water.

## SUMMARY

At the confluence of the Snake and Clearwater Rivers, the circulation dynamics are determined by both the discharge ratio and density difference (primarily a function of temperature) of both rivers. These processes were observed in the field during 2002, modeled numerically using a 3-D CFD model, and can now be predicted by examining the momentum balance between the two rivers.

Large differences in water temperature during the summer caused the Clearwater River flow to plunge beneath the Snake River flow at the confluence. Additional study is currently ongoing to understand the complete hydrodynamic characteristics of the summer plunge zone, including the temperature/discharge ratio at which this phenomenon occurs, turbulent mixing parameters, and the extent of cold intrusion up the Snake River arm (see Cook et al. (2003) for details).

The response of anadromous salmonids and other aquatic species to these circulation patterns is currently being studied by PNNL and other institutions. It is suspected that certain hydrodynamic patterns may be more beneficial than others for salmonid migration at the confluence. Once these patterns, and the corresponding biological response, are better understood, the beneficial patterns could then be produced at critical migration periods by adjusting the quantity and temperature of water releases from Dworshak Reservoir (Clearwater River) in response to the discharge and temperature of the upper Snake River.

## ACKNOWLEDGMENTS

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