Lee Nuclear Station Response to Request for Additional Information (RAI)

Attachment 63S-2

Geosyntec Consultants. 2009. Computational Fluid Dynamics Thermal Modeling Lee Nuclear Station: Cherokee County, South Carolina. Project Number GK4258.

Prepared for:

Duke Energy Carolinas, LLC
526 South Church Street
Charlotte, NC 28201

COMPUTATIONAL FLUID DYNAMICS THERMAL MODELING LEE NUCLEAR STATION SITE

CHEROKEE COUNTY, SOUTH CAROLINA

Prepared by:

Geosyntec consultants

&

MMI ENGINEERING LTD
a geosyntec company

Project Number GK4258

July 2009

Geosyntec consultants

MMI ENGINEERING LTD

Technical Report Cover Sheet

Client: Duke Energy Carolinas, LLC **Project:** Lee Nuclear Station Thermal Discharge Modeling **Project No.:** GK4258

Project Manager: Chris Robinson (MMI Engineering)

Principal-in-Charge: Terry Cheek (Geosyntec Consultants)

Report Title: *"Computational Fluid Dynamics Thermal Modeling; Lee Nuclear Station Site; Cherokee County, South Carolina".* **Document No.:** GA090113 **Date:** July 14, 2009

I received comments from the Reviewer. I state that all important issues raised by the Reviewer were resolved.

CHRIS ROBINSON	C Robinson	JULY 14TH 2009
(Printed Name of Project Manager)	(Signature of Project Manager)	(Date)

I received relevant portions of the proposal/contract to understand the required scope of services ☑ Yes ☐ No

I peer reviewed the report/letter ☑ Yes ☐ No

I gave a copy of the report with my comments to the Project Manager ☑ Yes ☐ No

I gave comments orally to the Project Manager ☑ Yes ☐ No

I confirmed that my comments were adequately resolved ☑ Yes ☐ No

My conclusions are:	Not Applicable	Peer Reviewer's Initials
1. The scope of the report is consistent with the required scope of services.	☐	JEC
2. The report's organization and clarity are satisfactory.	☐	JEC
3. The report presentation is satisfactory.	☐	JEC
4. The assumptions and approaches are technically appropriate.	☐	JEC
5. The technical components of the report (e.g., calculations, drawings, tables, figures, test results, test interpretation, specifications) have been checked.	☐	JEC
6. The conclusions, judgments, and recommendations are adequate.	☐	JEC
7. Assumptions, approximations, uncertainties, and limitations are clearly stated.	☐	JEC
8. The report is consistent with the Project Policies section of the company Risk Management Program.	☐	JEC

Terry E. Cheek	Terry E. Cheek	July 24, 2009
(Printed Name and Title of Reviewer)	(Signature of Reviewer)	(Date)

SIMON THURLBECK		JULY 14TH 2009
(Printed Name – Technical Manager)	(Signature of Technical Manager)	(Date)

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1. INTRODUCTION

Duke Energy Carolinas, LLC (Duke Energy) is proposing to construct and operate a new nuclear power plant (Lee Nuclear Station) near Gaffney, Cherokee County, South Carolina. The facility will have a total electric generating capacity of approximately 2,200 MWe. A Combined Construction and Operating License (COL) application was prepared for the facility in accordance with U.S. Nuclear Regulatory Commission (NRC) regulations, and submitted to NRC at the end of 2007. Plans are for Lee Nuclear Station to be operational by 2018.

Lee Nuclear Station (LNS) will use as its primary cooling water source and effluent discharge receiving waterbody, an existing impoundment/reservoir on the Broad River created by the Ninety-Nine Islands (NNI) Hydroelectric Project. The NNI Reservoir covers about 430 acres and has a total storage capacity of about 2,300 acre-feet. The reservoir is a "flow-through" reservoir with an average hydraulic retention time of about 3 hours under annual average flow conditions [1].

As a twin reactor/unit facility, LNS will require approximately 78 cubic feet per second (cfs) or 50 million gallons per day (MGD) of cooling water withdrawal from the Broad River for its closed-cycle cooling system. Approximately 71 percent (55 cfs) of the withdrawal will be consumptive due to evaporative and drift losses from the cooling towers, with 5 cfs returned to the river as screen wash water and 18 cfs returned to the river as cooling tower blowdown. In addition to blowdown, other waste streams of much lesser volume include facility process (125 gallons per minute (gpm)) and treated radionuclide wastewaters (4 gpm).

Duke Energy's conceptual design calls for the discharge of all facility-related wastewater effluents through a submerged multi-port diffuser to be located in the forebay (reservoir side) of the NNI Reservoir (attached to the face of the dam), just upstream from the dam and near the hydroelectric turbine intakes. The temperature for the LNS cooling tower system blowdown has the potential to exceed South Carolina's aquatic life-based water quality criteria for several hours during the hottest days of summer at the point of discharge to NNI Reservoir. The criteria provide that heated liquid discharges to surface waters not cause a rise in temperature greater than 5 °F (2.8 °C) above natural temperature conditions, and not exceed a maximum of 90 °F (32.2 °C) [2]. On extremely hot days, the temperature of the blowdown may reach 91 °F.

Where thermal discharge temperatures may exceed ambient water temperature criteria, facilities can seek a variance to the criteria as provided by Section (§) 316(a) of Clean Water Act (CWA), upon demonstration that the effluent limitation (based on the water quality criteria) is more stringent than necessary to assure the protection and propagation of a balanced, indigenous community of shellfish, fish, and wildlife in and on the body of water into which the discharge is made. Such demonstrations are often used to support decision making on effluent discharge mixing zones.

In discussions with regulatory agencies pertaining to the appropriate permitting approach for LNS, concerns were raised about the mixing behavior of the thermal discharge from the plant in the forebay and the potential effect of this discharge on the aquatic community; particularly on the smallmouth bass (*Micropterus dolomieui*) fishery present downstream of NNI Dam. The questions of interest were:

1. What are the mixing characteristics of the buoyant thermal plume exiting the multi-port diffuser into the forebay of the NNI Reservoir; as it is entrained through the turbine penstocks, and subsequently released into the dam tailrace?
2. Will the influence of the thermal plume exiting the multi-port diffuser in the reservoir forebay, entrained through the turbine penstocks, and released in the tailrace have a detrimental impact on the fish community in the forebay or on smallmouth bass habitat (i.e., thermal regime) in the Broad River downstream of NNI Dam?

To address these questions, Duke Energy contracted with Geosyntec Consultants and its wholly-owned subsidiary, MMI Engineering, to select and implement an appropriate modeling approach to definitively evaluate the complex mixing of the LNS thermal discharge in the NNI Dam forebay and predict discharge effects on water temperature in the forebay and at the dam turbine inlets; and thus, in Broad River below the dam. The modeling effort sought to determine the extent of the thermal plumes and temperature increases experienced under a number of river flows and corresponding NNI Dam operational scenarios described later in the text.

2. ENVIRONMENTAL AND OPERATIONAL SETTING

This section provides essential background information considered in the development of the modeling approach and used in interpreting model results. This information was obtained largely from Duke Energy's Environmental Report (Rev. 1) submitted to NRC as part of the LNS COL application; more detailed information can be obtained from that source [1] as well as other sources specifically cited in this section.

2.1 Broad River Description

The Broad River is the primary source of process and cooling water for LNS. Makeup water is withdrawn from the Broad River above NNI Dam, while cooling tower blowdown (and process water) discharge is diffused into the river at the upstream face of the NNI Dam near the intakes for the hydroelectric generating units.

The Broad River drainage basin above NNI Dam is located within the Upper Broad River basin watershed (U.S. Geological Survey [USGS] Hydrological Unit 03050105) and includes the Green River, First Broad River, Second Broad River, and Buffalo Creek as major tributaries. The Upper Broad River basin has an area of approximately 2,500 square miles and is situated in the western Piedmont of North Carolina and South Carolina. The drainage area of the Upper Broad River basin above the LNS site is approximately 1,550 square miles [1].

Alternating pools and riffles cut in bedrock are the dominant bedforms of the Broad River above and below LNS. Substrates are mostly composed of coarse sand, making scoured rock outcrops and sand beds the two common substrate types [1].

2.1.1 River Flows

Broad River discharge recorded at the USGS Station No. 02153551 located just below NNI Dam ranged from 138 cfs on September 14, 2002, to over 60,000 cfs in September 2004. The highest recorded flow at USGS Station No. 02153500 at Gaffney, South Carolina, was 119,100 cfs. Integrating data from two upstream gauges (Station No. 02153200 near Blacksburg and Station No. 02151500 near Boiling Springs) with the gauge at Gaffney results in an 81-year period of record for the Broad River at Gaffney.

Low-flow conditions on the Broad River are a function of natural flow in the rivers and streams, available storage capacity of upstream reservoirs, and regulated discharge flow from upstream dams. Low-flow conditions are generally defined as the lowest consecutive 7-day stream flow with a recurrence interval of 10 years (7Q10). Estimated long-term flows for the Broad River are based primarily on extrapolated USGS streamflow gauge datasets relative to the Gaffney Station (No. 02153500) due to its proximity to the LNS site and long record of data collection. Based on these data, the average annual flow of the Broad River is estimated to be 2,538 cfs and the 7Q10 low flow, 479 cfs.

Ninety-Nine Islands Dam impounds a 433-acre mainstem "run-of-the-river" reservoir with a normal water level at 511 feet (ft.) above mean sea level and a shoreline of approximately 14 miles. Based on an average annual flow of the Broad River of 2,538 cfs and effective storage capacity of just 650 acre-feet (ac-ft.) (see Section 2.4), the average transit time for water flow through the reservoir is approximately 3 hours. During low flow 7Q10 conditions, transit time slows to approximately 14 hours [1].

The NNI Hydroelectric Station operates under a Federal Energy Regulatory Commission (FERC) license. In addition to drawdown limitations, the FERC license for NNI Hydroelectric Station also specifies certain seasonally adjusted minimum flows to be maintained below the dam:

- 966 cfs January through April;
- 725 cfs May, June, and December; and,
- 483 cfs July through November.

These minimum flow requirements effectively fix the minimum flow below the dam to 483 cfs.

2.2 Aquatic Community

Ninety-Nine Islands Reservoir is the source of LNS cooling water as well as the receiving waterbody for the facility thermal and process water effluents. It is the principal aquatic environment potentially affected by the construction and operation of LNS. As part of the NRC licensing process, Duke Energy implemented field studies in 2006 designed to characterize the fishery and macroinvertebrate resources of Broad River in NNI Reservoir and in the river downstream of NNI Dam. Fish were sampled by electrofishing and gillnetting in NNI Reservoir in February, April, July, and October 2006. Macroinvertebrates were sampled in the river in April, August, and October 2006.

The results of these studies are summarized in the following sections.

2.2.1 Fish Community

A total of 41 species of fish representing seven families were collected during seasonal surveys conducted by Duke Energy biologists [3]. Bluegill (*Lepomis macrochirus*) and largemouth bass (*Micropterus salmoides*) dominated catches in the NNI Reservoir while spottail shiners (*Notropis hudsonius*), northern hog sucker (*Hypentelium nigricans*), and smallmouth bass (Micropterus dolomieu) dominated catches in the river downstream of the reservoir. Gillnet catches in two NNI Reservoir back water areas were dominated numerically by gizzard shad (*Dorosoma cepedianum*) followed by quillback (*Carpiodes cyprinus*) and black crappie (*Pomoxis nigromaculatus*), respectively.

Spring electrofishing of the Broad River upstream of NNI Reservoir in the area of the Cherokee Falls Dam targeted spawning sucker populations. Five catostomid species were collected, but only the quillback, brassy jumprock (*Scartomyzon* sp), and notchlip redhorse (*Moxostoma collapsum*) were collected in any abundance.

Results of the 2006 surveys were found to be similar to those noted in the same area from a previous study conducted in 1974 -1976 when 36 species of fish representing 8 families were collected [4]. The only family not found in 2006 that was collected in 1974-1976 was Poeciliidae, represented by the eastern mosquitofish (*Gambusia holbrooki*). Additionally, the fish community in the Broad River in 2006 in proximity of the LNS site was reported to be similar to other reaches of the Broad River upstream in a North Carolina portion of the river (49 species representing 9 families) and in a large expanse of the Broad River in South Carolina downstream of the Lee Nuclear Station site (43 species representing 9 families).

Fish populations downstream of the NNI Dam were found to be considerably more diverse and abundant than those in the reservoir; an observation reported by the investigators as likely attributable to habitat variables such as rock-rubble substrate as compared to sand-silt in the reservoir. Below NNI Dam, fish populations were comprised primarily of cyprinids, catostomids, and ictalurids, depending on the season, but were never dominated by centrarchids as was the case for all reservoir habitats sampled. Additionally, the number of fish species present below the dam was much more diverse than for all reservoir sampling locations with generally twice the number of species as found in the reservoir.

No endangered, threatened, or species of concern fish were collected during any of the sampling. Additionally, no state or federally listed species are known to occur from this area of the Broad River.

2.2.2 Macroinvertebrate Community

Macroinvertebrates were sampled in the river in April, August, and October 2006. The total number of macroinvertebrates collected varied among seasons and locations. The highest number for all locations combined occurred in April. The lowest number occurred in August and increased in October. The total numbers of taxa were consistently higher at locations upstream and downstream of NNI Dam than within NNI Reservoir itself. Total taxa ranged from 18 near the intake location (August) to 86 at the most upstream location below Cherokee Falls Dam (April).

With over 100 genera collected, the samples indicate a relatively diverse and abundant macroinvertebrate fauna typical of Piedmont rivers.

2.3 Lee Nuclear Station Operational Discharges

The LNS cooling water intake structure will withdraw 78 cfs or 3 percent of the mean annual flow of the Broad River. The cooling towers will consume 55 cfs or 2 percent of the mean annual flow as loss to evaporation and drift. When Broad River daily average flows drop below 538 cfs, (483 cfs NNI minimum flow + 55 cfs LNS consumptive use) the source of LNS cooling water withdrawals will shift proportionally to off-channel auxiliary storage reservoirs in order to maintain minimum flow requirements at NNI Dam (see Section 2.4 below). At times when LNS is aligned fully to the use of off-channel storage reservoirs (river flows < 483 cfs), the LNS discharge will augment Broad River flows at the NNI Dam and tailwater by approximately 18 cfs.

The plant will normally (greater than 95 percent of the time) return to Broad River 18 cfs as discharge consisting of cooling tower blowdown and treated process waters. Less than 5 percent of the time, blowdown discharge could be as low as 9 cfs or as high as 64 cfs [5]. The variation in atypical discharge flows are associated respectively with scheduled unit refueling outages and adjusted (lower) cooling tower cycling rates to manage high total solids originating from the cooling water source waterbody (e.g., during flood flows).

Discharge to Broad River will be via a submerged multi-port diffuser attached to the upstream face of the NNI Dam spillway in the western portion of NNI Reservoir forebay. The diffuser consists of a 65-ft.-long pipe, 36 inches in diameter and having 16 – 1 inch holes (ports) per square foot; a total of 1,040 ports. Extending horizontally along the dam, the diffuser will be positioned approximately 750 ft. from the west shore near the NNI Dam trash sluice structure, and submerged midway in the water column (centerline elevation 506.1 ft. msl). At normal water elevation of 511 ft. msl, the pipe will be submerged approximately 6 ft.; total depth at this location is approximately 12 ft.

The LNS cooling water system is designed to achieve a maximum discharge temperature of 91 °F under critical summertime conditions of high ambient river and air temperatures, and seasonally low flows. Typically, maximum discharge temperatures would be expected to occur during extreme summertime conditions when water temperature and ambient air temperatures are at their seasonal highs.

2.4 Ninety-Nine Islands Dam Operations

Duke Energy's NNI Dam is located on the Broad River approximately 4.5 river miles downstream from the Cherokee Falls Dam and is operated under a FERC license (FERC Project No. 2331) [6]. The NNI Dam and associated hydroelectric plant were constructed in 1910, and the dam structure is a concrete gravity dam. The facility operates as a modified peaking plant where the reservoir, augmented by inflow, supports daily operation but has no appreciable storage volume (available storage in the upper 2 ft. of the reservoir is 650 ac-ft).

Initially designed with six hydroelectric power turbine units; currently only four units are operable – Units 1-4. Units 5 and 6 have been inoperable for over five years and there are no plans to make then operable. Units are numbered sequentially from the east side of the powerhouse beginning with Unit 1. Thus, the two idled units are located most closely to the proposed LNS discharge diffuser. Range in approximate distance from the centerline of the diffuser to the turbine units is 75 ft. (Unit 6) to 200 ft. (Unit 1). Currently, the closest operable unit (Unit 4) is approximately 150 ft. from the diffuser location. At normal water elevation of 511 ft. msl, invert elevation of the turbine inlets (centerline) is approximately 494.1 ft. msl, or about 12 ft. deeper than the invert elevation of the proposed LNS discharge diffuser (506.1 ft. msl).

During normal river flows, the units are operated as the available flow dictates within the FERC license-specified drawdown limits[1] for the reservoir – 1 ft. below full reservoir (511 ft. above msl) from March through May and 2 ft. below full reservoir from June through February. Total hydraulic capacity of the 20 megawatt (MW) NNI Dam powerhouse (six units authorized) is 5,220 cfs. Hydraulic capacity of the four currently operable units (Nos. 1-4; rated at ~14,450 MW) total) is 3,510 cfs; thus, as currently configured/operated, flows in excess of this amount pass over the dam spillway.

In addition to drawdown limitations, the FERC license for NNI Dam also specifies certain seasonally adjusted minimum flows to be maintained below the dam:

- 966 cfs January through April;
- 725 cfs May, June, and December; and,
- 483 cfs July through November.

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[1] Drawdown limits may be temporarily modified in the event of operating emergencies beyond Duke Energy's control.

When river flow drops below these minimum flows, the inflow of the river to the reservoir must be discharged through the NNI Dam powerhouse. The ability to manage reservoir drawdown within a range of 2 ft. during months of low inflow allows for a short-term potential of zero flow discharge from the powerhouse to occur, immediately followed by the required minimum flow (i.e., a pulsed flow operational format). Because Duke Energy operates the hydroelectric station, Duke Energy has the ability to regulate flow and to mitigate low-flow concerns, within the confines of the FERC license.

The July through November minimum flow of 483 cfs approximates 7Q10 flow (479 cfs). Based on analysis of Broad River period of record flows (81 years) performed by Duke Energy contractor Devine, Tarbell & Associates (DTA), flows were greater than 483 cfs 98.2 percent of the time. Of the 30,316 days that flows were measured by USGS for Broad River since 1926, flows less than 483 cfs were recorded for just 532 days (1.8 percent). Consequently, pulsed flow operations of NNI hydroelectric power generation are rare events.

3.0 STUDY APPROACH

This section presents the rationale for selection of Computational Fluid Dynamics (CFD) modeling technology as an appropriate tool for the current evaluation of the LNS thermal discharge to Broad River. In addition, specific study objectives and the CFD model methodology are presented.

3.1 Model Selection

The LNS thermal discharge to Broad river was initially evaluated through limited work performed by Clemson University [7] researchers who employed simplifying assumptions and analytical calculation methods, in lieu of a three-dimensional model, to identify any “fatal flaws” in the discharge diffuser concept being developed at that time with regard to thermal gain in the NNI forebay and downstream of the dam. The results, not meant to be highly definitive, provided gross insight into the potential thermal effects of the LNS cooling water discharge in Broad River above and below NNI Dam. The Clemson researchers concluded that, based on conservative assumptions, thermal gain above the dam may range from 1.2 to 3.7 °F; with a thermal gain of up to 1.7 °F predicted for waters below the dam.

Additional modeling was conducted by Duke Energy contractor Enercon who used a more sophisticated modeling approach employing Cornell Mixing Zone Expert (CORMIX) modeling software (Version 4.3) to simulate the thermal plumes above and below NNI Dam [1]. CORMIX is widely used and recognized for discharge mixing-zone analyses. This effort was coupled with a mass balance analysis to determine expected temperature of water discharged by LNS after mixing with Broad River water in the hydroelectric station turbines.

Results of the CORMIX simulations predicted a small thermal plume that dissipates quickly. Results of the heat balance calculation indicated that the maximum temperature change downstream of NNI Dam is expected to be less than 1.4 °F.

The results of the CORMIX modeling, though more definitive by design than the Clemson work, still did not consider the important effects on LNS thermal discharge mixing characteristics brought about due to variation in reservoir bathymetry, flow velocity, and flow vector (direction) in the NNI Dam forebay at the diffuser location.

Likewise, the hydraulic influences of the NNI Dam hydroelectric generating units on thermal plume characteristics were not considered.

In order to more definitively characterize the LNS thermal discharge into the hydrodynamically and spatially complex mixing environment present in the NNI Reservoir forebay, a more robust modeling approach was needed. As such, three-dimensional CFD modeling technology was selected for the current project.

Computational Fluid Dynamics modeling is based on the Navier-Stokes equations for fluid motion which are simply an expression of Newton's laws of motion with additionally viscous stress terms required to calculate fluid flow [8]. The equations express the laws of conservation of mass, momentum and energy and are hence a "fundamental" set of equations (i.e., no assumptions are made in forming the basic equation set). However, due to the mathematical "stiffness" of the equation set it is not possible to solve them analytically for anything other than simple geometries (flow in a pipe, flow over a plate, etc). For a geometrically complex model, such as the NNI reservoir, it is necessary to discretize the equations. In this process the geometry is subdivided into a large number of computational cells – typically 100,000 to 1,000,000 cells and the Navier-Stokes equations are re-formed to calculate the values of pressure, velocity, temperature and turbulence in each cell. As these values in each computational cell are influenced by their neighboring cells an iterative solution technique must be used. The result is a three-dimensional flow-map of the entire geometry which can be interrogated to provide values of flow rate, temperature, chemical concentration, and other attributes throughout the domain, as appropriate to specific study objectives. The full form of the Navier-Stokes equations includes the influence of temporal variation; hence, CFD results can be generated for time-dependent and steady-state flows.

For the current study, water temperature predicted at the turbine inlets was the primary attribute of interest. In the CFD model, a temperature transport model derived from the law of conservation of energy is included. Temperature is transported in the domain by convection with the water flow, and molecular and turbulent diffusion. It has an influence on the flow profile as the heated water plumes rise – this is included in the calculations via the Boussinesq buoyancy model. As the temperature and flow fields are interdependent it is essential that the flow, turbulence and temperature equations are calculated simultaneously. Heat can also be lost or gained through the model boundaries – for example, heat lost or gained through the free surface will modify the temperature in the reservoir and this can be included in the calculation by selection of appropriate boundary conditions. However, when the Duke Energy temperature data measured at the LNS cooling water intake and forebay were compared, it was apparent that the ambient heating and cooling effects were non-uniform (see section 3.3.2). It is likely that heating and cooling in the forebay is influenced by river temperature, air temperature, cloud cover, sun elevation, shading by vegetation and other effects. Without full knowledge of these variables, heat loss/gain through the free surface could not be calculated accurately; instead, adiabatic conditions were specified at the free surface.

Computational Fluid Dynamics modeling has been used successfully for over 40 years in a variety of industrial and environmental applications. Similar to its use in the current study, the Tennessee Valley Authority (TVA) used CFD modeling to evaluate the multiport diffused thermal discharge from its Browns Ferry Nuclear Power Plant to Wheeler Reservoir in north Alabama [9]. The CFD model allowed TVA to determine thermal plume mixing and temperature rise patterns as well as other hydrodynamic features of the discharge. Notably, TVA found close agreement between CFD model-predicted water temperatures and direct temperature measurements at the operating diffusers.

Other examples of CFD environmental applications include: the U.S. Department of Energy's Pacific Northwest National Laboratory who used CFD to evaluate hydrodynamics of the North Fork Dam forebay on the Clackamas River in Oregon, and to model the three-dimensional velocity field below Bonneville Dam to enhance fish passage [10]; and, investigation of increased discharge associated with the re-powering of an existing power plant [11].

In our specific case, the CFD model accommodated incorporation of bathymetry data and water column acoustic Doppler velocity and vector data directly measured by Duke Energy for the NNI Reservoir forebay. This and other CFD model spatial and temporal features supported a more definitive evaluation of the influences of the LNS thermal discharge on ambient forebay temperatures and prediction of water temperatures at the NNI Dam turbine inlets, and thus, temperature discharged to the Broad River below the dam.

3.2 Study Objectives

Specific LNS thermal discharge study objectives are to:

1. Simulate the flow distribution in the forebay/lower reservoir of the NNI Dam under representative steady state flow conditions (as defined below).
2. Illustrate the degree of horizontal and vertical mixing in the forebay through the use of graphical output from the CFD model. These outputs will identify any undesirable pockets of retained warm water that are bypassed by the flow en-route to the dam turbines.
3. Determine the temperature of water passing through the NNI Dam turbines and into the lower watercourse of the Broad River.
4. Determine the optimal and maximum temperature requirements and associated behavioral response of smallmouth bass in South Carolina and other southeastern streams employing available literature and other reliable sources.

To meet these study objectives, CFD models were developed to calculate the LNS thermal discharge characteristics for two primary flow scenarios: (i) mean annual flow of 2,538 cfs to represent average conditions; and (ii) low flow of 483 cfs to represent a practicable worst case scenario. As presented earlier, flows of less than 483 cfs occur rarely; less than 2 percent of the time based on an 81-year record of Broad River flows. Nonetheless, an extreme low flow scenario was also modeled considering river flow of 157 cfs to evaluate plume characteristics at a time when the NNI Dam hydroelectric facility would operate in a pulsed rather than continuous mode.

To validate the CFD models, a further case was studied and the results compared with flow measurements by DTA [12]. A discussion of the validation study is included in this report.

3.3 Methodology

Geosyntec/MMI Engineering uses a variety of classical and computational analysis techniques to assess the performance of fluid systems and processes. For detailed CFD analysis, calculations are made with the general purpose, commercial CFD code ANSYS-CFX Version 11 [13]; the CFD model code selected for the current analysis.

3.3.1 Geometry Definition

The extent of the NNI Reservoir/Broad River environment in the CFD models included:

- The NNI Dam, forebay, turbine intakes, and LNS cooling water discharge;
- the backwater areas in the locality of the forebay; and,
- a reach of Broad River extending approximately 0.5 mile upstream of the forebay; this is one-third of the distance from the forebay to the LNS cooling water intakes.

Total surface area of the modeled domain was approximately 61 acres. A plan view of the model geometry included is shown in Figure 1.

Bathymetry data for the reservoir forebay area and river was provided by DTA [12] in the form of point-depth measurements in a series of transects. These point data were interpolated to form the river/reservoir bed in the CFD models. The data received did not include the dam or turbine intakes which were incorporated into the model by reference to the civil engineering drawings of the NNI hydropower station [14, 15]. The bathymetric profile is discussed in more detail in Appendix A.

The LNS cooling water discharge was defined in the CFD models based on reference to the Duke Energy drawings of the discharge [16, 17]. The location of the discharge relative to the turbine intakes is shown in Figure 2. Only the discharge diffuser detail was included in the model; the remainder of the discharge pipe work has no significant effect on plume behavior. See Appendix A for further details of the computational mesh.

3.3.2 River Flow & Temperature Boundary Conditions

Flow Boundaries

Mean annual flow of 2,538 cfs was obtained from LNS COL application Environmental Report as determined by DTA for the Broad River period of record flows. This flow value represented the model boundary condition under the mean annual flow, continuous NNI Dam operational scenario.

Devine, Tarbell & Associates has determined that 7Q10 low flow is 479 cfs; however, the NNI Dam FERC license minimum flow requirement for July through November is 483 cfs. As such, the FERC license minimum flow effectively establishes the minimum downstream flow and was used as a constant in evaluating LNS thermal discharges during low flow conditions. Thus, a flow of 483 cfs represented the model boundary condition under the low flow, continuous NNI Dam operational scenario.

At some combination of low flow and NNI operation (i.e., pulsed) it was anticipated that heat might accumulate in the forebay as a result of the LNS thermal discharge. Because running the model is computationally intensive (~one week to perform the CFD calculations for one scenario) it was necessary to select an extreme low flow condition with a high likelihood of demonstrating heat accumulation (if present) to avoid multiple model runs in establishing this condition. From this exercise it would be possible to extrapolate a combination of Broad River flow and NNI Dam pulsed operation under which accumulation of heat in the reservoir forebay would not be expected to occur. To accomplish this objective, a Broad River flow value of 157 cfs was established as the extreme low flow rate to be considered in the CFD model, even though there were very few occasions when such a low flow was recorded. In fact, based on the Broad River period of record, flows less than 200 cfs occurred just 0.18 percent of the time (55 days out of the total record 30,316 days). Thus, a flow of 157 cfs represented the model boundary condition under the extreme low flow, pulsed NNI operational scenario.

Temperature Boundaries

The CFD models require a temperature specified at the "inlet" to the model. The upstream limit of the model is approximately 0.5 mile upstream of the NNI Reservoir forebay; the LNS intake structure is approximately 1 mile further upstream from there. Please note: the "inlet" temperature when defined in the model is the Broad River background temperature entering the model domain and not the temperature at the LNS intake structure.

For each flow scenario studied, river temperature boundary conditions were taken from ambient temperature monitoring data provided by Duke Energy [18]. Hourly data for 2007 and 2008 were obtained from water temperature recording devices at locations in the forebay and near the proposed cooling water intake. Ideally, it would be preferable to have a complete record of water temperature measurements for the discharge diffuser location in the forebay, matched with the flow scenarios under review, to provide a consistent method/approach for establishing river background temperatures associated with each modeled scenario. However, at the time the CFD modeling project was initiated in August 2008 temperature data for the forebay were only available for the period March through July 2008. Data were available for the LNS cooling water intake location since 2007. As the modeling progressed and additional data were available, they were included in the analysis. This resulted in the development of background temperatures, using methods appropriate to the dataset at hand and to the scenario being modeled.

The available temperature measurements demonstrated that there are natural heating and cooling effects in Broad River between the LNS cooling water intake upstream of NNI Dam and the discharge point at the NNI Reservoir forebay. For the flow scenarios defined (i.e., mean annual flow and extreme low flow), the mean natural heating and cooling effect between the LNS cooling water intake and discharge was typically -0.4 to 1.6 °F. The origins of these heating and cooling effects were not known although possible influences include: direct solar heating on cloudless days, solar heating on overcast days, shading from vegetation, heat exchange with river bed or air and hot/cool bodies of water heated in an upstream reservoir passing to NNI Reservoir with time lag.

In establishing an appropriate Broad River background temperature for the mean annual flow scenario it was necessary to consider the temperature datasets for both the LNS intake location and the forebay; specifically for January and March when historical flow data indicated the mean annual flow of 2,538 cfs was likely to occur. As the forebay temperature data were only available over 7 months, it was deemed inappropriate to base the CFD model inlet temperature (i.e., river background temperature) on the forebay temperature alone. Instead the more complete temperature data for the LNS intake area were extrapolated to the forebay area. This was accomplished by first determining the mean natural environment heating/cooling effect between the LNS intake and NNI forebay by analysis of the March 2008 data set available for both the intake location and forebay. The data set for LNS intake temperatures for January and March 2007; and March 2008 was then used with the calculated natural heating/cooling effect (in this case -0.4 °F) to determine the estimated model inlet temperature at mean annual flow for the CFD model (and hence, the river background temperature in the model). This approach incorporated both the available data for natural environment heating and the longest period of temperature measurements available. Based on this approach an average daily maximum temperature of 52.7 °F was established as the inlet/background temperature for modeling the mean annual flow scenario.

A similar approach was used to establish background temperature for the extreme low flow scenario for which all days in the summer months (June, July, August) with extreme low flows less than 200 cfs were considered. Using the same temperature data sets as for the mean annual flow scenario, the mean natural environment heating/cooling effect between LNS intake and NNI forebay was determined by analysis of the available data set for matching days (intake location and forebay). The natural heating effect (in this case, +1.6 °F) was then applied to the LNS intake temperature data for the summer months of June-August to estimate forebay temperatures. Based on this approach an average daily maximum temperature of 84.0 °F was established as the inlet/background temperature for modeling the extreme low flow scenario.

Additional temperature data were available for the forebay with which to establish inlet/background temperature for the low flow scenario. This data set extended from March 2008 through December 2008. Based on review of flow records for the past ten years [19], low flow (~483 cfs) conditions, when present, occurred most often during July and August. To fully encompass summertime conditions, forebay temperature data for June–August 2008 were analyzed. In this case no adjustments were made for any natural heating or cooling effect between the LNS cooling water intake and forebay, as this is already implicitly included in the forebay temperature measurements. Daily average maximum forebay temperatures were determined for each 24-hour period (max=87.9 °F) and segregated by day (max=87.6 °F) and night (max=88.2 °F) for the June-August period. To establish worst case critical conditions for evaluating the LNS thermal discharge during the low flow scenario, 88.2 °F was selected as the inlet/background temperature for the model boundary.

The Broad River low flow scenario is considered to be the most practicable worst case scenario for the LNS thermal discharge; having perhaps the greatest potential for adverse impact to the aquatic community; as compared to extreme low flow (<200 cfs), low flow conditions (~483 cfs) will occur at a statistically greater frequency. As such, selection of the highest daily maximum forebay temperature for the model represents a conservative approach to the analysis.

3.3.3 LNS Discharge Flow & Temperature Boundary Conditions

As presented previously, greater than 95 percent of the time the LNS blowdown discharge to Broad River will be at a rate of about 18 cfs. As such, and more precisely, the model input for the LNS cooling water discharge was set at a constant rate of 18.3 cfs [1]. When discharge rates are lower, the effects of the thermal discharge will obviously be less than reported herein. Maximum discharge rates are associated with adjusted (lower) cooling tower cycling rates to manage high total solids originating from the cooling water source waterbody (e.g., during flood flows) and would be expected to occur at a time when the ratio of discharge flow, relative to ambient river flows, are at seasonal lows; thereby minimizing any potential effects.

The LNS cooling water system is designed to achieve a maximum discharge temperature of 91 °F under critical summertime conditions of high ambient river and air temperatures, and seasonally low flows. As such, the model input for the LNS discharge temperature was set at 91 °F for all three scenarios. In the unlikely event that a maximum discharge temperature of 95 °F could occur, additional calculations were carried out with the model input for the LNS discharge temperature also set at 95 °F. This gave the practicable worst case low flow scenario analysis added conservatism (i.e., the low flow scenario was modeled twice).

It is important to note that use of a discharge temperature of 91 °F for the mean annual flow scenario represents a very conservative approach in the modeling. Maximum temperature rise across the LNS steam condensers is expected to be on the order of 20 °F to 25 °F; prior to entry to the cooling towers. For example, in the absence of cooling towers, water drawn into the plant during cooler months at 40 °F would be no more than about 65 °F at the discharge point. However, use of the cooling towers substantially reduces discharge temperature to comply with ambient water quality standards.

Note that no cooling water discharge is used for the validation case calculations.

In the CFD models, the cooling water discharge was applied as a mass source at the location of the cooling water discharge diffuser and allowed to diffuse equally in all directions.

Boundary conditions established for the CFD models are provided in Table 1 below.

Table1. Model Boundary Data

Scenario	*Description*	*Broad River Flow (cfs)*	*NNI Forebay & Model Inlet Temp (°F)*	*Discharged Cooling Water*		*Turbine Unit in Operation*
				Flow (cfs)	*Temp (°F)*	
	Validation	691	48.0	-	-	1
1.	Mean Annual Flow	2,538	52.7	18.3	91	4, 3, 2
2a.	Low Flow	483	88.2	18.3	91	4
2b.	Low Flow	483	88.2	18.3	95	4
3.	Extreme Low Flow	157	84.0	18.3	91	4

For mean annual flow conditions, three NNI hydro turbines are used to discharge flow from the forebay to the tailrace (Broad River). At low flow one turbine is required.

For the extreme low flow scenario, power generation at NNI Dam also includes the use of a single turbine, but via pulsed (on/off) operation of the turbine unit (Unit 4 was used in the model). The CFD model assumed that for the first 40.4 minutes of an hourly cycle there was no river flow discharge to the tailrace. As a result, river and LNS cooling water flow accumulates in the forebay. During the remaining 19.6 minutes the single turbine discharges flow at a rate of 483 cfs.

In terms of the maximum temperature rise due to the LNS cooling water discharge, the worst case occurs when the closest turbine to the LNS discharge diffuser is operating as this gives the least opportunity for mixing.

3.3.4 CFD Modeling Approach

In all cases the free surface was represented as a frictionless wall where the river/reservoir flow is constrained by the free-surface, but there is no shear stress at this surface.

The density, ρ [kg/m^3], dynamic viscosity, μ [kg/ms], specific heat capacity at constant pressure, C_p [J/kgK] and thermal conductivity, k [W/mK] of water were defined by polynomial functions of temperature, T [K]. All calculations used higher order (second order accurate) spatial discretization schemes. The validation, mean annual flow and low flow scenarios were steady state calculations. Convergence was monitored by root mean square momentum residuals reducing to below 1^{e-4}. In addition to this, monitor points were created to monitor the temperature and velocity at three positions within the dam forebay area; the calculation finished when these were judged to be a steady value.

The extreme low flow scenario required transient calculations. A one-hour cycle was calculated starting with zero flow. A uniform initial temperature field was specified by the forebay temperature (Table 1). The time step was two seconds; a second order accurate time discretization scheme was used; convergence within a time step was judged by convergence of the root mean square momentum residuals reducing to below 1^{e-4}. All steady state calculations use the shear-stress transport (blended k-ε/k-ω) model for turbulence and transient calculations use the k-ε model for turbulence.

4. CFD MODELING RESULTS

4.1 Validation Case

This was the first case calculated and used to validate the CFD model by comparison with the flow measurements conducted by DTA [12]. As the results do not provide any information on the performance of the LNS cooling water discharge they are included in Appendix B rather than the body of the report. The results of the validation study did however, demonstrate that the measured flow features in the river/reservoir were reasonably well-represented by the CFD model. Where differences did exist between the measurements and calculations, these could be largely accounted for by the measurements being of instantaneous flow velocities (with variations due to turbulent eddies etc); whereas, the CFD models provide stochastic mean velocity profiles and indicate the average condition of the river/reservoir for a given flow scenario.

4.2 General Results for All Scenarios

The principal results required from the CFD models are the maximum temperature increase at the turbine inlets – this determines the temperature transferred to the tailrace – and the areas of the $\Delta T \geq 5$ °F and $\Delta T \geq 1$ °F surface plumes. These are shown in Table 2 below.

Table 2. Maximum temperature increase at turbine inlets in each scenario.

Scenario	*Description*	*NNI Turbine Unit Operating*	*Intake Area Temp (°F)*	*NNI Forebay & Model Inlet Temp (°F)*	*Max ΔT at NNI Turbine Inlets (°F)*	*Area of $\Delta T \geq 5$°F Plume (acre)*	*Area of $\Delta T \geq 1$°F Plume (acre)*
1.	Mean Annual Flow (91 °F Discharge)	4,3,2	52.3	52.7	0.72, 0.06, 0.00	0.02	0.04
2a.	Low Flow (91 °F Discharge)	4	86.3	88.2	0.10	--	0.08
2b.	Low Flow (95 °F Discharge)	4	86.3	88.2	0.26	0.002	0.19
3	Extreme Low Flow (91 °F Discharge)	4	82.4	84.0	0.38	0.01 (max)	1.15 (max)

4.3 Results for Mean Annual Flow Condition of 2,538 cfs

At mean annual flow three NNI hydro turbines operate to discharge flow from the forebay to tailrace. The calculation used turbine Units 4, 3 and 2 and the maximum temperature increase at the turbines was 0.72, 0.06 and 0.00 °F, respectively. As the Broad River background temperature was 52.7 °F these corresponded to absolute inlet temperatures of 53.4, 52.8, and 52.7 °F. Considering the combined/mixed flow of the three turbine units, a temperature rise of 0.27 °F is estimated for water ultimately discharged to the tailrace.

The heated plumes from the LNS cooling water discharge were small, and contained entirely within the forebay immediately in front of the turbines. The maximum acreage of the $\Delta T \geq 5$ °F plume surface was 0.02 acres and for the $\Delta T \geq 1$ °F plume, 0.04 acres.

Figure 3 shows contours of the heated plume discharged from the LNS cooling water discharge diffuser and demonstrate how at mean annual flow the plumes are well contained within the immediate vicinity of the discharge and turbines.

4.4 Results for Low Flow Condition of 483 cfs

Under low flow regimes only a single turbine is used by Duke Energy to release water from the reservoir. The calculations used turbine Unit 4 and were performed with the LNS discharge temperature model input set to 91 °F and 95 °F.

At a discharge temperature of 91 °F, maximum temperature rise at the turbine inlet was determined to be 0.10 °F. At a discharge temperature of 95 °F, maximum temperature rise at the turbine inlet was determined to be 0.26 °F.

Although there is lower flow in Broad River (forebay) to mix with the cooling water discharge (compared with mean annual flow), the background temperature of the river is higher; hence, the temperature rise is lower. The background temperature was 88.2 °F and the corresponding mean absolute temperatures at turbine Unit 4 were 88.3 and 88.5 °F, respectively.

The modeled plumes remained small relative to the forebay and contained within the immediate vicinity of the turbine intakes. For the low flow condition the maximum acreage for the ΔT≥1 °F plume surface was 0.08 acres (91 °F discharge) and 0.19 acres (95 °F discharge). The ΔT≥5 °F plume acreages were negligible.

As with the mean annual flow case, the modeled plumes remained small relative to the forebay and well within the immediate vicinity of the cooling water discharge and turbine penstocks. Figure 4 shows the extent of the ΔT ≥ 1 °F plume for the 91 °F discharge and Figure 5 shows the extent of the ΔT ≥ 1 °F and ΔT ≥ 5 °F plumes for the 95 °F discharge. Figure 5a shows an alternative view for the 95 °F discharge from behind the face of the dam to provide greater detail of the plumes; Figure 5b shows this alternative view zoomed out, so that the small extent of the plume may be visualized in the full context of the NNI Reservoir and forebay area. The model predicted maximum plume surface acreage of 0.19 acre for the low flow condition and 95 °F discharge (ΔT ≥ 1 °F) represents less than 2 percent of the total estimated forebay surface acreage in the immediate area of the discharge diffuser (~10 acres).

4.5 Results for Extreme Low Flow Condition of 157 cfs

As noted previously, flows less than 483 cfs occur 1.8 percent of the time, based on Broad River period of record flows. The extreme low flow of 157 cfs is too low to be continuously discharged through a single NNI hydro turbine and maintain FERC-specified water level objectives in NNI Reservoir. Consequently, in line with the FERC license conditions[2], a pulsed regulated flow through turbine Unit 4 was used for modeling purposes. During the first 40.4 minutes of an hourly cycle it was assumed that no discharge occurred to the tailrace and flow accumulated in the forebay. During the remaining 19.6 minutes of the hour, flow was discharged through Unit 4 at 483 cfs.

The area-mean temperature at the turbine penstock varies throughout the hourly cycle modeled. Under typical conditions, the peak temperature rise calculated at the turbine inlet is 0.38 °F. The river background temperature is 84 °F; hence, the absolute temperature at the turbine inlet is 84.4 °F. The temperature rise at the Unit 4 turbine inlet over the hourly cycle modeled is shown in Figure 6.

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[2] "If inflow is less than 483 cfs during any period ... the licensee shall ... operate one unit at its minimum hydraulic output for that portion of every hour which is necessary to discharge the approximate accumulated inflow." NNI FERC license.

The volume of the heated plume also develops during the hourly cycle (Figure 7). As shown, the volume of the plume with ΔT ≥5 °F reaches a steady size of about 250 cubic feet after about 10 minutes. At this time the turbine is still "off" and cooling water discharge is accumulating. As heat is still being input to the forebay, but the volume of water at ΔT ≥5 °F is constant, the temperature of water contained within this volume must be increasing. Essentially, as there is no flow through the forebay, there is little mixing, the plume volume (i.e., ΔT ≥5 °F) remains static and increases in temperature up to a maximum ΔT of 7 °F (91 °F minus 84 °F).

At 40.4 minutes when the turbine is switched "on", flow through the forebay commences and mixing occurs. This spreads the heated plume and as sufficient heat had previously built up, the volume of water at ΔT ≥5 °F increases in size due to mixing. Before the end of the one-hour cycle, the volume of water at ΔT ≥5 °F starts to decrease in response to turbine operation, but it is still present at the end of the cycle (see Figure 8).

The conditions in the forebay at the end of the cycle are therefore not the same as at the beginning of the cycle – some residual heat remains for the next cycle. This may have been an artifact of the modeling (e.g., "starting effect") which occurred as the calculated cycle started from a uniform temperature field set to the background temperature of the river. However, it is possible that heat may accumulate over a number of cycles causing the temperatures at the turbine inlet to increase.

The development of the heated plume during the one-hour cycle is shown in Figure 8. Although the ΔT ≥1 °F heated plume (blue plume) has a greater extent than either of the mean annual flow or low flow conditions, it was still held well within the forebay and did not penetrate into the backwater regions of the reservoir/river system. For the extreme low flow condition (one-hour cycle) the maximum acreage of the heated plume for the ΔT≥5 °F plume surface was 0.01 acres; the ΔT≥1 °F plume surface was 1.15 acres.

The CFD modeling has thus established that the LNS thermal discharge may result in the accumulation of heat in the NNI Reservoir forebay under highly infrequent extreme low flow conditions in the Broad River when combined with pulsed operation of the NNI Dam powerhouse. From the model results it is possible to make a first estimate at what combination of Broad River flows and NNI Dam pulsed operation that this accumulation of heat would not be expected to occur.

In the final 10 minutes of the hourly cycle, the free-surface area extent of the $\Delta T \geq 5$ °F plume decreased almost linearly. Extrapolating this decrease indicated that it would take an additional 20 minutes to remove the $\Delta T \geq 5$ °F plume. The current turbine cycle time for 157 cfs extreme low flow is 40 minutes "off" / 20 minutes "on". By assuming that an additional 20 minutes is required to remove the entire heated plume, the cycle time would have to be modified to 20 minutes "off" / 40 minutes "on". For one turbine unit discharging flow at 483 cfs, this new cycle of operation provides a mean flow over the hourly cycle of 322 cfs. Based on Broad River historical flow records, flows less than 322 cfs occurred just 0.52 percent of the time; thus conditions favoring accumulation of heat in the forebay due to the LNS thermal discharge are expected to be very rare.

4.6 Extent of 90 °F Thermal Plume

The extent of the 90 °F thermal plume is of interest from a regulatory/discharge permitting standpoint. For all four flow cases considered the extent of the 90 °F thermal plume has been determined. These are shown graphically in Figure 9: note that the result for the extreme low flow scenario is shown at t=43 minutes in the hourly cycle, which corresponds with the maximum extent of the $\Delta T \geq 5$ °F plume.

For the mean annual flow and extreme low flow cases the NNI forebay temperature (background) was sufficiently low (52.7 °F and 84.0 °F, respectively), in comparison with the 91 °F LNS discharge temperature, that the LNS thermal discharge water was immediately cooled below 90 °F. Hence, no 90 °F contour is visible in Figure 9 for these two cases[3]. For the mean annual flow scenario, the small fraction of the discharge flow (18 cfs) compared to ambient river flow (2,538 cfs) was also an important factor precluding the development of a 90 °F plume.

For the low flow scenario with LNS discharges of 91 °F and 95 °F the forebay temperature was higher, 88.2 °F. This was sufficiently high that a 90 °F thermal plume

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[3] In reality there will be a very small region of 90 °F water surrounding the diffuser, but this was too small to be determined by the model.

forms. However, in both instances the thermal plumes are small and remain in the immediate vicinity of the diffuser and hydro turbine intakes.

The maximum areal extent (0.166 acre) and peak depth (3.19 ft.) of the 90 °F plume were determined to occur under the low flow scenario assuming an LNS discharge temperature of 95 °F. Recall that at normal water elevation of 511 ft. above msl, total depth at the location of the discharge diffuser in the forebay is approximately 12 ft [1]. As such, the 90 °F plume will not present a blockage to fish movement into, within, or out of the NNI forebay.

The aerial extent, volume, and peak depth of the 90 °F thermal plume is provided in Table 3.

Table 3. Extent of 90 °F thermal plume in each scenario.

Scenario	*Description*	*NNI Forebay & Model Inlet Temp (°F)*	*LNS Cooling Water Discharge Temp (°F)*	*90 °F Thermal Plume*		
				Aerial Extent (Acres)	*Volume (Acre-ft)*	*Maximum Depth (ft)*
1.	Mean Annual Flow	52.7	91.0	-	-	-
2a.	Low Flow	88.2	91.0	0.025	0.057	2.11
2b.	Low Flow	88.2	95.0	0.166	0.484	3.19
3.	Extreme Low Flow	84.0	91.0	-	-	-

5. SMALLMOUTH BASS LITERATURE REVIEW

The CFD thermal modeling study was conducted in large part to respond to comments received by the NRC on the LNS COL. The South Carolina Department of Natural Resources (SCDNR) expressed specific concerns associated with the potential effects of the thermal discharge on the smallmouth bass fishery downstream of the NNI dam. Their specific concerns were related to the potential of the thermal discharge to potentially impact smallmouth bass habitat (i.e., thermal regime) in the river.

A review of relevant technical literature on the thermal requirements of smallmouth bass was conducted to assist in the interpretation of the CFD modeling results with respect to potential cooling water discharge impacts to the existing stocked fishery in the Broad River downstream of NNI dam. The search utilized established internet scientific journal search sites and other reliable sources to retrieve information on the optimal and maximum temperature requirements, and associated behavioral responses, of smallmouth bass.

To determine the existence and accessibility of site-specific information, SCDNR fisheries biologist, Jason Bettinger, was contacted in November 2008. He was unaware of any previous studies assessing the distribution and movements of smallmouth bass in the Broad River downstream of NNI Dam. Based on his experience, smallmouth bass were specifically known to inhabit the reach of river below NNI dam near King's Creek on a year-round basis; typically found in deeper holes during summer. He further advised that SCDNR was currently conducting a project to evaluate smallmouth bass stocking contribution to year-class strength; but had no written documentation to provide at the time. The only other information regarding the smallmouth bass fishery is electrofishing data which are included in the SCDNR Broad River Basin Aquatic Inventory.

5.1 Literature Review Approach

This literature review was not intended to be an exhaustive compilation and review of <u>all</u> information available on temperature requirements of fish; specifically, smallmouth bass. Rather, emphasis was placed on the more current and classic works. Literature sources searched included: U.S. Fish and Wildlife Service resource publications, Transactions of the American Fisheries Society, U.S. Environmental Protection Agency research publications, and Journal of the Fisheries Research Board of Canada. In many cases, the published material was itself a review of literature on the topic of temperature requirements of fish, including smallmouth bass. As a result, it was possible to efficiently obtain relevant information from an exhaustive list of published research by reviewing a smaller subset of the literature.

5.2 Focus of the Review

Because the CFD modeled increase in water temperature at the turbine inlets attributable to the LNS cooling water discharge is predicted to be small (<1 °F in all scenarios examined), it was determined that published critical thermal maxima for smallmouth bass would be the most appropriate metric for evaluating potential impacts of the discharge in Broad River below NNI dam. Such minimal increases in water temperature during cooler months when the ratio of seasonally high river flows relative to the cooling water discharge are greatest, are not likely to have a measurable effect on smallmouth bass reproduction and growth. However, during critical conditions of summer when river flows are lowest and water temperatures are at seasonal highs, it is important to know if the LNS cooling water discharge could incrementally increase water temperature in Broad River below the NNI dam above those necessary to support smallmouth bass.

5.3 Review Summary

Based on review of the technical literature, it is well-established that smallmouth bass are tolerant to relatively high water temperatures. Several documents report tolerable thermal maxima for smallmouth bass above 86 °F, with some reported as high as 95 °F. More detailed information on specific findings has been compiled in annotated bibliography format and is presented in Appendix C. These findings are put into perspective for the LNS discharge to Broad River in the next section.

6. STUDY CONCLUSIONS

6.1 CFD Thermal Modeling

Mean annual flow, low flow and extreme low flow scenarios were conservatively calculated using CFD models to determine the potential effects of the LNS cooling water discharge on the Broad River and NNI Reservoir environments.

In all the cases studied the maximum temperature rise at the NNI hydro turbine intakes and; hence, passed through to the NNI Dam tailrace was 0.72 °F. This was determined for the mean annual flow scenario conservatively assuming a discharge temperature of 91 °F at a time when seasonally appropriate Broad River background temperatures were less than 53 °F. However, seasonally adjusted discharge temperature is anticipated to be much less than 91 °F. Consequently, the actual temperature increase is expected to be much less than that predicted. For all other scenarios examined, predicted water temperature rises at the turbines were less than 0.4 °F.

Within the NNI Reservoir forebay, water temperature did increase by $\Delta T>5$ °F in most cases. However, this was expected since the cooling water discharge temperature modeled was typically more than 5 °F greater than the reservoir/river background temperature (not the case for the low flow, 91 °F discharge scenario). However, the $\Delta T\geq 5$ °F plumes were small and always held within the immediate vicinity of the cooling water discharge and NNI turbine intakes. The maximum surface area of any discharge plume with $\Delta T \geq 5$ °F was 0.02 acre; this was associated with modeling of the mean annual flow scenario. Similarly the $\Delta T\geq 1$ °F plumes were small and typically remained within an area local to the cooling water discharge and NNI turbine powerhouse.

Modeling of the extreme low flow scenario resulted in the largest $\Delta T \geq 1$ °F discharge plume predicted at 1.15 acres (maximum turbine inlet temperature was 0.38 °F) based on a one hour cycle of pulsed operation. This effort also predicted that under certain conditions heat may accumulate in the forebay if the pattern of pulsed flow operation is insufficient to fully remove heat LNS discharge heat addition. A pulsed flow operational pattern matched to 322 cfs was extrapolated from this modeling exercise that was predicted to preclude accumulation of heat in the forebay. Based on Broad River historical flow records, flows less than 322 cfs are very rare (< 0.52 percent of the time).

Under all but the most extreme low flow conditions, the maximum predicted plume size occupied less than 2 percent of the forebay surface area immediate to the discharge diffuser. In all cases examined, there was no significant transport of heated water into the backwater areas.

Should Duke Energy re-activate NNI turbine Units 5 and 6 (not anticipated), some increase in water temperature at the turbine inlets is to be expected given their closer proximity to the LNS discharge diffuser, which provides for reduced mixing with ambient waters. However, material changes to turbine inlet temperatures are not expected. Importantly, Duke Energy has some flexibility over turbine unit selection during low flows and can, as necessary, exercise that flexibility to manage the temperature of water discharged to the NNI Hydroelectric Station tailrace.

The CFD models were conservatively applied in this study and clearly demonstrate the minimal impact the LNS thermal discharge is predicted to have on the thermal regime of Broad River and NNI Reservoir forebay; particularly with regard to the fish and macroinvertebrate communities. This finding is not surprising given the size of the LNS discharge flow relative to ambient Broad River flows. Typical discharge flow of 18 cfs represents less than 4 percent of the near 7Q10 flow of 483 cfs (low flow scenario). Based on analysis of Broad River period of record flows (81 years), flows were greater than 483 cfs 98.2 percent of the time. Thus, even greater mixing of the thermal discharge would be expected to occur throughout most years of operation.

Importantly, the sizes of the thermal plumes predicted are not expected to create a significant impediment to the movement of fish to and from the reservoir and forebay, or within the forebay itself. Also, given the buoyant nature of the thermal plume, no appreciable adverse impacts are expected to occur to the benthic macroinvertebrate community resident in the forebay area. As discussed in the next section, impacts to the smallmouth bass fishery in the river downstream of NNI Dam are also expected to be unappreciable.

6.2 Thermal Discharge Impacts on Smallmouth Bass

The technical literature supports the conclusion that smallmouth bass are tolerant of warm temperatures found in southern stream systems during summer. Their viable presence in the Broad River in the Piedmont of South Carolina attests to this conclusion. Duke Energy has deployed continuous water temperature recording devices at several locations in Broad River including: the NNI forebay[4] and NNI tailrace above and below the confluence of King's Creek. The maximum hourly NNI dam forebay temperature recorded during July-August 2008 was 89.2 °F; at three monitoring locations in the tailrace, maximum hourly temperatures ranged from 95 °F to 98.4 °F during the same period. On an instantaneous basis, maximum water temperatures in Broad River below NNI dam in the summer of 2008 exceeded South Carolina's aquatic life-based water quality criteria for temperature of 90 °F. These higher temperatures below the dam are likely the result of solar heating of the predominately shallow water habitats present.

Thus, before the addition of the LNS cooling water discharge, maximum temperatures in the tailrace have been documented to exceed forebay maximum temperatures by approximately 6 to 9 °F. Under these pre-LNS conditions, a viable smallmouth bass population has been supported in Broad River below NNI Dam. Considering that the maximum rise in Broad River water temperatures at the turbine inlets during summer conditions of low flow (or extreme low flow) and high ambient water temperatures is predicted to be no more than 0.38 °F after LNS start-up, no substantive changes to the summertime thermal regime currently existent in the tailrace are reasonably anticipated. As a result, no detrimental impacts to the smallmouth bass fishery in Broad River below NNI dam are likewise anticipated.

6.3 Implications for Permitting & Environmental Compliance

As confirmed by the CFD models, surface water temperatures at the point of LNS diffuser discharge to Broad River are predicted to potentially exceed South Carolina's aquatic life-based water quality instantaneous maximum temperature criterion for "free flowing" freshwaters of 90 °F; and at times, may result in temperatures of more than 5 °F above "natural temperature conditions" for the receiving waterbody. The areal dimensions of the predicted plumes where such conditions could occur are predicted to be quite small; and as such, no appreciable impacts to the resident aquatic community of Broad River/NNI Reservoir are expected. Further, no state or federally listed species are known to occur from this area of the Broad River.

It is important to note that the determination of "natural temperature conditions" as a baseline for determining compliance with any thermal effluent limits established for the

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[4] Continuous temperature recorders were first deployed in the forebay in March 2008.

LNS discharge may not be a straightforward exercise. Commonly, the compliance format would include use of the temperature at the intake area, uninfluenced by the facility discharge, in establishing the "natural temperature conditions". As suggested by the current temperature data set, temperatures measured at the LNS cooling water intake location are not always representative of water temperatures in the forebay at the site of LNS discharge diffuser. In the analysis of these data for the current study, natural heating and cooling effects were noted between the two locations that may warrant further analysis from a regulatory compliance perspective. Notably, the spatial aspects of the CFD modeling suggest a monitoring point could be placed in the forebay itself that would be uninfluenced by the LNS thermal discharge and establish a meaningful "natural" temperature condition for compliance purposes.

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7. REFERENCES

1. Duke Energy Combined Construction and Operating License Application for William States III Nuclear Station; Environmental Report (Rev.1). http://adamswebsearch2.nrc.gov/idmws/ViewDocByAccession.asp?AccessionNumber=ML090990348

2. South Carolina Regulation 61-68 – Water Classifications and Standards: Section E.12). http://www.scdhec.gov/environment/water/regs/r61-68.pdf

3. Duke Energy Report dated 15 December 2006: "*Fishery Resources Associated with the Lee Nuclear Station Site; Cherokee County, South Carolina*". Authors: D.H. Barwick, D.J. Coughlan, G.E. Vaughn, B.K. Baker, and W.R. Doby. Duke Energy Carolinas, LLC

4. Duke Energy Report: "*Baseline Environmental Summary Report on the Broad River in the Vicinity of Cherokee Nuclear Station*". L. L. Olmsted and A. S. Leiper, eds. Duke Power Company, Charlotte, NC. 1978.

5. Duke Energy e-mail communication to Geosyntec (Bowling to Cheek) dated 04 May 2009 conveying information attributed to Shaw Nuclear, prime engineering contractor for the LNS project.

6. Amendment to Exhibit A & B and Authorized Installed Capacity for Ninety-Nine Islands Project 2331 dated January 26, 2007. FERC "eLibrary": http://elibrary.ferc.gov/idmws/nvcommon/NVViewer.asp?Doc=11345136:0

7. "Hydrodynamic Assessment of Discharge from Cooling Tower Blowdown to Broad River, Lee Nuclear Station, Cherokee County, South Carolina" Clemson University, The Strom Thurmond Institute of Government & Public Affairs. Clemson, SC. September 20, 2007.

8. Henk Kaarle Versteeg and Weeratunge Malalasekera. 2007. "*An Introduction to Computational Fluid Dynamics: The Finite Volume Method*". Second Edition. Pearson Education, Ltd., 503pp.

9. Fangbiao Lin and George E. Heckler, Alden Research Laboratory, Inc., Holden, MA; and Brennan T. Smith and Paul N. Hopping, Tennessee Valley Authority, Knoxville, TN. "*Nuclear Power Plant Thermal Discharge*", Fluent News, Spring 2004 and associated reference: D.F.R. Hardeman, L.C. Hall, and T.G. Curtis. "*Thermal Diffusion of Condenser Water in a River during Steady and Unsteady Flows with Application to the TVA Browns Ferry Nuclear Power Plant*". Hydrodynamics Laboratory Report No. 111, Massachusetts Institute of Technology, Cambridge, MA, September 1968.

10. "*Computational Fluid Dynamics Modeling of the North Fork Dam Forebay, Clackamas River, Oregon*" and "*Bonneville Tailrace Project: Three-Dimensional CFD Models and Flow Measurements*". Pacific Northwest National Laboratory, Richland, WA.

11. Liaqat A. Khan, Edward A. Wicklein, and Mizan Rashid. "*A 3D CFD Model Investigation of an Outfall Reservoir Hydraulics for Repowering a Power Plant*". Examining the Confluence of Environmental and Water Concerns; Proceedings of the World Environmental and Water Resources Congress. 2006.

12. Devine Tarbell & Associates, Inc., Ninety-Nine Islands Bathymetry and Velocity Study Report, May 2008.

13. ANSYS,Inc., Southpointe, 275 Technology Drive, Canonsburg, PA 15317. http://www.ansys.com/default.asp.

14. Duke Energy Drawing: Ninety-Nine Islands Hydro Station, Plan, Profile and Spillway Rating Curve. (Exhibit L Sheet 1) undated. Forwarded to Geosyntec Consultants as "99 Islands Hydro_20080604074757.pdf".

15. Duke Energy Drawing: Ninety-Nine Islands Hydro Station, Plan, Profile and Spillway Rating Curve. (Exhibit F Sheet 2) undated. Forwarded to Geosyntec Consultants as "SFX43A.pdf".

16. Duke Energy Drawing: WWS Discharge General Area Plan. WLG-3900-P6H-001.pdf dated 07/24/08.

17. Duke Energy Drawing: Discharge Pipe Support Details. WLG-3900-P6H-002.pdf dated 07/24/08.

18. Duke Energy Temperature Measurements in Broad River and NNI Islands Forebay. Forwarded to Geosyntec Consultants as MS Excel files "LNSupres2007all.xls" and "LNSupres2008all.xls".

19. USGS Blacksburg gauge flow measurements available via the online database: http://waterdata.usgs.gov/nwis/dv/?site_no=02153200&PARAmeter_cd=00060

REPORT FIGURES

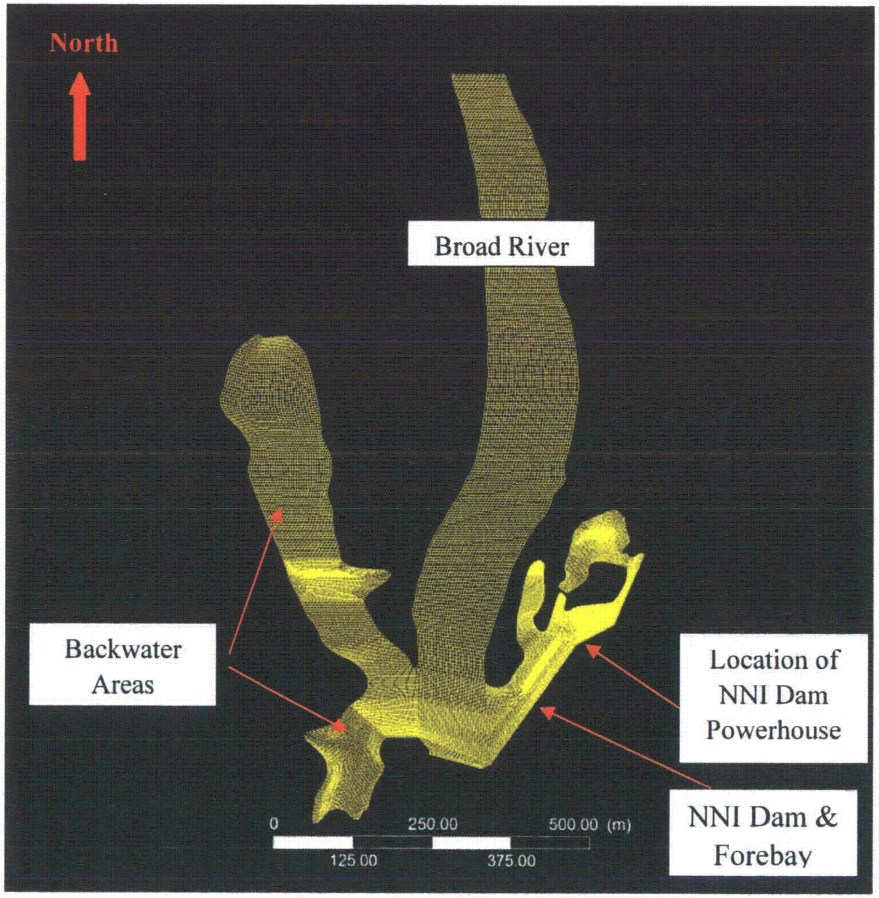


Figure 1. Model plan view of Broad River and NNI Reservoir included in CFD models.

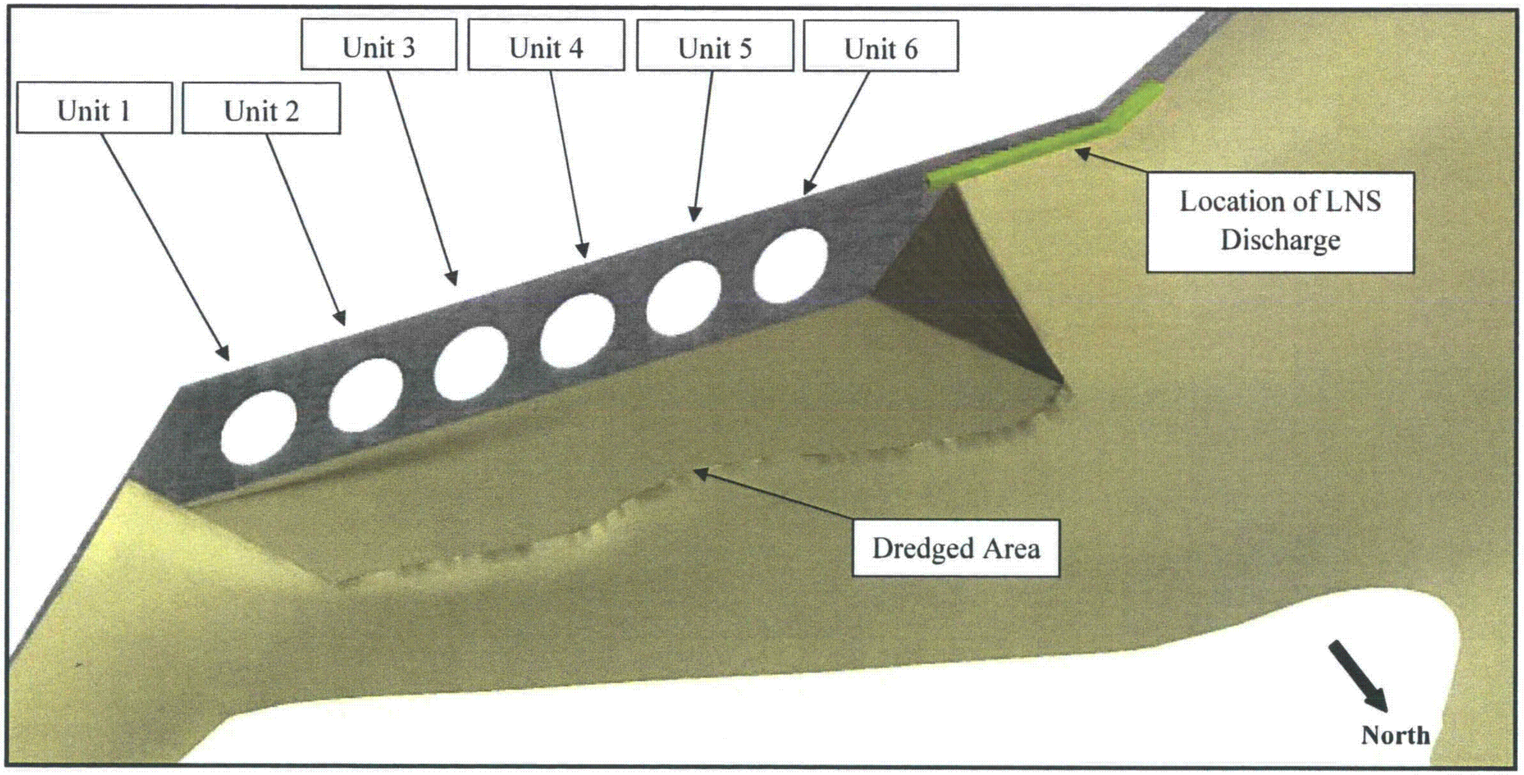


Figure 2. Model view of NNI Dam forebay and cooling water discharge.
Note that turbine units 5 and 6 are currently non-operable and are not anticipated to be restored to service.

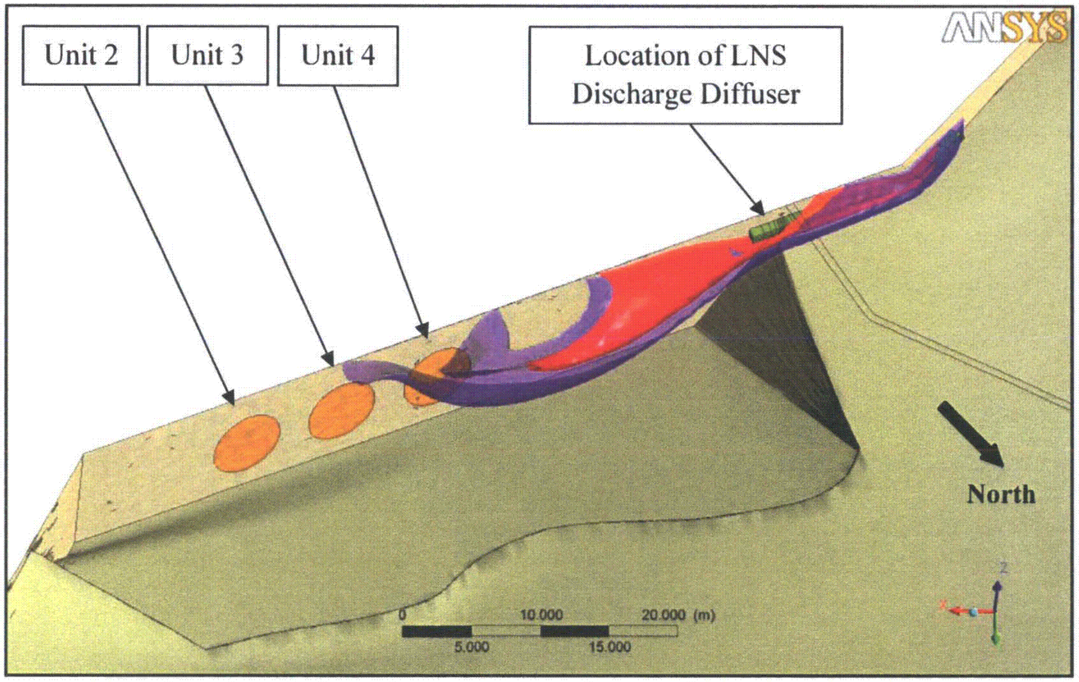


Figure 3. Contours of ≥ 5 °F (red) and ≥ 1 °F (blue) heated plumes from the LNS cooling water discharge at mean annual flow.

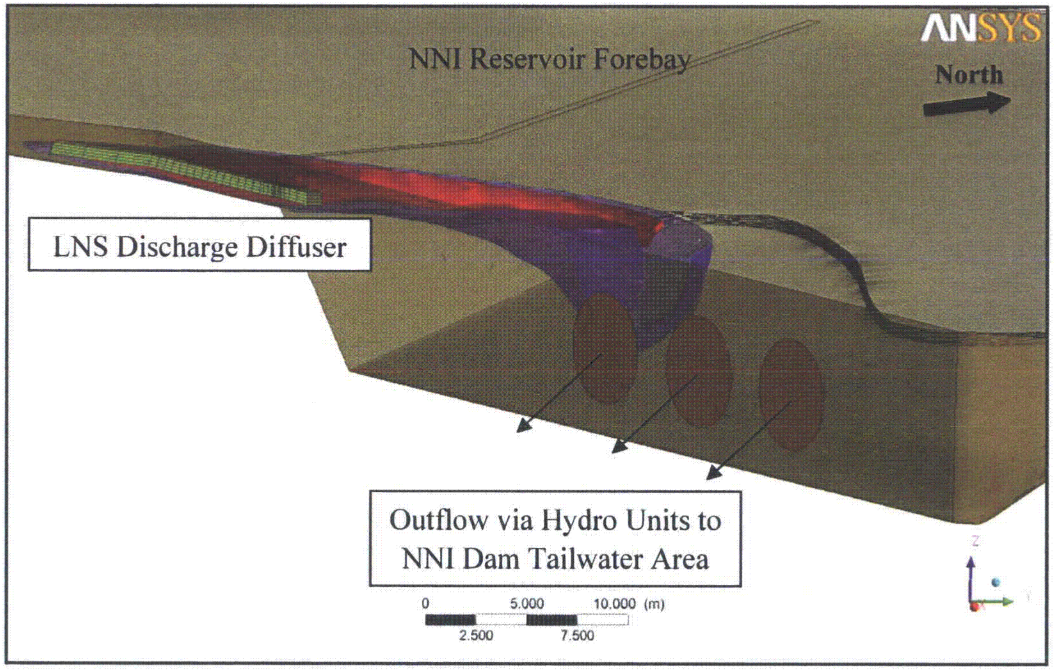


Figure 3a. Contours of ≥ 5 °F (red) and ≥ 1 °F (blue) heated plumes from the LNS cooling water discharge at mean annual flow.

Alternative view from behind the face of the dam.

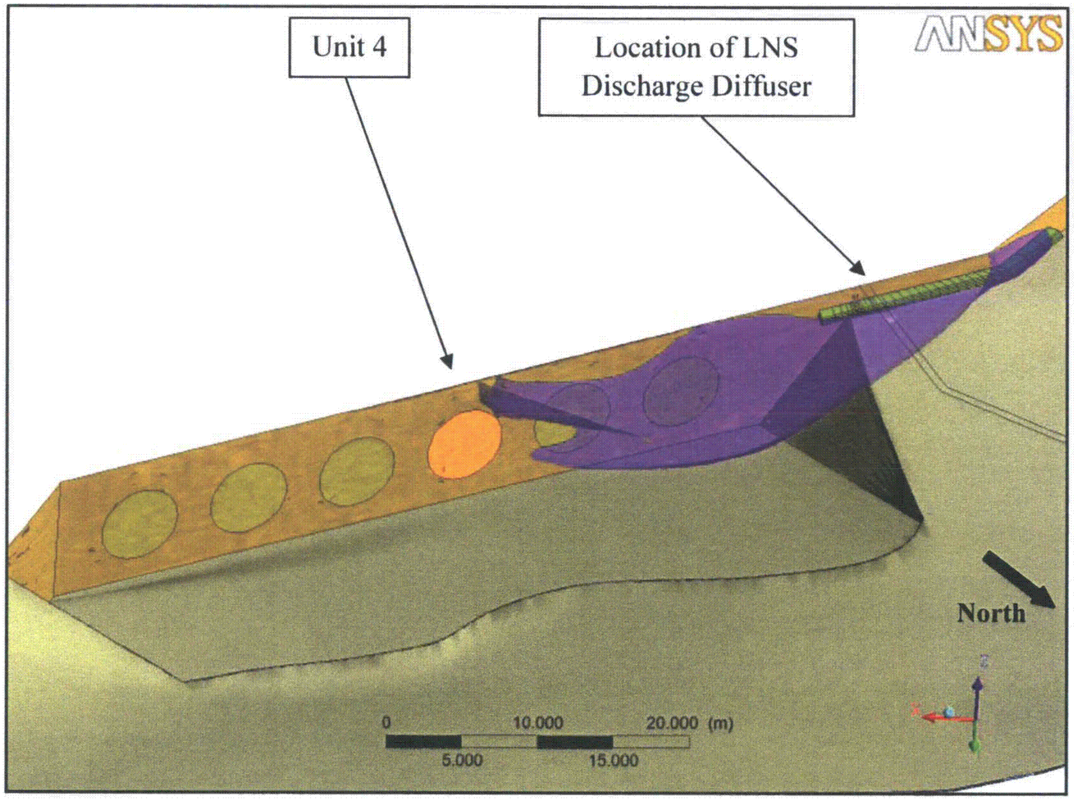


Figure 4. Contours of ≥5 °F (red) and ≥1 °F (blue) heated plumes from the LNS cooling water discharge at low flow – 91 °F discharge.

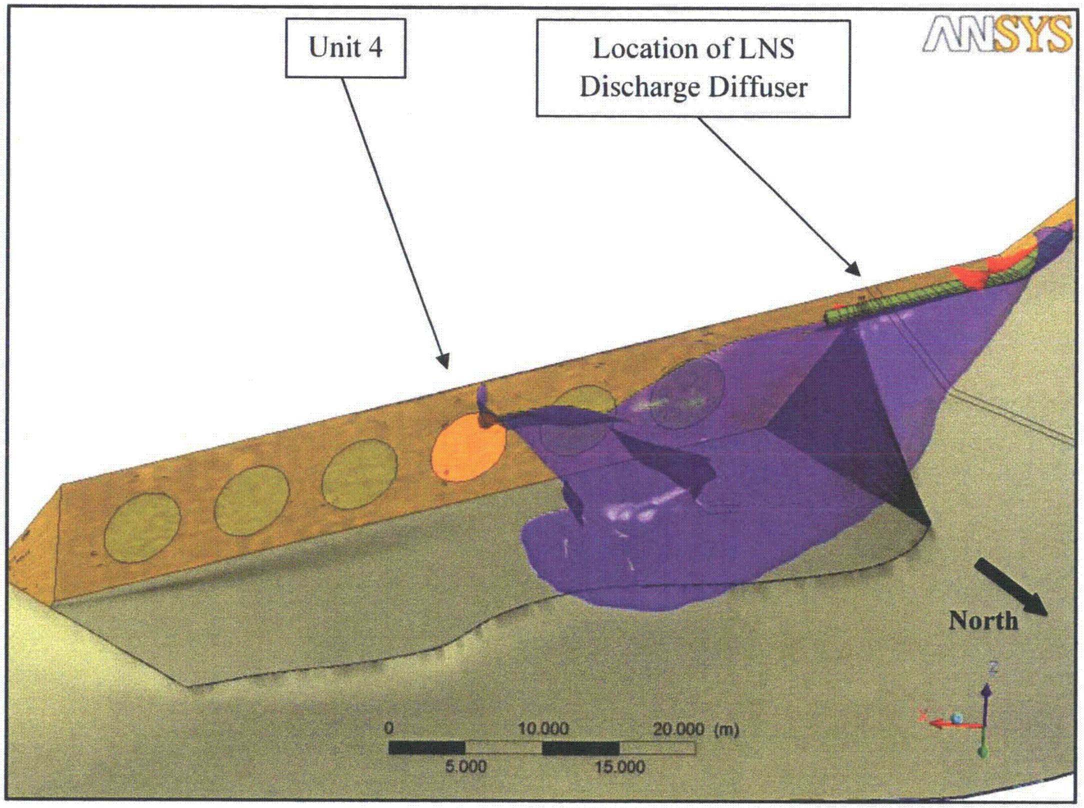


Figure 5. Contours of ≥5 °F (red) and ≥1 °F (blue) heated plumes from the LNS cooling water discharge at low flow – 95 °F discharge.

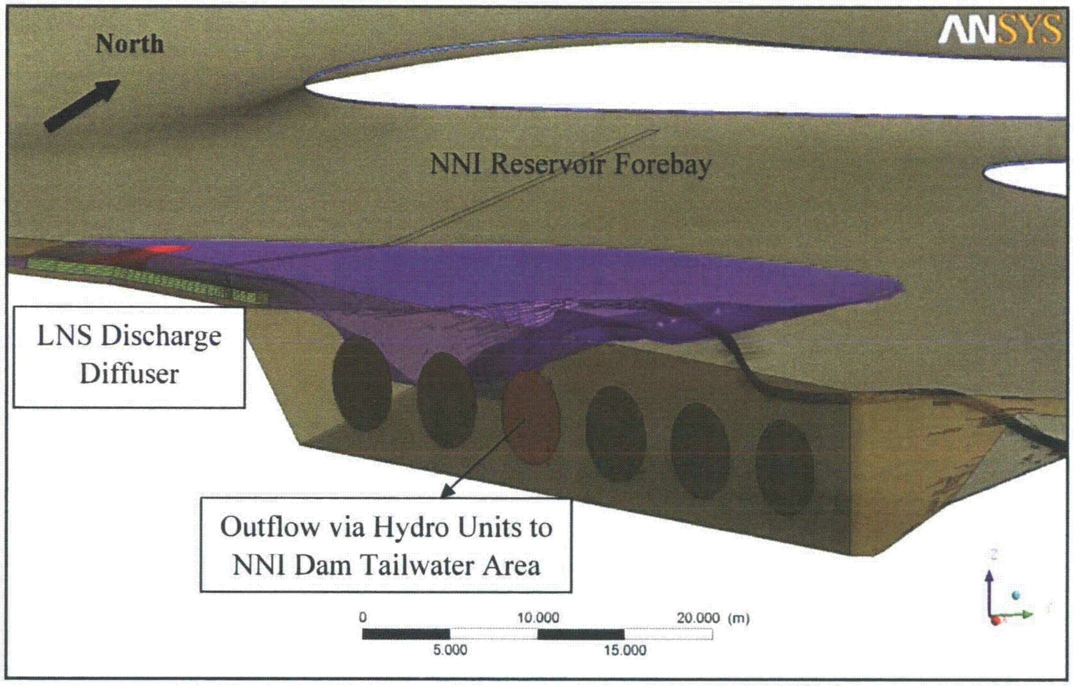


Figure 5a. Contours of ≥5 °F (red) and ≥1 °F (blue) heated plumes from the LNS cooling water discharge at low flow – 95 °F discharge.

Alternate view from behind face of dam

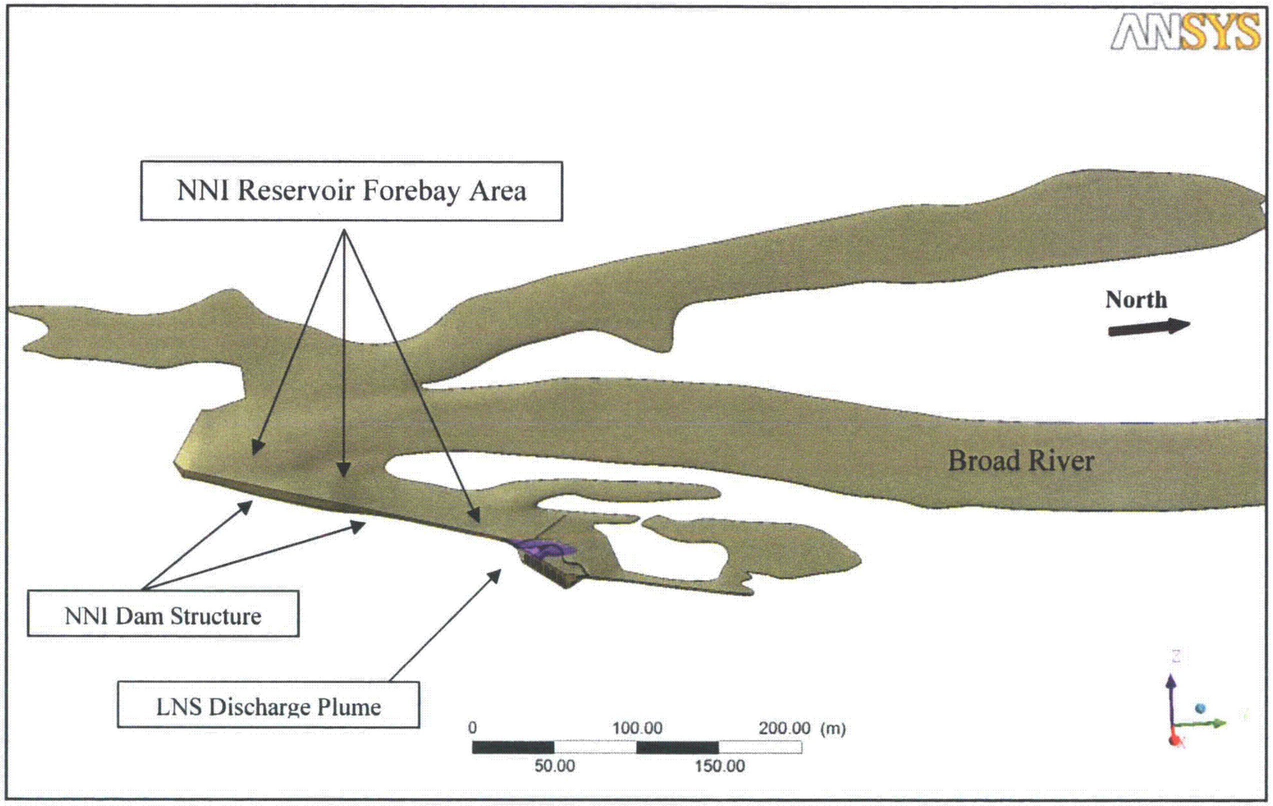


Figure 5b. Contours of ≥5 °F (red) and ≥1 °F (blue) heated plumes from the LNS cooling water discharge at low flow – 95 °F discharge.

{Same alternate view from behind the face of NNI Dam as Figure 5a but zoomed out to show the heated plume size in relation to the entire NNI Reservoir/Forebay area modeled}

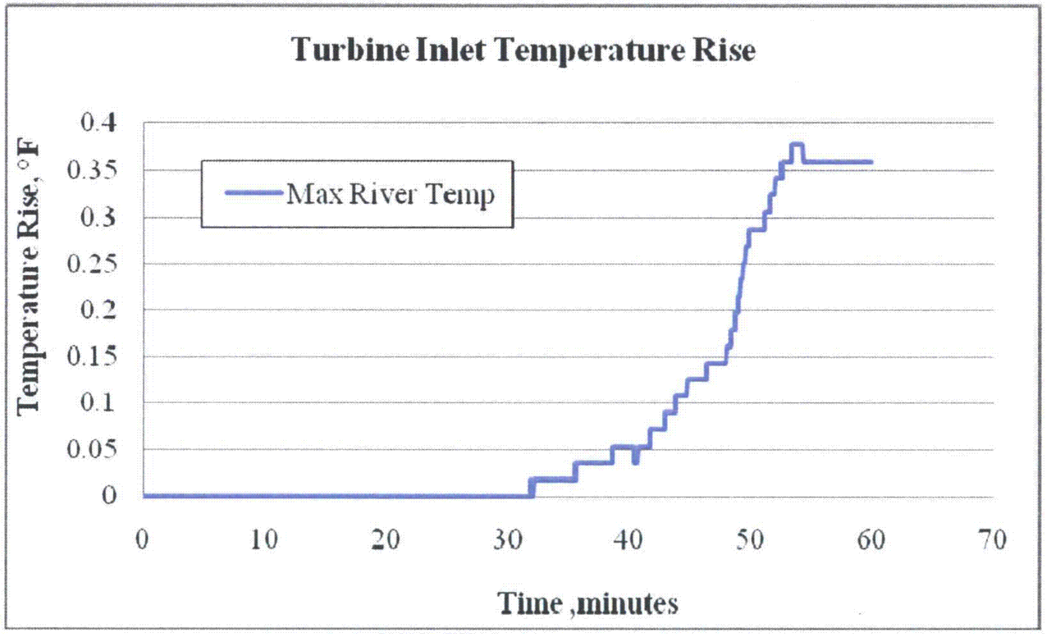


Figure 6. Change in temperature rises at the NNI Unit 4 turbine inlet over one hourly cycle during extreme low flow conditions. ("Max River Temp" refers to the calculation with 84.0 °F background temperature discussed in the text.)

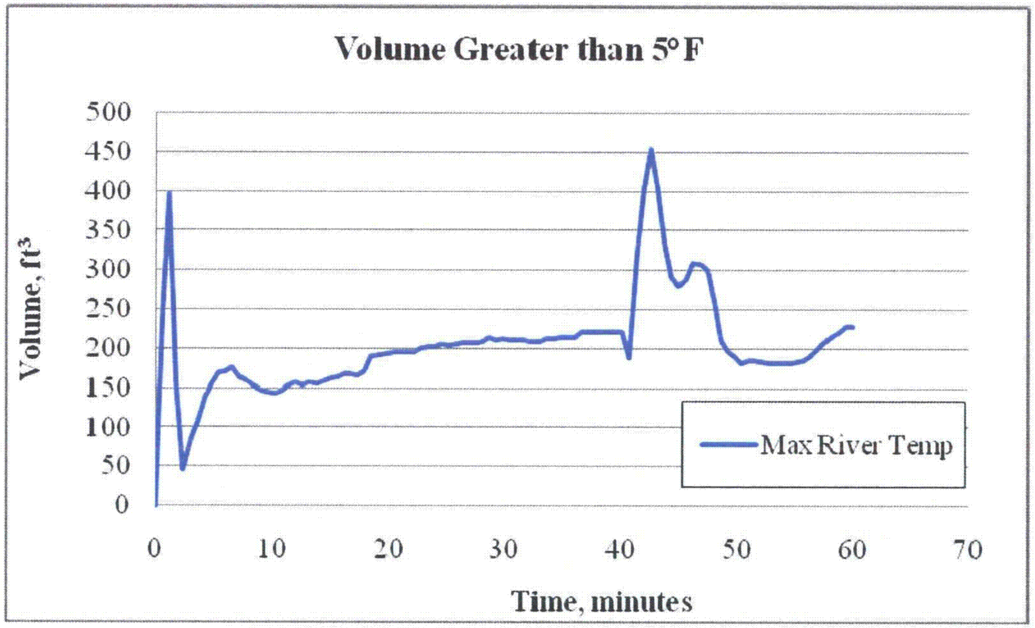


**Figure 7. Change in volume of the plume which has a temperature rise ΔT ≥ 5°F
("Max River Temp" refers to the calculation with 84.0 °F background temperature discussed in the text.)**

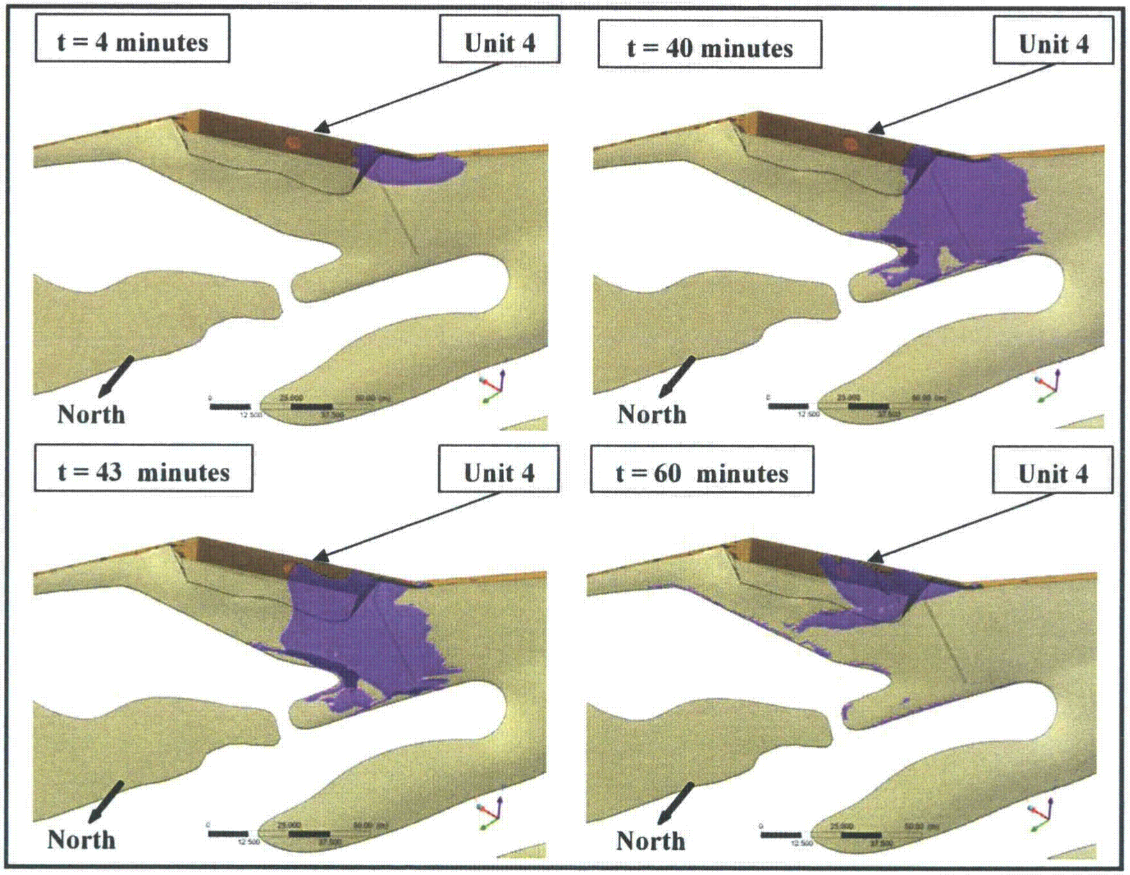
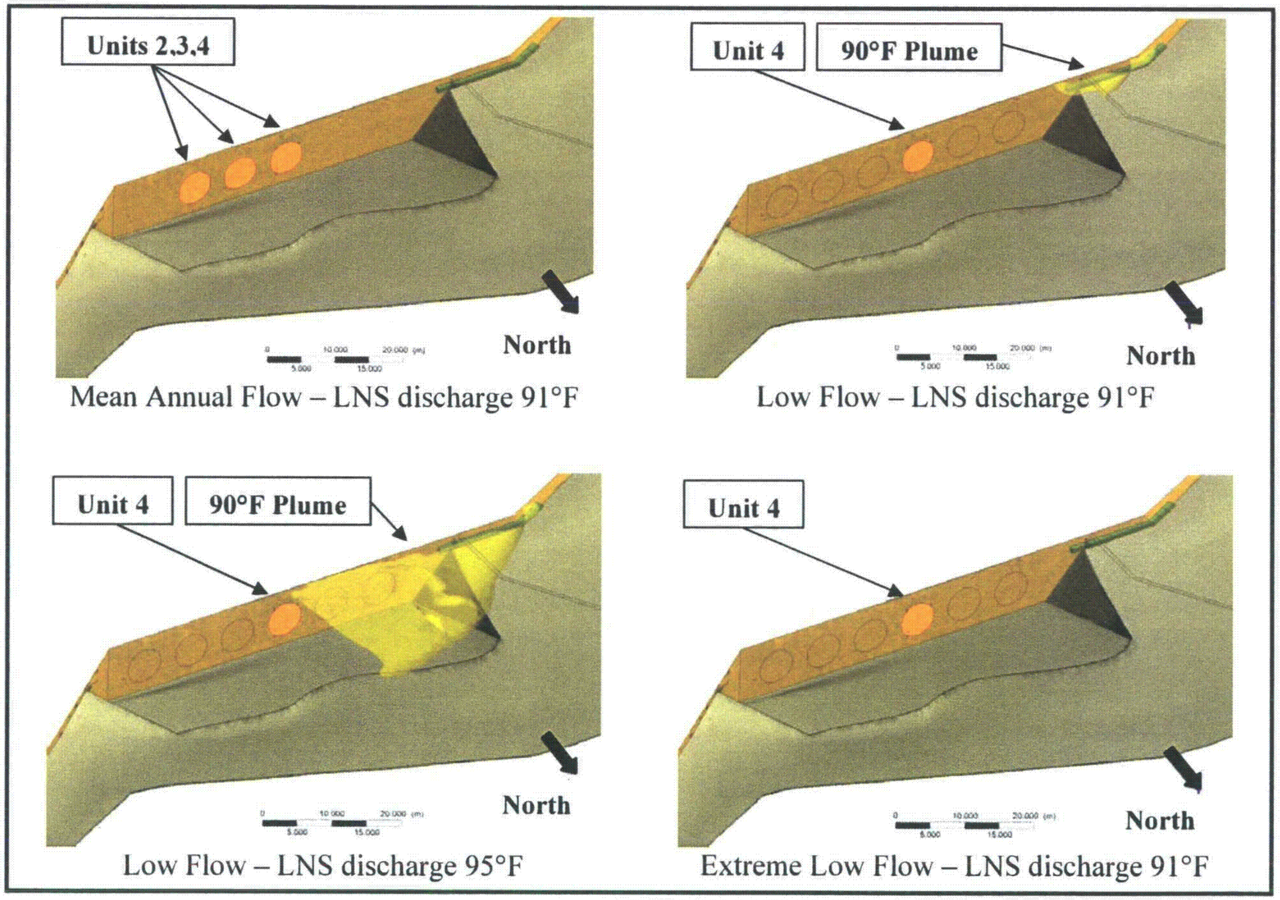


Figure 8. Development of ≥5°F (red) and ≥1°F (blue) heated plume during extreme low flow – reservoir with 84.0 °F background temperature.



Mean Annual Flow – LNS discharge 91°F

Low Flow – LNS discharge 91°F

Low Flow – LNS discharge 95°F

Extreme Low Flow – LNS discharge 91°F

Figure 9. Contours of 90°F temperature in NNI forebay for the four cases considered.

APPENDICES

APPENDIX A – CFD MODEL BATHYMETRY AND MESH DETAILS

Bathymetry

The bathymetry data for the reservoir/river was provided by DTA [12] in point format and was interpolated to provide the reservoir bottom surface in the CFD models. In some locations when the point data were interpolated to form the river/reservoir bed the data were not sufficiently detailed and an assumed bed profile was inserted instead.

One significant location was in front of the turbine intakes where the interpolated bathymetry had the surface at the mid-height of the turbine intakes; this was thought to be not feasible. The apparent error in the data was possibly due to "coarseness" in the point data leading to poor interpolation of the surface. The civil structure drawing [14] shows a "dredged" region in front of the turbines with the reservoir floor 30 ft. below the turbine intake (Figure A-1). This is not supported by the DTA measurements but was used to define the CFD model as it provided a more realistic surface profile (Figure A-2).

Mesh Resolution

A hexahedral, structured, body-fitted mesh was used to define the computational domain for the CFD models. A sample of the computational mesh demonstrating the degree of refinement at the forebay and final section of Broad River is shown in Figure A-3.

To resolve velocity profiles from the base of the reservoir to the free surface, the computational mesh typically used 15 cells to represent the river/reservoir depth. In areas where NNI Reservoir has greater depth and more detail of calculated velocity profiles (e.g., in front of the turbines) the number of computational cells spanning the depth was increased to 53.

Variation in Free Surface Level

During the extreme low flow scenario flow accumulates, is then discharged, and the water level in the forebay rises and falls accordingly. This is included in the CFD models by using a deforming mesh which moves to match the changing water level. Table 3 gives the elevation of the free surface during the extreme low flow calculations. It can be seen that at the end of 40.4 minutes the increase in the height of the free surface is just less than 2 inches.

Table A-1. Flow rates and free surface elevation during "extreme low flow".

Time	*Flow rate (cfs)*			*Free Surface Elevation (ft)*
(mins)	*River*	*Cooling Water*	*Turbine*	
0				510.94
40.4	157.0	18.3	0	511.10
60	157.0	18.3	-483	510.96

APPENDIX A - FIGURES

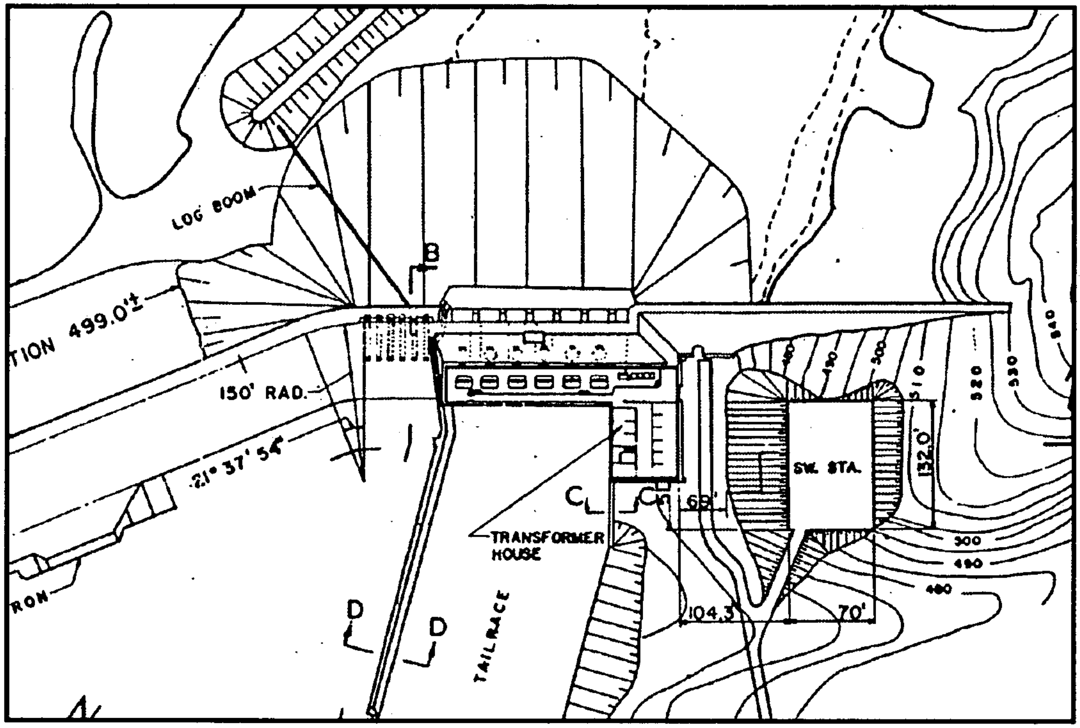


Figure A-1. Section of NNI Dam civil drawing showing location of "dredged" profile in front of the turbine intakes.

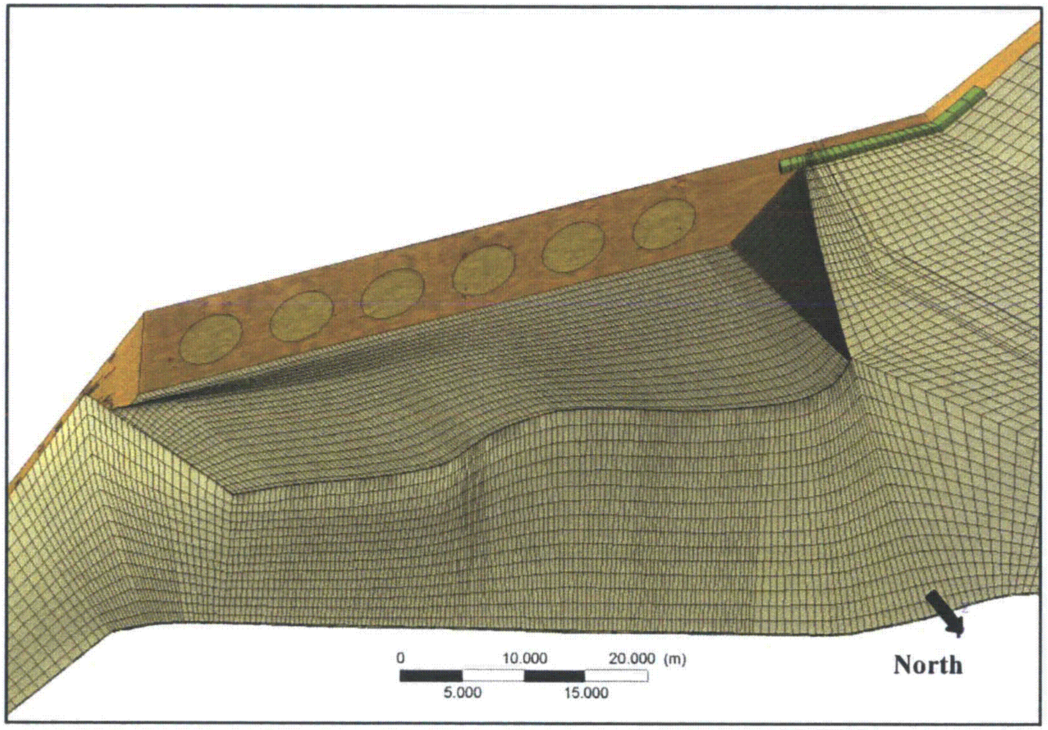


Figure A-2. Showing the equivalent profile of "dredged" region in front of turbine intakes in the CFD model.

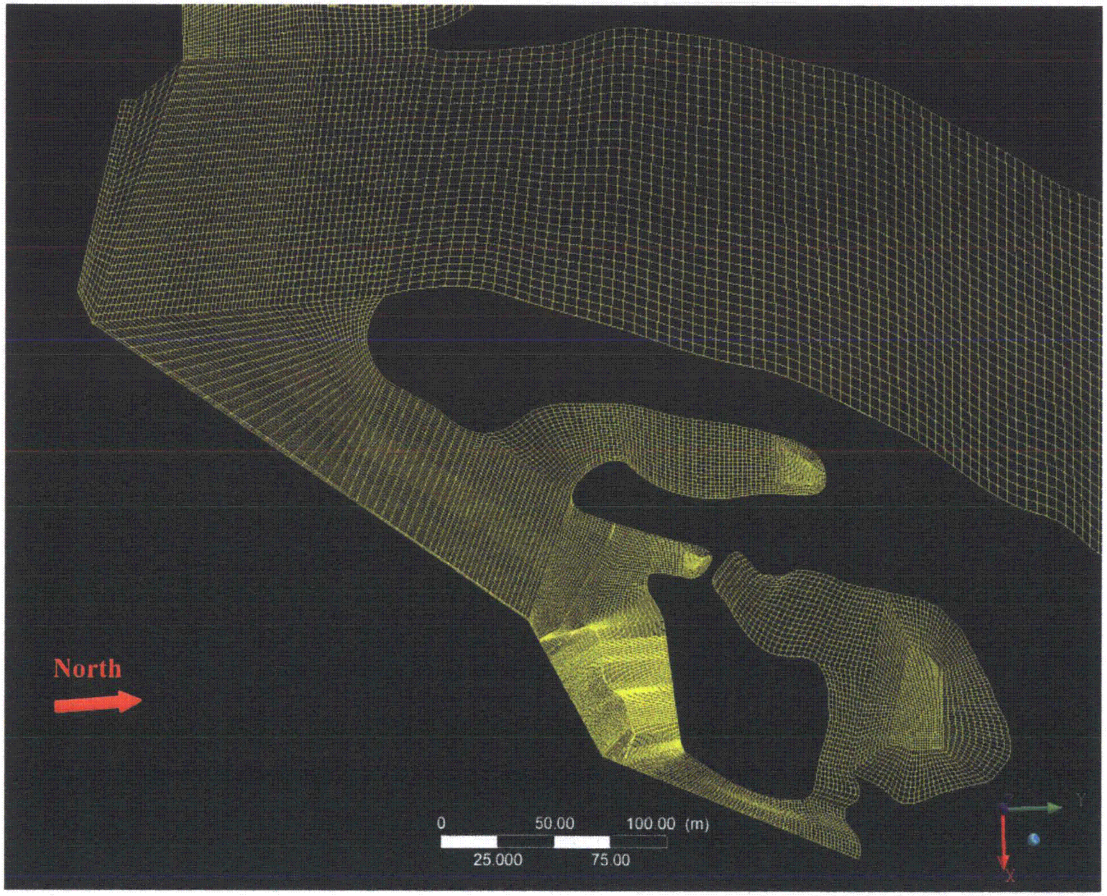


Figure A-3. Plan view of computational mesh for the CFD models.

APPENDIX B – VALIDATION FLOW SCENARIO RESULTS

Devine, Tarbell & Associates took velocity readings in NNI Reservoir on December 4th and 5th, 2007. At that time the flow in Broad River was approximately 691 cfs; this flow was discharged from the reservoir forebay to the tailrace through NNI hydro turbine Unit 1. Velocimetry data measured by DTA [12] has over 15,000 data points for which some locations have multiple readings at different depths. Analysis of the data showed that there are 2,704 coordinates with measurements at multiple depths.

The velocity measurements are compared with the calculated flow from the CFD model in Figure B-1 and Figure B-2; these show depth-averaged or point velocity vector measurements and CFD calculated surface vectors.

The CFD calculation shows a clear region of flow recirculation at point 'A' and the separation streamline has been marked by a red line. The measurements in this region are less clear, but the region of reversed flow vectors and the estimated separation streamline is similar to the calculation.

At point 'B' in the forebay, measurements and CFD calculation both show flow recirculation which appears stronger in the CFD model. This may be due to the CFD results being surface vectors and the measured values being depth-averaged velocities.

At point 'C' along the face of the NNI dam, measured and calculated velocities compare favorably in the range 0.51 - 0.75 feet per second (fps) (0.155-0.23 meters per second (m/s)). At point 'D', immediately in front of the turbine penstocks measured and calculated velocities compare favorably. The CFD results show greater detail of the shear flow at the turbines which cannot be determined in the more coarsely spaced measurements.

For direct comparison between the measurements and CFD model results it is important to ensure that the same velocity variables are considered. In a turbulent flow, such as in Broad River, turbulent eddies or velocity fluctuations are always present. The instantaneous velocity at any location varies as the eddies accelerate and decelerate the flow. The instantaneous velocity, U^* can be considered as consisting of the mean velocity, U, and turbulent fluctuation, u, where $U^*=U+u$.

Figure B-4 compares the CFD depth-averaged velocity with the measured velocity distribution across the river at the location marked in Figure B-3. The CFD model calculates statistical mean velocities, *U*, providing the 'flat' velocity profile, whereas the measurements have much more variation. This suggested that these are measurements of instantaneous velocity, *U**, which have not been statistically averaged to find the mean velocity.

It is not possible to calculate the instantaneous velocity flow field for direct comparison with these measurements, as the instantaneous velocity depends on the turbulent and essentially random eddies passing the velocity meter as the measurement was taken. However, if the calculated mean velocities lie within the range of measured instantaneous velocity it is fair to assume agreement between the measurements and calculations.

Figure B-5 shows the location of four velocity profiles where the CFD results are compared with measurements in front of the turbine intakes, Figure B-6 to Figure B-9. In profiles 1, 2 and 4 the CFD results follow the measured data reasonably well while in profile 3 the CFD calculated velocities are generally lower than the measurements.

Within the limitations of the measured data, the results show that the CFD model is appropriate to calculate flows in Broad River and NNI Reservoir.

APPENDIX B - FIGURES

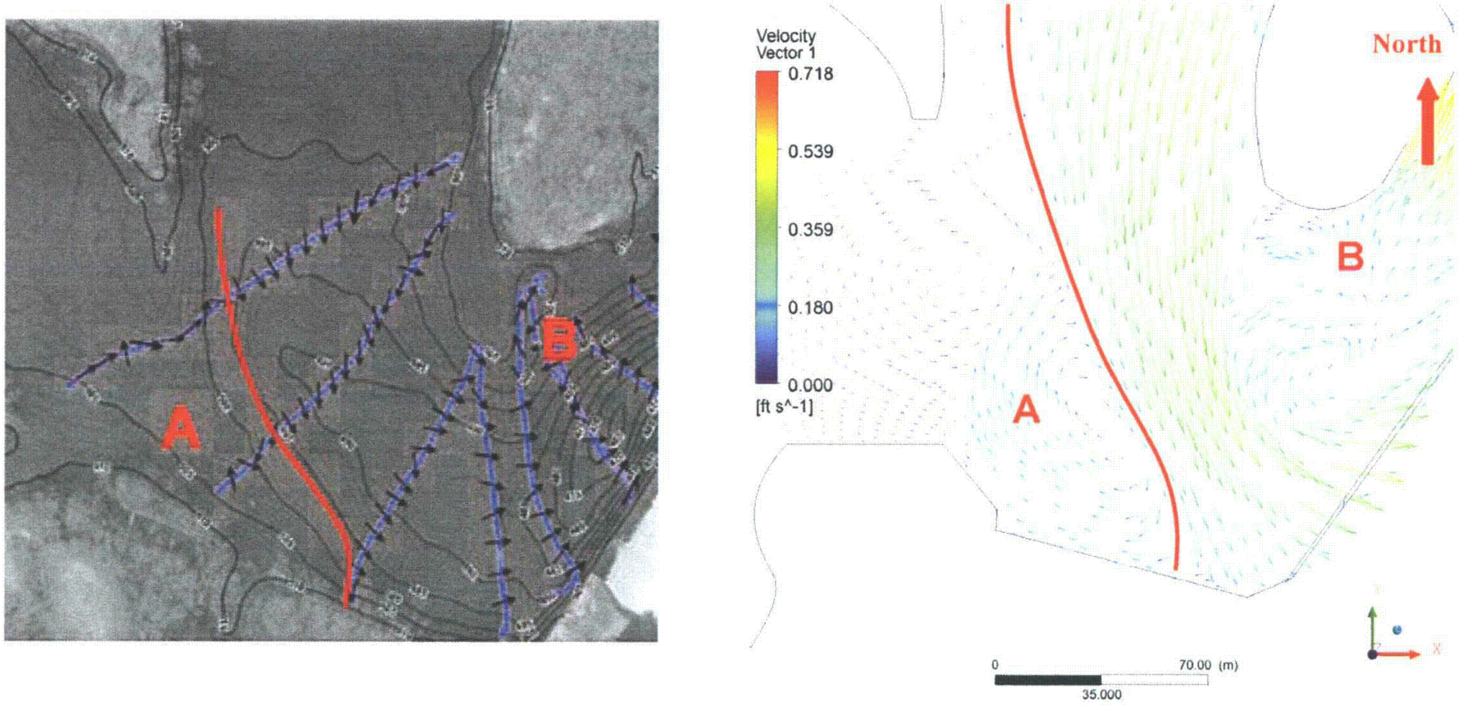


Figure B-1. Comparison between measured velocity vectors (left) and CFD results (right) where the river merges with the forebay.

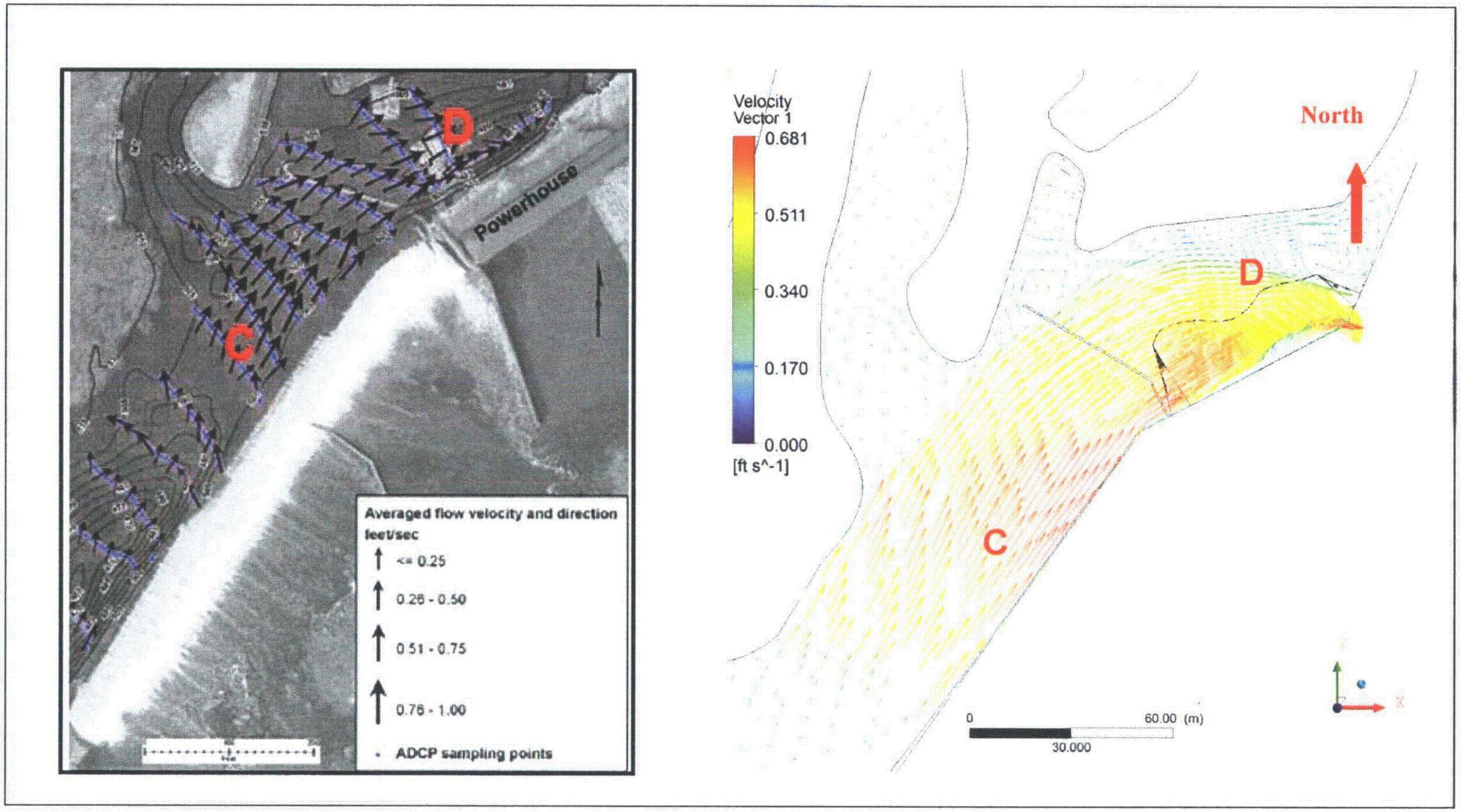


Figure B-2. Comparison between measured velocity vectors (left) and CFD results (right) along the face of NNI Dam and at the turbines.

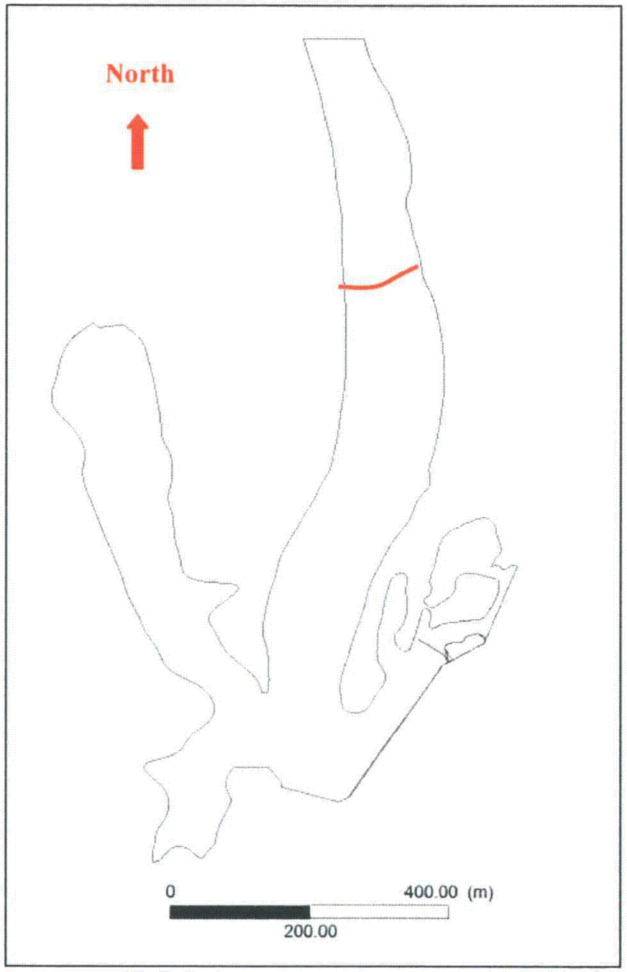


Figure B-3. Location of velocity measurements at upstream river section.

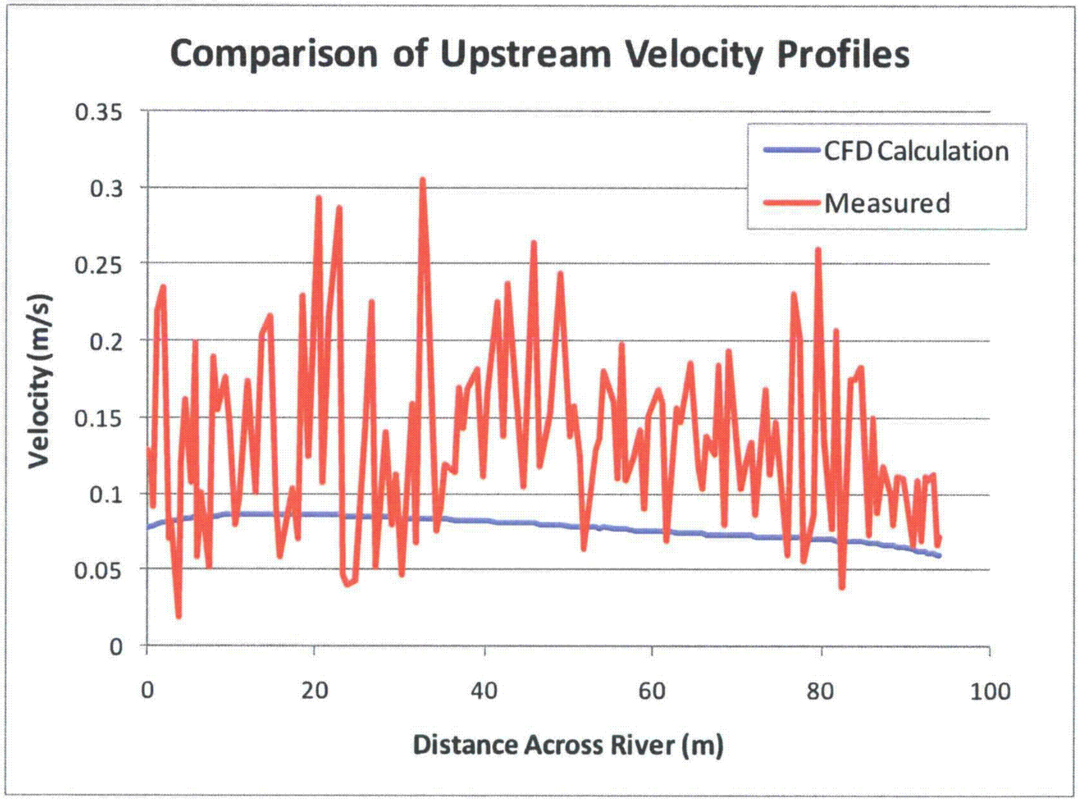


Figure B-4. Comparison of upstream velocity profiles across the river.

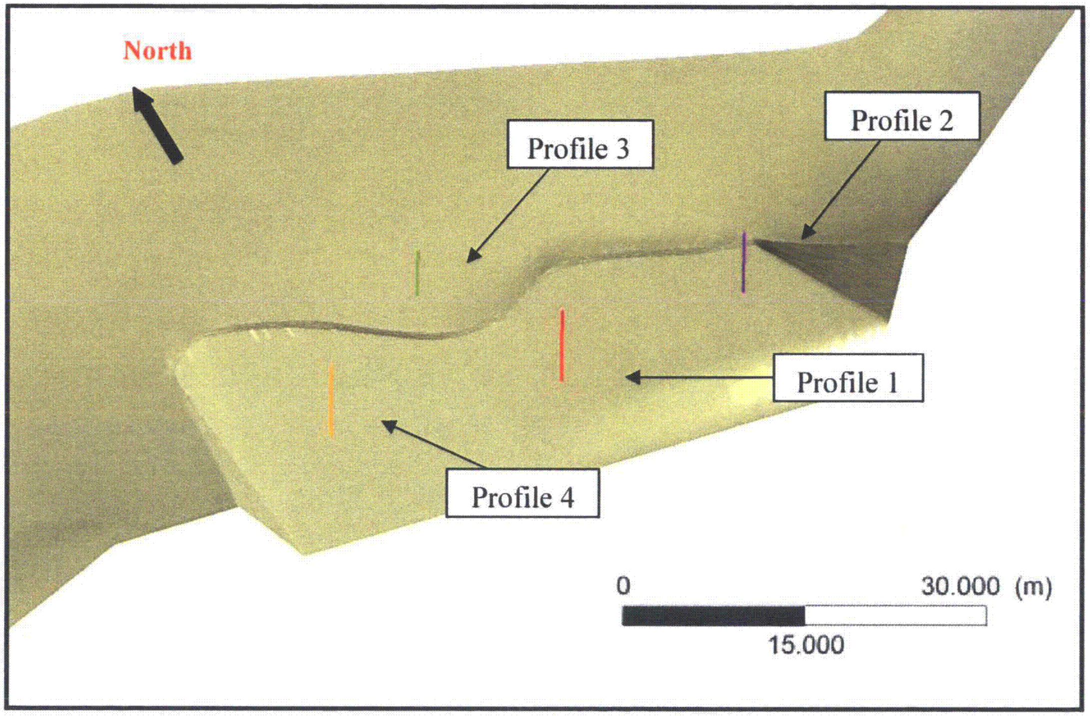


Figure B-5. Location of velocity profiles in NNI Reservoir forebay immediately in front of the turbine penstocks.

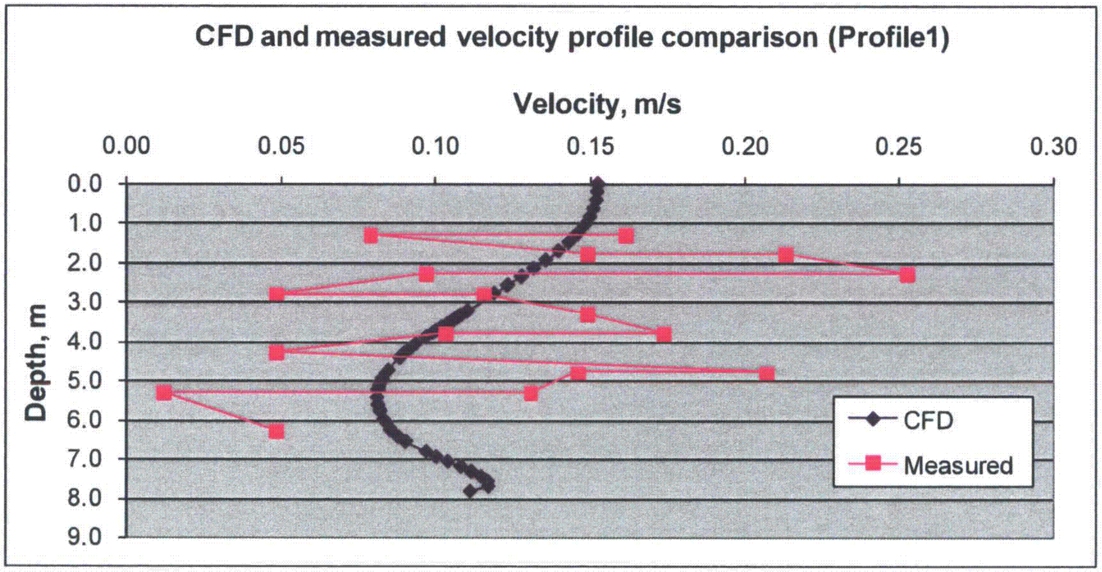


Figure B-6. Comparison between CFD velocity and measured velocity at Profile 1.

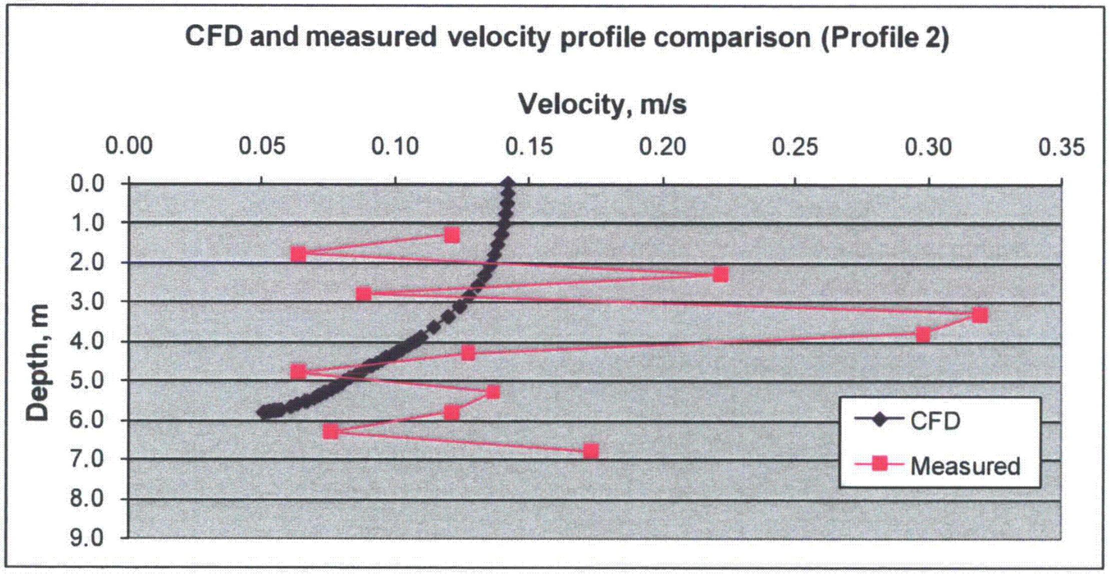


Figure B-7. Comparison between CFD velocity and measured velocity at Profile 2.

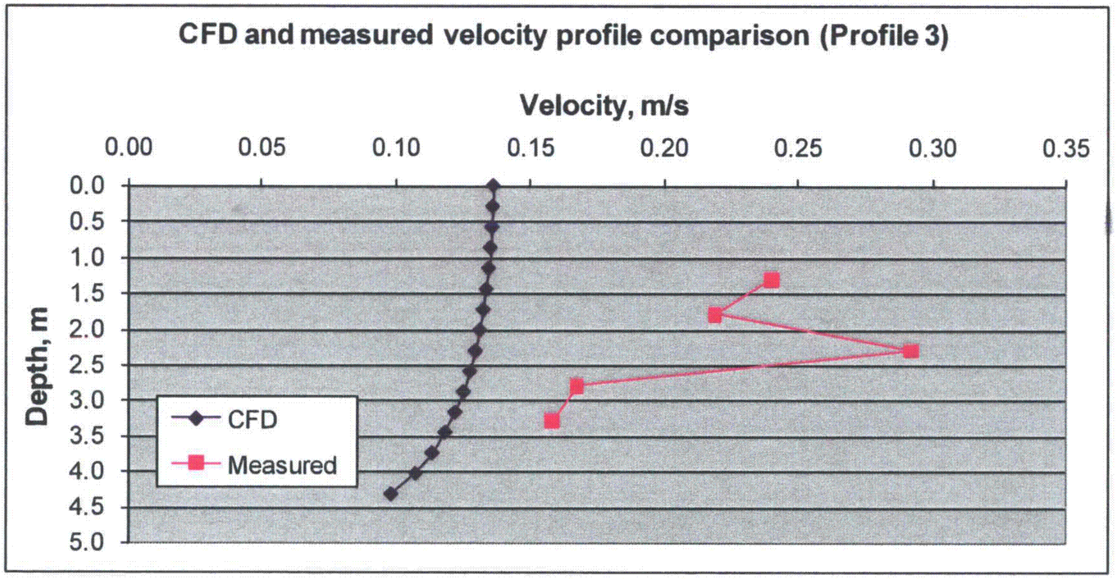


Figure B-8. Comparison between CFD velocity and measured velocity at Profile 3.

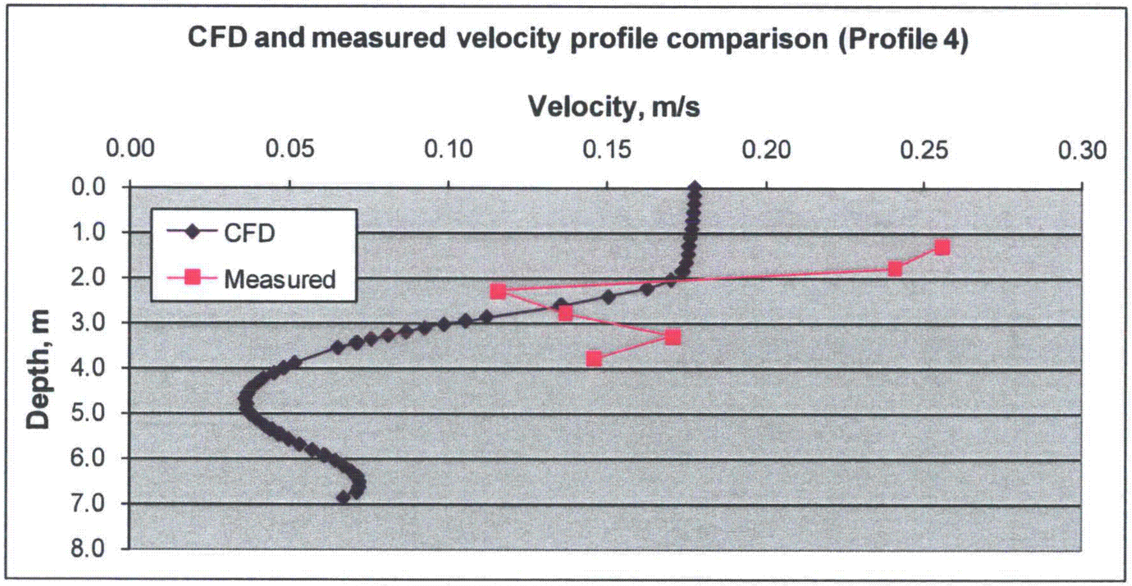


Figure B-9. Comparison between CFD velocity and measured velocity at Profile 4.

APPENDIX C – SMALLMOUTH BASS TEMPERATURE REQUIREMENTS

The CFD thermal modeling study was conducted in large part to respond to comments received by the NRC on the LNS COL. The comments expressed concerns for the potential effect the thermal discharge from the plant might have on the smallmouth bass fishery they manage/maintain downstream of the NNI Dam.

A review of relevant technical literature on the thermal requirements of smallmouth bass was conducted to assist in the interpretation of the CFD modeling results with respect to potential cooling water discharge impacts to the existing stocked fishery in the Broad River downstream of NNI Dam. The search utilized established internet scientific journal search sites and other reliable sources to retrieve information on the optimal and maximum temperature requirements, and associated behavioral responses, of smallmouth bass.

An annotated bibliography of key publications supporting the conclusions in Sections 5 and 6 of this study is provided below.

Armour, C.L. 1993. *Evaluating temperature regimes for protection of smallmouth bass*. Resource Publication 191. U.S. Fish and Wildlife Service, Washington, D.C. 26 pp.

This paper summarizes existing literature on smallmouth bass temperature requirements at the time of writing and presents concepts for evaluating the suitability of alternative temperature regimes for smallmouth bass through experimentally derived data, including ultimate incipient lethal temperatures and maximum weekly average, short-term maximum, and final preferendum temperatures. Also, concepts are described for basing evaluations on temperature tolerances for periods including spawning, egg and larval incubation, growth, and winter survival in the first year of life. The author reports that smallmouth bass "*are tolerant to relatively high temperatures*" and cites a Tennessee study where adult bass tagged with temperature sensitive transmitter tags remained in water exceeding 28 °C (82.4 °F) during summer, though cooler water existing in the thermally stratified and well-oxygenated reservoir habitat. Another study cited indicated conditions tolerated by smallmouth bass in Virginia streams included ambient temperatures of up to 35 °C (95 °F).

Bevelhimer, M.S. 1996. Relative importance of temperature, food, and physical structure to habitat choice by smallmouth bass in laboratory experiments. Transactions of the American Fisheries Society 125:274-283.

The premise for this work was field studies suggesting that the preference for an optimal temperature is often overridden by a stronger preference for other habitat variables such as physical structure. A temperature gradient tank was used with various treatments of ration, prey availability, and cover to test the relative importance of these factors in conjunction with temperature on habitat selection by individual smallmouth bass. The presence of food and cover significantly affected the temperature selected by smallmouth bass. Fish presented with a limited amount of food at a position of greater than preferred temperature in the tank increased the time spent at high temperatures, whereas fish allowed to feed till satiated retreated to the cold end of the lank for most of the day. When cover was present at the warm end of the tank, the mean time spent in this area was five times greater than when no cover was present in the tank. In conducting the laboratory studies, the author assumed smallmouth bass juveniles preferred a temperature range of 26 to 31 °C (78.8 to 87.8 °F) ; and adults, 21-26 °C (69.8 to 78.8 °F). The author also cites the same Tennessee study as Armour (1993) where adult bass tagged with temperature sensitive transmitter tags remained in water exceeding 28 °C (82.4 °F) during summer.

Brungs, W.A., and B.R. Jones. 1977. *Temperature criteria for freshwater fish: protocol and procedures.* EPA-600/3-77-061. U.S. Environmental Protection Agency, Environmental Research Laboratory, Duluth, MN. 129 pp.

This paper presents temperature criteria for freshwater fish expressed as mean and maximum temperatures. Mean temperatures are cited as important for controlling various life functions such as embryogenesis, growth, maturation and reproductively; maximum temperatures provide protection for all life stages against lethal conditions. Temperature criteria are provided for 34 freshwater fish species based on a number of field and laboratory studies. For juvenile and smallmouth bass, the maximum weekly average temperature (MWAT) for growth during summer is reported as 29 °C (84 °F); insufficient data were available to determine the maximum temperature for survival of short term exposure.

Coutant, C.C., 1977. *Compilation of temperature preference data.* Journal of the Fisheries Research Board of Canada 34:739-745.

This paper summarizes current (at the time) information on temperature selection by fishes based on field and laboratory studies and includes a tabulation of final temperature "preferenda" and upper and lower avoidance temperatures. For smallmouth bass, final temperature preferendum in summer ranged from 30 to 31 °C (86 to 87.8° F) for adult and young-of-the-year (YOY) life stages, respectively. Upper avoidance temperatures were reported as 35 °C (95 °F) for YOY and 33 °C (91.4 °F) for adult bass. The original source for these data was controlled laboratory studies.

Cherry, D.S., K.L. Dickson, and J. Cairns, Jr. 1975. *Temperatures selected and avoided by fish at various acclimation temperatures.* Journal of the Fisheries Research Board of Canada 32:485-491.

These researchers studied temperature preferences for 13 young-of-the-year freshwater fish species using a portable laboratory located at a thermal discharge site where most of the species occurred. Temperature selection and avoidance trials were performed in specialized apparatuses over a series of progressively decreasing acclimation temperatures to simulate transition from summer to winter conditions. Temperatures selected and avoided by fish subjects declined as acclimation temperatures decreased. Based on replicate trials, smallmouth bass acclimated at 27 °C (80.6 °F) preferred temperatures of 30.1 °C (86.2 °F); those acclimated at 30 °C (86 °F) selected temperatures of 31.3 °C (88.3 °F). At higher acclimation temperatures (> 18 °C; 64.4 °F), smallmouth bass selected temperatures that were equal to or slightly less than those preferred by bluegill sunfish (*Lepomis macrochirus*). Upper and lower avoidance temperatures for smallmouth bass were 31 and 24° C (87.8 and 75.2 °F), respectively for fish acclimated at 27 °C (80.6 °F); and, 33 and 26 °C (91.4 and 78.8 °F) for fish acclimated at 30 °C (86 °F). Eurythermal species (e.g., smallmouth bass) were characterized in this work by relatively wide ranges between upper and lower avoidance temperatures indicating a greater tolerance or flexibility of the fish to temperature changes.

Eaton, J.G., J.H. McCormick, B.E. Goodno, D.G. O'Brien, H.G. Stefany, M. Hondzo, and R.M. Scheller. 1995. A field information-based system for estimating fish temperature tolerances. Fisheries 20(4):10-18.

This technical article describes the state of the Fish and Temperature Database Matching System (FTDMS), its usage to estimate thermal requirements for fishes, some proposed maximum temperature tolerances for several freshwater fish species, and the way these FTDMS-derived values relate to various laboratory test results. The FTDMS utilizes existing records of water temperature obtained from U.S. Geological Survey monitoring stations coincident with nearby fish species occurrence data in estimating the maximum weekly mean temperature tolerance for 30 common fish species. The 95th percentile of the weekly mean temperatures was used to estimate the maximum temperatures tolerated by a particular species. For smallmouth bass, the FTDMS-based analysis indicated a temperature tolerance of 29.5 °C (85.1 °F). Maximum weekly mean species-specific temperatures derived from FTDMS were always less than laboratory-determined lethal temperatures (maximum 35 °C; 95 °F) and were similar to temperature criteria obtained from laboratory data through the U.S. Environmental Protection Agency interpolation procedures (29 °C; 84.2 °F).

Hokanson, K.E.F. 1990. A national compendium of freshwater fish and water temperature data. Volume II: Temperature requirements for thirty fishes. Archive of laboratory database available from Technical Information Office, Document No. ERL-DUL-2338. U.S. Environmental Protection Agency, Environmental Research Laboratory, Duluth, MN.

This document is a compilation of temperature requirements for freshwater fishes obtained from over 500 previously published temperature studies. The author evaluates and critiques the laboratory test/field conditions used in the published works and discusses sources of variation in the resulting temperature data. The "best available" thermal criteria are presented for survival, growth, and reproduction based on laboratory studies meeting minimum testing specifications determined by the author. Optimum temperature for smallmouth bass growth is reported as 29 °C (84.2 °F); "maximum final preferendum" temperature is reported as 31 °C (87.8 °F). Lethal temperatures reported ranged from 35 to 38 °C (95 to 100.4 °F).

Shuter, B.J., D.A. Wismer, H.A. Gegier, and J.E. Matuszek. 1985. An application of ecological modeling: impact of thermal effluent on a smallmouth bass population. Transactions of the American Fisheries Society 114:631-651.

This document presents a 20-year integrated field, laboratory, and simulation study of the impact of thermal effluent from a nuclear power plant on smallmouth bass in Lake Huron near Baie du Doré. At the time of the study, Bruce Nuclear Generating Station consisted of four 750 megawatt reactors operating in open-cycle (once-through) cooling mode. At maximum capacity the facility discharged over 6,074 cubic feet per second (cfs) of cooling water warmed as much as 11 °C (~20° F) over ambient lake water temperature. A quantitative model was constructed to forecast the range of likely effects of the plant on the population. The model was based on the findings of 50 years of basic research on smallmouth bass ecology in Ontario and on 15 years of environmental and biological data collected in Lake Huron near the site before the power plant became operational. Five years of monitoring data, collected after the plant became operational, were used to evaluate the forecasts of the model. In summary, the modeling effort supported by the empirical data did not demonstrate a substantial change in either the locations of adult pre-spawning and nesting areas, or nursery and over-wintering areas for young-of-the-year smallmouth bass. The data also suggests that the discharge area attracts many young-of-the-year and adult bass during summer and early fall. Mean daily water temperature in the discharge area during August was reported as 25.8 °C (78.4 °F).

Smale, A.M. and C.F. Rabeni. 1995. Hypoxia and hyperthermia tolerances of headwater stream fishes. Transactions of the American Fisheries Society 124:698-710.

The objective of this study was to determine the relative degree of fish tolerance to low dissolved oxygen (hypoxia) and high water temperature (hyperthermia) for species commonly found in small headwater streams of Missouri. Based on a consistent laboratory testing protocol, the authors developed a reference base of relative hypoxia and hyperthermia tolerance rankings for common, small stream fish species. Fish collected from the wild during late summer or early fall were acclimated to laboratory conditions at 26 °C (78.8 °F) over a 63 to 160-day period. They were then exposed to either progressively increasing temperatures or to decreasing dissolved oxygen concentrations over a 4 to 6-hour period. The temperature at which a fish lost equilibrium or the oxygen concentration at which it ceased ventilating was recorded as the end point. No significant differences in critical maximum temperatures (hyperthermia tolerance) or critical minimum oxygen concentrations (hypoxia tolerance) occurred in any of the five comparisons between fish of the same species collected from different locations in Missouri. Neither the hypoxia nor hyperthermia tolerance values varied with fish size for any species. Among the 35 species tested, hypoxia tolerance means ranged from 0.49 to 1.59 milligrams per liter (mg/L). Among the 34 species tested, hyperthermia tolerance means ranged from 34.9 to 38.8 °C (94.8 to 101.8 °F). For smallmouth bass ranging in weight from 2.4 to 9.6 grams, critical mean dissolved oxygen level (hypoxic tolerance) was 1.19 mg/L. Critical mean temperature (hyperthermal tolerance) for smallmouth bass ranging in weight from 4.2 to 13.5 grams was 36.9 °C (98.4 °F). Of the 34 fish species tested, smallmouth bass ranked 23rd most tolerant to elevated temperatures. Largemouth bass (*M. salmoides*) ranked 14th most tolerant.

Wrenn, W.B. 1980. *Effects of elevated temperature on growth of smallmouth bass.* Transactions of the American Fisheries Society 109:617-625.

Wrenn studied the long-term effects (one-year study) of elevated temperature on smallmouth bass (age 0+ at stocking) in four outdoor channels located on the Tennessee River in Alabama, the southern limit of the native range of this species. Substantial growth occurred throughout a temperature range of 20 to 32 °C (68 to 89.6 °F). After 322 days, net biomasses of smallmouth bass in the four thermal regimes evaluated were not significantly different. Reproduction at age I occurred in all four thermal regimes. Wrenn concluded that the broad thermal requirements for growth and survival of smallmouth bass measured in the study were characteristic of warmwater species. To protect smallmouth bass from elevated temperature, Wrenn concluded that a mean weekly average temperature of 32 to 33 °C (89.6 to 91.4 °F) would permit satisfactory growth; and a maximum temperature of 35 °C (95 °F) would avoid potential lethal effects for short-term exposure during the summer growth period. The author further concluded that the upper lethal temperature limit (or upper ultimate incipient lethal temperature [UUILT]) was "*probably as high as 37 °C*" (98.6 °F).

Wrenn, W.B. 1984. *Smallmouth bass reproduction in elevated temperature regimes at the species' native southern range.* Transactions of the American Fisheries Society 113:295-303.

Building upon his previous 1980 work, Wrenn evaluated the effects of elevated temperatures on smallmouth bass spawning time and reproductive success using outdoor channels located at a nuclear power plant on the Tennessee River in Alabama. Replicated treatments included ambient temperature of the Tennessee River with increments of 3, 6, and 9 °C above ambient (December-October). He observed that peak egg deposition was advanced about 8 days for every 3 °C increase over ambient, but occurred at temperatures (18-22 °C) within the normal range reported for spawning smallmouth bass (15-26 °C). Duration of spawning periods (11 to 19 days) in the four temperature treatments evaluated was consistent with the literature on natural populations. Survival rates from egg deposition to emergence from the nest were about 90 percent in all treatments. Wrenn concluded that a maximum weekly average temperature of 26 °C during the spawning season would allow for survival of smallmouth bass eggs and larvae. This study indicated that the southern limit of the original range of smallmouth bass was not determined by the influence of temperature on reproduction and that above-normal temperatures would not affect reproduction and recruitment to the extent that low temperatures affect northernmost populations.

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