TEMPERATURE AND DISSOLVED OXYGEN

NANTAHALA RIVER

NANTAHALA PROJECT

INTRODUCTION

Even though the North Carolina Department of Environment and Natural Resources, Division of Water Quality (NCDENR-DWQ) has reported that the water quality in the Nantahala River supported its designated use, the measurement of water quality is a portion of the basic information requirement of 18CFR4.51 and 18CFR4.61. Pursuant to obtaining a Federal Energy Regulatory Commission (FERC) license, a State 401 water quality certification (maintenance of water quality standards associated with a project) is required for the project.

Traditionally, temperature and dissolved oxygen are the primary water quality parameters used to assess the habitability and suitability for many aquatic organisms. The NCDENR-DWQ has established water quality standards for these parameters for all waters of the State. The standards involve two primary considerations: first, the designated water uses for each reach of stream (Table 1), and, second, water quality limits required to protect those uses. The applicable water quality limits are summarized as follows (NCDENR-DWQ, 2002a):

> (b) Dissolved oxygen: not less than 6.0 mg/l daily average for trout waters; for non-trout waters, not less than a daily average of 5.0 mg/l with a instantaneous minimum value of not less than 4.0 mg/l. Swamp waters, lake coves, or backwaters, and lake bottom waters may have lower values if caused by natural conditions;
>
> (j) Temperature: not to exceed 2.8 degrees C (5.04 degrees F) above the natural water temperature, and in no case to exceed 29 degrees C (84.2 degrees F) for mountain and upper piedmont waters and 32 degrees C (89.6 degrees F) for lower piedmont and coastal plain waters. The temperature for trout waters shall not be increased by more than 0.5 degrees C (0.9 degrees F) due to the discharge of heated liquids, but in no case to exceed 20 degrees C (68 degrees F);

The NCDENR water quality temperature standard for designated trout waters is an upper limit of 20°C. However, in much of the United States, ambient water temperatures often exceed 20º C, even in natural trout streams (Ruane, 2002). Wildlife resource agencies (most notably the North Carolina Wildlife Resources Commission and the United States Fish and Wildlife Service) have requested the characterization of the water temperature and dissolved oxygen regimes in the Tuckasegee River system to provide information regarding the management of aquatic wildlife.

The objectives of this report are to describe the temperature and dissolved oxygen concentrations in the Nantahala Reservoir and the subsequent use of that water for power generation on the downstream temperatures and dissolved oxygen concentrations in the Nantahala River.

Table 1. Temperature and Dissolved Oxygen Sampling Locations Associated with the Nantahala Hydroelectric Project - Period of Deployments, Stream Classifications, and Available Historical Data

Site Location	**River Mile**	**Current Study** *Period of Deployment (% Data Recovery)*		**Historical Data** *Period of Record (Stream Classification)*		
		Temperature Loggers	**Hydrolabs 2001**	**NCDENR-DWQ**	**Fish and Wildlife Associates, Inc.**	**Tennessee Valley Authority**
Nantahala River - Nantahala **Reservoir** Forebay	N/A	N/A	N/A	*Lake Profiles 1989, 1991, 1993-94 (B; Tr)*	Lake Profiles 1999 - 2000	Lake Profiles 1983
Nantahala River - Nantahala By-Pass upstream of Dicks Creek	20.7	10 May, 2001 to 15 May, 2002 *(100%)*	23 Sep - 28 Sep *(100 %)*	N/A *(B; Tr)*	N/A	N/A
Dicks Creek - 200 meters upstream of confluence with Nantahala By-pass	N/A	10 May, 2001 to 15 May, 2002 *(98%)*	23 Sep - 28 Sep *(100 %)*	N/A *(C; Tr)*	N/A	N/A
Nantahala River - Nantahala By-Pass upstream of White Oak Creek	17.5	10 May, 2001 to 15 May, 2002 *(100%)*	23 Sep - 28 Sep *(100 %)*	N/A *(B; Tr)*	N/A	N/A
White Oak Creek - 100 meters upstream of confluence with Nantahala By-pass	N/A	10 May, 2001 to 15 May, 2002 *(100%)*	23 Sep - 28 Sep *(100 %)*	N/A *(C; Tr)*	Lake Profiles 1999 - 2000	N/A

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Nantahala River - Nantahala By-Pass upstream of Queens Creek Powerhouse	14.5	10 May, 2001 to 15 May, 2002 *(100%)*	23 Sep - 28 Sep *(100 %)*	N/A *(B; Tr)*	Lake Profiles 1999 - 2000	N/A
Nantahala River - Nantahala Powerhouse Flow	13.6	10 May, 2001 to 15 May, 2002 *(92%)*	Monthly ‘Grab’ Samples May - Dec 2001	N/A *(B; Tr)*	N/A	N/A
Nantahala River - upstream of Queens Creek and Winding Stair Road (Pattons Run)	12.2	10 May, 2001 to 15 May, 2002 *(98%)*	N/A	(Old USGS Gage) 1969 - 1984 *(B; Tr)*	N/A	N/A
Nantahala River - at Nantahala Outdoor Center (NOC), upstream of NPDES discharge	5.2	10 May, 2001 to 15 May, 2002 *(100%)*	N/A	N/A *(B; Tr)*		

Stream Classification		**Water Quality Standards**	
Symbol	**Designated Use**	**Temperature**	**Dissolved Oxygen**
B	Primary Recreation	less than 29°C	5 mg/l daily mean, 4 mg/l minimum
C	Secondary Recreation	less than 29°C	5 mg/l daily mean, 4 mg/l minimum
Tr	Trout Water	less than or equal to 20°C	6 mg/l daily mean, 5 mg/l minimum

METHODS

In May 2001, recording thermistors (StowAway®Tidbit®, Onset Computer Corp.) were programmed by Duke Power Company (DPC) to record temperatures at 15-minute intervals. The temperature loggers were deployed in the Nantahala River system at eight locations (Figure 1 and Table 1). The thermistors were deployed beginning on 10 May 2001 and recorded temperatures for a period of 370 days.

The loggers were attached to a loop of ⅛" wire rope cable. The loop was crimped with stainless steel sleeves. The tethered loggers were usually placed in a deep pool. The shore end of the cable was looped around an inconspicuous tree (or other permanent object), and again crimped with stainless steel sleeves. Two temperature loggers were deployed at each location (Figure 1 and Table 1) to provide redundancy in the event of logger failure and to minimize the loss of data due to vandalism (most loggers were deployed on individual tethers).

Data were downloaded from the loggers at approximately monthly intervals. For each deployment period, data editing involved plotting and comparing the data from individual loggers from each site and then comparing the similarity in trends and magnitude of differences to data from the nearest upstream or downstream location. Data that were obviously erroneous were discarded. The process of double deployment and monthly data retrieval resulted in a temperature data recovery of 100 % from all but three of the Nantahala River sites (Table 1). Data lost from the Dicks Creek site and from the Patton's Run site were the result the loggers found on the bank of the river. The loss of data from the Nantahala powerhouse canal was the result of a faulty 'data Shuttle' supplied by Onset Computer Corporation. After the loss of data from that site, data were downloaded directly into a computer and the 'data shuttle' was not used for any other data retrieval. The 15-minute temperature data from each location were averaged from midnight to midnight resulting in the daily average temperatures for each river location. Daily minimum and maximum values represent the range of individual readings during the given 24-hr period.

Monthly measurements of water quality (dissolved oxygen, temperature, conductivity, and pH) were obtained from the Nantahala powerhouse canal during times of generation using a calibrated Hydrolab DataSonde®.

Dissolved oxygen measurements (as well as conductivity, temperature, and depth) were collected with programmable Hydrolab DataSondes® in the Nantahala By-pass reaches. The Hydrolabs were deployed at the time that the controlled releases were made from the Nantahala dam tainter gate for the recreational angling and boating studies. The DataSondes were suspended off the bottom by an anchored float (Knight, 1998) at five locations in the Nantahala By-pass (Table 1). The Hydrolabs were programmed to record data at 5-minute intervals during a 4-day period in September 2001. One hundred percent of the data was obtained from the Hydrolabs.

Even though the North Carolina Certified Laboratory Procedures only require calibration of *in situ* monitors according to the manufacturer's recommendation, additional quality control procedures designed to measure the accuracy and precision of the instruments were employed prior to and after the river deployments. The recording thermistors were placed in a controlled temperature oil bath (traceable to NBS standards). The oil bath was adjusted in ~5C° increments while the instruments recorded the temperature at minute intervals. These data were within the manufacturer's specifications.

The Hydrolab DataSondes® were calibrated for dissolved oxygen, conductivity, and depth prior to each deployment. After initial calibration, the instruments were placed in a circulating water bath. The oxygen concentrations in the water bath were lowered by bubbling nitrogen or increased by bubbling oxygen. The DataSondes recorded the changes at one-minute intervals. After each change of oxygen concentration, a Winkler determination was made from the water bath. The dissolved oxygen concentrations recorded by the Hydrolabs and the Winkler method were compared over the range of dissolved oxygen concentrations. Results showed that the Hydrolab DataSonde dissolved oxygen concentrations were within the manufacturer's specifications prior to deployment; but, after deployment, the oxygen concentrations recorded by the Hydrolabs were slightly lower than the concentrations determined by the Winkler method. This instrument drift indicated slight membrane fouling during the time the instruments were in the river. No attempt was made to adjust the data recorded during the river deployments for this fouling. Therefore, the oxygen concentrations reported would represent slight underestimates of the actual river concentrations.

Reservoir temperature and dissolved oxygen profiles were obtained from TVA (storet files), Fish and Wildlife Associates, Inc., and the NCDENR-DWQ (Table 1). Reservoir morphometry (elevations, storage, structures, etc.) were obtained from the original drawings associated with the project (Nantahala Power and Light, 2002a) and the various metrics were calculated according to Hakanson (1981). Hourly generation data was provided by Duke Power Company, Hydro Operations (Holland, 2002). Bryson City meteorological data was obtained from the NCDENR - Division of Air Quality (Mullur, 2002). Historical records of the inflows to Nantahala Lake were obtained from Nantahala Power and Light operational data (change in lake storage corrected for outflow).

Historical records of water quality (temperature and dissolved oxygen, monthly grab samples) collected at RM 10.7 (Old USGS gage, 1969- 1984) were obtained from NCDENR-DWQ (Sauber, 2002).

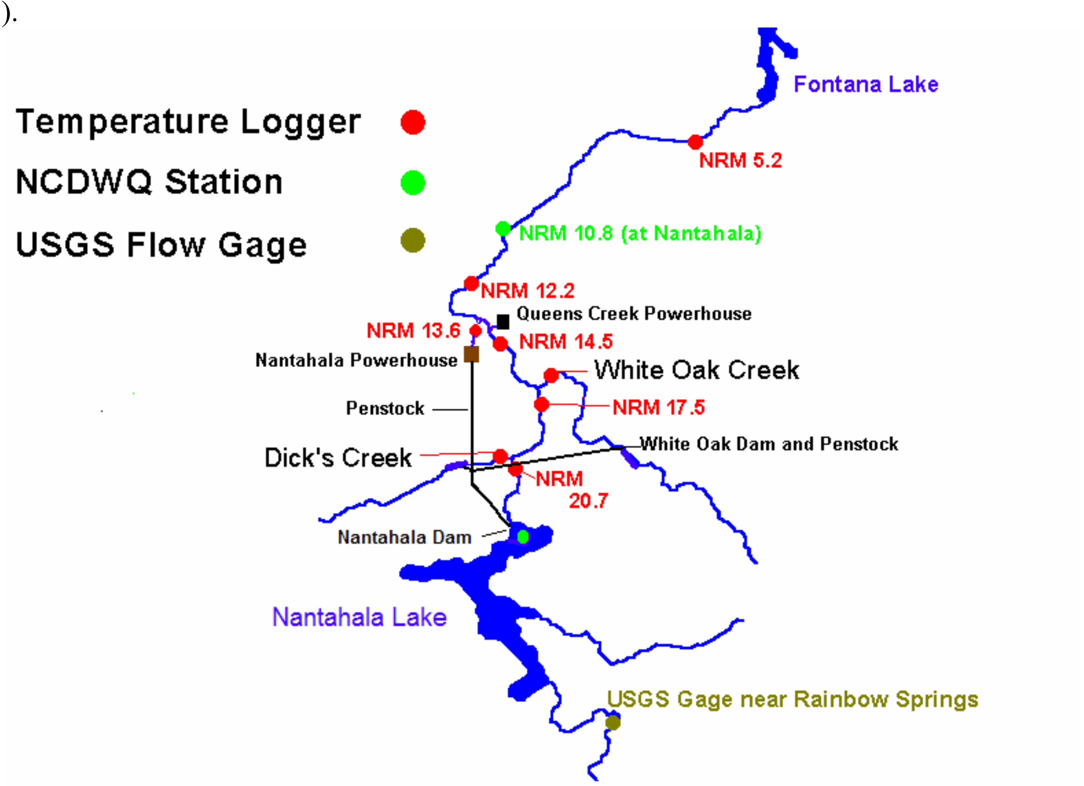

Figure 1. Map of Temperature and Dissolved Oxygen Sampling Locations in the Nantahala River - River Miles and Historical Data Collection Sites**SITE DESCRIPTION**

Nantahala River

The Nantahala River basin is located in Southwestern North Carolina between the Little Tennessee and Hiwasee River Basins. The Nantahala Dam was built in 1942 on the Nantahala River, 22.9 miles upstream from the confluence of the Little Tennessee River. From Nantahala Lake, also called Lake Aquone (Figure 1 and Table 2), a 29,654 ft. long tunnel-penstock supplies water to the Nantahala hydroelectric facility. The 9.3 mile long river channel from the Nantahala Lake dam to the Nantahala powerhouse canal confluence is referred to as the Nantahala Bypass. The bypass channel receives leakage and/or spill from Nantahala Lake as well as flow from the immediate drainage area and the two major tributaries, White Oak and Dicks Creek. One hundred meters upstream of the Nantahala powerhouse canal confluence with the bypass; Queens Creek powerhouse releases 22 cfs during generation into the Nantahala River channel. Since the Queens Creek FERC license requires 1 cfs to be diverted into Queens Creek during the summer and 2 cfs during the winter, these flows result in an average annual reduction of 18.8% water entering the Nantahala River from the Queens Creek powerhouse diverted to Queens Creek, 1.4 miles downstream of the Queens Creek powerhouse. The combined flow from the Nantahala powerhouse, Queens Creek powerhouse, and the Nantahala bypass travels approximately 8.7 miles through the Nantahala gorge to Lake Fontana, a TVA storage reservoir on the Little Tennessee River. From 12 November – 7 December 2001, the Nantahala River did not receive flows from the Nantahala powerhouse due to a scheduled outage.

A significant portion of the Nantahala River basin is managed by the US Forest Service and is a primary recreational area in Southwestern North Carolina. The NCDENR-DWQ (2002b) has based water quality standards for the entire Nantahala River for trout sustaining trout populations and for primary aquatic recreation. The NCWRC (Yow, 2002) manages the Nantahala River system as 'Wild Trout Waters'. The Nantahala Bypass is managed as a Hatchery Supported trout fishery with the section from White Oak Creek to the Nantahala powerhouse canal designated as Delayed Harvest. The Nantahala River downstream of the powerhouse canal (Nantahala Gorge) is also heavily used during the summer months for white-water rafting and boating; many 'white-water' businesses are located in the Nantahala Gorge.

Dicks Creek and White Oak Creek

Dicks Creek and White Oak Creek, the primary tributaries of the Nantahala Bypass, were dammed in 1948 and 1949, respectively, to supply additional water for electrical generation at the Nantahala powerhouse. Water from the Dicks Creek dam flowed through a 3875 ft. penstock to the connection with the Nantahala penstock. Water from White Oak Creek flows through 11445 ft. tunnel/penstock to the Nantahala penstock. Since the crests of these tributary dams are approximately 10 feet higher than the full pond level of Nantahala Lake, water from these tributaries flowed into the Nantahala penstock to Nantahala powerhouse during periods of electrical generation. When the Nantahala power plant was not generating, water flowed from the tributaries into the penstock to Nantahala Lake.

Under the current FERC license, the Dicks Creek penstock was closed, which diverted all of Dicks Creek water (≈12 cfs) into the Dicks Creek channel. In addition, a valve on the White Oak penstock (at Dicks Creek) diverted a portion of the White Oak water (≈ 8 cfs) into Dicks Creek. The combined flow entered the Nantahala Bypass. On 13 September 2001, a vehicle struck and punctured a hole in the White Oak penstock. This accident forced the isolation of the penstock and water from White Oak Creek dam flowed into the Nantahala Bypass through the White Oak Creek channel until the penstock was repaired and returned to service on the 24th of October.

Table 2. Morphometric Characteristics of Nantahala Lake

Full Pond Elevation	(m-msl)	918.1
	(ft-msl)	3012.16
Tainter Gate Bottom Elevation	(m-msl)	912.3
	(ft-msl)	2993.2
Penstock Center Elevation	(m-msl)	877.6
	(ft-msl)	2879.2
Penstock Invert Elevation	(m-msl)	875.4
	(ft-msl)	2872.2
Volume	(m^3)	1.690E+08
	(acre-ft)	137,000
Area	(m^2)	6.423E+06
	(acre)	1587.0
Maximum Depth	(m)	65.8
	(ft)	216.0
Mean Depth	(m)	26.3
	(ft)	86.3
Relative Depth	(%)	2.3
Mean Daily Inflow+	(cms)	10.08
	(cfs)	356.0
Mean Retention Time	(days)	194

\+ not including 12 cfs from Dicks Creek or 8 cfs from White Oak Creek

RESULTS

Temperature

The daily average temperatures calculated from the Nantahala powerhouse flow (RM 13.6) and Nantahala River at the Nantahala Outdoor Center (NOC) (RM 6.2) sites revealed significant colder temperatures from April through September compared to sites on the lower Tuckasegee River (Nantahala Power and Light, 2002b), Hiwassee River (Nantahala Power and Light, 2002c), and the Cullasaja River (Nantahala Power and Light, 2002d) (Figure 2). Water temperatures at those latter three sites were clearly in response to the prevailing meteorological conditions (evidenced by the changes in water temperature to changes of the daily mean air temperature[1]). Also, the water temperatures measured at those latter sites represent the probable water temperatures of the Nantahala River without the hypolimnetic withdrawal from the Nantahala hydroelectric project (Table 2). This hypolimnetic use by the project, and subsequent release of the cool water downstream, has permitted the NCWRC (and the NCDENR-DWQ) to manage a trout fishery in the lower Nantahala River. The temperature increase measured in the Nantahala River at the NOC represents the warming of the water used for generation as it traveled through the Nantahala Gorge as well as contributions from the Nantahala Bypass and tributary inflow. This report addresses the availability of the hypolimnetic cold water resource and the temperatures measured in the Nantahala Bypass

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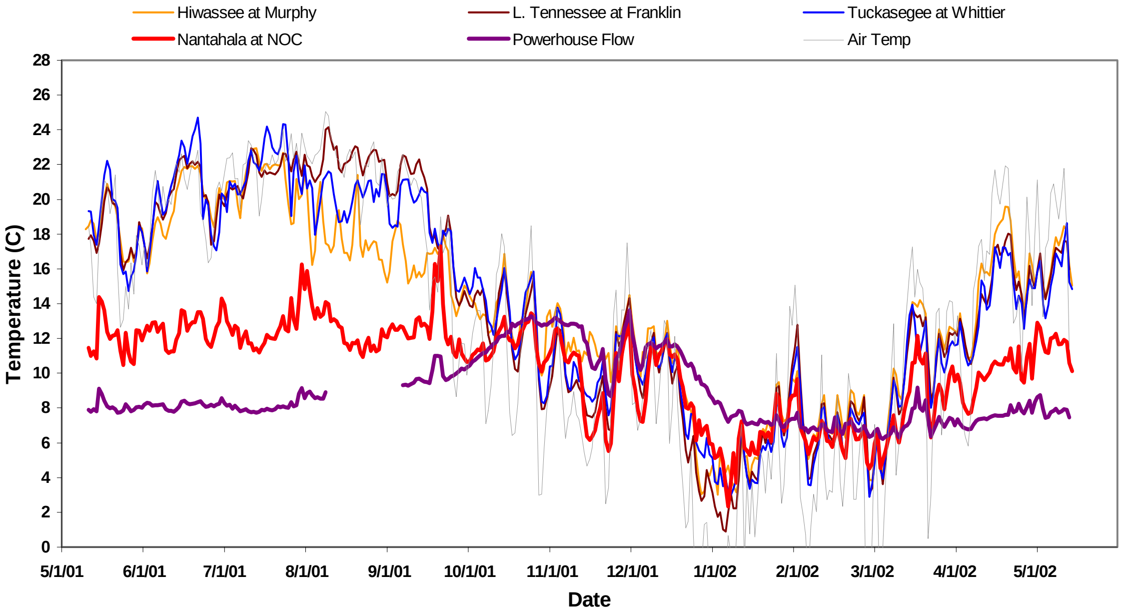

Figure 2. Comparison of the Nantahala River at the NOC (RM 6.2) and the Nantahala Powerhouse Flow (RM 13.6) Temperatures to the Temperatures Measured in the Tuckasegee River at Whittier (RM 19.2), Hiwassee River (RM 99.1), and Cullasaja River (RM 1.2)

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[1] Air Temperature is used in this report as a surrogate for equilibrium temperature (the theoretical temperature that the water would achieve under the prevailing meteorological conditions)

Nantahala Lake

As with most reservoirs in the Southeastern United States, Nantahala Lake exhibited characteristics of a warm, monomictic lake (Figure 3). The reservoir exhibited one mixing period during the winter and a prolonged, thermally stratified period during the spring-summer-fall months. The minimum water temperature (and the time of occurrence of the minimum temperature) was a function of the severity of the winter weather conditions. The temperatures at the bottom of the lake did not change during the stratified period (Figure 5) indicating that the bottom temperatures recorded from the various years (Figure 4) were indicative of the severity of the winter meteorological conditions. Nantahala Lake's large relative depth (measure of the resistance to deep water mixing), long retention time (Table 2), and summer/fall heat storage greatly impacted the extent of mixing and the minimum water column temperatures. As the weather warmed and solar radiation increased during the spring, the surface heating of the reservoir initiated thermal stratification. The timing of the vernal stratification was dependent upon the late winter/early spring meteorology. As Nantahala Lake's surface water continued to warm, water density gradients were formed, isolating the lower depths from atmospheric heat exchange (Figures 3 and 5). Thus, the amount of heat dissipated from the lake to the atmosphere during the winter dictated the amount of cold water stored in Nantahala Lake for the proceeding stratified period.

Maximum summer surface temperature usually occurred in August (Figure 5). Although the patterns of heating and cooling were unique for each summer, the summer surface water temperatures were similar between the various years (Figure 4) since the summer meteorological conditions between the years was also similar. Since the surface water temperatures were a function of the atmospheric heat exchange across the air/water interface, diel heating and cooling during the summer (as well as the limited wind fetch) contributed to the depth of the epilimnion (upper mixed layer).

Similar to the initiation of thermal stratification in the spring, the meteorological conditions in the fall and winter determined the timing and the extent of reservoir cooling and subsequent mixing. For example, by the middle of October 2000 (Figure 5), the loss of heat to the atmosphere had mixed the water column to a depth of 30 meters. In 1983 (Figure 3) mixing began in late September and continued through December. Complete water column mixing had not occurred by the end of that year. Evidence of Nantahala Lake mixing was also apparent from the temperatures recorded from the Nantahala powerhouse flow (Figure 2). As air temperatures rapidly decreased from mid-December to mid-January, a similar decrease was observed in the canal temperatures (Figure 2). These data indicate that Nantahala Lake was mixed to at least the depth of the penstock opening by mid-December when the powerhouse canal temperatures began to decrease significantly. This trend of decreasing temperatures continued until mid-January, indicating the lake was still cooling and mixing until weather conditions warmed to prevent further cooling

The most notable differences of water column temperatures during all of the stratified periods were observed in the metalimnetic region (region of increased thermal gradients) (Figures 3, 4, and 5). Unlike natural lakes where the formation of the metalimnion is solely a function of wind fetch and diel convection, thermal stratification patterns in reservoirs are also strongly influenced by advection. In the case of Nantahala Lake, cold water was removed from the lake via the deep-water penstock thereby deepening the metalimnion and warming the successive upper layers. As long as water was removed during the stratified period, this warming would continue to the depths of the penstock (Figure 3). The rate of heating of the metalimnion was a function of the rate of deep-water removal from Nantahala Lake (Figure 6). The average daily penstock flow to Nantahala powerhouse (calculated from June through August for each year) removed the cooler water from the lake at the penstock depth, this cooler water was 'replaced' by warmer water from above. Of all of the summers

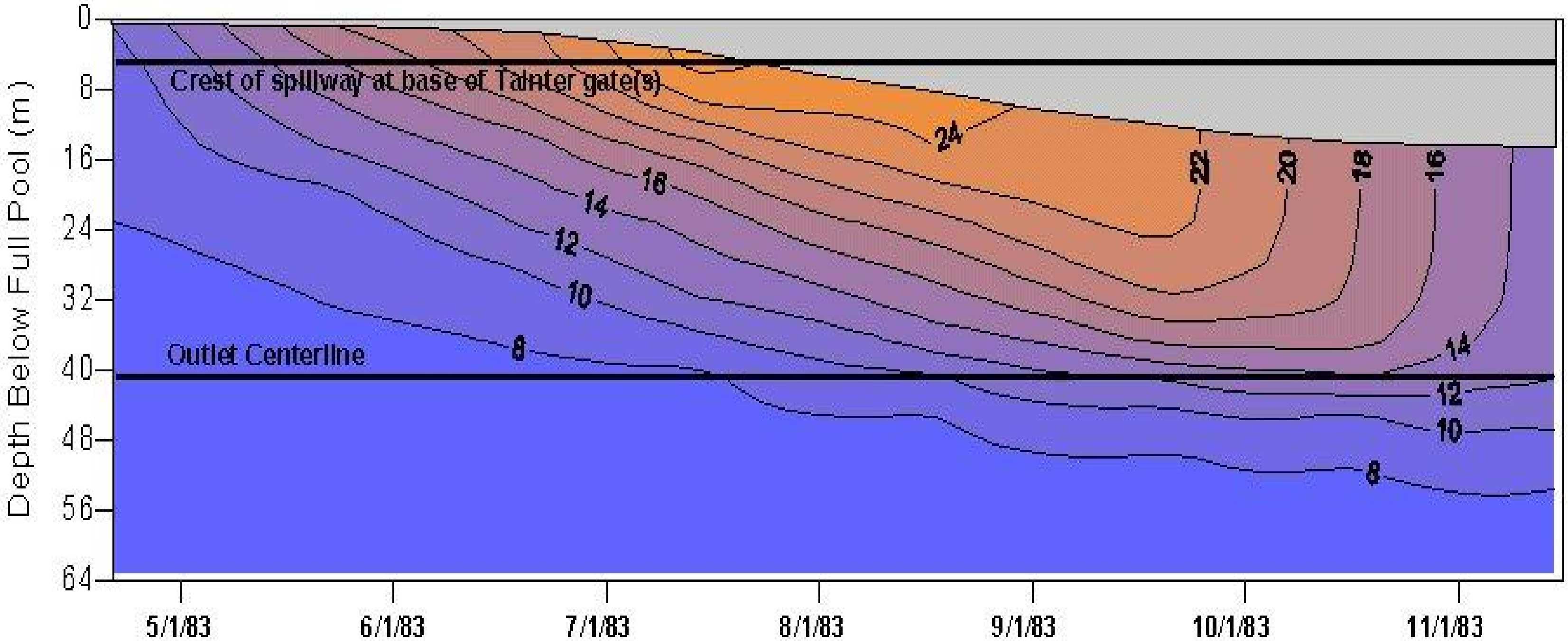

Figure 3. 1983 Temperature Isopleths in Nantahala Lake

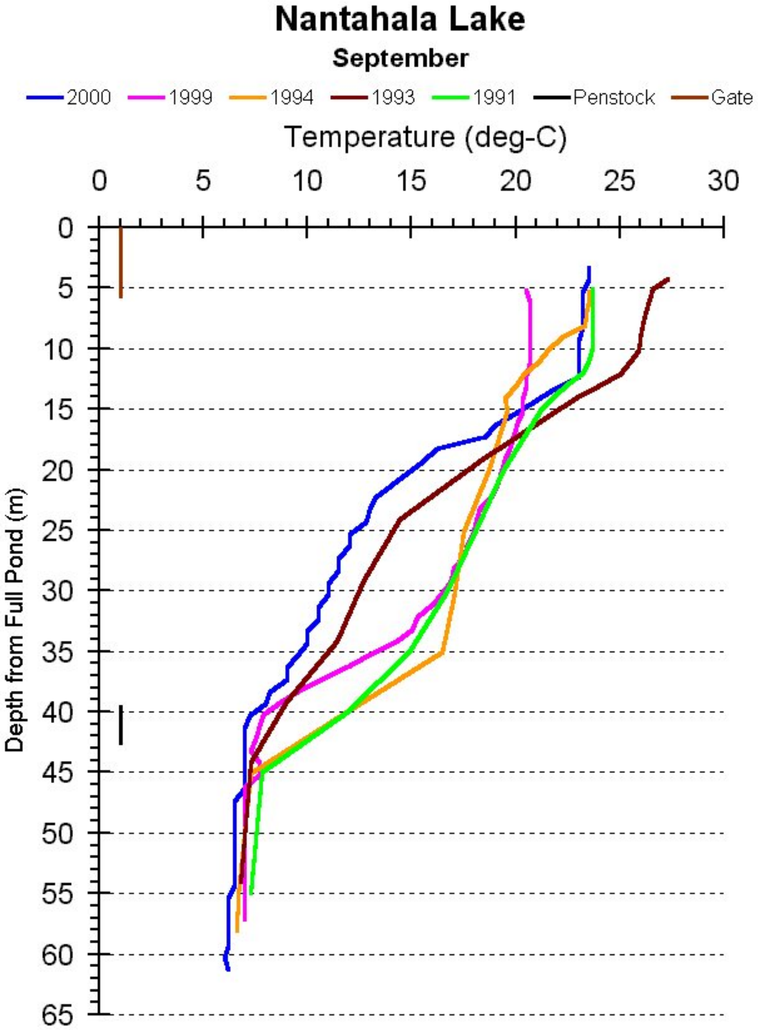

Figure 4. September Temperature Profiles in Nantahala Lake - 1991, 1993, 1994, 1999, and 2000.

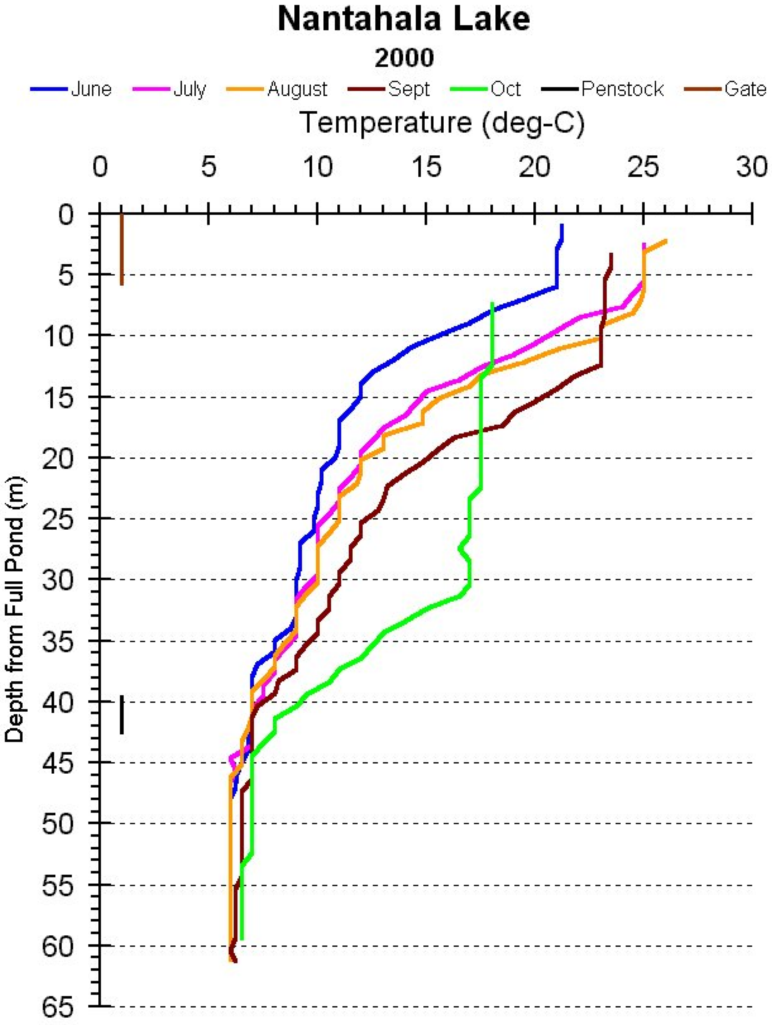

Figure 5. 2000 Summer Temperature Profiles in Nantahala Lake

where data was available (Figure 4), the rate of the hypolimnetic loss was most pronounced in 1994, where the average flow through the penstock was 473 cfs. In contrast, 2000 exhibited minimal hypolimnetic loss since only an average of 137 cfs was used by Nantahala hydro. Coincidentally, the y-intercept of the depths of the isotherms (Figure 6 at zero flow) corresponded to the theoretical thermocline depth[2] calculated for natural lakes (Lerman ,1978).

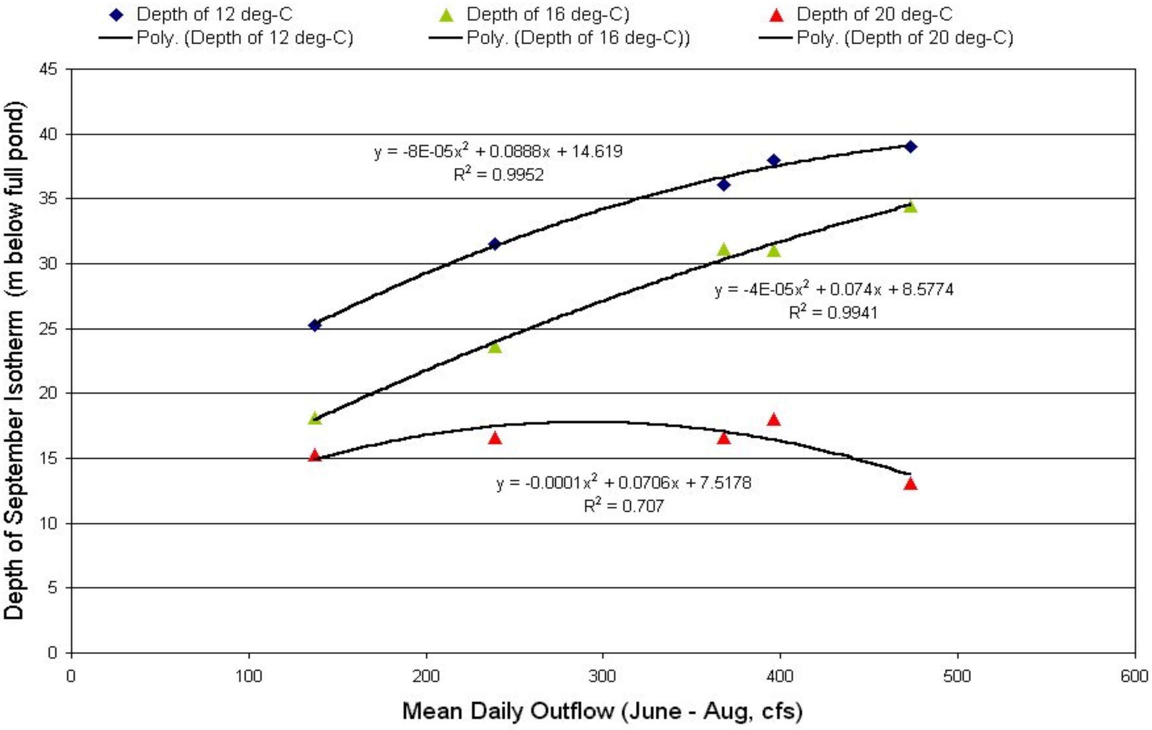

Figure 6. Regression Analysis of the September Depth of the 12º, 16º, and 20º Isotherms in Nantahala Lake as a Function of the Mean Daily Summer Outflow

Since the amount of cold water stored in Nantahala Lake was determined at the beginning of the stratified period and since this cold water is supplied to the Nantahala River via Nantahala hydro, the management of the rate of warming in the deeper depths of Nantahala Lake becomes very significant to the water quality objectives in the Nantahala River. Unlike the empirical relationship (Figure 6), which used the arbitrary time frame of June - August, the availability of cold water[3] throughout the stratified period was calculated based upon the amount of water stored in Nantahala Lake (Figure 7). Using the 20ºC temperature standard for trout as an example[4], the number of days that water equal to or less than 20ºC that may be released from Nantahala Lake was calculated for various flow rates (Figure 8). The flow rates used for the calculations were derived from the historical inflows[5] to Nantahala Lake The results of the calculations revealed that the total amount of water used from the penstock must be considered for both lake level and downstream temperature management

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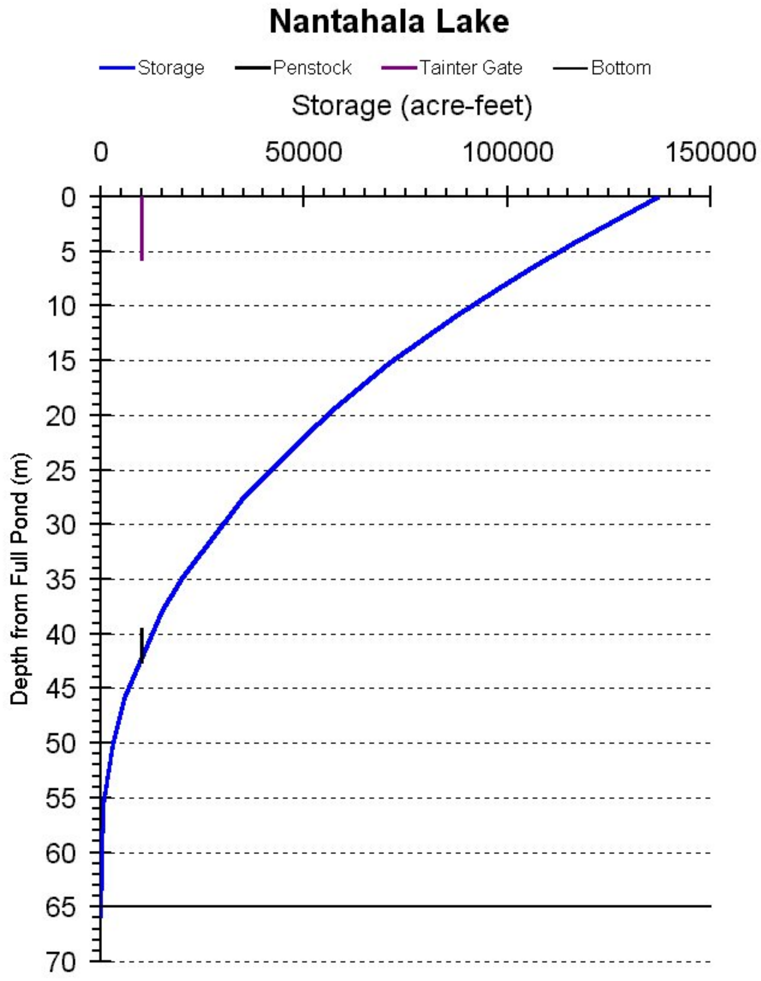
[2] Since natural lakes do not have a deep-water withdrawal, the thermocline depth is a function of the wind fetch of a lake, Nantahala Lake's average fetch was estimated at 1.9 km.

[3] The actual temperature of the water was a function of the winter meteorological severity.

[4] The same calculation may be made for any desired temperature.

[5] The use of the statistically derived inflows (1955-1999) for the calculation was based upon keeping the lake level constant during the stratified period, if the outflows exceed the inflows (as in Figure 6), the lake level would drop, but the prediction in Figure 8 would remain the same.



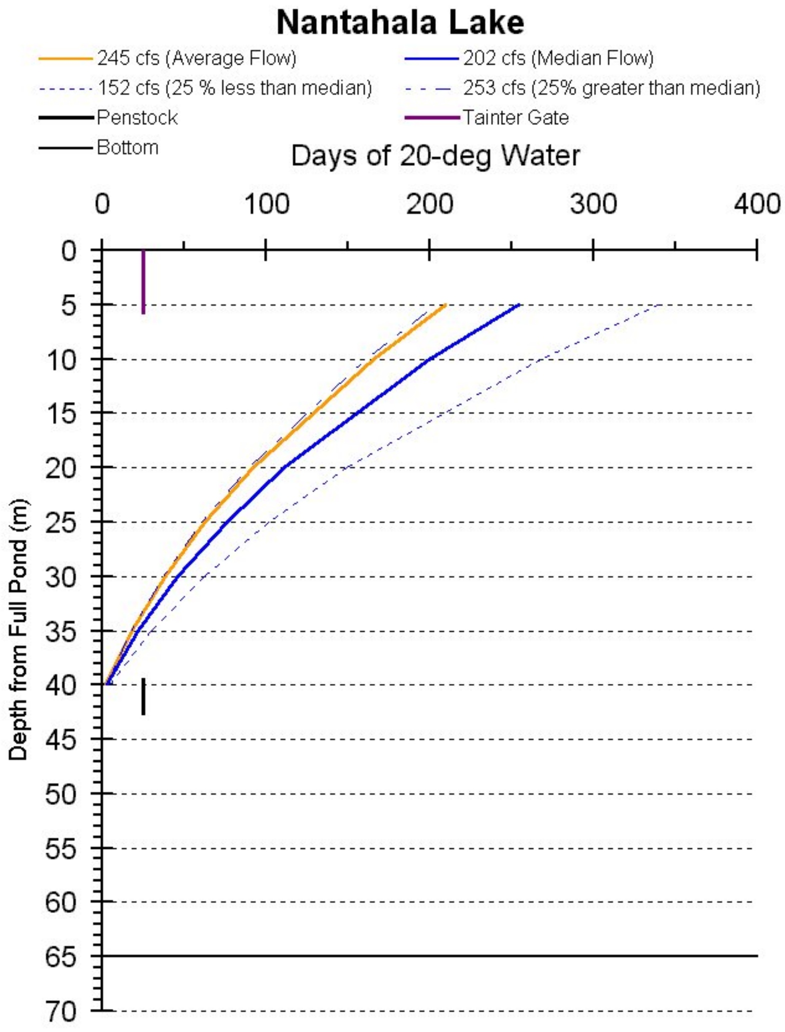


Figure 8. Nantahala Lake Storage Curve

Figure 9. Potential Days of 20ºC (or less) Water Released from Nantahala Hydroelectric Station at Various Summer Tributary Inflows

Nantahala Bypass

The daily average, minimum, and maximum temperatures calculated from the 15-minute temperature recordings from the 3 sites in the Nantahala Bypass (Figures 10, 11, and 12) paralleled the mean daily air temperatures. Within the general seasonal trends of temperature patterns, shorter intervals of heating and cooling periods were observed, indicating a rapid response of river temperatures to the prevailing meteorological conditions. Temperatures in the bypass exhibited warmest temperatures during July and August with coolest temperatures in late January and early February. Even though the bypass temperatures were a function of the meteorological trends, the bypass temperatures were cooler than those measured from other river sites (Figure 3). This was not surprising since the bypass was at a greater altitude (cooler meteorological conditions) and was shaded from the underbrush and the surrounding mountains more than the larger rivers. Rarely did the mean daily temperatures from any of the sites exceed the 20ºC state temperature standard for trout, but the daily maximum temperatures routinely exceeded 20ºC during the summer months.

Comparison of the daily mean summer temperatures from the 3 sites in the Nantahala Bypass (Figure 13) reveals that all three sites exhibited very similar temperature patterns. The upper and lower sites (immediately upstream of Dicks Creek and just upstream of Queens Creek powerhouse, respectively) exhibited almost identical daily mean temperatures, indicating that the water temperatures were at or very close to meteorological equilibrium. However, the stream temperatures recorded immediately upstream of White Oak Creek were slightly cooler than the upper and lower locations due to the contribution of water from tributary inflow, primarily Dicks Creek.

The daily average, minimum, and maximum temperatures of the major tributaries to the Nantahala Bypass, Dicks Creek and White Oak Creek, followed the same pattern as did the temperatures in the bypass (Figures 14 and 15). However, during the summer months, these tributaries exhibited slightly cooler water than the bypass, with Dicks Creek slightly cooler than White Oak (Figure 16).

The three periods of Nantahala tainter gate releases (spill) into the bypass that were conducted for the recreational and IFIM studies provides an opportunity to evaluate the heating and cooling of the bypass water under various conditions (Figures 17-19). Since the epilimnetic water from Nantahala Lake that was released into the bypass was warmer than the water in the bypass, the three spill periods (22-23 August, 19–20 September, and 25-27 September) resulted in the daily average temperature ‘spikes’ observed in the bypass (Figures 10, 11, and 13).

The August spill test (Figure 17) was conducted to determine the tainter gate settings needed to provide the desired flow for the September IFIM and recreational studies. Prior to and after the spill, the low flow (6.2 cfs) in the 3.1-mile long bypass upstream of Dicks Creek appeared to be in equilibrium with the metrological conditions. The cooler Dicks Creek water (supplemented by the White Oak penstock water) added 11.4 cfs to the bypass. The resulting flow of 17.6 cfs warmed as it traveled the 3.2 miles to the confluence of White Oak Creek. The temperatures immediately upstream of White Oak Creek were less than a degree difference than the water upstream of Dicks Creek. White Oak Creek supplied an additional 15.7 cfs of water to the bypass. Even though White Oak Creek supplied additional cool water to the bypass, by the time the combined flow of 33.3 cfs traveled the 3 miles to the Queens Creek powerhouse, the water had warmed to temperatures slightly greater than those observed above Dicks Creek.

When 36 cfs of warm, epilimnetic Nantahala Lake water was. added to the bypass (total combined flow upstream of Dicks Creek = 42 cfs), the warm water extended downstream to Dicks Creek (Figure 17). However, significant cooling occurred in the first 3.1 miles downstream of the dam as suggested by the comparison of the temperatures recorded under high flow. Substantial cooling

continued

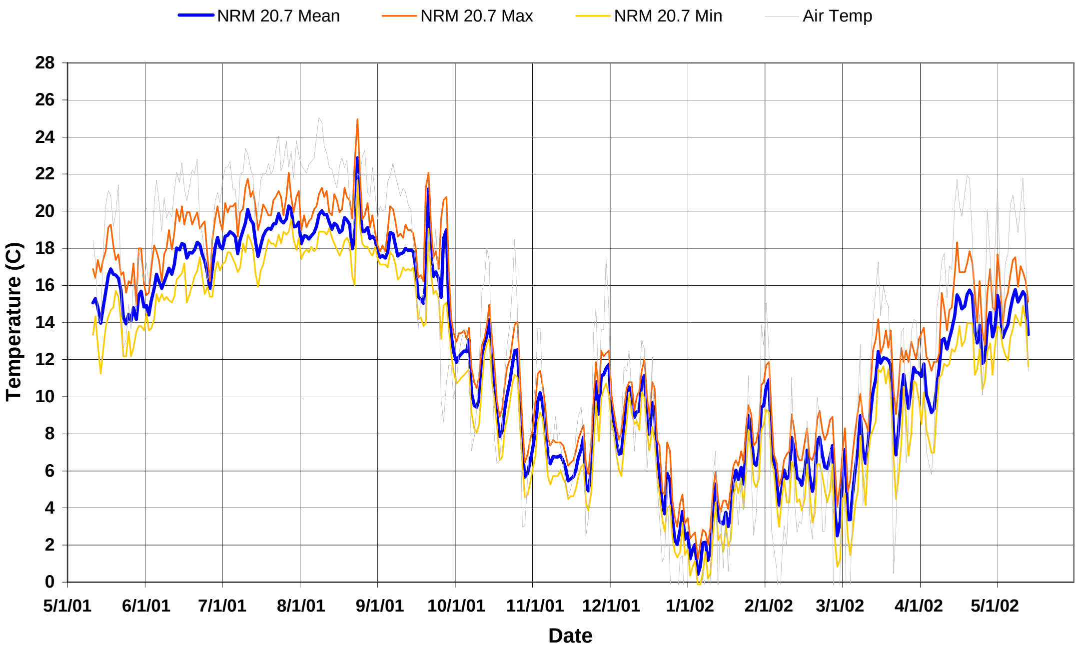


Figure 10. Mean, Minimum, and Maximum Daily Water Temperatures, Nantahala Bypass, upstream of Dicks Creek.

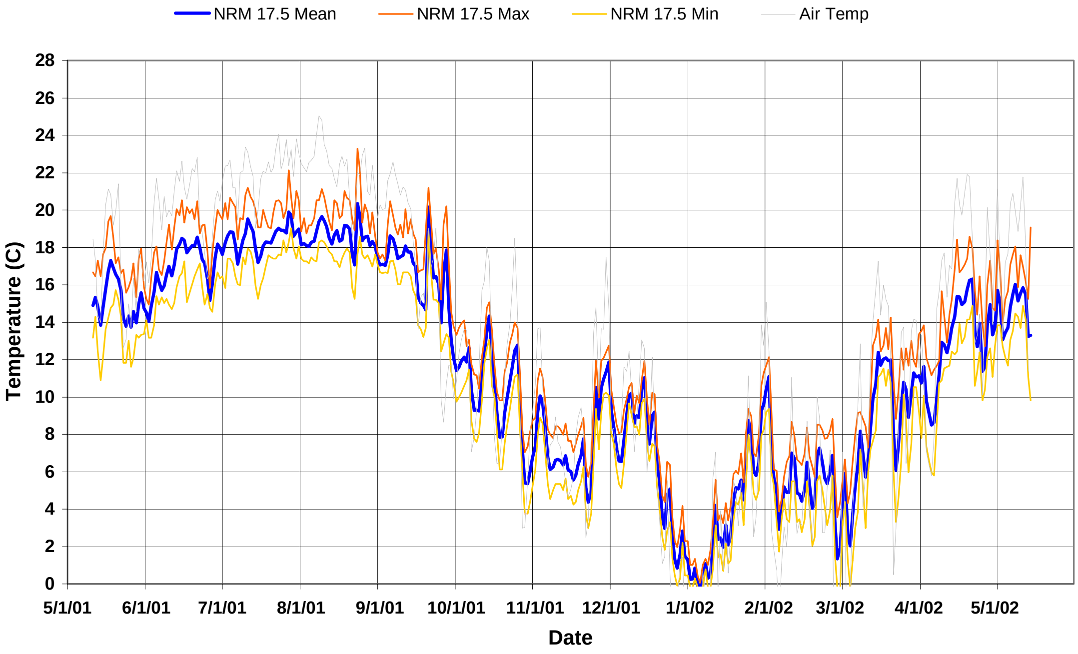


Figure 11. Mean, Minimum, and Maximum Daily Water Temperatures, Nantahala Bypass, upstream of White Oak Creek

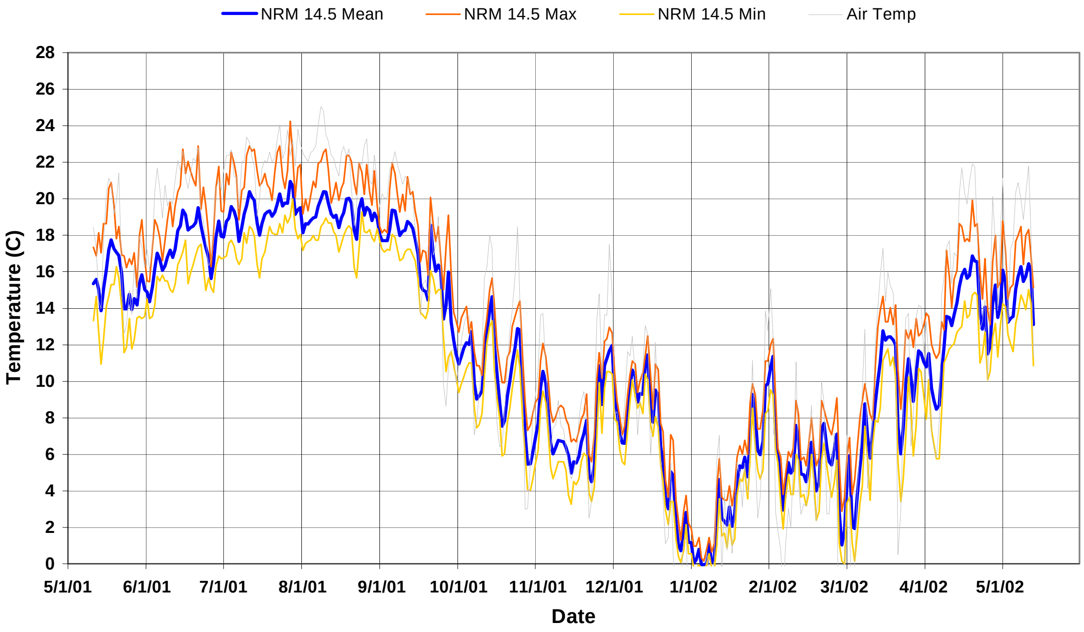


Figure 12. Mean, Minimum, and Maximum Daily Water Temperatures, Nantahala Bypass, upstream of Queens Creek powerhouse

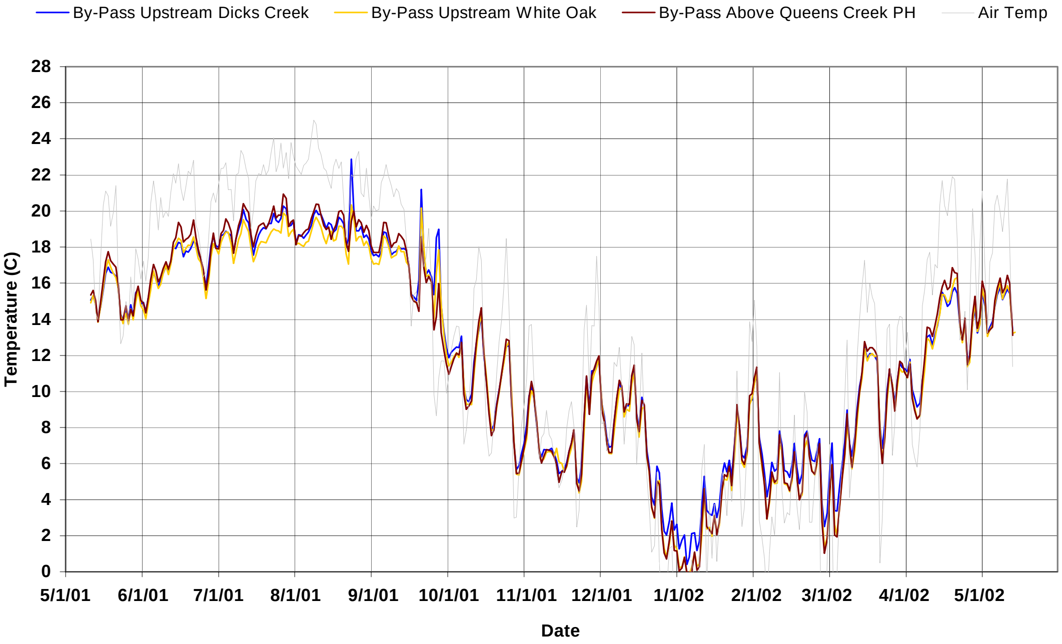


Figure 13. Comparison of Mean Daily Temperatures from the 3 sites in the Nantahala Bypass

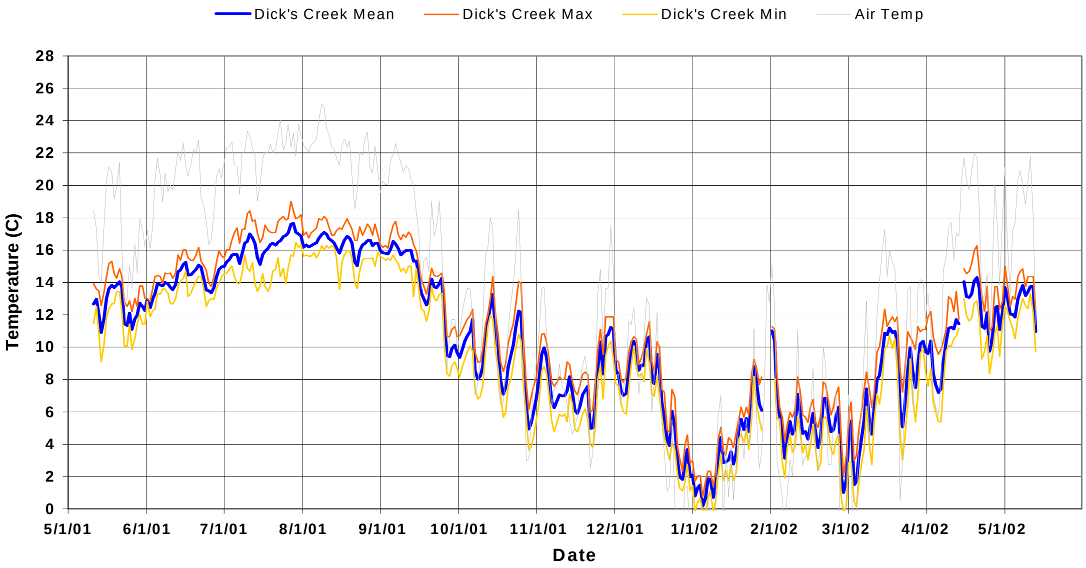


Figure 14. Mean, Minimum, and Maximum Daily Water Temperatures, Dicks Creek, upstream of Nantahala Bypass

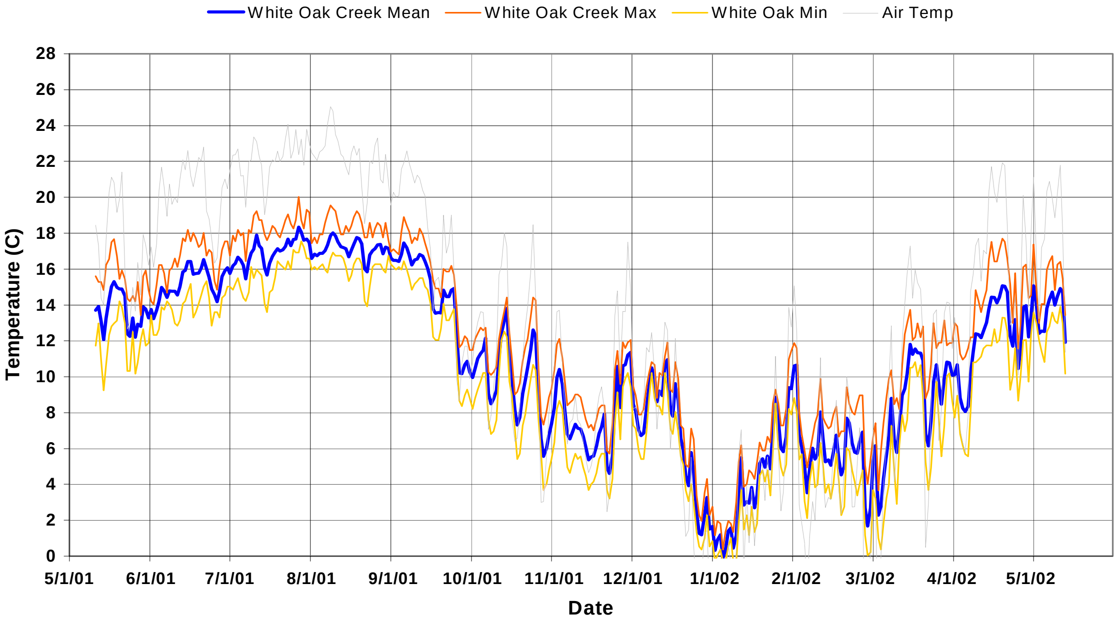


Figure 15. Mean, Minimum, and Maximum Daily Water Temperatures, White Oak Creek, upstream of Nantahala Bypass

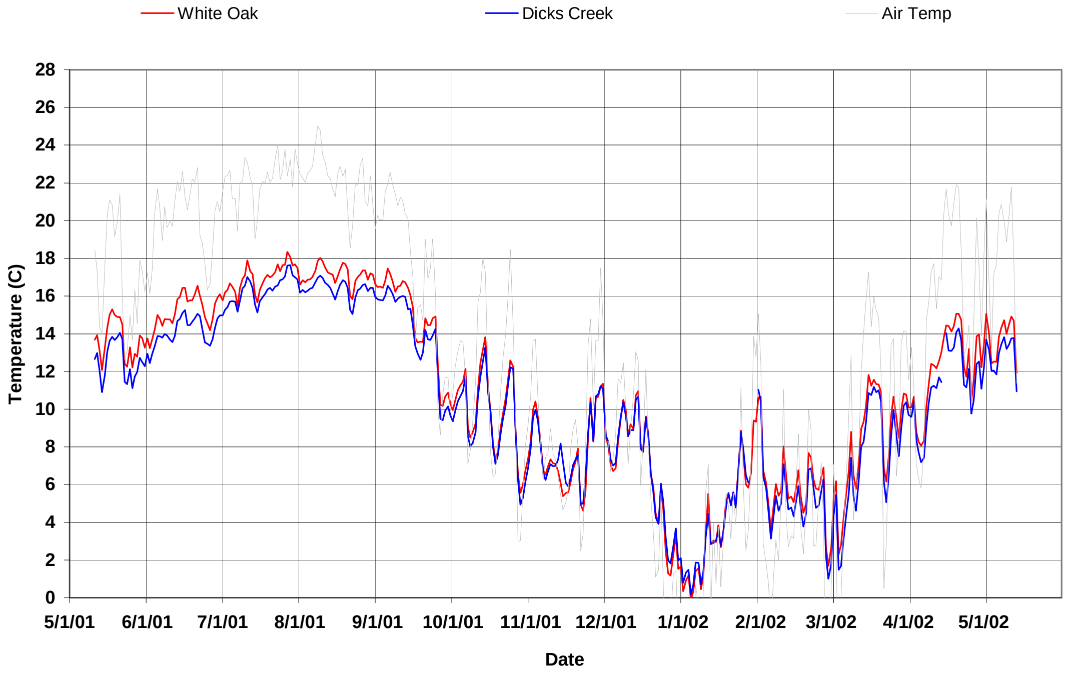


Figure 16. Comparison of Mean Daily Temperatures from Dicks Creek and White Oak Creek

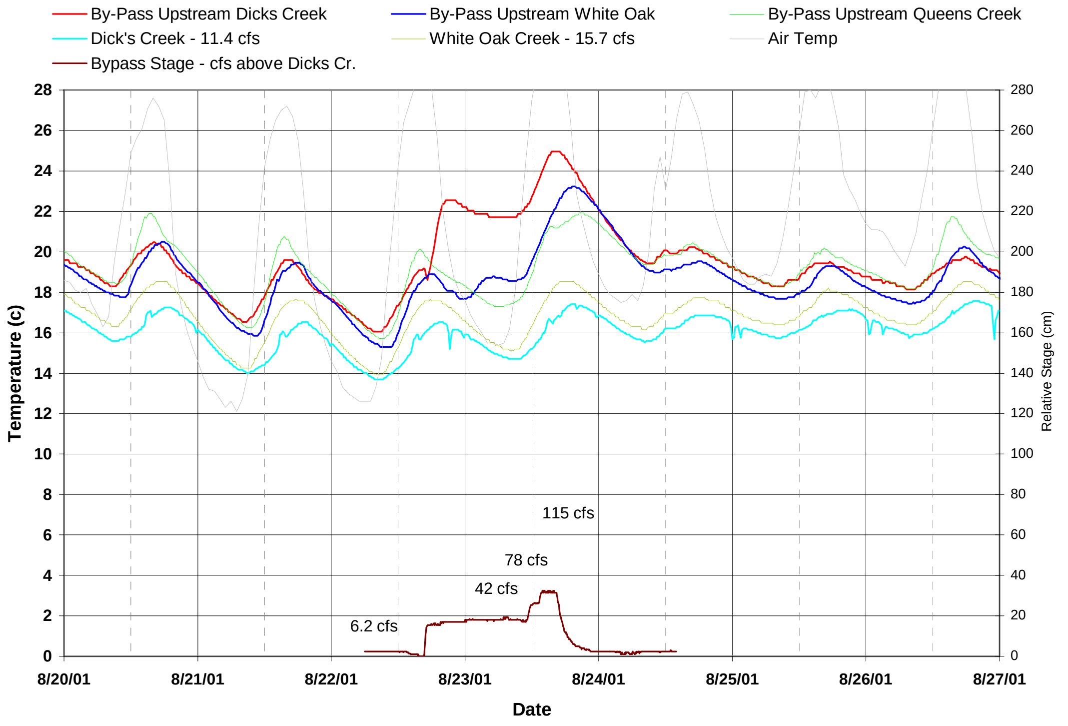


Figure 17. Comparison of the 15 minute Water Temperatures of the Nantahala Bypass During the August Spill Test

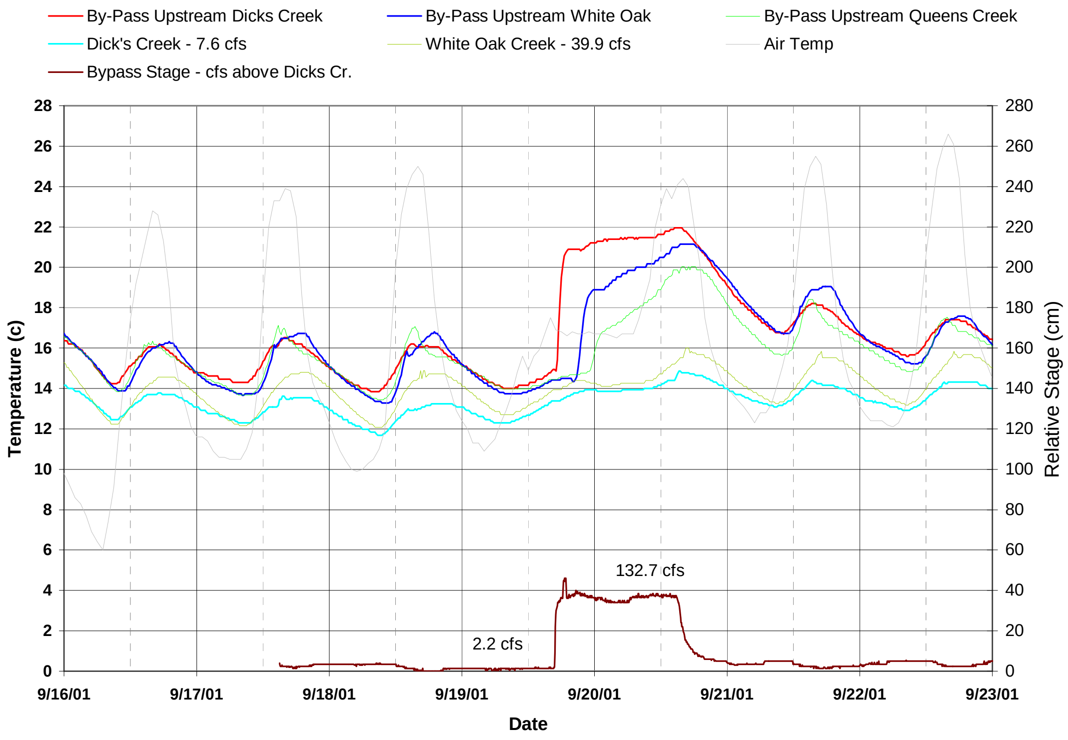


Figure 18. Comparison of the 15 minute Water Temperatures of the Nantahala Bypass During the September Nantahala Lake Spill to Supply the Mid-Flow for the Nantahala River IFIM

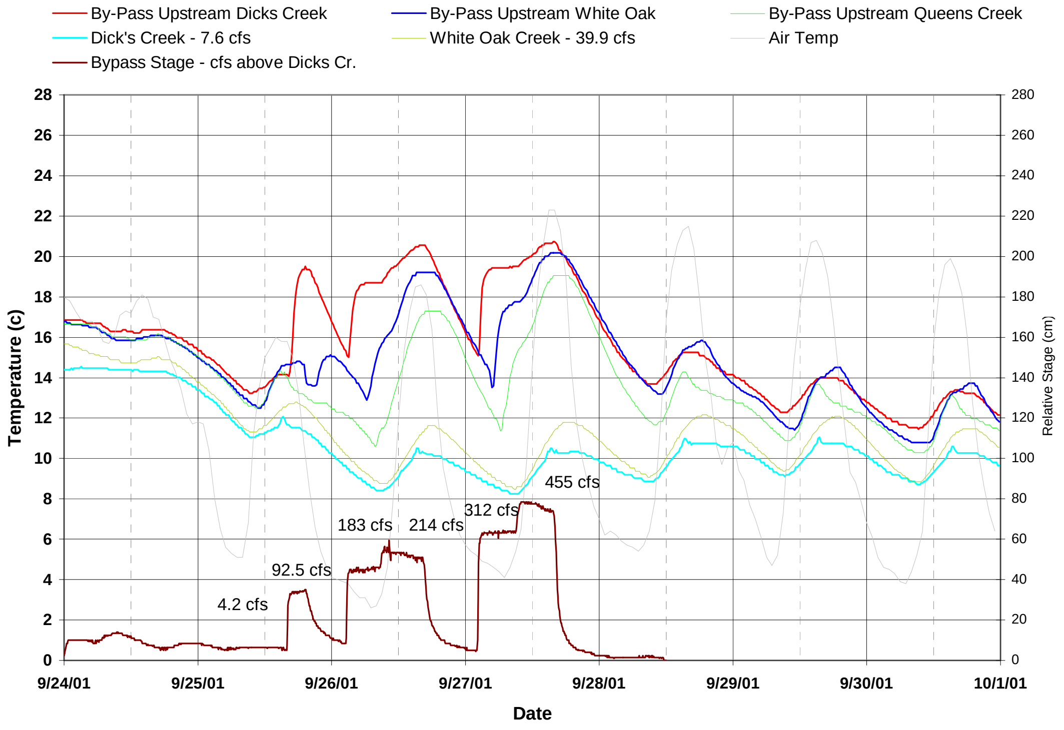


Figure 19. Comparison of the 15 minute Water Temperatures of the Nantahala Bypass During the September Bypass Recreational Studies (Angling and Boating)

through the next 3.2 miles. to the White Oak Creek confluence. Downstream of White Oak Creek confluence, the water cooled slightly to temperatures observed prior to the spill indicating that the water had reached meteorological equilibrium. At the highest spill flow, 109 cfs, much less cooling took place throughout the bypass and the warm water temperatures extended to the Queens Creek powerhouse.

During the next two spill studies (Figures 18 and 19) the same patterns were observed as in the August test. However, in September, the meteorological temperatures were lower creating conditions favorable for rapid heat loss in the bypass. At higher spill flows, the cooler meteorological conditions enabled a greater rate of cooling than that observed in the August test.

These tests suggest that as low flow, the temperature of the water added to the bypass will quickly reach meteorological equilibrium as the water travels downstream. However, under high flow conditions (such as those tested for recreational boating), the temperature of the source water will extend throughout the entire bypass. Therefore, the seasonal timing of the high flow releases is critical for temperature management of the Nantahala Bypass.

Nantahala River (Downstream of the Nantahala Powerhouse)

The daily average, minimum, and maximum temperatures calculated from the 15-minute temperature data recorded from the Nantahala Powerhouse canal (RM 13.6), the Nantahala River at Patton's Run (RM 12.2), and the Nantahala River downstream of the Nantahala Outdoor Center (RM 5.2) illustrate the dynamic temperature regime of the river (Figures 20-22). The average daily temperatures throughout the year were below the 20ºC temperature standard for trout water. In addition, maximum daily temperatures rarely achieved 20ºC.

Since the Nantahala River received water from both the Nantahala Bypass and the water from the hypolimnion of Nantahala Lake via the powerhouse, the water temperatures downstream reflect temperatures from both sources (Figure 23). The minimum water temperatures recorded in the powerhouse canal during the spring, summer, and fall were indicative of the temperatures of the hypolimnion of Nantahala Lake. As was observed with the use of Lake Glenville at the Thorpe Hydro (Nantahala Power and Light, 2003), hypolimnetic water was removed from the lake throughout the summer months via the Nantahala penstock. As the winter stored water was depleted and replaced with warmer water, temperatures in the powerhouse canal progressively increased during the fall, prior to winter mixis. Once the deeper region of the lake began to cool, the temperatures in the powerhouse canal also cooled. Minimum temperatures recorded in the canal during the winter were a result of meteorological cooling during non-generation periods.

Temperatures recorded in the Nantahala River at Patton's Run (Figure 21) reflected the temperatures of either the generation flow from the Nantahala Hydro (minimum temperatures) or the maximum water temperatures indicative of the water from the Nantahala bypass. The average daily temperatures at Patton's Run were a function of the time periods of generation and non-generation. The maximum temperatures recorded at the NOC (Figure 22) were generally cooler than the maximum temperatures recorded at Patton's Run while the minimum temperatures at the NOC were about two degrees warmer. Since the average daily temperature was lower at the NOC than at Patton's Run, the water appeared to loose heat during the summer months as it traveled downstream through the Nantahala Gorge (Figure 23) However, since the travel time through the gorge was about 3 hours during generation flows, (Nantahala Power and Light, 2001), the meteorological induced heating was probably minimal under high flows but significant at low flows.

A detailed comparison of the 15-minute data during a typical generation cycle in August (Figure 24) reveals the complexity of temperatures in the Nantahala River. As water was released from the Nantahala powerhouse during generation, a slight temperature drop, followed by a sharp peak of warmer water, followed by a long period of cold water was observed in the powerhouse canal. This repeatable pattern was attributed to the release of water stored in the long penstock with the initial temperature drop caused by Nantahala Lake water followed by White Oak Creek water that accumulated in the penstock during non-generation times followed by water from Nantahala Lake. (This peak of warmer temperatures was not observed when the White Oak penstock was out of service, Figure 25). The small temperature peak from White Oak Creek was observed both at Patton's Run and, to a lesser extent, at the NOC indicating the travel time of the mass of water. After the small temperature rise, cold water persisted in the river while generation continued. Immediately after generation stopped, the powerhouse canal remained cold, but the temperatures increased very rapidly at Patton's Run due to the bypass water displacing and mixing with the generation water remaining in the Nantahala channel. As the flows diminished at the NOC, the water began to warm, probably meteorologically induced in addition to water contributed from the bypass. At this time, the maximum diel temperatures were observed. After generation began, the warmer water in the Nantahala channel and the water in the channel from the bypass was quickly mixed and displaced downstream as the generation water moved downstream.

The role of generation flow controlling the Nantahala River temperatures was also very noticeable during the Nantahala River IFIM study period (Figure 25). For 4 days in September the Nantahala power plant was not operated. The flows were controlled by either supplementing the bypass base flow with Queens Creek powerhouse or spill flow from Nantahala Lake. During this time, the water in the Nantahala River followed typical diel patterns of meteorologically controlled temperatures with all sites (except the cold powerhouse canal) exhibiting similar temperatures. As soon as generation from the Nantahala hydro commenced, the river temperatures exhibited similar responses to those observed in August.

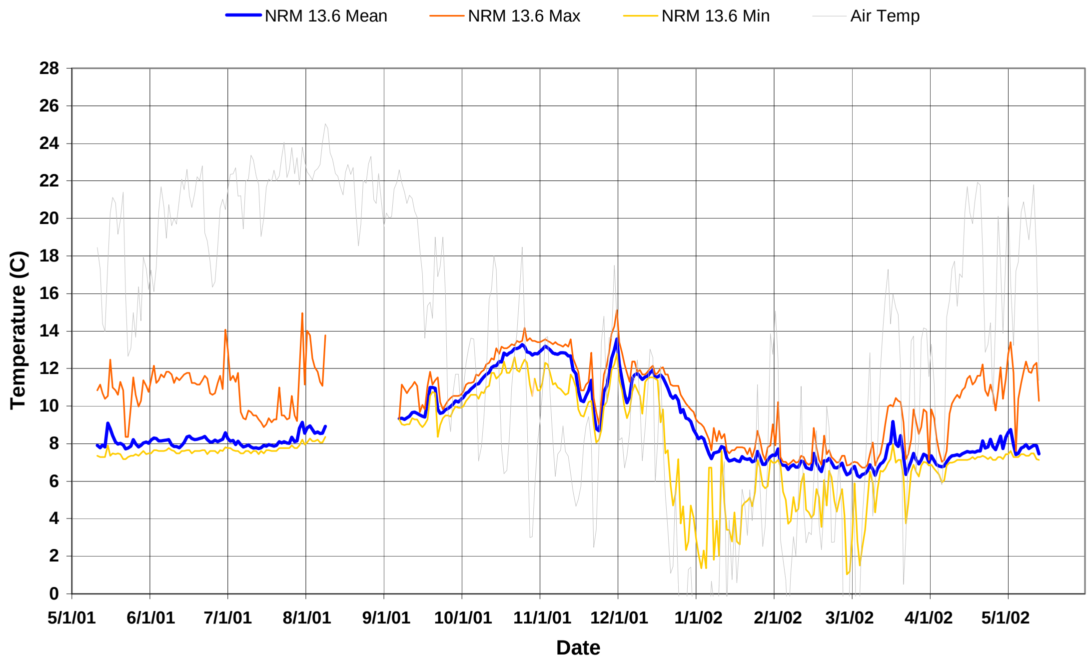


Figure 20. Mean, Minimum, and Maximum Daily Water Temperatures, Nantahala Powerhouse Canal

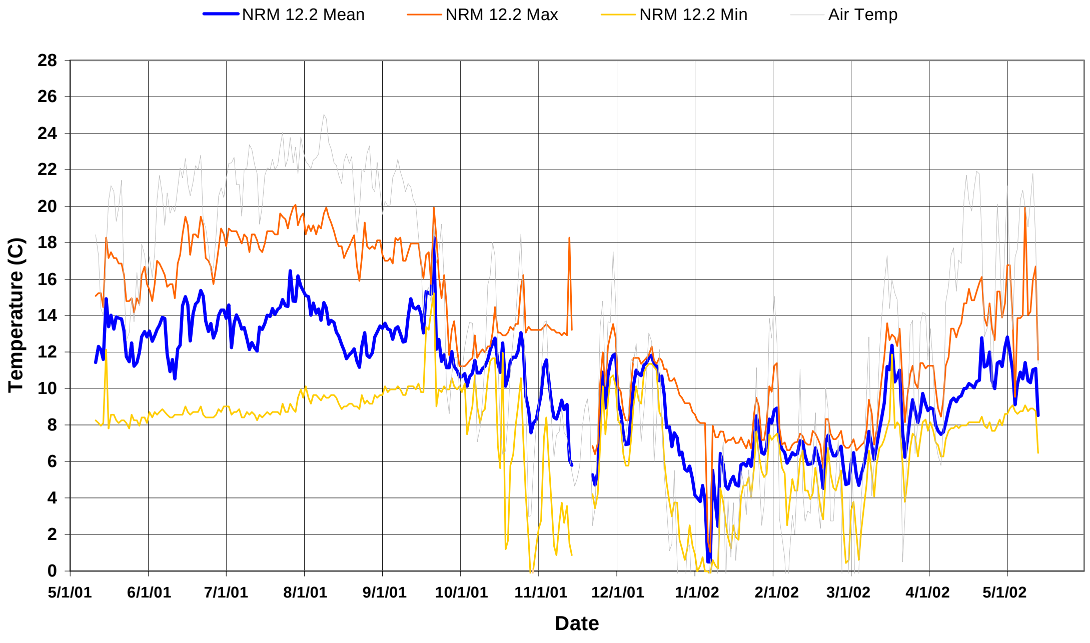


Figure 21. Mean, Minimum, and Maximum Daily Water Temperatures, Nantahala River at Patton's Run

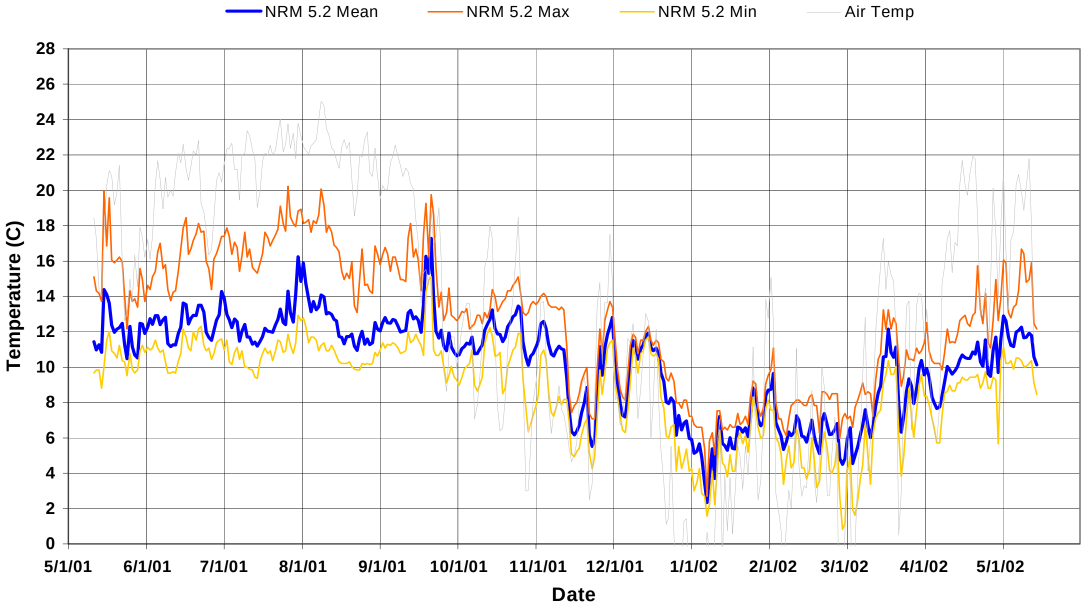


Figure 22. Mean, Minimum, and Maximum Daily Water Temperatures, Nantahala River at Nantahala Outdoor Center

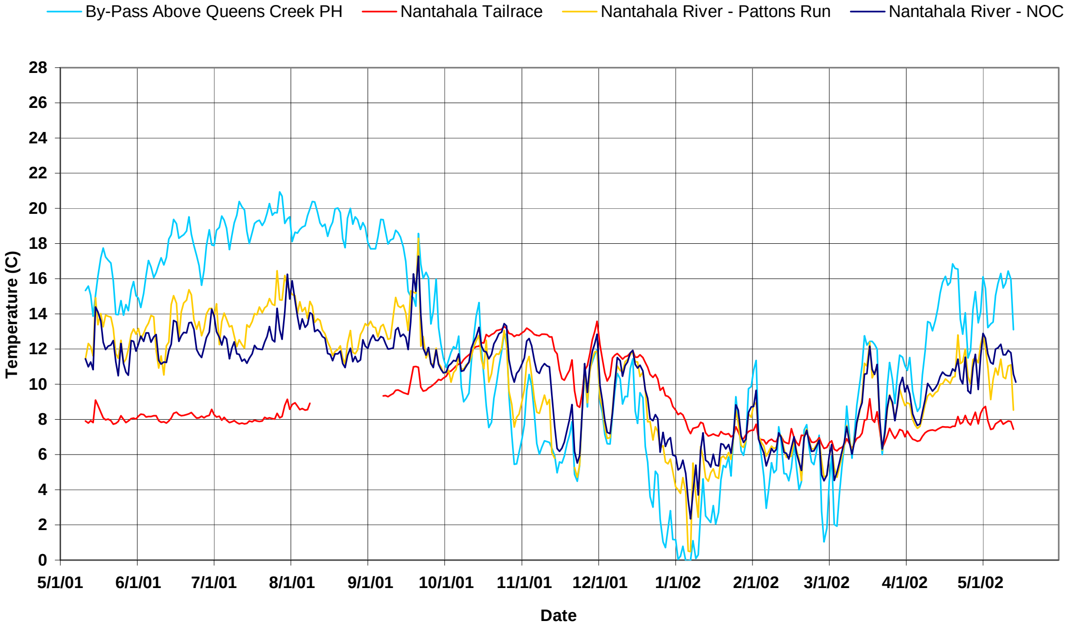


Figure 23. Comparison of Mean Daily Temperatures from the 4 sites in the Nantahala River

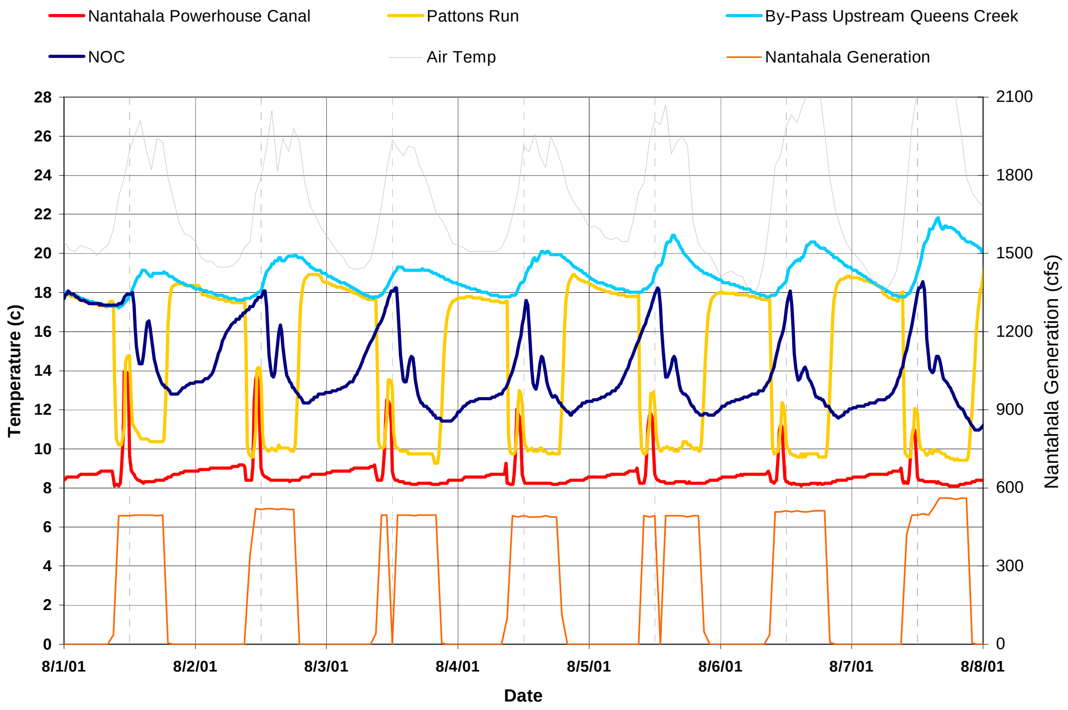


Figure 24. Comparison of August 15 minute Water Temperatures of the Nantahala River

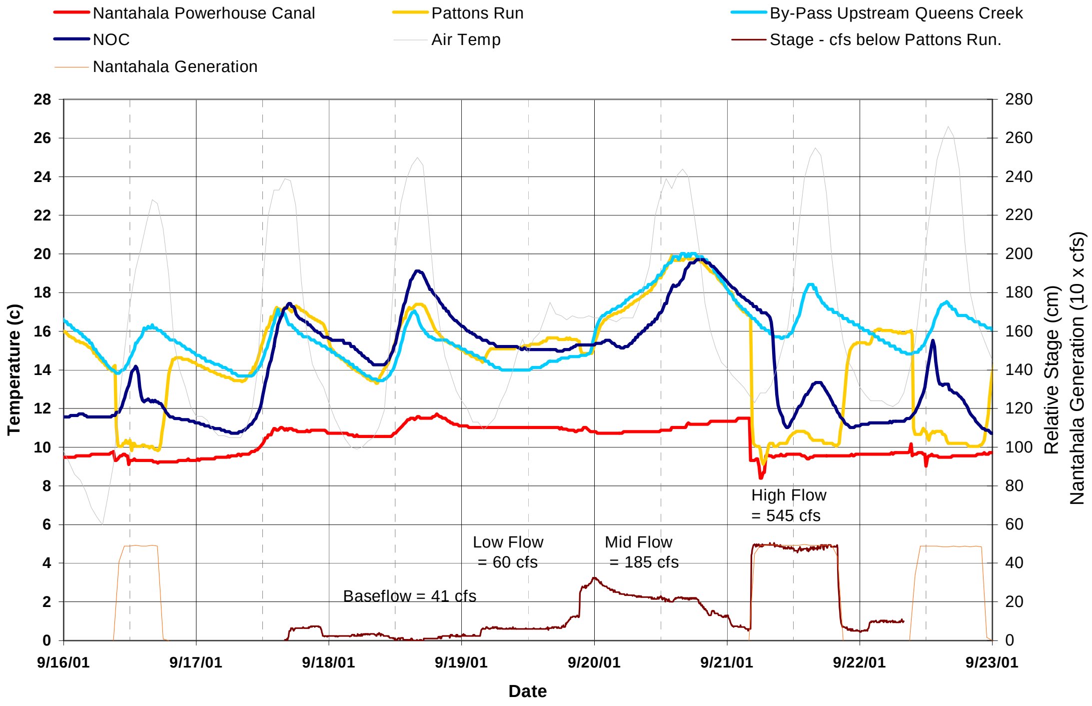


Figure 25. Comparison of the 15 minute Water Temperatures of the Nantahala River During the September Nantahala River IFIM

Historical Water Temperature

The sixteen years of monthly 'grab' temperature data collected by the NCDENR-DWQ at the old USGS gage on the Nantahala River (Figure 26) revealed temperatures that were rarely greater than the state water quality standard of 20ºC for Class B trout waters. The monthly 'grab' samples illustrated a high degree of variability between the various years in the Nantahala River. This variability is not unexpected since, as mentioned in the previous sections, the river temperatures responded very rapidly to generation flow and bypass temperatures. Hence, the water temperatures collected as 'grab' samples only reflect the river conditions immediately prior to sampling. .

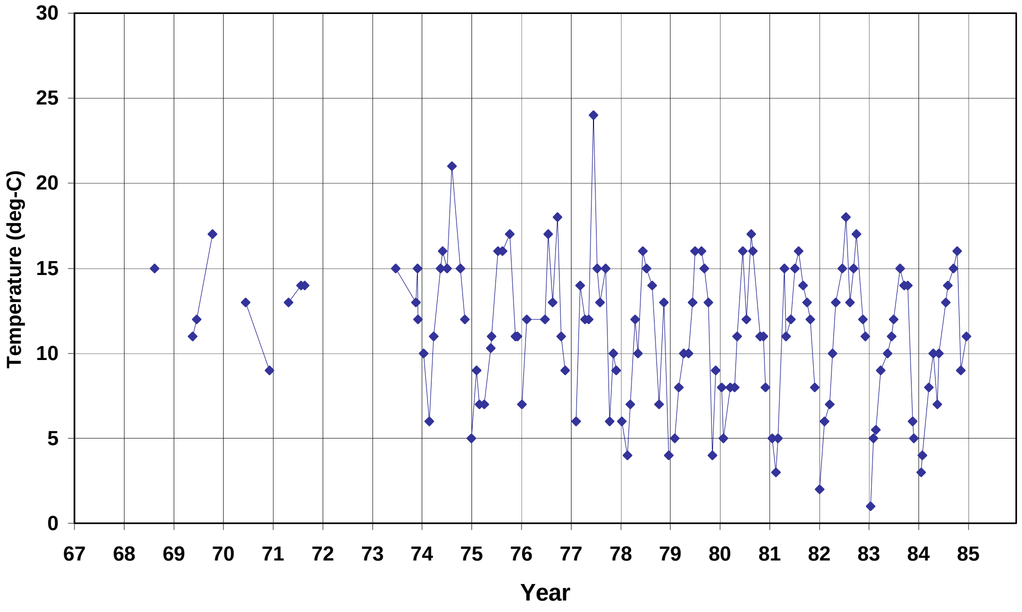


Figure 26. Monthly 'grab' Temperatures Collected by NCDENR-DWQ at RM 10.8, Nantahala River at the Old USGS Gage

Dissolved Oxygen

The dissolved oxygen concentrations in an aquatic system are a function of the interrelationships and relative rates of physical, chemical, and biological processes. The construction of deep reservoirs on the Nantahala River has slowed and deepened the 'old' river. This combination has resulted in increased retention times and incomplete vertical mixing (stratification) of the reservoir.

As a general rule, the shorter time the water is in the reservoir, the greater the similarity of water quality coming into the reservoir and the water going out of the reservoir. Conversely, with increased retention times, the amount and type of dissolved or particulate material is progressively altered within the reservoir, by chemical or biological activity. The oxygen concentrations within a reservoir are a function of allochthanous (externally derived, from either point or non-point sources) organic loading and the autochthonous (internal) organic production. As the reservoir receives organic compounds from the watershed (external), these materials oxidize (consume oxygen) by bacterial decomposition. Additionally, inorganic nutrients (primarily phosphorus and nitrogen) are also transported from the watershed. These nutrients stimulate algal growth within the reservoir (internal); which, while growing, produce oxygen, but as they sink and decompose, consume oxygen. The relative rates of the 'BOD' from either source are a function of how much material was added to the reservoir and over what period of time the organic material decomposes.

In reservoirs, different layers of water form as a result of reduced vertical mixing (thermal stratification). Complete vertical mixing (water in contact with the atmosphere) is reduced or eliminated with the onset of vernal warming of the surface water. This warmer water, exhibiting less specific gravity due to increased temperatures, floats over the cooler, denser water (hypolimnion). As radiant energy and air temperatures increase, the top layer (epilimnion) is further warmed, thereby creating a stronger vertical temperature gradient. As the thermal gradient intensifies, the cool, lower layers become increasingly isolated from the atmosphere. Dissolved oxygen progressively decreases in the lower layers due to the bacterial decomposition of organic material derived from the watershed or from the 'algal rain' from the upper layer where the algae were produced. The downstream release of this deep, cool, low oxygenated water via the powerhouse penstocks typically results in the concern for depressed oxygen concentrations in the tailwaters of the hydroelectric facilities.

Nantahala Lake

The dissolved oxygen concentrations in Nantahala Lake (Figures 27 and 28) were typical for a warm, monomictic, unproductive southeastern reservoir. Dissolved oxygen concentrations were highest in the spring due to the mixing of the water column and subsequent atmospheric reaeration throughout the winter. The maximum water column concentration achieved in the spring was a function of the extent and duration of the mixing period. As reservoir stratification became more pronounced (Figure 4), the dissolved oxygen concentrations progressively decreased throughout the water column. Typically, the decomposition of organic material (either supplied by the inflow and/or algal production within the reservoir) would be centered in the metalimnetic region (layer of maximum thermal gradients). However, the uniform concentrations and lack of biological structure indicate that the lake is very unproductive and received little particulate or dissolved material from the watershed. Dissolved oxygen concentrations remained high throughout the summer months, particularly in the deeper waters at the penstock level. These data indicate very little dissolved oxygen problems with the Nantahala powerplant withdrawal.

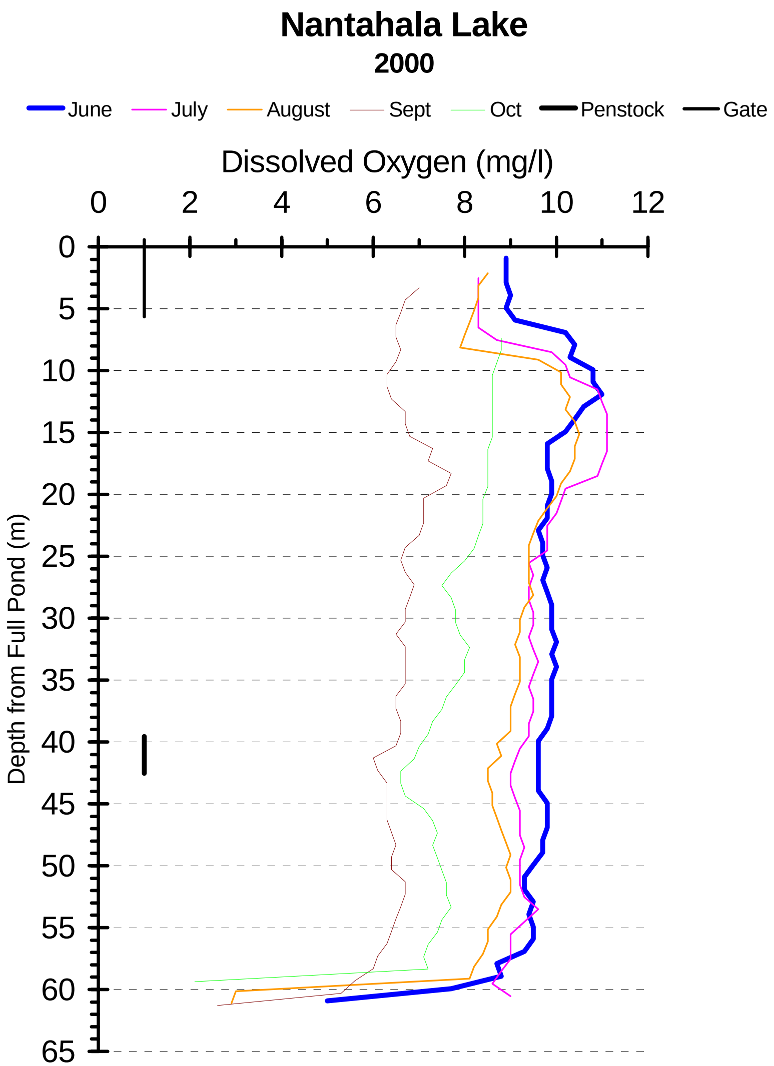


Figure 27. 2000 Summer Dissolved Oxygen Profiles in Nantahala Lake

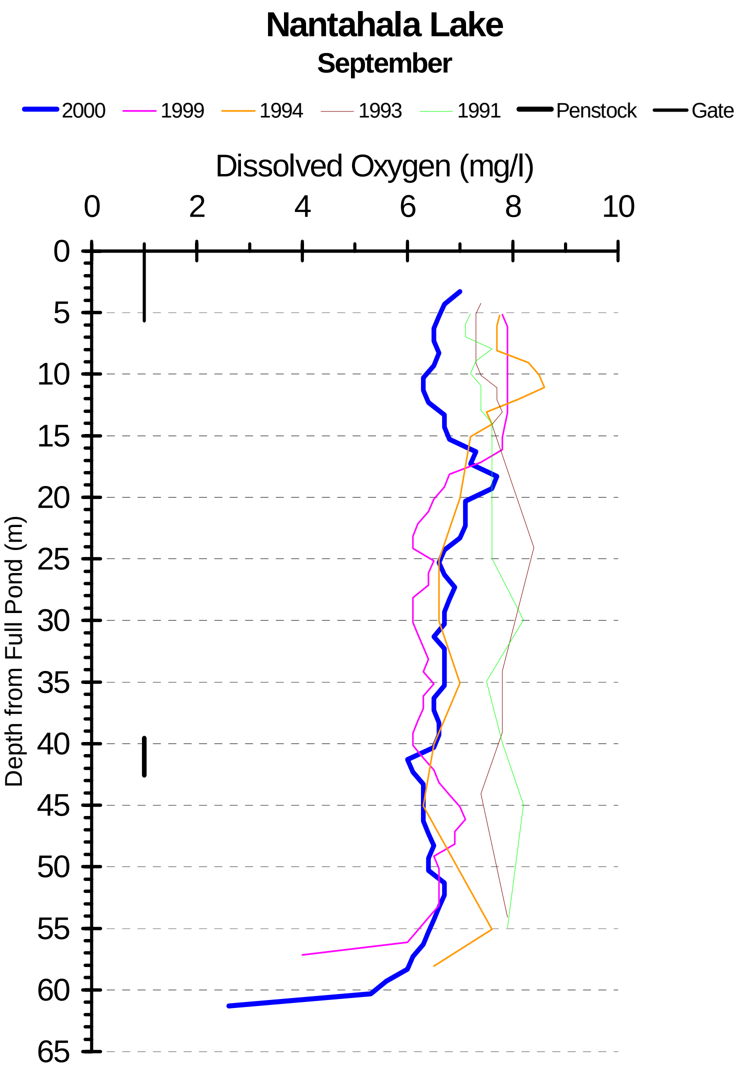


Figure **28** Summer Dissolved Oxygen Profiles in Nantahala Lake , 1991, 1993, 1994, 1999, and 2000

Nantahala Bypass

Minimum dissolved oxygen concentrations in rivers typically are observed during the late summer when temperatures were warm and the growing season of aquatic plants had peaked. At warmer water temperatures, the amount of dissolved oxygen in equilibrium with the atmosphere (saturation) decreases, while biological metabolism (photosynthesis and respiration rates) increases. Hence, the lowest dissolved oxygen concentrations were expected during August and September. However, the resuspension and subsequent oxygen consumption by allochthanous material that had accumulated in the river channel since the last large spill was also of concern.

The dissolved oxygen concentrations measured at 5-minute intervals in Dicks Creek and White Oak Creek were saturated with oxygen, the diel changes of oxygen were consistent with water in equilibrium with the atmosphere and responded to temperature changes (Figure 29). The dissolved oxygen concentrations in the Nantahala Bypass downstream of the confluence with Dicks Creek were approximately 90% saturated with oxygen. The variability of oxygen was less defined than DO in the tributaries. Although temperature, flow, and resuspension probably contributed to the dissolved oxygen patterns, concentrations were consistently above 8 mg/l. The lower dissolved oxygen concentrations in the bypass upstream of Dicks Creek were the result of poor deployment. At baseflow conditions, the very shallow depth did not allow the Hydrolab to remain suspended in the water, consequently the circulation of water around the sensors was impaired. However, at higher flows, the movement of water around the sensors was improved and the dissolved oxygen concentrations increased. Assuming that the recordings at the higher flows were accurate, the concentrations were slightly lower than the epilimnion of Nantahala Lake water, indicating that some resuspension of material contributed to slightly lower oxygen concentrations.

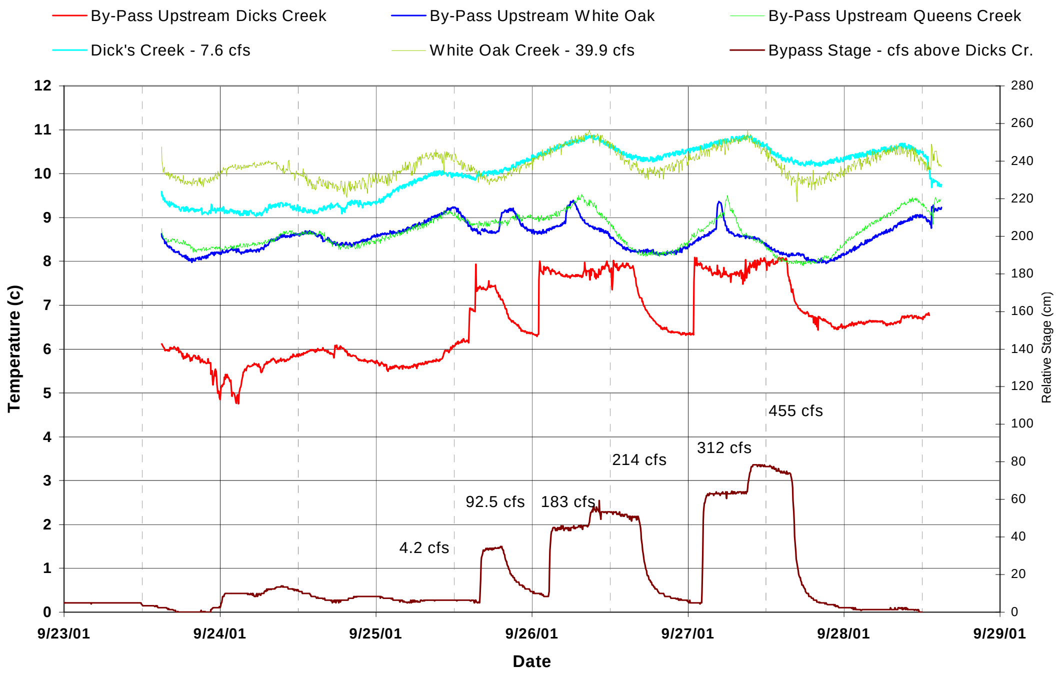


Figure 29. Comparison of the observed 5 minute Dissolved Oxygen Concentrations and Flow in the Nantahala Bypass during the September 2001 Recreational Study

Nantahala River

As mentioned in the Methods Sections, the temperature data were downloaded from the 'Tidbits' at approximately monthly intervals. During these monthly trips, water quality data were measured with a calibrated Hydrolab in the immediate tailrace of the Nantahala Hydroelectric Station (Table 3). Temperature, dissolved oxygen concentrations, and pH were well within state water quality standards. Conductivity values, a measure of total dissolved solids (no state standard applies), were extremely low indicating very low capability for autochthonous production.

Table 3. Water Quality 'Grab' Samples, Nantahala River, Nantahala Powerhouse Canal, 2001.

NANTAHALA POWERHOUSE DISCHARGE

DATE	TIME	TEMP deg-C	DO mg/l	COND uSi/cm	pH units	REMARKS
5/17/01	11:35 PM	7.6	11.8	12	6.6	generation flow
6/10/01	12:00 PM	8.1	11.2	12	6.9	generation flow
7/10/01	3:30 PM	12.9	8.9	19	6.6	generation flow
8/8/01	1:10 PM	13.4	10.2	16	6.9	generation flow
9/5/01	5:00 PM	9.3	10.3	12	6.7	generation flow
10/2/01	9:30 AM	10.7	9.7	12	6.4	generation flow
11/19/01						Turbine down for maintance
12/28/01	11:45 AM	9.8	9.5	13	6.6	generation flow

Historical Dissolved Oxygen Concentrations

The sixteen years of monthly 'grab' dissolved oxygen data collected by the NCDENR-DWQ at the old USGS gage on the Nantahala River (Figure 30) revealed dissolved oxygen concentrations that were consistently greater than the state water quality standard of 6 mg/l for trout waters. Given the consistency of the dissolved oxygen concentrations in the source water (hypolimnions of Nantahala Lake), the monthly 'grab' samples illustrated a remarkable similarity between the various years in the Nantahala River. The dissolved oxygen concentrations were at or near saturation with the atmosphere throughout the seasons.

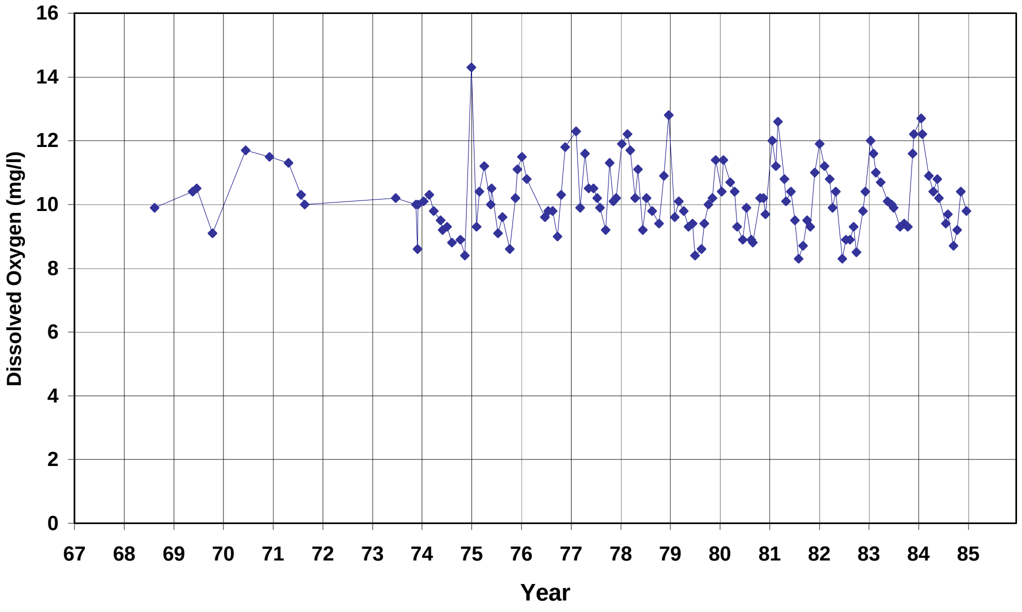


Figure 30. Monthly 'grab' Dissolved Oxygen Concentrations Collected by NCDENR-DWQ at RM 10.8, Nantahala River at the Old USGS Gage

SUMMARY OF RESULTS

Reservoir Summary

Source Water - Reservoirs	Factors Controlling Temperatures	Use
Epilimnion **Historical Summer Temperatures** **Nantahala Lake** Mean = 23.4ºC Range = 20º – 25.9ºC	Epilimnetic Temperatures are a function of the meteorological conditions exchanging heat with surface water. Temperatures will warm or cool towards the meteorological equilibrium temperatures. The epilimnetic temperature change is delayed due to large volume of water (cooler during the spring warming and warmer during the fall cooling periods, small response to diel heating and cooling)	**Primary Use**: Warm water Fishery in Reservoir **Secondary Use**: Potential for supplemental flow in by-pass
Hypolimnion **Historical Summer Temperatures** **Nantahala Lake** (7.8º - 11.5ºC)	Minimum temperatures are determined by winter meteorology – both intensity and duration of severity. Maximum temperatures are determined once stratification starts, finite amount of winter stored cold water, the higher the flows from penstocks the more rapidly winter stored cold water is depleted ….cooler water may be added during stratified period by interflows from tributaries	**Primary Use**: Power Generation Coldwater species in Tailwater **Secondary Use**: Cold water fishery in Reservoir Potential for supplemental flow in by-pass

Summary of Factors Controlling Temperatures in Rivers

1. All heating and cooling is driven by the meteorological conditions, water temperature will warm or cool, driven by the water temperature relative to the equilibrium temperature set by the meteorological variables. The cooler the water temperature (relative to the equilibrium temperature), the faster the water will warm.
2. The volume of water (per surface area) determines the amount of heat needed for the water to gain or loose to reach meteorological equilibrium, assuming water is well mixed vertically (as in shallow rivers), the volume of water per surface area may be expressed as depth. Therefore, shallow water will heat or cool faster than deeper water.
3. The faster the water moves downstream, the less time per distance traveled the water has to gain or loose heat. Increasing flow in a river increases depth and velocity, which allow for less heat exchange per volume of water per distance traveled.
4. Water from tributaries will mix with main flow at some distance downstream from confluence. Resulting temperature is a function of the temperature and volume of both streams.

Bonas Defeat and Wolf Creek By-pass Summary

By-pass Current Conditions	By-Pass water temperatures are currently at or near equilibrium with meteorology…temperatures respond very rapidly to changing meteorology. Dissolved oxygen is at or near saturation; this condition would be maintained at any supplemental flow.
Source Water	**Probable Outcome**
By-pass Supplemental Flow – Epilimnion (Tainter Gate) **Low Flow:** Up to 10 cfs supplemental flow	On a daily average basis, the water in the reservoir epilimnions were within a few degrees of the current by-pass temperatures, at low flows, this water would quickly equilibrate with the prevailing meteorological conditions, weather induced diel changes would be slightly less due to deeper water in the by-pass channel.
Mid Flow: 10 – 60 cfs supplemental flow	At these flows, the travel time in the channels is much reduced, and the average water depth increases significantly, therefore, the epilimnetic water temperatures would prevail much further downstream of the supplemental flow, diel changes would be drastically reduced, the most rapid heat exchange towards meteorological equilibrium would occur as major weather changes occurred.
High Flows: Greater than 60 cfs	As with the mid flows, the travel time in the channels is further reduced and the water depth continues to increase drastically reducing the heat exchange with the atmosphere. The temperature of the source water would probably be maintained throughout the entire by-pass. Supplemental flows of this magnitude should be timed when the epilimnions are within the temperature range for the aquatic organisms of interest in the bypasses.

By-Pass Supplemental Flow – Hypolimnion	The major consequence of using hypolimnetic water for supplemental flow in the by-passes is that the more hypolimnetic water is used for the by-passes, the amount of cold water available for Nantahala River temperature management is decreased–
Low Flow: Up to 10 cfs supplemental flow	On a daily average basis, the water in the reservoir hypolimnions were much colder than the current by-pass temperatures, at low flows, as with epilimnetic water, the hypolimnetic water would quickly equilibrate (warm) with the prevailing meteorological conditions. Dissolved oxygen concentrations, if low, would quickly reaerate at these low flows.
Mid Flow: 10 – 60 cfs supplemental flow and/or **High Flows:** Greater than 60 cfs	Very impractical due to access of the hypolimnion water at these high flow rates, even if hypolimnion water could be supplied at these rates, the by-pass channels would tend to heat and follow the same patterns as described for the epilimnetic source water. If hypolimnetic water were used at these high rates, severe depletion of hypolimnetic water would occur from the upper reservoirs (unavailable for Nantahala River management). Dissolved oxygen concentrations, if low, would progressively increase as the water traveled downstream.

CONCLUSIONS

The Nantahala River basin is located between the Hiwassee and Little Tennessee Rivers in Southwestern North Carolina. The Nantahala River has a relatively large storage impoundment, Nantahala Lake, which provides water to Nantahala Power and Light's Nantahala Hydroelectric Project via a 29654 ft. long penstock. The diversion of the majority of the water through the long penstock to supply water to the Nantahala powerhouses has minimized the flow in the river channel bypassing the penstocks. The combined flow from the Nantahala Bypass, Queens Creek Powerhouse, and the Nantahala Powerhouse travels approximately 8.7 miles northerly through the Nantahala Gorge to Lake Fontana (a large TVA storage reservoir).

Since the entire Nantahala River system has water temperatures suitable for trout, the NCWRC manages the river system for wild trout. The deep-water penstock from Nantahala Lake supplements cold water to the downstream reaches of the Nantahala River. In addition, the high generation flows, coupled with the high gradient Nantahala River has provided a significant recreational opportunity for whitewater boating through the Nantahala Gorge.

Wildlife resource agencies (most notably the NCWRC and USFWS) have requested the characterization of the water temperature and dissolved oxygen regimes in the Nantahala River system (including the bypass reaches) to provide information regarding the management of aquatic wildlife. The objectives of this report are to describe the temperature and dissolved oxygen concentrations in the Nantahala impoundment and the subsequent use of that water for power generation on the downstream temperatures and dissolved oxygen concentrations in the Nantahala River.

Nantahala Lake exhibited characteristics of warm, monomictic reservoirs. The reservoir experiences a prolonged mixing period during the fall and winter months whereby temperatures decrease and dissolved oxygen increased throughout the reservoir depths. As springtime conditions warmed the surface layers, the reservoir thermally stratified preventing additional atmospheric cooling or atmospheric oxygen exchange with the deeper water. As the deep, cold water was progressively released downstream via the deep-water penstock, the deeper water was subsequently replaced by warmer water. Since the reservoir has limited storage, this process is delayed with minimum volumes used for electrical generation and accelerated with larger volumes released downstream. This process continued until the meteorological conditions cooled enough to initiate the fall mixing period. The seasonal management, i.e. use of the deep, cold water resource, is the key issue in maintaining desired temperatures downstream.

The temperatures of the Nantahala Bypass were a function of the meteorological heat exchange at all times during the year. Even with the cooler water supplied to the bypass from Dicks Creek and White Oak Creek, the bypass quickly equilibrated with the prevailing meteorological conditions The supplemental flow from the Nantahala Lake tainter gates supplied water for the recreational studies performed in August and September 2001 The temperatures recorded in the bypass reaches during these studies suggests that at low flow, the temperature of the water added to the bypass will quickly reach meteorological equilibrium as the water travels downstream. However, under high flow conditions (such as those tested for recreational boating), the temperature of the source water will extend throughout the entire bypass. Therefore, the seasonal timing of the high flow releases is critical for temperature management of the Nantahala Bypass.

The temperatures in the lower Nantahala River were a function of the generation flow. During non-generation times, the Nantahala Bypass water flowed through the Nantahala Gorge. Since the bypass water was equilibrated with the prevailing meteorological conditions, the water in the Nantahala River warmed or cooled under these bypass flows. However, as soon as the Nantahala Hydro began generation, the high flows of cold water traveled downstream; rapidly mixing with and displacing the warmer water downstream. Since the travel time of the water at the generation flows was about 3 hours, little meteorological heat exchange took place. When generation stopped, the small volume of cold water in the Nantahala River channel began to respond rapidly to the prevailing meteorological conditions in addition to replacement with the inflow from the bypass.

The historical records for Nantahala Lake suggest that the lake is very unproductive since very little hypolimnetic oxygen was consumed during the stratified period. These relatively high dissolved oxygen levels provided high quality water released from the penstocks at the Nantahala Hydro. The deep water released from the reservoir was consistently greater than the minimum standard for North Carolina trout waters. Based upon dissolved oxygen data collected in 2001 and the NCDENR-DWQ historical data, oxygen concentrations consistently exceeded the minimum concentrations established by State water quality standards for the Nantahala River.

Dissolved oxygen concentrations in the Nantahala Bypass, even with high supplemental flow, were consistently greater than the state water quality standards established for trout waters.

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