TENNESSEE VALLEY AUTHORITY
River Operations

Ambient Temperature and Mixing Zone Studies for Sequoyah Nuclear Plant as Required by NPDES Permit No. TN0026450 of September 2005

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EXECUTIVE SUMMARY

The August 2001 National Pollutant Discharge Elimination System (NPDES) Permit for Sequoyah Nuclear Plant (SQN) required a number of studies related to Section 316 of the Clean Water Act. Due to the short span of the 2001 permit, these studies were carried forward in the current NPDES permit, effective September 2005. The studies are related to the plant diffuser discharge to the Tennessee River, identified in the NPDES permit as Outfall 101. This report provides data, analyses, and conclusions for two of these studies—the ambient temperature study and the mixing zone study.

Due to the evolution in understanding of the hydrothermal and biological characteristics of Chickamauga Reservoir, as well as the operational aspects of the nuclear plant and river system, modifications have been necessary over the years in the thermal criteria and monitoring of Outfall 101. A chronology of these modifications is summarized herein. The most recent modification, implemented as part of the August 2001 permit, involved changing the period of averaging for the downstream temperature $\mathbf{T_d}$ and temperature rise $\mathbf{\Delta T}$ from hourly to 24-hours. This was done because changes in river flow due to hydro peaking operations were causing unexpected swings in the river temperature that could require a near immediate response by SQN. Because SQN does not control hydro operations and because the time required to plan and safely implement procedures for cooling tower operation and/or changes in unit generation can be in excess of the time required to respond to swings in the river temperature, hourly averaging placed the plant in situations where thermal violations possibly could not be averted. Previous studies showed that a change from hourly averaging to 24-hour averaging would have no adverse impact on the hydrothermal and biological aspects of Chickamauga Reservoir. However, as part of this change, two special studies were added in the NPDES permit of 2001—one to confirm the adequacy of the ambient temperature measurement and one to confirm the configuration of the mixing zone.

As background for the summary that follows, the basic thermal limits for Outfall 101 specified in the current NPDES permit include: a maximum 24-hour average downstream temperature $\mathbf{T_d}$ of 86.9ºF (30.5ºC), a maximum 24-hour average temperature rise $\mathbf{\Delta T}$ of 5.4 Fº (3.0 Cº) for April through October, a maximum 24-hour average temperature rise $\mathbf{\Delta T}$ of 9.0 Fº (5.0 Cº) for November through March, and a maximum hourly average temperature rate-of-change $\mathbf{dT_d/dt}$ of ±3.6 Fº/hour (±2 Cº/hour). The November through March limit for $\mathbf{\Delta T}$ was obtained by a 316(a) variance request in 1989. Additional details associated with these limits are provided in this report.

Ambient Temperature Study

For the ambient temperature study the permit states *"TVA shall conduct a study to evaluate the spatial distribution of water temperature in the overbank and main channel regions of Chickamauga Reservoir upstream of the plant diffuser. The study shall supplement data from previous evaluations, as needed, by measuring temperature profiles at selected sites in the reservoir. The study shall consider both winter and summer hydrothermal regimes, and both 1-hour and 24-hour averaging. The goal of the study is to determine the major factors* *contributing to the interaction between main channel and overbank flows, the impacts on water temperatures in the thermal mixing zone, and optimal location of monitors to record the ambient temperature."*

At the time of the 2001 permit, the ambient temperature for the mixing zone was measured at Station 13. This station is situated on the plant intake skimmer wall and about 1.1 miles upstream of the discharge diffusers. The results of previous evaluations indicated that this location was adequate for the ambient temperature measurement. However, to confirm the earlier evaluations and to collect data to better satisfy the goal of the ambient temperature study, three ambient temperature deployments were performed. Two of the deployments included the installation of temporary temperature stations at a number of sites in the main channel and overbanks upstream of the mixing zone. The first, for summer conditions, was performed from July 23 through August 4, 2003. The second, for winter conditions, was performed from January 21 through February 2, 2004. During these deployments, rainfall was abundant, resulting in high daily average river flows—typically between 25,000 cfs and 40,000 cfs. Although the river flow included periods with heavy peaking operations, the temperatures measured at Station 13 and other sites further upstream were within normal expectations. That is, the first two deployments suggested that Station 13 was adequate for measuring the ambient temperature.

In March 2006, the current drought first began to influence conditions in Chickamauga Reservoir, compelling TVA to reduce daily average flows in the river to levels as low as 4000 cfs. At about the same time, Station 13 began recording water temperatures that were unexpectedly high, even for periods of intense solar heating. Since the plant diffuser discharge is the only other nearby source of heat in the reservoir, it was immediately suspected that thermal effluent from the mixing zone was migrating upstream far enough to reach Station 13. This, of course, reduces the plant-induced temperature rise and underestimates the impact of the SQN thermal discharge on the receiving water. As a result, on March 29, the ambient temperature measurement was changed to a location 6.8 miles upstream of the discharge diffusers. The new location, labeled Station 14, was approved by TDEC in a meeting on April 7, 2006.

The third ambient temperature deployment was performed from May 18 through June 2, 2006 to confirm the adequacy of the location of Station 14. In contrast to the first two deployments, the third deployment included temperature readings along the center of the river, starting from the mixing zone and extending upstream to Station 14. The measurements found that Station 14 was free of any impacts due to the local buildup of heat arising from the SQN thermal discharge, at least for the prevailing river conditions during the deployment.

With this background, the following items summarize key conclusions from the ambient temperature study:

- The major factors contributing to the interaction between main channel and overbank flows in Chickamauga Reservoir include meteorology, hydrology, river geomorphology, and in the vicinity of SQN, the action of the plant diffusers. In the deployments, these factors resulted in temperature differences between the main channel and overbanks areas in the vicinity of SQN as large as 3 F° (1.7 C°).

- Velocity gradients created by boundary resistance, shoreline irregularities, and bends in the river create recirculation zones and mixing in the overbanks that can transport heat upstream, even though the average flow in the reservoir is in the downstream direction.

- At river discharges below the range of from 17,000 cfs to 25,000 cfs, the action of the SQN diffusers can promote recirculation between the main channel and overbank regions of the flow. This occurs as a result of the high velocity jets issuing from the diffuser, which entrain ambient flow in the river. If the amount of flow entrained by the jets is larger than the flow in the river, part of the effluent mixture will be transported through the sides of the mixing zone, feeding into the overbanks.

- Deployments involving temperature measurements along the center of the river suggest that for lower river flow, the upstream migration of heat from the SQN mixing zone can extend further upstream as a result of peaking operations compared to that which occurs for steady operation of the river.

- Prior to the NPDES permit of August 2001, the only recognized mechanism responsible for the upstream migration of thermal effluent from SQN was mean flow advection as a result of reservoir sloshing from peaking operations. Previous evaluations suggested that by this mechanism, the upstream migration from the diffusers would not travel more than half the distance between the mixing zone and Station 13. However, the studies summarized herein indicate that heat from the mixing zone can be carried upstream beyond Station 13.

- Temperature measurements along the center of the river suggest that Station 14 is free from any effects of the SQN thermal effluent for steady river flows as low as about 6000 cfs and for peaking operations with daily average river flows as low as about 13,000 cfs. This covers the range of river operations experienced since April 2006 of the current drought.

- There presently is no reliable method to estimate the additional warming in the mixing zone due to the impact of solar heating in the overbanks verses that due to recirculation of the plant thermal effluent. Consequently, SQN is operated in a manner to keep the total temperature rise below the NPDES standard, whether or not the source of the temperature rise is from the diffuser discharge or from a combination of the diffuser discharge and overbank heating.

- Exceedance probabilities suggest that over most of the range of observed ambient temperatures, there is very little difference in the duration of occurrence for hourly averaging verses 24-hour averaging. Near the annual maximum and minimum temperatures, the difference between the hourly average and 24-hour average is less than 0.5 F° at an exceedance of 0.5 percent (i.e., a total of about 48 hours over the entire year).

Mixing Zone Study

For the mixing zone study the permit states *"TVA shall conduct a study to evaluate the dynamic behavior of thermal plume from the plant diffuser. The study shall examine the justification for the existing mixing zone and supplement data from previous evaluations, as needed, by measuring temperature profiles at selected sites in and about the mixing zone. The study shall consider both winter and summer hydrothermal regimes, and both 1-hour and 24-hour averaging. The goal of the study is to better determine the impact of hydro peaking operations on the behavior of the thermal plume, and to determine if there is any need to redefine the extent of the mixing zone."*

The NPDES permit specifies the existing mixing zone as an area 750 feet wide and extending 1500 feet downstream and 275 feet upstream of the diffusers. The justification for the mixing zone is based on a physical model study of the discharge diffusers, which examined the thermal effluent over a wide range of plant and river conditions, including reverse flows in the reservoir. Between the startup of SQN and the NPDES permit of August 2001, eleven field surveys were performed to verify the compliance model and document the extent of the thermal effluent from the diffusers. All of these surveys confirmed the adequacy of the mixing zone. However, most of the surveys encompassed only short periods of time (e.g., hours) with near-steady conditions. To examine the dynamic behavior of the thermal effluent and evaluate hourly verses 24-hour averaging, three new mixing zone temperature deployments were conducted.

The deployments for the mixing zone included temporary temperature stations around the entire perimeter of the mixing zone. In contrast to previous mixing zone surveys, the deployments provided measurements allowing evaluations of temperatures concurrently for all faces of the mixing zone and over periods long enough to examine the dynamic behavior of the mixing zone based on hourly averaging and 24-hour averaging. In addition, measurements also were made across the mixing zone to map the approximate spatial distribution of the thermal effluent during periods of near steady flow.

The mixing zone deployment for summer conditions was performed from August 11 through August 24, 2004. Hydro peaking operations were common in this period, with daily average river flows as low as 10,000 cfs and as high as 40,000 cfs. The deployment for winter conditions was performed from January 21 through February 2, 2004. The river flow during the winter deployment was high—initially near 40,000 cfs. However, special hydro operations were arranged to produce one event with reverse river flow, and one day with a river flow of about 18,000 cfs for measurements with steady conditions.

The third deployment was performed to check the mixing zone after the onset of the current drought. The deployment was between September 19 and September 22, 2007. The river flow was steady at about 9000 cfs. In addition to these three deployments, an abbreviated survey of the mixing zone was conducted on November 4, 2007. This survey was conducted as part of an NPDES requirement to confirm the calibration of the compliance model for downstream river temperature. The river flow for this survey was about 6000 cfs and extremely steady, as was the ambient river temperature. For these reasons, the results of the November 4, 2007 survey are expected to be representative of the 24-hour average behavior.

With this background, the following items summarize key conclusions from the mixing zone study:

- For high river flows, above about 25,000 cfs, almost all of the thermal effluent in the diffuser mixing zone is assimilated in the downstream direction. Temperatures in the mixing zone tend to be suppressed.

- For river flows in the range of about 17,000 cfs to 25,000 cfs, part of the thermal effluent begins to be assimilated upstream and laterally through the sides of the mixing zone. Temperatures in the mixing zone tend to become elevated. Areas of recirculation can begin to form between the mixing zone and adjacent shorelines. These can be responsible for feeding thermal effluent into the overbanks. For river flows below about 17,000 cfs, temperatures in the mixing zone become further elevated and the quantity of thermal effluent assimilated through the sides and upstream of the mixing zone increases.

- The thermal effluent in the mixing zone appears to shifts towards the right side of the mixing zone for high river flow and towards the left side of the mixing zone for low river flow (i.e., facing downstream).

- The impact of peaking operations causes the thermal effluent in the diffuser mixing zone to transition between the basic behaviors described above. During the peak when river flows are high (e.g., above 25,000 cfs), all of the diffuser effluent is assimilated downstream and water temperatures in the mixing zone are suppressed. During offpeak hours when low and reverse river flows occur (e.g., less than 17,000 cfs), the thermal effluent is assimilated in all directions and water temperatures in the mixing zone are elevated. Periods of reverse river flow likely provide the greatest assimilation of effluent in the upstream direction, but such periods are short, usually less than three hours per event.

- The impact of peaking operations is basically the same for winter and summer conditions.

- Measurements found that the average temperature along the downstream face of the mixing zone, which is used to calibrate the NPDES compliance model, is usually among the highest of all the faces and provides a good estimate of the average temperature around the perimeter of the mixing zone. In the new deployments, the average temperatures for the individual faces, as well as that for all faces combined, were contained within the NPDES limits for the downstream temperature and temperature rise. That is, the mixing zone study provided no indication that the mixing zone needs to be redefined at this time.

- Exceedance probabilities suggest that over most the range of observed downstream mixing zone temperatures, there is very little difference in the duration of occurrence for hourly averaging verses 24-hour averaging. Near the annual maximum and minimum temperatures, the difference between the hourly average and 24-hour average is again less than 0.5 F° at an exceedance of 0.5 percent (i.e., a total of about 48 hours over the entire year).

Observations in the mixing zone study, as well as those in the ambient temperature study, recognize that at low river flow, effluent from the mixing zone can become re-entrained into the water diluting the diffuser plume. This local buildup of heat in the river was not included in the version of the compliance model in use before the drought. To correct this situation, changes have been made in the model to simulate the local warming of the water entering the mixing zone at low river flow.

Overall Conclusions

Examining the ambient temperature study and mixing zone study collectively, the following overall conclusions are provided:

- Since the startup of the plant in 1981, SQN has always sought to expand TVA's understanding of the hydrothermal aspects of the combined operation of the Tennessee River and the plant. SQN has regularly conducted comprehensive surveys of the plant thermal effluent, averaging about one survey every for every 18 months of operation.

- As a result of the studies summarized herein, changes have been successfully made in the location of the ambient temperature measurement and in the mixing zone compliance model. These changes were needed to account for the local buildup of heat in the river that occurs at low river flow.

- Field testing and operating experience suggest that based on current procedures to monitor and operate the plant, the ambient temperature measurement and mixing zone configuration are adequate for steady river flows as low as about 6000 cfs. For peaking operations, the ambient temperature measurement is estimated to be adequate for daily average river flows as low as about 13,000 cfs and the mixing zone for daily average flows as low as about 10,000 cfs. If TVA anticipates operating at conditions below these levels, additional measurements will be taken to continue to confirm the adequacy of the ambient temperature measurement and the mixing zone.

- On an annual basis, exceedance probabilities suggest that there is little difference between the duration and frequency of ambient and mixing zone temperatures monitored using 24 hour averaging verses hourly averaging. NPDES monitoring with 24-hour averaging for the downstream temperature $\mathbf{T_d}$ and the temperature rise $\mathbf{\Delta T}$ has been in effect since August 2001 with no evidence of any adverse impact to the balanced indigenous population of shellfish, fish, and wildlife in Chickamauga Reservoir. Furthermore, the results of studies summarized herein suggest that based on current procedures for monitoring the plant thermal compliance, it is very likely that any changes in the plant operation to protect the NPDES limits based on 24-hour averaging will also attenuate the most extreme hourly average temperature excursions. That is, the most extreme hourly average temperature excursions usually coincide with the most extreme 24-hour average temperatures, wherein cooling tower operation or changes in unit generation are needed to maintain NPDES compliance for $\mathbf{T_d}$ or $\mathbf{\Delta T}$. For these reasons, and since 24-hour averaging is more synchronous with the time required to make safe changes in plant operation, SQN believes that the NPDES requirements for the downstream temperature and temperature rise can safely continue to be based on 24 hour averaging.

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AMBIENT TEMPERATURE AND MIXING ZONE STUDIES FOR SEQUOYAH NUCLEAR PLANT AS REQUIRED BY NPDES PERMIT NO. TN0026450 OF SEPTEMBER 2005

1.0 INTRODUCTION

Part III, Section F of the National Pollutant Discharge Elimination System (NPDES) Permit TN0026450 for Sequoyah Nuclear Plant (SQN) of August 2001 included a number of requirements related to the evaluation of Section 316 of the Clean Water Act. Due to the short span of the 2001 permit, these requirements were carried forward in the current NPDES permit, effective September 2005. The requirements address questions concerning Outfall 101, which includes, among other constituents, the discharge of waste heat into Chickamauga Reservoir through two submerged, multiport diffusers in the main channel of the Tennessee River. This report summarizes studies that have been completed by TVA to fulfill two of the Section F requirements. These are as follows:

> *To determine the adequacy of measurements for ambient river temperature, TVA shall conduct a study to evaluate the spatial distribution of water temperature in the overbank and main channel regions of Chickamauga Reservoir upstream of the plant diffuser. The study shall supplement data from previous evaluations, as needed, by measuring temperature profiles at selected sites in the reservoir. The study shall consider both winter and summer hydrothermal regimes, and both 1-hour and 24-hour averaging. The goal of the study is to determine the major factors contributing to the interaction between main channel and overbank flows, the impacts on water temperatures in the thermal mixing zone, and optimal location of monitors to record the ambient temperature.*

> *To determine the adequacy of the mixing zone, TVA shall conduct a study to evaluate the dynamic behavior of thermal plume from the plant diffuser. The study shall examine the justification for the existing mixing zone and supplement data from previous evaluations, as needed, by measuring temperature profiles at selected sites in and about the mixing zone. The study shall consider both winter and summer hydrothermal regimes, and both 1-hour and 24-hour averaging. The goal of the study is to better determine the impact of hydro peaking operations on the behavior of the thermal plume, and to determine if there is any need to redefine the extent of the mixing zone.*

The first of these studies is identified as the *ambient temperature study*. The second is identified as the *mixing zone study*. As background for the supplemental data that have been collected for the ambient temperature and mixing zone studies, a review is first provided of the SQN thermal criteria and monitoring requirements, ambient temperature measurement, and mixing zone requirements. This review includes work from the startup of the plant through the NPDES permit of August 2001. For this same period, a summary of the original diffuser physical model study and subsequent field verification studies also is given. The results of new studies targeting the specific issues identified in Section F are then presented. These include additional field deployments to measure water temperatures upstream of the plant and around the diffuser mixing zone. As a result of the new studies, changes have been made in the methods of monitoring SQN thermal compliance, including the location of the ambient temperature monitor and the formulation of the numerical model for the thermal plume in the mixing zone. These charges are presented herein alongside the results of the new studies.

2.0 BACKGROUND THROUGH 2001

2.1 SQN Thermal Criteria and Monitoring Requirements

Operating SQN in a fashion to fulfill TVA's goals of supplying low-cost reliable power and supporting a thriving river system is no trivial task. The awareness and understanding of the ever changing biological, hydrothermal, and operational aspects of Chickamauga Reservoir and SQN continue to evolve. It is no surprise, therefore, that modifications of the SQN thermal criteria and monitoring requirements have been needed to accommodate issues important to both TVA and the regulatory community.

The initial thermal criteria for SQN were based on temperature limits adopted by the Tennessee Water Quality Board in December 1971 and approved by the Environmental Protection Agency (EPA) in June 1972. The criteria include:

- A maximum instream temperature $\mathbf{T_d}$ of 86.9ºF (30.5ºC).
- A maximum instream temperature rise $\mathbf{\Delta T}$ of 5.4 Fº (3.0 Cº).
- A maximum instream temperature rate-of-change $\mathbf{dT_d/dt}$ of ±3.6 Fº/hour (±2 Cº/hour).

The monitoring requirements for these criteria were first specified in the Sequoyah NPDES permit effective July 1979. The criteria were applied to the area outside of a mixing zone of size appropriate for the multiport diffusers. The requirement for temperature rise was applied between this area and a suitable upstream control point, the latter which defines the ambient temperature for the thermal discharge. The locations of monitoring points, shown in Figure 1, were as recommended by TVA in February 1979 (TVA, 1979a). The upstream control point included a water temperature station located at the skimmer wall of the plant intake, Station 13. The area outside of the mixing zone was monitored by two water temperature stations located near the downstream corners of the mixing zone, Stations 8 and 11. The temperature at these stations was determined as the average of individual sensor readings at water depths of about 3 feet, 5 feet, and 7 feet (1.0 meter, 1.5 meter, and 2.0 meter). The thermal criteria did not identify a "time scale" in computing the temperature parameters. However, TVA agreed to parameters (i.e., $\mathbf{T_d}$, $\mathbf{\Delta T}$, and $\mathbf{dT_d/dt}$) that were determined as hourly averages, computed every 15 minutes by averaging the current and previous four 15-minute readings.

In the early eighties an issue arose concerning the validity of the downstream temperature measurements at Station 8 and Station 11. Field data found that temperatures from these monitors were, at times, not representative of the cross-sectional average temperature at the end of the mixing zone. Since the mixing zone resides in the navigation channel, instream temperature stations cannot be placed at locations optimal for obtaining a good cross-sectional average temperature. To reduce the uncertainty of the instream mounting of Figure 1 vs. the actual impact of the SQN thermal discharge, a hydrothermal model capable of predicting the temperature at the downstream end of the mixing zone was developed. The basic requirements for the model were outlined in the NPDES permit effective April 1983, which stated *"upon* *approval by the Director, Water Management Division, and the State Director, compliance with the river limitations shall be monitored by means of a numerical model that solves the thermo-hydrodynamic equations governing the flow and thermal conditions in the reservoir."* Field tests were conducted to verify the diffuser performance for the model and the model subsequently was found to provide a better representation of the downstream temperature than that of the instream monitors (TVA, 1983). In March 1984, approval was granted for TVA to use the numerical model to monitor compliance of the NPDES temperature requirements.

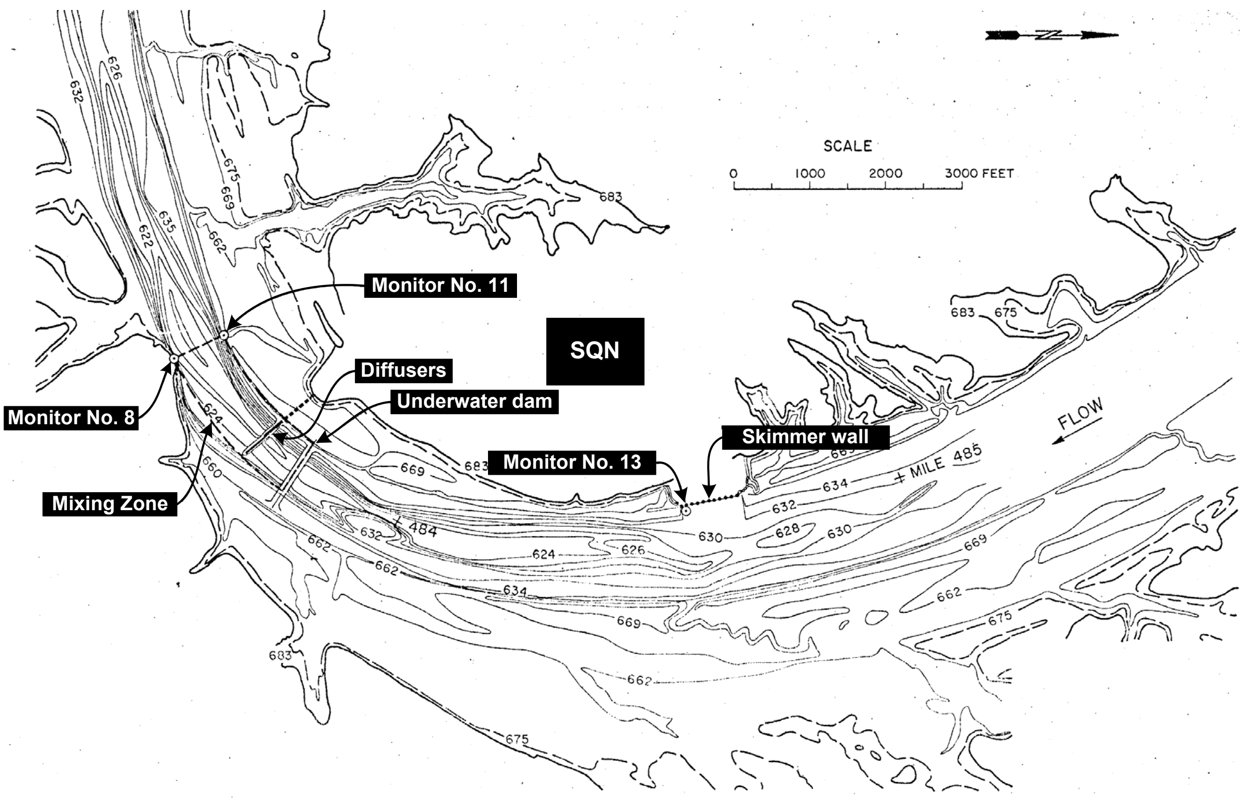


Figure 1. Water Temperature Station Locations for Initial Operation of SQN
(after TVA, 1979b)

Briefly, the hydrothermal model solves the fundamental equations for the conservation of mass, momentum, and thermal energy to determine the average temperature along the centerline of the thermal discharge from a submerged diffuser in a stratified, ambient cross flow. The basic parameters required by the original model are shown in Figure 2, and include the temperature and flow of water in the river, the depth of flow of the river, and the temperature and flow from SQN. Values for these parameters are determined from measurements at the SQN water temperature stations, shown in Figure 3, and at the hydro plants immediately upstream and downstream of SQN. The upstream ambient river temperature T_R was measured at Station 13. The measurements at the 3-foot, 5-foot, and 7-foot depths are averaged to obtain the upstream temperature $\mathbf{T_u}$. Note that $\mathbf{T_u}$ is required to determine the temperature rise $\mathbf{\Delta T=T_d-T_u}$.

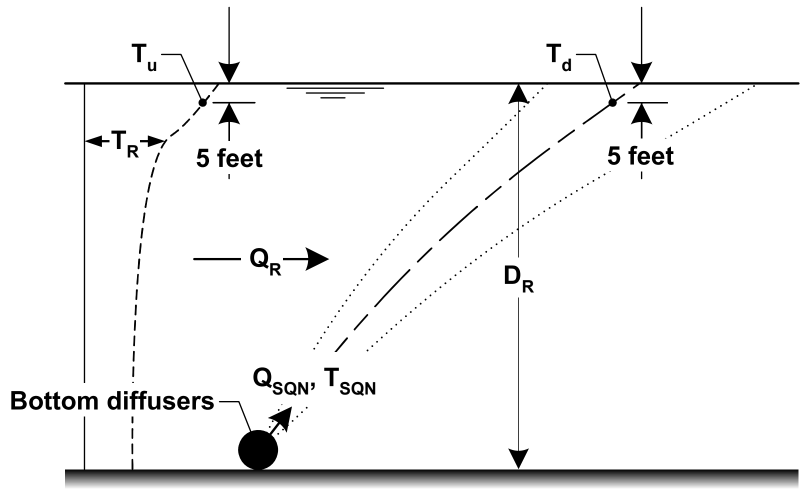


Figure 2. Basic Parameters for SQN Hydrothermal Model

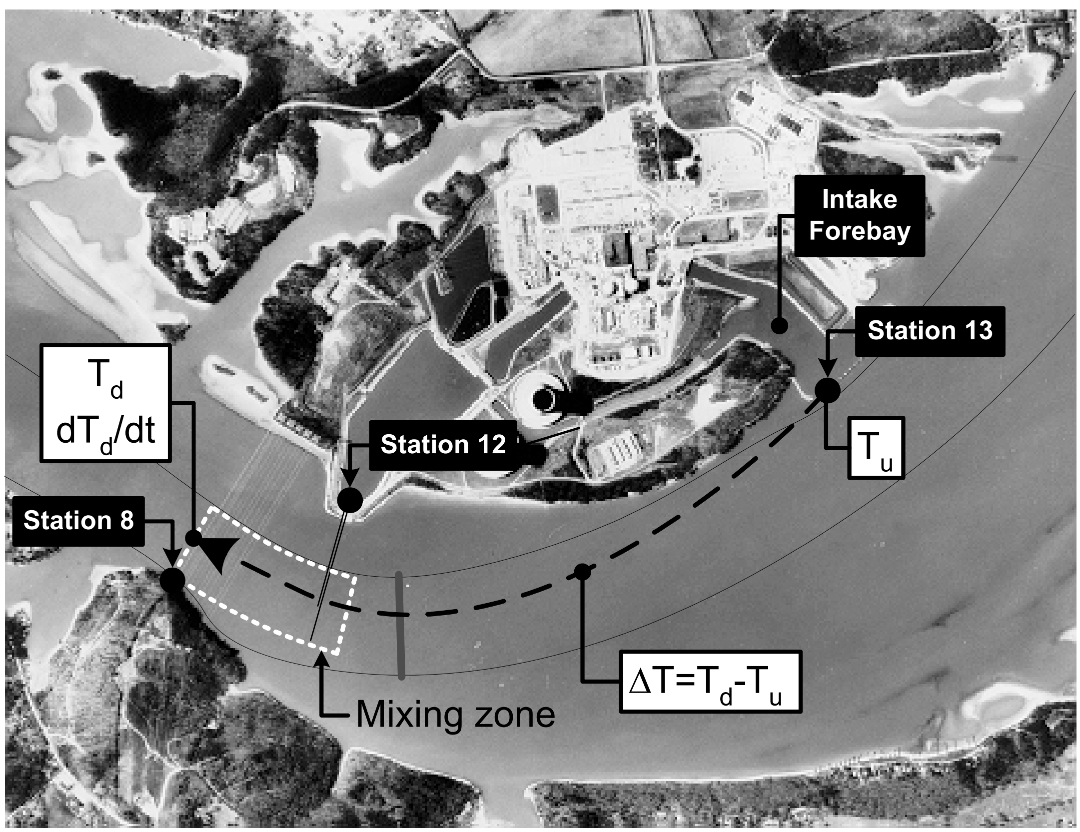


Figure 3. Water Temperature Stations for SQN Computed Compliance

The temperature of the effluent from Sequoyah T_{SQN} is measured at the entrance of the diffuser conduits at Station 12, located in a pond situated between the outlet of the plant and the river. In addition to temperature, Stations 12 and 13 also contain a stage recorder to measure, respectively, the water surface elevation in the diffuser pond and the water surface elevation in the river. The water surface elevation in the river is used to determine the depth of flow at the diffusers D_R. The discharge of effluent from Sequoyah Q_{SQN} is determined based on a calibrated rating curve giving Q_{SQN} as a function of the difference in water surface elevation between the diffuser pond and river. The river discharge at Sequoyah Q_R is computed based on a calibrated, one-dimensional flow model of Chickamauga Reservoir. The flow model requires discharges measured at the Watts Bar Hydro plant (WBH), located 45.5 miles upstream of SQN, and the Chickamauga Hydro plant, located 13.5 miles downstream of SQN. All of this information is collected over communication links by an Environmental Data Station (EDS) located at Sequoyah. The model computes the compliance temperatures $\mathbf{T_d}$, $\mathbf{\Delta T}$, and $\mathbf{dT_d/dt}$ every 15 minutes. Hourly average values are computed as previously summarized. Additional details about the model formulation are presented later in this report.

In implementing the "computed compliance," Station 11 was removed from service. Station 8, however, was retained to provide a backup for the downstream temperature measurement in the event of failure of the computed compliance system and to verify general trends determined by the hydrothermal model. In this arrangement it is emphasized that because Station 8 resides on the outer edge of the mixing zone, it can be dominated by processes significantly different from those in the mixing zone, such as heating and cooling in overbank and embayments areas in the immediate vicinity of the station.

The next significant issue to emerge occurred in the mid-eighties and involved problems related to the cooling towers. During periods of low flow in the wintertime, operation of the cooling towers was needed to prevent exceedances of the criterion for maximum temperature rise (i.e., 5.4 F°/3.0 C°). However, due to cold air temperatures, use of the cooling towers during these periods induced severe ice damage in the towers, which is costly and jeopardized the availability of the towers for subsequent months, particularly the summer. This prompted a 316(a) demonstrative request in 1989 to increase the $\mathbf{\Delta T}$ limits during the months November through March from 5.4 F° to 9.0 F° or 3.0 C° to 5.0 C° (TVA, 1989). TVA analyses found that this increase would not adversely impact the balanced, indigenous population of shellfish, fish, and wildlife in Chickamauga Reservoir. The request to raise the temperature rise limit was accepted by EPA and the State of Tennessee in the Sequoyah NPDES permit effective September 1993. With this, the thermal criteria became:

- A maximum instream temperature $\mathbf{T_d}$ of 86.9°F (30.5°C).
- A maximum instream temperature rise $\mathbf{\Delta T}$ of 9.0 F° (5.0 C°) for November thru March (i.e., "wintertime" operation).
- A maximum instream temperature rise $\mathbf{\Delta T}$ of 5.4 F° (3.0 C°) for April thru October (i.e., "summertime" operation).
- A maximum instream temperature rate-of-change $\mathbf{dT_d/dt}$ of ±3.6 F°/hour (±2 C°/hour).

The overall monitoring requirements for the new criteria remained largely unchanged. That is, the hydrothermal modeling system was considered adequate for determining the temperature in the mixing zone and the thermal criteria continued to be interpreted on an hourly average basis.

The most recent issues emerged in the mid-nineties and involved the effects on Sequoyah of certain unsteady behaviors in Chickamauga Reservoir. The behaviors are caused primarily by two processes. The first is the daily variation of river flow that occurs as a normal part of peaking operations at TVA hydro plants, and the second is fluctuations in the ambient river temperature. Depending on the exact circumstances, these processes can give rise to individual events threatening the limit for $\mathbf{T_d}$, $\mathbf{\Delta T}$, or $\mathbf{dT_d/dt}$. Those for $\mathbf{dT_d/dt}$ are the most problematic and occur in both the winter and summer. In the winter, cooling tower operation cannot reliably be used to control $\mathbf{dT_d/dt}$, again due to potential icing. In the summer, the $\mathbf{dT_d/dt}$ events occur in the ambient temperature upstream of the plant and cannot be controlled by tower operation. Events threatening the limits for $\mathbf{T_d}$ are related to the unpredictability of summertime upward swings in the ambient temperature and the rate of onset of these swings. In the hydrothermal model, the impact of the waste heat from Sequoyah is superimposed on the ambient temperature to yield the downstream temperature. Thus, unexpected increases in the upstream temperature also occur in the downstream temperature. In some cases, the cooling towers can be used to control fluctuations in downstream temperature; but, due to the inherent complexity of the equipment, the towers cannot be brought into service on short notice, as may be required to respond to the rapid onset of temperature increases. Problems for $\mathbf{\Delta T}$ occur primarily in April and May, when river flows are restricted to help fill TVA reservoirs.

In light of the inability of SQN to fully control these events, and to avoid derating the plant, special operations of the river system were regularly used to maintain compliance of the thermal criteria. Due to the large extent of these special operations, a supplemental 316(a) demonstration was performed in 1996 to make additional changes in the thermal criteria and monitoring requirements (TVA, 1996). The proposed changes included the following:

- Increase the maximum instream temperature rate-of-change $\mathbf{dT_d/dt}$ from ±3.6 F°/hour to ±9.0 F°/hour (from ±2 C°/hour to ±5 C°/hour).

- Include April and May in the period of wintertime operation, allowing a maximum instream temperature rise $\mathbf{\Delta T}$ of 9.0 F° (5.0 C°) for November thru May.

- Monitor the instream temperature $\mathbf{T_d}$ and instream temperature rise $\mathbf{\Delta T}$ based on a 24-hour average.

As before, TVA analyses found that the proposed changes would not adversely impact shellfish, fish, and wildlife in Chickamauga Reservoir. In ensuing debate, however, the first two items were denied by the State. The third item, though, was accepted, because it did not involve an additional change in the thermal standards via the 316(a) process. That is, the magnitudes of the limits for instream temperature $\mathbf{T_d}$ and instream temperature rise $\mathbf{\Delta T}$ remained the same as before–only the time scale for computing the parameters was adjusted. Since this did not resolve the problems related to the temperature rate-of-change, and since SQN was not directly responsible for unsteady behaviors resulting from daily variations in river flow, TVA proposed an alternate method for monitoring $\mathbf{dT_d/dt}$. In the method, unexpected swings in ambient reservoir conditions are handled by using 24-hour average values in the hydrothermal model for the river conditions, specifically, the ambient river temperature, river discharge, and river depth (i.e., T_R, Q_R, and D_R in Figure 2). The impact of short-term variations in the SQN thermal discharge is added to the 24-hour average river conditions by using 15-minute values for the flow and temperature of the Sequoyah effluent (i.e., Q_{SQN} and T_{SQN} in Figure 2) in computing $\mathbf{dT_d/dt}$. The hourly average temperature rate-of-change due to these variations is computed, as before, using the current and previous four 15-minute $\mathbf{dT_d/dt}$ values.

Monitoring $\mathbf{dT_d/dt}$ by 24-hour averaging of the river conditions was approved by the State, subject to the hydrothermal studies summarized herein. It is important to note that this type of averaging is used only for the computation of $\mathbf{dT_d/dt}$. For $\mathbf{T_d}$ and $\mathbf{\Delta T}$, 15-minute values are yet determined solely from 15-minute values of the model parameters identified in Figure 2. It again is emphasized that in approving the changes for $\mathbf{T_d}$, $\mathbf{\Delta T}$, and $\mathbf{dT_d/dt}$ there were no additional changes in the fundamental thermal criteria. That is, the supplemental 316(a) proposed in 1996 was not invoked—changes in the requirements for monitoring were made outside of the 316(a) process. With these changes, the basic thermal criteria and monitoring requirements found in the Sequoyah NPDES permit effective August 2001 included the following:

- A maximum instream temperature $\mathbf{T_d}$ of 86.9ºF (30.5ºC).
- A maximum instream temperature rise $\mathbf{\Delta T}$ of 9.0 Fº (5.0 Cº) for November thru March.
- A maximum instream temperature rise $\mathbf{\Delta T}$ of 5.4 Fº (3.0 Cº) for April thru October.
- A maximum instream temperature rate-of-change $\mathbf{dT_d/dt}$ of ±3.6 Fº/hour (±2 Cº/hour).
- $\mathbf{T_d}$ and $\mathbf{\Delta T}$ are to be monitored based on 24-hour average values, calculated every 15-minutes by averaging the current 15-minute values with the previous ninety-six 15-minute values.
- $\mathbf{dT_d/dt}$ is to be monitored based on an hourly average value, calculated every 15 minutes by averaging the current 15-minute value with the previous four 15-minute values, where each 15-minute value is determined based on the 24-hour average river conditions (i.e., T_R, Q_R, and D_R) and current 15-minute plant conditions (i.e., Q_{SQN} and T_{SQN}).

In addition to the above, it is noted that other concerns over the years have led to other specific monitoring requirements. For example, the following items also are found in the current NPDES permit:

- To allow operation of the plant when the ambient temperature exceeds the thermal criteria, when the 24-hour average upstream temperature $\mathbf{T_u}$ exceeds 84.9ºF (29.4ºC), the

24-hour average downstream temperature $\mathbf{T_d}$ may exceed 86.9ºF (30.5ºC), if the plant is operating the cooling towers with at least three lift pumps per operating unit.

- In no case shall the 1-hour average downstream temperature $\mathbf{T_d}$ exceed 93.0ºF (33.9ºC) without consent of the permitting authority.

2.2 SQN Ambient Temperature

The specifications for monitoring the SQN upstream ambient temperature were originally recommended by TVA in February 1979 (TVA, 1979a). The State granted approval of the recommendations in the NPDES permit effective July 1979. As previously summarized, the ambient temperature was measured at Station 13, located on the reservoir-side of the plant intake skimmer wall, and was computed as the average of sensor readings at depths of 3 feet, 5 feet, and 7 feet. At that time, Station 13 obviously was considered to be beyond the zone of impact of the plant thermal discharge and a good location for measurement of the temperature of water entering the plant. Station 13 also borders the main channel of the river, which provides the main source of water for dilution of the thermal effluent from the plant diffusers (see Figure 3).

In the NPDES permit effective April 1983, the State emphasized the requirement that *"under no conditions shall the thermal plume be allowed to reach the ambient temperature recorder."* If the plume reached the ambient temperature recorder, the temperature rise $\mathbf{\Delta T}$ would be biased low, thereby underestimating the impact of the SQN thermal discharge on Chickamauga Reservoir. Subsequent analyses by TVA indicated that the probability of a surface thermal wedge from the diffusers extending upstream 3000 feet, about one-half the distance to the Station 13 monitor, is of magnitude 0.0008 percent. This conclusion was based on an analysis of the computed magnitude and duration of reverse flow events at the site due to hydro peaking operations of the river. As presented later with the new studies, this analysis has been found to be erroneous. This is because the analysis assumed the upstream propagation of heated effluent from the diffusers was limited by the extent of a thermal wedge, which was assumed to expand at a rate roughly equivalent to the cross-sectional average velocity in the river. In reality, TVA has learned that other transport mechanisms exist that can spread residual heat from the mixing zone significantly further upstream than the extent of a thermal wedge.

Problems with swings in the ambient temperature occur during high river flow. An example event with swings in the ambient temperature is given in Figure 4. The figure shows the calculated river discharge at SQN along with the measured ambient temperature at Station 13 and the resulting ambient temperature rate-of-change. The event occurred the first two days of June 2000. The temperatures include both 15-minute and hourly average data. It is emphasized that in June 2000 the plant was operating under the NPDES permit effective September 1993 and did not include 24-hour averaging of ambient river conditions for the temperature rate-of-change. During afternoon peaking operations, when the river flow exceeds about 30,000 cfs, it can be seen that the ambient temperature begins to fluctuate in a manner creating 15-minute variations that at times surpass ±2 Fº (1.1 Cº). On June 2, the resulting hourly average value hit the compliance limit of ±3.6 F°/hour (±2 C°/hour). These ambient variations, in turn, were superimposed by the hydrothermal model on the compliance parameters computed at the downstream end of the mixing zone.

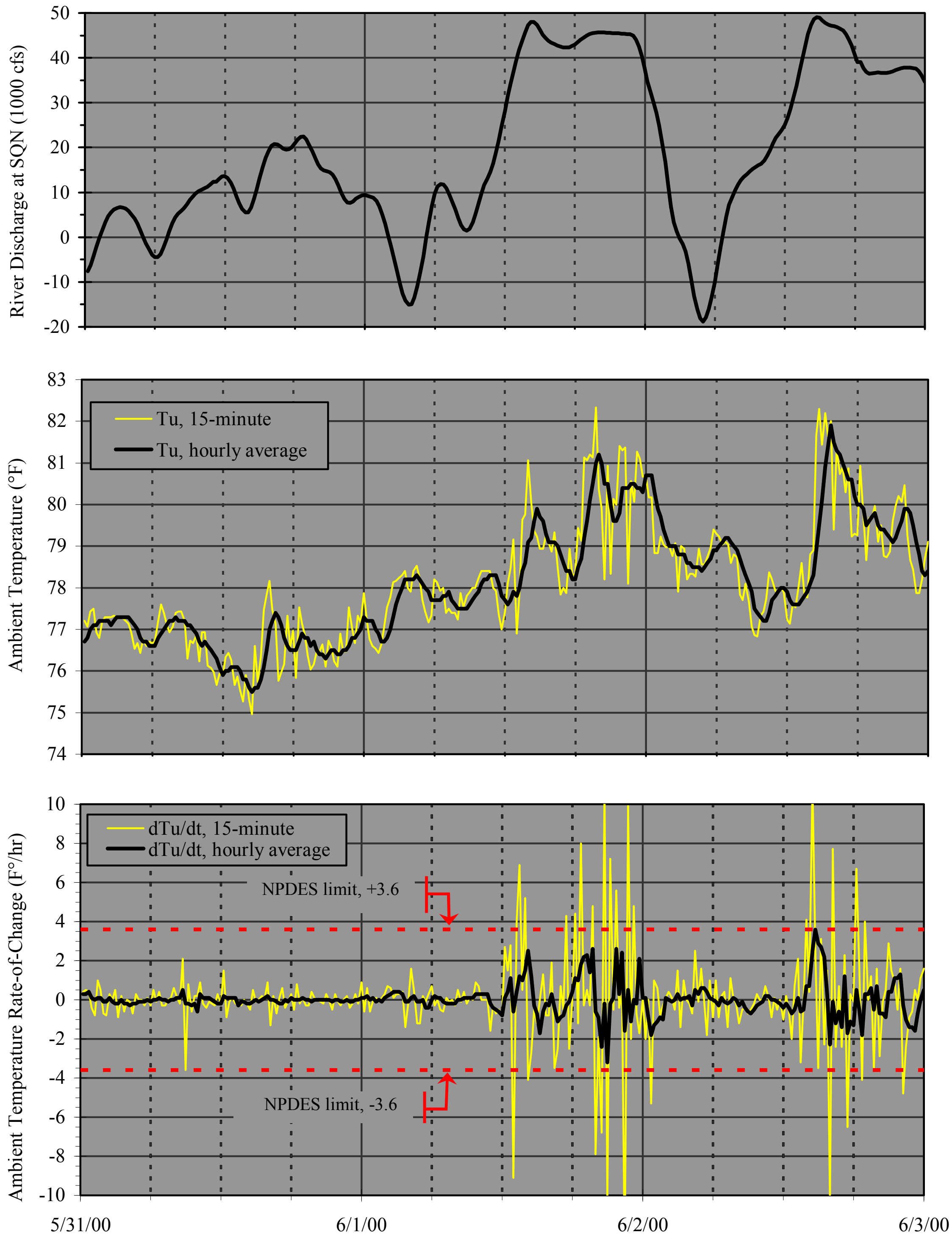


Figure 4. Hydrothermal Event with Spiking in Ambient Temperature at Station 13

In part, it appears that troublesome swings in the ambient temperature occur when the river discharge exceeds about 38,000 cfs. It is speculated that the reason why ambient spiking had not been problematic in the years prior to the mid-nineties is related to the condition of the hydro plant at Chickamauga Dam. Over the past 50 years, plant equipment had degraded to a point where the maximum discharge through the hydraulic turbines was limited to about 38,000 cfs. Between 1994 and 1997 the hydro units and other related equipment were upgraded, allowing the Chickamauga discharge to match levels similar to the capacity of the original turbines, over 45,000 cfs. This, in turn, has allegedly resulted in ambient temperature events that until recently had never been observed in the life of SQN.

Several processes are envisioned as potentially playing a role in ambient temperature spiking. In the summer, late afternoon solar heating can cause the water temperature in the near surface region of the flow to become much warmer than the water at a depth of 5 feet. Higher levels of flow turbulence caused by high river discharges can mix the surface water downward to the 5-foot depth and create intermittent temperature fluctuations. In the winter, a similar phenomenon can occur with surface cooling, which is exacerbated by the fact that such cooling is innately unstable (i.e., cool water underlain by warmer water is unstable). In addition to vertical variations in temperature, fluctuations also can occur as a result of lateral differences between the main channel and overbanks. Water in shallow overbank areas will heat up and cool off much faster than water in the deep main channel. At high river flow, mixing between the main channel and overbank areas can entrain parcels of water from the overbanks, again creating intermittent fluctuations. As shown in Figure 5, shallow overbank areas prevail in the areas surrounding SQN, particularly on the east side of the reservoir across from and upstream of the plant. Both Station 13 and Station 8 are positioned in regions that could potentially be influenced by turbulent interactions between the main channel and overbanks.

Whereas the above processes depend on turbulent interactions, unexpected increases in the ambient temperature might also occur due to advection from different areas by the mean flow. For example, as a part of routine river operations, Chickamauga Reservoir can undergo daily and weekly cycles of drawdown and filling. A common occurrence is for the water level to drop (i.e., drawdown) during afternoon peaking operations and rise (i.e., fill) during early morning periods of low flow. Weekly variations occur for mosquito control. In these processes, water will fill into and drain out of the overbanks, embayment areas, and creeks. In the summer, water from these areas will likely be warmer than that in the main channel, and vice versa in the winter. When parcels of water from these areas are transported past a monitoring station, the temperature, subsequently, will fluctuate. In the summer, Soddy Creek and Opossum Creek, located upstream of SQN, are potential sources for parcels of warm water in Chickamauga Reservoir. Another mean flow process is related to the curvature of the river. Such curvature, which exists in the vicinity of SQN, will cause secondary currents to develop in directions transverse to the centerline of the river. This again can potentially cause the exchange of water between the main channel and overbanks, yielding fluctuations in the ambient temperature.

Overall, depending on the magnitude and extent of these processes, it may be that another more suitable location exists to measure the ambient temperature. This indeed is what has been discovered in recent work, as presented later with the new studies.

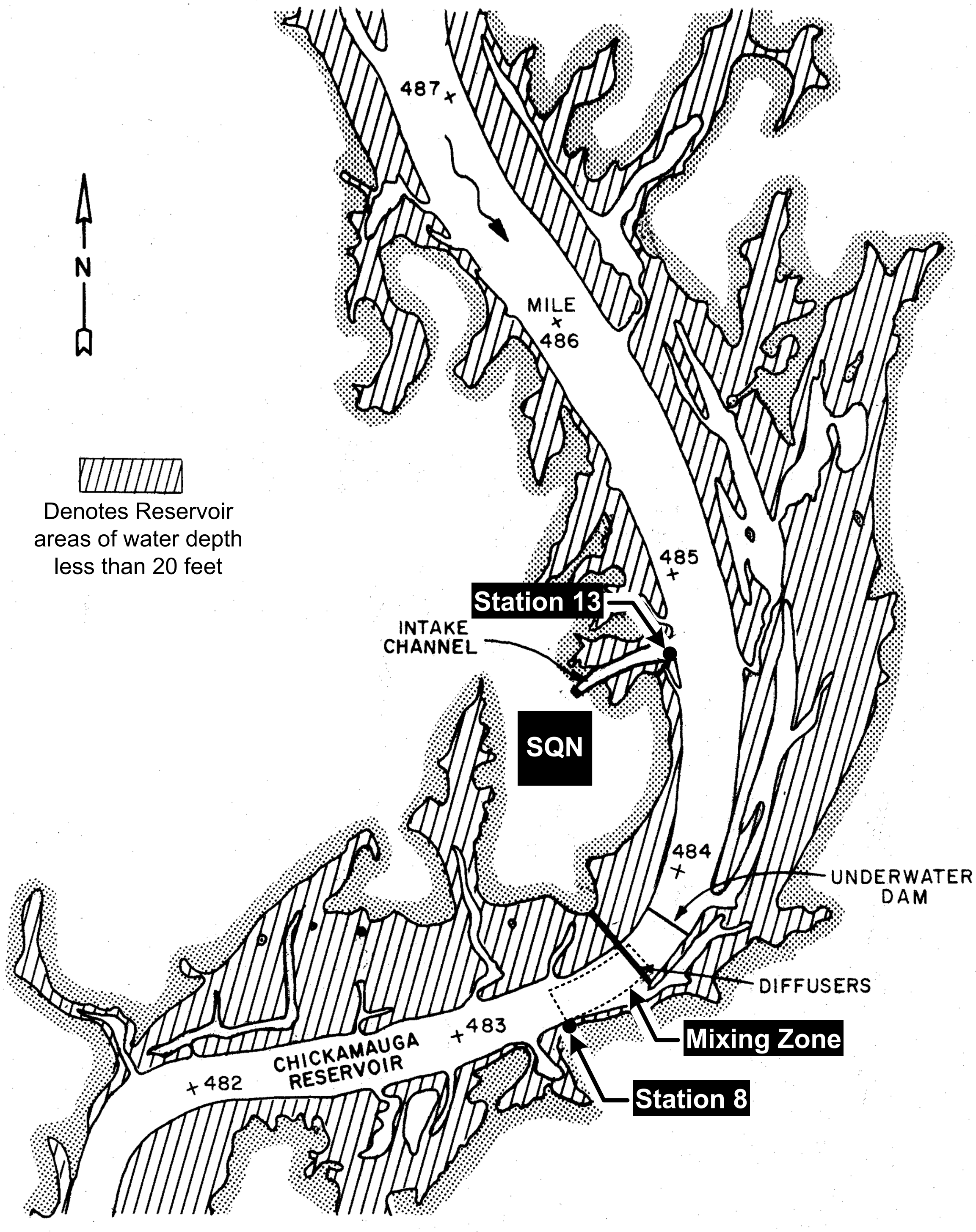


Figure 5. Main Channel and Overbank Areas near SQN
(after TVA, 1978)

2.3 SQN Mixing Zone

The mixing zone for SQN was proposed by TVA based on a physical model study of the discharge diffusers conducted at the TVA Engineering Laboratory (TVA, 1978). The initial recommendation included a zone 750 feet wide and 1500 feet long, extending downstream from the diffusers over the entire depth of flow. In subsequent discussions with EPA and the State, the extent of the mixing zone was modified to provide for upstream excursions of a thermal wedge on the water surface during low and reverse river flow events. The permit effective July 1979 thus provided an additional area extending 275 feet upstream of the diffusers with a depth that varied linearly from the water surface at 275 feet to the top of the diffuser pipes. This mixing zone has been certified by the State from 1979 to the current NPDES permit. The present permit also specifies that if SQN is operated in closed mode, the mixing zone shall include the intake forebay of the plant (see Figure 3).

In general, prior to the current permit, there have been no issues concerning the definition of the mixing zone for SQN. As summarized later, studies have been performed regularly to evaluate water temperatures in and around the mixing zone. Whereas most of these studies have examined conditions with steady flows, recent concerns are more focused on the behavior of the thermal effluent for unsteady conditions stemming from hydro peaking operations.

3.0 PREVIOUS STUDIES THROUGH 2003

3.1 Physical Model Study

In general, releasing heat through multiport diffusers situated on the bottom of the river hastens mixing of the effluent with the receiving water and significantly reduces the required size of the mixing zone (i.e., compared to side-channel discharges into the surface layer of the river, which were common at that time). The design of the submerged multiport diffusers for SQN was based on experience developed in the design of diffusers for the TVA Browns Ferry Nuclear Plant (BFN). The BFN analyses included a two-dimensional physical model study at the Massachusetts Institute of Technology (Harleman et al., 1968) and a three-dimensional physical model study at the TVA Engineering Laboratory (TVA, 1972).

Despite the confidence of the BFN work, a physical model study also was conducted for the proposed SQN diffusers (TVA, 1978 and TVA, 1979c). The objectives of the SQN model were to evaluate the performance of the diffusers for the specific conditions expected at the site and to determine empirical coefficients required to estimate the ambient entrainment and dilution of the diffuser discharge. The model was constructed at a scale of 1:90 in a 10-foot wide flume at the TVA Engineering Laboratory. The model corresponded to a section of the main channel about 900 feet wide and 6300 feet long. The overbanks were not modeled because it was estimated that they contribute little flow for the dilution of the thermal discharge. Also, because secondary currents were estimated to have only a minor impact on mixing, the model was constructed as a straight section of river rather than a curved channel. The model did include, however, an underwater dam located about 350 feet upstream of the diffusers.

The SQN model included tests for prototype river flows varying between -5000 cfs (reverse flow) to 30,000 cfs and diffuser discharges corresponding to both one- and two-unit operation of the plant. Effluent temperatures were tested at 10 F°, 20 F°, 30 F° above the ambient (upstream) temperature (5.56 C°, 11.11 C°, 16.67 C°). Roughly 100 thermistors were used to measure water temperatures in the model. The major findings from the model include the following:

- For the cases examined, the initial temperature difference between the ambient and SQN effluent is quickly reduced by the action of the diffuser jets to values below the thermal criteria (i.e., 5.4 Fº/3.0 Cº).
- A stratified surface layer is formed in nearly all the cases tested and extends upstream of the diffusers.
- The major portion of the jet mixing occurs within 500 feet downstream of the diffusers.
- The thermal criteria could be threatened for reverse flows of duration in excess of two hours, and may require cooling tower operation to prevent exceeding the temperature limits. (Note: this finding is based on the thermal criteria of 1979, which included hourly averaging for the temperature rise.)
- The underwater dam does not adversely affect diffuser mixing.

- The underwater dam limits the thickness of stratified layers (thermal wedge) that may propagate upstream for low and reverse flow conditions.

- The experimentally determined entrainment coefficients yield mixed temperatures that are slightly conservative (i.e., lower) than those of the design theory.

Overall, the model study supports the adequacy of the diffuser design for efficiently mixing the thermal effluent in the receiving water. The model study also provided a good basis for defining the mixing zone. Although a large amount of the mixing occurs in the first 500 feet downstream of the diffuser, a length of about 1500 feet is needed, based on the overall design of the SQN heat dissipation system, to provide adequate dilution for the State thermal criteria. Confirmation of the diffuser performance and mixing zone, at least for the type of conditions examined in the model, is found in field studies, discussed in the following.

3.2 Field Studies

Field studies of the SQN thermal discharge have been ongoing since the plant began releasing heat to Chickamauga Reservoir. The NPDES permit effective July 1979 stated that the *"permittee shall implement a field program to verify model predictions and document the three-dimensional extent and configuration of the thermal plumes in the intake basin, diffuser pond, and Tennessee River."* The permit required studies for both one-unit and two-unit operation and specified that subsequent reports shall be submitted annually, if necessary.

Commercial operation of Unit 1 began in early July 1981. Subsequently, on July 24, TVA conducted the first hydrothermal study for the diffuser discharge (TVA, 1982). A summary of river conditions and plant conditions for the test is given in Table 1. The river discharge was about 27,000 cfs with an ambient water temperature of 81.1°F (27.3°C) and about 0.5 F° (0.3 C°) of stratification. SQN was operating in open mode, discharging about 1240 cfs through the upstream diffuser at a temperature about 20.9 F° (11.6 C°) above the ambient (5-foot) temperature. The study included measurements of water temperature in and around the diffuser mixing zone, allowing the development of isothermal plots to examine the three-dimensional extent of the thermal plume. Example plots are given in Figure 6. In general, it was found that:

- The measured dilution of the thermal discharge was greater than that predicted by theory based on physical model tests.

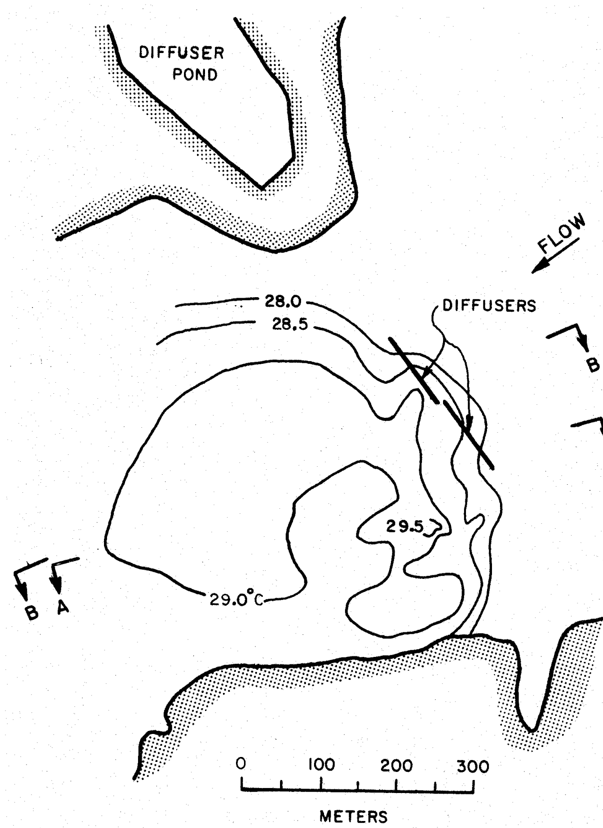
- Intense initial mixing occurred with the cool bottom water in the immediate vicinity of the diffuser.

- Further mixing occurs at shallower depths, with the thermal plume emerging at the water surface about 660 feet downstream of the diffusers.

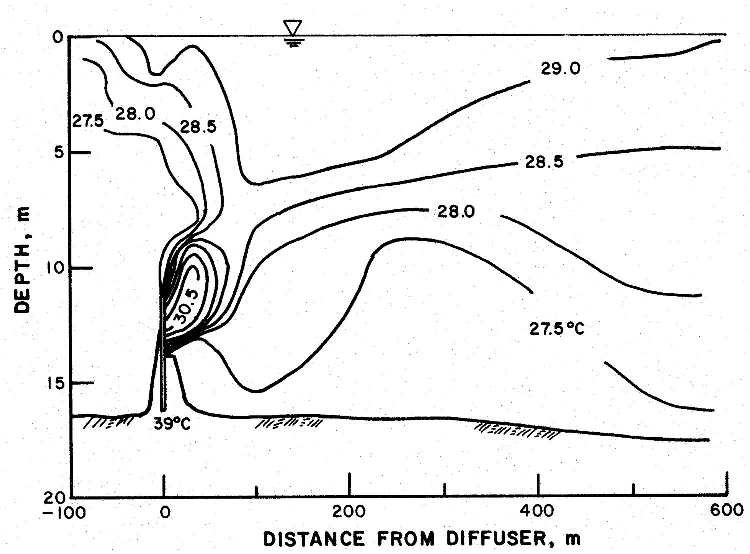
Table 1. Field Studies for Sequoyah Nuclear Plant

Date	River Conditions (A)			Sequoyah Conditions (A)							Measured NPDES Thermal Compliance (A)	
				Generation			Diffuser Operation					
	Discharge (cfs)	Ambient Temp (B) (°F)	Stratification (C) (F°)	Units	Total MWe	Mode	Legs (D)	Total Discharge (cfs)	Discharge Temp (°F)	Discharge Temp Rise (E) (F°)	Downstream Temperature (F) (°F)	Temperature Rise (G) (F°)
Jul 24, 1981	26,700	81.1	0.5	1	1100	Open	U/S	1240	102.0	20.9	84.0	2.9
Apr 4, 1982	20,000	57.2	0.9	1 & 2	2290	Open	U/S&D/S	2580	81.4	24.2	61.3	4.1
May 14, 1982	8,000	73.7	11.8	1 & 2	1460	Open	U/S&D/S	2550	80.5	6.8	72.6	-1.1
Sep 2, 1982	38,000	77.9	0.4	1 & 2	2260	Open	U/S&D/S	2550	102.8	24.9	80.4	2.5
Nov 10, 1982	35,000	59.0	0.2	1	1150	Open	U/S	1287	93.2	34.2	60.7	1.7
Mar 31, 1983	9,000	51.5	1.8	1 & 2	2100	Helper	U/S	2580	65.9	14.4	54.6	3.1
May 11, 1983	25,000	64.4	3.3	1 & 2	2350	Open	U/S&D/S	2580	88.0	23.6	68.7	4.3
Mar 1, 1996 (H)	20,000 to 43,000	46.0	-0.1	1 & 2	2300	Open	U/S&D/S	2490	73.2	27.2	Unsteady	Unsteady
Jul 24, 1997	40,000	83.9	3.6	1 & 2	2310	Open	U/S&D/S	2470	107.3	23.4	84.6	0.7
Mar 24, 1999	35,000	51.8	0.0	1 & 2	2080	Open	U/S&D/S	2490	76.0	24.2	53.8	2.0
Aug 2, 2000	9,000	82.1	0.2	1 & 2	2300	Helper	U/S&D/S	2480	100.2	18.1	85.7	3.6
Jul 27, 2002 (I)	17,000	84.0	1.7	1 & 2	2290	Helper	U/S&D/S	2610	99.3	15.3	86.6	2.6
Apr 23, 2003 (I)	30,000	63.2	1.1	1	1180	Open	U/S&D/S	1260	88.3	25.1	64.6	1.4

Notes:
(A) Approximate average values throughout duration of field study. Hourly conditions often vary throughout the study depending on the diurnal changes in meteorology, turbulent fluctuations, and perhaps other unsteady undulations in the mean flow.
(B) Ambient water temperature measured at 5-foot depth at Station 13 (SQN intake skimmer wall).
(C) Stratification computed as the difference in water temperature between the 5-foot depth and skimmer wall bottom opening.
(D) U/S = upstream diffuser leg and D/S = downstream diffuser leg.
(E) Diffuser discharge temperature rise computed as the difference between the diffuser discharge water temperature and the ambient water temperature.
(F) Downstream temperature as given by the average of field measurements at the 5-foot depth across the downstream edge of mixing zone.
(G) Temperature rise computed as the difference between the measured downstream water temperature and the ambient water temperature.
(H) Field study of March 1, 1996, conducted with unsteady river flows to evaluate temperature rate-of-change.
(I) Field studies of July 27, 2002, and April 23, 2003, included temperature measurements only at the downstream end of mixing zone.



(a) Water Temperature Distribution at 5-Foot Depth



(b) Water Temperature Distribution along Section B-B

Figure 6. Water Temperature Measurements from Field Study of July 24, 1981
(after TVA, 1982)

- After breaching the surface, the plume continued to spread, extending over a substantial depth at the downstream end of the mixing zone.

- A thermal wedge extended upstream of the diffuser about 300 feet.

- Water temperatures at the boundary of the mixing zone were well within NPDES limits.

As required by the permit, the hydrothermal study also included the diffuser pond, where it was found that the water temperature was fairly uniform and not significantly different from the temperature of that exiting the plant. This is because:

- The pond is small compared to the volume of water passing through the pond.

- The turbulence in the flow is strong enough to produce well-mixed conditions with little stratification.

- The surface area of the pond is small, resulting in very little heat loss to the atmosphere.

Because of these properties, it was concluded that the water temperature in the pond during helper mode operation, when the cooling towers are in service, would likely exhibit the same basic characteristics. Hence, no further hydrothermal studies were conducted for the pond. The diffuser pond, although part of the treatment system for SQN waste heat, is not naturally connected to Chickamauga Reservoir. As such, beginning with the NPDES permit effective September 1993, the diffuser pond is no longer recognized as waters of the State and is not included as part of the mixing zone.

It should be emphasized that the same is not true of the intake forebay, which consists of an embayment connected to the main channel of the river. As previously indicated, during closed mode operation, the intake forebay is considered part of the mixing zone. SQN has operated in closed mode only once, about ten days in January 1985. This event occurred when severe cold weather entered the Southeast coincident with a period of low river flow. Due to the need for power, it was undesirable to derate the plant. Thus, to prevent violation of the temperature rise criterion, SQN initiated closed mode operation (i.e., at that time the **ΔT** limit included a maximum hourly average of 5.4 F°/3.0 C° at all times). Due to the unexpected nature of the event and the harsh winter conditions, it was not possible to perform a hydrothermal study of the forebay. It also is worth noting that in this event ice created about $1.2 million in damage to the cooling towers (1985 dollars). With the current thermal criteria and monitoring requirements, SQN should never again need to enter closed mode operation. However, if this were to change, and if sufficient time is available, TVA would perform appropriate studies of the intake forebay to determine the characteristics of the thermal discharge, per the intent of the NPDES permit of 1979, and to monitor indigenous populations of shellfish, fish, and wildlife.

Because not all the studies required by the 1979 permit were completed, the NPDES permit effective April 1983 again stated that the *"permittee shall implement a field program to verify model predictions and document the three-dimensional extent and configuration of the thermal plumes in the intake basin, diffuser pond, and Tennessee River."* In addition, to support the validity of implementing a computed compliance, the 1983 permit also specified *"field tests shall be conducted to establish the diffuser performance characteristics to be used in the numerical model."* These requirements were satisfied by six field studies conducted between April 1982 and May 1983 and summarized in a report dated August 1983 (TVA, 1983). The basic conditions of these tests again are given in Table 1. They include springtime studies conducted on April 4, 1982; May 14, 1982; March 31, 1983; and May 11, 1983; and fall studies conducted on September 2, 1982, and November 10, 1982. Depending on the specific study, the river discharge varied between about 8,000 cfs and 35,000 cfs and the ambient water temperature between about 51.5°F and 77.9°F (10.8°C and 25.5°C). In one case, stratification was essentially nonexistent (i.e., study of November 10, 1982) and in another it was as large as 11.8 F° or 6.6 C° (May 14, 1982). SQN operation also varied among the studies, including both one-unit and two-unit operation, open and helper mode operation, and single and dual diffuser leg operation. The diffuser discharge temperatures varied between 6.8 F° or3.8 C° (May 14, 1982) and 34.2 F° or 19.0 C° (November 10, 1982) above the ambient (5-foot) temperature. The studies included measurements of water temperature at depths of 3 feet, 5 feet, and 7 feet (1.0 meter, 1.5 meters, and 2.0 meters) along several cross sections, including:

- Longitudinal sections along the left and right sides of the mixing zone, and along the centerline of the mixing zone (looking downstream).

- Lateral sections at the downstream end of the mixing zone.

- Lateral sections along three transects within the mixing zone (March 31, 1983, and May 11, 1983, only).

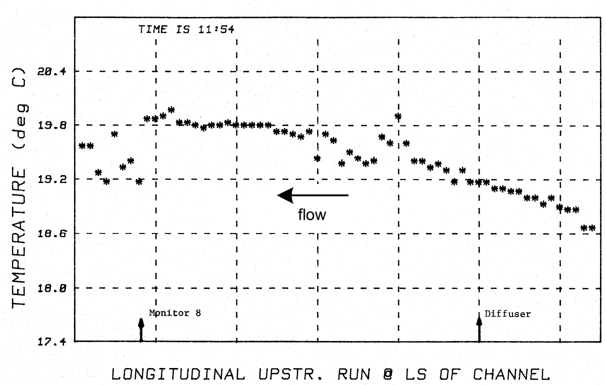
The temperatures at the three depths were averaged to produce plots of the temperature at the 5-foot depth. An example for the study of May 11, 1983, is provided in Figure 7. This information, subsequently, was used to examine the three-dimensional extend of the thermal plumes. From the 1982 and 1983 tests it was found that:

- When hydrothermal conditions allow the thermal plumes to reach the surface, it usually does so very close to the diffusers.

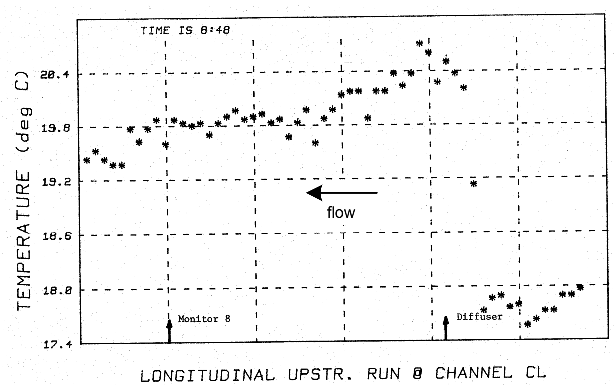
- In some cases, the plumes extend upstream of the diffusers as a thermal wedge, the extent of which depends on the prevailing flow conditions.

- For studies conducted at higher river flows, 35,000 cfs and above, the thermal plumes are forced downstream (i.e., no thermal wedge extending upstream).

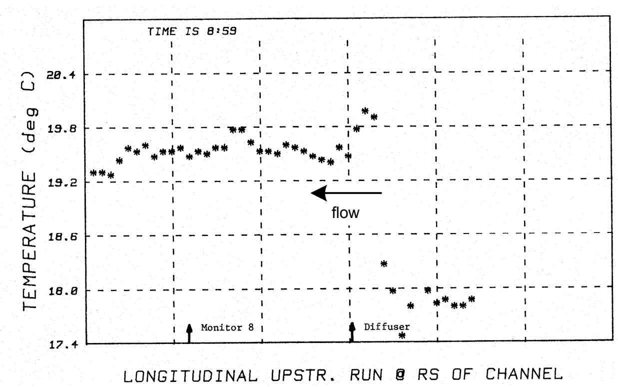
- For conditions with strong stratification, the thermal plumes can be diluted by cool bottom water before reaching the water surface, causing the plumes to remain submerged at depths perhaps greater than the 5-foot compliance depth (May 14, 1982).



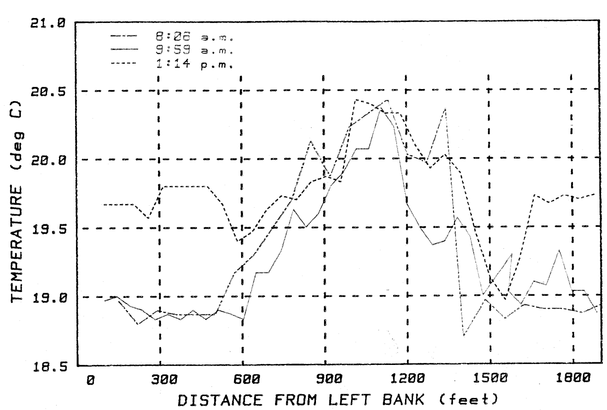
(a) Approx left-hand side of mixing zone



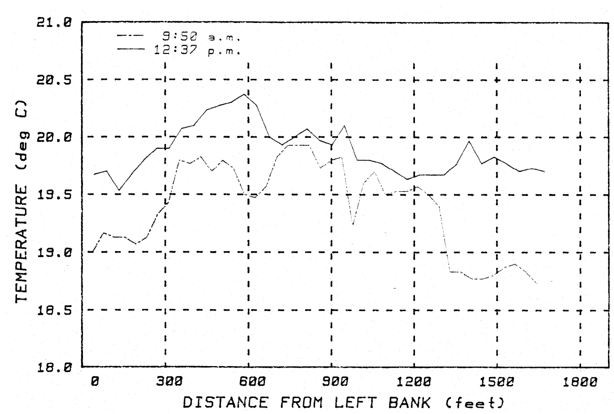
(b) Approx centerline of mixing zone



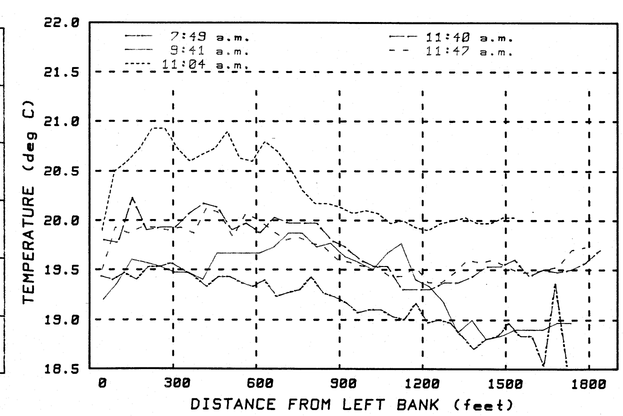
(c) Approx right-hand side of mixing zone



(d) Approx 500 feet downstream of diffusers



(e) Approx 1000 feet downstream of diffusers



(f) Approx 1500 feet downstream of diffusers
(downstream end of mixing zone)

Figure 7. Water Temperature Measurements from Field Study of May 11, 1983
(after TVA, 1983; plots a, b, c based on facing northern side of main channel; plots d, e, f based on facing downstream)

- The thermal plumes are often asymmetric relative to the center of the mixing zone, with cooler water residing on the right side of the plume (facing downstream).

- The region where the thermal discharge raises the water temperature above ambient extends beyond the NPDES-defined mixing zone, and can be as much as 1500 feet wide at the downstream end of the mixing zone with both diffusers in operation.

- If the plume is defined by contours depicting the thermal criteria (e.g., for $\mathbf{T_d}$, the locations where the downstream temperature is 86.9ºF (30.5ºC); for $\mathbf{\Delta T}$, the locations where the temperature rise is 5.4 Fº (3.0 Cº)), the plume always remains within the NPDES-defined mixing zone.

Regarding the computed compliance, it was found that the hydrothermal model performed better in reproducing the measured temperature at the downstream end of the mixing zone than that of the Station 8 and Station 11 monitors (e.g., see Figure 1). The average discrepancy of the monitoring stations was about 0.72 Fº (0.40 Cº), whereas that of the numerical model was only 0.40 Fº (0.22 Cº).

Based on the results of the field studies summarized above, in March 1984 the State granted approval for SQN to use the numerical model to monitor compliance with the NPDES requirements, provided *"TVA verify that the measurement of the temperature of the water at the skimmer wall is not effected by the presence of the underwater dam and that this underwater dam has negligible effect upon the computed compliance model."* Later, in June 1984, TVA provided a short report containing measurements from a field test that included water temperature at the skimmer wall and the underwater dam (TVA, 1984). The measurements showed that the skimmer wall and underwater dam temperatures usually agree within 1.8 F° (1 C°). The report also pointed out that any impact of the underwater dam would be properly incorporated into the computed compliance because the numerical model is validated based on data from field studies that include the effects of the dam on the mixing of the thermal discharge.

The next concern prompting requirements for field studies arose out of a meeting between TVA and the State in November 1986 (TVA, 1986 and TDWPC, 1987). The purpose of the meeting was to discuss reservoir dynamics, hydrothermal processes, power plant operation, and other factors influencing compliance with thermal water quality standards. In the meeting, it was agreed that TVA develop a quality assurance (QA) program consisting of field verification tests to ensure that the plant-induced effects on water temperature were being determined accurately and consistently. In response to this agreement, TVA issued a QA program in September 1987 calling for verification studies to be performed for a variety of river and plant conditions (TVA, 1987). These conditions are summarized in Table 2. Briefly, conditions for river flow Q_R were divided into four ranges: Q_R<10,000 cfs, 10,000 cfs ≤Q_R<25,000 cfs, 25,000 cfs ≤Q_R<35,000 cfs; and Q_R≥35,000 cfs. For each range it was desirable to perform a study for each season of the year. The largest release of heat will include SQN operation with two units. The original plan called for a winter study at low flow with one rather than two units, but the recommendation for this case has since shifted to a two-unit study. The QA program also provided a description of the proposed field testing, which included measurements at depths and locations somewhat similar to those of previous studies. In the QA program some of the recommended field studies were already fulfilled by previous tests, as summarized above.

Table 2. Field Studies by TVA QA Plan of 1987

Season		Spring (Mar ~ May)		Summer (June ~ Aug)		Fall (Sept ~ Nov)		Winter (Dec ~ Feb)	
SQN Operation		1-Unit	2-Unit	1-Unit	2-Unit	1-Unit	2-Unit	1-Unit	2-Unit
River Discharge (cfs)	<10,000		5/14/82 (B) 3/31/83 (B)					**Neglect**	Add
	10,000 to 25,000		4/4/82 (B) 5/11/83 (B)		8/2/00 (C)				
	25,000 to 35,000		3/1/96 (C)	7/24/81 (A)	7/24/97 (C)	11/10/82 (B)			
	>35,000		3/24/99 (C)				9/02/82 (B)		

Notes
A. Field study summarized in report by TVA (1982).
B. Field studies summarized in report by TVA (1983).
C. Field studies summarized in this report.

It is important to note that the NPDES permit effective April 1983 was designated to expire in March 1988. However, in late 1986, both units at Sequoyah were removed from service due to nuclear safety concerns. Unit 2 did not return to service until May 1988 and Unit 1 did not return to service until November 1988. Due to this, and due to ongoing studies and negotiations related to the 316(a) variance request of 1989, the plant continued to operate under the NPDES permit of 1983. The next permit was finally issued in September 1993. The 1993 permit did not reference the TVA QA program of 1987, but did require that *"the permittee shall perform instream surveys for the plume volume and area during November to March of 1992-1993 and 1993-1994 when the temperature rise is within the range of 3 C° to 5 C°."* In this statement, the period *November to March of 1992-1993* must have been a misprint because it preceded the effective date of the permit (i.e., September 1993). As such, this requirement was interpreted to include November to March of 1993-1994 and 1994-1995.

In the ensuing periods (i.e., November to March of 1993-1994 and 1994-1995), the river flow and water temperature did not reach conditions suitable for a field study to be performed for a temperature rise in the range of 5.4 F° to 9.0 F° (3.0 C° to 5.0 C°). Short-term variations in the temperature rise occurred, but did not persist for a period long enough to mobilize equipment and personnel for field measurements. Under these conditions, TVA moved forward to perform field studies as summarized by the QA program summarized in Table 2. Note that this program yet recommends wintertime studies at low river discharge, which produces a large temperature rise of the type stipulated for study in the NPDES permit of September 1993.

The field tests conducted during the tenure of the NPDES permit effective September 1993 are given in Table 1. They include spring studies on March 1, 1996, and March 24, 1999, and summer studies on July 24, 1997, and August 2, 2000. The study of March 1, 1996, was conducted in support of the supplemental 316(a) demonstration of 1996. The purpose of the study was to determine the zone of impact for the temperature rate-of-change. To create a rate-of-change event, the river discharge was altered in a short period from a flow of about 43,000 cfs to a flow of 20,000 cfs. The focus of the study was to examine the longitudinal (i.e., downriver) extent of the temperature rise created by the event. In this manner, the study did not include detailed measurements of the three-dimensional configuration of the thermal discharge, but only temperature profiles along the center of the river. The study found that the longitudinal extent of the mixing zone (i.e., 1500 feet) was sufficient for maintaining the wintertime criteria for instream temperature rise (i.e., 9.0 Fº/5.0 Cº).

In contrast, the studies of July 24, 1997, March 24, 1999, and August 2, 2000, were designed to evaluate the three-dimensional extent and configuration of the thermal discharge, as specified in the TVA QA program of 1987. Results of these studies are shown in Figure 8 through Figure 11. Each figure contains: (a) a plot of the water temperature distribution at the 5-foot compliance depth, and (b) plots of the water temperature and water temperature rise along transects across the mixing zone at the sections about where the thermal plumes breach the water surface and at the downstream end of the mixing zone, again at the 5-foot depth. It is important to note that these measurements were made by trolling temperature sensors through the water from a boat. The boat tracks are shown in the figures. The temperatures were measured with sensors having an accuracy of about ±0.25 F° (±0.14 C°) and a response time of about 0.7 second. Based on the boat speed and sampling frequency, the sensor readings represent near-instantaneous temperatures taken at intervals roughly every four to six feet along the boat tracks. It is emphasized that although the plots in Figure 8 through Figure 11 were created from instantaneous measurements, they do not represent an instantaneous snapshot of the thermal discharge. Depending on the study, the time required for the boat to traverse the indicated tracks varied between about 65 minutes and 135 minutes. In this manner, due to the time-varying turbulent motions in the flow, the plots represent "blurred" rather than "clear" images of the thermal discharge at the 5-foot depth. If additional data sets were collected, the general location of the thermal discharge would likely remain unchanged. However, the shape of the temperature distributions would shift over distances associated with the size of the dominant turbulent motions in the flow. From a statistical standpoint, the plots represent "probable" rather than "definite" images of the thermal discharge. With this understanding, the following general comments are provided for each field study.

3.2.1 *July 24, 1997 Study*

The study of July 24, 1997 (Figure 8) included a high river discharge, about 40,000 cfs, and a relatively high ambient water temperature, 83.9°F (28.8°C). Stratification was moderate, with water at the channel bottom about 3.6 F° (0.3 C°) cooler than the ambient temperature (5-foot depth). SQN was operating in open mode with both units, discharging about 2470 cfs through both diffusers at a temperature of about 23.4 F° (13.0 C°) above the ambient temperature at Station 13. The following features are noted (Figure 8).

- Even though both diffusers are operating, the thermal discharge seems to breach the 5-foot depth as a single plume in the center of the main channel. It is emphasized that the diffusers are approximately 40 feet below the 5-foot depth. Depending on the magnitude and direction of the mean and turbulent motions in the flow, it is reasonable to expect the plumes at the 5-foot depth to drift from side-to-side in the mixing zone. It seems unlikely, however, that the discharge from each diffuser would coalesce into a single plume. One thought is that perhaps parts of the diffusers were clogged. Such clogging, however, would have produced an unusually high water level in the diffuser pond, which was not observed. Other possible factors include the following:

    ✓ Due to moderate stratification, parts of the thermal effluent are significantly cooled and reach a level of neutral buoyancy below the 5-foot depth. The high river discharge also would promote mixing and "bending" of the thermal discharge, sweeping it downstream before reaching the 5-foot depth. Perhaps the only parts of the plumes containing sufficient buoyancy to reach the water surface were those in the middle of the river, emerging side-by-side in what appears to be a single plume.

    ✓ Part of the thermal effluent was undetected in the field study due to undulations in the flow and an insufficient number of measurements in the region where the plumes breach the surface. If undulations temporarily submerge the plume below the 5-foot depth, and if they occur at a time-scale longer than that for the survey boat to traverse the breaching area, it is possible for part of the plume to go undetected. The first transect downstream of the diffuser was at about 500 feet. Additional transects may have revealed evidence of two plumes (i.e., one plume for each diffuser).

- Due to high river flow, there is a sharp gradient between the upstream ambient temperature and the plume temperature. There is no thermal wedge propagating upstream in the surface layer of the flow.

- The mixing zone maintains the thermal discharge below the NPDES thermal criteria (i.e., max $\mathbf{T_d}$ of 86.9ºF/30.5ºC and max $\mathbf{\Delta T}$ of 5.4 Fº/3.0 Cº).

- North and south of the mixing zone, natural heating creates high temperatures in the overbanks (plot "a" of Figure 8). In some areas, the overbank temperature is higher than that in the mixing zone (yet below the NPDES thermal criteria). These results emphasize the difficulty of tracking SQN thermal compliance by measurements at the outer edges of the mixing zone, as was done in the early 1980s, and the strength of using a computed compliance, which keeps an accurate accounting of the amount of heat added to the reservoir by the plant.

At the section where the plume breaches the water surface (plot "b" of Figure 8), the water temperature is below the ambient temperature for all except the center of the plume (i.e., the local temperature rise is less than zero, except near the center of the plume). This is a consequence of stratification. The ambient water temperature measured at the 5-foot depth at Station 13 is 83.9°F (28.8°C); whereas that near the bottom of the main channel is closer to about 80.0°F (23.7°C). Due to the upward flux of the diffuser discharge and entrainment of ambient flow, the cooler bottom water is forced to the surface, yielding temperatures in parts of the mixing zone that are lower than the ambient temperature measured upstream.

3.2.2 *March 24, 1999 Study*

The study of March 24, 1999 (Figure 9) again included a relatively high river discharge, about 35,000 cfs. As a springtime test, however, the ambient water temperature was cooler, 51.8°F (28.8°C), and contained essentially no stratification. SQN was operating in open mode with both units, discharging about 2490 cfs through both diffusers at a temperature about 24.2 F° (13.4 C°) above the ambient temperature at Station 13. The following features are noted (Figure 9).

- Two plumes breach the 5-foot depth, one for each diffuser leg.

- The peak temperature for the diffuser located in the northern side of the main channel is about 2 F° (1.1 C°) warmer than that located in the southern side of the main channel (i.e., at the 5-foot depth where the plumes breach the water surface).

- Due to high river flow, there is a sharp gradient between the upstream ambient temperature and the plume temperatures. There is no thermal wedge propagating upstream in the surface layer of the flow.

- The mixing zone maintains the thermal discharge below the NPDES thermal criteria (i.e., max $\mathbf{T_d}$ of 86.9ºF/30.5ºC and max $\mathbf{\Delta T}$ of 9.0 Fº/5.0 Cº).

- For the prevailing river and plant conditions, the thermal plumes appear to spread into the overbank on the north side of the main channel. This is likely a consequence of currents created by river curvature. At high river flow, water moving through the bend in the river upstream of the mixing zone will tend to flow "straight" and impact the southern shoreline opposite the diffusers. That is, at high river flow, water velocities on the outside of the bend will tend to be higher than those on the inside of the bend. Moving downstream from this point, it appears that the alignment of the shoreline (with higher river velocities) will tend to push the thermal plume away from the shoreline towards the northern edge of the mixing zone. For this reason, measurements from Station 8 will likely underestimate the temperature at the downstream end of the mixing zone for high river flow (i.e., supporting the use of the hydrothermal compliance model). Other factors, however, also may be responsible, at least in part, for this behavior, including the following:

- ✓ Recirculation: A zone of separation created by the shoreline protrusion at the diffusers (see Figure 9) may exist. If it exists, recirculation could entrain thermal effluent from the northern edge of the mixing zone, but at water temperatures below the NPDES criteria. Again, this type of behavior would be significant only at higher river discharges, where there is ample river flow for dilution of the plant thermal effluent.

- ✓ Wind: Other TVA studies have found that wind can have a significant effect on water motions in the surface layer of the flow (TVA, 1998). During the study of March 24, 1999, a sustained wind was blowing out of the south at about 6 mph, perhaps inducing the plume in the surface layer to spread more northward into the right overbank (i.e., compared to quiescent wind conditions).

- ✓ Insufficient data: Note that the boat transects are sparse in the downstream half of the mixing zone. It may be that the plumes also exist in this area, but were not measured. Concurrently, unsteady undulations in the flow, as described above, could also add bias to the survey results.

It is interesting to note that even though the study of July 24, 1997, was conducted at high river flow, it did not appear to exhibit spreading towards the northern overbank as in the study of March 24, 1999 (i.e., compare Figure 8 and Figure 9). In reality, such spreading may exist, albeit unnoticeable in the measurements. Also recall that the study of July 24, 1997, contained moderate stratification, which could perhaps disrupt secondary river currents or other spreading processes.

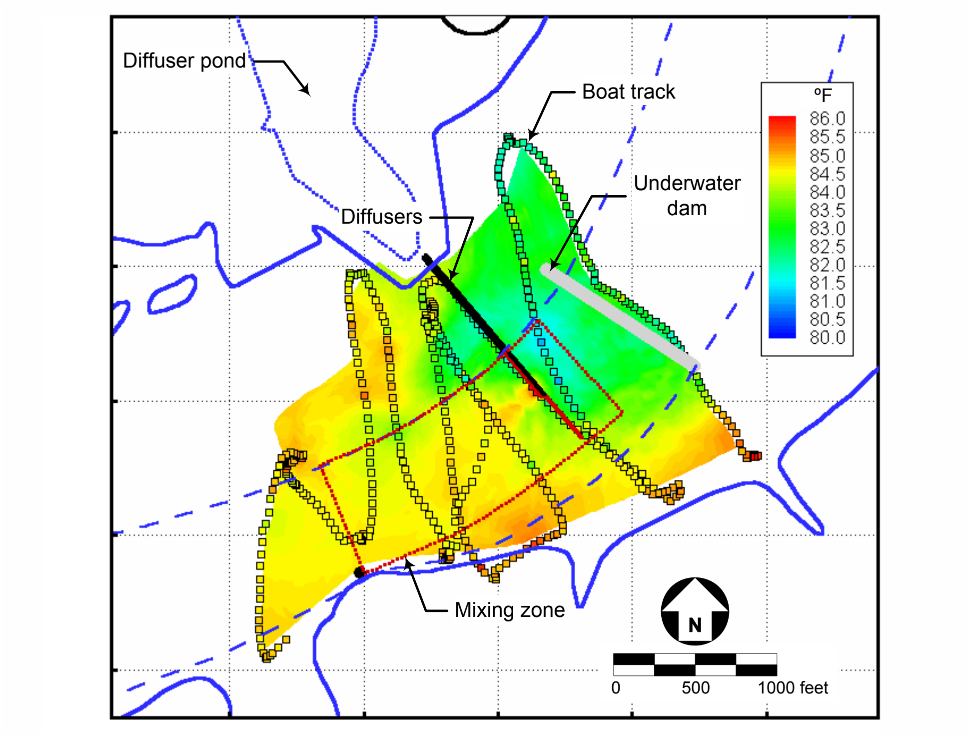
3.2.3 *August 2, 2000 Study*

The study of August 2, 2000 included a low river discharge, only about 9,000 cfs, with a relatively high ambient water temperature, 82.1°F (27.8°C). Stratification was essentially nonexistent. SQN was generating with both units, but because of the high ambient temperature and low river flow, the plant was operating in helper mode (i.e., cooling towers in service). Under these conditions, the plant was discharging about 2480 cfs through both diffusers at a temperature of about 18.1 F° (10.1 C°) above the ambient temperature at Station 13. Two passes were made with the survey boat, an early morning pass (Pass 1—Figure 10) and a late morning pass (Pass 2—Figure 11). The following features are noted.

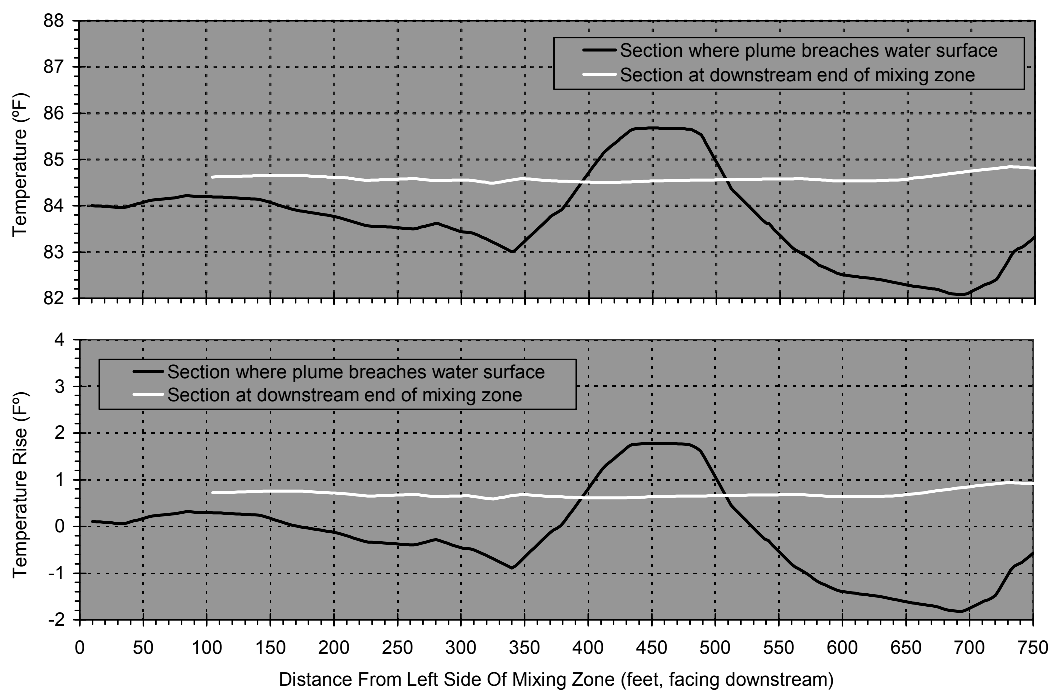
- Two plumes breach the 5-foot depth, one for each diffuser leg. The plumes emerge within 500 feet of the diffusers and are evenly spaced in the mixing zone.
- For Pass 1, the peak temperature for the diffuser located in the northern side of the main channel is about 1 F° (0.6 C°) cooler than that located in the southern side of the main channel (i.e., at the 5-foot depth where the plumes breach the water surface). Note that this is opposite of that which was observed in the test of March 24, 1999.
- For Pass 2, the peak temperatures at the 5-foot depth, where the plumes breach the water surface, are about 0.4 F° (0.2 C°) cooler than those for Pass 1. The peak temperature for the northern side of the main channel is still about 1 F° (0.6 C°) cooler than that for the southern side of the main channel. Also note that the number of boat transects for Pass 2 are less than that for Pass 1, which somewhat diminishes the confidence in the resolution of the plume shown in Figure 10.
- Due to low river flow, the plume in the surface layer of the flow forms a thermal wedge that propagates upstream of the diffuser.
- The mixing zone maintains the thermal discharge below the NPDES thermal criteria (i.e., max $\mathbf{T_d}$ of 86.9ºF/30.5ºC and max $\mathbf{\Delta T}$ of 5.4 Fº/3.0 Cº).
- The thermal plumes spread into areas outside of the mixing zone, but at levels below the NPDES thermal criteria.

3.2.4 *Studies in 2002 and 2003*

Two field studies were performed under the NPDES permit of August 2001—a summer study on July 27, 2002, and a spring study on April 23, 2003. Results from these studies are summarized in Table 1. In contrast to the studies above, these 2002 and 2003 studies included instream measurements only at the downstream end of the mixing zone. The purpose of the studies was to collect information for calibration of the numerical model used for the computed compliance and did not include measurements to assess the ambient river temperature or the three-dimensional extent of the thermal plume from the discharge diffusers.

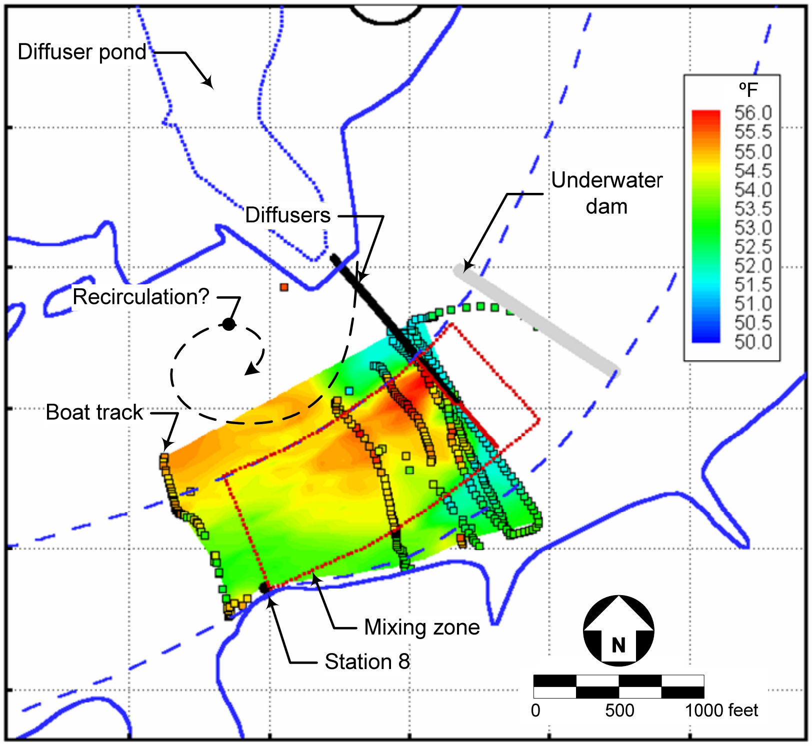


(a) Water Temperature Distribution at 5-Foot Depth

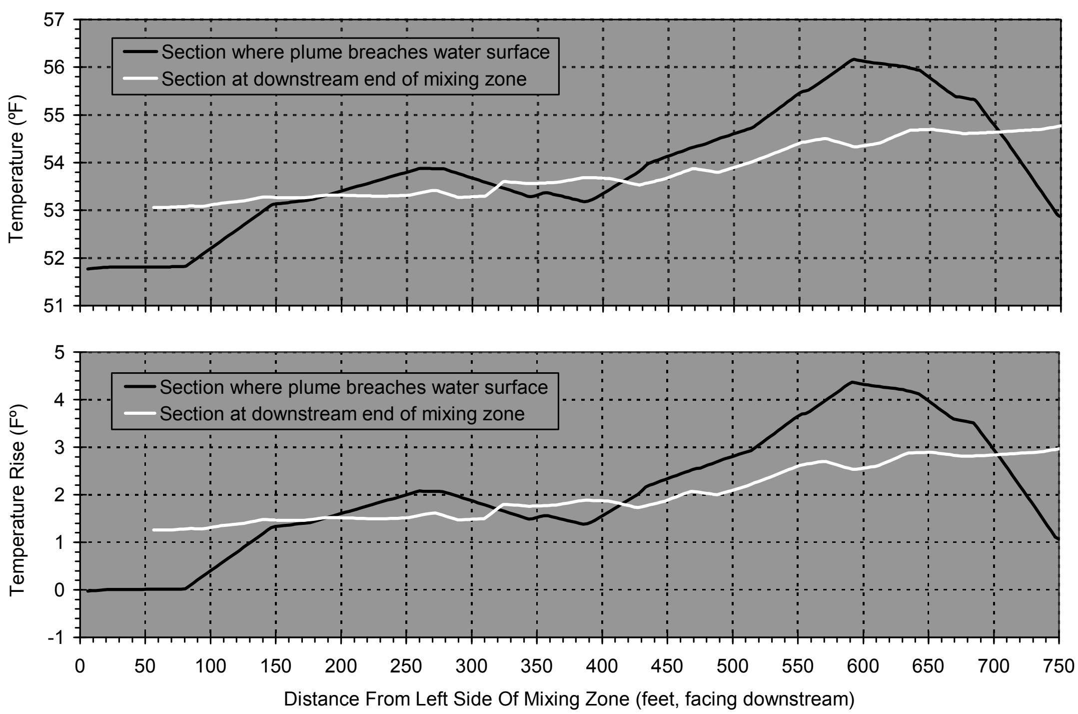


(b) Water Temperatures Across Mixing Zone at 5-Foot Depth

Figure 8. Water Temperatures from July 24, 1997 Study

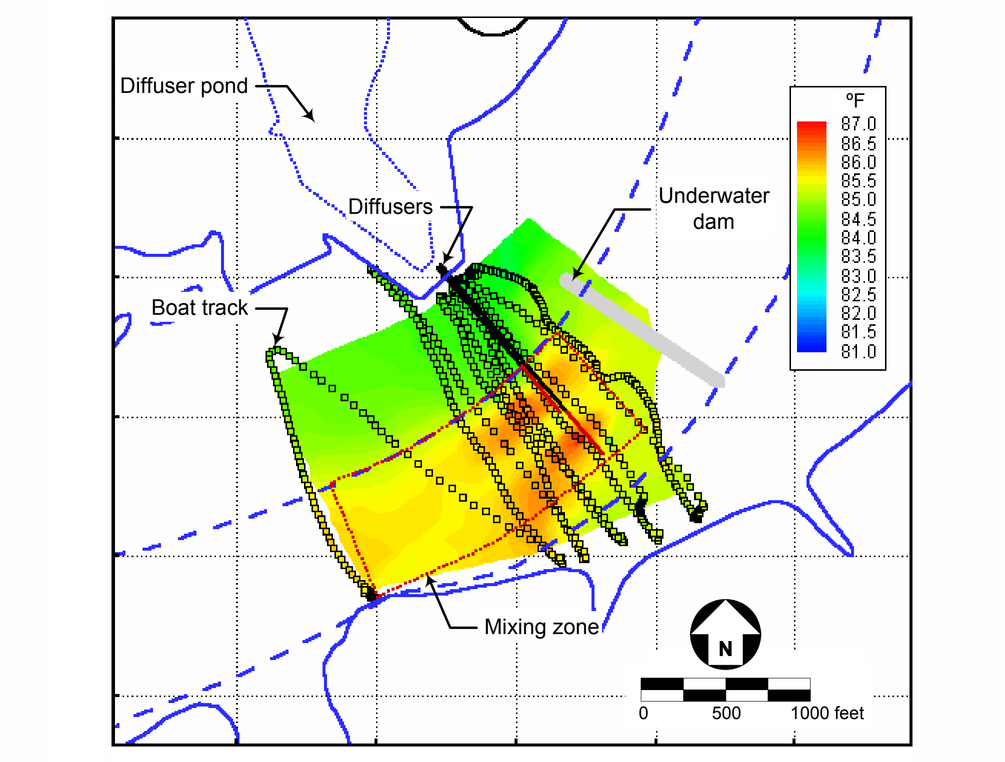


(a) Water Temperature Distribution at 5-Foot Depth

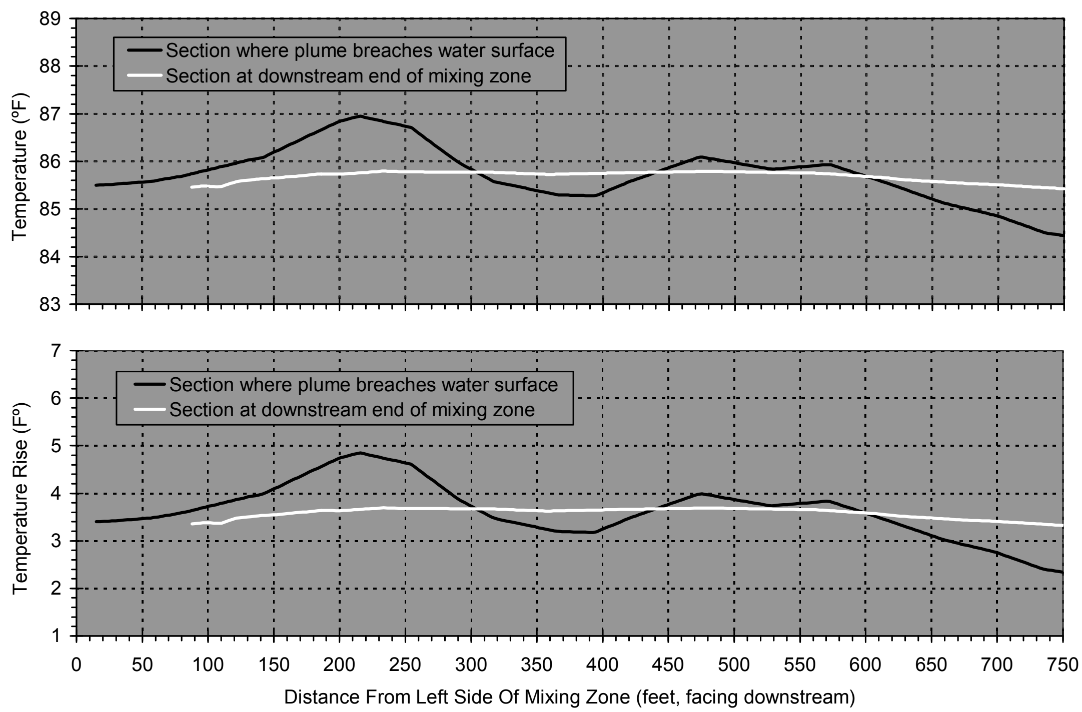


(b) Water Temperatures Across Mixing Zone at 5-Foot Depth

Figure 9. Water Temperatures from March 24, 1999 Study

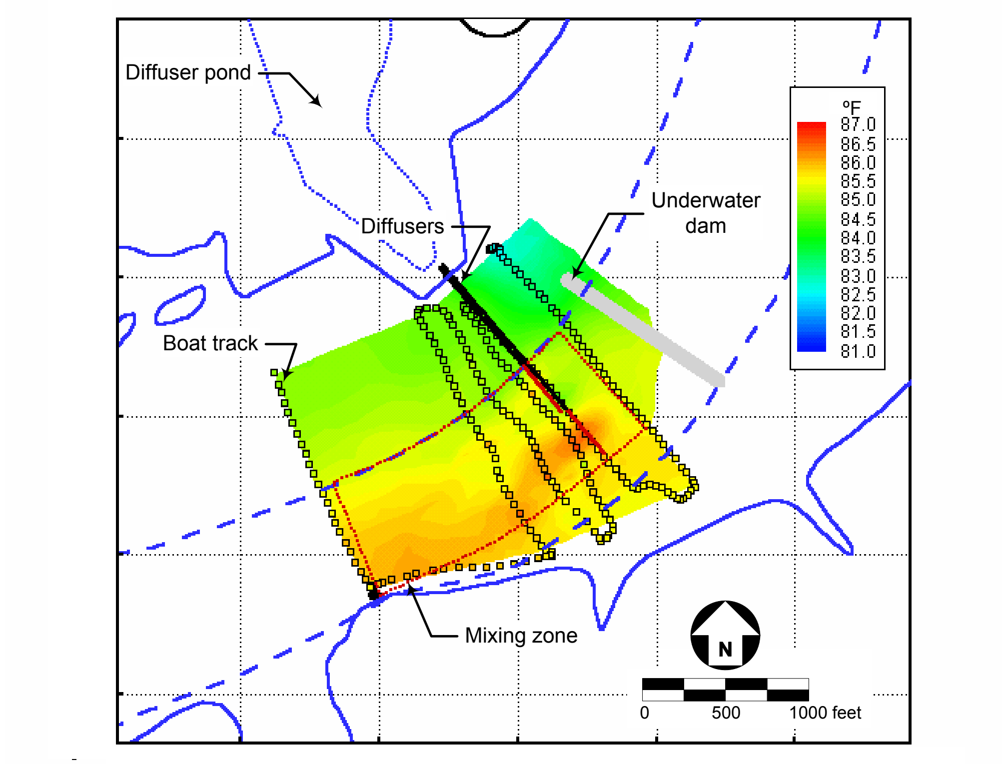


(a) Water Temperature Distribution at 5-Foot Depth

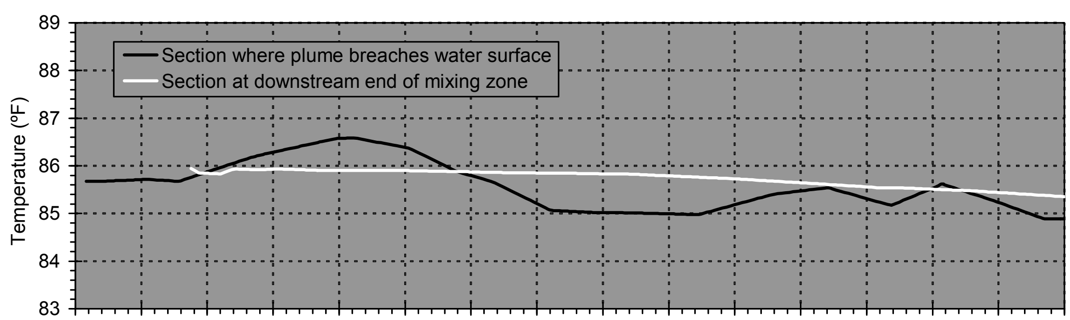


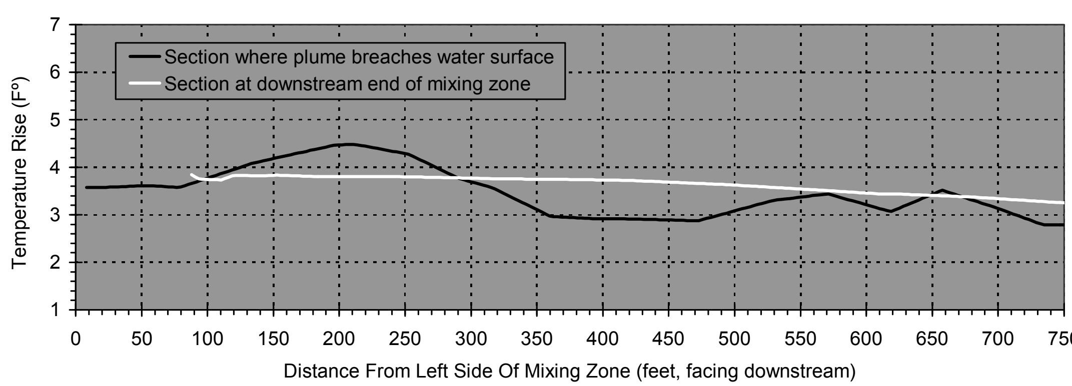
(b) Water Temperatures Across Mixing Zone at 5-Foot Depth

Figure 10. Water Temperatures from August 2, 2000 Study, Pass 1



(a) Water Temperature Distribution at 5-Foot Depth





(b) Water Temperatures Across Mixing Zone at 5-Foot Depth

Figure 11. Water Temperatures from August 2, 2000 Study, Pass 2

4.0 NEW STUDIES IN 2004 THROUGH 2007

Results from the *ambient temperature study* and *mixing zone study* are summarized in this chapter. As required in the NPDES permit of September 2005, data from previous studies have been supplemented with new temperature measurements. This includes measurements for both the winter and summer hydrothermal regimes. As a result of the *ambient temperature study*, a new location is now used to measure the ambient river temperature for the plant. And as a result of the *mixing zone study* the compliance model has been modified to better include the buildup of heat that occurs locally in the reservoir at low river flow. Both of these changes are presented in more detail in the following sections.

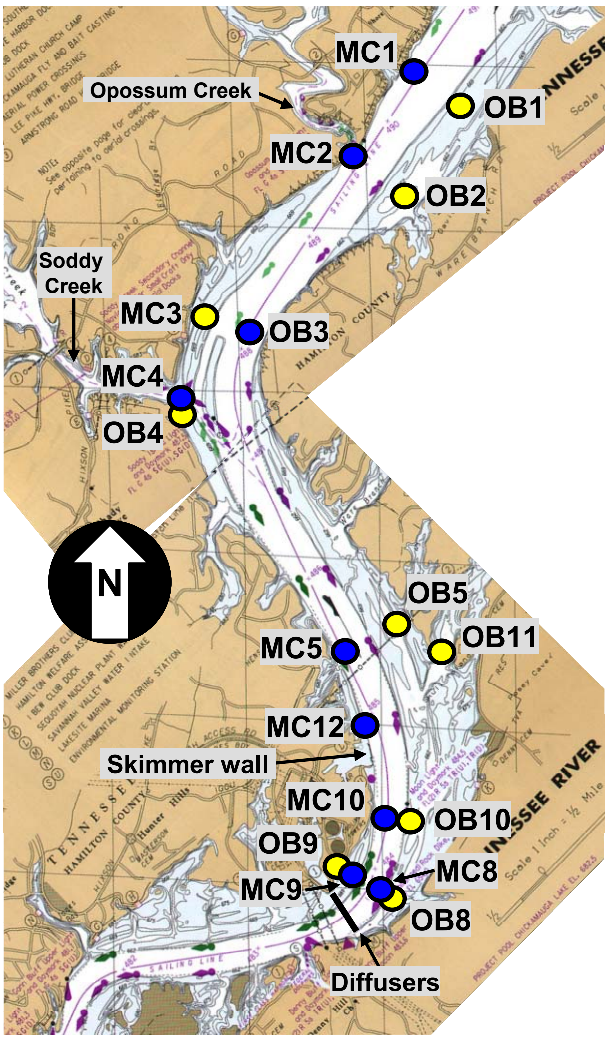
4.1 Ambient Temperature Study

The ambient temperature study included new temperature measurements in three deployments. The summer deployment took place from July 23 through August 4, 2003. The winter deployment took place between January 21 and February 2, 2004. The third deployment took place from May 18 through June 2, 2006.

For the summer and winter studies, nine pairs of temporary water temperature stations were deployed, from just upstream of the diffusers to about seven miles upstream of the plant. Figure 12 shows the station locations. Each pair included one station in the main channel (MC) and one station at roughly the same river mile but in a nearby overbank (OB). As shown, five of the station pairs were located relatively close to the plant, and four pairs were located further upstream. The most upstream station pair, MC1/OB1, was located 6.8 miles upstream of the plant diffusers, whereas the most downstream station pairs, MC8/OB8 and MC9/OB9, were located just 0.3 miles upstream of the diffusers. Two tributaries flow into the reservoir within the monitoring zone, Opossum Creek and Soddy Creek.

The temperature sensors collected data at intervals about every 5 minutes. The devices employed for these studies were HOBO™ monitors, which were positioned at depths of 0.5, 3, 5, and 7 feet below the water surface. Figure 13 is a schematic of the temporary stations, which include an assembly containing a tire float with a flashing beacon light, a string of HOBO™ water temperature sensors, and anchor weights to maintain the station at the desired location. The HOBO™ units are completely sealed and self contained with an infrared communication port for programming and data retrieval. The units are about the size of a laboratory test tube. The accuracy of their temperature sensor is about ±0.4 F° (0.22 C°) with a resolution of about 0.04 F° (0.022 C°). This is consistent with other temperature measurements used for TVA hydrothermal compliance. A Global Positioning System (GPS) device was used to place the stations at the desired locations.

The water temperature at the compliance depth was obtained by calculating the hourly average temperature at the 5-foot depth. To be consistent with the NPDES monitoring requirements for ambient temperature, the temperature is determined as the average of individual sensor readings at the 3 foot, 5 foot, and 7 foot depths. Hourly averages are computed every 15 minutes by averaging the current and previous four 15-minute readings, as specified in the NPDES permit.



Station Pair or Landmark	River Mile
MC01	490.4
OB01	490.4
Opossum Creek	*489.7*
MC02	489.6
OB02	489.6
MC03	488.1
OB03	488.1
Soddy Creek	*487.6*
MC04	487.5
OB04	487.6
MC05	485.4
OB05	485.4
MC12	484.9
OB11	485.2
Intake Skimmer Wall Station 13	*484.7*
MC10	484.2
OB10	484.2
MC08	483.9
OB08	483.9
MC09	483.9
OB09	483.9
Discharge Diffusers	*483.6*

Notes: MC = Main Channel
OB = OverBank

Figure 12. Sampling Locations For Ambient Temperature Study

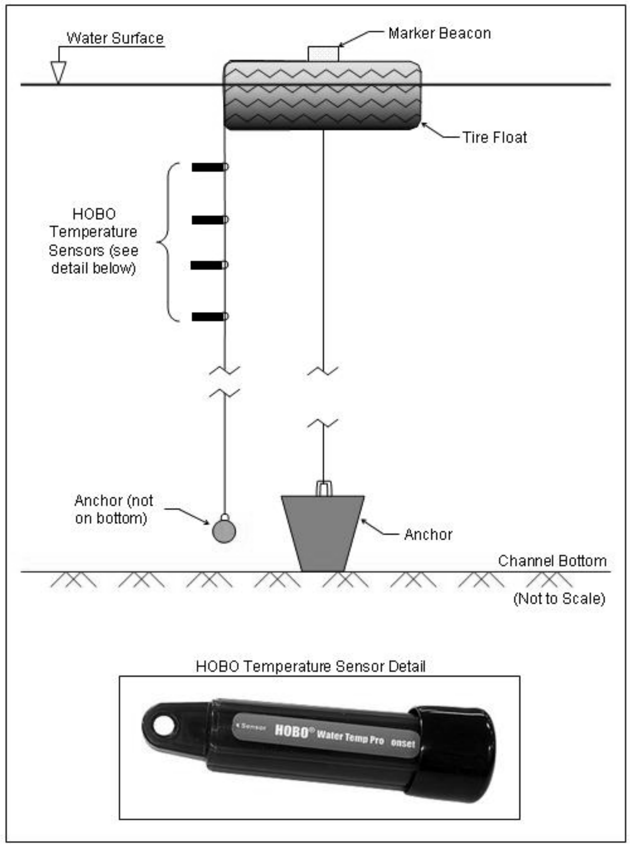


Figure 13. Schematic of HOBO™ Water Temperature Monitoring Station

4.1.1 *Summer Deployment July 23 through August 4, 2003*

During the summer deployment, the river flow was high, averaging about 40,000 cfs most of the time. Meteorologically, it was a wet period, with above average rainfall across the entire Tennessee Valley. Therefore, a low flow test was not possible during this deployment. However, peaking operations were performed during the deployment period to evaluate impacts that occur due to such operations. The deployment started during a cooling trend, with daily average air temperatures in the low 70's. After about three days, the average air temperature warmed to the upper 70's. A slight cooling trend returned at the end of the deployment. The days were mostly sunny with slight winds, varying between about 0 mph and 5 mph.

Figure 5 and Figure 12 show the existence of wide, shallow overbank areas upstream and downstream of the plant. During periods of natural reservoir heating, particularly in the spring and summer, the temperature of the water in shallow overbanks tends to be warmer than water in the deeper main channel. This is because solar radiation penetrates the full depth of the shallow areas, warming the bottom sediments, which radiates back into the water. Due to tributary inflows and mixing of bottom sediments, shallow areas also tend to have higher turbidity, which promotes greater absorption of heat than water with lower turbidity in the main channel. During periods of natural reservoir cooling, particularly in the winter, the opposite occurs. The heat loss in the overbank areas is greater than that in the main channel, often resulting in cooler water temperatures in the overbanks.

It is important to note that during periods of natural heating, the contribution of solar radiation in warming the water in Chickamauga Reservoir can rival that of the thermal discharge from SQN, particularly in the months of April and May when the river transitions from cool wintertime conditions to warm summertime conditions. Natural heating in the overbank and main channel areas of the reservoir will produce a nonzero **ΔT** from upstream to downstream of the plant even in the absence of any thermal discharge from SQN.

Water temperature data from all nine station pairs are shown in Figure 14 through Figure 22. The figures are arranged sequentially by station pair from upstream to downstream (see Figure 12). The water temperature data are plotted along with meteorological data and river flow to reveal potential correlations. The following basic features are noted:

- In general, the temperatures vary diurnally in response to the daily variation in air temperature and solar radiation (i.e., higher during the day and lower at night). Air temperature and solar radiation cause differences between main channel and overbank areas, with the shallow overbank areas typically responding more quickly to changes than the main channel (i.e., cooling or warming more quickly than the main channel).

- For a number of station pairs, and as expected, the overbank temperatures tend to be warmer than the main channel temperatures (MC01/OB01—Figure 14, MC02/OB02—Figure 15, MC05/OB05—Figure 18, MC12/OB11—Figure 19). This is particularly true for the warm period from about noon on July 26 through about noon on August 1. Temperature differences as large as 3 F° (1.7 C°) were observed between the main channel and overbanks.

- For the MC03/OB03 pair (Figure 16), the overbank temperature tends to exhibit the opposite behavior (i.e., is cooler at times than the main channel). This likely is due to the location of these stations relative to the local characteristics of the river (see Figure 12). MC03 is situated on the inside of a bend in the river and downstream of the large overbank area containing OB01 and OB02. In this manner, even though in the main channel, the source of the water on the inside of the river bend may be from the warm overbank area immediately upstream. In a similar manner, OB03 is on the outside of the river bend, and due to secondary currents (which tend to move water at the surface from the inside to the outside of the bend), it is likely to receive cooler water from the main channel of the river.

- The MC04/OB04 pair (Figure 17) tend to have very similar temperatures. This is due to the close proximity of the stations to one another in an area of the river that obviously is well mixed, just downstream of the inflow from Soddy Creek.

- The MC05/OB05 pair (Figure 18) shows a slight correlation between water temperature in the overbank and river flow during peaking operations. This is evident in the low flow events that occurred in the early morning on July 30, July 31, and August 1. On July 31, peaking operations created a short-term reverse flow at the site of about 20,000 cfs. In each of these events, the overbank temperature became elevated, even though during hours of darkness (i.e., no solar heating).

- In contrast to MC05/OB05, the MC12/OB11 pair, located a short distance downstream (Figure 19), did not exhibit significant flow-related elevated temperatures. However, after July 26, the overbank temperature is substantially warmer than the corresponding main channel temperature (compared to other station pairs). This is likely due to the fact that OB11 was located in an overbank area that was more isolated from the main body of the river (e.g., embayment type morphology). In this manner, the conditions at OB11 are more sluggish and subject to a greater amount of solar heating. Also shown in Figure 19 is the temperature measured at Station 13, which is in close proximity to MC12. As shown, the temperature at MC12 tracks closely with that of Station 13, providing validity to the latter, at least for the flow conditions that existed during the deployment (i.e., high daily average flows).

- Temperatures for the MC10/OB10 pair (Figure 20) track somewhat close to one another, suggesting that the river is fairly well mixed at this location. The reverse flow event in the early morning of July 31 appears to have caused elevated temperatures at both the main channel and overbank stations.

- Temperatures for the MC08/OB08 and MC09/OB09 pairs (Figure 21 and Figure 22, respectively) show the influence of mixing from the diffusers, which are located only a short distance downstream. This is demonstrated by the fact that like MC10/OB10, the temperatures track somewhat close to one another (i.e., somewhat well mixed). The temperatures also increased for lower hourly flows, suggesting the influence of reservoir sloshing causing upstream movement of the plant thermal effluent in the region of the mixing zone, at least in the surface layer of the reservoir.

- All of the sites located downstream of Station 13 experienced temperature events that would make them unsuitable for ambient monitoring. The measurements at Station 13, however, appeared to be uninfluenced by the diffuser discharge, at least for the daily average river flows prevailing during the deployment.

Overall, the summer deployment of July 23 through August 4, 2004 demonstrates that not only are meteorology and river discharge important factors in the interaction between main channel and overbank flows, but also the geomorphology of the river. Changes in the shape and alignment of the river, as well as the presence of local tributaries, create secondary currents and mixing that can promote transport between the main channel and overbanks and locally influence corresponding temperatures. Sloshing of the reservoir obviously has an impact on temperatures for stations located a short distance upstream of the diffusers.

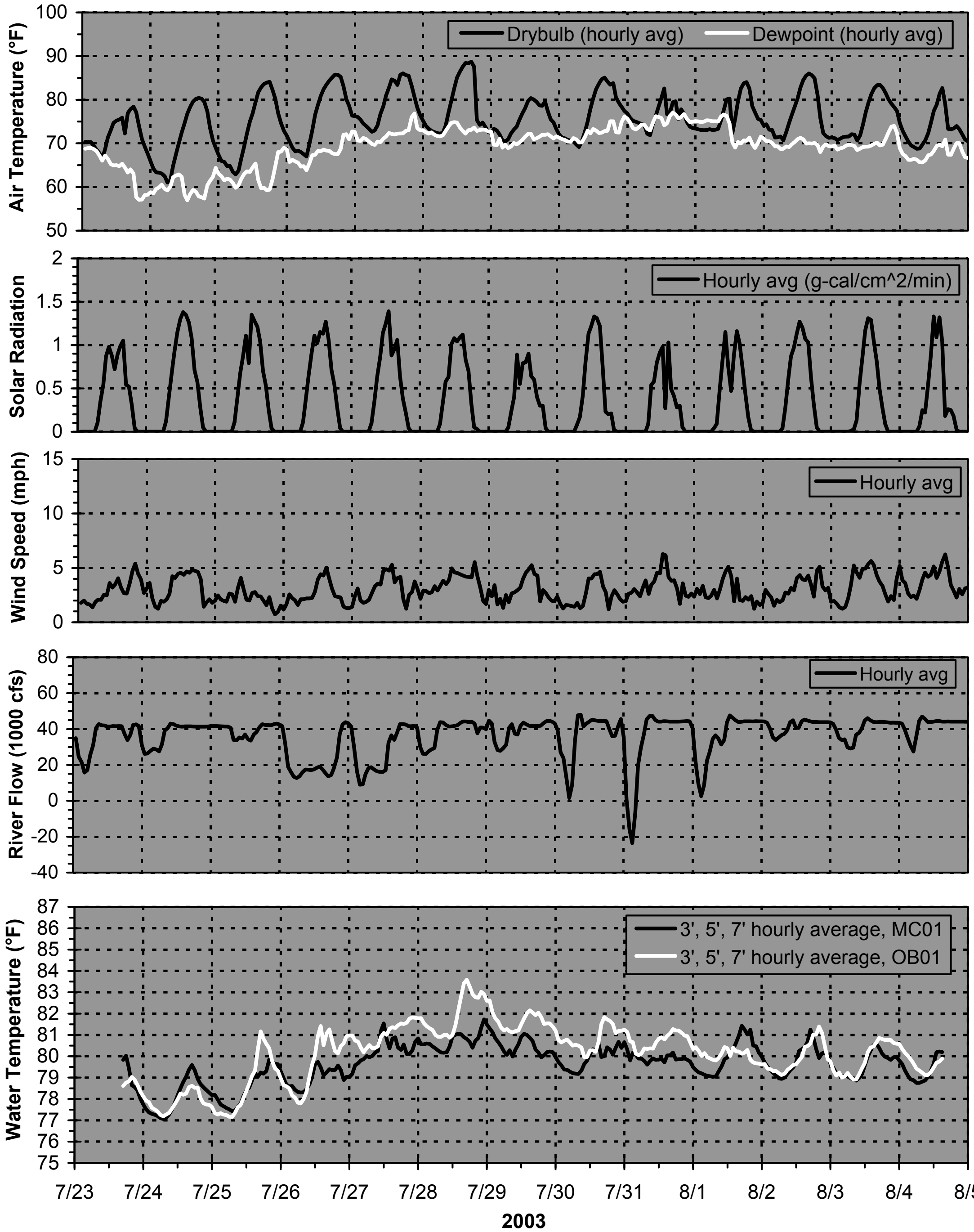


Figure 14. Main Channel and Overbank Stations MC01 and OB01 for Summer Deployment

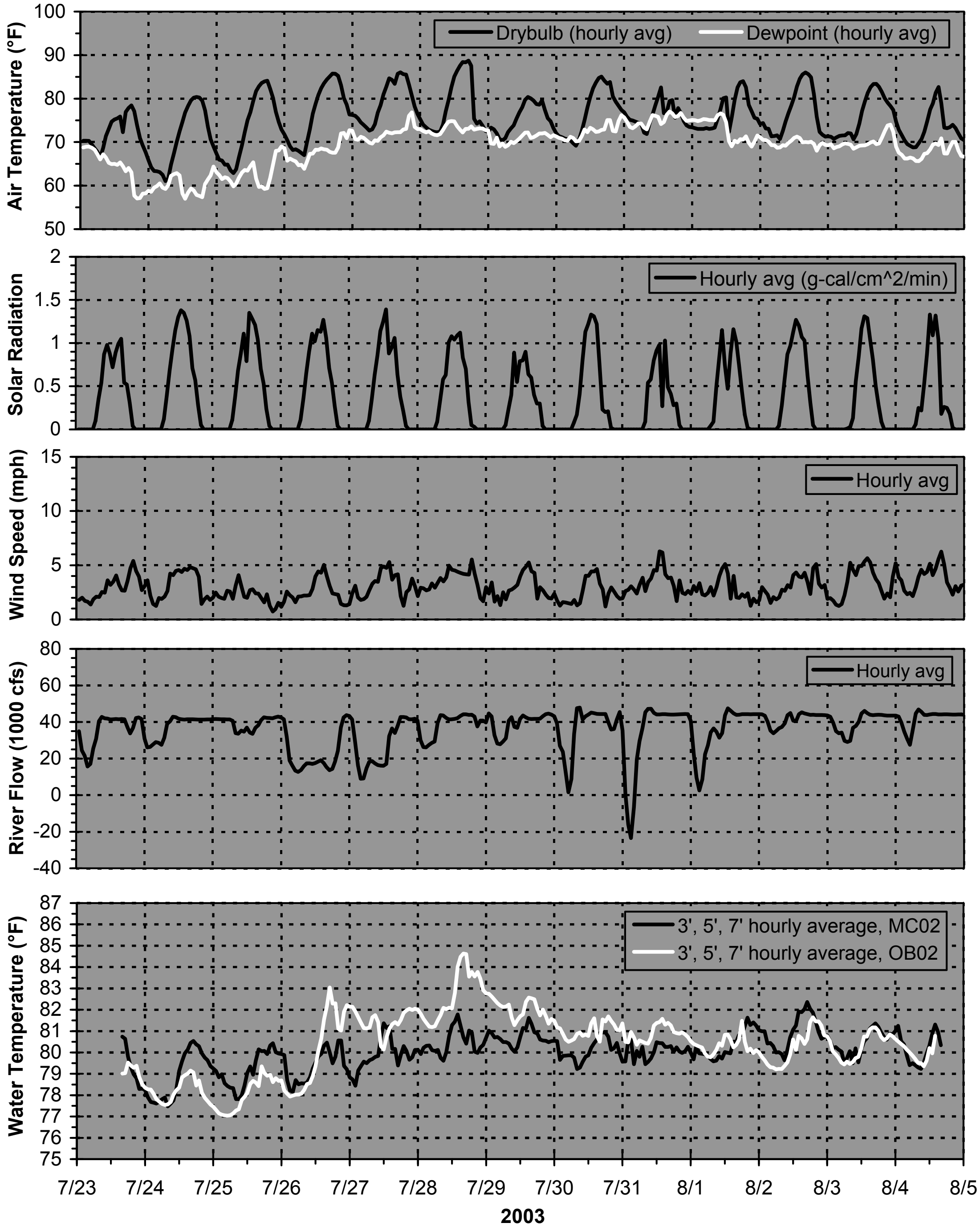


Figure 15. Main Channel and Overbank Stations MC02 and OB02 for Summer Deployment

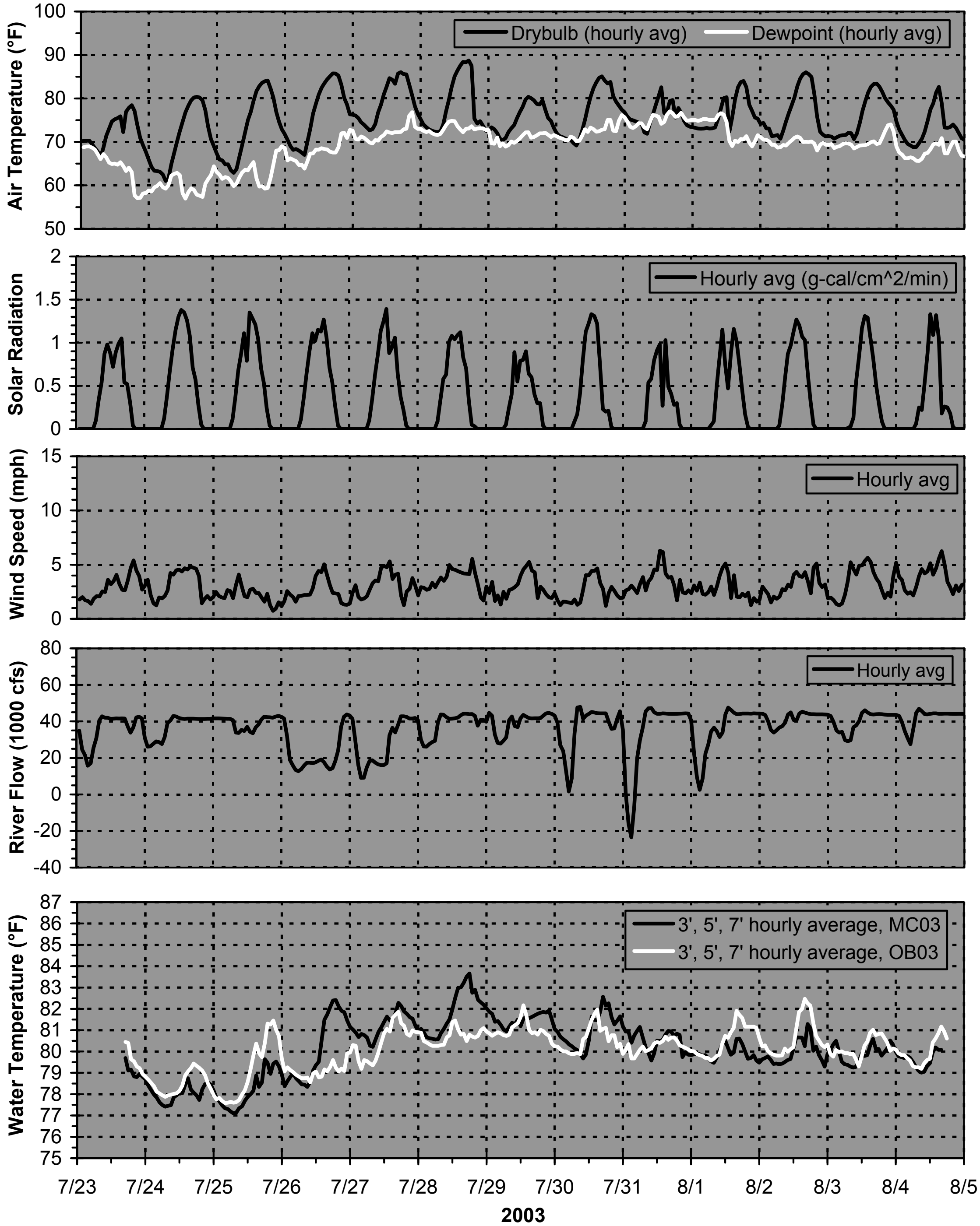


Figure 16. Main Channel and Overbank Stations MC03 and OB03 for Summer Deployment

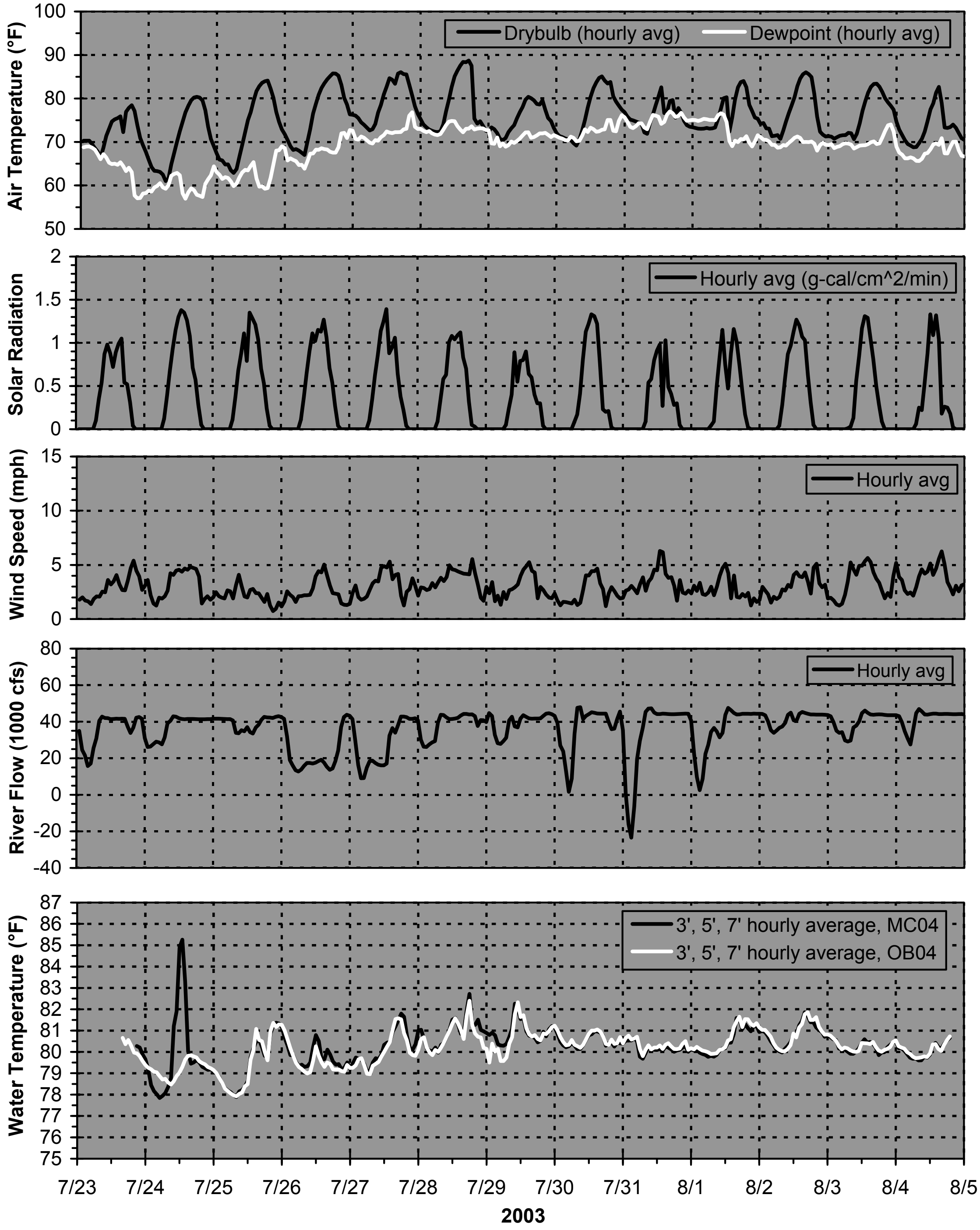


Figure 17. Main Channel and Overbank Stations MC04 and OB04 for Summer Deployment

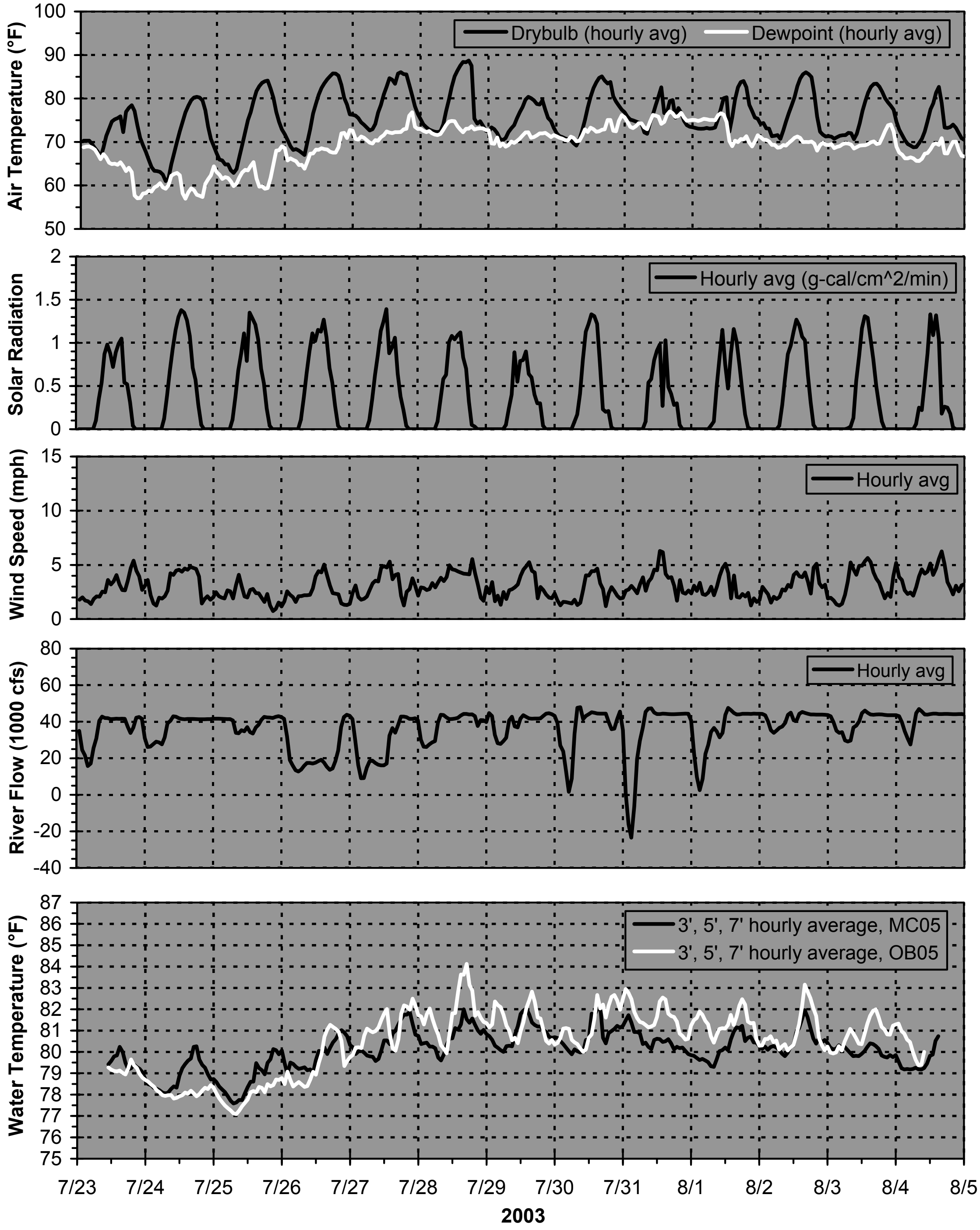


Figure 18. Main Channel and Overbank Stations MC05 and OB05 for Summer Deployment

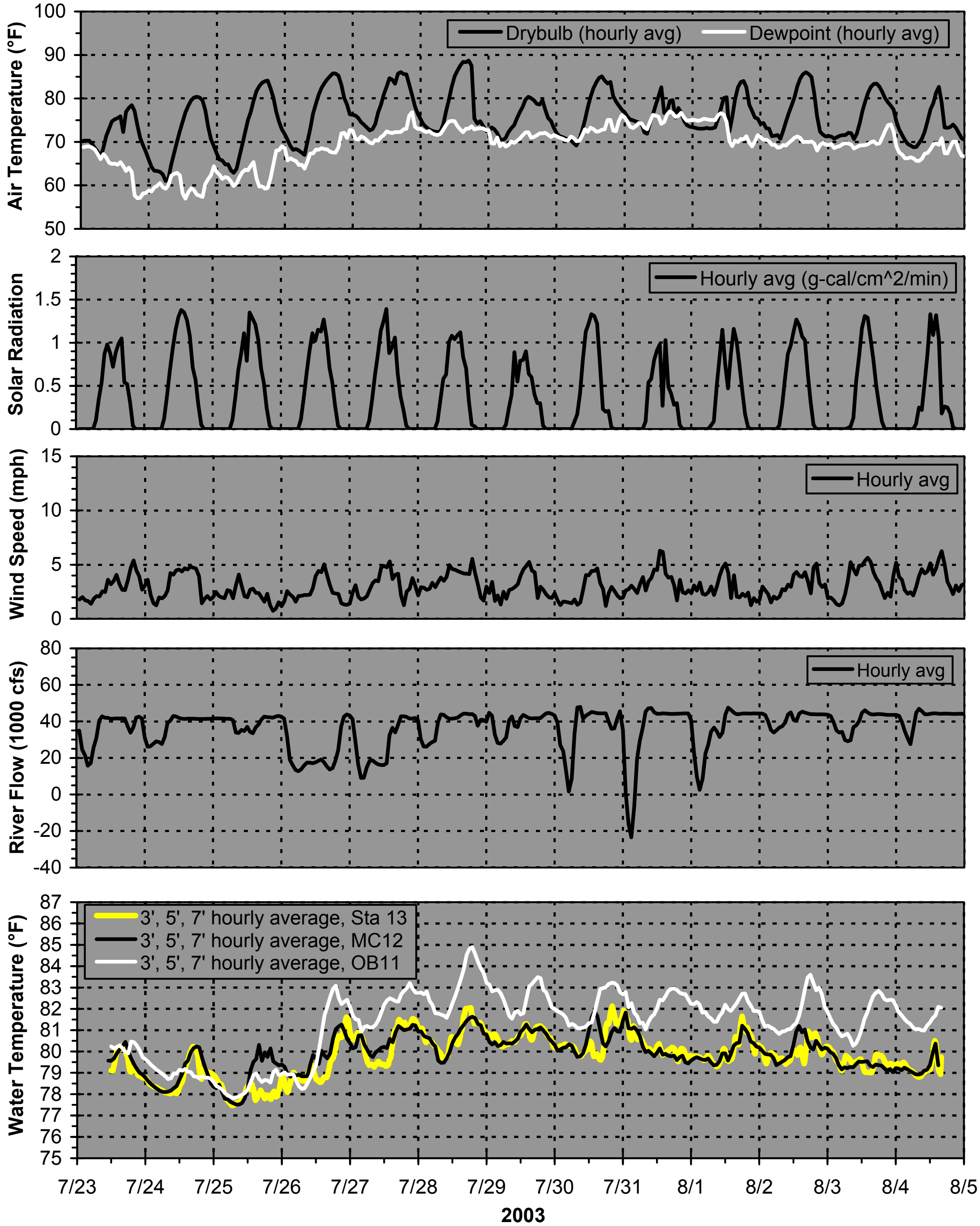


Figure 19. Main Channel and Overbank Stations MC12, OB11, and Station 13 for Summer Deployment

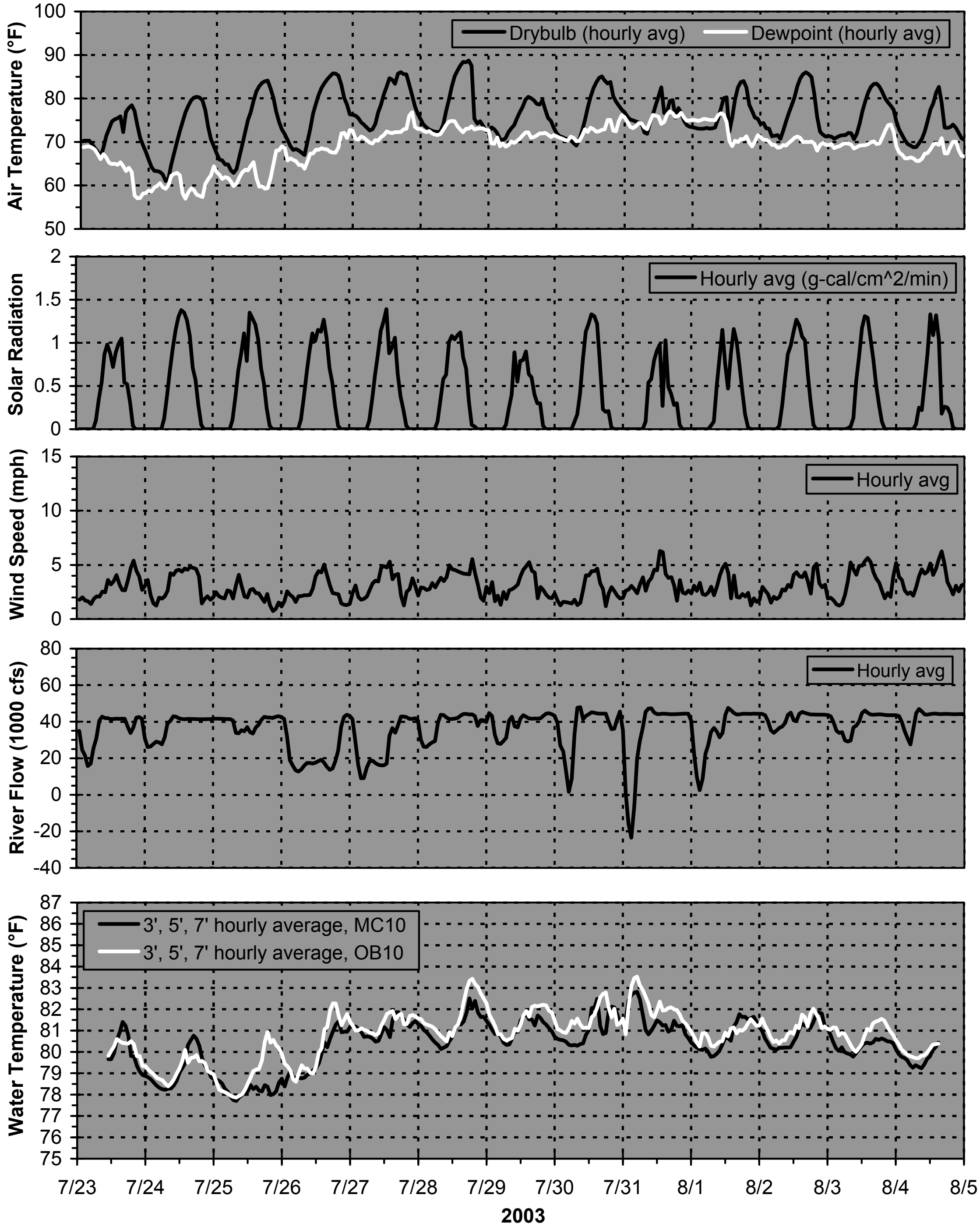


Figure 20. Main Channel and Overbank Stations MC10 and OB10 for Summer Deployment

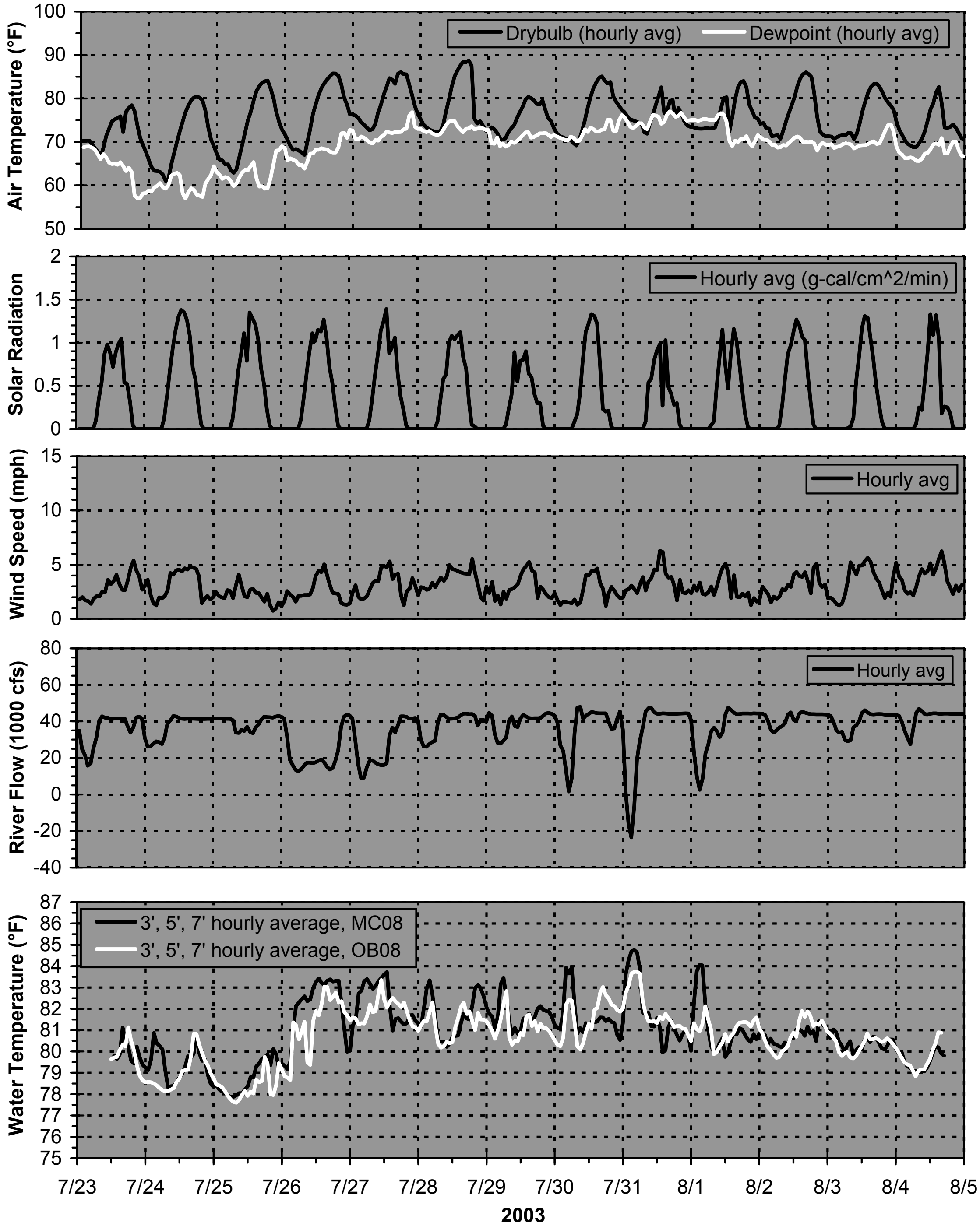


Figure 21. Main Channel and Overbank Stations MC08 and OB08 for Summer Deployment

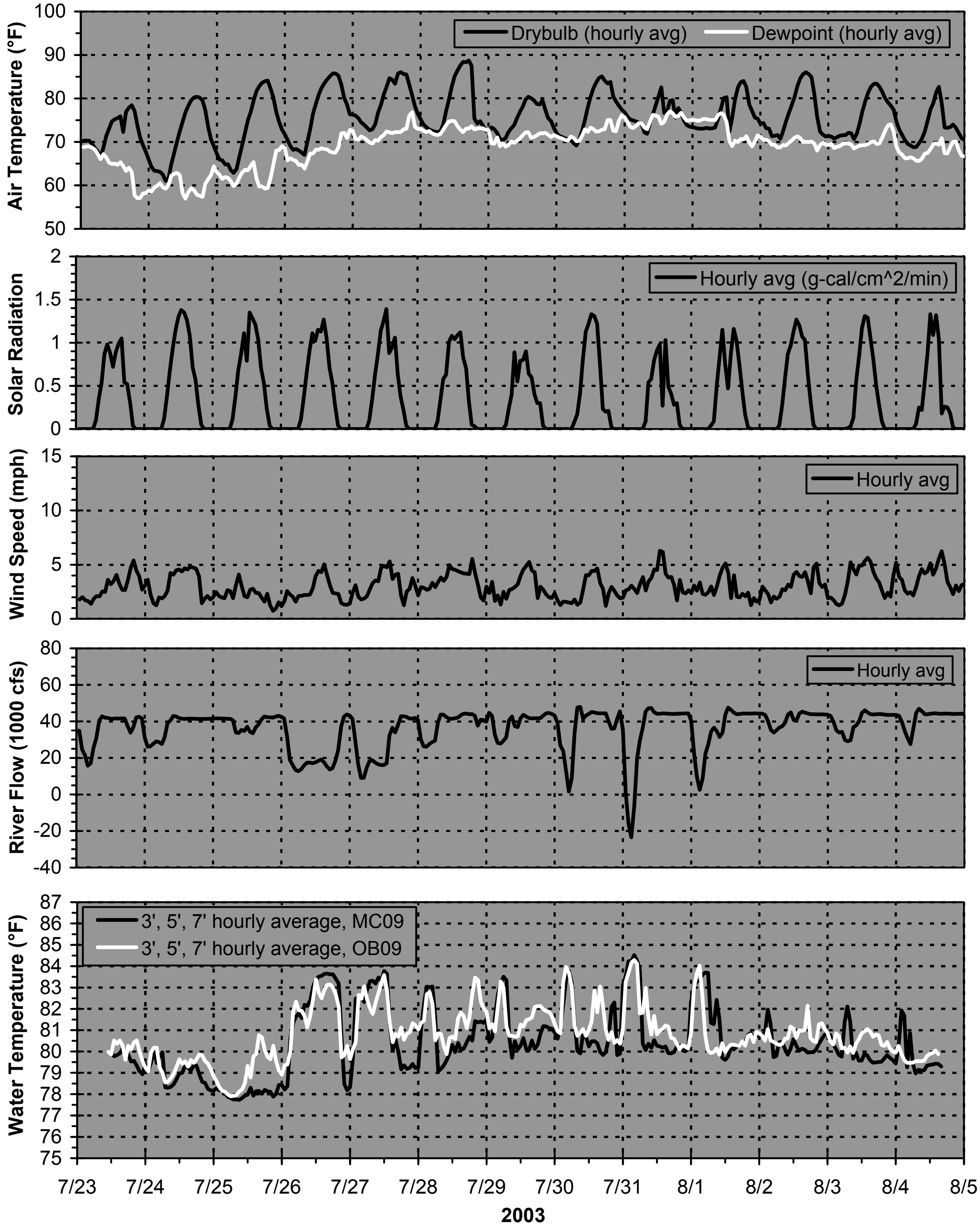


Figure 22. Main Channel and Overbank Stations MC09 and OB09 for Summer Deployment

4.1.2 *Winter Deployment January 21 through February 2, 2004*

The same nine station pairs were used for the winter deployment as in the summer deployment. During the winter deployment, the daily average river flow was near or above 40,000 cfs for all days except January 25 and January 26 (about 28,000 cfs), and January 31 through February 1 (about 19,000 cfs). On the lower flow days, peaking operations were performed, creating sloshing in the reservoir with reverse flows perhaps as high as 15,000 cfs. Daily average air temperatures during the deployment varied between 29°F or -1.7°C (January 31) and 48°F or 8.9°C (January 24). The average air temperature during the entire deployment was about 37°F (2.8°C). Most days were sunny, except for the three day period from January 25 through January 27 where cloudy conditions significantly reduced solar radiation. The wind speed was variable throughout the deployment, with hourly values ranging between near 0 mph and over 10 mph.

Water temperature data from all nine station pairs are shown in Figure 1 through Figure 31. As before, the figures are arranged sequentially by station pair from upstream to downstream (see Figure 12) and show not only the water temperature data but also meteorological data and river flow. The following basic features are noted:

- In general, the temperatures vary diurnally in response to the daily variation in air temperature and solar radiation (i.e., higher during the day and lower at night). During the period from January 25 through January 27, when the cloud cover significantly reduced solar radiation, changes between nighttime and daytime water temperatures were much smaller in both the main channel and overbanks.

- Air temperature and solar radiation cause differences between main channel and overbank areas, with the shallow overbank areas typically responding more quickly to changes than the main channel (i.e., cooling or warming more quickly than the main channel). This is particularly true for the winter deployment. For most station pairs, overbank temperatures tend to be cooler than main channel temperatures (but not in all cases), and at night cool off much faster than the main channel temperatures. MC01/OB01 (Figure 23) and MC02/OB02 (Figure 24) provide good examples. Nighttime cooling in the overbank was much more dramatic on January 23 and January 31 when nighttime air temperatures dropped to near 20°F (-6.7°C).

- The MC04/OB04 pair (Figure 26) tend to have very similar temperatures. As emphasized in the summer deployment, this is due to the close proximity of the stations to one another in an area of the river that obviously is well mixed, just downstream of the inflow from Soddy Creek.

- For the MC05/OB05 pair (Figure 27), the overbank temperature is consistently lower than the main channel temperature throughout the deployment period, except for January 29. On the 29th, it appears that a combination of higher air temperature, solar radiation and wind were perhaps responsible for warming the overbank above that of the main channel. Also, in contrast to observations in the summer deployment, there is no significant correlation between water temperature in the overbank and river flow during peaking operations (January 25, January 26, and February 1).

- The MC12/OB11 pair, located a short distance downstream (Figure 28), exhibited a behavior similar to MC05/OB05, but the difference in temperature between the overbank and main channel was not as large. Furthermore, there is no significant correlation between the measured water temperatures and river flow during peaking operations (January 25, January 26, and February 1). Also shown in Figure 28 is the temperature measured at Station 13, which is in close proximity to MC12. As shown, the temperature at MC12 tracks closely with that of Station 13, providing validity to the latter, at least for the flow conditions that existed during the deployment (i.e., high daily average flows).

- Temperatures for the MC10/OB10 pair (Figure 29) track somewhat close to one another, suggesting that the river is fairly well mixed at this location. Low flow events during peaking operations on January 25, January 26, and February 1 appear to have caused elevated temperatures at both the main channel and overbank locations.

- Temperatures for the MC08/OB08 and MC09/OB09 pairs (Figure 30 and Figure 31, respectively) show the influence of mixing from the diffusers, which are located only a short distance downstream. This is demonstrated by the fact that like MC10/OB10, the temperatures track somewhat close to one another (i.e., somewhat well mixed). The temperatures also increase for lower hourly flows, suggesting the influence of reservoir sloshing causing upstream movement of the plant thermal effluent in the region of the mixing zone, at least in the surface layer of the reservoir. This behavior seems to be more dominant on left-hand-side of the river (facing downstream), which contains a larger overbank. This is because on January 31, which contained a period of river flow below 20,000 cfs, MC08/OB08 exhibited elevated temperatures for both the main channel and overbank, whereas for MC09/OB09, only the main channel exhibit elevated temperatures.

- All of the sites located downstream of Station 13 experienced temperature events that would make them unsuitable for ambient monitoring. The measurements at Station 13, however, appeared to be uninfluenced by the diffuser discharge, at least for the daily average river flows prevailing during the deployment.

Overall, the winter deployment of January 21 through February 2, 2004 again demonstrates that meteorology, river discharge, and geomorphology of the river are important factors in the interaction between main channel and overbank flows. Sloshing of the reservoir obviously has an impact on temperatures for stations located a short distance upstream of the diffusers. But in the winter deployment, sloshing was not observed as far upstream as in the summer deployment of July 23 through August 4, 2004. In the summer deployment, elevated temperatures due to sloshing were observed at OB05 (1.8 miles upstream of the diffusers), whereas for the winter deployment, no elevated temperatures were observed above the MC10/OB10 pair (0.6 miles upstream of the diffusers). This likely is due to heat loss to the atmosphere in the winter verses that in the summer. In the winter, due to lower drybulb and dewpoint temperatures, and higher wind speed, the loss of heat to the atmosphere is much greater than that of the summer. Under these conditions, the temperature of any diffuser effluent migrating upstream in the winter will cool to ambient conditions sooner than that in the summer.

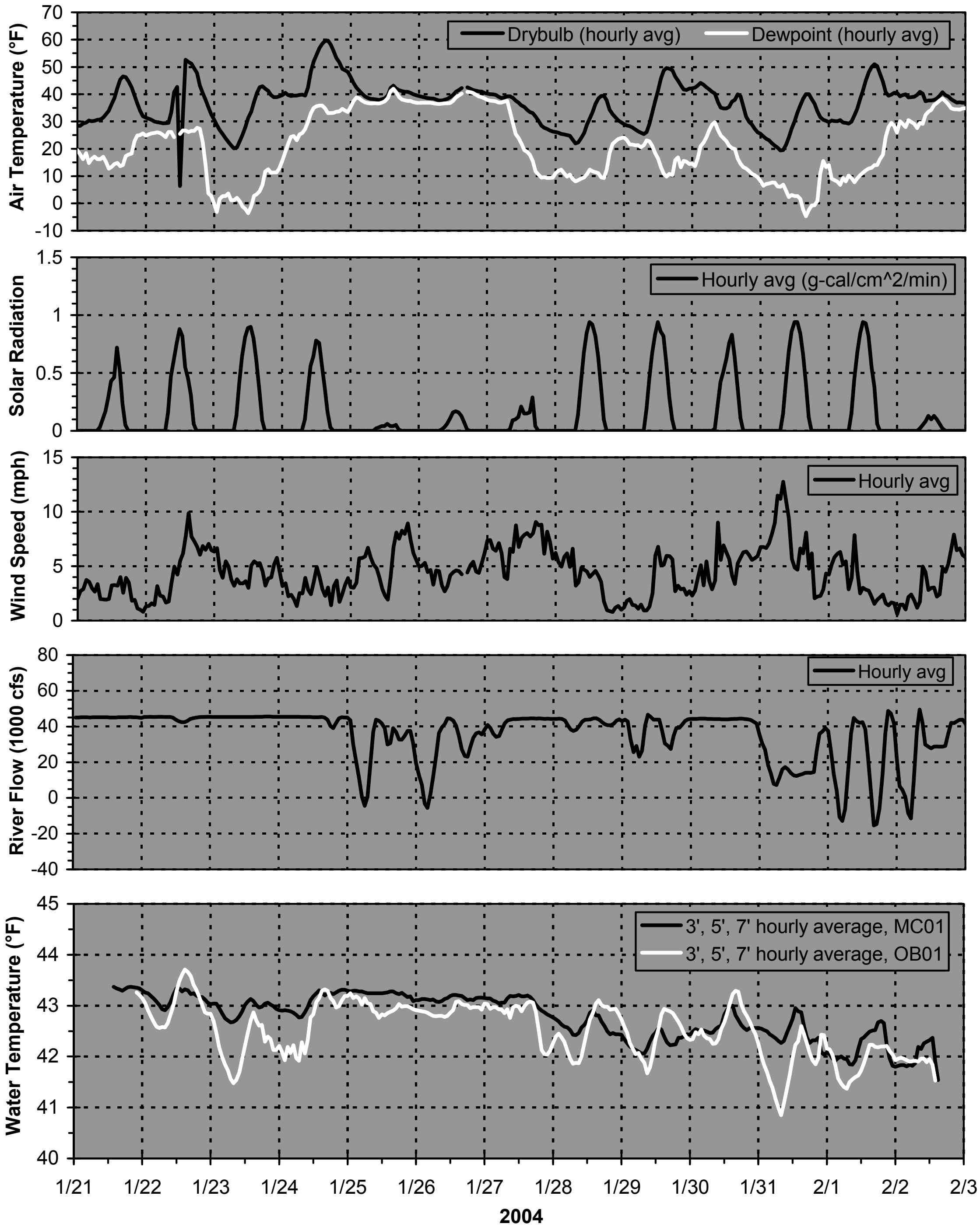


Figure 23. Main Channel and Overbank Stations MC01 and OB01 for Winter Deployment

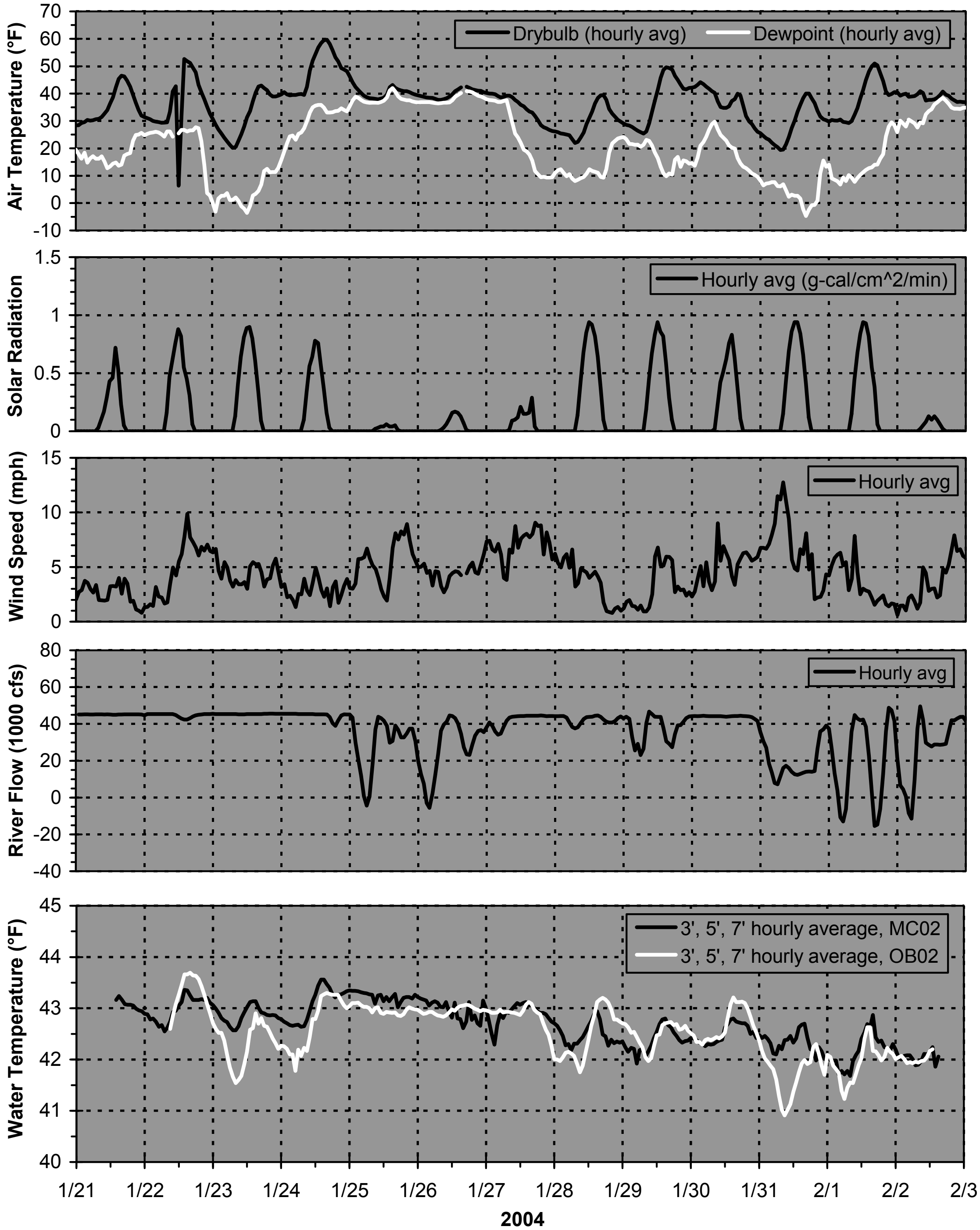


Figure 24. Main Channel and Overbank Stations MC02 and OB02 for Winter Deployment

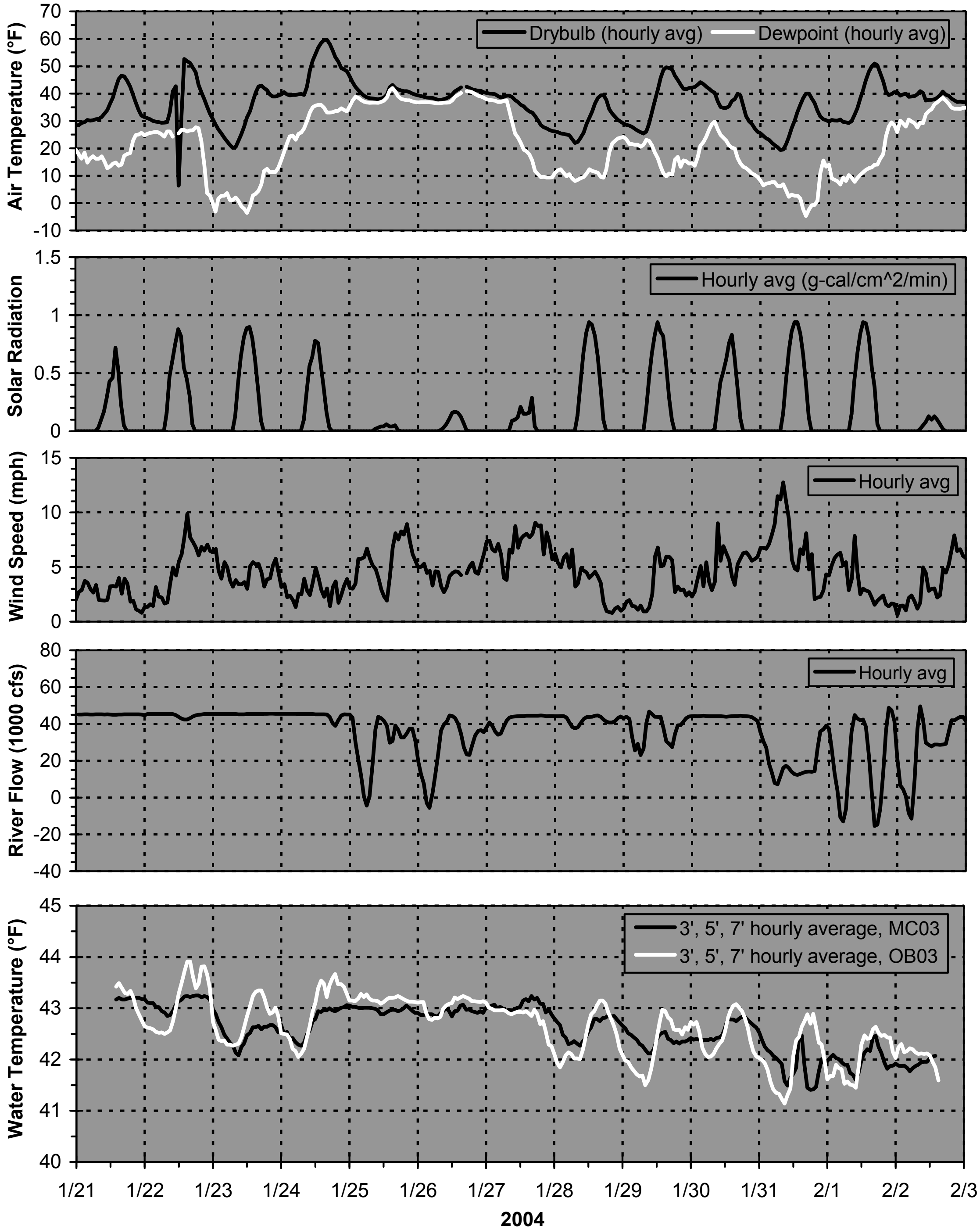


Figure 25. Main Channel and Overbank Stations MC03 and OB03 for Winter Deployment

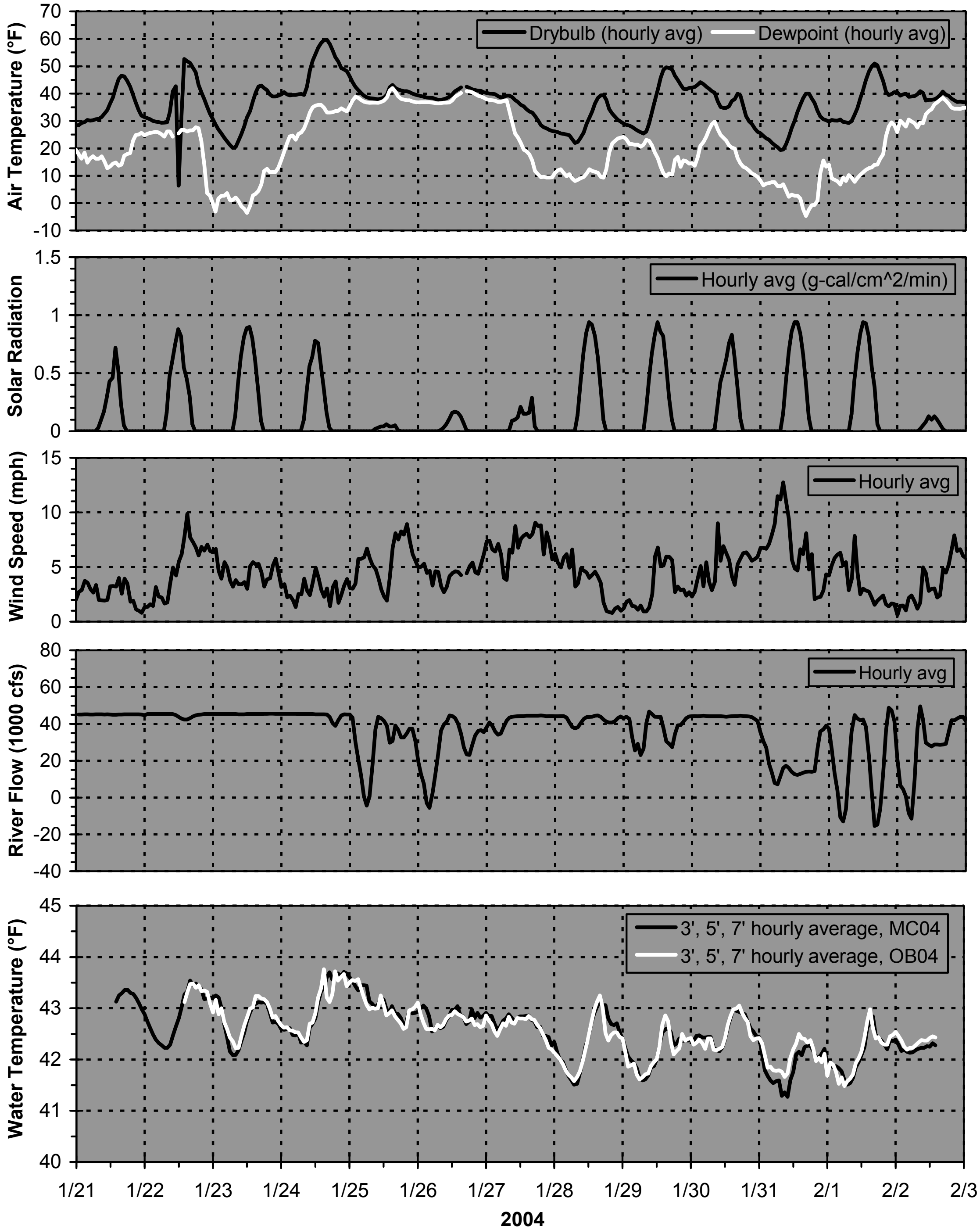


Figure 26. Main Channel and Overbank Stations MC04 and OB04 for Winter Deployment

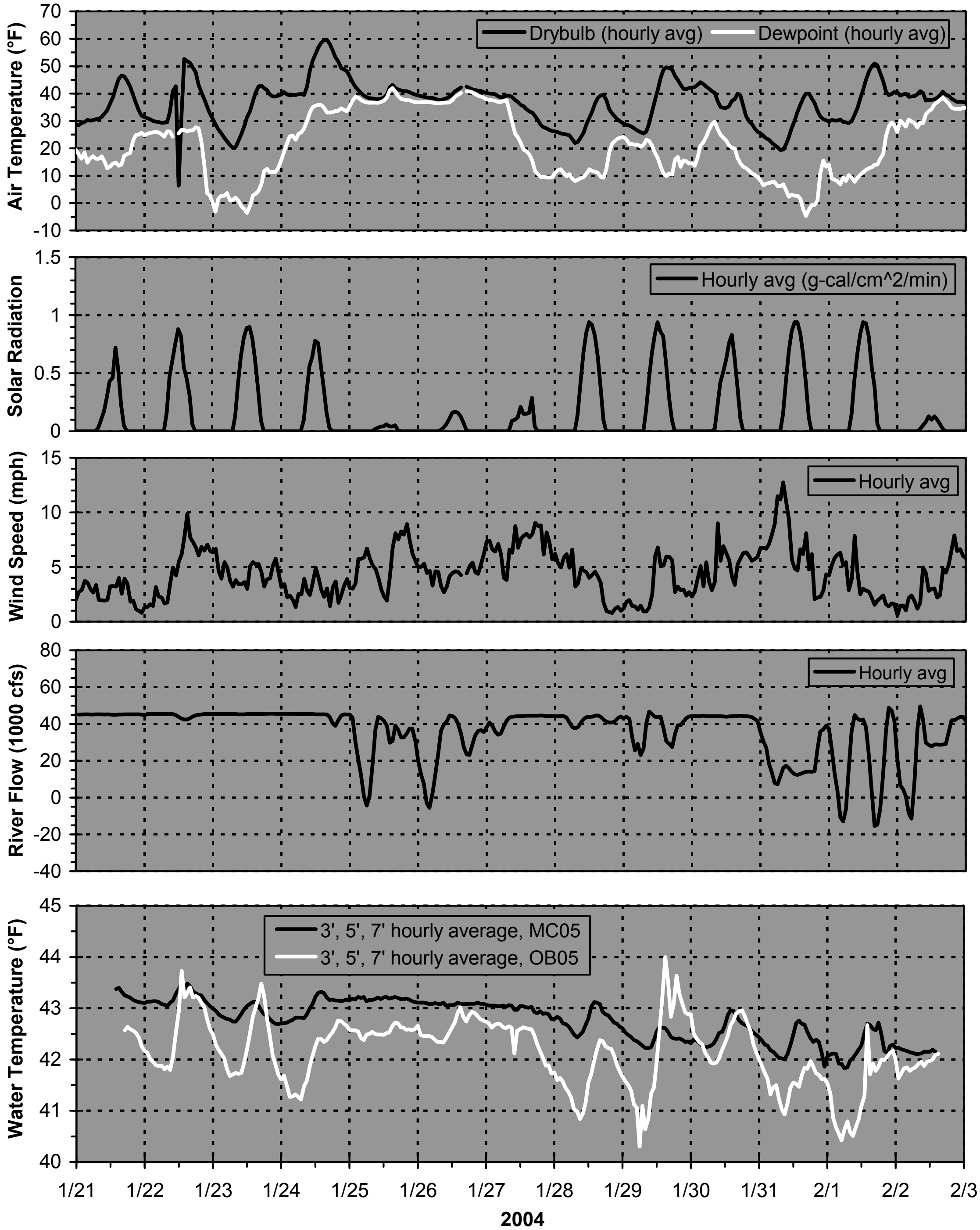


Figure 27. Main Channel and Overbank Stations MC05 and OB05 for Winter Deployment

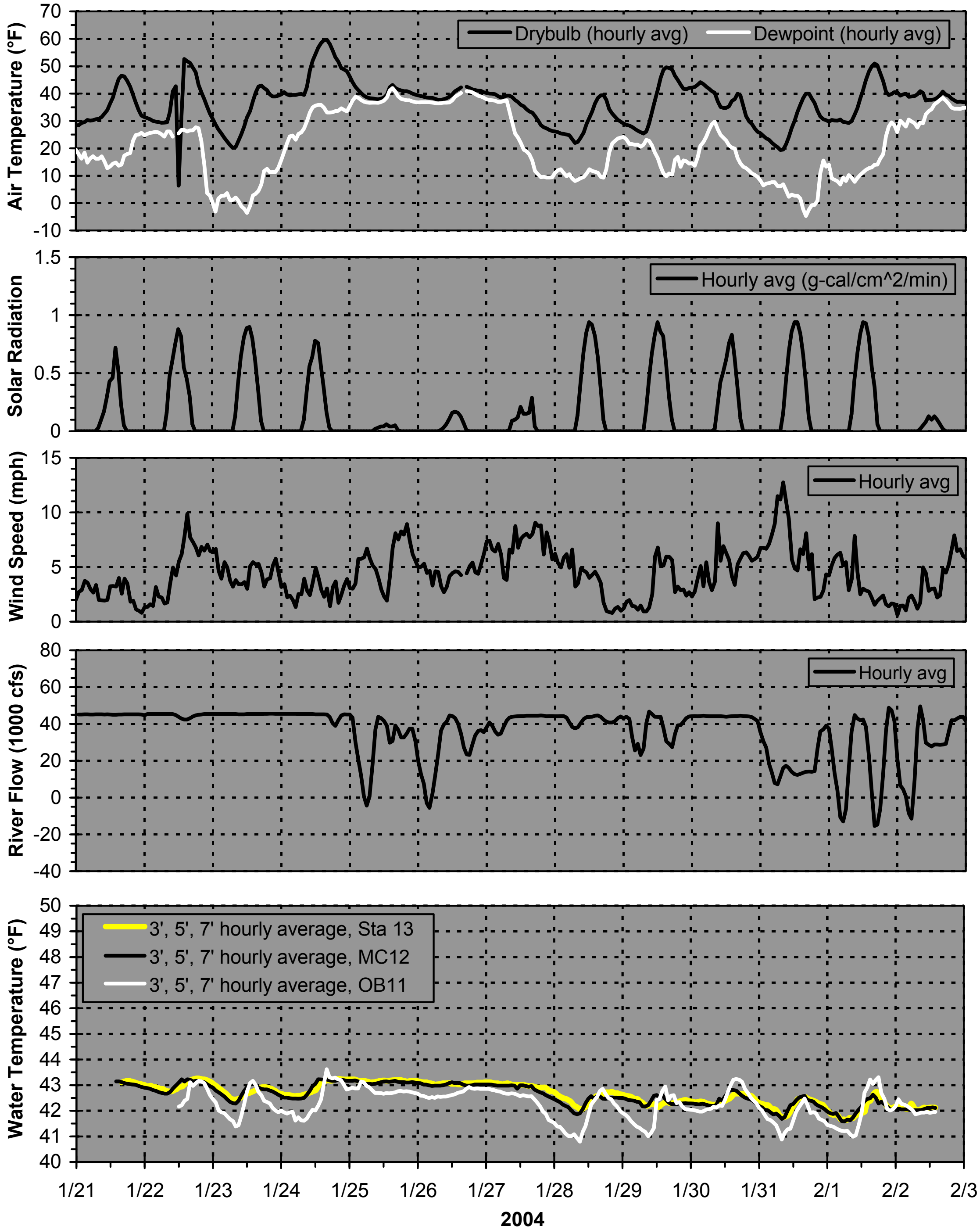


Figure 28. Main Channel and Overbank Stations MC12, OB11, and Station 13 for Winter Deployment

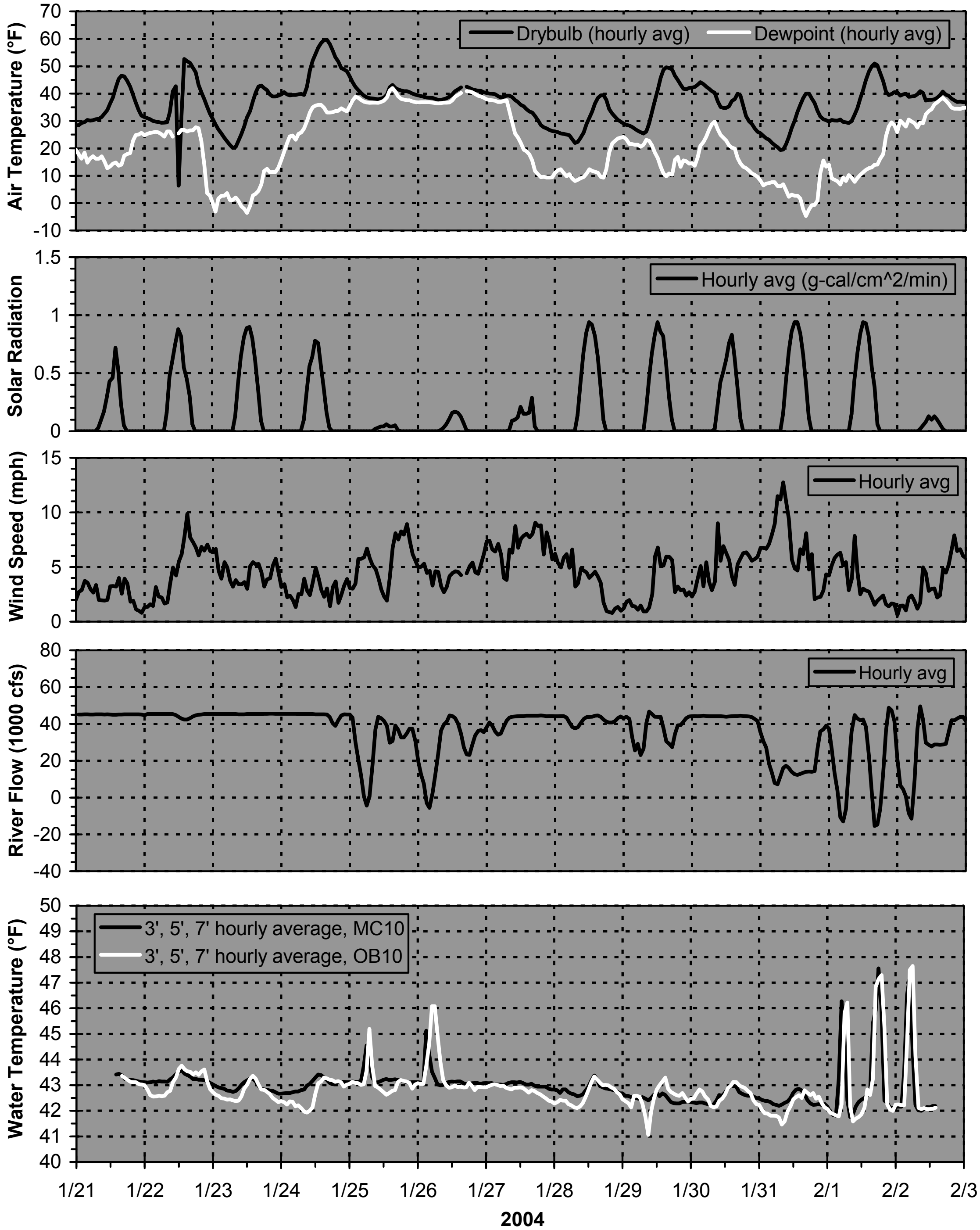


Figure 29. Main Channel and Overbank Stations MC10 and OB10 for Winter Deployment

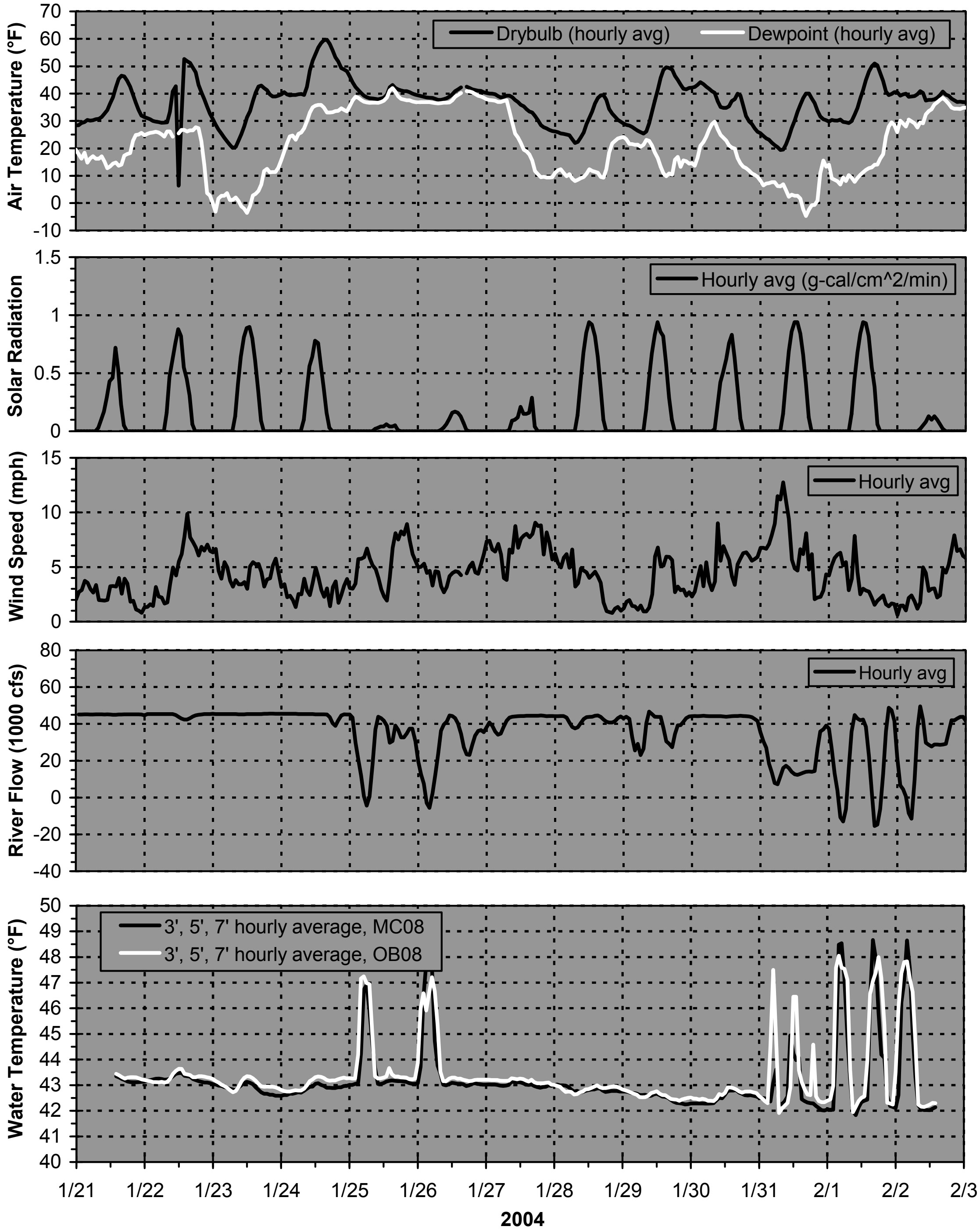


Figure 30. Main Channel and Overbank Stations MC08 and OB08 for Winter Deployment

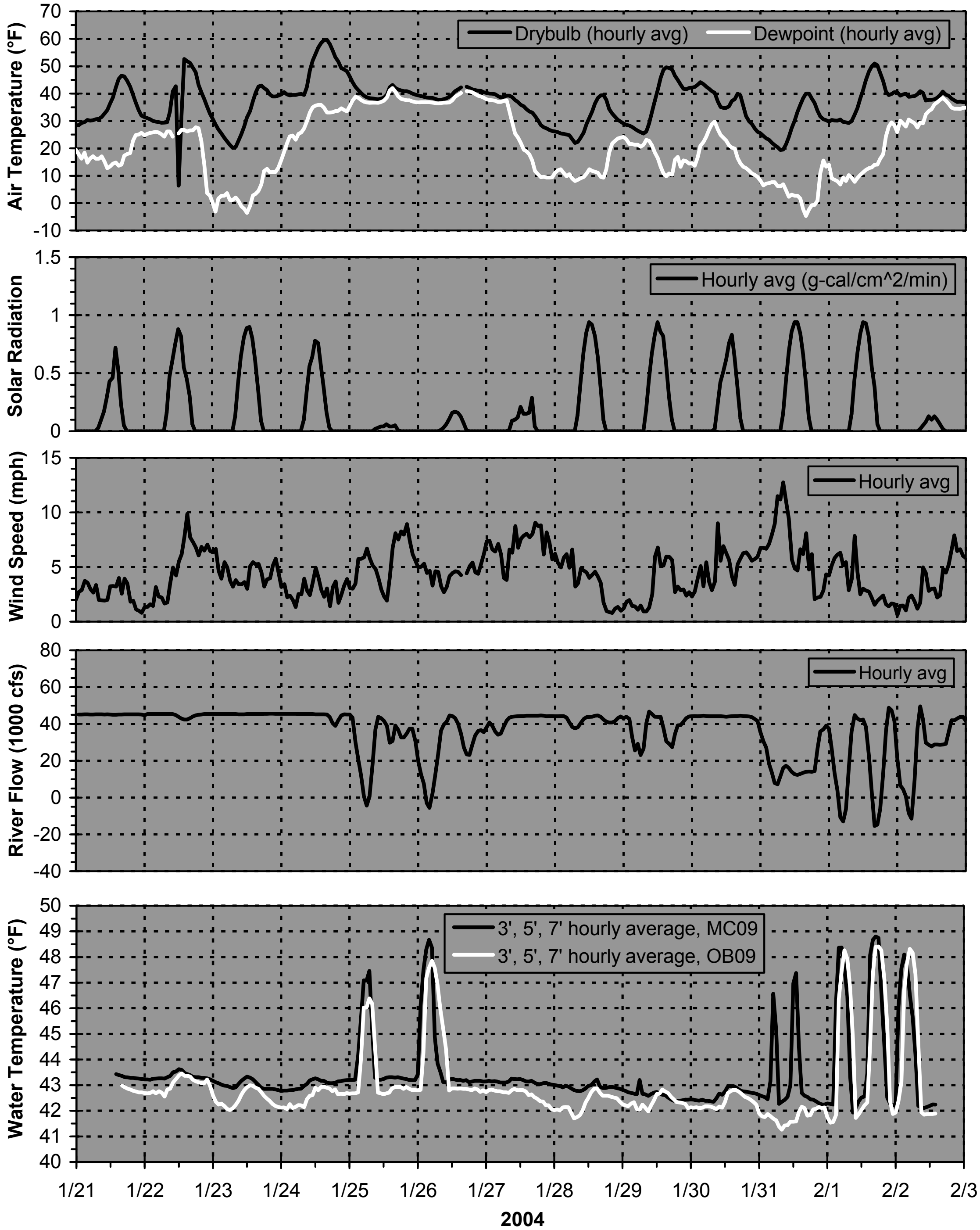


Figure 31. Main Channel and Overbank Stations MC09 and OB09 for Winter Deployment

4.1.3 *Relocation of Ambient Monitoring Station, March 2006*

The May 18 through June 2, 2006 deployment was in response to drought conditions in the Tennessee Valley. In the summer and winter deployments of 2003 and 2004, respectively, the river flows typically ranged between 20,000 and 40,000 cfs, due to abundant rainfall. Even with heavy peaking operations, the measured temperatures at Station 13 (and other stations deployed further upstream) were within normal expectations, based on the observed meteorology and the differences in water temperature between the main channel and overbank portions of the reservoir.

In March 2006, drought conditions began to noticeably impact flows in Chickamauga Reservoir. By early April, valley precipitation for the previous six months was 72 percent of normal, and runoff was 57 percent of normal. During the last week of March, 2006, runoff into the TVA reservoir system above Chattanooga ranked 98 out of 104 years of record. For the last two weeks of March, 2006, releases from Chickamauga Dam were the lowest since 1981, and were slightly lower than those observed in 1988, another year of extremely low flows.

With low inflows into the reservoir system, TVA began reducing releases from upstream dams to conserve water (e.g., for water quality, water supply, and navigation). A plot of the actual daily average releases into and out of Chickamauga Reservoir is given in Figure 32. At Watts Bar Dam, releases were reduced to about 3,000 cfs on March 30. At Chickamauga Dam, flows dropped below 10,000 cfs on March 28, and were further reduced to about 4,000 cfs on March 31. In contrast, for these days, the historic average daily flows from these projects (from 1981 through 2005) are well above 20,000 cfs.

On March 29, data from the plant ambient temperature monitor (Station 13) recorded water temperatures unexpectedly high for that time of the year. The temperatures are shown in Figure 33, which includes measurements from sensors throughout the depth of flow (e.g., 0.5 feet deep to about 40 feet deep). The temperatures indicate heating of the water in the early morning hours, and a sharp increase in surface temperatures in the afternoon that are greater than might be expected from solar heating alone. Nighttime excursions in temperature are not uncommon in the warmer months when there is significant uneven heating in different parts of the reservoir (e.g., overbanks vs. main channel), but in March, when reservoir temperatures tend to be uniform, such excursions are unusual. Since the diffusers represent the only other nearby source of heat, it was suspected that the excursions were attributable to the plant thermal discharge. As summarized earlier (Section 2.2), previous studies have documented the upstream movement of heated effluent from the plant diffusers due to reverse flows, but they did not conclude that the upstream movement would be large enough to influence Station 13 at the skimmer wall.

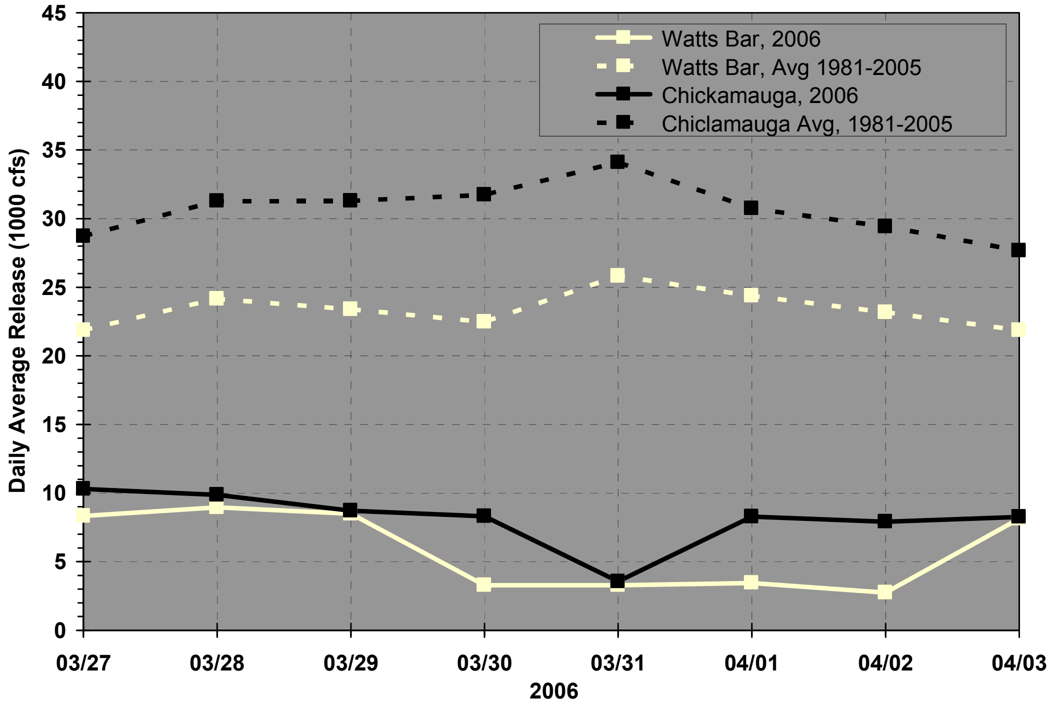


Figure 32. Releases Upstream (Watts Bar) and Downstream (Chickamauga) of SQN

Based on additional measurements in 2006, the location for the ambient river temperature was changed on March 31, 2006. The new site, entitled Station 14, is shown in Figure 34 and Figure 35. Station 14 is in the same general location as Station MC1 used in the summer and winter ambient temperature measurements summarized above (see Figure 12). The location of the new site was approved by TDEC on April 7, 2006. Later, the deployment of May 18 through June 2, 2006 was implemented to confirm the adequacy of the new site and examine potential processes that may be responsible for the upstream movement of the thermal effluent at low river flow.

It is important to note that for the low flow in years 1981 and 1988, the operation of SQN was very different than it is now. In March 1981, only Unit 1 was in service, and in March 1988, both units were out of service. Under these conditions, the behavior identified in Figure 33 would have been greatly reduced or nonexistent. However, since low daily average river flow is possible even in years with higher reservoir releases, it is likely that events such as the one observed on March 29 have occurred before. Based on previous understanding of the behavior of the effluent, such events did not suggest a need for action.

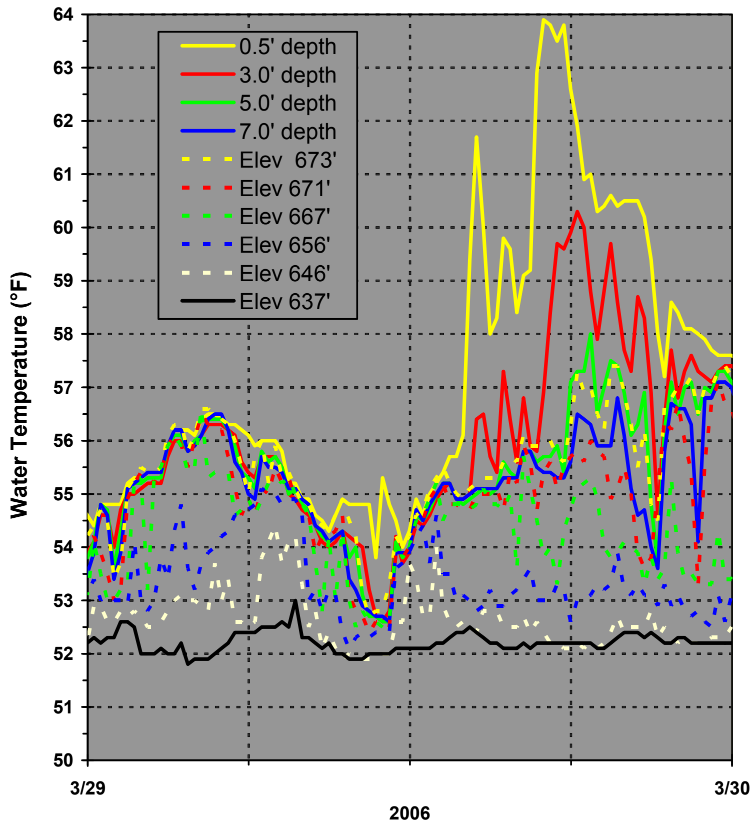


Figure 33. SQN Ambient River Temperatures Measured at Station 13 on March 29, 2006

Figure 34. Station 14 Floating Water Temperature Station

Figure 35. Location of New Ambient Temperature Station

4.1.4 *Third Deployment May 18 through June 2, 2006*

Instrumentation for the deployment of May 18 through June 2, 2006 was different than that of the previous ambient temperature deployments. Temperature measurements were made using resistance temperature detectors (RTDs) rather than HOBO^{TM} devices. The RTDs were attached to a cable and suspended from a boat at depths of 3-feet, 5-feet, and 7-feet. The boat slowly trolled the center of the river from downstream of the diffuser mixing zone to Station 14. A GPS location and time stamp were recorded simultaneously with the temperature measurements. The RTDs had a resolution of about 0.1 F° (0.056 C°), accuracy of about 0.25 F° (0.14 C°), and time constant of about 0.7 second. The temperatures, boat position and time stamp were recorded at a sampling rate of 0.25 Hertz. Based on the boat speed, this provided temperature samples about every ten to fifteen feet along the center of the river. Although measurements were made every day of the deployment, results from only a few days are needed to illustrate key behaviors of the flow in the reach upstream of the plant between the mixing zone and ambient temperature monitor.

Measurements were made for two cases—near steady operation of the river, and following a period of unsteady hydro peaking operations. Figure 36 and Figure 37 illustrate results for steady operation and show the change in river temperature relative to the ambient temperature measured in the vicinity of Station 14 (i.e., river temperature rise from the temperature measured near Station 14). The change in temperature was computed based on the average of the RTD readings at the 3-foot, 5-foot, and 7-foot depths. The measurements in Figure 36 were made on May 20 and included a river flow of about 8,000 cfs. For this day, the overall river temperature rise measured between the ambient temperature monitor, Station 14, and the downstream end of the mixing zone, Station 8, was about 2.6 F° (1.4 C°). The measurements in Figure 37 were made on May 23 and included a river flow of about 18,000 cfs. For this day, the overall river temperature rise measured between Station 14, and Station 8, was about 1.3 F° (0.7 C°). The following basic features are noted:

- Figure 36 and Figure 37 both confirm that after leaving the diffuser mixing zone, thermal effluent from the plant diffusers can migrate upstream beyond Station 13, as speculated based on the events of March 29, 2006.

- For a steady river flow of 8,000 cfs (Figure 36), thermal effluent reached about TRM 487.2 before being re-entrained into the flow moving downstream and cooling to ambient conditions by heat loss to the atmosphere. This represents an upstream migration of about 2.5 miles above Station 13. The temperatures in the box identified as B, which includes the area of Station 13, are about 2 F° (1.1 C°) above the ambient temperature in the vicinity of Station 14.

- For a steady river flow of about 18,000 cfs (Figure 37), heated effluent had been "pushed" downstream. The downstream movement of the thermal front can be identified by the box identified as A. After the flows had increased, all of the thermal effluent had moved out of box A, down to about TRM 486.2, or 1.5 miles above Station 13. Compared to 8,000 cfs (Figure 36), the temperatures upstream in box A were reduced between 1 F° to 1.5 F° (0.6 C° to 0.8 C°), and in the vicinity of the plant intake, box B, temperatures were reduced by about 1 F° (0.6 C°). In the area of the mixing zone, identified as box C, temperatures were also reduced by about 1 F° (0.6 C°). It should be emphasized that these measurements were made within 24 hours after the flow had been increased to 18,000 cfs. Over a longer period of time, this flow would have perhaps pushed the thermal effluent even further downstream.

Based on these observations and the results of a 3D numerical flow model of the river in the vicinity of Sequoyah nuclear plant, TVA has identified the basic mechanism responsible for the upstream migration of thermal effluent at steady, low river flow. This is presented graphically in Figure 38. At low flow, the water in the river moves primarily in the main channel of the river (the green area in Figure 38). This flow is drawn into and entrained by the jets issuing from the diffuser ports. The mixture emerges in the surface layer of the river in the diffuser mixing zone.

At low river flow, the discharge is insufficient to transport all of the mixture downstream. As a result, part of the thermal effluent moves out of the mixing zone and “backs-up” in the river. Two mechanisms that “feed” the effluent out of the mixing zone are shown in Figure 38. One is a thermal wedge that spreads upstream of the diffuser plume at the river water surface (red area in Figure 38). The other is identified as the near-field diffuser plume wrap-around zone (orange area in Figure 38). In the wrap-around zone, the effluent mixture is transported out of the mixing zone by recirculation zones on the sides of the mixing zone. These recirculation zones move the effluent mixture upstream around the thermal wedge. The northern side of the wrap-around zone is limited by the flow moving downstream in the main channel of the river (green area in Figure 38). The southern side of the wrap-around zone, however, feeds the effluent mixture into a migration zone that moves upstream through the overbank along the southern side of the river (blue area in Figure 38). The upstream migration travels all the way to the river bend upstream of the plant. At the river bend, the flow in the main channel “pinches-off” the upstream migration such that most of the upstream movement is hindered and the thermal effluent becomes entrained in the main channel and is carried downstream.

The overall large-scale recirculation pattern with flow moving downstream in the main channel and upstream in the overbank is a consequence of several factors. One is the flow in the main channel, creating zones of reverse flow and mixing in the overbank areas. Another is related to the flow around the bend in the river upstream of the plant. The flow coming around the bend creates a separation zone, or wake, on the inside and downstream of the bend. The flow in a separation zone characteristically creates a recirculation pattern that moves the flow upstream along the lower boundary of the separation zone, in this case along the reservoir shoreline. Finally, and perhaps rather significant, is the action of the SQN diffusers. The high velocity jets issuing from the diffusers entrain water from upstream in the main channel. At low river flow, this process can pull water much lake a jet pump, locally accelerating the flow in the main channel above that of the average river flow. After mixing with the diffuser effluent, and to preserve continuity, any entrainment in excess of the average river flow moves into the adjacent overbank areas where it is transported upstream as depicted in Figure 38. This process is described in further detail later in discussions about the mixing zone.

Nested between the downstream flow in the main channel and the upstream flow through the southern overbank is a recirculation zone (yellow area in Figure 38). As its name suggests, the flow in this zone is characterized by recirculation areas driven around and around by the adjacent flow. The recirculation zone also feeds heat into main channel of the river. This is accomplished by the mixing action of the recirculation areas, which can carry the effluent moving upstream along the overbank through the recirculation zone to the flow moving downstream and into the main channel.

Figure 39 illustrates results for the change in river temperature following a period of unsteady operation of the river, characterized by three days of peaking operations with daily average flows of about 14,000 cfs. The measurements were collected on May 27. For this day, the overall river temperature rise measured between the ambient temperature monitor, Station 14, and the downstream end of the mixing zone, Station 8, was 2.6 F° (1.4 C°). In this case, thermal effluent reached about TRM 488.7 before being re-entrained into the flow moving downstream and cooling to ambient conditions. This represents an upstream migration of about 4.0 miles above Station 13, but did not reach Station 14. Overall, though, the upstream migration for peaking operations exceeded that of steady operations (Figure 36 and Figure 37). More than likely this is due to the fact that in addition to some of the steady flow transport mechanisms depicted in Figure 38, peaking operations also create sloshing, or reverses cross-sectional average flows in the river. In this case, the additional transport was enough to apparently move heat slightly around the river bend.

Additional comments concerning the magnitude of daily average river flows responsible for the movement of flow out of the mixing zone and in the upstream are presented later in discussions related to the mixing zone study. Here it is only emphasized that as the daily average river flow increases, the magnitude of the transport mechanisms as shown in Figure 38 diminish, and for high enough river flow, disappear almost altogether. Also, as experienced in the wintertime deployment presented above, during those times of the year characterized by reservoir cooling (e.g., fall and winter), the upstream migration of heat during low river flows is likely to be diminished due to a greater amount of heat loss to the atmosphere.

Finally, it needs to be reemphasized that some of the heat displayed in Figure 36, Figure 37, and Figure 39 may be the result of solar heating, since this deployment also contained days with high air temperatures and solar radiation. At this time TVA does not have a good method to separate the impact of temperature rise due to solar heating from the total temperature rise between Station 14 and the downstream end of the plant mixing zone. Under these conditions, SQN continues to operate the plant cooling system in a manner to keep the total temperature rise below the NPDES standards, whether or not the source of heat buildup in the river is from the diffuser discharge or a combination of the diffuser discharge and solar heating.

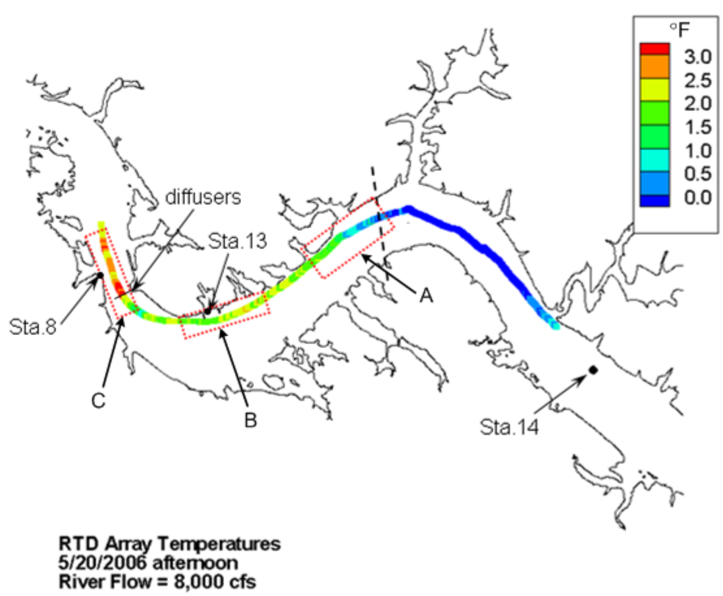


Figure 36. Temperature Rise along Center of River for Steady River Flow of 8000 cfs

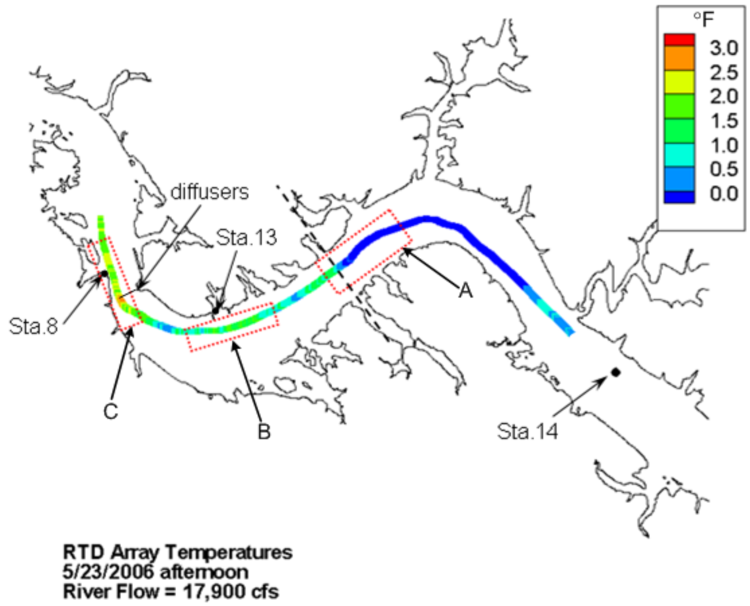


Figure 37. Temperature Rise along Center of River for Steady River Flow of 18,000 cfs

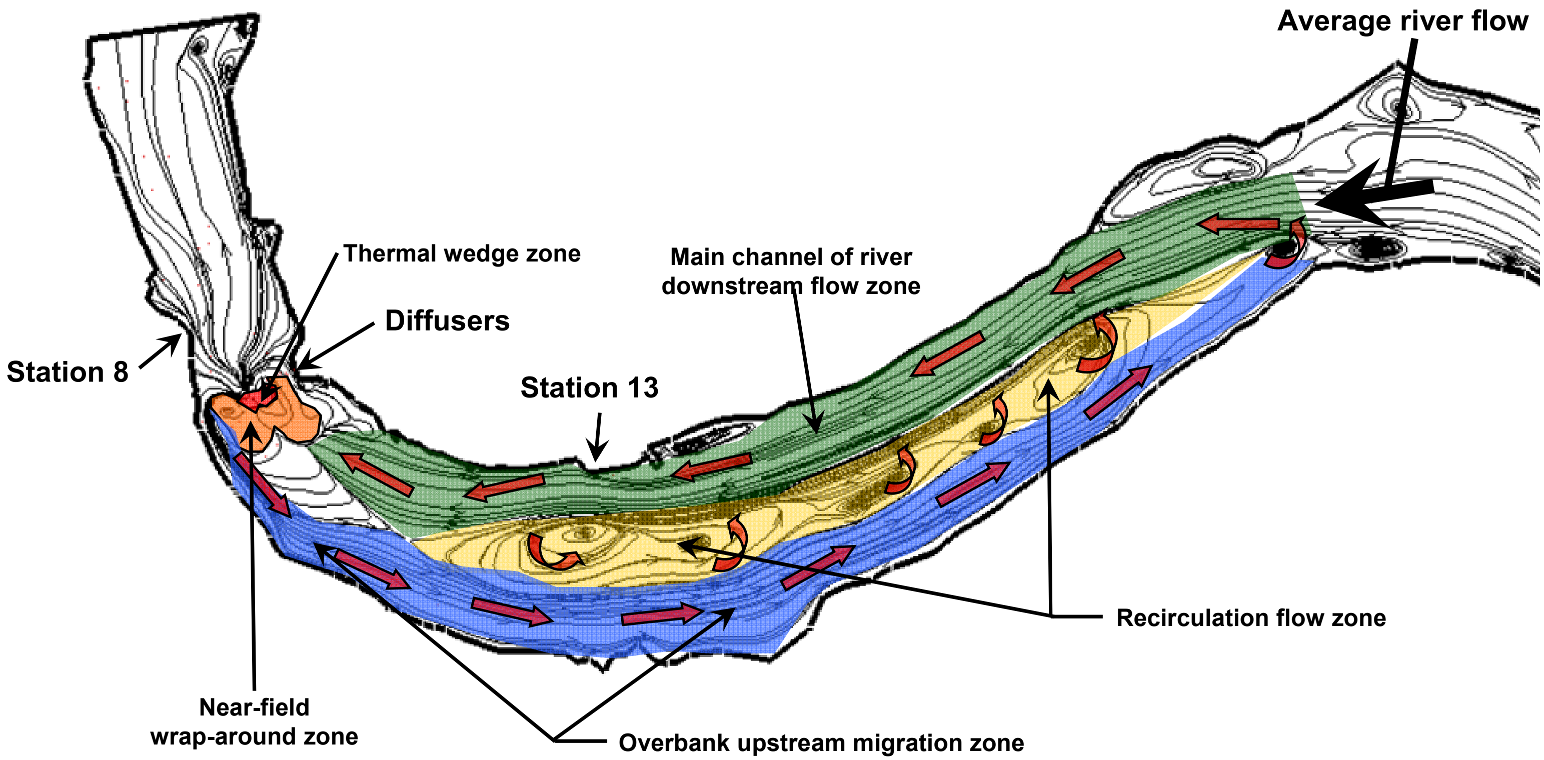


Figure 38. Upstream Migration of Thermal Effluent for Steady, Low River Flow

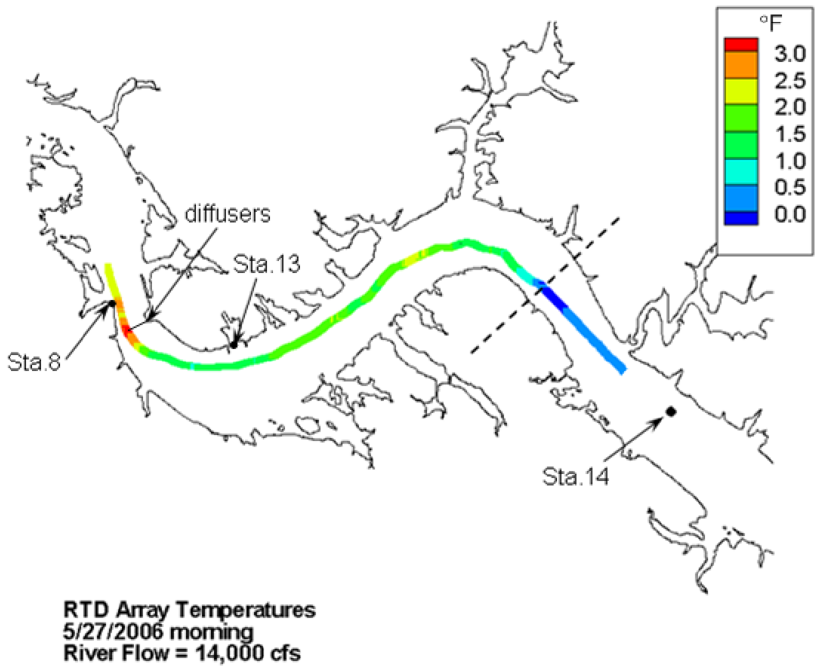


Figure 39. Temperature Rise along Center of River following Peaking Operations at 14,000 cfs

4.1.5 *Hourly and 24-Hour Averaging*

The difference between hourly and 24-hour averaging can be examined from ambient temperature measurements at Station 14 in 2007. This was the first full calendar year of service for Station 14 and presents an extreme case, due to the 2007 drought. Rainfall in East Tennessee was 31.2 inches, 18.8 below normal and the lowest in 119 years of record. The corresponding runoff was 9.9 inches, 13.3 below normal and the lowest in 134 years of record. The annual average river flow past SQN was about 14,000 cfs, compared to a historical average of about 32,000 cfs. The year was not only dry, but it was also warm. The air temperature in Chattanooga for June, July, and August was about 3 F° (1.7 C°) above normal (the third warmest year since 1948).

A plot of the computed river flow at SQN for 2007 is given in Figure 40. Both the hourly average and 24-hour average flows are also given. For average daily flows below about 10,000 cfs, the river flows are fairly steady (e.g., from late March through late May, mid September, and again in mid to late December). For higher daily flow rates, hydro peaking operations create larger variations in the hourly river flow, (e.g., June and July).

The 2007 ambient river temperature measured at Station 14 is given in Figure 41. Both the hourly average and 24-hour average values are given. The minimum ambient temperature occurred in mid February, at about 41°F (5.0°C). In late March, above-normal meteorology caused the ambient temperature to climb above 65°F (18.3°C). Subsequently, a strong cold front in early April reduced the water temperature back to a more seasonable level. The maximum ambient temperature occurred in August, with a sustained warm, high pressure system that produced daytime high air temperatures regularly above 90°F (32.2°C). The maximum ambient temperature occurred on August 11 with a hourly average value of about 88°F (31.1°C) and a 24-hour average value of 86.2°F (30.1°C). The ambient temperature is determined as the average of sensor readings at the 3-foot, 5-foot and 7-foot depths. Deeper in the water column, water temperatures were cooler, typically between 80°F (26.7°C) and 83°F (28.3°C) during the period of peak summertime heating.

The difference between the hourly average and 24-hour average ambient temperature can be characterized by the exceedance probabilities. These are plotted in Figure 42. Over most of the temperature range, there is virtually no difference in the percent of time exceeded for hourly averaging verses 24-hour averaging. The only notable exceptions are near the extreme temperatures (i.e., annual maximum and minimum temperatures) where the number of occurrences of hourly average temperature increases is "too low" to affect the 24-hour average values. This is emphasized in Figure 42, which provides an expanded view of the ambient temperatures that occur less than 5 percent of the time. Even in this range, the difference between the hourly average and 24-hour average is very slight and infrequent, less than 0.5 F° (0.3 C°) at an exceedance of 0.5 percent (i.e., about 48 hours per year). This suggests that under the natural reservoir conditions that exist at Station 14, there is very little difference in duration of the ambient temperature based on 24-hour averaging vs. hourly averaging.

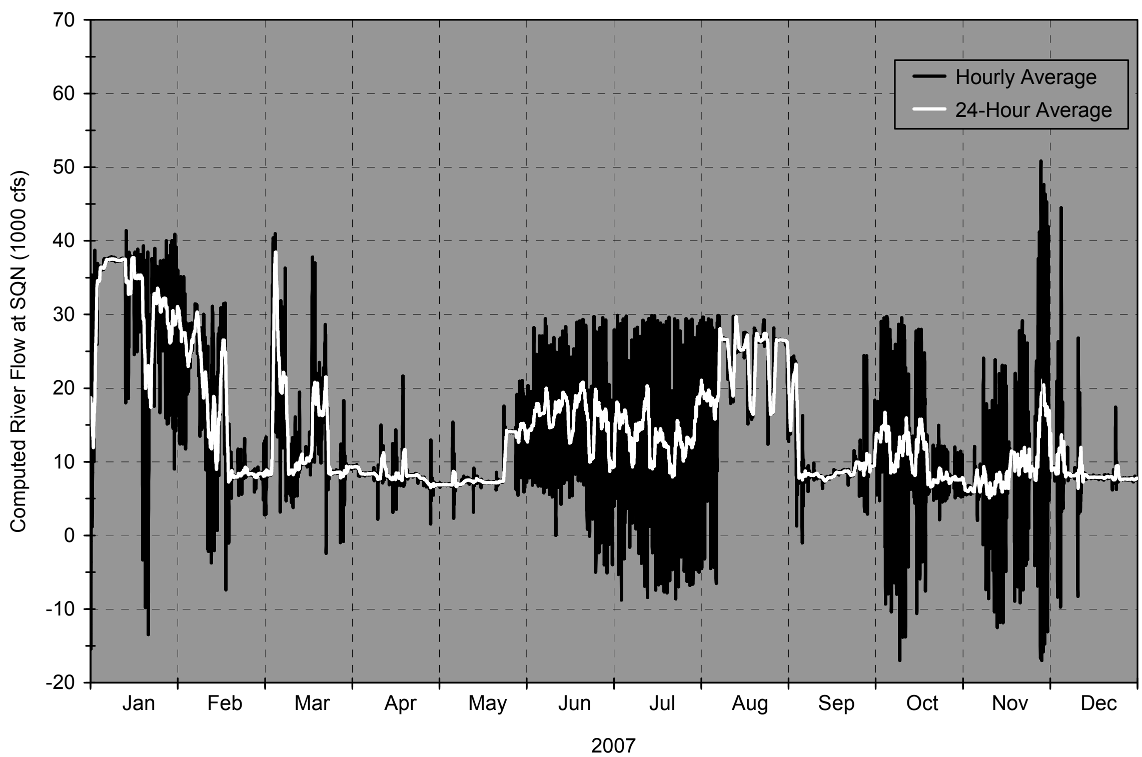


Figure 40. Computed River Flow at SQN for 2007

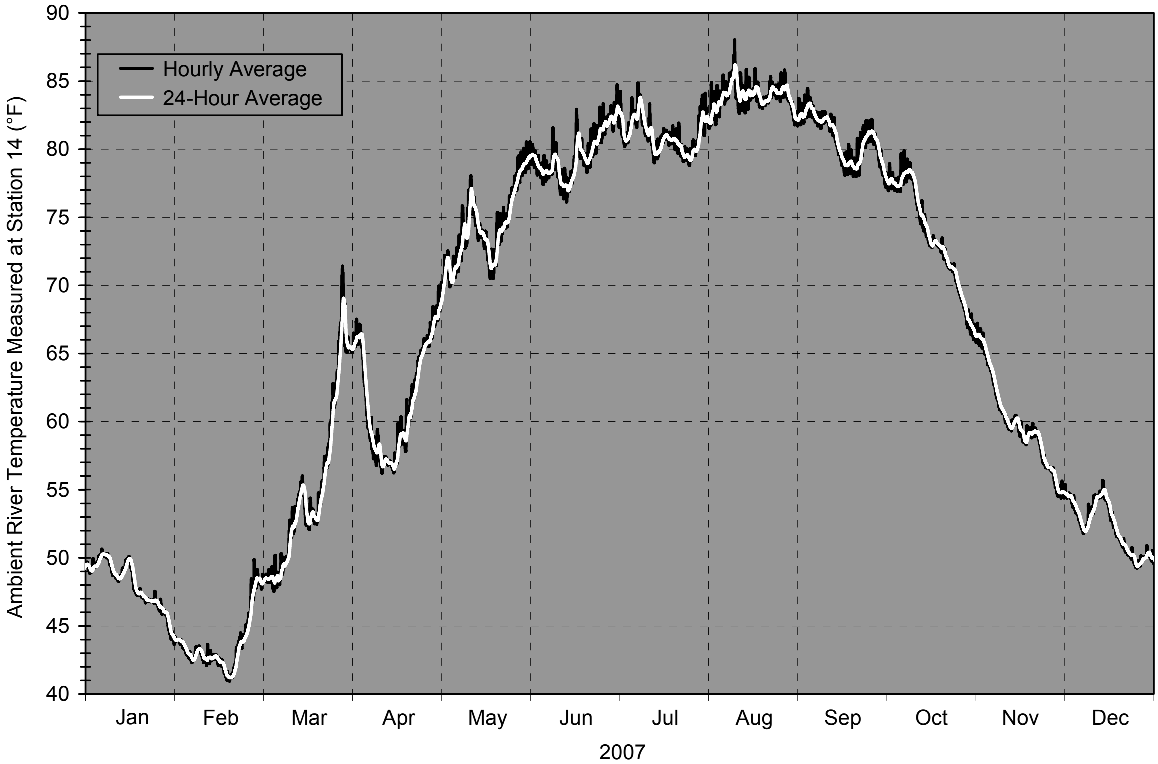


Figure 41. Ambient Water Temperature Measured at SQN Station 14 for 2007

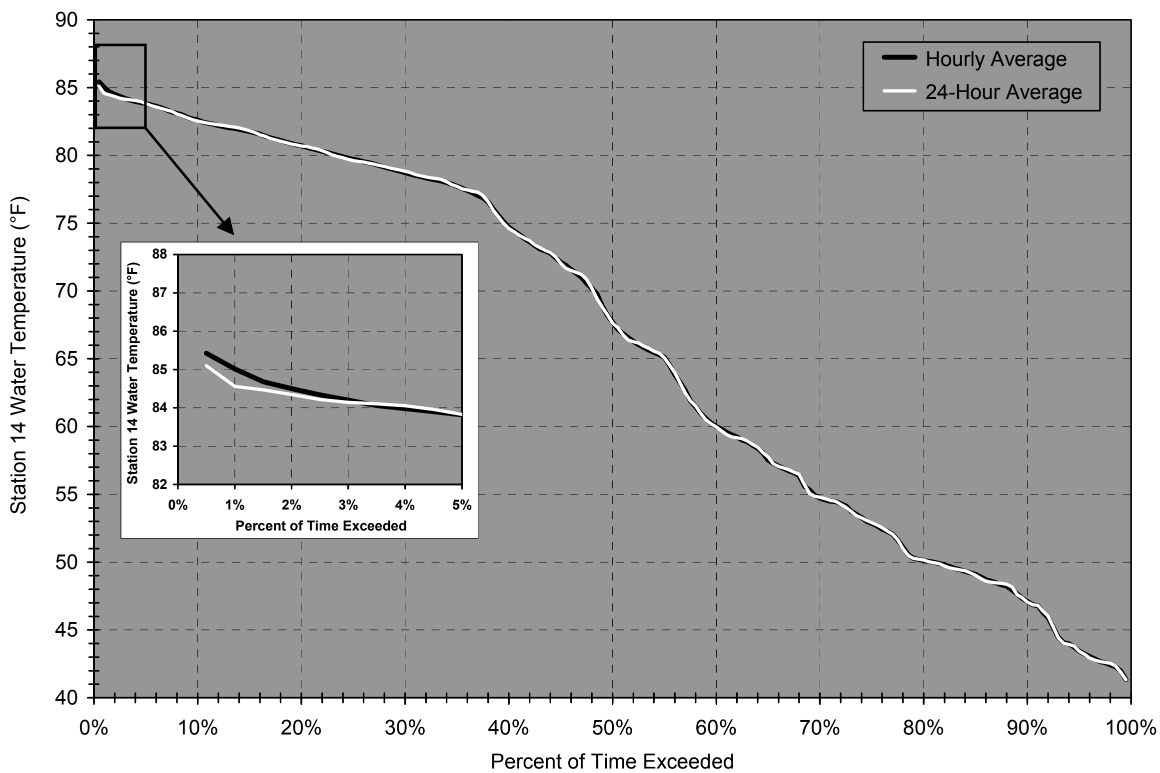


Figure 42. Exceedance Probability for Ambient Water Temperature at Station 14 for 2007

4.2 Mixing Zone Study

The mixing zone study includes new temperature measurements in three deployments. The summer deployment took place from August 11 through August 24, 2004. The winter deployment took place from February 12 through February 23, 2004. The third deployment took place between September 19 and September 22, 2006. In order to facilitate interpretation of results from the three deployments, a brief hydrothermal overview of the diffuser discharge and effluent plume is presented first. The second section of this chapter provides a general discussion of monitoring for the deployments. The last three sections present the deployment results.

4.2.1 *Basic Hydrothermal Aspects of Diffuser Discharge and Effluent Plume*

The basic design features of the Sequoyah discharge diffusers are shown in Figure 43. Effluent from the plant is released to the Tennessee River through two diffuser conduits (or legs). The upstream and downstream conduits are 17 feet and 16 feet in diameter, respectively, and are situated in the 900-foot wide navigation channel (i.e., deepest part of the river). Each diffuser includes a section of pipe 350 feet long that contains outlet ports. Together, the pipe sections containing the outlet ports occupy the 700 feet of the navigation channel closest to the plant. The outlet ports are situated in the downstream, upper quadrant of the diffuser pipes and include seventeen 2-inch diameter holes per foot of pipe. This arrangement places the ports in the wake of the diffuser pipe, which enhances the release and mixing of the thermal effluent. At the normal minimum pool in Chickamauga Reservoir, the diffuser ports are about 35 feet below the water surface, and at the normal maximum pool about 43 feet below the water surface.

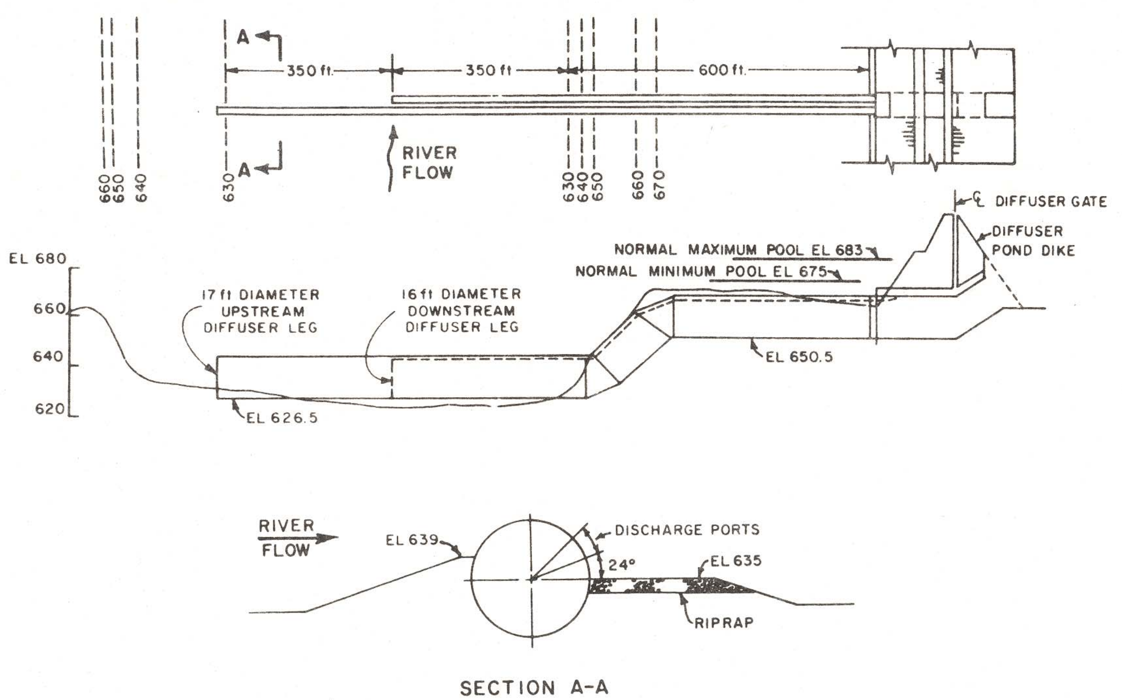


Figure 43. Basic Design Features of Sequoyah Diffusers

The fundamental behavior of the effluent plume from the diffusers can be described using the schematic in Figure 44. Q_R is the river discharge, Q_{SQN} the diffuser discharge, and Q_E the ambient river water entrained by the diffuser plume.

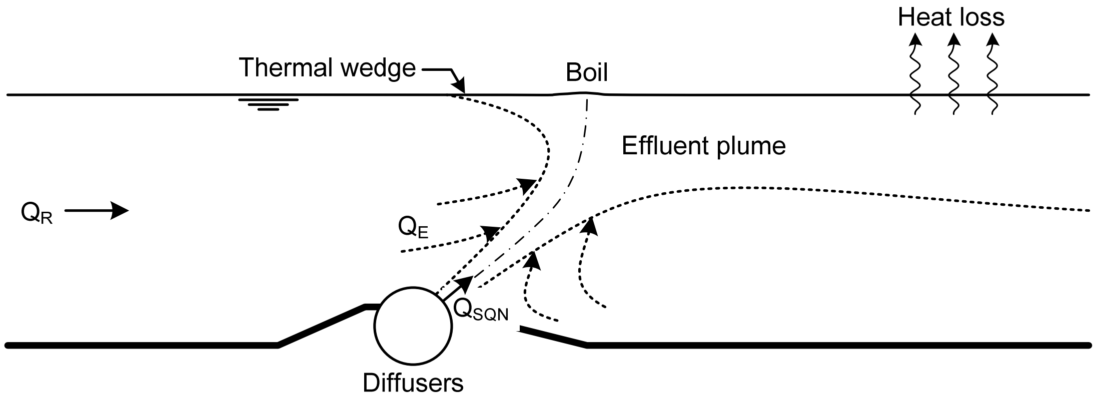


Figure 44. Basic Behavior of Effluent Plume

The number and size of the diffuser ports provides a discharge velocity of about 9.5 feet per second (fps) for the jets issuing from the ports. The jets are directed downstream, pointing upward between about 24° and 43° from the horizontal. In contrast, the range of water velocity in the river varies between only about 0.8 fps in the downstream direction to about 0.3 fps in the upstream direction. The former number corresponds to the maximum river discharge with the hydroturbines at Watts Bar Dam (upstream) and Chickamauga Dam (downstream) operating at maximum load (about 46,000 cfs), whereas the latter corresponds to a typical maximum, short-term reverse flow event due to hydro peaking at the same dams (reservoir sloshing creating 20,000 cfs in the upstream direction). Thus, by comparison, the velocity of the effluent exiting the diffuser ports is between about 12 and 32 times greater than the river velocity for these extreme river conditions, and even higher for river discharges between these extremes. Under these conditions, for nearly all expected river flows (excluding perhaps flood events), mixing of the effluent plume is heavily dominated by the momentum of the jets from the diffuser ports. And in a similar manner, the trajectory of the effluent plume is dominated by the momentum of the jets. In confirmation of this, theoretical computations, the original physical model studies, and observations in the field all show that based on the location of the boil, where the effluent plume breaches the water surface, the effluent mixing occurs primarily in the region immediately downstream of the diffuser conduits.

Due to the transfer of momentum away from the diffuser jets by fluid shear, the effluent discharge entrains the ambient water as it issues from the diffuser ports and streams towards the water surface. Low pressure at the diffuser ports and buoyancy of the effluent also play a part in the entrainment process. Depending on the momentum of the river flow verses the momentum and buoyancy of the effluent plume at the water surface, a thermal wedge may propagate upstream of the boil. As the effluent mixture is transported from the mixing zone, the excess heat in the flow escapes to the atmosphere, slowly cooling the river back to natural conditions.

Due to the transfer of momentum away from the diffuser jets by fluid shear, the effluent discharge entrains the ambient water as it issues from the diffuser ports and streams towards the water surface. Low pressure at the diffuser ports and buoyancy of the effluent also play a part in the entrainment process. Depending on the momentum of the river flow verses the momentum and buoyancy of the effluent plume at the water surface, a thermal wedge may propagate upstream of the boil. As the effluent mixture is transported from the mixing zone, the excess heat in the flow escapes to the atmosphere, slowly cooling the river back to natural conditions.

The major factor affecting the transport of the thermal effluent from the mixing zone is the magnitude of river flow. TVA experience with diffuser mixing suggests that the amount of ambient river water that is naturally entrained into the diffuser plume (Q_E) falls in the range of from $7 \times Q_{SQN}$ to $10 \times Q_{SQN}$ (TVA, 1972). At Sequoyah, for operation of both units, Q_{SQN} is about 2500 cfs. Thus, the natural "demand" of ambient entrainment by the effluent plume is estimated to be in the range of from about 17,000 cfs to 25,000 cfs (i.e., for operation of both units at SQN). For a river discharge Q_R above 25,000 cfs, the entrainment demand is fully satisfied and any river flow in surplus of this demand passes the diffusers unmixed. In this case all of the diffuser effluent is transported downstream and a thermal wedge is virtually nonexistent. A good example of this flow condition is the effluent plume measured in the field study depicted in Figure 9, which was performed for a river discharge of about 35,000 cfs.

For a river discharge between 17,000 cfs to 25,000 cfs, most of the river flow is drawn into the effluent plume, satisfying the natural demand for Q_E. This occurs primarily near the diffusers where effluent velocities are higher. After reaching the surface of the river, the majority of the effluent again will move downstream, but as the ambient water is drawn into the mixing zone, recirculation zones are likely to begin to emerge in the regions between the sides of the mixing zone and the adjacent river shorelines, including the overbanks. These side regions become increasingly "slow-moving" at lower river discharges because the river flow resides primarily in the main channel. The recirculation zones are shown schematically in Figure 45. For this case, a small thermal wedge also is likely to propagate upstream of the boil.

For a river discharge below about 17,000 cfs, the diffuser jets will begin to locally entrain and mix more water than what is coming down the river. In this case, the mixed effluent Q_E+Q_{SQN} is larger than Q_R, and the amount of the mixture in excess of Q_R will spread locally in the river to provide the heat loss to the atmosphere. The local spreading will occur as transport out of the mixing zone by the thermal wedge and by recirculation zones on the side of the mixing zone (which will become stronger at lower river discharges). The recirculation zones will feed the mixed effluent into other regions of the river where it may be transported upstream by other transport processes (e.g., as depicted in Figure 38). The mixed effluent also can become re-entrained into the river flow Q_R, thereby warming the water that provides the source of cooling for the effluent plume (i.e., Q_E). An example of the effluent plume measured in this flow range is the field study depicted in Figure 10, which was performed for a river discharge of about 9,000 cfs. The measurements show a thermal wedge upstream of the diffusers, but there is little evidence of heated effluent in adjacent recirculation zones. This may be because during the measurements the plant was operating in helper mode and reducing the amount of released through the diffusers, in order to maintain the NPDES temperature limits for the mixing zone.

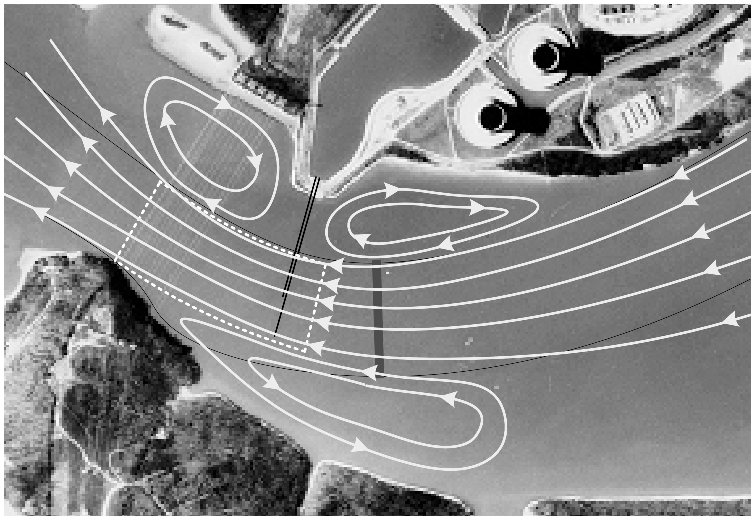


Figure 45. Recirculation Zones Created By Diffuser Mixing

It is emphasized that this discussion has focused on the effect of river flow, and in a somewhat simplistic manner. Stratification can also play a significant role in plume behavior. Here it is only emphasized that in the presence of solar heating, river stratification can exceed 10 F° or 5.6 C° (i.e., difference in temperature between the surface and bottom layers of the river). In the presence of strong stratification, the diffuser effluent can cool to a temperature that is less than that of the temperature of the surface layer of the river. In some cases the plume can reach an elevation of neutral buoyancy and remain submerged below the surface layer of the river. In other situations (depending on river flow) the effluent plume can breach the surface layer of the river, upwelling water in the boil that is cooler than the upstream ambient temperature, resulting in a drop in river temperature at the compliance depth (i.e., producing a negative temperature rise). Such behaviors are common in April and May when the river transitions from cool wintertime conditions to warm summertime conditions.

4.2.2 *Monitoring of Diffuser Mixing Zone*

In general, the flow in the Tennessee River, and particularly in the SQN mixing zone, is unsteady. On an instantaneous basis, turbulence is created as a consequence of the non-linear behavior of fluid motion, particularly for arrangements such as high velocity jets issuing from a diffuser. Furthermore, as a natural waterbody, the hourly mean flow also is unsteady. Peaking operations create variations in the hourly flow; however, even if releases from upstream and downstream dams are provided in a steady manner, hourly flows in the river yet remain somewhat unsteady. The diversity in flow characteristics between the main channel and overbanks, the flow through river bends, reflections off of irregular shorelines, wind, diurnal variations in solar heating, etc. all contribute to this unsteadiness.

These unsteady behaviors create variations in the mean flow and intermittent, turbulent eddy structures that cause the effluent plume in the surface layer of the river to undulate much like a flag in the wind. Given that undulations of the plume on a short-term basis can cross the boundaries of the mixing zone, averaging must be used to provide a meaningful method to monitor the plant effluent plume. If stations could be deployed without posing a threat to navigation, perhaps the ideal method to monitor the mixing zone would be to provide temperature sensors around the entire perimeter of the mixing zone, such as that illustrated in Figure 46. The average of all monitors would then be used to demonstrate that the temperature of the water outside the mixing zone fulfills the NPDES standards. Averaging would be performed on a 24-hour basis for 24-hour average limits and for a hourly basis for hourly average limits.

Figure 46 shows location of the measurements made for the mixing zone study and follows from specifications in the NPDES permit for taking measurements by boat at the downstream end of the mixing zone. If required, boat measurements are to be made at "quarter points and mid-channel". Using temporary stations of the same type as those used in the ambient in temperature study (i.e., see Figure 12), measurements in the mixing zone deployments were made around the entire perimeter of the mixing zone over a period of several days. On the sides of the mixing zone, the stations were situated primarily in the region where the plume from the diffusers is expected breach the water surface. Using GPS devices, HOBO water temperature sensors were positioned at the waypoints shown, again including measurements at depths of 0.5, 3, 5, and 7 feet below the water surface. The measurements required the field staff to tend the stations around-the-clock. To safely avoid collisions with watercrafts, the stations were temporarily moved for large vessels (i.e., tows). Smaller vessels were escorted through the area between the monitors.

In contrast to previous mixing zone tests, the deployment in Figure 46 allows the concurrent measurement of temperatures around the entire perimeter of the mixing zone. Furthermore, by providing a deployment for one or more days, it also allows the mixing zone to be analyzed based on both hourly averaging and 24-hour averaging. With this deployment, the integrity of the mixing zone was judged by comparing the average temperature around the perimeter of the mixing zone with the NPDES temperature requirements. The mixing zone study also included measurements with a precision RTD sensors to define the general location of the effluent plume at the 5-foot depth, much like the results depicted in Figure 8 through Figure 11. Please recall that in contrast to the HOBO deployments, results from the RTD array provide only a blurred image of the thermal discharge over a time-scale of duration equivalent to that required to troll the RTD array back and forth through the study area. That is, measurements with the RTD sensors do not provide hourly or 24-hour averages of the effluent plume.

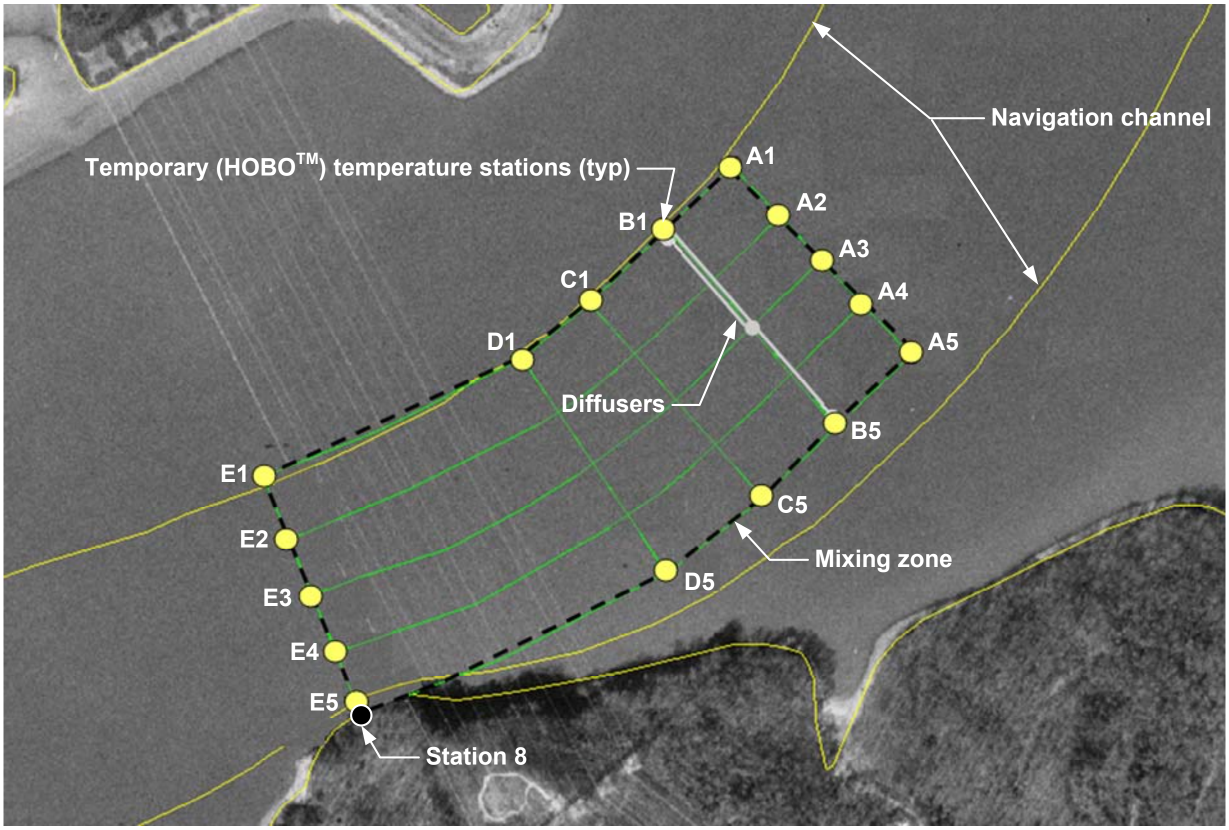


Figure 46. Location of Stations for Mixing Zone Temperature Measurements

4.2.3 *Summer Deployment August 11 through August 24, 2004*

Results from the deployment of August 11 through August 24, 2004 are shown in Figure 47, Figure 48, Figure 49, and Figure 50. Figure 47 and Figure 48 provide results from the HOBO™ temperature stations positioned around the perimeter of the mixing zone and Figure 49 and Figure 50 provide results from measurements with the RTD sensors.

For Figure 47 and Figure 48 three plots are provided—hourly average mixing zone temperatures (top), 24-hour average mixing zone temperatures (middle), and computed hourly average and 24-hour average river flow at SQN (bottom). In Figure 47, the mixing zone temperatures are provided for each face of the mixing zone as well as the entire perimeter (i.e., all four faces). The individual faces include the left side and right side, and the upstream and downstream sides (facing downstream). Values for the faces were obtained by averaging the temperature measurements for the HOBO™ stations along each face—A5-B5-C5-D5-E5 for the left side, A1-B1-C1-D1-E1 for the right side, A1-A2-A3-A4-A5 for the upstream, and E1-E2-E3-E4-E5 for the downstream side (see Figure 46). Again, the results are for the temperatures at the compliance depth, obtained by averaging the readings for the sensors at the 3-foot, 5-foot, and 7-foot depths. In Figure 48 the measured mixing zone temperatures are provided only for the downstream face and all four faces. However, to examine compliance with NPDES requirements for temperature rise, the measured ambient temperature and measured ambient temperature plus an additional 5.4 F° (3.0 C°) are also provided (i.e., hourly in top plot and 24-hour average in middle plot). Recall that the discovery of effluent reaching the Station 13 monitor, and subsequently the deployment of Station 14 (i.e., new ambient temperature monitor) did not occur until March 2006. Thus, at the time of the summer deployment of August 11 through August 24, 2004, the ambient temperature for the mixing zone was yet measured at Station 13.

For the summer deployment, peaking operations were performed each day except August 22 and August 23. During the peaking operations, the hourly average river flow ranged between daily maximum values of 35,000 cfs and 50,000 cfs in the downstream direction, with short-term reverse flow events as high as 15,000 cfs in the upstream direction. The 24-hour average river flow ranged between about 10,000 cfs and 40,000 cfs (in the downstream direction). Periods of steady flow were established on August 22 and August 23 for measurements with the RTD sensors. On August 22, the average river flow for the RTD measurements was about 13,000 cfs (low flow), and for the measurements on August 23 the average river flow for the RTD measurements was about 39,000 cfs (high flow). The average ambient river temperature during the summer deployment was about 79.2°F or 26.2°C (Station 13). The average ambient river stratification, measured as the difference between the water temperature at the 5-foot depth and the water temperature near the bottom of river at Station 13, was only about 0.6 F° (0.3 C°). During the deployment, SQN was operating in open mode with both units, discharging about 2470 cfs through both diffusers at a temperature of about 26.4 F° (14.7 C°) above the ambient temperature. The following features are noted for each figure.

<u>Figure 47</u>

- Hourly average mixing zone temperatures are higher during low and reverse hourly river flow and lower during high river flow, as expected (top plot). This is because low river flow provides low dilution of the plant thermal effluent and high river flow provides high dilution of the plant thermal effluent.

- In general, the hourly average temperatures for the left, right, and downstream faces of the mixing zone track within about 1 F° (0.56 C°) of each other (top plot). For high river flow (e.g., above about 25,000 cfs), the hourly average temperature for the upstream face usually drops about 2 F° (1.1 C°) lower that of the other faces. This is because at high river flow all of the plant effluent is transported downstream, with near ambient conditions prevailing at the upstream face of the mixing zone—there is no upstream migration of a thermal wedge. At low river flow, however, the thermal effluent also is assimilated upstream, yielding hourly average temperature for the upstream face of the mixing zone that are comparable to that of the other faces.

- It appears that a tendency exists for the diffuser plume to shift towards the left side of the mixing zone for low river flow and towards the right side of the mixing zone for high river flow, at least for the prevailing conditions of the summer deployment. A good example of this behavior occurred on August 22 and August 23 (top plot). On August 22, with a river flow of about 13,000 cfs (i.e., low), the temperature on the left face of the mixing zone is slightly higher than that of the right face. On August 23, with a river flow of about 39,000 cfs (i.e., high), the temperature on the right face of the mixing zone is slightly higher than that of the left face. This behavior is likely due to the hydraulic aspects of the river bend and the alignment of the shoreline on the left-hand-side of the river (facing downstream). For flow around a bend, secondary currents in the surface layer of the river create a cross flow from the inside to the outside of the bend (i.e., towards the left side of the mixing zone). At low river flow, this cross flow may create the observed shift of the diffuser plume towards the left side of the mixing zone. At high river flow this cross flow also occurs, however the left shoreline of the river protrudes outward into the river, creating a contraction at the downstream end of the mixing zone (e.g., see Figure 3). At high river flow, the momentum of the water moving along the shoreline and through this contraction may dominate over the cross flow and "kick" the diffuser plume towards the right side of the mixing zone.

- On a 24-hour average basis (middle plot), mixing zone temperatures behave in a fashion somewhat similar to that for the hourly average temperatures. That is, the 24-hour average temperatures for the left, right, and downstream faces of the mixing zone track close to one another, whereas the temperature for the upstream face tracks lower, except for cases when the 24-hour average river flow is low. Shifting of the diffuser plume for high and low river flow also is observable. Examples of low river flow include events on August 16 and August 22 when the 24-hour average river flow dropped to about 10,000 cfs. In these events the 24-hour average temperature on the left face of the mixing zone is slightly higher than that on the right face (and vice versa for high river flows).

- The thermal effluent along the perimeter of the mixing zone is below the NPDES thermal limit of $\mathbf{T_d}$=86.9ºF (30.5ºC) on both an hourly average basis and a 24-hour average basis. This is true for the individual faces as well as all faces.

- If it were possible to monitor the entire perimeter of the mixing zone with instream temperature stations, the line entitled all faces would represent the compliance temperature. The computer model used to monitor SQN thermal compliance is calibrated based on measurements at the downstream end of the mixing zone. In general, for both hourly average temperatures and 24-hour average temperatures, the temperature for the downstream face of the mixing zone is very near or higher than the temperature for all faces (top and middle plots). Thus, in this manner, monitoring of thermal compliance based on matching measurements for the downstream end of the mixing zone provides a reliable and perhaps slightly conservative method for monitoring SQN thermal compliance.

<u>Figure 48</u>

- Although touching the upper limit in several short, peak events, the hourly average mixing zone temperature for all faces, as well as that for the downstream face, fall within the band represented by the measured hourly average ambient temperature and the measured hourly average ambient temperature plus 5.4 F° or 3.0 C° (top plot). Thus, the mixing zone is adequate for the average hourly temperature in regards to the NPDES thermal limit of $\mathbf{\Delta T}$=5.4 Fº (3.0 Cº) in the summer.

- The 24-hour average mixing zone temperature for all faces, as well as that for the downstream face, fall well within the band represented by the measured 24-hour average ambient temperature and the measured 24-hour average ambient temperature plus 5.4 F° or 3.0 C° (middle plot). Thus, the mixing zone is adequate for the 24-hour average temperature in regards to the NPDES thermal limit of **ΔT**=5.4 Fº (3.0 Cº) in the summer.

Figure 49

Figure 49 includes RTD mapping of the plant thermal discharge at the 5-foot compliance depth for low river flow, about 13,000 cfs. In addition to temperature contours, the boat/measurement tracks are also shown.

- The plume from each diffuser breaches the 5-foot depth in the immediate vicinity of the diffusers.

- After breaching the surface, the thermal effluent is assimilated in all directions—left, right, upstream, and downstream.

- The plume for the diffuser on the right-hand-side of the mixing zone appears to be spread over a larger area than the diffuser on the left-hand-side of the mixing zone.

- The temperatures observed at the 5-foot depth are all below about 85.5°F (29.7°C). That is, for the prevailing plant and river conditions, the thermal effluent from the plant was safely diluted within the mixing zone to a temperature below the NPDES thermal limit of $\mathbf{T_d}$=86.9°F (30.5°C).

Figure 50

Figure 50 includes RTD mapping of the plant thermal discharge at the 5-foot compliance depth for high river flow, about 39,000 cfs. In addition to temperature contours, the boat/measurement tracks are also shown.

- The plume from each diffuser breaches the 5-foot depth a short distance downstream of the diffusers.

- After breaching the surface, the thermal effluent is assimilated primarily in the downstream direction. There is a sharp gradient between the upstream ambient temperature and the plume temperature with only a slight thermal wedge propagating upstream in the surface layer of the flow, at least for the diffuser on the right-hand-side of the mixing zone.

- The temperatures observed at the 5-foot depth are all below about 84.0°F (28.9°C). That is, for the prevailing plant and river conditions, the thermal effluent from the plant was safely diluted within the mixing zone to a temperature below the NPDES thermal limit of $\mathbf{T_d}$=86.9°F (30.5°C).

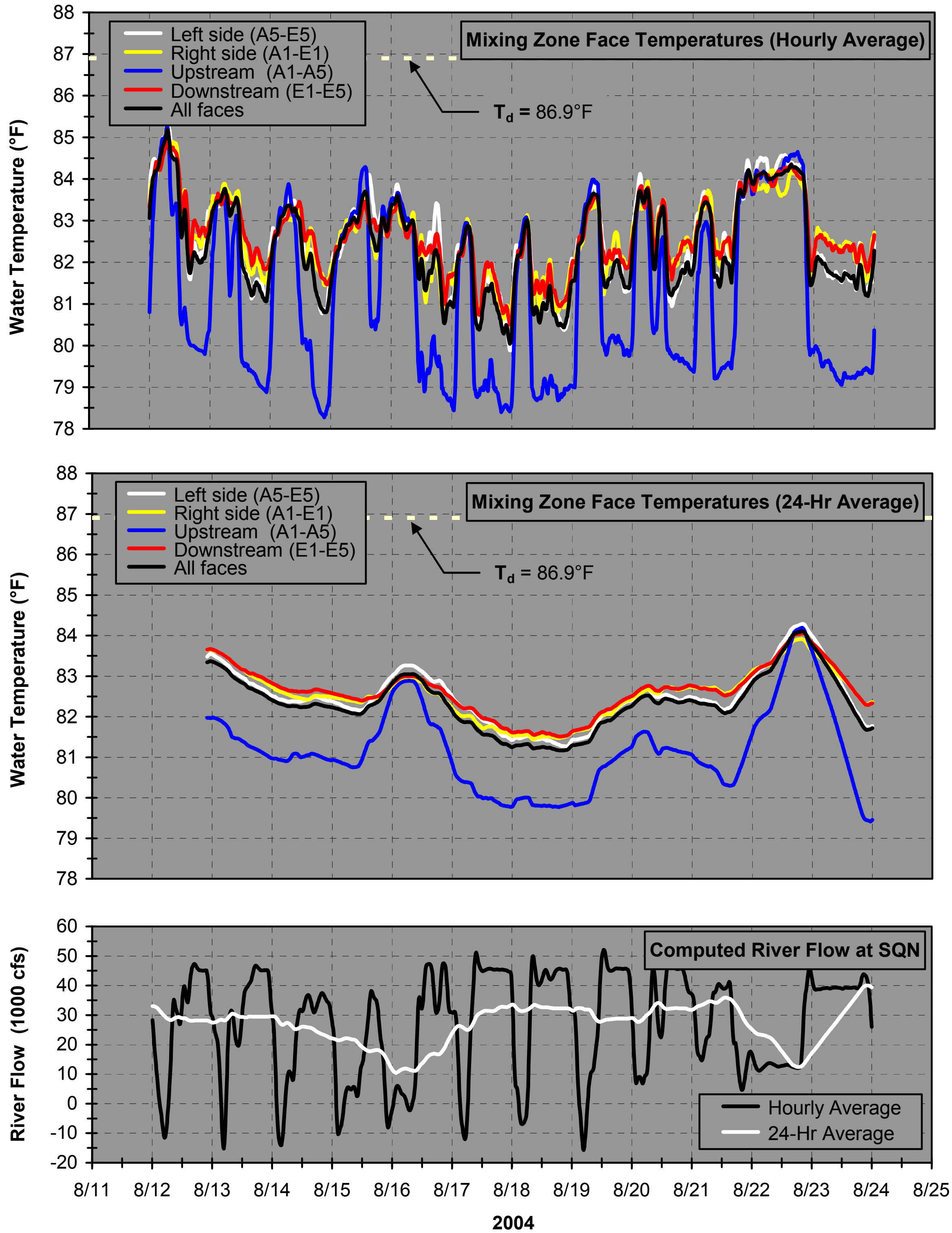


Figure 47. Mixing Zone Temperatures For Summer Deployment

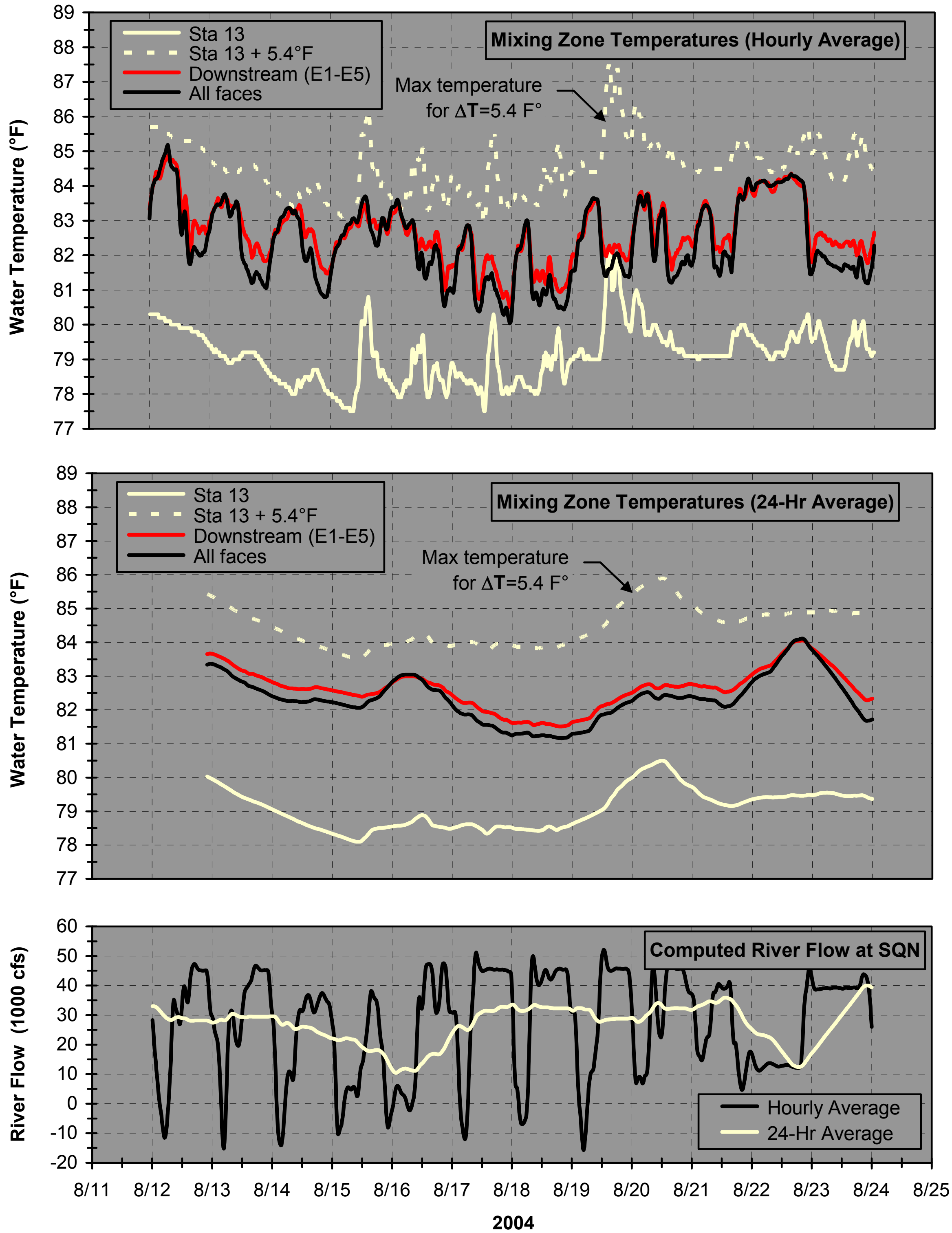


Figure 48. Mixing Zone Temperatures For Summer Deployment Showing Temperature Rise

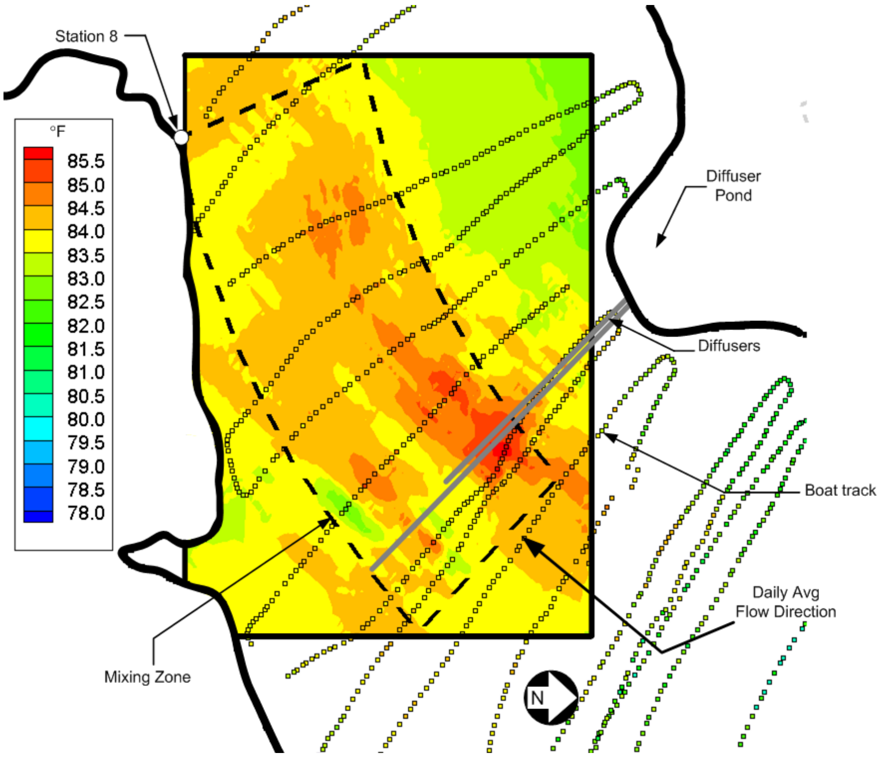


Figure 49. Water Temperature Measurements at 5-foot depth for August 22, 2004

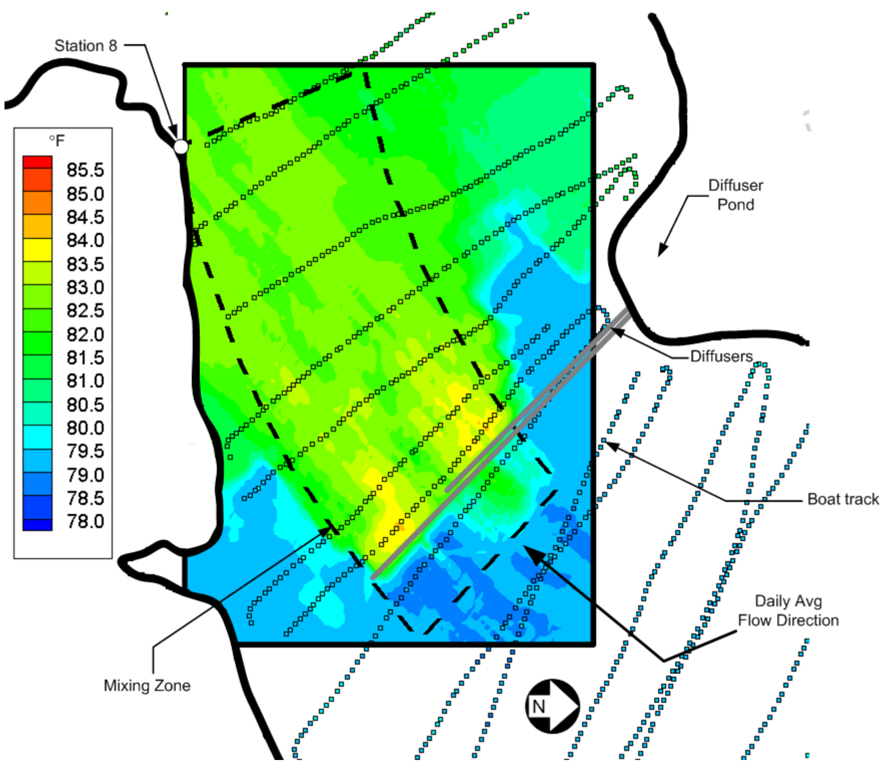


Figure 50. Water Temperature Measurements at 5-foot depth for August 23, 2004

4.2.4 *Winter Deployment February 12 through February 23, 2004*

Results from the deployment of February 12 through February 23, 2004 are shown in Figure 51, Figure 52, Figure 53, and Figure 54. Figure 51 and Figure 52 provide results from the HOBO™ temperature stations positioned around the perimeter of the mixing zone and Figure 53 and Figure 54 provide results from measurements with the RTD sensors.

As before, three plots are provided in Figure 51 and Figure 52—hourly average mixing zone temperatures (top), 24-hour average mixing zone temperatures (middle), and computed hourly average and 24-hour average river flow at SQN (bottom). There was considerable disruption of the HOBO™ stations by tows during the early part of the winter deployment, requiring the stations to be removed from the navigation channel. The only period within the winter deployment wherein all the stations were positioned around the entire perimeter of the mixing zone was between February 19 and February 23. Mixing zone temperatures are again provided for each face of the mixing zone as well as the entire perimeter (i.e., all four faces) and represent average readings from the sensors at the 3-foot, 5-foot, and 7-foot depths. In Figure 52 the measured mixing zone temperatures are provided only for the downstream face and all four faces. To examine compliance with NPDES requirements for temperature rise, the measured ambient temperature and measured ambient temperature plus an additional 9.0 F° (5.0 C°) are also provided (i.e., recall that the NPDES limit for **ΔT** is 9.0 F° (5.0 C°) for the months of November through March). Yet again, the discovery of effluent reaching the Station 13 monitor, and subsequently the deployment of Station 14 (i.e., new ambient temperature monitor) did not occur until March 2006. Thus, at the time of the winter deployment of February 12 through February 23, 2004, the ambient temperature for the mixing zone was still measured at Station 13.

For the winter deployment, there was an excess amount of water in the river system and power demand was consistently high (due to cold meteorology), so peaking operations could be performed only for one day—February 21. During the peaking operations, the hourly average river flow ranged between a maximum of about 45,000 cfs in the downstream direction and 20,000 cfs in the upstream direction. The 24-hour average river flow between February 19 and February 23 ranged from about 20,000 cfs and about 45,000 cfs (in the downstream direction). Periods of steady flow were established on February 22 and February 23 for measurements with the RTD sensors. On February 22, the average river flow for the RTD measurements was about 18,000 cfs (medium flow), and for the measurements on February 23 the average river flow for the RTD measurements was about 44,000 cfs (high flow). The average ambient river temperature during the winter deployment was about 45.0°F or 4.4°C (Station 13). There was virtually no river stratification. During the deployment, SQN was operating in open mode with both units, discharging about 2420 cfs through both diffusers at a temperature of about 27.4 F° (15.2 C°) above the ambient temperature. The following features are noted for each figure.

Figure 51

- As before, the hourly and 24-hour average mixing zone temperatures are higher for low river flow and lower for high river flow (top and middle plots). A good example of this dynamic is the drop in temperatures from February 22 (18,000 cfs river flow) to February 23 (45,000 cfs river flow).

- In general, compared to the summer deployment, there are greater differences for the winter deployment among the hourly average temperatures, and subsequently the 24-hour average temperatures (top and middle plots). The right and downstream faces of the mixing zone track rather close to one another but the left face is consistently lower, between 1 F° to 2 F° (0.6 C° to 1.1 C°) lower. The upstream face is even lower, between 2 F° to 4 F° (1.1 C° to 2.2 C°) lower. Again, however, for low river flow, the thermal effluent is assimilated in all directions, yielding hourly average temperatures for the upstream and left faces of the mixing zone that are comparable to that of the downstream and right faces (top plot). The sole example of a low flow situation for the winter deployment is the peaking operation that occurred early in the morning on February 21. The greater differences in temperatures may be due to reduced mixing by buoyancy, which occurs at lower ambient river temperature.

- The tendency for the diffuser plume to shift towards the left side of the mixing zone for low river flow and towards the right side of the mixing zone for high river flow prevailed during the winter deployment. The hourly average temperature on the right face of the mixing zone was consistently higher than that of the left side in all but the low flow peaking event of February 21 (top plot).

- The thermal effluent along the perimeter of the mixing zone is well below the NPDES thermal limit of $\mathbf{T_d}$=86.9ºF (30.5ºC) on both an hourly average basis and a 24-hour average basis. This is true for the individual faces as well as all faces.

- In general, for both hourly average temperatures and 24-hour average temperatures, the temperature for the downstream face of the mixing zone is consistently higher than the temperature for all faces (top and middle plots). Thus, monitoring of thermal compliance based on matching measurements for the downstream end of the mixing zone again provides a reliable, conservative method for monitoring SQN thermal compliance.

<u>Figure 52</u>

- The hourly average mixing zone temperature for all faces, as well as that for the downstream face, fall well within the band represented by the measured hourly average ambient temperature and the measured hourly average ambient temperature plus 9.0 F° (5.0 C°) (top plot). Thus, the mixing zone is adequate for the average hourly temperature in regards to the NPDES thermal limit of $\mathbf{\Delta T}$=9.0 Fº (5.0 Cº) in the winter.

- The 24-hour average mixing zone temperature for all faces, as well as that for the downstream face, fall well within the band represented by the measured 24-hour average ambient temperature and the measured 24-hour average ambient temperature plus 9.0 F° or 5.0 C° (middle plot). Thus, the mixing zone is adequate for the 24-hour average temperature in regards to the NPDES thermal limit of $\mathbf{\Delta T}$=9.0 Fº (5.0 Cº) in the winter.

Figure 53

Figure 53 includes RTD mapping of the plant thermal discharge at the 5-foot compliance depth for a medium river flow, about 18,000 cfs. The mapping was performed in terms of temperature rise, which is of primary concern for the winter. In addition to temperature contours, the boat/measurement tracks are also shown.

- The plume from each diffuser breaches the 5-foot depth a short distance downstream of the diffusers.

- After breaching the surface, the thermal effluent is assimilated primarily in the downstream direction. There is a sharp gradient between the upstream ambient temperature and the plume temperature with only a slight thermal wedge propagating upstream in the surface layer of the flow, at least for the diffuser on the right-hand-side of the mixing zone.

- The plume for the diffuser on the right-hand-side of the mixing zone appears to be spread over a larger area than the diffuser on the left-hand-side of the mixing zone.

- The temperature rise observed at the 5-foot depth is all below about 7.0 F° (3.9 C°). That is, for the prevailing plant and river conditions, the thermal effluent from the plant was safely diluted within the mixing zone to a temperature below the NPDES thermal limit of **ΔT**=9.0 F° (5.0 C°) for the winter.

Figure 54

Figure 54 includes RTD mapping of the plant thermal discharge at the 5-foot compliance depth for low river flow, about 44,000 cfs. Again, the mapping was performed in terms of temperature rise, which is of primary concern for the winter. In addition to temperature contours, the boat/measurement tracks are also shown.

- The plume from each diffuser breaches the 5-foot depth a short distance downstream of the diffusers.

- After breaching the surface, the thermal effluent is assimilated in the downstream direction. There is a sharp gradient between the upstream ambient temperature and the plume temperature in the mixing zone with no upstream propagation of a thermal wedge.

- The temperature rise observed at the 5-foot depth is all below about 5.0 F° (2.8 C°). That is, for the prevailing plant and river conditions, the thermal effluent from the plant was safely diluted within the mixing zone to a temperature below the NPDES thermal limit of **ΔT**=9.0 F° (5.0 C°) for winter.

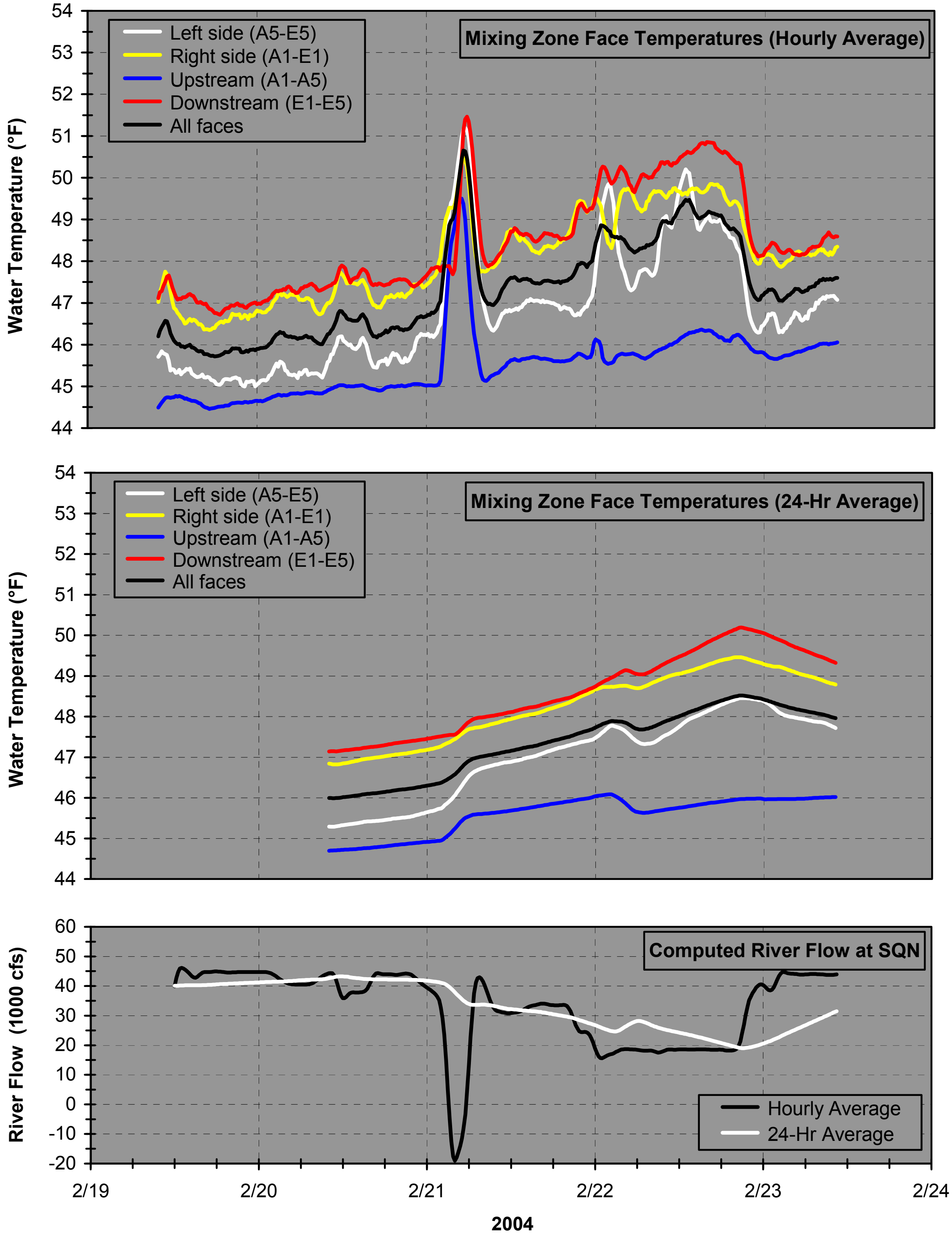


Figure 51. Mixing Zone Temperatures For Winter Deployment

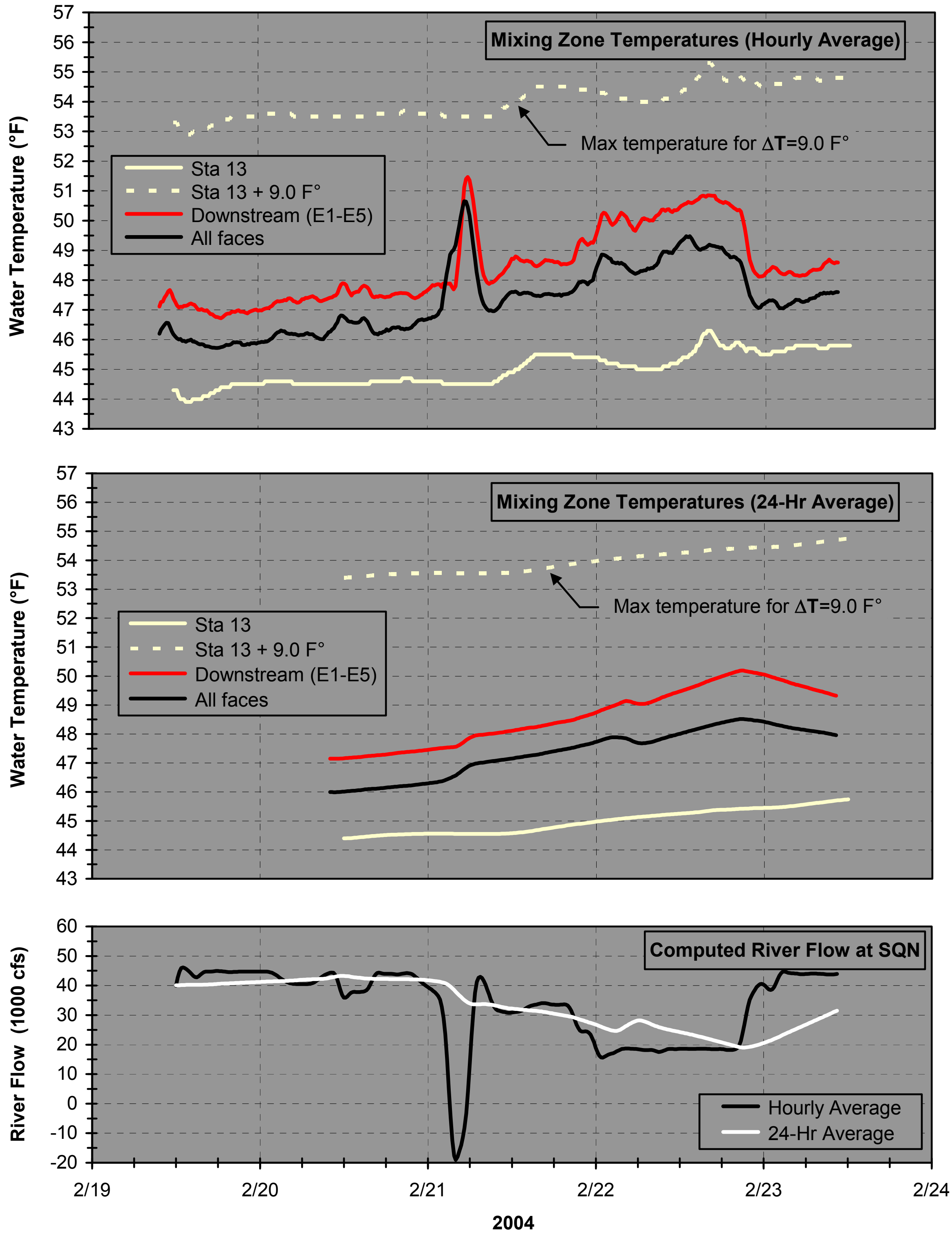


Figure 52. Mixing Zone Temperatures For Winter Deployment Showing Temperature Rise

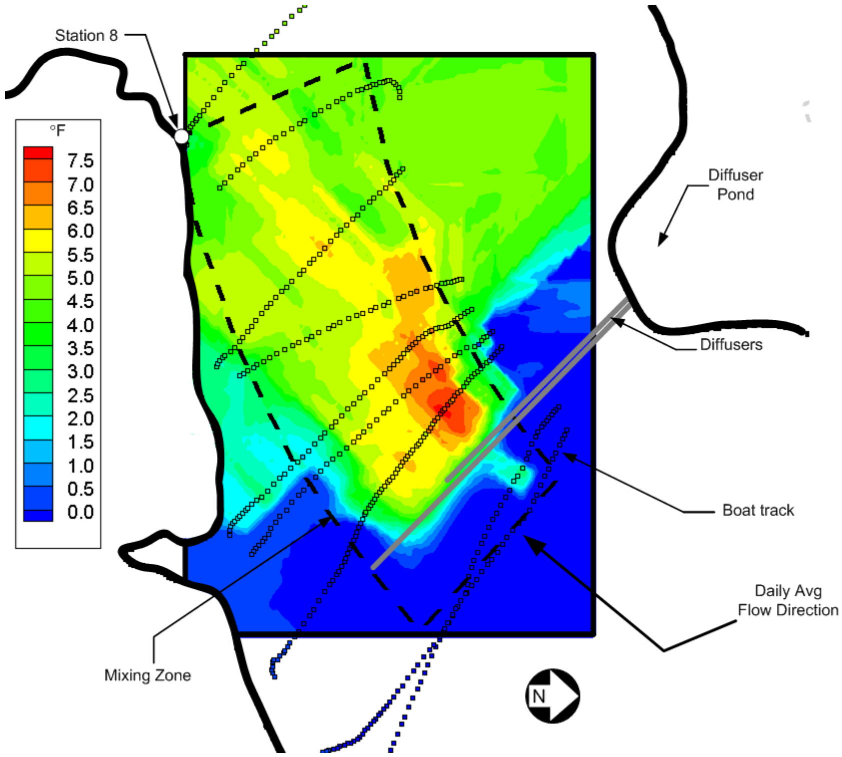


Figure 53. Temperature Rise Measurements at 5-foot depth for February 22, 2004

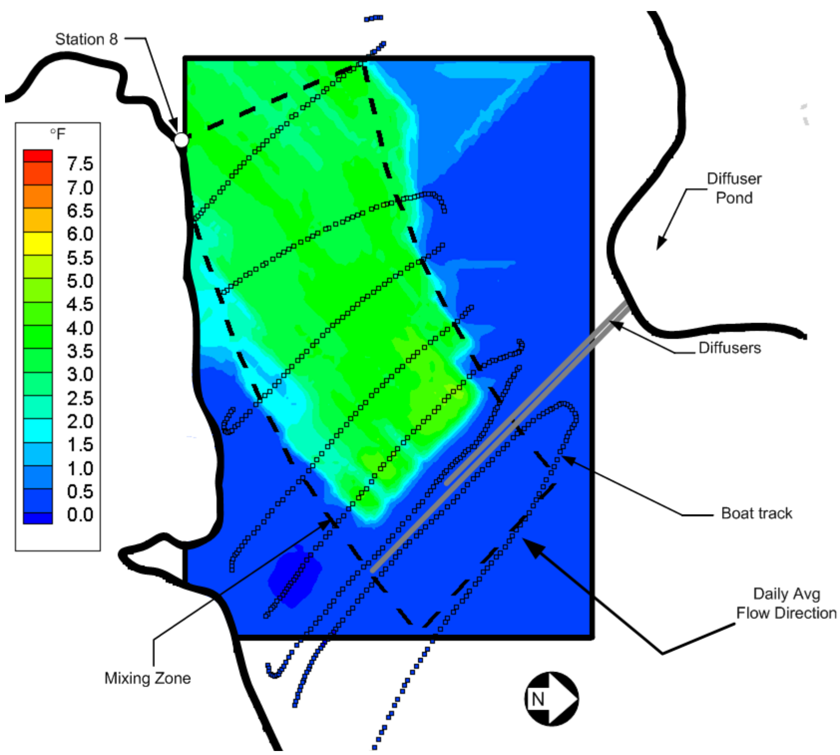


Figure 54. Temperature Rise Measurements at 5-foot depth for February 23, 2004

4.2.5 *Third Deployment September 19 through September 22, 2007*

The deployment of September 19 through September 22, 2007 was performed to capture mixing zone conditions during the drought of 2007. The results are shown in Figure 55 and Figure 56. Both these figures show measurements from the HOBO™ temperature stations positioned around the perimeter of the mixing zone. Figure 57 provide results from measurements with the RTD sensors on September 21 of the deployment.

Yet again, three plots are provided for Figure 55 and Figure 56—hourly average mixing zone temperatures (top), 24-hour average mixing zone temperatures (middle), and computed hourly average and 24-hour average river flow at SQN (bottom). The temperatures are as previously defined and again apply at the compliance depth, obtained by averaging the readings for the sensors at the 3-foot, 5-foot, and 7-foot depths. In Figure 56, to examine compliance with NPDES requirements for temperature rise, the measured ambient temperature and measured ambient temperature plus an additional 5.4 F° (3.0 C°) are provided (i.e., hourly in top plot and 24-hour average in middle plot). In contrast to the summer and winter deployments presented above, the ambient temperature for the mixing zone in 2007 was measured at Station 14, not Station 13.

For this deployment, and because of the drought, the river flow was maintained as steady as possible, in this case at about 9000 cfs. The average ambient river temperature during the deployment was about 79.1°F or 26.2°C (Station 14). The average ambient river stratification, measured as the difference between the water temperature at the 5-foot depth and the water temperature at a depth of 30 feet at Station 14, was about 1.0 F° (0.6 C°). During the deployment, SQN was operating in helper mode with both units, discharging about 2510 cfs through both diffusers at a temperature of about 15.7 F° (8.7 C°) above the ambient temperature. The following features are noted for each figure.

<u>Figure 55</u>

- With steady river flow, changes in the hourly average mixing zone temperatures are due primarily to diurnal variations in solar heating (top plot). During the deployment period, the river was slowly cooling, producing lower temperatures for the mixing zone from one day to the next. Consequently, the 24-hour average mixing zone temperatures also exhibited a downward trend (middle plot).

- In general, the hourly average temperatures for all faces of the mixing zone track within about 1 F° (0.6 C°) of each other (top and middle plots). This is consistent with observations at low river flow for the summer and winter deployments presented above.

- The tendency for the diffuser plume to shift towards the left side of the mixing zone for low river flow again prevails for this deployment. That is, the temperature on the left face of the mixing zone is higher than that of the right face (top and middle plots).

- The thermal effluent along the perimeter of the mixing zone is below the NPDES limit of $\mathbf{T_d}$=86.9ºF (30.5ºC) on both an hourly average basis and a 24-hour average basis. This is true for the individual faces as well as all faces combined.

- In general, for both hourly average temperatures and 24-hour average temperatures, the temperature for the downstream face of the mixing zone is consistently higher than the temperature for all faces (top and middle plots). Thus, this deployment again suggests that monitoring of thermal compliance based on matching measurements for the downstream end of the mixing zone provides a reliable, conservative method for monitoring SQN thermal compliance.

<u>Figure 56</u>

- The hourly average mixing zone temperature for all faces, as well as that for the downstream face, fall well within the band represented by the measured hourly average ambient temperature and the measured hourly average ambient temperature plus 5.4 F° or 3.0 C° (top plot). Thus, as found previously for summer conditions, the mixing zone is adequate for the average hourly temperature in regards to the NPDES thermal limit of **ΔT**=5.4 Fº (3.0 Cº).

- The 24-hour average mixing zone temperature for all faces, as well as that for the downstream face, fall well within the band represented by the measured 24-hour average ambient temperature and the measured 24-hour average ambient temperature plus 5.4 F° or 3.0 C° (middle plot). Thus, as found previously for summer conditions, the mixing zone is adequate for the 24-hour average temperature in regards to the NPDES thermal limit of **ΔT**=5.4 Fº (3.0 Cº).

<u>Figure 57</u>

Figure 57 includes RTD mapping of the plant thermal discharge at the 5-foot compliance depth for the prevailing river flow, about 9,000 cfs. Temperature contours and the boat tracks are shown.

- The plume from the diffuser on the left-hand-side of the mixing zone breaches the 5-foot depth immediately downstream of the diffuser, whereas the plume from the diffuser on the right-hand-side of the mixing zone breaches the 5-foot depth about at the same location as the diffuser.

- The plume on the left-hand-side of the mixing zone is warmer and more discernable than that on the right-hand-side of the mixing zone. In part, this may be due to the fact that sampling in the vicinity of the mixing zone is sparse where the plume from the right-hand diffuser would have breached the water surface.

- After breaching the surface, the thermal effluent from the diffuser is assimilated in all directions—left, right, upstream, and downstream. However, as observed in other deployments, the effluent in the mixing zone appears to shift towards the left-hand-side of the mixing zone (i.e., for low river flow, such 9000 cfs of this deployment).

- The temperatures observed at the 5-foot depth are all below about 84.0°F. That is, for the prevailing plant and river conditions, the thermal effluent from the plant was safely diluted within the mixing zone to a temperature below the NPDES thermal limit of $\mathbf{T_d}$=86.9°F (30.5°C).

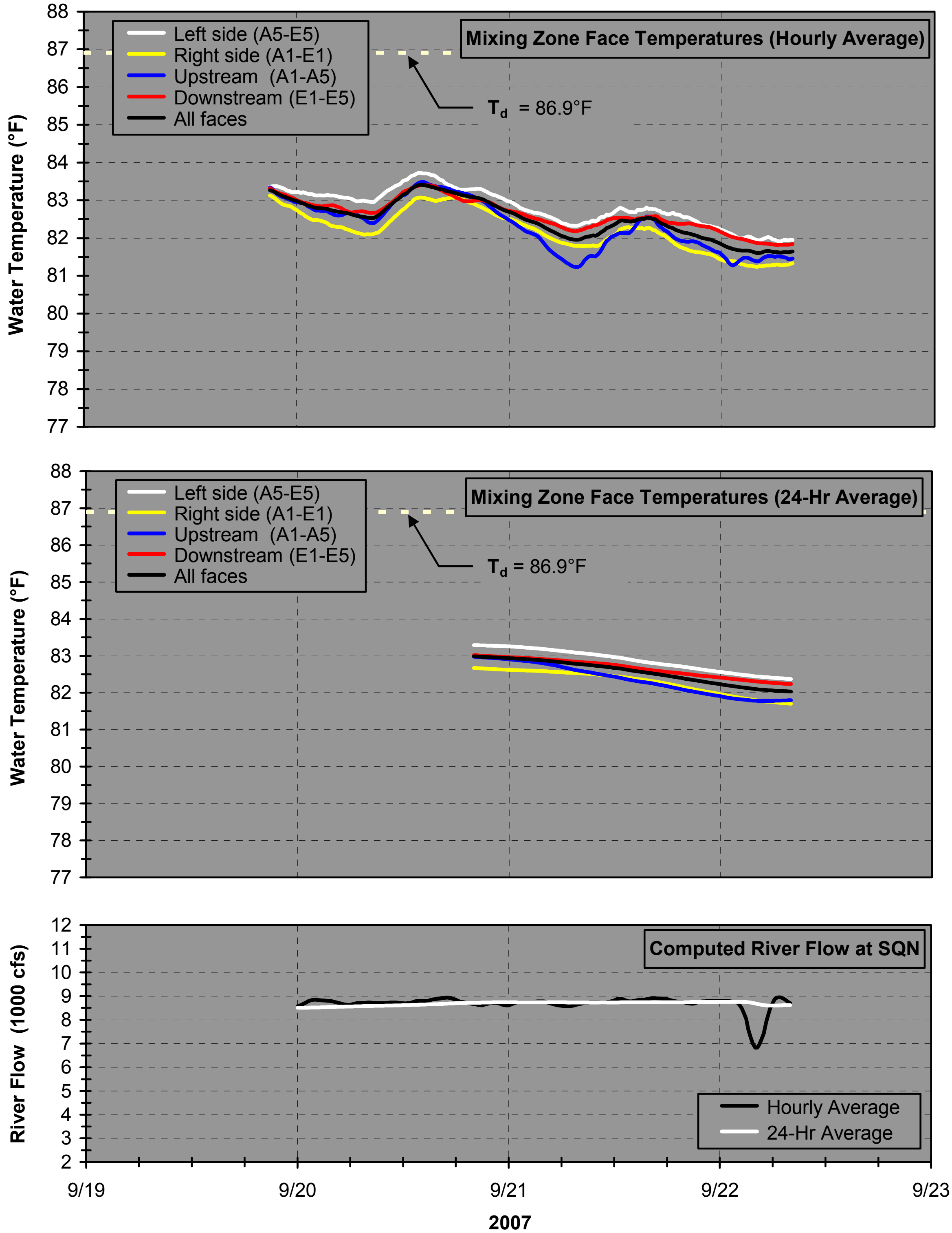


Figure 55. Mixing Zone Temperatures For Third Deployment

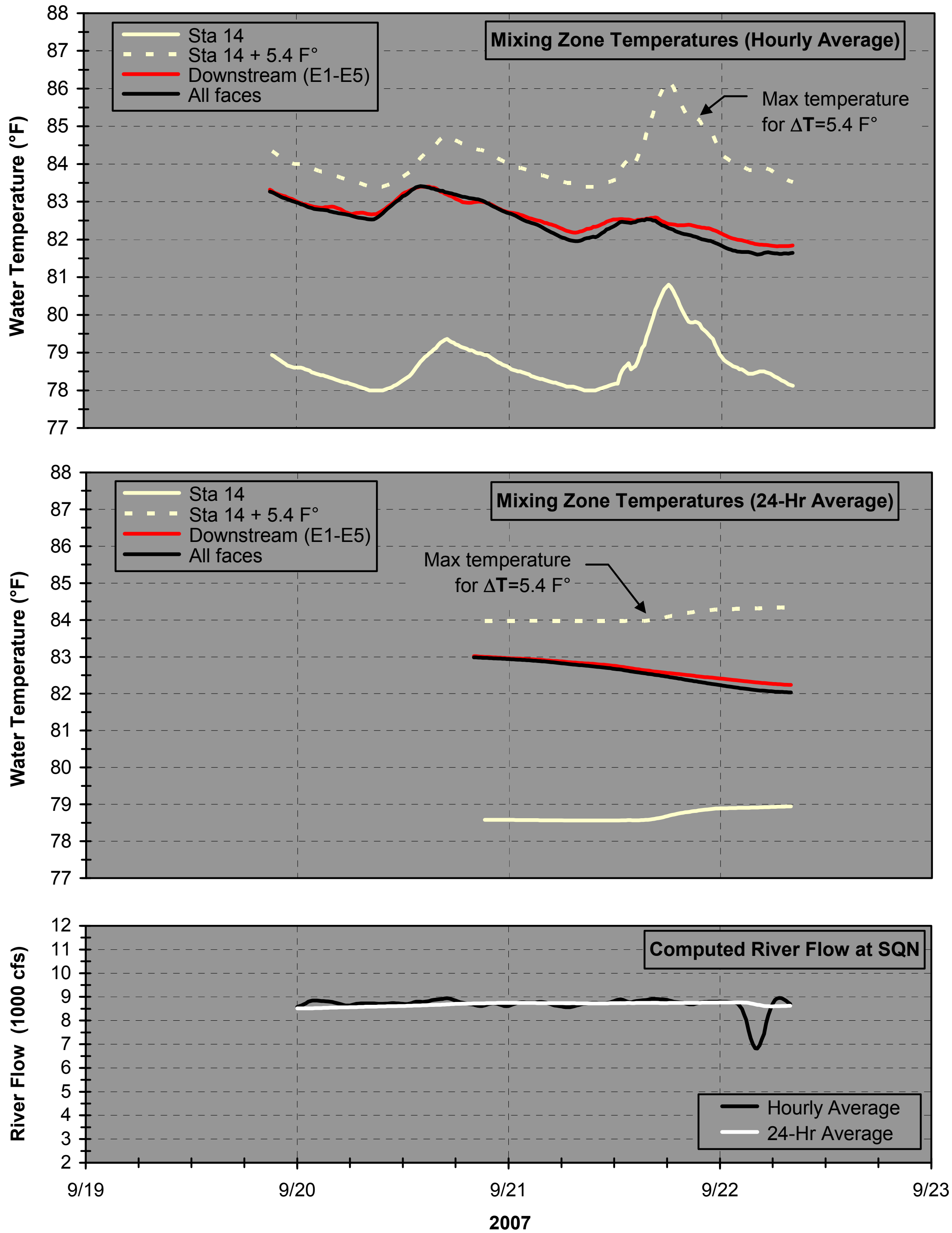


Figure 56. Mixing Zone Temperatures For Third Deployment Showing Temperature Rise

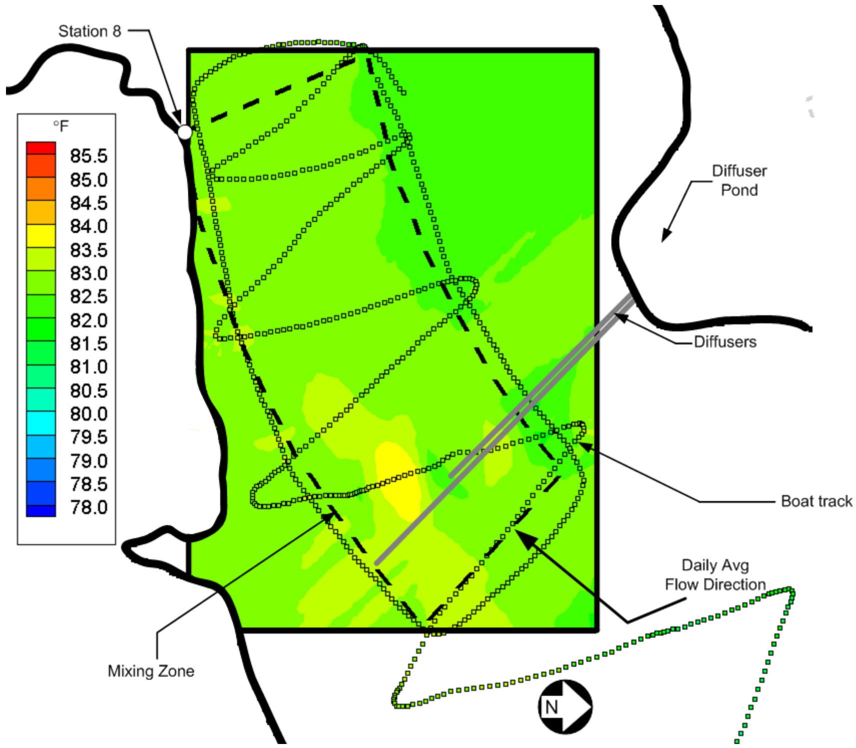


Figure 57. Water Temperature Measurements at 5-foot depth for September 21, 2008

4.2.6 *Other Mixing Zone Studies*

Part III, Section G of the NPDES permit requires SQN once per permit cycle to confirm the calibration of the compliance model for downstream river temperature. As part of this process, temperature measurements of the mixing zone are made concurrently with the measurement of the flow through the discharge diffusers. The field study to conduct these measurements was performed on November 4, 2007. Based on the findings of the deployments presented above (i.e., the temperature at the downstream face of the mixing zone yields an adequate measure of the temperature around all faces), and to be consistent with procedures outlined in the NPDES permit (for sampling by boat), instream measurements for temperature were made only at the downstream end of the mixing zone. That is, temporary HOBO™ temperature stations were deployed only at locations E1, E2, E3, E4, and E5 in Figure 46. Detailed measurements to map the three-dimensional extent of the thermal plume were not conducted as part of the study; however, one set of RTD measurements was collected around the perimeter of the mixing zone.

One of the primary reasons for choosing November 4, 2007 for this study was because of the extremely low river flow. Chickamauga Reservoir was operating in a near steady manner with a flow of only about 6000 cfs past SQN. The average ambient river temperature during the study was about 65.1°F or 18.4°C (Station 14). The average river stratification was small, only about 0.4 F° (0.2 C°). During the deployment, SQN was operating in open mode with one unit in service. The discharge through the diffusers, determined by velocity measurements in plant diffuser pond, was about 1290 cfs (total through both diffusers). The temperature of the diffuser discharge was about 25.3 F° (14.1 C°) above the ambient temperature.

Results of the November 4, 2007 measurements are shown in Figure 58 and Figure 59. Figure 58 gives the results from the HOBO™ temperature stations and Figure 59 gives results from the RTD measurements. Figure 58 provides average readings from sensors positioned at the 3-foot, 5-foot, and 7-foot depths. Included are the measured hourly average temperature at the downstream end of the mixing zone (top plot) and the computed hourly average river flow at SQN (bottom plot). To examine compliance with NPDES requirements for temperature rise, the measured ambient temperature and measured ambient temperature plus an additional 9.0 F° (5.0 C°) are also given (i.e., recall that the NPDES limit for **ΔT** is a 24-hour average of 9.0 F° (5.0 C°) for the months of November through March). The ambient temperature was from Station 14. The deployment for the November 4, 2007 study was only for a period of about 8 hours, thus 24-hour average information cannot be determined. Conditions, however, were very steady during the study, so the hourly results likely provide a good estimate of the 24-hour average behavior. The following features are noted for each figure.

<u>Figure 58</u>

- The hourly average temperature for the downstream face of the mixing zone, as well as the hourly average ambient temperature, were relatively steady, varying less than 0.5 F° (0.28 C°) during the entire 8 hour deployment.

- The hourly average temperature for the downstream face of the mixing zone varied between 69.2ºF and 69.5ºF (20.7°C and 20.8°C) and fell well within the band represented by the measured hourly average ambient temperature and the measured hourly average ambient temperature plus 9.0 F° or 5.0 C° (top plot). Thus, for the prevailing conditions, the mixing zone is adequate for the average hourly temperature in regards to the NPDES thermal limit of **ΔT**=9.0 Fº (5.0 Cº) in the winter.

<u>Figure 59</u>

The RTD results in Figure 59 are for water temperature measurements at the 5-foot compliance depth. The data are presented in terms of temperature rise, which is of primary concern for the winter. In the figure, the boat track is color-coded corresponding to the observed temperature rise at each measurement location. As shown, there was very little variability along the track—the temperature rise was consistently between 3.5 F° and 4.0 F° (1.9 C° and 2.2 C°) with an average of 3.6 F°. This is slightly lower than the average temperature rise determined from the temporary HOBO™ stations, which was about 4.3 F° (2.4 C°). In part, this may be because the boat track extended beyond the boundary of the mixing zone along the upstream and left faces (i.e., the water may have been cooler away from the true mixing zone boundary). Alternatively, previous deployments have shown that the average temperature along the downstream face of the mixing zone (and subsequently the temperature rise), may be higher than the average temperature around the entire perimeter (all faces) of the mixing zone.

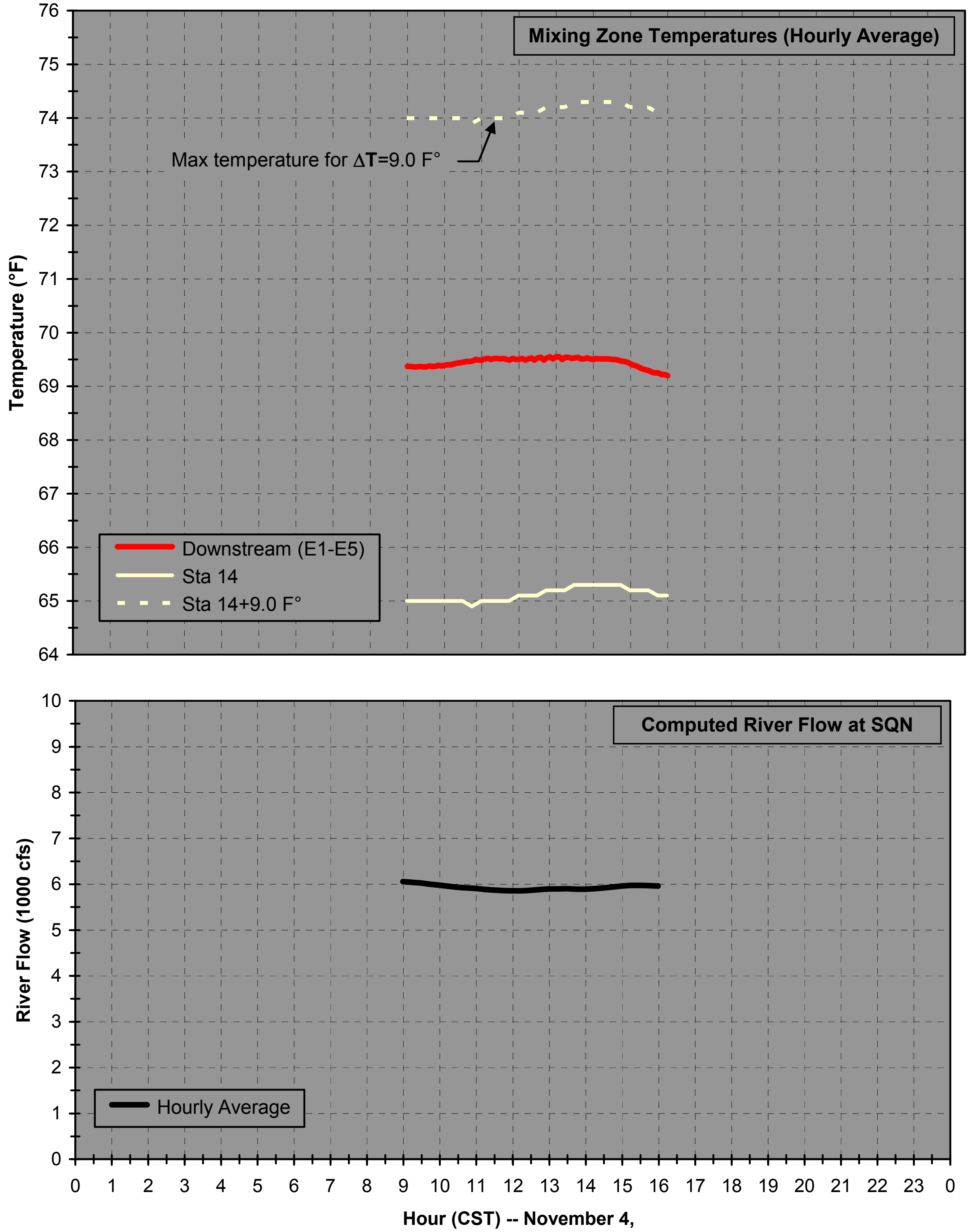


Figure 58. Temperatures for Mixing Zone Survey of November 4, 2007

Figure 59. RTD Measurements at 5-Foot Depth Around Mixing Zone for November 4, 2007

4.2.7 *Hourly and 24-Hour Averaging*

The difference between hourly averaging and 24-hour averaging was examined in the results of the mixing zone deployments presented above. It was demonstrated that peaking operations have a significant impact on hourly mixing zone temperatures; however, when averaged over 24 hours, they are not significant. In a manner similar to that used to evaluate temperatures for Station 14, hourly averaging vs. 24-hour averaging for the mixing zone also can be examined by considering exceedance probabilities for the downstream temperature. In this case, 2008 is the best year to perform such an analysis (i.e., rather than 2007, which was used in the Station 14 evaluation). This is because 2008 was the first full calendar year that the most recent version of the compliance model was used to monitor SQN thermal compliance. The most recent version of the model includes modifications to estimate the impact of re-entrainment of the plant thermal effluent under sustained, low river flows. These modifications are discussed in more detail later in this report.

Year 2008 also is a good year to examine hourly averaging vs. 24-hour averaging because it again presents an extreme case with drought conditions. For 2008, rainfall in the East Tennessee was 40.3 inches, 9.6 inches below normal and the 11th lowest in 119 years of record. The corresponding runoff was 12.1 inches, 11.0 inches below normal and the 4th lowest in 134 years of record. A plot of the computed river flow at SQN for 2008 is given in Figure 60. The annual average river flow past SQN in 2008 was about 16,000 cfs, compared to a historical average annual flow of about 32,000 cfs (i.e., 50 percent of normal). Both the hourly average and 24-hour average flows are given. In 2008, for 24-hour average flows below about 13,000 cfs, the river was operated in a manner to produce somewhat steady flow, for example from mid-April through June, and again from September through November. For higher 24-hour average flows, hydro peaking created larger variations in the hourly river flow, such as from January through mid-April, and again in late August. The summertime meteorology also was warmer than normal, with the average air temperature in Chattanooga about 1.6 F° (0.9 C°) above normal.

With this hydrology and meteorology, the temperature at the 5-foot depth computed at the downstream end of the mixing zone by the compliance model is given in Figure 61. Both the hourly average and 24-hour average values are provided. The minimum temperature for 2008 occurred in late January with an hourly average of 44.1°F (6.7°C) and a 24-hour average of 47.2°F (8.4°C). The maximum hourly temperature occurred in early August at 86.6°F (30.3°C) and the maximum 24-hour average temperature occurred near mid-July at 85.8°F (29.9°C).

The difference between the hourly average and 24-hour average computed downstream temperatures for 2008 is illustrated by the exceedance probabilities given in Figure 62. As shown, over most the temperature range, there is virtually no difference in the percent of time exceeded for hourly averaging verses 24-hour averaging. The only exceptions are near the annual maximum and minimum values where the number of occurrences of hourly average temperature increases is too sparse to result in 24-hour average values of similar magnitude. For the minimum temperature, hourly averages tend to be lower than 24-hour averages, and for the maximum temperature, hourly averages tend to be higher than 24-hour averages. For the maximum temperature the difference is very slight and infrequent, less than 0.5 F° (0.3 C°) at an exceedance of 0.5 percent (i.e., about 48 hours per year). This suggests that under warm, drought conditions there is very little difference in duration of the computed downstream temperature based on 24-hour averaging vs. hourly averaging.

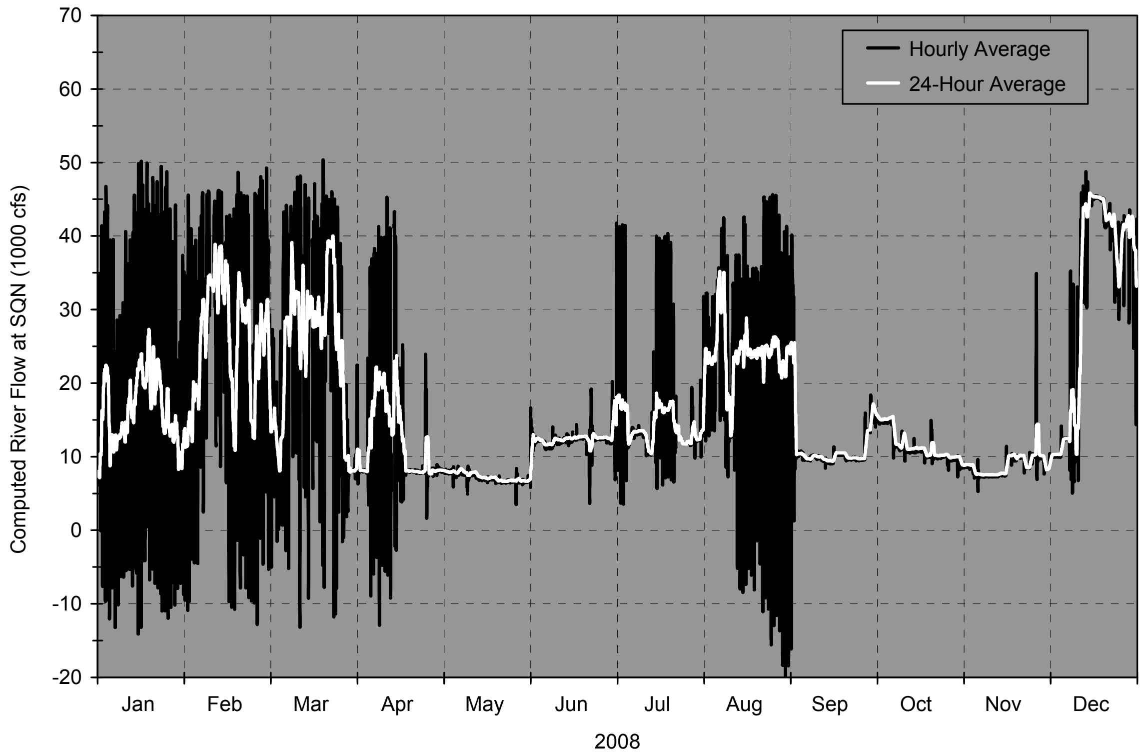


Figure 60. Computed River Flow at SQN for 2008

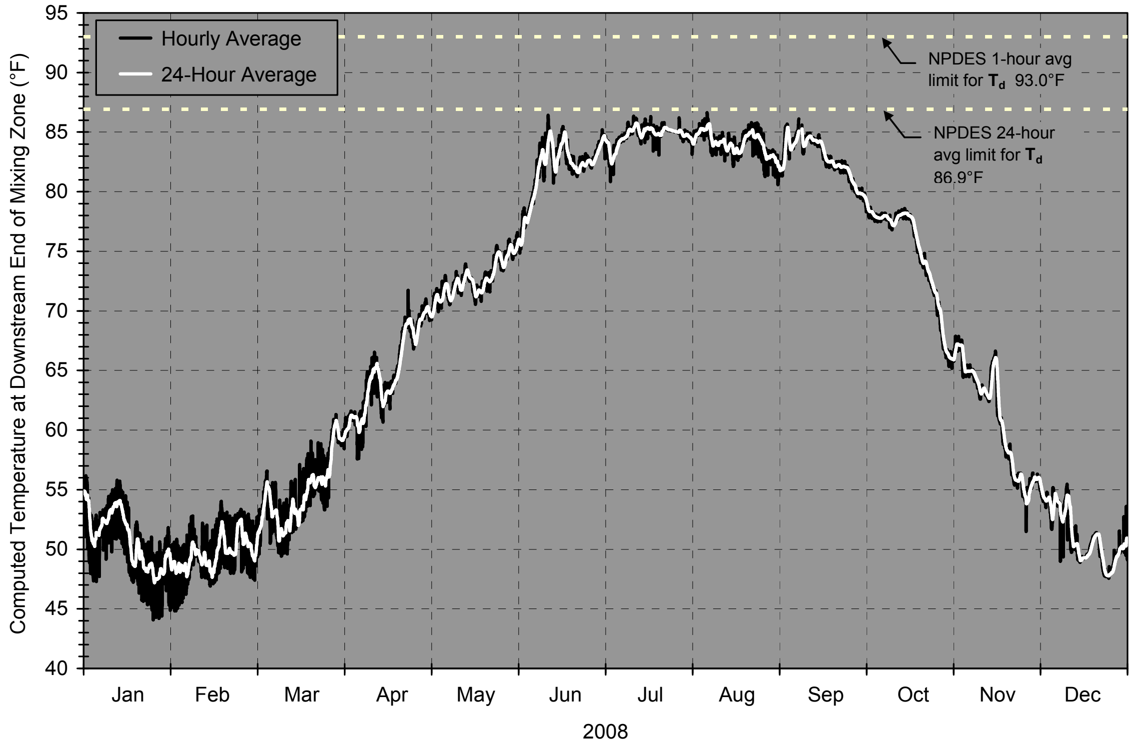


Figure 61. Computed Temperature at Downstream End of Mixing Zone for 2008

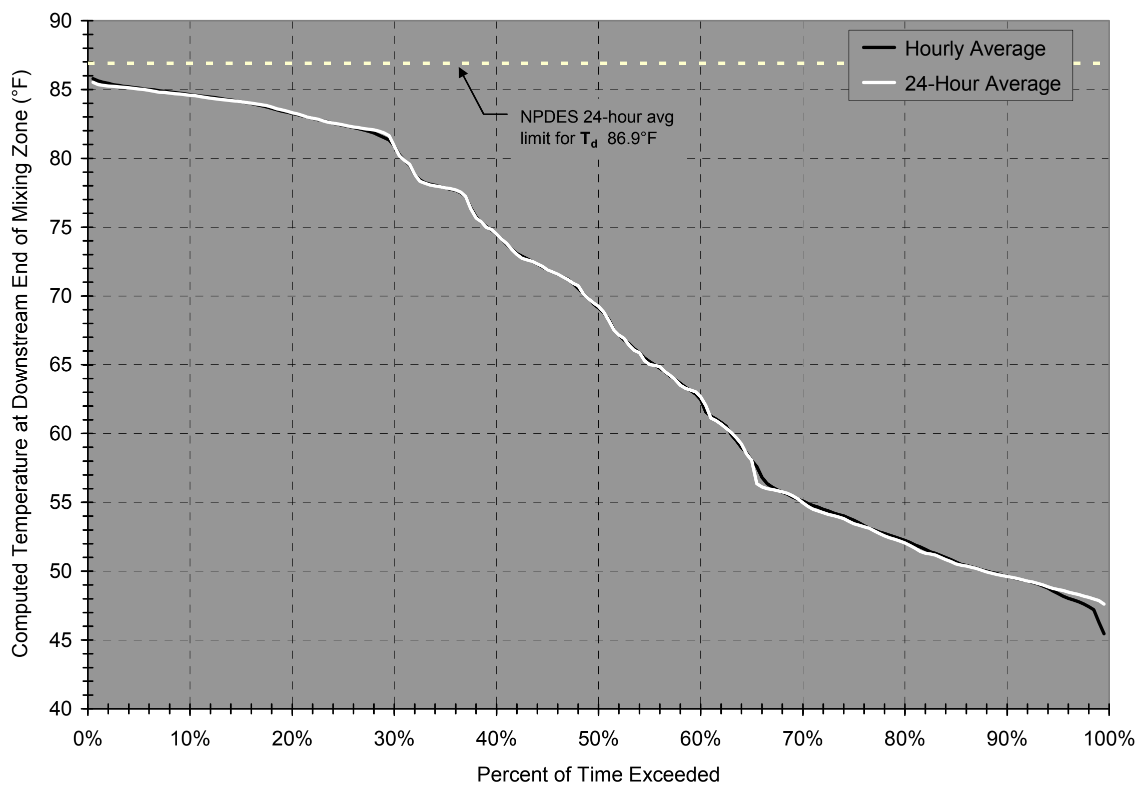


Figure 62. Exceedance Probability for Computed Temperature at Downstream End of Mixing Zone for 2008

4.2.8 *Modified Compliance Model For Downstream River Temperature*

The basic features of the compliance model are summarized in Section 2.1. Prior to the hydrothermal event of March 2006, the compliance model did not include re-entrainment of the plant thermal effluent under sustained, low river flows. The ambient temperature study and mixing zone study both provided evidence that re-entrainment occurs. To simulate this situation the compliance model was modified to better reflect the local buildup of heat that occurs in the river under sustained, low flows. This section summarizes modifications that have been made to the compliance model.

In general, the model treats the effluent discharge from the diffusers as a fully mixed, plane buoyant jet with a two-dimensional (vertical and longitudinal) trajectory. This is shown schematically in Figure 63. The jet discharges into a temperature-stratified, uniform-velocity channel flow and entrains ambient fluid as it evolves along its trajectory. The width, *b*, of the jet and the dilution of the effluent heat energy increase along the jet trajectory, decreasing the bulk mixed temperature along its path.

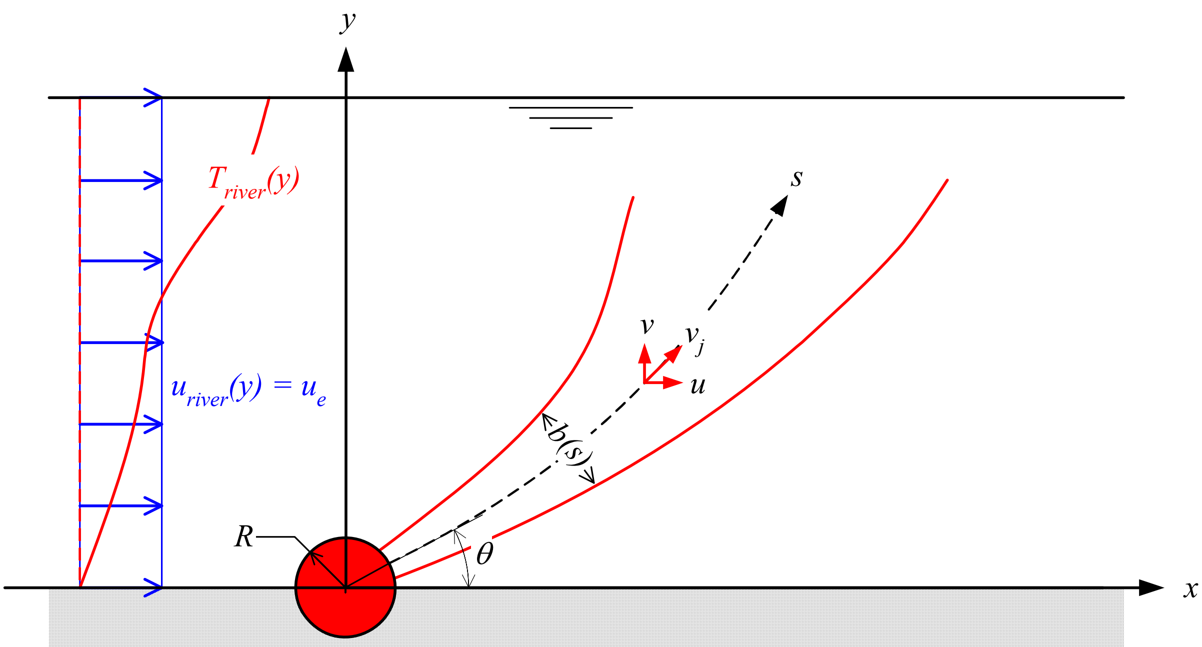


Figure 63. Two-Dimensional Plane Buoyant Jet Model for a Submerged Diffuser

Consideration of the mass, momentum, and energy for a cross section of the plume orthogonal to the jet trajectory and having a differential thickness *ds,* yields the following system of ordinary differential equations (Benton, 2003),

$$\frac{d}{ds}\left(\rho_j v_j b\right) = m_e \text{ (conservation of mass in jet),} \tag{1}$$

$$\frac{d}{ds}\left(\rho_j v_j b u\right) = m_e u_e \text{ (conservation of x momentum in jet),} \tag{2}$$

$$\frac{d}{ds}\left(\rho_j v_j b v\right) = m_e v_e + bg\left(\rho_e - \rho_j\right) \text{ (conservation of y momentum in jet),} \tag{3}$$

$$\frac{d}{ds}\left(\rho_j v_j b c T_j\right) = m_e c T_e \text{ (conservation of thermal energy in jet),} \tag{4}$$

$$\frac{dx}{ds} = \frac{u}{v_j}\text{, and} \tag{5}$$

$$\frac{dy}{ds} = \frac{v}{v_j}\text{, (velocity of jet tangent to trajectory).} \tag{6}$$

The following auxiliary relationships also are needed to solve the differential equations,

$$m_e = \alpha \rho_e \left[\left(u_e - u\right)^2 + v^2\right]^{1/2}, \tag{7}$$

$$\rho_j = \rho_{water}\left(T_j\right), \tag{8}$$

$$\rho_e = \rho_{water}\left(T_e\right), \tag{9}$$

$$T_e = T_{river}\left(y\right), \tag{10}$$

$$u_e = u_{river}, \tag{11}$$

$$v_e = 0\text{, and} \tag{12}$$

$$v_j = \left(u^2 + v^2\right)^{1/2}. \tag{13}$$

In these equations, the subscripts *j* and *e* denote conditions within the buoyant *jet* and conditions within the water upstream of the mixing zone that is *entrained* by the jet, respectively. Thus, ρ_j denotes the density of water at a point inside the jet and ρ_e denotes the density of water entrained from upstream of the mixing zone. T_e denotes the temperature of the water upstream of the mixing zone that is entrained by the jet. The x-velocity of the entrained water, u_e, is the same as the river velocity, u_{river}, which is negligible in the vertical direction (i.e., $v_e = 0$). The magnitude of the velocity along the jet trajectory is denoted by v_j, with x- and y-components u and v, respectively. The individual jets issuing from the array of 2-inch diameter outlet ports of each diffuser are modeled as a plane jet issuing from a slot of width b_0. Ideally, the slot width is chosen to preserve the total momentum flux issuing from the circular ports of the diffuser. However, for this formulation, the slot width is used as a term to calibrate the numerical model. The river velocity u_{river} *is* computed by a one-dimensional unsteady flow model of Chickamauga Reservoir. Apart from information for the reservoir geometry, the basic input for the flow model includes the measured hydro releases at Watts Bar Dam and Chickamauga Hydro Dam and the measured river water surface elevation at SQN.

The transverse gradients of velocity, temperature, and density that exist within the jet due to turbulent diffusion of the effluent momentum and energy are modeled as an entrainment mass flux, m_e, induced by the vectorial difference between the velocity of the jet and that of the river flow upstream of the mixing zone. Empirical relationships for the entrainment coefficient α are based on arguments of jet self-similarity and asymptotic behavior. These relationships incorporate non-dimensional parameters, such as a Richardson or densimetric Froude number, that describe the relative strengths of buoyancy and momentum flux in the jet (e.g., see Fischer et al., 1979). For the Sequoyah model, the entrainment coefficient, like the slot width, is adjusted as part of the model calibration process.

The initial conditions required by the model include,

$$b\big|_{s=s_0} = b_0 , \tag{14}$$

$$x\big|_{s=s_0} = R\cos\theta , \tag{15}$$

$$y\big|_{s=s_0} = R\sin\theta , \tag{16}$$

$$u\big|_{s=s_0} = \frac{q_0}{b_0}\cos\theta , \tag{17}$$

$$v\big|_{s=s_0} = \frac{q_0}{b_0}\sin\theta \text{, and} \tag{18}$$

$$T_j\big|_{s=s_0} = T_0 . \tag{19}$$

This system of differential equations, auxiliary equations, and initial conditions comprise a first-order, initial-value problem that can be integrated from the diffuser slot outlet ($s = s_0$) to any point along the plume trajectory. Note in the above that R is the radius of the diffuser conduit, b_0 is the "effective" width of the diffuser slot, θ is the exit angle of the diffuser jet, T_0 is the temperature of effluent issuing from the slot, and q_0 is the effluent discharge per unit length of diffuser. In practice, integration of the governing equations is halted when the jet centerline reaches a point five feet below the water surface (the regulatory compliance depth) or when the upper boundary of the jet reaches the water surface. The jet temperature, T_j, at this point is reported as the temperature $\mathbf{T_d}$ to which the thermal regulatory criteria are applied or to which monitoring station data at the edge of the regulatory mixing zone are compared. The integration is done with an adaptive step-size, fourth-order Runge-Kutta algorithm.

In the model, Station 13, located 1.1 miles upstream of the diffusers, is used to represent the temperature of the water entrained in the mixing zone, $T_e = T_{river}(y)$. Whereas this is a good assumption for river flows where the effluent plume is carried downstream, it begins to weaken for low river flows. Based on the understanding gained from the ambient temperature and mixing zone studies summarized herein, it is known that partial re-entrainment of the effluent plume occurs, increasing the temperature of the water entering the mixing zone above that represented by Station 13.

To simulate this phenomenon, the model has been modified to include an adjustment in the Station 13 temperature profile for low river flow. For each point in the profile, a local densimetric Froude number is computed as

$$F_r = \frac{u_{river}}{\sqrt{g\left(\frac{\rho_e - \rho_p}{\rho_e}\right)(Z_e - Z_b)}}, \tag{20}$$

where u_{river} is the average river velocity, Z_e-Z_b is the elevation of the profile point relative to the bottom elevation of the river, ρ_e is the entrainment water density at that elevation, and ρ_p is the density of the effluent plume at the 5-foot compliance depth. The densimetric Froude number represents the ratio of momentum forces to buoyancy forces in the river flow. If F_r is less than 1.0 (i.e., buoyancy greater than momentum), it is assumed that the buoyancy of the plume is sufficient to cause part of the plume to travel upstream and be re-entrained into the flow, thereby increasing the temperature of the water entering the mixing zone above that of Station 13. The modified entrainment temperature, T_e^N at the depth is then computed by repeatedly evaluating

$$T_e^n = R \times T_p + (1.0 - R) \times T_e^{n-1} \tag{21}$$

for values of n from 1 to N, where N, is the number of iterations of Eq. (21), and R is a re-entrainment fraction, $T_e^{n=0}$ is the original Station 13 temperature, and T_p is the computed plume temperature at the 5-foot depth. N and R are functions of the 24-hour average river velocity. After new Station 13 temperatures have been computed for the entire profile, the mixing zone computation is performed again, using the new profile to get a new plume temperature at the 5-foot depth. It is emphasized that the final result of the model is the computed temperature at the downstream end of the mixing zone. The instream temperature rise **ΔT** is still computed based on the temperature measurement at the new ambient temperature monitor, Station 14.

Values for N and R are determined via a calibrations study based on actual measurement at the downstream end of the diffuser mixing zone. Depending on the river stage, the modifications by Eq. (21) begin to take effect as the 24-hour average river flow drops through the range of 17,000 cfs to 25,000 cfs, and increases as the 24-hour average river flow continues to drop. For river flow above this range, no modification for re-entrainment is needed.

Results of the most recent calibration study are summarized by TVA (2009). In general, using the modified model, the average discrepancy between the measured and computed temperatures at the downstream end of the mixing zone was about 0.6 F° (0.3 C°). This represents an improvement of 0.1 F° (0.06 C°) over the previous version of the model (which did not include an adjustment for low river flow). The modified model and integrity of the mixing zone has been evaluated for daily average river flows as low as 6,000 cfs. If TVA ever needs to operate the river at flows less than 6,000 cfs, field testing will be required to further evaluate the compliance model and mixing zone.

5.0 CONCLUSIONS

TVA has completed studies for the ambient temperature and mixing zone as specified in Part III, Section F of the NPDES permit effective August 2001, and carried forward in the NPDES permit effective September 2005. Conclusions and recommendations for these studies are provided in the following sections.

5.1 Ambient Temperature Study

The goal of the ambient temperature study was to determine the major factors contributing to the interaction between main channel and overbank flows, the impacts on water temperatures in the thermal mixing zone, and optimal location of monitors to record the ambient temperature. In the study, the impacts of potential factors were inferred from observing data collected from the deployment of temporary temperature stations during summer conditions, winter conditions, and drought conditions. Temperatures at the 5-foot compliance depth were used in the evaluations. Results from a 3D numerical model of the river flow in the vicinity of the plant also aided in the interpretation of the data. In fulfillment of the goal of the ambient temperature study, and based on the results and discussions presented herein, the following basic conclusions are recognized:

- The major factors contributing to the interaction between main channel and overbank flows include meteorology, hydrology, river geomorphology, and the action of the SQN diffusers. The primary meteorological factors include the air temperature (drybulb and wetbulb), solar radiation, and wind speed. The key hydrologic factor is river flow. River geomorphology refers to the spatial variation in the depth, shape and alignment of the river. The action of the SQN diffusers refers to the energy that the effluent jets locally impart on the river flow.

- The impact of meteorology was noted primarily in combination with the depth of the river. Diurnal variations in the meteorology produce different rates and intensities of heating and cooling in deep, main channel areas of the river verses the shallow, overbank areas of the river. In the summer, overbank areas heat faster and are often warmer than adjacent main channel areas. In the winter the opposite occurs with the overbank areas cooling faster and at lower temperature than adjacent main channel areas. Knowledge of this behavior is nothing new, but data from the deployments show that temperature differences between the main channel and overbanks in the vicinity of SQN can become as large as 3 F°.

- Variations in the river discharge by hydro peaking operations, in combination with river geomorphology, provides a familiar mechanism for the interaction between main channel and overbank flows. Hydro peaking result in daily changes in the reservoir stage. During the peak hours of power demand, hydro releases are high and often result in a drawdown of the reservoir stage. In this process water is removed from storage in the overbank and embayment areas of the reservoir and is drawn into the main channel of the river. The opposite occurs during offpeak hours when low and reverse flows refill storage areas emptied during the peak.

- In addition to storage effects, interactions also occur due to boundary effects. In general, as a result of higher boundary resistance, river velocities in the shoreline areas of the river are more sluggish than river velocities in the main channel of the river, especially if the shoreline areas contain shallow overbanks. This spatial variation in velocity, or shear layer, creates vortices or eddies in the flow. Eddies can also be caused by vortex shedding from shoreline irregularities, such as outcroppings and coves. In the vicinity of SQN there is a 4 mile reach along the opposite shoreline and upstream of the diffusers that contains a significant area of shallow overbanks, coves, and embayments (e.g., see Figure 12). The eddies created by such features can cause mixing between the main channel and overbank areas of the flow. At high river discharges the intensity of the eddies is usually not large enough to overcome the mean velocity of the flow, and hence water in the overbanks tends to be transported downstream. However, at lower discharges, the intensity of the eddies can be significant compared to the mean velocity of the flow and cause water in the overbanks to move (or "eddy") upstream, even though the cross-sectional average discharge is in the downstream direction.

- Major changes in boundary configurations along the length of the river also promote interactions between the main channel and overbanks. A good example is an overbank area containing an outcropping at its downstream end. Near SQN, such a change in shoreline configuration occurs on the left-hand-side of the river across from Opossum Creek (e.g., see Figure 12). In this case water residing in the overbank is forced into the main channel by the outcropping. In the summertime this would perhaps contribute to the occurrence of patches of warm water in the main channel, and vise versa in the winter.

- Adding to boundary effects is the impact of river alignment, which can significantly intensify the movement of water in shoreline areas of the river. In the vicinity of SQN there are two bends in the Tennessee River. About 4.5 miles upstream of the diffusers there is a bend where the river direction changes from the southwest to the southeast. The second is at the plant, where the river changes direction from the southeast to almost entirely the west (e.g., see Figure 12). The flow around a bend creates secondary currents wherein the flow in the surface layer of the river moves towards the outside of the bend and the flow in the bottom of the river moves toward the inside of the bend. These secondary currents, subsequently, can move water between the overbanks and main channel of the river. However, perhaps more important is the flow separation, or wake, that occurs on the inside and downstream of river bends. This flow separation can promote the formation of a large-scale recirculation pattern between the bend and the point downstream where flow "reattaches" to the shoreline (i.e., downstream end of the wake). In this region, water along the shoreline is drawn upstream towards the bend, against the direction of the average flow in the river, where it is entrained into the flow coming around the bend.

- At river discharges below the range of from 17,000 cfs to 25,000 cfs, the action of the SQN diffusers can promote additional recirculation between the main channel and overbanks. This occurs as a result of the high velocity jets issuing from the diffuser ports. Energy from the jest is absorbed by the ambient flow in the river as it becomes entrained in the diffuser plume. If the amount of flow entrained by the jets is larger than the flow moving downstream, part of the effluent mixture will be transported through the left and right faces of the mixing zone, feeding into the overbank areas, and through the upstream face, feeding into the thermal wedge. That is, at low river discharges, the energy from the diffuser jets accelerates the flow locally in the river. Afterwards, in the process of decelerating the back to the normal river flow (an to maintain continuity), the thermal effluent from the mixing zone is assimilated not only downstream, but also in the lateral and upstream directions.

- Deployments involving temperature measurements longitudinally along the center of the river suggest that for lower river flow (e.g., 13,000 cfs and below), the upstream migration of heat from the SQN mixing zone can extend further upstream as a results of peaking operations compared to that which occurs for steady operation of the river. This likely is due to the fact that in addition to the mechanisms identified above, peaking operations are accompanied by short periods of reverse flow, or sloshing, in the reservoir.

- In periods of natural reservoir cooling and the winter months of the year, evaporation and the accompanying heat loss from the reservoir is much greater than during periods of natural reservoir heating and the summer months of the year. As a result, low flow migration of heat upstream of the mixing zone is not as extensive in periods of natural reservoir cooling, such as the winter. This occurrence was observed in the temperature data collected in the ambient temperature study.

- Prior to the new studies summarized herein, the only recognized mechanism responsible for the upstream migration of thermal effluent from the SQN diffuser mixing zone was mean flow advection as a result of peaking operations (i.e., river sloshing that accompanies peaking-related drawdown and filling of the reservoir). Previous evaluations suggested that by this mechanism, the upstream migration of thermal effluent would not travel more than perhaps fifty percent of the distance between the mixing zone and the ambient temperature monitor at the plant intake skimmer wall, Station 13. However, as a result of the current studies, it is now understood that by the mechanism identified above, the thermal effluent can be transported far enough upstream to impact Station 13, contributing to the problematic temperature excursions that have been observed at this location (e.g., recall Figure 4). In fact, for river flows below the range of from 17,000 cfs to 25,000 cfs (i.e., with both units in operation at SQN), eddy and recirculation patterns in the overbank along the left-hand shoreline of the reservoir opposite the plant can carry heat from the mixing zone up to and perhaps beyond the bend in the river that occurs about 4.5 miles upstream of the diffusers (e.g., see Figure 38). This awareness first emerged in March 2006 when the effects of the current drought first began to significantly impact discharges in Chickamauga Reservoir.

- To provide an ambient temperature reading beyond the potential influence of the plant thermal effluent, a new station was established 5.7 miles upstream of Station 13. The new ambient temperature station is called Station 14. Subsequent temperature measurements suggest that Station 14 is free from any effects of the SQN thermal discharge for steady river flows as low as about 6000 cfs and for peaking operations with daily average river flows as low as about 13,000 cfs. This covers the range of river operations observed in the current drought since March 2006.

- The fact that at low river discharges water from the overbanks can be transported into the main channel of the river, and the fact that flow in the main channel provides the major source of water for the mixing zone, implies that processes that warm or cool the overbank areas of the reservoir also will warm or cool the water that is used to dilute the thermal effluent from the diffusers. For cases where overbank areas are warm compared to the water in the main channel of the river, this will include heating from the solar activity as well as heating from any recirculation of diffuser effluent. At this time there is no reliable method to estimate the individual contributions of heating due to natural variations in meteorology verses that due to recirculation of the plant thermal effluent. As such, at this time, SQN is operated in a manner to keep the total temperature rise below the NPDES standard whether or not the source of heating in the river is from the diffuser discharge or a combination of the diffuser discharge and natural heating due to the prevailing meteorology.

The requirements for the ambient temperature study also included an evaluation of hourly verses 24-hour averaging of the ambient temperature measurement. This was examined by considering the hourly and 24-hour average exceedance probabilities for 2007, the first full calendar year of service for Station 14. Year 2007 also presents an extreme case because in 2007 rainfall in the East Tennessee was the lowest in 119 years of record and the corresponding runoff was the lowest in 134 years of record. The exceedance probabilities showed that over most the range of observed ambient temperatures, there were virtually no difference in the percent of time exceeded for hourly averaging verses 24-hour averaging. The only notable exceptions were near the extreme temperatures (i.e., annual maximum and minimum temperatures). But even in these ranges, the difference between the hourly average and 24-hour average is slight and infrequent, less than 0.5 F° (0.3 C°) at an exceedance of 0.5 percent (i.e., about 48 nonconcurring hours per year). This suggests that under the natural reservoir conditions that exist at Station 14, there is little difference in duration of the ambient temperature based on 24-hour averaging vs. hourly averaging.

5.2 Mixing Zone Study

The goal of the mixing zone study was to better determine the impact of hydro peaking operations on the behavior of the thermal plume, and to determine if there is any need to redefine the extent of the mixing zone. In the mixing zone study this was accomplished by deploying temporary temperature stations around the full perimeter of the mixing zone during summer conditions, winter conditions, and drought conditions. Temperatures at the 5-foot compliance depth again were used in the evaluations. The deployment of the temporary stations was based on specifications in the NPDES permit for taking grab samples at the downstream end of the mixing zone, which can be used to evaluate temperature requirements for the mixing zone in events wherein the compliance model is out of service. The deployment included five temperature stations along each side of the mixing zone, which allowed the analysis of the average temperature along the individual faces as well as the entire perimeter of the mixing zone. If it were possible to deploy permanent stations around the full perimeter of the mixing zone, the overall adequacy of the mixing zone and compliance with the NPDES requirements would be evaluated based on the average temperature determined from all of the stations. Such was the basis for evaluating the mixing zone in this study. In fulfillment of the goal of the mixing zone study, and based on the results and discussions presented herein, the following basic conclusions are recognized:

- For high river flows, above about 25,000 cfs, almost all of the thermal effluent in the diffuser mixing zone is assimilated in the downstream direction. Temperatures in the mixing zone tend to be suppressed.

- For river flows in the range of about 17,000 cfs to 25,000 cfs, part of the thermal effluent begins to be assimilated in other directions. That is, not only downstream, but upstream and laterally through the sides of the mixing zone. Temperatures in the mixing zone become elevated. A thermal wedge in the surface layer of the river begins to form upstream of where the diffuser plume breaches the water surface. Areas of recirculation are likely to begin forming between the sides of the mixing zone and the adjacent shorelines of the river. The recirculation areas can be responsible for feeding effluent in the mixing zone to adjacent areas of the river, including the overbanks.

- For river flows below the range of about 17,000 cfs to 25,000 cfs, including reverse flows, the quantity of thermal effluent assimilated through the sides and upstream of the mixing zone is strengthened and temperatures in the mixing zone become further elevated. Heat that is fed into areas adjacent to the mixing zone also is elevated and can become entrained into the flow that is drawn into the mixing zone by the diffuser jets to dilute the plant thermal effluent. In this manner, by the mechanisms previously discussed for the ambient temperature study, heat from the mixing zone can be carried upstream and assimilated over a distance of several miles.

- In the surface layer of the flow, the thermal plume from the diffusers likely undulates from side to side in the mixing zone in response to regulated variations in the river discharge (steady or unsteady), natural variations in reservoir conditions, and flow turbulence. Measurements in the mixing zone study, however, suggest that for sustained conditions, the thermal effluent in the mixing zone shifts towards the right side of the mixing zone for high river flow and towards the left side of the mixing zone for low river flow (i.e., facing downstream). This behavior likely is due to secondary motions induced by flow through the river bend at SQN and the configuration of the shorelines adjacent to the mixing zone.

- The impact of peaking operations causes the thermal effluent in the diffuser mixing zone to transition between the basic behaviors described above. During periods of peak power demand when river flow high (e.g., above 25,000 cfs), all of the effluent is assimilated downstream and water temperatures in the mixing zone are suppressed. During offpeak hours when low and reverse river flows can occur (e.g., less than 17,000 cfs), the effluent is assimilated in all directions and water temperatures in the mixing zone are elevated. Periods of reverse river flow likely provide the greatest assimilation of effluent in the upstream direction, but such periods are short, usually less than three hours per event.

- The impact of peaking operations is basically the same for winter and summer conditions. In the summer, strong stratification can cause the plume to reach an elevation of neutral buoyancy below the 5-foot compliance depth, reducing the amount of thermal effluent that breaches the surface layer of the mixing zone. Such behavior was not observed in the recent mixing zone study, but has been observed in earlier studies (e.g., study of May 14, 1982—see Table 1)

- Measurements in the mixing zone study found that the average temperatures at the compliance depth for the individual faces of the mixing zone (i.e., upstream, downstream, left and right), as well as that for all four faces combined, were always contained within the NPDES limits for the maximum instream temperature and the maximum instream temperature rise. This was true for winter and summer conditions and for both hourly and 24-hour average temperatures. Although not all of the studies included long-term deployments to evaluate 24-hour averages, this has been true of all the mixing zone studies that have been performed since the startup of the plant. This suggests that for the current procedures used to monitor and operate the plant, the mixing zone is adequate for regulating temperatures within the present NPDES limits, including a 316(a) variance increasing the maximum instream temperature rise **ΔT** from 5.4 F° (3.0 C°) to 9.0 F° (5.0 C°) for the months of November thru March. That is, the mixing zone study provided no indication that the mixing zone needs to be redefined at this time.

- The measurements in the mixing zone study found that the average temperature along the downstream face of the mixing zone, which is used to calibrate the NPDES compliance model, provides a good estimate of the average temperature around the perimeter of the mixing zone. The average temperature along the downstream face of the mixing zone also is usually among the highest of all the faces.

- Observations in both the mixing zone study and the ambient temperature study recognized that at low river flow the upstream migration of heat from the mixing zone can be re-entrained into the water used to dilute the thermal effluent from the diffusers. This buildup of heat in the river and warming of water entering the mixing zone was not included in the version of the compliance model that existed before the onset of these studies. As a result of the same low flow events that led to changing the location of the ambient temperature measurement (i.e., from Station 13 to Station 14), changes also were made to the compliance model. Specifically, a re-entrainment function was added in the model to simulate the local warming of the water entering the mixing zone that occurs at low river flow. With this modification, computed temperatures at the downstream end of the mixing are in better agreement with measured observations.

The mixing zone study also included requirements for evaluations of hourly verses 24-hour averaging of the mixing zone temperature. In part, this was completed by analyzing the data from the mixing zone deployments on an hourly basis as well as a 24-hour average basis, as summarized in the conclusions above. In a manner similar to that for the ambient temperature study, differences between hourly and 24-hour averaging also were examined by evaluating the exceedance probabilities of the computed temperature at the downstream end of the mixing zone. In this case, 2008 was chosen for the analysis because it was the first full calendar year of operation with the modified compliance model. Year 2008 also presents an extreme case because in 2008 rainfall in East Tennessee was the 11th lowest in 119 years of record and the corresponding runoff was the 4th lowest in 134 years of record. As for the ambient temperature, the exceedance probabilities showed that over most the range of computed downstream temperatures, there were virtually no difference in the percent of time exceeded for hourly averaging verses 24-hour averaging. The only notable exceptions were near the extreme temperatures (i.e., annual maximum and minimum temperatures). But even in these ranges, the difference between the hourly average and 24-hour average again is very slight and infrequent, less than 0.5 F° (0.3 C°) at an exceedance of 0.5 percent (i.e., about 48 nonconcurring hours per year). This suggests that for the current configuration of the mixing zone, in combination with the current methods to monitor and operate the plant, there is little difference in duration of the mixing zone temperatures based on 24-hour averaging vs. hourly averaging.

5.3 Overall Comments

Examining the results of the ambient temperature study and mixing zone study together, along with the other historical aspects of SQN thermal compliance presented herein, the following overall conclusions are recognized:

- Since the plant startup in 1981, and by a resolute commitment for proper monitoring and field testing, SQN has always sought to expand TVA's understanding of the ever changing hydrothermal aspects of the combined operation of the Tennessee River and the plant. Over this period SQN has conducted about 17 comprehensive surveys of the plant thermal effluent, averaging about one survey every for every 18 months of operation. This has provided valuable insight in the process of developing and modifying the plant NPDES temperature requirements and monitoring procedures, which have yielded a good balance between supplying low-cost, reliable power and supporting a thriving river system.

- As a result of the most recent studies, originally specified in the NPDES permit effective August 2001, and as a result of observations made during recent drought conditions in the East Tennessee, changes have been successfully made in the location of the ambient temperature measurement and in the mixing zone compliance model. These changes were needed to account for the local buildup of heat in the river from SQN that occurs at low river flow. The hydrothermal mechanisms responsible for this buildup were not understood prior to the new studies summarized herein.

- Field testing and operating experience, including that during the recent extreme drought, suggest that based on current procedures to monitor and operate the plant, the ambient temperature measurement and mixing zone configuration are adequate for steady river flows as low as about 6000 cfs. For peaking operations, the ambient temperature measurement has been shown to be adequate for daily average river flows as low as about 13,000 cfs and the mixing zone for daily average flows as low as about 10,000 cfs. If TVA anticipates operating at conditions below these levels, additional measurements should be taken to ensure the adequacy of the ambient temperature measurement and the mixing zone.

- On an annual basis, exceedance probabilities show that there is little difference between the duration and frequency of ambient and mixing zone temperatures monitored using 24 hour averaging verses that of hourly averaging. NPDES monitoring with 24-hour averaging for the downstream temperature $\mathbf{T_d}$ and the temperature rise $\mathbf{\Delta T}$ has been in effect since August 2001 with no evidence of adverse impact to the balanced indigenous population of shellfish, fish, and wildlife in Chickamauga Reservoir. Furthermore, the results of studies summarized herein suggest that based on current procedures for monitoring the plant thermal compliance, it is very likely that changes in the plant operation to protect the NPDES limits based on 24-hour averaging also attenuate the most extreme hourly average temperature excursions. That is, the most extreme hourly average temperature excursions usually coincide with the most extreme 24-hour average temperatures, wherein cooling tower operation or changes in unit generation are needed to reduce the release of heat through the diffusers to maintain NPDES compliance for $\mathbf{T_d}$ or $\mathbf{\Delta T}$. For these reasons, and since 24-hour averaging is more synchronous with the time required to plan and safely implement operating procedures for cooling tower operation and/or changes in unit generation, SQN believes that the NPDES requirements for the downstream temperature and temperature rise should continue to be based on 24-hour averaging.

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