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.

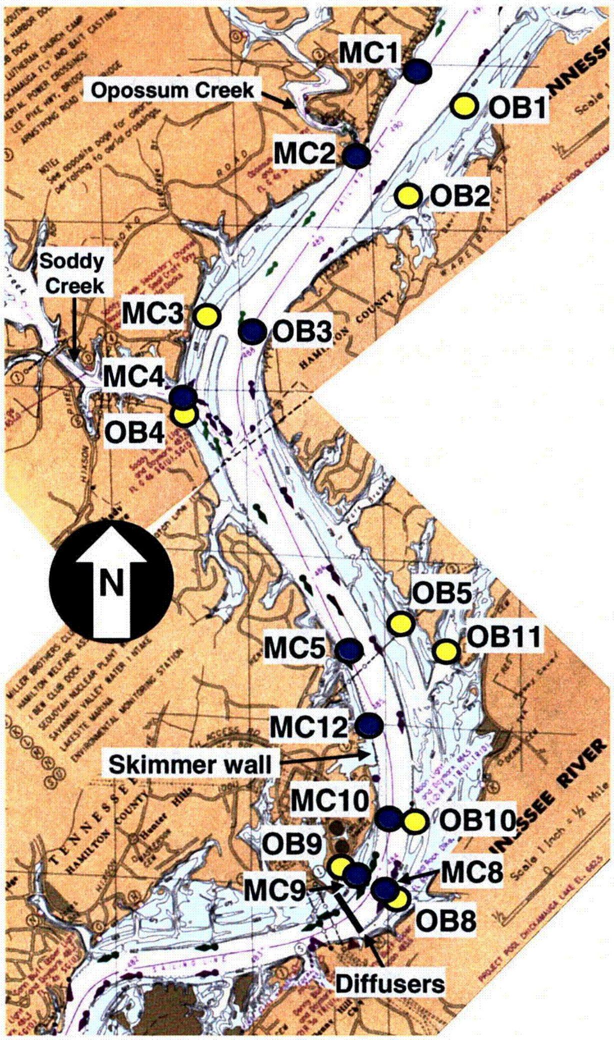
4.1 Ambient Temperature Study

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

Notes: MC = Main Channel
OB = OverBank

Figure 12. Sampling Locations For Ambient Temperature Study

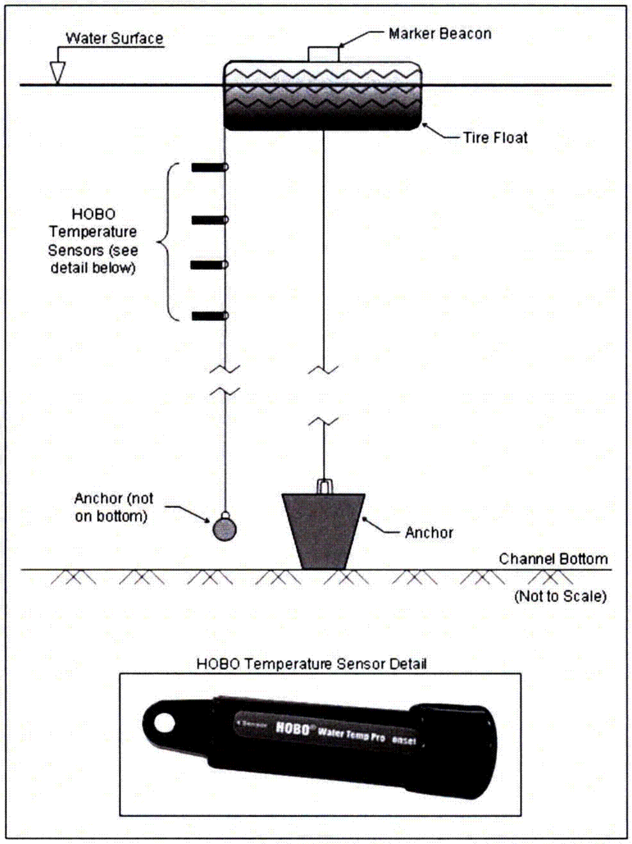


Figure 13. Schematic of HOBO™ Water Temperature Monitoring Station

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.

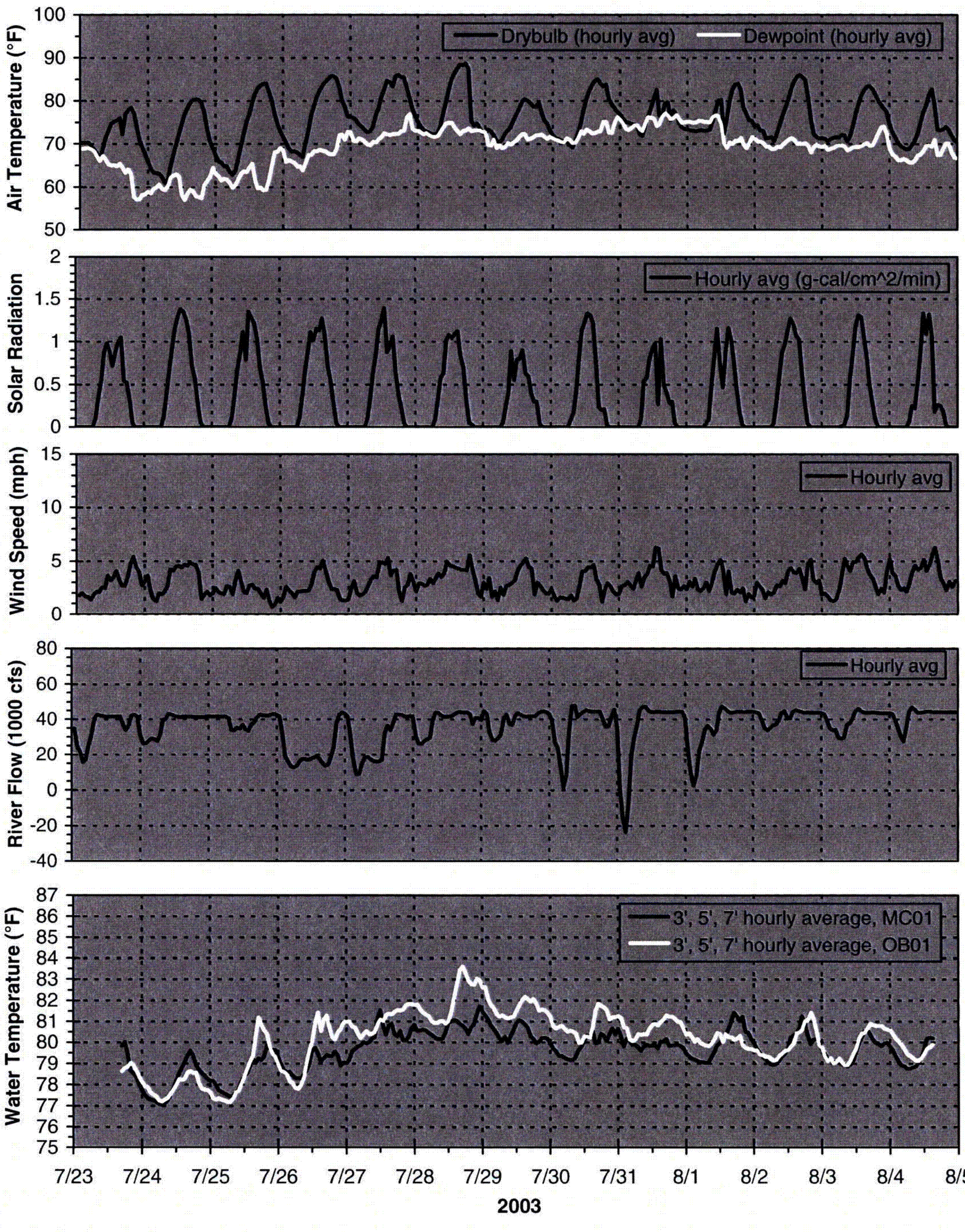


Figure 14. Main Channel and Overbank Stations MC01 and OB01 for Summer Deployment

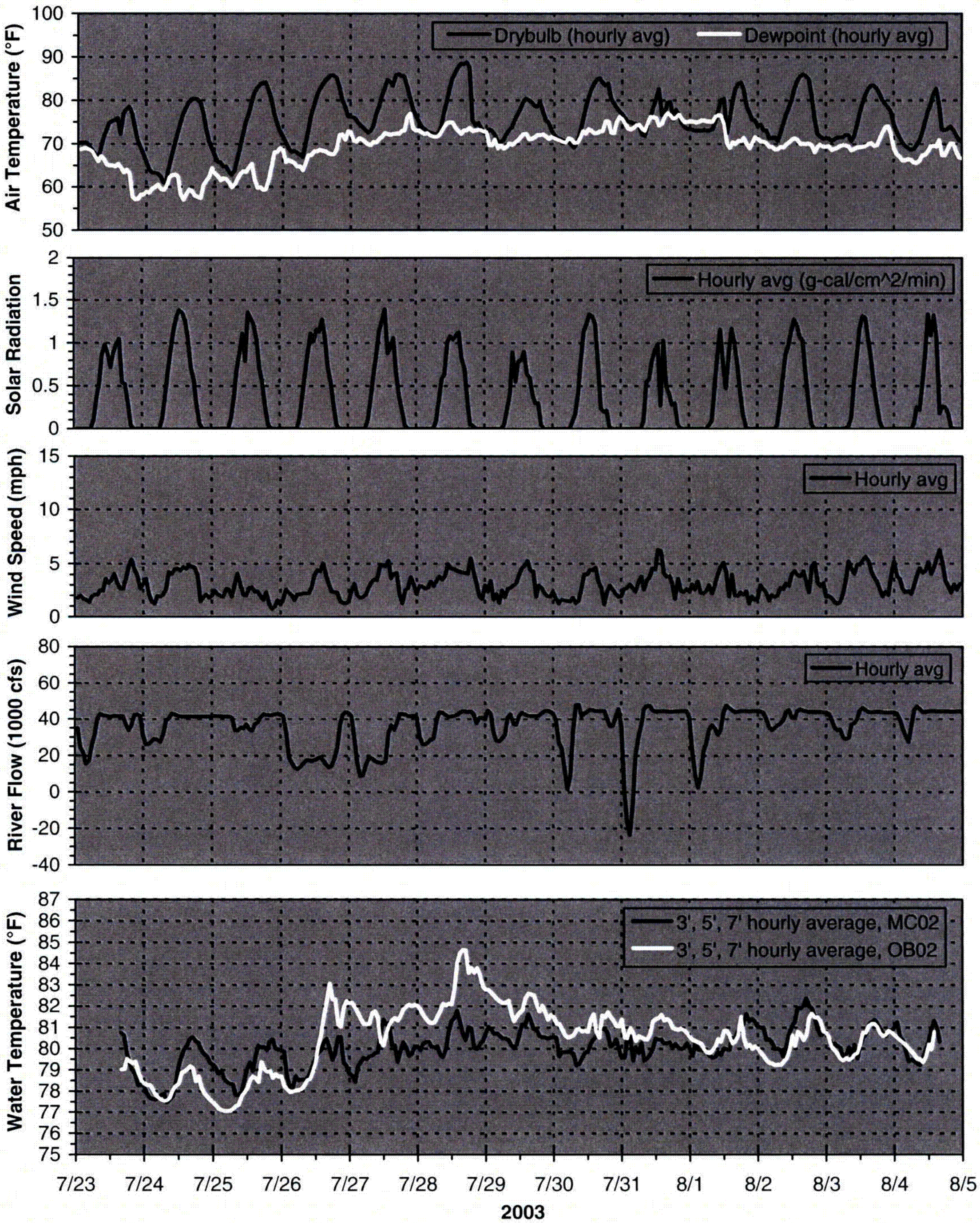


Figure 15. Main Channel and Overbank Stations MC02 and OB02 for Summer Deployment

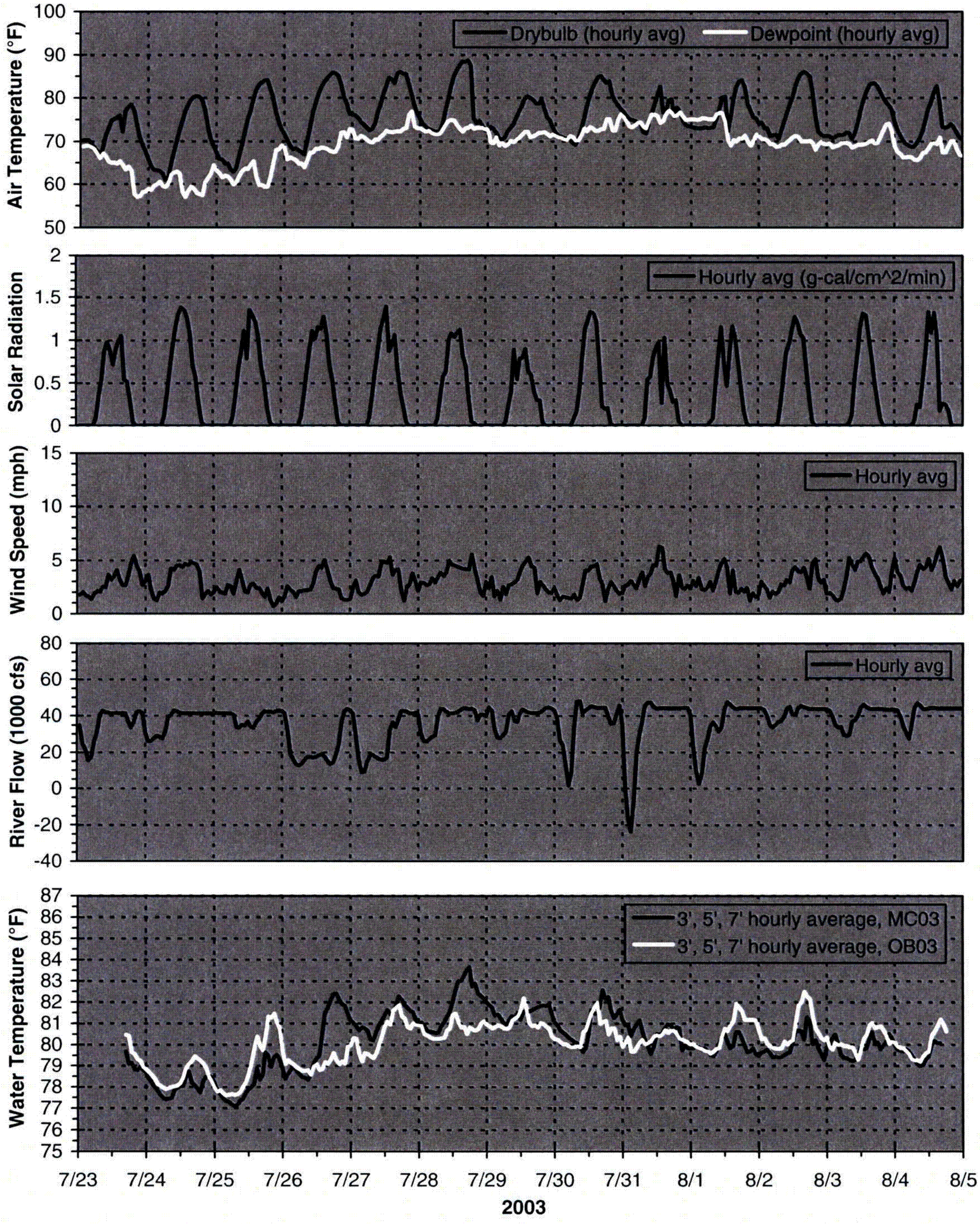


Figure 16. Main Channel and Overbank Stations MC03 and OB03 for Summer Deployment

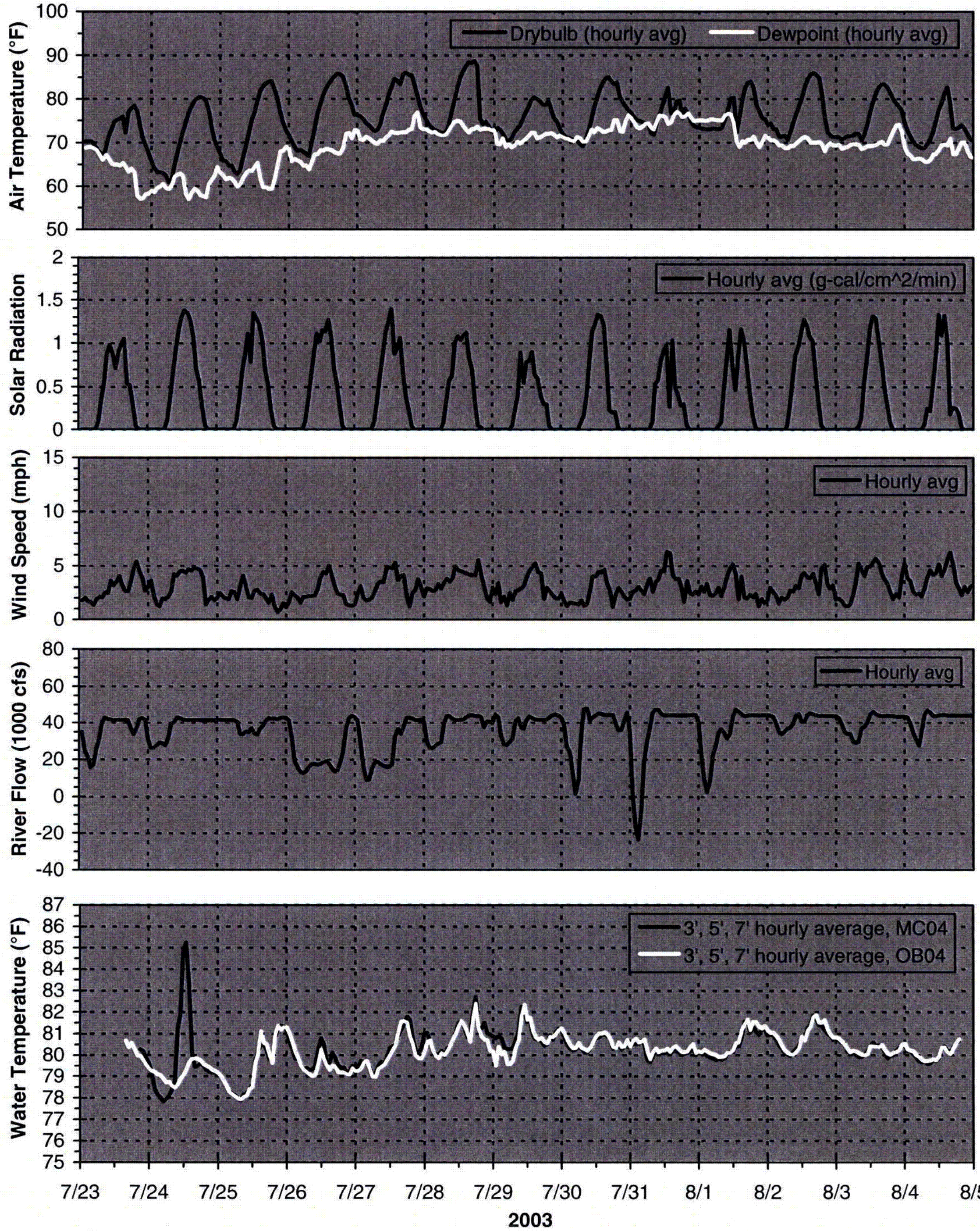


Figure 17. Main Channel and Overbank Stations MC04 and OB04 for Summer Deployment

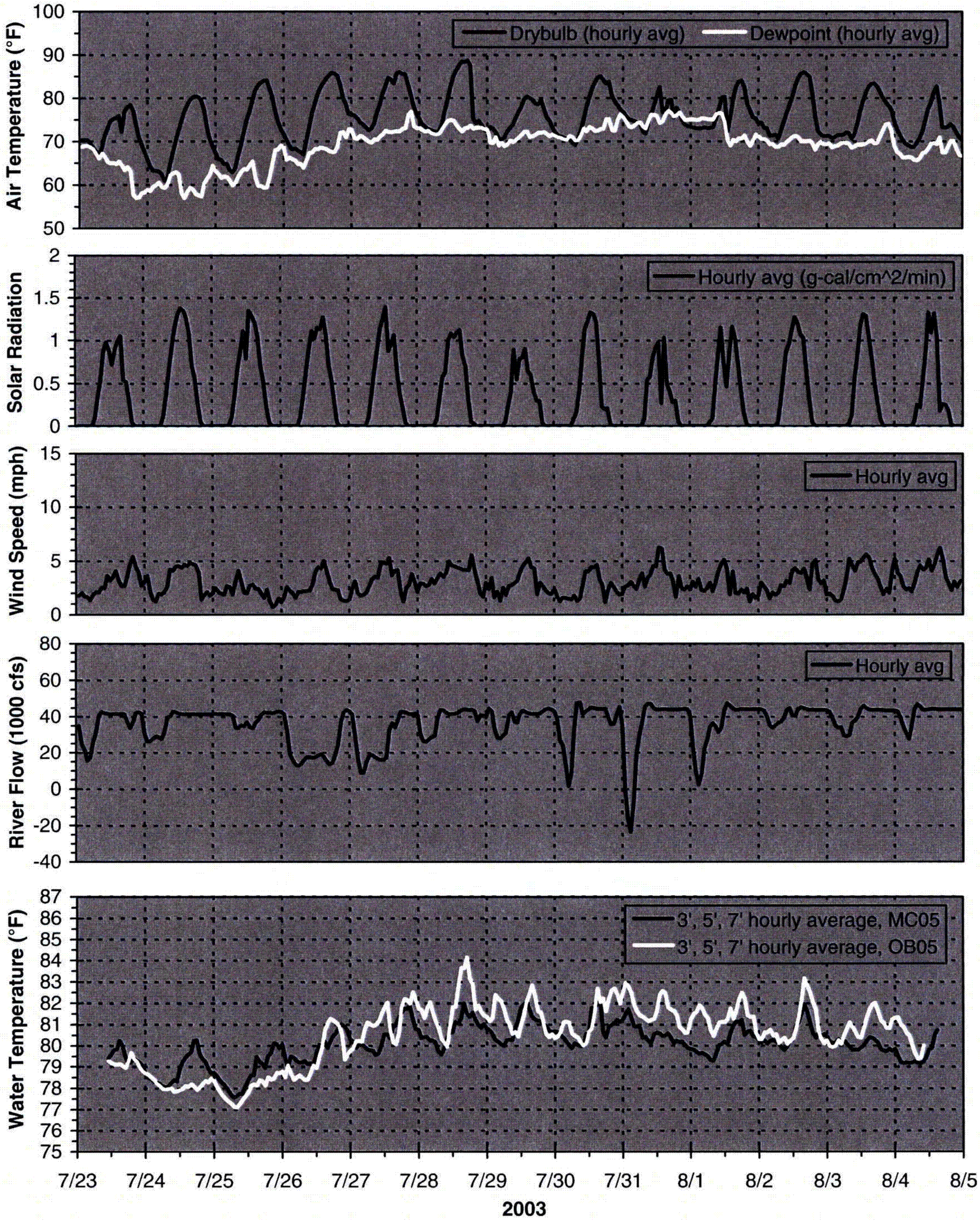


Figure 18. Main Channel and Overbank Stations MC05 and OB05 for Summer Deployment

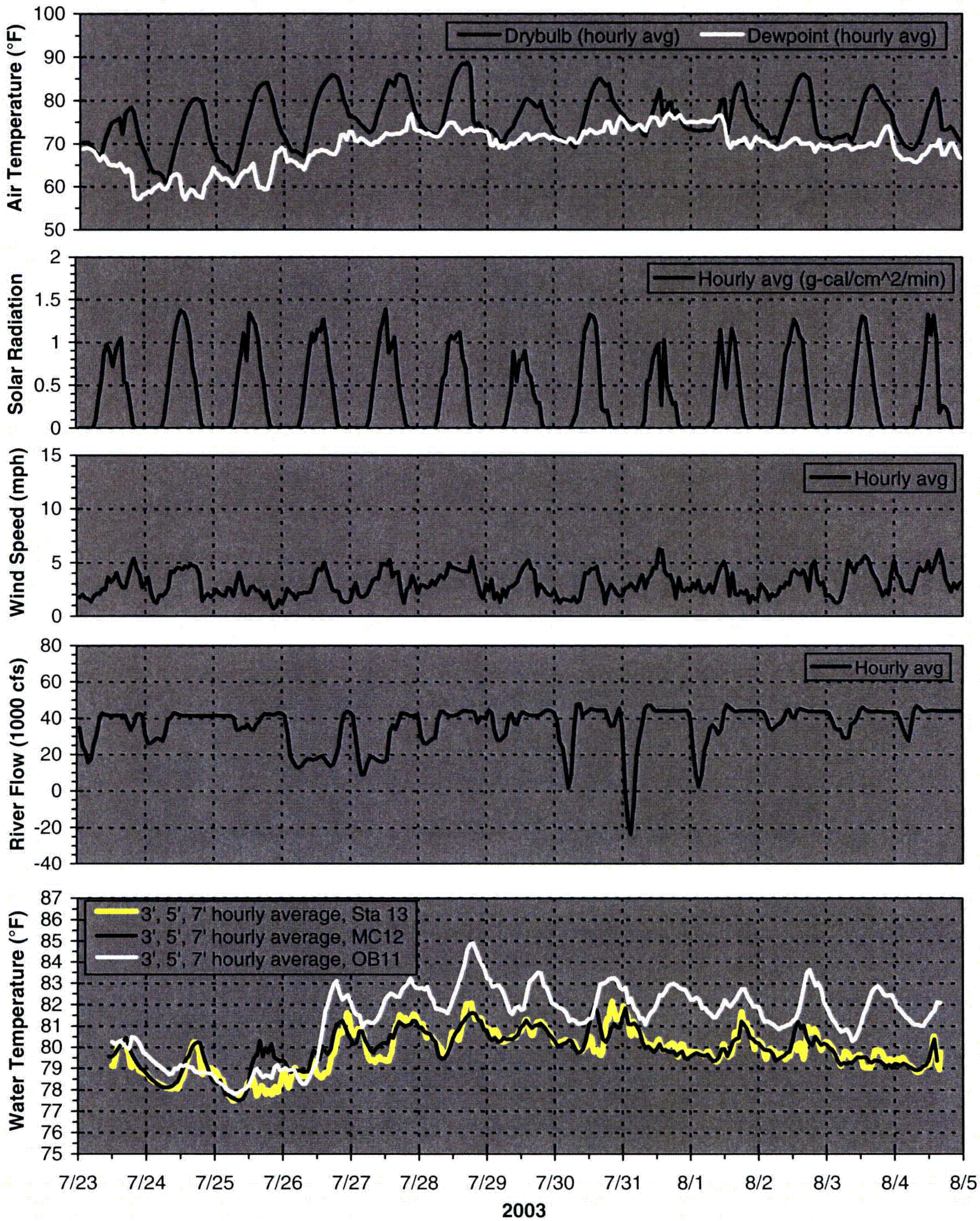


Figure 19. Main Channel and Overbank Stations MC12, OB11, and Station 13 for Summer Deployment

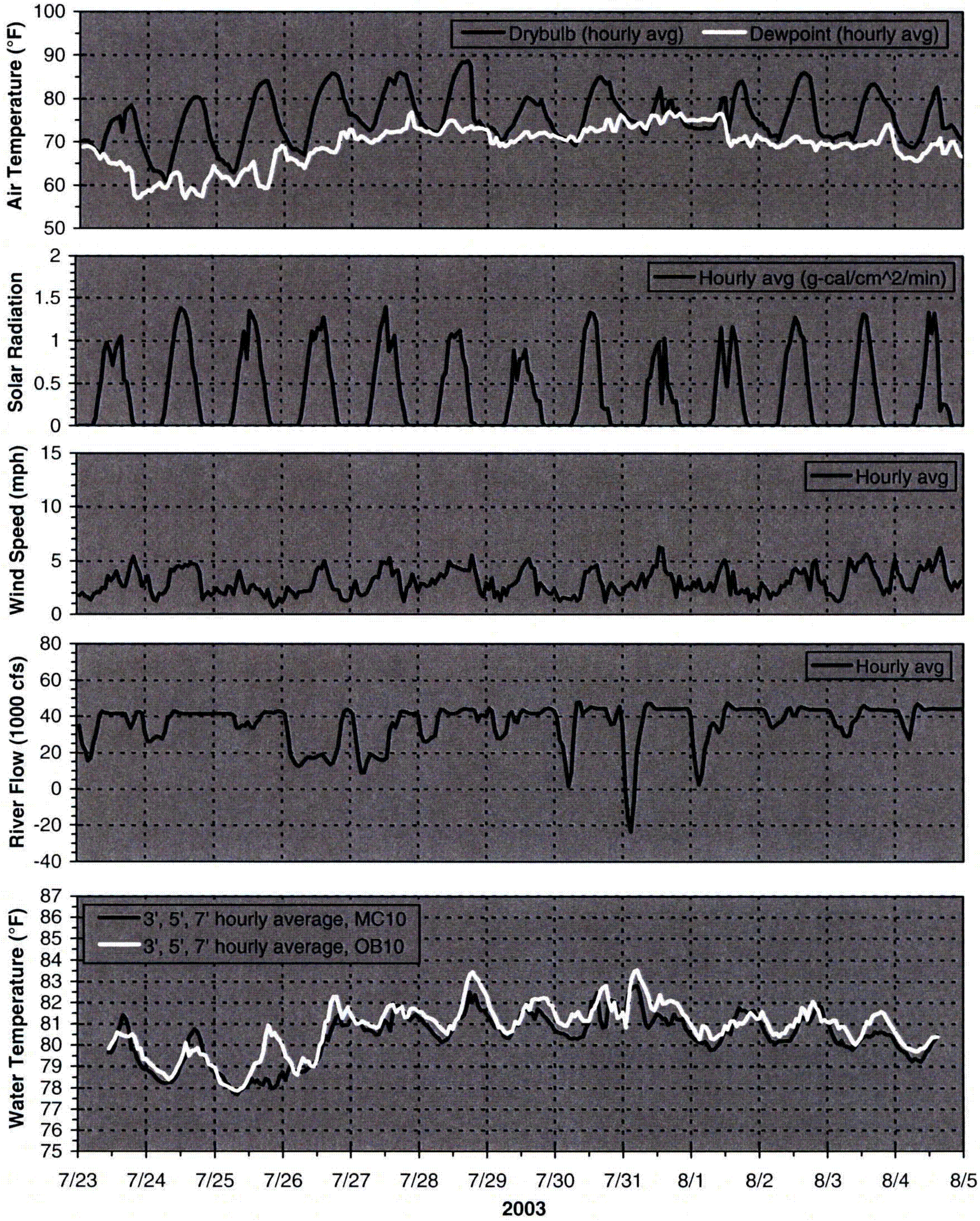


Figure 20. Main Channel and Overbank Stations MC10 and OB10 for Summer Deployment

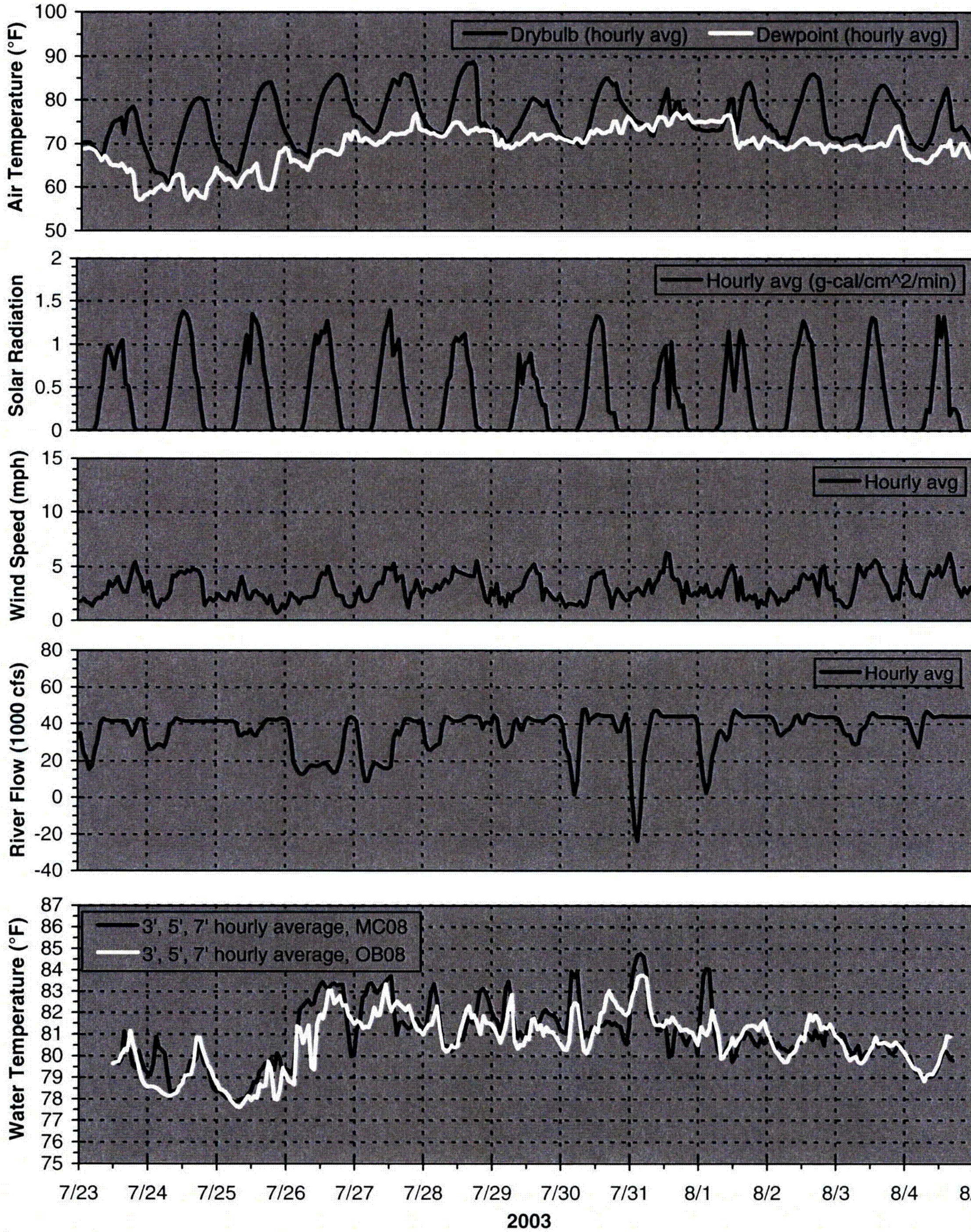


Figure 21. Main Channel and Overbank Stations MC08 and OB08 for Summer Deployment

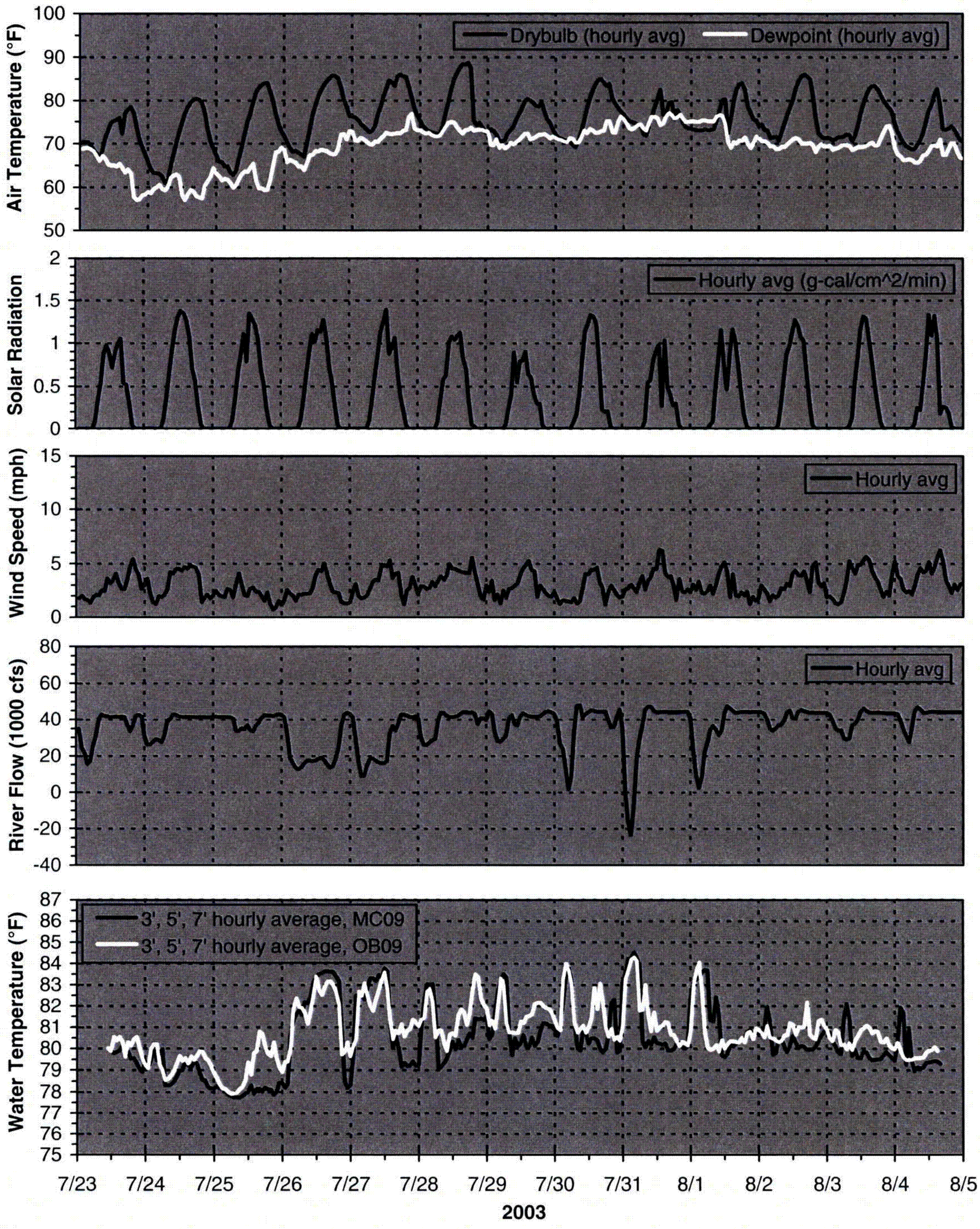


Figure 22. Main Channel and Overbank Stations MC09 and OB09 for Summer Deployment

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.

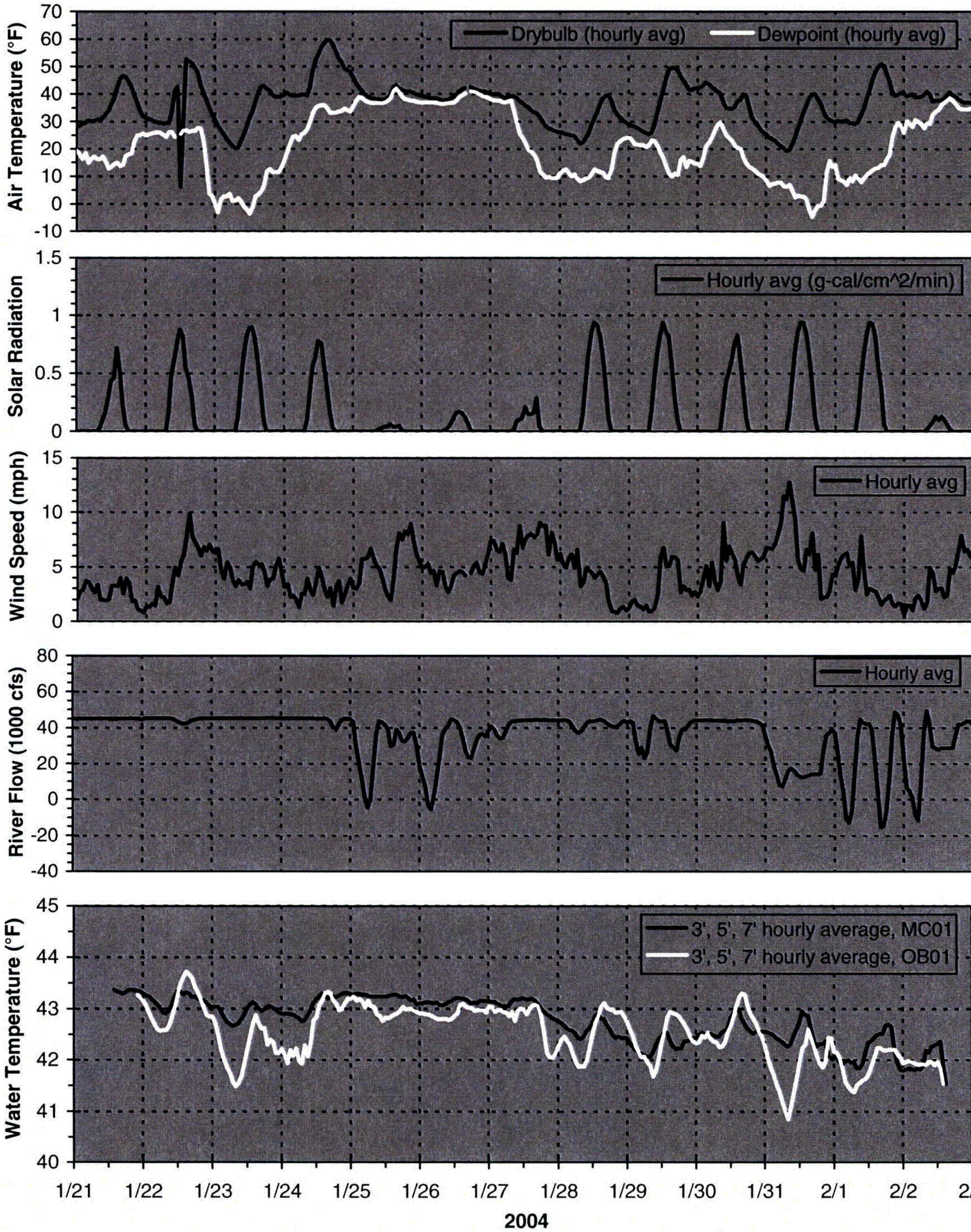


Figure 23. Main Channel and Overbank Stations MC01 and OB01 for Winter Deployment

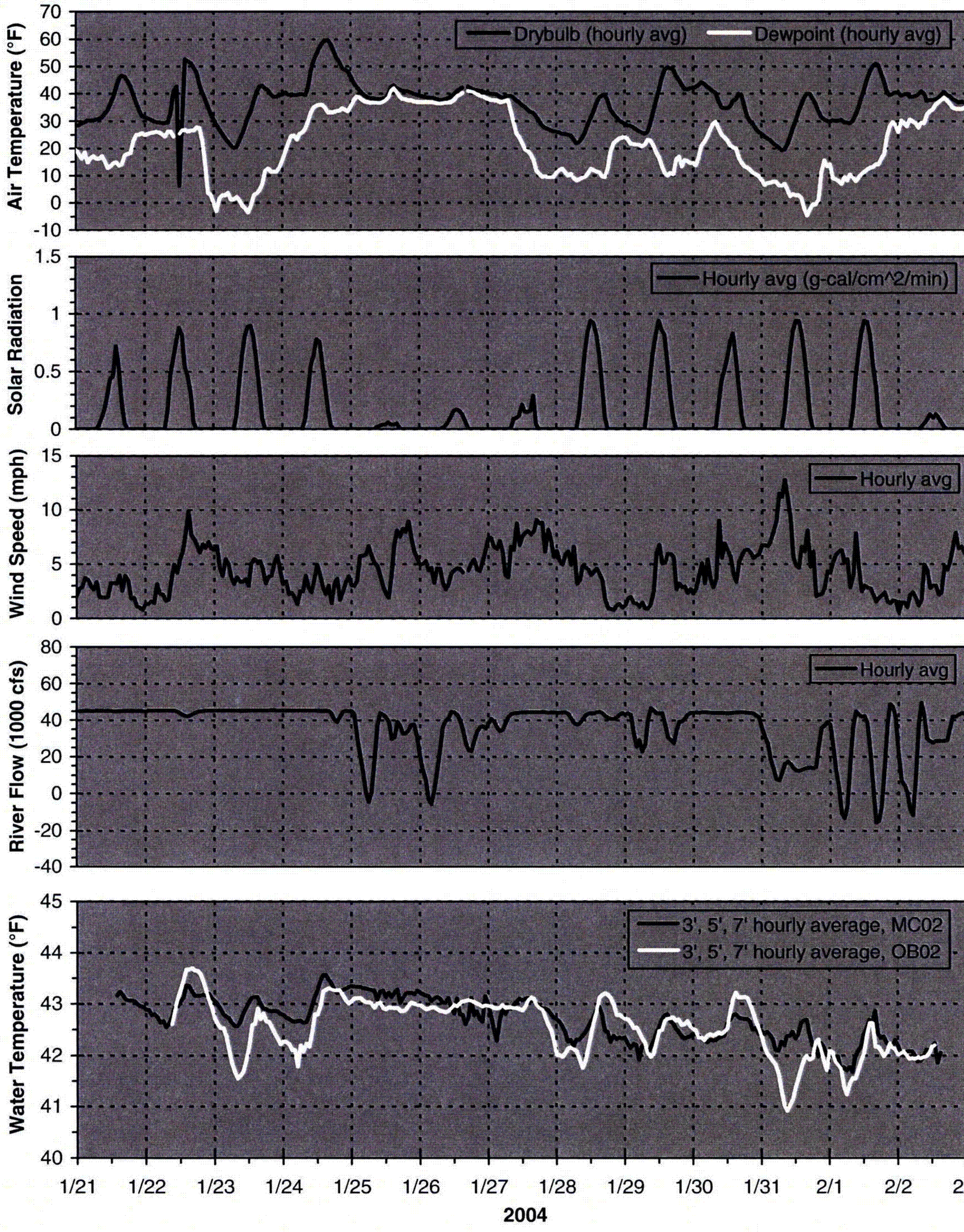


Figure 24. Main Channel and Overbank Stations MC02 and OB02 for Winter Deployment

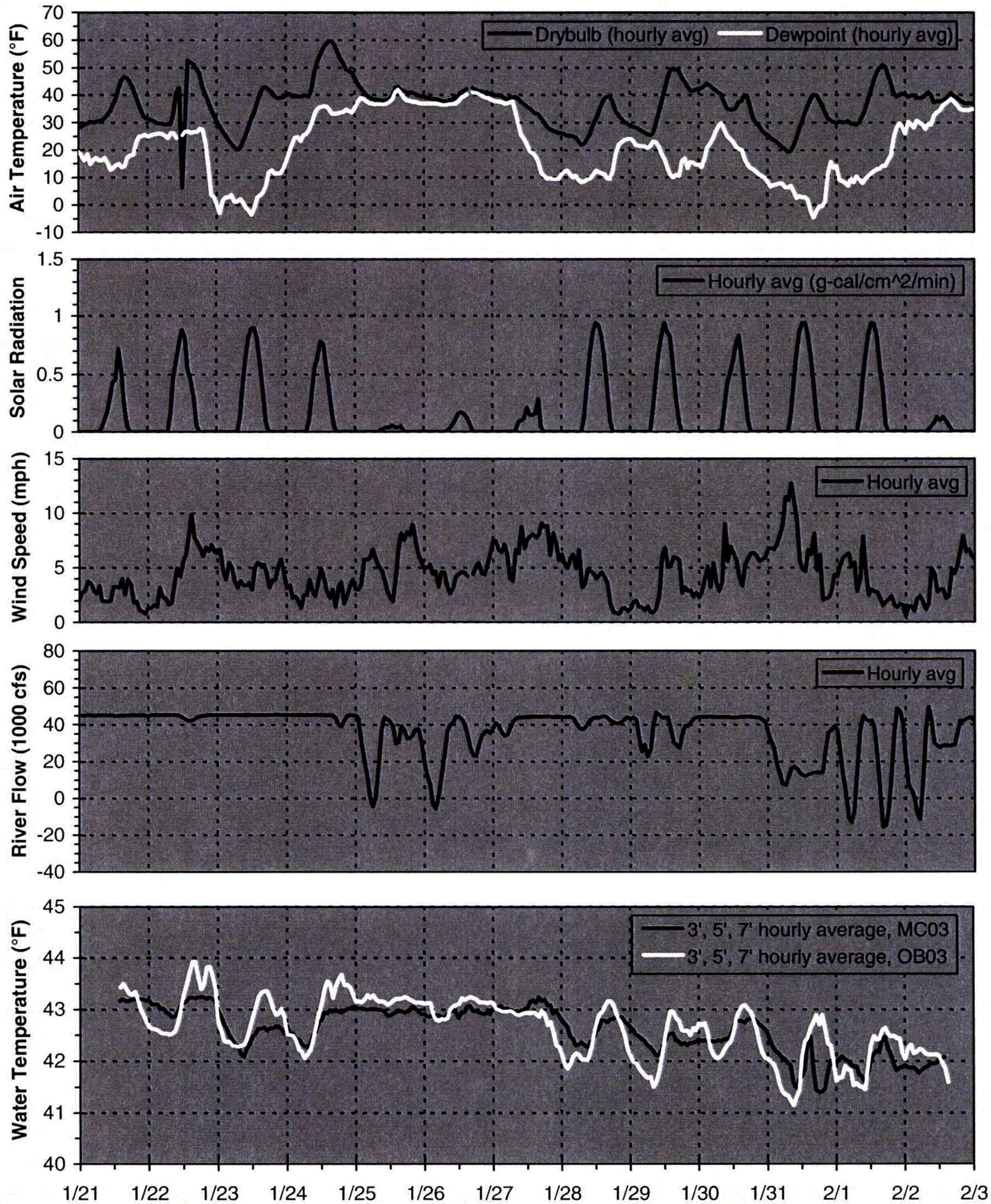


Figure 25. Main Channel and Overbank Stations MC03 and OB03 for Winter Deployment

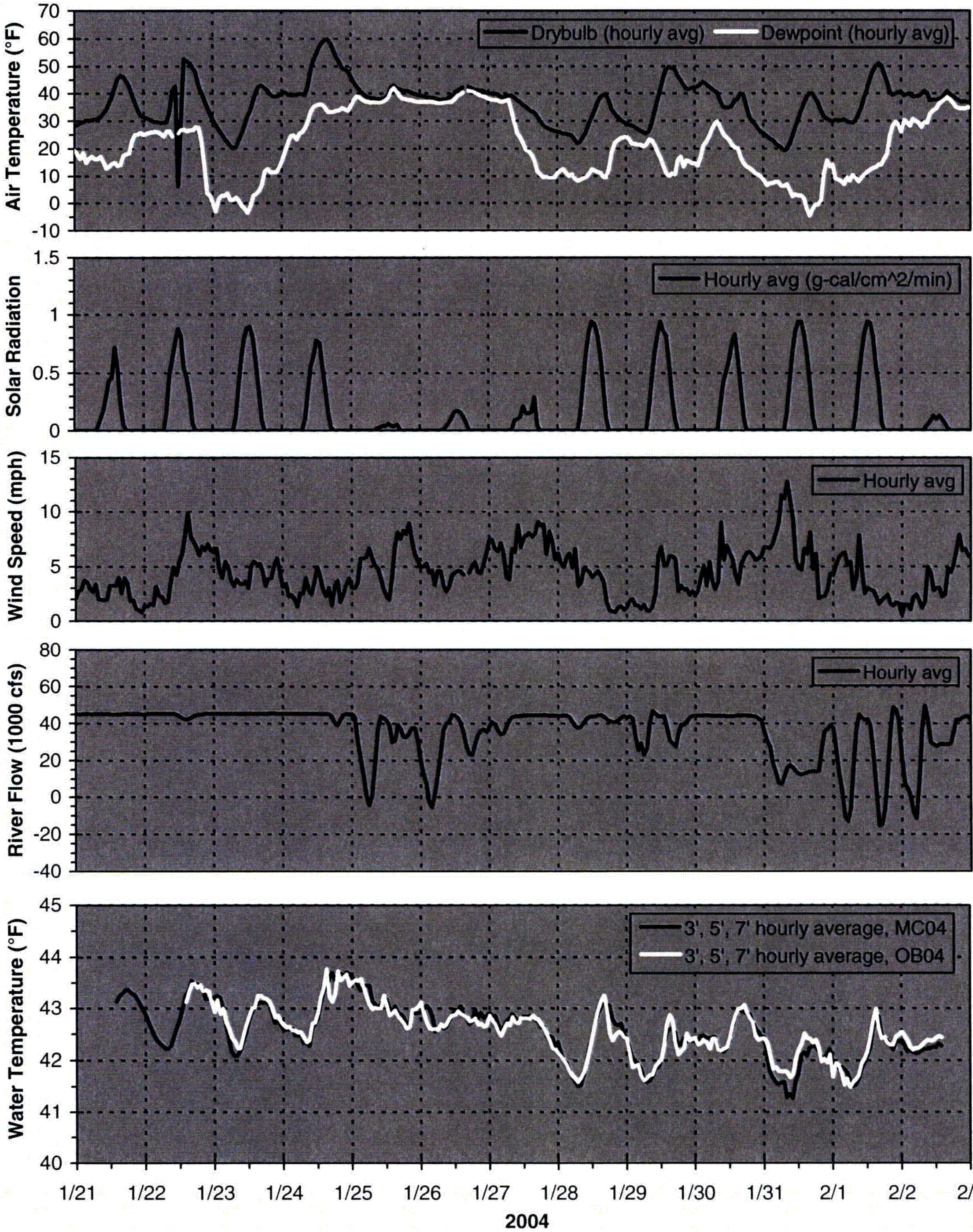


Figure 26. Main Channel and Overbank Stations MC04 and OB04 for Winter Deployment

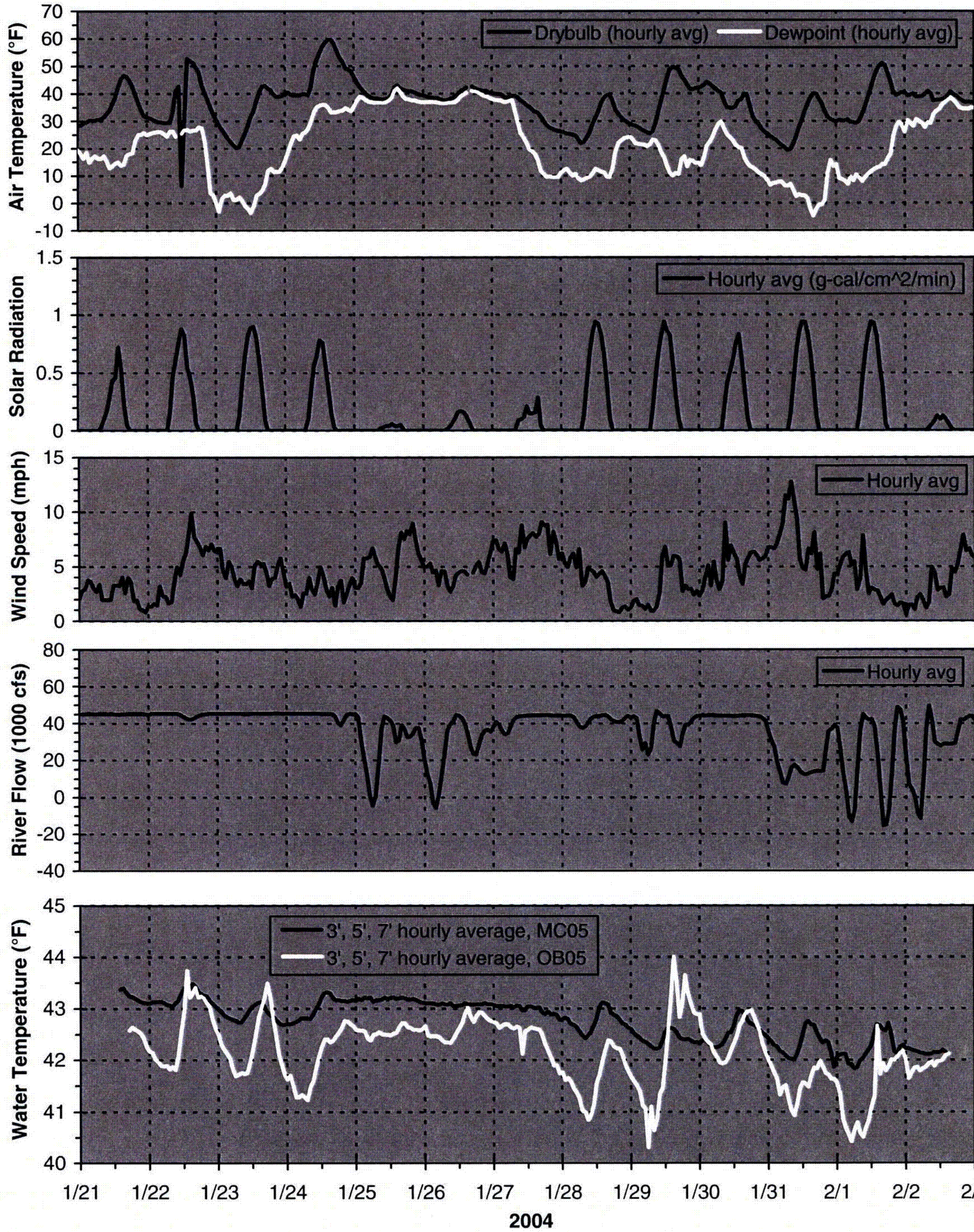


Figure 27. Main Channel and Overbank Stations MC05 and OB05 for Winter Deployment

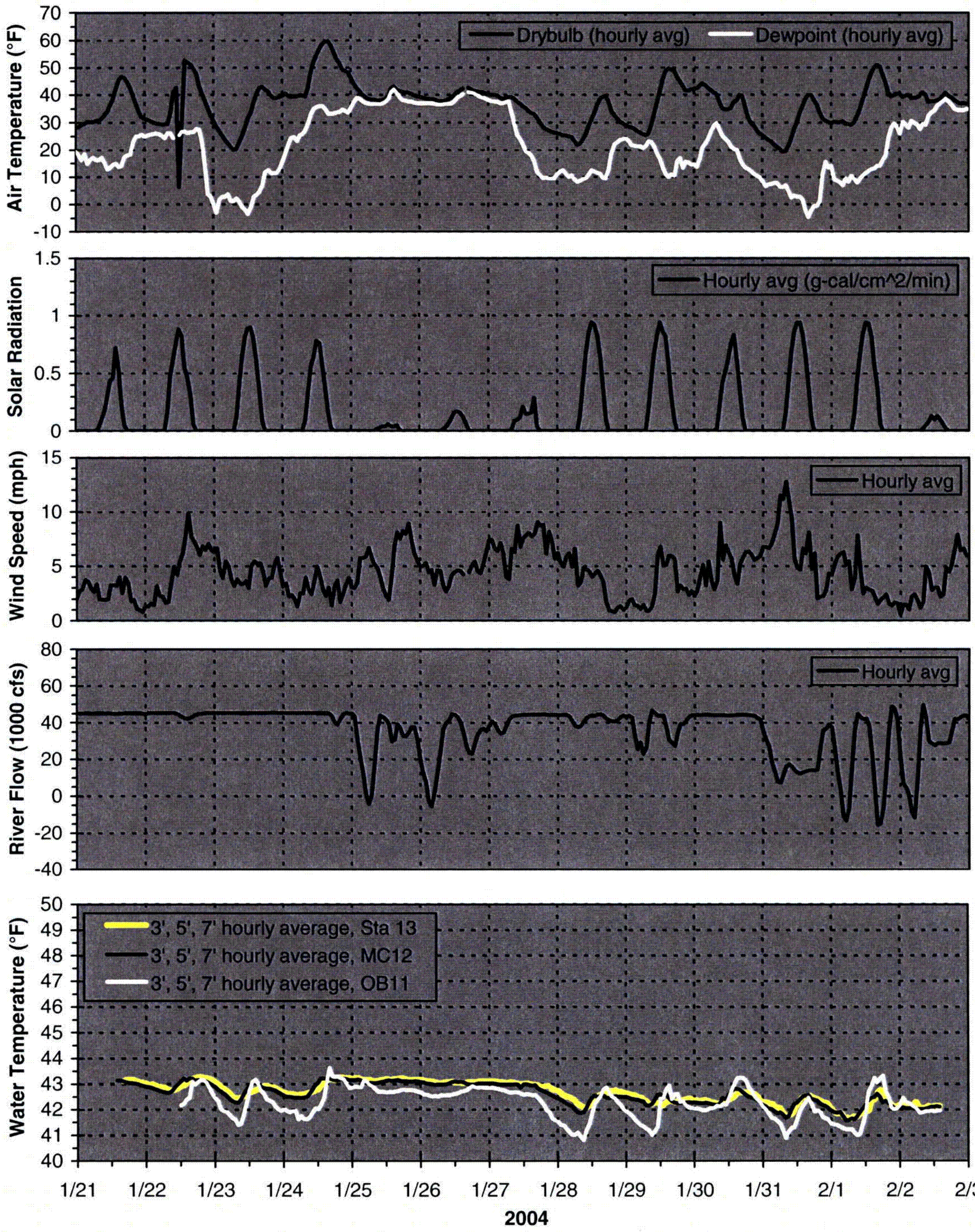


Figure 28. Main Channel and Overbank Stations MC12, OB11, and Station 13 for Winter Deployment

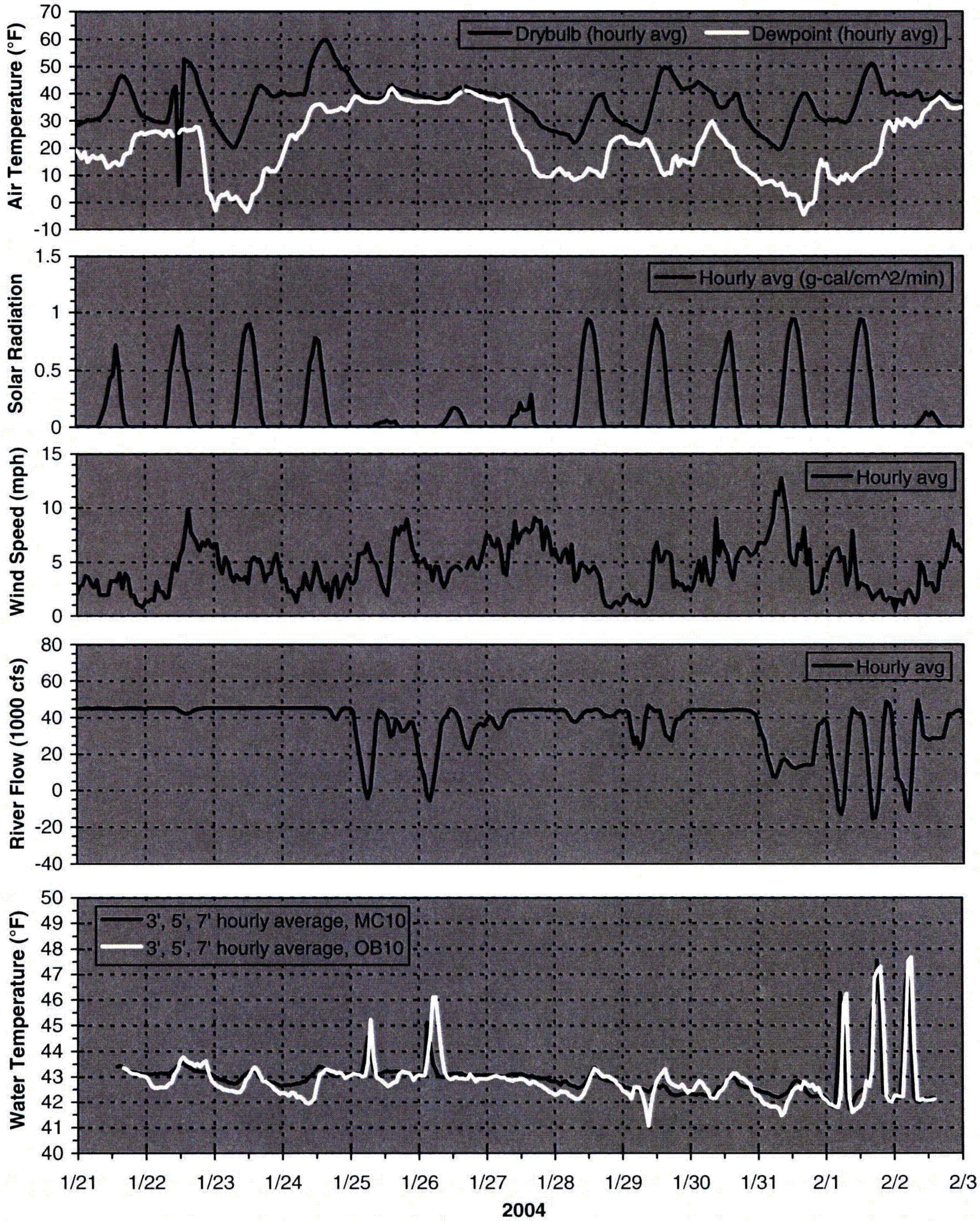


Figure 29. Main Channel and Overbank Stations MC10 and OB10 for Winter Deployment

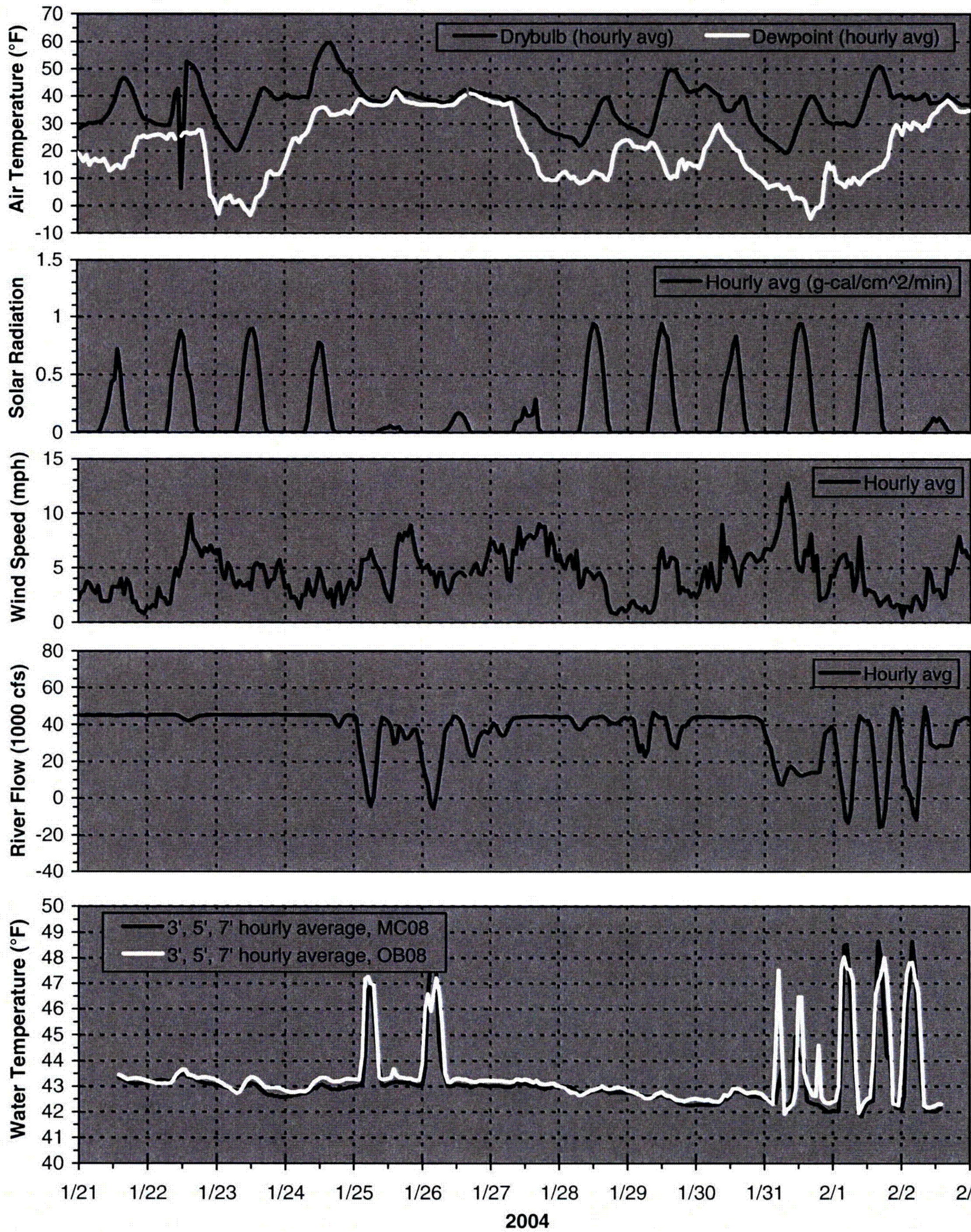


Figure 30. Main Channel and Overbank Stations MC08 and OB08 for Winter Deployment

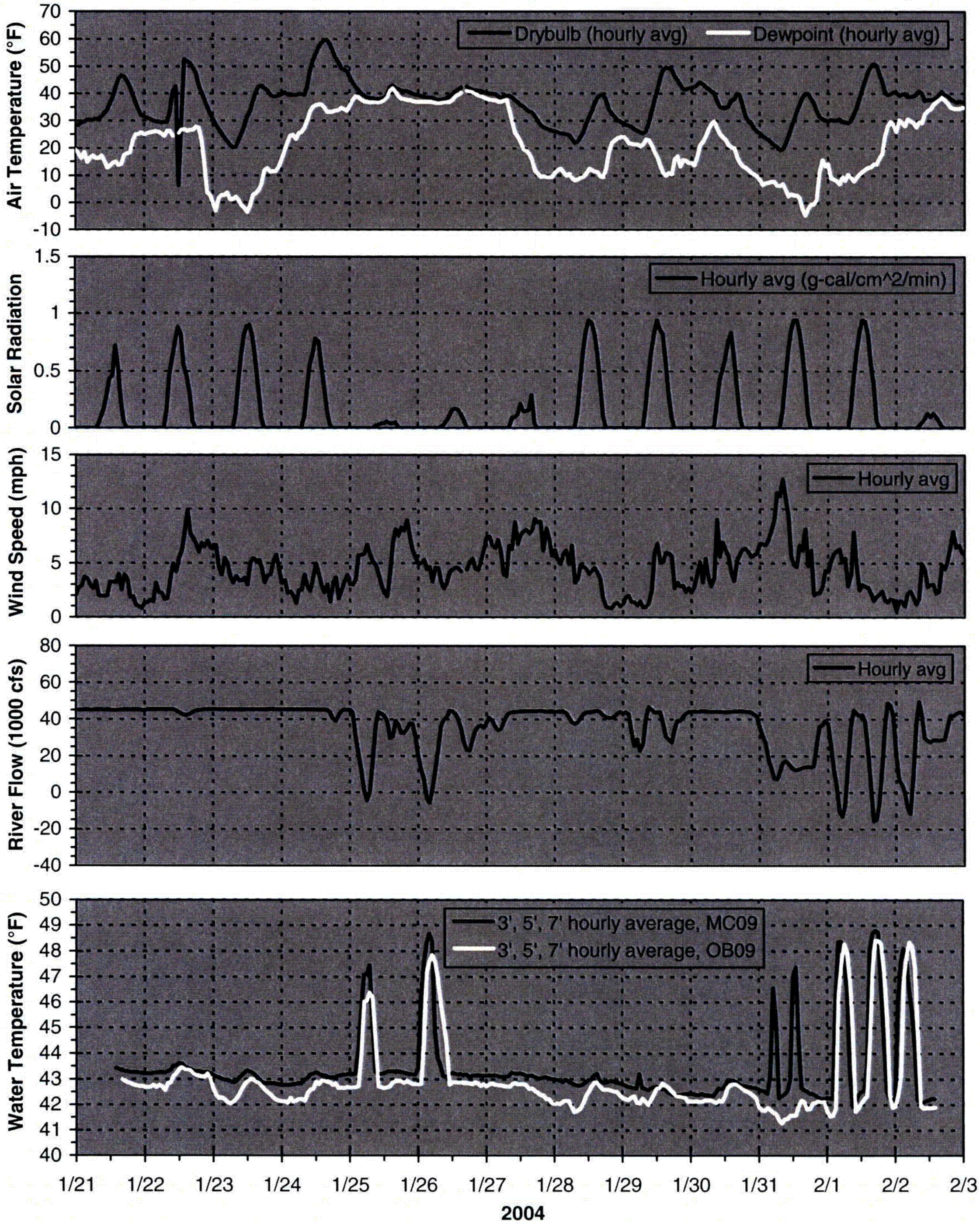


Figure 31. Main Channel and Overbank Stations MC09 and OB09 for Winter Deployment

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.

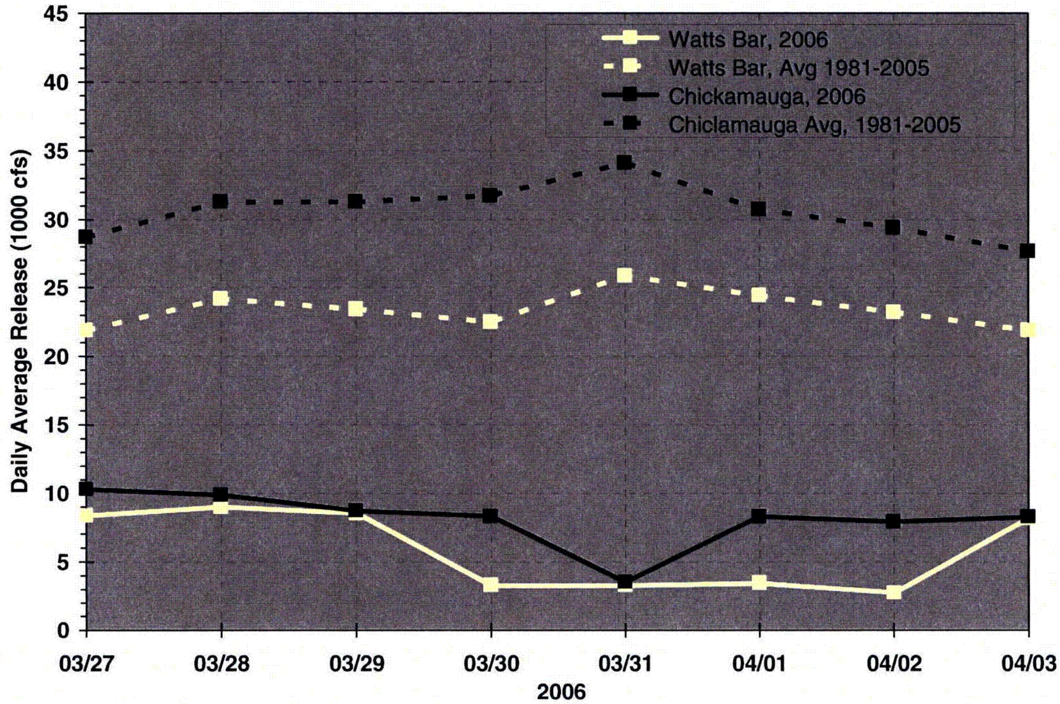


Figure 32. Releases Upstream (Watts Bar) and Downstream (Chickamauga) of SQN

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.

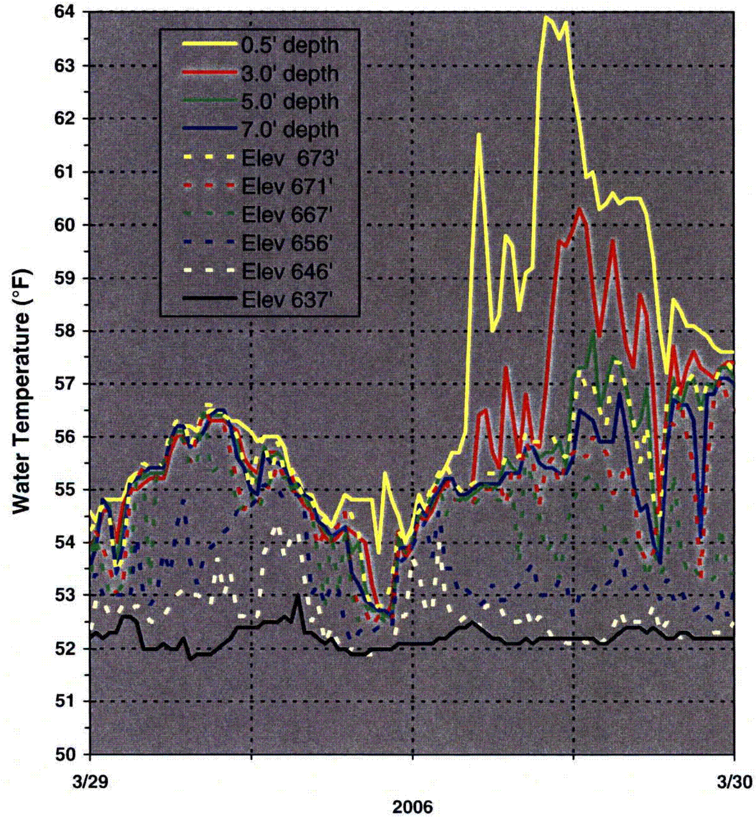


Figure 33. SQN Ambient River Temperatures Measured at Station 13 on March 29, 2006

Figure 34. Station 14 Floating Water Temperature Station

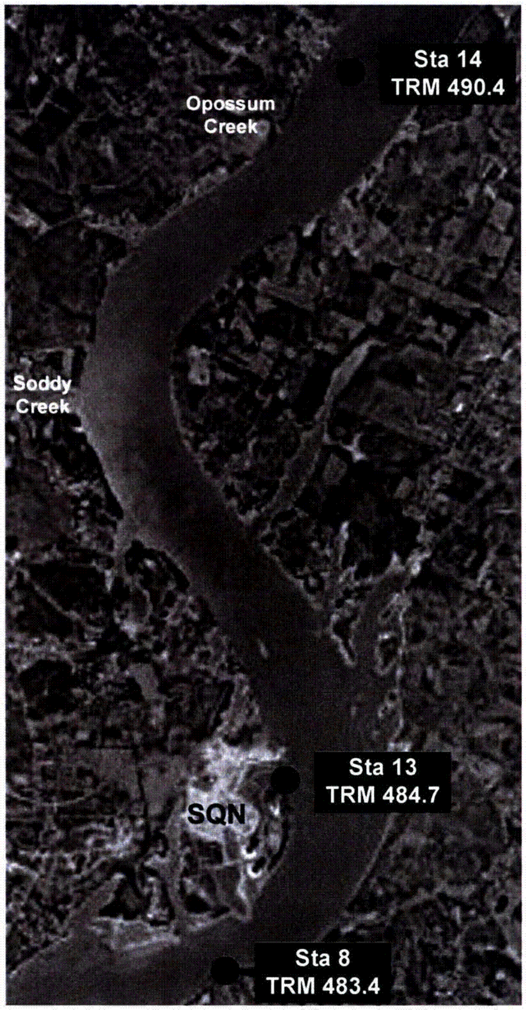


Figure 35. Location of New Ambient Temperature Station

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™ 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.

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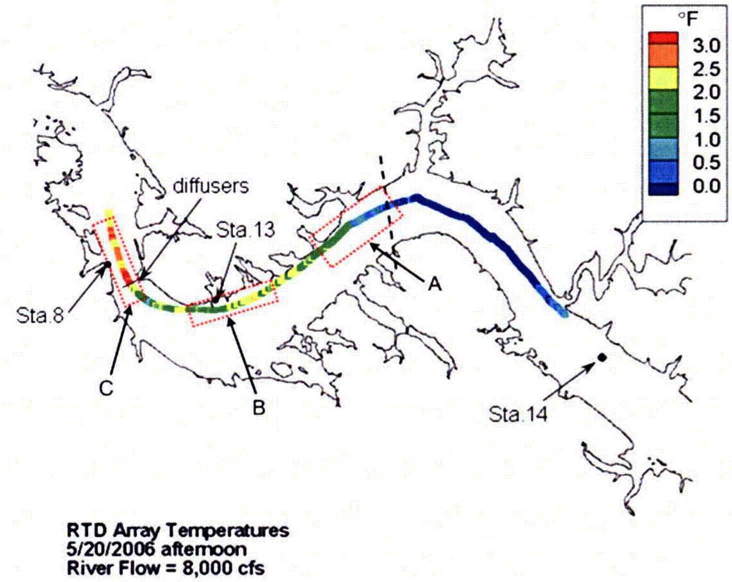

Figure 36. Temperature Rise along Center of River for Steady River Flow of 8000 cfs

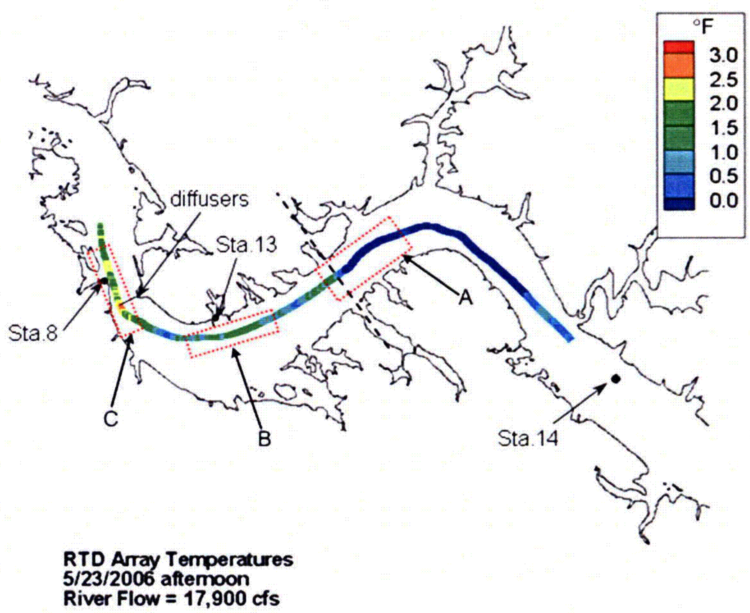

Figure 37. Temperature Rise along Center of River for Steady River Flow of 18,000 cfs

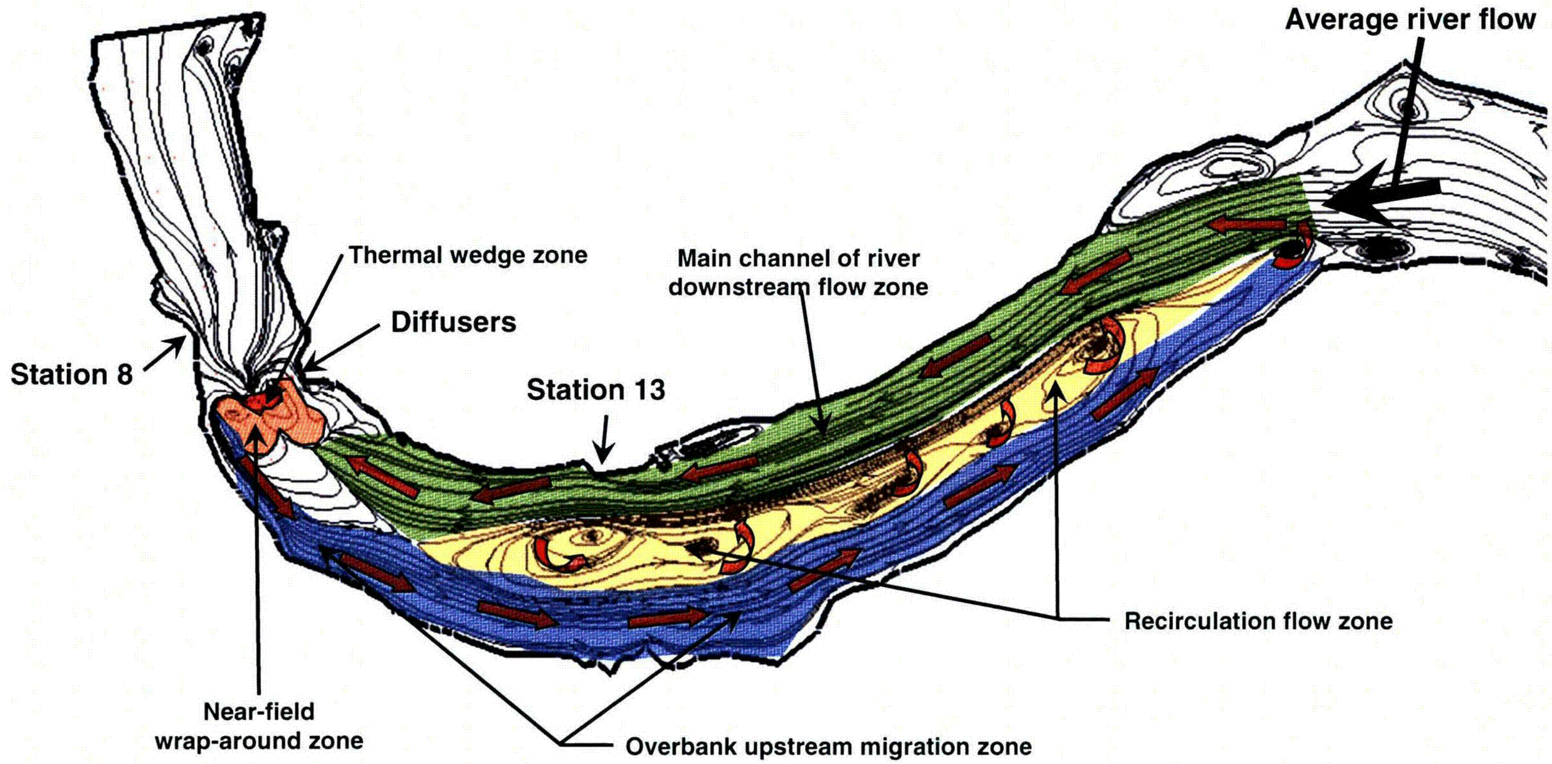

Figure 38. Upstream Migration of Thermal Effluent for Steady, Low River Flow

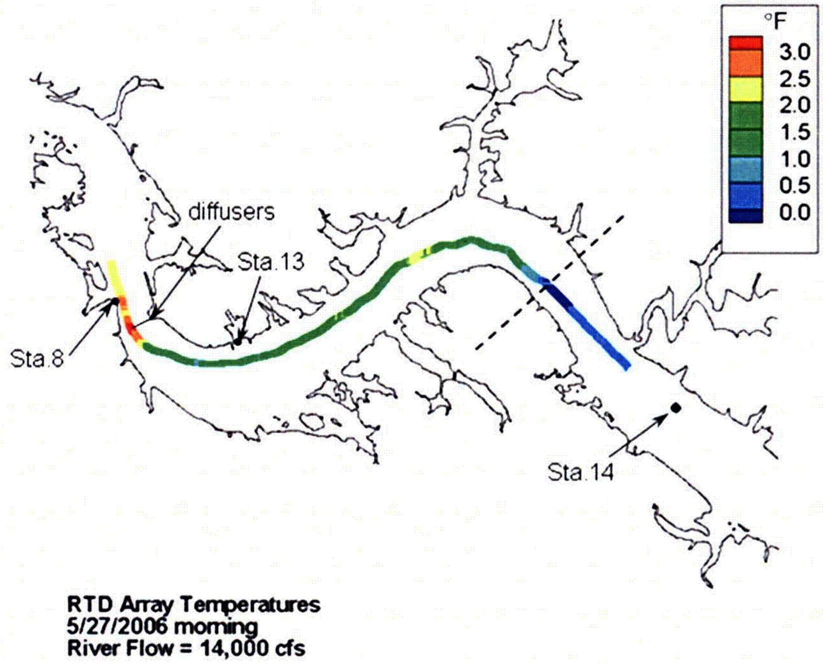

Figure 39. Temperature Rise along Center of River following Peaking Operations at 14,000 cfs

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.

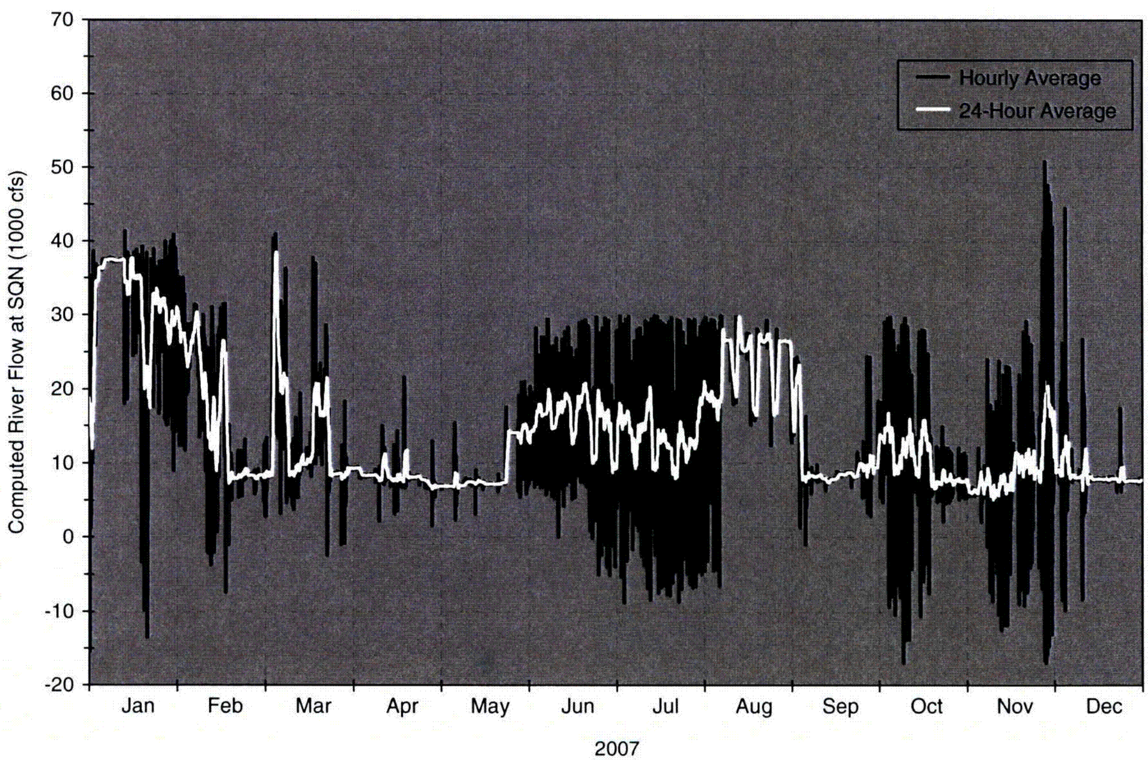

Figure 40. Computed River Flow at SQN for 2007

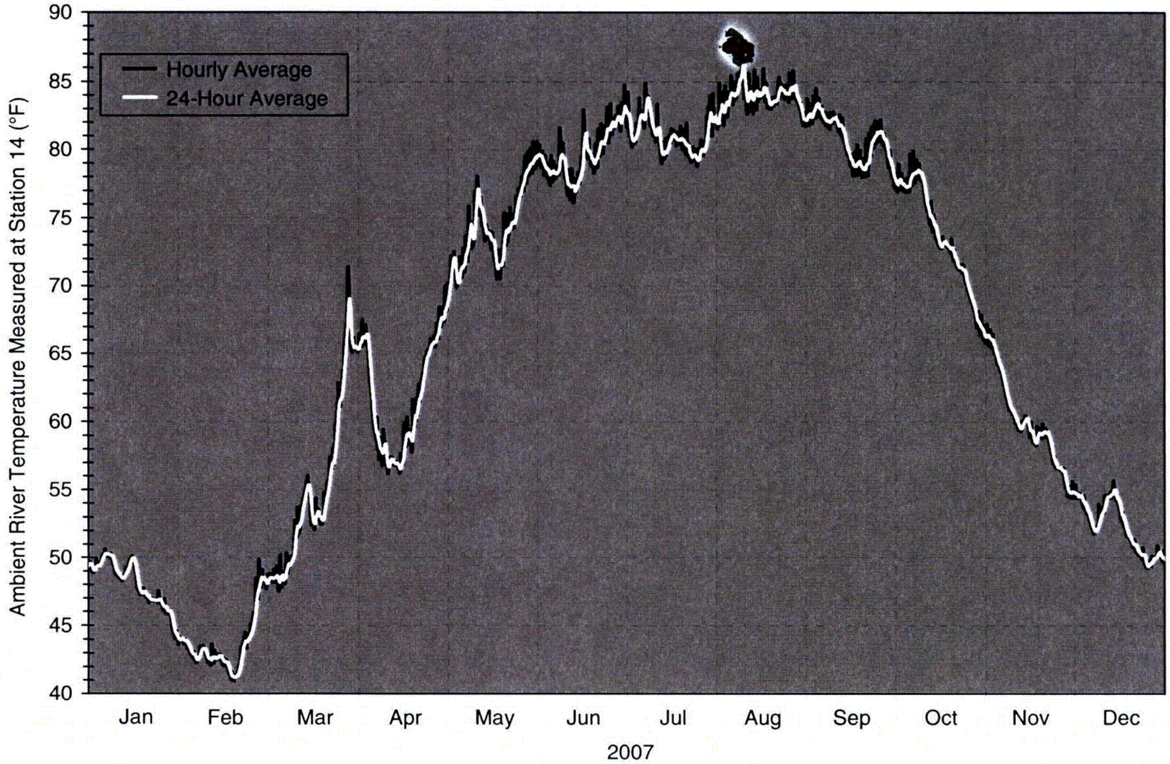

Figure 41. Ambient Water Temperature Measured at SQN Station 14 for 2007

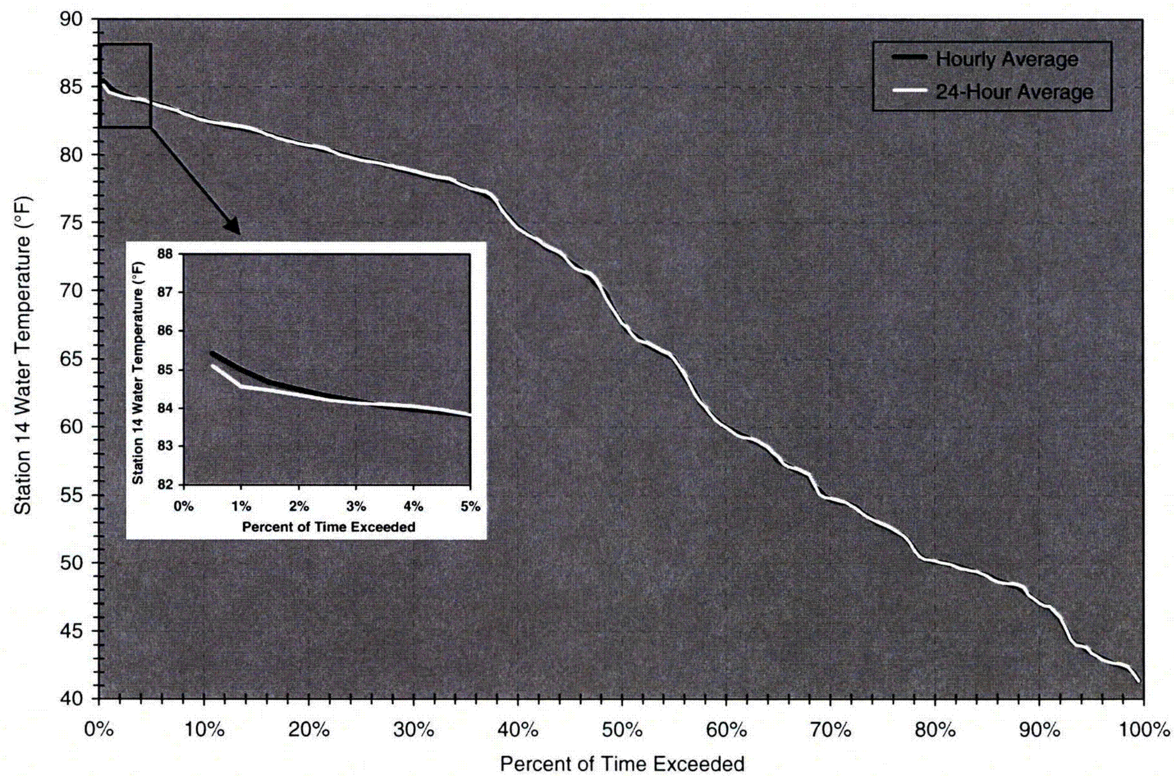

Figure 42. Exceedance Probability for Ambient Water Temperature at Station 14 for 2007

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.

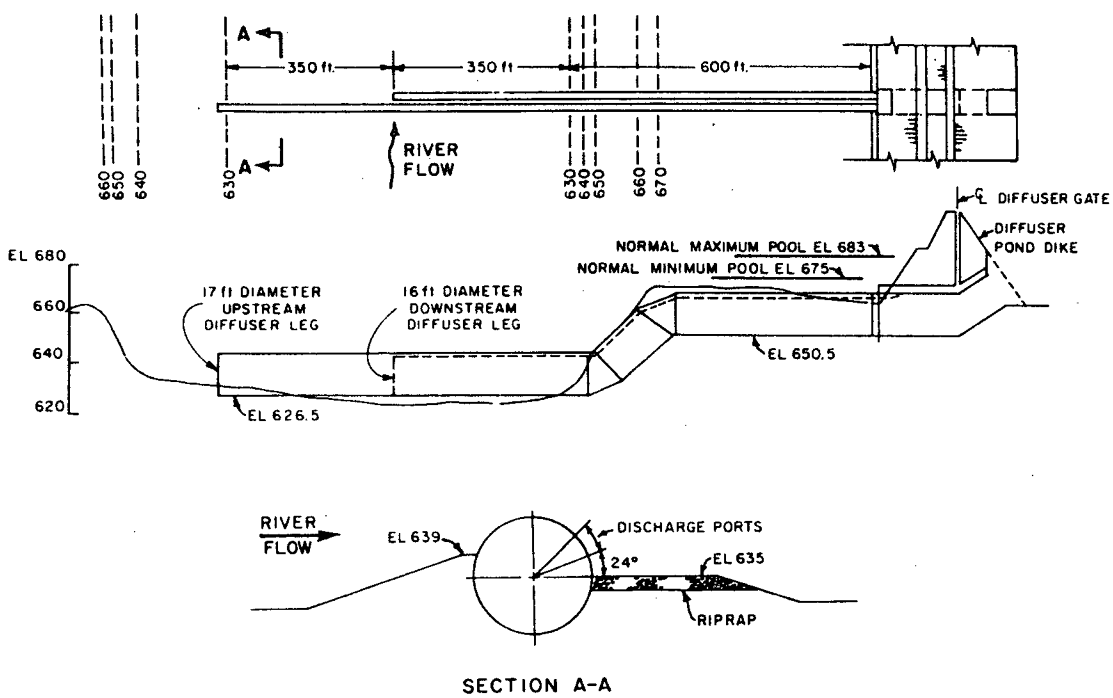

Figure 43. Basic Design Features of Sequoyah Diffusers

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.

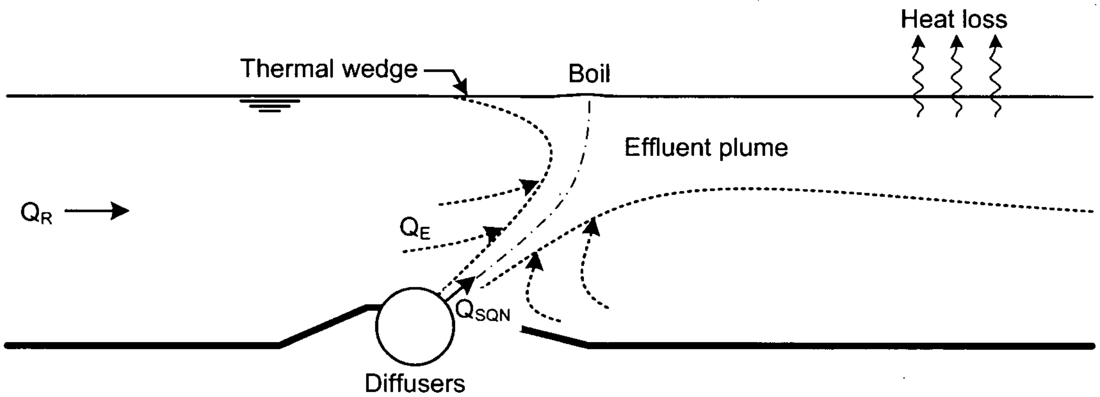

Figure 44. Basic Behavior of Effluent Plume

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.

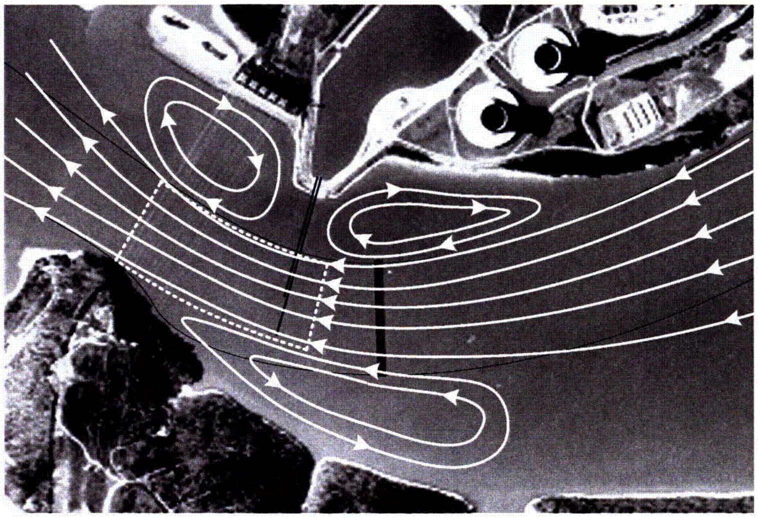

Figure 45. Recirculation Zones Created By Diffuser Mixing

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.

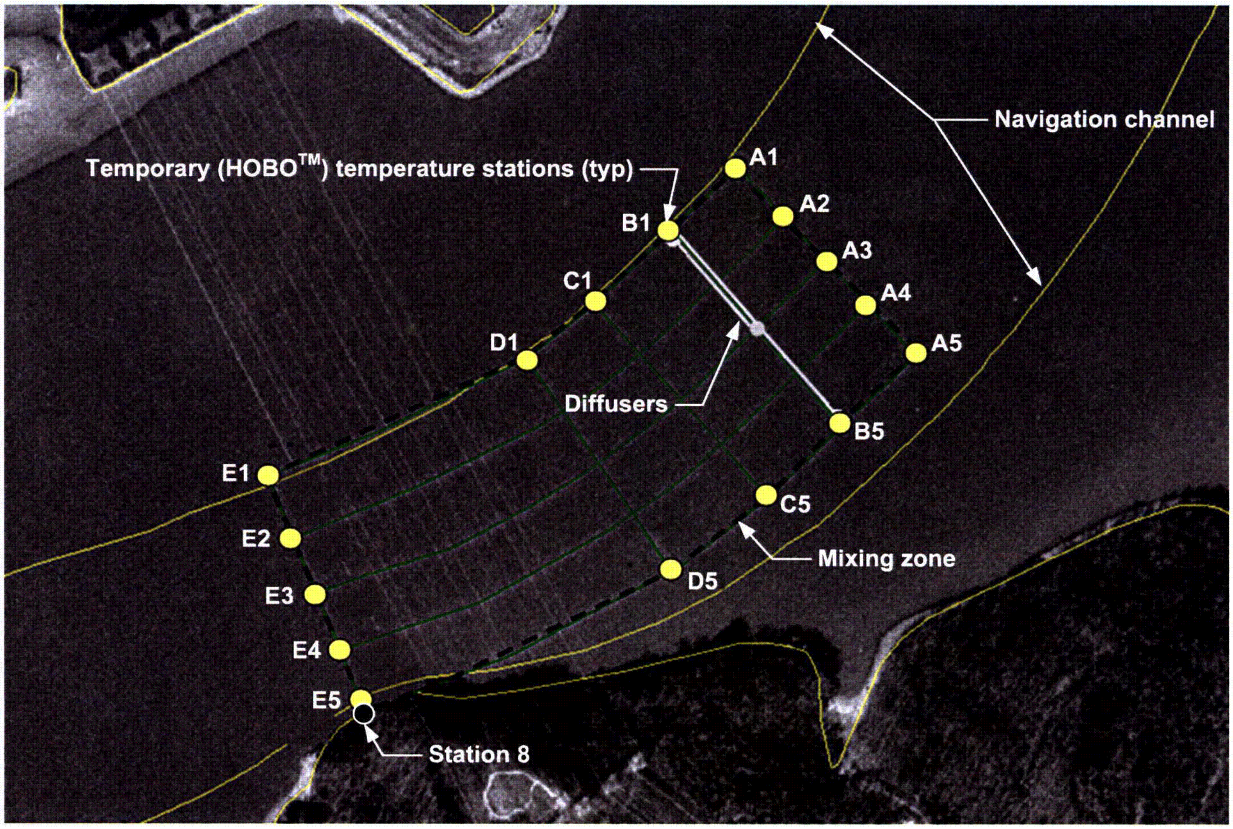

Figure 46. Location of Stations for Mixing Zone Temperature Measurements

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.

Figure 47

- 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 **ΔT**=5.4 F° (3.0 C°) 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 F° (3.0 C°) in the summer.

<u>Figure 49</u>

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).

<u>Figure 50</u>

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).

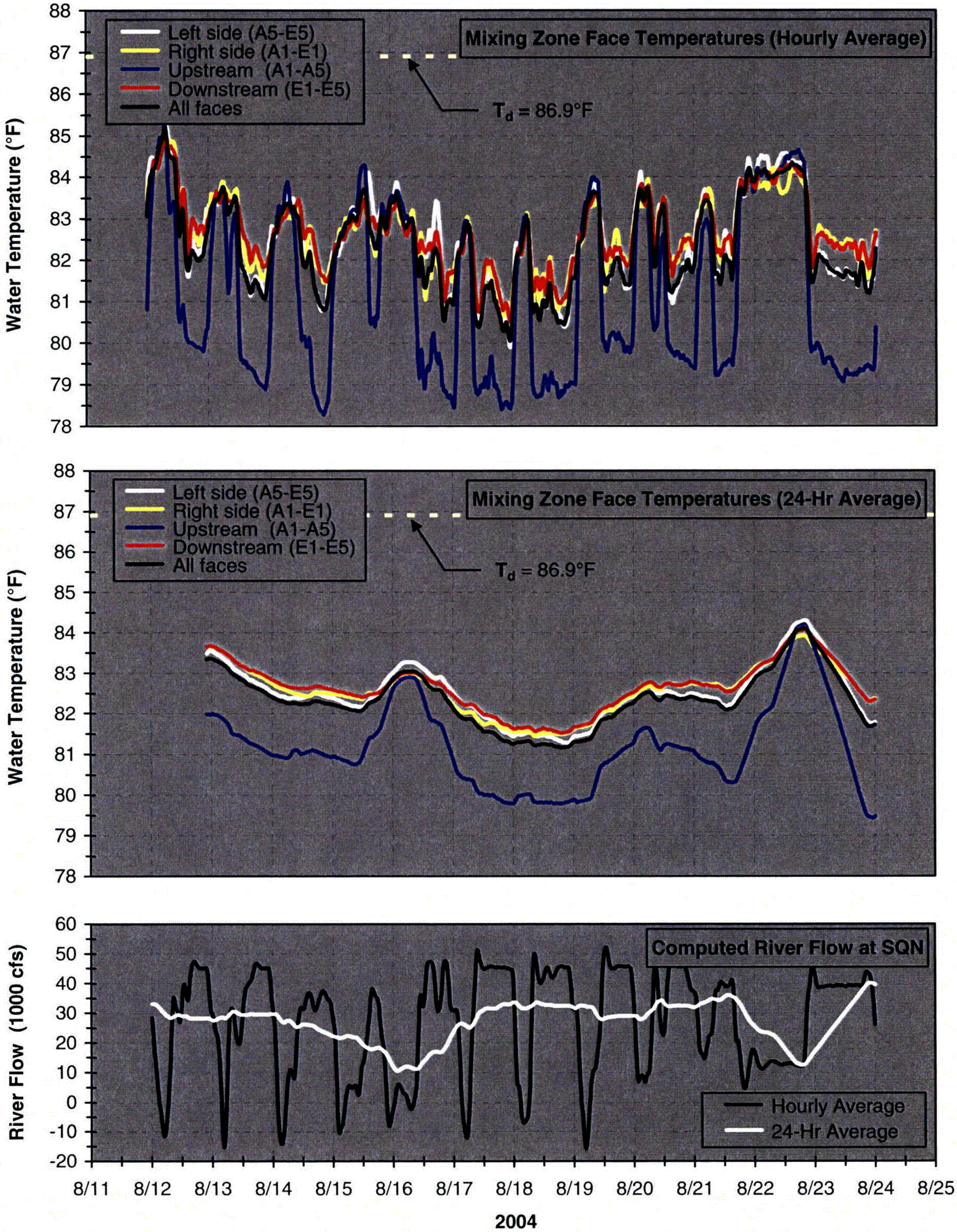

Figure 47. Mixing Zone Temperatures For Summer Deployment

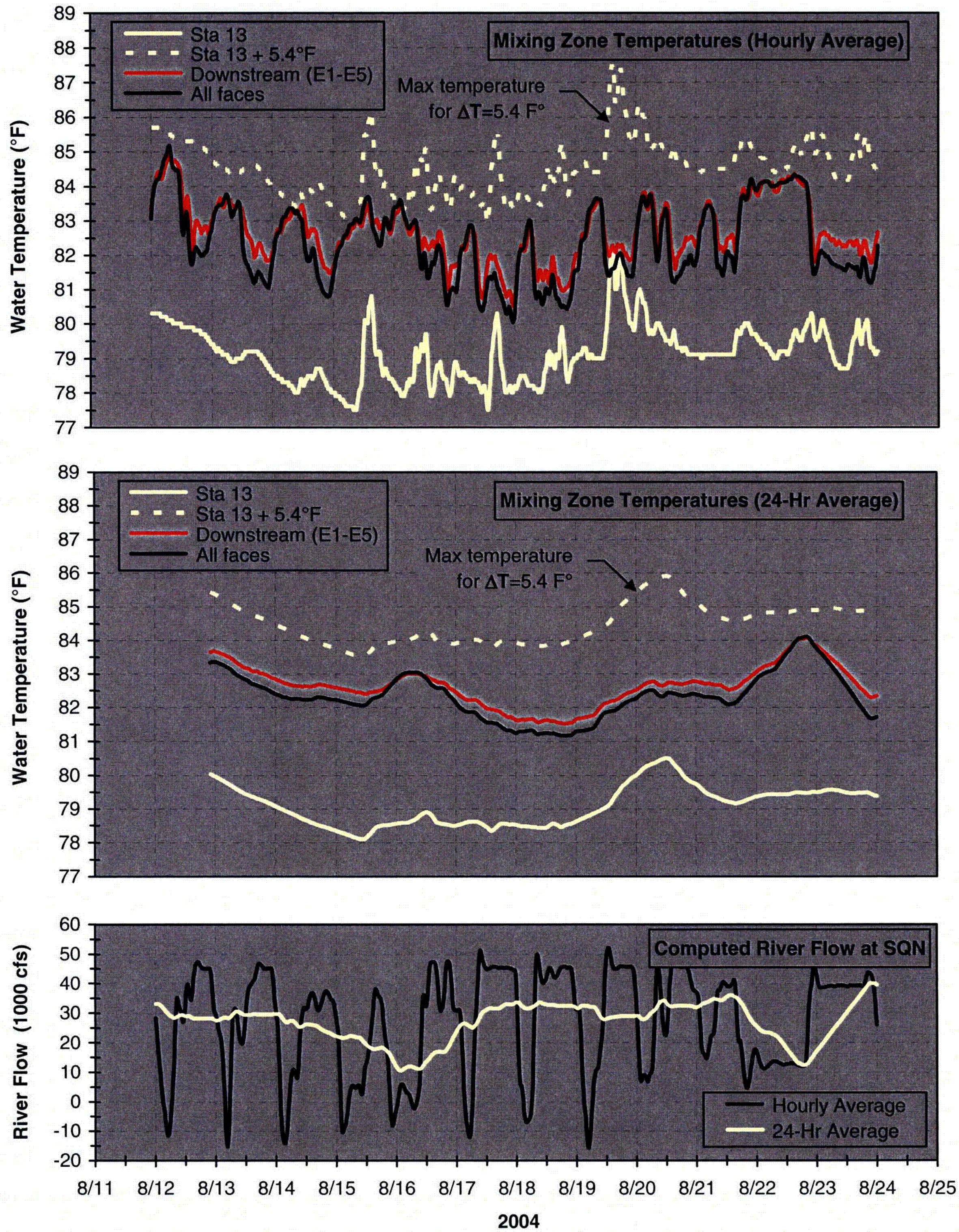

Figure 48. Mixing Zone Temperatures For Summer Deployment Showing Temperature Rise

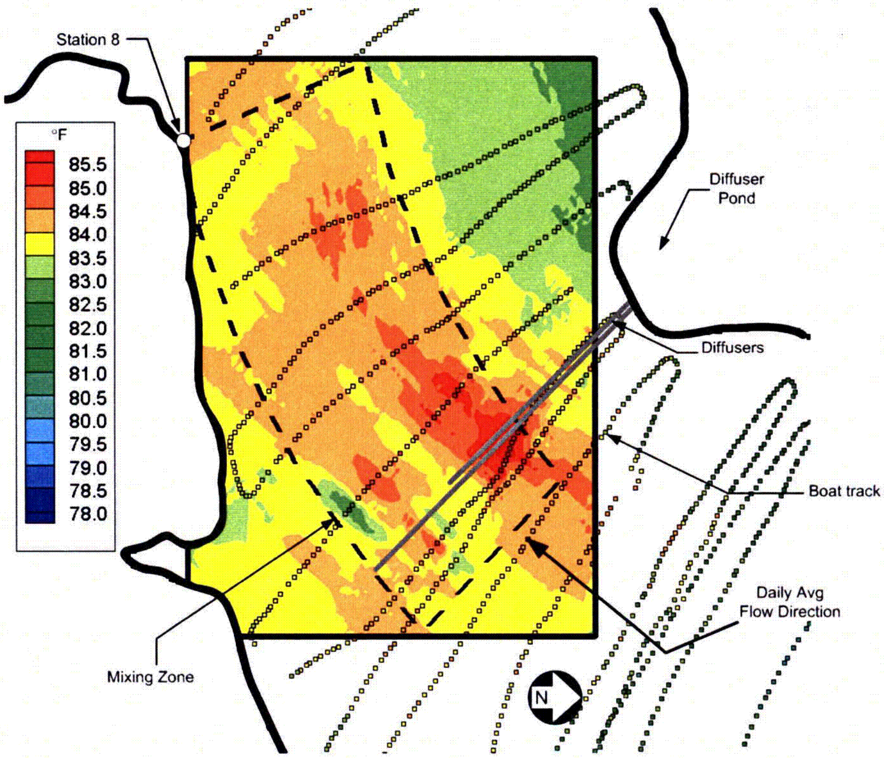

Figure 49. Water Temperature Measurements at 5-foot depth for August 22, 2004

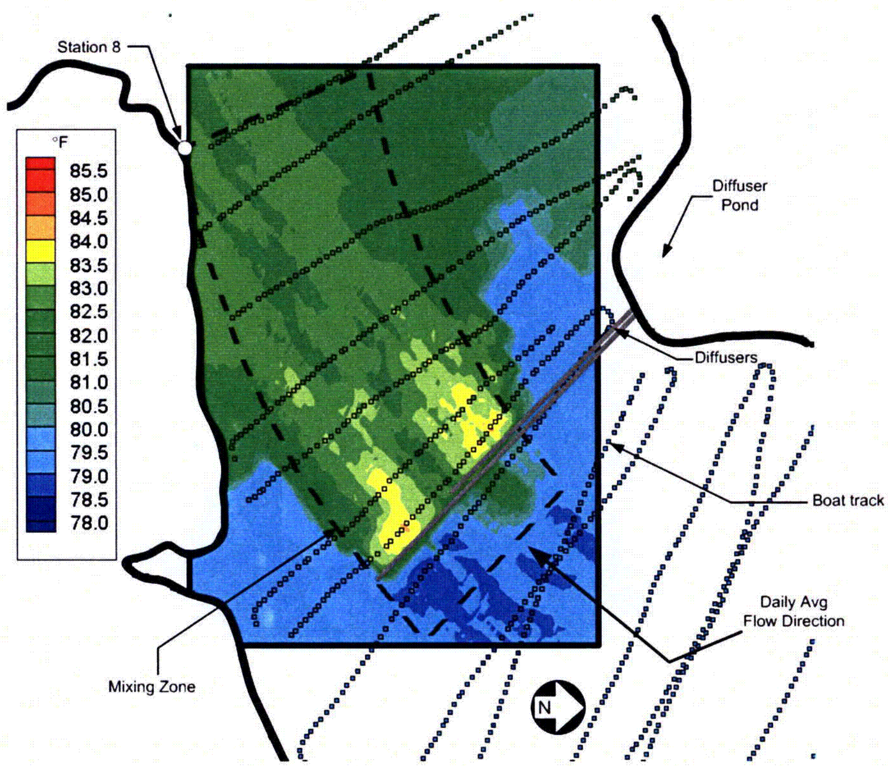

Figure 50. Water Temperature Measurements at 5-foot depth for August 23, 2004

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 $\mathbf{T_d}$=86.9°F (30.5°C) 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 **ΔT**=9.0 F° (5.0 C°) 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 **ΔT**=9.0 F° (5.0 C°) 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.

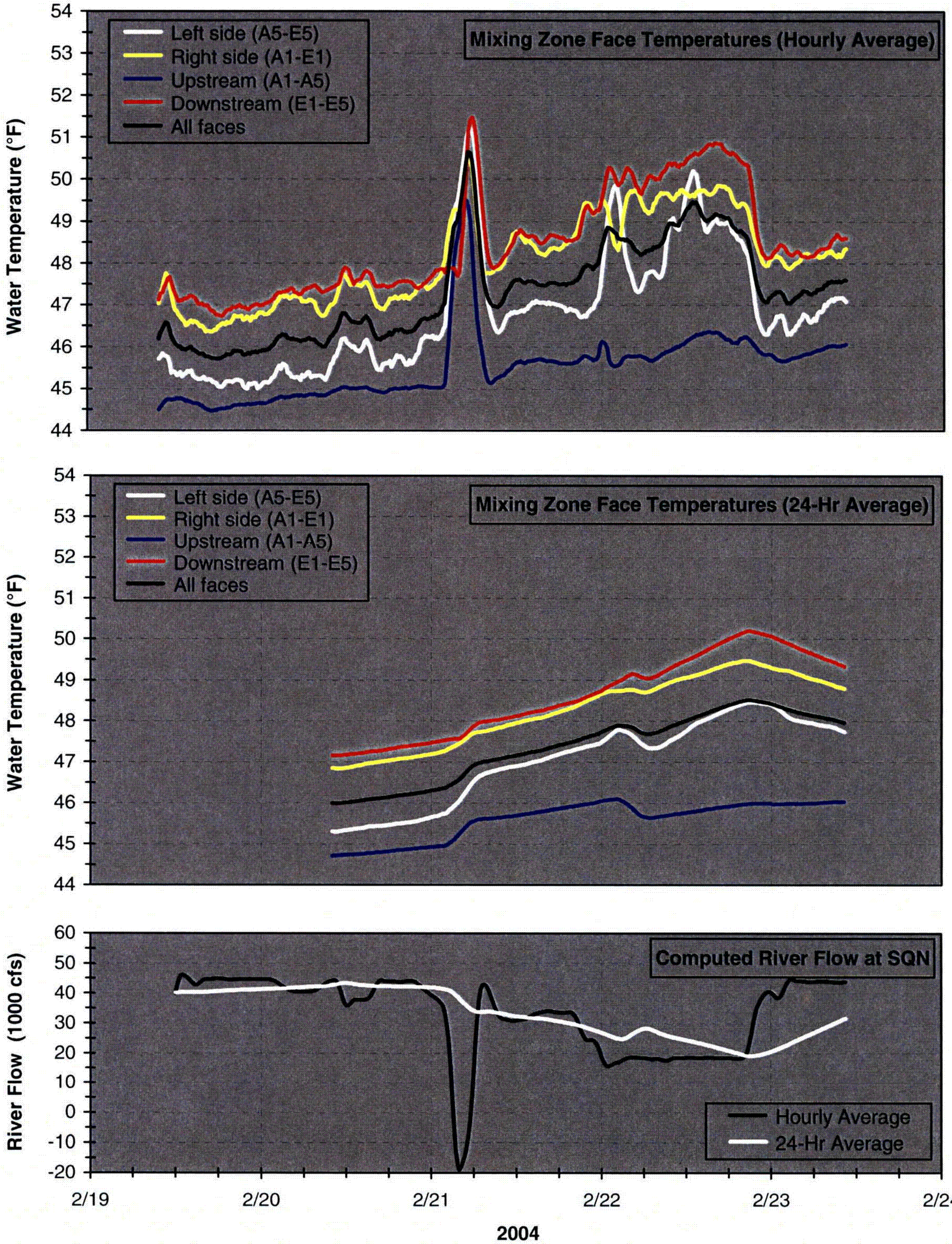

Figure 51. Mixing Zone Temperatures For Winter Deployment

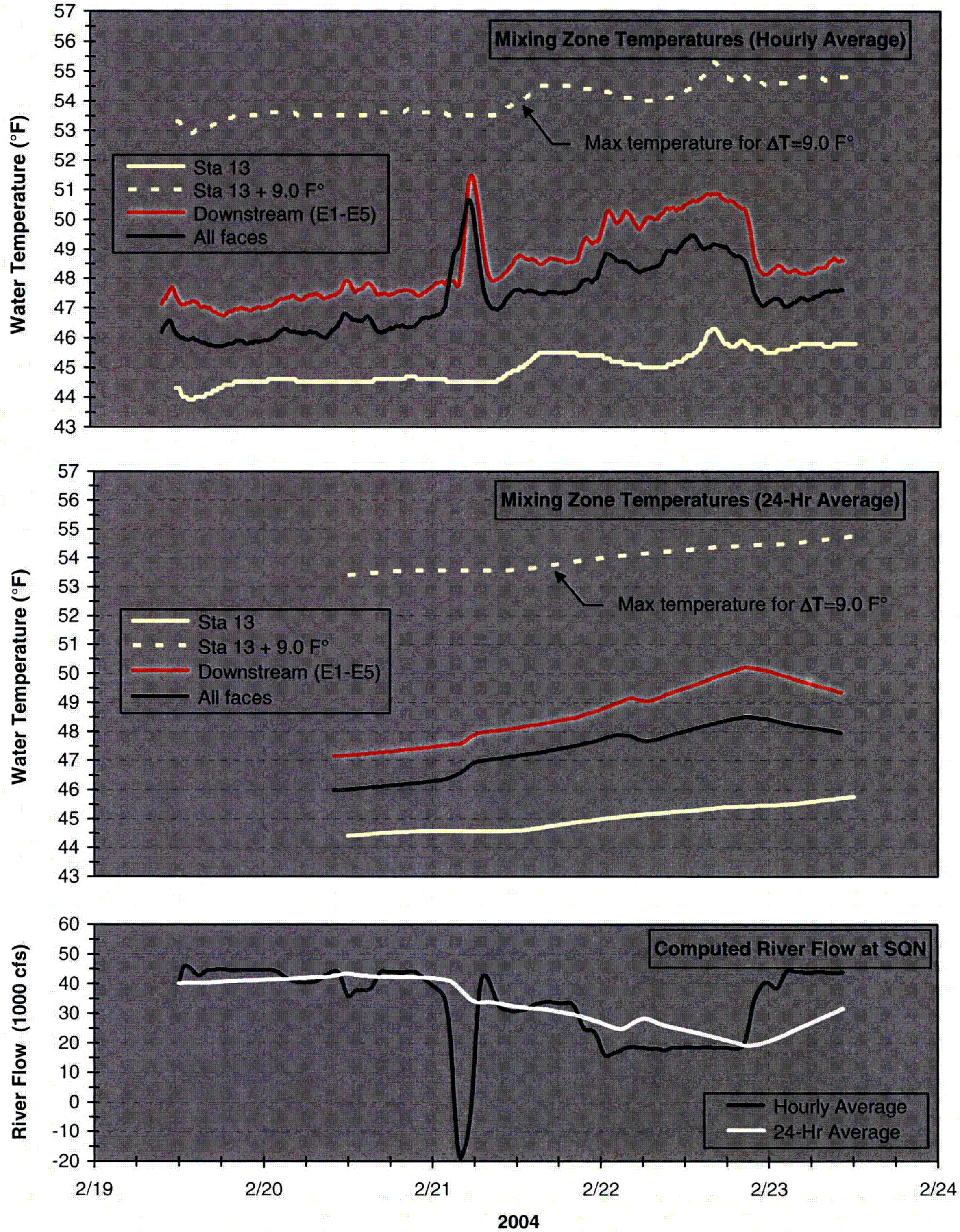

Figure 52. Mixing Zone Temperatures For Winter Deployment Showing Temperature Rise

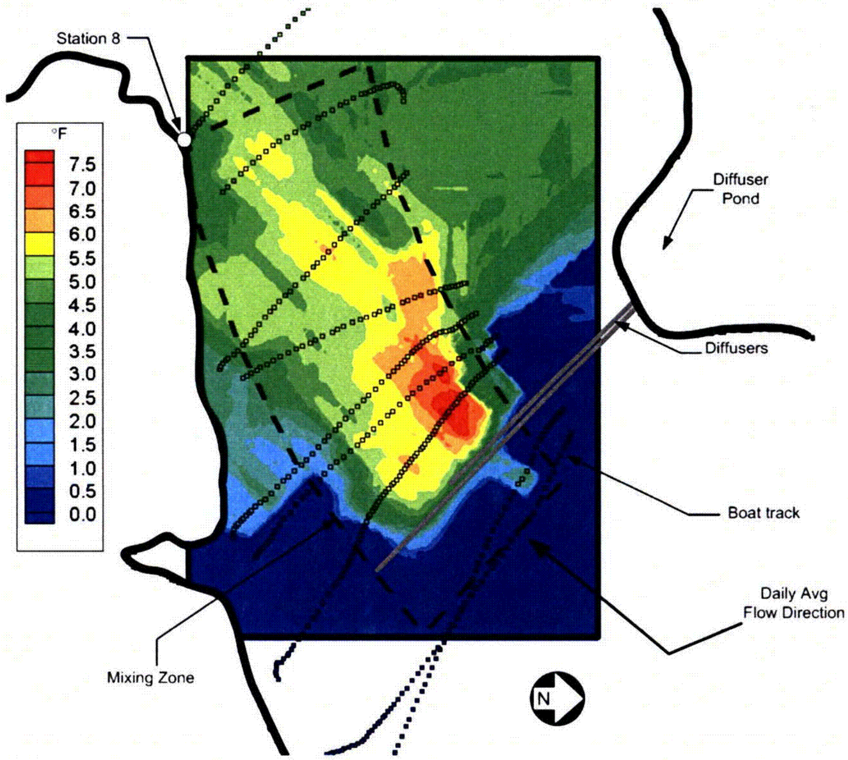

Figure 53. Temperature Rise Measurements at 5-foot depth for February 22, 2004

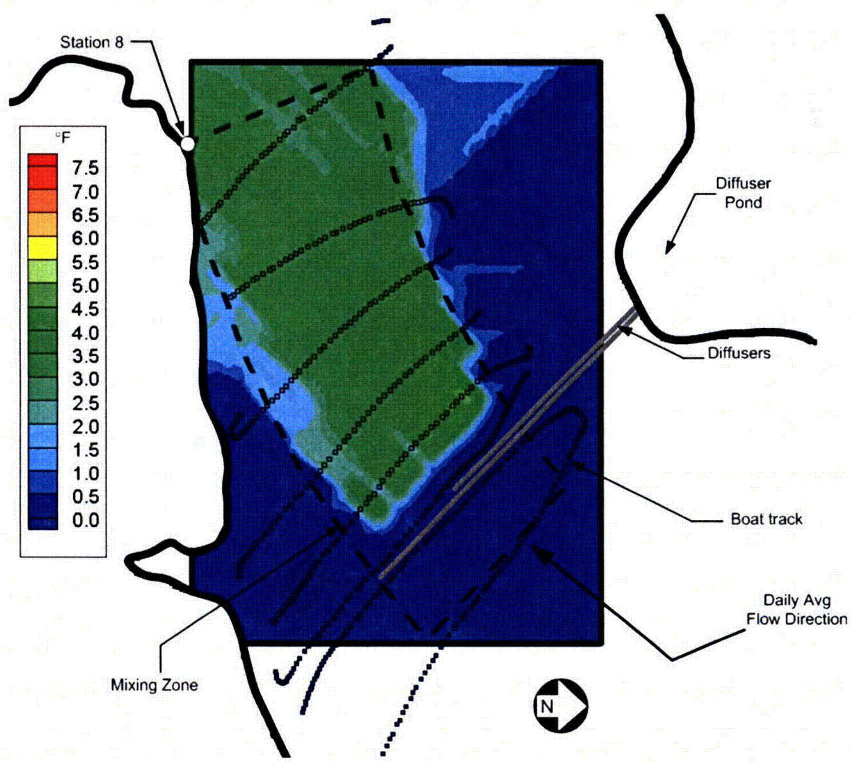

Figure 54. Temperature Rise Measurements at 5-foot depth for February 23, 2004

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 T_d=86.9°F (30.5°C) 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.

Figure 56

- 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 F° (3.0 C°).

- 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 F° (3.0 C°).

Figure 57

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).

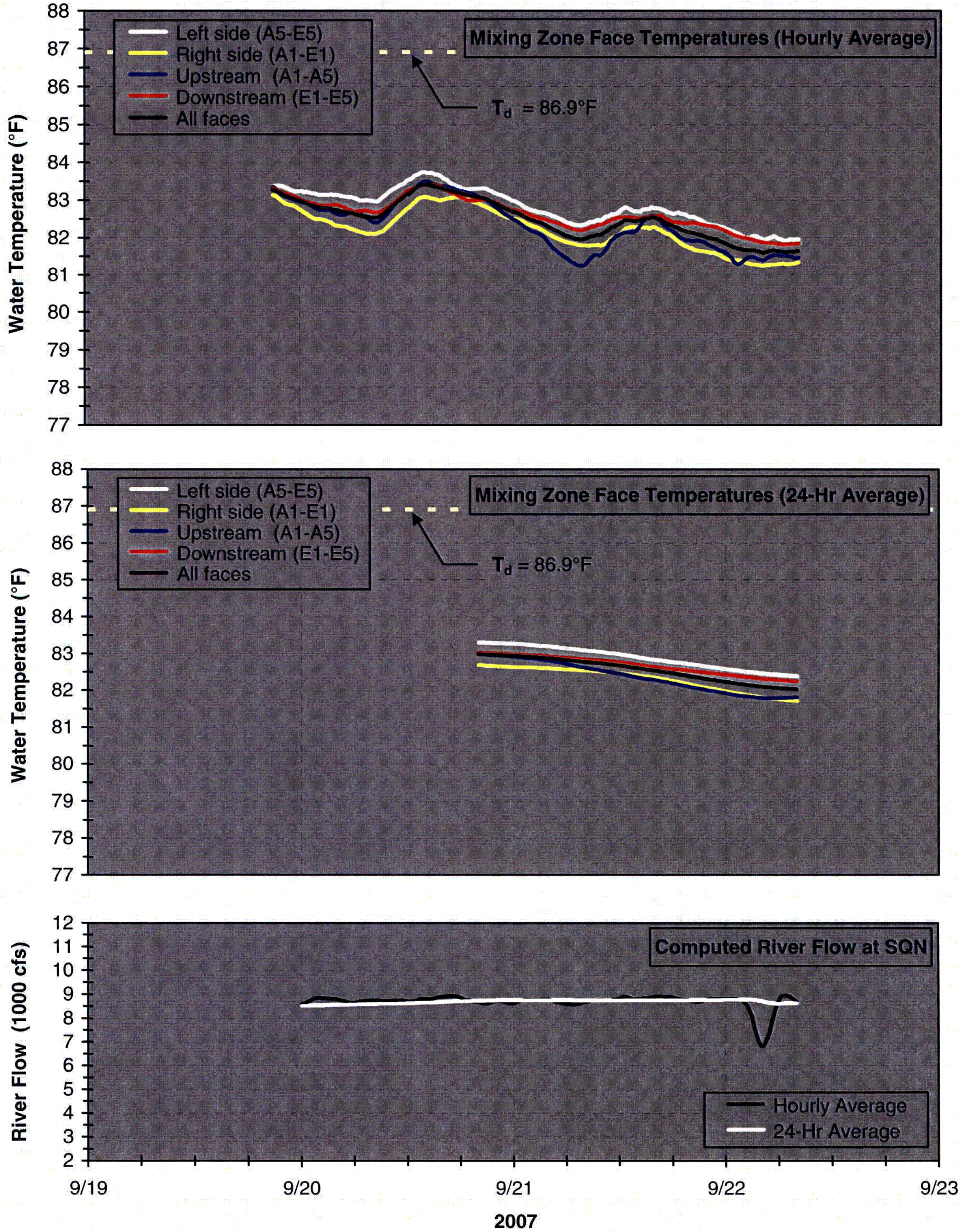

Figure 55. Mixing Zone Temperatures For Third Deployment

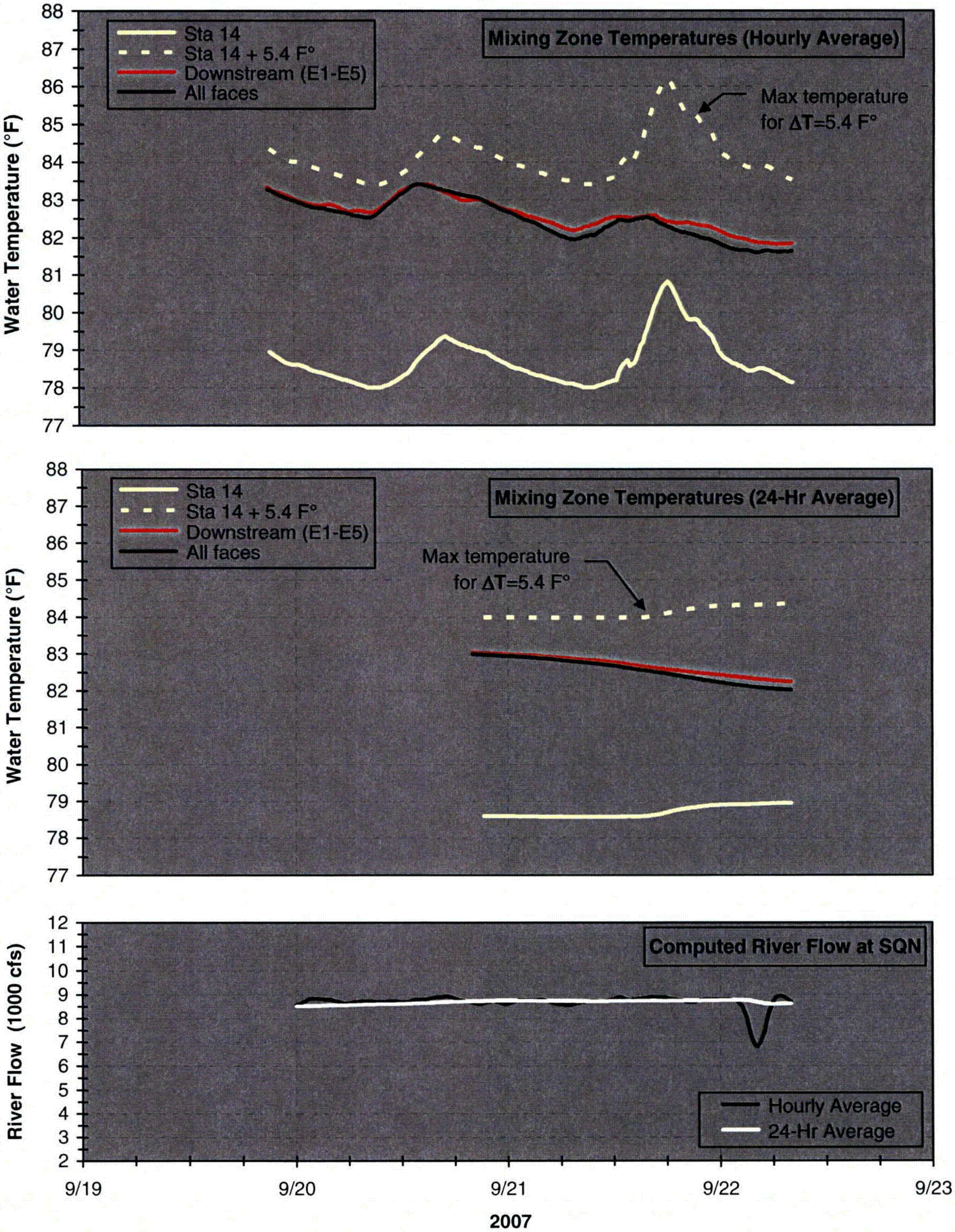

Figure 56. Mixing Zone Temperatures For Third Deployment Showing Temperature Rise

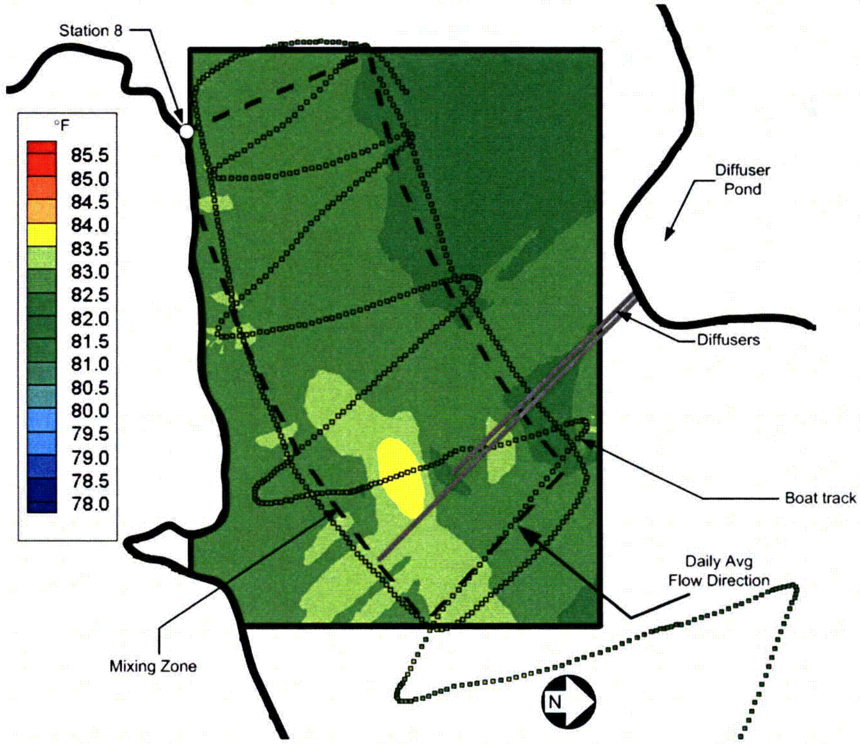

Figure 57. Water Temperature Measurements at 5-foot depth for September 21, 2008

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 69.2°F and 69.5°F (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 F° (5.0 C°) 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.

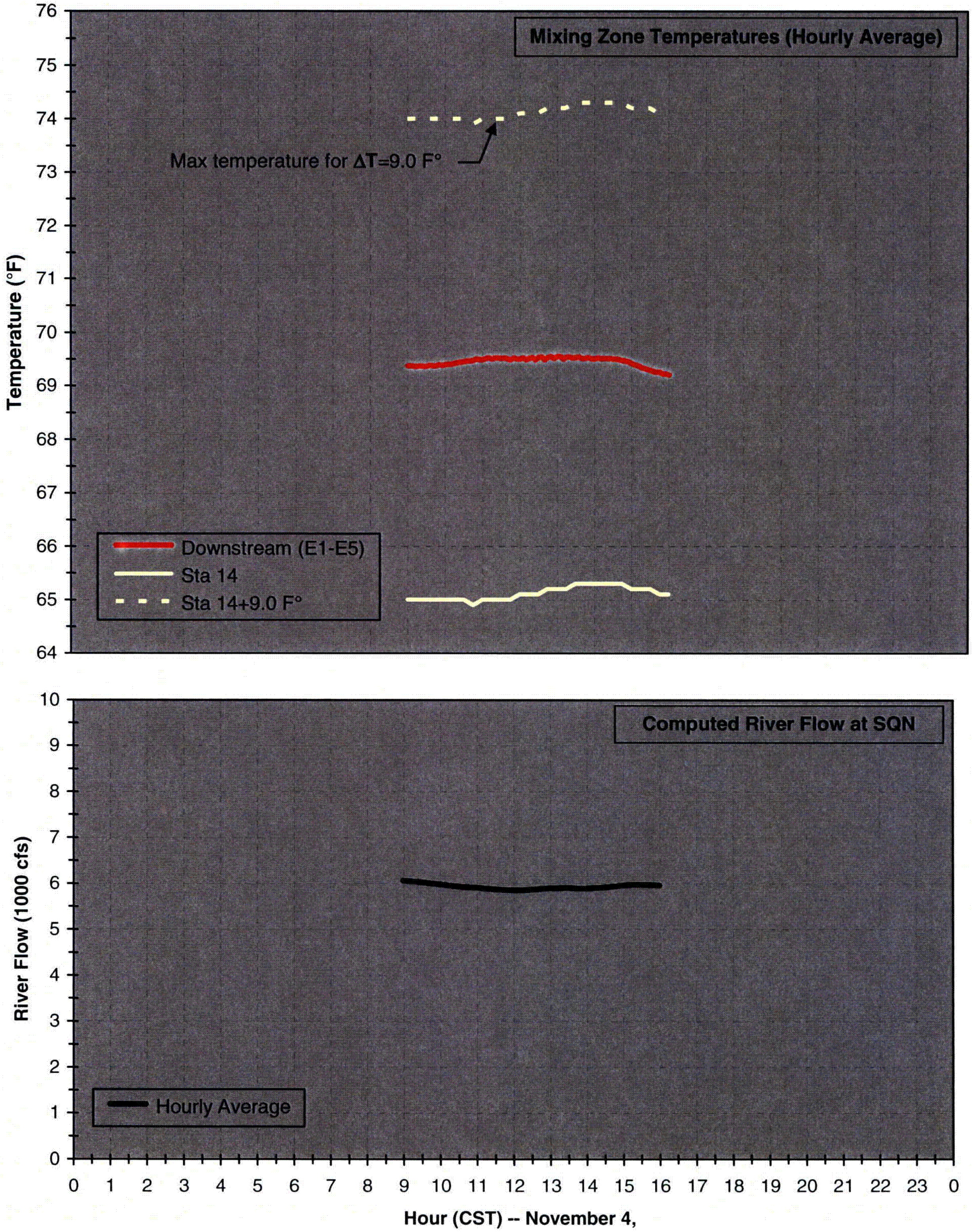

Figure 58. Temperatures for Mixing Zone Survey of November 4, 2007

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.

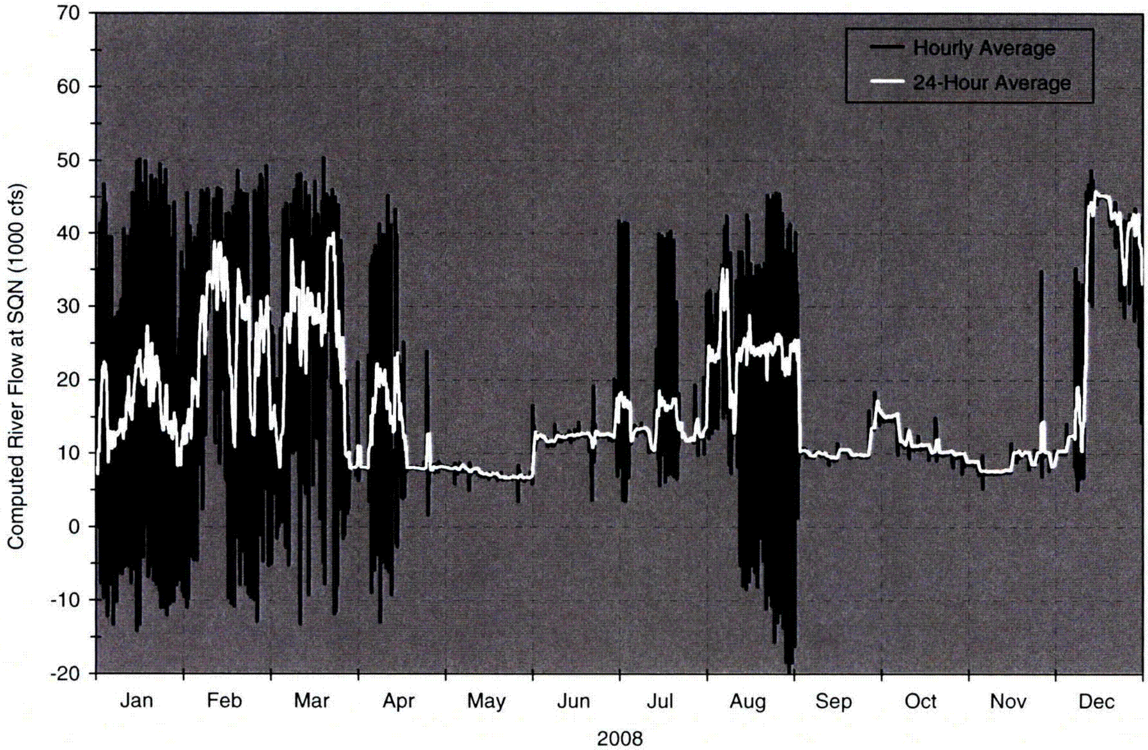

Figure 60. Computed River Flow at SQN for 2008

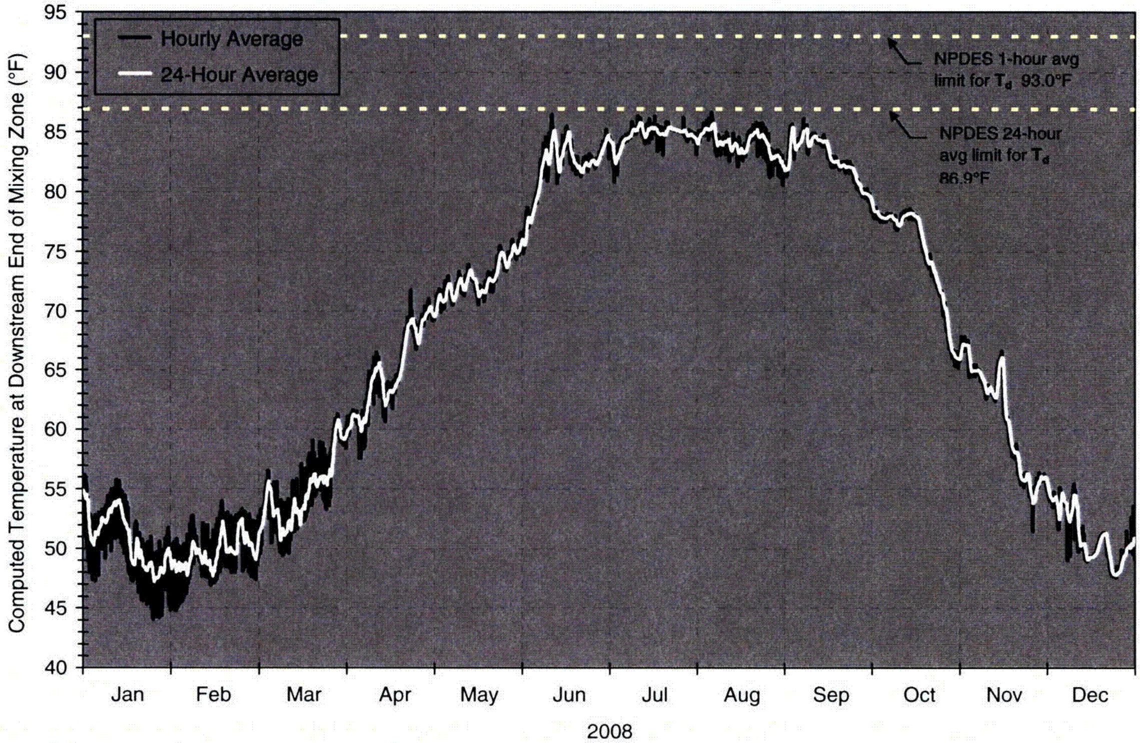

Figure 61. Computed Temperature at Downstream End of Mixing Zone for 2008

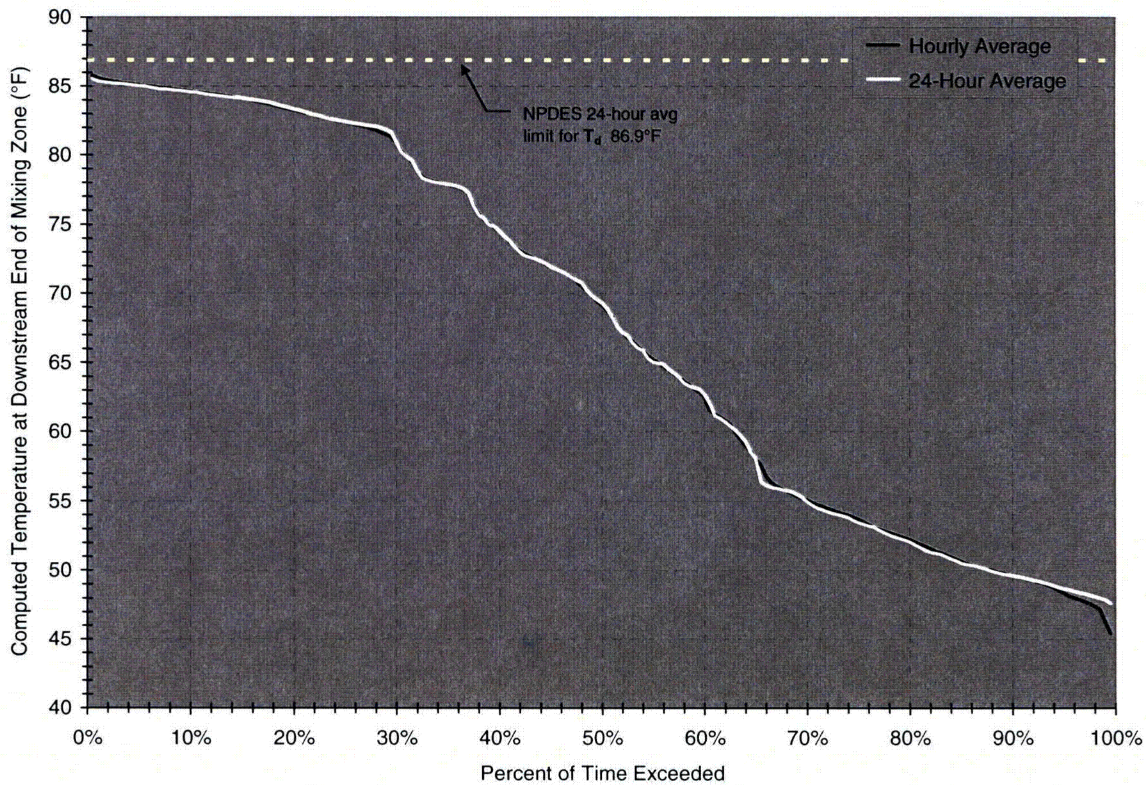

Figure 62. Exceedance Probability for Computed Temperature at Downstream End of Mixing Zone for 2008

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.

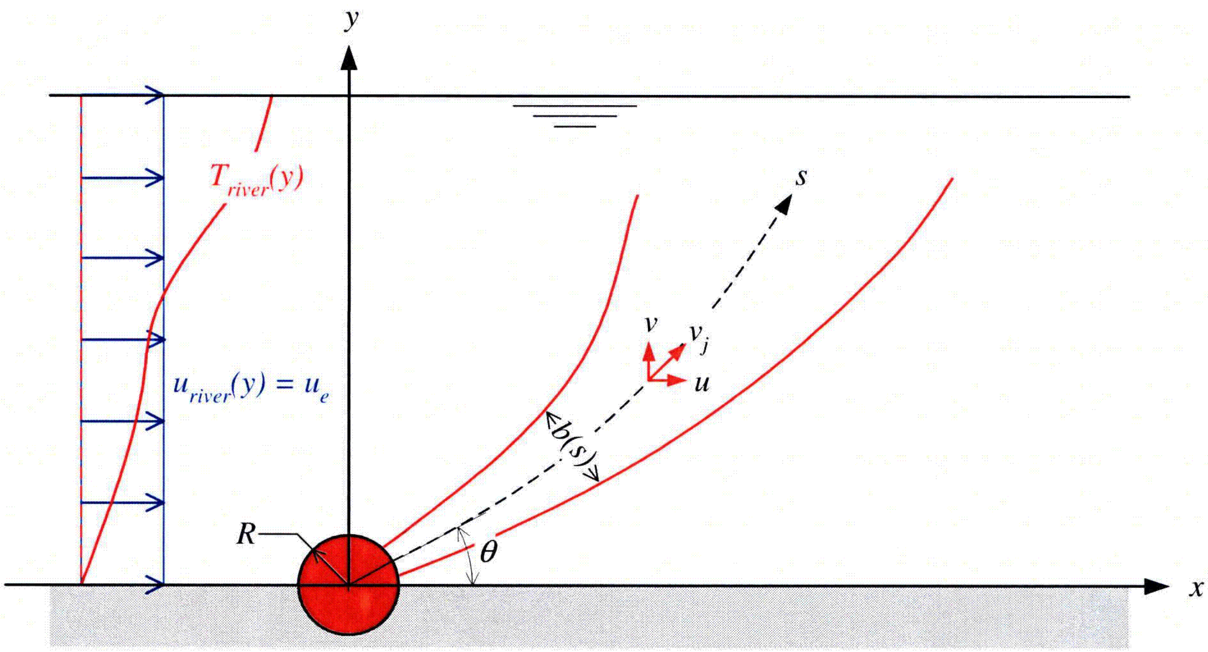

Figure 63. Two-Dimensional Plane Buoyant Jet Model for a Submerged Diffuser

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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TENNESSEE VALLEY AUTHORITY
River Operations

Study to Confirm the Calibration of the Numerical Model for the Thermal Discharge from Sequoyah Nuclear Plant as Required by NPDES Permit No. TN0026450 of September 2005

WR2009-1-45-150

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Knoxville, Tennessee

January 2009

EXECUTIVE SUMMARY

The National Pollutant Discharge Elimination System (NPDES) permit for Sequoyah Nuclear Plant (SQN) identifies the release of cooling water to the Tennessee River through the plant discharge diffusers as Outfall 101. The primary method to monitor compliance with the NPDES temperature limits for this outfall includes the use of a numerical model that solves a set of governing equations for the flow and hydrothermal conditions of the SQN release and the river discharge. The numerical model operates in real-time and utilizes a combination of measured and computed values for the temperature, flow, and stage in the river; and the temperature and flow from the SQN discharge diffusers. Part III, Section G of the permit states: *The numerical model used to determine compliance with the temperature requirements for Outfall 101 shall be subject of a calibration study once during the permit cycle. The study should be accomplished in time for data to be available for the next permit application for re-issuance of the permit. A report of the study will be presented to the division of Water Pollution Control.* This report is provided in fulfillment of these requirements.

The basic formulation of the numerical model is presented herein. Three empirical terms are used to calibrate the model. The first is the effective width of the diffuser slot and the second is a relationship used to compute the entrainment of ambient water along the trajectory of the plume. These two items were included in a calibration study performed in 2003 in support of the current NPDES permit (TVA, 2003). The third term, new in the updated calibration study summarized herein, is a relationship for the amount of diffuser effluent that is re-entrained into the diffuser plume for sustained low river flow. The need for this re-entrainment function was discovered as a result of the current drought in East Tennessee. Recent studies have provided evidence that such re-entrainment occurs due to the local buildup of heat in the river that occurs for low flows (TVA, 2009).

Temperature measurements across the downstream end of the SQN mixing zone from forty-nine sets of samples collected between 1982 and 2007 were used in the updated calibration study. These data were compared with computed downstream temperatures from the numerical model for the same periods of time. In this process, sensitivity tests were performed for the effective diffuser slot width, entrainment relationship, and plume re-entrainment function. The results showed acceptable agreement between computed and measured temperatures, particularly at river temperatures greater than 75°F. In the updated study, the overall average discrepancy between the measured and computed downstream temperatures was about 0.55 F° (0.31 C°). For downstream temperatures above 75°F, the average discrepancy improved to about 0.38 F° (0.21 C°). Compared to the previous model calibration this represents an overall improvement of 0.13 F° (0.07 C°), and for downstream temperatures above 75°F an improvement of 0.02 F° (0.01 C°).

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The Sequoyah Nuclear Plant (SQN) is located on the right bank of Chickamauga Reservoir at Tennessee River Mile (TRM) 484.5. As shown in Figure 1, the plant is northeast of Chattanooga, Tennessee, about 13.5 miles upstream and 45.4 miles downstream of Chickamauga Dam and Watts Bar Dam, respectively. As shown in Figure 2, the reservoir in the vicinity of SQN contains a deep main channel with adjacent overbanks and embayments. The main channel is approximately 900 feet wide and 50 to 60 feet deep, depending on the pool elevation. The overbanks are highly irregular and usually less than 20 feet deep.

SQN has two units with a total net generating capacity of 2440 MWe and an associated waste heat load of about 4800 MWe, or 16.4 x 10^9 Btu/hr. The heat transferred from the steam condensers to the cooling water is dissipated to the atmosphere by two natural draft cooling towers, to the river by a two-leg submerged multiport diffuser, or by a combination of both. The release to the river is identified in the National Pollutant Discharge Elimination System (NPDES) Permit as Outfall 101.

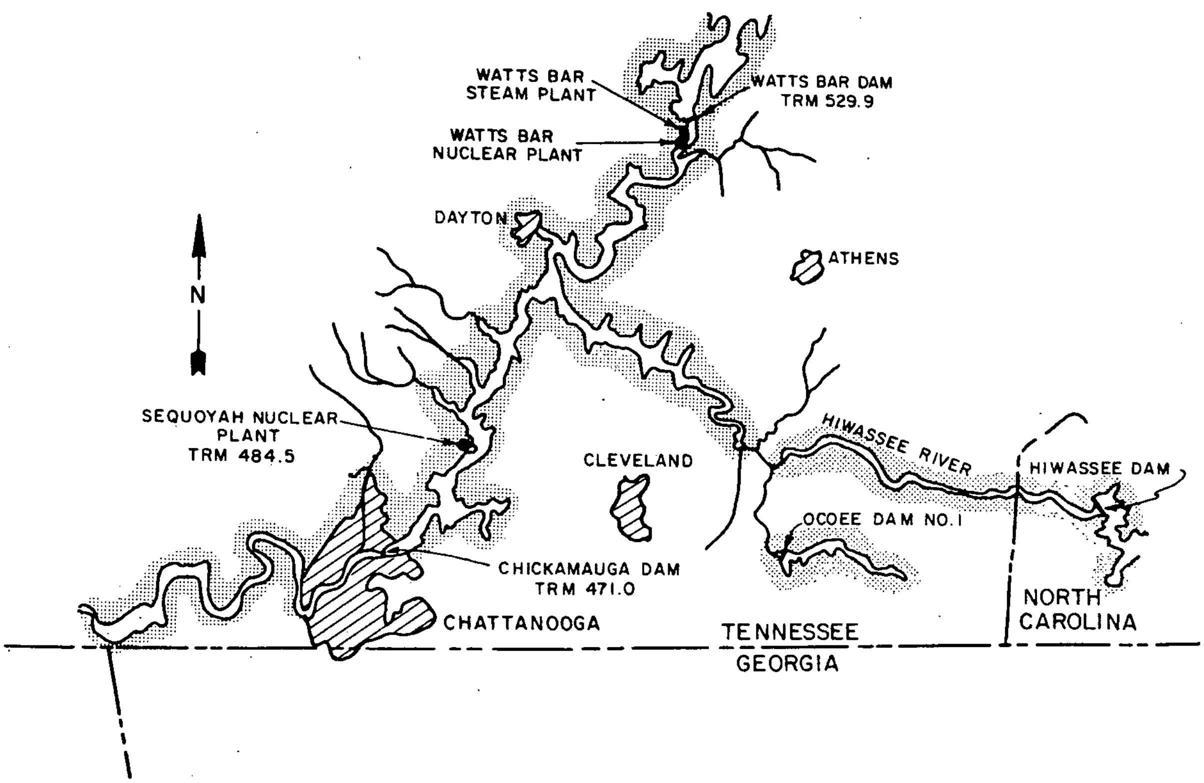

Figure 1. Location of Sequoyah Nuclear Plant

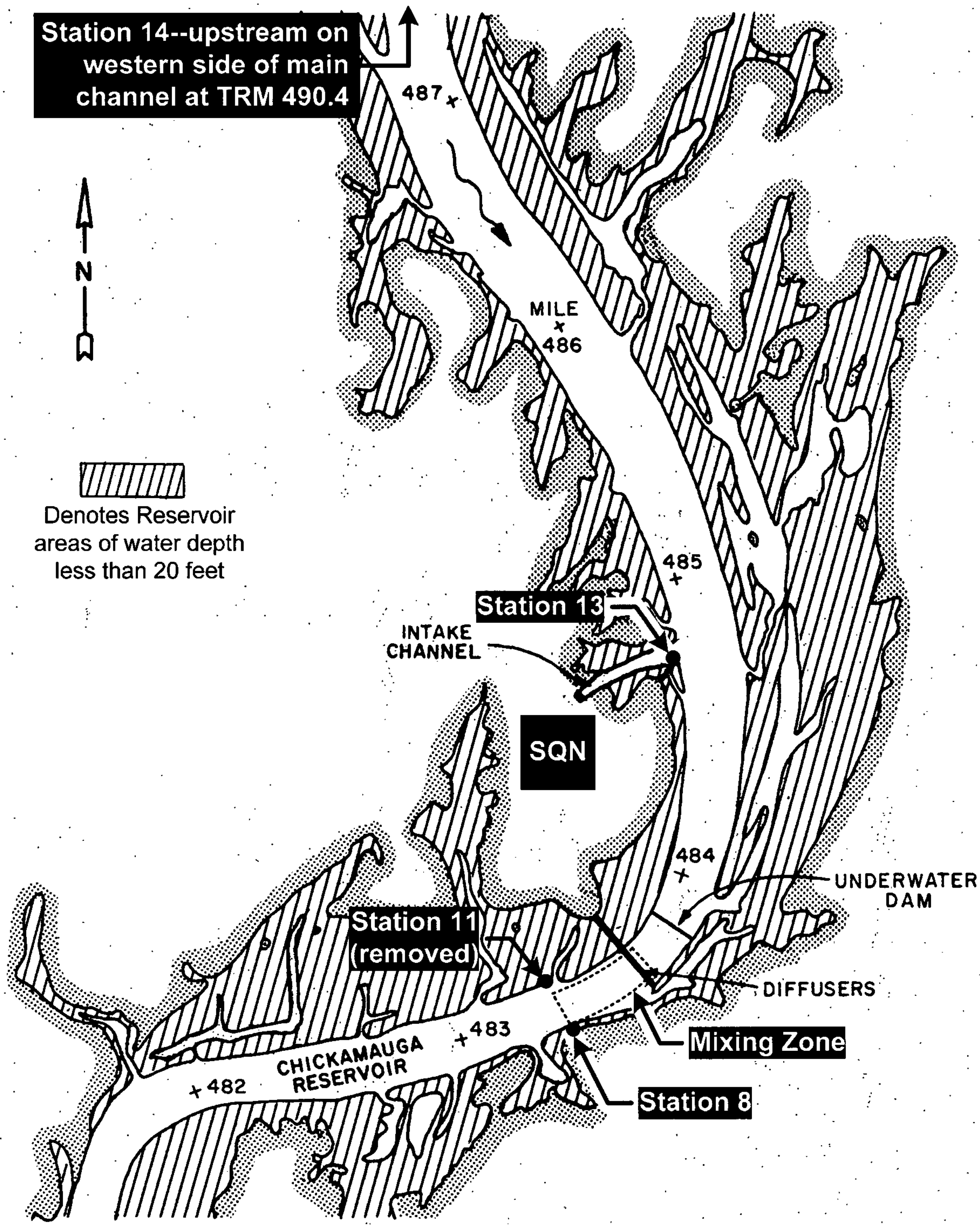

Figure 2. Chickamauga Reservoir in the Vicinity of Sequoyah Nuclear Plant

The compliance of SQN operation with the instream temperature limits specified in the NPDES permit (TDEC, 2005) is based on a downstream temperature that is calculated on a real-time basis by a numerical computer model. Part III, Section G of the permit states:

The numerical model used to determine compliance with the temperature requirements for Outfall 101 shall be subject of a calibration study once during the permit cycle. The study should be accomplished in time for data to be available for the next permit application for re-issuance of the permit. A report of the study will be presented to the division of Water Pollution Control. Any adjustments to the numerical model to improve its accuracy will not need separate approval from the Division of Water Pollution Control; however, the Division will be notified when such adjustments are made.

This report presents a summary of compliance model and the required calibration study.

BACKGROUND

The original method of monitoring thermal compliance for the SQN diffuser discharge (i.e., Outfall 101), included two temperature stations located near the downstream corners of the mixing zone, Station 8 and Station 11 (see Figure 2). Because of the necessity to keep the navigation channel free of obstructions, temperature stations could not be situated between these locations to monitor the center of the thermal plume. The upstream ambient river temperature was measured at Station 13, located on the plant intake skimmer wall. In August 1983, the Tennessee Valley Authority (TVA) reported the results of six field studies of the SQN diffuser performance under various river and plant operating conditions (TVA, 1983a). The data summarized in the report showed that based on measured temperature variations across the downstream edge of the mixing zone, Station 8 and Station 11 were inadequate in providing a representative cross-sectional average temperature of the thermal plume. In particular, it was found that Station 11 was often not in the main flow path of the thermal plume and did not always show elevated temperatures. The remaining downstream monitor, Station 8, also was not considered adequate because it again was located outside the navigation channel. In the report, TVA proposed an alternate method to monitor thermal compliance involving the use of a numerical model to simulate the behavior of the thermal plume in the mixing zone. The model would provide a real-time assessment of compliance with the thermal discharge limitations. Information required for the model included the ambient temperature upstream of the mixing zone (Station 13), the temperature and discharge of the water issuing from the diffusers (Station 12), and the depth and discharge of the river at SQN (determined from measurements at Chickamauga Dam and Watts Bar Dam). A microcomputer, located in the SQN Environmental Data Station (EDS), was to be used collect the required data, compute the thermal compliance parameters, and distribute the results to plant operartors (see TVA, 1983b). The August 1983 report presented results demonstrating the validity of using the numerical model for tracking compliance with the Outfall 101 thermal limitations.

The method of using the numerical model was sent to the Environmental Protection Agency (EPA) and the Tennessee Department of Environment and Conservation (TDEC), requesting approval for implementation as a valid means for monitoring SQN thermal compliance. The key advantage of the method includes a representation of the cross-sectional average downstream temperature that is at least as good as the instream temperature measurements from Station 8 and Station 11. The method also provides consistency with procedures that are used for scheduling releases from Watts Bar Dam and Chickamauga Dam, as well as procedures for operating Sequoyah Nuclear Plant. This consistency helps TVA minimize unexpected events that can potentially threaten the NPDES thermal limits for Outfall 101. In March 1984 approval was granted for TVA to use the numerical model as the primary method to track thermal compliance. Except for infrequent outages, the model has been in use ever since. Subsequently, Station 11 was removed from the river. However, Station 8 was retained to provide an optional method to track thermal compliance should there be a need to remove the model from service.

Due to the ever changing understanding of the hydrothermal aspects of Chickamauga Reservoir, as well as the operational aspects of the nuclear plant and river system, modifications have been necessary over the years for both the numerical model and thermal criteria for Outfall 101. The current version of the model is presented in more detail later. The current thermal criteria are presented in Table 1. The limit for the temperature at the downstream end of the mixing zone (T_d) is a 24-hour average value of 86.9°F (30.5°C) and an hourly average value of 93.0°F (33.9°C). The instream temperature rise (ΔT) is limited to a 24-hour average of 5.4 F° (3.0 C°) for months April through October, and 9.0 F° (5.0 C°) for months November through March. The latter "wintertime" limit was obtained by a 316(a) variance. The temperature rate-of-change at the downstream end of the mixing zone (dT_d/dt) is limited to ±3.6 F°/hr (±2 C°/hr). With the compliance model, dT_d/dt is based on 24-hour average river conditions and 15 minute plant conditions. Other details related to the temperature limits for Outfall 101 are provided in the notes that accompany Table 1. It is important to note that compliance with instream temperature limits are based on a computed downstream temperature at a depth of 5.0 feet. And in a similar fashion, the upstream temperature is measured at the 5.0 foot depth, based on the average of temperature readings at the 3-foot, 5-foot and 7-foor depths.

Originally, the ambient river temperature for the temperature rise was measured at Station 13, about 1.1 miles upstream of the discharge diffusers. At the onset of the current drought it was discovered that under sustained low flow conditions, heat from the diffusers could migrate far enough upstream to reach Station 13. In this manner, the ambient temperature can become elevated, thereby artificially reducing the measured impact of the plant on the river (i.e., ΔT). As such, in late March 2006, a new ambient temperature station was installed further upstream in the river at TRM 490.4, about 6.8 miles upstream of the diffusers. The location of the new monitor, entitled Station 14, is shown in Figure 3.

Table 1. Summary of SQN Instream Thermal Limits for Outfall 101

Type of Limit	Averaging (hours)	NPDES Limit[2]
Max Downstream Temperature, T_d	24	86.9°F (30.5°C)
Max Downstream Temperature, T_d	1	93.0°F (33.9°C)
Max Temperature Rise, ΔT	24	5.4 F°/9.0 F° (3.0 C°/5.0 C°)
Max Temperature Rate-of-Change, dT_d/dt	Mixed	±3.6 F°/hr (±2 C°/hr)

Notes:

1. Compliance with the river limitations (river temperature, temperature rise, and rate of temperature change) shall be monitored by means of a numerical model that solves the thermohydrodynamic equations governing the flow and thermal conditions in the reservoir. This numerical model will utilize measured values of the upstream temperature profile and river stage; flow, temperature and performance characteristics of the diffuser discharge; and river flow as determined from releases at the Watts Bar and Chickamauga Dams. In the event that the modeling system described here is out of service, an alternate method will be employed to measure water temperatures at least one time per day and verify compliance of the maximum river temperature and maximum temperature rise. Depth average measurements can be taken at a downstream backup temperature monitor at the downstream end of the diffuser mixing zone (left bank Tennessee River mile 483.4) or by grab sampling from boats. Boat sampling will include average 5-foot depth measurements (average of 3, 5, and 7-foot depths). Sampling from a boat shall be made outside the skimmer wall (ambient temperature) and at quarter points and mid-channel at downstream Tennessee River mile 483.4 (downstream temperature). The downstream reported value will be a depth (3, 5, and 7-foot) and lateral (quarter points and midpoint) average of the instream measurements. Monitoring in the alternative mode using boat sampling shall not be required when unsafe boating conditions occur.
2. Compliance with river temperature, temperature rise, and rate of temperature change limitations shall be applicable at the edge of a mixing zone which shall not exceed the following dimensions: (1) a maximum length of 1500 feet downstream of the diffusers, (2) a maximum width of 750 feet, and (3) a maximum length of 275 feet upstream of the diffusers. The depth of the mixing zone measured from the surface varies linearly from the surface 275 feet upstream of the diffusers to the top of the diffuser pipes and extends to the bottom downstream of the diffusers. When the plant is operated in closed mode, the mixing zone shall also include the area of the intake forebay.
3. Information required by the numerical model and evaluations for the river temperature, temperature rise, and rate of temperature change shall be made every 15 minutes. The ambient temperature shall be determined at the 5-foot depth as the average of measurements at depths 3 feet, 5 feet, and 7 feet. The river temperature at the downstream end of the mixing zone shall be determined as that computed by the numerical model at a depth of 5 feet.
4. Daily maximum temperatures for the ambient temperature, the river temperature at the downstream edge of the mixing zone, and temperature rise shall be determined from 24-hour average values. The 24-hour average values shall be calculated every 15 minutes using the current and previous ninety-six 15-minute values, thus creating a 'rolling' average. The maximum of the ninety-six observations generated per day by this procedure shall be reported as the daily maximum value. For the river temperature at the downstream end of the mixing zone, the 1-hour average shall also be determined. The 1-hour average values shall be calculated every 15 minutes using the average of the current and previous four 15-minute values, again creating a rolling average.
5. The daily maximum 24-hour average river temperature is limited to 30.5°C. Since the state's criteria makes exception for exceeding the value as a result of natural conditions, where the 24-hour average ambient temperature exceeds 29.4°C and the plant is operated in helper mode (full operation of one cooling tower, at least three lift pumps, per operating unit) the maximum temperature may exceed 30.5°C. In no case shall the plant discharge cause the 1-hour average downstream river temperature at the downstream of the mixing zone to exceed 33.9°C without the consent of the permitting authority.
6. The temperature rise is the difference between the 24-hour average ambient river temperature and the 24-hour average temperature at the downstream end of the mixing zone. The 24-hour average temperature rise shall be limited to 3.0 C° during the months of April through October. The 24-hour average temperature rise shall be limited to 5.0 C° during the months of November through March.
7. The rate of temperature change shall be computed at 15-minute intervals based on the current 24-hour average ambient river temperature, current 24-hour-hour average river flow, and current values of flow, and current 15-minute values of flow and temperature of water discharging through the diffuser pipes. The 1-hour average rate of temperature change shall be calculated every 15-minutes by averaging the current and previous four 15-minute values. The 1-hour average rate of temperature change shall be limited to 2 C° per hour.

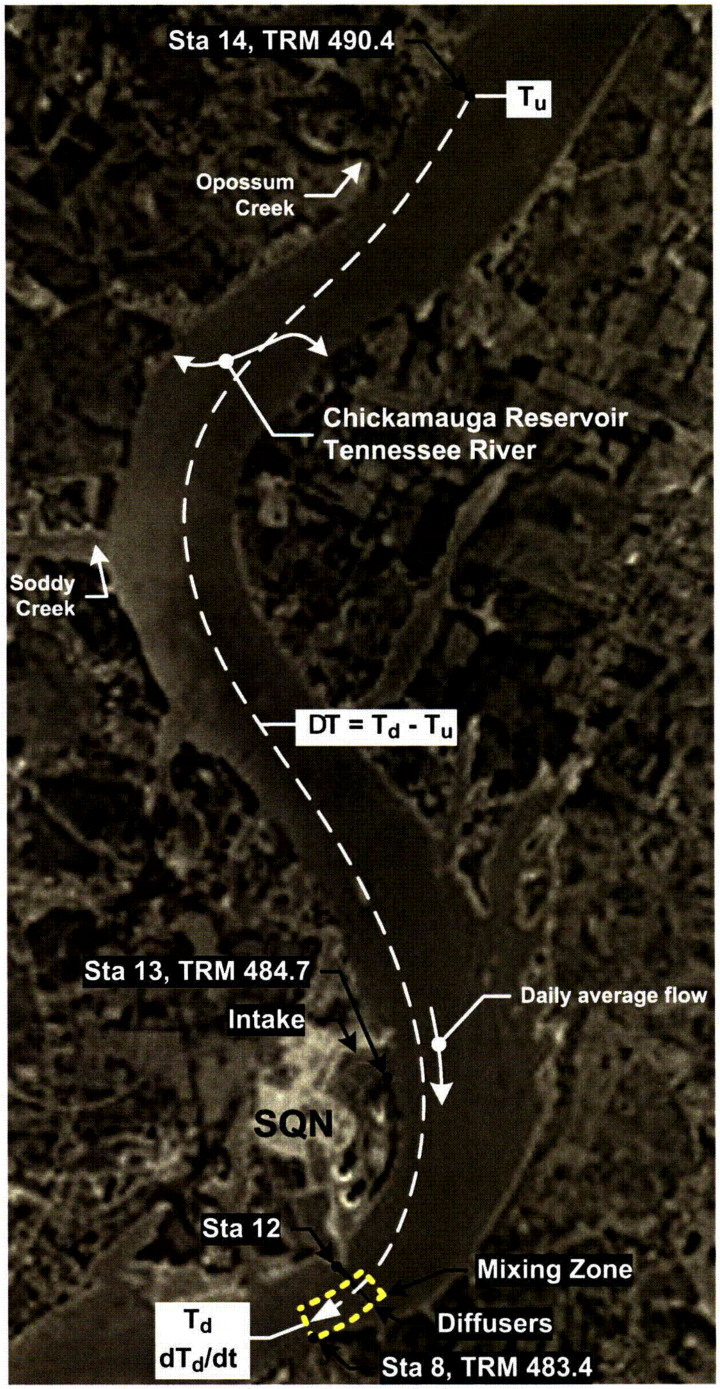

Figure 3. Locations of Instream Temperature Monitors for Sequoyah Nuclear Plant

NUMERICAL MODEL

The diffusers at SQN are submerged at the bottom of the navigation channel in Chickamauga Reservoir. As shown in Figure 4, each diffuser is 350 feet long, and contains seventeen 2-inch diameter ports per linear foot of pipe, arranged in rows over an approximately 18 degree arc of the diffuser conduit. The two diffuser legs rest on an elevated pad approximately 10 feet above the bottom of the river, occupying the 700 feet of navigation channel nearest the plant (right side of the channel, looking downstream). The flow in the immediate vicinity of the ports is far too complex to be analyzed on a real-time basis with current computer technology. Therefore, a simplifying assumption is made that the diffusers can be treated as a slot jet with a length equal to that of the perforated sections of the pipe. The width of this assumed slot is one of three empirical terms used to calibrate the model. The second is a relationship used to compute the entrainment of ambient water along the trajectory of the plume and the third is a relationship for the amount of diffuser effluent that is re-entrained into the diffuser plume for sustained low river flow.

The initial development of the numerical model is described in detail by Benton (2003). Prior to the current drought, the model did not include re-entrainment of the plant thermal effluent for sustained low river flows. However, recent studies have provided evidence that re-entrainment occurs (TVA, 2009). To simulate this situation, the numerical model has been modified to better reflect the local buildup of heat that occurs in the river under such conditions. Before presenting calibration results, it is appropriate first to provide a brief description of the model formulation.

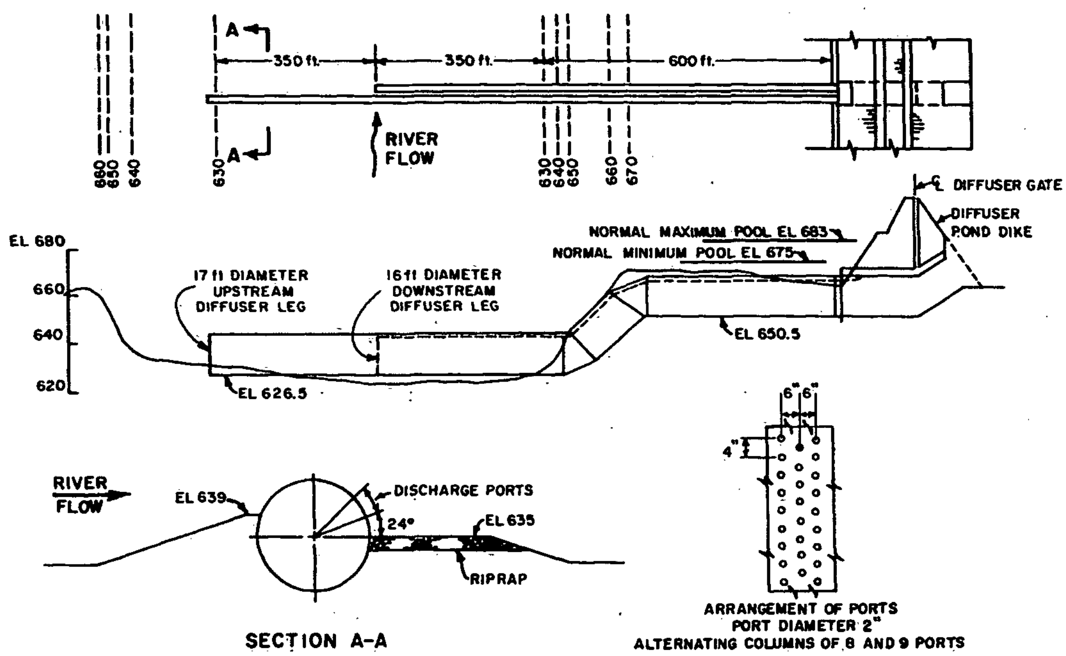

Figure 4. Sequoyah Nuclear Plant Outfall 101 Discharge Diffusers

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 5. The jet discharges into a temperature-stratified, uniform-velocity 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.

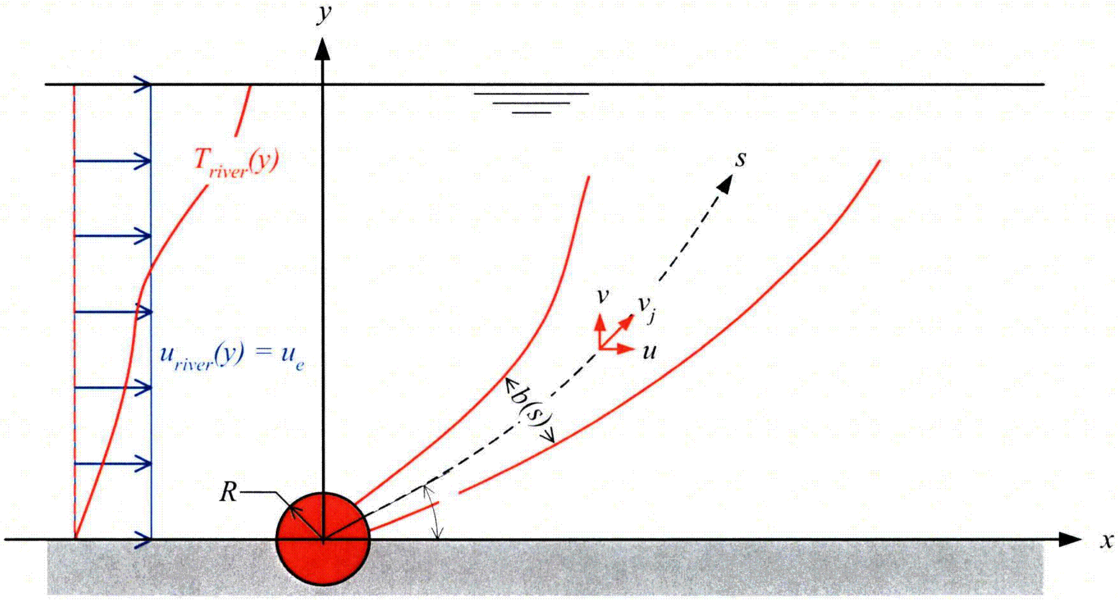

Figure 5. Two-Dimensional Plane Buoyant Jet Model for a Submerged Diffuser

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,

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

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

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

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

$$\frac{dx}{ds} = \frac{u}{v_j}\text{, and} \quad (5)$$

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

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

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

$$\rho_j = \rho_{water}(T_j), \quad (8)$$

$$\rho_e = \rho_{water}(T_e), \quad (9)$$

$$T_e = T_{river}(y), \quad (10)$$

$$u_e = u_{river}, \quad (12)$$

$$v_e = 0, \text{ and} \quad (13)$$

$$v_j = (u^2 + v^2)^{1/2}. \quad (11)$$

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, $_j$ denotes the density of water at a point inside the jet and $_e$ 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, as indicated earlier, 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 occur 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 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). Again, as indicated earlier, the entrainment coefficient, like the slot width, is adjusted as part of the calibration process.

The initial conditions required by the model include,

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

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

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

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

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

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

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, 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 fully-mixed temperature 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 weakens for low river flows. Based on the understanding gained in recent studies (TVA, 2009), it is known that partial re-entrainment of the effluent plume occurs at sustained low river flow, increasing the temperature of the water entering the mixing zone above that represented by Station 13. To simulate this phenomenon, the model modifies the Station 13 temperature profile for low river flows. 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 become re-entrained into the flow, thereby increasing the temperature of the water entering the mixing zone. The modified entrainment temperature T_e^N at each point in the Station 13 profile is 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), 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 modified 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 is still computed based on the temperature measurement at the new ambient temperature monitor, Station 14.

Values for N and R are calibrated based on observed temperatures at the downstream end of the diffuser mixing zone for low river flow conditions, as indicated earlier. 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 flows above this range, no modification is needed for re-entrainment.

The downstream temperature and instream temperature rise provided by the model are computed every 15 minutes, using instantaneous values of the measured diffuser discharge temperature (Station 12), measured upstream temperature profile (Station 13), measured ambient temperature (Station 14), measured river elevation (Station 13), and computed values of the river velocity (one-dimensional unsteady flow model of Chickamauga Reservoir) and diffuser discharge. The diffuser discharge is computed based on the difference in water elevation between the SQN diffuser pond (Station 12) and the river (Station 13). All computations are performed every 15 minutes to provide rolling hourly and 24-hour average values. The hourly averages are based on the current and previous four 15-minute values, whereas the 24 hour averages are based on current and previous ninety-six 15-minute values. The temperature rate-of-change is determined slightly different, being computed every 15 minutes based on current 24-hour average river conditions and current 15-minute values of the flow and temperature of water discharging from the SQN diffusers. This method was adopted in August 2001 in order to distinguish between rate-of-change events due to changes in SQN operations (i.e. changes in plant discharge flow and/or temperature) and those due to non-SQN changes in operations (e.g., changes in river flow). Prior to this change, SQN was held accountable for temperature rate-of-change events over which it had very little control or influence.

CALIBRATION

The numerical model is calibrated to achieve the best match between computed downstream temperatures and field measurements at the downstream end of the mixing zone. Field measurements at the downstream end of the mixing zone are of two types—those including samples from field surveys across the entire width of the mixing zone and those from Station 8, which includes samples only at the left-hand corner of the mixing zone (e.g., see Figure 2). Higher priority is given to matching data from field surveys, since such measurements are made across the entire width of the plume mixing zone and are more representative of the average temperature in the thermal plume at the 5-foot compliance depth.

Previous Calibration Data and Calibration Work

Prior to the NPDES permit of September 2005, field surveys were performed in 1981, 1982, 1983, 1987, 1996, 1997, 1999, 2000, 2002, and 2003. In July 1981, TVA conducted the first field survey of the SQN thermal discharge (TVA, 1982). The results of the field surveys were compared to projections from modeling relationships developed from mixing theory and a physical model test of the discharge diffusers. Adequate agreement was achieved between measured data and model projections. In cases where there were discrepancies, the model under-predicted the observed dilutions (i.e., over-predicted temperatures).

Between April 1982 and May 1983, five field surveys containing seventeen sets of samples across the downstream end of the mixing zone were performed to acquire data for validation of the computed compliance technique (TVA, 1983a). The results of these surveys are given in Table 2. Only one SQN unit was operating during the March 1983 test—the other five tests were for operation with two units. The results of the numerical model compared favorably with the field-measured downstream temperatures. On average, the discrepancy between the measured and computed downstream temperatures was about 0.40 F° (0.22 C°). Since the accuracy of the temperature sensors used by TVA are only about ±0.25 F° (±0.14 C°), the agreement between the field measurements and the computer model was considered good. A similar comparison between the Station 8 and Station 11 temperatures and the measured average temperatures across the downstream edge of the mixing zone revealed that the discrepancy for Station 8 was about 0.79 F° (0.44 C°) and for Station 11 about 0.65 F° (0.36 C°). Consequently, it was concluded that the numerical model is not only an accurate representation of the downstream temperature but also is likely superior to the monitoring approach using Station 8 and Station 11.

In September 1987, TVA released a report describing the field surveys in support of the validation and calibration of the SQN numerical model that had been performed up to that date (TVA, 1987). In the report, a chart was introduced that described the ambient and operational conditions for which field surveys had been performed. This chart indicated combinations of river flow, season, and number of operating units, showing what tests had been performed, and assigning relative priorities for tests to be performed in the future. With this guidance, six more field surveys were performed between March 1996 and April 2003, to measure downstream temperatures for various river flows and at different times of year. The results of these surveys produced ten sets of samples across the downstream end of the mixing zone, as given in Table 3.

Table 2. Thermal Surveys at SQN from April 1982 through March 1983

Date	Approx Time	River		Temperatures (5-foot depth)		
		Flow (cfs)	Stage (ft MSL)	T_u Measured (F)	T_d Measured (F)	T Measured (F)
04/04/1982	0900 CST	19900	676.46	56.8	61.9	5.1
04/04/1982	1000 CST	19800	676.46	56.7	60.1	3.4
04/04/1982	1100 CST	19600	676.47	56.7	61.2	4.5
04/04/1982	1200 CST	19700	676.50	57.2	61.9	4.7
04/04/1982	1300 CST	19700	676.45	57.4	62.2	4.8
05/14/1982	0900 CDT	7200	682.43	74.5	71.8	-2.7
05/14/1982	1100 CDT	9100	682.40	73.4	71.8	-1.6
05/14/1982	1300 CDT	6300	682.42	72.1	73.6	1.5
09/02/1982	1400 CDT	38500	680.30	78.1	80.1	2.0
11/10/1982	1300 CST	36200	677.57	59.0	60.1	1.1
11/10/1982	1400 CST	31600	677.59	59.0	60.6	1.6
11/10/1982	1500 CST	32300	677.58	59.0	60.4	1.4
03/31/1983	1100 CST	9800	676.34	51.4	54.3	2.9
03/31/1983	1200 CST	9400	676.34	50.4	54.7	4.3
03/31/1983	1300 CST	9300	676.34	52.5	54.5	2.0
03/31/1983	1400 CST	9500	676.34	51.4	54.9	3.5
03/31/1983	1500 CST	9400	676.36	51.4	54.9	3.5

Table 3. Thermal Surveys at SQN from March 1996 through April 2003

Date	Approx Time	River		Temperatures (5-foot depth)		
		Flow (cfs)	Stage (ft MSL)	T_u Measured (F)	T_d Measured (F)	T Measured (F)
03/1/1996	1100 CST	42456	676.96	45.9	48.8	2.9
03/1/1996	1445 CST	28136	677.04	46.2	50.2	4.0
03/1/1996	1600 CST	21962	677.00	46.1	51.4	5.3
03/1/1996	1700 CST	20280	677.00	46.0	51.5	5.5
07/24/1997	1550 CDT	40441	682.57	83.5	84.7	1.2
03/24/1999 *	1250 CST	35731	677.46	51.9	54.5	2.7
08/2/2000	1000 CDT	12472	682.20	82.1	85.1	3.0
08/2/2000	1100 CDT	8624	682.20	82.1	85.3	3.1
07/27/2002	1250 CDT	17231	682.37	84.0	86.6	2.6
04/23/2003	1445 CDT	34178	682.53	63.7	64.2	0.5

* The survey of 03/24/1999 is lacking valid upstream temperature data.

Prior to the work summarized herein, the most recent calibration of the numerical model was performed in support of the NPDES permit of September 2005 (TVA, 2003). The results in both Table 2 and Table 3 were used in the model calibration, which includes a total of twenty-seven sets of samples containing temperature measurements across the downstream end of the diffuser mixing zone. In the calibration, the average discrepancy between the measured and computed temperatures at the downstream end of the mixing zone was about 0.68 F° (0.38 C°). For downstream temperatures above 75°F, which is more important in terms of peak summertime stress on aquatic organisms, the average discrepancy was only 0.40 F° (0.22 C°).

New Calibration Data and Calibration Work

Since February 2004 a number of additional field surveys have been performed, providing twenty-three more sets of samples containing temperature measurements across the downstream end of the diffuser mixing for various river flows and at different times of the year. The results of these surveys are given in Table 4. Altogether, therefore, fifty data points with sets of temperature samples across the downstream end of the mixing zone are available for updating the model calibration (i.e., Table 2, Table 3, and Table 4).

Table 4. Thermal Surveys at SQN from February 2004 through November 2007

Date	Approx Time	River		Temperatures (5-foot depth)		
		Flow (cfs)	Stage (ft MSL)	T_u Measured (F)	T_d Measured (F)	T Measured (F)
02/14/2004	0600 CST	51133	677.50	43.7	46.3	2.6
02/22/2004	1800 CST	18468	678.40	45.8	50.5	4.7
08/22/2004	1800 CST	12340	682.00	79.8	84.1	4.3
08/23/2004	1800 CST	39238	682.20	79.8	82.4	2.6
04/01/2006	1915 CST	7084	677.20	59.7	63.5	3.8
04/04/2006	0015 CST	7996	677.70	59.3	63.9	4.6
04/04/2006	1105 CST	8251	677.80	59.6	61.3	1.7
04/04/2006	2030 CST	8258	678.00	59.0	63.2	4.2
04/05/2006	0915 CST	7917	678.20	59.2	62.8	3.6
04/05/2006	2215 CST	8277	678.40	60.4	64.2	3.8
04/06/2006	0915 CST	8174	678.50	59.7	63.3	3.6
04/06/2006	2315 CST	8077	678.70	61.0	64.5	3.5
04/07/2006	0840 CST	8162	678.80	59.9	63.9	4.0
04/07/2006	1435 CST	7889	678.80	60.0	64.7	4.7
05/22/2006	1445 CST	14511	682.00	73.4	72.9	-0.5
05/23/2006	1455 CST	17878	682.20	73.5	73.9	0.4
05/28/2006	1440 CST	13396	682.30	76.6	76.7	0.1
05/29/2006	1435 CST	13713	682.40	77.5	77.6	0.1
05/30/2006	1425 CST	14304	682.40	79.7	79.2	-0.5
09/20/2007	1200 CST	8545	681.80	79.3	83.4	4.1
09/21/2007	1300 CST	8629	681.70	80.6	82.5	1.9
09/22/2007	0600 CST	6969	681.70	79.5	81.8	2.3
11/04/2007	1200 CST	7664	678.70	64.9	69.5	4.6

Diffuser Slot Width

The effective slot width for a multiport diffuser of the type at SQN can be assumed to fall somewhere between the width of a rectangle with length equal to that of the diffuser section and area equal to the total area of the ports; and the width a rectangle with length equal to that of the diffuser section and area equal to the arc length of the perforated section of the diffuser. For the SQN diffuser, this slot width would be between 0.37 feet and 2.67 feet. Five slot widths in this range were evaluated and compared with forty-nine measured data points from the field surveys (i.e., from Table 2, Table 3, and Table 4). The results, given in Figure 6, show that larger slot widths yielded better agreement with the measured data. The nominal arc length of the perforated section of the diffuser (i.e., 2.67 feet) was selected as the best diffuser slot width to be used in the numerical model.

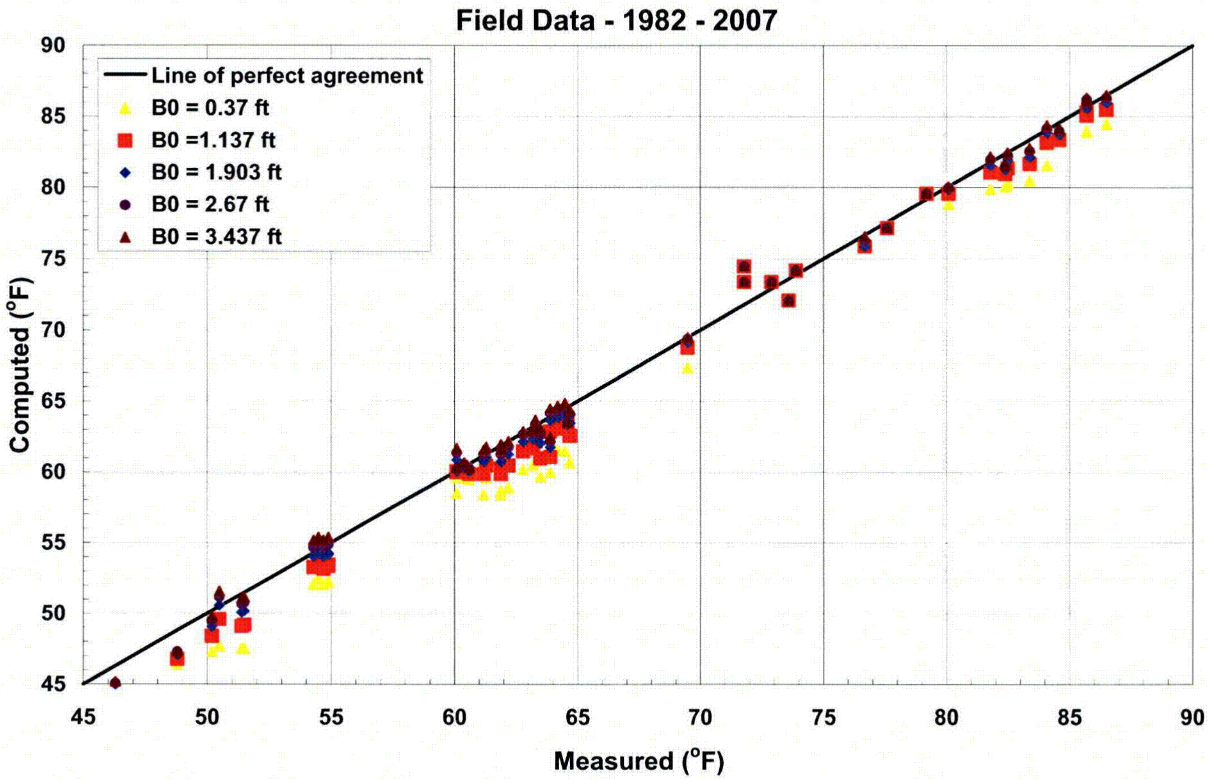

Figure 6. Sensitivity of Computed Temperature T_d to Diffuser Effective Slot Width

Plume Entrainment Coefficient

Two empirical relationships for the plume entrainment coefficient were evaluated in the calibration study. The first, developed by McIntosh, was inferred from a relationship for the entrainment coefficient determined from the data reported in 1983 (TVA, 1983a) and is given by

$$\alpha = \begin{cases} 0.27 \ \ for\ F_d < 0.75 \\ \dfrac{0.27}{F_d^{2.5}}\ for\ 0.75 \le F_d \le 1.00, \\ 0.55\ for\ F_d > 1.00 \end{cases} \qquad (22)$$

where F_d is the densimetric Froude number of the diffuser discharge defined by

$$F_d = \frac{w_d}{\sqrt{g b_o \dfrac{(\rho_d - \rho_o)}{\rho_o}}}. \qquad (23)$$

The term w_d is the velocity of the diffuser discharge, g is the gravitational constant, b_0 is the diffuser slot width, $_d$ is the density of the diffuser discharge, and $_o$ is the density of the ambient river water at the discharge depth.

The second entrainment coefficient, based on laboratory data, was originally developed by Benton in 1986 and is given by

$$\alpha = 0.31 + 1.69\left[\frac{1 + tanh(6.543 * rmf - 2.0584)}{2}\right], \qquad (24)$$

where

$$rmf = u_{river}^3 / b, \qquad (25)$$

and

$$b = Q_0\left(\frac{g}{l}\right)\left(\frac{\rho_o - \rho_d}{\rho_o}\right). \qquad (26)$$

Term u_{river} is the ambient river velocity, as previously defined, Q_0 is the diffuser discharge flowrate, and l is the length of the ported section of the diffuser.

Figure 7 shows the comparison with measured data of downstream temperatures computed with the McIntosh (Eq. 22) and Benton (Eq. 24) entrainment coefficients, again based on forty-nine data points from the field surveys in Table 2, Table 3, and Table 4. Both entrainment coefficients result in relatively close matches with the measured data. Although the McIntosh coefficient seems to perform better at low ambient river temperatures, temperatures computed using the Benton coefficient more closely match measured downstream temperatures at higher river temperatures. Since the accuracy of the computation is more critical at temperatures approaching the NPDES limit for downstream temperature, the Benton coefficient, Eq. (24) is currently used in the compliance model.

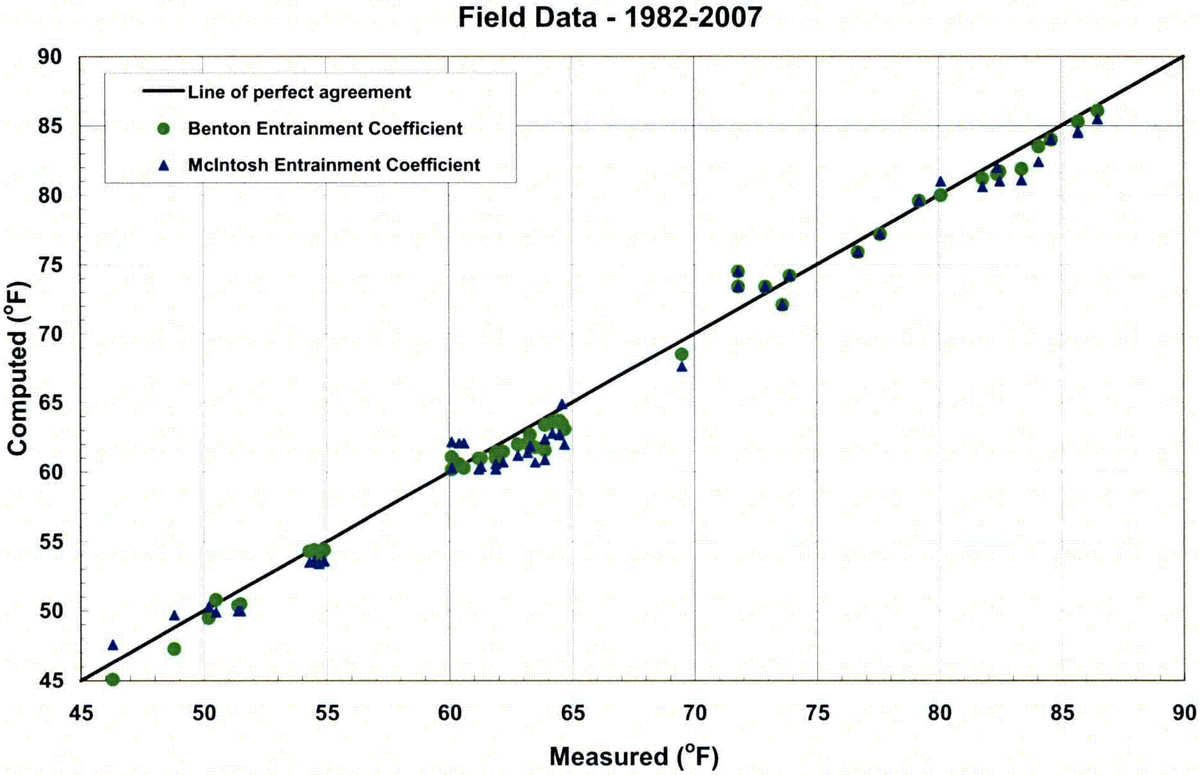

Figure 7. Sensitivity of Computed Temperature T_d to Plume Entrainment Coefficient

Diffuser Effluent Re-Entrainment

Partial re-entrainment of the diffuser plume is known to occur under conditions of low river flow. When the diffuser plume attempts to entrain an amount of ambient flow greater than what is available from further upstream, the upper portions of the plume tend to migrate upstream and plunge downward to be mixed with the flow in the lower portion of the river. The formulation to simulate this phenomenon was presented earlier (Eqs. 20 and 21). The unknown coefficients to be determined in the calibration process are the number of iterations N and re-entrainment fraction R in Eq. (21), which are functions of the 24-hour average river velocity. Based on the evaluation of numerous combinations of N and R, Table 5 gives the values that resulted in computed downstream temperatures that most closely matched measurements in the field surveys (i.e., forty-nine data points from Table 2, Table 3, and Table 4). For river velocities between the values given in Table 5, the re-entrainment factor R is interpolated between the table values. The number of iterations N is interpolated and then rounded to the nearest integer. No re-entrainment correction is performed for 24-hour river velocities greater than the highest value in the table.

Figure 8 shows the comparison of measured and computed downstream temperatures with and without the correction for plume re-entrainment as given in Table 5. Temperatures computed using the plume re-entrainment correction more closely matched measured values for twenty-seven of the forty-nine data points. Temperatures computed without using the plume re-entrainment correction more closely matched measured values for five data points, with no significant differences for the remaining data points. This is considered sufficient improvement to incorporate the plume re-entrainment correction into the computed compliance model.

Table 5. Plume Re-Entrainment Iteration Numbers and Factors

River Velocity (ft/sec)	Number of Iterations *N*	Re-entrainment Factor R
0.000	3	0.21930
0.050	3	0.13300
0.075	3	0.11000
0.100	3	0.10000
0.200	3	0.02670
0.300	3	0.03507
0.400	3	0.00893
0.500	3	0.00447
0.600	0	0.00000

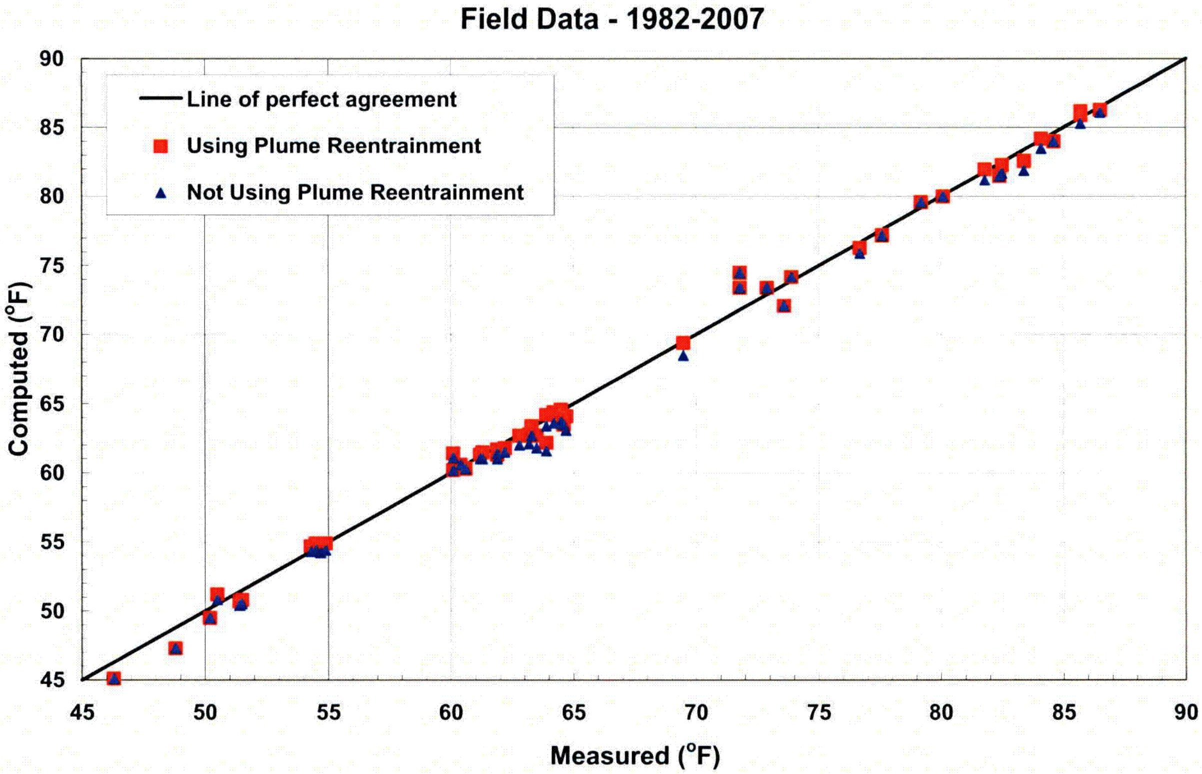

Figure 8. Sensitivity of Computed Temperature T_d to Effluent Re-Entrainment Function

Results of Updated Calibration

For the assumed diffuser slot width and entrainment coefficient, and updated calibration including the re-entrainment function for low river flow, the computed and measured downstream temperatures for the forty-nine downstream temperature data points collected in SQN field surveys since March 1982 are shown in Figure 9. The average discrepancy between the measured and computed downstream temperatures was about 0.55 F° (0.31 C°). For downstream temperatures above 75°F, the average discrepancy improved to about 0.38 F° (0.21 C°). Compared to the previous model calibration performed in 2003 (TVA, 2003) this represents an overall improvement of 0.13 F° (0.07 C°), and for downstream temperatures above 75°F an improvement of 0.02 F° (0.01 C°).

To be consistent with the 24-hour averaging specified in the current NPDES permit, the 24-hour average temperatures measured at the downstream temperature monitor, Station 8, are compared to those computed by numerical model in Figure 10. As before, the measured temperatures correspond to the average of sensor readings at the 3-foot, 5-foot, and 7-foot depths. The figure shows data collected for calendar year 2006, which included a period of exceptional drought in East Tennessee. The overall average discrepancy between the measured and computed 24-hour average downstream temperatures was about 0.51 F° (0.28 C°), and about 0.34 F° (0.19 C°) for downstream temperatures above 75°F. Measured downstream hourly average temperatures for the same time period are compared to those computed by numerical model in Figure 11. The data includes a period in February 2006 when one of the temperature probes temporarily failed, resulting in erroneously low measurements. As expected, the temperature data are much more scattered for the hourly temperatures. The average discrepancy between the measured and computed hourly average downstream temperatures was 0.81 F° (0.45 C°) for the full range of river temperatures, decreasing to 0.54 F° (0.30 C°) for downstream temperatures above 75°F. It needs to be emphasized that in Figure 10 and Figure 11, the data from Station 8 is not necessarily representative of the average temperature across the downstream end of the mixing zone. However, in monitoring the NPDES compliance for Outfall 101, data from Station 8 is considered valuable for verifying basic trends in the downstream temperature as determined by the numerical model, thus providing the motivation for presenting the comparisons given in these figures.

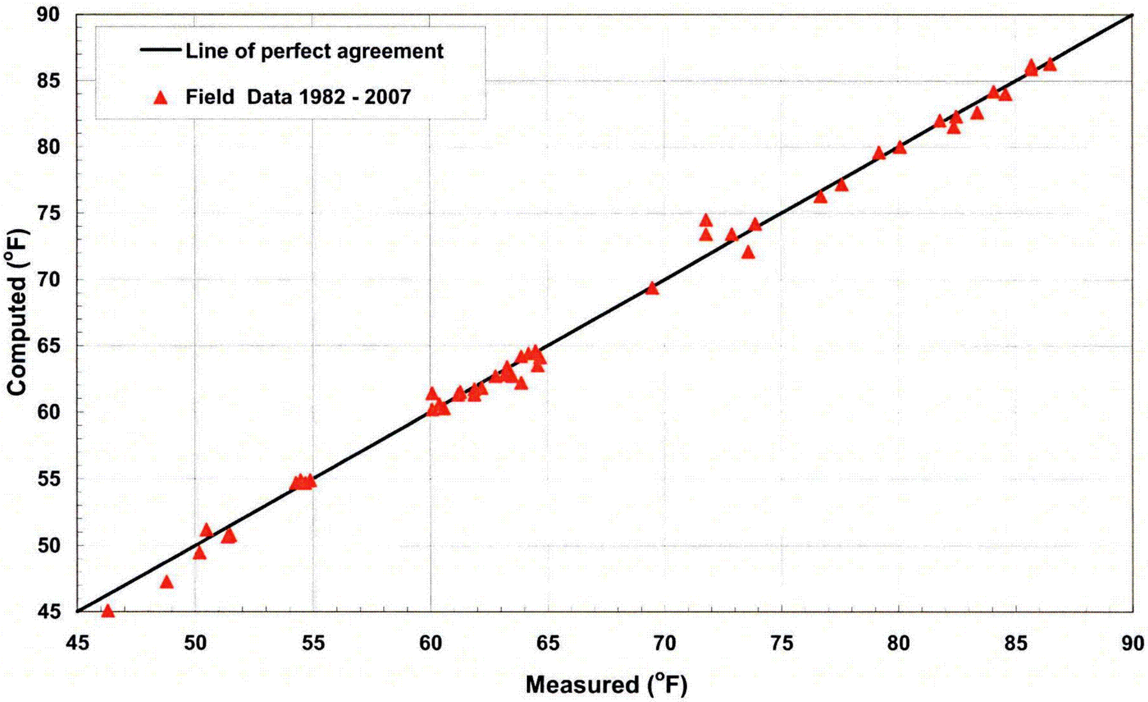

Figure 9. Comparison of Computed and Measured Temperatures T_d for Field Studies from April 1982 through November 2007

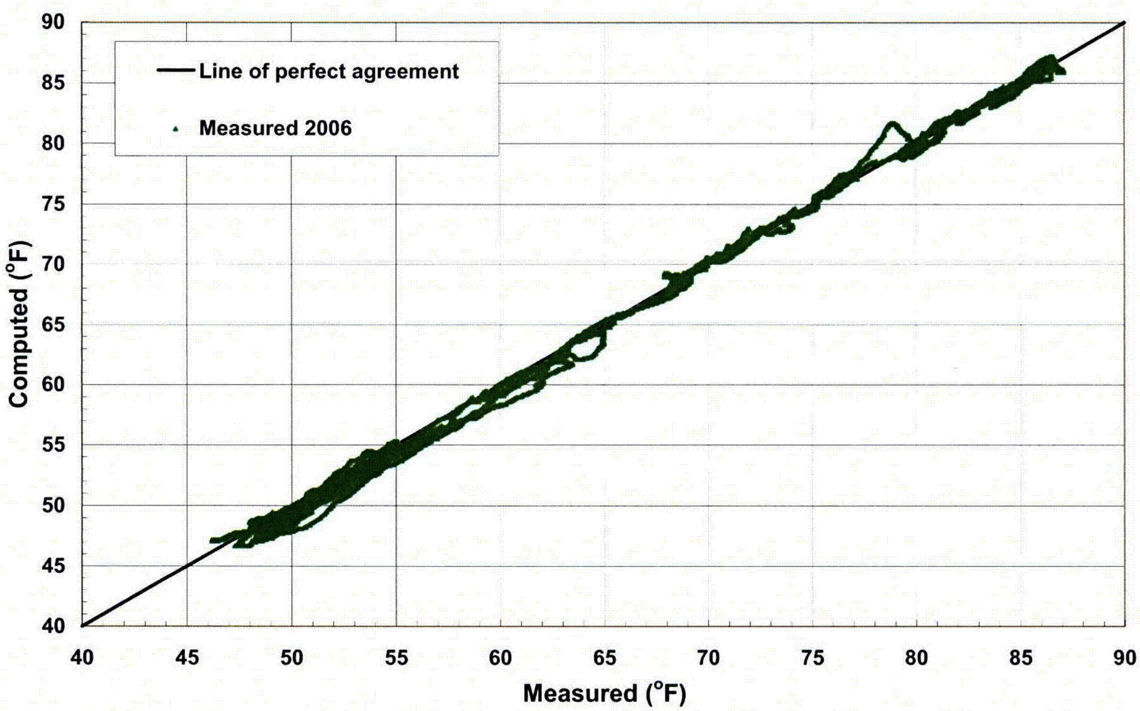

Figure 10. Comparison of Computed and Measured 24-hour Average Temperatures T_d for Station 8 for 2006

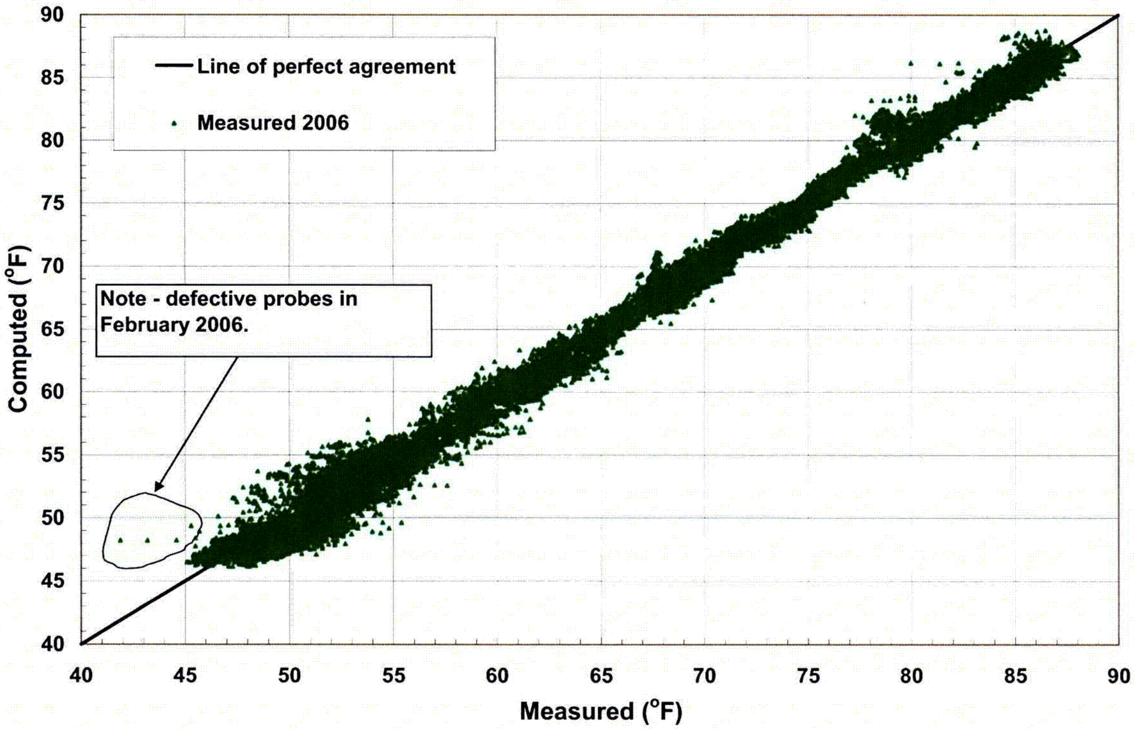

Figure 11. Comparison of Computed and Measured Hourly Average Temperatures T_d for Station 8 for 2006

CONCLUSIONS

The numerical model for the SQN effluent discharge computes the temperature at the downstream end of the mixing zone with sufficient accuracy for use as the primary method of verifying thermal compliance for Outfall 101. Due to observations from the current drought, the numerical model has been modified with a re-entrainment function to better reproduce the local buildup of heat that occurs in the river for sustained low river flow. With this modification, the discrepancy between the measured and computed downstream temperature has improved over that of the previous model calibration that was performed in 2003. Results also show that the model calibration is more accurate at higher river temperatures than at lower temperatures (i.e., above 75°F). This is considered valuable because accuracy is more crucial as the downstream temperatures approach the NPDES temperature limit. In the updated calibration study summarized herein, which used the results from forty-nine sets of temperature samples across the downstream end of the diffuser mixing zone, the average discrepancy between the measured and computed downstream temperatures was about 0.55 F° (0.31 C°). For downstream temperatures above 75°F, the average discrepancy improved to about 0.38 F° (0.21 C°).

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December 9, 2008

Stephanie Howard, SB 2A-SQN

SEQUOYAH NUCLEAR PLANT DIFFUSER DISCHARGE CALIBRATION

As required by NPDES Permit TN0026450 for Sequoyah Nuclear Plant effective September 1, 2005, the calibration has been updated for the discharge through the plant diffusers. Part III, Section G of the permit states that, *"The permittee shall calibrate the flowrate characteristics through the diffusers on a schedule of at least once every two years."* The most recent test was conducted on November 4, 2007. Plant conditions for the test included the operation of three CCW pumps and four ERCW pumps. The test included measurements to determine the flowrate through the diffusers and measurements to determine the diffuser head.

The results of the measurements are given in Attachment 1, which includes a summary of all tests from 1986 through 2007. The rating curve for computing the diffuser flow, given in Attachment 2, has been updated based on the new information. As shown in Attachment 2, the results of all valid tests fall within ±10 percent of the rating curve. This demonstrates that the hydraulic characteristics of the diffusers continue to provide a good method to measure the flow from the plant to the Tennessee River. The updated rating curve was incorporated in the compliance model on November 26, 2007.

It also is noted that the permit states *"For this permit period, such calibration shall be coordinated with the evaluation of the numerical modeling."* To fulfill this requirement, the river temperature at the downstream end of the mixing zone also was measured in the test of November 4, 2007. The results of these measurements will be provided in a separate report summarizing the results of a calibration study of the compliance model, also required by Part II, Section G of the permit.

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PNH:JGP
Attachments
cc (Attachments):
Boualem Hadjerioua, WT 10B-K
Ann Hurt, SB 2A-SQN
EDMS, WT 10C-K

Attachment 1

Calibration Data for SQN Diffuser Discharge, 1986 – 2007

Test Date	Number Of Pumps		Field Measurements				
			Discharge Measurement Method (A)	Water Surface Elevation (B)		Diffuser Head H	Diffuser Discharge Q
				Diffuser Pond	River		
	CCW	ERCW		(feet MSL)	(feet MSL)	(feet)	(cfs)
12/18/1986	2	4	MM	678.03	677.00	1.03	889
12/17/1986	3	4	MM	678.46	676.90	1.56	1,297
12/18/1986	4	4	MM	680.41	676.90	3.51	1,686
12/19/1986	6	4	MM	683.53	677.17	6.36	2,490
03/28/1989	5	4	MM	680.80	676.46	4.34	2,015
03/29/1989	5	4	MM	680.82	676.35	4.47	2,161
03/22/1990	2	3	MM	678.44	677.27	1.17	943
04/05/1990	3	4	MM	680.57	678.54	2.03	1,470
10/05/1990	3	4	MM	682.30	680.20	2.10	1,457
12/19/1990	6	4	MM	682.54	676.26	6.28	2,350
04/03/1991	6	4	MM	684.20	678.18	6.02	2,511
05/22/1991	6	4	MM	688.70	682.60	6.10	2,451
12/10/1991	5	4	MM	682.70	677.90	4.80	2,213
04/10/1992	2	3	MM	680.13	679.12	1.01	879
02/18/1994 (C)	2	3	MM	679.42	678.13	1.29	871
06/14/1994	6	4	MM	688.50	682.00	6.50	2,507
04/03/1997 (D)	3	3	MM	679.50	677.30	2.20	1,223
05/23/1997	6	3	MM	688.40	681.80	6.60	2,551
05/06/1998	6	3	ADCP	688.20	681.70	6.50	2,345
05/11/1999	6	3	ADCP	689.20	682.60	6.60	2,274
10/10/2001	6	3	ADCP	687.10	680.30	6.80	2,359
07/272002	6	4	ADCP	689.40	682.40	7.00	2,759
04/23/2003 (E)	3	4	ADCP	684.05	682.20	1.85	1,552
03/07/2006	6	3	ADCP	682.06	675.97	6.09	2,511
11/04/2007	**3**	**4**	**ADCP**	**680.88**	**678.66**	**2.22**	**1,291**

Notes:

(A) MM=Marsh-McBirney instrumentation. ADCP=Acoustic Doppler Current Profiler instrumentation.

(B) Water surface elevations for the diffuser pond and river recorded by instrumentation of the SQN Environmental Data Station. MSL=Mean Sea Level.

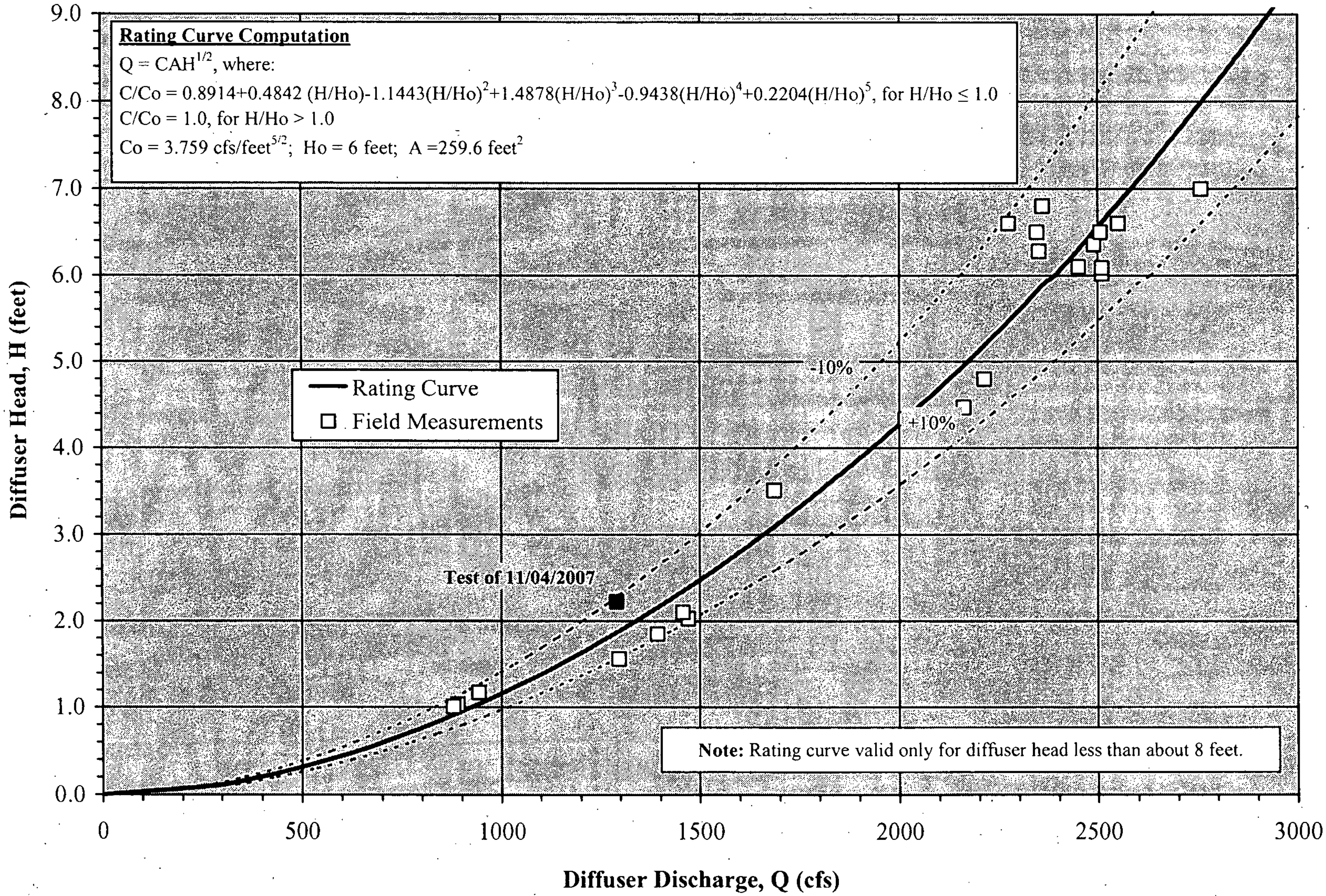
(C) The test of 02/18/94 was performed with very windy conditions, making it difficult to keep the boat steady. Due to the potential error introduced by these conditions, the resulting measurement was not used to determine the head-discharge relationship for the diffuser discharge.

(D) The test of 04/03/97 included a malfunction of the Marsh-McBirney compass, which prohibited the collection of data for flow direction. The diffuser discharge is based on an assumed flow direction. Due to the potential error introduced by these conditions, the resulting measurement was not used to determine the head-discharge relationship for the diffuser discharge.

(E) The test of 04/23/03 was performed with an ADCP setting that likely overestimated the volume of water passing through the diffuser pond. The resulting discharge significantly exceeded the capacity of pumps in service at the time. Due to the potential error introduced by these conditions, the resulting measurement was not used to determine the head-discharge relationship for the diffuser discharge.

Attachment 2

Rating Curve for SQN Diffuser Discharge



Tennessee Valley Authority, Post Office Box 2000, Soddy-Daisy, Tennessee 37384-2000

February 28, 2006

Dr. Richard Urban
State of Tennessee
Department of Environment and Conservation
Chattanooga Environmental Assistance Center
Division of Water Pollution Control
State Office Building, Suite 550
540 McCallie Avenue
Chattanooga, Tennessee 37402-2013

Dear Dr. Urban:

SEQUOYAH NUCLEAR PLANT (SQN)
DIESEL FUEL OIL INTERCEPTOR SYSTEM: TRIAL CLOSURE

The Diesel Fuel Oil Interceptor System was placed into operation at Sequoyah Nuclear Plant (SQN) in April 1994. The system was designed to intercept diesel fuel oil accidentally released from transfer lines. In accordance with interim monitoring procedures, biweekly monitoring of fuel oil product, groundwater levels, and water quality has been conducted to assure system functionality. Additionally, groundwater discharge from the system to the CCW Channel has been monitored for diesel range organics and extractable petroleum hydrocarbons for compliance purposes.

The attached report summarizes operation and monitoring data at the site from installation through December 2003. Data collected at the site subsequent to December 2003 show negligible differences in field and analytical results. Since May 2000, fuel oil product thickness has been almost immeasurable. Product thicknesses in trench extraction wells (EXT-1 to EXT-3) have shown no measurable product since January 2001. Only two occurrences of measurable product thickness (0.01 ft) have been observed at EXT-4 since January 2001. Groundwater samples of trench effluent (collected biweekly to monthly) indicate decreases in EPH concentrations to detection levels since February 2003. Furthermore, during construction of the Independent Spent Fuel Storage Installation in the 2001/2002 time period, 6300 yd^3 of soil was removed with approval from TDEC Solid Waste Division from an area partially overlapping where the fuel oil leak originally occurred.

The data collected to date and a thorough review of site hydrogeologic characteristics and engineered features at the release location, clearly indicate there is no risk to human health or the environment. Therefore, TVA proposes a trial closure of the diesel interceptor system as described in detail in Section 4 of the attached report. Initially, trial closure shall consist of turning off all pumps while continuing to monitor water/product levels and water quality (EPH) and maintaining visual observations along the CCW channel. The trial closure will extend for a period of two years. Daily inspections (5/week) are conducted of all site impoundments and this will continue through the trial closure period. If visual observations of the CCW Channel indicate fuel oil releases or a product thickness of greater than 0.1 ft are noted in routine monitoring of extraction or monitoring wells, the interceptor system will be immediately returned to operation and water/product level monitoring frequencies will revert to the original schedule.

As indicated in Section 4.3 of the attached report, water quality monitoring shall continue at well EXT-4 upgradient of the interceptor trench, wells 22 and 23 downgradient of the interceptor trench, and the CCW Channel on a quarterly frequency for the 2-year trial closure period. Due to its unique geographical location, there are no downgradient water supply wells located between the SQN site and the Tennessee River. Therefore, we propose the use of wells 22 and 23 for point-of-compliance. If EPH concentrations at either of these wells exceed 10 mg/L EPH, confirmatory sampling will be conducted within two weeks following receipt of analytical results. If subsequent results confirm EPH concentrations greater than 10 mg/L EPH, the interceptor system will be immediately returned to operation and water/product level monitoring frequencies will revert to the original schedule.

At the end of the two-year monitoring period, TVA will submit a report to TDEC documenting results from trial closure and providing recommendations for final closure and well/trench abandonment.

If this proposal meets with your approval, please contact us so that we can initiate trial closure activities. We respectfully request an April 10th concurrence date in order to initiate trial closure during higher precipitation months (worst case scenario).

Sincerely,

Stephanie A. Howard

Stephanie A. Howard
Principal Environmental Engineer
Signatory Authority for
J. Randy Douet
Site Vice President
Sequoyah Nuclear Plant

Tennessee Valley Authority
Energy Research & Technology Applications
Environmental and Engineering Services
Special Projects

SQN INTERCEPTOR SYSTEM
INTERIM MONITORING AND TRIAL CLOSURE

Prepared by
Hank E. Julian, P.E., P.G.

Research & Technology Applications
Knoxville, Tennessee

January 2006

TVA

TABLE OF CONTENTS

SQN INTERCEPTOR SYSTEM
INTERIM MONITORING AND TRIAL CLOSURE

1.0 INTRODUCTION

The Diesel Fuel Interceptor System was placed into operation at Sequoyah Nuclear Plant (SQN) in April 1994. The system was designed to intercept diesel fuel oil accidentally released from underground transfer lines. In accordance with interim monitoring procedures, biweekly monitoring of fuel oil product and groundwater levels has been conducted to assure system functionality. Additionally, groundwater discharge from the system to the Condenser Cooling Water (CCW) Channel has been monitored for total petroleum hydrocarbons and diesel range organics for compliance purposes. The purpose of this report is to evaluate data collected at the interceptor trench site since May 1995 and provide recommendations for trial closure and monitoring of the system.

2.0 INTERCEPTOR SYSTEM DESCRIPTION

The fuel oil interceptor system consists of a single interceptor trench containing three (3) 12-inch diameter groundwater/free product extraction wells (EXT-1, 2, and 3). The trench location is shown in Figure 2.1. In addition to the interceptor trench extraction wells, one 8-inch diameter extraction well (EXT-4) has been installed for groundwater/product removal. The system has been designed to operate by maintaining a constant water level within the trench using automated groundwater depression pumps that are coupled to a floating free product removal system.

Groundwater from the depression pumps is discharged to the CCW Channel via underground PVC lines. A valve box exists on the line behind the oil containment building for gathering routine groundwater samples. Oil from the free product pumps is discharged to drums in the oil containment building. Full drum sensors have been installed to prevent accidental overflows.

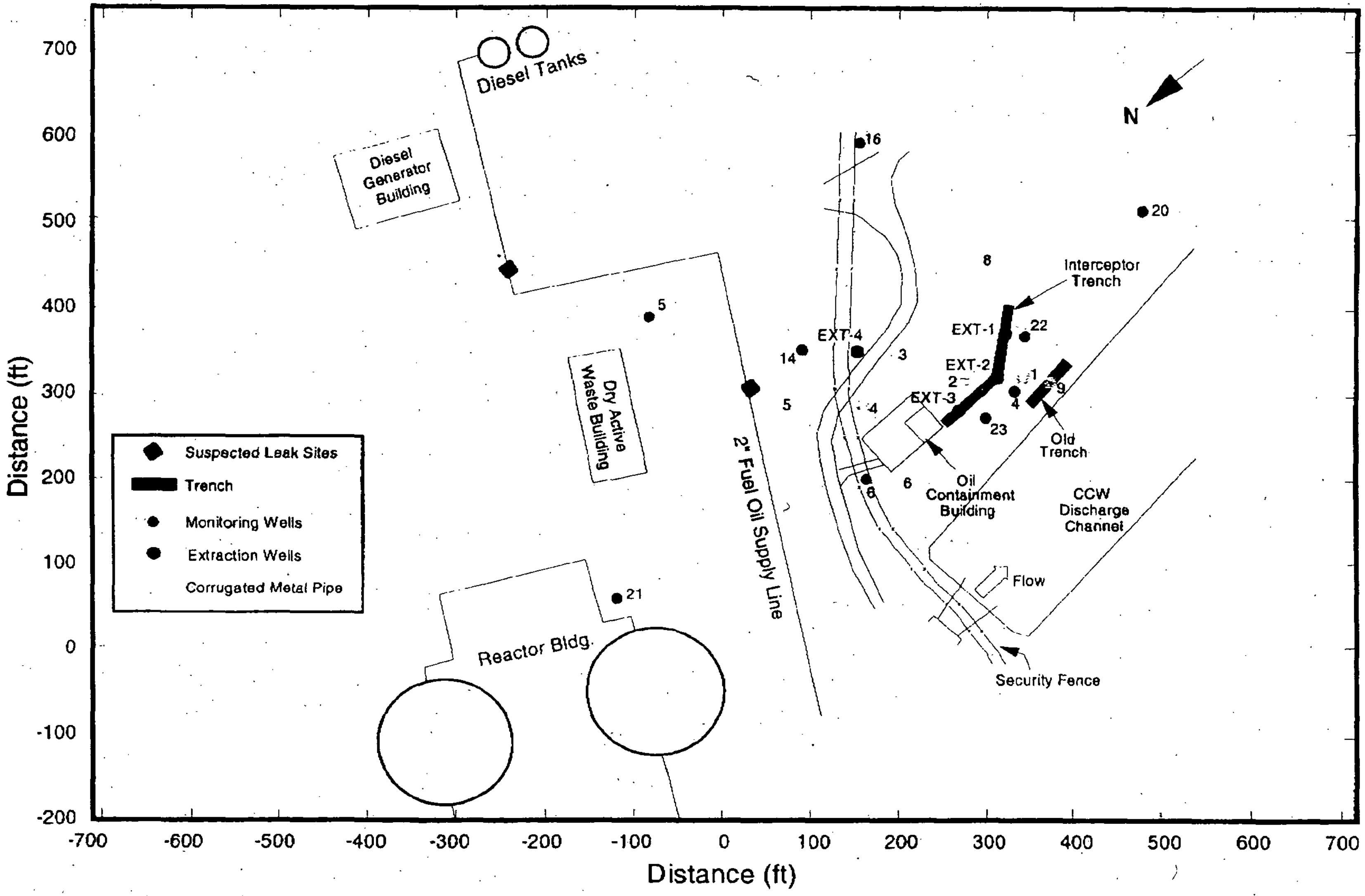
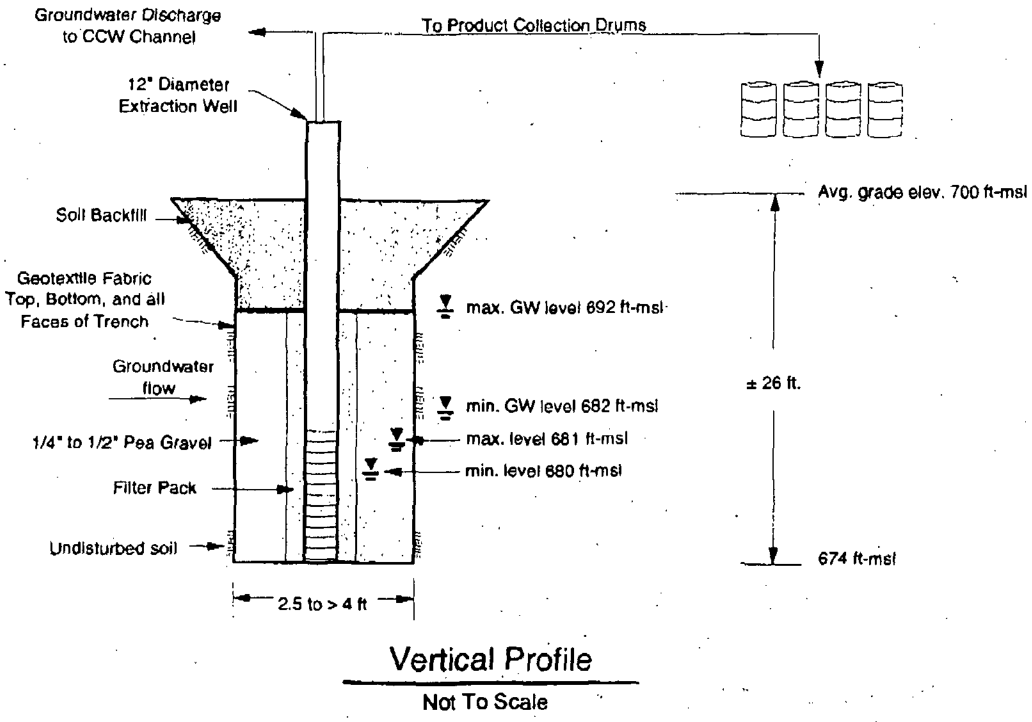


Figure 2.1 Site Map Showing Location of Interceptor Trench



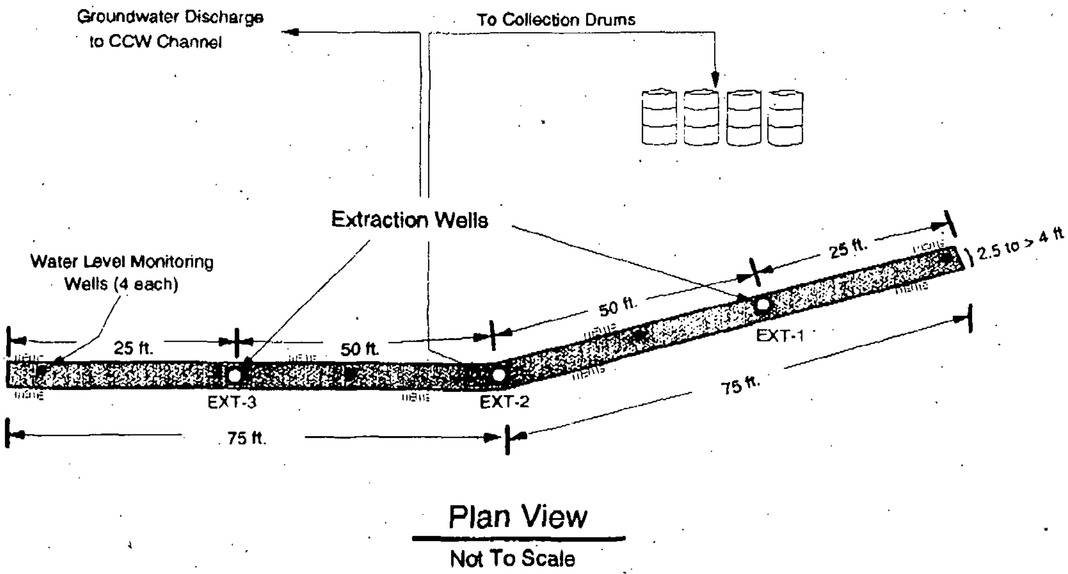


Figure 2.2 Schematic of Interceptor Trench

The interceptor trench was constructed as shown in Figure 2.2, noting that the trench width is variable, but generally increases from bottom to top. After extraction and monitoring well installation, geosynthetic fabric was installed along excavated faces of the trench and pea gravel was used as porous fill. The upper horizon of the trench was capped with natural backfill. Control parameters influencing the trench design were as follows:

1. Groundwater Levels Outside of Trench
    - Anticipated high of 692 ft-msl
    - Anticipated low of 682 ft-msl
2. Controlled Groundwater Level Inside Trench
    - Minimum of 680 ft-msl
    - Maximum of 681 ft-msl
3. Extraction Wells (EXT-1, 2, and 3)
    - 12-inch diameter wire-wrapped stainless steel screen at 0.04-inch slot
    - Screen from 674 to 684 ft-msl
    - Filter Pack is a graded coarse silica sand
4. Monitoring Ports (4 each)
    - 2-inch schedule 40 PVC
    - 0.02-inch machine cut slots
    - Screen from 674 to 695 ft-msl
    - No filter pack required

The location of EXT-4, which was near the centroid of the free product plume originally observed from subsurface investigations at the site, is shown on Figure 2.1. Free-product and groundwater depression pumping equipment is generally the same as that specified for trench. EXT-4 is 8 inches in diameter, continuously-wound schedule-40 PVC, 31 feet deep, screened from 5 feet below ground surface to the bottom of the well, possesses a graded medium-sand filter pack, 2-foot bentonite seal above screen, and is grouted to ground surface above the bentonite seal. The water table depression pump in EXT-4 was originally designed to maintain groundwater levels from 685 to 686 ft-msl but levels were modified in the field.

A description of pumping equipment is as follows:

a. Free Product Removal Pumps
    - Electric down-hole product pump (115 VAC, 60 Hz, Single-Phase)
    - Water-free oleophilic/hydrophobic screen
    - Floating intake with minimum 1-ft travel
    - Two sensors inside hydrocarbon reservoir to actuate product and water depression pumps
    - Flow rate of 0.25 to 0.5 gpm at 90 feet TDH
    - 100 mesh screen
    - Explosion proof cast aluminum construction
    - Circuit protection
    - Drum full sensor to prevent overflows

b. Water Depression Pumps
    - Side deployment with free-product pump
    - Electric submersible Grundfos pumps
    - Flow rate of 1 to 7 gpm
    - Actuated by sensors inside hydrocarbon reservoir and water level probe

The oil containment building is located on the old EMB slab and houses four drums for collecting free-product. The discharge lines from the product pumps have been installed in a manifold assembly for flexibility of operation. It is possible to fill one or two drums at a time with the apparatus and have two drums reside as spares for changeover. Two magnetic overflow prevention sensors that fit the bungholes of the drums have been installed to prevent accidental overflows. The sensors are interfaced with the controls to turn off product pump(s) when a drum nears the full level.

3.0 INTERIM OPERATION AND MONITORING RESULTS

3.1 Water Levels and Product Thickness

3.1.1 Extraction Wells

Figure 3.1 shows the results of biweekly monitoring of groundwater levels in extraction wells EXT-1 through EXT-4. As shown, groundwater levels in EXT-1 through EXT-3 are identical with few exceptions. EXT-4 resides upgradient of the interceptor trench where groundwater levels are higher. Prior to May 1996, groundwater levels within the interceptor trench were relatively high. However, since that time groundwater levels have generally been maintained within operational levels of 680 to 683 ft-msl except during brief outages. Groundwater levels at EXT-4 are more variable. The occasional spikes observed in groundwater levels are primarily increases, possibly from recharge by precipitation. Groundwater level increases also occur when the depression pumps are turned off for maintenance or due to control panel problems from power surges (e.g. lightning). There are no correlations in groundwater levels of extraction wells and surface water elevations.

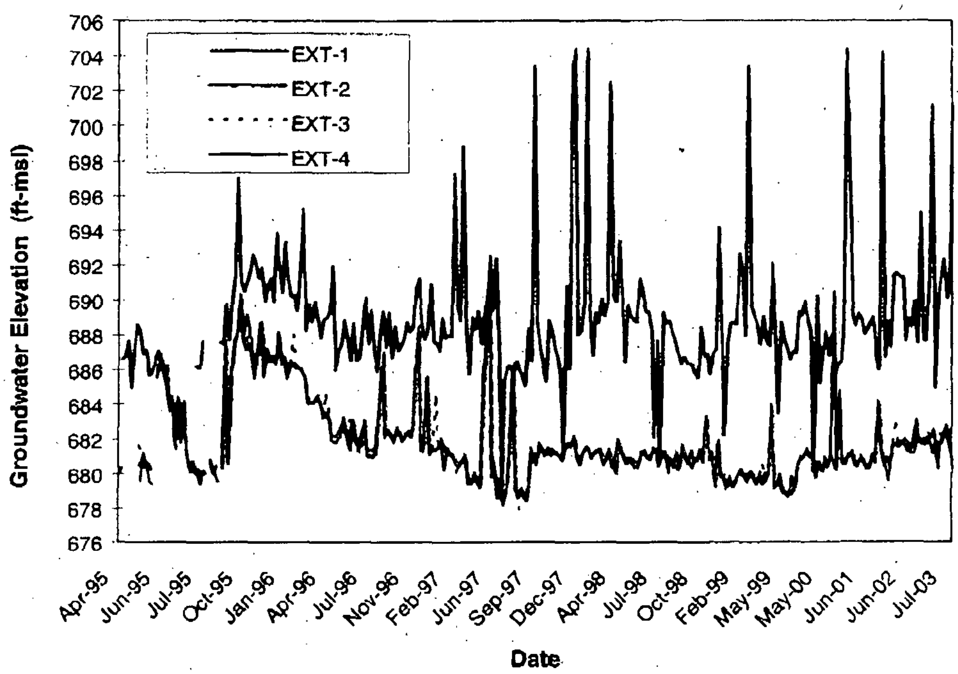


Figure 3.1 Groundwater Levels at Extraction Wells

Figures 3.2 through 3.5 show groundwater levels and product thickness at extraction wells with time. Collectively, the product thickness measurements suggest that fuel oil product has been removed from the subsurface episodically since the interceptor system went online. The current data also indicate declining levels of product at the locations of all extraction wells (Figure 3.6) with product from EXT-4 accounting for the vast majority of accumulated fuel oil. Since May 2000, product thickness has been almost immeasurable. Product thickness in trench extraction wells (EXT-1 to EXT-3) has shown no measurable product since January 2001. Only two occurrences of measurable product thickness (0.01 ft) have been observed at EXT-4 since January 2001.

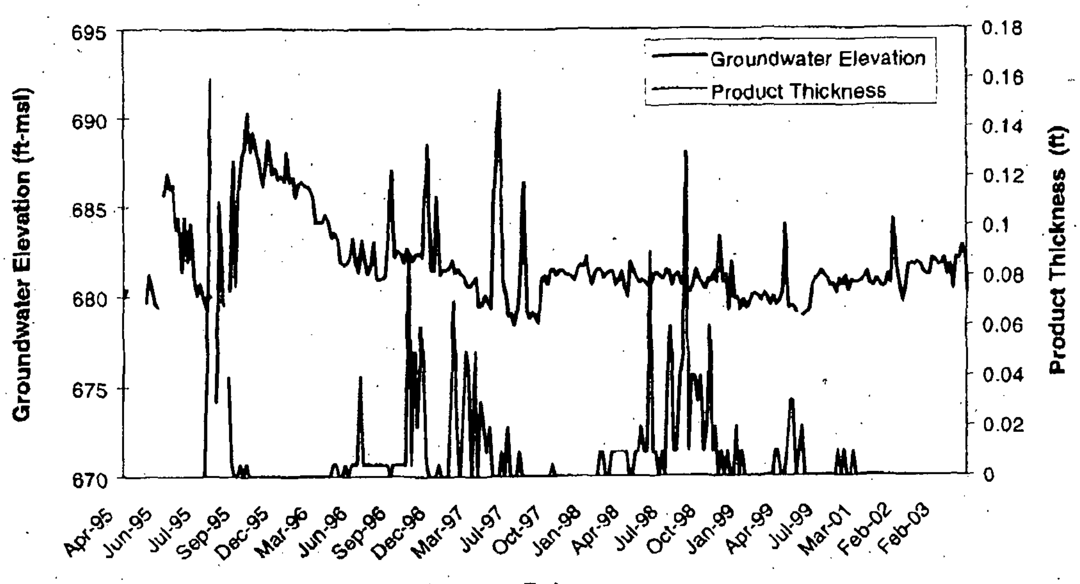


Figure 3.2 Groundwater Elevation and Product Thickness at Extraction Well 1

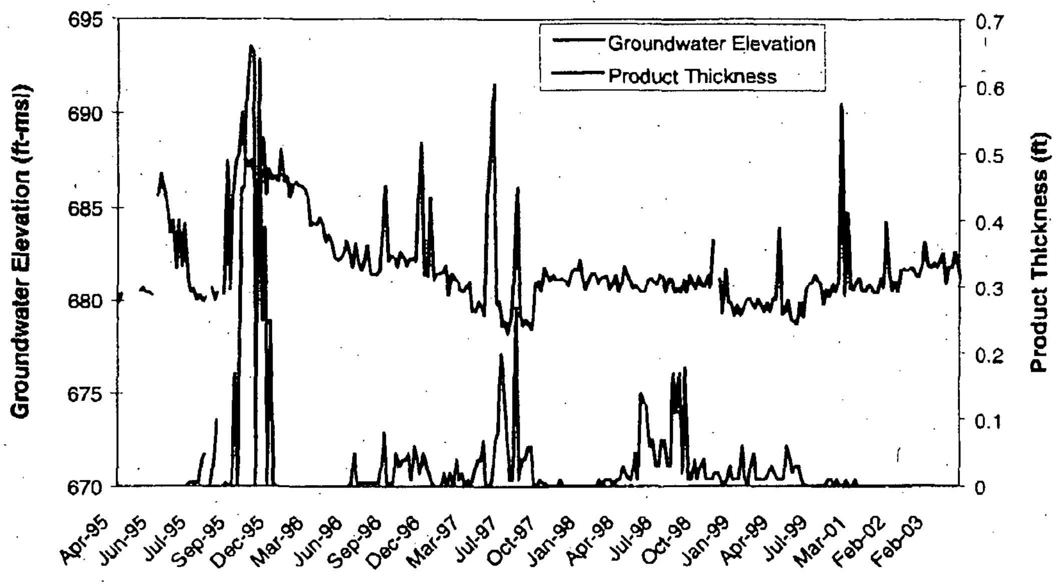


Figure 3.3 Groundwater Elevation and Product Thickness at Extraction Well 2

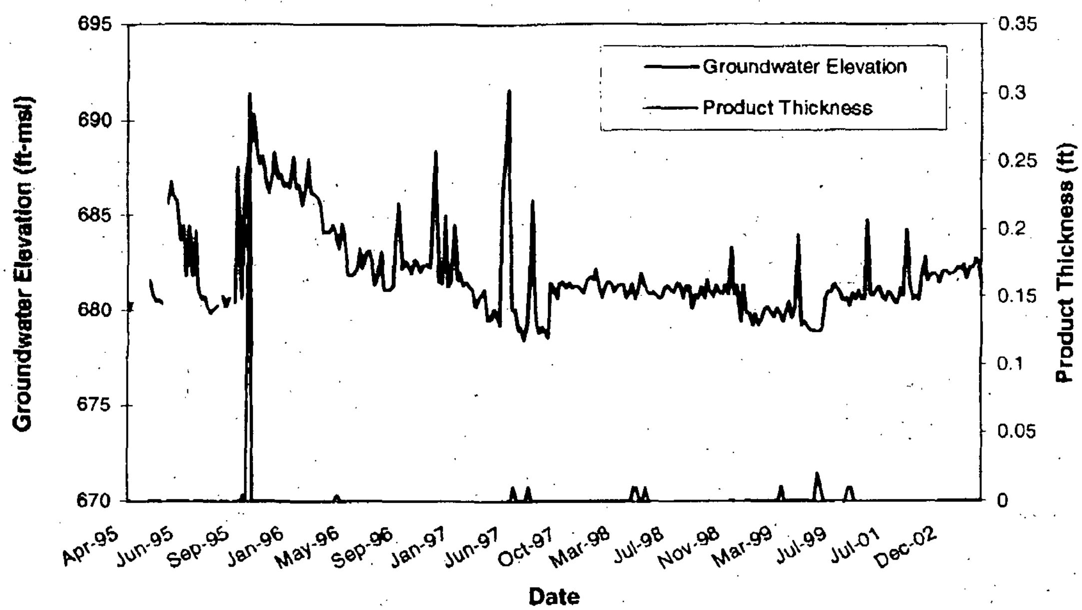


Figure 3.4 Groundwater Elevation and Product Thickness at Extraction Well 3

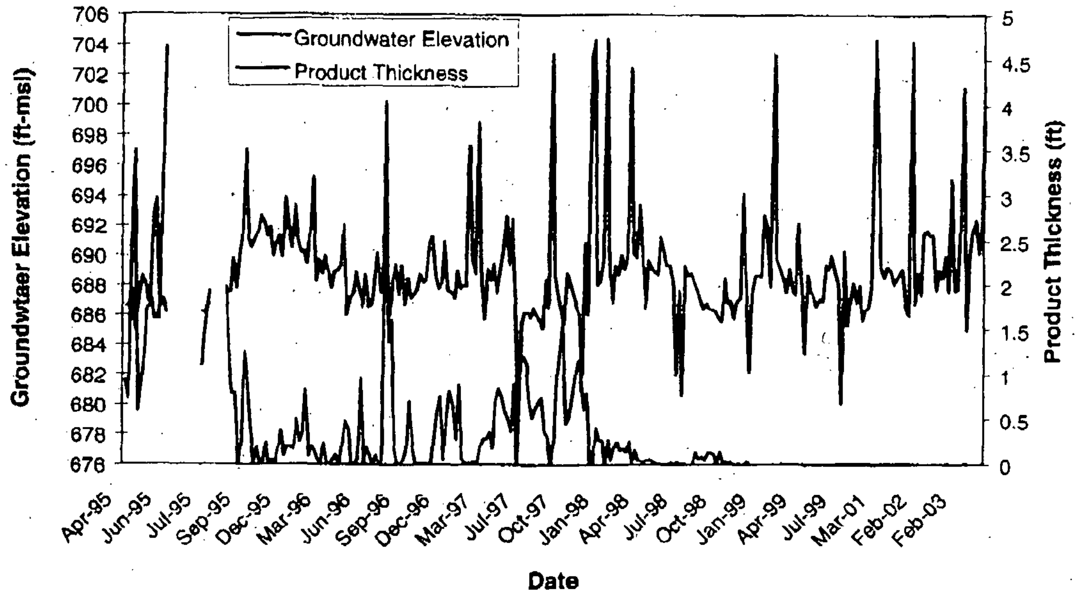


Figure 3.5 Groundwater Elevation and Product Thickness at Extraction Well 4

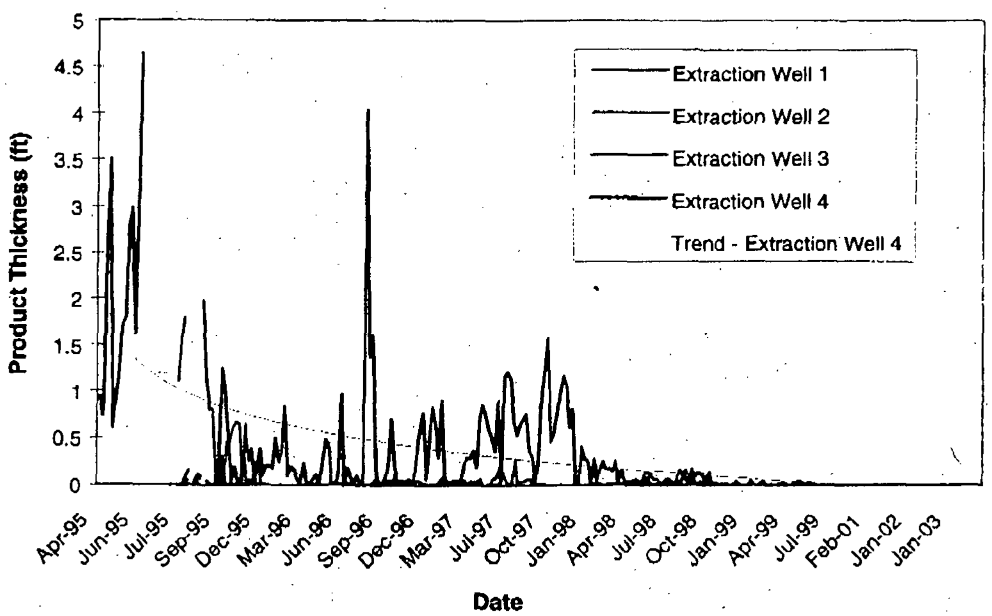


Figure 3.6 Product Thickness at Extraction Wells

3.1.2 Monitoring Wells

Figure 3.7 shows the results of biweekly water level monitoring at wells 4, 22, 23, and the CCW Channel. CCW Channel measurements were obtained from continuous (15-minute frequency) surface water level measurements in the Diffuser Pond. During the monitoring period from May 1995 to September 2003, the CCW Channel water surface has varied from 678.3 to 691.9 ft-msl with an average elevation of 685.9 m-msl. As shown in Figure 3.7, all monitoring wells exhibit slight correlation with water levels in the CCW Channel. With few exceptions, groundwater levels outside of the interceptor trench have remained within a range 682 to 692 ft-msl, which was estimated during design stage of the interceptor system.

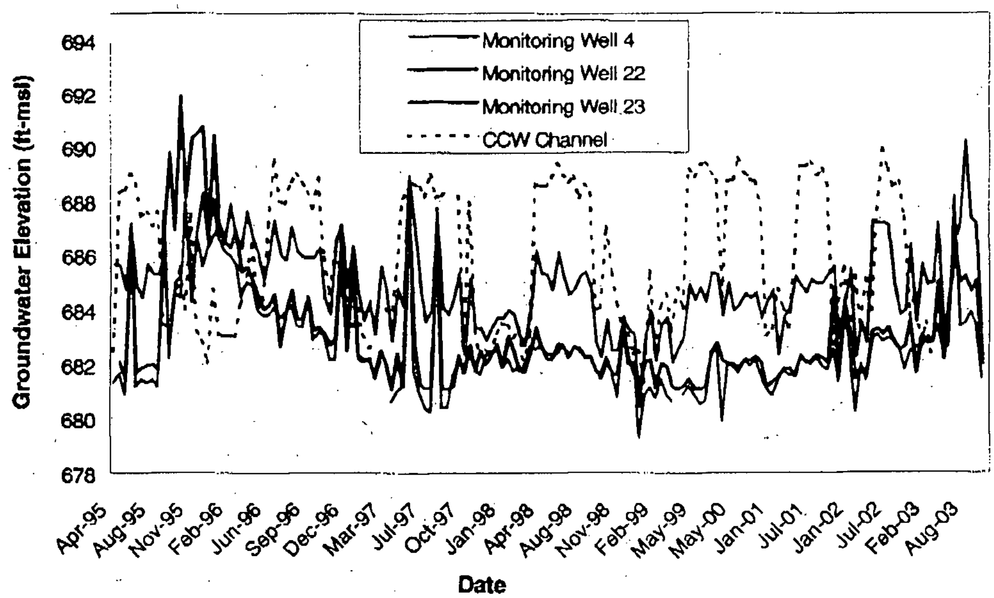


Figure 3.7 Water Levels at Monitoring Wells and CCW Channel

Figures 3.8 through 3.10 show groundwater level and product thickness at monitoring wells with time. The product thickness measurements suggest that fuel oil product is being actively removed from the downgradient (west) side the interceptor trench. Similar to product extraction wells, the current data also indicate declining levels of product at the locations of these monitoring wells. Since July 2001, product thickness has been immeasurable at these locations.

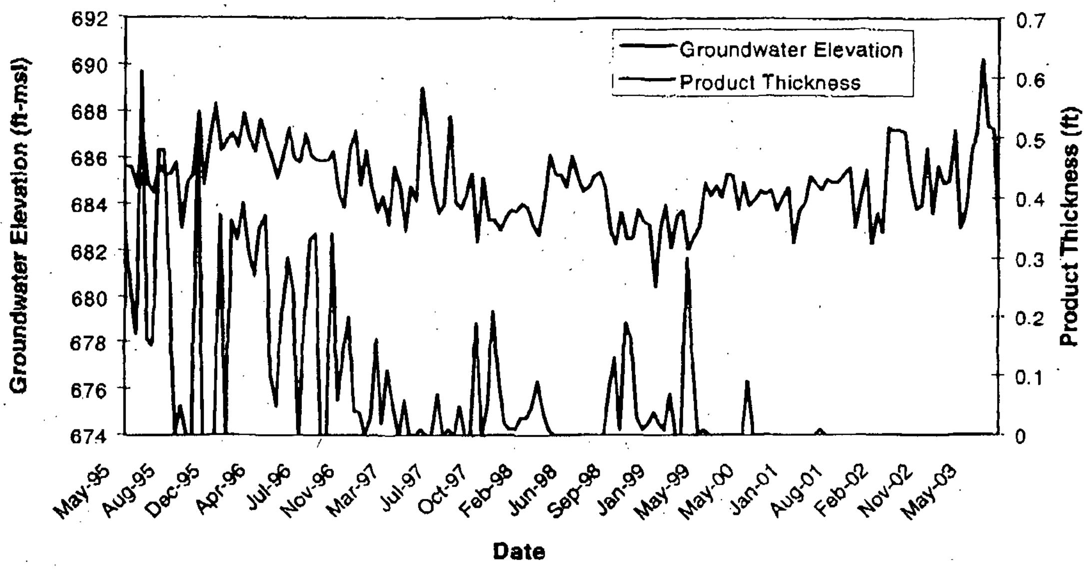


Figure 3.8 Groundwater Elevation and Product Thickness at Monitoring Well 4

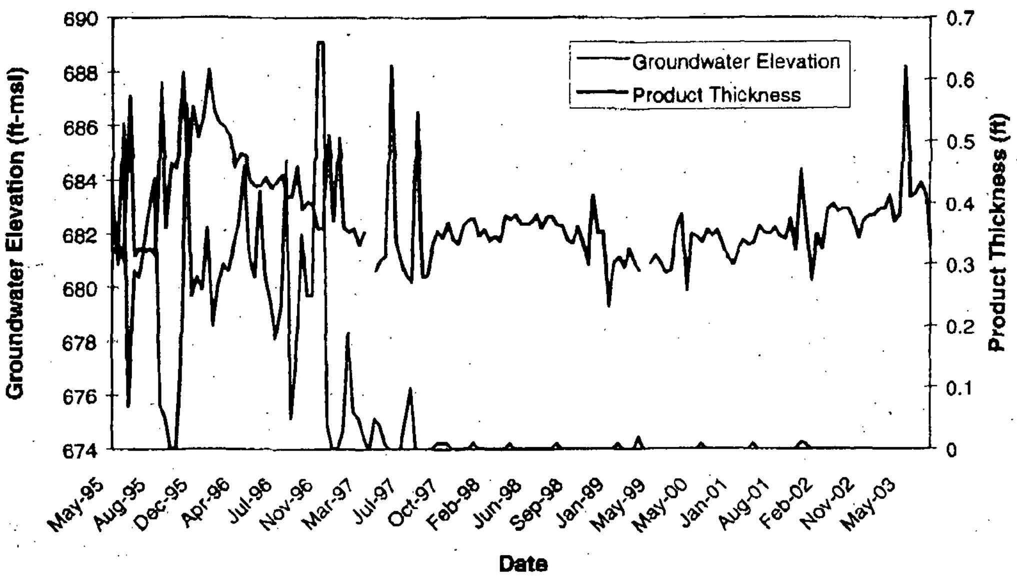


Figure 3.9 Groundwater Elevation and Product Thickness at Monitoring Well 22

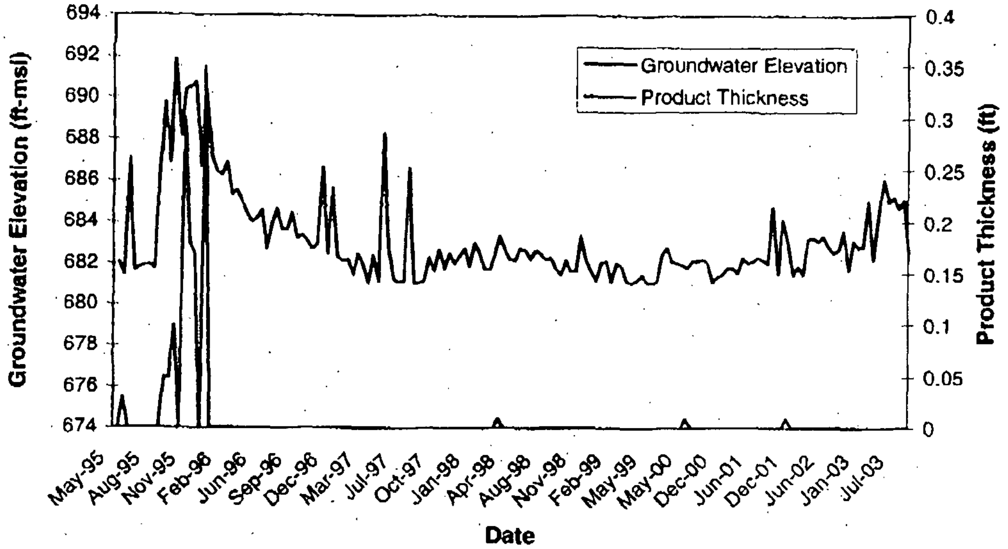


Figure 3.10 Groundwater Elevation and Product Thickness at Monitoring Well 23

Figure 3.11 shows the potentiometric surface at the site from February 10, 2003 based on water level measurements at extraction wells, monitoring wells, and the CCW Channel. The data indicates that drawdown produced by the interceptor trench is within acceptable ranges and the system is performing in accordance with original design.

3.2 Water Quality

3.2.1 Trench Effluent

Currently, groundwater samples of trench effluent are collected biweekly to monthly from a sampling port on the PVC discharge line to the CCW Channel (Figure 3.12). The water quality of effluent from the interceptor trench has been gauged by measurements of TPH and DRO from November 1994 to January 2002, and by EPH analysis since January 2002. TPH measurements have been negligible, and therefore are not shown in Figure 3.12. DRO concentrations ranged from <0.1 to 21 mg/L and the average was 1.1 mg/L from November 1994 – January 2002. EPH concentrations ranged from <0.5 to 4.4 mg/L and the average was 0.9 mg/L from January 2002 to September 2003. As shown in Figure 3.12, data indicate a decreasing trend in petroleum hydrocarbon concentrations with EPH concentrations at or just above detection levels since February 2003.

13

Figure 3.11 Potentiometric Surface at Site from February 10, 2003

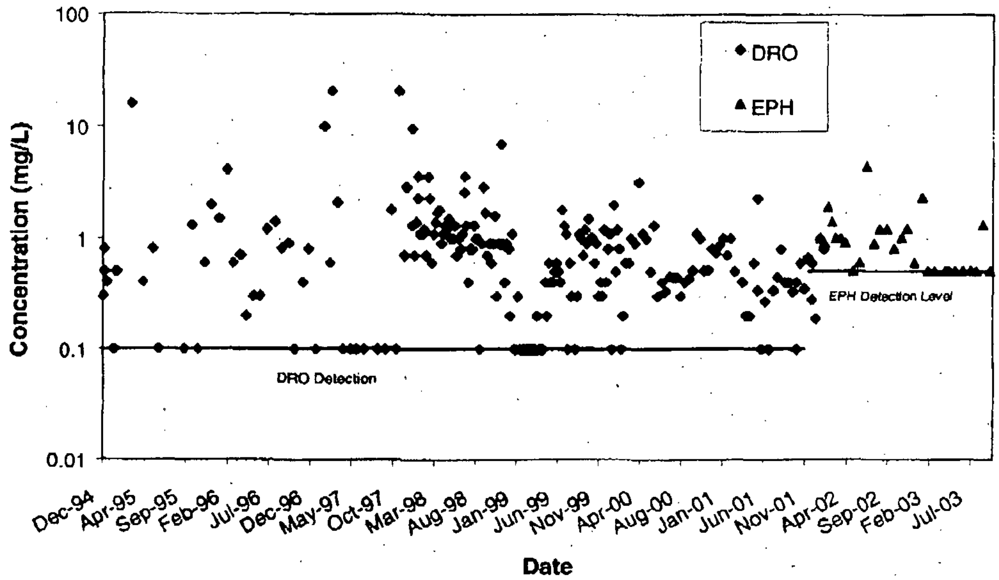


Figure 3.12 DRO and EPH Measurements of Trench Effluent

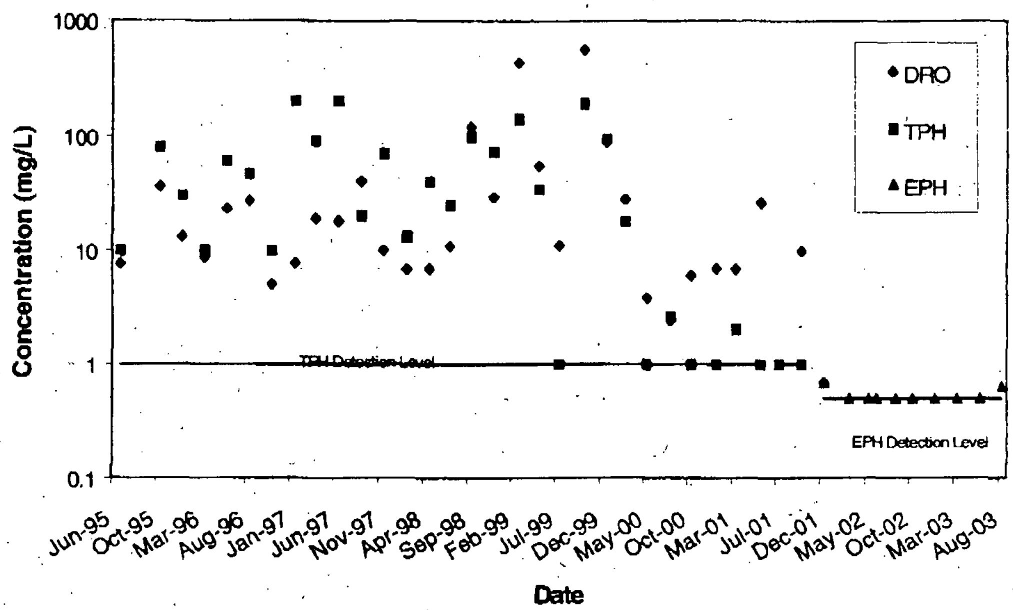


Figure 3.13 DRO, TPH, and EPH Measurements at EXT-4

3.2.2 CCW Channel

Currently, aqueous samples of the CCW Channel are collected monthly at a sampling location downstream of the Interceptor Trench. The water quality of the CCW Channel has been gauged by measurements of TPH and DRO from November 1994 to January 2002, and by EPH analysis since January 2002. With only one exception of DRO (0.51 mg/L on 12/19/01) all measurements of TPH, DRO, and EPH have been less than minimum detection levels.

3.2.3 Extraction Well 4 (EXT-4)

The groundwater samples of EXT-4 are currently collected on a bi-monthly basis. The water quality of EXT-4 has been gauged by measurements of TPH and DRO from November 1994 to January 2002, and by EPH analysis since January 2002. DRO concentrations ranged from <0.1 to 560 mg/L and the average was 52.3 mg/L from November 1994 – January 2002. TPH concentrations ranged from <1.0 to 200 mg/L and the average was 49.9 mg/L from November 1994 – January 2002. As shown in Figure 3.13, data indicate a decreasing trend in petroleum hydrocarbon and diesel range organic concentrations with EPH concentrations at or just above detection levels since January 2002.

4.0 RECOMMENDATIONS FOR TRIAL CLOSURE AND MONITORING

The data collected to date, and a thorough review of site hydrogeologic characteristics and engineered features at the release location, clearly indicate there is no risk to human health or the environment. Therefore, TVA proposes a trial closure of the diesel interceptor system; i.e., turning off all pumps while continuing to monitor water/product levels and water quality (EPH) and maintaining visual observations along the CCW channel. The trial closure will extend for a period of two years. Daily inspections are conducted of all site impoundments and this will continue through the trial closure period. Due to its unique geographical location, there are no downgradient wells located between the site and the Tennessee River. Therefore, the point of compliance will be the CCW Channel. If visual observations of the CCW Channel indicate fuel oil releases or a product thickness of >0.1 ft are noted in extraction or monitoring wells, the interceptor system will be immediately returned to operation and water/product level monitoring frequencies will revert to the original schedule.

At the end of the two-year monitoring period, TVA will submit a report to the Tennessee Department of Environment and Conservation (TDEC) documenting results from trial closure and providing recommendations for final closure and well/trench abandonment.

4.1 Pumping Equipment and Control Panels

Pumping equipment (i.e., depression and product pumps) will be turned off but shall remain in place for the first four months of the trial closure. The equipment shall be maintained on a routine basis to assure operability. Emergency spill equipment and media will be maintained at the site in case of emergency events. Site personnel will follow all other routine maintenance recommendations from vendors for pumping equipment and control panels. If the first four months of trial closure indicate no visual observations of fuel oil releases to the CCW Channel and product thickness remains <0.1 ft (without extraction), pumping equipment will be removed from extraction wells and placed in site storage for the remaining term of trial closure.

4.2 Water and Product Levels

Measuring and recording of groundwater/product levels in all site extraction wells and monitoring wells (except wells 5, 16, and 21) will continue on a bi-weekly basis for three months. The frequency shall be reduced to monthly for the second quarter and subsequently quarterly for one and one-half (1.5) years. Visual monitoring of the CCW Channel will be conducted on a routine basis to inspect for fuel oil sheens near the interceptor trench embankment. An existing telemetry system exists for monitoring water levels in the Diffuser Pond at 15-minute intervals. Assuming no head loss between the CCW Channel gate structure and the Diffuser Pond, this data provides suitable real-time monitoring of CCW Channel levels.

4.3 Water Quality Monitoring

Water quality monitoring shall be conducted at well EXT-4 upgradient of the interceptor trench, wells 22 and 23 downgradient of the interceptor trench, and the CCW Channel (Figure 2.1) on a quarterly frequency for the 2-year monitoring period. Laboratory analysis shall consist of EPH via U.S. EPA Method 8015B.

Signature Page

We, the undersigned, certify under penalty of law, including but not limited to penalties for perjury, that the information contained in this report form and on any attachments, is true, accurate, and complete to the best of our knowledge, information, and belief. We are aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for intentional violations.

TVA Sequoyah Nuclear	Stephanie A. Howard	2/28/06
Owner/Operator (Print name)	Signature	Date
Signatory authority for J. Randy Douet, Site Vice President	Principal Environmental Engineer	
	Title (Print)	
Henry E. Julian, P.E., P.G.		2/10/2006
P.E. or P.G. (Print name)	Signature	Date
	PE: 021114 PG: TN3790	
	Tennessee Registration #	

Note: Each of the above signatures shall be notarized separately with the following statement.

STATE OF Tennessee COUNTY OF Knox

Sworn to and subscribed before me by Teresa M. Householder on this date

February 10, 2006. My commission expires June 7, 2008

Teresa M. Householder	Teresa M. Householder	2-10-06
Notary Public (Print name)	Signature	Date

Stamp/Seal

TERESA M. HOUSEHOLDER
STATE OF TENNESSEE NOTARY PUBLIC
KNOX COUNTY