TENNESSEE VALLEY AUTHORITY
River Operations & Renewable

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 March 2011

WR2013-1-45-152

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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 hydrothermal conditions produced in the river by the interaction 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 parameters 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. The third parameter is a relationship for the amount of diffuser effluent that is re-entrained into the diffuser plume for periods of sustained low river flow.

Temperature measurements across the downstream end of the SQN mixing zone from fifty samples collected between 1982 and 2012 were used in this calibration study. These observed 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 show acceptable agreement between computed and measured temperatures, particularly at river temperatures greater than 75ºF. The overall average discrepancy between the measured and computed downstream temperatures was about 0.55 Fº (0.31 Cº). For downstream temperatures above 75ºF, the average discrepancy was about 0.38 Fº (0.21 Cº). There was no significant change in the model performance compared to the previous calibration, and as a result, no update was required in the model parameter set.

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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 in Chickamauga Reservoir. The overbanks are highly irregular and usually less than 20 feet deep.

SQN has two units with a total summertime gross generating capacity of about 2350 MWe and an associated waste heat load of about 15.6×10^9 Btu/hr (TVA, 2010). 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.

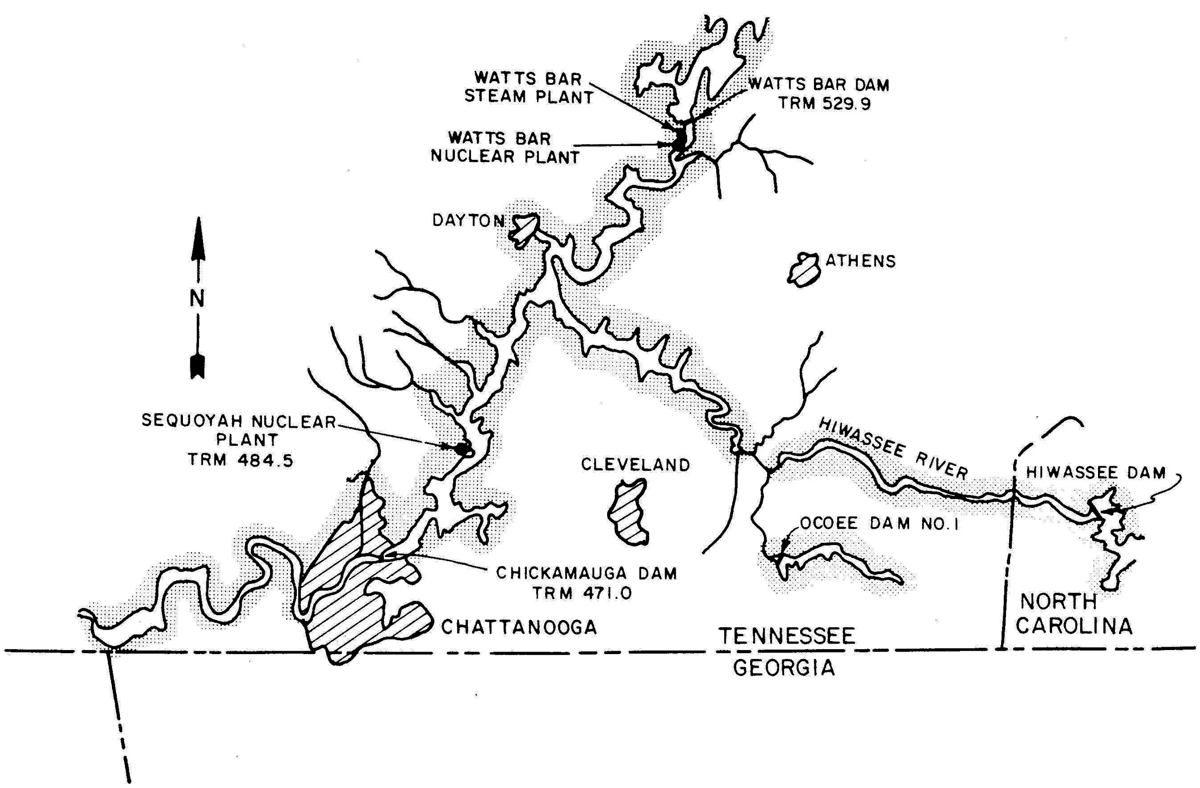

Figure 1. Location of Sequoyah Nuclear Plant

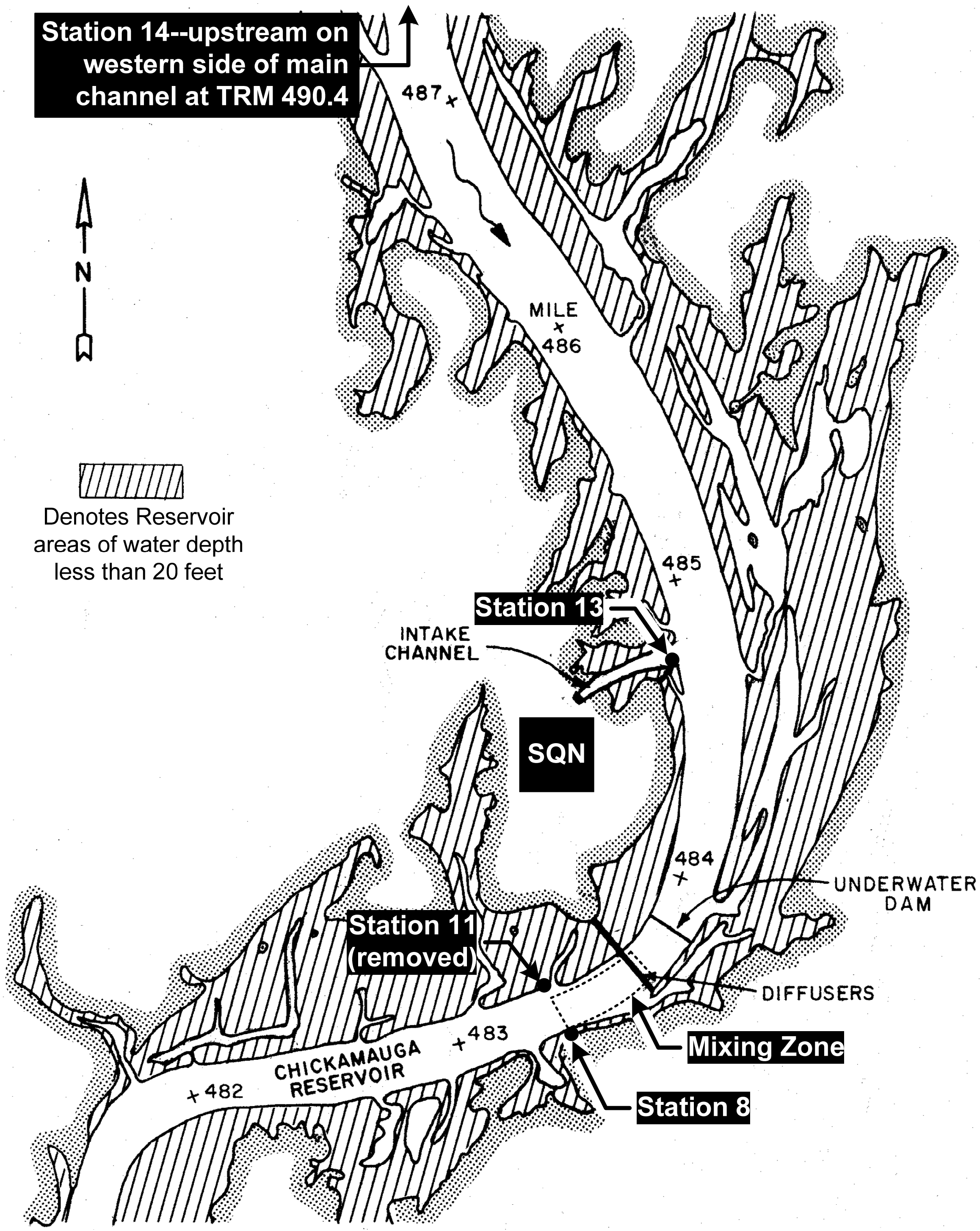

Figure 2. Chickamauga Reservoir in the Vicinity of Sequoyah Nuclear Plant

The compliance of SQN operation with the instream temperature limits specified in the NPDES permit (TDEC, 2011) 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 often was not in the main path of flow 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 river temperature upstream of the diffuser mixing zone (measured at Station 13, see Figure 2), the discharge in the river at SQN (determined from measurements at Watts Bar Dam and Chickamauga Dam), the depth of flow in the river (measured at Station 13), the temperature of the flow issuing from the plant diffusers (measured at Station 12, see Figure 2), and the discharge of the flow issuing from the diffusers (determined from measurements at both Station 12 and Station 13). A PC, 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 operators (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 Cº) for months April through October, and 9.0 F° (5.0 Cº) 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 Cº/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 accompanying 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. However, under sustained low flow conditions, it was discovered that heat from the diffusers can migrate upstream and reach the area of 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 in the river further upstream 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 86.9°F (30.5°C). Since the state's criteria makes exception for exceeding the value as a result of natural conditions, when the 24-hour average ambient temperature exceeds 84.9°F (29.4°C) and the plant is operated in helper mode, the maximum temperature may exceed 86.9°F (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 93.0°F (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 measured at Station 14 and the computed 24-hour average temperature at the downstream end of the mixing zone. The 24-hour average temperature rise shall be limited to 5.4F° (3.0 C°) during the months of April through October. The 24-hour average temperature rise shall be limited to 9.0F° (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 the 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 3.6F° (2 C°) per hour.

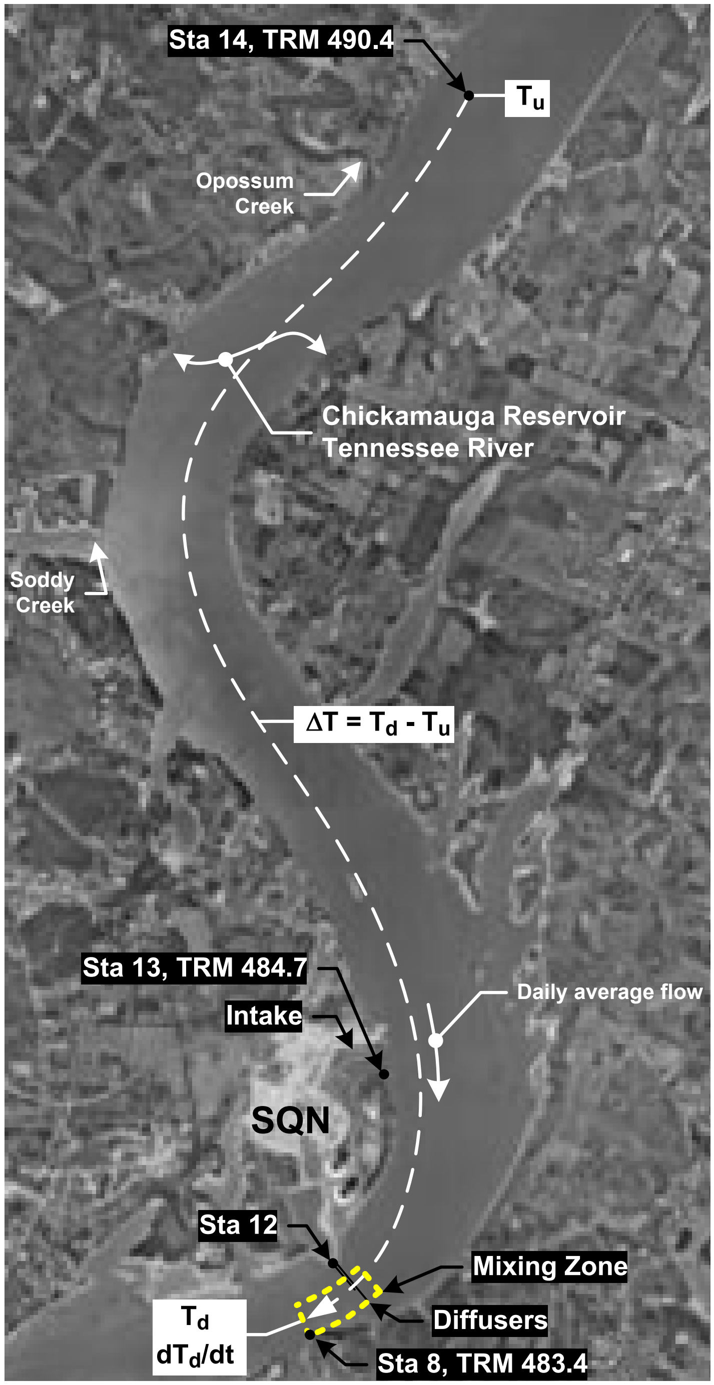

Figure 3. Locations of Instream Temperature Monitors for Sequoyah Nuclear Plant

NUMERICAL MODEL

The diffusers at SQN are located on 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 arc of approximately 18 degrees in the downstream upper quadrant 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 on the plant-side of the river (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 parameters 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). Based on later studies that provided evidence that re-entrainment occurs (TVA, 2009), the original numerical model was 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.

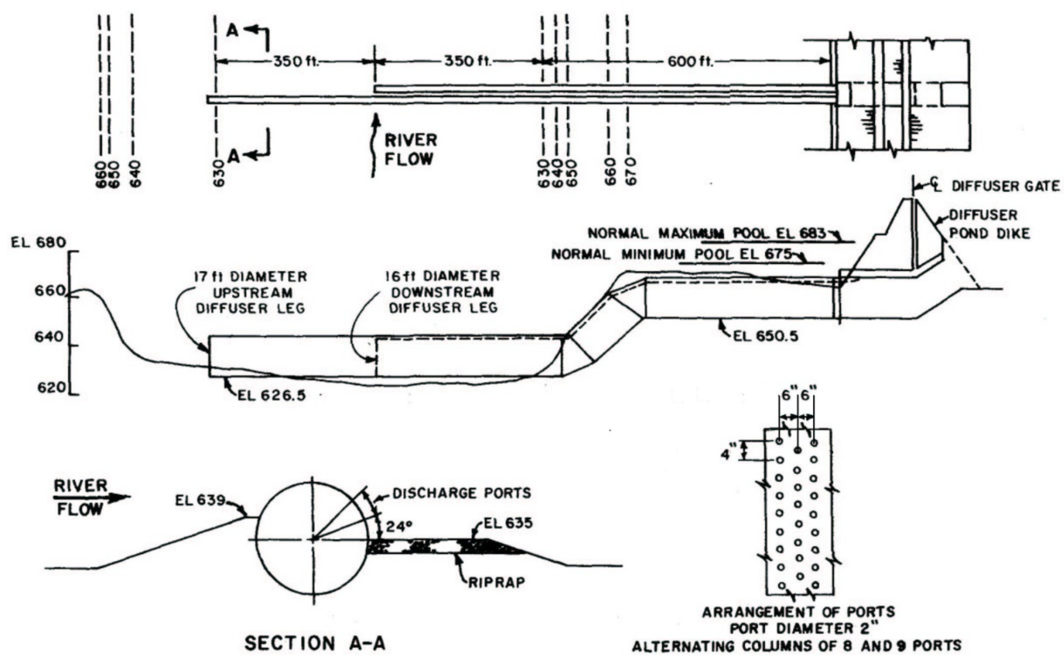

Figure 4. Sequoyah Nuclear Plant Outfall 101 Discharge Diffusers

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.

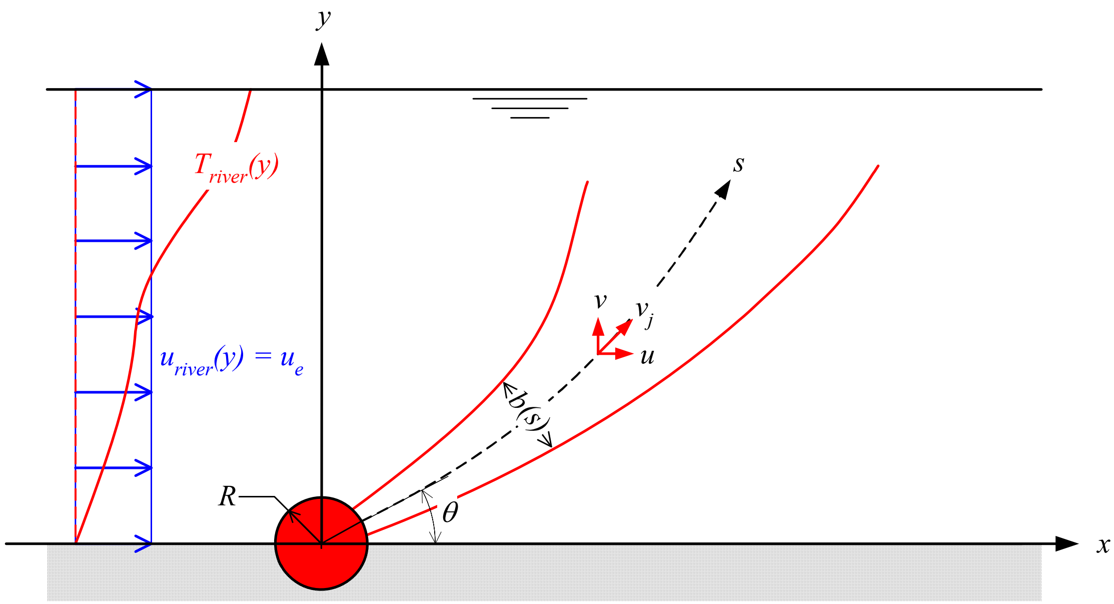

Figure 5. Two-Dimensional Plane Buoyant Jet Model for a Submerged Diffuser

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,

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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, 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 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). 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, 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 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 (Figure 2), 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

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

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 Equation 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.

Plume Entrainment

Two empirical relationships for the plume entrainment coefficient are available in the numerical model. 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

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

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

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

The term w_d is the velocity of the diffuser discharge, g is the gravitational constant, b_0 is the diffuser slot width, ρ_d is the density of the diffuser discharge, and ρ_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

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

where

$$rmf = u_{river}^3 / b, \tag{25}$$

and

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

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.

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.

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 March 2011, field surveys were performed in 1981, 1982, 1983, 1987, 1996, 1997, 1999, 2000, 2002, 2003, 2004, 2006, and 2007. 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 March 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.

Between 2004 and 2007 a number of additional field surveys were 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.

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	T_d	ΔT
				Measured (°F)	Measured (°F)	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)	ΔT Measured (°F)
03/01/1996	1100 CST	42456	676.96	45.9	48.8	2.9
03/01/1996	1445 CST	28136	677.04	46.2	50.2	4.0
03/01/1996	1600 CST	21962	677.00	46.1	51.4	5.3
03/01/1996	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
08/02/2000	1000 CDT	12472	682.20	82.1	85.1	3.0
08/02/2000	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 and was not used in the calibration.

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)	ΔT 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

The most recent calibration of the numerical model was performed in 2009 to support the NPDES permit of September 2005 (TVA, 2009). The data from Table 2, Table 3, and Table 4 were used in this calibration. The average overall discrepancy between the measured and computed downstream temperatures was about 0.55 Fº (0.31 Cº). For downstream temperatures above 75ºF, the average discrepancy improved to about 0.38 Fº (0.21 Cº).

New Calibration Data and Calibration Work

Since the 2009 model calibration, an additional field study was performed in November 2012 (Table 5). The study included the operation of one unit at SQN and was conducted concurrently with independent measurements for the discharge through the diffusers (TVA, 2013). With this, altogether fifty data points with sets of temperature samples across the downstream end of the mixing zone were available for updating the model calibration (i.e., Table 2 through Table 5).

Table 5. Thermal Surveys at SQN from November 2012

Date	Approx Time	River		Temperatures (5-foot depth)		
		Flow (cfs)	Stage (ft MSL)	T_u	T_d	ΔT
				Measured (°F)	Measured (°F)	Measured (°F)
11/16/2012	1400 CST	12599	678.62	57.0	60.3	3.3

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. Multiple slot widths in this range were evaluated and compared with fifty measured data points from the field surveys (i.e., from Table 2 through Table 5). 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. This is the same value used in the 2009 model calibration.

Plume Entrainment Coefficient

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 fifty data points from the field surveys in Table 2 through Table 5. 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 used in the compliance model.

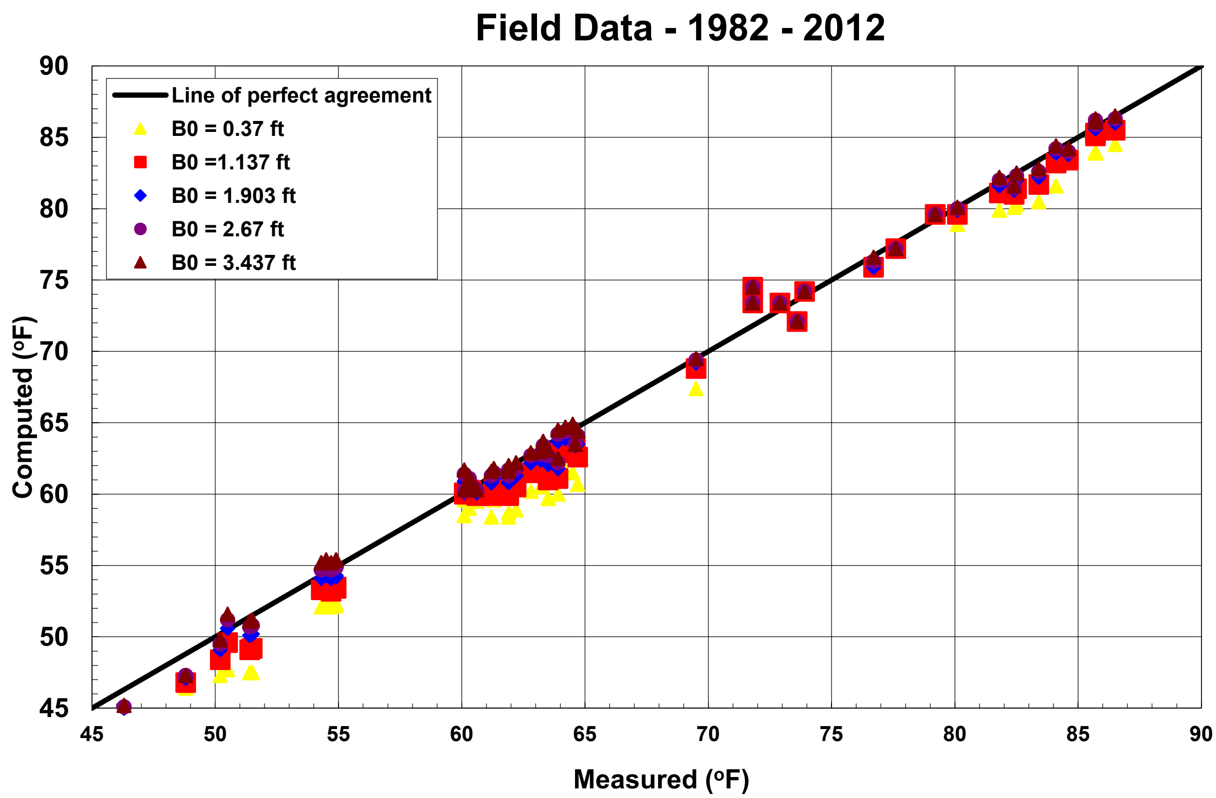

Figure 6. Sensitivity of Computed Temperature T_d to Diffuser Effective Slot Width

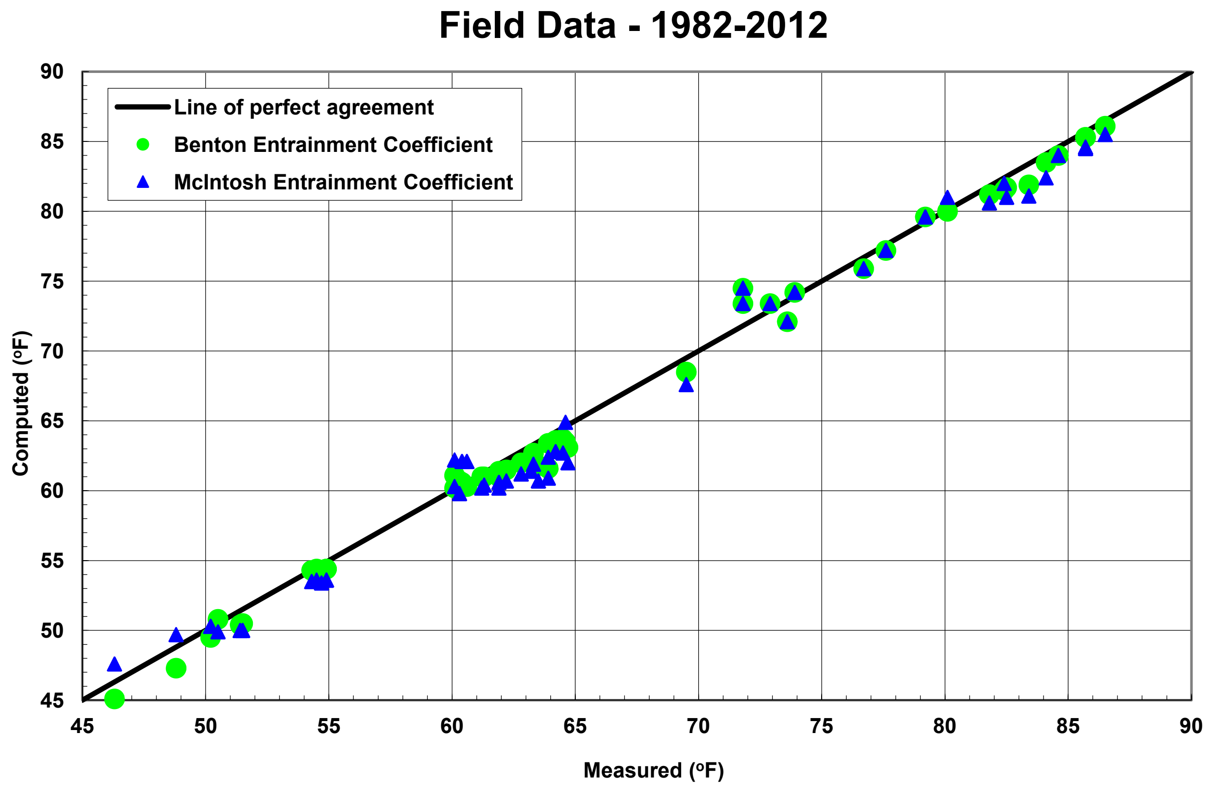

Figure 7. Sensitivity of Computed Temperature T_d to Plume Entrainment Coefficient

Diffuser Effluent Re-Entrainment

Based on the evaluation of numerous combinations of *N* and *R* for diffuser effluent re-entrainment (Eq. 20 and 21), Table 6 gives the values that resulted in computed downstream temperatures that most closely matched measurements in the field surveys (i.e., fifty data points from Table 2 through Table 5). For river velocities between the values given in Table 6, 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 6. Temperatures computed using the plume re-entrainment correction more closely matched measured values for twenty-seven of the fifty data points. Temperatures computed without using the plume re-entrainment correction more closely matched measured values for six data points, with no significant differences for the remaining data points. Based upon these results the re-entrainment correction method is used.

Table 6. 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

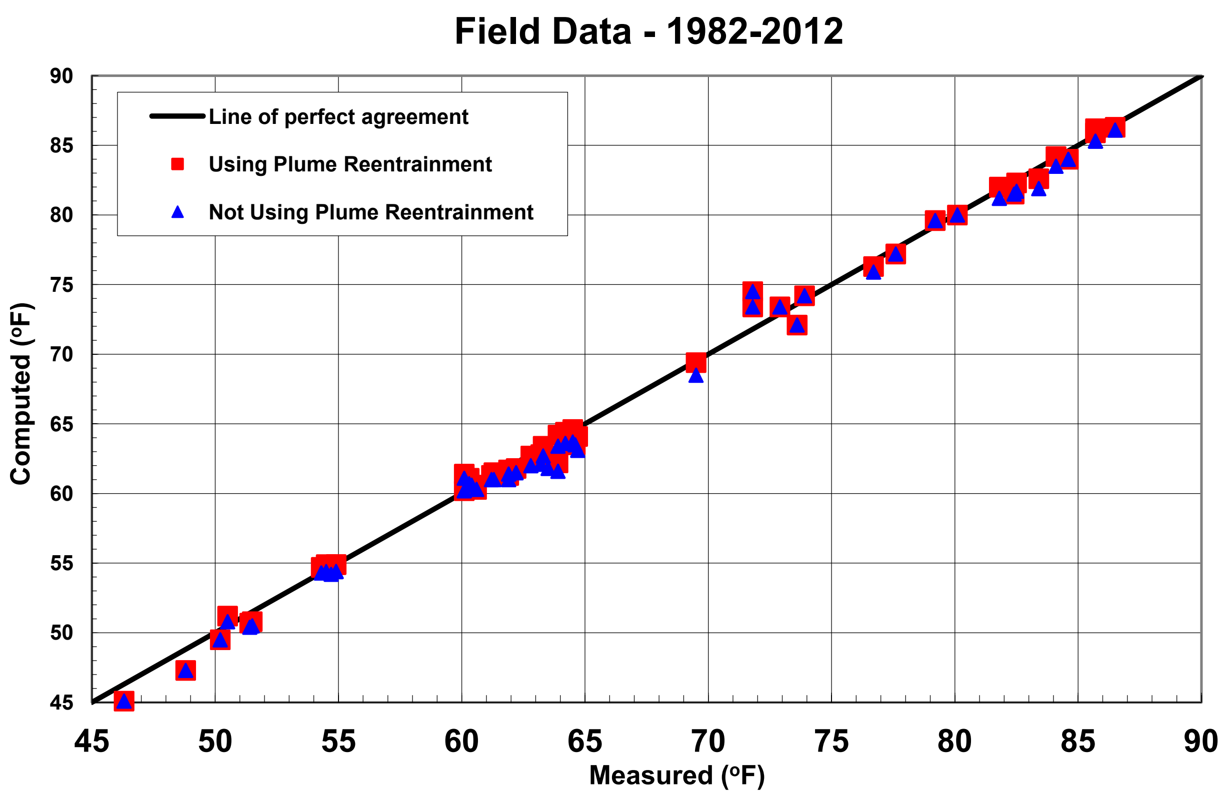

Figure 8. Sensitivity of Computed Temperature T_d to Effluent Re-Entrainment Function

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 fifty 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 Fº (0.31 Cº). For downstream temperatures above 75ºF, the average discrepancy was 0.38 Fº (0.21 Cº). There was no significant change in the model performance compared to the previous calibration.

To be consistent with the 24-hour averaging specified in the current NPDES permit, the 24-hour average temperatures measured in 2010 at the downstream temperature monitor, Station 8, are compared to those computed by numerical model in Figure 10. 2010 was selected because it represents a new climatic extreme in East Tennessee for the period of record for this model. As before, the measured temperatures correspond to the average of sensor readings at the 3-foot, 5-foot, and 7-foot depths. The overall average discrepancy between the measured and computed 24-hour average downstream temperatures was about 0.71 Fº (0.39 Cº), and about 0.63 Fº (0.35 Cº) for downstream temperatures above 75ºF.

Measured downstream hourly average temperatures for the same time period are compared to those computed by numerical model in Figure 11. 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 0.86 Fº (0.48 Cº) for the full range of river temperatures, decreasing to 0.71 Fº (0.39 Cº) for downstream temperatures above 75ºF.

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.

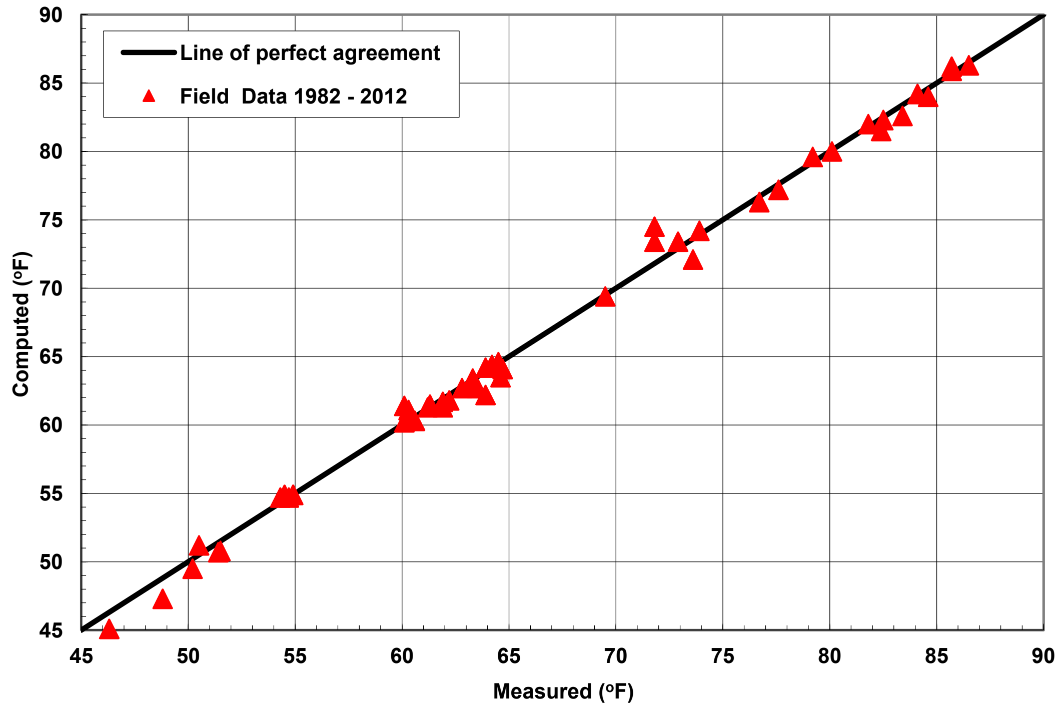

Figure 9. Comparison of Computed and Measured Temperatures T_d for Field Studies from April 1982 through November 2012

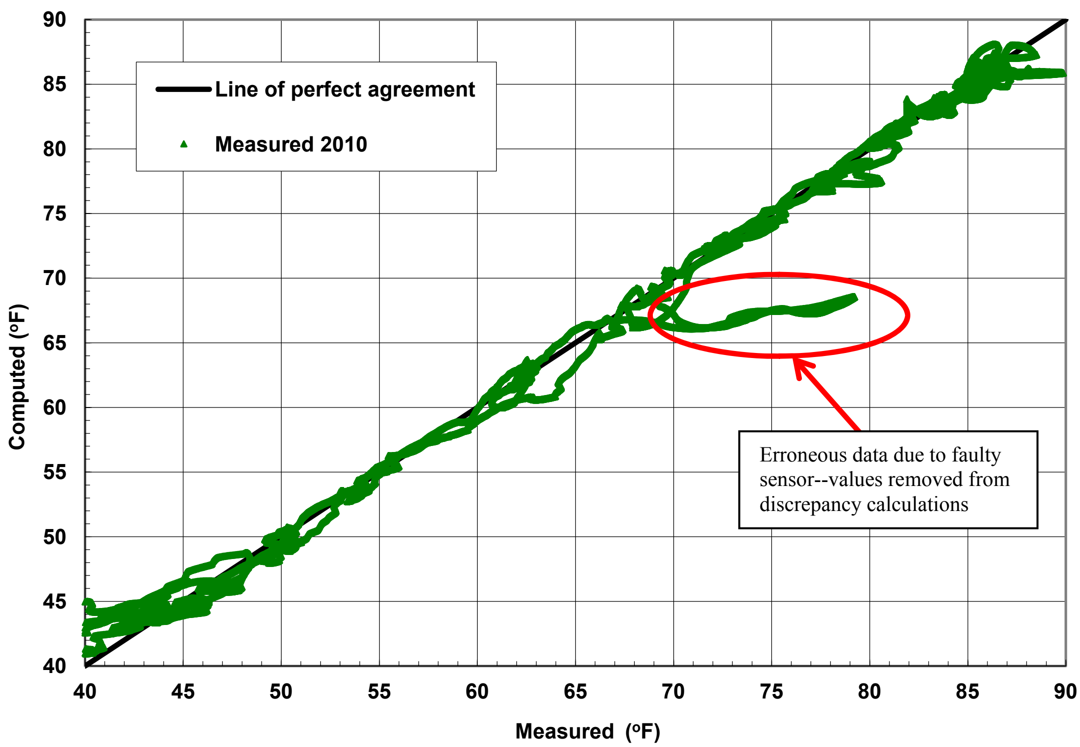

Figure 10. Comparison of Computed and Measured 24-hour Average Temperatures T_d for Station 8 for 2010

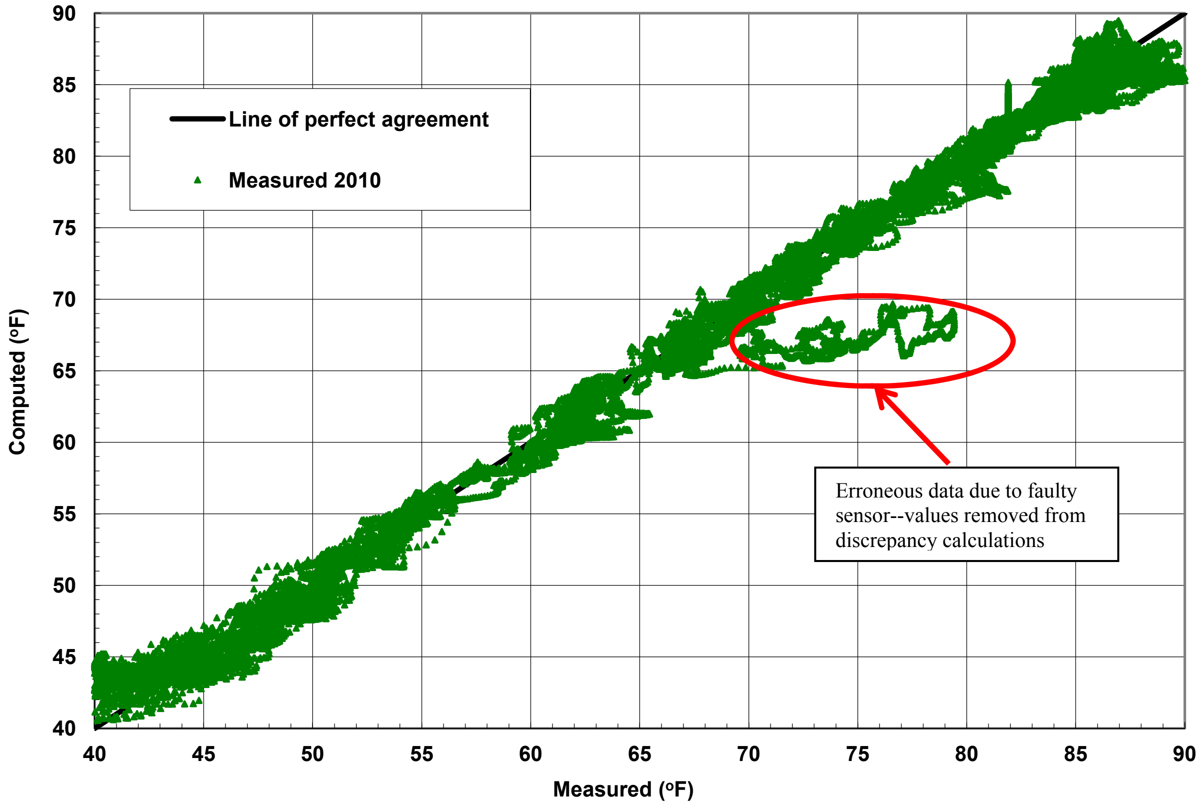

Figure 11. Comparison of Computed and Measured Hourly Average Temperatures T_d for Station 8 for 2010

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. In the updated calibration study summarized herein, which used the results from fifty 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°). There was no significant change in the model performance compared to the previous calibration, and as a result, no update was required in the model parameter set.

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