# TVA's Browns Ferry Nuclear Plant
# Thermal/Hydraulic Model

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## INTRODUCTION

Federal Register listing 66 FR 10557 No. 32, February 15, 2001, outlines TVA's plans to prepare a Supplemental Environmental Impact Statement (SEIS) to evaluate the impacts associated with acquiring license extensions for each BFN unit and for the possible restart of Unit 1. Although the plant has previously operated with all three units in service, the Unit 1 restart could potentially occur with all the units operating at power levels as large as 120 percent of the original plant design. Under these conditions, the SEIS must consider alternatives for dissipating the additional waste heat created by the new power levels.

### Description of Plant

The Tennessee Valley Authority (TVA) Browns Ferry Nuclear Plant (BFNP) is located in Limestone County, Alabama, on the northern shore of Wheeler Reservoir, at Tennessee River Mile 294. BFNP has 3 General Electric (GE) boiling water reactor (BWR) units, each originally with a nominal rating of 3300 megawatts thermal (MWt) and 1100 megawatts electric (MWe). Units 2 and 3 are currently in service; but Unit 1 has been idle since 1983.

### Description of Heat Rejection System

Condenser Cooling Water (CCW) for BFN is obtained from Wheeler Reservoir by an intake pumping station immediately upstream of the plant that can withdraw as much as 42.6 cubic meters per second (cms) (1540 cubic feet per second (cfs)) per unit. The plant increases the CCW temperature by about 12°C (22°F) and returns the waste heat to Wheeler Reservoir through three multi-port diffusers situated on the bottom of the main channel.

### Description of Cooling Modes

If the cooling water flows directly from the condensers to the river this operation is called "open" mode. If the cooling water flows from the condensers through the cooling towers and then out to the river this operation is called "helper" mode. If the cooling water flows from the condensers through the cooling towers and back to the intake this operation is called "closed" mode.

### Description of the Diffusers

Each diffuser pipe contains a 183 m (600 foot) long discharge section with ports spaced in alternating columns of six and seven 5.1 cm (2 inch) diameter holes, situated 15 cm (6 inches)) apart on-center, both vertically and horizontally (about 7,000 ports per diffuser). The ports face downstream, and depending on the location in the port column, contain a discharge angle between 24°and 45°from horizontal. The discharge sections of the diffusers are situated in succession across the 550 m (1800 foot) width of the main channel. The upstream diffuser, for Unit 2, is 6.25 m (20.5 feet) in diameter and is situated with the discharge section in the south side of the main channel. The middle diffuser, for Unit 1, is 5.79 m (19.0 feet) in diameter and is situated with the discharge section in the middle of the main channel. The downstream diffuser, for Unit 3, is 5.18 m (17.0 feet) in diameter and is situated with the discharge section in the north side of the channel.

### Description of the Thermal Plume

The temperature of the water flowing out of the holes in the diffusers depends on plant operation, the performance of the cooling towers, and the weather. The water may be discharged hotter or, in some cases, colder than the water in the river surrounding the diffusers. The mixing and dilution of the discharge depends on many things, including its temperature and velocity, as well as the temperature and velocity of the river. The resulting plume impacts the flow and temperature in the river, which, in turn, influences the temperature and movement of the plume. The mixing process is complex, even on a large scale, and difficult to accurately model. On a small scale, considering the thousands of ports, modeling would be even more complex. Both small and large scale physical and numerical models have been applied to this complex process.

## DIFFUSER MODEL

Small scale modeling of a single jet discharging into essentially infinite receiving water has been relatively successful; but does not provide the large scale information needed for evaluating aquatic conditions. Large-scale one-dimensional and two-dimensional models have also been applied with adequate success for the purposes of estimating an effective downstream mixed temperature; but these analyses cannot provide information for aquatic conditions such as fish passage. A fully three-dimensional model is required for estimating fish passage. The proposed 3D hydrodynamic model would span the channel in depth, width, and length across the diffusers, and would incorporate empirical relationships obtained from small scale modeling, but would not go to the level of detail of modeling individual ports.

### Model Development

The model would have a 3D finite difference grid fitted to the bottom of the channel from the upstream intake downstream of the diffusers, extending across the channel and all 3 diffusers and from the bottom to the surface. The discharge from each diffuser would be handled separately so that any combination of active and inactive diffuser operation could be modeled. An initial estimate for the model grid is approximately 25 cells in each dimension for a total of 15,625. EPA's 3D Environmental Fluid Dynamics Code would be ideal for this application. The model requires grid geometry and properties, boundary conditions, and initial conditions. Calibration/validation of the model based on field measurements would also be necessary. A range of operations would be modeled in order to provide sufficient information for evaluating the aquatic conditions.

### Bathymetry

The bathymetry in a 5.6 km by 4.8 km (3.5 mile by 3.0 mile) region around the Plant was digitized. The bathymetry contours cover 11 sq. km (4.2 sq. miles) within this region. The figure showing the bathymetric data can be found in several of the reports obtained from TVA. This figure also shows the shoreline, navigation channel, and river miles, but does not show global coordinates.

A 4 m by 4 m (13 foot by 13 foot) geographic map was obtained from the USGS showing the shoreline, navigation channel, river miles, powerhouse, cooling towers, and intake structure. This map is overlaid with a Zone 16 Universal Transverse Mercator (UTM) grid. Thirty-two distinct points were identified on the two maps and used to index the UTM coordinates to the bathymetry. The spatial transformation has an $R^2$ of 0.92, indicating an acceptably accurate mapping.

The bathymetric data consist of lines of constant elevation. A Digital Elevation Model (DEM) was created from these data by inverse-distance interpolation using quadrant-based nearest-neighbors followed by Laplacian relaxation. The DEM was created using TP2, the second generation Tplot. The resolution of the original DEM is 2 m by 2 m (6.6 foot by 6.6 foot) or 2801 by 2401 points making 6,725,201 interpolated elevations, 2,756,938 of which are within the extended model domain. A 5 m by 5 m (16 foot by 16 foot) DEM, a 10 m by 10 m (33 foot by 33 foot) DEM, a 25 m by 25 m (82 foot by 82 foot) DEM, and a 50 m by 50 m (160 foot by 160 foot) DEM were also created by reduction.

## Diffuser Details

There are 3 diffuser pipes. The center pipe is designated 1, the upstream pipe is designated 2; and the downstream pipe is designated 3.

The diameters of the pipes are 5.79, 6.25, and 5.18 m (19.0, 20.5, and 17.0 feet) for 1, 2, and 3, respectively; or 6.25, 5.79, and 5.18 m (20.5, 19.0, and 17.0 feet) from upstream to downstream.

Plant North is 38° east of True North (38° compass or 52° trigonometric). The centerline of the diffusers is 77°30' south of Plant West (230°30' compass or 219.5° trigonometric).

The diffuser pipes exit the concrete discharge structure 131 m (431 feet) from the centerline of the reactors. The drawings show a gap of about 4 m (13 feet) after which the length of the diffusers is detailed.

The total lengths (not including the 4 m gap) of the diffusers are 308, 491, and 674 m (1010, 1610, and 2210 feet), for the downstream, center, and upstream diffusers, respectively.

The discharge ports begin 125, 308, and 491 m (410, 1010, and 1610 feet) out from the concrete discharge structure (not including the 4 m gap) for the downstream, center, and upstream diffusers, respectively. The ports extend over 183 m (600 feet) on each pipe.

The discharge ports are 5.1 cm (2 inch) diameter holes drilled on 15 cm (6 inch) centers in staggered rows of 6 or 7. There are approximately 7000 ports per diffuser.

The discharge ports begin at an inclination from the horizontal of 24° and extend 21° to an inclination of 45°.

## Mixing Zone and Compliance Boundary

The Mixing Zone is 610 m (2000 feet) wide and extends from 45.7 m (150 feet) upstream to 732 m (2400 feet) downstream of the diffusers. The extent of the Mixing Zone defines the Compliance Boundary.

The maximum plant-impacted downstream temperature is defined, for the purposes of compliance, as the temperature averaged over the upper 1.5 m (5.0 feet) at the downstream boundary of the Mixing Zone.

Plant-induced temperature rise is defined, for the purpose of compliance, as the temperature averaged over the upper 1.5 m (5.0 feet) at the downstream boundary of the Mixing Zone minus the temperature averaged over the upper 1.5 m (5.0 feet) at the upstream boundary. The calculation is further qualified by limiting the lateral average to only those diffusers in operation.

If one or two of the diffusers are discharging at a lower temperature due to reduced unit load or cooling tower usage, this colder water would be included in the plant-induced rise calculation; however, this would not directly affect the calculation of a maximum downstream temperature.

## Diffuser Placement

The loose earth along the channel bottom was first excavated before the diffusers were laid in place. The pipes were arranged 1.5 m (5 feet) apart and the area back-filled with crushed stone. The crushed stone generally extends up to the centerline of each pipe on the downstream side where the discharge ports are located. The crushed stone extends up to 1.5 m (5 feet) above the centerline on the upstream side of the pipes. The crushed stone extends away from the pipes to the channel bottom at a slope of 1:3.

The diffuser placement drawing was digitized in order to obtain the elevation of the bottom of the pipes along their length, or the depth of excavation. The diffuser pipes are not flat along the channel bottom. There is 2.1 m (6.8 feet) difference between the lowest point (at the center) and the highest point on the river side and 2.0 m (6.4 feet) difference between the lowest point and the highest point on the plant side.

The normal water surface elevation is 169.5 m (556.0 feet) above MSL. At this surface elevation the depth of water above Diffuser 1 (center) is 7.89 m (25.9 feet). The minimum depth of water above Diffuser 2 (upstream and furthest from the plant) is 5.36 m (17.6 feet) and the average depth over the active zone is 6.38 m (20.9 feet). The minimum depth of water above Diffuser 3 (downstream and closest to the plant) is 6.55 m (21.5 feet) and the average depth over the active zone is 7.92 m (26.0 feet).

The river flow tends toward the center of the channel so that the velocities are higher across the center diffuser (1) than the outboard two. The thermal plume has more opportunity to rise and spread in deeper water. Considering these two factors, the potential for dilution of the plume emerging from the center diffuser may be significantly larger than for the outboard two. The outboard plumes can entrain water from the outer edge; but this is also where the depth is least. The active length of each diffuser is 183 m (600 feet); whereas the depth at the edges is only 6.5 m (21 feet); therefore, the greater depth of the center diffuser should be more significant than the edge of the outboard two. It should not be surprising if a fully three-dimensional model predicts significant differences in dilution between the three diffusers with the center being the most effective.

The diffuser placement drawing also shows some variation in the depth of the crushed stone. This was also digitized and included in the model.

## Model Construction

The term model includes many things: the input data sets (including the DEM, the diffuser bottom excavation depth, the crushed stone depth, the diffuser location and angle, the diffuser diameters, and active length), the model boundary polygon (including shoreline, upstream inlet, and downstream outlet), the boundary conditions (including river flow, water surface elevation, and upstream temperature profile), the thermal impact of the plant (including circulating water flow, heat input, and cooling tower heat rejection), the preprocessor (Ferry3D builds all of the input files for EFDC), the actual 3D hydrodynamic model (EFDC), the postprocessor (EFDCpost extracts time series and snapshots and prepares files for plotting), the graphics engines (TP2 and Tecplot), and the animator (RMedit for editing, LZlive for compressing, and LiveDemo for playing).

Digitizing and regression programs are used to prepare data which describe the model physically. After all of the input data sets have been created the model boundary is selected and boundary conditions are specified. The preprocessor, Ferry3D, builds all of the input files for EFDC. The hydrodynamic model, EFDC, computes the temperatures and velocities. The postprocessor, EFDCpost, summarizes the results and prepares files for plotting. The graphics engines, TP2 and Tecplot, are used to generate individual graphical images. RMedit is used to edit and assemble a sequence of frames into an animation. LZlive compresses the animation and embeds the Windows player, LiveDemo, in the animation to make it self-playing.

All of these steps are required in order to qualify the results and get them to the point where they can be interpreted. In a sense any and all parts of this sequence can be considered part of the Model.

## Model Boundaries

The preprocessor, Ferry3D, is currently set up to create 3 different model boundaries. The largest model boundary is from 1760 m (5770 feet) to 2510 m (8240 feet) wide by 4590 m (15,100 feet) long and spans the entire domain of input data. This model boundary extends from 2520 m (8270 feet) upstream of the diffuser to 2060 m (6760 feet) downstream of the diffuser, covering 11 sq. km (4.3 sq. miles).

The intermediate model boundary is from 860 m (2820 feet) to 1190 m (3900 feet) wide by 1420 m (4660 feet) long, and contains the Mixing Zone and Intake Region. This model boundary extends from 730 m (2400 feet) upstream of the diffuser to 690 m (2260 feet) downstream of the diffuser, covering 1.4 sq. km (0.87 sq. miles).

The smallest model boundary is 780 m (2560 feet) wide by 820 m (2690 feet) long and contains only the Mixing Zone. This model boundary extends from 120 m (390 feet) upstream of the diffuser to 700 m (2300 feet) downstream of the diffuser, covering 0.66 sq. km (0.25 sq. miles).

## Boundary and Initial Conditions

All scenarios will be run at the normal mean surface elevation, which is 169.5 m (556.0 feet) above MSL.

Waldrop, Ungate, and Almquist (1977) defined high flow as 1420 cms (50,000 cfs), intermediate flow as 708 cms (25,000 cfs), low flow as 396 cms (14,000 cfs), very low flow as 142 cms (5000 cfs), and reverse flow as -283 cms (-10,000 cfs). The low flow scenarios will be run at 142 cms (5000 cfs) and the high flow scenarios will be run at 708 cms (25,000 cfs).

The expected cooling water flow per unit is 42.9 cms (680,000 gpm) with 3 CCW pumps operating. The expected cooling water flow per unit is expected to be only 33.4 cms (530,000 gpm) with 2 CCW pumps operating. All scenarios will be run using 42.9 cms (680,000 gpm) per unit; because this is preferable for hot weather operation of the steam system.

The critical upstream temperature is 31.1°C (88°F). This value will be used for upstream temperature over the entire depth for all scenarios without stratification.

If stratification is added to any scenario the temperature difference will be deducted from the upstream and this colder water be used as the plant intake temperature.

At 120% power input the condenser rise is expected to be 15.4°C (27.7°F). If the intake temperature is 31.1°C (88°F) then the discharge temperature would be 46.5°C (115.7°F). This value will be used for the water emerging from the diffuser for any units operating in open mode.

If all of the cooling towers are renovated, in good working condition, and fully utilized, the exiting water temperature under correspondingly severe conditions is expected to be 33.5°C (92.3°F). This value will be used for the water emerging from the diffuser for any units operating in helper mode.

## Mixed-Mode Scenario

Perhaps the most interesting scenario to be considered is where Units 2 and 3 are operated fully on cooling towers and Unit 1 is operated without cooling towers. This would result in significantly hotter water being discharged through the center diffuser than the outboard two. The potential for dilution with the center diffuser may be significantly greater than for the outboard diffusers; so that the combined result may satisfy compliance and enable the Plant to restart Unit 1 without extreme modifications to the cooling tower.

# THERMAL MODEL OF THE PLANT

A sufficiently detailed computer model of the thermal systems of a nuclear power plant includes many sub-models of the various components, which comprise the system. These components and their function are:

- The reactor is the source of thermal power.
- The steam turbines convert this thermal power into mechanical power.
- The generators convert the mechanical power into electrical power.
- The condenser removes the waste heat from the steam system.
- The cooling towers transfer waste heat to the atmosphere.
- The diffusers transfer waste heat to the river.

### Condenser

The condensers have three sequential cooling zones into which the turbines exhaust. The turbines are constructed of several identical sections. Specifically, the turbine sections, which exhaust into the three sequential condenser zones are identical. The pressure inside the condensers increases with each zone, with the third zone being the highest. The pressure at which the turbines exhaust into the condensers is called the backpressure. The third section (or zone 3) is the critical turbine backpressure. The pressure in zone 3 must not exceed some value. The pressure inside the condensers is below atmospheric (i.e., a slight vacuum) and is measured in inches of mercury (in.Hg). The normal operating range for turbines of this type is from 1 to 4 in.Hg. Operation for extended periods of time (i.e., days) above 5.5 in.Hg is not recommended. These turbines can operate at pressures as high as 7.5 in.Hg for brief periods of time (i.e., hours) without problems. The turbines can be modified with newer technology to enable them to run at higher pressures longer.

### Heat Rate

Heat rate is a measure of the inefficiency of the steam system, and is defined as the thermal power (or heat) input in BTU/hr (British Thermal Units per hour) divided by the electrical power output in KWe (kilowatts electrical). The use of heat rate as a standard parameter in the power industry began as a matter of convenience in coal-fired plants when the rate of burn was measured in BTUs per hour and the generator output in watts.

### Thermal Cycle Components

The thermal cycle components of the model include: the reactor, steam turbines, generator, and condenser. The expected generator output and heat rejection to the condenser for a given reactor heat input under baseline operating conditions is provided by the turbo-generator manufacturer, in this case Westinghouse, on drawings which are called heat balances. Baseline operating conditions include a constant backpressure. Turbo-generator manufacturers supply a set of correction curves, which are to be used in adjusting calculations from the baseline conditions to a range of operating conditions. The backpressure correction curves provide an adjustment to heat rate. The generator output as a function of backpressure for various levels of reactor heat input is shown in Figure 8. The backpressure correction curves are shown in Figure 9.

## Condenser Cooling Water System

The condenser cooling water system is essential to the operation of any steam plant, coal-fired or nuclear. Virtually all of the waste heat is removed from the steam system at the condenser. The waste heat is transferred to the cooling water in the condenser, thus entering the environment. Modern power plants are designed to minimize waste heat, which is the same as maximizing efficiency; however, waste heat is an unavoidable by-product of thermal exchange processes. The environment is the ultimate destination of all consumed energy resources, whether this occurs immediately at the plant, or shortly thereafter at a factory or house. The waste heat leaving the plant at the condenser is not something that can be shut-off. It is this necessity for waste heat rejection into the environment that is the cause for this analysis. The condenser heat rejection as a function of backpressure for various levels of reactor heat input is shown in Figure 10.

Water is drawn from one location in the river and forced through thousands of long tubes within the condenser. The water flows out of the condenser and back into a different location in the river downstream. Within the condenser, the steam is cooled and condenses on the outside of the tubes; while the water is heated on the inside of the tubes. The heat lost by the steam is gained by the water. This exchange of heat in the condenser must occur continuously in order for the plant to operate.

Cooling water is fed to the condenser by three pumps per unit, operating in parallel. These pumps are dynamic machines. Their performance depends on the operating conditions. The resistance to flow increases with increasing flow. Condenser cooling water pumps do not add like batteries. Two pumps do not provide twice the flow of one; nor do three provide half-again the flow of two. In order to compute the flow of cooling water through the condensers, the performance of the pump(s) must be matched to the flow resistance. An iterative calculation is required to determine the operating point. This matching is illustrated graphically by the intersection of the pump performance and system resistance curves in Figure 11.

## Cooling Towers and Diffuser Pond

The cooling towers provide a means for dissipating waste heat to the environment. Water is pumped from the river to the condensers, where it is heated, and then flows to the cooling towers. These are large natural draft cooling towers with cross flow fill. The performance is characterized by exiting water temperature, which is drawn on several figures for various ambient conditions and cooling range (inlet minus exit water temperature). The manufacturer's curves were digitized and a multivariate regression used to implement this aspect of the operation. Before going out the diffusers, water is discharged to a pond. The area and volume of the pond are shown in Figure 12. Wind has some cooling effect on the water in the pond. This impact is shown in Figure 13.

# SIMULATION DATA

The basic components of the plant model have been described above. Additional code description is given in Appendix B. The next phase of the analysis is to select an input data set that will provide the basis of simulations.

### The Necessity of Historical Data

Detailed historical data are essential to accurately quantifying the conditions under which a power plant must operate. Statistical measures of the environment, such as minimum, maximum, and average temperatures and flows are important; however, these do not provide sufficient information to accurately quantify the performance of the plant. Environmental extremes do not occur simultaneously. For instance, the lowest flow of many rivers occurs in the winter when the temperatures are lowest. The highest flows often occur in the spring when the temperatures are also low. Summertime flows for many rivers are closer to the mean and are accompanied by the hottest temperatures. This situation is further complicated when considering that wet-bulb, rather than dry-bulb temperature is the environmental measure of interest when considering evaporative cooling. The coincidence of various environmental conditions cannot be inferred from summary measures. The joint probabilities can not be determined by any combination of the individual statistics; as the desired information is not contained in summary measures. In order to quantify the performance of a power plant and its susceptibility to environmental conditions, it is essential that actual data be used.

### Historical Meteorology

The National Weather Service (NWS) has operated four meteorological stations in the Browns Ferry vicinity: Station #14881 from 1901 through 1925, Station #14892 from 1926 through 1942, Station #14834 from 1946 through 1953, and station #94846 from 1958 through the present. Stations #14881, #14892, and #14834 were all near Huntsville, Alabama. Wind speed data are necessary for modeling the cooling towers. Wind speed data are only available from Station #94846 and only available from 1985 through the present. Data from these stations were obtained from the National Climate Data Center (NCDC). These data consist of daily minimum and maximum temperature, humidity, and wind speed. The probabilities of dry-bulb and wet-bulb temperature seasonally and yearly are shown in Figures 14 and 15.

Wind speed data are necessary for modeling the cooling towers. Wind speed data are only available from Station #94846 and only available from 1985 through the present. The existing wind data were analyzed statistically by year and month and were cross-correlated with the other meteorological data. Probability distribution functions were constructed from these data and used to fill in the data gaps where actual wind data were not available. The probability of wind speed seasonally and yearly is shown in Figure 16.

### Historical River Flows

The U. S. Geological Survey (USGS) has maintained a stream gage and data collection station #05527500 on the Tennessee River near Decatur, Alabama, from 1913 to the present. These data were obtained from the USGS for the period of 1915 through 1993. The rating curve (or flow vs. stage relationship) was also obtained from the USGS. The historical flows for the Tennessee River are shown in Figure 17. The mean (or average) river flow (4356 cfs) and the maximum 2-unit condenser flow (3252 cfs) are also shown in this figure. The probability of river flows is shown along with the minimum (1452 cfs) and maximum 2-unit condenser flow and the median (or centrally probable) river flow (2729 cfs). The mean and median flows are not the same. The mean flow is simply the average. The median flow indicates the 50% probability. Half of the time over the 79 years of record, the river flow has been below 2729 cfs; and half of the time it has been above.

## Computed River Temperatures

Daily values of river temperature over such a long time span is unavailable for the Tennessee. In order to provide this essential information, another computer model was used. This transient river temperature model was developed by the author for the Tennessee Valley Authority (TVA) and has been applied to several unregulated rivers (i.e., a river not impounded above and below by dams). This model has been validated for several rivers in the Tennessee and Ohio Valleys. Figure 18 shows the measured temperatures at several depths and Figure 19 shows the calculated temperatures at these same times and depths. Clearly, not all of the surface effects are accounted for in the colder months; however, this is not critical to thermal compliance. More detail is shown in Figures 20 and 21.

## Simulation Data Set

The computer model requires all of the environmental conditions for each period of operation. Some gaps exist in the data, but the collected set spans the years from 1915 through 1993 with two meteorological conditions per day, making a total of 49,696 data points. This is a sufficient quantity of data and span so as to provide a statistically significant sample of the expected operational conditions for Browns Ferry.

## Simplified Diffuser Model Component

The TVA long-term plant simulation model will be referred to hereafter as the TVA Plant Model. The diffuser model component of the existing TVA Plant Model will be referred to hereafter as the TVA Diffuser Model Component. The TVA Diffuser Model Component is zero-dimensional in that it yields a value of dilution based on a single calculation at a point and does not account for any spatial variability. The TVA Diffuser Model Component is semi-empirical in that the functional form was obtained from analytical solutions and the single adjustable coefficient was selected based on field data. The underlying diffuser calculation will be referred to hereafter as the Almquist Diffuser Calculation (Almquist et al., 1977). The Almquist Diffuser Calculation was subsequently modified to account for the three separate diffusers competing for the same cooling water in the river. This modified calculation will be referred to hereafter as the Stolzenbach Modification (Stolzenbach et al., 1979). The Stolzenbach Modification is used to compute the dilution in the TVA Diffuser Model Component.

The TVA Diffuser Model Component does account for the diffuser length, diffuser flow, diffuser discharge temperature, river flow, and river depth. The TVA Diffuser Model Component uses a single value for the depth of all three diffusers, but could easily be modified to use separate depths. The TVA Diffuser Model Component utilizes a single value of upstream river temperature; thus, it does not account for thermal stratification upstream of the diffuser.

Dilution of the thermal effluent is accomplished by entrainment of the ambient water. The entrainment of ambient water depends on the movement and condition of the plume relative to the ambient water. The movement and condition of the plume depends on the conditions when it is discharged and the entrainment. The movement and condition of the plume are, thus, linked to the entrainment; therefore, the processes must be computed simultaneously. This will require at least a one-dimensional model. The one-dimensional Diffuser Model is the least complicated formulation that can capture the variation of entrainment with depth and, thus, account for thermal stratification upstream of the diffuser. The 1-D Diffuser Model is a numerical solution to three simultaneous nonlinear ordinary differential equations for the conservation of mass, momentum, and energy.

In addition to the basic hydrothermal equations of conservation, it is necessary to develop a relationship for the entrainment coefficient in order to provide closure for the 1-D Diffuser Model. The asymptotic behavior of the dilution is known to be linear for large river flow; therefore, the entrainment coefficient must be formulated so that this behavior results. The Almquist Diffuser Calculation exhibits this behavior. For all values of positive river flow up to 250,000 cfs and uniform upstream ambient temperature the 1-D Diffuser Model matches the Almquist Diffuser Calculation to an average of 2%.

The asymptotic behavior of the dilution is known to increase with the one-half to three-fifths (0.5 to 0.6) power of the depth. The Almquist Diffuser Calculation has the dilution varying linearly with depth. This is not a deficiency as it has been used in the TVA Diffuser Model Component; because the depth of water above the diffusers varies little; and the empirical coefficient has been adjusted to agree with field data; however, the entrainment must be integrated over the depth in order to account for stratification in the upstream ambient temperature; therefore differentiation of the Almquist Diffuser Calculation does not provide a mathematical foundation on which to build the 1-D Diffuser Model.

The TVA 2-Dimensional Plume Model (Benton, 1981) was developed for the diffusers at the Sequoyah Nuclear Plant and tested with laboratory and field data. This model does produce results for dilution that vary with the three-fifths power of the depth. The TVA 2-Dimensional Plume Model was configured for the Browns Ferry diffusers and the 1-D Diffuser Model entrainment function was calibrated to the results. The maximum error was 6% and the average error less than 3%. The 1-D Diffuser Model is much less complicated and executes much faster than the TVA 2-Dimensional Plume Model yet obtains results that are adequate for the revised long term plant simulation model, the Plant Model.

It is significant that the dilution of the plume increases with the three-fifths power of the depth. This means that more entrainment occurs at the bottom near the discharge ports than as the plume approaches the surface. This follows logically from the observation that the difference between the velocity and temperature of the plume and the velocity and temperature of the ambient is most pronounced at the ports; and it is this difference that drives the entrainment. As the entrainment varies with the three-fifths power of the depth, 25% of the total entrainment occurs within the first 10% of the depth and 50% of the total entrainment occurs within the first 30% of the depth. If the dilution increased with the one-half power of the depth this effect would be more pronounced. Only 20% of the entrainment occurs within the last 30% of the depth. The temperature of the ambient water in the bottom 30% of the depth has 2½ times greater impact on the plume than the ambient water in the upper 30% of the depth.

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### Software

The Environmental Fluid Dynamics Code (EFDC) was developed by John Hamrick of TetraTech under contract to the USEPA. Tecplot was developed by Amtec Engineering. Digitize, EFDCpost, Ferry3D, LiveDemo, LZlive, RMedit, TP2, and Tplot were developed by this author.

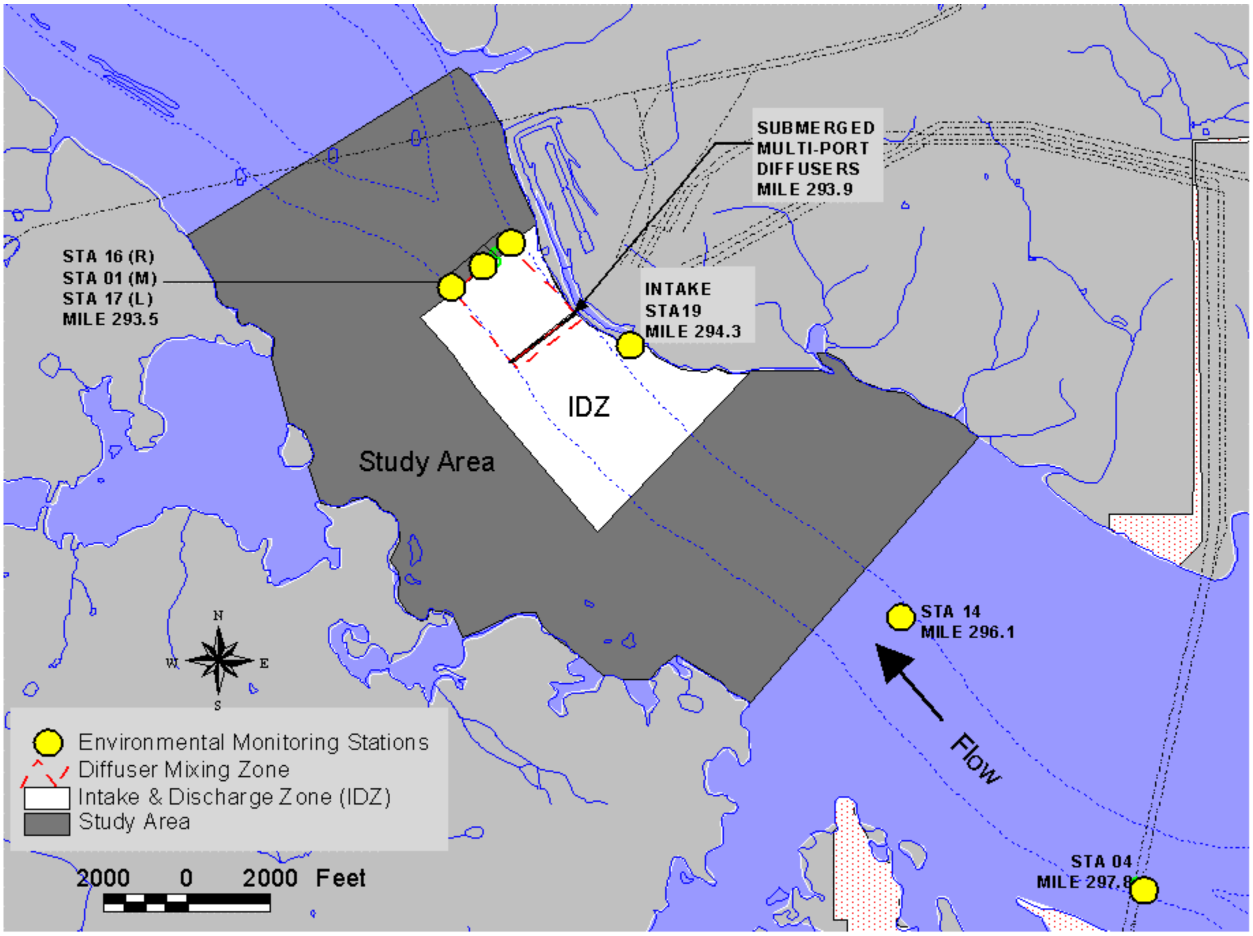


**Figure 1. Overview of Area**

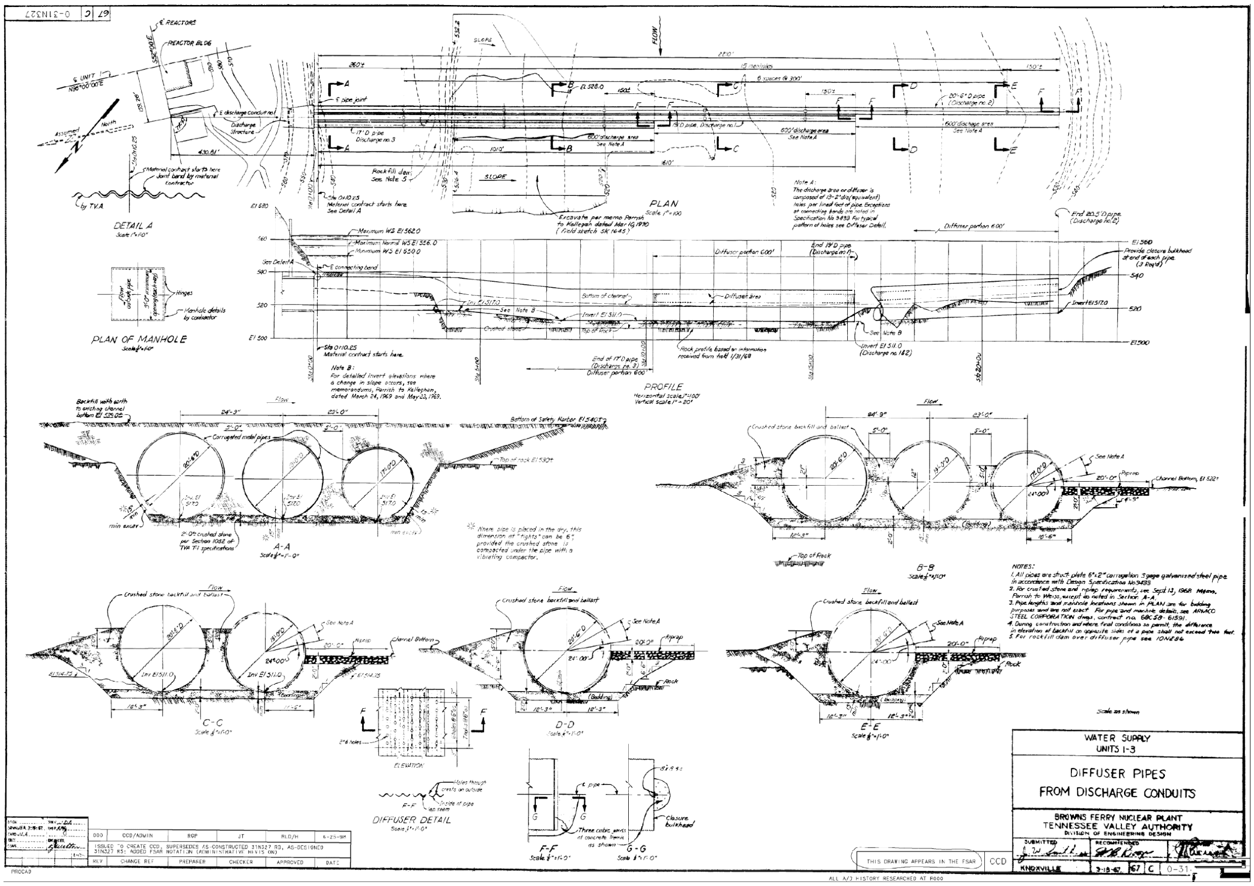


**Figure 2. Diffuser Details**

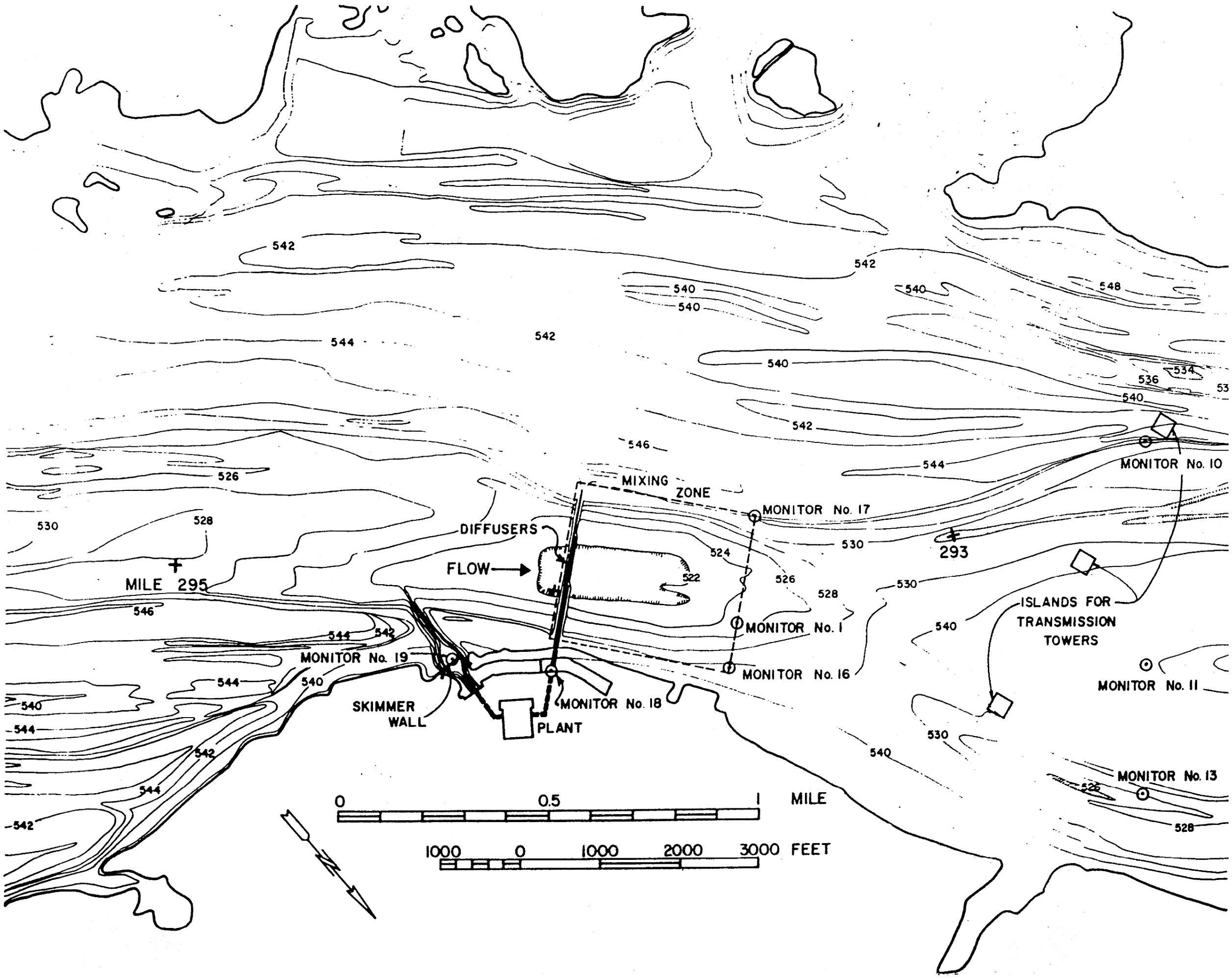


**Figure 3. Bathymetry**

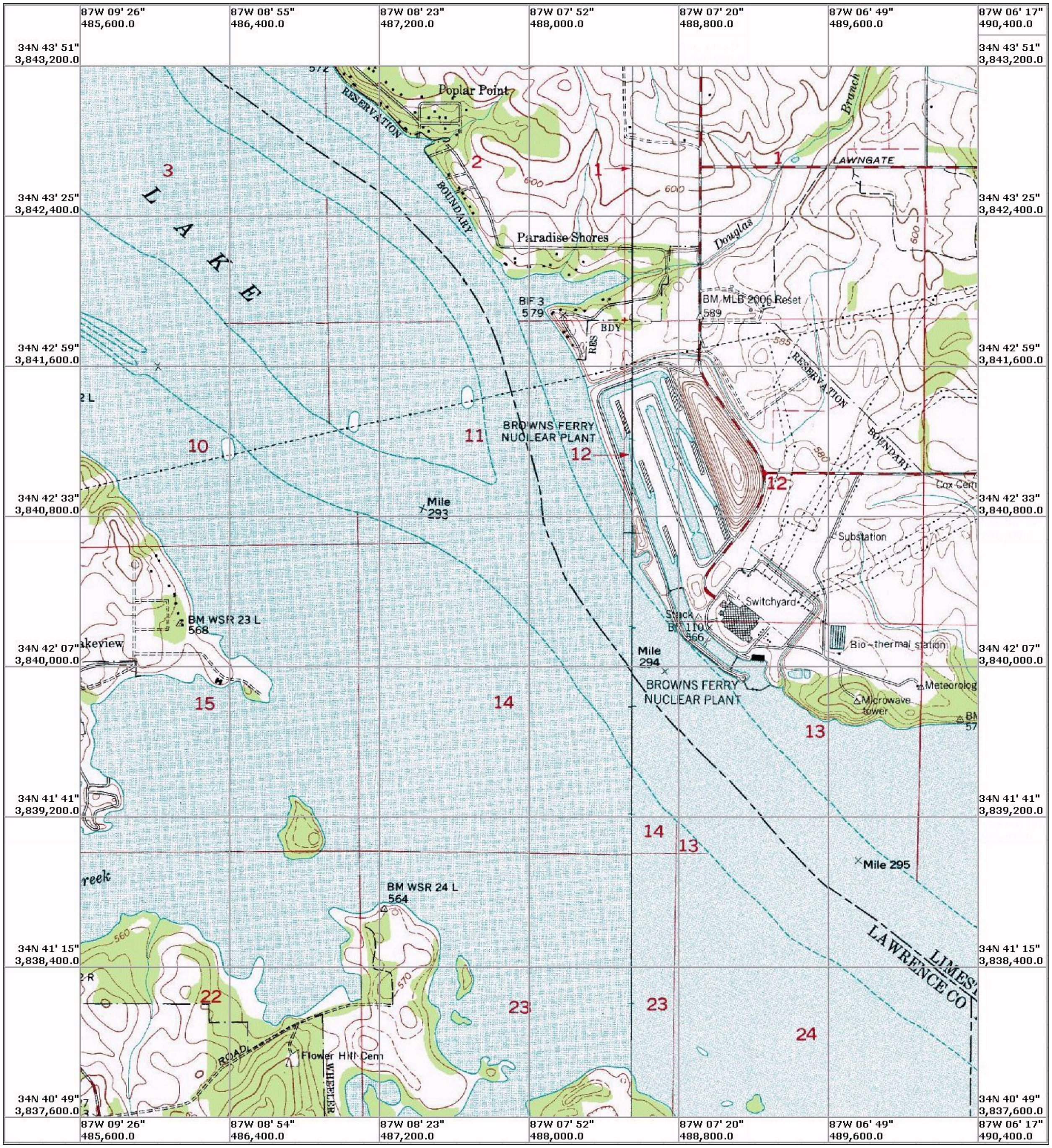


**Figure 4. Channel Details**

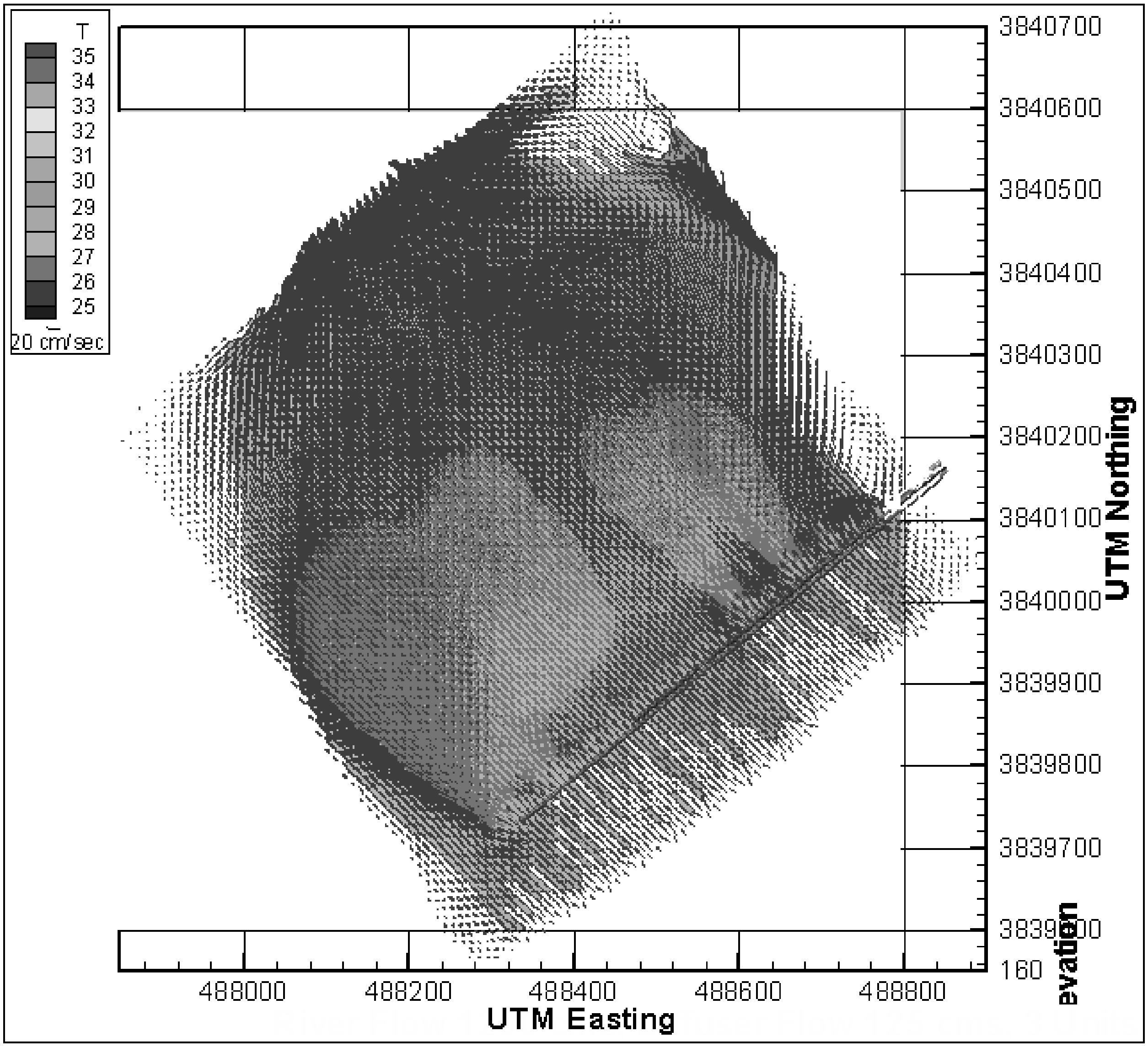


**Figure 5. Typical 3D Velocity Vectors in Plan View**

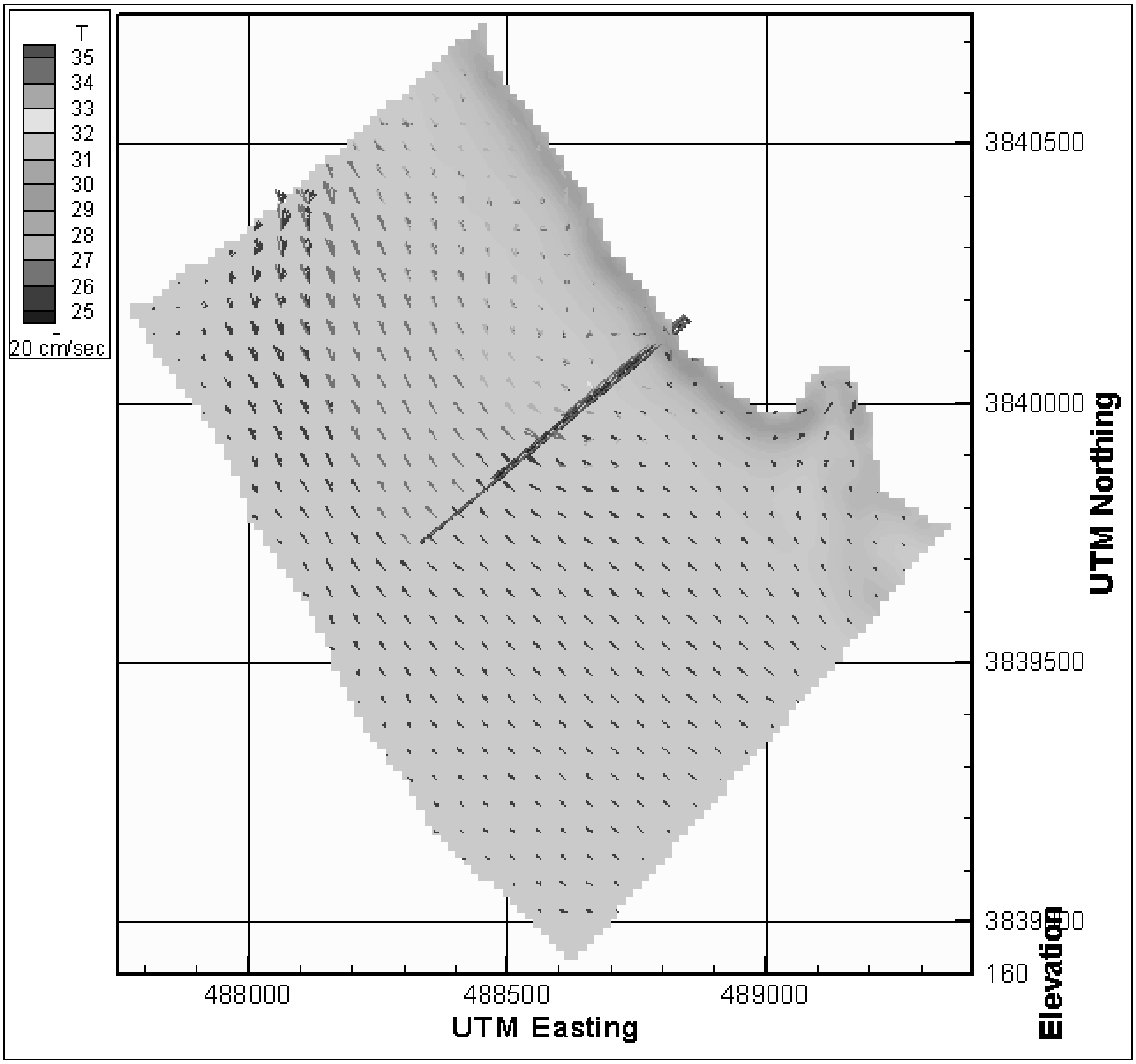


**Figure 6. Reduced Velocity Vectors in Plan View**

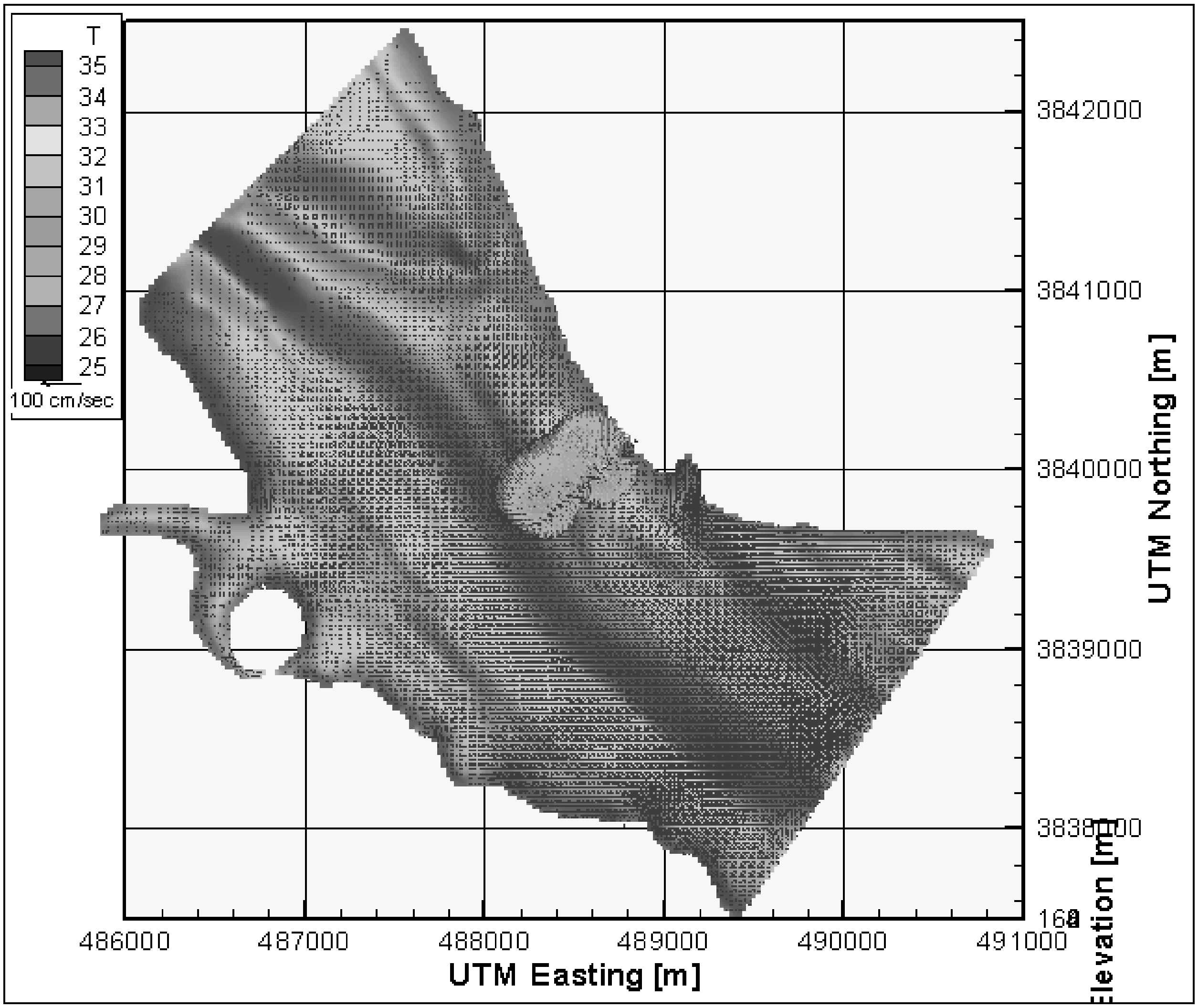


**Figure 7. Velocity Vectors with Bathymetry Details**

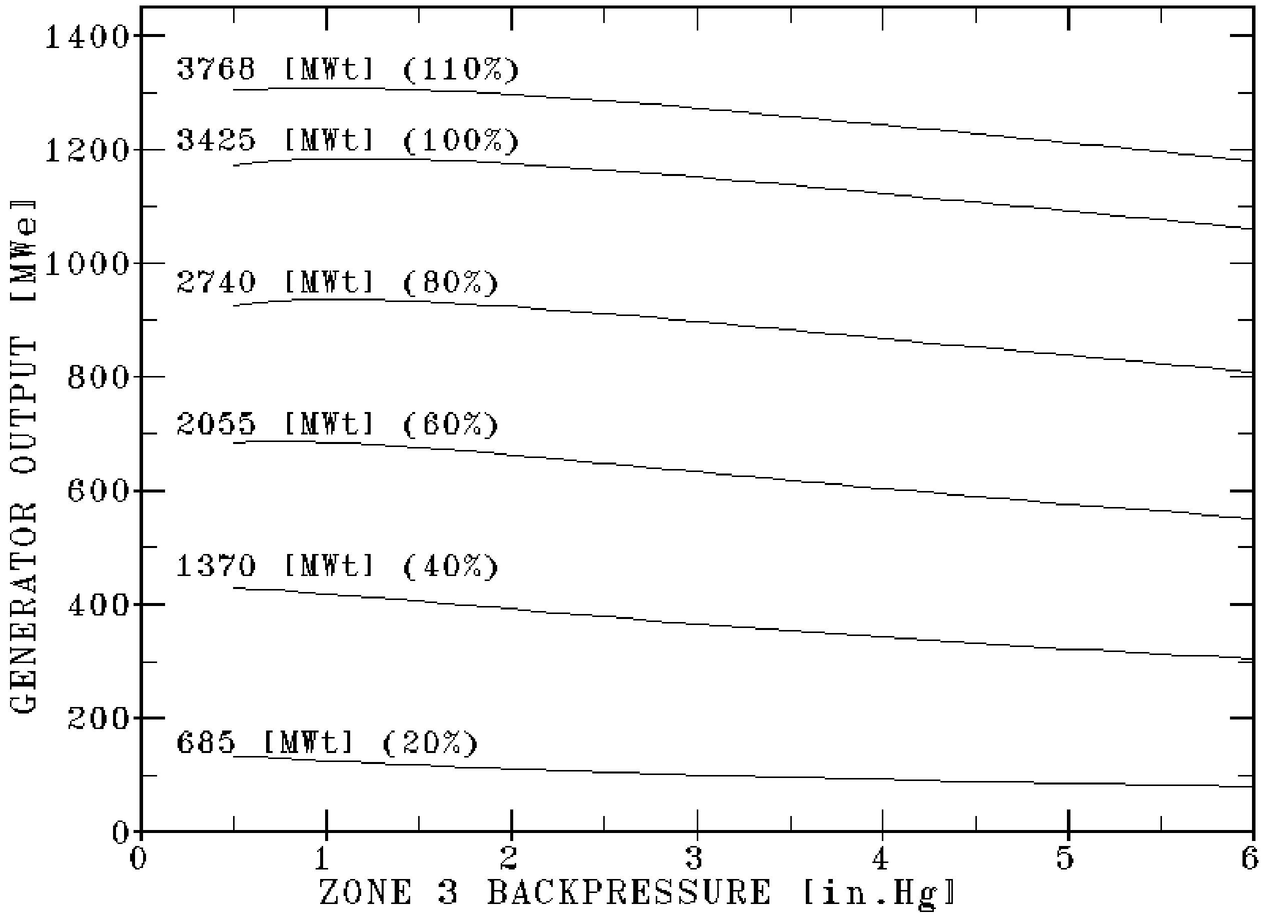


**Figure 8. Generator Output vs. Zone 3 Backpressure**

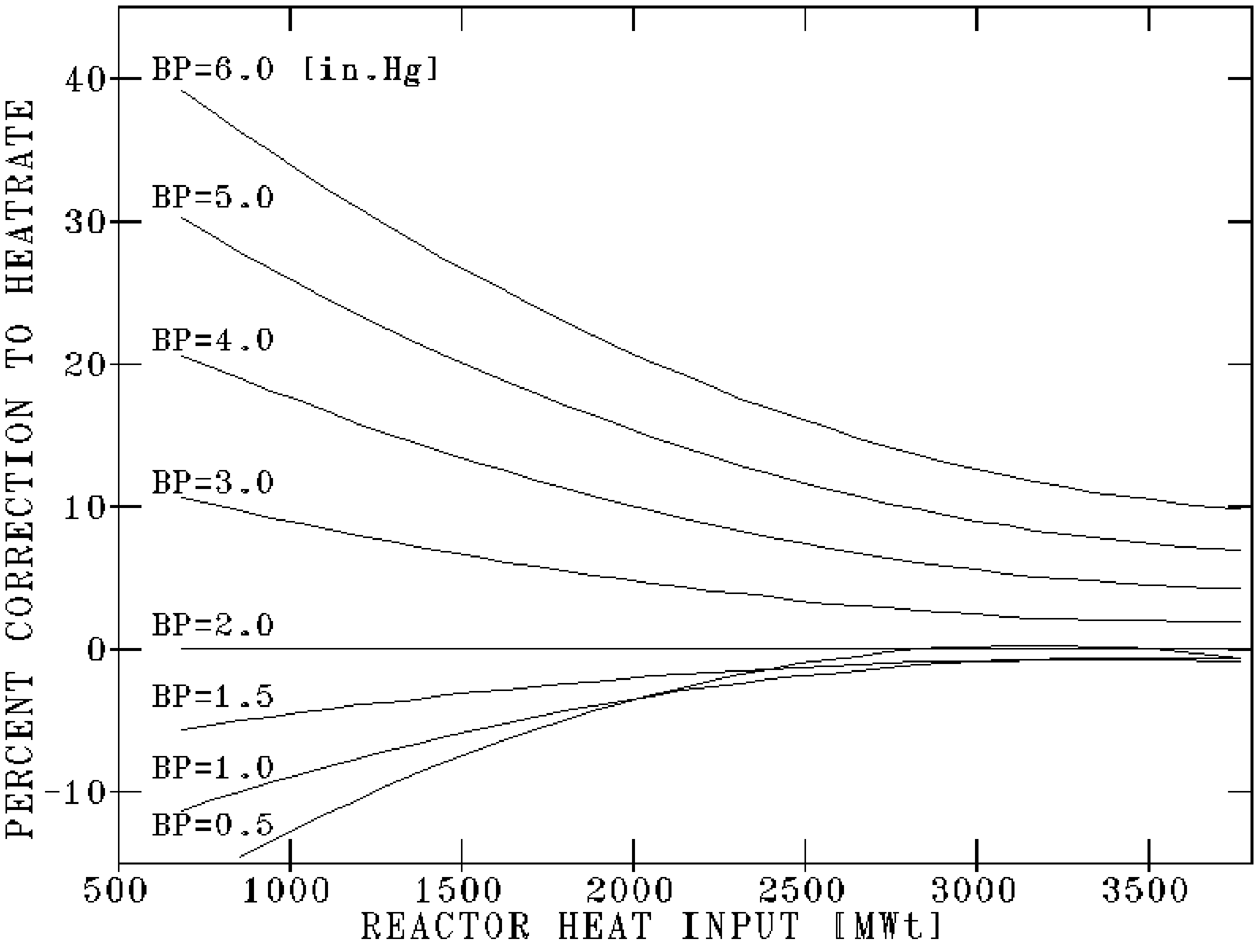


**Figure 9. Backpressure Correction to Heat Rate**

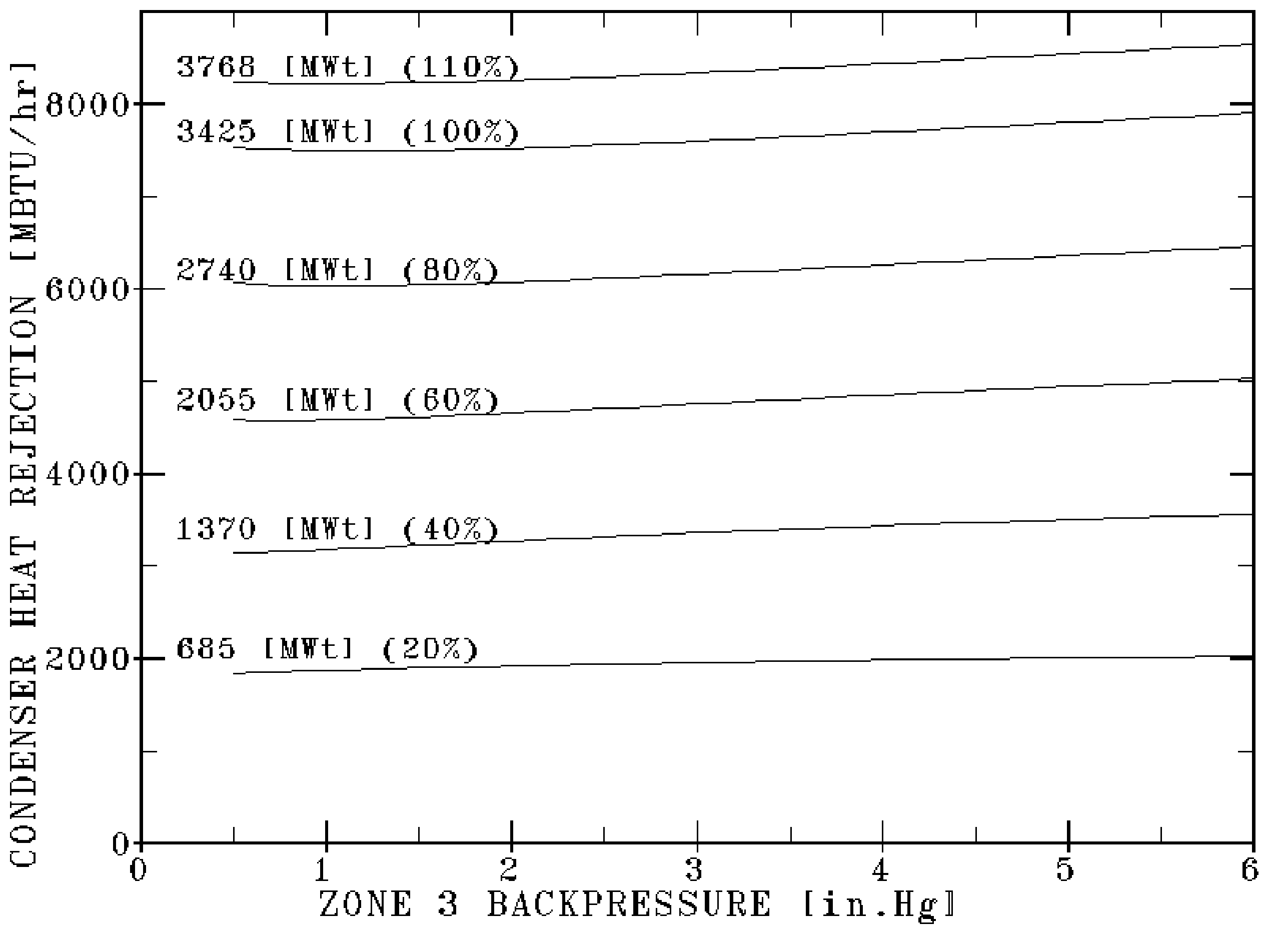


**Figure 10. Condenser Heat Rejection**

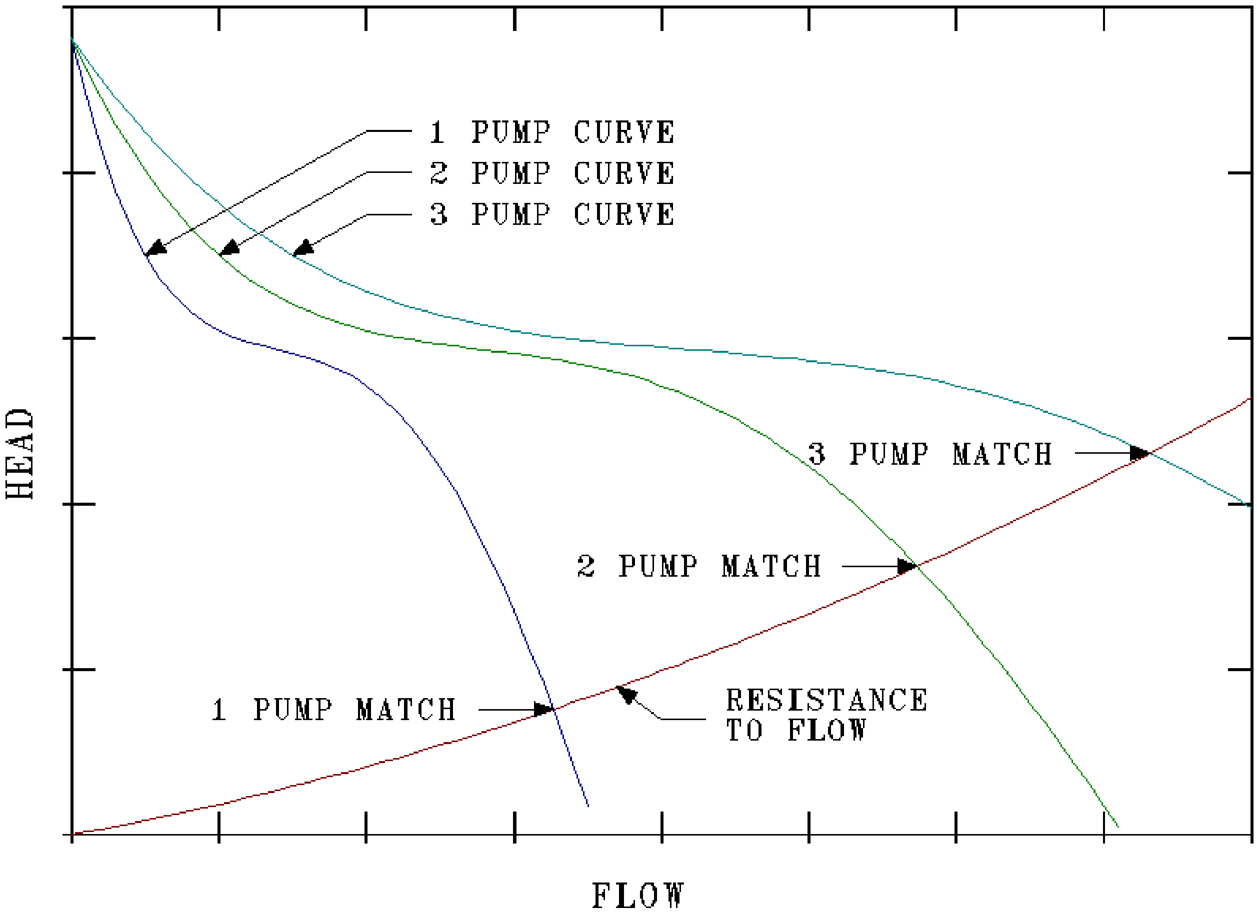


**Figure 11. Matching Pump Curves and System Head**

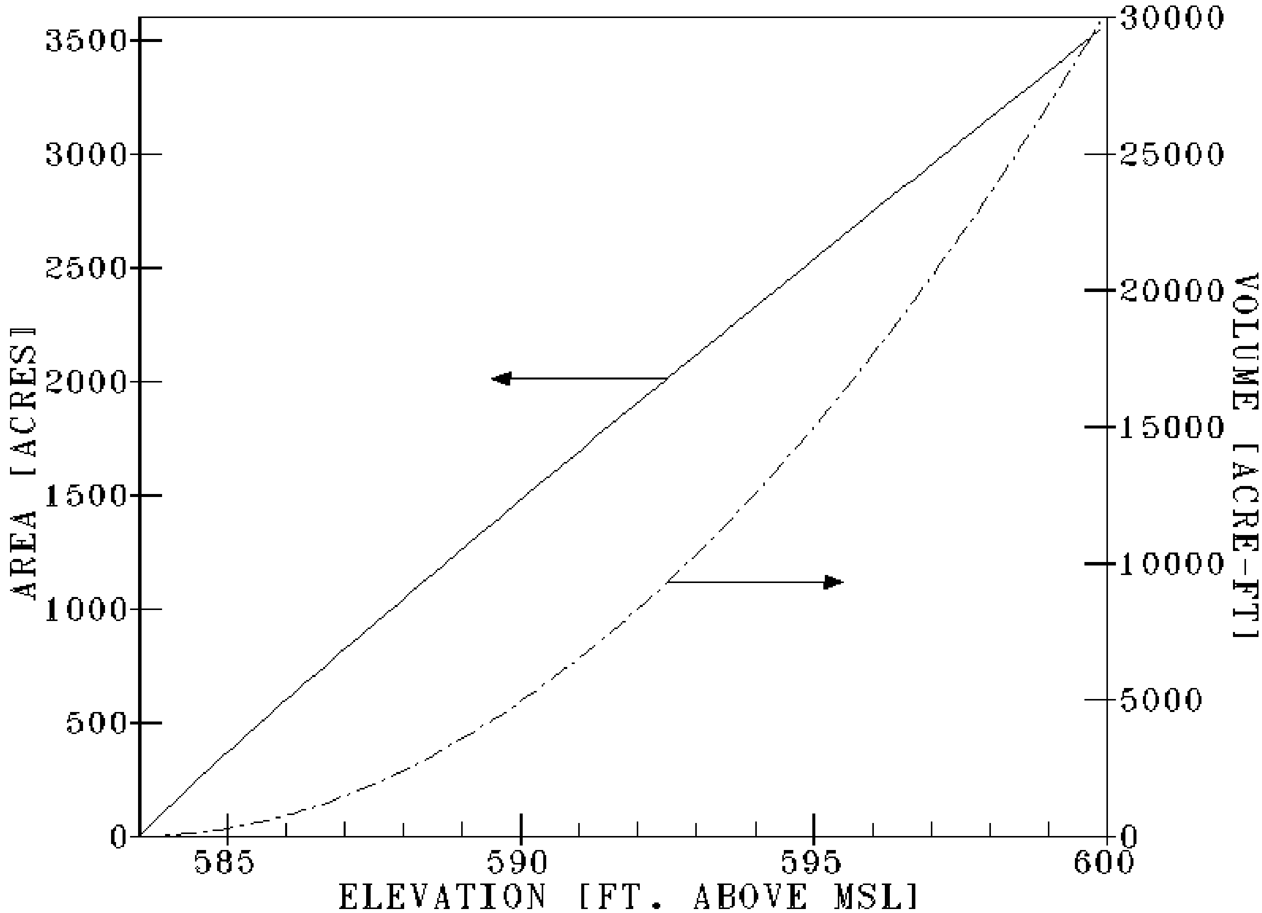


**Figure 12. Diffuser Pond Area and Volume**

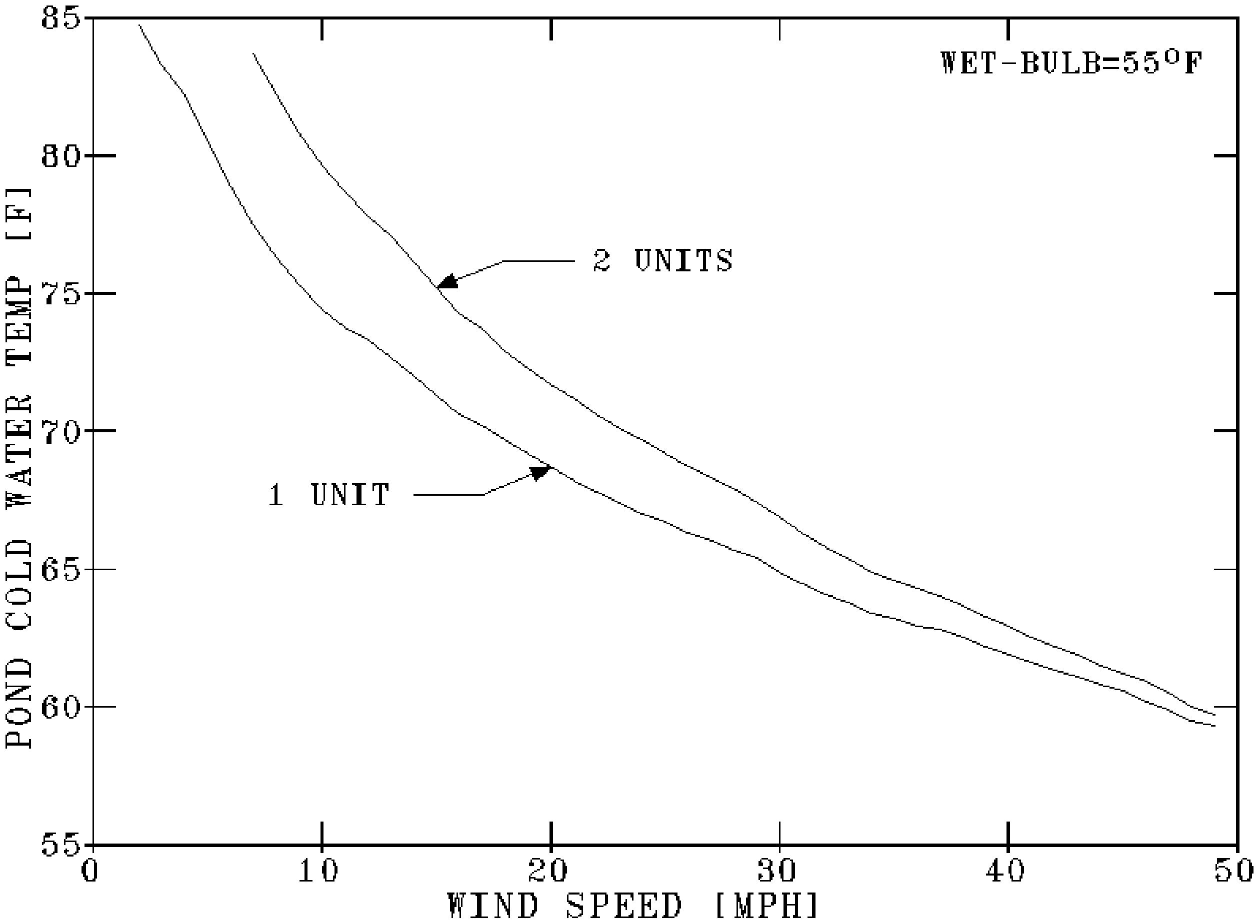


**Figure 13. Impact of Wind Speed on Pond Temperature**

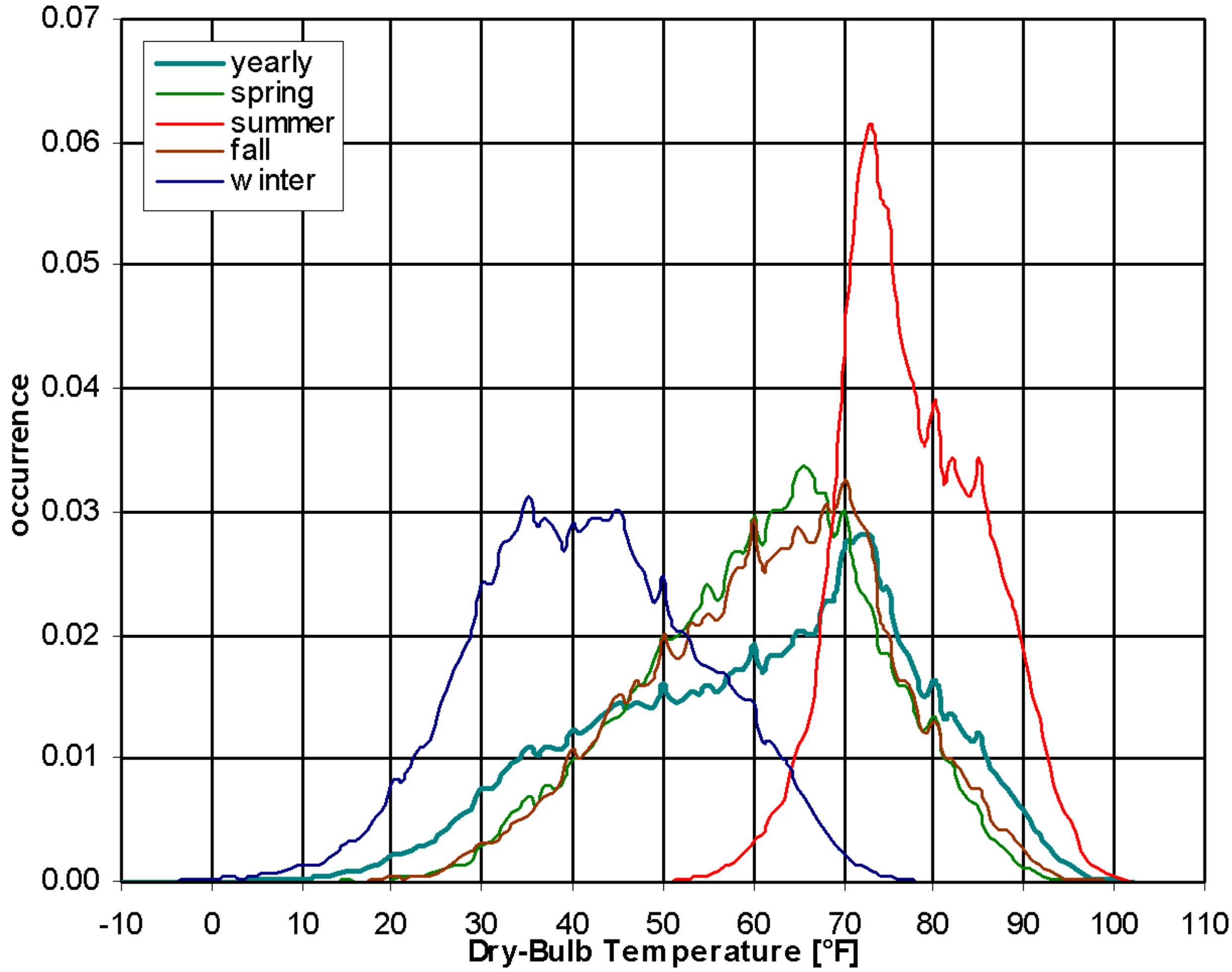


**Figure 14. Dry-Bulb Temperature Probabilities**

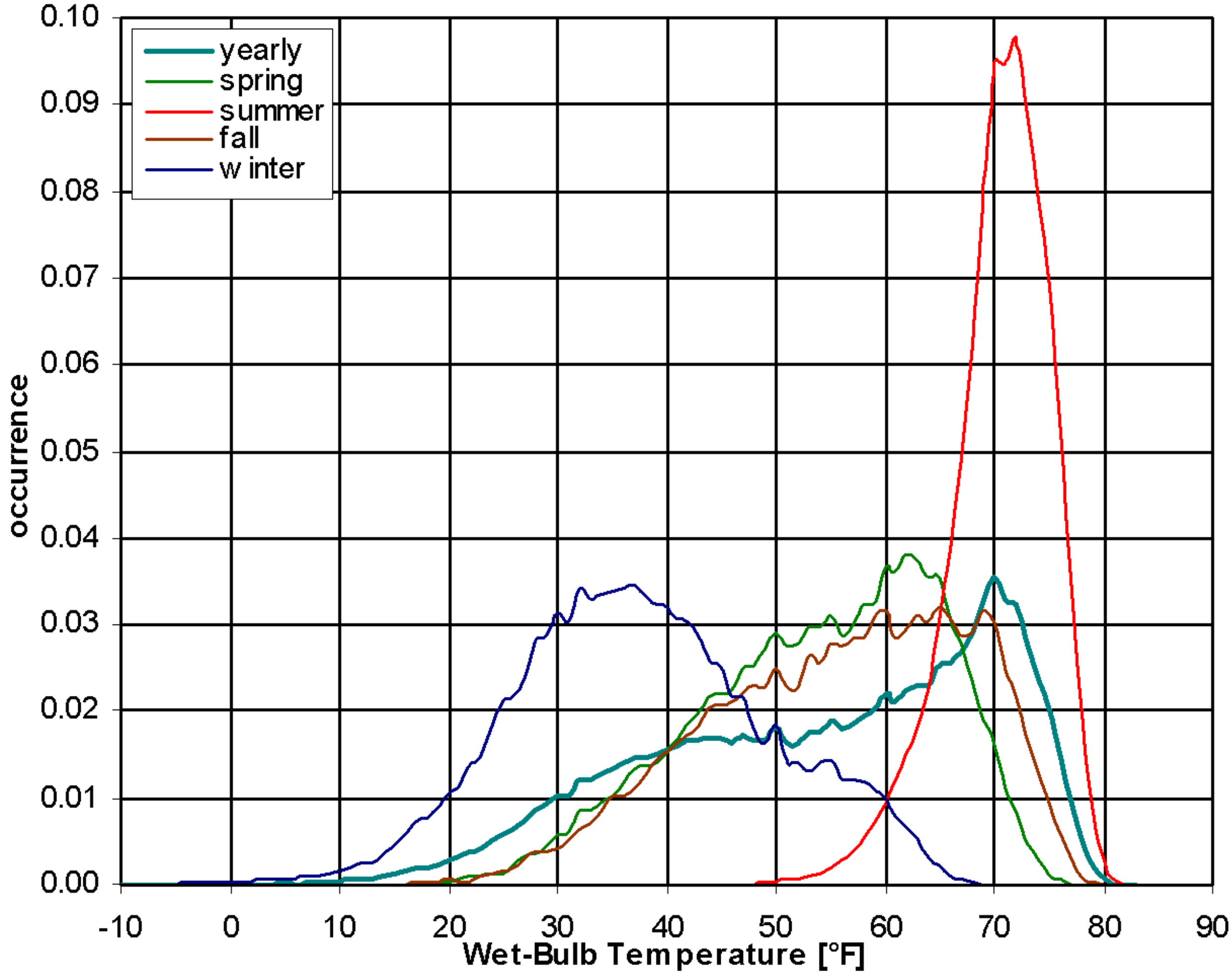


**Figure 15. Wet-Bulb Temperature Probabilities**

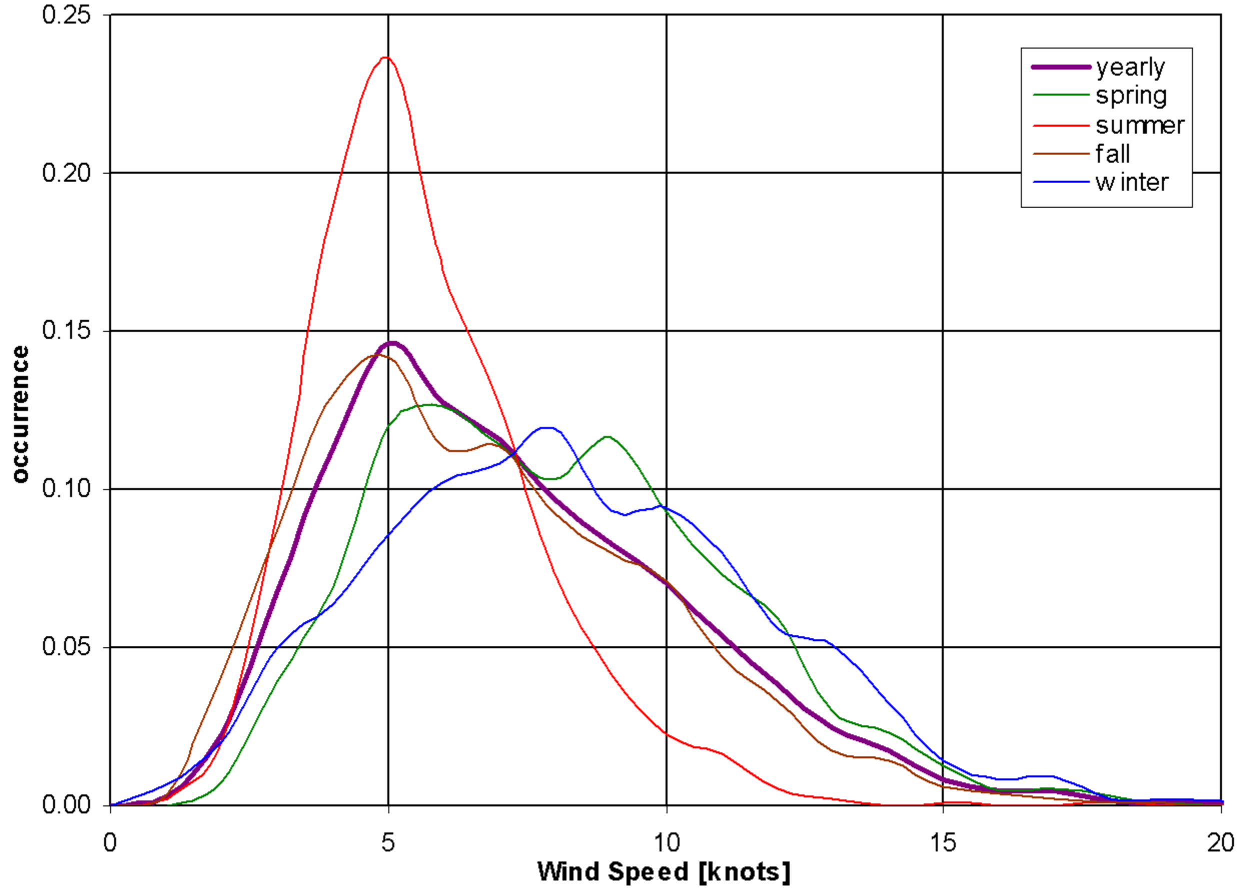


**Figure 16. Wind Speed Probabilities**

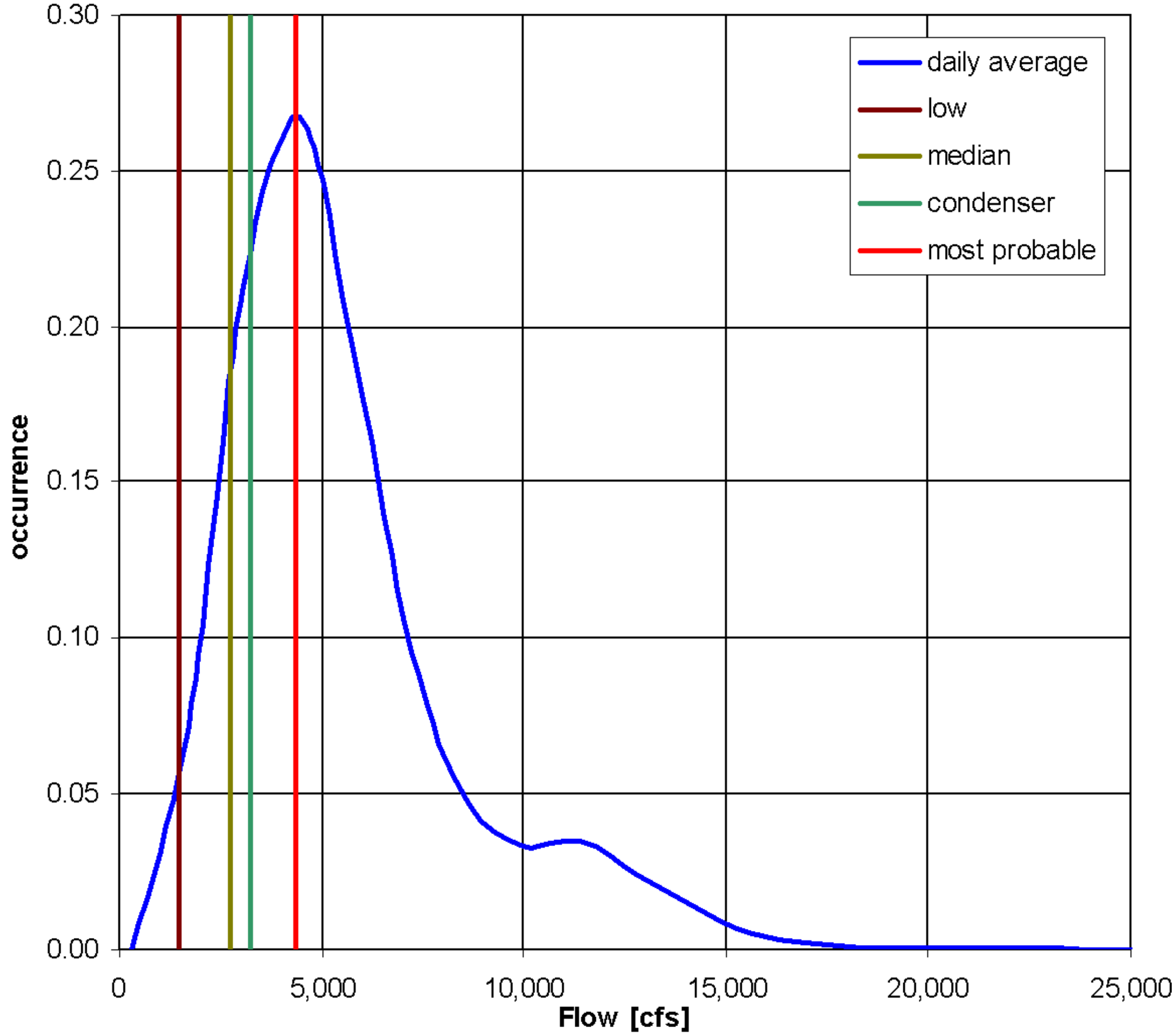


**Figure 17. River Flow Probabilities**

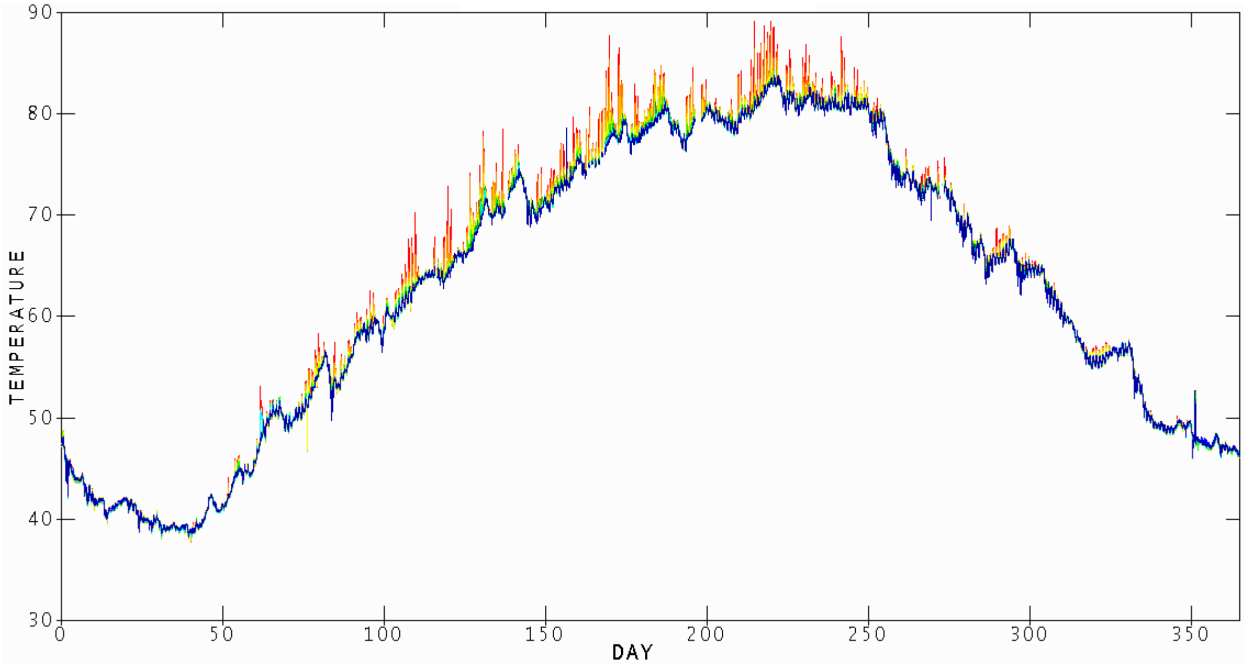


**Figure 18. Measured River Temperatures**

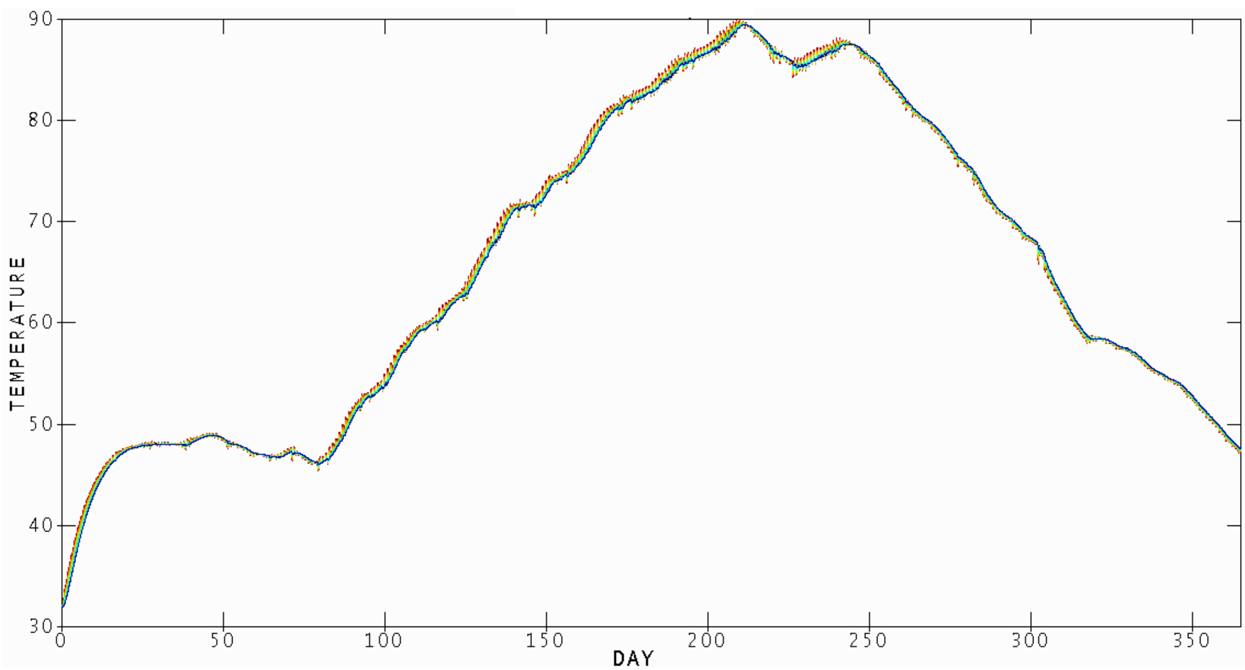


**Figure 19. Calculated River Temperatures**

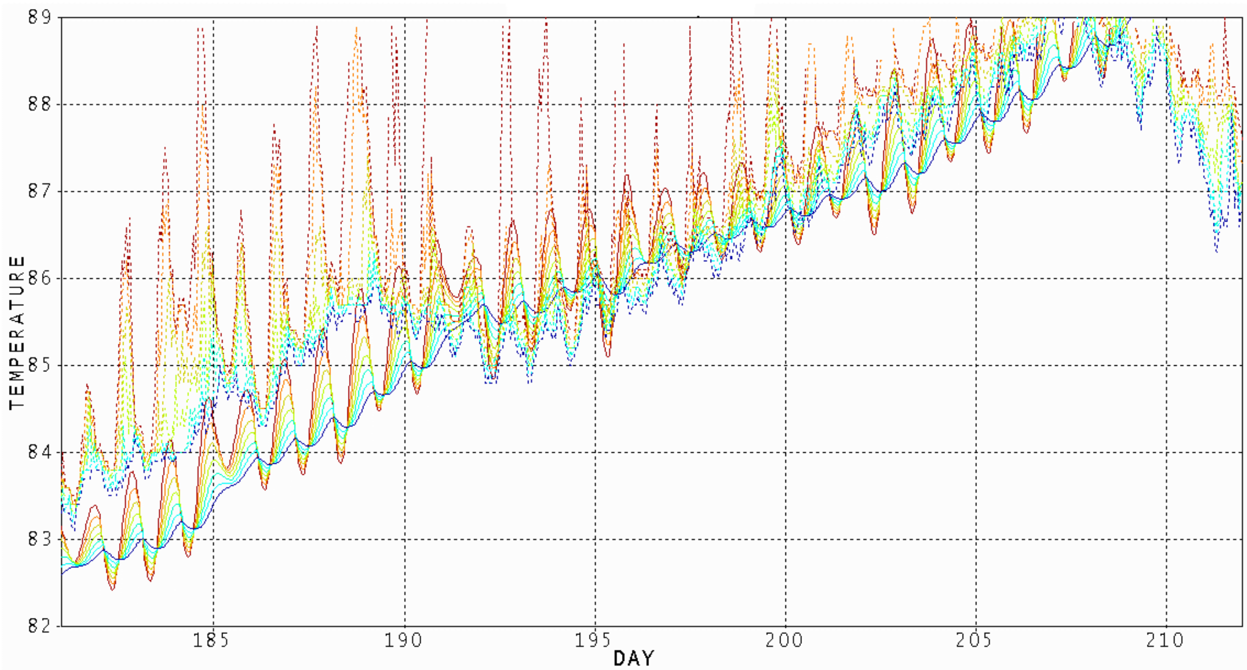


**Figure 20. Measured (dotted) and Calculated (solid) Temperatures (July)**

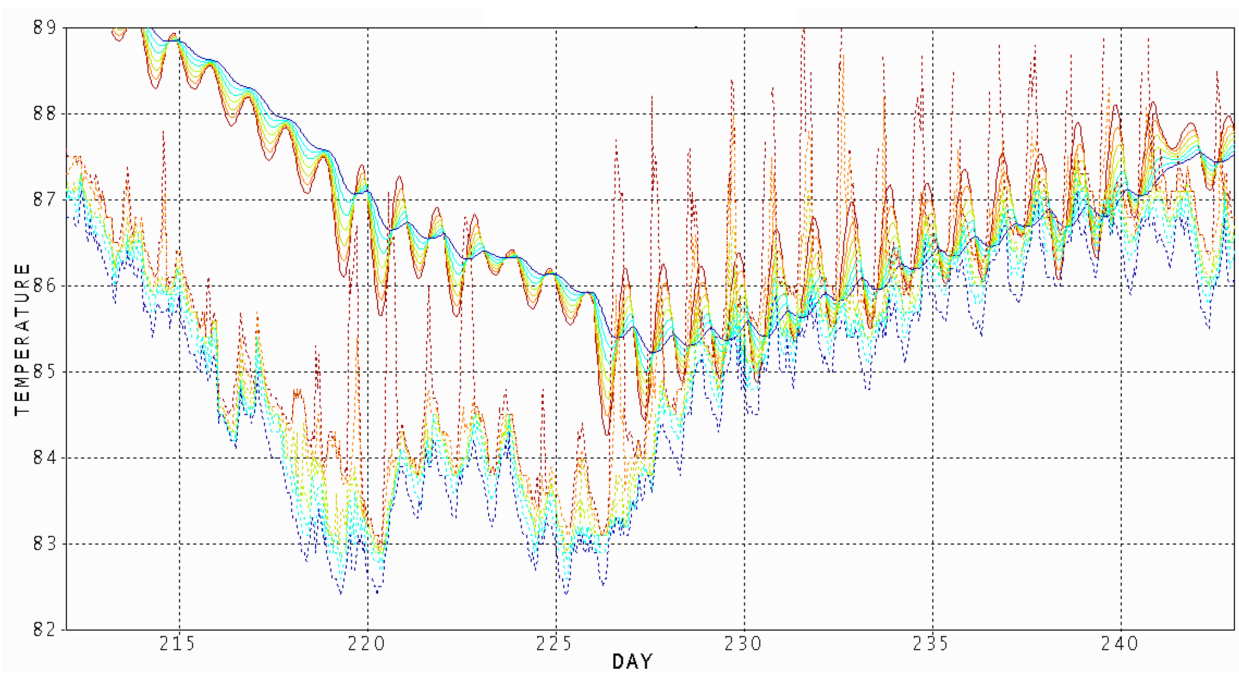


**Figure 21. Measured (dotted) and Calculated (solid) Temperatures (August)**