AREVA NP Inc.,
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Susquehanna River Thermal Plume and Dilution Modeling Bell Bend Nuclear Power Plant

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RESPONSIBLE STAFF

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UNITS

Conventional units are used in the analysis (foot-pound-seconds) rather than SI units (meters-kilograms-seconds). Conventional units were used because nearly all the data sources use those units and because Pennsylvania water quality standards are also written in conventional units. For significant results, SI units are noted in parentheses.

Temperatures are denoted "F", as in "the maximum Susquehanna River was observed to be 86.5 F". Temperature differences are denoted "°F", as in "the maximum temperature rise is 33.8°F.

OBJECTIVE

ERM's Surfacewater Modeling Group has been contracted by AREVA NP Inc. (AREVA), to compute the size and configuration of the thermal plume from the cooling tower blowdown discharge at the proposed Bell Bend Nuclear Power Plant (BBNPP) and to compute the dilution rates for this same discharge for various locations of interest.

Specifically, the assignment included the following tasks:

- Assemble relevant information
- Review applicable agency standards for thermal discharges
- Perform CORMIX computations for centerline dilution and lateral distribution
- Compute 50 mile dilution
- Provide dilution and travel time estimates at additional locations, namely
  - the nearest shoreline,
  - the maximum impacted shoreline,
  - the point on the shoreline where the site property ends,
  - the nearest recreational shore (beach),
  - the nearest public water supply intake, and
  - the plant's cooling water intakes for all units.
  - 50 ft from the discharge

2. METHODOLOGY

To compute the size and configuration of the thermal plume and provide the dilution rates at the specified locations identified by AREVA, two types of models were used. These models are CORMIX for the near-field and GEMSS® for the far-field. To show the cumulative thermal effects of the BBNPP, the size and configuration of the thermal plume from the existing cooling tower blowdown discharge from the Susquehanna Steam Electric Station (SSES) was also computed.

Descriptions of the two models are presented in the following sections; Table 1 summarizes their characteristics (U.S. Atomic Energy Commission, 1974).

Table 1 Characteristics of the models

		CORMIX	GEMSS
Field		(1) Near-field	(4) Complete-field
Dimension	Longitudinal	Yes	Yes
	Lateral	Yes	Yes
	Vertical	Yes	Yes
Mathematical approach		(1) Phenomenological	(3) Finite difference
Approximations		(not strictly applicable for phenomenological models)	(2) Boussinesq; (3) Hydrostatic pressure
Model verification		Yes	Yes
Computer program		(1) Proprietary (must be purchased, source code unavailable)	(2) Available on request (open source but requires user registration to obtain)

2.1. CORMIX

The Cornell Mixing Zone Expert System (CORMIX) is primarily a design tool that has also been used by regulatory agencies to estimate the size and configuration of proposed and existing mixing zones resulting from wastewater discharges. CORMIX is a near-field model, i.e., it applies to the region adjacent to the discharge structure in which the wastewater plume is recognizable as separate from the ambient water and its trajectory is dominated by the discharge rate, effluent density, and geometry of the discharge structure. The CORMIX calculation is based on defining the various hydraulic zones an effluent plume traverses when introduced into a receiving waterbody, then applying an analytical solution or empirical relationship to compute the plume trajectory and dilution rate in each zone. Each of these analytical solutions and empirical relationships has been validated by the developers and other researchers against laboratory and field studies. CORMIX has been applied to many cases and is recognized by the USEPA as an appropriate model.

CORMIX v5.0GT (the latest version) was used for the BBNPP calculations (MixZon Inc. 2007).

CORMIX has several limitations. It assumes steady-state conditions and unidirectional, uniform flow in the receiving waterbody. Secondly, CORMIX has simplified geometric capabilities. It assumes an idealized waterbody with straight sides and a single, positive bottom slope or no slope at all. CORMIX cannot consider multiple discharge structures with overlapping plumes.

Because CORMIX does not apply to the far-field, which is the region in the receiving waterbody in which the ambient flow fields dominate the transport of wastewater, a three-dimensional hydrodynamic, transport, and fate model is generally used to compute the trajectory and dilution of the wastewater plume in the far-field.

2.2. *GEMSS*

The hydrodynamic model chosen to assess the far-field characteristics of the thermal plume and dilution is the Generalized Environmental Modeling System for Surface Waters (GEMSS®). GEMSS is an integrated system of 3-D hydrodynamic and transport modules embedded in a geographic information and environmental data system. GEMSS is in the public domain and has been used for similar studies throughout the USA and worldwide. ERM's Surfacewater Modeling Group has special expertise with the model in that ERM staff contributes to the source code and has completed many applications with the model.

GEMSS® includes a grid generator and editor, control file generator, 2-D and 3-D post processing viewers, and an animation tool. It uses a database approach to store and access model results. The database approach is also used for field data; as a result, the GEMSS viewers can be used to display model results, field data or both, a capability useful for understanding the behavior of the prototype as well as for calibrating the model. The field data analysis features can be used independently using GEMSS modeling capability.

GEMSS® was developed in the mid-1980's as a hydrodynamic platform for transport and fate modeling. The hydrodynamic platform ("kernel") provides 3-D flow fields from which the distribution of various constituents can be computed. The constituent transport and fate computations are grouped into modules. GEMSS modules include thermal analysis, water quality, sediment transport, particle tracking, oil and chemical spills, entrainment, and toxics.

The theoretical basis of the hydrodynamic kernel of GEMSS is the three-dimensional Generalized, Longitudinal-Lateral-Vertical Hydrodynamic and Transport (GLLVHT) model which was first presented in Edinger and Buchak (1980) and subsequently in Edinger and Buchak (1985). The GLLVHT computation has been peer reviewed and published (Edinger and Buchak, 1995; Edinger, et al., 1994). The kernel is an extension of the well known longitudinal-vertical transport model that forms the hydrodynamic and transport basis of the Corps of Engineers' water quality model CE-QUAL-W2. Improvements to the transport scheme, construction of the constituent modules, incorporation of supporting software tools, GIS interoperability, visualization tools, graphical user interface (GUI), and post-processors have been developed by Kolluru et al. (1998; 1999; 2003a; 2003b).

Applications of GEMSS® and its individual component modules have been accepted by regulatory agencies in the U.S. and Canada. GEMSS-based studies have been accepted by the U.S. Environmental Protection Agency (EPA), and state agencies including those of California, Massachusetts, Pennsylvania, Louisiana, Texas, New York, and Delaware. Washington State's Department of Ecology has adopted GEMSS as a tool for estuarine and water quality modeling. Most recently GEMSS has been published as a recommended three-dimensional hydrodynamic and water quality model in studies funded by EPA and by the Water Environment Research Foundation (WERF).

has been used for ultimate heat sink analyses at Comanche Peak, Farley, and Arkansas Nuclear One. In Pennsylvania, it has been applied at PPL's Brunner Island Steam Electric Station on the lower Susquehanna River, Exelon's Cromby and Limerick Generating Stations on the Schuylkill River, and at several other electric power facilities. River applications for electric power facilities have been made on the Susquehanna (Brunner Island), the Missouri (Labadie), the Delaware (Mercer and Gilbert), the Connecticut (Connecticut Yankee), and others.

A GEMSS® application requires two types of data: (1) spatial data, primarily the waterbody shoreline and bathymetry, but also the locations, elevations, and configurations of man-made structures and (2) temporal data, that is, time-varying boundary condition data defining tidal elevation, inflow rate and temperature, inflow constituent concentration, outflow rate, and meteorological data. All deterministic models, including GEMSS, require uninterrupted time-varying boundary condition data. There can be no long gaps in the datasets and all required datasets must be available during the span of the proposed simulation period.

For input to the model, the spatial data is encoded primarily in two input files: the control and bathymetry files. These files are geo-referenced. The temporal data is encoded in many files, each file representing a set of time-varying boundary conditions, for example, meteorological data for surface heat exchange and wind shear, or inflow rates for a tributary stream. Each record in the boundary condition files is stamped with a year-month-day-hour-minute address. The data can be subjected to quality assurance procedures by using GEMSS to plot, then to visually inspect individual data points, trends and outliers. The set of input files and the GEMSS® executable constitute the model application.

The theory, assumptions, and basis for applicability of GEMSS are presented in Appendix A: GEMSS Theory, Assumptions and Applicability. Inasmuch as the BBNPP is a proposed facility, the model has not been verified for this application by comparing computed and observed values.

3. DATASETS

The datasets used to apply CORMIX and GEMSS to the BBNPP site are described below.

3.1. SPATIAL DATA

The spatial data required for the near- and far-field models (CORMIX and GEMSS, respectively) are the Susquehanna River depths and widths (the "bathymetry") and the location of the shoreline. For use in GEMSS, the spatial data are required to be geo-referenced to Pennsylvania State Plane – North, ft.

The bathymetry and shoreline datasets were obtained from the US Army Corps of Engineers, Philadelphia District (USACE), who provided digital terrain maps (TIN's), shoreline data in ARC/INFO interchange file format (e00), and cross-section data from their FEMA HEC-RAS model (Arabatzis, 2008). The transmittal letter contains a qualifier that "this data may not be suitable for other engineering design purposes". The data coverage was from River Mile 205 (Scranton) to River Mile 104 (Millersburg, halfway between Sunbury and Harrisburg). The BBNPP site is at River Mile 165. The cross-section data were converted to a point bathymetry file with an approximate spacing of 500 ft longitudinally. More spatially-detailed bathymetric contours in the immediate vicinity of the SSES intake and discharge were obtained from Pennsylvania Power and Light Company (1978), FIGURE 2.4-3.

The contours were digitized and geo-referenced and combined with the data obtained from the USACE. The combined dataset was used to create the GEMSS finite difference grid, shown in Figure 1. The grid extends from 4,500 ft upstream of the SSES intake to 15 miles downstream, with decreasing detail in the downstream direction. Typical horizontal resolution near the BBNPP site is 30 ft by 50 ft, and 85 ft by 5500 ft at the downstream end. The vertical layers (not shown) are 1 ft thick so that there are typically 8-12 layers representing the depth of the Susquehanna River near the BBNPP site.

Values of the depth and width for CORMIX's simpler representation of the Susquehanna in the vicinity of the BBNPP were also derived from the USACE and the Pennsylvania Power and Light Company (1978) FIGURE 2.4-3. The elevation of the bottom of the Susquehanna River at the BBNPP discharge was found to be at 476 ft. The CORMIX parameter values are shown in Table 2; the scenarios are introduced and discussed in Section 4.

Table 2 CORMIX bathymetric-related parameter values

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Average depth, ft	11.5	10	13.8	10.8	13.8
Depth at the discharge, ft	11.5	10	13.8	10.8	13.8
Width, ft	750	680	790	720	790

3.2. BOUNDARY CONDITION DATA

Boundary condition data are used to estimate surface heat exchange at the water surface and to compute the flow of mass and energy entering and leaving the model domain. All simulations used steady values of the boundary condition data.

All values for the boundary conditions discussed in the following sections are summarized in Table 4.

To capture the seasonal behavior of the thermal plume, a summer and a winter period were chosen for simulation. Inasmuch as the boundary condition datasets are cataloged monthly, this approach required choosing a single month to represent these periods and obtaining the corresponding boundary condition data. The representative summer and winter months were chosen on the basis of the observed occurrences of the maximum and minimum temperature, described below.

Susquehanna River temperature and solids data

Ecology III has measured water temperatures 1620 ft upstream of the SSES intake structure on the west bank of the Susquehanna River daily beginning in 1974 (Ecology III, Inc., 2008). Maximum and minimum temperatures occur in August and January and these months were selected to be representative of summer and winter conditions. The maximum water temperature of 86.5 F was recorded on 15 Aug 1988 and 4 Aug 2007. A minimum water temperature of 32.0 F was recorded numerous times in January.

Total mineral solids (TMS) values for the Susquehanna River were obtained from Sargent & Lundy (2008b), Att. 3, Table 4, using the "SSES" values for 2/23/2006 for winter and 8/18/2006 for summer.

Susquehanna River flow and water surface elevation data

Flow rates in the Susquehanna River are measured at United States Geological Survey (USGS) sites upstream of the BBNPP site at Wilkes-Barre (Station No. 01536500) and downstream of the site at Danville (Station No. 01540500). In addition there are several statistical summaries of low and mean flows at these stations. These summaries are discussed below.

USGS flow data and statistics for the stream gauges at Wilkes-Barre and at Danville are found at the USGS website http://waterdata.usgs.gov/pa/nwis/inventory/?site_no=01536500&amp and http://waterdata.usgs.gov/pa/nwis/inventory/?site_no=01540500&amp, respectively. Screenshots of both are provided as Figure 2 and Figure 3. For the selected January and August simulations, mean and low flows at the site are required to show the extremes of the computed size of the thermal plume and the downstream dilution values. Data and statistics for the Wilkes-Barre gauge, upstream of the site, were used in this analysis.

Low flow frequency statistics generated by Pennsylvania Department of Environmental Protection (PA DEP) for the Wilkes-Barre gauge can be found at the PA DEP website http://pa.water.usgs.gov/pc38/flowstats/lowflow.ASP?WCI=stats&WCU;ID=2415. A screenshot of the web site is provided as Figure 4. This website provides a value of 880 cfs for the annual 7-day, 10-year low flow (7Q10) rate over the post-regulation period in the Susquehanna River, 1980 to 1996. This annual 7Q10 value was multiplied by the PA DEP's default multiplier to convert the annual 7Q10 to a monthly 7Q10 rate. The default multiplier for January is 3.2, and the default multiplier for August is 1.4 (PA DEP, 2003).

The monthly mean flows used in the simulations for January and August were derived from the historical record at the Wilkes-Barre stream gauge for the period 1980 to 1996. These data were retrieved from the USGS website referenced above for Wilkes-Barre. The monthly data are provided in Figure 5.

For each selected flow, the corresponding water surface elevation was obtained from the rating table presented as Attachment 7 in Ecology III (1991).

Meteorological data

To compute surface heat exchange, the coefficient of surface heat exchange (K) and equilibrium temperature (E) method was used. Monthly average and extreme values of K and E for National Weather Service sites in the USA are cataloged by the Environmental Protection Agency (Environmental Protection Agency, 1971). The nearest cataloged site to BBNPP is Avoca, Pennsylvania (WBAN 14777), 27 miles to the northeast. Other candidate sites considered for this study were located at Williamsport-Lycoming County Airport (WBAN 14778), which is 43 miles WNW of the site and at Penn Valley Airport, Selinsgrove (WBAN 14770) which is 43 miles WSW of the site. Values from the Avoca site were chosen because of its nearness to the BBNPP site.

For these simulations, the extreme values shown in FIGURE 104 (Environmental Protection Agency, 1971) were used.

Susquehanna Steam Electric Station (SSES) data

The location of the SSES intake and discharge structures was obtained from PP&L Drawing No. E105151. This drawing was scanned, digitized and geo-referenced to Pennsylvania State Plane – North, ft. The general configuration and dimensions of the SSES discharge structure were obtained from Bechtel DRAWING No. C-95. The SSES intake structure was assumed to draw from the bottom of the Susquehanna River.

For implementation in CORMIX, the discharge structure-related parameter values are shown in Table 3.

Table 3 CORMIX discharge structure-related parameter values

CORMIX parameter	Value
Surface, single- or multi-port	Multi-port with 72 individual ports
Opening diameter, in	4
Horizontal angle, degrees	0
Vertical angle, degrees	45
Height, ft	0 (at river bottom)

The CORMIX variable "height" is the distance of the ports above the waterbody bottom. Bechtel DRAWING No. C-95 indicates rocks placed nearly to the height of the ports (15 in above the nominal bottom). For this calculation, it was assumed the ports are located at the bottom.

The SSES intake and discharge rates and temperature rise were obtained from PPL Susquehanna, LLC (2006b) Page 4.1-1 and 4.1-2.

Total mineral solids (TMS) values for the SSES discharge were obtained from Sargent & Lundy (2008b), Att. 3, Table 4, using the "BLOW DOWN" values for 2/23/2006 for winter and 8/16/2006 for summer. These values represent a concentration factor of about four times.

Bell Bend Nuclear Power Plant (BBNPP) data

The location of the BBNPP intake and discharge structures was obtained from Sargent & Lundy DRAWING NO. CSK-014, REV 1. The drawing contained the site utilization plan for BBNPP overlaid on the existing SSES site. The BBNPP discharge structure was assumed to be identical to the SSES discharge structure. The BBNPP intake structure was assumed to draw from the bottom of the Susquehanna River.

Maximum and average intake and discharge rates for the BBNPP were obtained from Sargent & Lundy (2008b), Page 4 of 33.

Discharge temperature rises for BBNPP were derived as follows:

The discharge temperature rise for the summer (August) scenario was calculated by subtracting the maximum observed summer ambient temperature of 86.5 F from the 90 F discharge temperature provided by Sargent & Lundy (2008a). The 90 F discharge temperature represents Option 1b, i.e., no auxiliary heat exchanger (Page 4), yielding a discharge temperature rise of 3.5°F.

The temperature rise for the winter (January) scenario was calculated as follows. First the discharge temperature was estimated by assuming the MDT1 option (conservative in that the approach temperature is higher than for the other options), then by choosing the January average wet bulb temperature of 23.8 F (Page 9, Sargent & Lundy, 2008a) and an approach temperature of 30°F (Fig. 6-1 of that same report), and finally by incrementing the latter by 6°F, as noted on Page 24 of that same report for the 90 F approach curve. The resulting discharge temperature for the January scenario is 65.8 F. The January ambient temperature was subtracted from the January discharge temperature to obtain the discharge temperature rise of 33.8°F.

Total mineral solids (TMS) values for BBNPP discharge were assumed to be equal to the SSES values.

Table 4 Parameter values for the simulations

Parameter	Units	Winter	Source	Summer	Source
Month		January		August	
Extreme ambient temperature	F	32.0	Ecology III, Inc., 2008	86.5	Ecology III, Inc., 2008
Discharge temperature	F	65.8	Sargent & Lundy, 2008a	90.0	Sargent & Lundy, 2008b
Temperature rise	°F	33.8	calculated	3.5	calculated
Discharge TMS	mg/l	556	Sargent & Lundy, 2008b	642	Sargent & Lundy, 2008b
Average intake rate	gpm	27,850	Sargent & Lundy, 2008b	27,850	Sargent & Lundy, 2008b
Maximum intake rate	gpm	34,460	Sargent & Lundy, 2008b	34,460	Sargent & Lundy, 2008b
Average discharge rate	gpm	9,290	Sargent & Lundy, 2008b	9,290	Sargent & Lundy, 2008b
Maximum discharge rate	gpm	11,170	Sargent & Lundy, 2008b	11,170	Sargent & Lundy, 2008b
Low Susquehanna River flow	cfs	2,848	PA DEP, 2003 / USGS website	1,246	PA DEP, 2003 / USGS website
Low Susquehanna River elevation	ft	486.8	Ecology III, Inc., 1991	486.0	Ecology III, Inc., 1991
Mean Susquehanna River flow	cfs	12,482	USGS website	4,473	USGS website
Mean Susquehanna River elevation	ft	489.8	Ecology III, Inc., 1991	487.5	Ecology III, Inc., 1991
Susquehanna river TMS	mg/l	134	Sargent & Lundy, 2008b	196	Sargent & Lundy, 2008b
Heat exchange coefficient (K)	BTU ft^{-2} day^{-1} $°F^{-1}$	58	Environmental Protection Agency, 1971	104	Environmental Protection Agency, 1971
Equilibrium Temperature (E)	F	34	Environmental Protection Agency, 1971	85	Environmental Protection Agency, 1971

4. SIMULATIONS AND RESULTS

Five scenarios were simulated with both CORMIX and GEMSS®. The scenarios are summarized in Table 5 and consist of combinations of summer and winter mean and low Susquehanna River flow conditions. For each scenario, design values of the SSES and BBNPP intake and discharge rates, temperatures, and total dissolved minerals were used as shown in Table 5. Parameters common to all scenarios are shown in Table 4.

For both models, the term "excess temperature" is used. Excess temperature is the increase in temperature over background temperature ("ambient" or "natural") due to a heated water discharge.

To show both the incremental impact of the BBNPP thermal plume as well as the cumulative impact of the combined SSES and BBNPP thermal plumes, two sets of simulations were made with GEMSS for each scenario. In the first set of simulations a single excess temperature was included in the model, the sources of which were the temperature rises for the SSES discharge and for the BBNPP discharge. This set of simulations showed the combined thermal plume for two discharges, i.e., the cumulative plume. The second set of simulations included only the BBNPP discharge as the source of excess temperature, but did include the SSES discharge to correctly model its effect on the ambient temperature. This set of simulations showed the thermal plume due solely to the BBNPP discharge, i.e., the incremental plume.

Including both discharges in a single CORMIX simulation is not possible because CORMIX is incapable of modeling two plumes simultaneously. For the near-field, only the BBNPP was modeled. This approach is satisfactory because in the near-field, the plumes do not overlap due to the 380 ft separation of the SSES and BBNPP discharges.

Table 5 Simulation summary with scenario descriptions

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Description	**Summer mean flow (August)**	**Summer low flow (August)**	**Winter mean flow (January)**	**Winter low flow (January)**	**Annual mean flow (January)**
Susquehanna River flow, cfs	4,473	1,246	12,482	2,848	12,800
Water surface elevation, ft	487.5	486.0	489.8	486.8	489.8
Susquehanna River Temperature, F	86.5	86.5	32.0	32.0	32.0
SSES					
Temperature rise, deg F	12.5	12.5	31.0	31.0	31.0
Intake rate, gpm	42,300	42,300	42,300	42,300	42,300
Discharge rate, gpm	11,200	11,200	11,200	11,200	11,200
BBNPP					
Temperature rise, deg F	3.5	3.5	33.8	33.8	33.8
Intake rate, gpm	34,458	34,458	34,458	34,458	34,458
Discharge rate, gpm	11,172	11,172	11,172	11,172	11,172

4.1. *THERMAL PLUME CONFIGURATION AND SIZE*

The thermal plume was first modeled using CORMIX for the near-field region and then using GEMSS® for the far-field region. Use of these two models provides a detailed near-field plume configuration along with the far-field plume behavior for non-uniform channel geometry.

Near-field

CORMIX was used for near-field modeling of the thermal plume. The winter scenarios (Scenarios 3, 4 and 5) used an ambient river temperature of 32 F (0 C). CORMIX has an inherent limitation that requires that the ambient temperature be at least 39.2 F (4 C). In CORMIX, the ambient temperature is used to compute density and to establish the buoyancy differential between the effluent and ambient water. Since water has its maximum density at 4 C which decreases with both increasing and decreasing temperature, there are temperatures above 39.2 F with densities identical to temperatures below this value. In this case 46 F (7.8 C) has a density identical to the density of water at 32 F. This temperature was used in the winter CORMIX simulations.

The BBNPP discharge structure was assumed to be identical in configuration to the SSES diffuser. The ambient and effluent characteristics were taken directly from Table 2 through Table 5 and the discharge was modeled in CORMIX as a heated discharge using the heat loss coefficients listed in Table 5. The near-field plumes from the five scenarios are shown in Figure 6 for Scenario 1, Figure 7 for Scenario 2, Figure 8 for Scenario 3, Figure 9 for Scenario 4, and Figure 10 for Scenario 5. Note that CORMIX automatically sets the spatial scaling and thus the scales varies from one diagram to the next. The wide discharge line passing through the origin (0,0,0) along the y-axis depicts the diffuser of length 108 ft in all these diagrams.

Scenario 2 with the smallest Susquehanna River flow has the largest near-field plume as there is limited mixing near the diffuser, resulting in an expanded near-field region. Scenario 4 has the plume with the highest peak temperature due to the largest temperature rise (33.8°F) combined with the lowest Susquehanna River flow. During the summer period, Scenario 2 has the plume with the higher peak temperature due to lower Susquehanna River flow compared to Scenario 1. The excess temperature values in the near-field along the downstream distance for all five scenarios are shown in Figure 11.

In the near-field, the excess temperature decreases to small values due to rapid mixing. During the summer period, the discharge has an excess temperature of 3.5°F (1.9°C) which decreases to 0.13°F (0.07°C) and to 0.29°F (0.16°C) within 50 ft of the discharge for Scenarios 1 and 2, respectively. The winter period shows excess temperatures decreasing to 0.5°F (0.3°C), 1.75°F (0.97°C) and 0.5°F (0.3°C) for Scenarios 3, 4 and 5, respectively at 50 ft.

It is also desirable to compute the surface area and volume of the plume at different temperature rise isotherms. These areas and volumes provide an estimate of how much of the waterbody is affected by the thermal discharge. Figure 12 shows the area of the plume and Figure 13 shows the volume of the plume for the five scenarios against the temperature rise on the x-axis. A larger area (and volume) of the waterbody is impacted at lower temperature rise levels. These areas and volumes decrease with increasing temperature rise levels. A summary of these plots is shown in Table 6 which lists the areas and volumes for preset temperature rise levels.

Table 6 Near-field plume area (ft^2) and volume (ft^3)

Excess, °F	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	Area	Volume	Area	Volume	Area	Volume	Area	Volume	Area	Volume
10	-	-	-	-	98	12.8	118	15.4	91	12.0
5	-	-	-	-	118	15.5	569	305.7	110	14.4
3	21	2.8	26	3.4	152	27.6	1739	2851.5	133	21.9
2	67	8.8	83	10.9	352	136.8	4034	15759.5	314	118.3
1	113	14.8	296	89.8	1462	2358.6	Not achieved in near-field	Not achieved in near-field	1285	1960.4

Table 7 Near-field plume area (m^2) and volume (m^3)

Excess, °C	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	Area	Volume	Area	Volume	Area	Volume	Area	Volume	Area	Volume
5.6	-	-	-	-	9	1.2	11	1.4	8	1.1
2.8	-	-	-	-	11	1.4	53	28.4	10	1.4
1.7	2	0.3	2	0.3	14	2.6	162	264.9	12	2.0
1.1	6	0.8	8	1.0	33	12.7	375	1464.1	29	11.0
0.6	10	1.4	28	8.4	136	219.1	Not achieved in near-field	Not achieved in near-field	119	182

Far-field

GEMSS® was set up to model the far-field thermal plume emerging from the BBNPP discharge for the five scenarios. All five scenarios were run under two different setups to capture both the cumulative and incremental thermal plume. The first setup included both the SSES and BBNPP discharges as excess temperature sources while the second setup included only the BBNPP discharge as an excess temperature source. This approach facilitated studying the thermal plume from BBNPP combined with the SSES thermal plume as well as studying it separately.

Scenarios 2 and 4 represent the low flow conditions during summer and winter periods, respectively. In general, during these conditions, the thermal plume is able to spread out due to decreased ambient velocities. The diffuser is closer to the western shore and thus Scenarios 1 and 3, which represent the mean flow conditions for summer and winter respectively, show that the thermal plume is pushed towards the western shore due to higher ambient velocities. Scenario 5, which is similar to Scenario 3, exhibits similar plume characteristics. This process, however, does not decrease the overall mixing of the discharge because during the high flow periods there is more water available to mix and the river surface elevations are higher.

The cumulative impacts of the SSES and the BBNPP for the surface and bottom thermal plumes are shown in Figure 14 and Figure 15 for Scenario 1, Figure 18 and Figure 19 for Scenario 2, Figure 22 and Figure 23 for Scenario 3, Figure 26 and Figure 27 for Scenario 4, and finally in Figure 30 and Figure 31 for Scenario 5. During the summer period, the excess temperature from BBNPP is small (3.46°F). However, the thermal plume at the bottom shows excess temperatures greater than the BBNPP temperature rise because the temperature rise from the SSES discharge is large (12.5°F). The extent of this combined thermal plume, however, is very small. The surface excess temperatures are less than 0.2°F (0.1°C) for Scenario 1, less than 0.8°F (0.4°C) for Scenario 2, less than 0.6°F (0.3°C) for Scenario 3, less than 0.6°F (0.3°C) for Scenario 4 and less than 0.6°F (0.3°C) for Scenario 5. Since the discharge is located near the river bottom, the combined thermal plume near the bottom shows a slightly increased maximum excess temperature with less than 2.7°F (1.5°C) for Scenario 1, less than 3.0°F (1.7°C) for Scenario 2, less than 13.5°F (7.5°C) for Scenario 3, less than 25.0°F (13.9°C) for Scenario 4 and less than 13.5°F (7.5°C) for Scenario 5. The extent of these plumes at the bottom are, however, very small (2.7°F contour for Scenario 1 near BBNPP discharge is only 75 ft). Both mean flow simulations (Scenario 1 and Scenario 3) have lower maximum excess temperature compared to their respective low flow counterparts for the period (Scenario 2 and Scenario 4). The plumes for Scenario 1, Scenario 3 and Scenario 5 are pushed against the western shoreline while the plumes for Scenario 2 and Scenario 4 are more spread out laterally. Scenario 5 (also Scenario 3 which is very similar) has the highest river flow which pushes the plume further towards the western shoreline compared to the other scenarios and, when combined with the shallow, near-shore bathymetry produces a small recirculation eddy that helps replace the water withdrawn from the intakes. This phenomenon results in the thermal plume extending upstream as seen in Figure 30 and Figure 31.

The second setup shows the thermal plume attributable only to the BBNPP discharge, i.e, the incremental impact. Under this setup the thermal plumes for the summer period are considerably smaller (Figure 16 and Figure 17 for Scenario 1 and Figure 20 and Figure 21 for Scenario 2) as the BBNPP discharge has a small excess temperature (3.5°F). During the winter period, the BBNPP excess temperature from the discharge is higher at 33.8°F (18.8°C). The maximum excess temperature seen at the surface are at less than 0.04°F (0.02°C) for Scenario 1, less than 0.3°F (0.2°C) for Scenario 2, less than 0.35°F (0.20°C) for Scenario 3, less than

0.3°F (0.2°C) for Scenario 4 and less than 0.35°F (0.20°C) for Scenario 5. The bottom excess temperatures are, however, in the same range as the combined thermal plume with maximum values at less than 2.5°F (1.4°C) for Scenario 1, less than 3.0°F (1.7°C) for Scenario 2, less than 13.0°F (7.2°C) for Scenario 3, less than 25.0°F (13.9°C) for Scenario 4 and less than 13.0°F (7.2°C) for Scenario 5. The plumes are shown in Figure 24 and Figure 25 for Scenario 3, Figure 28 and Figure 29 for Scenario 4, and Figure 32 and Figure 33 for Scenario 5. The extent of the bottom plume is very small (the 0.25°F contour is only 400 ft from the discharge for Scenario 1, 0.30°F is only 300 ft from the discharge for Scenario 2, 1.3°F is only 600 ft from the discharge for Scenario 3, 2.5°F is only 650 ft from the discharge for Scenario 4 and 1.3°F is only 580 ft from the discharge for Scenario 5)

4.2. PENNSYLVANIA STANDARDS

Pennsylvania provides the following criteria for temperature (Pa. Code, Chapter 93. Water Quality Standards, § 93.7. Specific water quality criteria):

> "Maximum temperatures in the receiving water body resulting from heated waste sources are regulated under Chapters 92, 96 and other sources where temperature limits are necessary to protect designated and existing uses. Additionally, these wastes may not result in a change by more than 2°F during a 1-hour period."

The protected water use for the Susquehanna River adjacent to BBNPP is Warm Water Fishery (WWF), as shown in Pa. Code, Chapter 93. Water Quality Standards, § 93.9k. Drainage List K as WWF ("Warm Water Fishes—Maintenance and propagation of fish species and additional flora and fauna which are indigenous to a warm water habitat") for the reach from the Lackawanna River to West Branch Susquehanna River. The WWF temperatures and temperatures for two other protected uses are presented in Table 8. These values represent the maximum allowable water temperatures at an unspecified distance downstream of the discharge where fully-mixed conditions occur.

Table 8 Protected use receiving water body temperatures, F

CWF=Cold Water Fishes; WWF=Warm Water Fishes; TSF=Trout Stocking

SYMBOL:	$TEMP_1$	$TEMP_2$	$TEMP_3$
CRITICAL USE:	CWF	**WWF**	TSF
PERIOD			
January 1-31	38	**40**	40
February 1-29	38	**40**	40
March 1-31	42	**46**	46
April 1-15	48	**52**	52
April 16-30	52	**58**	58
May 1-15	54	**64**	64
May 16-31	58	**72**	68
June 1-15	60	**80**	70
June 16-30	64	**84**	72
July 1-31	66	**87**	74
August 1-15	66	**87**	80
August 16-30	66	**87**	87
September 1-15	64	**84**	84
September 16-30	60	**78**	78
October 1-15	54	**72**	72
October 16-31	50	**66**	66
November 1-15	46	**58**	58
November 16-30	42	**50**	50
December 1-31	40	**42**	42

The SSES NPDES permit does not contain specific discharge temperature limits (PPL Susquehanna, LLC, 2006a), although the station is required to meet WWF water temperatures (Table 8) and to limit temperature changes to 2°F per hour.

Experience with other sites and an examination of the language in the PA DEP guidance document (PA DEP, 2003) indicates PA DEP may include in the NPDES permit for BBNPP an end-of-pipe limit of 110 F and a heat load limit based on the difference between ambient temperature and the critical use temperatures shown in Table 8. Because actual limits are set when the NPDES permit is issued, no definitive statement can be made regarding the thermal discharge limits that will be set for the BBNPP, except to note that SSES does not have either the 110 F or the heat load limit. In developing the NPDES permit conditions for BBNPP, PA DEP may choose to consider the cumulative effects of the combined SSES and BBNPP thermal.

Because the WWF temperature limits vary by season as shown in Table 8, limiting blowdown temperatures to less than the maximum WWF temperature of 87 F does not guarantee that the system will be in compliance with WWF temperatures at other times. To assess compliance at seasonal extremes, additional near-field simulations were made to determine the size of the thermal plume under conditions when blowdown temperatures are at a maximum and Susquehanna River temperatures are at a minimum, yielding the maximum temperature rise in the River. These simulations utilized average Susquehanna River flows to represent a severe, but not extreme, case. The comparison metric is the distance along the centerline downstream of the BBNPP discharge where WWF temperatures are attained. These distances are shown in Table 9. In this table, the blowdown temperature rise is the difference between the blowdown temperature and the WWF ambient stream temperature (PPL Susquehanna, LLC, 2006a). The

WWF ambient stream temperature is an assumed natural temperature typically used by the PA DEP in computing waste heat load allocations. The target excess temperature in Table 9 is the difference between the WWF ambient temperature and the WWF temperature limit; this difference represents the excess temperature isotherm at which the WWF temperature limit is attained.

Table 9 Extreme period analysis of plume size

Period	WWF, F	WWF ambient, F	Blowdown temperature, F	Blowdown temperature rise, °F	Target excess temperature for compliance, °F	Centerline distance to WWF, ft
January 1-31	40	35	65.8	30.8	5.0	1.0
July 1-31	87	75	90	15.0	12.0	0.3
August 1-15	87	74	90	16.0	13.0	0.3
August 16-30	87	74	90	16.0	13.0	0.3

Centerline distances are very small and none of the target excess temperature contours reach the water surface. The results of this calculation indicate that BBNPP blowdown plume will be in compliance with WWF temperatures during other WWF periods.

4.3. DILUTION RESULTS

Using the near-field and far-field models, dilution of a numerical, non-decaying dye representing only the BBNPP discharge was computed along with the thermal plume. The dye was released at a nominal concentration of 100 mg/l. The results are reported as "dilution", defined as in Equation 1 where $C_{Discharge}$ is the concentration of dye released from the discharge (100 mg/l) and C is the concentration at a particular location of interest. To obtain the concentration of any other constituent at a location at which dilution is available, Equation 2 can be used.

Equation 1

$$Dilution = \frac{C_{Discharge}}{C}$$

Equation 2

$$C = \frac{C_{Discharge}}{Dilution}$$

Near-field

CORMIX simulations for thermal plume provided near-field dilution values. These dilution values are shown in Figure 34 and in Table 10 for all five scenarios. Note that Scenario 2 has the lowest dilution as this is the scenario with the lowest Susquehanna River flow while Scenario 3 has the highest dilution due to high Susquehanna River flow. The dilution values range from 11 to 70 near the end of the near-field region. Any subsequent dilution occurs in the far-field region and was modeled using GEMSS®.

Table 10. Near-field dilution values

Scenario	Dilution (50') from BBNPP Discharge
Scenario 1	26.9
Scenario 2	11.8
Scenario 3	67
Scenario 4	19.2
Scenario 5	68.7

Far-field

The far-field dilution values obtained from GEMSS® at different locations of interest (shown in Figure 35) are listed in Table 15, shown in Section 7 Landscape-formatted tables and figures. The model was run for a period of 21 days which was sufficient to achieve a steady state. The numerical dye used to compute dilution values eventually spreads across the entire cross-section of the river resulting in fully-mixed conditions. The distance at which these fully-mixed conditions are achieved varies with different scenarios and is also listed in Table 11. All locations beyond this fully-mixed region will have same fully-mixed concentration that can be computed using Equation 3. Figure 36 shows the fully-mixed concentrations obtained from GEMSS® for the five scenarios. The italicized numbers on the plots show values computed from Equation 3 for these scenarios. Equation 4 shows an example calculation for Scenario 1.

Equation 3

$$C_{FullyMixed} = \frac{C_{River} * Q_{River} + C_{BBNPP} * Q_{BBNPP}}{Q_{River} + Q_{BBNPP}}$$

Equation 4

$$C_{FullyMixed} = \frac{0.0 * 4351.83 + 100.0 * 24.89}{4351.83 + 24.89} = 0.57 mg/l$$

Scenario 2 again has the highest fully-mixed concentration and the lowest dilution while Scenario 3 has the lowest fully-mixed concentration and the highest dilution.

Table 11 Distance from BBNPP discharge

Location	Distance from the BBNPP discharge (ft)	Distance from the BBNPP discharge (m)
SSES cooling water intake	1050	320
BBNPP cooling water intake	650	198
Nearest Shoreline	300	91
Maximum impacted shoreline	Scenario dependent (see Table 15)	Scenario dependent (see Table 15)
Property boundary	330	101
S Hicks Ferry Rd	3250	991
Fully-mixed	Scenario dependent (see Table 15)	Scenario dependent (see Table 15)
Public water supply intake (Danville)	158,400	48,280
Recreational shore (Sunbury)	264,000	80,467

4.4. *TRAVEL TIMES*

For the near-field, CORMIX provided the travel time for the peak to reach a distance 50 ft from the discharge. For the far-field, travel times were computed by releasing a numerical dye from the BBNPP discharge structure, then determining its arrival time at the locations of interest with GEMSS. The dye was released over a 1-hour duration at a concentration of 100 mg/l. The concentrations of the dye were then studied at the locations listed in Table 11 to obtain the time of arrival of the peak concentration. The arrival time was used to compute the travel time from the BBNPP discharge.

Near-field

As stated, CORMIX provided the travel times for the spill to reach a distance 50 ft from the discharge. Travel times for the five scenarios in the near-field are listed in Table 12. Scenario 3 with the highest Susquehanna River flow rate has the shortest travel time of 45 seconds, while Scenario 2 with the lowest Susquehanna River flow rate has the longest travel time of 110 seconds.

Table 12 Near-field travel times obtained from CORMIX simulations

Scenario	Travel Time (minutes)	Travel Time (seconds)
Scenario 1	1.38	83
Scenario 2	1.83	110
Scenario 3	0.75	45
Scenario 4	1.63	98
Scenario 5	0.74	44

Far-field

The 1-hour dye release from the BBNPP discharge was simulated and then the concentrations at various locations were studied to detect the passage of the peak concentration. The difference in times between the release and the peak at these locations was used to estimate the travel time to these locations. Locations downstream of the GEMSS® grid were also beyond the fully-mixed location as seen in Table 11. Thus, the travel times to these locations were computed by adding the time needed to travel to these locations from fully-mixed location using the average flow velocity and the time taken to reach the fully-mixed location as shown in Equation 5 and Equation 6. The travel times to these locations are listed in Table 13 in hours and in Table 14 in minutes.

As was the case for the near-field times, the travel times are usually shortest for Scenario 3 and longest for Scenario 2. However, there are two locations (nearest the shoreline and nearest the property boundary) where Scenario 4 has the longest travel time. This result is due to the plume configuration and the location of interest relative to the discharge. Scenario 4 has a higher Susquehanna River flow rate than Scenario 2. The higher rate pushes the plume further downstream. The near-shore and property boundary locations are close to the discharge and thus the plume takes longer to get to these locations once it has been pushed away from the BBNPP discharge.

Equation 5

$$TravelTime_{Loc} = Time_{FullyMixed} + \frac{D_{Loc} - D_{FullyMixed}}{u_{avg}}$$

Equation 6

$$u_{avg} = \frac{Q_{Riv}}{CSArea_{Riv}}$$

$TravelTime_{Loc}$ = *travel time to the location of interest*

$Time_{FullyMixed}$ = *travel time to the fully-mixed location*

D_{Loc} *and* $D_{FullyMixed}$ = *distance to the location of interest and fully-mixed location*

$CSArea_{Riv}$ *and* Q_{Riv} = *cross-sectional area and flow rate for Susquehanna River*

Table 13 Travel times (hours) for various locations of interest

Location		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
SSES cooling water intake	Surface	2.92	6.67	2.08	5.58	2.00
	Bottom	3.08	7.00	2.08	5.42	2.00
BBNPP cooling water intake	Surface	2.33	3.58	1.67	4.83	1.58
	Bottom	2.33	3.83	1.58	4.83	1.50
Nearest Shoreline	Surface	1.92	1.33	1.17	2.58	1.17
	Bottom	1.92	1.42	1.08	2.25	1.08
Property boundary	Surface	1.67	1.17	1.08	2.25	1.08
	Bottom	1.67	1.17	1.00	1.92	1.00
Maximum impacted shoreline	Surface	2.08	5.50	1.25	3.50	1.25
	Bottom	2.17	5.75	1.33	2.83	1.25
S Hicks Ferry Rd	Surface	2.08	3.08	1.42	2.50	1.42
	Bottom	2.08	3.58	1.42	2.67	1.42
Public water supply intake (Danville)	Surface	154	480	64	220	63
	Bottom	154	480	64	220	63
Recreational shore (Sunbury)	Surface	290	925	119	420	117
	Bottom	290	925	119	420	117

Table 14 Travel times (minutes) for various locations of interest

Location		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
SSES cooling water intake	Surface	175	400	125	335	120
	Bottom	185	420	125	325	120
BBNPP cooling water intake	Surface	140	215	100	290	95
	Bottom	140	230	95	290	90
Nearest Shoreline	Surface	115	80	70	155	70
	Bottom	115	85	65	135	65
Property boundary	Surface	100	70	65	135	65
	Bottom	100	70	60	115	60
Maximum impacted shoreline	Surface	125	330	75	210	75
	Bottom	130	345	80	170	75
S Hicks Ferry Rd	Surface	125	185	85	150	85
	Bottom	125	215	85	160	85
Public water supply intake (Danville)	Surface	9240	28800	3840	13200	3780
	Bottom	9240	28800	3840	13200	3780
Recreational shore (Sunbury)	Surface	17400	55500	7140	25200	7020
	Bottom	17400	55500	7140	25200	7020

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6. *PORTRAIT-FORMATTED FIGURES*

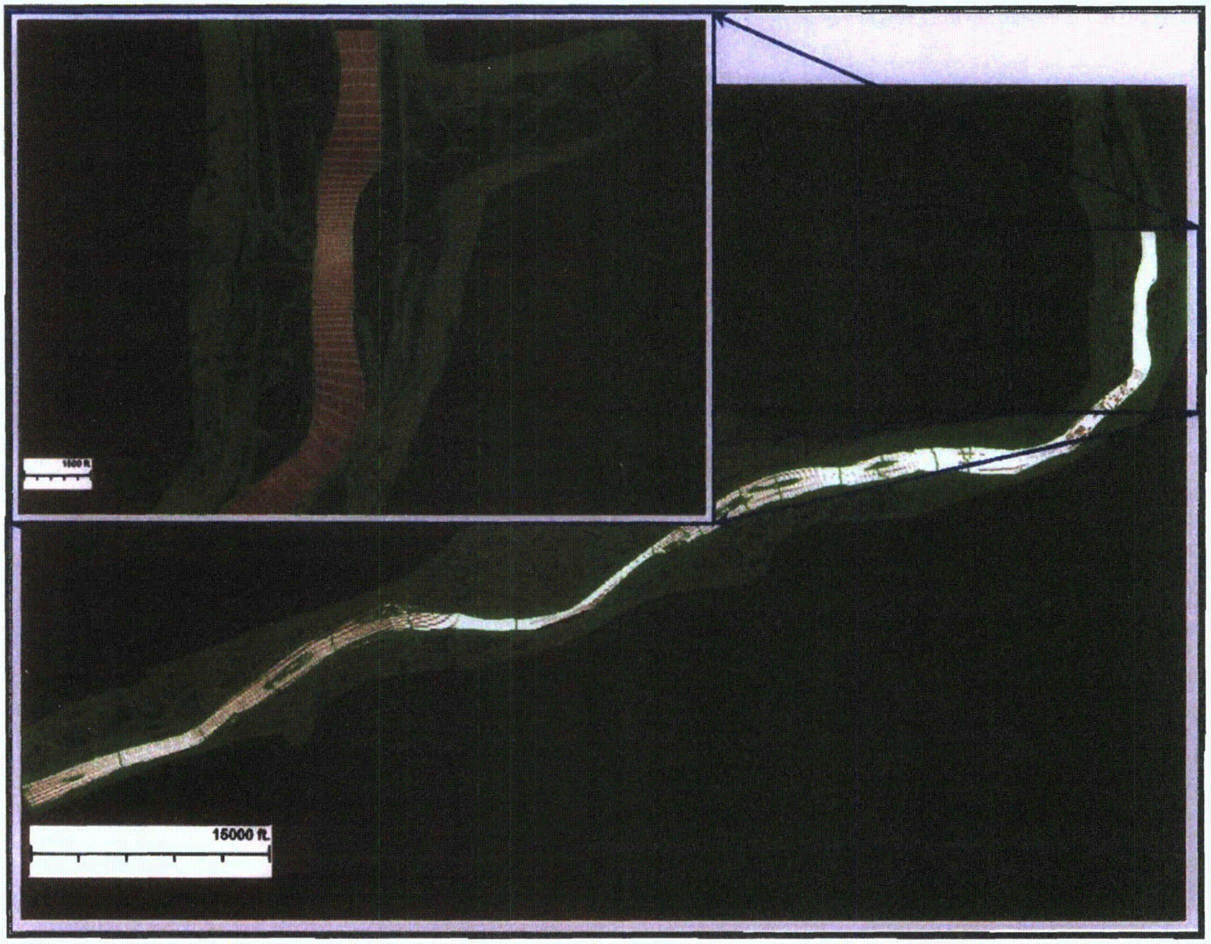

Figure 1 GEMSS finite difference grid

The green lines are surface contours.

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USGS 01536500 Susquehanna River at Wilkes-Barre, PA

Available data for this site: SUMMARY OF ALL AVAILABLE DATA GO

Stream/River Site

LOCATION

Latitude 41°15'03", Longitude 75°52'52" NAD27
Luzerne County, Pennsylvania , Hydrologic Unit 02050107

DESCRIPTION

Drainage area: 9,960 square miles
Datum of gage: 510.86 feet above sea level NAVD88.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	This is a real-time site		
Daily Data			
Discharge, cubic feet per second	1899-04-01	2008-04-27	39838
Daily Statistics			
Discharge, cubic feet per second	1899-04-01	2007-09-30	39629
Monthly Statistics			
Discharge, cubic feet per second	1899-04	2007-09	
Annual Statistics			
Discharge, cubic feet per second	1899	2007	
Peak streamflow	1786-10-05	2007-03-16	122
Field measurements	1899-03-30	2008-04-11	752
Field/Lab water-quality samples	1963-10-17	2007-03-19	10

OPERATION:

Record for this site is maintained by the USGS Pennsylvania Water Science Center
Email questions about this site to Pennsylvania Water-Data Inquiries

ADDITIONAL INFORMATION

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STATION.--01536500 SUSQUEHANNA RIVER AT WILKES-BARRE,
PA
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Figure 2 USGS Station No. 01536500 (Susquehanna River at Wilkes-Barre) information sheet

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USGS 01540500 Susquehanna River at Danville, PA

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Stream/River Site

LOCATION

Latitude 40°57'29", Longitude 76°37'10" NAD27
Montour County, Pennsylvania , Hydrologic Unit 02050107

DESCRIPTION

Drainage area: 11,220 square miles
Datum of gage: 431.29 feet above sea level NGVD29.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Real-time	This is a real-time site		
Daily Data			
Temperature, water, degrees Celsius	1945-10-01	1976-09-30	7126
Discharge, cubic feet per second	1905-04-01	2008-04-27	37648
Specific conductance, water, unfiltered, microsiemens per centimeter at 25 degrees Celsius	1945-10-01	1976-09-30	6164
Suspended sediment concentration, milligrams per liter	1962-03-13	1976-09-30	932
Suspended sediment discharge, tons per day	1962-03-13	1976-09-30	932
Daily Statistics			
Discharge, cubic feet per second	1905-04-01	2007-09-30	37438
Suspended sediment concentration, milligrams per liter	1962-03-14	1976-09-30	931
Suspended sediment discharge, tons per day	1962-03-14	1976-09-30	931
Monthly Statistics			
Discharge, cubic feet per second	1905-04	2007-09	
Suspended sediment concentration, milligrams per liter	1962-03	1976-09	
Suspended sediment discharge, tons per day	1962-03	1976-09	
Annual Statistics			
Discharge, cubic feet per second	1905	2007	
Suspended sediment concentration, milligrams per	1962	1976	

Figure 3 USGS Station No. 01540500 (Susquehanna River at Danville) information sheet

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science for a changing world

Low-Flow Statistics for Pennsylvania Streams

Developed by the U.S. Geological Survey for the Pennsylvania Department of Environmental Protection

Pennsylvania Low-Flow Statistics - Query Results

LOW-FLOW STATISTICS

[All flow statistics in cubic feet per second (ft^3/s)]

Mouse over or click on table headings to view definition of statistic

STREAM NAME: Susquehanna River
GAGE OR BRIDGE SITE: bridge
REFERENCE GAGE[1]: 01536500

COUNTY: Luzerne
USGS QUAD: Wilkes-Barre West

LATITUDE: 411456
LONGITUDE: 755307
DRAINAGE AREA (sq. mi.): 9960

Entire Period of Record [2]	$Q_{1,10}$	$Q_{7,10}$	$Q_{30,10}$	MEAN	MEDIAN	HARMONIC MEAN
1930-06	841	890	1070	12800	8820	4520

FLOW DURATION TABLE (Probability of Exceedance)										
F5	F10	F20	F30	F40	F50	F60	F70	F80	F90	F95
49800	24110	21940	15610	11830	8320	6870	5230	3580	2300	1760

[1] Reference Gage indicates which USGS gage was used in the computation of lowflow statistics for the specified locations
[2] Period of Record for climatic year, April 1 through March 31.
[3] Period of record refers to pre-regulation conditions
[4] Period of record refers to post-regulation conditions
** Statistics not computed due to insufficient data

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Figure 4 Low flow statistics at Wilkes-Barre

USGS Surface-Water Monthly Statistics for the Nation

The statistics generated from this site are based on approved daily-mean data and may not match those published by the USGS in official publications. The user is responsible for assessment and use of statistics fr this site. For more details on why the statistics may not match, click here.

USGS 01536500 Susquehanna River at Wilkes-Barre, PA

Time-series: Monthly statistics GO

Luzerne County, Pennsylvania
Hydrologic Unit Code 02050107
Latitude 41°15'03", Longitude 75°52'52" NAD27
Drainage area 9,960 square miles
Gage datum 510.86 feet above sea level NAVD88

Output formats

HTML table of all data
Tab-separated data
Reselect output format

00060, Discharge, cubic feet per second,
Monthly mean in cfs (Calculation Period: 1980-01-01 -> 1996-12-30)

Period-of-record for statistical calculation restricted by user

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1980	7,779	3,326	31,090	37,530	11,500	3,701	4,497	1,975	1,152	1,762	4,645	7,363
1981	2,290	40,790	12,550	11,970	15,020	8,667	3,694	2,535	3,769	14,000	16,970	11,510
1982	10,240	16,870	32,180	30,600	7,935	20,780	7,588	2,458	1,339	1,267	3,487	8,053
1983	6,995	18,160	19,070	51,430	31,020	8,614	3,637	1,877	1,171	1,338	5,446	34,770
1984	5,548	36,800	15,660	50,110	31,200	14,800	10,800	7,481	3,254	1,995	4,493	19,310
1985	9,432	8,869	21,270	14,260	5,520	3,692	2,828	1,806	4,752	6,413	17,260	17,210
1986	12,160	18,620	42,820	21,230	10,770	11,930	6,083	8,627	2,561	6,454	21,960	20,430
1987	8,313	4,682	24,780	35,420	6,451	4,690	5,725	2,001	8,459	5,971	8,365	14,200
1988	6,334	16,060	19,730	13,220	19,150	4,155	2,357	1,965	3,293	2,888	12,090	5,955
1989	5,107	7,206	13,360	25,890	38,140	24,420	6,988	2,695	3,167	8,989	14,190	5,239
1990	14,550	37,320	17,650	22,600	21,320	6,815	5,823	3,874	2,957	24,180	22,160	28,540
1991	20,800	19,540	27,590	21,420	10,990	2,712	1,311	1,346	1,209	1,919	5,246	11,190
1992	12,460	8,367	24,330	26,780	14,270	10,660	6,203	10,040	7,683	9,541	22,550	15,820
1993	23,150	5,857	22,170	100,000	12,800	4,445	2,039	1,589	2,166	3,162	16,940	19,600
1994	6,917	17,430	43,670	61,030	11,450	11,680	9,344	19,560	7,105	5,358	10,760	18,080
1995	19,380	8,199	20,670	14,180	6,508	4,091	1,841	1,352	1,079	9,809	15,750	10,600
1996	40,740	19,470	21,020	32,350	36,730	8,321	8,785	4,846	4,778	13,040	29,540	44,610
Mean of monthly Discharge	12,500	16,900	24,100	33,500	17,100	9,070	5,270	4,470	3,520	6,950	13,600	17,200

** No Incomplete data have been used for statistical calculation

Figure 5 Monthly statistics at Wilkes-Barre

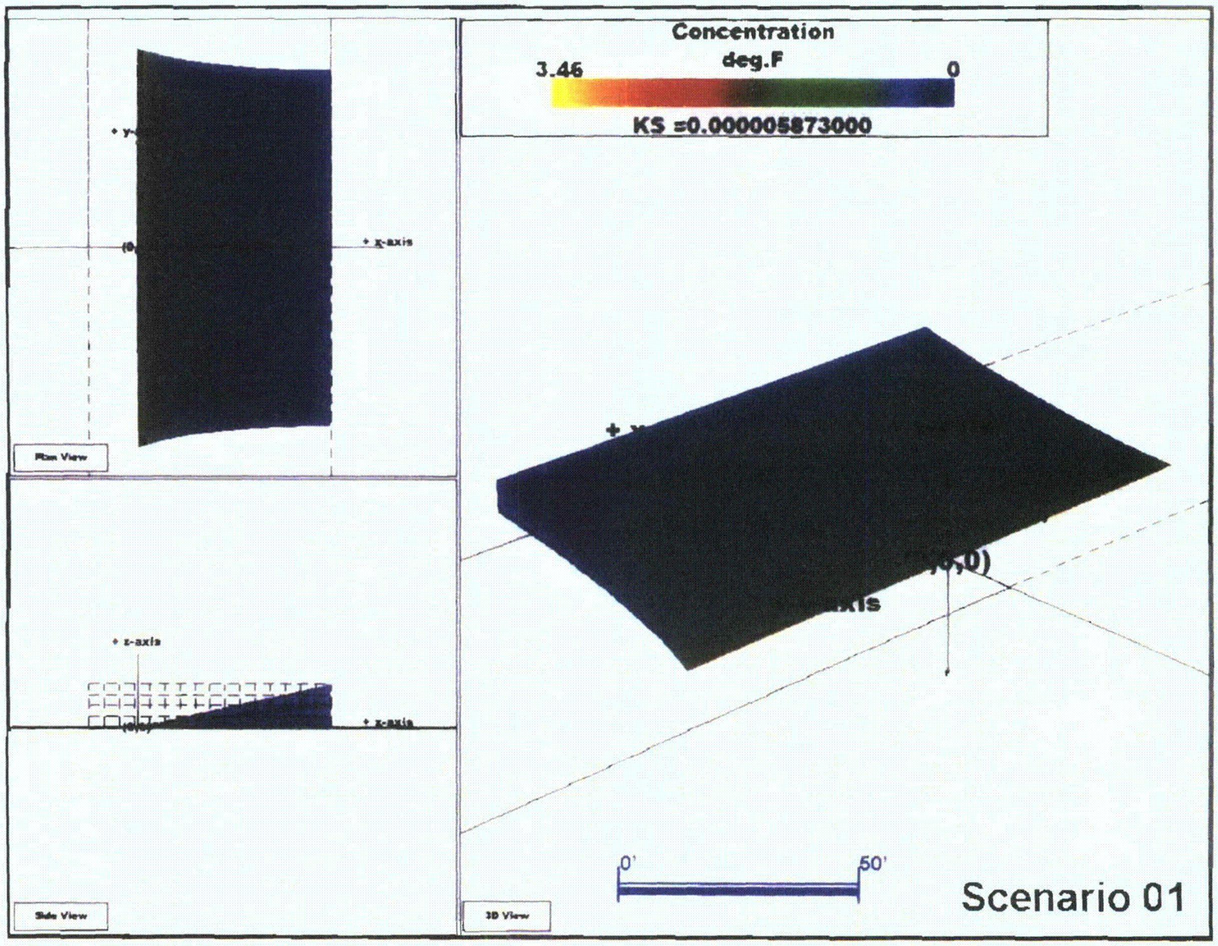

Figure 6 Near-field thermal plume orientation and size for Scenario 1

Scenario 1 is summer mean flow. The CORMIX graphical engine automatically scales diagrams; scales vary from one figure to the next.

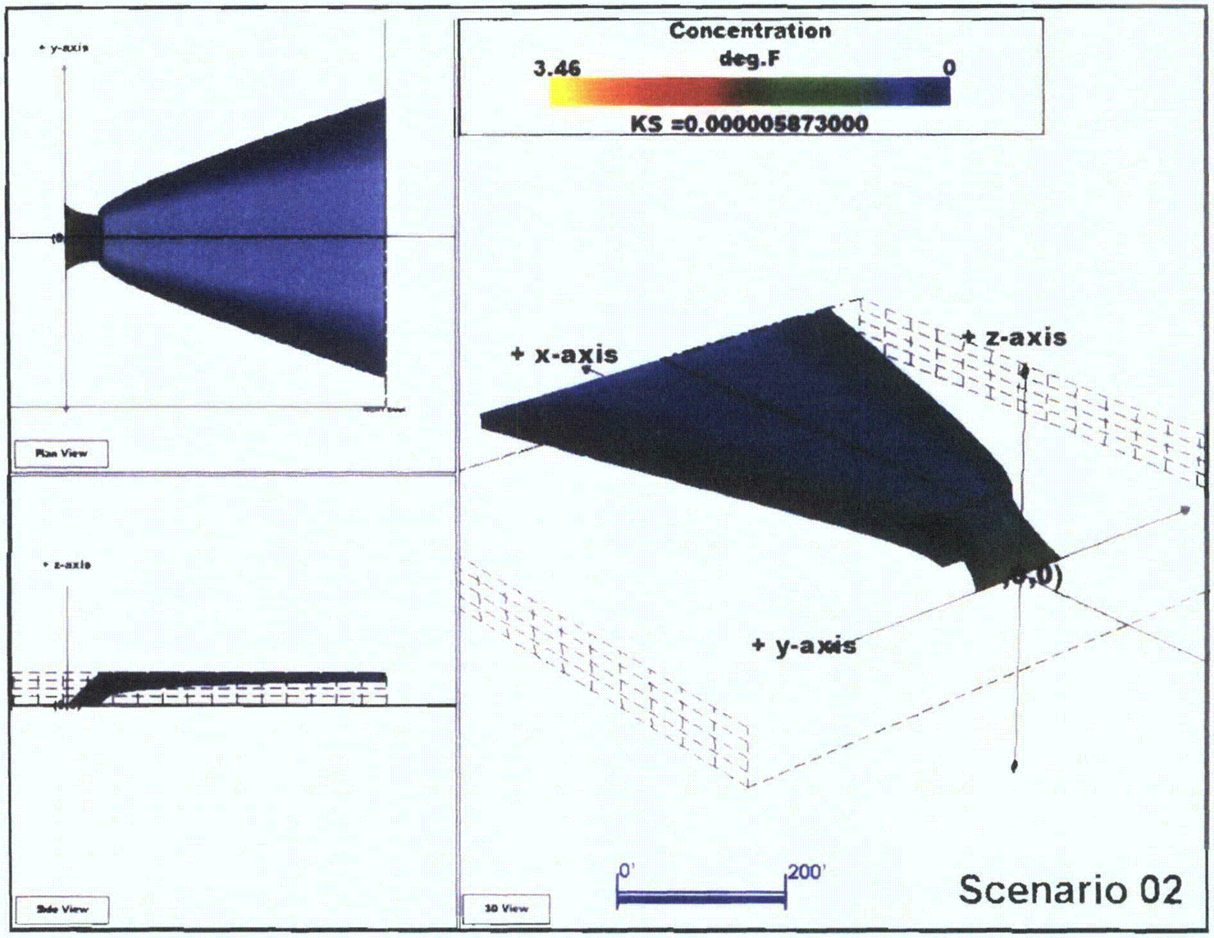

Figure 7 Near-field thermal plume orientation and size for Scenario 2

Scenario 2 is summer low flow.

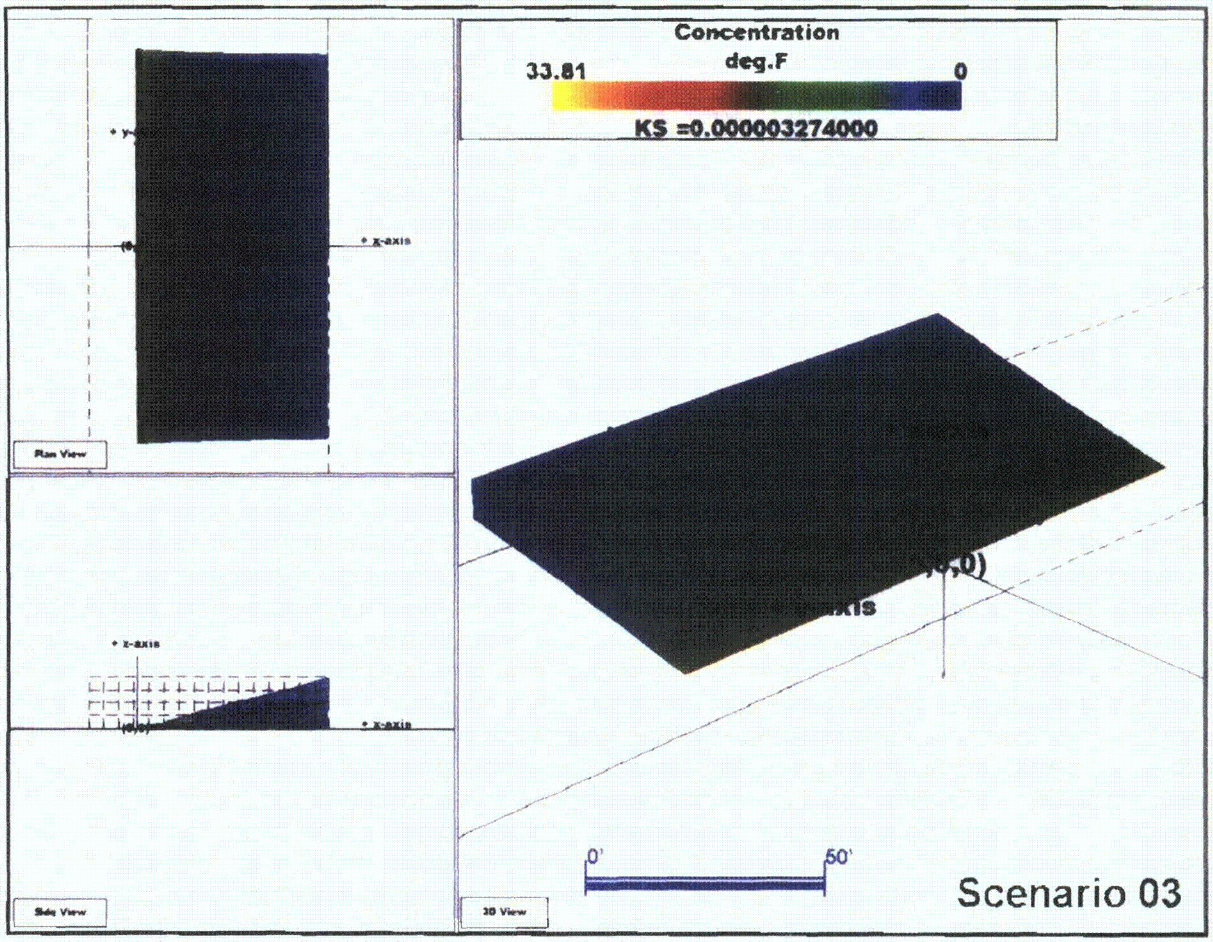

Figure 8 Near-field thermal plume orientation and size for Scenario 3

Scenario 3 is winter mean flow. The CORMIX graphical engine automatically scales diagrams; scales vary from one figure to the next.

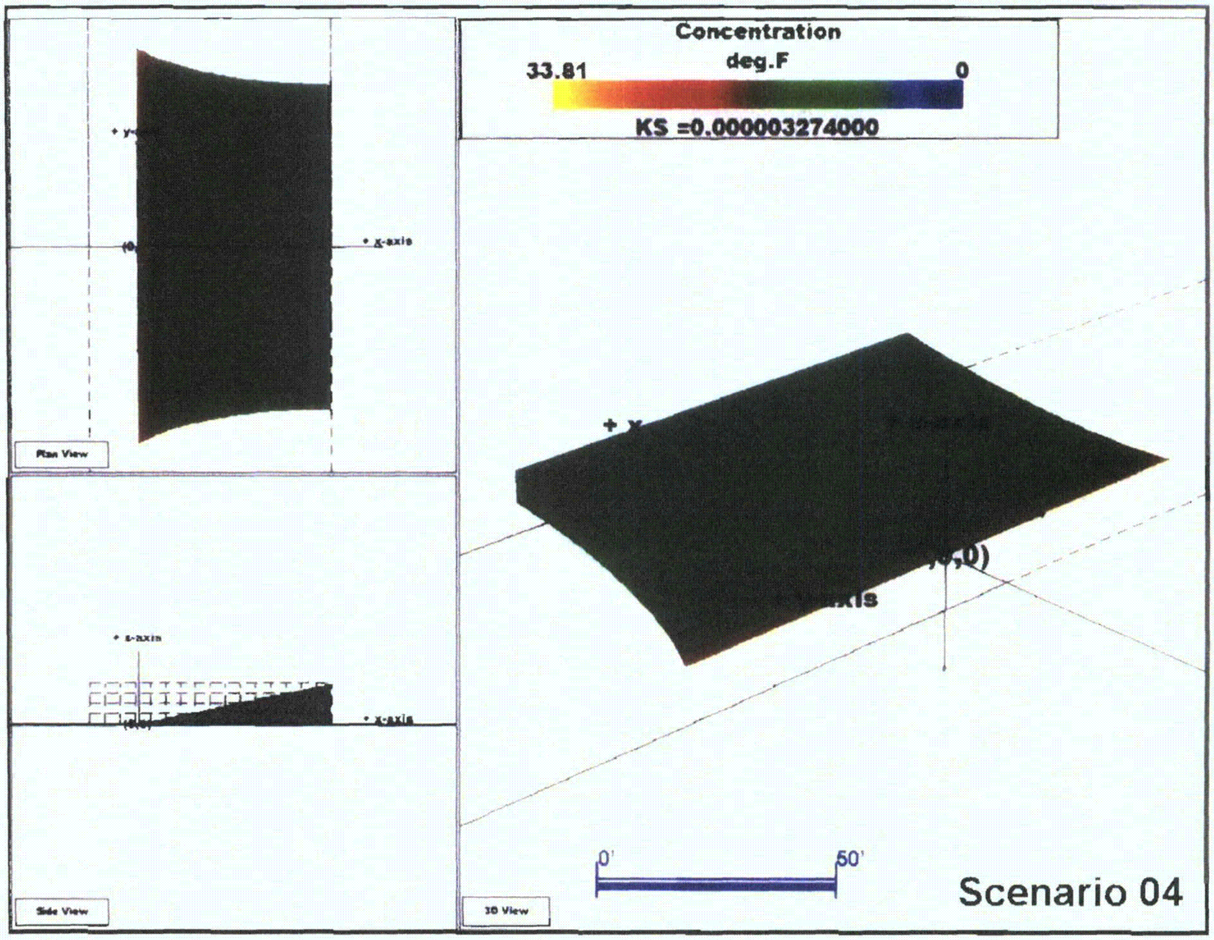

Figure 9 Near-field thermal plume orientation and size for Scenario 4

Scenario 4 is winter low flow.

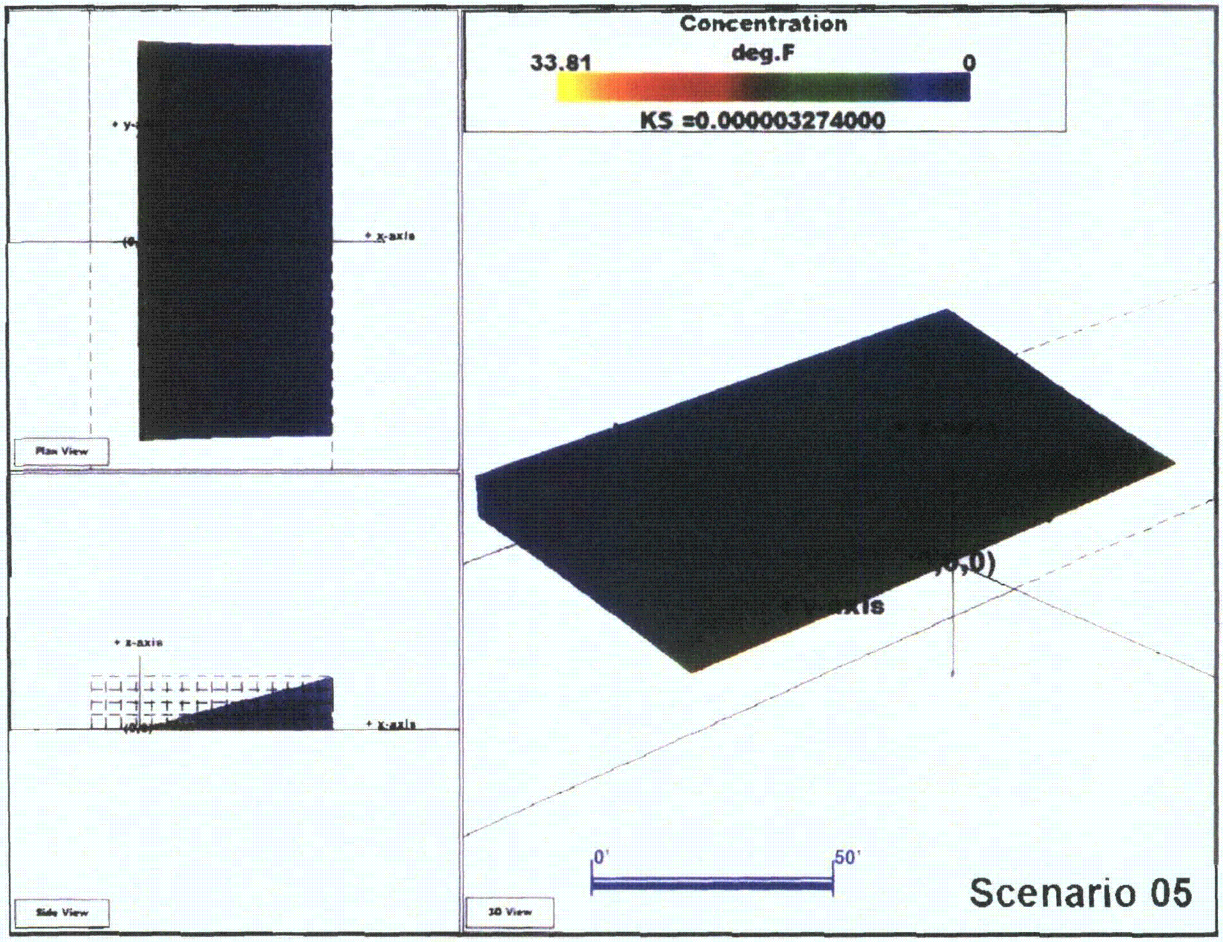

Figure 10 Near-field thermal plume orientation and size for Scenario 5

Scenario 5 is average annual flow.

7. *LANDSCAPE-FORMATTED TABLES AND FIGURES*

Table 15 Dilution values and related distances for various locations of interest

The location of the property boundary was taken from PETERS CONSULTANTS, INC. (2008).

Dilution at...	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
SSES cooling water intake	2598	2623	Does not reach	Does not reach	289	167	Does not reach	Does not reach	287	166
BBNPP cooling water intake	936	918	Does not reach	Does not reach	285	179	Does not reach	Does not reach	279	176
Nearest Shoreline	623	623	Does not reach	Does not reach	208	138	Does not reach	Does not reach	200	134
Maximum impacted shoreline	101	90	44	44	108	85	106	106	108	86
Distance of maximum impacted shoreline from BBNPP Discharge (ft)	*3000*	*2275*	*8000*	*8000*	*1750*	*1975*	*8000*	*4450*	*1750*	*1975*
Property boundary	620	620	9265	13233	224	132	Does not reach	5850	216	128
S Hicks Ferry Rd	101	101	57	53	109	102	Does not reach	5850	216	128
Fully-mixed	175	175	46	46	500	500	111	111	500	500
Distance to fully-mixed (ft)	*41300*		*53000*		*66300*		*26150*		*66300*	
Locations Beyond Fully-mixed Region										
Public water supply intake (Danville)	175	175	46	46	500	500	111	111	500	500
Recreational shore (Sunbury)	175	175	46	46	500	500	111	111	500	500

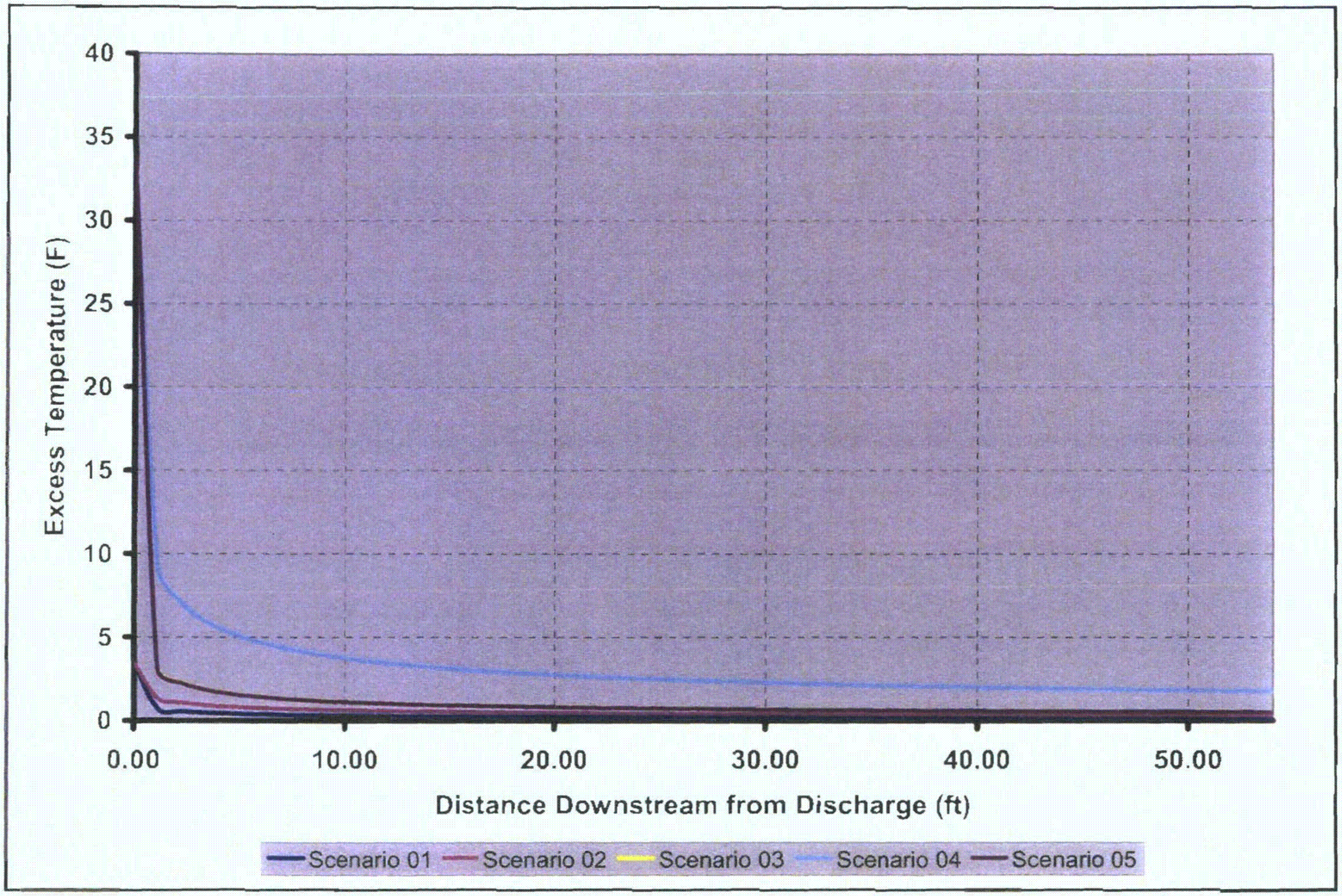

Figure 11 Excess temperature versus downstream distance for all five scenarios

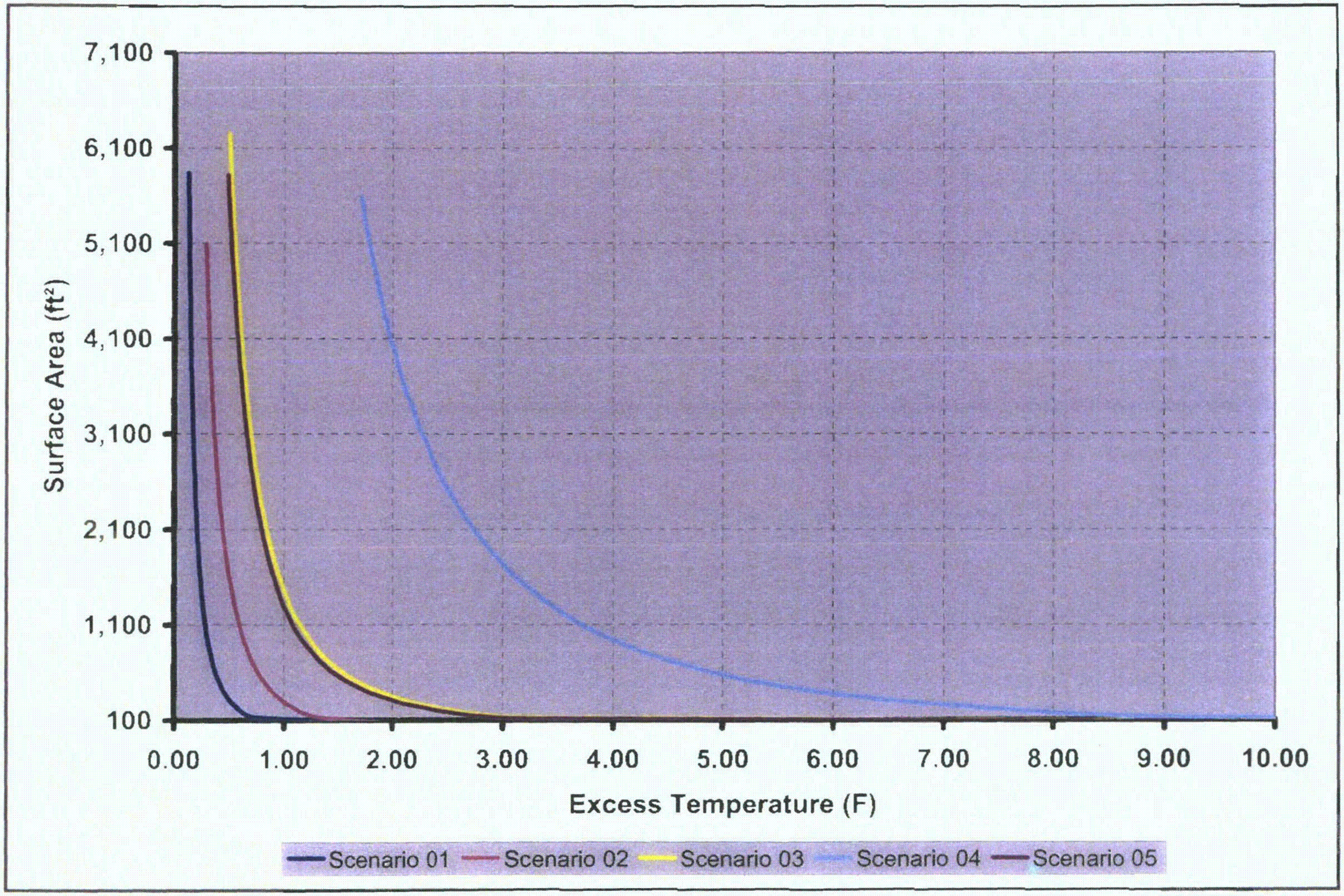

Figure 12 Near-field plume surface area versus temperature rise isotherms for all five scenarios

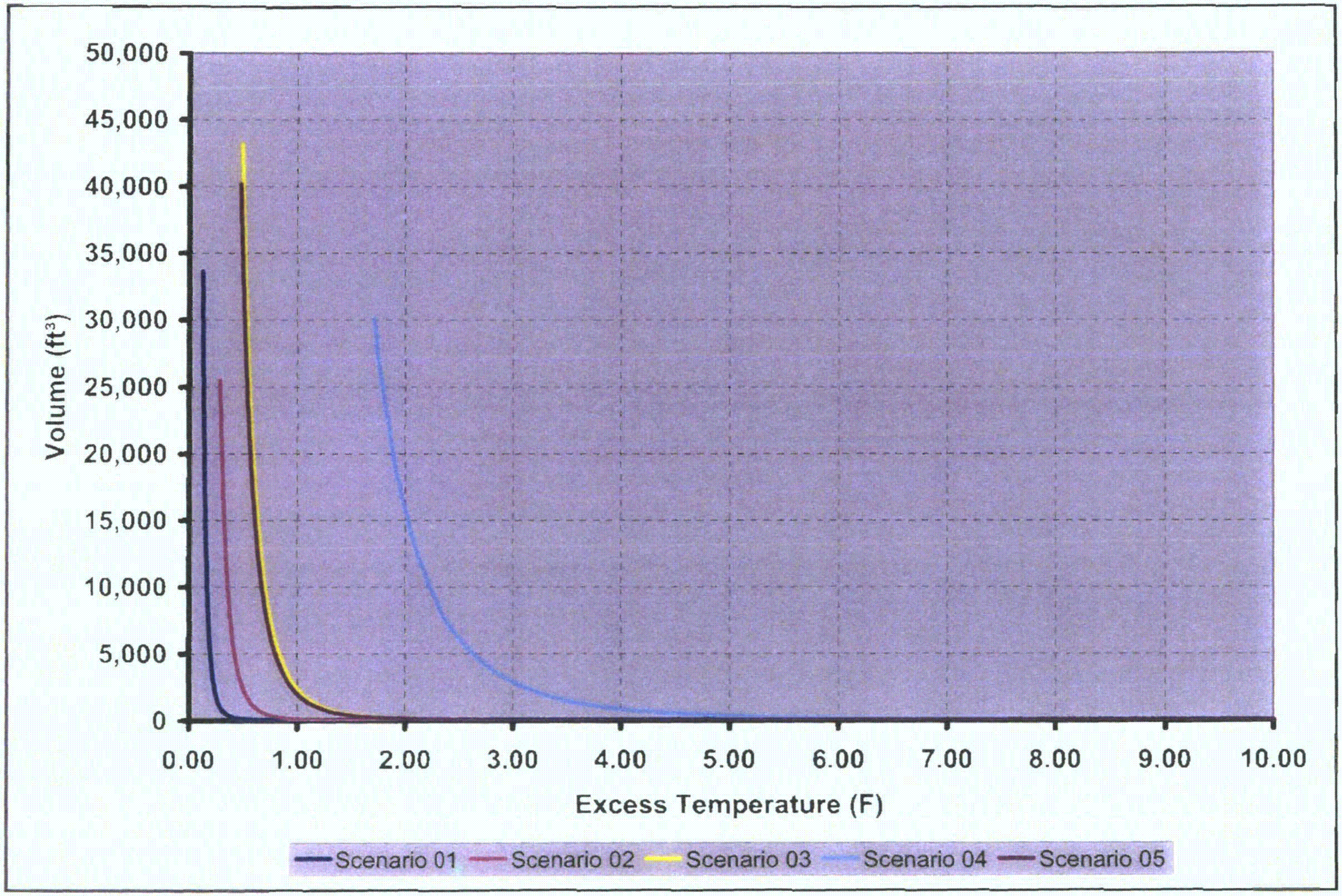

Figure 13 Near-field plume volume versus temperature rise isotherms for all five scenarios

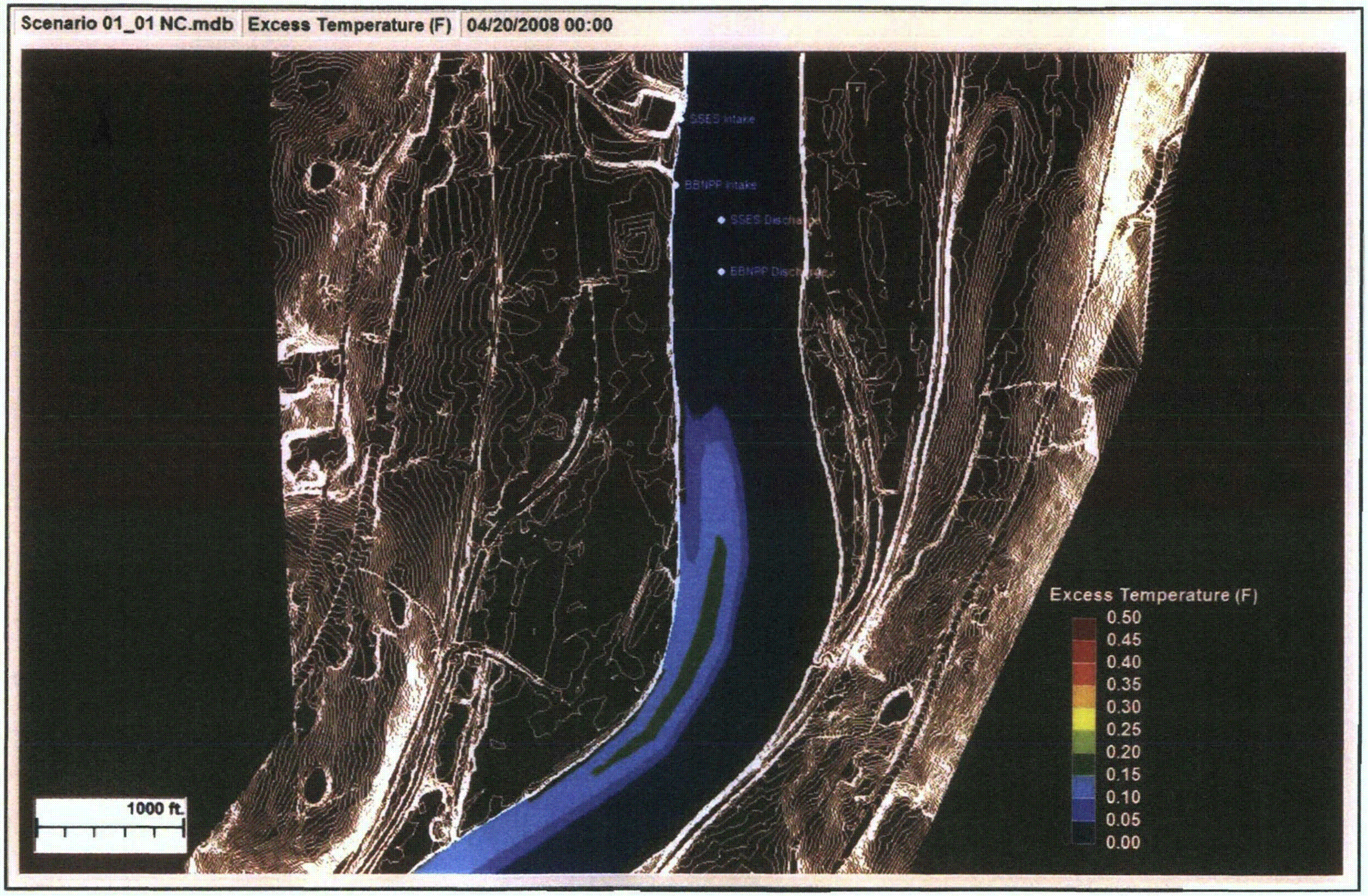

Figure 14 Excess temperature at the surface for cumulative SSES and BBNPP impacts for Scenario 1

Scenario 1 is summer mean flow; note that the temperature scale varies from diagram to diagram.

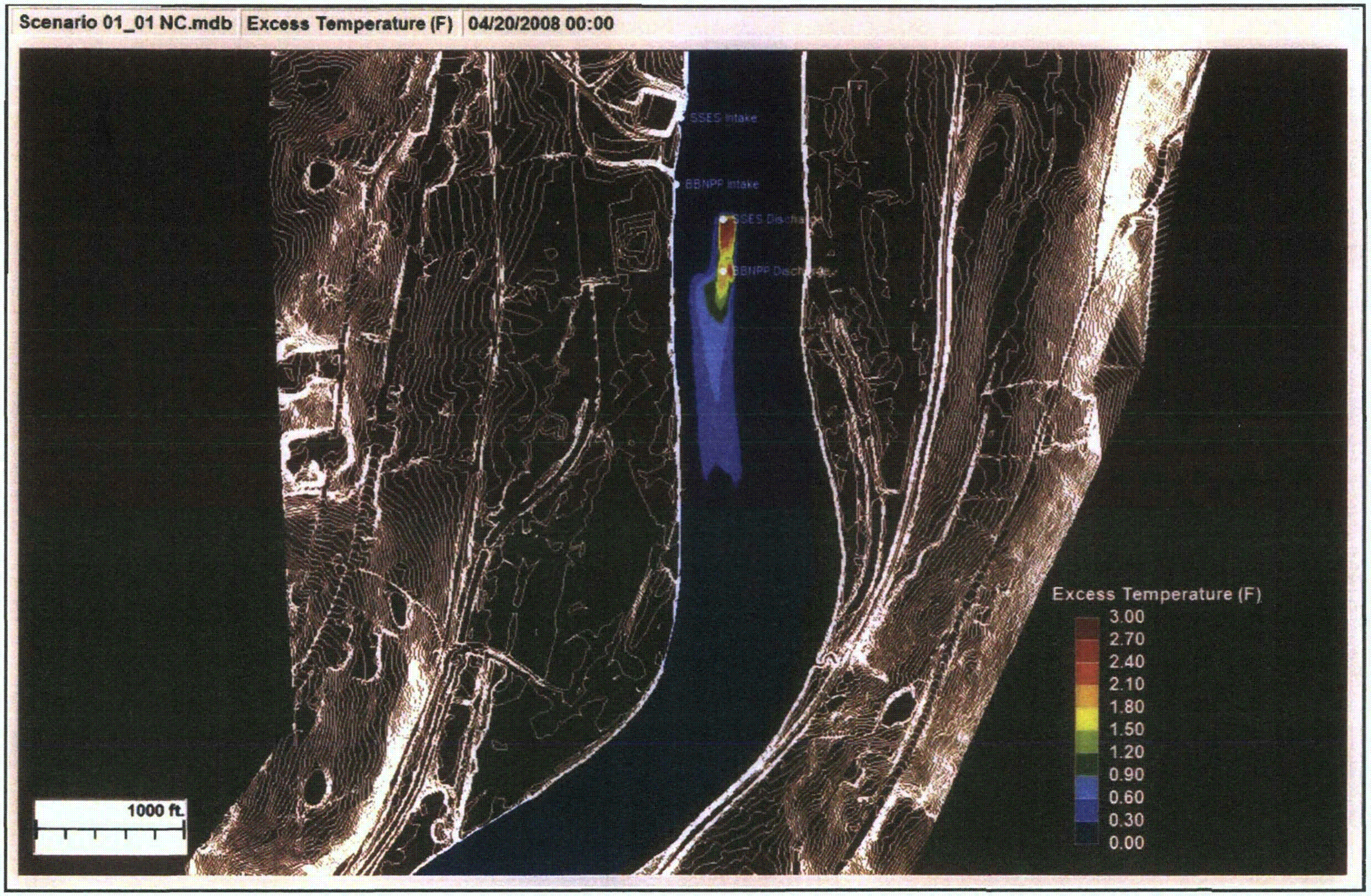

Figure 15 Excess temperature at the bottom for cumulative SSES and BBNPP impacts for Scenario 1

Scenario 1 is summer mean flow.

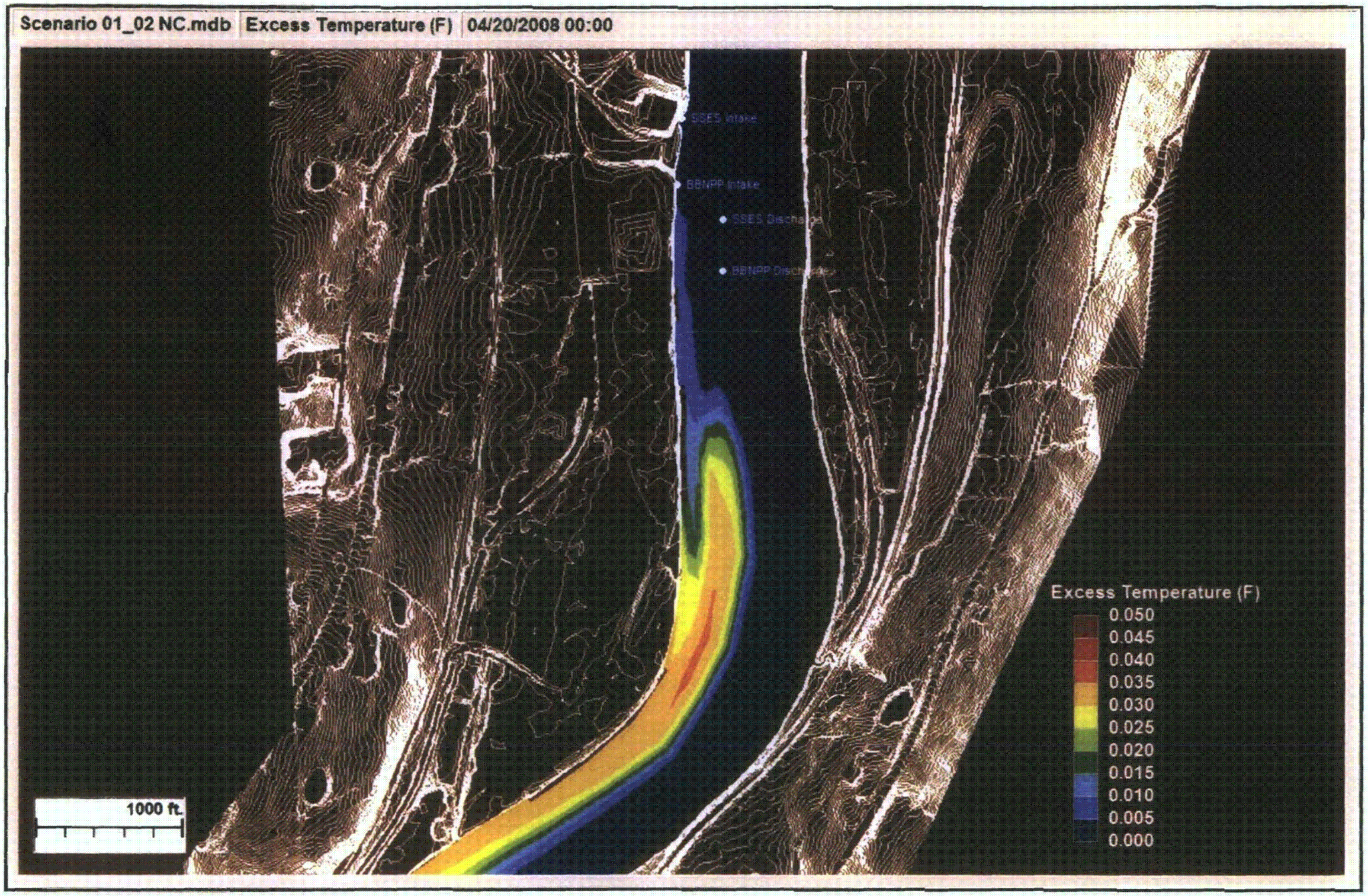

Figure 16 Excess temperature at the surface for incremental BBNPP impact for Scenario 1

Scenario 1 is summer mean flow.

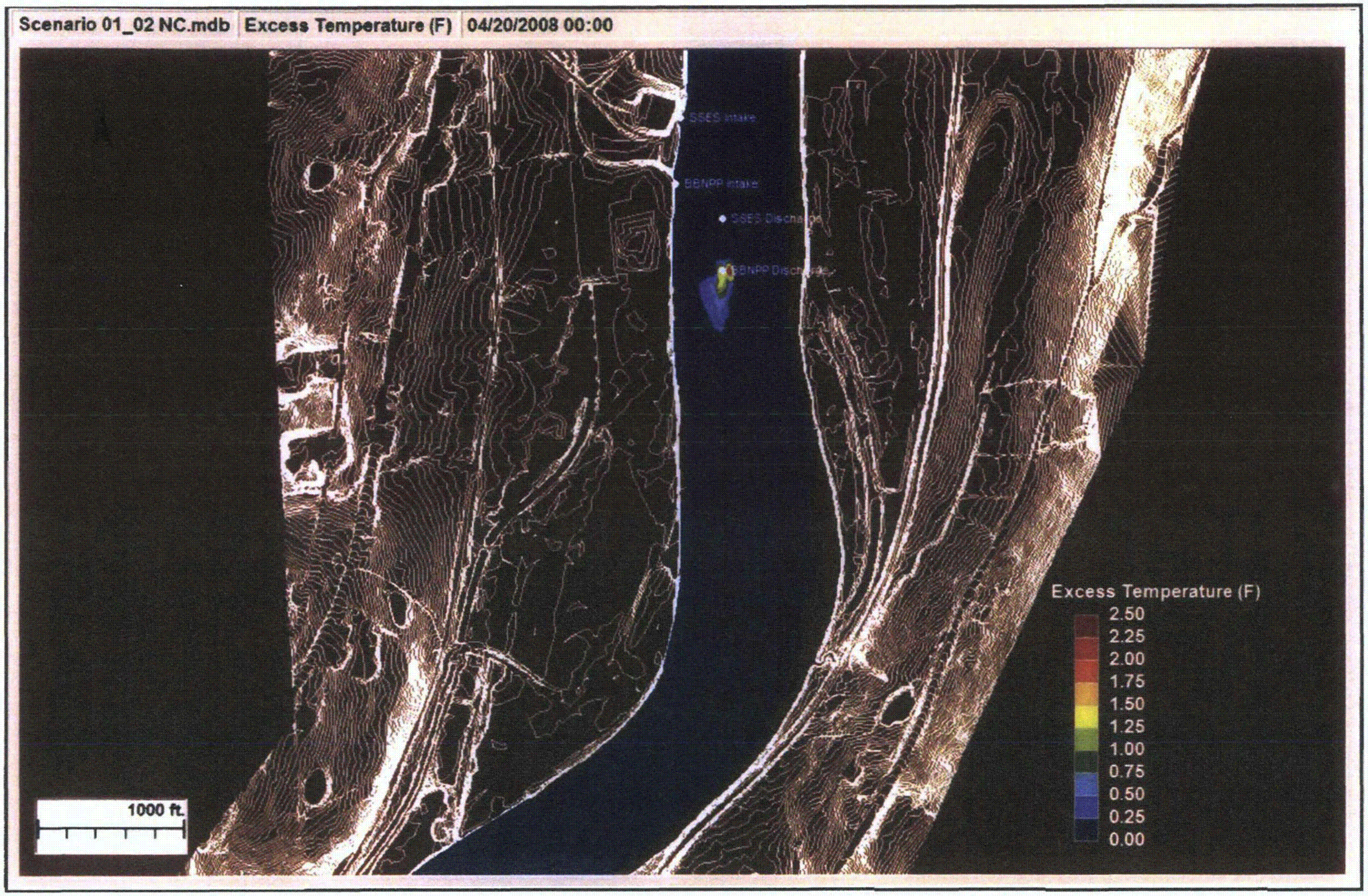

Figure 17 Excess temperature at the bottom for incremental BBNPP impact for Scenario 1

Scenario 1 is summer mean flow.

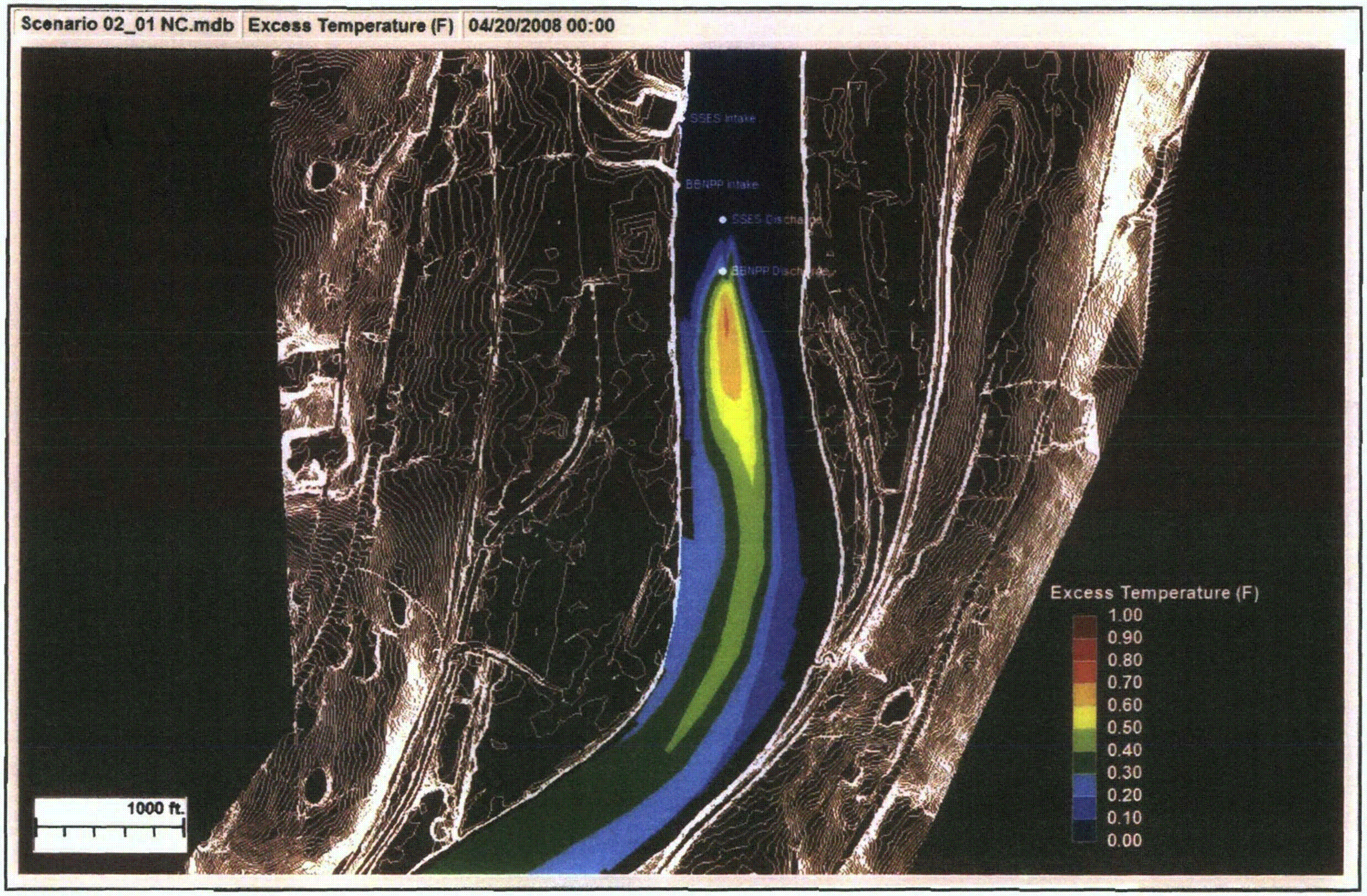

Figure 18 Excess temperature at the surface for cumulative SSES and BBNPP impacts for Scenario 2

Scenario 2 is summer low flow.

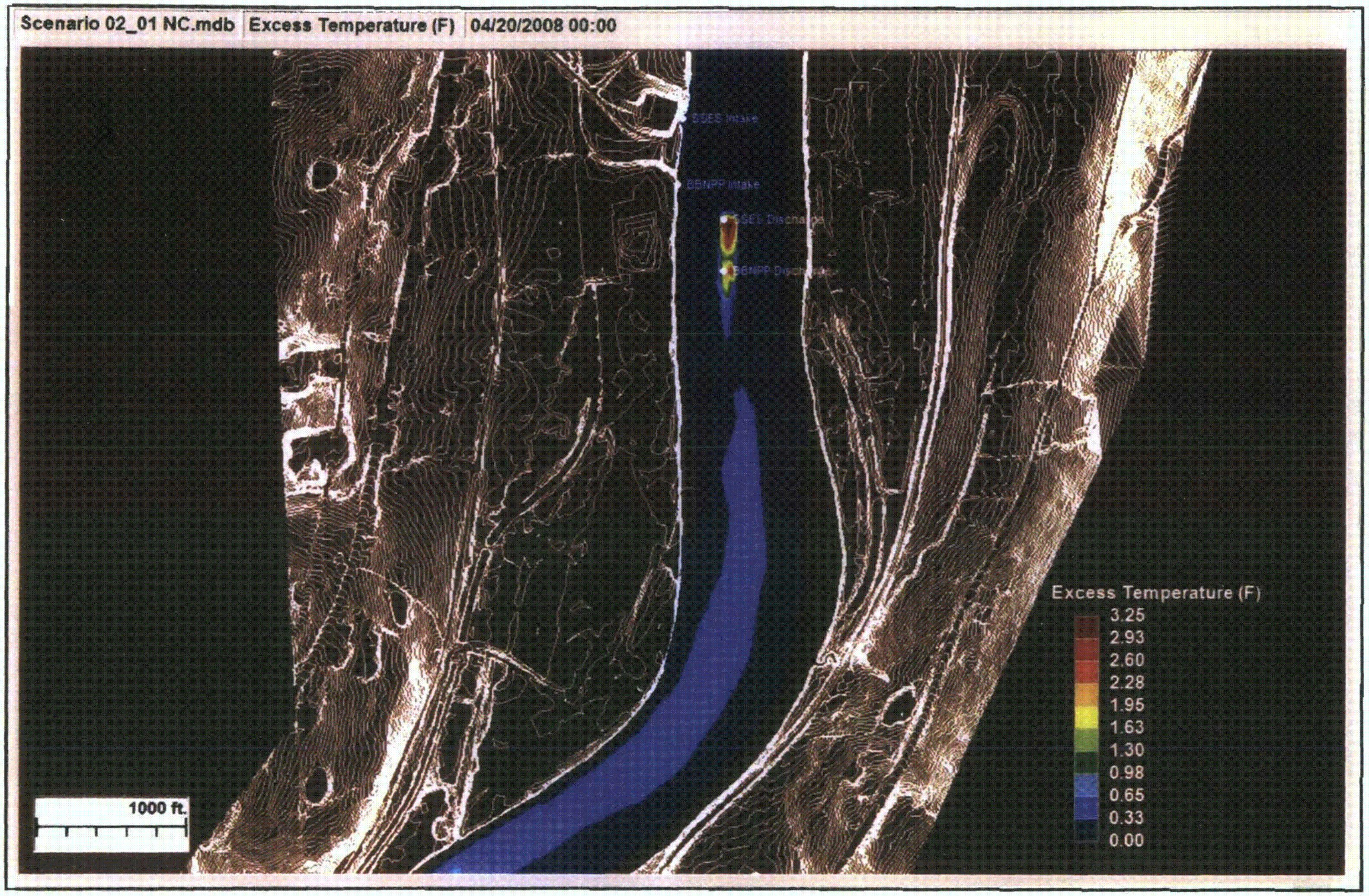

Figure 19 Excess temperature at the bottom for cumulative SSES and BBNPP impacts for Scenario 2

Scenario 2 is summer low flow.

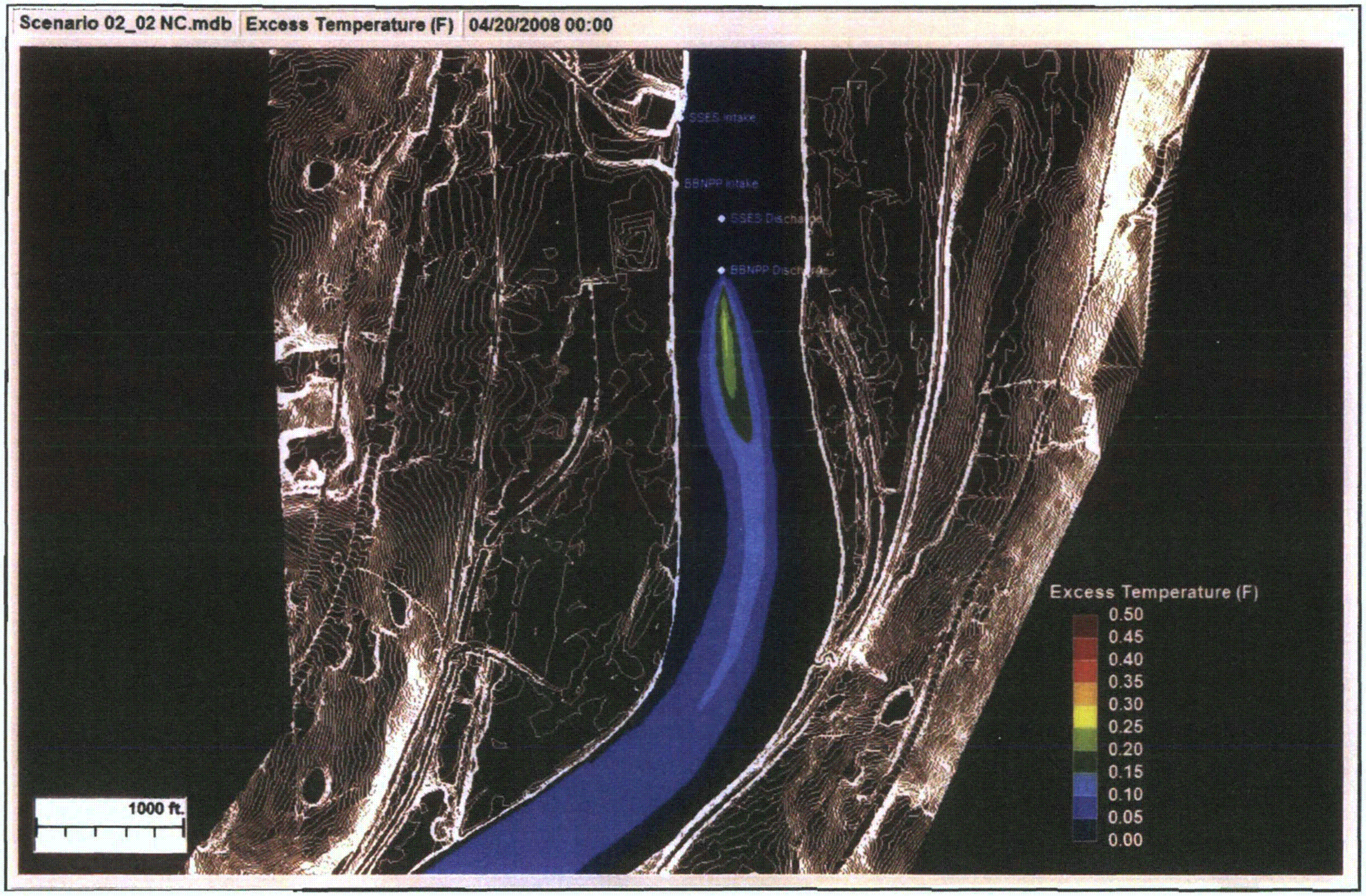

Figure 20 Excess temperature at the surface for incremental BBNPP impact for Scenario 2

Scenario 2 is summer low flow.

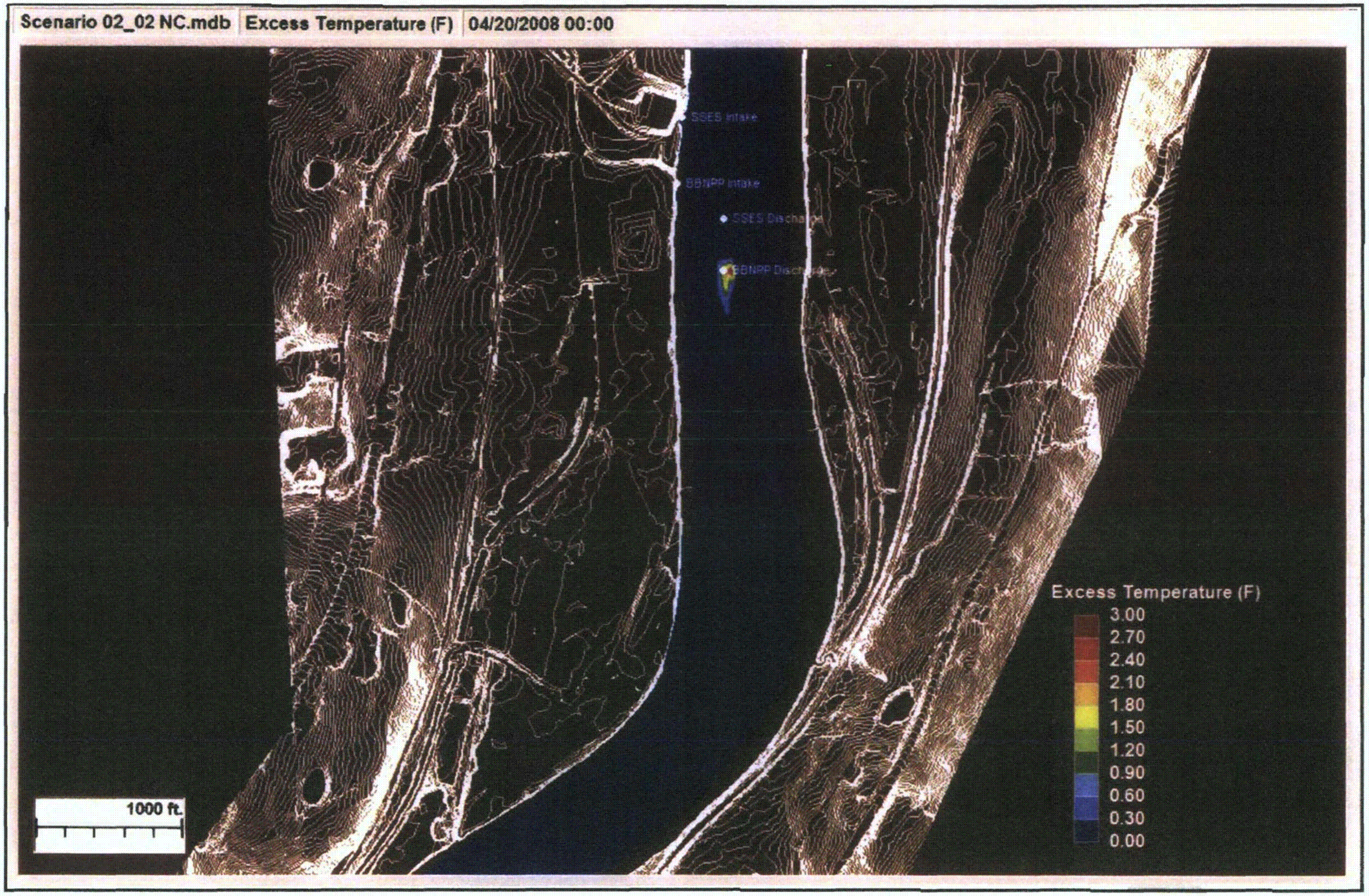

Figure 21 Excess temperature at the bottom for incremental BBNPP impact for Scenario 2

Scenario 2 is summer low flow.

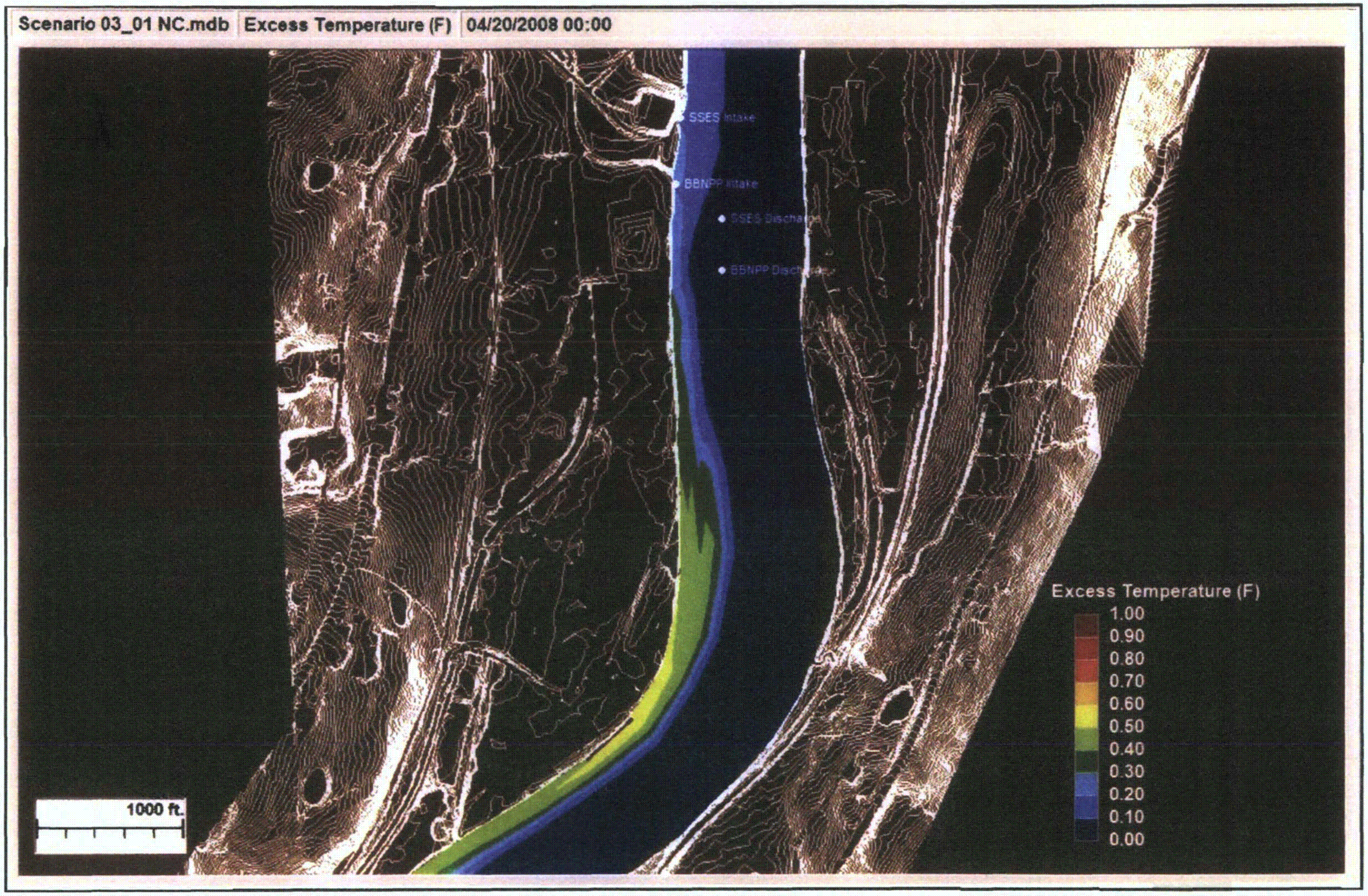

Figure 22 Excess temperature at the surface for cumulative SSES and BBNPP impacts for Scenario 3

Scenario 3 is winter mean flow.

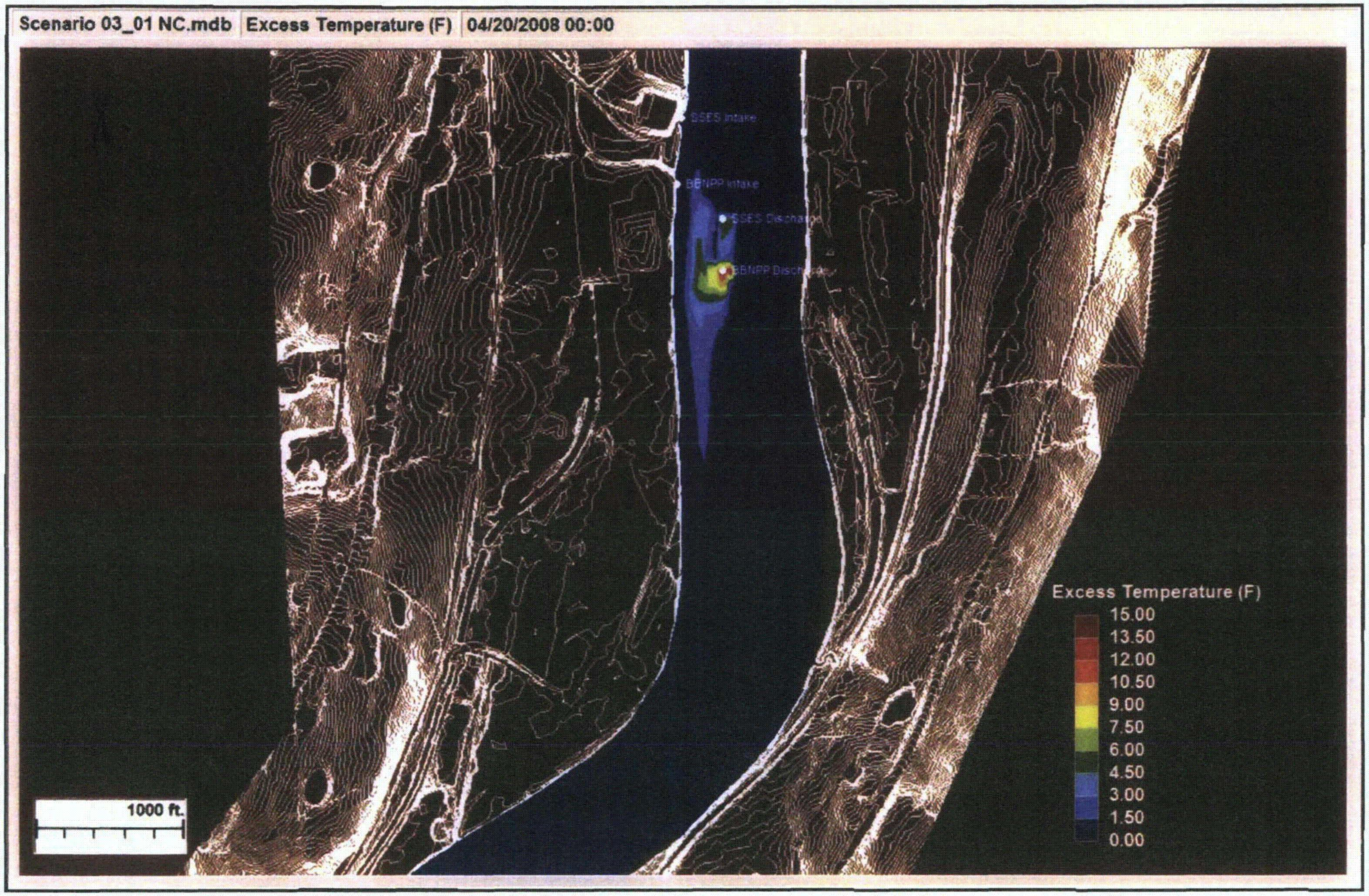

Figure 23 Excess temperature at the bottom for cumulative SSES and BBNPP impacts for Scenario 3

Scenario 3 is winter mean flow.

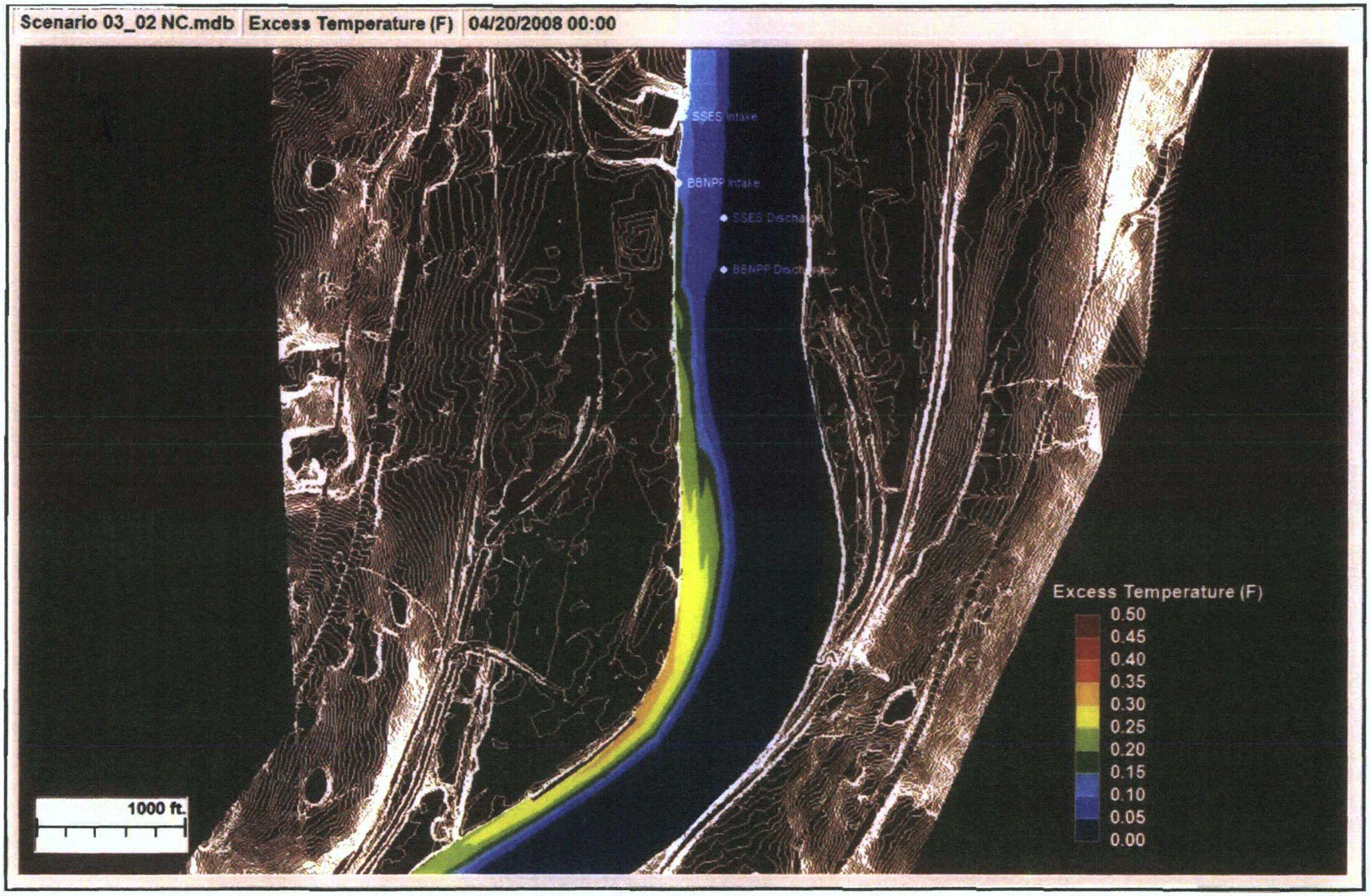

Figure 24 Excess temperature at the surface for incremental BBNPP impact for Scenario 3

Scenario 3 is winter mean flow.

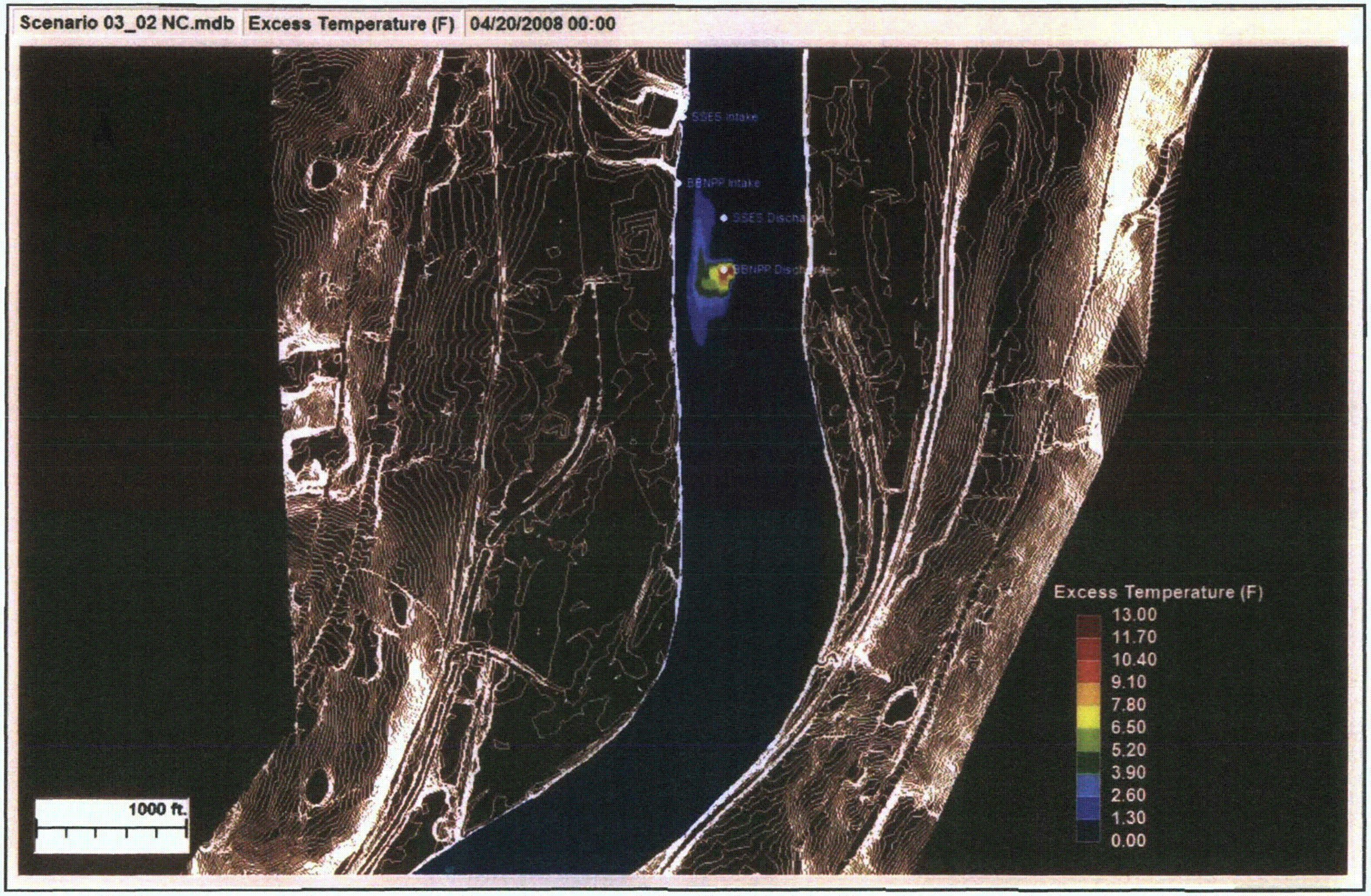

Figure 25 Excess temperature at the bottom for incremental BBNPP impact for Scenario 3

Scenario 3 is winter mean flow.

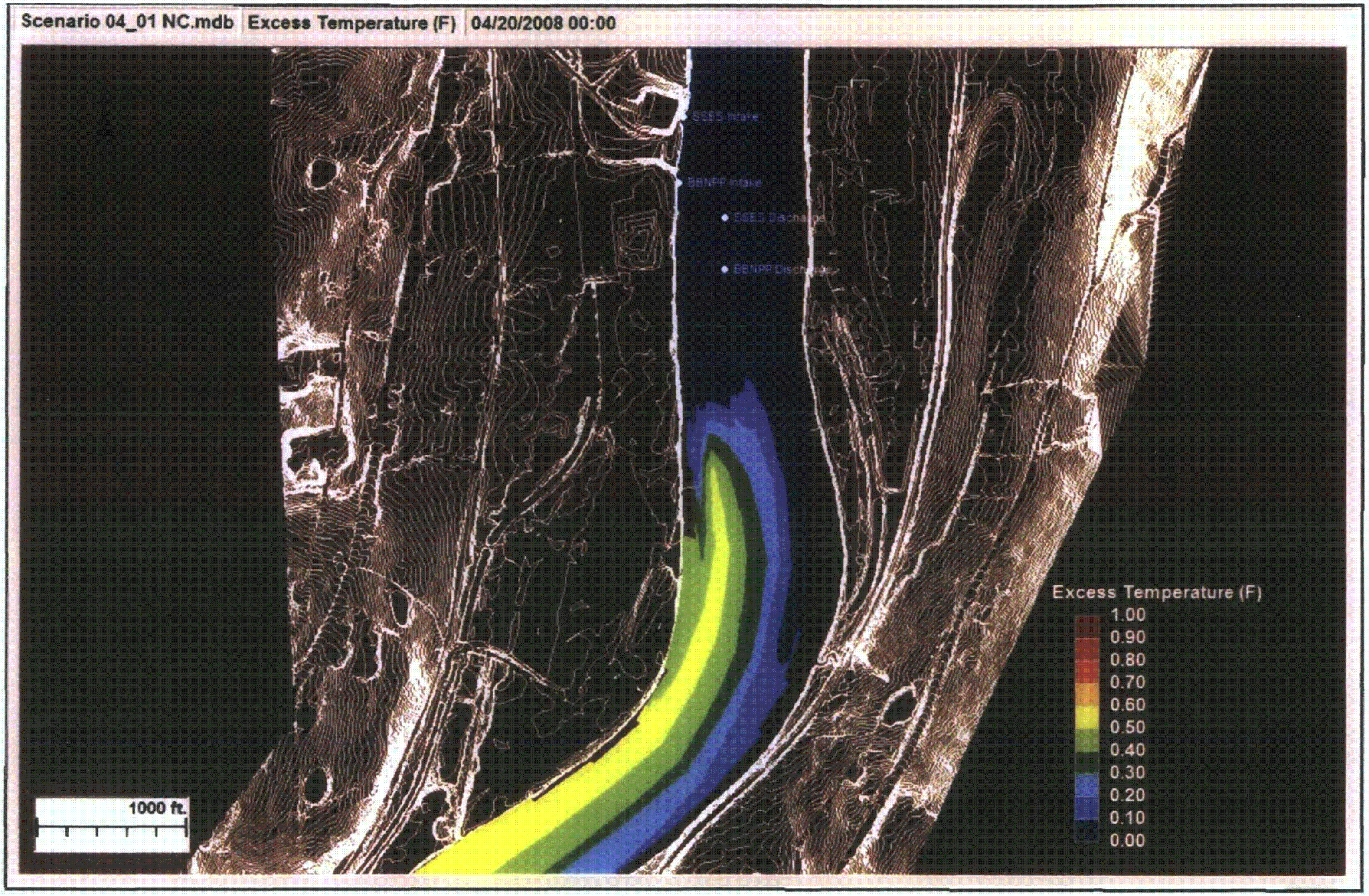

Figure 26 Excess temperature at the surface for cumulative SSES and BBNPP impacts for Scenario 4

Scenario 4 is winter low flow

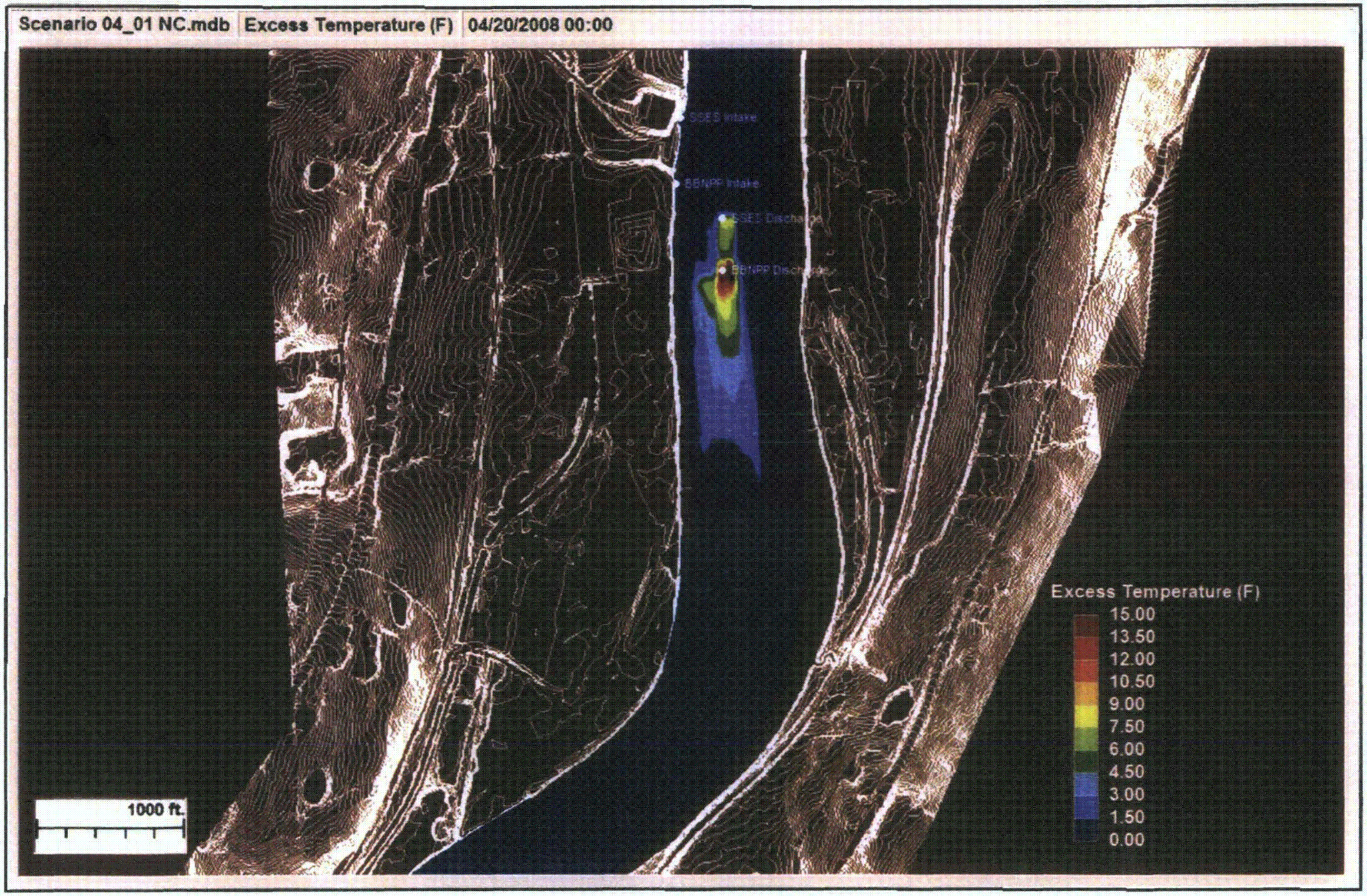

Figure 27 Excess temperature at the bottom for cumulative SSES and BBNPP impacts for Scenario 4

Scenario 4 is winter low flow.

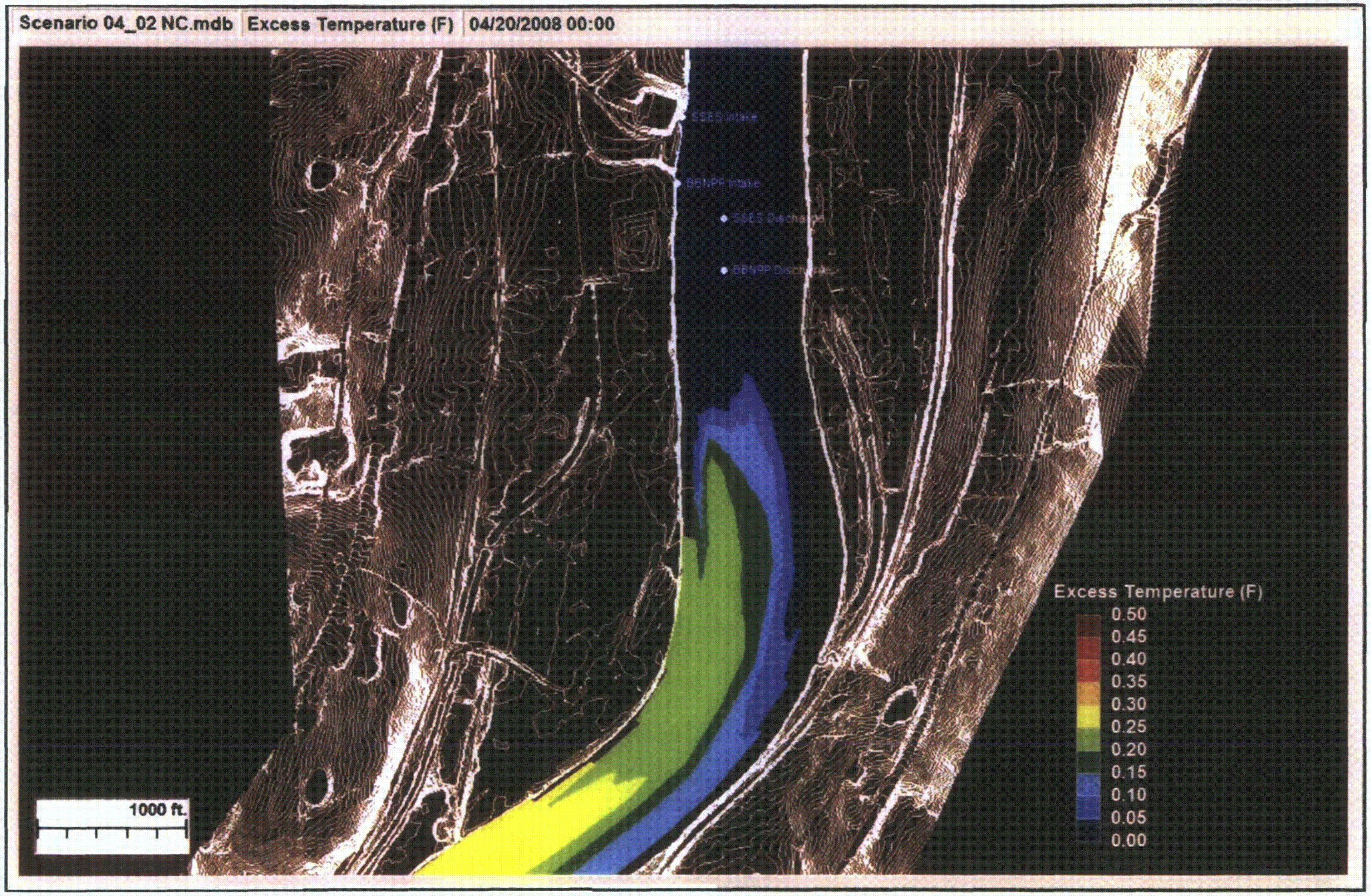

Figure 28 Excess temperature at the surface for incremental BBNPP impact for Scenario 4

Scenario 4 is winter low flow.

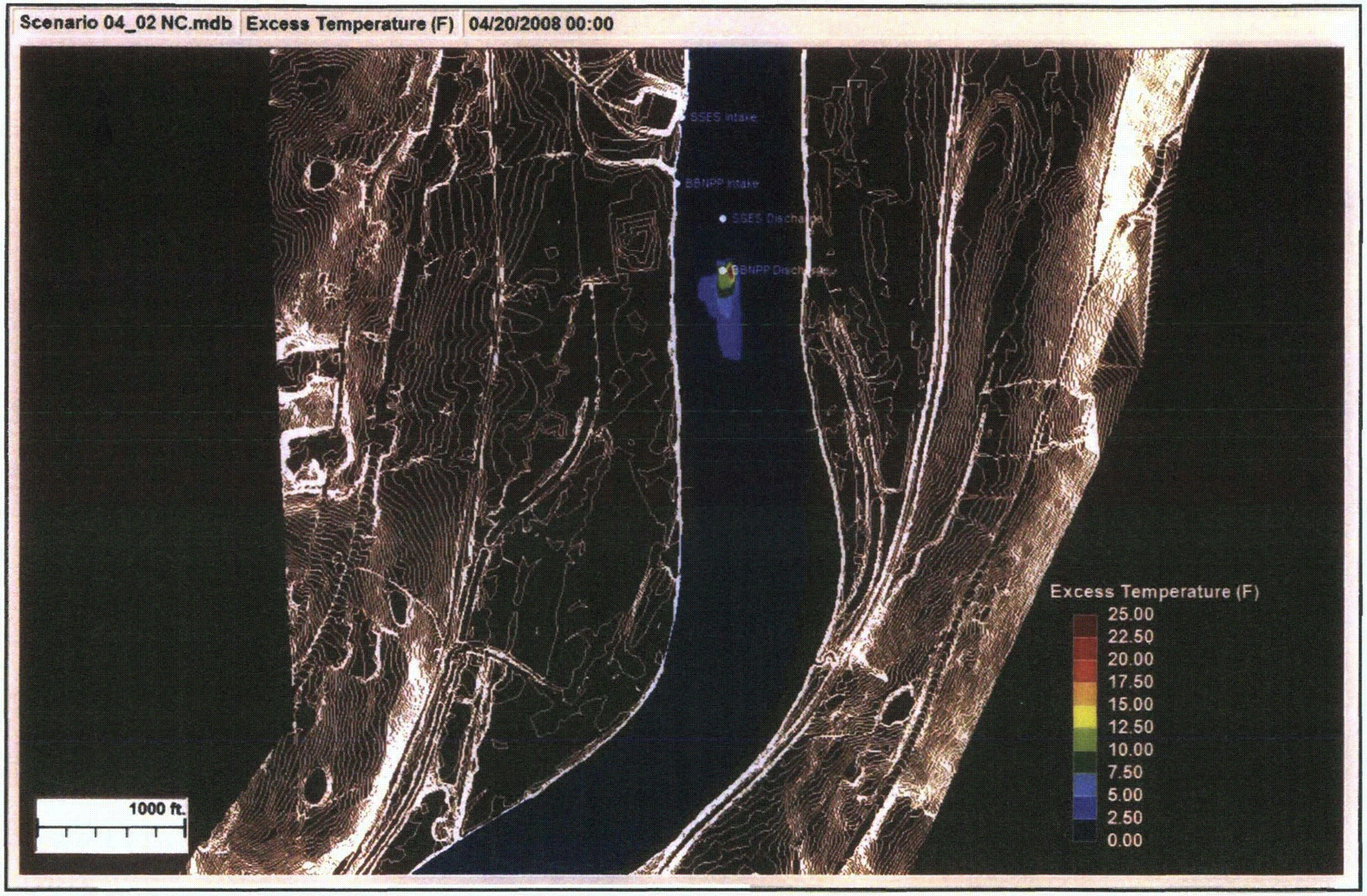

Figure 29 Excess temperature at the bottom for incremental BBNPP impact for Scenario 4

Scenario 4 is winter low flow.

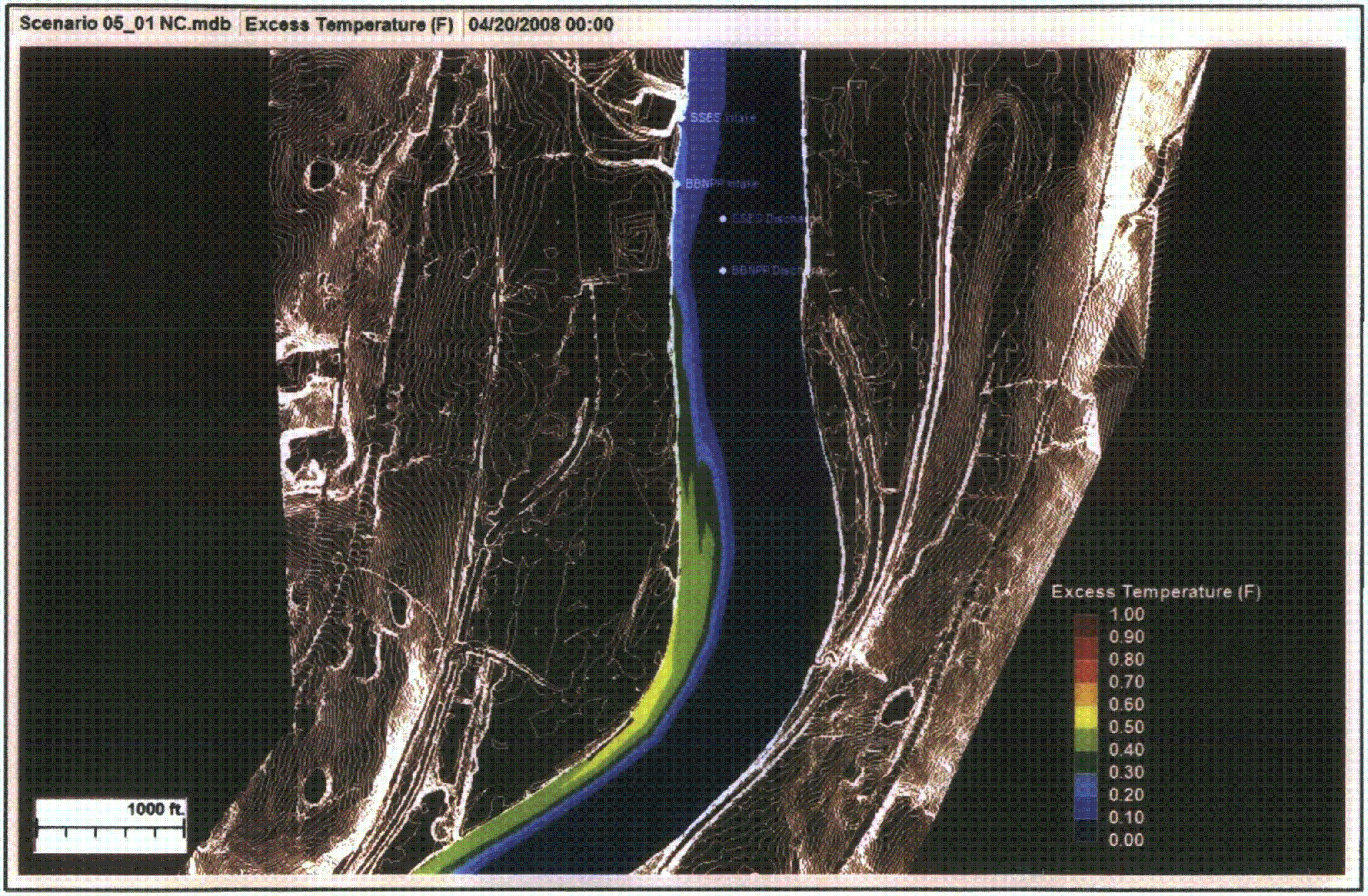

Figure 30 Excess temperature at the surface for cumulative SSES and BBNPP impact for Scenario 5

Scenario 5 is average annual flow.

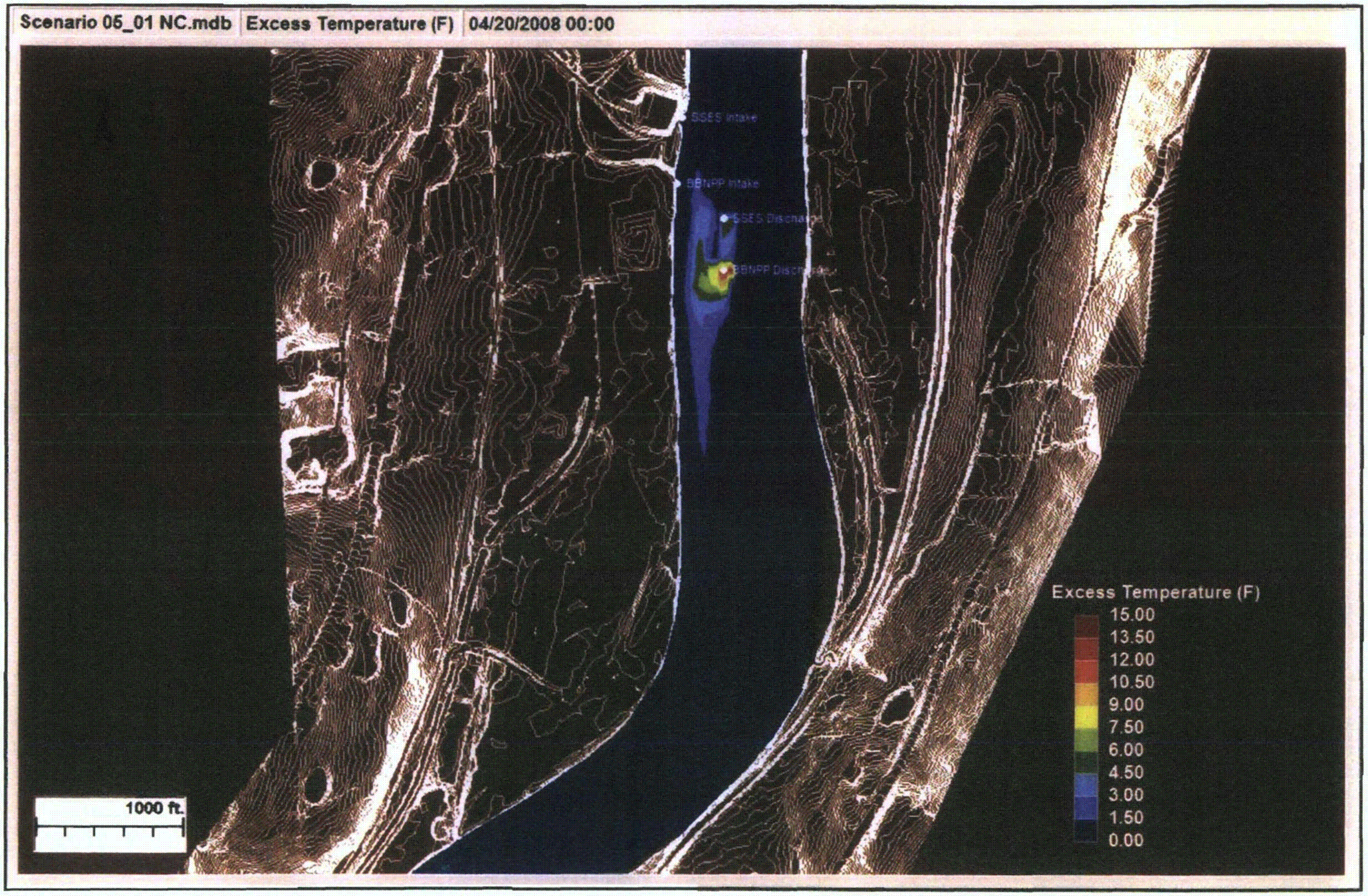

Figure 31 Excess temperature at the bottom for cumulative SSES and BBNPP impact for Scenario 5

Scenario 5 is average annual flow.

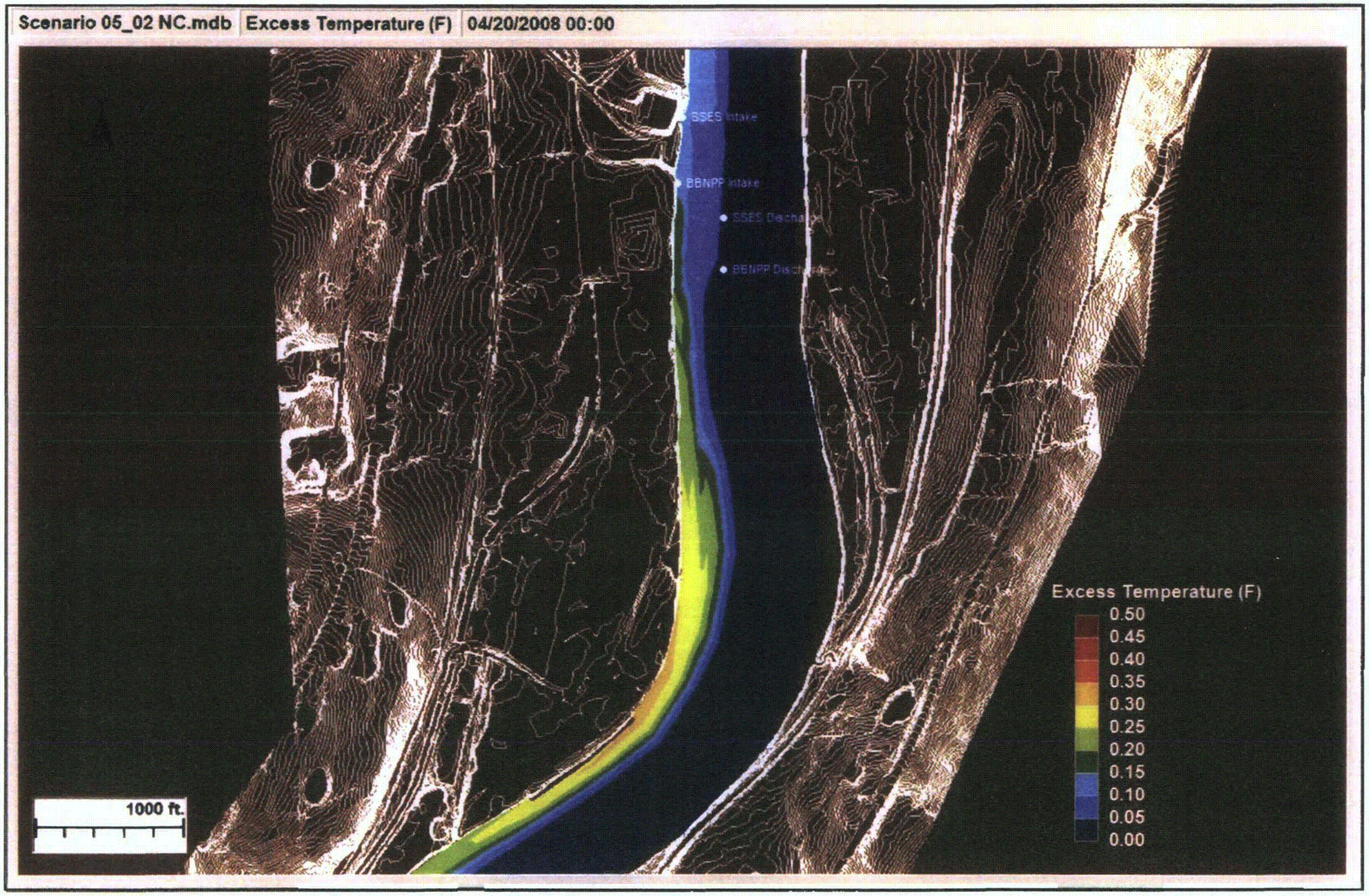

Figure 32 Excess temperature at the surface for incremental BBNPP impact for Scenario 5

Scenario 5 is average annual flow.

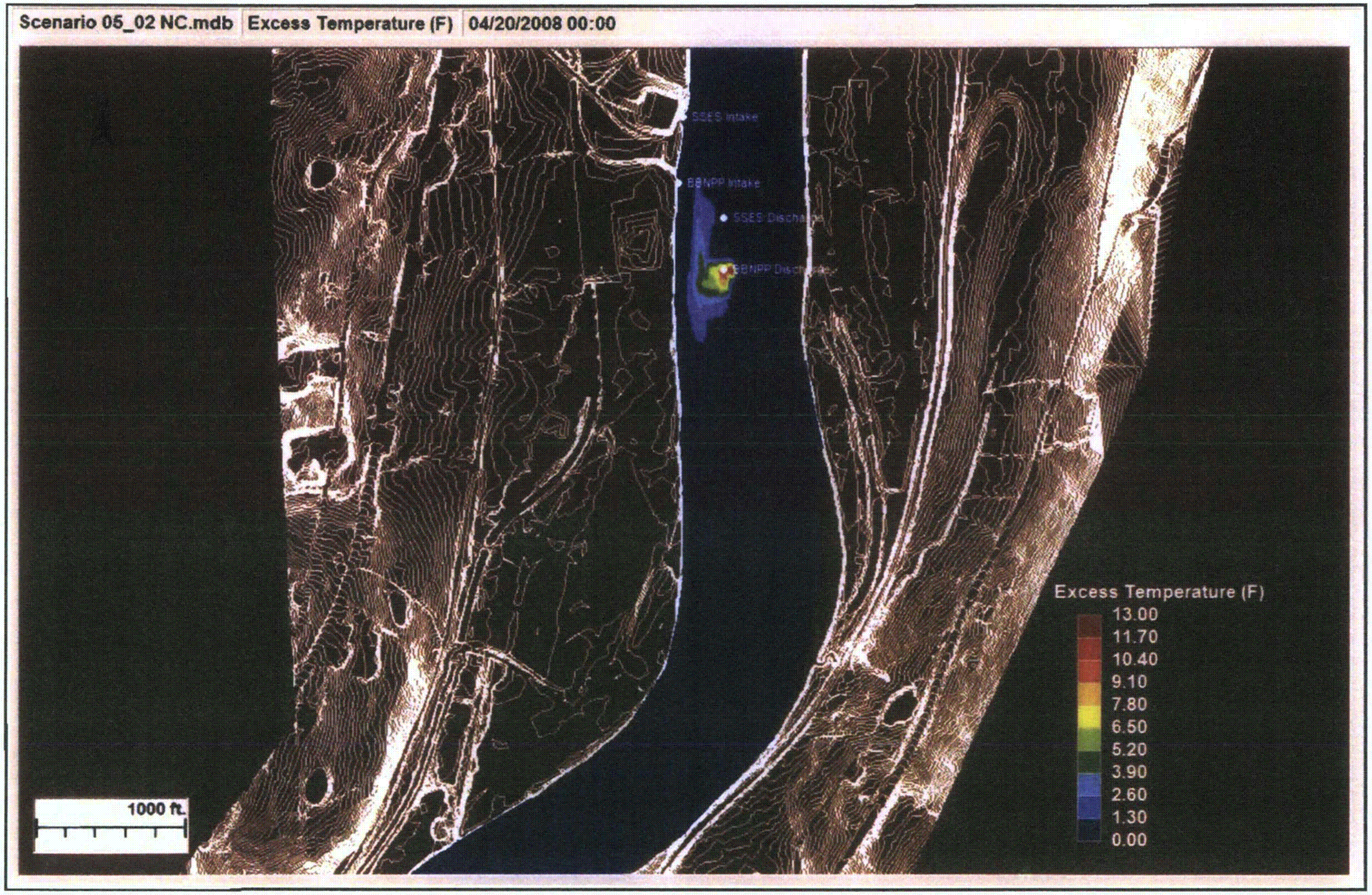

Figure 33 Excess temperature at the bottom for incremental BBNPP impact for Scenario 5

Scenario 5 is average annual flow.

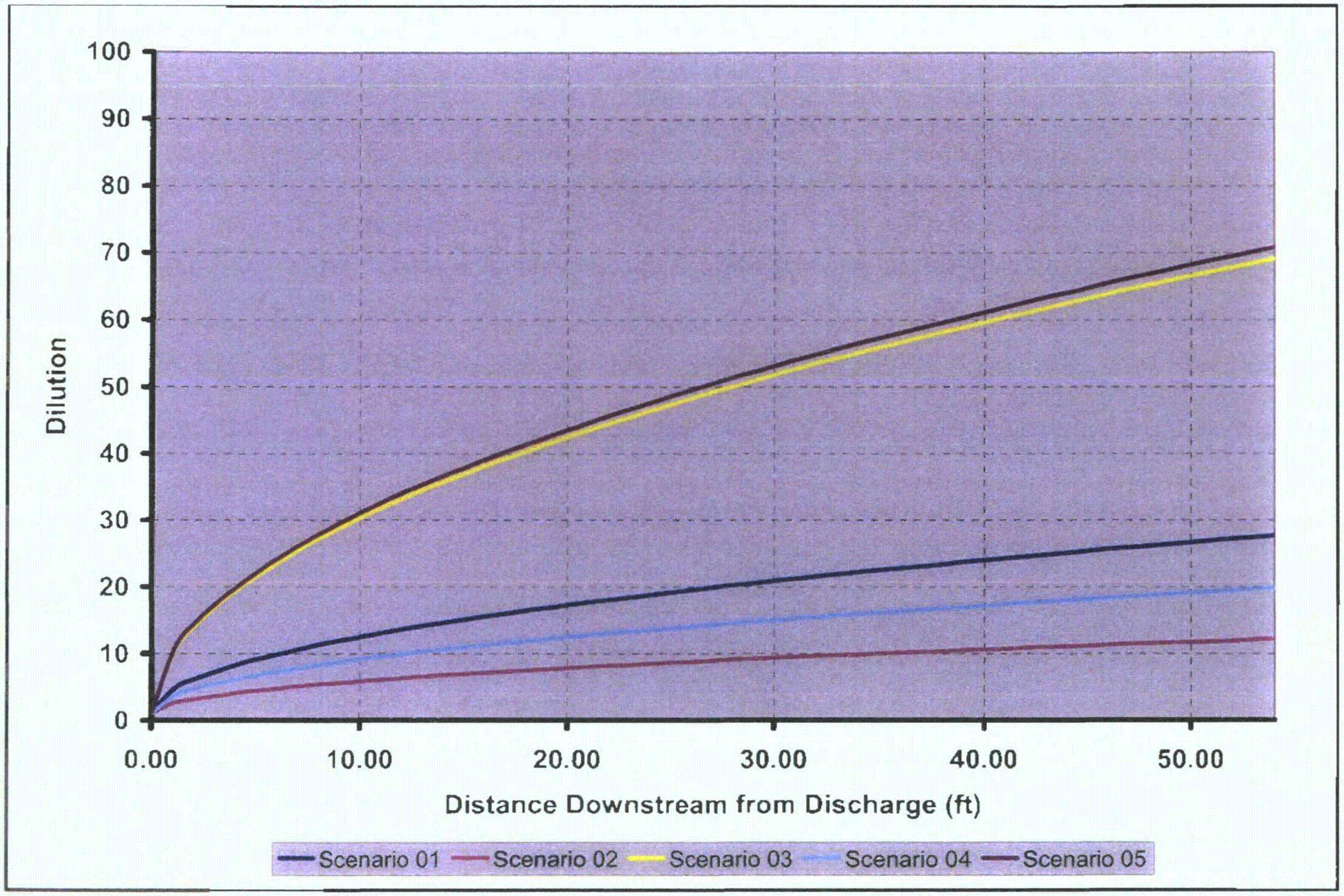

Figure 34 Near-field dilution versus downstream distance for all five scenarios

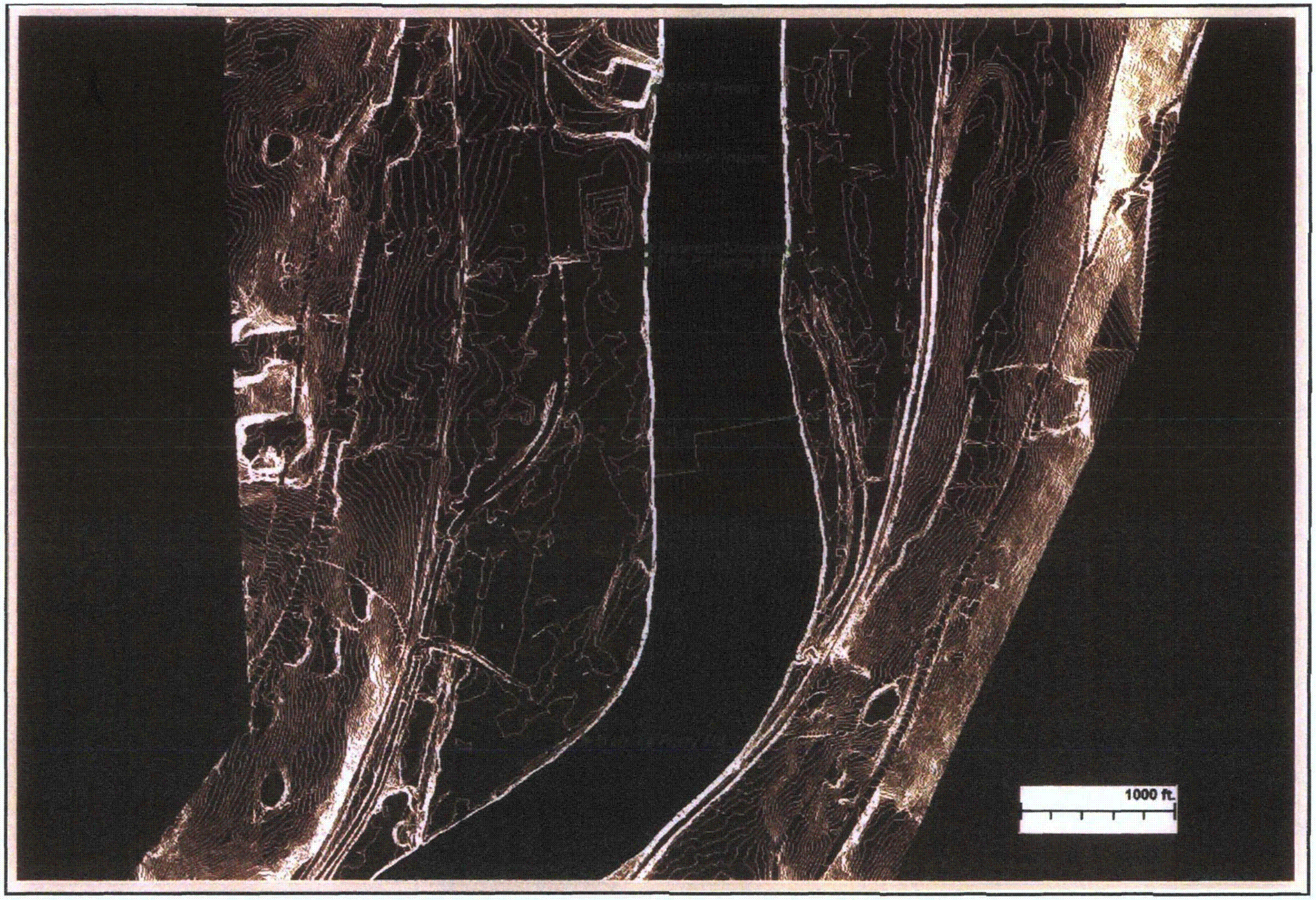

Figure 35 Dilution value locations

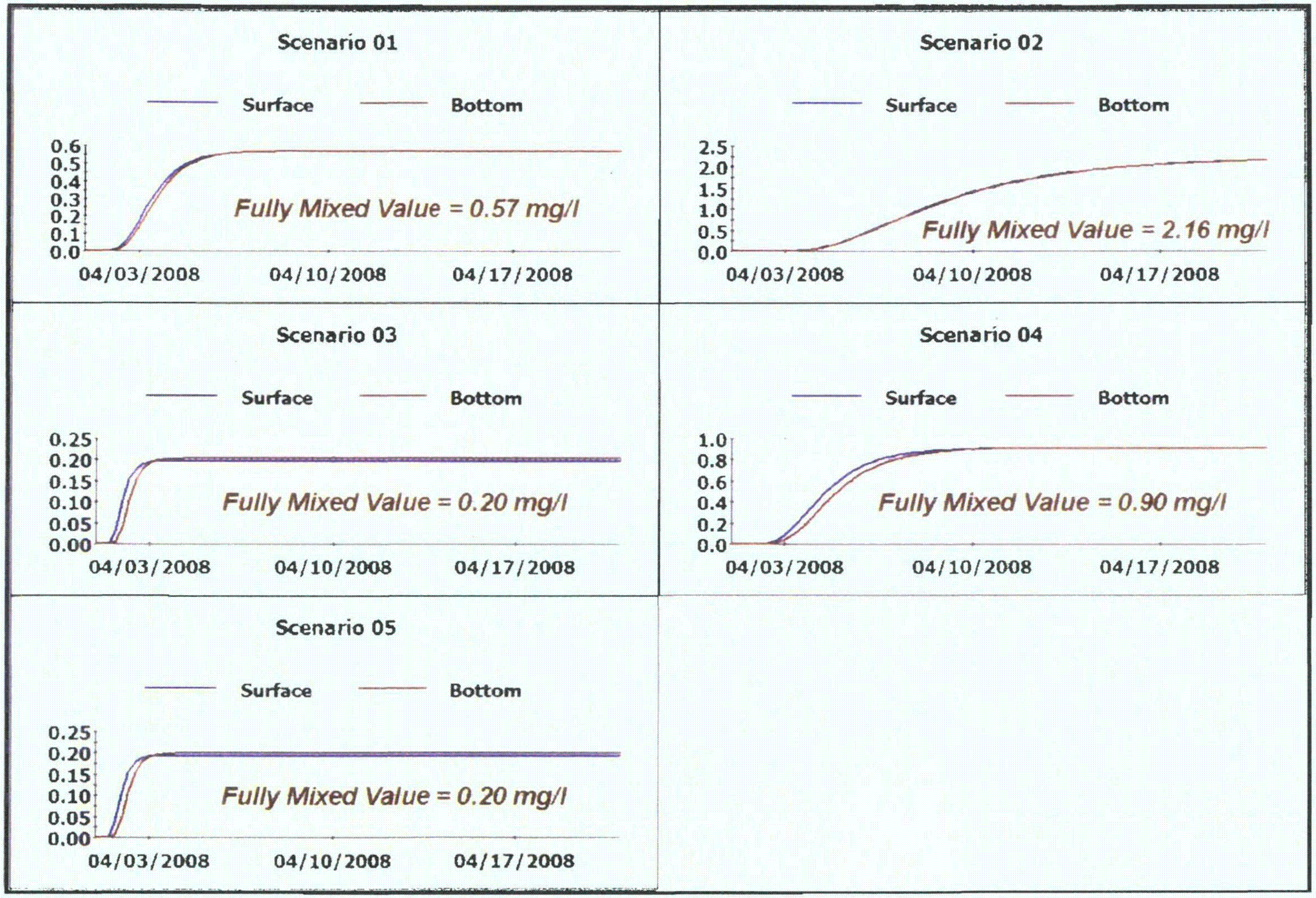

Figure 36 Fully-mixed concentrations for dilution study

Curves show values obtained from GEMSS simulations and the italicized text shows values obtained from fully-mixed analytical calculation (Equation 3).

APPENDIX A: GEMSS THEORY, ASSUMPTIONS AND APPLICABILITY

GEMSS® uses many models written in FORTRAN code that computes time-varying velocities, water surface elevations, and water quality constituent concentrations in rivers, lakes, reservoirs, estuaries, and coastal waterbodies. The computations are done on a horizontal and vertical grid that represents the waterbody bounded by its water surface, shoreline, and bottom. The water surface elevations are computed simultaneously with the velocity components. The water quality constituent concentrations are computed from the velocity components and elevations. Included in the computations are boundary condition formulations for friction, wind shear, turbulence, inflow, outflow, surface heat exchange, and water quality kinetics.

The flow and constituent fields are discretized in time, and the computation marches forward in time steps of 100 s to 900 s, computing the dependent variables throughout the grid at each of these steps. To march the calculations through time, boundary condition data consisting of meteorological data; inflow rates, temperatures, and constituent concentrations; and outflow rates are required. These boundary conditions data are assembled as separate input files.

The theoretical basis of the three dimensional model was first presented in Edinger and Buchak (1980) and subsequently in Edinger and Buchak (1985) under the previous name called GLLVHT. It provides three-dimensional, time-varying simulations of rivers, lakes, impoundments, estuaries and coastal water bodies. GEMSS has been peer reviewed and published (Edinger and Buchak, 1995; Edinger, et al., 1994 and 1997). The fundamental computations are an extension of the well known longitudinal-vertical transport model that was developed by J. E. Edinger Associates, Inc. beginning in 1974 and summarized in Buchak and Edinger (1984). This model forms the hydrodynamic and transport basis of the Corps of Engineers' water quality model CE-QUAL-W2 (U. S. Army Engineer Waterways Experiment Station, 1986).

The hydrodynamic and transport relationships used in the GLLVHT are developed from the horizontal momentum balance, continuity, constituent transport and the equation of state. The basic relationships are given in Edinger and Buchak (1980, 1985 and 1995). These relationships have six unknowns (U, V, W - velocities in x, y and z directions, respectively, η - water surface elevation, ρ - density, C_n - constituent n) in six equations with the momentum and constituent dispersion coefficients (A_x, A_y, A_z, D_x, D_y, D_z) evaluated from velocities and the density structure.

In the x and y momentum balances, the forcing terms are the barotropic or water surface slope, the baroclinic or density gravity slope, the Coriolis acceleration, the advection of momentum in each of the three coordinate directions, the dispersion of momentum in each of the coordinate directions and the specific momentum as would apply to a high velocity discharge. The baroclinic and barotropic slopes are arrived at from the hydrostatic approximation to vertical momentum and horizontal differentiation of the density-pressure integral by Leibnitz' rule. The baroclinic slope is seen to be the vertical integral of the horizontal density gradient and becomes the major driving force for density-induced flows due to discharge buoyancy.

The hydrodynamic equations are semi-implicit in time. The semi-implicit integration procedure has the advantage that computational stability is not limited by the Courant condition that $\Delta x/\Delta t$, $\Delta y/\Delta t < (gh_m)^{1/2}$ where h_m is the maximum water depth that can lead to inefficiently small time steps of integration. Since the solutions are semi-implicit (for example, explicit in the constituent transport and the time lagged momentum terms) the stability is controlled by the Torrence condition ($U\Delta t/\Delta x$, $V\Delta t/\Delta y < 1$; Δx and Δy are grid sizes in x and y directions, respectively). Hence, the integration time step can be chosen to realistically represent the details of the boundary data which is about 15 minutes for tides and up to one hour for meteorological data.

The vertical momentum dispersion coefficient and vertical shear is presently (but not limited to) evaluated from a Von Karman relationship modified by the local Richardson number, Ri, which is defined as the ratio of vertical buoyant acceleration to vertical momentum transfer (Leendertse, 1989). Higher order turbulence closure schemes (two equations k-ω second moment closure model by Mellor and Yamada, 1982) are also included in the module. The longitudinal and lateral dispersion coefficients are scaled to the dimensions of the grid cell using the dispersion relationships developed by Okubo and modified to include the velocity gradients of the velocity field using Smagorinsky relationship. The wind stress and bottom shear stress are computed using quadratic relationships with appropriate friction coefficients.

A summary of the hydrodynamic model characteristics is given in Table 1.

Table 1 Features of GEMSS-HDM

Property	Description	Advantage
ΔX, ΔY, ΔZ	Variable from cell to cell. Curvilinear	Fit shorelines precisely, provide more refined grid detail where needed. Each cell has its own orientation for accurate orientation of winds
Layer/ cell addition subtraction	Yes	Allows adding and subtracting layers over large water surface elevation changes. Flooding and drying of tidal flats and marshes.
Interior Boundaries	Yes	Representation of interior structures such as breakwaters, marinas, underflow/overflow curtain walls.
Vertical momentum	Included. Relaxes Hydrostatic Approx.	Important for draw down at outflow structures, mixing devices, and accurate representation of water surfaces in regions of large horizontal velocity changes.
Discharge Momentum	All three directions	Used for proper representation of high velocity discharges.
Time Stepping Solution	Implicit solution over all space on each time step.	Not limited by the Courant wave speed criterion of $\Delta t < \Delta x/(gHmax)^{0.5}$. Typical time step for 3-D baroclinic circulation is approximately 15 minutes
Coriolis Acceleration	Variable with latitude. Incorporated in implicit part of the time step computations.	Can do large water bodies with large time steps.
Transport Scheme	Quickest, Ultimate	Better prediction of constituent profiles in regions of sharp changes
Turbulence Closure	Higher Order Schemes	Better description of turbulence in regions of rapid changes in bathymetry and around structures. Also at density interfaces.
Wind Speed	Variable through time and across grid	Realistic representation of wind events on a water body.

Property	Description	Advantage
Surface Heat Exchange	Time varying term by term heat budget	Accurate representation of diurnal variations in heat exchange.
Linkage to Water Quality Models	Coupled with water quality models of different levels of complexity	More realistic representation of processes taking place.
Other Supported Routines and Processes	Sediment transport Spill Model Toxics Model Intake Entrainment Model.	Additional routines can be included in a modular fashion and run directly in GLLVHT on a real time basis.

The model is built to accept a large number of transport constituents and constituent relationships depending on the water quality model being used. The list of transport variables available in GLLVHT to analyze flushing, entrainment, thermal pollution, boundary exchange, etc. is given below.

- Temperature
- Salinity
- Excess Temperature
- Instantaneous Tracer Dye
- Continuous Tracer Dye

1. MATHEMATICAL FORMULATION

1.1 MODEL DESCRIPTION

The hydrodynamic and transport relationships used in the GLLVHT are developed from the horizontal momentum balance, continuity, constituent transport and the equation of state. The horizontal momentum balances for the horizontal velocity components, U and V in the x- and y-coordinate horizontal directions, with z taken positive downward are

$$\partial U/\partial t = g\,\partial z'/\partial x - g/\rho \int_{z'}^{z} (\partial \rho/\partial x)\,\partial z + fV - \partial UU/\partial x - \partial VU/\partial y - \partial WU/\partial z + SM_x$$
$$+ \partial A_x(\partial U/\partial x)/\partial x + \partial A_y(\partial U/\partial y)/\partial y + \partial A_z(\partial U/\partial z)/\partial z \qquad \text{(A-1)}$$

$$\partial V/\partial t = g\partial z'/\partial y - g/\rho \int_{z'}^{z} (\partial \rho/\partial y)\partial z - fU - \partial UV/\partial x - \partial VV/\partial y - \partial WV/\partial z + SM_y$$
$$+ \partial A_x(\partial V/\partial x)/\partial x + \partial A_y(\partial V/\partial y)/\partial y + \partial A_z(\partial W/\partial z)/\partial z \qquad \text{(A-2)}$$

Local continuity for the vertical velocity component W is

$$\partial W/\partial z = - \partial U/\partial x - \partial V/\partial y \qquad \text{(A-3)}$$

Vertically integrated continuity for the surface elevation, z', is

$$\partial z'/\partial t = - \int_{z}^{h} (\partial U/\partial x)\,dz - \int_{z}^{h} (\partial V/\partial y)\,dz \qquad \text{(A-4)}$$

The constituent transport relationship for n number of constituents (for example, salinity, dye and sediment) is

$$\partial C_n/\partial t = - \partial UC_n/\partial x - \partial VC_n/\partial y - \partial WC_n/\partial z + \partial(D_x\partial C_n/\partial x)/\partial x$$

$$+ \partial(D_y\partial C_n/\partial y)/\partial y + \partial(D_z\partial C_n/\partial z)/\partial z + H_n \quad \text{(A-5)}$$

And, the equation of state relating density, r, to constituents is

$$\rho = f(C_1,C_2,...,C_n) \quad \text{(A-6)}$$

These relationships have six unknowns (U, V, W, z', r, C_n) in six equations, assuming that the momentum and constituent dispersion coefficients (A_x, A_y, A_z, D_x, D_y, D_z) can be evaluated from velocities and the density structure.

In the x and y momentum balances, the right-hand terms are successively the barotropic or water surface slope, the baroclinic or density gravity slope, the Coriolis acceleration, the advection of momentum in each of the three coordinate directions, the dispersion of momentum in each of the coordinate directions and the specific momentum as would apply to a high velocity discharge.

The baroclinic and barotropic slopes are arrived at from the hydrostatic approximation to vertical momentum and horizontal differentiation of the density-pressure integral by Leibnitz' rule. The baroclinic slope is seen to be the vertical integral of the horizontal density gradient and becomes the major driving force for density-induced flows due to discharge buoyancy.

The specific momentum terms, SM_x and SM_y, are evaluated from the velocity and flow rate of a discharge into a model cell as Udis*Qdis/(Dx*Dy*Dz) where Dx, Dy and Dz are the model cell dimensions. The specific momentum is directed vectorially parallel to the direction of the discharge velocity.

1.2 NUMERICAL SCHEME

The hydrodynamic relationships are integrated numerically, implicitly forward in time, by evaluating the horizontal momentum balances as

$$\partial U/\partial t = g\partial z'/\partial x + F_x \quad \text{(A-7)}$$

$$\partial V/\partial t = g\partial z'/\partial y + F_y \quad \text{(A-8)}$$

where U, V and z' are taken simultaneously forward in time and all the other terms are incorporated in the forcing functions F_x and F_y and are lagged in time. Equations (A-7) and (A-8) are substituted (either by cross-differentiation or algebraically from the finite difference forms) into vertically integrated continuity to give the surface wave equation of

$$\partial^2 z'/\partial t^2 + g\partial(H\partial z'/\partial x)/\partial x + g\partial(H\partial z'/\partial y)/\partial y = \partial/\partial x\left(\int_{z'}^{h} F_x \partial z\right) + \partial/\partial y\left(\int_{z'}^{h} F_y \partial z\right) \quad \text{(A-9)}$$

where z' is the surface displacement and H is the total water column depth. The surface wave equation has second order derivative in time which makes solving of Equation (A-9) quite cumbersome. So, the second order time derivative is converted to first order by expanding $\delta^2 z'/\delta t^2$ using Equation (A-4).

The computational steps in GLLVHT on each time step of integration are: (1) to evaluate F_x and F_y from U, V, W, r known from the previous time step; (2) to solve the surface wave equation for new z' for the spatial grid using a modified form of Gauss-Jordan elimination by back substitution; (3) to solve for new U and V using Equations (A-7) and (A-8); (4) to solve for W using Equation (A-3); (5) to re-evaluate z' from Equation (A-4) for precision; and, (6) to solve the constituent relationships, Equations (A-5).

The semi-implicit integration procedure has the advantage that computational stability is not limited by the Courant condition that Dx/Dt, Dy/Dt < $(gh_m)^{1/2}$ where h_m is the maximum water depth that can lead to inefficiently small time steps of integration. Since the solutions are semi-implicit (for example, explicit in the constituent transport and the time lagged momentum terms) the stability is controlled by the Torrence condition (UDt/Dx, VDt/Dy < 1). Hence, the integration time step can be chosen to realistically represent the details of the boundary data which is about 15 minutes for tides and up to one hour for meteorological data.

There are a number of auxiliary relationships which enter the computations. First, the vertical momentum dispersion coefficient and vertical shear is presently (but not limited to) evaluated from a Von Karman relationship modified by the local Richardson number, Ri, (the ratio of vertical buoyant acceleration to vertical momentum transfer) as

$$A_z = kLm^2/2[(\partial U/\partial z)^2 + (\partial V/\partial z)^2]^{1/2}Exp(-1.5Ri) \quad \text{(A-10)}$$

where k is the Von Karman constant; Lm is a mixing length that can be a function of depth; and, Ri is the local Richardson number. The Richardson number function is from Leendertse and Liu (1975). The longitudinal and lateral dispersion coefficients are scaled to the dimensions of the grid cell using the dispersion relationships developed by Okubo (1971) of

$$D_l = 5.84 \times 10^{-4}(L_l)^{1.1} \quad \text{(A-11)}$$

where D_l is the longitudinal or lateral dispersion coefficient in square meters per second and L_l is the longitudinal or lateral cell dimension in meters.

Wind surface stress enters the relationships for each of the coordinate directions as

$$A_z\partial U/\partial z \,|_{z'} = WS_x \quad \text{(A-12)}$$

and,

$$A_z\partial V/\partial z \,|_{z'} = WS_y \quad \text{(A-13)}$$

where $W(W_x)$ and $W(W_y)$ are surface shear functions of wind speed.
Bottom friction enters the computations through a Chezy friction relationship as

$$A_z \partial U/\partial z \,|_h = (g/C_h^2)U^2 \qquad \text{(A-13)}$$
$$A_z \partial V/\partial z \,|_h = (g/C_h^2)V^2$$

where C_h is the local Chezy friction coefficient and h is the bottom elevation at which bottom friction is evaluated.

Transport computation is explicit in time. It is developed so that transport coefficients can be computed once and used for all constituents during that time step at a given "n", "k" location. The solution time is not too sensitive to the number of constituents being examined. Constituent computations are performed using a higher order transport scheme. This scheme uses second order upwind differencing following the method of Mei and Plotkin (1985). The scheme includes an adjustment factor to account for "undershoots" and "overshoots" that normally occurs in any higher order scheme in the presence of sharp gradients. The adjustment factor is computed using local second order and first order gradients similar to ULTIMATE (1988).

The model is built to accept a large number of transport constituents and constituent relationships. The basic parameter obtained from the water quality model is the constituent flux, H(n,k,nc). For example $H(n,k,4) = -KR_4*C(n,k,4)*dxdydz$ for the decay of constituent 4. Dxdydz is the volume of the grid cell and KR_4 is the decay constant).

2. NUMERICAL CONFIGURATION

2.1 GRID AND COORDINATE TRANSFORMATIONS

Rectilinear (quasi-curvilinear) grid for mapping to different detail in different parts of a waterbody is used in GEMSS. Horizontal grid dimensions changing with depth is also used. The model domain is a space staggered finite difference grid with elevations and constituent concentrations computed at cell centers and velocities through cell interfaces. This scheme facilitates implementation of control volume approach resulting in perfect water balance.

Both Z-level and sigma level methods are used for gridding in the vertical direction. Z-level allows the use of variable layer thicknesses in the vertical direction and facilitates implementation of the layer cell add and subtract algorithm for modeling tidal flats; It also allows the use thicker layers in deeper water. Sigma level model is described in Section 7.

The curvilinear model grid is obtained using GridGen tool of GEMSS. GridGen is an automated grid generation tool which is a menu and mouse driven graphical software that allows the user to develop rectilinear as well as curvilinear coordinates from digitized maps containing shorelines and bathymetric soundings, transects and contours. These maps are loaded in GEMSS using widely used shaped file format (.shp, .dbf, .shx, .sbn, .sbx, .prj files) of ESRI. For applications where no digital maps are available, GEMSS has a unique format .GShp which can be used to draw waterbodies and specify depths for subsequent gridding. This format is normally used to set up some simple waterbodies such as rectangular basin etc.

2.2 Wetting and drying

The basic model variable for water surface elevation, Z, is relative to a local datum at the top of a fixed horizontal layer, KT. When the water surface rises so that it enters a new layer, the current thick layer is divided into two, Z is modified and KT is decremented by 1. The reverse action is taken on falling water surface. When the rising surface floods dry cells, they are also activated (and deactivated when dried again). Wetting and drying is important to account for tidal flats and wetlands.

2.3 Array structure

Hydrodynamic variables identified by surface cell number "n" and vertical layer "k" as for example U(n,k), V(n,k), W(n,k), Az(n,k). Constituent and water quality variables identified with a water quality constituent number, "nc", as C(n,k,nc). This approach reduces array storage and simplifies computational loops.

2.4 Solution method

HDM used a family of fully implicit schemes, either the banded matrix solver (small grids) or the preconditioned conjugate gradient, successive over relaxation, or modified strongly implicit methods (large grids). After performing a series of numerical experiments on conventional problems as well as real world applications, the preconditioned conjugate gradient method is the ultimate solution method used in HDM because of its less computer storage, CPU time and high convergence speed.

2.5 Sources, sinks and specific momentum

Discharges/Intakes (e.g. river inflows, outfalls, marine disposals, thermal intakes and discharges etc.) are introduced as sources/sinks to the continuity and transport equations; in addition, sub grid scale jet discharge can be accommodated using a source term for the momentum equations as discussed in the description section. Sources and sinks for continuity equation are applied using the flow rate variable Q(n,k) and for transport equations using the constituent flux variable, H(n,k,nc). Constituent fluxes are also computed from water quality routines.

3. Program Structure

3.1 Model design

The unique design of GEMSS gives the user the power of writing adaptation routines to introduce different initial conditions, time variant boundary conditions, replace existing algorithms for source and sink computations related to water quality, sediment transport etc. and nonstandard features or customize the output. In this scheme GEMSS-HDM behaves like a black box. Efficient routines for specifying input time varying data to the model such as meteorological data, inflows, discharge loads, time series boundary data using standards formats (e.g., Microsoft Excel csv format). Separate control switches and input "cards" for hydrodynamics and water quality constituents. Examples of input cards for hydrodynamics include specifying time of beginning and ending computations; types of outputs and their starting and ending times and frequencies; location and characteristics of inflows, discharges and intakes including recirculation coupling; control cards for water quality routines include in addition specification of rate parameters and specifying different combinations of constituents that might be required for a particular simulation.

3.2 Interface to other models

The design structure of GLLVHT is very flexible to accommodate different three dimensional water quality models. Examples include 1) EPA's EUTRO and the Corps' CE-QUAL-ICM (Integrated Compartment Model), sources of water quality kinetics routines.

3.3 Programming Language and Operating System

GEMSS numerical models are written in FORTRAN 90 and developed on Compaq's Visual Fortran compiler that runs on Windows NT and XP operating systems. We have also developed add-on tools for GEMSS that takes advantage of multi language programming (e.g. linking Visual Basic or Visual C++ with FORTRAN) available in Visual Fortran.

4. Boundary Conditions

The model handles a wide variety of boundary conditions through the use of control file generator module of GEMSS and they are listed below.

1. Fresh water inflows and outflows.
2. Outfall discharges.
3. Water intakes.
4. Powerplant intake and discharges. Specific discharge momentum for high velocity discharges.
5. Instantaneous dye releases; useful for flushing and each water parcel residence time computations.
6. Continuous dye releases; useful for dilution computations for wastewater discharges; screening tool for design scenarios.
7. Intantaneous and continuous oil, chemical and sewage spills.
8. Forced open boundary; option for different types of distribution along the boundary, tidal elevation amplification factor, tidal elevation lag time.
9. Free open boundary; use of first and higher order derivations of elevation, velocity and constituents.
10. Radiation boundary; used for elevation, velocity and constituents.
11. Slugging different regions of water body.
12. Interior boundaries for representation of interior structures such as breakwaters, marinas, weirs, gates, culverts, underflow/overflow curtain walls.
13. Surface precipitation/exchange.
14. Bottom deposition/releases.
15. Re-circulation boundary.
16. Entrainment source and target; used for larval and bio-organisms entrainment computations in water intakes.
17. Velocity boundary; used when no information is available other than field data from current meters.
18. Bubblers;
19. Distributed flows; used for representing non-point sources.
20. Grid cell activation/non-activation; quick way to alter the grid pattern.

The transport module in GEMSS-SHWET is capable of running in fully explicit to fully implicit mode in vertical direction while performing explicit computations in the horizontal direction. A Finite difference scheme is based on control volume (cv) approach. Let's assume transport in 1-D as shown in figure 1.

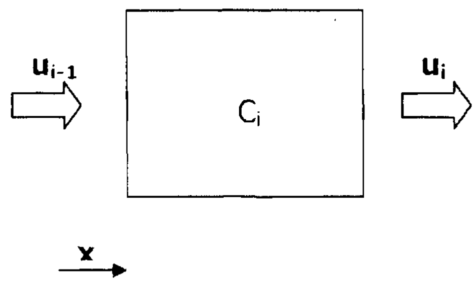

Figure 1 1-D transport schematic

The mass balance based on the CV approach can be written as:

$$C^{n+1} = C^n - (Mass)_{in} + (Mass)_{out} \quad (1)$$

$$Mass_{in} = (adv)_w + (Dif)_w \quad (2)$$
$$Mass_{out} = (adv)_E + (Dif)_E \quad (3)$$

$$(Adv)_w = Cour_w * C_{fw} \quad (4)$$
$$(Adv)_E = Cour_E * C_{fE} \quad (5)$$

$$Cour_E = \frac{u_E * dt}{dx} \quad (6)$$

Where, C_{fw} and C_{fE} are the face concentration values at the west and east cell faces respectively. $Cour_w$ and $Cour_E$ are the courant numbers defined at the west and the east cell faces respectively. Unlike velocities, concentrations are defined at the cell centers in GEMSS and thus interpolation needs to be done in order to calculate the required face concentrations. The various transport schemes used in GEMSS differ in the interpolation scheme used to calculate these face concentration.

The transport scheme can also be Explicit or Implicit. In a fully explicit scheme, all the terms used to calculate the face concentrations are from the current time step while in a fully implicit scheme the face concentrations are calculated based on the concentrations at the next time step. Implicit formulation requires solving matrix and thus is computationally expensive. On the other hand implicit formulation relaxes the time step constraints. In GEMSS, the vertical transport can be solved using the implicit scheme. It also allows for different combinations (weightage) of Explicit-Implicit formulation. This weightage can be specified in the form of two parameters θ_a and θ_d. The variable θ_a specifies the contribution of implicit formulation for advective transport in the vertical direction and the variable θ_d specifies the contribution of implicit formulation for diffusive transport. The transport equation in 3 -dimension with implicit and explicit formulation can thus be written as

$$\frac{C_i^{n+1} - C_i^n}{\Delta t} = (Adv)_{EX} + (Adv)_{EY} + (Dif)_{EX} + (Dif)_{EX} + (1-\theta_a)(Adv)_{EZ} + \theta_a (Adv)_{IZ} + (1-\theta_d)(Dif)_{EZ} + \theta_d (Dif)_{IZ} \tag{7}$$

Where, $(Adv)_{EX}$, $(Adv)_{EY}$ and $(Adv)_{EZ}$ are the explicit part of the advective fluxes in the x, y and z directions respectively and $(Dif)_{EX}$, $(Dif)_{EY}$ and $(Dif)_{EZ}$ are the explicit part of the diffusive fluxes in the x, y and z directions respectively. $(Adv)_{IZ}$ and $(Dif)_{IZ}$ are the implicit part of the advective and diffusive fluxes in the z direction.

When $\theta_a = \theta_d = 0$, then the transport equation is completely explicit and when $\theta_a = \theta_d = 1$, then the transport equation is completely implicit in the z direction. Note that the transport in x and y are always solved explicitly. When $\theta_a = \theta_d = 0.55$, then the transport scheme is called Crank-Nicholson in the z direction.

The explicit transport schemes used in GEMSS are:

a) Upwind
b) QUICKEST
c) QUICKEST + ULTIMATE

5.1 Upwind Scheme

Upwind is the simplest transport scheme of first order with the upstream bias. That is it assumes that the concentration at the face is equal to the concentration of the grid upstream of the face. So, if the velocity at the right face is positive (left to right) then the concentration at the right face is C_i and if the velocity at the right face is negative then the concentration at the right face will be C_{i+1}. Figure 2 shows the choice of these concentration values.

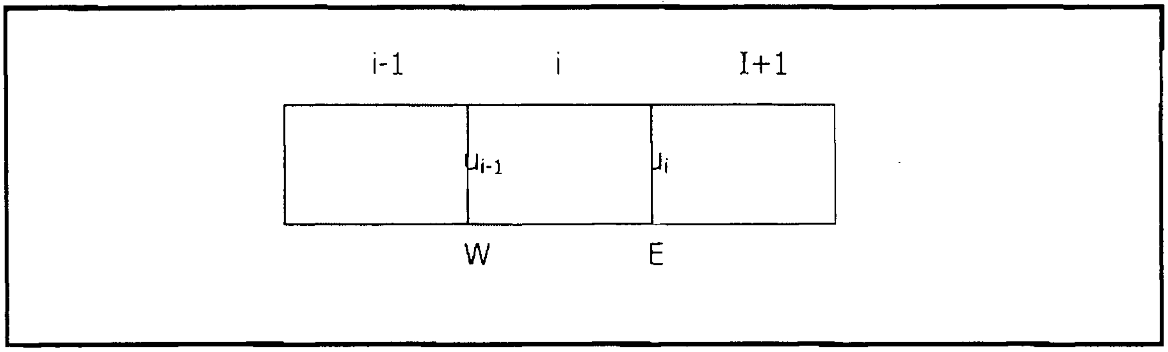

Figure 2 1-D transport schematic with face values for UPWIND scheme

For the East face (E),

If $u_i \geq 0$ then,
$C_{fe} = C_i$

If $u_i \leq 0$ then,
$C_{fe} = C_{i+1}$

For the West face (W)

If $u_{i-1} \geq 0$ then,
$C_{fw} = C_{i-1}$

If $u_{i-1} \leq 0$ then,
$C_{fw} = C_i$

Using these face values, the advective flux is calculated. For the diffusive flux, central differencing at the cell face is applied. This gives, for the east face, the following expression for diffusion:

$$(Dif)_E = \alpha_E (C_{i+1} - C_i) \tag{8}$$

$$\alpha_E = \frac{D_x * dt}{(\Delta x)^2} \tag{9}$$

where D_x is the horizontal diffusion coefficients in x –direction.

5.2 QUICKEST SCHEME

The QUICKEST (Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms) scheme originally developed by Leonard (1979) has been extended to three dimensions and incorporated in GEMSS. Unlike upwind scheme, it is third order accurate and performs well for sharp gradients. Both advection and diffusion are solved using the QUICKEST algorithm with the diffusion flux calculation based on Spasojevic et. al. (1994). QUICKEST employs a three point upstream biased interpolation scheme to calculate the face concentrations for the cell. The selection of Upstream (**U**), Current(**C**) and Downstream (**D**) cells is according to the following figure 3

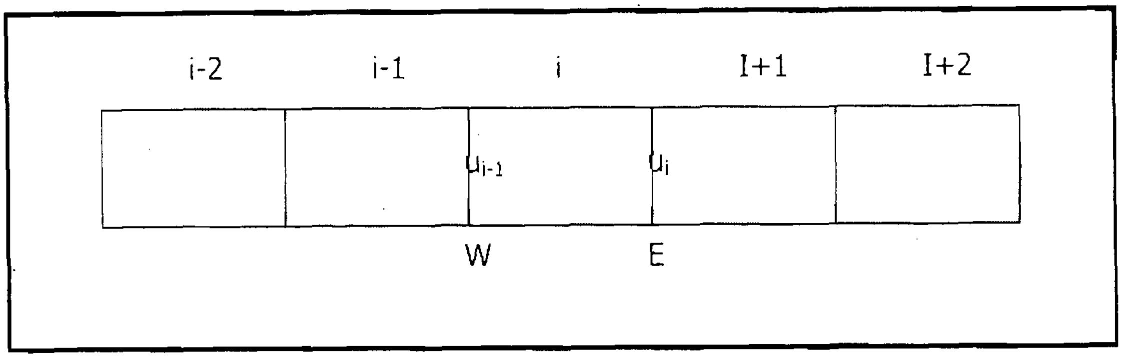

Figure 3 1-D transport schematic with face values for QUICKEST scheme

For the East face (E),

If $u_i \geq 0$ then,
U = i-1, **C** = i and **D** = i+1

If $u_i \leq 0$ then,
U = i+2, **C** = i+1 and **D** = i
For the West face (W)

If $u_{i-1} \geq 0$ then,
U = i-2, **C** = i-1 and **D** = i

If $u_{i-1} \leq 0$ then,
U = i-1, **C** = i and **D** = i+1

Using this nomenclature, the concentrations are defined as C_U, C_C and C_D for the upstream, current and the downstream cell respectively. Then the face concentration for west face is written, using QUICKEST interpolation, as

$$C_{fw} = \frac{C_i + C_{i-1}}{2} + \frac{Cour_w}{2}(C_i - C_{i-1}) - \frac{1}{6}\left(1 - Cour_w^{\,2}\right)\left(C_U - 2 * C_C + C_D\right) \tag{10}$$

Similarly for the east face the concentration is,

$$C_{fe} = \frac{C_i + C_{i+1}}{2} + \frac{Cour_e}{2}(C_{i+1} - C_i) - \frac{1}{6}\left(1 - Cour_e^{\,2}\right)\left(C_U - 2 * C_C + C_D\right) \tag{11}$$

Using these face concentration, the advective fluxes are calculated in all the three directions. The diffusive fluxes are given in the form of following equations 12 and 13

$$(Dif)_w = \alpha_w \left[(C_i - C_{i-1}) - \frac{Cour_w}{2}(C_U - 2*C_C + C_D) \right] \tag{12}$$

$$(Dif)_E = \alpha_E \left[(C_{i+1} - C_i) - \frac{Cour_w}{2}(C_U - 2*C_C + C_D) \right] \tag{13}$$

5.3 QUICKEST WITH ULTIMATE

The QUICKEST scheme is not monotonous, i.e., it produces overshoots and undershoots. Thus in order to avoid these oscillations, a universal limiter based on Leonard's work (1991) can also be applied. This limiter is called ULTIMATE (Universal Limiter for Transient Interpolation Modeling of the Advective Transport Equation) and is applied to each cell faces individually. The algorithm requires the calculation of the CURV and DEL as defined in the equations 14 and 15

$$CURV = C_D + C_U - 2*C_C \tag{14}$$
$$DEL = C_D - C_U \tag{15}$$

Depending on the values of CURV and DEL, the ULTIMATE limiter is applied to maintain it monotonic.

- If $|CURV| \leq 0.6\ |DEL|$, then the face concentration calculated by QUICKEST is used.
- If $|CURV| \geq |DEL|$, then $C_f = C_c$.
- Otherwise C_{REF} is computed according to the equation 16

$$C_{REF} = C_U + \frac{C_C - C_U}{Cour_f} \tag{17}$$

If DEL > 0, chose C_f so that $C_C < C_f < \min\ [C_{REF}, C_D]$
If DEL < 0, chose C_f so that $\max\ [C_{REF}, C_D] < C_f < C_C$

5.4 EXAMPLE APPLICATION

In order to further illustrate the difference in these algorithms consider a 2-D problem. The following results are obtained for a simplified reservoir problem with transport only in x and Z direction. The grid sizes are uniform. The reservoir is subjected to meteorology data and the results were plotted for different combination of explicit-implicit transport schemes. The results shown here are for the three explicit schemes with three different combinations of θ_a and θ_d. The chosen values for θ_a ($=\theta_d$) are 0.00, 0.55 and 1.00. A schematic of the reservoir is shown in figure 4.

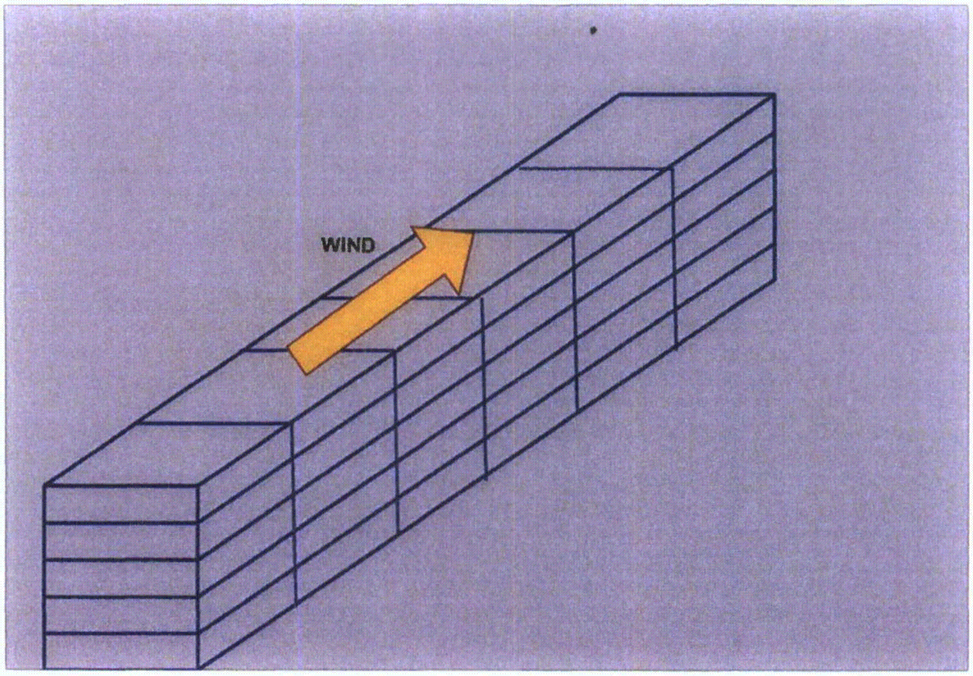

Figure 4 Schematic of 2-D transport problem to illustrate the difference between various transport schemes

The results for this problem are shown in Figures 5 through 7 using the three transport schemes and 3 different values of implicit weighting. It is expected that the reservoir will be stratified and the formation of this stratification (temperature vertical profile) is more realistic when higher order schemes, QUICKEST or QUICKEST+ULTIMATE, are used.

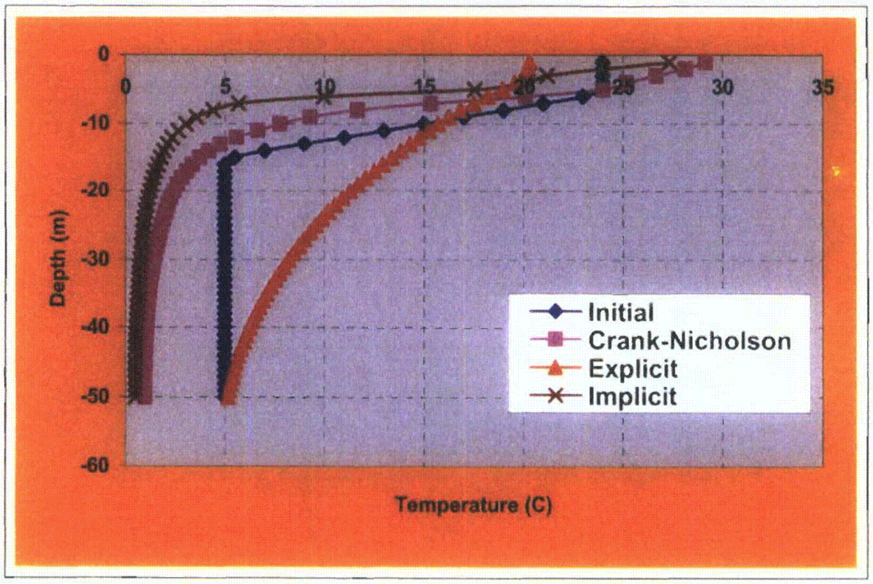

Figure 5 Vertical profile of temperature using UPWIND

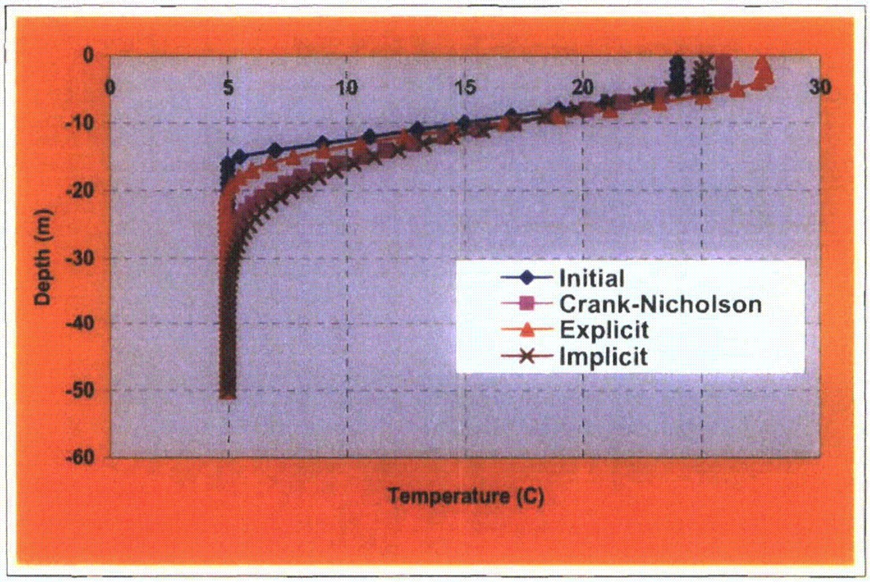

Figure 5 Vertical profile of temperature using QUICKEST

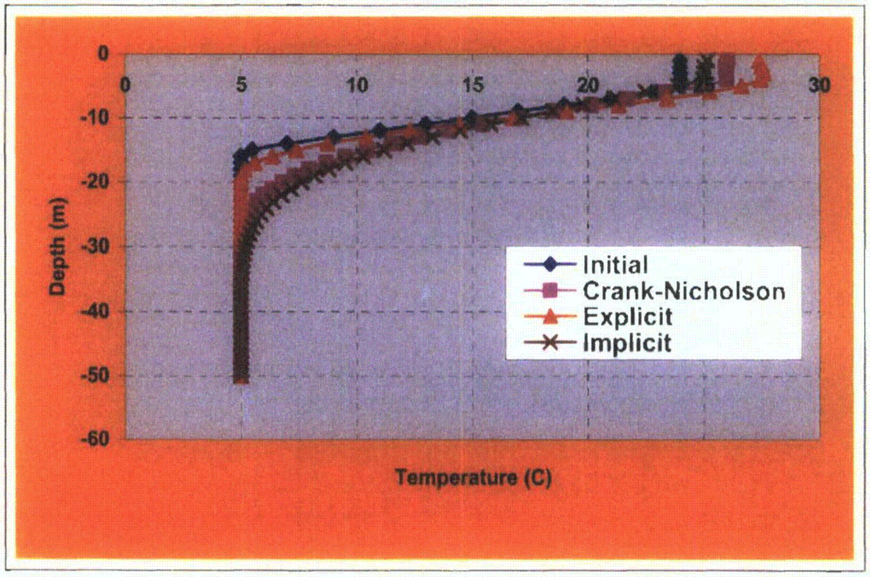

Figure 5 Vertical profile of temperature using QUICKEST with ULTIMATE

The scheme selection should be problem and goal specific. When the focus is on computational efficiency UPWIND can be used. This computational efficiency is compromised when the higher order schemes are adopted but they result in much better stratification and also QUICKEST+ULTIMATE smoothes out any computational overshoots/undershoots.