

ATTACHMENTS

Prepared for

South Carolina Electric and Gas
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**THERMAL MIXING ZONE EVALUATION
VIRGIL C. SUMMER NUCLEAR STATION
NPDES PERMIT
FAIRFIELD COUNTY, SOUTH CAROLINA**

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1. INTRODUCTION

South Carolina Electric and Gas (SCE&G, a subsidiary of SCANA Corporation) is making an application to the South Carolina Department of Health and Environmental Control (DHEC) for a renewal of its National Pollutant Discharge Elimination System (NPDES) permit for Unit 1 of the Virgil C. Summer Nuclear Generating Station (V. C. Summer Station) located in Fairfield County near Jenkinsville, South Carolina.

This document presents background and technical information supporting formal requests to DHEC for the thermal mixing zone for the V. C. Summer Station cooling water effluent discharge to the Monticello Reservoir pursuant to Rule 61-68 (Water Classifications and Standards) Section C.10.

Facility Description

Summer Station is a single-unit, 974-megawatt (MW) nuclear-fueled electric power generating facility that operates as a base-load facility. It uses a once-through cooling water system that withdraws cooling water from Monticello Reservoir via a single shoreline-positioned cooling water intake structure (CWIS) located at the south end of the reservoir. After the cooling water leaves the condensers, the heated water is conveyed to a “discharge bay” and then through a 1,000 foot (ft) discharge canal leading into Monticello Reservoir.

Monticello Reservoir is a 6,800-acre (ac) freshwater impoundment that was built in the Frees Creek valley in 1978 to serve both as the cooling water source for Summer Station and the upper pool for the Fairfield Pumped Storage Facility (FPSF). The Federal Energy Regulatory Commission (FERC) regulates water levels in Monticello Reservoir through the hydropower license for SCE&G’s Parr Shoals (Broad River) Hydroelectric Project (FERC License No. 1894), of which FPSF is a part. The FERC license for Parr Shoals establishes water surface elevation guidelines for Monticello Reservoir between 425.0 feet (ft) above mean sea level (msl) (high water level) and 420.5 ft msl (low water level). Reservoir levels may fluctuate daily within this 4.5-ft operating band as a result of FPSF operation.

The operation of the FPSF will vary depending on the season and system power needs. In summer, the facility generally pumps water from Parr Reservoir to Monticello Reservoir between the hours of 11:00 pm and 8:00 am and generates power by releasing



water between the hours of 10:00 am and 11:00 pm. In winter, FPSF generally pumps water daily from Parr Reservoir to Monticello Reservoir between 11:00 pm and 6:00 am and generates between the hours of 6:00 am and 1:00 pm. Pumping to Monticello Reservoir is normally done at maximum capacity during off-peak periods. The power output for FPSF varies from one generator up to the maximum output from eight generators, depending on demand. Consistent with its operation as a peaking facility, maximum output of FPSF may not be necessary on all days.

Permitting History

The NPDES permitting history for the Summer Station discharge extends from the mid-1970s when the facility was first permitted. Operating as a once-through cooling water system, thermal addition to Monticello Reservoir is substantial with discharge flow rates up to 532,000 gallons per minute (768 million gallons per day). To comply with South Carolina Department of Health and Environmental Control (DHEC) water quality standards for temperature in lakes, SCE&G conducted studies to successfully support alternate thermal effluent limitations under Clean Water Act Section 316(a) per South Carolina Regulation 61-68 – Water Classifications and Standards: Section E.12.c.)¹. The following numeric effluent limitations for temperature were established for Summer Station Outfall 001 in the initial permit:

- a daily maximum temperature of 113°F to be measured “in pipe” prior to discharge;
- a monthly average temperature of 90°F measured at the FPSF intake structure (considered the mixing zone boundary);
- a maximum thermal plume size of 6,700 acres; and

¹ The weekly average water temperature of all Freshwaters which are lakes shall not be increased more than 5°F (2.8°C) above natural conditions and shall not exceed 90°F (32.2°C) as a result of the discharge of heated liquids unless a different site-specific temperature standard as provided for in C.12. has been established, a mixing zone as provided in C.10. has been established, or a Section 316(a) determination under the Federal Clean Water Act has been completed (South Carolina Regulation 61-68 – Water Classifications and Standards: Section E.12.c.).



- a monthly average temperature rise (ΔT) within the plume of 3°F measured between the FPSF intake structure and a point at the northern end of the reservoir.

Based on several years of monitoring, DHEC ultimately eliminated the plume size and ΔT limitations leaving in place the 113°F daily maximum limit and 90°F monthly average limit in subsequent permits.

Thermal discharges and repeated continuation of alternate thermal limits (variances) in NPDES permits that are based on historical 316(a) demonstration study data have come under increased scrutiny by the U.S. Environmental Protection Agency (USEPA) who oversees the DHEC NPDES program. Recently, DHEC and SCE&G have had discussions relative to renewal of the current NPDES permit for V. C. Summer Station concerning the level of information needed to support the continued discharge temperature limits for the facility. There have been no substantive changes² to V. C. Summer Station operations since issuance of the initial NPDES permit in the mid-1970s. As such, SCE&G believes that reevaluation of the thermal mixing zone characteristics and boundaries via updated hydrodynamic modeling (in complement to the earlier 316(a) demonstration study data) will provide the quantitative information needed by DHEC to support a decision maintaining the current temperature limits for Summer Station that is consistent with South Carolina Regulation 61-68, Section E.12.

Related Modeling Work

The primary modeling study related to the thermal plume characteristics of the cooling water discharge for the V. C. Summer Station was carried out by NUS Corporation in 1985 [1] and updated in 1989 [2]. A mathematical model of the lake was created which accounted for discharge and atmospheric parameters and calculated the thermal plume based on assumed vertical temperature profiles. The conclusions of the study showed that the VC Summer Station would not violate any of the three quantitative temperature limits in the NPDES permit at the time, even under extreme meteorological conditions.

² Licensed power output of the V.C. Summer Station Unit 1 has been increased, but due to some cooling loads being handled by a small cooling tower, the heat loading to the reservoir has not changed significantly. Additionally, the discharge canal was dredged (canal is now deeper than it was originally) to alleviate fish kills in the discharge bay area.



While certainly an advanced and comprehensive analysis at the time, the NUS study did not consider several important features of the thermal discharge. In particular, the Unit 1 cooling water discharges into a small basin (approximately 600 ft x 600 ft surface dimension), which is connected to the reservoir through a channel approximately 900 ft in length and 200 ft wide. The dynamics in the basin and channel are complex; recirculating flows in the basin, and an unusual return flow of cold water flowing along the bottom of the channel from the reservoir to the basin. These features could not have been reasonably accounted for and calculated by the NUS study, and neither can they be calculated with more modern tools such as CORMIX [3], since in both these cases underlying assumptions are made regarding the temperature profiles.

In order to more definitively characterize the V. C. Summer Station Unit 1 thermal discharge into the hydrodynamically and spatially complex mixing environment in the basin, channel and reservoir, a more robust modeling approach was needed. As such, three-dimensional Computational Fluid Dynamics (CFD) modeling effort was conducted.

CFD modeling is based on the Navier-Stokes equations for fluid motion, which are simply an expression of Newton's laws of motion with additional viscous stress terms required to calculate fluid flow [4]. The equations express the laws of conservation of mass, momentum and energy and are hence a "fundamental" set of equations (i.e., no assumptions are made in forming the basic equation set).

CFD modeling has been used successfully for over 40 years in a variety of industrial and environmental applications. The Tennessee Valley Authority (TVA) used CFD modeling to evaluate the thermal discharge from its Browns Ferry Nuclear Power Plant to Wheeler Reservoir in north Alabama [5]. The CFD model allowed TVA to determine thermal plume mixing and temperature rise patterns as well as other hydrodynamic features of the discharge. Notably, TVA found close agreement between CFD model predicted water temperatures and direct temperature measurements at the operating diffusers.

More recently, Geosyntec Consultants and MMI Engineering employed CFD to model the complex thermal plume characteristics of the proposed William States Lee III Nuclear Generating Station, as part of the NPDES permit application for the site submitted by Duke Energy to DHEC. Similar to the current study, the thermal plume



was affected by operations in the receiving water body that significantly affected the surface elevation.

Other examples of CFD environmental applications include the U.S. Department of Energy's Pacific Northwest National Laboratory use of CFD in the hydrodynamic evaluation of the North Fork Dam forebay on the Clackamas River in Oregon and to model the three-dimensional velocity field below Bonneville Dam to enhance fish passage [6]. CFD has also been used to investigate the increased discharge associated with the re-powering of an existing power plant [7].

2. GENERATION OF THE COMPUTATIONAL MODEL

Geosyntec/MMI Engineering uses a variety of classical and computational analysis techniques to assess the performance of fluid systems and processes. For detailed CFD analysis, calculations are made with the general purpose, commercial CFD code ANSYS-CFX Version 12 [8]. This is the CFD model code selected for the current analysis. Full details of the computational model are given in Appendix A.

The extent (geometry) of the Monticello Reservoir and discharge bay and canal environment in the CFD models included:

- the Unit 1 discharge bay and canal;
- the Fairfield Pumped Storage Facility intakes;
- the backwater areas in the locality of the canal; and,
- a section of the Monticello Reservoir extended approximately 1.6 miles north of the discharge structure.

Total surface area of the modeled domain was approximately 1800 acres, or approximately 25% of the total surface area of the reservoir.

Bathymetry data in the discharge bay and canal, and in part of the Monticello Reservoir, was collected by Geosyntec in the form of point-depth measurements in a series of transects. These point data were interpolated to form part of the reservoir bed in the CFD models. For the areas of the model that were not covered by the bathymetry data, a contour map was provided to MMI/Geosyntec (a section of this map is shown in



Figure 3) and was digitized by MMI/Geosyntec to create approximately 10,000 additional data points (Figure 4) that were combined with the collected bathymetry data to form the entire model (see Figure 5 and Figure 6). A more detailed view of the model in the vicinity of the discharge, showing the bay and canal, is shown on Figure 7 and Figure 8.

Detailed drawings of the discharge structure were not available; however the shape of the structure and its dimensions and exact location can be calculated from aerial photographs. The discharge pipe diameter is 144" [9], and in the model this was represented as a square cross-section (rather than circular) of the same area as the circular pipe. This ensures the correct mass, energy and momentum input into the model and the highly turbulent flows near the discharge would quickly smooth out small differences in the shape of the discharge pipe.

Views of the computational mesh, which contained approximately 500,000 cells with 20 cells in the depth direction, are shown on Figure 9 and Figure 10.

3. SCENARIOS

The following modeling scenarios were run to capture the expected worst case results (thermally and spatially) for the Summer Station thermal discharge:

- **Scenario 1** – Thermal discharge under peak load and discharge flow with Monticello Reservoir elevation under high water-slack conditions (no flow through FPSF).
- **Scenario 2** – Thermal discharge under peak load and discharge flow with Monticello Reservoir elevation under low water-slack conditions (no flow through FPSF).
- **Scenario 3** – Thermal discharge under peak load and discharge flow with Monticello Reservoir elevation under low water-rising conditions (FPSF pump-back); and
- **Scenario 4** – Thermal discharge under peak load and discharge flow with Monticello Reservoir elevation under high water-falling conditions (FPSF generation).

Each scenario was modeled under critical conditions of summer when ambient reservoir and discharge temperatures are expected to be greatest and have the most potential for acute effects to aquatic life. This will allow evaluation of thermal plume mixing characteristics and spatial dimensions in the context of the DHEC 90°F temperature criterion. Based on data transmitted to MMI/Geosyntec [10], the ambient reservoir temperature was set to 86.4°F as this was the highest monthly-average temperature recorded at the Unit 1 intakes in 2010. The discharge temperature was set to 113.0°F which was measured during August 2011, and is approximately 1°F higher than the recorded highest monthly-average discharge temperature in 2010.

Additionally, each scenario was also modeled under winter conditions when differential between the plume temperature and ambient temperature (i.e., ΔT) are expected to be greatest. This will allow evaluation of thermal plume mixing characteristics and spatial dimensions in the context of the DHEC 5°F ΔT temperature criterion. Based on data transmitted to MMI/Geosyntec [10], the highest monthly-averaged ΔT for 2010 occurred in November, where the monthly-average reservoir temperature was recorded at 66.6°F and the monthly-average discharge temperature was 98.7°F, resulting in a ΔT of 32.1°F. These temperature values were used to represent winter conditions.

In all cases, the discharge flow rate was set to 532,000 gpm which is the flow rate through the Unit 1 intake with all three intake pumps fully operational. Based on data transmitted to MMI/Geosyntec [11], the flow rate for FPSF pump-back was set to 41,800 cfs and the flow rate for FPSF generation was set to 50,400 cfs.

4. VALIDATION OF THE COMPUTATIONAL MODEL

Geosyntec collected temperature and velocity profiles during a data survey conducted on the Monticello Reservoir in August 2011. The most useful “snapshot” of the temperature of the thermal plume was taken at around 2pm on August 3rd 2011 in the form of five temperature profiles extending to a maximum depth of 25ft. These profiles are shown on Figure 11 (note that the temperature scale is in degrees Celsius). At the time of the measurements, the discharge temperature was 44.1°C (111.4 °F) and this is shown for reference on Figure 11 by the broken purple line on the right. The most striking feature of the measurements is the difference between the discharge temperature and the measured temperature in the discharge bay (i.e. almost immediately downstream of the discharge). This profile is shown in blue in the figure. If the water in the discharge bay were from the discharge alone, then a temperature near to 44.1°C



would be expected as the only losses would be minor. However, the measurements show temperatures around 40°C in the discharge bay. An indication of the explanation for this can be deduced from the temperature profile taken at the confluence of the discharge bay and canal (shown in red). For depths below 15 ft, the temperature reduces rapidly to less than 34°C. The profile taken at the mouth of the discharge canal (green) has a similar dramatic reduction in temperature below 10 ft depth, to just above 30°C near the bottom, which is approximately the same as the recorded background temperature (light blue). It appears from the data that it is likely that these temperature profiles comprise discharge (hot) water in the upper layer and ambient (cold) water in the lower layer, which, since this pattern is repeated at in the discharge bay (red line) suggests that cold water is flowing from the reservoir into the bay along the bottom of the discharge canal, and hot water is flowing in the opposite direction near the surface. Indeed, this phenomenon of warm water flowing over cool water in the discharge canal was explained to MMI/Geosyntec staff by SCE&G staff prior to the measurements being taken. The field measurements confirmed this.

A somewhat less expected feature of the temperature profiles is the apparent inversion in the upper 5ft of the profiles, where the temperature reduces significantly, suggesting a cooler, more dense layer near the surface on top of a warmer and less dense layer below (in opposition to the natural tendency of buoyancy). The only physical explanation for this reduction in temperature is a very high rate of heat loss at the surface, much higher than one would expect by classical heat loss calculations alone. This may be linked to waves generated by the discharge or the wind, or churning aeration of the very upper layer.

To investigate the accuracy of the computational model, a simulation was run to approximate the thermal plume as closely as possible at the time the measurements were taken. The discharge temperature was set to 44.1°C (111.4 °F) and the flow rate was set to 532,000 gpm. The surface elevation of the reservoir was set to 423.5 ft msl which was calculated from level-loggers installed by Geosyntec. In addition, a surface shear stress was applied that was equivalent to a 10 ft/s north-easterly wind which was recorded on the day.

Figure 12 shows a contour plot of temperature on the surface of the reservoir resulting from the simulation. The blue coloration indicates the ambient temperature of the reservoir (set as 32.0°C) while the red coloration indicates a temperature equal to the discharge temperature. The plume can be seen to gradually reduce in temperature away

from the discharge bay and canal. Interestingly, the oranges and yellows in the discharge bay as predicted in the CFD model indicate much lower temperatures than in the discharge pipe. To investigate this further, two contour plots were produced of temperature on the surface and at 18 ft depth – these are shown on Figure 13 (a) and (b) respectively. Figure 13 (a) shows a close view of the contour plot in Figure 12, and surface temperatures of approximately 41.0°C can be observed. However, Figure 13 (b) which is the temperature at 18 ft depth, shows much cooler (blue) temperatures near the bottom of the discharge canal, as was observed in the field measurements. A clear visualization of this phenomenon can be seen on Figure 14, where velocity vectors are shown on a vertical cut-plane in the center of the canal, and are colored by temperature rather than velocity. There is a clear flow of cold water from the reservoir to the discharge bay in the lower layers, and a flow of hot water in the reverse direction in the upper layers.

Qualitatively the model thus agrees with the anticipated flows, despite these flows being unusual. A quantitative comparison is shown on Figure 15 where the lines indicate results from the CFD model and the circles indicate measured data. The colors of the lines and circles match where the profiles were taken at the same locations. The CFD results in the discharge bay (blue line) shows that the temperature has decreased in the discharge bay by approximately the correct amount. This is due to the counter-flow of cold water into the bay from the reservoir, which is shown by the CFD model results at the confluence of the discharge bay and canal (red line). The sharp decrease in temperature mirrors the measured temperature gradient well. The major differences between the model and measured temperature profiles exist within the upper layer, where the inversion is not predicted by the CFD model. This is not unexpected since it is difficult to account for the inversion recorded by the data. However, it is important to note that the differences between the model and the data result in a higher surface temperature being predicted by the CFD model, showing that the model results will in general be conservative. At the mouth of the discharge canal (green line) the surface temperature is again over-predicted, but the sharp temperature gradient seen below 5 ft depth is captured, albeit at a slightly shallower depth in the model than was measured. Importantly, the model and data match well in the region halfway between the canal and exclusion buoys (orange), as the edges of the thermal plume are expected near this region. The last profile comparison (light blue line) is simply the background profile, which was set as constant in the CFD model but showed slight variation with depth in the measured data, probably due to naturally formed thermoclines rather than the



thermal plume itself given the distance between the measurement and the discharge (approximately 2 miles).

The validation effort therefore shows that the CFD model qualitatively predicts the correct behavior, particularly with respect to the known unusual flows in the discharge canal. The agreement between the model and measured data is generally good, with the greatest discrepancies near the surface of the reservoir. Where these discrepancies occur, the CFD model over-predicts the measured data, so the model results are conservative with respect to surface temperature and therefore the size and magnitude of the thermal plumes.

5. MODEL RESULTS – T = 90°F PLUME

The four scenarios listed in §3 were run under summer conditions to evaluate the size of the 90°F thermal plume, as these conditions represent the worst-case scenarios for this plume. In all scenarios the discharge temperature was set to 113.0°F and the ambient reservoir temperature was 86.4°F. The scenarios for summer conditions are referred to as 1S, 2S, 3S and 4S in the text and figure captions, and the input parameters and results are summarized in §7 for reference.

The surface temperature for scenario 1S is shown on Figure 16. In this scenario, the reservoir surface elevation is high (425.0 ft msl) and the FPSF flow rate is zero (slack conditions). This figure provides a full view of the thermal plume in plan view, although it must be remembered that the analysis is three-dimensional so variations in temperature in the depth direction are captured. As anticipated, the hot plume spreads and cools as it mixes with the ambient water downstream of the discharge canal (the red areas in the figure represent temperatures about 112.0°F and the blue indicates less than 87.0°F). The 90°F plume is difficult to distinguish from the contour plot, so it is shown more clearly on Figure 17 where the purple area shows the 90.0°F. Note that the area shown on this figure does not necessarily extend vertically down to the bottom of the reservoir, as the temperature gradients highlighted in the validation study will also exist here. The dimensions of the thermal plume account for these variations as the computational model is three-dimensional. The volume of the 90.0°F plume for scenario 1S is 1,418 acre-ft and the surface area is 128 acres. The maximum length of the plume, which is taken from the end of the discharge pipe to the point in the plume furthest away from the pipe, is 4,332 ft, while the width of the plume (the maximum width in approximately an east-west direction) is 3,312 ft. Note that although the



maximum depth of the plume is 40 ft, the average depth of the plume is only 6.4 ft, indicating that the majority of the plume is relatively shallow.

Scenario 2S is the same simulation as scenario 1S but at a low surface elevation (420.5 ft). As the volume of the ambient water is reduced in the reservoir, but the flow rate from the discharge remains the same, it might be expected that the plume would be slightly larger in volume than the previous scenario. This is indeed the case – the volume of the 90°F plume is 1,627 acre-ft and the surface area is 150 acres. The temperature contours and 90°F plume for this case are shown on Figure 19.

When the FPSF is pumping under low surface elevation, approximately 41,800 cfs is injected into the reservoir at the ambient reservoir temperature. This is the situation modeled in scenario 3S. The velocity vectors on the surface of the reservoir are shown on Figure 20 where the scale is from zero velocity (blue) to 3 ft/s (red). Although the jet from the FPSF is set almost directly from west to east in the model, the proximity and angle of the coast just to the south of the FPSF causes the jet to turn south, resulting in a large recirculation region bounded by the jetty and the island. Although the change to the flows in the western region of the lake are significantly changed, the raised jetty effectively shields the thermal plume, so that neither the temperature contours (Figure 21) or the 90°F plume (Figure 22) are changed from slack conditions (compare to scenario 2S). Indeed, the 90°F plume are very similar to those in scenario 2S: the plume volume is 1,626 acre-feet, the surface area is 150 acres and the maximum length and width are 4,699 ft and 3,830 ft respectively.

The final scenario under summer conditions is 4S, where the FPSF is generating, removing 50,400 cfs of flow from the reservoir. This generates a velocity field pointing towards the FPSF intakes, as shown by the velocity vectors on Figure 23 (the scale in this figure is from zero (blue) to 1 ft/s (red)). Note that the influence of the FPSF is lesser when the flow is being withdrawn from the reservoir rather than injected, since the flow is withdrawn from all angles rather than the highly directional jet seen in Figure 20. The withdrawal of fluid from the reservoir does have the effect of “pulling” the plume and results in a stretched but shallower thermal plume – the maximum length and width of the plume are 4,775 ft and 3,705 ft respectively, but the average depth has reduced to 6.1 ft. Overall the 90°F plume is largest in this flow regime, with a volume of 1,790 acre-ft and a surface area of 163 acres. The reason why the generating rather than pumping regime increases the plume size is twofold: first, the “pulling” of the fluid is less turbulent and does not cause additional mixing; second, the flow does not sharply

turn, as was shown by the vectors near the island for the previous scenario. The surface temperature contours and 90°F plume for this case are shown on Figure 24 and Figure 25 respectively.

A summary of these results is given by the table in §7.

6. MODEL RESULTS – $\Delta T = 5^\circ\text{F}$ PLUME

The worst case for the $\Delta T = 5^\circ\text{F}$ thermal plume is under winter conditions where the temperature difference between the background and discharge is greatest. As explained in §3, this occurs in November where the monthly-average ambient reservoir temperature is 66.6°F and the discharge temperature is 98.7°F, a ΔT of 32.1°F. These temperatures were set for all four winter scenarios, and are referred to as 1W, 2W, 3W and 4W in the text and figure captions, and the input parameters and results are summarized in §8 for reference.

The surface temperature for scenario 1W (high surface elevation, slack conditions) is shown on Figure 26. Similar to the figures for the summer conditions, the blue coloration indicates ambient temperatures and red indicates temperatures similar to the plume; however in winter the ambient temperature is now 66.6°F and the plume temperatures is 98.7°F. In this color scale the thermal plume appears to be similar in shape and size to the summer plumes, but it is the $\Delta T = 5^\circ\text{F}$ rather than the 90°F plume that is of interest here. This is shown for scenario 1W by the green area in Figure 27. This plume is visibly smaller than the 90°F plumes in the previous section. The volume of the $\Delta T = 5^\circ\text{F}$ for this scenario is 799 acre-feet and the surface area is 77 acres. The maximum length and width are 3,391 ft and 2,763 ft respectively, while the average depth is 6.5 ft.

The same simulation but for low surface elevation of 420.5 ft msl was run as scenario 2W. For the summer simulations, the reduced surface elevation resulted in a larger thermal plume, and this is also the case for the winter conditions, as the volume has increased to 1,005 acre-ft and the surface area has increased to 107 acres. Similarly, the maximum length and width have increased to 4,129 ft and 3,190 ft respectively, but the plume on average is shallower with an average depth of 5.5 ft. The temperature contours and plume can be seen on Figure 28 and Figure 29.



A large recirculation zone was observed in the summer simulation with the FPSF pumping, and this is also seen under winter conditions in Figure 30, which shows velocity vectors (blue is zero, red is 3 ft/s) for scenario 3W. The vectors are very similar to those for scenario 3S, which is expected as the FPSF pumping flow rate is the same in both cases. However, unlike the summer scenario where an almost identical plume resulted with the FPSF pumping, in this case the plume is slightly bigger. This is not noticeable on the temperature contours (Figure 31) or the plume visualization (Figure 32) but the statistics show a marginal increase in plume size, to 1,148 acre-ft volume and 120 acres surface area. The maximum length and width has also increased to 4,219 ft and 3,325 ft respectively, but the average depth remains the same as scenario 2W at 5.5 ft.

Scenario 4W is the final scenario under winter conditions, simulating FPSF generating flow (50,400 cfs removed from the reservoir). The velocity vectors for this scenario are shown on Figure 33, which show the effect of the flow being removed from the reservoir. Similar to the results for summer conditions, the generating condition for the FPSF results in an extended but shallower plume; the surface area is 110 acres and the average depth is 5.8 ft. The plume dimensions are 3,183 ft for maximum width and 3,901 ft for maximum length, and result in an increase in volume over scenario 1W to 1,043 acre-feet.



7. RESULTS SUMMARY – T = 90°F PLUME

	Scenario 1S	Scenario 2S	Scenario 3S	Scenario 4S
Description	<i>Summer, high water, slack</i>	<i>Summer, low water, slack</i>	<i>Summer, low water, pumping</i>	<i>Summer, high water, generating</i>
Reservoir Surface Elevation	425.0 ft msl	420.5 ft msl	420.5 ft msl	425.0 ft msl
Reservoir Temperature	86.4°F	86.4°F	86.4°F	86.4°F
Discharge Flow	532,000 gpm	532,000 gpm	532,000 gpm	532,000 gpm
Discharge Temperature	113.0°F	113.0°F	113.0°F	113.0°F
FPSF Operation	0 cfs	0 cfs	+ 41,800 cfs	- 50,400 cfs
Dimensions of the T = 90°F Thermal Plume				
- Volume	1,418 acre-ft	1,627 acre-ft	1,626 acre-ft	1,790 acre-ft
- Surface area	128 acre	150 acre	150 acre	163 acre
- Average Depth/Thickness	6.4 ft	6.0 ft	5.9 ft	6.1 ft
- Maximum Depth/Thickness	40 ft	36 ft	36 ft	40 ft
- Maximum Width	3,312 ft	3,840 ft	3,830 ft	3,705 ft
- Maximum Length³	4,332 ft	4,699 ft	4,699 ft	4,775 ft

³ Calculated from the end of the discharge pipe.

8. RESULTS SUMMARY – $\Delta T = 5^\circ F$ PLUME

	Scenario 1W	Scenario 2W	Scenario 3W	Scenario 4W
Description:	<i>Winter, high water, slack</i>	<i>Winter, low water, slack</i>	<i>Winter, low water, pumping</i>	<i>Winter, high water, generating</i>
Reservoir Surface Elevation	425.0 ft msl	420.5 ft msl	420.5 ft msl	425.0 ft msl
Reservoir Temperature	66.6°F	66.6°F	66.6°F	66.6°F
Discharge Flow	532,000 gpm	532,000 gpm	532,000 gpm	532,000 gpm
Discharge Temperature	98.7°F	98.7°F	98.7°F	98.7°F
FPSF Operation	0 cfs	0 cfs	+ 41,800 cfs	- 50,400 cfs
Dimensions of the $\Delta T = 5^\circ F$ Thermal Plume				
- Volume	799 acre-ft	1,005 acre-ft	1,148 acre-ft	1,043 acre-ft
- Surface area	77 acre	107 acre	120 acre	110 acre
- Average Depth/Thickness	6.5 ft	5.5 ft	5.5 ft	5.8 ft
- Maximum Depth/Thickness	40 ft	36 ft	36 ft	40 ft
- Maximum Width	2,763 ft	3,190 ft	3,325 ft	3,183 ft
- Maximum Length⁴	3,391 ft	4,129 ft	4,219 ft	3,901 ft

⁴ Calculated from the end of the discharge pipe.



9. RELEVANCE TO THE THERMAL MIXING ZONE RENEWAL

The results of the thermal modeling relative to the thermal mixing zone are as follows.

For the $T = 90^{\circ}\text{F}$ plume:

- The maximum plume dimensions occur in summer, when the reservoir is at high surface elevation (425.0 ft msl) and the FPSF is generating.
- The maximum volume is 1,790 acre-ft.
- The maximum surface area is 163 acres.
- The maximum length is 4,775 ft.
- The maximum width is 3,705 ft.

For the $\Delta T = 5^{\circ}\text{F}$ plume:

- The maximum plume dimensions occur in winter, when the reservoir is at low surface elevation (420.5 ft msl) and the FPSF is pumping.
- The maximum volume is 1,148 acre-ft.
- The maximum surface area is 120 acres.
- The maximum length is 4,219 ft.
- The maximum width is 3,325 ft.

The above results indicate that the $T = 90^{\circ}\text{F}$ plume has a larger impact than the $\Delta T = 5^{\circ}\text{F}$ plume.



10. REFERENCES

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<http://www.ansys.com/default.asp>.
- [9] *Piping Yard Plan – Non Nuclear*, SCE&G Drawing E-303-202.
- [10] *Email correspondence*, from Summer, S. (SCE&G) to Heynes, O. (MMI) on 11/28/11 at 12:15 PM.
- [11] *Email correspondence*, from Summer, S. (SCE&G) to Heynes, O. (MMI) on 11/28/11 at 12:07 PM.

11. FIGURES



Figure 1 – Aerial photograph of the Monticello Reservoir and V. C. Summer Station



Figure 2 – Close aerial photograph of the Monticello Reservoir and V. C. Summer Station

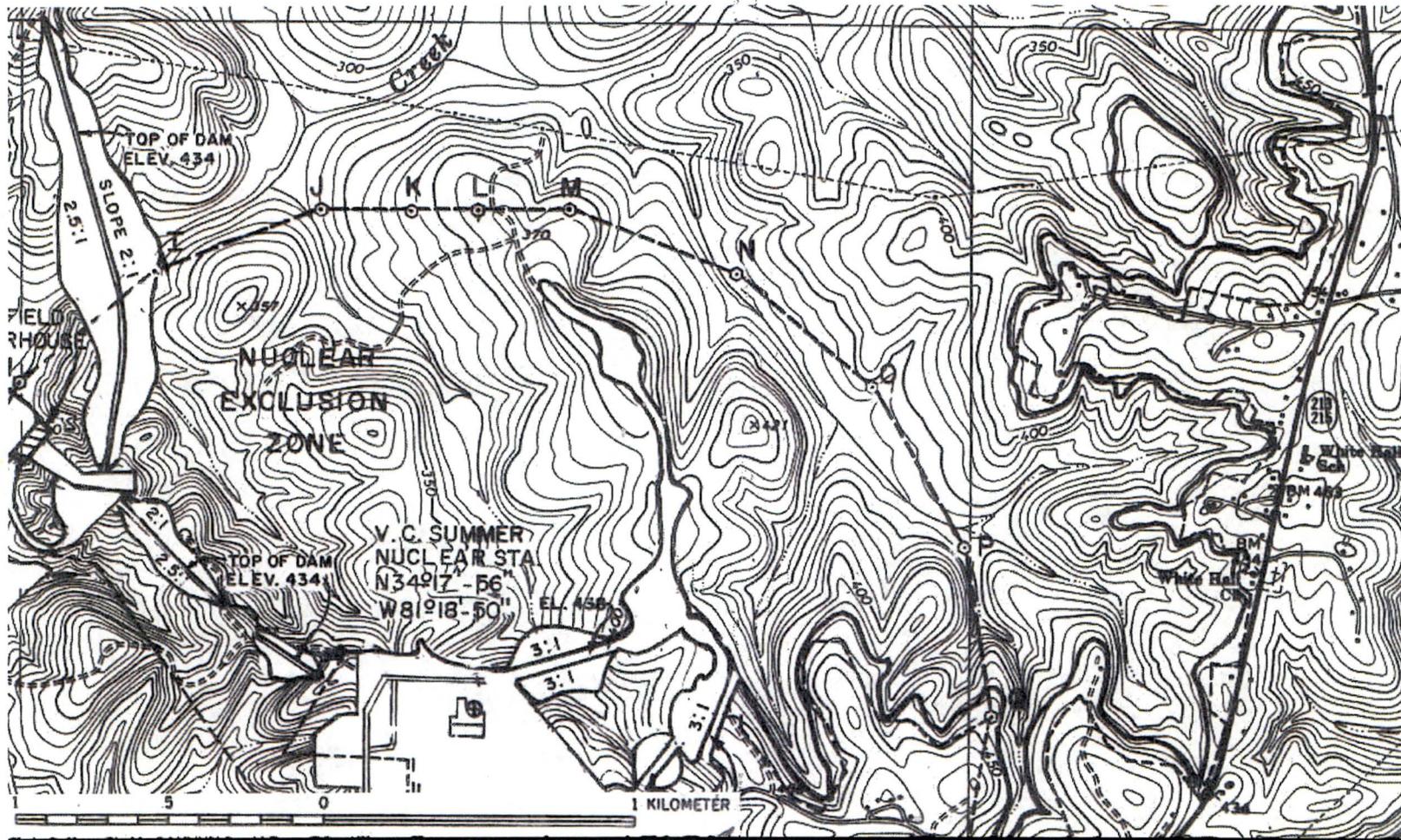


Figure 3 – Contour map of the Monticello Reservoir in the vicinity of the Unit 1 thermal discharge.

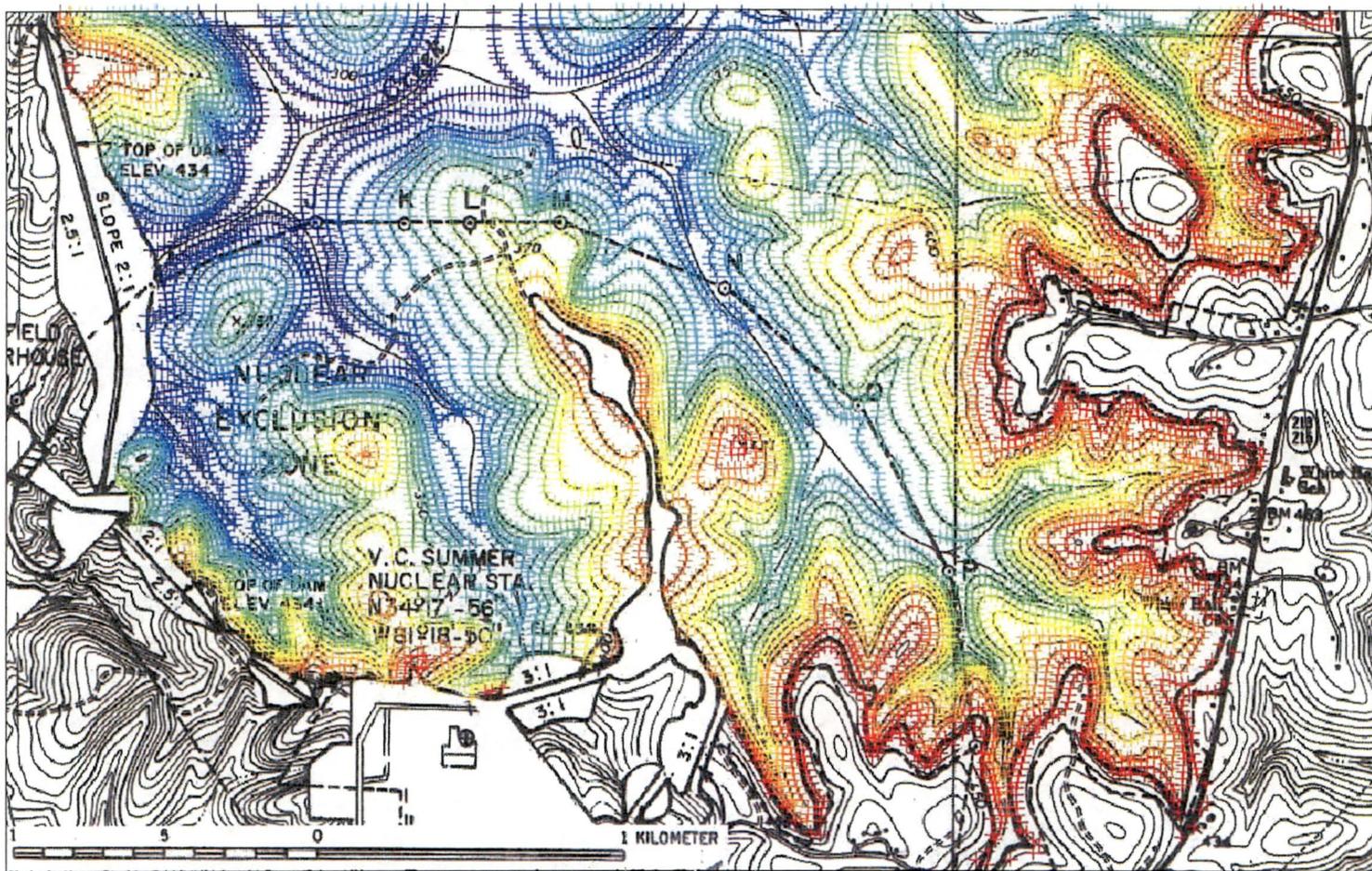


Figure 4 – Digitized points from the contour map, colored by elevation (red is 430 ft msl, blue is 270 ft msl).

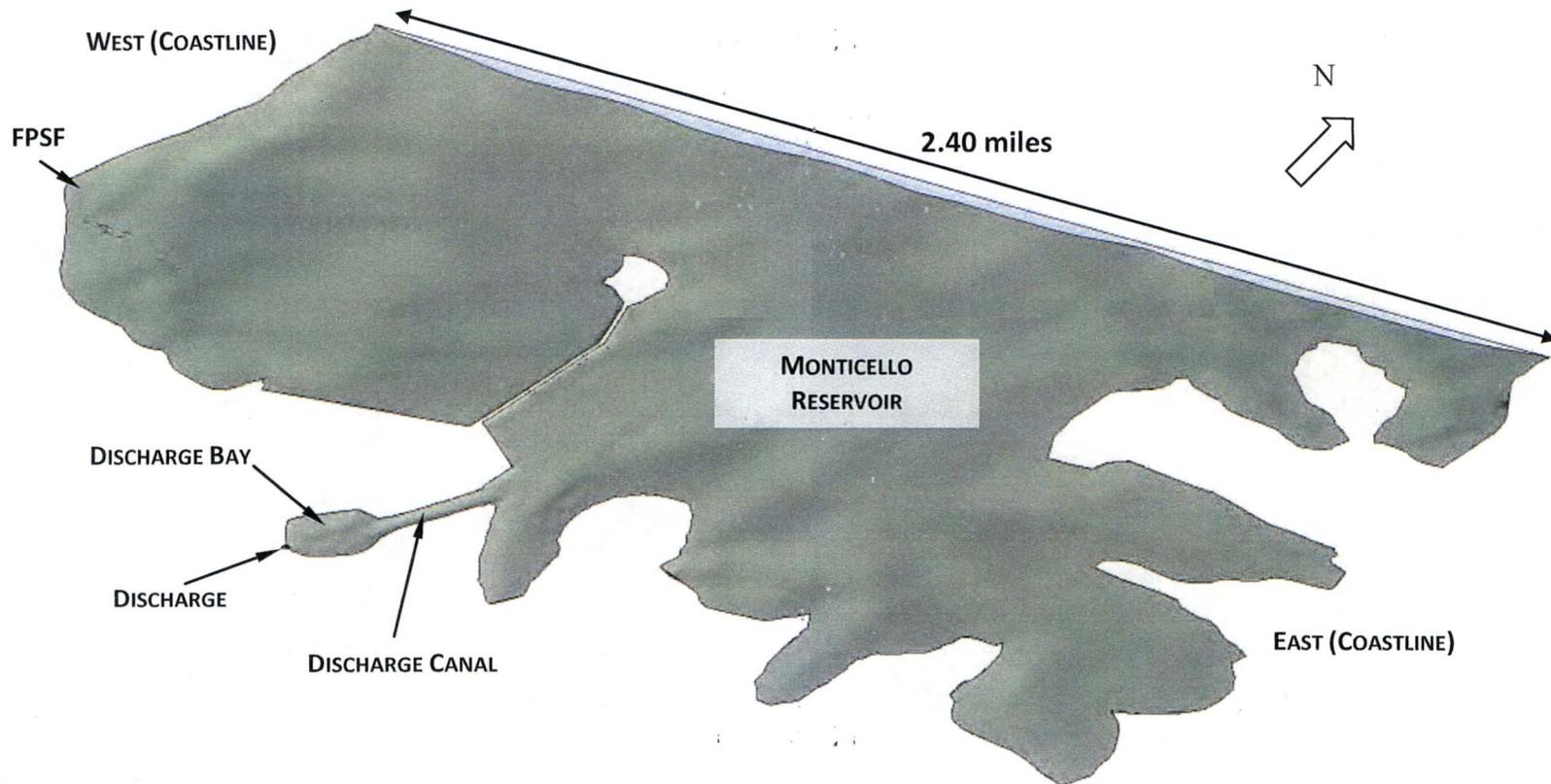


Figure 5 – Perspective view of the computational model.

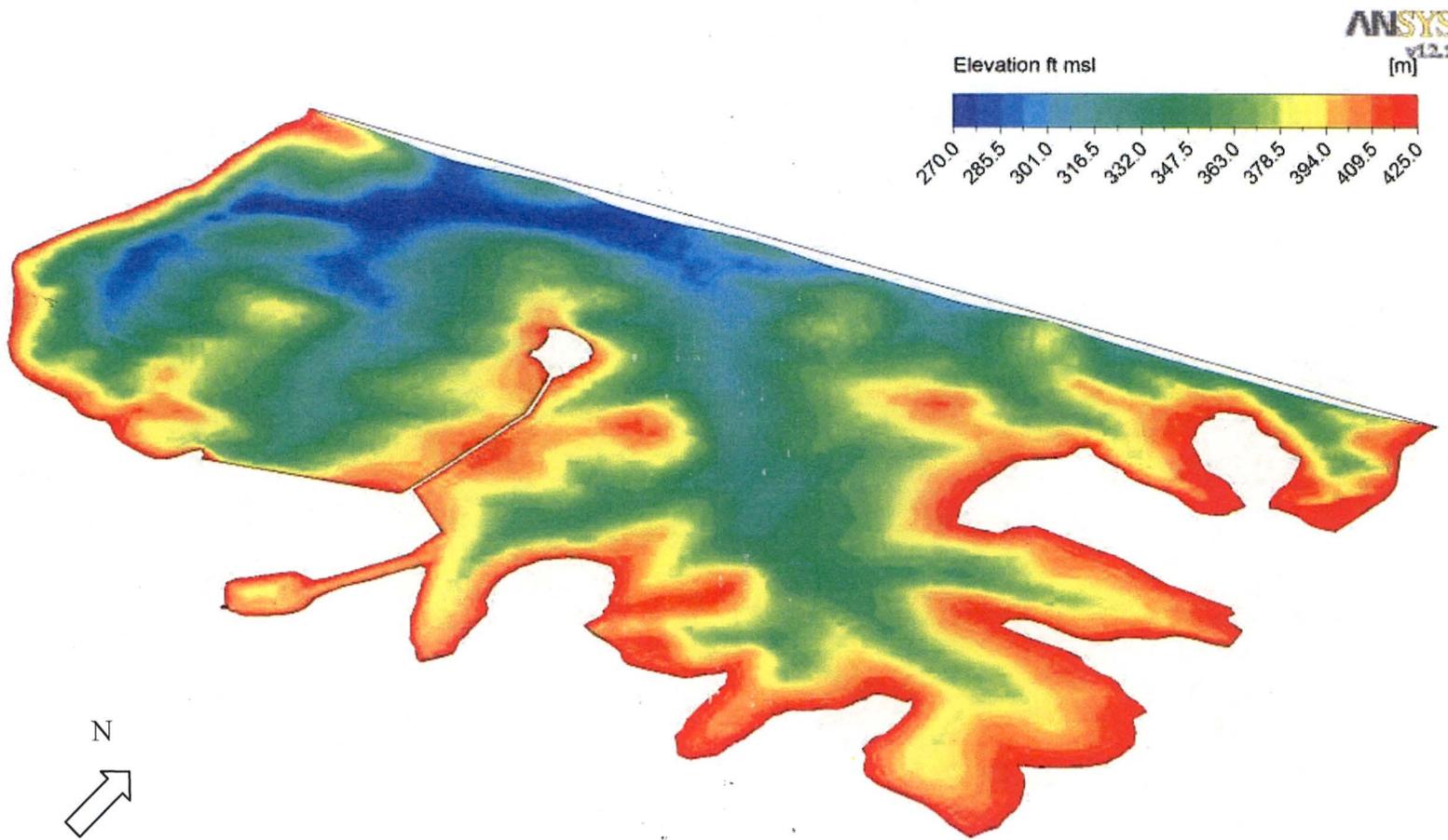


Figure 6 – Contour map showing surface elevation in the computational model.

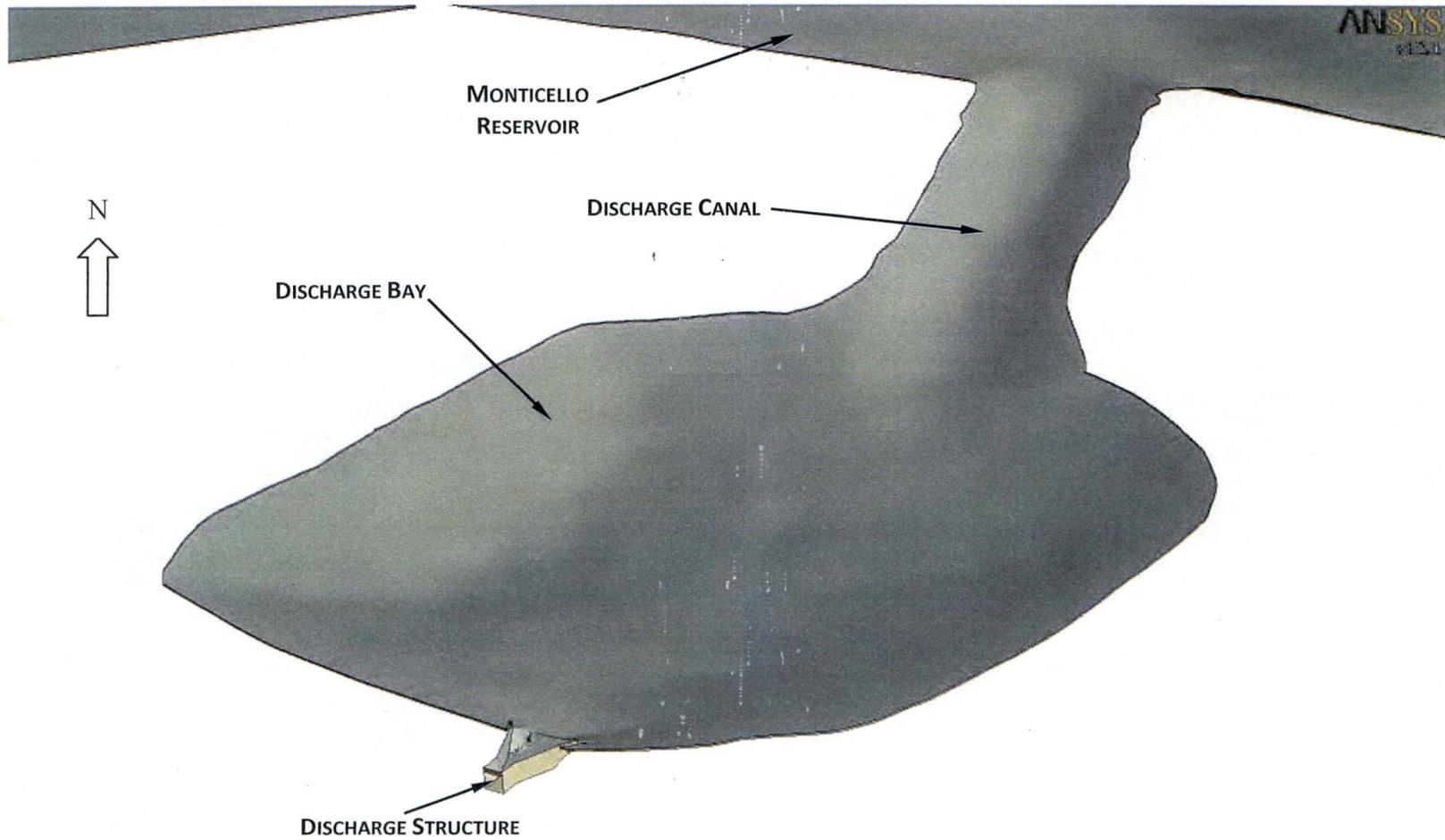


Figure 7 – View of the model near the discharge structure, bay and canal.

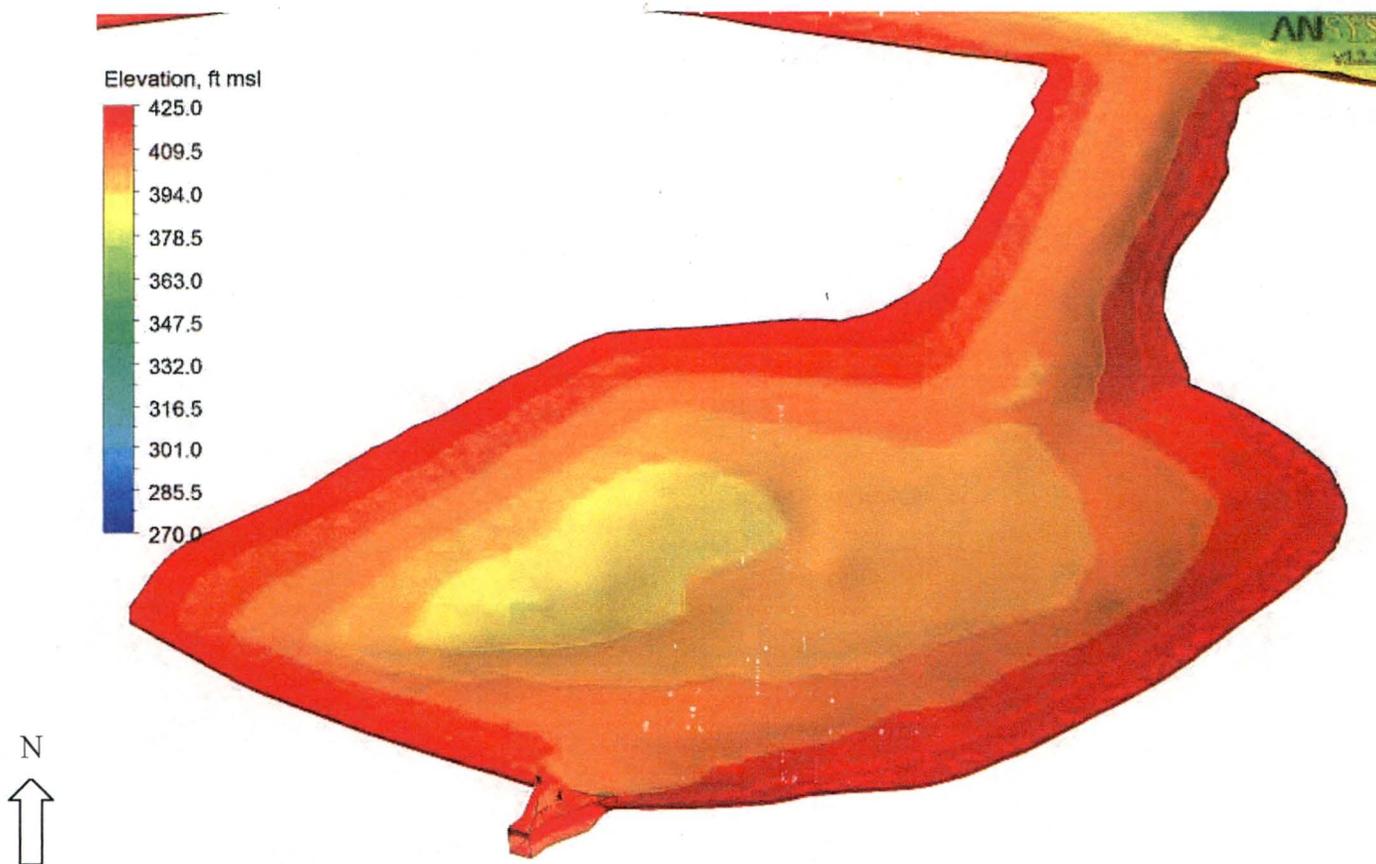


Figure 8 – Elevation contour plot near the discharge structure, bay and canal.

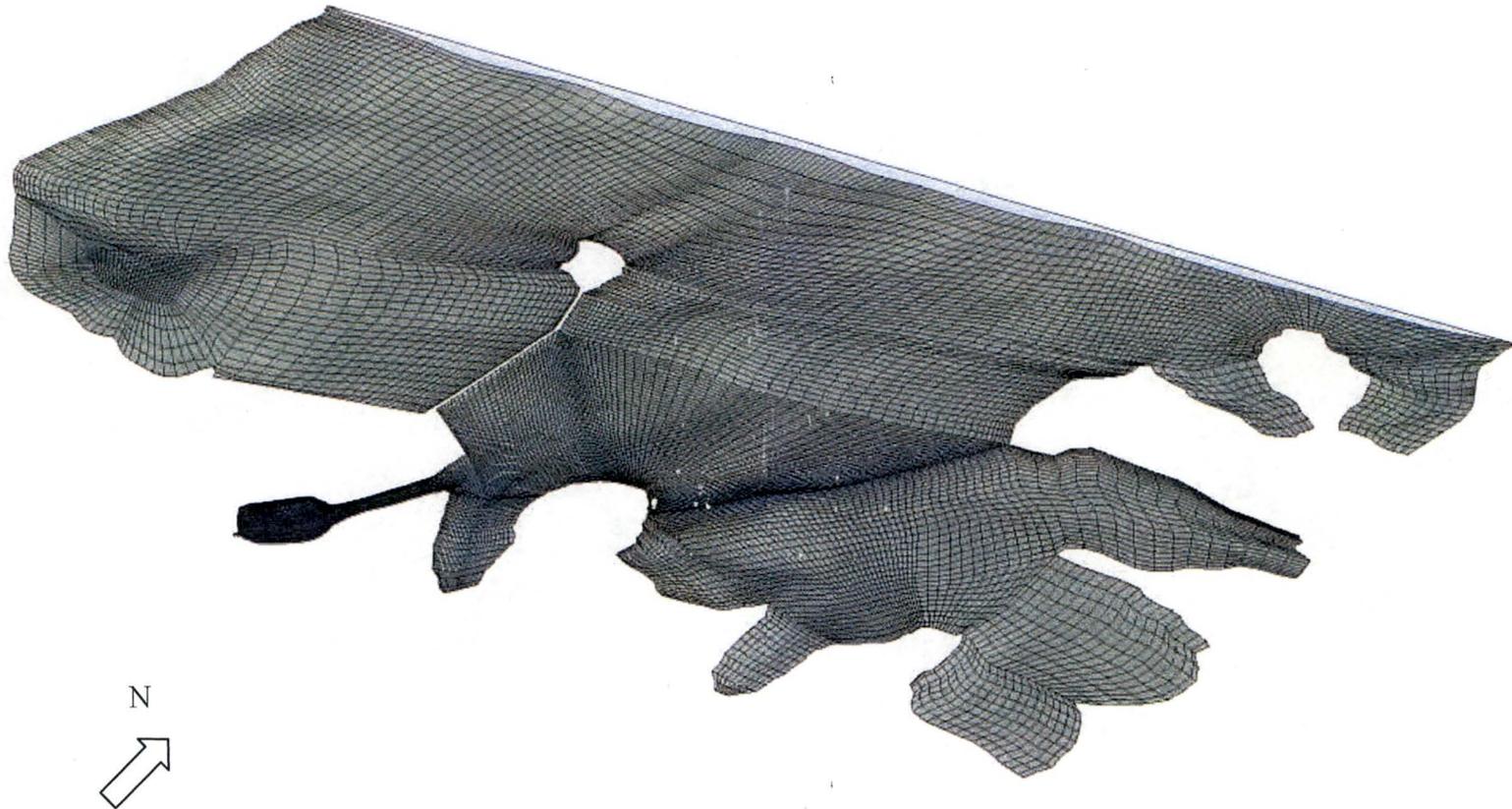


Figure 9 – Computational mesh.

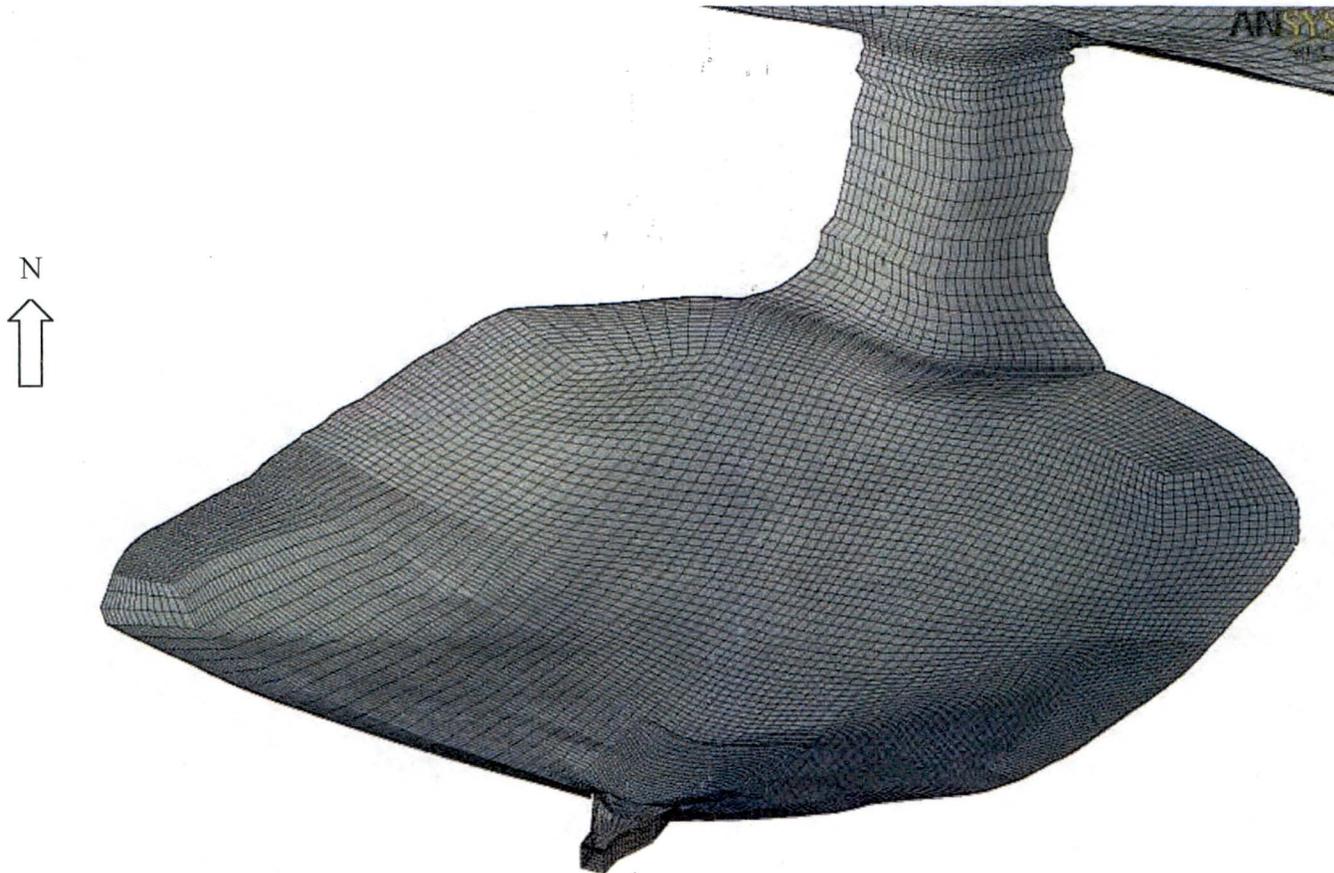


Figure 10 – View of the computational mesh near the discharge structure.

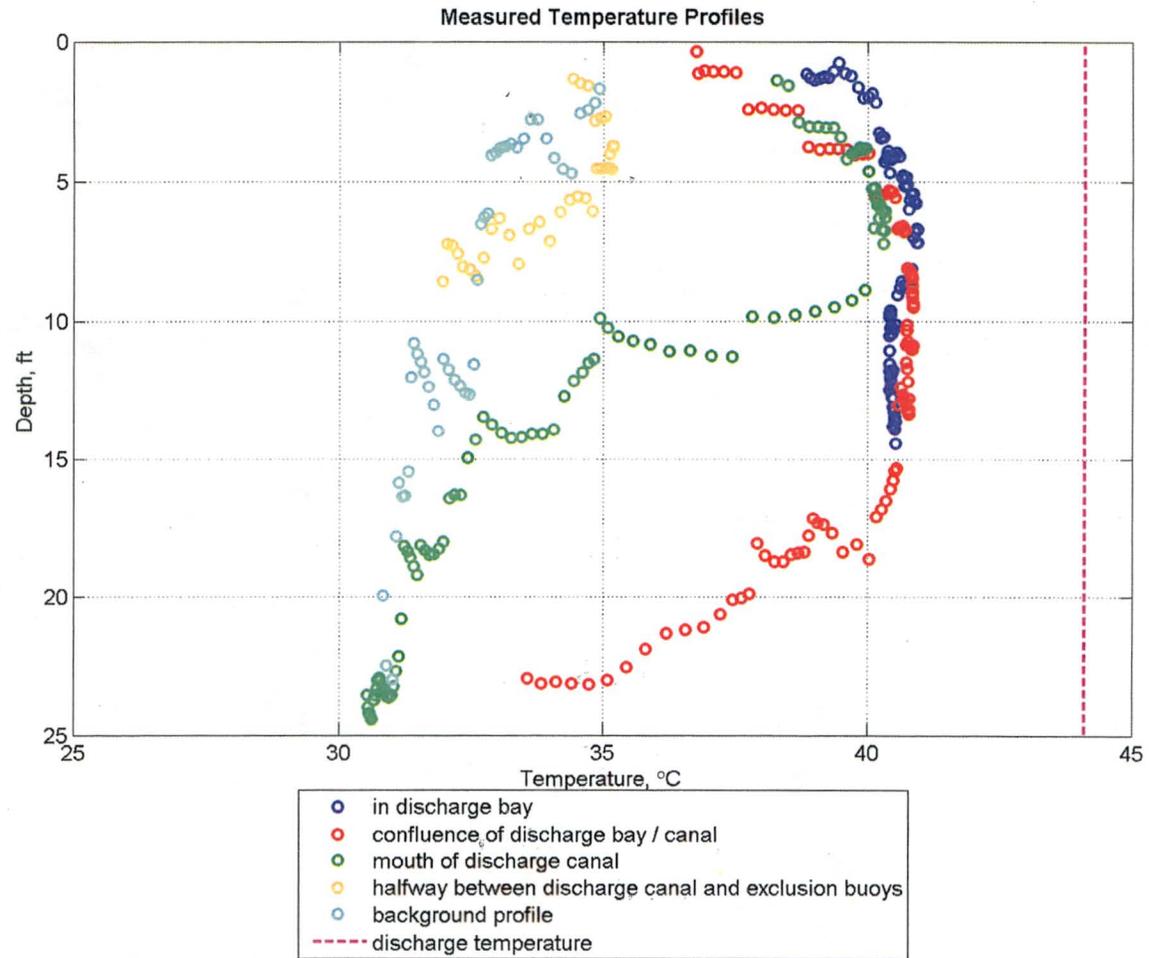


Figure 11 – Temperature profiles collected for validation.

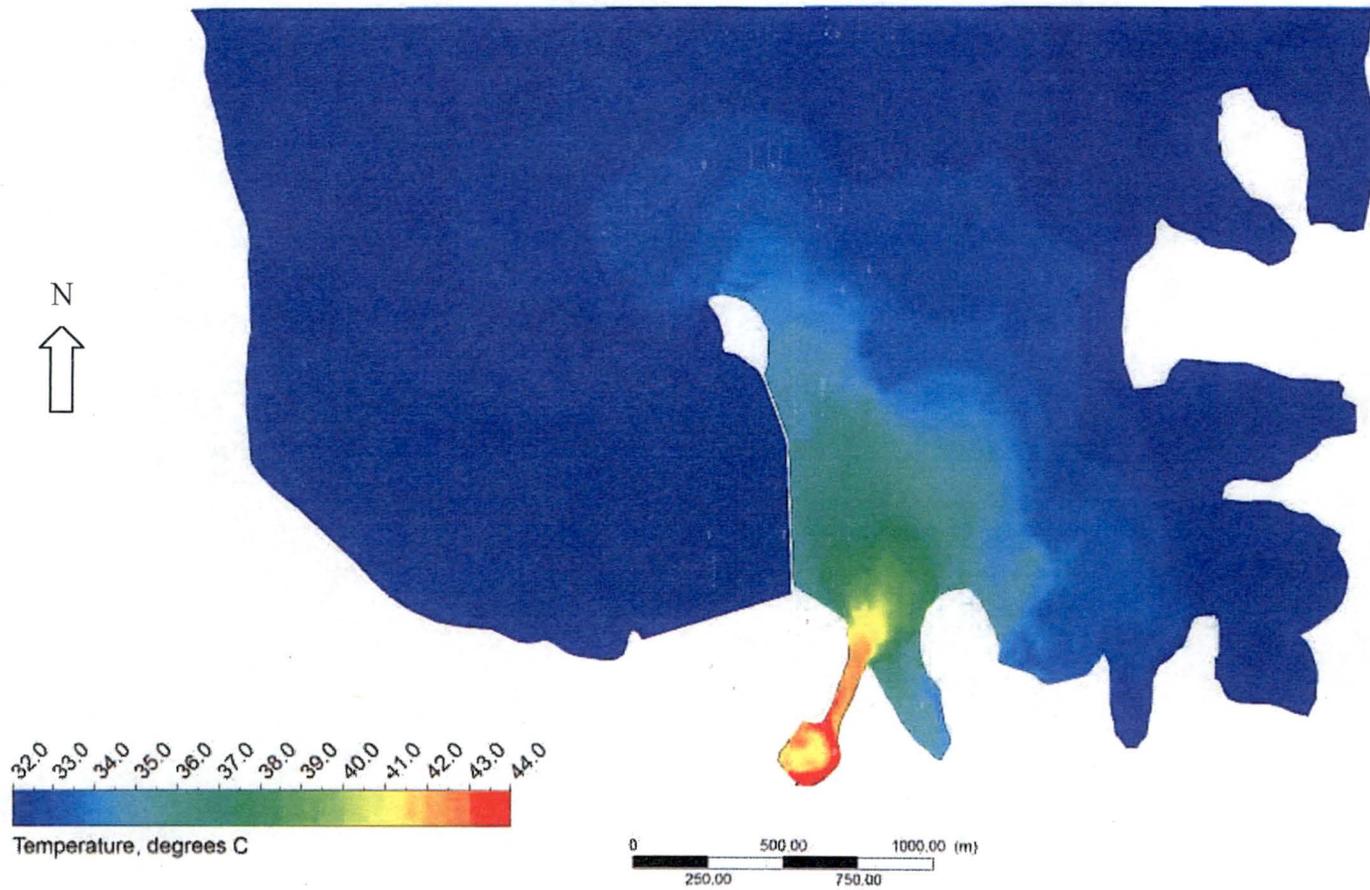


Figure 12 – Contour plot of surface temperature in the numerical model for validation.

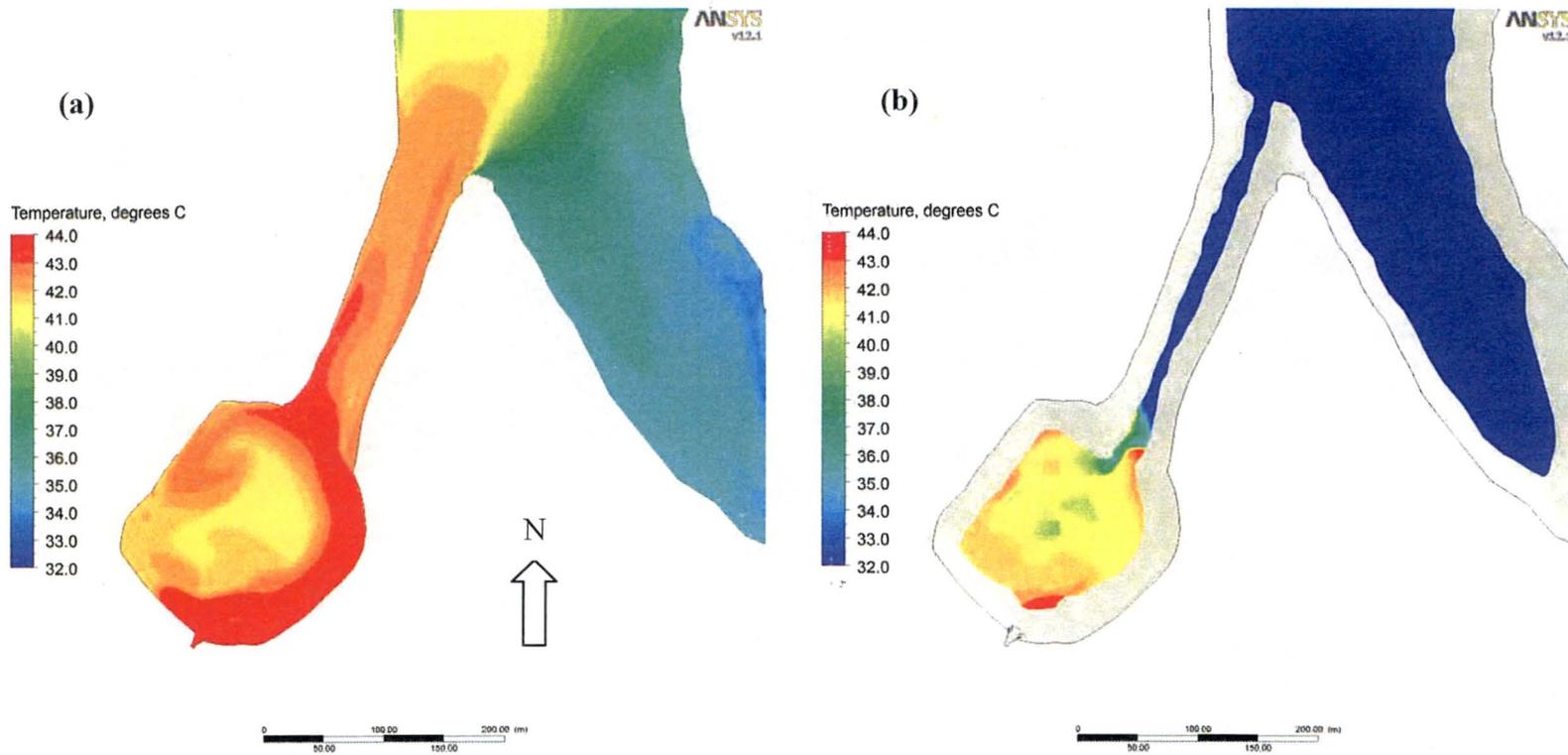


Figure 13 – Contour plot of temperature near the discharge bay at (a) the surface, and (b) 18 ft depth.

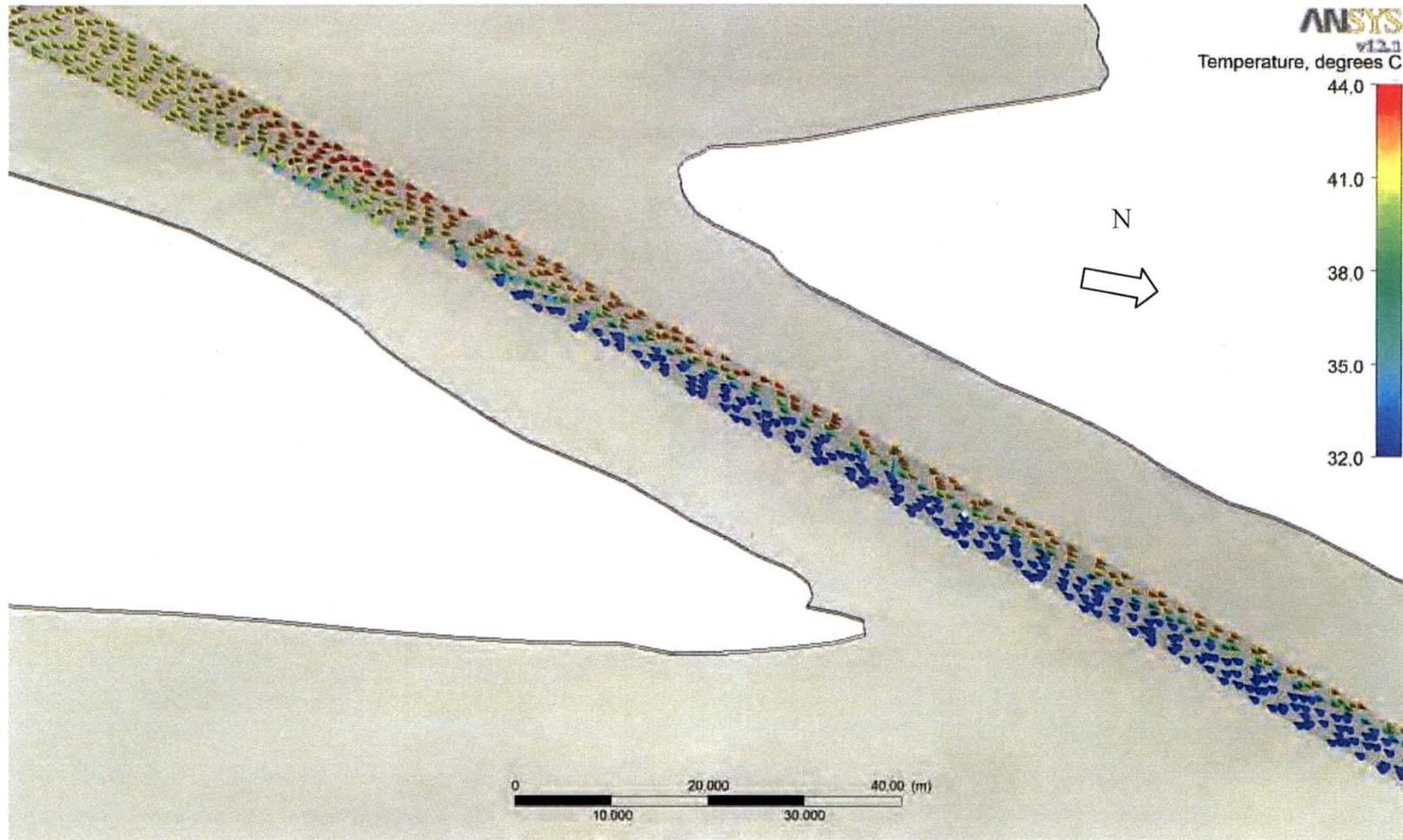


Figure 14 – Velocity vectors in the discharge canal colored by temperature.

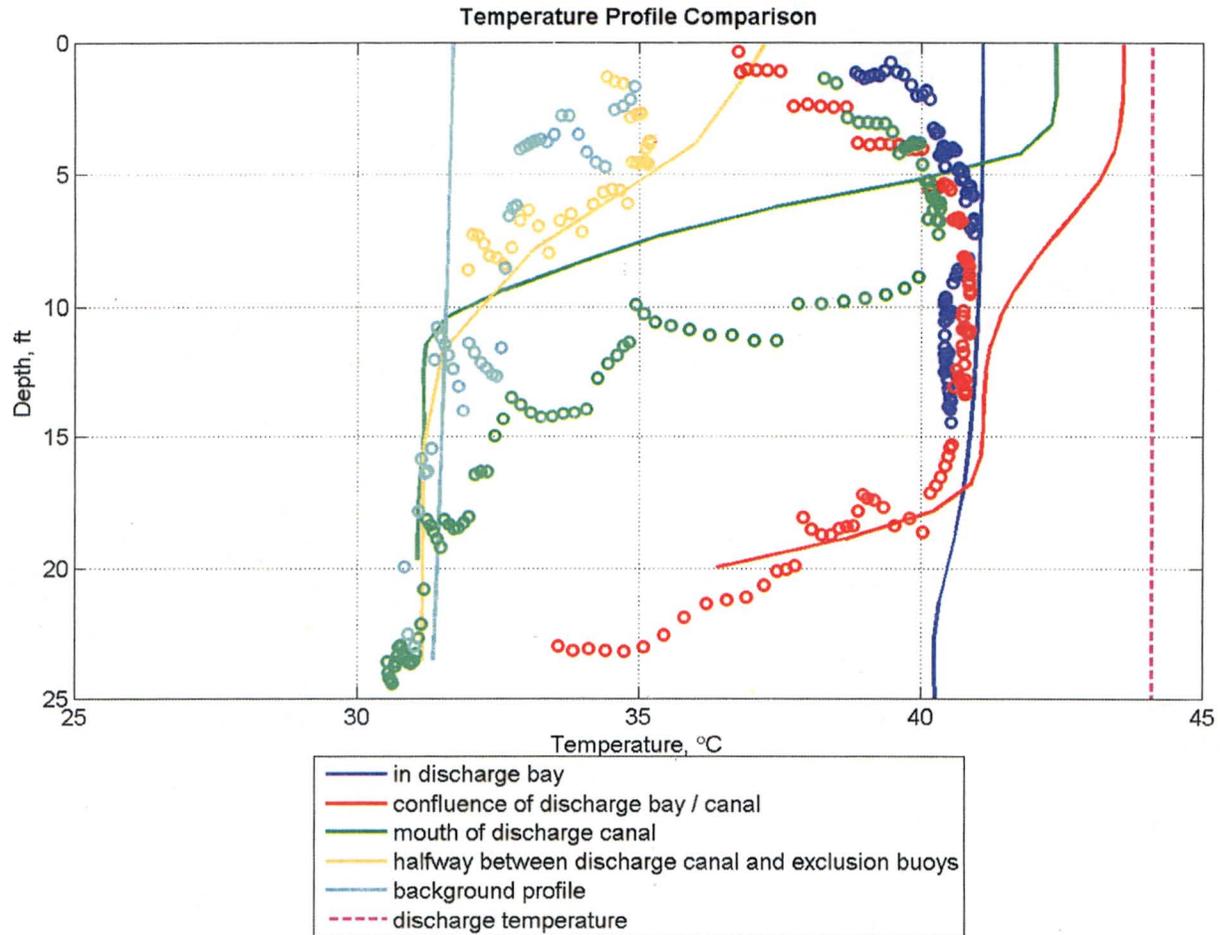


Figure 15 – Comparison between the CFD and collected temperature data.

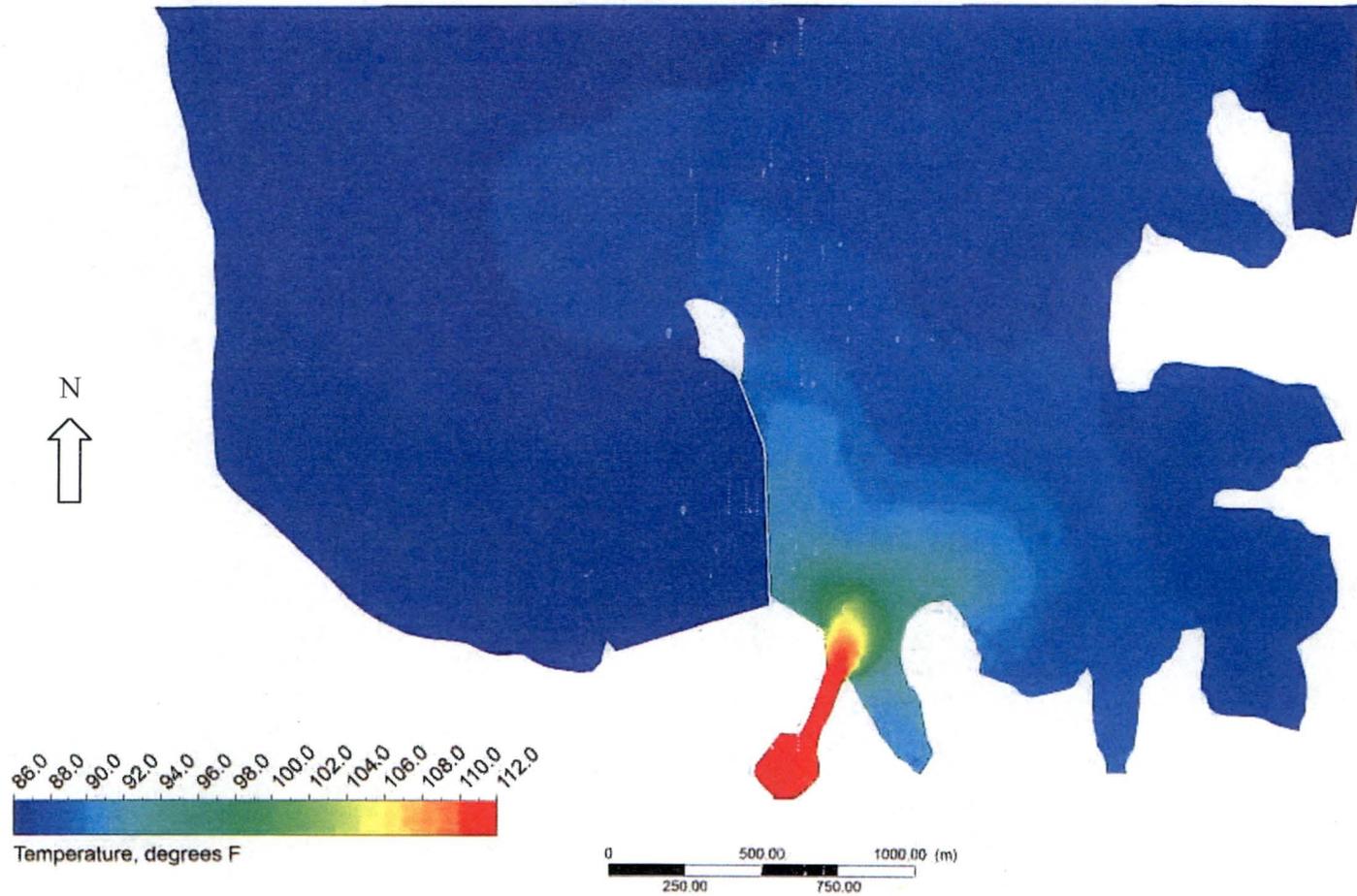


Figure 16 – Scenario 1S, surface temperature.

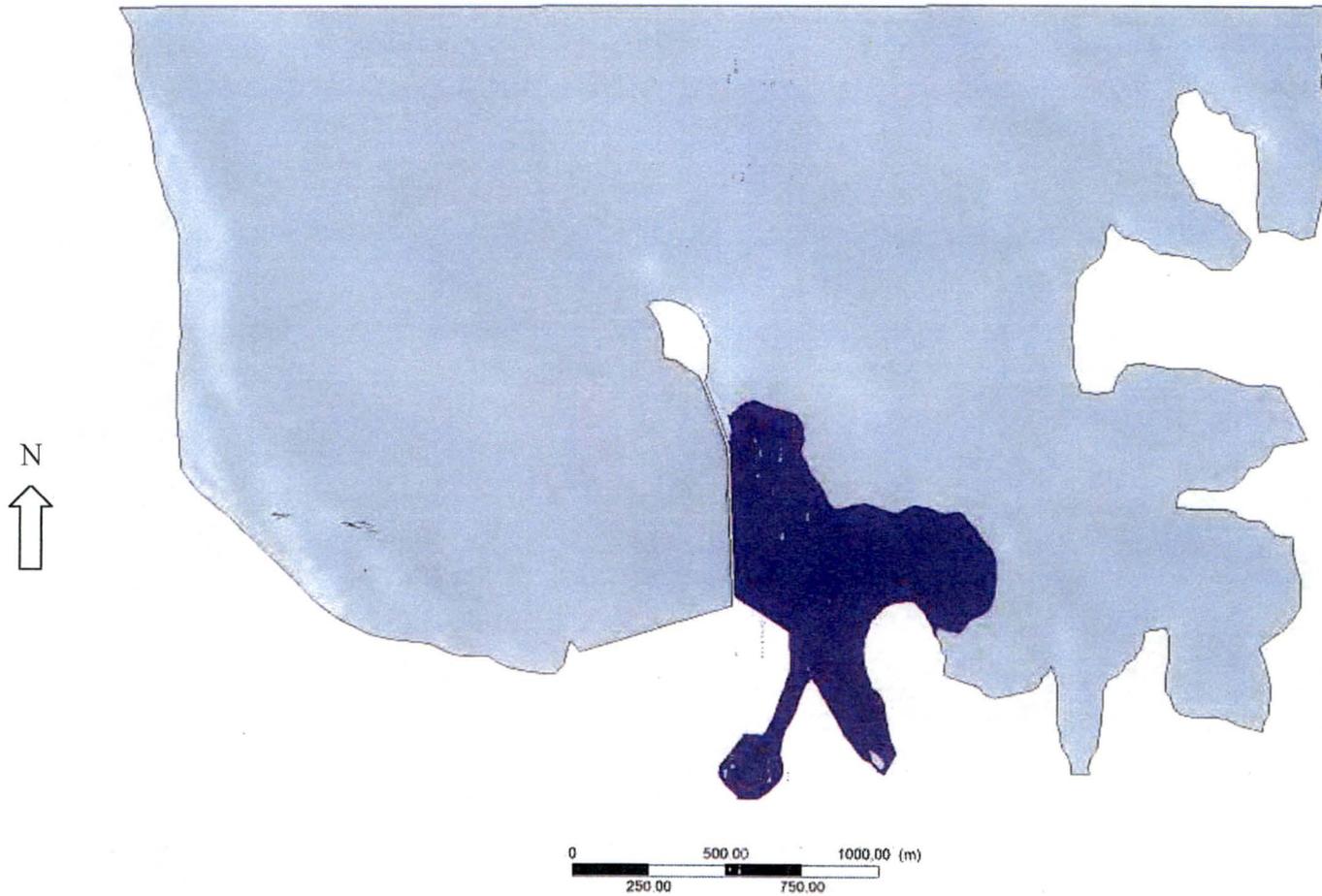


Figure 17 – Scenario 1S, 90°F thermal plume (purple).

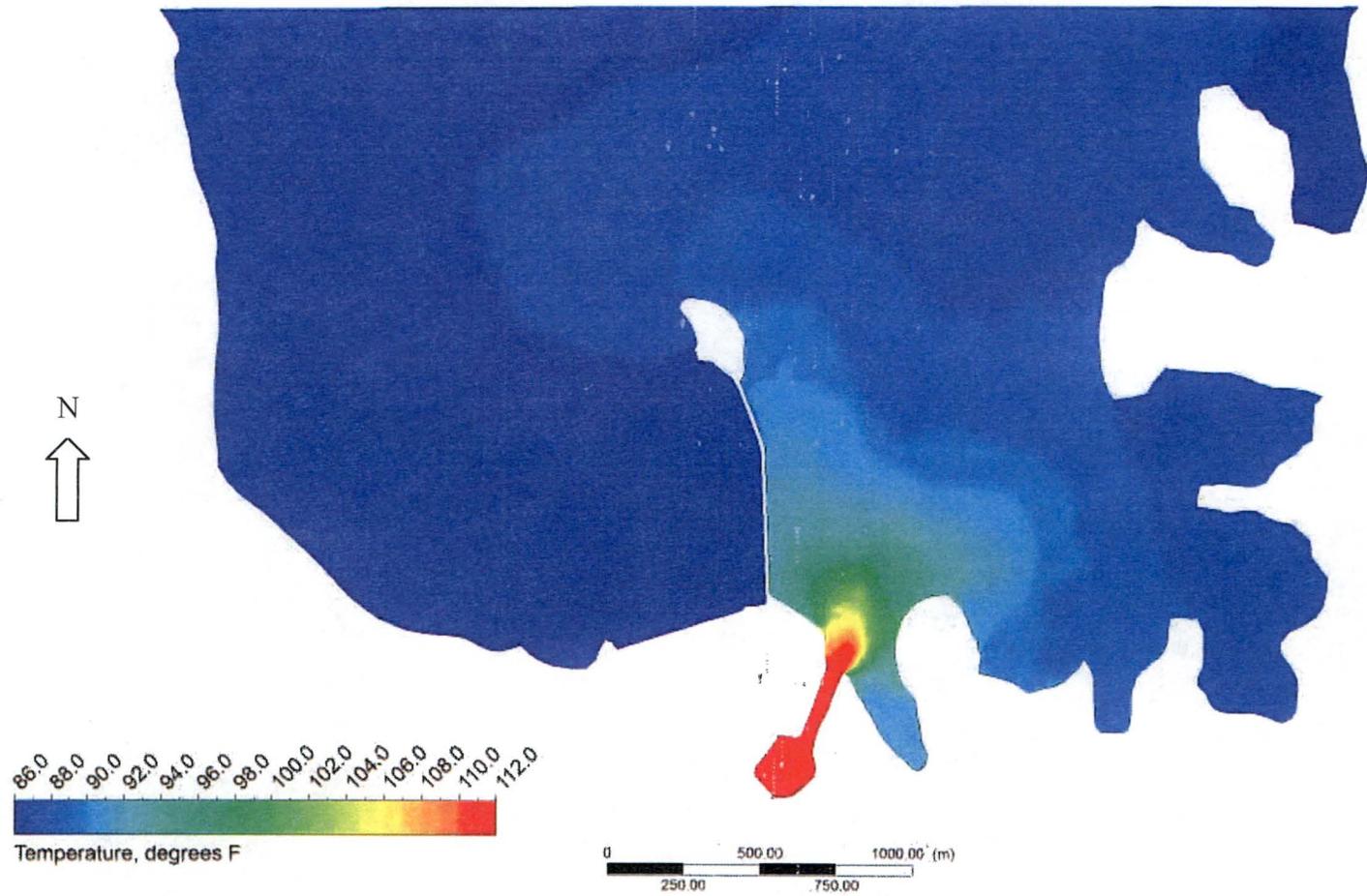


Figure 18 – Scenario 2S, surface temperature.

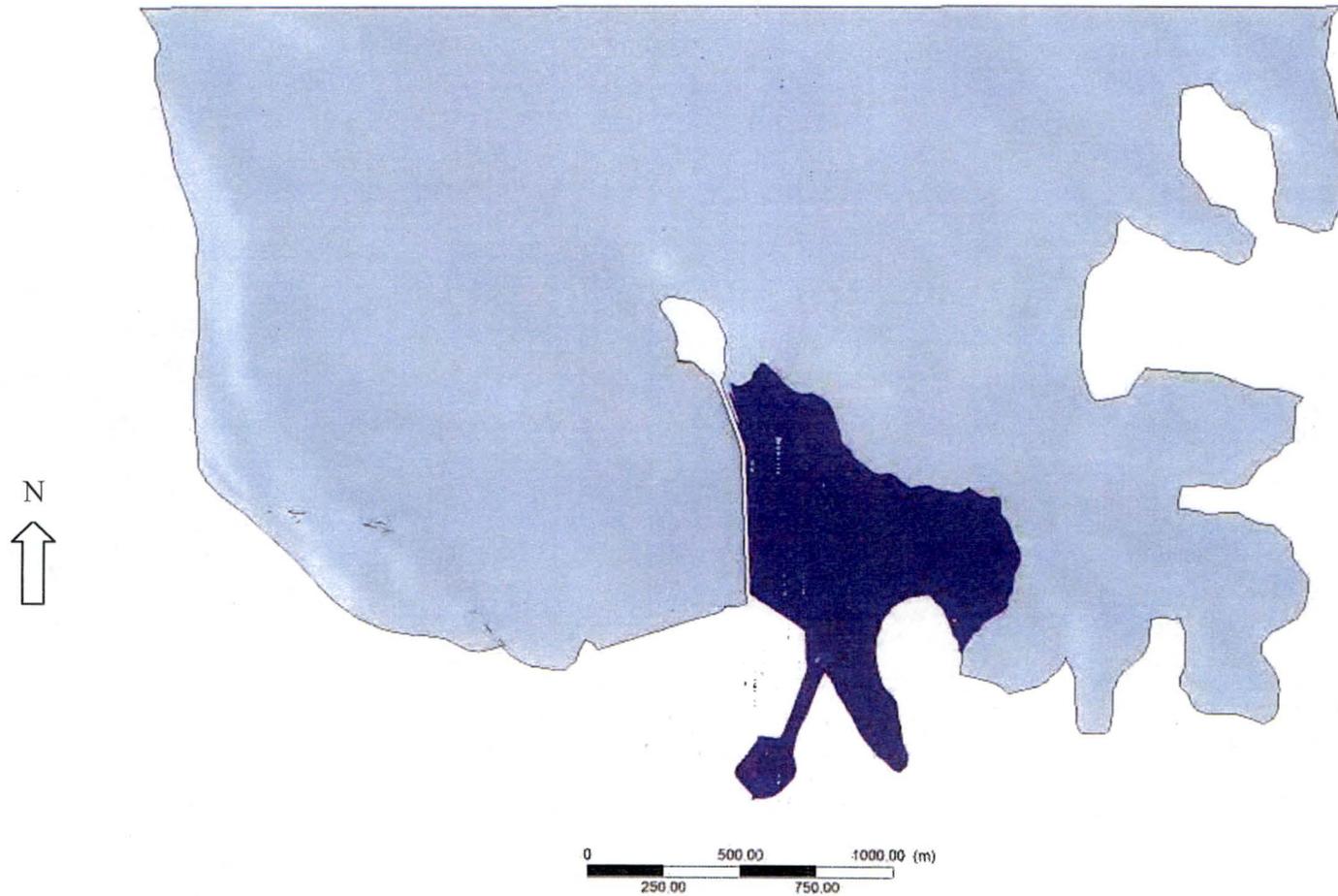


Figure 19 – Scenario 2S, 90°F thermal plume (purple).

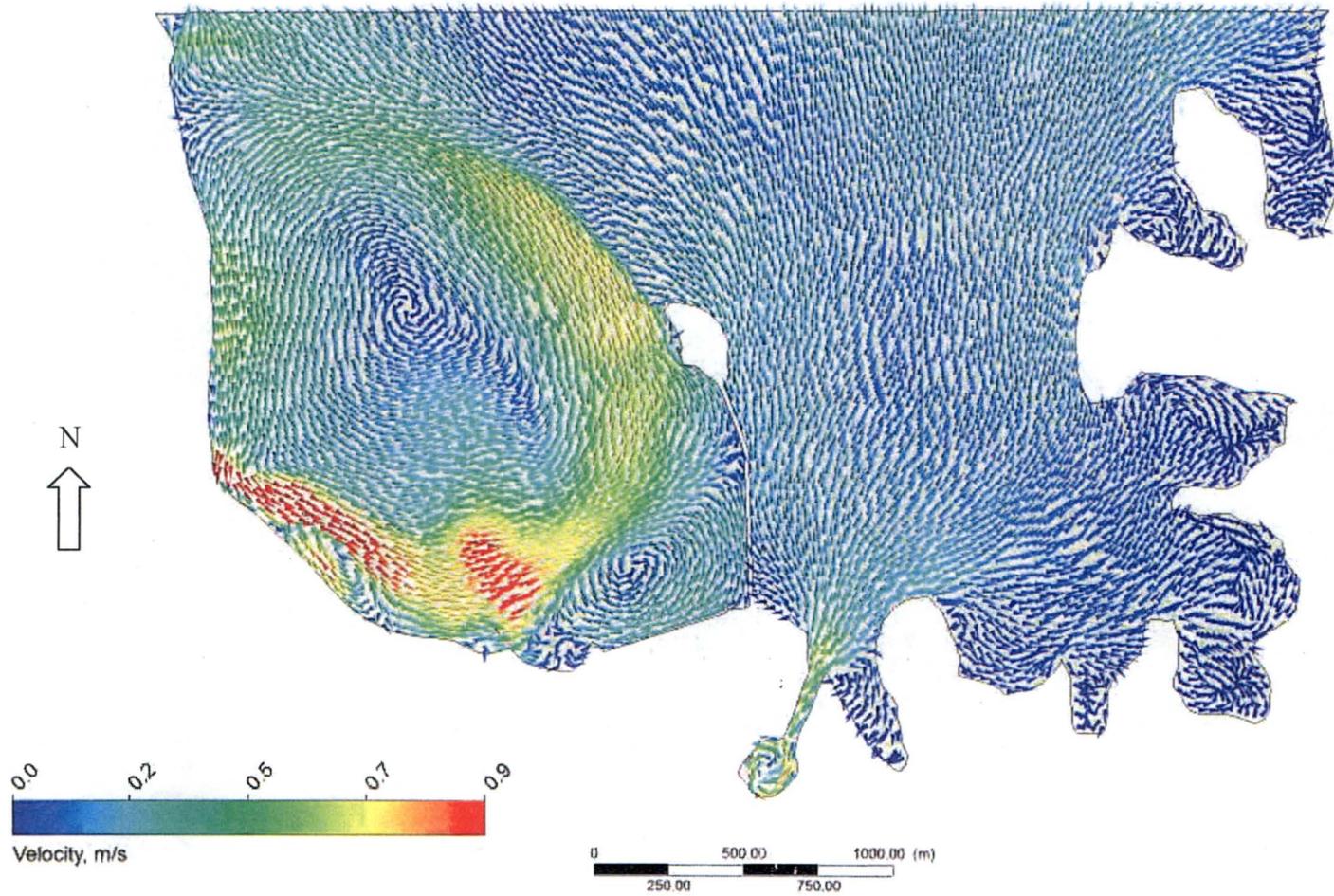


Figure 20 – Scenario 3S, surface velocity vectors.

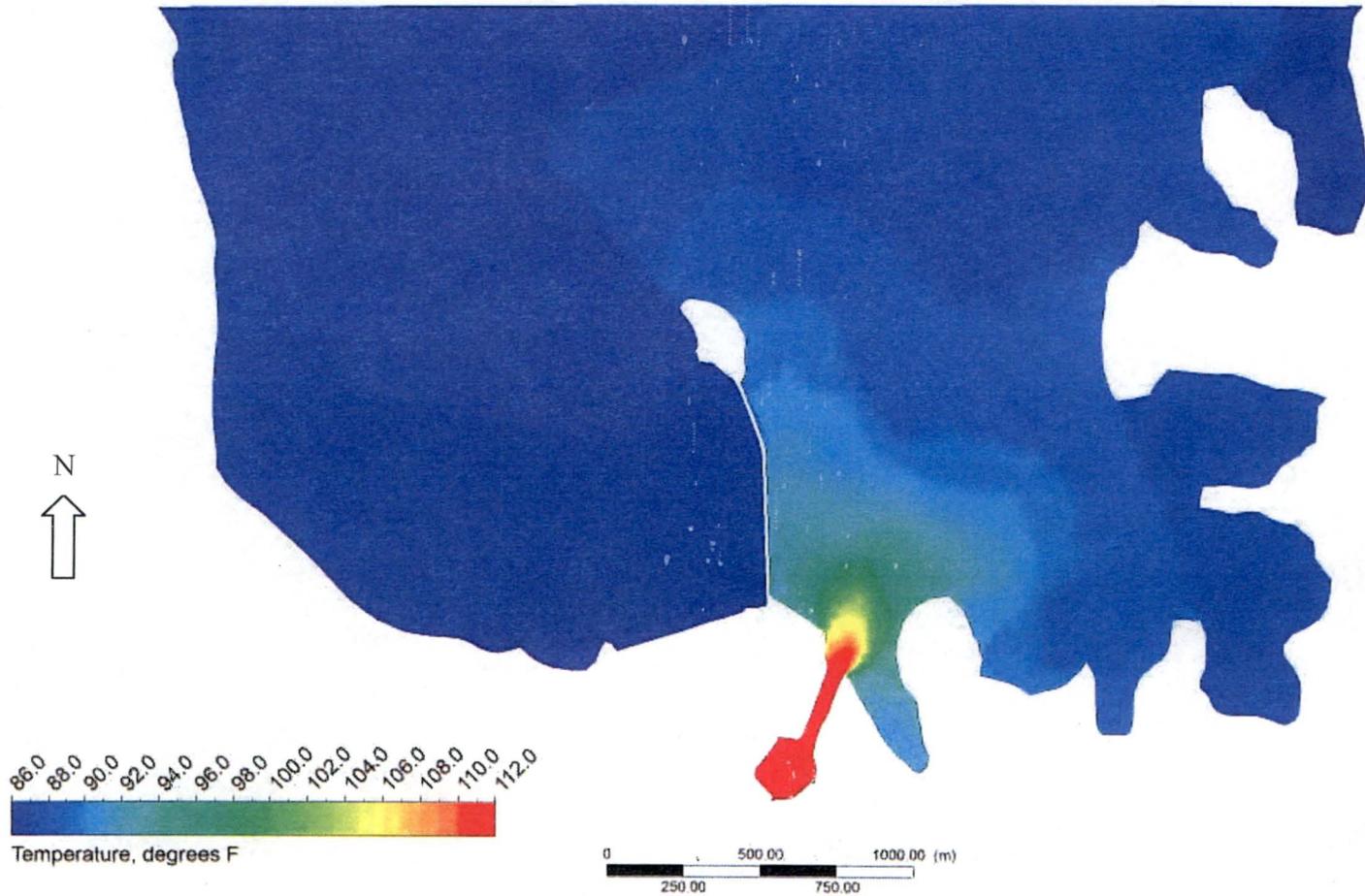


Figure 21 – Scenario 3S, surface temperature.

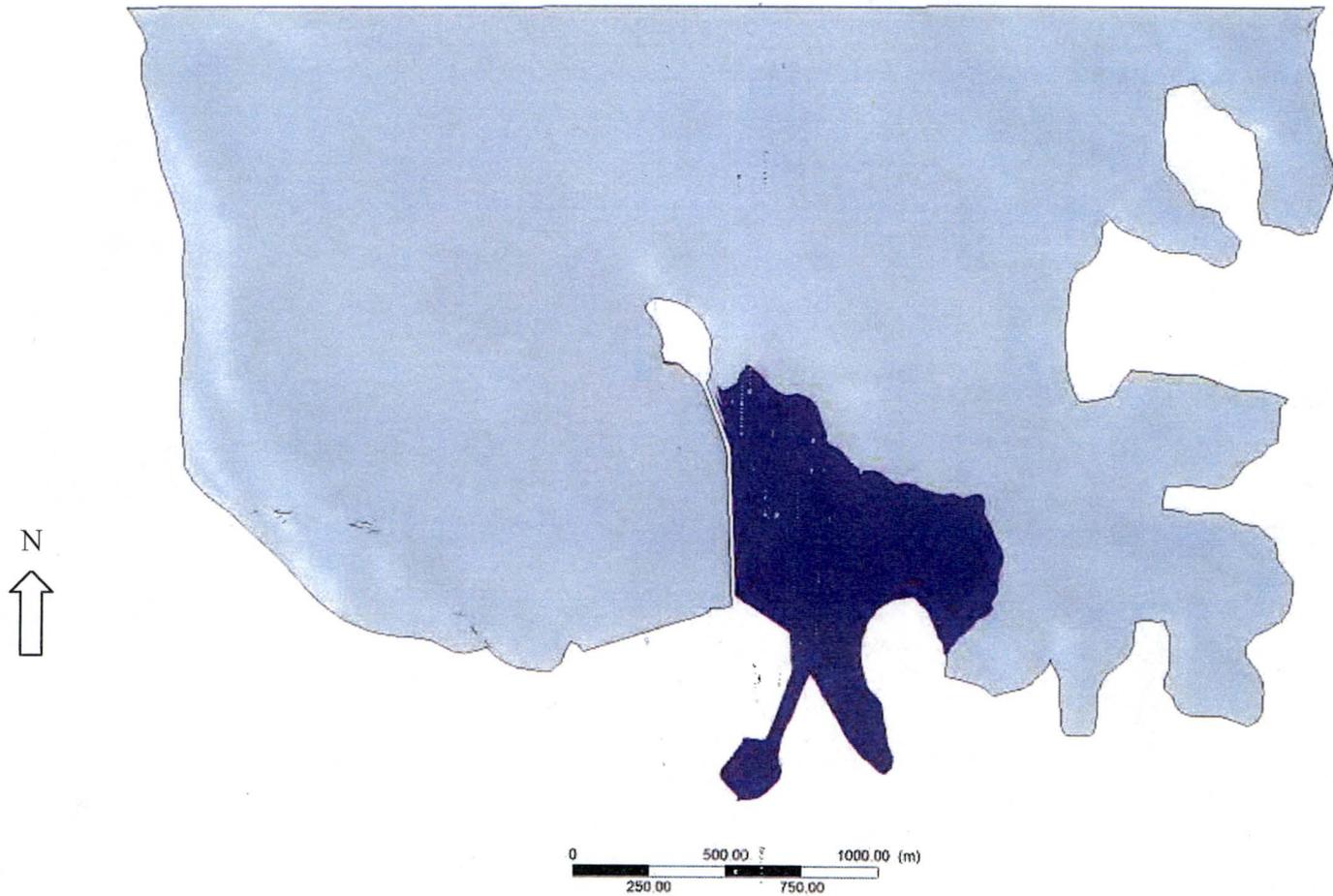


Figure 22 – Scenario 3S, 90°F thermal plume (purple).

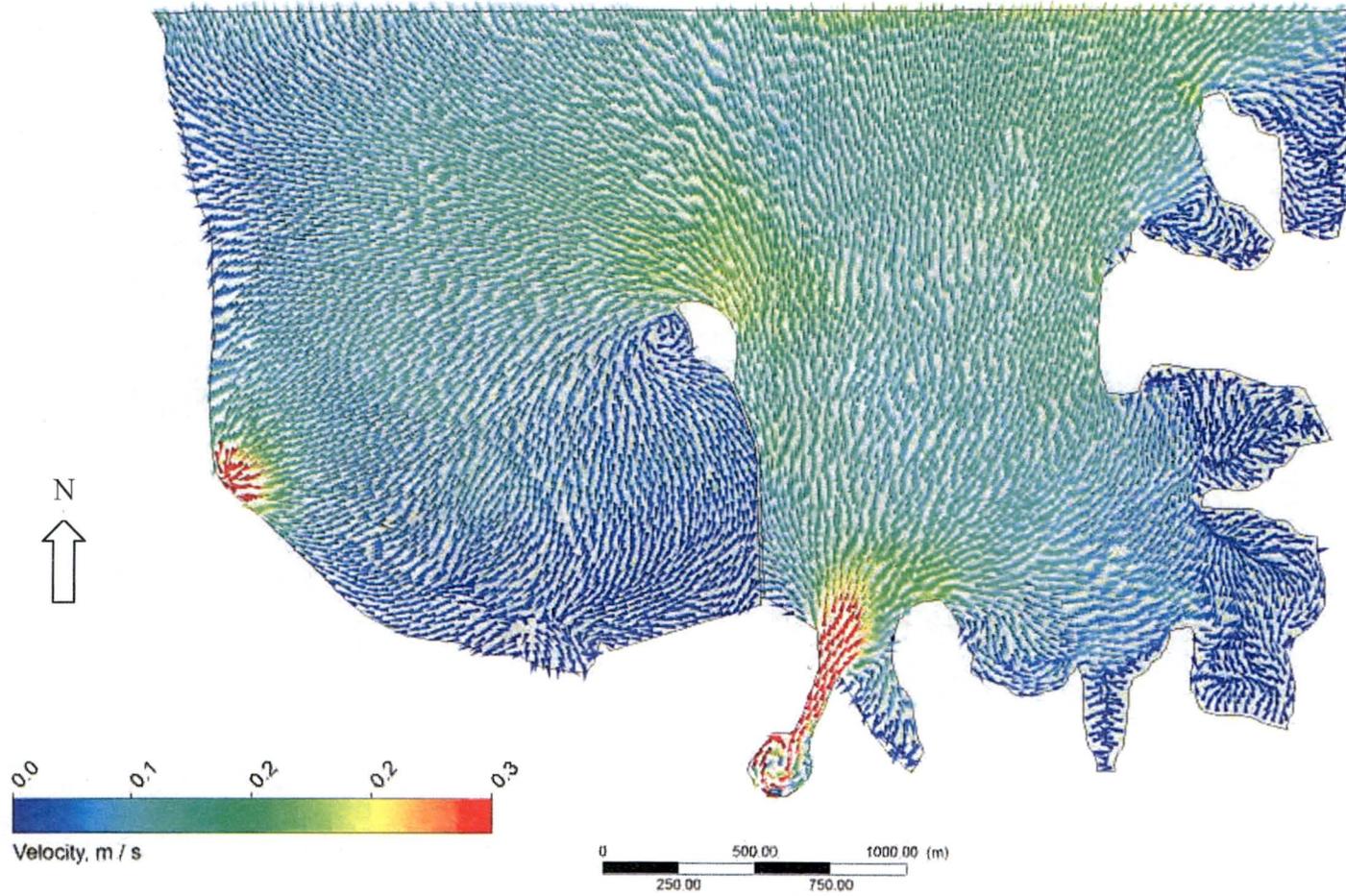


Figure 23 – Scenario 4S, surface velocity vectors.

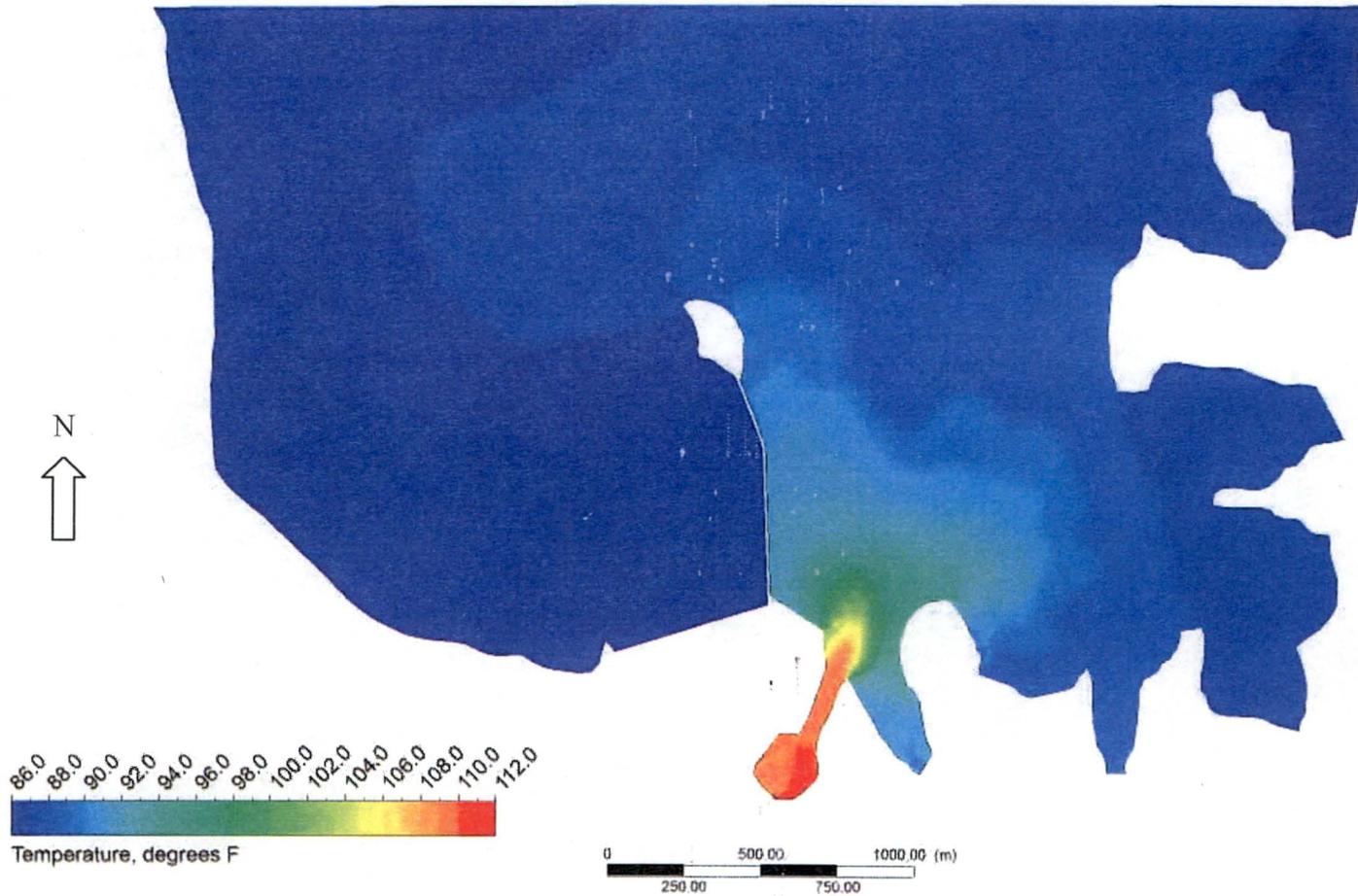


Figure 24 – Scenario 4S, surface temperature.

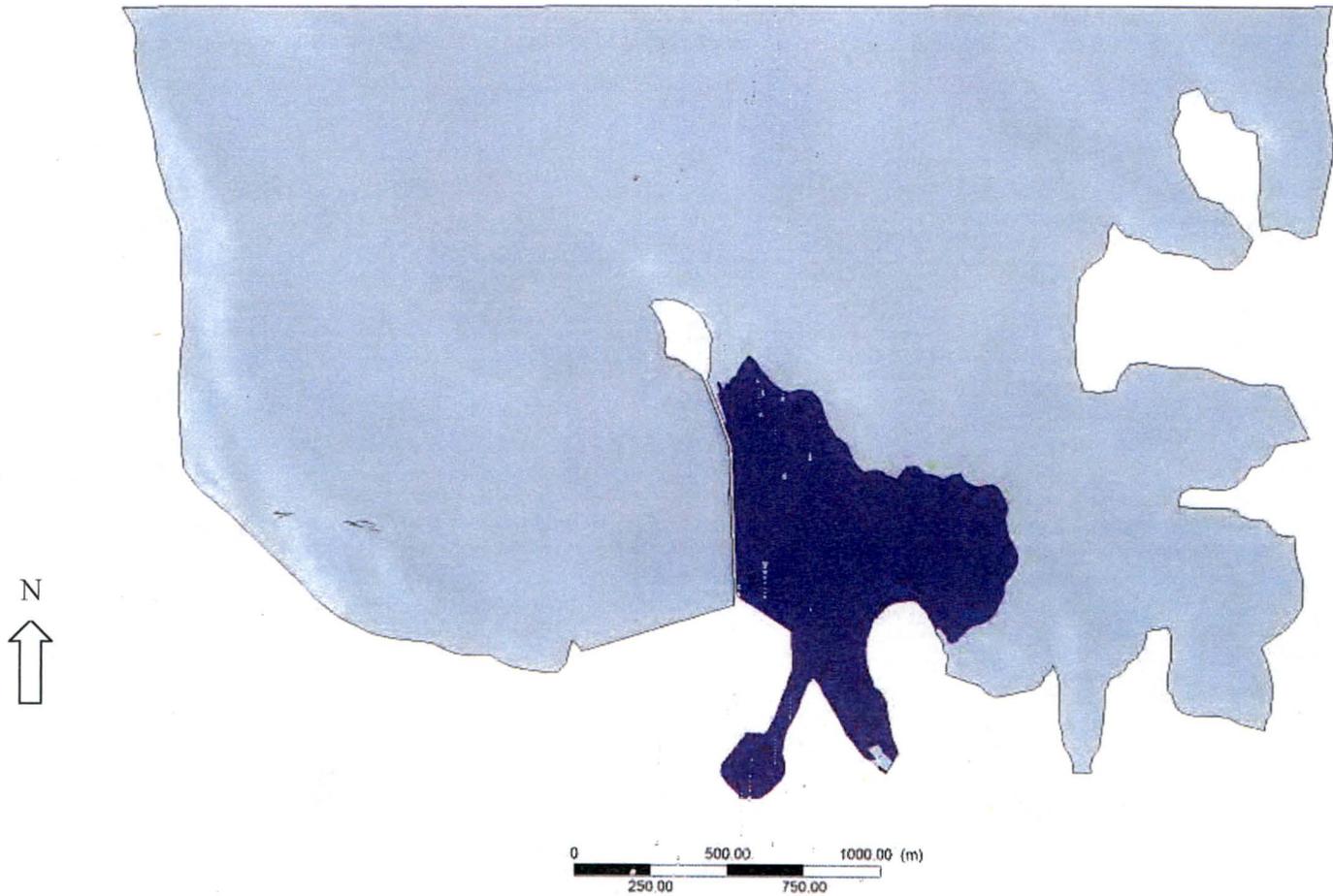


Figure 25 – Scenario 4S, 90°F thermal plume (purple).

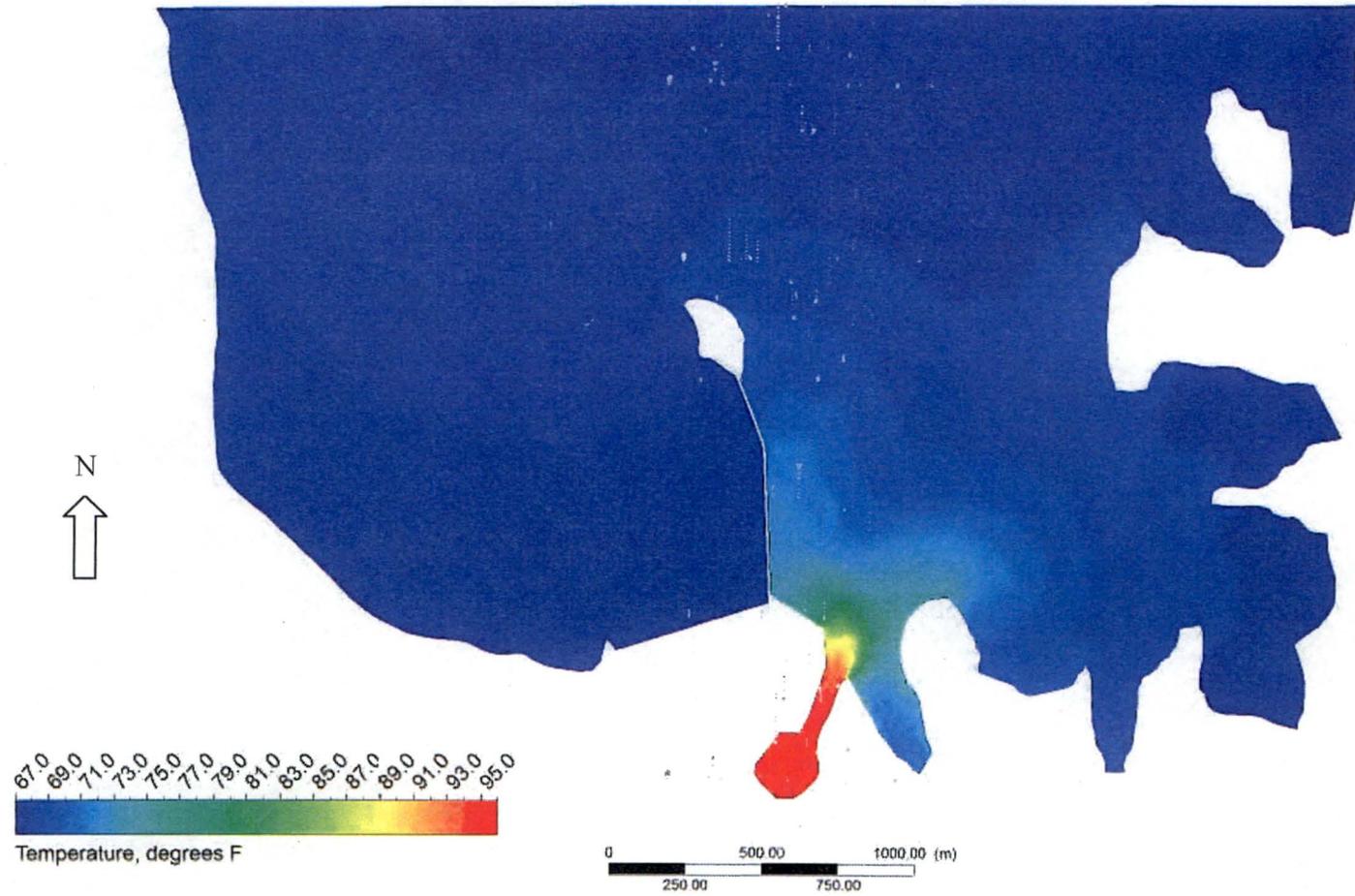


Figure 26 – Scenario 1W, surface temperature.

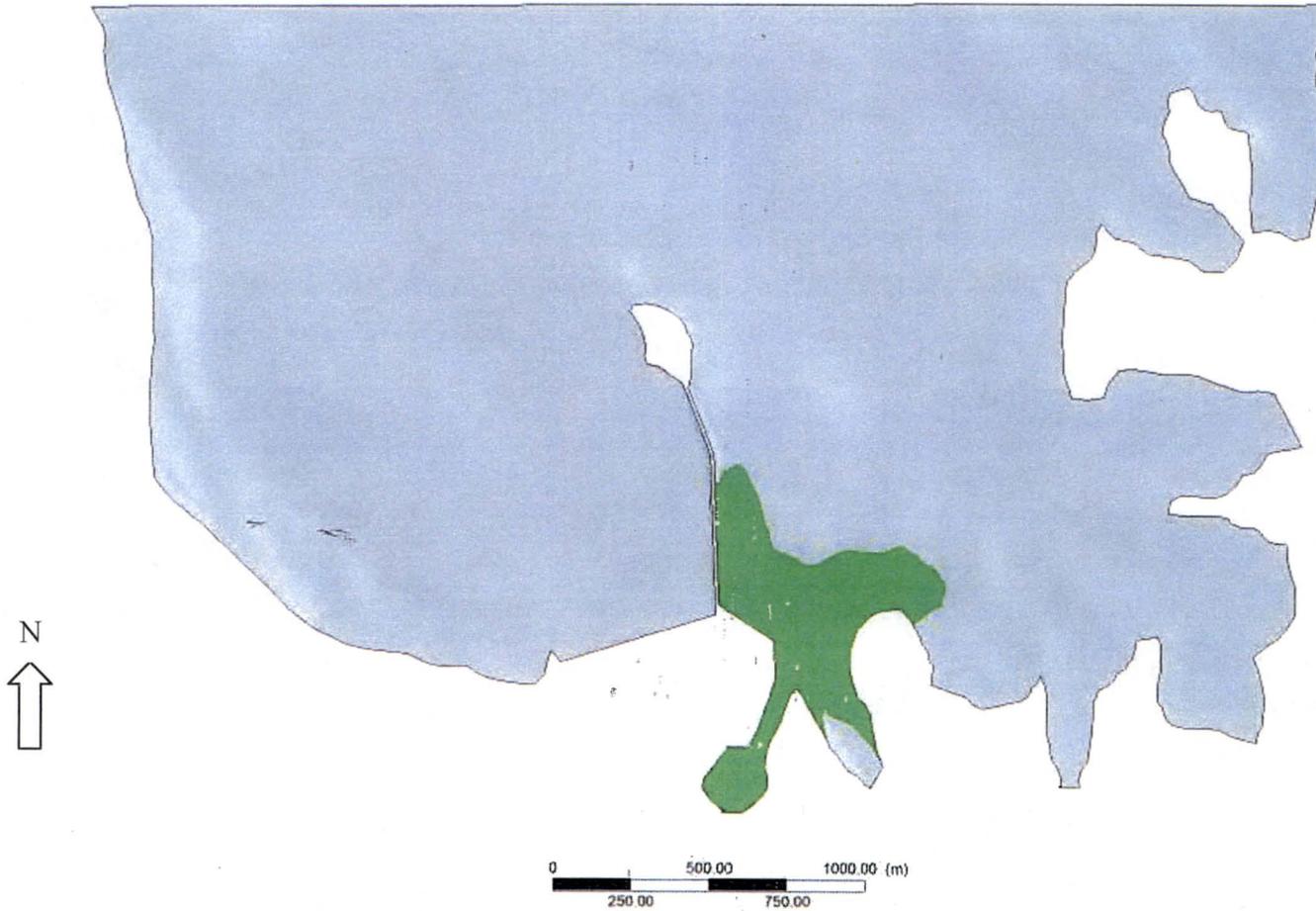


Figure 27 – Scenario 1W, $\Delta T = 5^{\circ}\text{F}$ thermal plume (green).

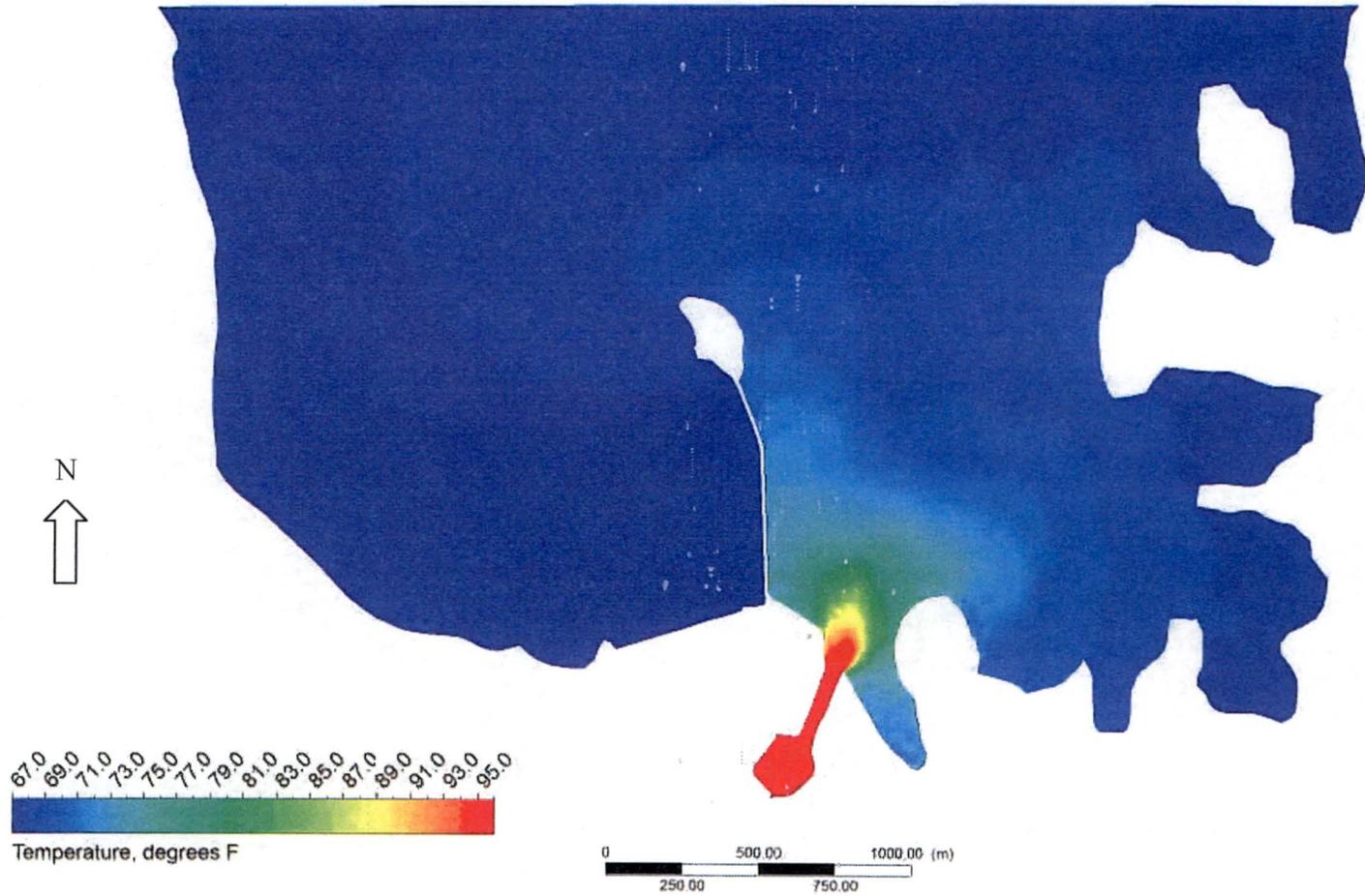


Figure 28 – Scenario 2W, surface temperature.

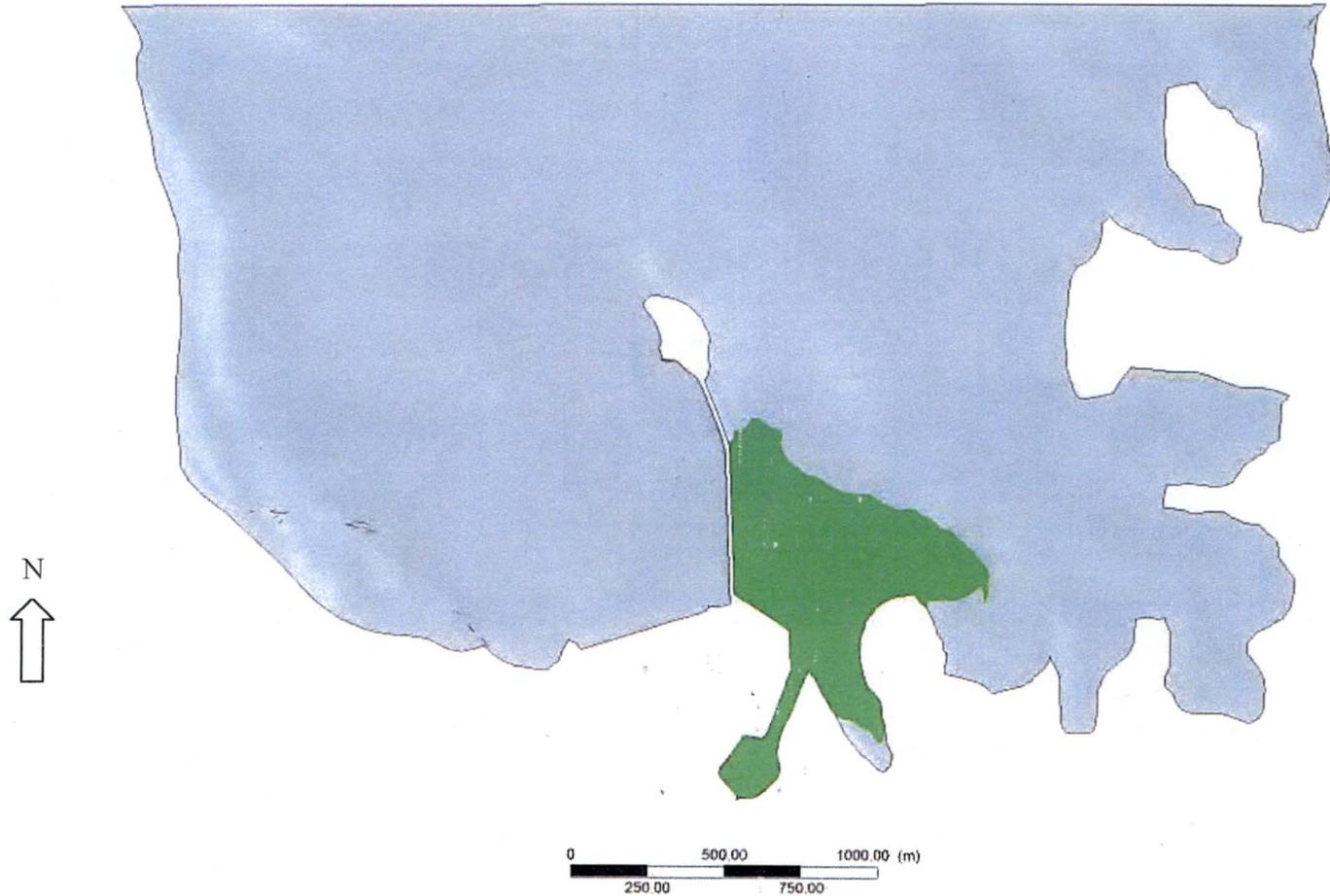


Figure 29 – Scenario 2W, $\Delta T = 5^{\circ}\text{F}$ thermal plume (green).

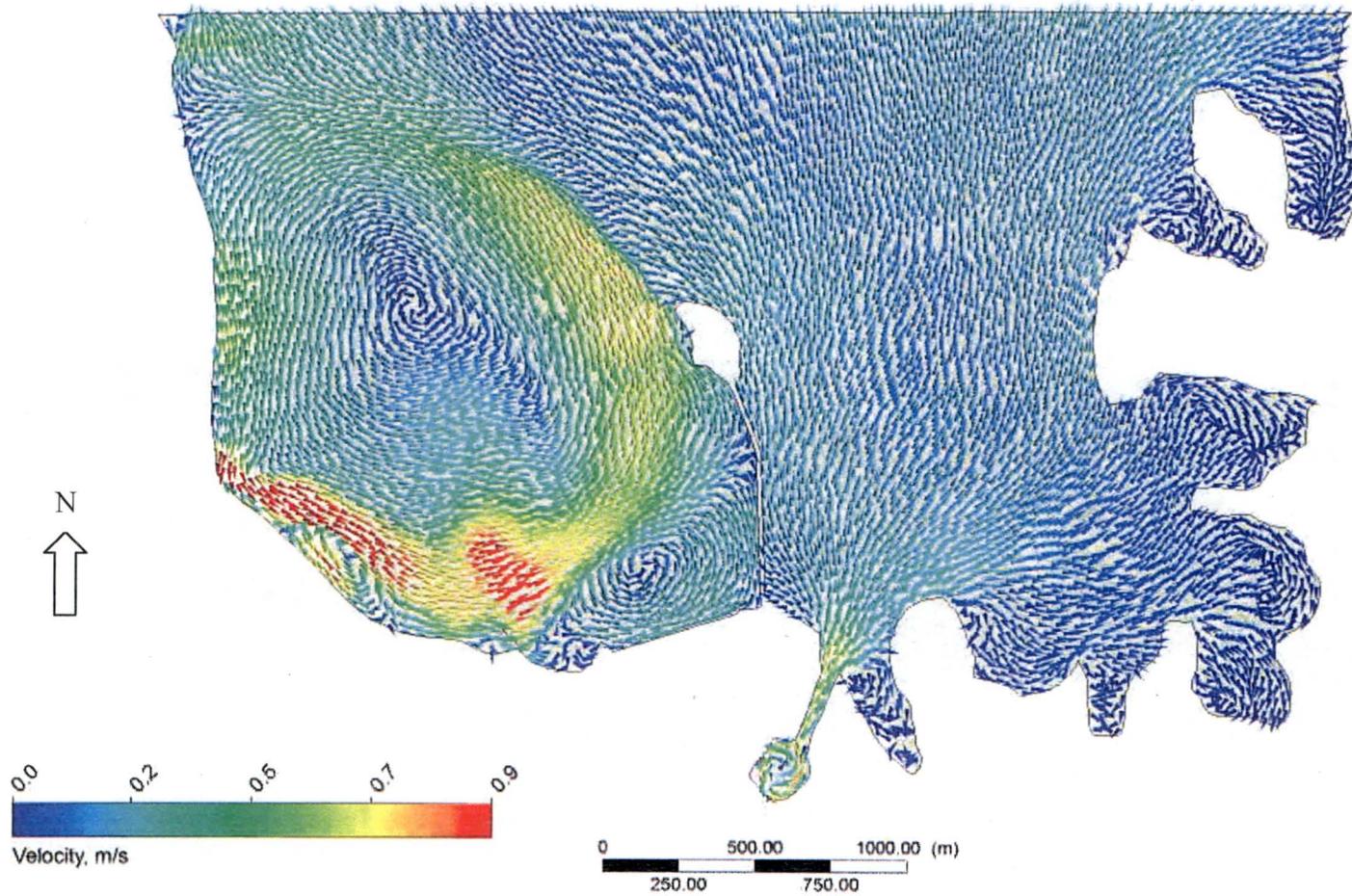


Figure 30 – Scenario 3W, surface velocity vectors

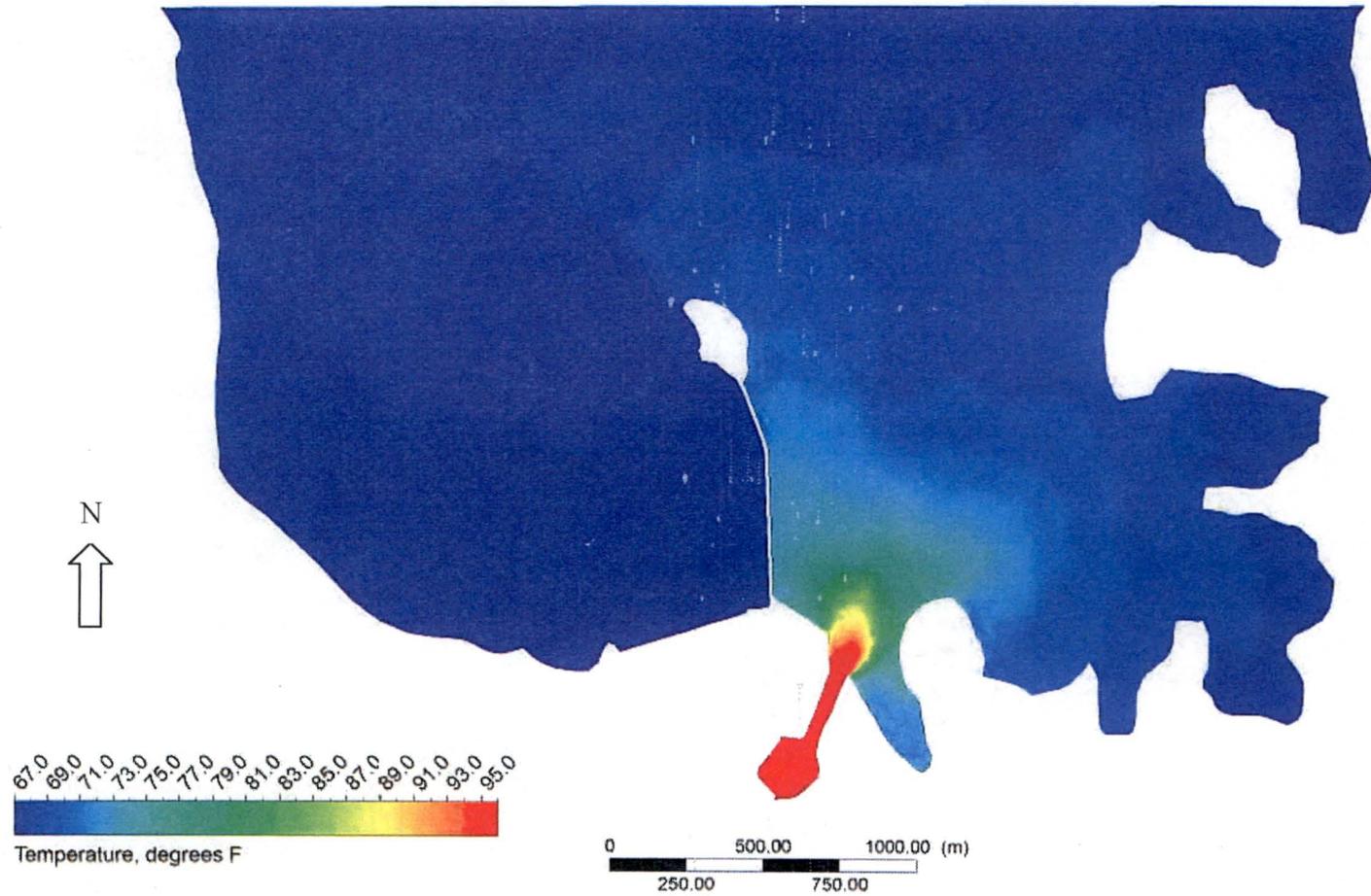


Figure 31 – Scenario 3W, surface temperature.

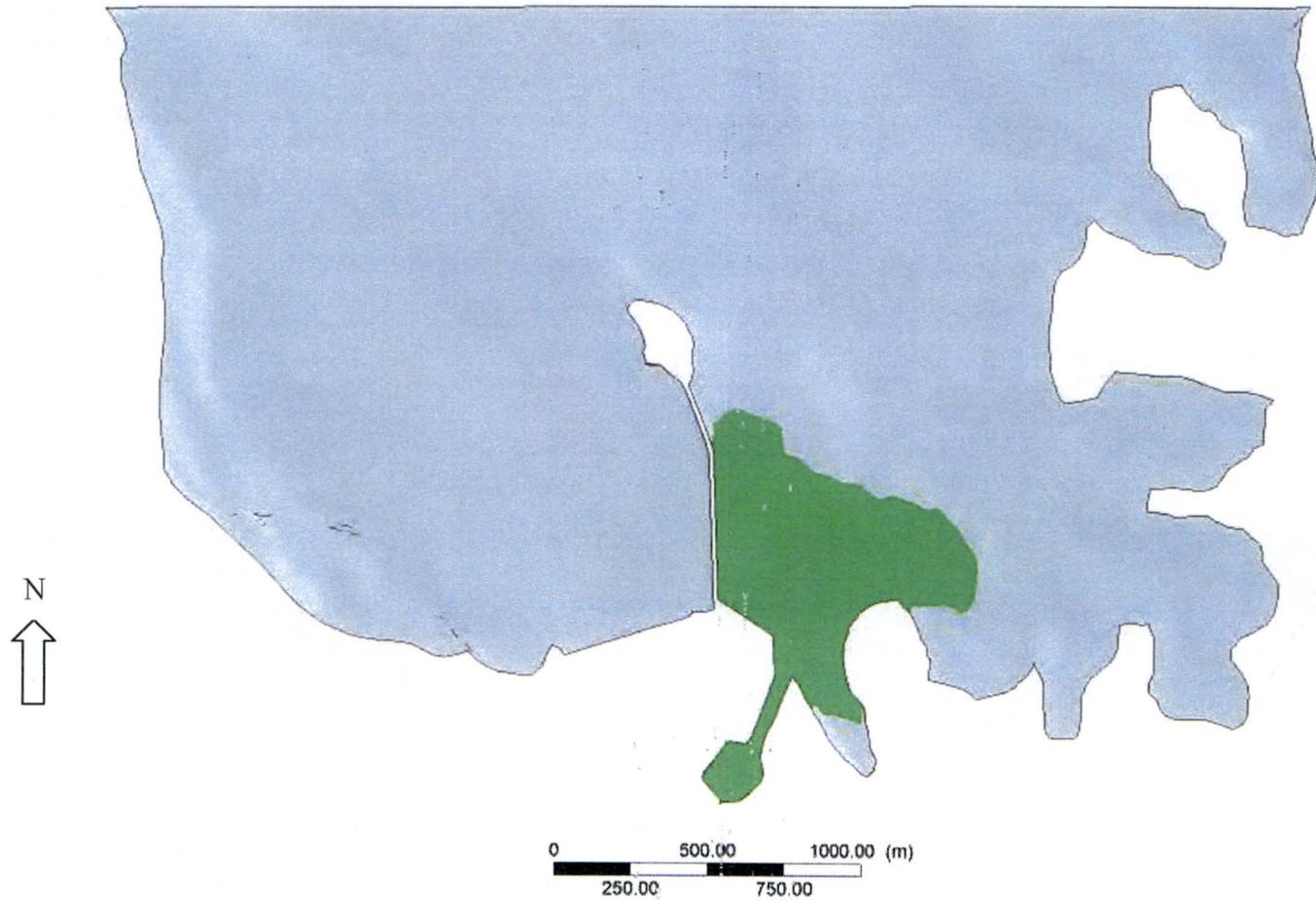


Figure 32 – Scenario 3W, $\Delta T = 5^{\circ}\text{F}$ thermal plume (green).

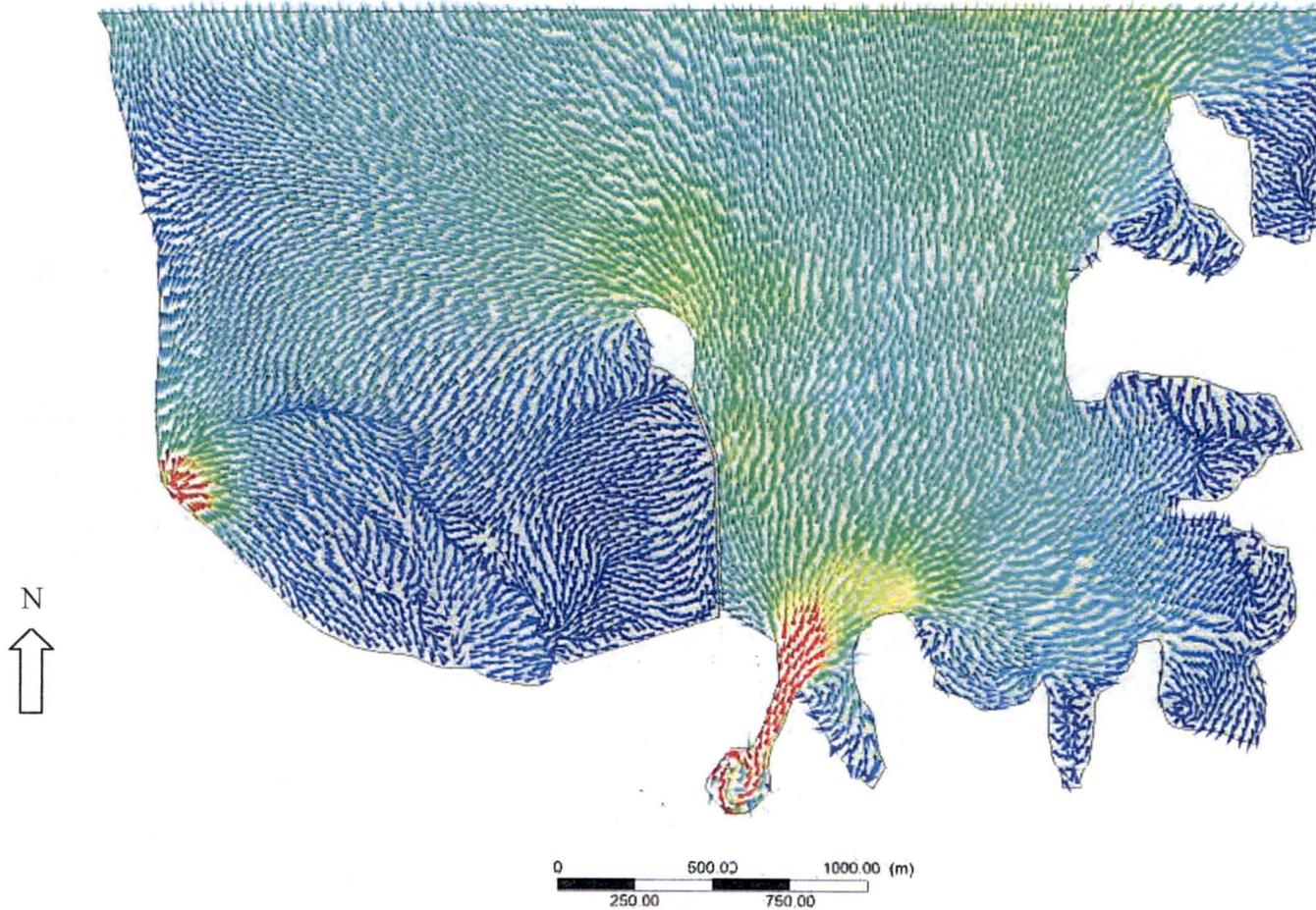


Figure 33 – Scenario 4W, surface velocity vectors

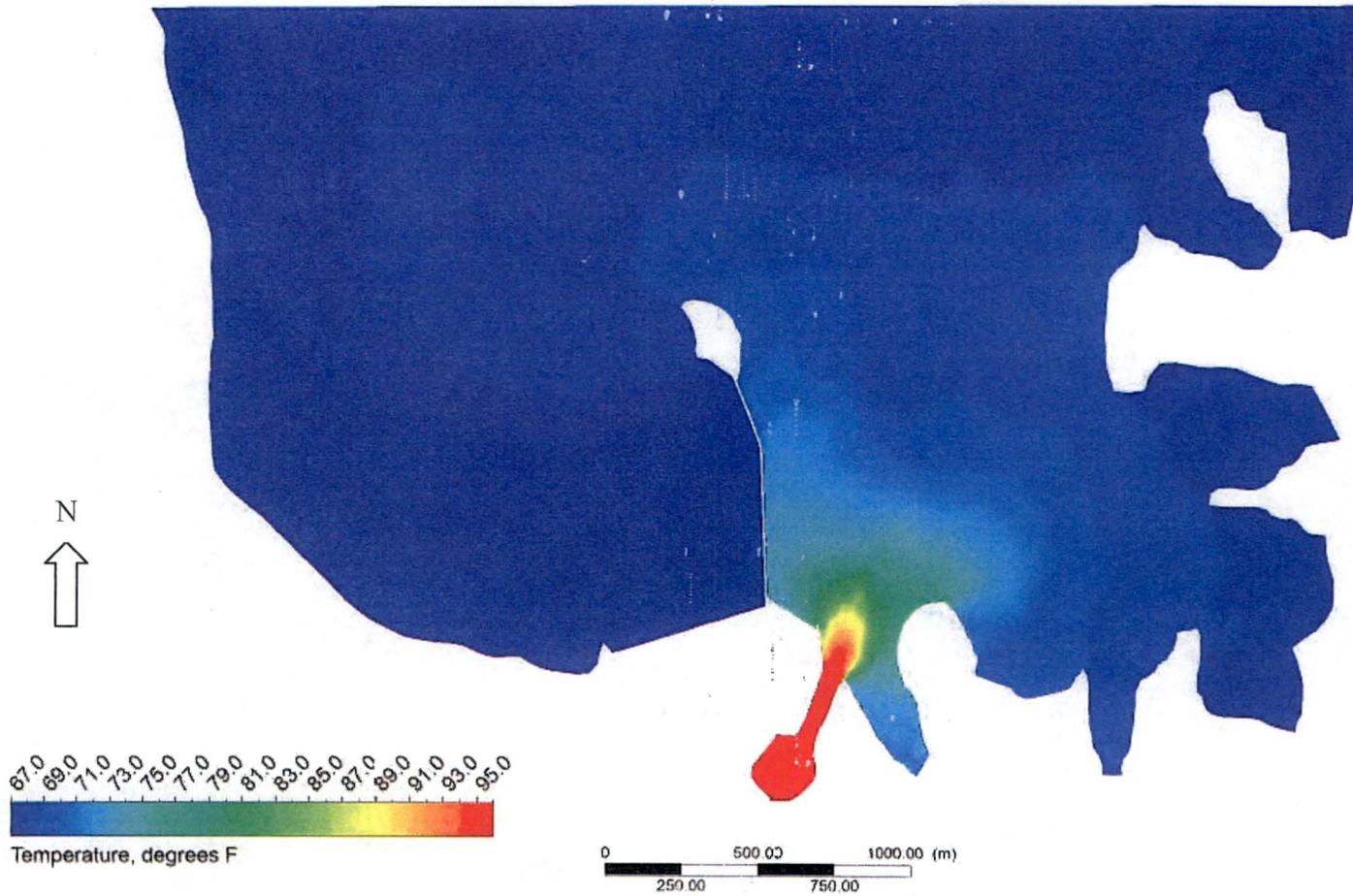


Figure 34 – Scenario 4W, surface temperature.

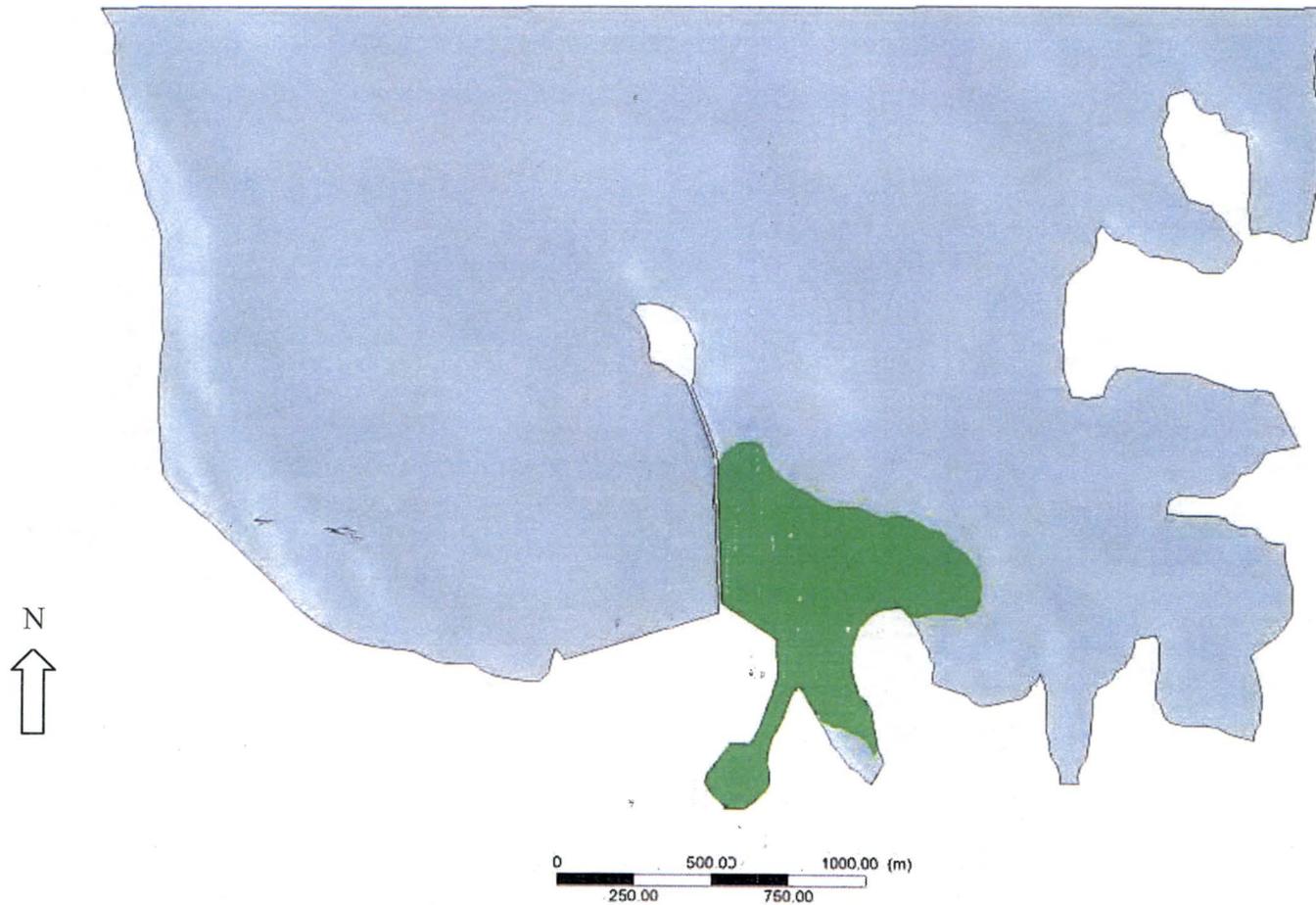


Figure 35 – Scenario 4W, $\Delta T = 5^{\circ}\text{F}$ thermal plume (green).

12. APPENDIX A – DETAILS OF THE NUMERICAL MODEL

Geometry and Mesh

The geometry and mesh generation were described in §2 of this report. A custom-built digitizer in Matlab was used to digitize the contour map, and produce a surface. This surface was read into the ICEM mesh generator to create the meshes.

Boundary Conditions

The primary boundary condition in the CFD model was the flow rate and temperature applied discharge. In all simulations, a point source (or sink) was used to represent the flow being withdrawn through the cooling water intakes. Similarly, where the FPSF was operating, a mass and directional momentum point source was employed. The north surface of the domain was a zero-pressure “opening”. This allows fluid to flow into the domain through the north boundary without exerting unphysical influence on the flow. The bottom surface of the domain was set to a “wall” and the top surface, representing the water surface, was set to a “smooth wall” (i.e. no shear stress).

Computational Models

Thermodynamic

The density of water in the domain depended on temperature only, using a tested polynomial relationship between density and temperature.

Turbulence

The shear-stress transport model (SST) was used for all simulations, which is a blend of the well-recognized $k-\varepsilon$ and $k-\omega$ turbulence models.

Numerics

Model

All simulations were performed using Ansys-CFX 12.0, a widely recognized industrial CFD software package. The model was run in steady-state mode as transient instabilities were not observed.

Discretization

For the simulation, a specified blend factor of 0.5 was used, which is a blend between first- and second-order schemes. This scheme was used to provide a balance between numerical accuracy and stability.

The temporal term in the transient simulations was discretized using a second-order implicit Euler scheme.

Convergence

The root-mean-square residuals were less than $1e-04$ for all transport equations solved. This level of convergence is acceptable for a transient simulation, especially as the volume of the thermal plumes was not observed to change. Imbalances for all conserved variables were less than 1%.