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By:

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NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

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**by**

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NWRI Cont. # 97-125

## MANAGEMENT PERSPECTIVE

**Title: Impact of Proposed Hydro-electric Power Development at Hugh Keenleyside Dam on the Arrow Lakes, B.C.**

**Author(s):** *P.Hamblin AERB .*

**NWRI Publication #:** 97-125

**Citation:** *Unpublished.*

**EC Priority/Issue:** *At the request of DFO and DOE, Pacific and Yukon Region this mathematical modelling study of the sensitivity of the thermal regime of the Arrow Lakes was undertaken to assist in the assessment of the environmental impact of proposed hydroelectric power generation of the thermal regime of the Arrow Lakes*

**Current Status:** *This document reports on the temperature, total dissolved solids distributions and exchange flows which justify the model assumptions as well as the model results. These results could form the basis for future work should the ecosystem of the Columbia River Basin prove critical to the predicted changes.*

**Next Steps:** *These results will be disseminated to the appropriate persons making the environmental assessment and have been discussed in detail at the Arrow Lakes thermal workshop which was convened by the environmental assessment review committee for the project.*

**Abstract**

In response to proposed changes in the operation the Hugh Keenleyside Dam on the Arrow Lakes Reservoir for hydro-electric power generation purposes, a field investigation of the baseline physical limnology was undertaken. In the first part of this study an analysis of water temperature and conductivity is aimed at establishing the rational for mathematical modelling of the impact of the proposed alteration of the outflow on the reservoir thermal regime. The main findings are that the most important variation in properties is in the vertical direction thereby justifying the assumption of vertical one-dimensionality in the model. Second, despite the rise of 20m in water level to form the reservoir the exchange from the Lower to the Upper Arrow Lake is argued to be sufficiently limited that the two water bodies can be modelled independently. In the second part of the study the model and its application to the two Arrow Lakes are described and sensitivity to operational changes provided. If the relatively minor impacts of the proposed scheme on the thermal regime of the Lower Arrow Lake Reservoir prove to be critical to the ecosystem of the Columbia River Basin then recommendations for a more refined field observation and modelling programme are made.

**Introduction**

The Arrow Lakes are ultra-oligotrophic fjordic lakes situated in the Columbia River system between Revelstoke and Castlegar, British Columbia. As a result of the construction of the Hugh Keenleyside Dam at their outflow in 1968 the water level was raised about 20m to form the present pair of interconnected lakes. Despite much attention to the fishery and contaminant loading of the Columbia River downstream of the dam, to the author's knowledge there has been no study of the limnology of the post-development Arrow Lakes. The only limnological investigation is that of Davidson and Thuesen (1963) who observed the summer distributions of temperature, conductivity and dissolved oxygen in the preimpoundment lakes.

Present interest in the limnology of the Arrow Lakes stems from a proposal by the Columbia Power Corporation to change the operation of the Keenleyside dam from storage and flood control to include the generation of hydroelectric power. The alteration of the outflow and effective withdrawal depths of the outflow at the dam could have potential impacts on the limnology of the lakes especially the thermal regime. Secondly, on a longer term there is concern that the upstream impoundments on the Columbia River may trap incoming nutrients needed to sustain a productive ecosystem as is the case with Kootenay Lake (Ashley, 1994). Understanding of the limnology of the Arrow Lakes would be required in order to assess the effectiveness of such remediation strategies as lake fertilization.

Hamblin and McAdam (1997), henceforth known as H&M (1997), have reported on a reservoir-wide survey of the wind field and temperature and total dissolved solids distributions in the Arrow Lakes Reservoir during a one week period in September, 1996. In this report a further analysis and presentation of those observations taken of their baseline survey of the limnology of the Arrow Lakes that bear on the question of the impact of the proposed hydroelectric project is provided. As well as the analysis of the supporting field observations a water quality model is applied to the two water bodies and the sensitivity of the temperature distribution and outflow water temperatures to the proposed alteration of the lake outflow is examined.

**Analysis of Field Observations**

Contoured Transects of Temperature and Conductivity

A simplifying assumption for the application of a water quality model which will be employed to assess the impact of proposed changes to the outflow is that the main variation in water properties is in the vertical direction. H&M (1997) displayed their temperature and conductivity data as vertical profiles. Therefore, to evaluate the suitability of a one-dimensional approach in modelling a long narrow water body such as the Arrow Lakes, the data collected by H&M (1997) are plotted as horizontal transects both along and across the lake axis. In addition, characteristics of lake circulation can often be inferred from three-dimensional distributions of conductivity and temperature.

Lower Arrow Lake, September 13 and 14, 1996

The longitudinal transect of Figure 1 based on the data collected at the mid-lake stations in the Lower Lake on September 13 and 14 shows that the main variation in properties is in the vertical direction. However, a warming of the epilimnion is observable in the downstream direction. The thermocline at a depth of about 20m is not very distinct despite the rapid cooling that should take place in September. As is typical in lakes conductivity is less in the epiliminion likely due to photosynthetic activities there. Noticeable is a slight drawing up of the colder water from the deeper layers as the outflow is approached as evidenced by the 9° C and 160 μS/cm contours. This is due to the relatively strong current associated with the outflow and is in accordance with selective withdrawal theory, Fischer et al. (1979). Figures 2 to 8 demonstrate very weak crosslake gradients in properties. Transects 4, 5 and 7 have higher hypolimnetic conductivities on the south western shore suggesting either transverse seiches or a weak hypolimnectic circulation. Further observation is needed to establish whether these features are transient or not.

Upper Arrow Lake, September 14 and 15, 1996

Similarly, data from September 14 and 15 in the Upper Lakes also shown in Figure 1 exhibit many of the same features as the Lower Lake. In Figure 1, depths in excess of 247m are estimated from the hydrographic charts and properties are extrapolated from shallower depths. However, in contrast to the Lower Lake, surface water temperatures are colder and hypolimnetic conductivities are higher. Beaton Arm conductivities are considerably higher as seen in the profiles of Appendix III of H&M (1997) but are unlikely to be the source of the higher hypolimnetic conductivities due to a sill at a depth of 15m separating the two bodies. Columbia River water enters the Upper Lake at about 11.5°C which would interflow at a depth of around 20m. This is from 2 to 3°C colder than the surface water. Both the temperature and conductivity support a pronounced tilting of the lower hypolimnion with a depression of the isotherms and conductivity isopleths in the northern end. Again, further investigation is needed to establish if this is a permanent chararacteristic of the Upper Lake.

It is interesting that in all conductivity plots as well as the profiles presented in the appendices of H&M (1997) that there is no evidence of a halocline as found in the hypolimnion of Kootenay Lake and which has been successfully modelled by Patterson et al. (1984) unless it is present below 247m, the maximum depth registered by the profiler. This is supported by the temperature profiles especially in the Upper Lake which indicate temperatures very close to the temperature of maximum density. This has important implications for mixing and the resuply of nutrients to the photic zone. It suggests that the entire water column completely turns over at least once per year. On account of the extreme depth of the lakes they may otherwise have been expected to be oligomictic.

Exchange between the Two Lakes of Arrow Lakes Reservoir

The topic of exchange between the two lakes has implications for the modelling strategy taken. If the flow from the Lower Lake to the Upper Lake is limited then the thermal model can be applied to each water body separately, greatly simplifying the undertaking. Furthermore, in the event that nutrients are artificially added to the Arrow Lakes it is essential to understand the patterns of flow which would transport and disperse fertilizer from the source locations to the body of the lakes.

Davidson and Thuesen (1963) reported that the "river current" through the preimpoundment lakes is confined mainly to the surface waters. However, since H&M (1997) found that the Columbia River water now interflows, it is likely that the "river current" is more uniformly distributed over the transverse cross-section. To estimate the approximate magnitude of this current, assume for the moment that it is evenly distributed over a cross-section. A typical cross-section in the lower lake, for example, Transect S13tr4 (see Figure 5) has an area of approximately $4.56 \times 10^5 m^2$. Based on a typical through flow during the experimental period of $1600 m^3/s$ the cross-sectionally averaged current would be only 3.5mm/s. In the Upper Lake Transect S15tr5 (see Figure 11) has an area of $6.58 \times 10^5 m^3$ and an average flow of 2.4mm/s. This contrasts, however, with the flow in the Narrows region (Figure 15) for example transect S14tr5 (see Figure 16), which has an area of $1.6 \times 10^4 m^2$ and which yields a detectable flow of 9.4cm/s. For this reason the following analysis of current will be focused on transect S14tr5. In the following application a method of inferring the distribution of current from water density is described which is based on the dynamical method of classical oceanography (Fomin, 1964).

In the absence of wind forcing and frictional drag the steady flow is governed by a balance of geostrophic and pressure (p) forces which may be represented in a right handed co-ordinate system with the x-axis positive from east to west and v, the current to the south in the downstream direction.

$$\rho f v = \frac{\partial p}{\partial x} \qquad (1)$$

$$\rho g = -\frac{\partial p}{\partial z} \qquad (2)$$

where f is the Coriolis parameter taken as $10^{-4} s^{-1}$, $\rho$ the density, g the acceleration of gravity and z the vertical co-ordinate. Equations (1) and (2) may be combined under the usual Bousinesq approximation to find the current distribution, v(x,z), over the cross-section.

$$v(x,z) = \frac{g}{f}\int_0^z \frac{\partial\, \rho(x,z')}{\partial\, x}dz' + C \qquad (3)$$

The constant of integration in equation (3) is determined by the requirement for the flow over the cross-section to match the steady through flow. The through flow at S14tr5 was estimated to be the discharge at the Dam of 1590m$^3$/s at the time of the transect less the draw down of the Lower Lake of 0.04m/d amounting to approximately 20m$^3$/s. Figure 16 implies that the density structure is tilted with the lighter water on the right hand side which supports the assumption of the geostrophic balance assumed in Equation (1). The observed temperature and conductivity were used to calculate the density from the expression of Chen and Millero (1977 and 1986) for lake water in general. The application of their relation assumes that the ionic composition of the Arrow Lakes does not differ appreciably from standard lake water but this assumption remains to be tested by further investigation. Vertical profiles in 0.5 depth increments of lateral density gradients were estimated midway between the three station locations across the transect. Density was estimated at standard depths from linear interpolation from surrounding depths. Discharge across each 0.5m depth interval was integrated by linear extrapolation and interpolation of the v component of current between the two midway locations. By summation of the contributions from each 0.5m segment it was found that 3cm/s had to be added to the currents to balance the measured discharge. Contours of current based on the above calculations suggest in Figure 17 that rather than a uniform distribution of flow over the section that the effect of the stratification is to concentrate the flow into a mid depth jet which is skewed to the western portion of the cross section. The magnitudes of the current are sufficiently large that they ought to exceed the threshold of an acoustic doppler profiler. An explanation is in order why S14tr5 was chosen to demonstrate the application of the geostrophic method among the other possible transects in the Narrows region. From the location chart of the Narrows region in Figure 15 it is evident that there are three sharp 90° bends along the channel. At a bend to the left in the downstream direction there is a tendency to augment the cross channel tilt of the isopycnals due to the addition of centrifugal forces to Coriolis forces while a right turn opposes the tilt due to conservation of vorticity. It is supposed that the flow has adjusted to the left hand turn at S14tr6 by the time it reaches S14tr5.

Once the flow in the Narrows region has been estimated for the September 1996 survey, the question arises of whether the downstream flow can be reversed at other times leading to exchange of properties from the Lower Lake to the Upper Lake. A strong wind blowing up the Lower Lake from southeast to northwest resulting in a wind stress of $10^{-4}$ Pa should cause the water level in the narrows to rise by about 2cm according to a simple balance of pressure and wind friction forces. As the head loss through the narrows region would be less than a centimetre as deduced from an application of the Manning equation (Henderson, 1966), a strong southerly wind ought to reverse the flow in the narrows. However, the exchange depends on the excursion of the reversed flow. Since the Narrows region is relatively long the excursion length may only rarely exceed the connecting channel length consequently, leading to small exchanges in general.

Large vertical displacements of the thermal structure by internal waves known as internal bores or surges have been observed in British Columbian lakes by Wiegand and Carmack (1986) and Farmer (1978). Another aspect of the exchange is the propagation of internal surges from the Lower Lake to the Upper Lake. Since Figure 16 demonstrates a fairly uniform rate of temperature stratification the appropriate propagation speed of the internal surge is given by the product of the stability frequency of the water column times the average depth, giving a speed of 14cm/s during the experimental period. This is somewhat greater than the average downstream speed of 9.4cm/s so that it should be possible for some internal disturbances in the Lower Lake to enter the Upper Lake but likely with greatly reduced energy.

Since as will be shown below the discharge peaks annually at about the time of the survey, it may be supposed that the current through the Narrows is weaker at other times of the year. Compensating for the fourfold variation in the annual discharge is a corresponding change in the water level which results in a reduced cross-sectional area. This effect is illustrated for the cross-section of minimum area at the cable ferry crossing in Figure 18. Monthly averaged water levels were used to estimate the cross-sectional area and which was then divided into the monthly inflow values. It is evident that the highest currents are early in the year and they vary only by about a factor of two over the year. The background current is evidently relatively high over the stratified period during the summer months.

The transverse distributions of temperature in the Upper and Lower Lakes do not exhibit in Figures 2 to 14 the pronounced tilting seen in the narrows region. A persistent lens of warmer and lighter water in the middle from transects S15tr3 to S15tr5 suggests that there may be a clockwise gyre in the northern half of the Upper Lake. In the southern portion of the Upper Lake this feature gives way to lighter water along the eastern shoreline at the surface from stations S15tr6 to S15tr8. Whether this is a persistent feature or a manifestation of a wind driven internal seiche will have to be resolved by further studies. Conductivity can often yield insight into the general circulation. For example, somewhat higher conductivity at depth along the western shoreline of the northern half of the Upper Lake may indicate past inflow from the high conductivity of the hypolimnion of Beaton Arm. This feature appears to diffuse away by the time the southern half of the lake is reached. In the Lower Lake the evidence for warmer and lighter near surface water at mid-lake is weaker but some transects suggest this. This may be an indication of intensified of flow to the outflow along the northeastern shoreline. Again, conductivity clearly demonstrates a tendency for higher values along the western and southwestern portion of the hypolimnion. What the interpretation is of this feature in terms of the hypolimnetic circulation is not known.

In summary, it appears that the dynamic method of classical oceanography is limited to the narrows zone where confinement of the flow results in speeds as strong as wind generated flows and furthermore to those transects where the channel curvature is not too large. Elsewhere, despite the relatively large through flow other neglected effects such as friction, wind forcing, and transients limit the quantitative application of this method. The analyses in this section are supportive of the subsequent modelling strategy, that it is valid to model the Upper Lake independently of the Lower Lake and to specify the outflow to the Lower Lake based on the output from the Upper Lake model.

**Thermal Modelling**

In order to assess the impact of proposed alteration to the outflow regime on the thermal structure a dynamic water quality simulation model was applied to each of the Upper and Lower Arrow Lakes. On account of the wide use that the model DYRESM has seen in lakes, for example, Kootenay Lake (Patterson et al. 1984), the first lake to which it was applied, DYRESM was selected. The underlying principle on which the model is based is to represent the dominant physical processes responsible for the spatial and temporal distribution of water quality parameters in the model. A schematic diagram (Figure 19) is taken from Fischer et al. (1979) who provide a good description of the model and its physics as well as Fischer (1981). Figure 19 shows the processes of inflow, outflow, and vertical mixing by wind stirring, convective cooling and internal seiches which are included in the model. It may be noted that the model was originally developed for application to reservoirs which usually have a vertical wall at the outflow. While Patterson et al. (1984) adapted the model to lake applications they did not modify the outflow routine to allow for shoaling topography near the outflow as this effect would be beyond the scope of a one-dimensional model. Apart from a few changes to the vertical mixing scheme in the hypolimnion a notable modification to the standard lake model for cold deep lakes is that the influence of compressibility of water is taken into account when the densities of two water parcels are compared in the vertical direction in order to determine the stability of the water column. Due to the question of the effect of the shoaling bathymetry near the outlet, the temperature data of September 16, 1996 are plotted in Figure 20. This longitudinal section demonstrates the effect of the concentration of flow on the isotherms. Similarly to Figure 1 cooler water is upwelled near the outflow. The approach taken is the modelling exercise is conservative or a worst possible case approach. Since the shoaling near the outlet restricts withdrawal from the deeper layers, ignoring this effect would lead to a conservative error, that is, the outflow temperatures are colder than they otherwise would be and the thermal response to surface outflow is augmented.

The model requires various inputs, namely the basin geometry in the form of hypsographic curves, the lake hydrology in the form of inflows and their properties and outflows or surface water level and the daily meteorological forcing as represented by short and longwave radiation, wind speed and direction, air temperature and relative humidity. Unfortunately the volume and area curves versus depth are not known for the Arrow Lakes but will be computed once digital topography is available. Instead, estimates of the surface area were obtained from BC Hydro and maximum depths from the CHS bathymetric charts for each basin and were used to scale the non dimensional hypsographic curve of Kootenay Lake. The non dimensional area-depth curve for Kootenay Lake is compared to three other British Columbian and Yukon fjord-like lakes in Figure 21. Kootenay Lake and Kamloops Lake illustrate a U-shaped distribution which is typical of glaciated lake basins. It is assumed that the Arrow Lakes are more similar to this type of lake than the inverted U-shaped curves for Babine and Laberge Lakes. Peterson and Withler (1965) have remarked on the steep-sided shorelines of the preimpoundment Arrow Lakes. Once the area curve is scaled it can be integrated vertically to yield the volumetric distribution.

Based on the estimated volumes for each basin it is of interest to calculate the residence times. Since precipation and evaporation are in close balance the retention and residence times are nearly identical. Table 1 provides maximum and minimum residence time based on the inflow extrema over a five year average (see Figure 22). Residence times for the entire system can be obtained by adding the values from the individual basins.

| | Upper Arrow Lake | Lower Arrow Lake |
|---|---|---|
| Depth (m) | 290 | 194 |
| Area ($km^2$) | 306.3 | 171.1 |
| Volume ($km^3$) | 118.7 | 44.3 |
| Residence Time (yr) max/min | 6.94/1.78 | 2.59/0.66 |

Table 1. Estimated Physical Characteristics of the Two Arrow Lake Basins

The daily inflow of the Columbia River based on a five year average from 1990 to 1995 was prepared as model input along with the associated water level at the Fauquier gauge. Both series are depicted in Figure 22 and show a bimodal distribution of inflow more typical of reservoirs than natural systems. As well as the water quantity, information on inflow temperature and conductivity is required. Water temperature was estimated by fitting a cosine curve to spot temperature reading taken below the Revelstoke Dam over a number of years. Accordingly, inflow temperatures varied from 11°C on August 1 to 2°C at the end of January. The unknown conductivity was assumed to be constant and was specified from the observed value of H&M (1997) of 130 µS/cm. The inflow to the Lower Lake and its temperature and conductivity were specified from the simulated outflow of the Upper Lake which is based on the water balance of the Upper Lake and the selective withdrawal routine in the model (Fischer et al., 1979).

H&M (1997) have established that the land-based winds at the Castlegar Airport are not representative of the overlake wind field. Thus, for the purposes of testing the sensitivity of the thermal regime of the Lower Arrow Lake Reservoir to alteration of the outflow it is assumed that the meteorological data observed at buoys on Kootenay Lake is sufficiently representative. Patterson et al.(1984) have displayed most of the daily meteorology employed in their model of the water quality of Kootenay Lake and in this simulation. Finally, initial vertical profiles of temperature and conductivity were specified for two basins based approximately on the lake-wide survey of H&M (1997) and the coefficient of extinction appropriate for ultra-oligotrophic lakes of 0.5 $m^{-1}$ was assumed.

The output of the model has been presented in the form of contours of temperature and conductivity as a function of depth and time over a one year simulation period in Figure 23. Since the values of contours do not repeat at the end of the calculation, the assumed initial conditions are not in equilibrium with the specified meteorology and hydrology. However, this is a common situation in any system with an interannual variation so it does not indicate that the results are invalid. Attention is drawn to the 3.7C isotherm which is considered to accurately represent the winter period. It persistence beyond the overturn period in April indicates correct treatment of vertical mixing in the presence of a density extremum and is supported by the temperature profiles of H&M (1997).

At present the Lower Arrow Lake withdraws at an elevation of 10m below CHS chart datum which ranges from 1 to 14m below the surface depending on the time of year. At times, water is spilled over the dam but these surface withdrawals are ignored in the thermal simulation so as to represent the most extreme case. The simulations of the current thermal regime of the Lower Lake based on the appropriate hypsographic data and identical meteorology to the Upper Lake, seen in Figure 24, have somewhat higher surface temperatures in summer than the Upper Lake in keeping with the observations of H&M (1997). As well, the temperature profiles at the end of the simulation are closer to initial profiles which likely indicates that the influence of the unknown Columbia River inflow properties is less apparent in the Lower Lake.

The proposed change in the outflow effectively withdraws water from a higher level. Again, adopting a worst case approach, it is assumed that outflow in the altered case is taken from the crest level of the Lower Arrow Lake Reservoir. Since the two simulations were so similar, the sensitivity of the changes of outflow is shown in Figure 25 as the differences between the two cases. At most, surface water temperatures are seen to decrease by about 2°C for a brief period during the restratification period in June due to the export of warmer near surface water over the crest of the dam. Figure 26 plots the predicted outflow temperature from the Lower Lake and compares it to the altered regime, again by means of temperature differences. The proposed outflow temperature evidently peaks at 2.2°C warmer than existing conditions temporarily in June but most of the time is less than 0.5°C from the present state. The variability of the outflow temperature is noteworthy. Vertical displacements of the isotherms caused by internal seiches are not taken into account in the model. Therefore, the variability of the outflow temperature must reflect the fluctuations in the rates of heating and cooling as storms pass through the area. Thus, a portion of the variability of the outflow temperatures observed by R.L. &L. (1997) during the summer of 1996 could be attributed to heating and cooling of the epilimnion.

**Conclusions and Recommendations**

The development of new electronic instrumentation has greatly facilitated the field measurement of physical characteristics in lakes and permitted rapid three-dimensional coverage of two large interconnected lake basins. The results of this survey have been analysed to justify the approach taken the modelling of the impact of proposed outflow changes on the thermal regime of the Lower Arrow Lake Reservoir. The main variation of physical properties is vertical with a secondary trend to warmer water temperature closer to the outlet. Lateral variations do not appear to be persistent except in the Narrows region where they indicate a concentration of the flow from one basin to another. Calculations made herein suggest limited exchange of the Lower Lake with the Upper Lake. This simplifies the modelling as it is assumed the Lower Lake has only one outflow, through the Hugh Keenleyside Dam.

The assessment of the impact of proposed changes to the outflow of Lower Lake has been hampered by the lack of field data, for example, bathymetric information which is currently not available in digital form as is the case for many other major BC lakes. Due to the lack of data and the assumption one one-dimensionality in the model, it is recommended that the results of the sensitivity tests performed in this report be considered to be preliminary in nature and that if the findings presented are considered to be critical to the Columbia River ecosystem that more refined modelling be undertaken in conjunction with further observations of the causative factors and validating data.

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**List of Figure captions**

1)Longitudinal temperature transect (upper left panel) and conductivity of Lower Arrow Lake, September 13 to 14, 1996 based on mid lake profiles. Note temperature contours at 16, 14, 12, 9, 7, 5 and 4°C.and conductivity (lower left panel) at 140, 150, 160, and 170 µS/cm. Positions of the transverse transects are indicated. The right hand panels are for the Upper Arrow Lake, September 14 to 15, 1996. Note temperature contours at 13, 12, 10, 8 ,6,4 and 3.6°C and conductivity contours at 140, 150, 160, 170 and 174 µS/cm. The x-axis is the distance from the Hugh Keenleyside Dam.

2) Temperature (upper) and conductivity (lower) with same units as Figure 1 for transverse transect 1, September 13, 1996.

3) Same as Figure 2 but for transverse transect 2.

4) Same as Figure 2 but for transverse transect 3.

5) Same as Figure 2 but for transverse transect 4.

6) Same as Figure 2 but for transverse transect 5.

7) Same as Figure 2 but for transverse transect 6.

8) Same as Figure 2 but for transverse transect 7.

9) Same as Figure 2 but for transverse transect 3, September 15, 1996.

10) Same as Figure 9 but for transverse transect 4.

11) Same as Figure 9 but for transverse transect 5.

12) Same as Figure 9 but for transverse transect 6.

13) Same as Figure 9 but for transverse transect 7.

14) Same as Figure 9 but for transverse transect 8.

15) Location of stations in the Narrows region.

16) Same as Figure 9 but for the Narrows region, September 14, 1995, transect S15tr5. Temperature contours 13.5 to 9.7 °C and conductivity contours 138.9 to 145.3 µS/cm.

17) Same as Figure 16 but isopleths of flow component into page and towards the outflow in the lower panel.

18) Estimated monthly current from the Upper to Lower Arrow Lakes based on five-year average inflows and water levels.

19) Schematic of many of the physical processes taken into account in the vertically one-dimensional water quality model, DYRESM, after Fischer et al. (1979).

20) Longitudinal temperature transect on September 16, 1996. The x-axis is the distance from the Hugh Keenleyside Dam.

21) Non dimensional area versus depth curves for four long, deep and narrow intermontane lakes in the temperate zone.

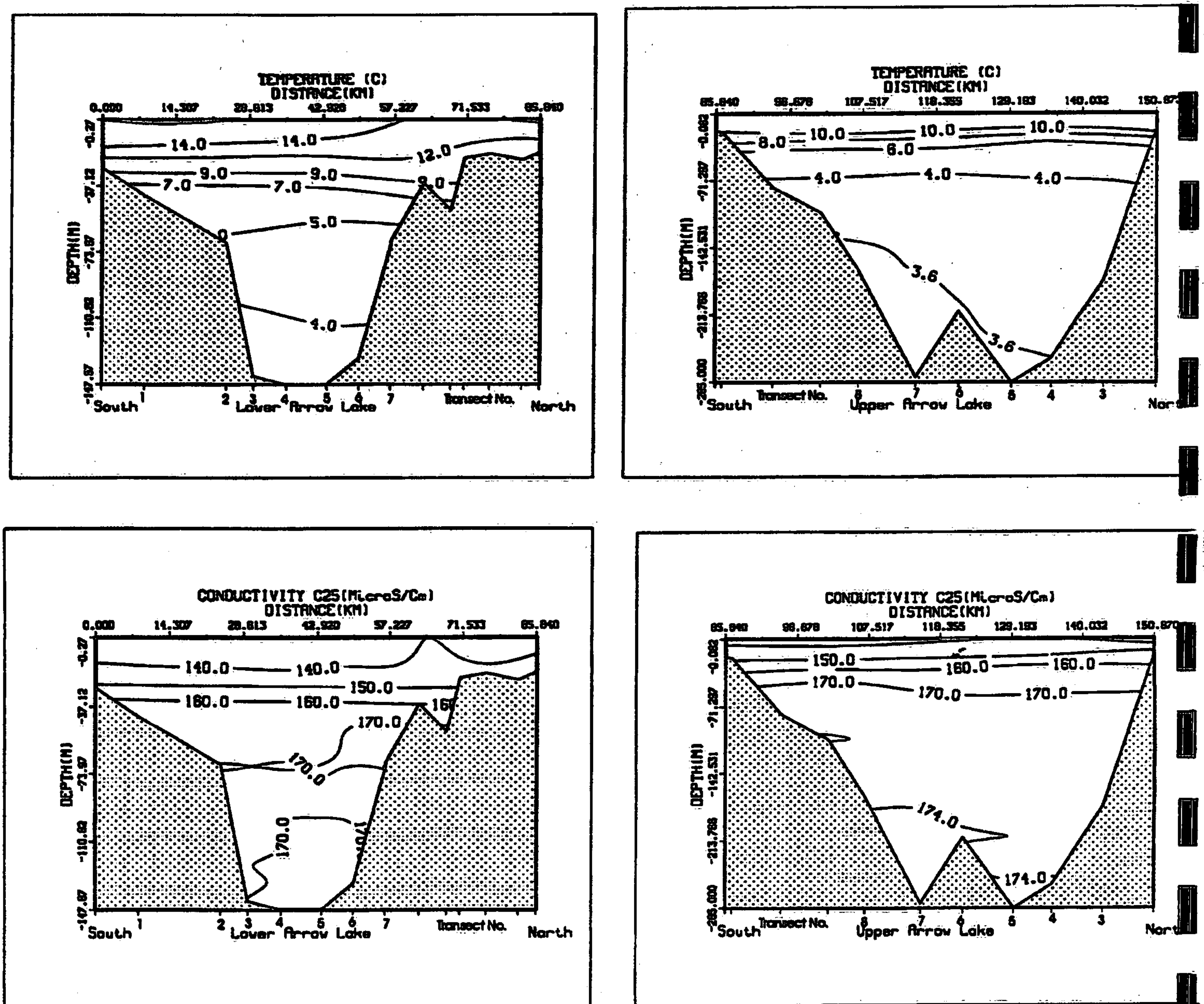
22) Daily averaged inflow to the Upper Arrow Lake (solid curve) and water level at Fauquier (dashed curve)

23) Modelled depth and time distributions of temperature (upper) and conductivity (lower) for the Upper Arrow Lake Reservoir

24) Same as Figure 23 but for the Lower Arrow Lake Reservoir.

25) Differences in properties with depth and time for the Lower Arrow Lake Reservoir between the present and proposed outflow cases. Top withdrawal is current practice while the crest withdrawal is the proposed case.

26) Predicted outflow water temperatures (upper) and conductivity (lower panel) from the Lower Arrow Lake Reservoir (solid line) and dashed line, the difference (proposed minus present operation).


TEMPERATURE (C)
DISTANCE(KM)
DEPTH(M)
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12.0
9.0
7.0
5.0
4.0
South
Lower Arrow Lake
Transect No.
North
TEMPERATURE (C)
DISTANCE(KM)
DEPTH(M)
10.0
8.0
4.0
3.6
South
Transect No.
Upper Arrow Lake
CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(KM)
DEPTH(M)
140.0
150.0
160.0
170.0
South
Lower Arrow Lake
Transect No.
North
CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(KM)
DEPTH(M)
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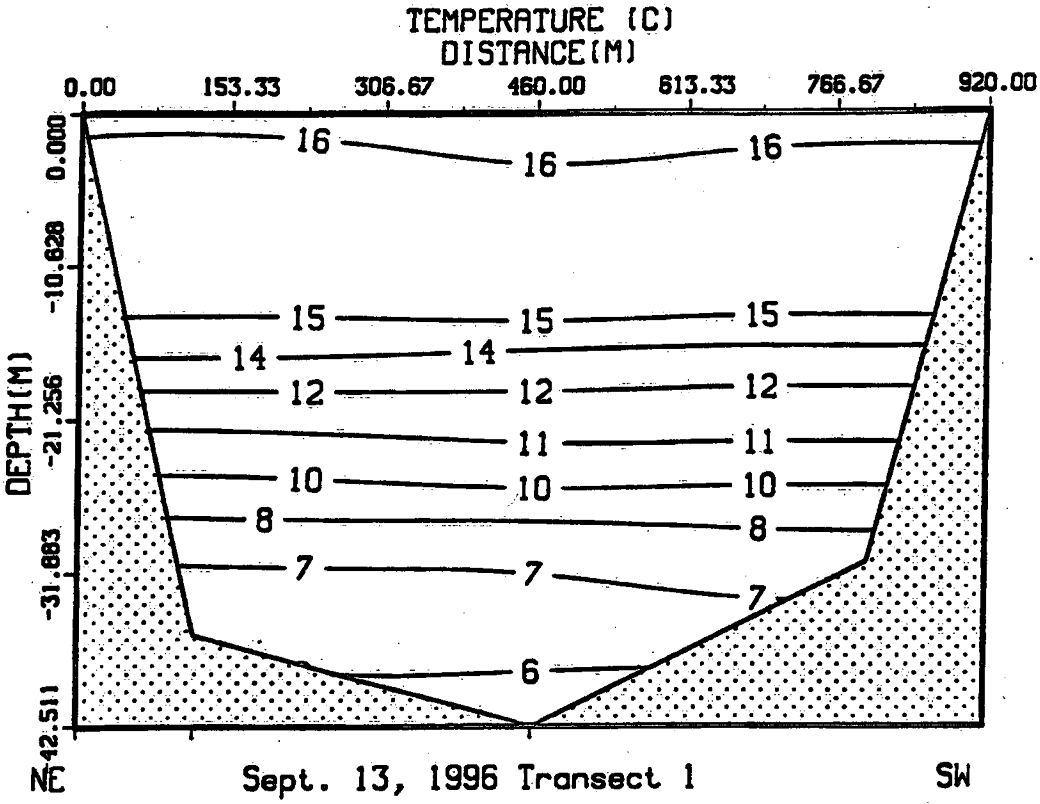
160.0
170.0
174.0
South
Transect No.
Upper Arrow Lake

FIGURE 1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DEPTH(M)
0.000
-10.628
-21.256
-31.883
-42.511
16
15
14
12
11
10
8
7
6
NE
Sept. 13, 1996 Transect 1
SW

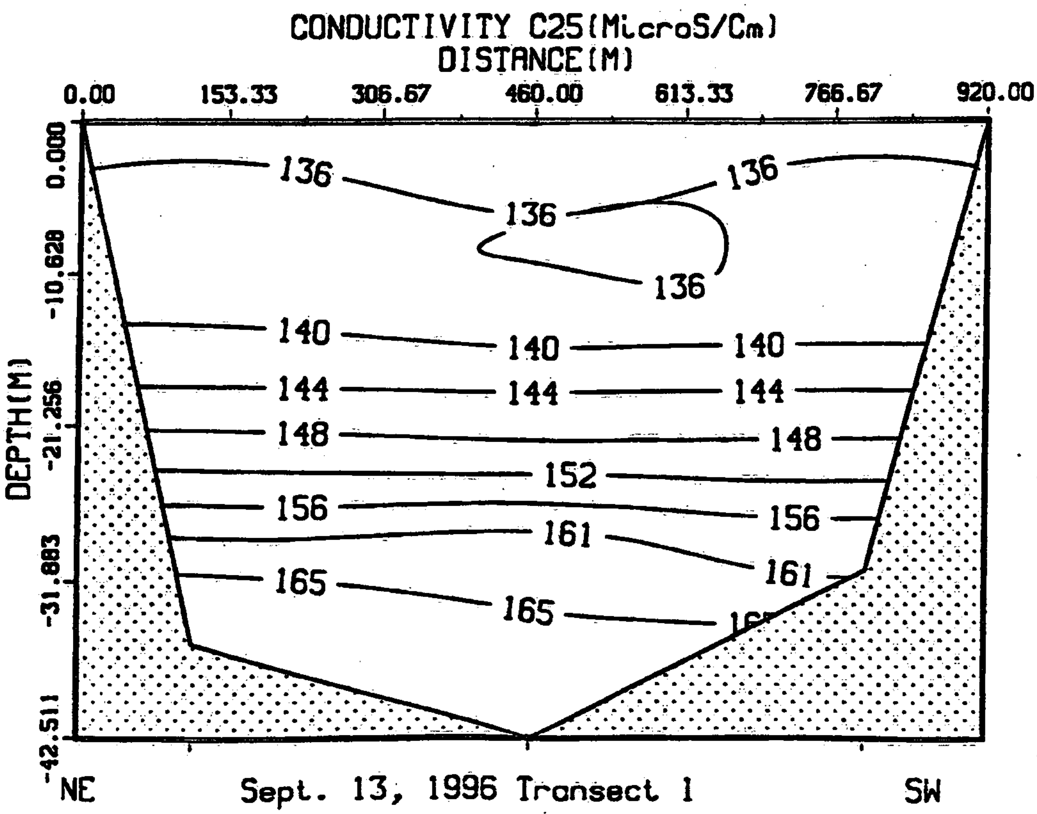
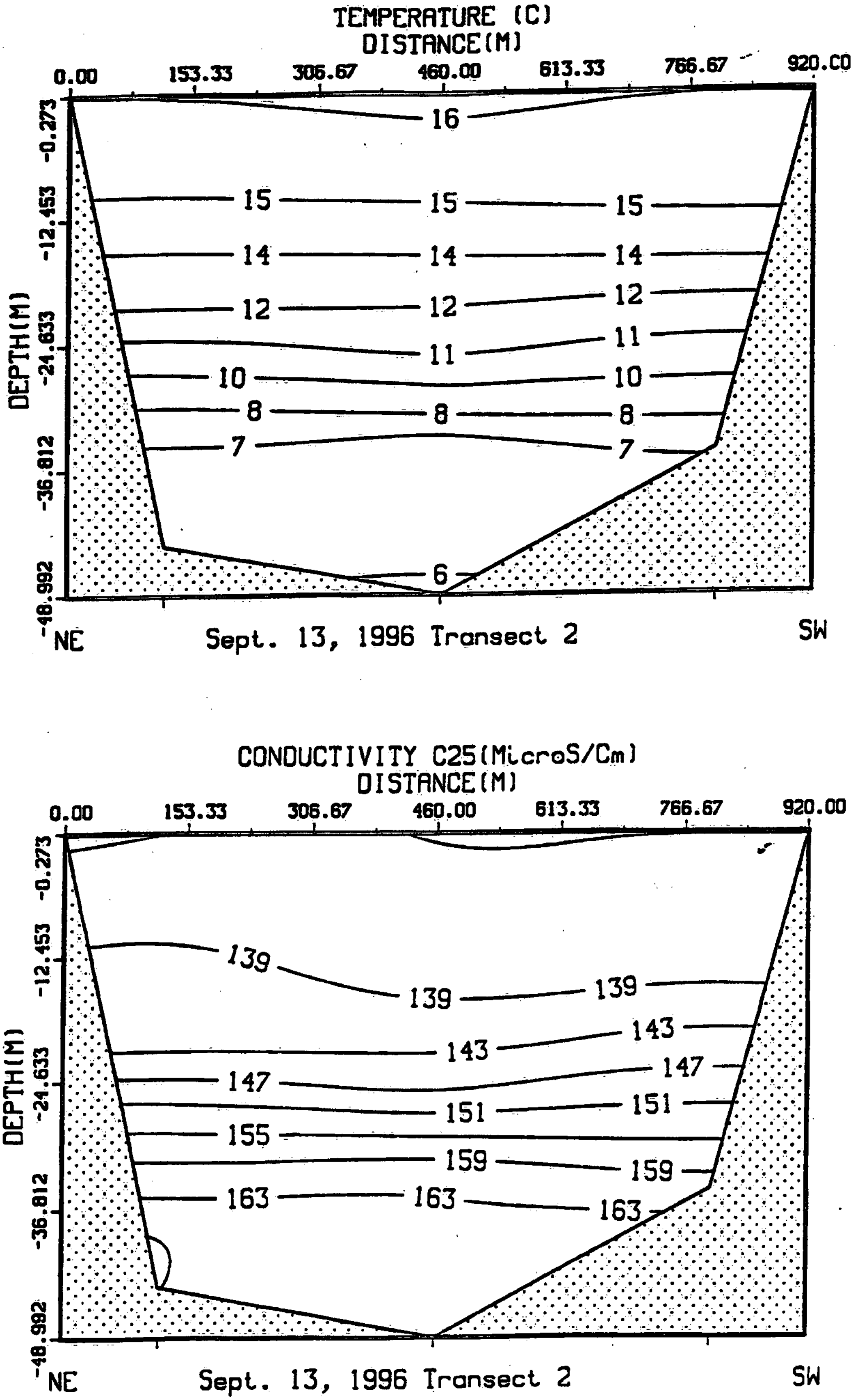

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.00
153.33
306.67
460.00
613.33
766.67
920.00
DEPTH(M)
0.000
-10.628
-21.256
-31.883
-42.511
136
140
144
148
152
156
161
165
NE
Sept. 13, 1996 Transect 1
SW

FIGURE 2



TEMPERATURE (C)
DISTANCE(M)
0.00
153.33
306.67
460.00
613.33
766.67
920.CO
DEPTH(M)
-0.273
-12.453
-24.633
-36.812
-48.992
16
15
15
15
14
14
14
12
12
12
11
11
10
10
8
8
8
7
7
6
NE
Sept. 13, 1996 Transect 2
SW
CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.00
153.33
306.67
460.00
613.33
766.67
920.00
DEPTH(M)
-0.273
-12.453
-24.633
-36.812
-48.992
139
139
139
143
143
147
147
151
151
155
159
159
163
163
163
NE
Sept. 13, 1996 Transect 2
SW

FIGURE 3

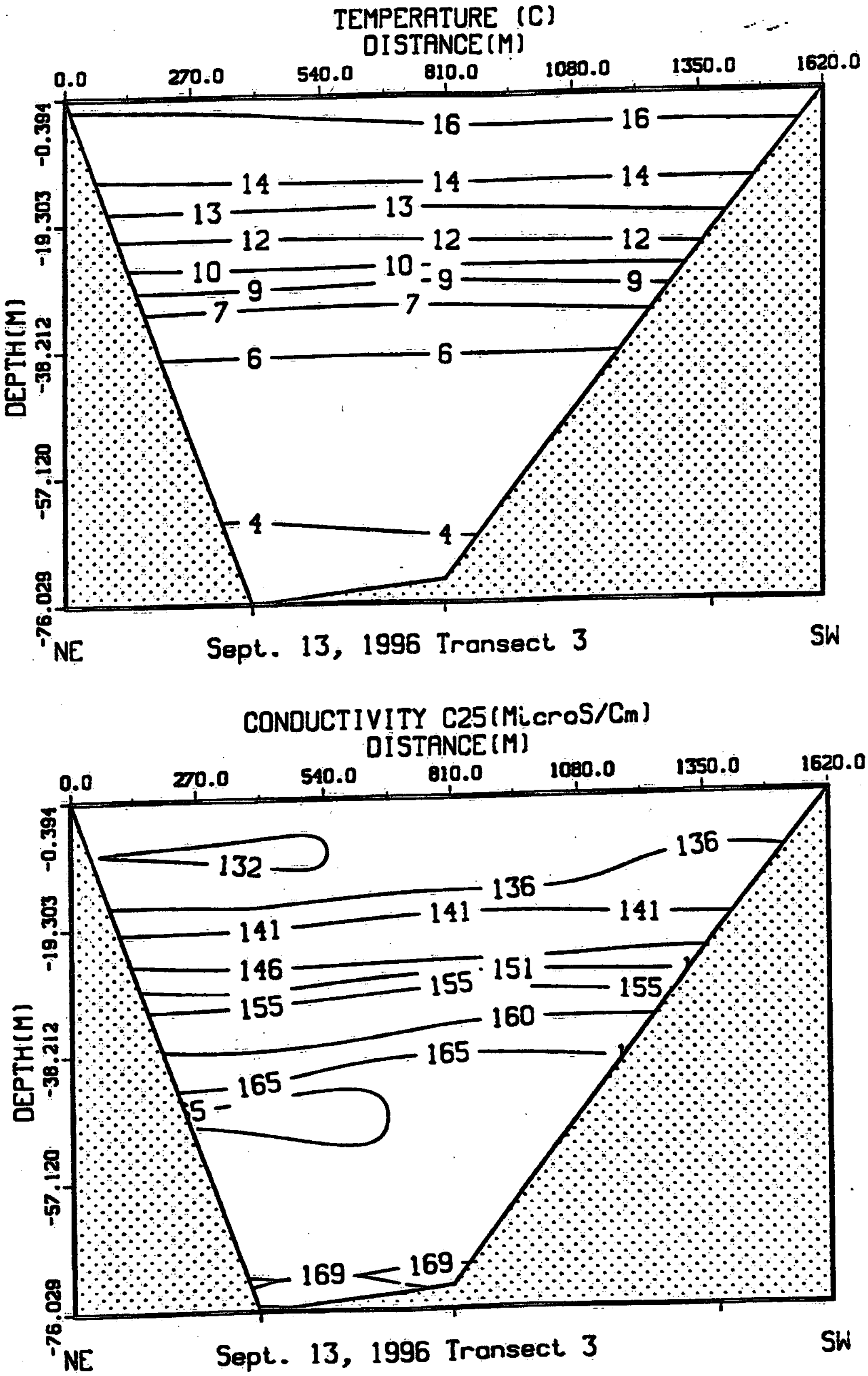

TEMPERATURE (C)
DISTANCE(M)
0.0
270.0
540.0
810.0
1080.0
1350.0
1620.0
DEPTH(M)
-0.394
-19.303
-38.212
-57.120
-76.029
16
14
13
12
10
9
7
6
4
NE
Sept. 13, 1996 Transect 3
SW
CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.0
270.0
540.0
810.0
1080.0
1350.0
1620.0
DEPTH(M)
-0.394
-19.303
-38.212
-57.120
-76.029
132
136
141
146
151
155
160
165
169
NE
Sept. 13, 1996 Transect 3
SW

FIGURE 4

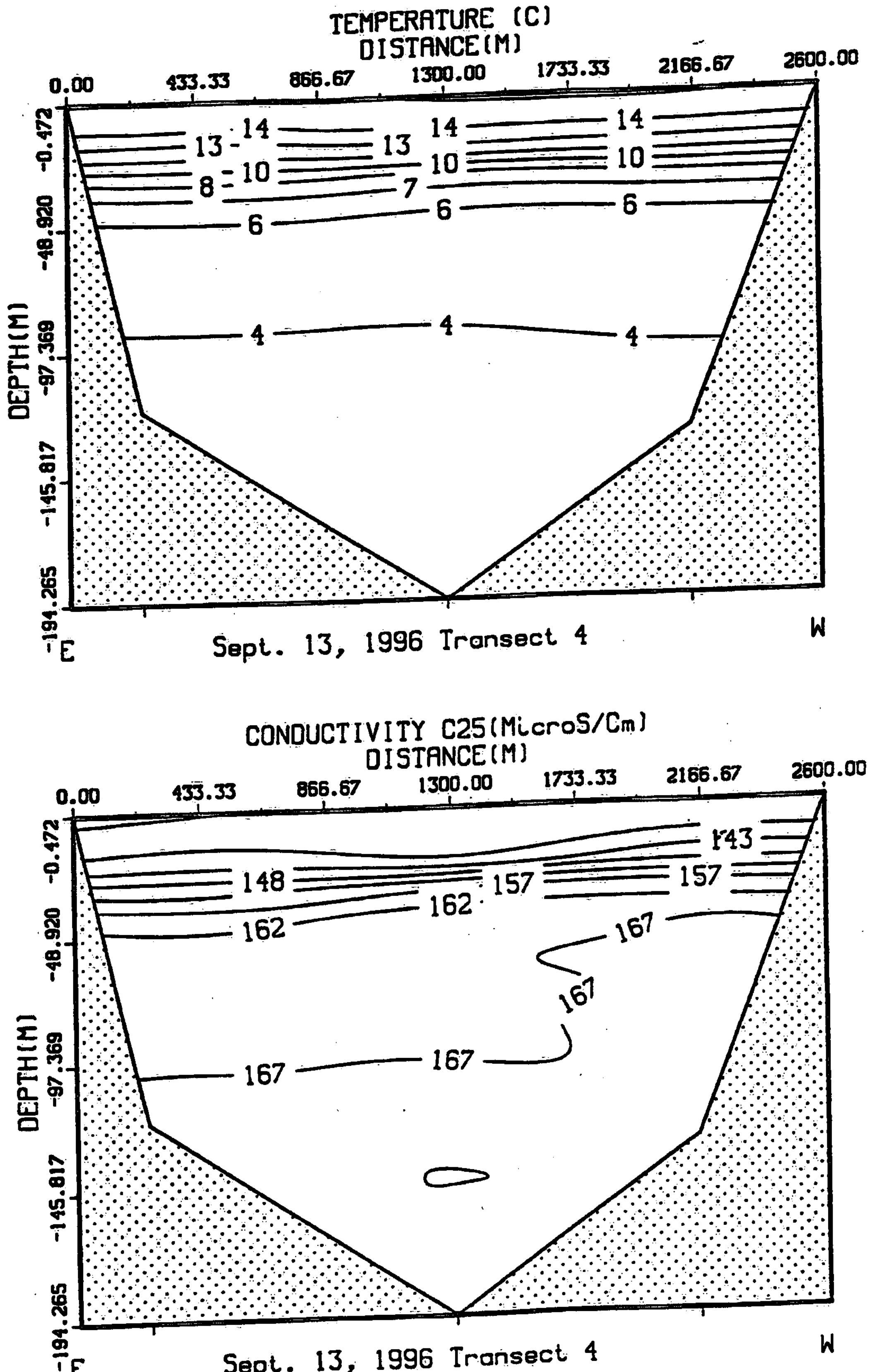
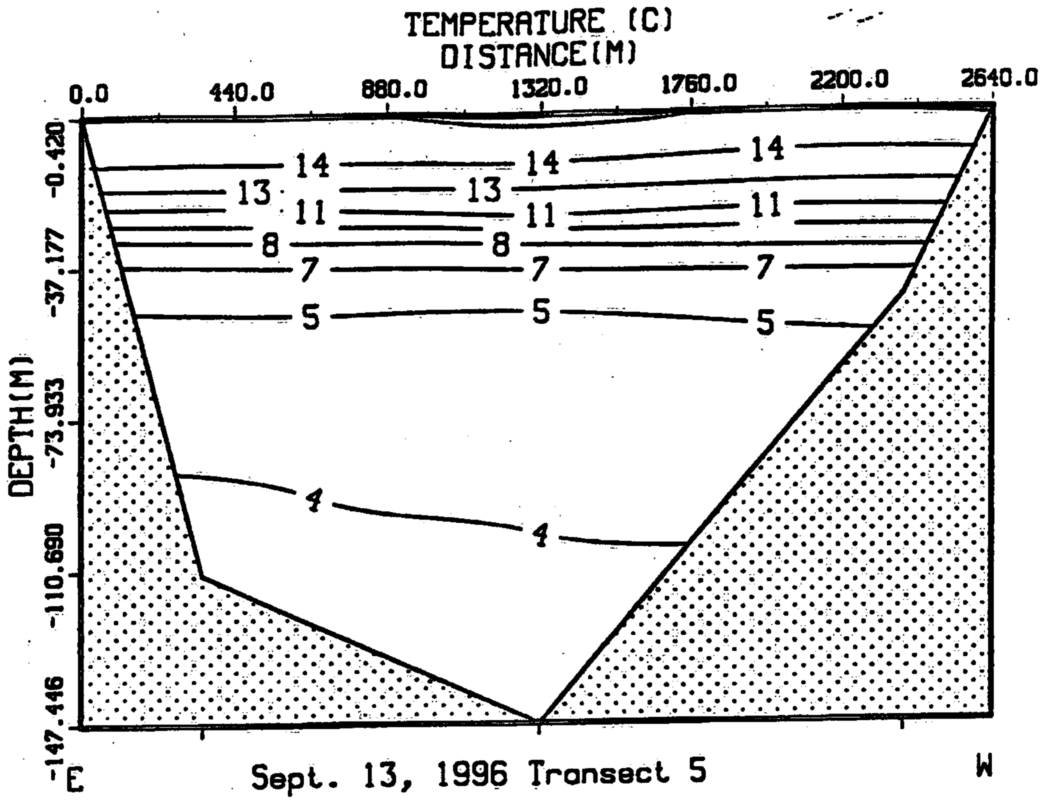

TEMPERATURE (C)
DISTANCE(M)
0.00
433.33
866.67
1300.00
1733.33
2166.67
2600.00
DEPTH(M)
-0.472
-48.920
-97.369
-145.817
-194.265
14
13
10
8
7
6
4
E
W
Sept. 13, 1996 Transect 4
CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.00
433.33
866.67
1300.00
1733.33
2166.67
2600.00
DEPTH(M)
-0.472
-48.920
-97.369
-145.817
-194.265
143
148
157
162
167
E
W
Sept. 13, 1996 Transect 4

FIGURE 5


TEMPERATURE (C)
DISTANCE(M)
0.0
440.0
880.0
1320.0
1760.0
2200.0
2640.0
DEPTH(M)
-0.420
-37.177
-73.933
-110.690
-147.446
14
13
11
8
7
5
4
E
W
Sept. 13, 1996 Transect 5

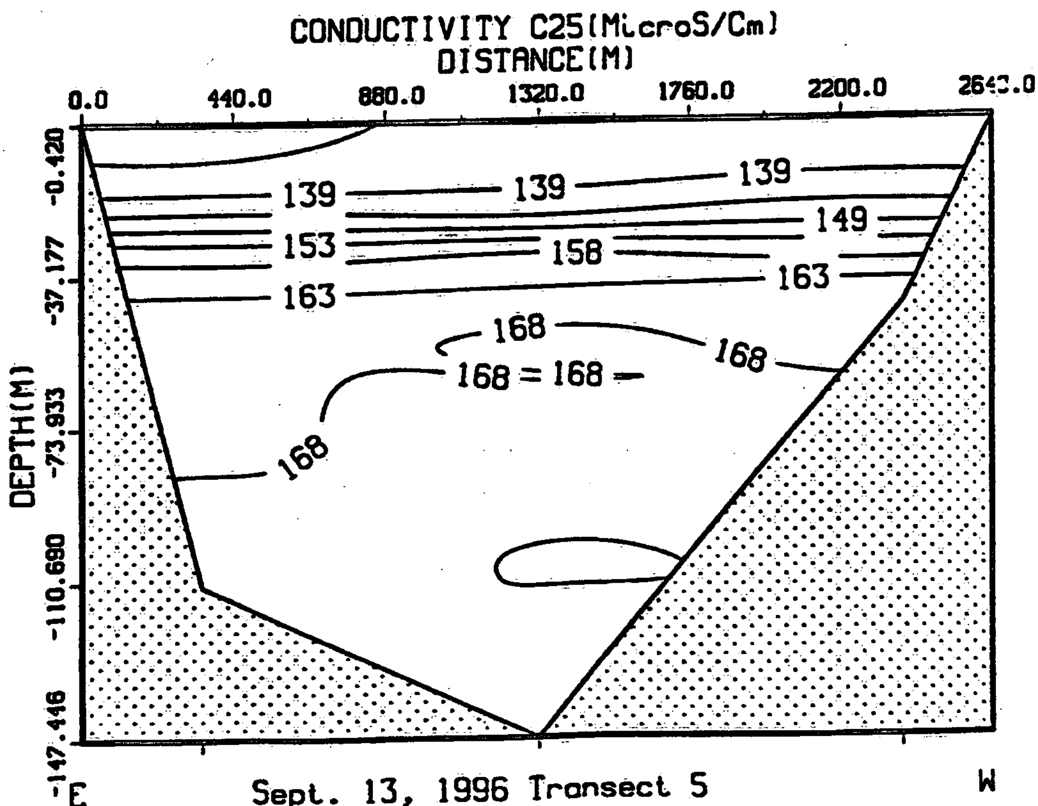
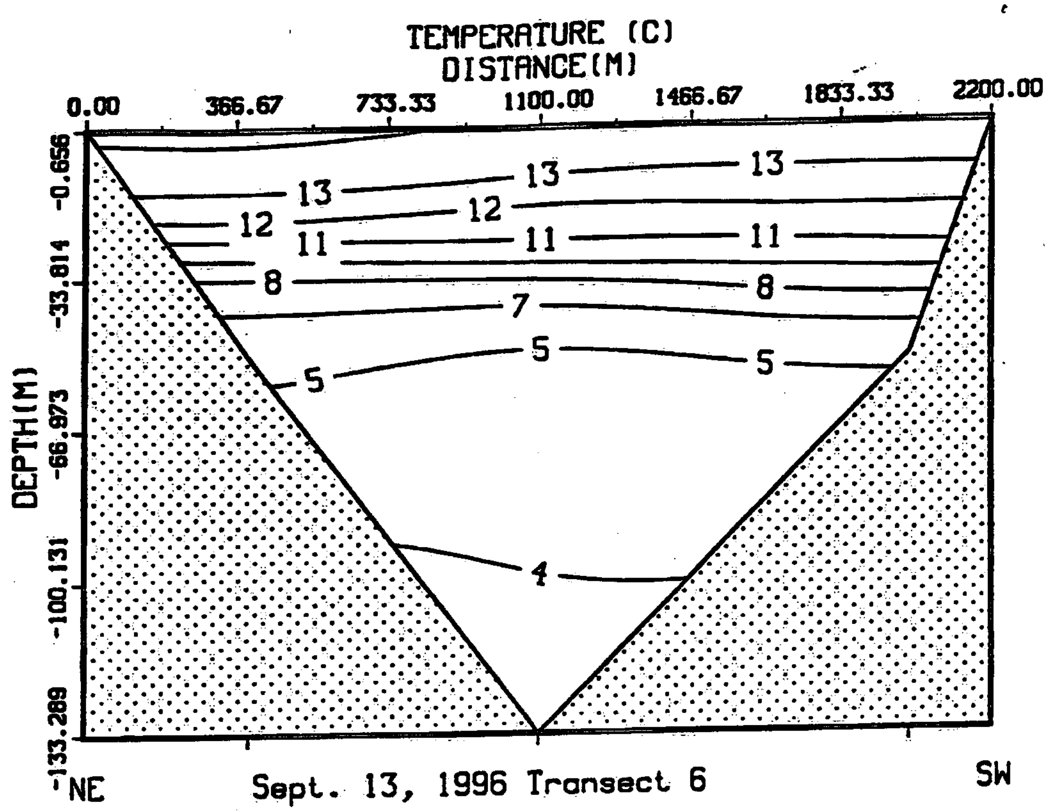
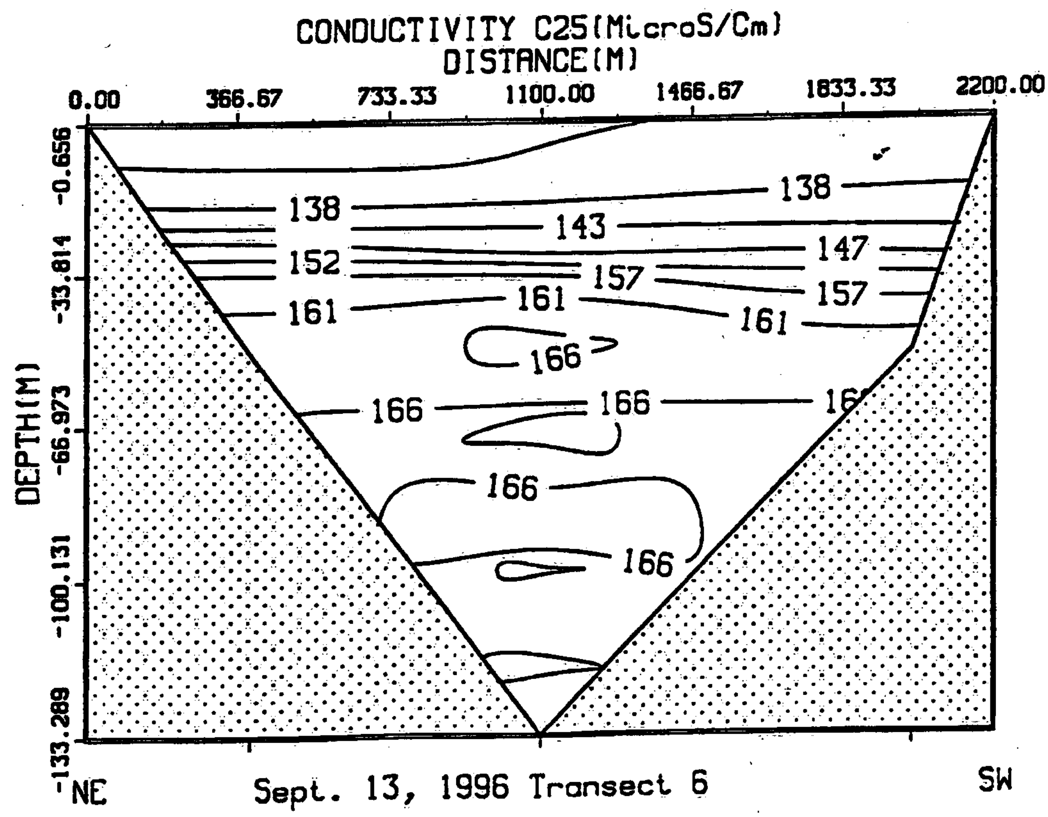

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.0
440.0
880.0
1320.0
1760.0
2200.0
DEPTH(M)
-0.420
-37.177
-73.933
-110.690
-147.446
139
149
153
158
163
168
E
W
Sept. 13, 1996 Transect 5

FIGURE 6

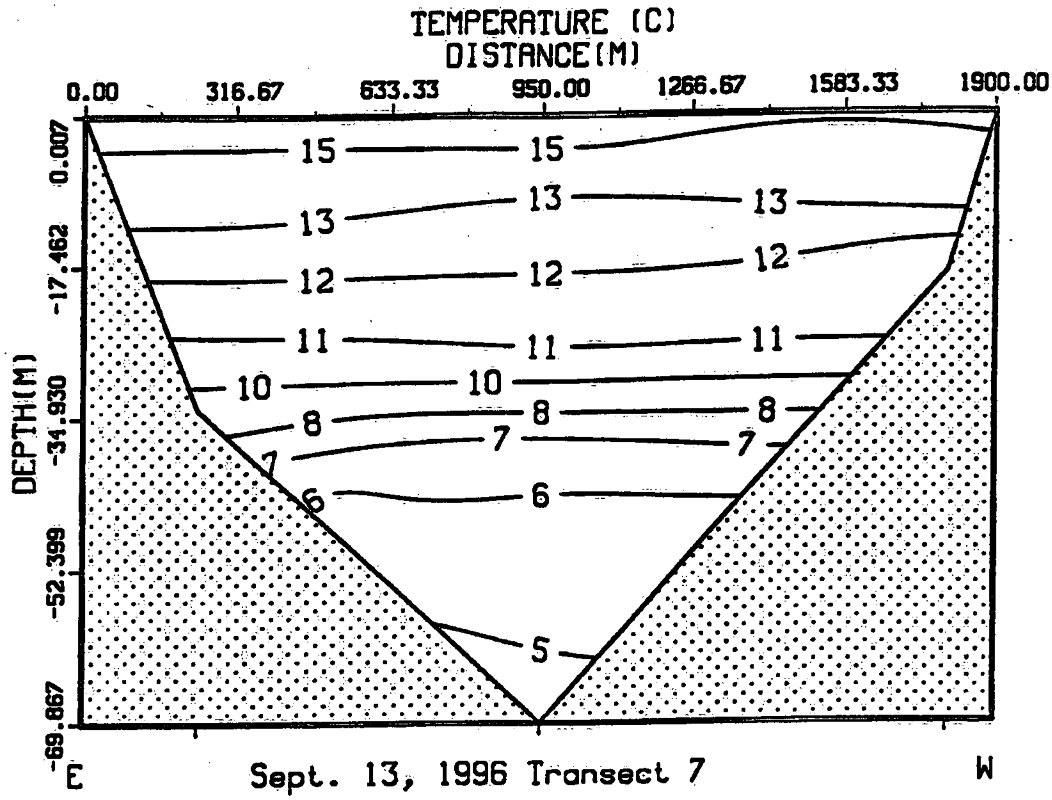


TEMPERATURE (C)
DISTANCE(M)
0.00
366.67
733.33
1100.00
1466.67
1833.33
2200.00
-0.656
-33.814
-66.973
-100.131
-133.289
DEPTH(M)
13
13
13
12
12
11
11
11
8
8
7
5
5
5
4
NE
Sept. 13, 1996 Transect 6
SW

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.00
366.67
733.33
1100.00
1466.67
1833.33
2200.00
-0.656
-33.814
-66.973
-100.131
-133.289
DEPTH(M)
138
138
143
147
152
157
157
161
161
161
166
166
166
166
166
NE
Sept. 13, 1996 Transect 6
SW


FIGURE 7


TEMPERATURE (C)
DISTANCE(M)
0.00
316.67
633.33
950.00
1266.67
1583.33
1900.00
DEPTH(M)
0.007
-17.462
-34.930
-52.399
-69.867
15
13
12
11
10
8
7
6
5
E
Sept. 13, 1996 Transect 7
W

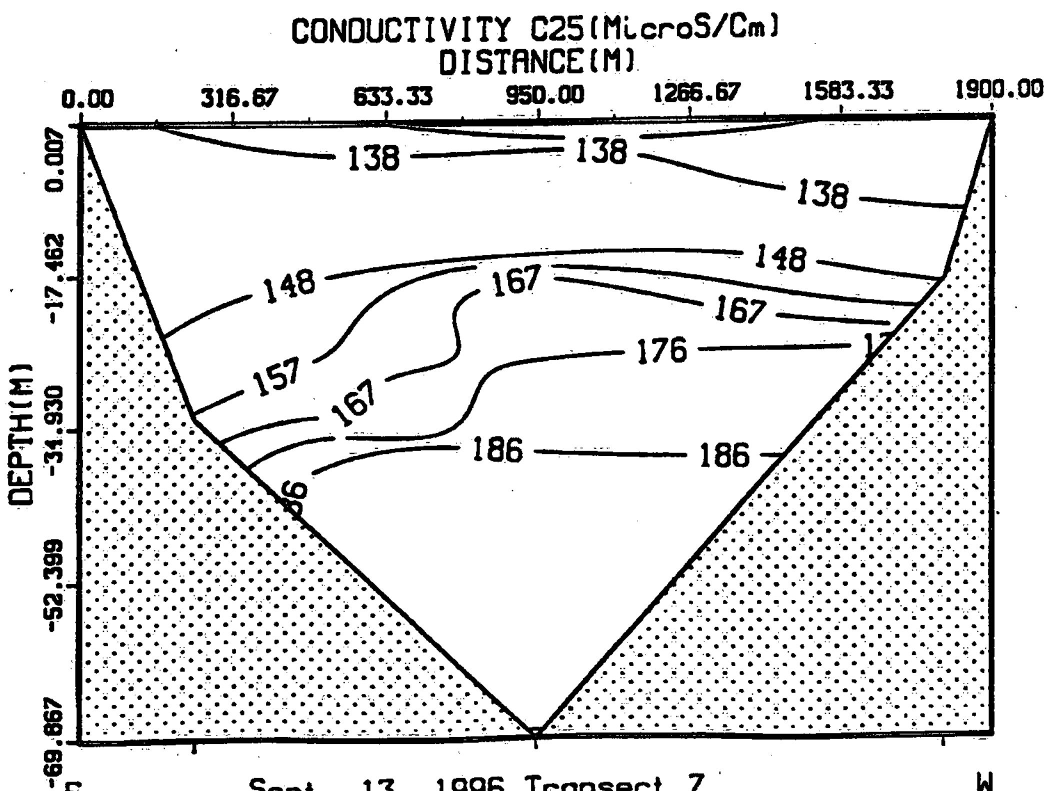
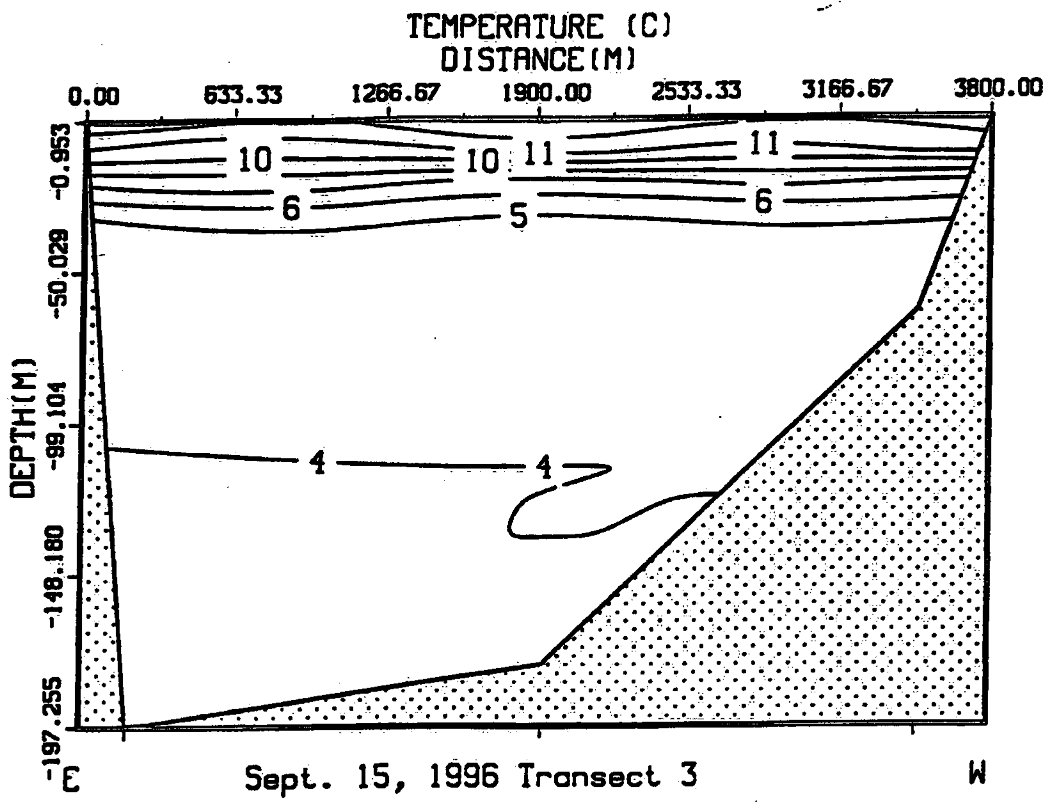

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.00
316.67
633.33
950.00
1266.67
1583.33
1900.00
DEPTH(M)
0.007
-17.462
-34.930
-52.399
-69.867
138
148
157
167
176
186
E
Sept. 13, 1996 Transect 7
W

FIGURE 8


TEMPERATURE (C)
DISTANCE(M)
0.00
633.33
1266.67
1900.00
2533.33
3166.67
3800.00
DEPTH(M)
-0.953
-50.029
-99.104
-148.180
-197.255
10
10
11
11
6
5
6
4
4
E
Sept. 15, 1996 Transect 3
W

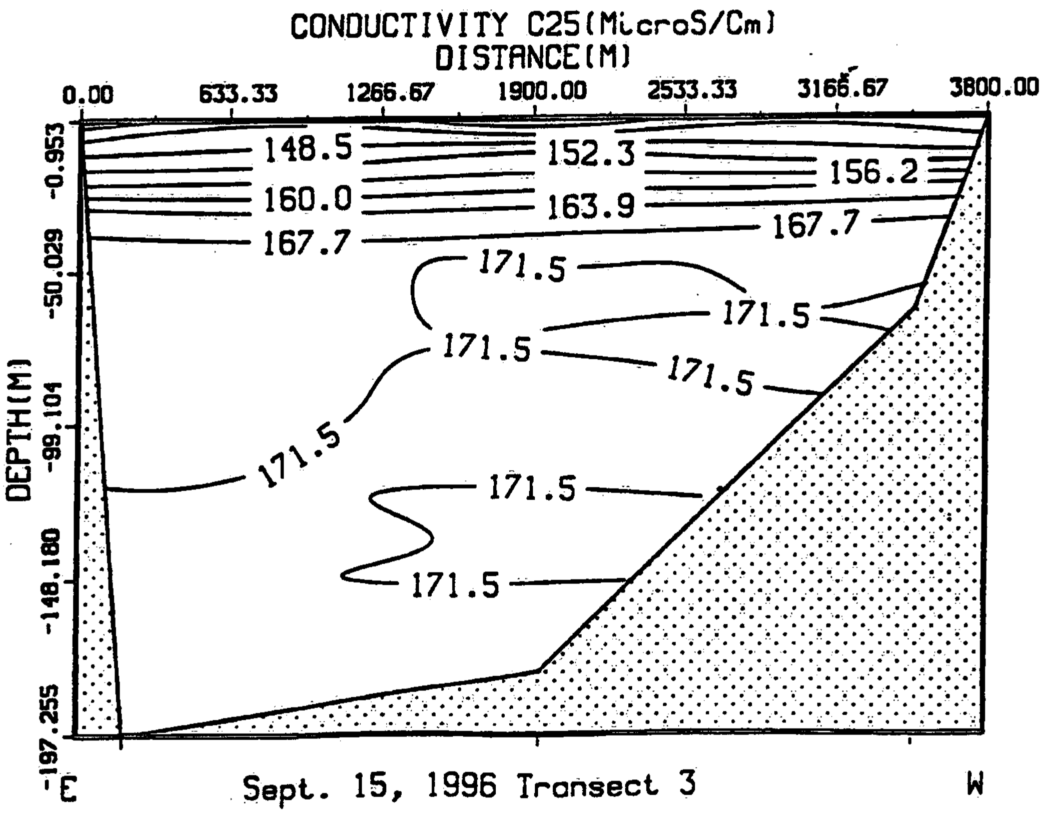
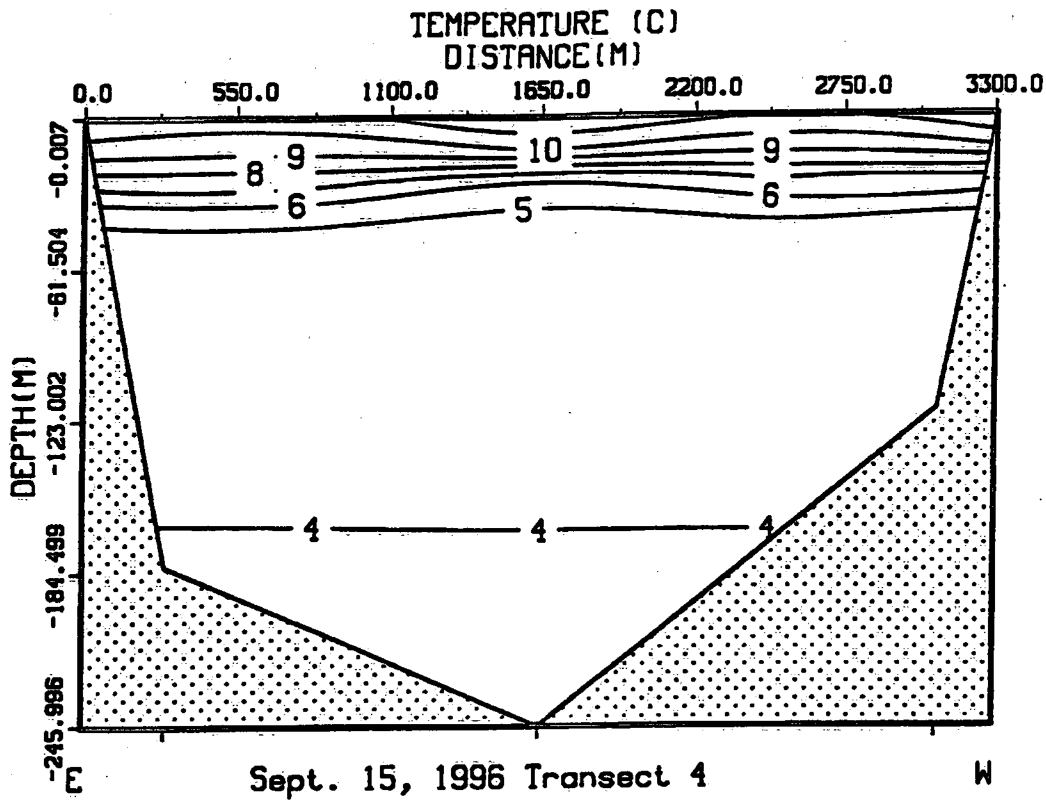

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.00
633.33
1266.67
1900.00
2533.33
3166.67
3800.00
DEPTH(M)
-0.953
-50.029
-99.104
-148.180
-197.255
148.5
152.3
156.2
160.0
163.9
167.7
167.7
171.5
171.5
171.5
171.5
171.5
171.5
171.5
E
Sept. 15, 1996 Transect 3
W

FIGURE 9


TEMPERATURE (C)
DISTANCE(M)
0.0
550.0
1100.0
1650.0
2200.0
2750.0
3300.0
DEPTH(M)
-0.007
-61.504
-123.002
-184.499
-245.996
10
9
8
6
5
4
E
W
Sept. 15, 1996 Transect 4

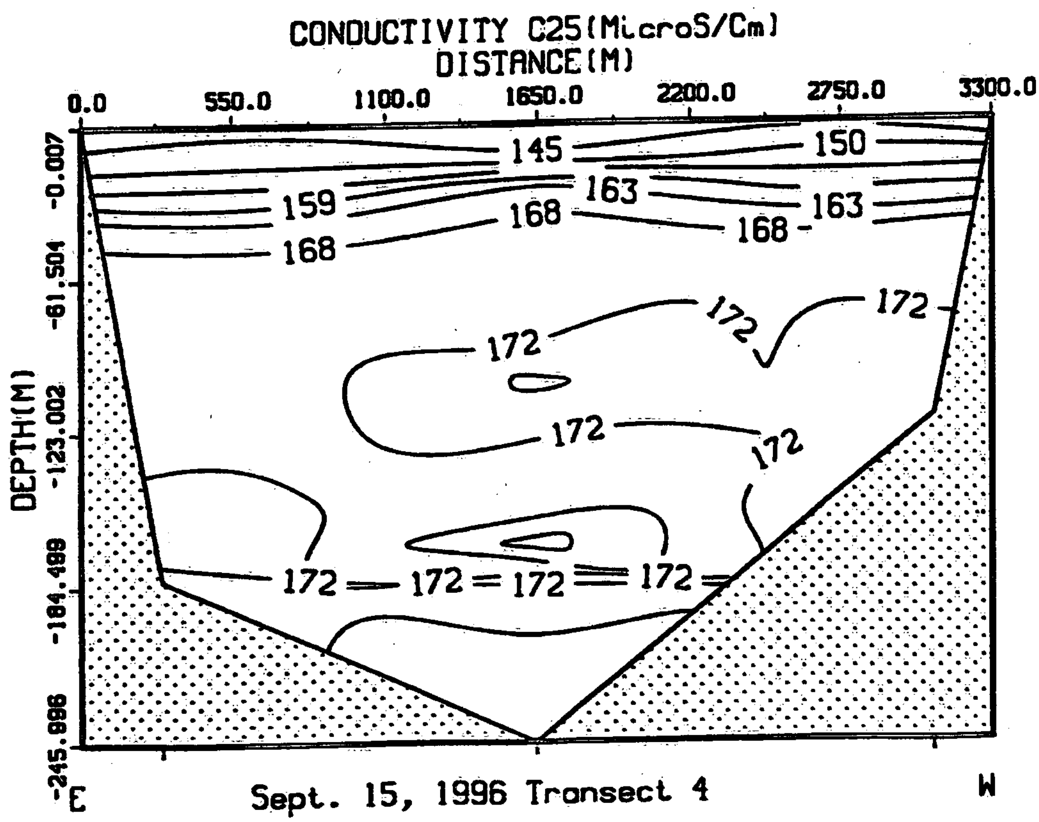

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.0
550.0
1100.0
1650.0
2200.0
2750.0
3300.0
DEPTH(M)
-0.007
-61.504
-123.002
-184.499
-245.996
145
150
159
163
168
172
E
W
Sept. 15, 1996 Transect 4

FIGURE 10

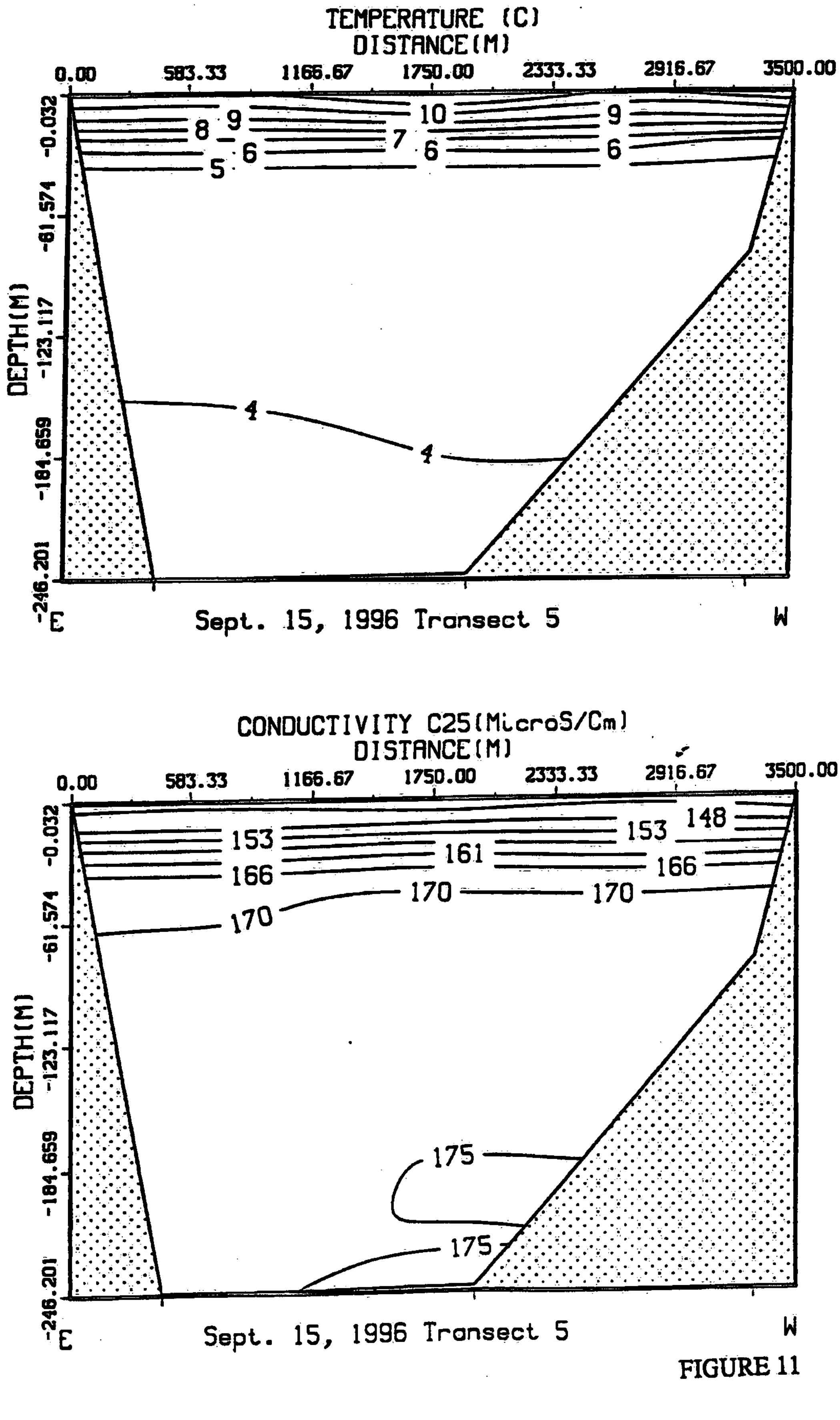
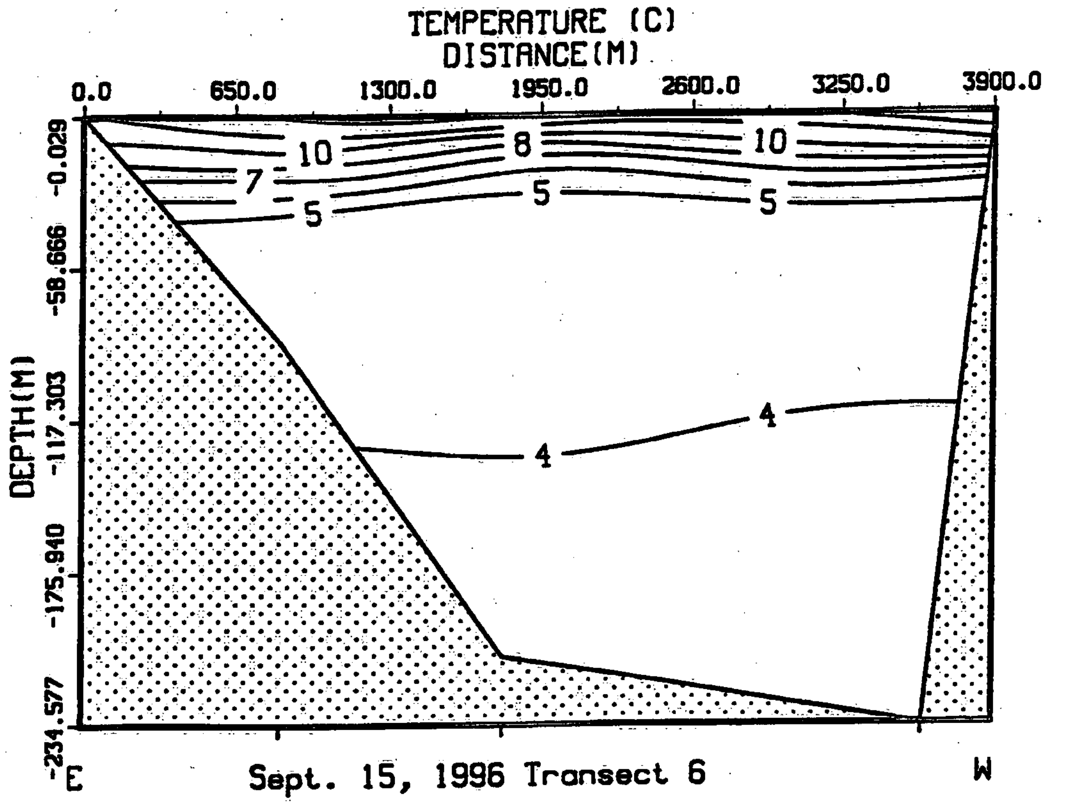

TEMPERATURE (C)
DISTANCE(M)
0.00
583.33
1166.67
1750.00
2333.33
2916.67
3500.00
DEPTH(M)
-0.032
-61.574
-123.117
-184.659
-246.201
10
9
8
7
6
5
4
E
W
Sept. 15, 1996 Transect 5
CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.00
583.33
1166.67
1750.00
2333.33
2916.67
3500.00
DEPTH(M)
-0.032
-61.574
-123.117
-184.659
-246.201
148
153
161
166
170
175
E
W
Sept. 15, 1996 Transect 5

FIGURE 11


TEMPERATURE (C)
DISTANCE(M)
0.0
650.0
1300.0
1950.0
2600.0
3250.0
3900.0
DEPTH(M)
-0.029
-58.666
-117.303
-175.940
-234.577
10
8
10
7
5
5
5
4
4
E
Sept. 15, 1996 Transect 6
W

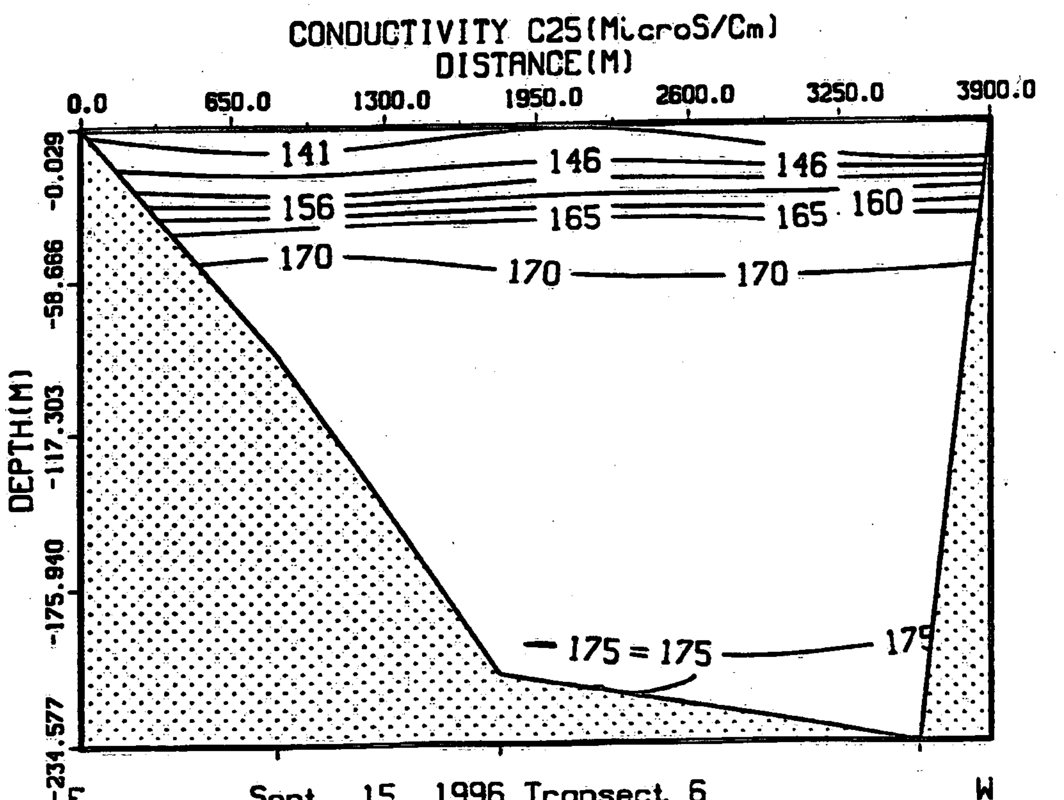
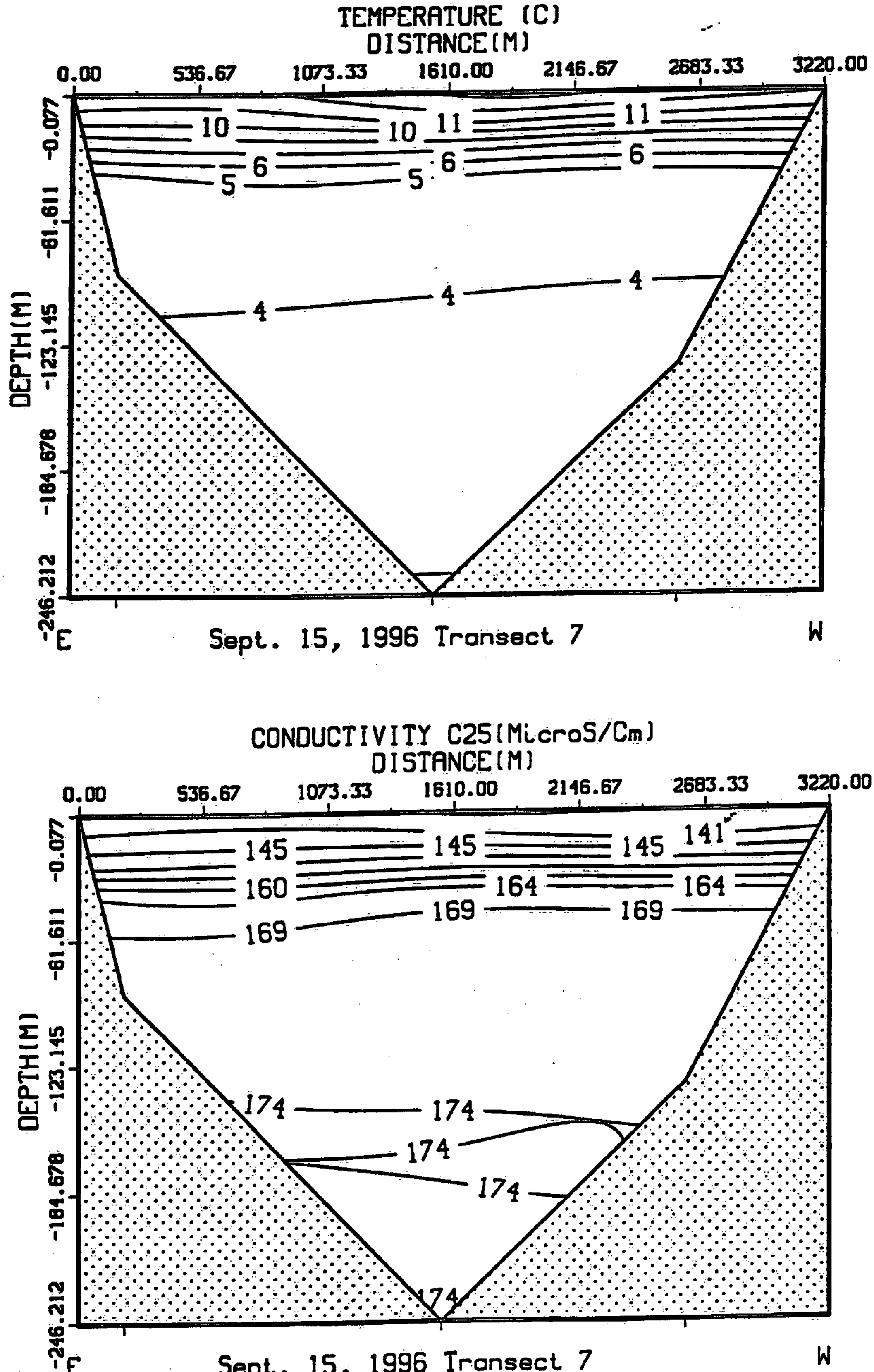
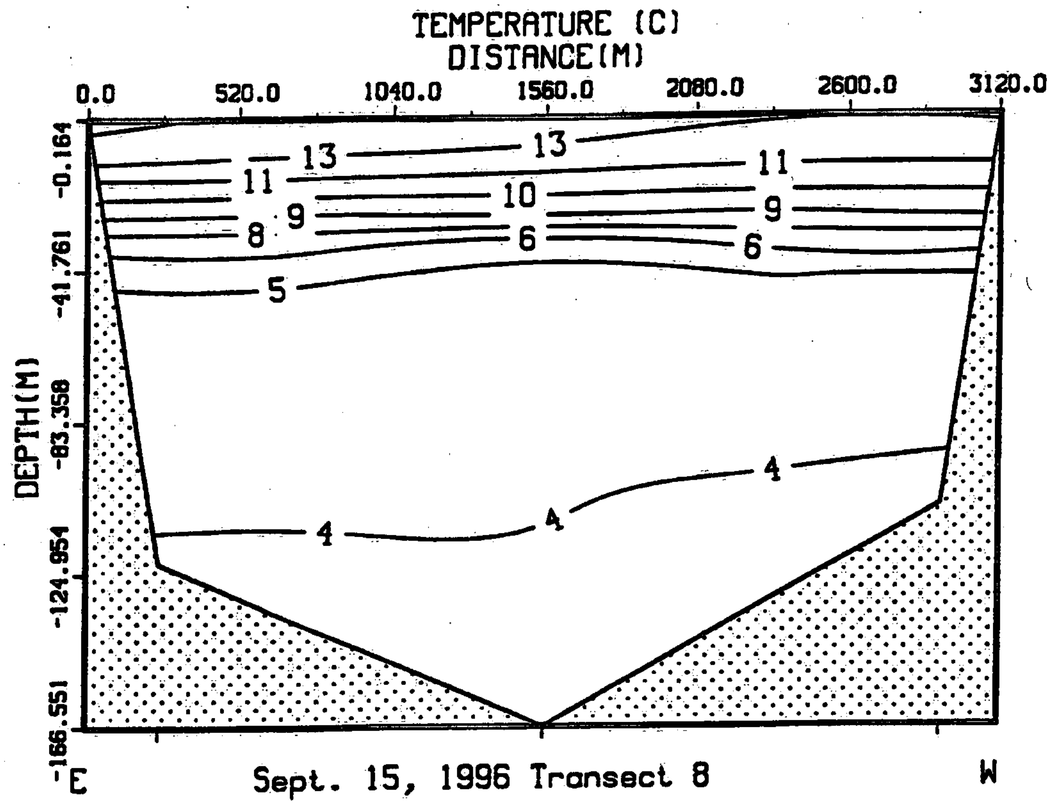

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.0
650.0
1300.0
1950.0
2600.0
3250.0
3900.0
DEPTH(M)
-0.029
-58.666
-117.303
-175.940
-234.577
141
146
146
156
165
165
160
170
170
170
175
175
E
Sept. 15, 1996 Transect 6
W

FIGURE 12



TEMPERATURE (C)
DISTANCE(M)
0.00
536.67
1073.33
1610.00
2146.67
2683.33
3220.00
DEPTH(M)
-0.077
-61.611
-123.145
-184.678
-246.212
10
10
11
11
6
6
6
5
5
4
4
4
E
Sept. 15, 1996 Transect 7
W
CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.00
536.67
1073.33
1610.00
2146.67
2683.33
3220.00
DEPTH(M)
-0.077
-61.611
-123.145
-184.678
-246.212
145
145
145
141
160
164
164
169
169
169
174
174
174
174
174
E
Sept. 15, 1996 Transect 7
W


FIGURE 13


TEMPERATURE (C)
DISTANCE(M)
0.0
520.0
1040.0
1560.0
2080.0
2600.0
3120.0
DEPTH(M)
-0.164
-41.761
-83.358
-124.954
-166.551
13
13
11
11
10
9
9
8
6
6
5
4
4
4
E
W
Sept. 15, 1996 Transect 8

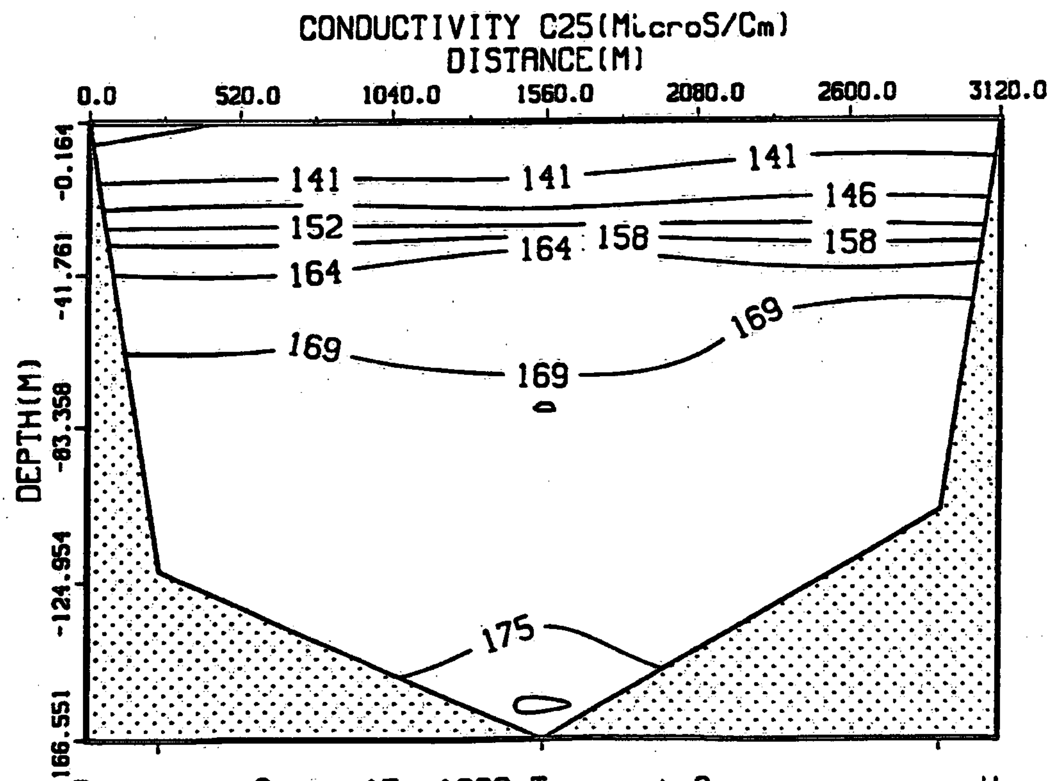

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.0
520.0
1040.0
1560.0
2080.0
2600.0
3120.0
DEPTH(M)
-0.164
-41.761
-83.358
-124.954
-166.551
141
141
141
146
152
164
158
158
164
169
169
169
175
E
W
Sept. 15, 1996 Transect 8

FIGURE 14

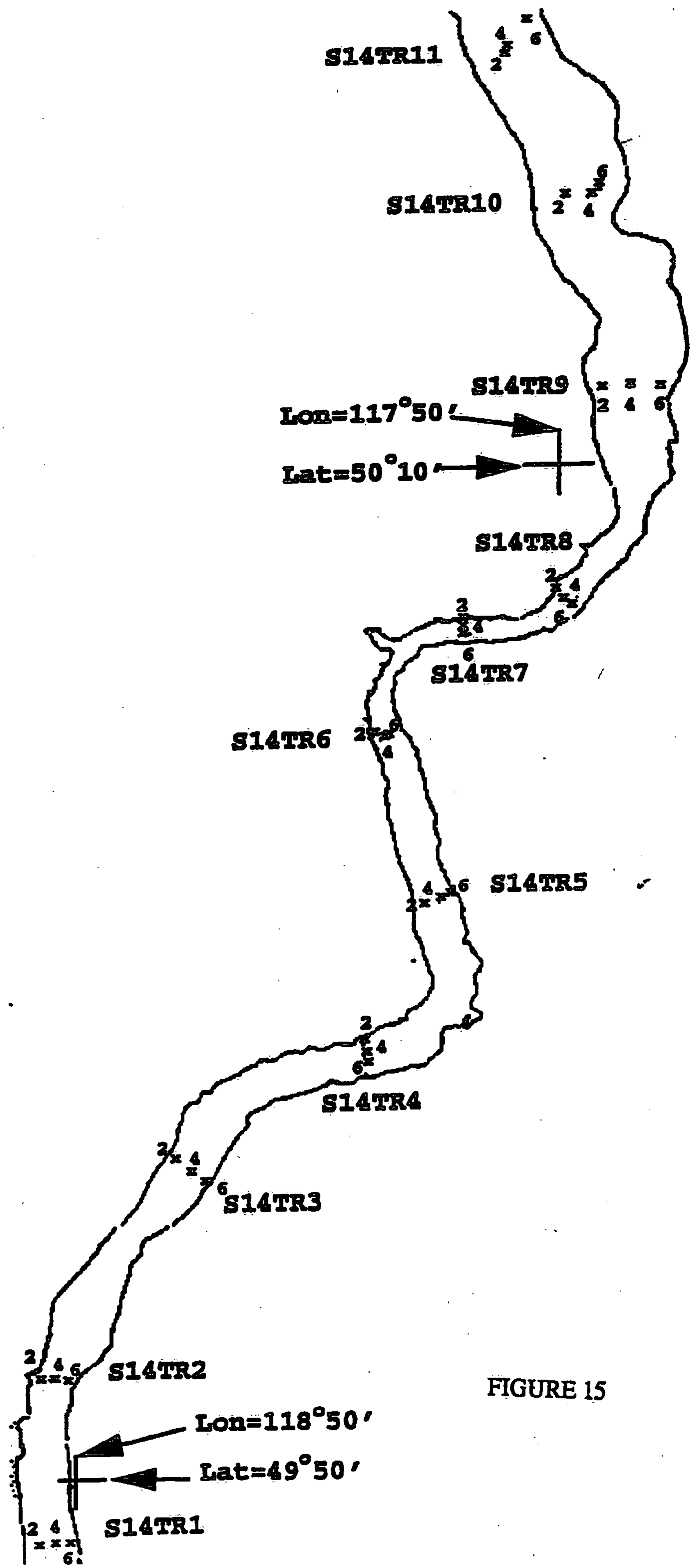
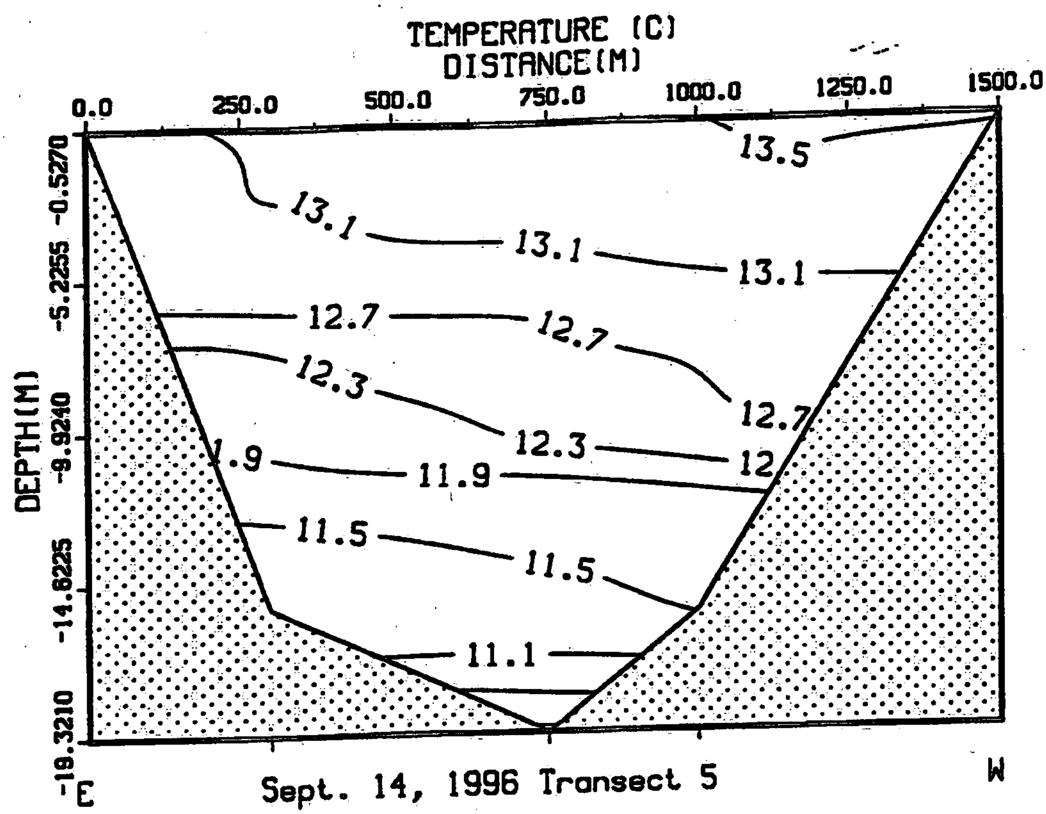

S14TR11
S14TR10
S14TR9
Lon=117°50′
Lat=50°10′
S14TR8
S14TR7
S14TR6
S14TR5
S14TR4
S14TR3
S14TR2
Lon=118°50′
Lat=49°50′
S14TR1

FIGURE 15


TEMPERATURE (C)
DISTANCE(M)
0.0
250.0
500.0
750.0
1000.0
1250.0
1500.0
DEPTH(M)
-0.5270
-5.2255
-9.9240
-14.6225
-19.3210
13.5
13.1
13.1
13.1
12.7
12.7
12.7
12.3
12.3
12
1.9
11.9
11.5
11.5
11.1
E
W
Sept. 14, 1996 Transect 5

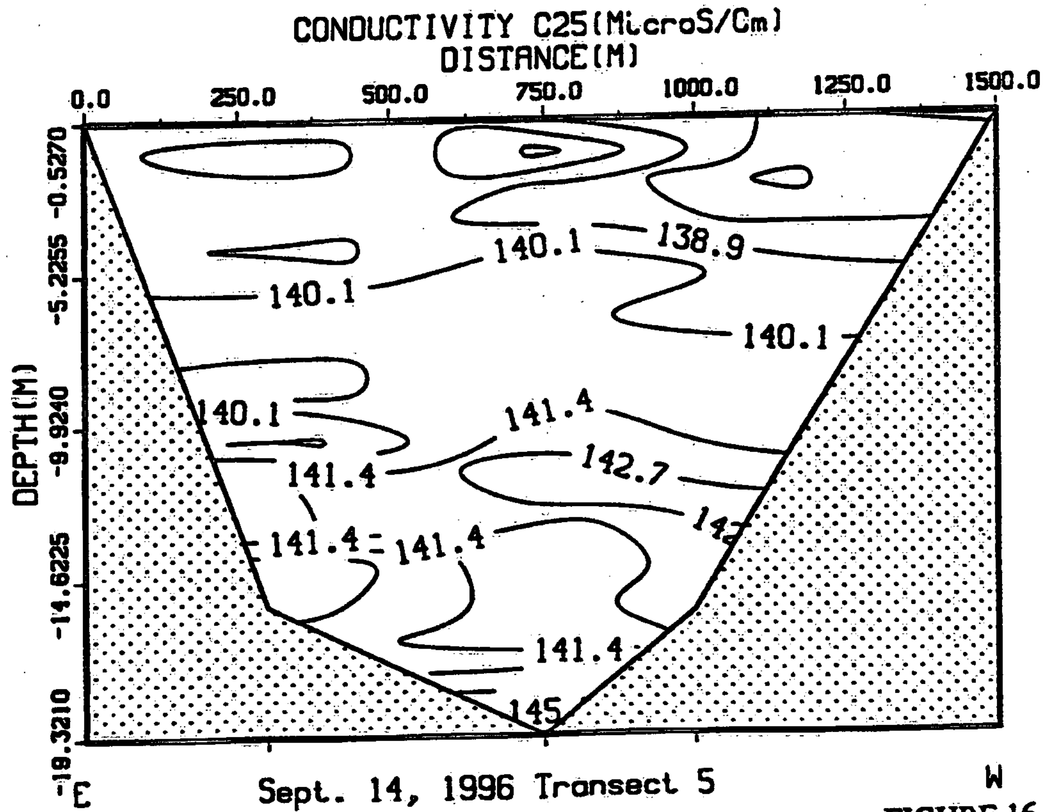

CONDUCTIVITY C25(MicroS/Cm)
DISTANCE(M)
0.0
250.0
500.0
750.0
1000.0
1250.0
1500.0
DEPTH(M)
-0.5270
-5.2255
-9.9240
-14.6225
-19.3210
140.1
138.9
140.1
140.1
140.1
141.4
141.4
142.7
141.4
141.4
141.4
145
E
W
Sept. 14, 1996 Transect 5

FIGURE 16

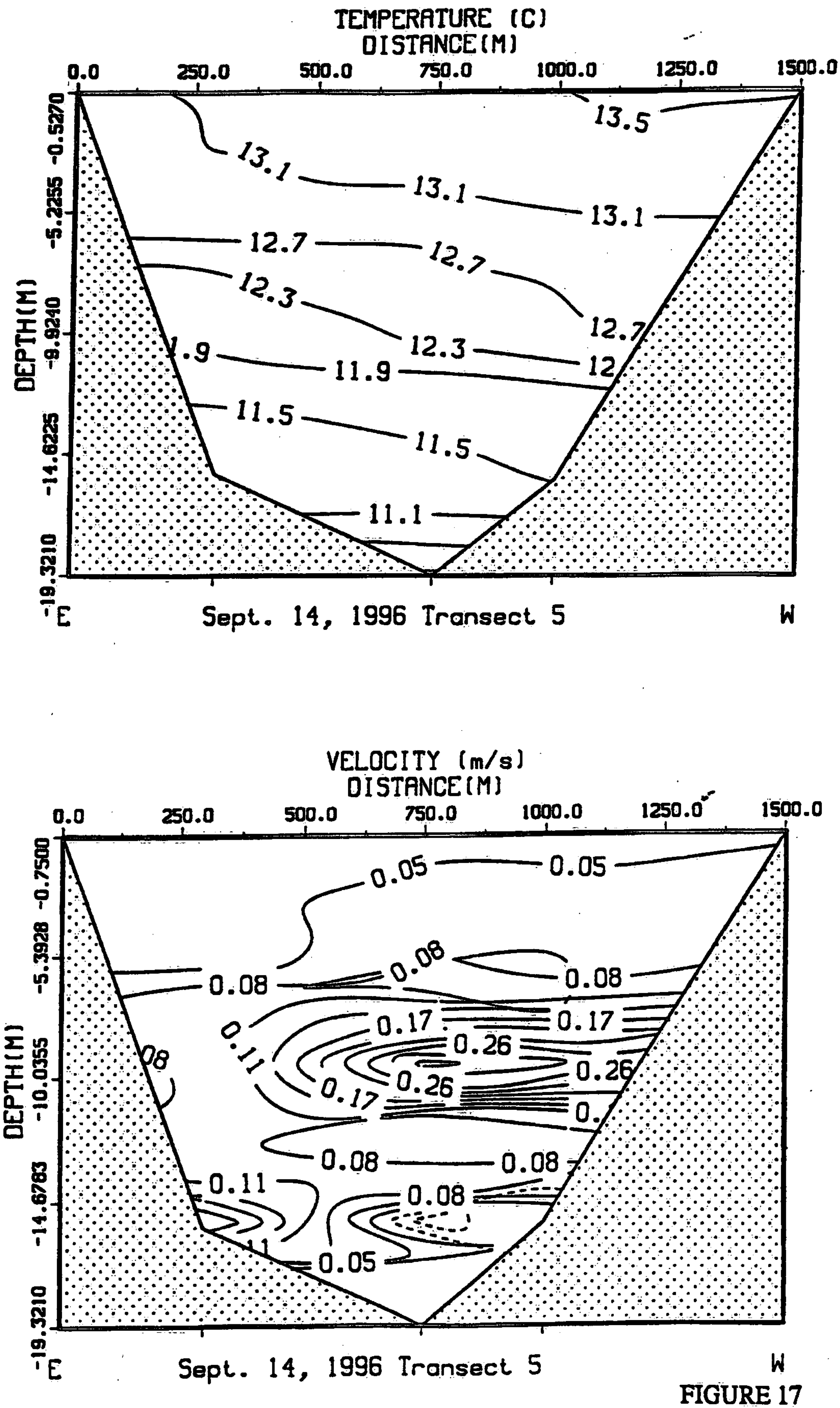

TEMPERATURE (C)
DISTANCE(M)
0.0
250.0
500.0
750.0
1000.0
1250.0
1500.0
DEPTH(M)
-0.5270
-5.2255
-9.9240
-14.6225
-19.3210
13.5
13.1
12.7
12.3
11.9
11.5
11.1
E
Sept. 14, 1996 Transect 5
W
VELOCITY (m/s)
DISTANCE(M)
0.0
250.0
500.0
750.0
1000.0
1250.0
1500.0
DEPTH(M)
-0.7500
-5.3928
-10.0355
-14.6783
-19.3210
0.05
0.08
0.17
0.26
0.11
E
Sept. 14, 1996 Transect 5
W

FIGURE 17

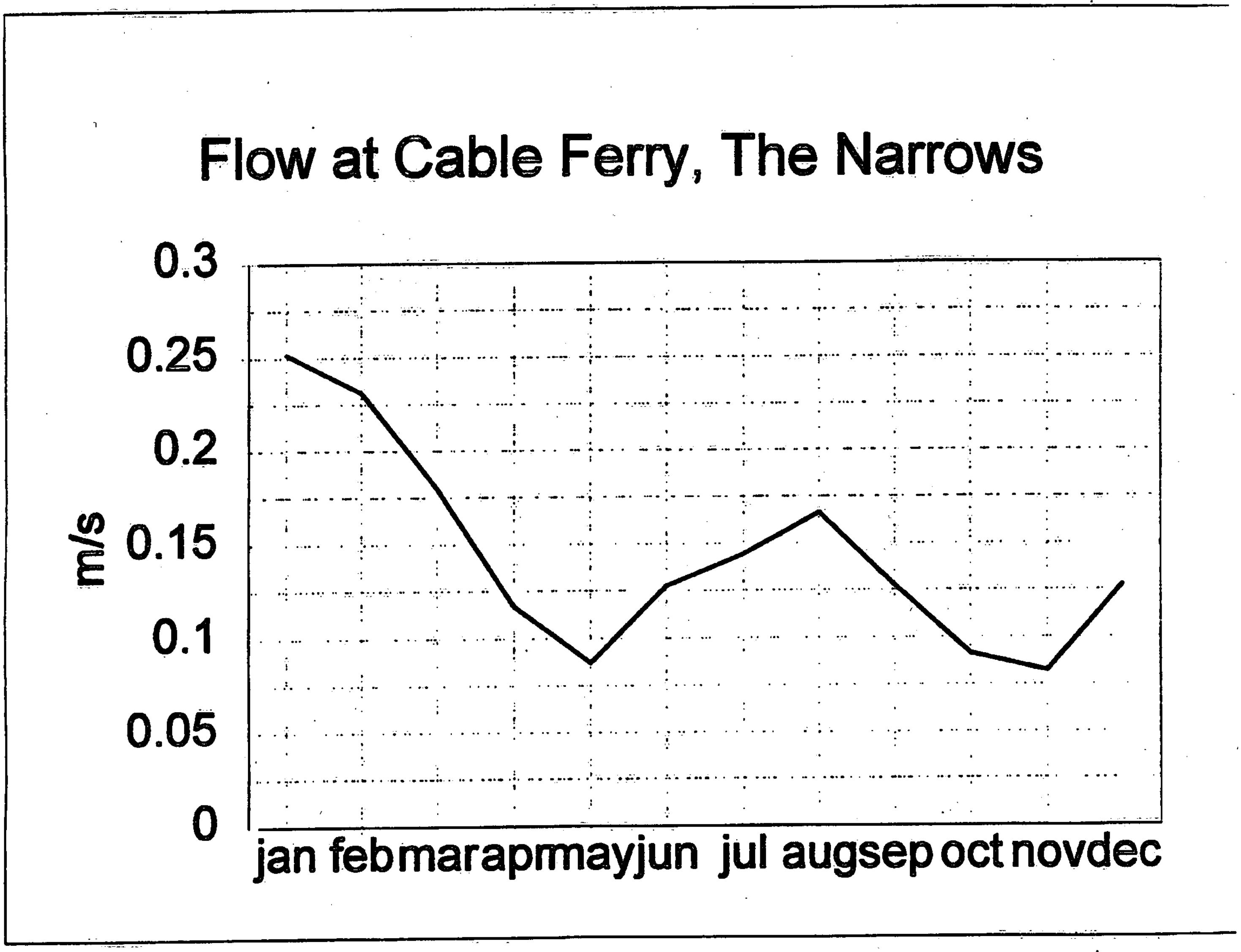

Flow at Cable Ferry, The Narrows
0.3
0.25
0.2
m/s
0.15
0.1
0.05
0
jan feb mar apr may jun jul aug sep oct nov dec

FIGURE 18

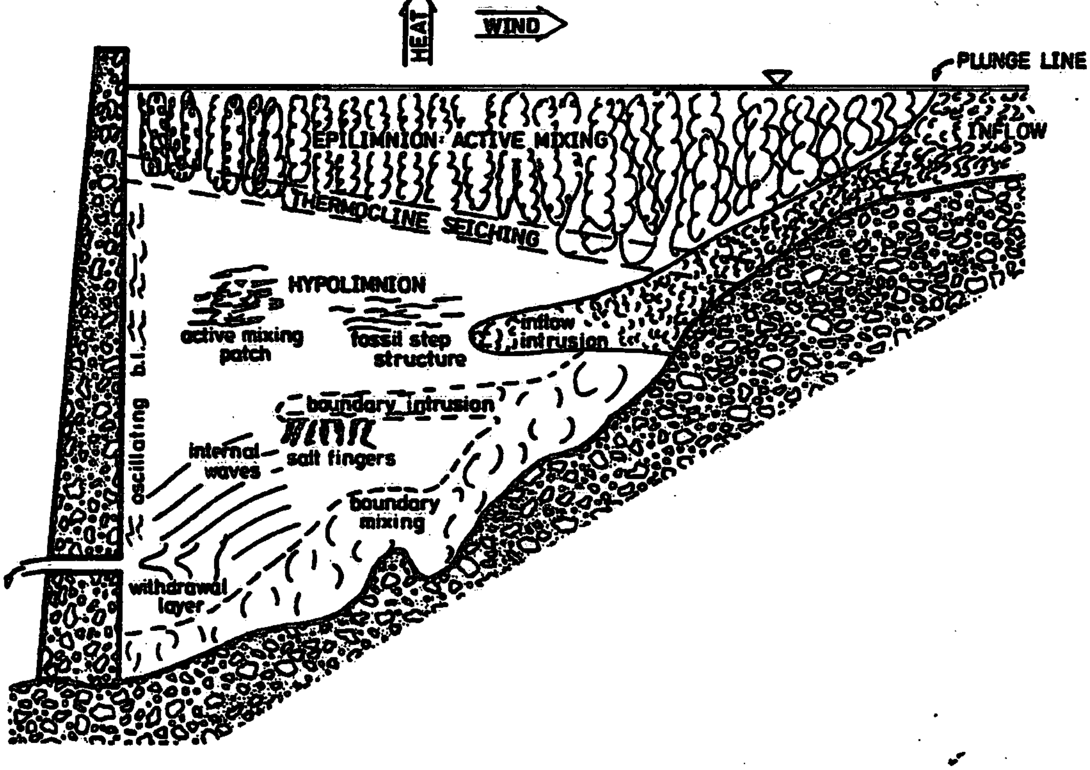

HEAT
WIND
PLUNGE LINE
INFLOW
EPILIMNION: ACTIVE MIXING
THERMOCLINE SEICHING
HYPOLIMNION
active mixing patch
fossil step structure
inflow intrusion
boundary intrusion
internal waves
salt fingers
boundary mixing
oscillating b.l.
withdrawal layer

FIGURE 19

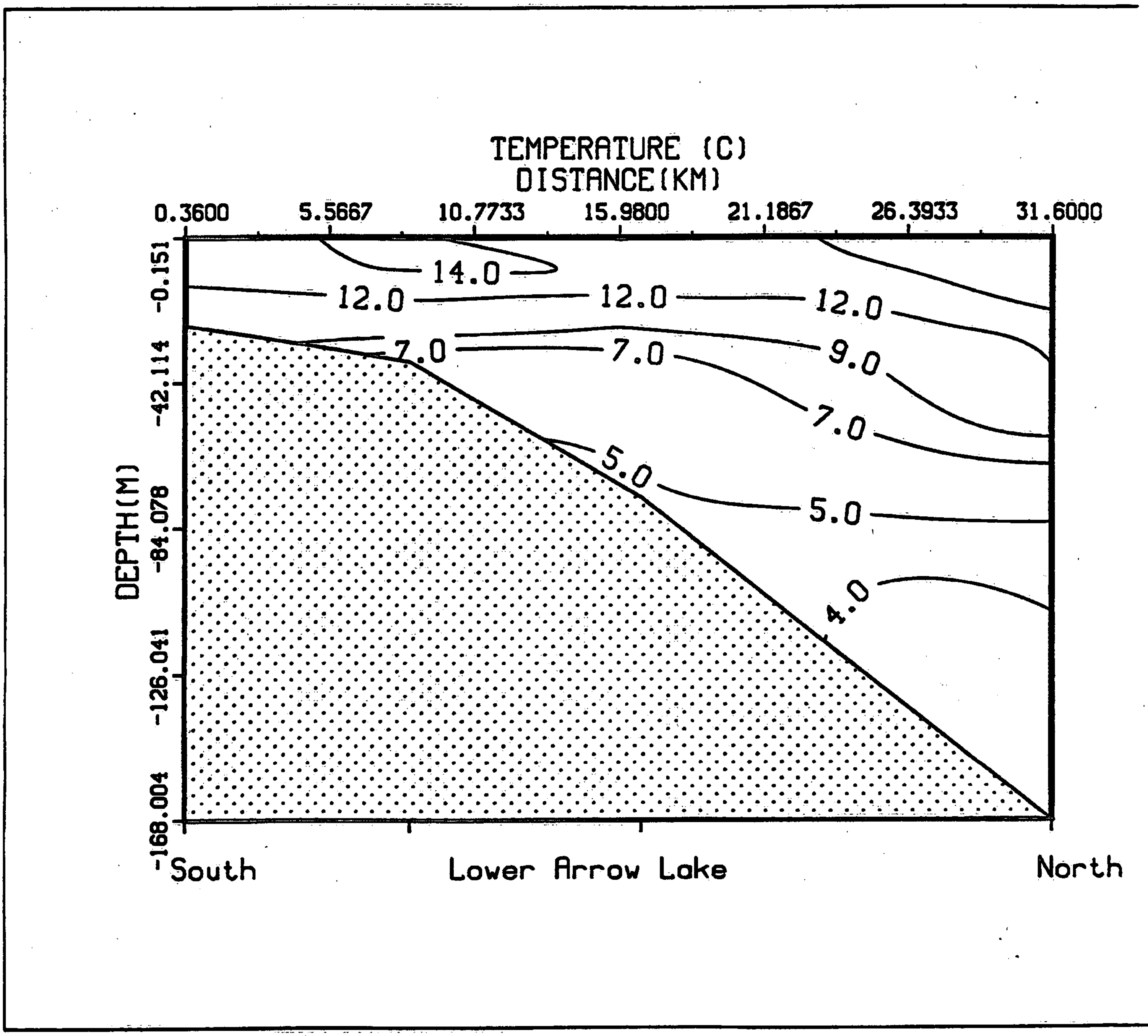

TEMPERATURE (C)
DISTANCE(KM)
0.3600
5.5667
10.7733
15.9800
21.1867
26.3933
31.6000
DEPTH(M)
-0.151
-42.114
-84.078
-126.041
-168.004
14.0
12.0
12.0
12.0
7.0
7.0
9.0
7.0
5.0
5.0
4.0
South
Lower Arrow Lake
North

**FIGURE 20**

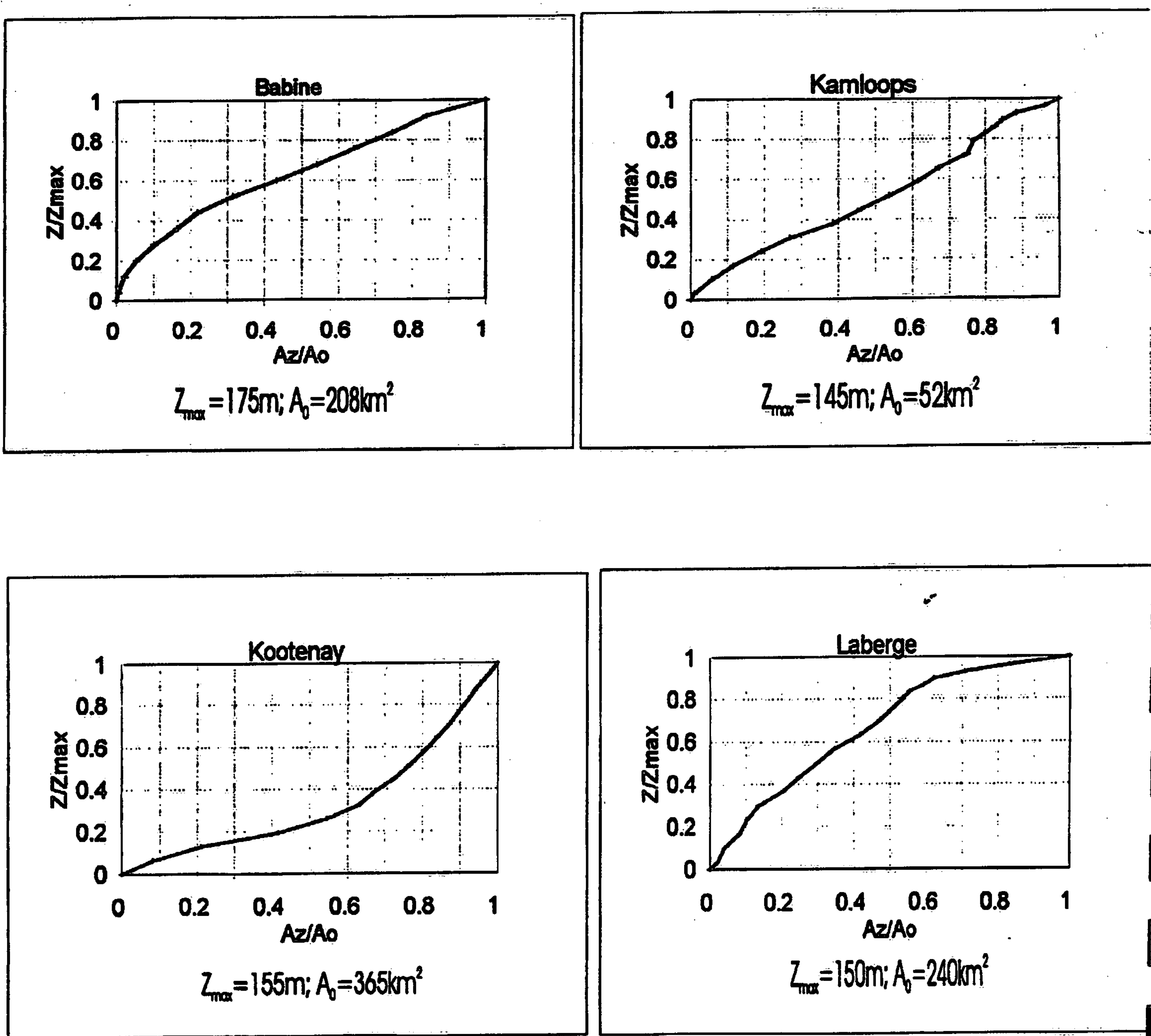

Babine
Z/Zmax
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
Az/Ao
$Z_{max}$=175m; $A_0$=208km$^2$
Kamloops
Z/Zmax
Az/Ao
$Z_{max}$=145m; $A_0$=52km$^2$
Kootenay
Z/Zmax
Az/Ao
$Z_{max}$=155m; $A_0$=365km$^2$
Laberge
Z/Zmax
Az/Ao
$Z_{max}$=150m; $A_0$=240km$^2$

FIGURE 21

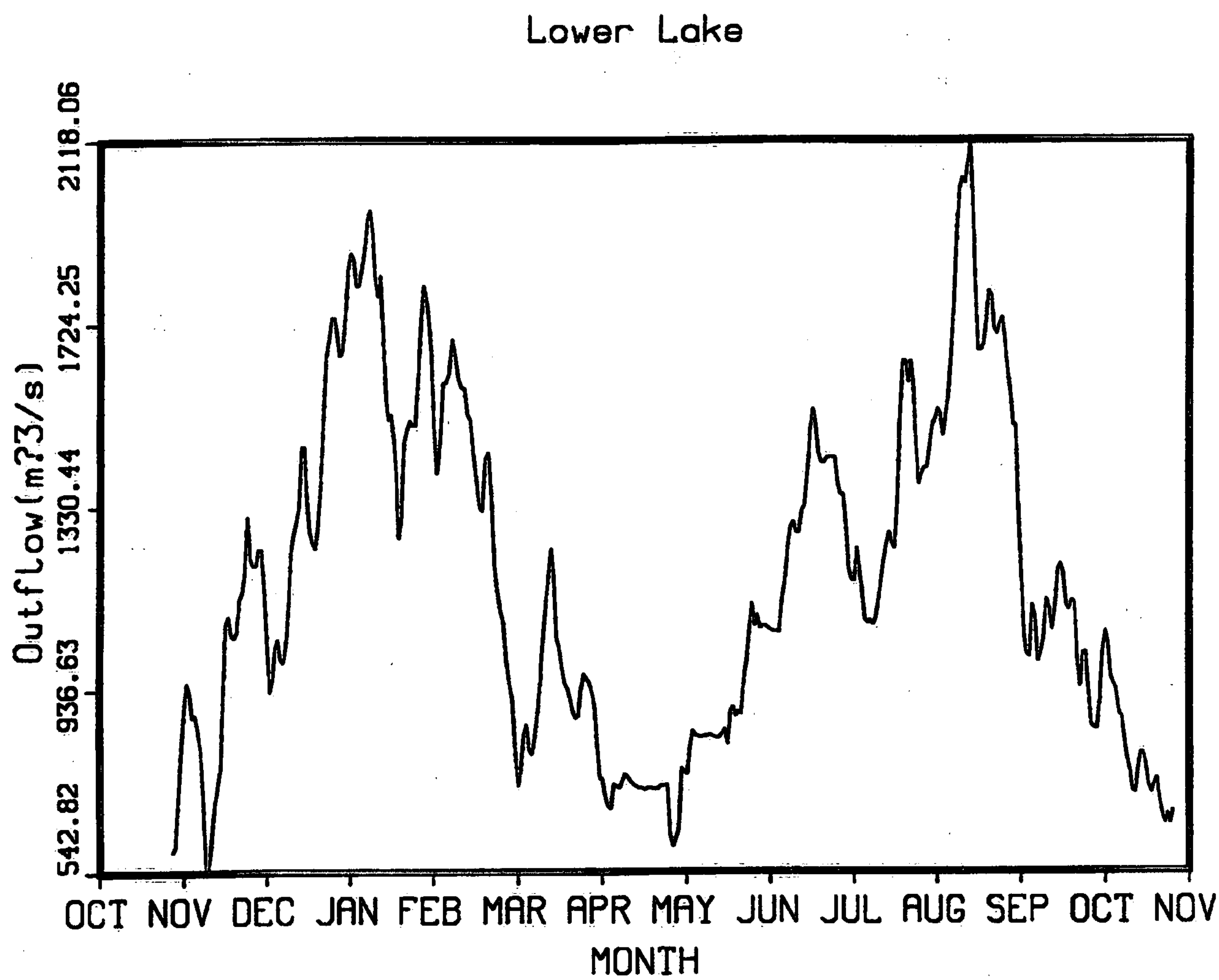
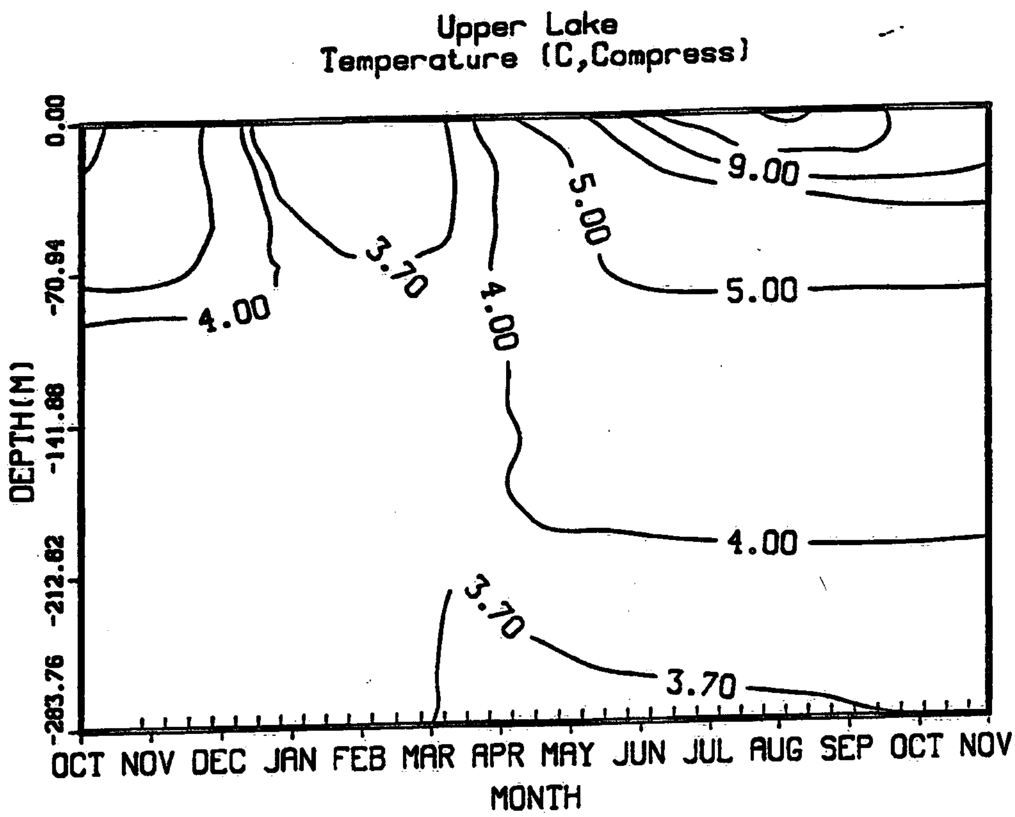

Lower Lake
Outflow(m?3/s)
2118.06
1724.25
1330.44
936.63
542.82
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH

**FIGURE 22**


Upper Lake
Temperature (C,Compress)
0.00
-70.94
-141.88
-212.82
-283.76
DEPTH(M)
9.00
5.00
5.00
3.70
4.00
4.00
4.00
3.70
3.70
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH

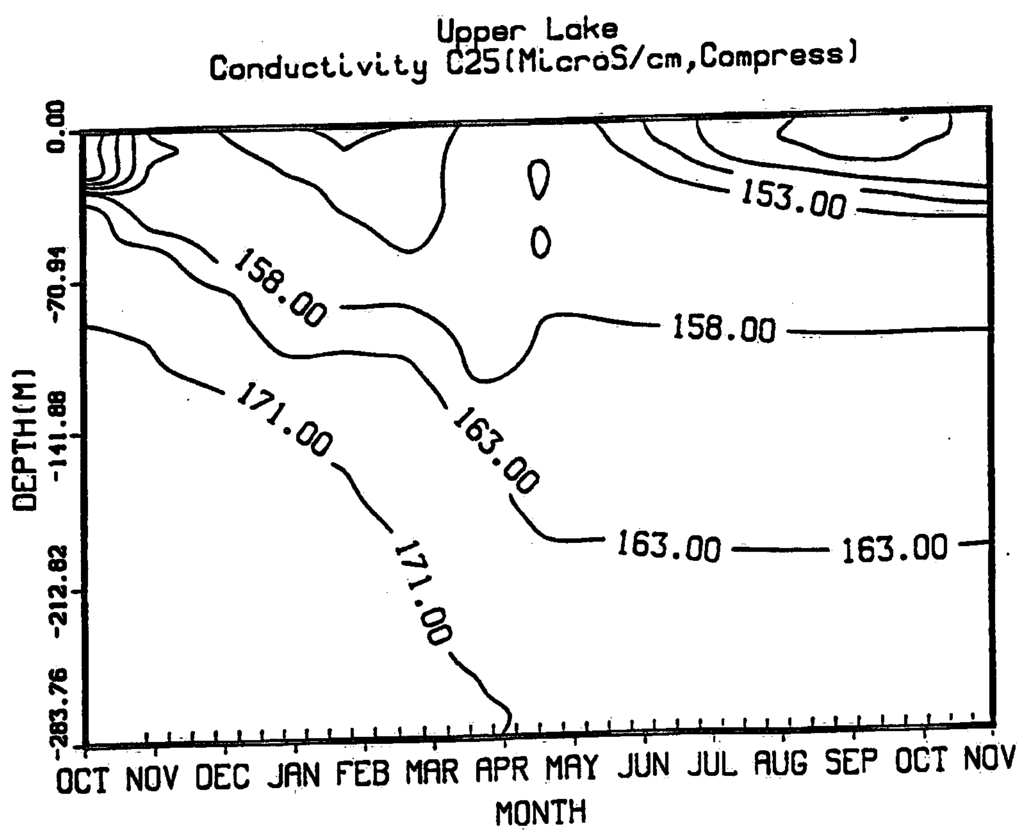
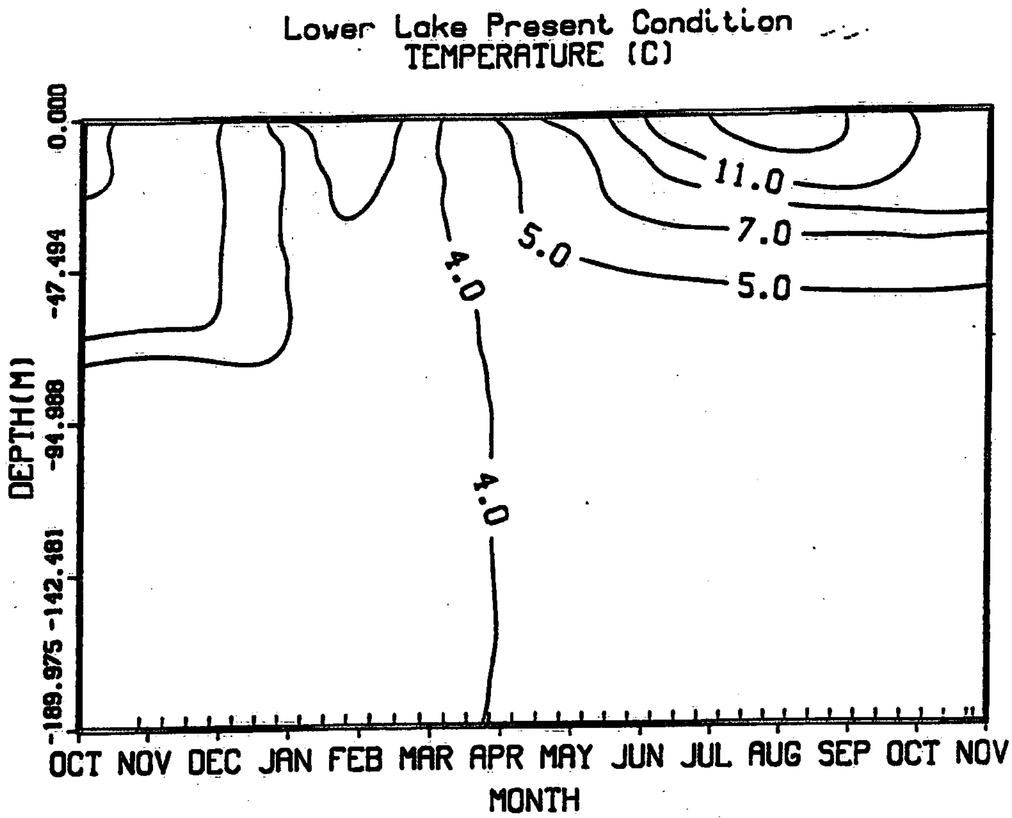
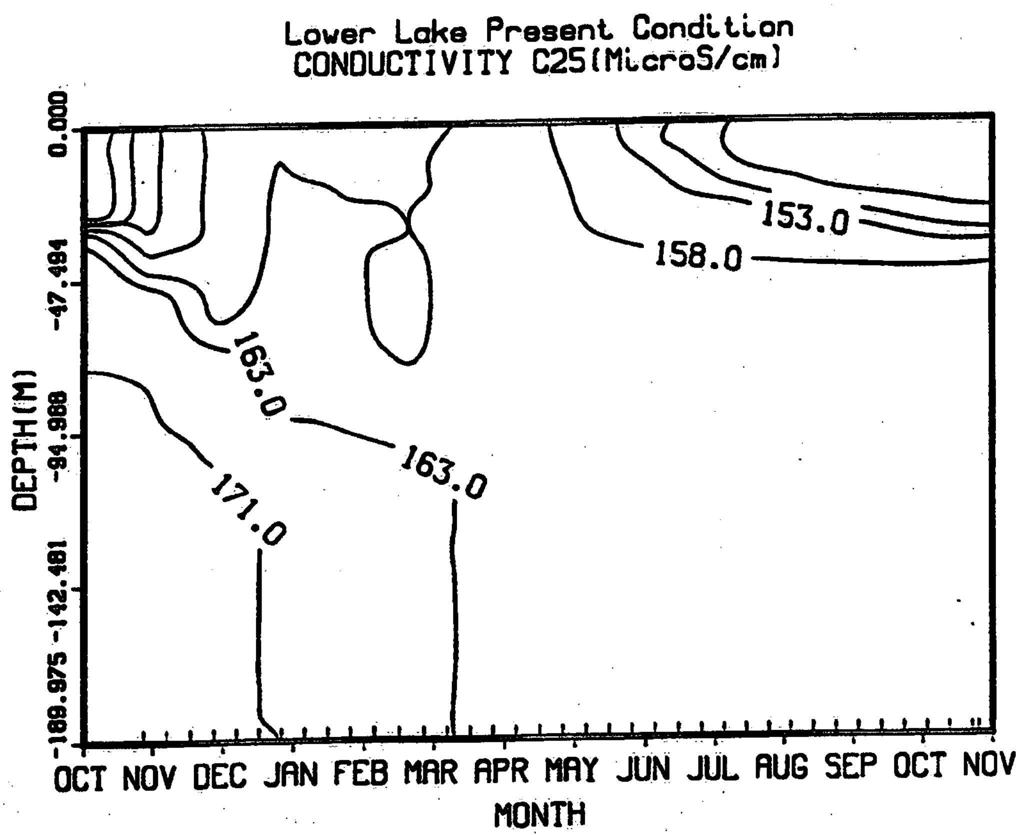

Upper Lake
Conductivity C25(MicroS/cm,Compress)
0.00
-70.94
-141.88
-212.82
-283.76
DEPTH(M)
153.00
158.00
158.00
171.00
163.00
163.00
163.00
171.00
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH

**FIGURE 23**

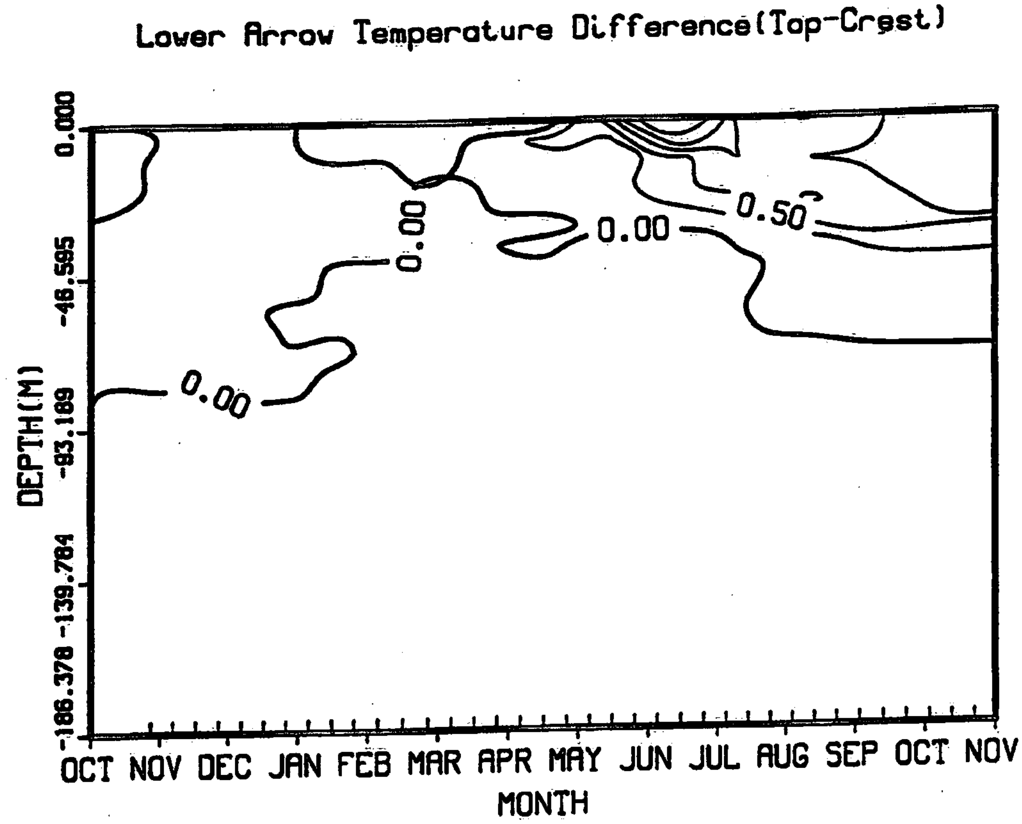


Lower Lake Present Condition
TEMPERATURE (C)
DEPTH(M)
0.000
-47.494
-94.988
-142.481
-189.975
11.0
7.0
5.0
5.0
4.0
4.0
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH

Lower Lake Present Condition
CONDUCTIVITY C25(MicroS/cm)
DEPTH(M)
0.000
-47.494
-94.988
-142.481
-189.975
153.0
158.0
163.0
163.0
171.0
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH


FIGURE 24


Lower Arrow Temperature Difference(Top-Crest)
0.000
-46.595
-93.189
-139.784
-186.378
DEPTH(M)
0.00
0.50
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH

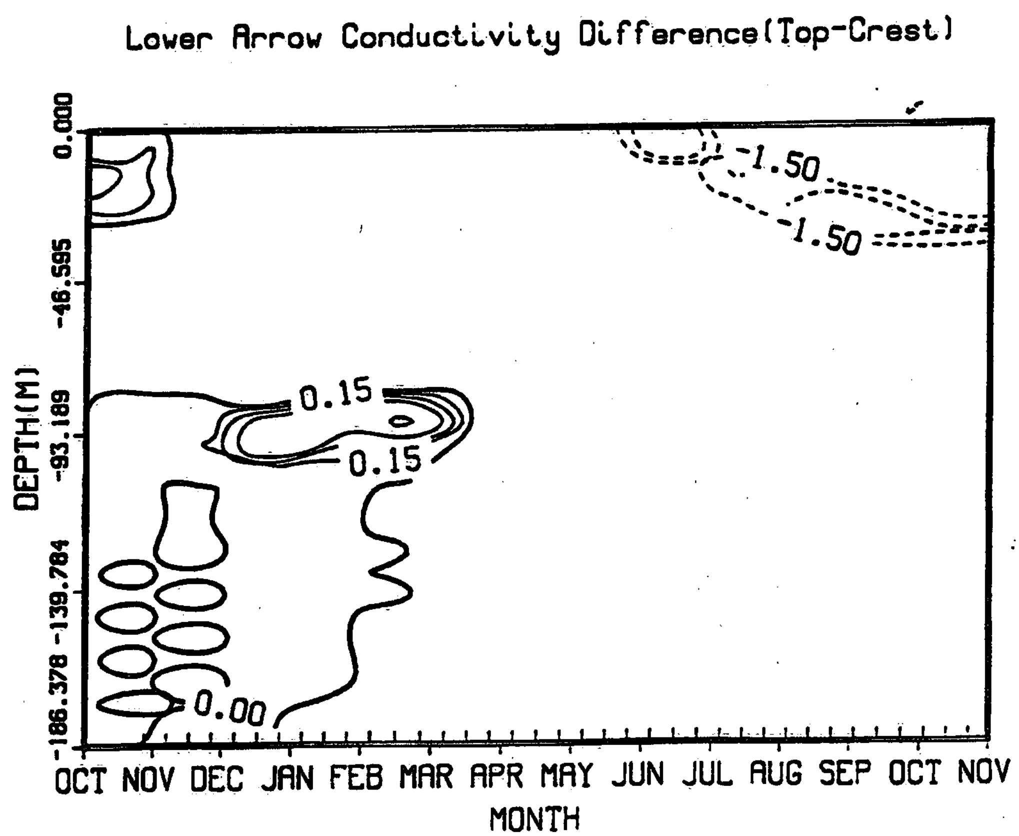
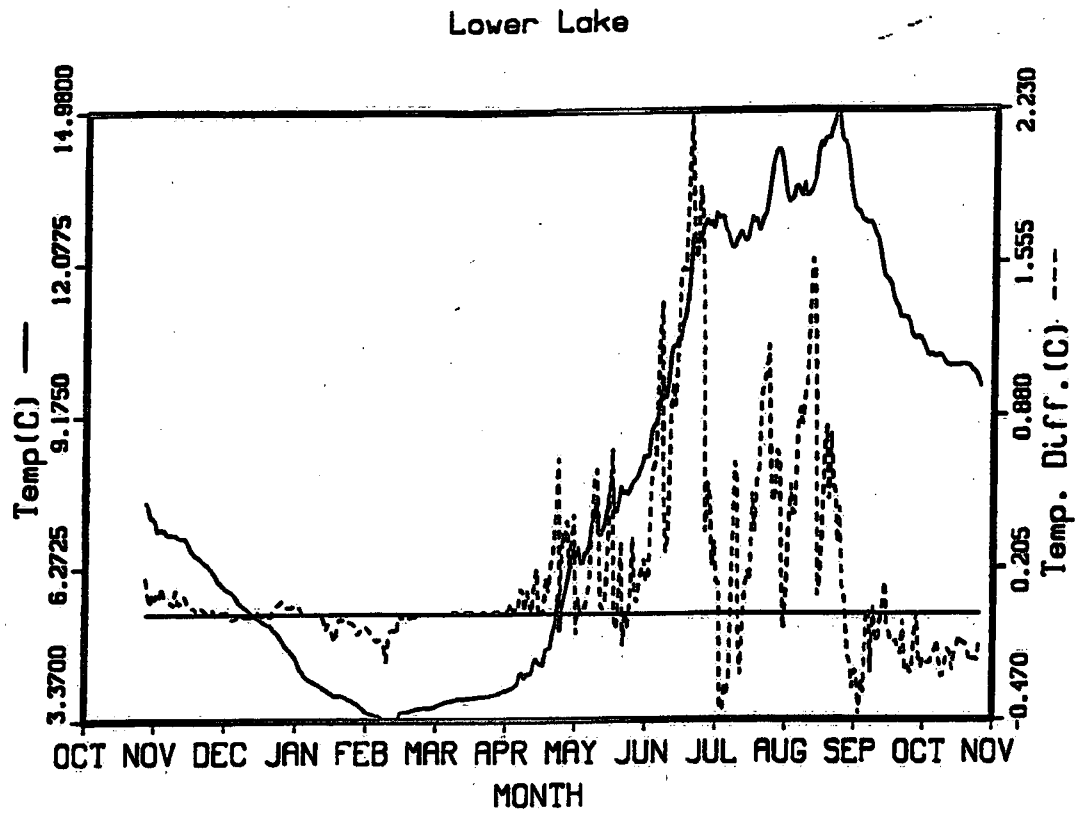

Lower Arrow Conductivity Difference(Top-Crest)
0.000
-46.595
-93.189
-139.784
-186.378
DEPTH(M)
-1.50
0.15
0.00
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH

**FIGURE 25**


Lower Lake
Temp(C) —
Temp. Diff.(C) ---
14.9800
12.0775
9.1750
6.2725
3.3700
2.230
1.555
0.880
0.205
-0.470
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH

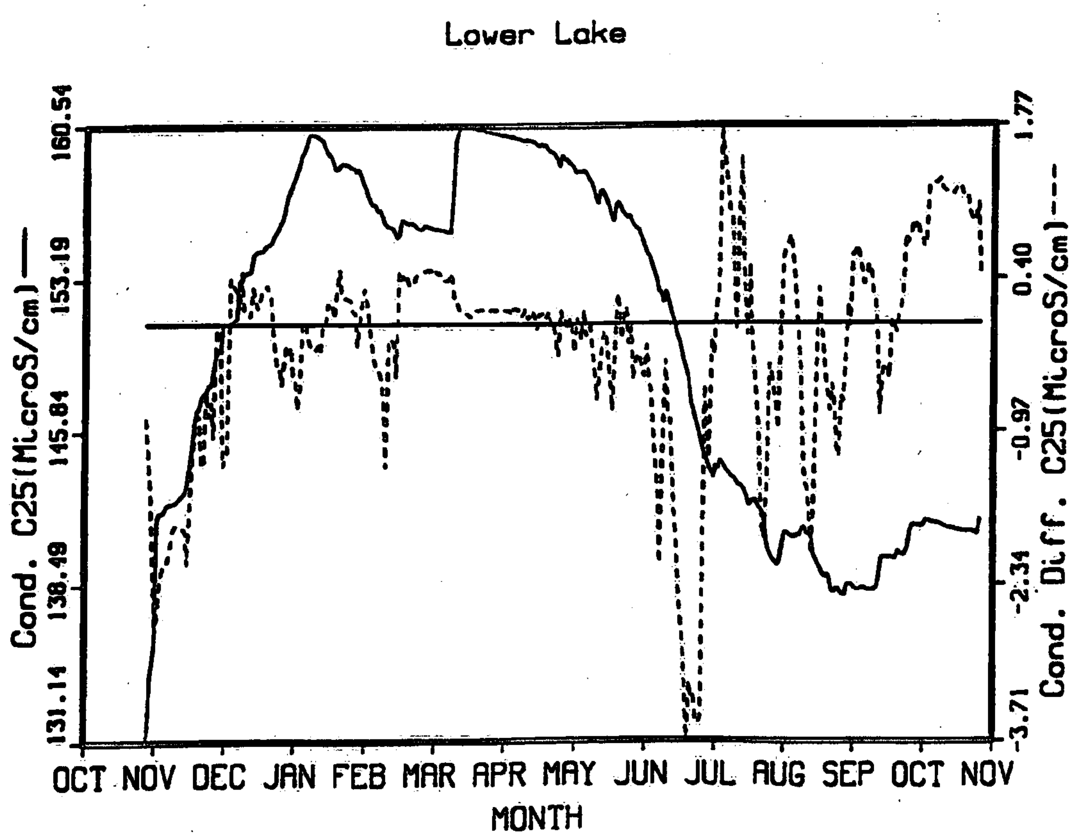

Lower Lake
Cond. C25(MicroS/cm) —
Cond. Diff. C25(MicroS/cm) ---
160.54
153.19
145.84
138.49
131.14
1.77
0.40
-0.97
-2.34
-3.71
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
MONTH

FIGURE 26

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