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BASELINE PHYSICAL LIMNOLOGY OF THE LOWER ARROW LAKES RESERVOIR

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Baseline Physical Limnology of the Lower Arrow Lakes Reservoir

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MANAGEMENT PERSPECTIVE

At the request of the B.C. Ministry of Environment this observational study of the circulation regime of the Arrow Lakes was undertaken to assist in the assessment and optimization of a strategy for the artificial fertilization of the reservoir. The biodiversity of the lake is at risk with the sudden decline of the kokanee sports fishery.

This document reports on the temperature and flows at critical areas in the system that could be surveyed within the limitations of the instrumentation. The results could form the basis for future lake remediation employing nutrient addition.

These results will be disseminated to the appropriate persons making the decisions on how best to mitigate the collapse of the Arrow Lakes sports fishery.

Caractéristiques fondamentales de la limnologie physique du réservoir inférieur des lacs Arrow

P. Hamblin

Sommaire à l'intention de la direction

À la demande du ministre de l'Environnement, on a entrepris cette étude d'observation du régime de la circulation dans les lacs Arrow afin de faciliter l'évaluation et l'optimisation d'une stratégie de fertilisation artificielle du réservoir. La biodiversité du lac est menacée, comme le montre le déclin soudain de la pêche sportive au kokani.

Ce document présente un compte rendu de la température et des écoulements dans des zones critiques du réseau qui pourraient faire l'objet de relevés dans les limites de l'instrumentation. Les résultats obtenus pourraient contribuer à déterminer des mesures de remise en état par l'ajout de nutriments.

On fera parvenir les résultats de cette étude à ceux qui devront choisir la meilleure façon de limiter l'effondrement de la pêche sportive dans les lacs Arrow.

Résumé

En août 1997, on a mesuré des observations sur place les profils des températures et des courants dans le réservoir inférieur des lacs Arrow afin de déterminer ses caractéristiques limnologiques fondamentales, au cas où on déciderait d'entreprendre des opérations de fertilisation de ces lacs afin de rétablir la pêche sportive au kokani, actuellement en déclin. Ce rapport présente les points saillants de ces observations et des analyses.

La plus grande partie de cet effort portait sur un point situé près de l'exutoire du lac, pour lequel on a établi un profil tridimensionnel complexe de la circulation, influencée par plusieurs facteurs comme la structure de prélèvement du barrage Hugh Keenleyside, la stratification de l'eau, la bathymétrie de la zone de décharge et la rotation de la terre. De plus, on a évalué simultanément des nouveaux instruments dans ce lac ultraoligotrophe.

Abstract

Field observations of temperature and current profiles were taken during August 1997 in the Lower Arrow Lakes Reservoir for the purposes of determining the baseline limnology in the event that lake fertization would be undertaken to restore the declining kokanee sports fishery. Highlights and analyses of these observations are provided in this report.

Most of the effort was devoted to a location near the outflow of the lake where it was found that the circulation has a complex three-dimensional pattern dictated by the withdrawal structure of the Hugh Keenleyside dam, the water stratification, the bathymetry of the outflow zone and the earth's rotation. At the same time some novel instrumentation were evaluated in this ultra oligotrophic lake.

Introduction

The British Columbia Ministry of Environment, Lands and Parks (MELP) has identified a need for baseline limnology of the Arrow Lakes Reservoir which has been stimulated by rapid ecological changes in the reservoir system as evidenced by the sudden decline of the kokanee sports fishery. Before a programme of lake fertilization can be successfully initiated, as in the nearby Kootenay Lake, (Ashley et al., 1997, Rae et al.,1996), it is desirable to assess the likelihood of success. This necessitates some understanding of limnology of the system. As one component of the study, currents and water temperatures were measured during the period from August 19 to August 28, 1997. This report is intended to provide some displays and analyses of these field observations.

At the same time there is much interest in the physical limnology in the vicinity of the Hugh Keenleyside Dam in order to provide an assessment of the likely alteration to the thermal regime from the proposed development of a hydroelectric generating station at the dam. A previous field survey of the temperature and total dissolved solid distributions in the early autumn has been reported by Hamblin and McAdam (1997) and by Hamblin (1997), undertaken to familiarize those responsible for the environmental assessment with the baseline limnology. In this first of two reports additional data are taken which also may provide information on the question of the impact of further development on the Lower Lake's thermal regime.

In the report of Hamblin (1997) some initial water quality modelling was undertaken which focused on the thermal and total dissolved solid regimes of the Lower Lake. Hamblin (1997) identified the need for knowledge of the bathymetry of the two lake basins in electronic form so that more accurate numerical modelling could be performed. Part of the present report deals with the reduction of recently purchased digital bathymetry into forms suitable for vertical one-dimensional modelling and three-dimensional modelling.

As one component of an integrated study of the limnology of the Arrow Lakes Reservoir currents were measured in this survey by means of an acoustic doppler profiler (ADCP) configured so that currents profiles could be measured while the supporting survey vessel was underway. Despite the high frequency of this device (1200 KHz) there was concern that the lack of suspended particles which act as scatterers of the acoustic signal would render the meter inoperable. Evidently, Secchi depths as high as 26m have been observed in this ultra oligotrophic lake. Part of this report is devoted to an evaluation of the performance of the broadband ADCP in this unusual environment. A similar instrument was operated successfully in Kootenay Lake in 1993 (Hamblin et al., 1995) but only after the study area had been fertilized sufficiently to build up the concentration of scatterers. Because of the known interaction of flow and density stratification attempts were made to simultaneously sample current and temperature. As well, Hamblin and McAdam (1997) found that an autonomous Global Positioning System (GPS) worked erratically with frequent large errors in horizontal location that had to resolved with reference to an echo sounder and bathymetric charts. Attention is given to an assessment of a base-station differential GPS which was integrated directly into the recording system of the ADCP. Recommendations are made on the future use of the new technology used in this study.

Bathymetric and Hypsographic Analyses

As input of basin geometry for such one-dimensional water quality models as DYRESM (Hamblin, 1997), area and volume distributions as a function of depth or distance above the bottom must be specified. Furthermore, three-dimensional transport and circulations models require basin geometry at model mesh points. For example, the automated mesh generator, TRIGRID, needs as input the lake's shoreline configuration as a continuous sequence of positions in a clockwise sense around the perimeter of the lake. While the input of topography can be either in continuous contour or random form, continuous bathymetric contours are particularly convenient for the calculation of the areas enclosed by a given contour.

As a first step, the Canadian Hydrographic Service (CHS) charts of the Arrow Lakes, CH3056 and CH3057 were purchased in electronic format from Nautical Data International. These data proved to be extremely difficult to process as all features such as the land and map features were included. The CHS staff at the Canada Centre for Inland Waters kindly reduced these data to two files per depth contour and chart, one for the forward side and the other for the back side of each chart with specialized software in their possession. A composite file was constructed for each contour of a given lake basin by concatenation of these individual files. Next, a computer program was written to identify as many 400 individual arcs for a given contour, convert the geographic coordinates to eastings and northings in metres according to a Universal Transverse Mercator projection and plot the arc numbers. The sequence of continuous arcs was then noted manually and fed into another program that plotted the position of every 10th point both as a dot and also as a curve joining adjacent points. In this way missing arcs were identified as well as arcs reversed in direction. Finally, the positions going from one arc to another between arcs were visually examined as a final stage of error checking. Sometimes, duplicate arcs or overlapping arcs were identified and eliminated in this way. Plots of the shoreline, 10m, 50m and 100m depth contours are shown in Figures 1 to 4. The 2m depth contour was not processed in the interest of time and was considered to be little different from the shoreline contour. It is noteworthy that the 50m depth contour is divided into three separately closed contours.

The area bounded by each contour was calculated from Green's theorem,

$Area = \frac{1}{2}\oint_c x\,\partial y - y\,\partial x$. The x and y denote the east and north coordinates of each successive point along the contour.

Once the area was known, the volume was calculated from the expression; $Volume = \int_0^{Sfc} area(z)\,\partial z$.

Plots of the area and volume curves with depth are shown in Figure 5 based on the data tabulated in Table 1.

Depth (m)	Area (Km^2)	Volume (Km^3)
194	0	0
100	48.58	2.283
50	64.69	5.115
10	154.81	9.505
0	177.24	11.1

Table 1. Hypsographic Data, Lower Arrow Lake

The area-depth curves of four intermontane lakes in British Columbia and the Yukon Ter. were compared in Hamblin (1997). It is seen that the curve in Figure 5 differs from that of Kootenay Lake (Hamblin, 1997). In that modelling exercise it was assumed that the Kootenay Lake data applied to the Arrow Lakes which is not true for the Lower Arrow Lake. It is interesting that Kootenay Lake has more than 50% of the surface area at mid depth unlike Lower Arrow, Babine, Laberge and Kamloops Lake, suggesting a different origin for Kootenay Lake from other similar lakes. It will be interesting to see if the hypsographic curves for Upper Arrow Lake are similar to those of Kootenay or the Lower Arrow Lake.

When the total volume is compared to that estimated by Hamblin (1997) based on the Kootenay Lake hypsographic data it is seen that the former estimate is four times too large, due in part to the unusual distribution of volume in Kootenay Lake. Thus, the maximum and minimum residence times were overestimated. The correct times for the Lower Lakes are 7.8 and 2 months respectively.

Field Experiments

(a) Experimental Methods

The acoustic doppler current profiler is capable of measuring three components of flow while underway as illustrated schematically in Figure 6. As well, water temperature at the head, depth and acoustic backscatter intensity are recorded. If the system is equipped with an electronic navigation device such as the differential Global Positioning System shown in Figure 6 the survey vessel's position may be recorded as well. As the doppler shifts of the frequency of the backscattered acoustic energy indicate the total speed of the instrument it is necessary to measure and correct for the speed of the vessel over the bottom. This is done automatically based on the doppler returns from a separate set pulses reflected off the bottom. In the event that the water column is too deep to detect these reflections then it may be possible to estimate the vessel speed from velocities output by the differential GPS. According to the manufacturer currents are accurate to within a cm/s while bottom tracked ship speed errors are in the order of a mm/s.

The basic instrument used in the survey was a 1200 KHz broadband ADCP mounted over the side of a 7m fibre glass cruiser on a swivel bracket which permitted rapid deployment of the sensor head and easy removal between study sites. This instrument as well as a ADCP of 300KHz frequency intended for mooring were manufactured by RDI. The 1200KHz underway instrument was configured for a vertical resolution of 0.5m with the first usuable bin of acoustic data starting at 1.8m below the surface. The inboard motor launch was equipped with a radar but no echo sounder.

A downrigger reel was mounted on a bracket at the stern of the motor launch. The same temperature profiler as that used by Hamblin and McAdam (1997), an OS-200 profiler, was attached to approximately 300m of monofilament line. This system was much easier to operate than the handline method of Hamblin and McAdam. Continuous temperature profiling was attempted but only when the launch was unpowered.

A differential base-station GPS was set up on the shoreline within several kilometres from each study site (see Figure 6). Usually the shore site was located at a Canadian Hydrographic Service (CHS) bench mark of known position but in some experiments the nearest bench mark could not be found. In these cases the positions are relative. During an experiment the relative positions were considered to be accurate to within the specifications of the navigation system. For the combination of the Novatel base-station and Magnevox 300 GPS receiver the accuracy is about 1m. Ship positions when converted to Universal Transverse Mercator coordinates are shown for the various field experiments in the figures to follow together with a portion of the nearby shoreline contour for reference. Since the position of the CHS bench march was given with reference to the North American 1927 (NAD27) datum whereas the CHS charts use the NAD 83 the positions of the ship tracks had to be adjusted.

(b) ADCP Observations August 19, 1997

The August 19 study area was chosen as test site for the initial operation of the survey system for logistical reasons. Besides, it could provide useful information on the temperature and flow fields in the vicinity of the proposed hydroelectric power facility.

The location of the detailed study area is shown in Figure 1. A differential base-station GPS was set up on a CHS bench mark of known position several km to the west of the study site. Ship positions when converted to coordinates are shown for the field experiment in Figure 7 along with the a portion of the shoreline contour from Figure 1. Since the position of the CHS bench march was given with reference to the North American 1927 (NAD27) datum whereas the CHS charts use the NAD 83 the positions of the ship tracks had to be adjusted. According to published information the two datums at this location should differ by 81m in the east direction and 16m in the north direction. However, the best match between the shoreline and ship tracks appeared to be for a shift of 40m in each direction, which was used in the preparation of Figure 7. The ship track data were based on 1683 10s averages of 1s acoustic doppler and positional data over the approximately three-hour long survey period. It may be noted that the ship tracks are not smooth. The breaks in the continuous steaming of the vessel mark approximately were the vessel was stopped to permit the lowering of the temperature profiler.

Underway examination of the ADCP data suggested that there were sufficient backscatterers present in the water column to produce reasonable estimates of the flow over a depth range from 1.75 to about 20m. In other applications of the ADCP the range of the instrument exceeded the bottom depth . This was not the case here so that the noisy data below 20m had to be edited and set to a missing value identifier. Interestingly, on the likely account of a low concentration of scatterers the depth of penetration of the bottom tracking pings ranged to about 45m, a depth not encountered in previous applications. This was fortunate as it meant that the velocity of the moving platform was known throughout the study area. In turn, this reference velocity was required to correct the measured velocity profiles. Although 36 temperature profiles were taken, due to an intermittent fault in the profiler only 24 profiles reached the bottom. These good profiles were merged with the ADCP data set as an additional channel according to the closest match in sample times. The vast majority of ADCP profiles not having temperature profiles were set for later processing with missing value identifiers.

It will be evident from the bathymetric contour plots of Figures 1 through 4 that there are no contours between 10 and 50m in the study area but that most of depths occur between these two contours. Therefore, to obtain more detailed bathymetry which is responsible for steering the lines of flow, the shoreline, 10m and the ADCP bottom-tracked depths were combined and contoured. At the time of the survey water levels peaked and were 5.7m above chart datum. As a result the CHS contours were assigned depths of 5.7 and 15.7m. Unfortunately, the errors in the ADCP depths of 1.4m were much larger than the CHS depth errors estimated to be 0.3m. In order to combine data having differing uncertainties in an interpolation scheme an error weighted least squares approach was developed. First, the study region was subdivided into 100m by 100m cells, 25 along the lake and 10 across. For each cell, whether it was empty or contained data, either a quadratic or linear polynomial was fitted locally to the neighbouring depths according to weighted least squares using a singular value decomposition algorithm (Press et al., 1986). The resulting polynomial was evaluated at the centre of the cell for the interpolated depth and then contoured by the public domain contouring routine of GNUPLOT package The result is shown in Figure 8 and shows a maximum smoothed depth of around 36m. There is some evidence of the predevelopment river channel.

The above analysis of the depth distribution is based on the assumption that the locations of the ADCP-based depths are correct. These positions are derived from a base-station differential GPS which was deployed for the first time in this field experiment. The impression given from Figure 7 is that the ship tracks may be in error in the north south directions as they do not cross the lake as experienced during the survey. Owing to the deep bathymetry the survey was conducted as close to the shoreline as possible coming considerably closer to the shoreline than the 100-200m distance suggested by Figure 7. In order to further evaluate the accuracy of this novel electronic navigation system and to assess the suitability of a differential GPS in supplying the ship reference velocity, should bottom tracking fail in the experiments conducted in the Narrows and Upper Arrow Lake regions, the question of the velocity associated with the GPS is examined.

Until this point 10s averages of 1s data have been analysed. In order to compare ship velocities with primary data, differential GPS velocities at 1s intervals were vectorially averaged to 5s intervals, the sampling period of the unaveraged ADCP data. Figures 9 and 10 compare the two independent estimates of ship speed. On the whole the agreement is close but with a root mean squared error of 24.2 cm/s for the east component and 27.1 for the north, the differential GPS determined velocity errors are much too large for general use in supplying reference velocities in deep lakes. The errors in acoustic bottom tracking are quoted by the manufacturer to be in the order of mm/s and the computed error from the four acoustic beam solution has a typical value in this experiment of less than 1% of the ship speed. It may noted from the figures that the GPS velocities lag the ADCP ship speeds. When the ADCP velocities were lagged by two sampling intervals or 10s to match the GPS series the rms errors reduced to 17.9 and 14.7 cm/s respectively. Since the ship trajectory shown in Figure 7 indicates frequent ship accelerations during which the differences might be expected to be exaggerated, the differences between successive bottom tracked velocities are examined in Figure 11. As most of the extreme accelerations occur at speed differences over 15cm/s between 10s samples this criterion was chosen to reject unsteady cases. Based on the more steady ship travel the rms differences reduce to 11.3 and 8.4 cm/s for the east and north components. In the case of high flow and steady ship heading and speed, ship speeds obtained by differential GPS may supply the reference velocities although they would be at least an order of magnitude greater than the acoustically determined reference velocities.

Data Display

Merged position, current profile and temperature data were interpolated to a regular three-dimensional mesh of size 10X10X88 by a use of the three nearest observation points. The resulting three-dimensional data set is depicted on either horizontal or vertical surfaces with the basin bathymetry in perspective view in Figures 12 to 17. It is seen in Figures 12 and 15 that the flow varies from approximately 40 to 10cm/s from the surface down to 16m depth, close to the range limit of the profiler. Near the surface there is some asymmetry of the flow with weaker flow in the vicinity of the proposed approach channel (Figure 7) and on the south side of the Hugh Keenleyside Dam. In Figure 13 the vertical velocity is contoured at a level slightly below the horizontal flow surface. As might be expected strong upwelling appears to be associated with the outflow at the Hugh Keenleyside Dam. In contrast, temperature contours on Figure 15 do not suggest a consistent gradient of decreasing water temperature as the Dam is approached that would be produced by upwelling. This may be due to the severe undersampling of temperature compared to the water currents. Deep currents in Figure 15 suggest bathymetric control of the flow in the submerged river channel before flooding. The longitudinal transect of Figure 16 indicates an possible vertical bifurcation of the flow as the Dam is approached. It is speculated that this could be the influence of the two outlets, one at the surface over the spillway and the other, a low level port at about 18m below the water surface (Columbia Power Corporation, 1997). Finally, a crosslake view in Figure 17 suggests the presence of cross channel or secondary circulation. A northerly directed jet at a depth of about 16m is an interesting feature but may be too close to the limit of resolution of the current profiler to be meaningful.

As well as the three-dimensional data displays which do not show temperature clearly, more conventional two-dimensional contour plots are provided in Figure 18 of the temperature and east component of flow along the first south-to-north transect seen in Figure 7. In the inset, the total flow or discharge across the lake is compared to that determined for August 19 from the water balance method, (R.Pieters, per. com.) shown in parentheses. The smaller directly observed discharge is attributed to the limited depth range of the ADCP of 20m or less. Thus, the transport in the deeper portion of the profile is not measured. Otherwise, the pattern of flow is typical of a large river. Another interesting feature is the pronounced thermal stratification in this region downstream from a shallow sill at Syringa Narrows (see Figure 1 and in more detail in Figure 21). It has been proposed that the Syringa constriction acts as a hydraulic control restricting the flow of hypolimnetic water through the Narrows, but it appears not to be the case on August 19. Further discussion and analysis of this question follows below.

Comparison of ADCPs and Electromagnetic current meter.

Comparisons of the 1200 and 300 KHz ADCPs were conducted at the mid lake temperature and current meter moorings on August 20 (Figure 1) while tethered to the surface meteorological float. The purpose of the comparison was to evaluate a 300 KHz ADCP for suitability for use in the Arrow Lakes Reservoir and to compare both instruments to the two electromagnetic current meters moored at the location at depths of 6 and 50m. Potentially, the 300 KHz ADCP has greater range than the higher frequency model. The electromagnetic current meter, model S4, was operated by the University of British Columbia and manufactured by InterOcean Systems Inc. From plots of speed and direction of the S4 current meter at 6m prepared by Dr. S. Pond (pers. com.) it is apparent that the flows were steady at a mean speed of 2.5 cm/s and direction of 220° during the period of comparison.

At the centre of the Lower Arrow Lake the water is far too deep for bottom speed reference of the 1200 KHz model and the 300 KHz instrument lacked bottom tracking. However, a base-station differential GPS provided estimates of the drift velocity of the surface buoy and attached survey vessel. Figure 19 depicts the trajectory of the survey vessel during the 1200 KHz experiment. The locations of the 10-min average are indicated. Based on 10-min averages the maximum drift speed was 1.5cm/s while the average was around 1.0 cm/s. Averaged drift velocities were subtracted the 10-min averages of the 1200 Khz ADCP. But in the case of the 300 KHz model the velocities remain uncorrected as the resident software did not permit the recording of location in the subsequent analysis. Due to logistical difficulties the two profilers were not operated concurrently. As the currents are much stronger during the 300Khz ADCP's sampling period this shortcoming is not considered serious.

On August 20, the 300 KHz device registered meaningful velocities as deeply as 30m but not at the 0.5m depth resolution of the higher frequency profiler but rather at 1m depth intervals. The maximum possible range of the lower frequency meter is 128m when set to resolve 1m bins. Comparisons of 10-min averages of velocity profiles of the two models are provided in Figure 20. Since there was no overlapping period it is impossible to say how close the correspondence in flow between the two models is. However, it is evident in Table II that the 300KHz profiler indicates flows at 6m that are much greater than the S4 currents especially in the east components while those measured by the 1200KHz device are in good agreement with the S4 measurements. Neither the 300KHz ADCP nor the 1200KHz registered current at the 50m depth. The electromagnetic current meter recorded 1-min averages of flow every 20 minutes. As the current profiles taken by the 300KHz ADCP are consistently high it is unlikely that the discrepancy is due to the 3m deep averaging interval or to the neglect of the reference velocity.

300 KHz ADCP	Time(GMT)	East (cm/s)	North (cm/s)	S4	Time (GMT)	East (cm/s)	North (cm/s)
	17:31-17:51	19.4	-2.9		17:40	-0.6	-1.2
	17.51-18:11	19.3	-3.2		18:00	-3.7	-3.0
	18: 1-18:21	21.6	-4.3		18:20	-1.4	-0.2
1200 KHz ADCP	21:: 2-21:22	-2.7	-1.8		21:20	-1.7	-0.6
	21:32-21:52	-2.2	-0.5		21:40	-3.0	-0.6
	21:52-22:12	-1.0	0.2		22:00	-1.5	-2.3

Table II. Comparison of ADCP and S4 currents at 6m depth mid lake on August 20. The two ADCPs are continuous averages over the period indicated while S4 are 1-min averages every 20 minutes.

Analysis of Hydraulic Control at Syringa Narrows

Unfortunately, the question of the possible hydraulic control presented by Syringa Narrows was not known by the author at the time of survey so that no ADCP or temperature observations were made in the Narrows area. As a result an analysis undertaken is based on theoretical fluid mechanics. The detailed bathymetry of Figure 21 shows that the minimum depth in the Narrows is slightly greater than 10m and the minimum breadth at the surface is 400m. According to chart CH3056 the depth is 21m to which 6m must be added to correct for the water level on August 19. Thus the minimum breadth at the surface would be 515m based on a simple triangular cross section.

Based of the thermal structure and discharges presented in Figure 18 for August 19 about three quarters of the outflow is drawn from the epilimnion while only a quarter is hypolimnetic flow. This agrees with the operation of the Hugh Keenleyside Dam as both overflow and the submerged port were operating. The submerged port at a depth of 18m may effectively draw water from higher levels due to its upward inclination. As both layers have flow in the same direction over the Syringa Narrows sill and the upper layer flow is much greater than the lower layer flow it is unlikely that there would be hydraulic control exerted. The question of internal hydraulic control may arise in the case when the outflow is drawn preferentially from the hypolimnion for the purposes of thermal mitigation of the reservoir operation.

The maximum lower layer or hypolimnetic flow permissible over a sill and through a narrows without drawing water from the epilimnion is given by the criterion of Farmer and Armi (1986) as the square root of the product of acceleration of gravity reduced by density and the depth of the lower layer at the narrows. For an assumed upper layer temperature of 16°C and lower layer temperature of 10°C the reduced gravity is 7.6×10^{-4} ms^{-2}. The unknown depth over the sill is calculated from the conservation of momentum using the Bernoulli equation for the lower layer. This equation is evaluated upstream of the sill assuming a thermocline depth of 10m, a beadth of 400m and a total depth of 40m and at the sill using the total sill depth of 27m and the unknown lower layer thickness. Setting the upstream Bernoulli value to that at the sill gives a critical depth of the lower layer at the sill of 16.6m and a discharge in the lower layer of $260m^3/s$ based on an assumed breadth of 200m at the sill.

The additional flow over the sill would be drawn according to the ratios of the cross sectional areas of the two layers. Assuming that the lower layer at the sill has 30% of the total area and that the total through flow is 2000 m^3/s, the total discharge from the lower layer would be 30% of 2000 minus 260 m^3/s or 522 plus 260 for a total of $782m^3/s$. The average temperature of the water flowing through the Narrows would be 13.7 °C. As this critical lower layer discharge is much larger than that estimated from the ADCP data of 380 m^3/s it is unlikely that the lower layer discharge is restricted by internal hydraulic control but rather by the withdrawal structure at the dam.

Conclusions

A high frequency acoustic doppler current meter worked better than anticipated for such an undernourished water body due in part to the relatively high flows in near the outflow. Fortuitously, the study period coincided with a peak in suspended material due either a high input of glacial flour or to increased primary production that may have improved the operation. The ADCP technology may not perform as well at other times. Although the profiling range was somewhat restricted the bottom tracking range appeared to be enhanced. From the favourable comparison of the 1200KHz ADCP with a moored electromagnetic current meter it is concluded that both were operating successfully but that the 300KHz model was not working properly for some unknown reason. It would be valuable to conduct a further evaluation of this device.

Unfortunately, water temperature can not yet be measured remotely and underway which results in a severe undersampling of water temperature using traditional techniques. An improved system of temperature profiling capable of more rapid sampling is recommended if currents are to be properly interpreted. The NWRI's OS200 temperature logger should be replaced by a more reliable model.

A focusing of the flow on the left hand side of the lake in the direction of flow was observed close to the outflow. Whether this effect was due to the earth's rotation or a combination of outflow geometry and bathymetric steering will have to await additional three-dimensional circulation modelling.

No evidence was found that cold hypolimnetic water is retained by the narrows upstream of the proposed approach channel although additional ADCP and temperature measurements would be useful to establish this likelihood. It is likely that the hypolimnetic discharge could be increased substantially before hydraulic control is exerted. Therefore, there ought to be a sufficient supply of cold water at the mouth the approach channel if thermal mitigation is found necessary by means of selective withdrawal using a temperature control curtain (Columbia Power Corporation, 1997).

An application of new electronic positioning technology in Lower Arrow Lake appears to be successful despite the mountainous terrain. The differential system greatly reduced the uncertainty in horizontal position but errors in velocity remained too large to supply ship reference velocities in most instances. Further evaluation of the positional accuracy will be attempted in the Upper Lake study. In future applications navigational data quality and possibly pseudoranges should be recorded in the navigation data file and all positions should be referenced to the same datum as the chart datum.

Information on the hypsography of the Lower Arrow Lake indicated that former estimates based on similarity to Kootenay Lake were incorrect and that inferences made of the sensitivity to proposed changes in the outflow of the lake may be affected. It is recommended that the prior thermal modelling be repeated with the new lake geometry and meteorological data measured as a component of this study.

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List of Figure Captions

Lower Arrow Lake Shoreline Contour

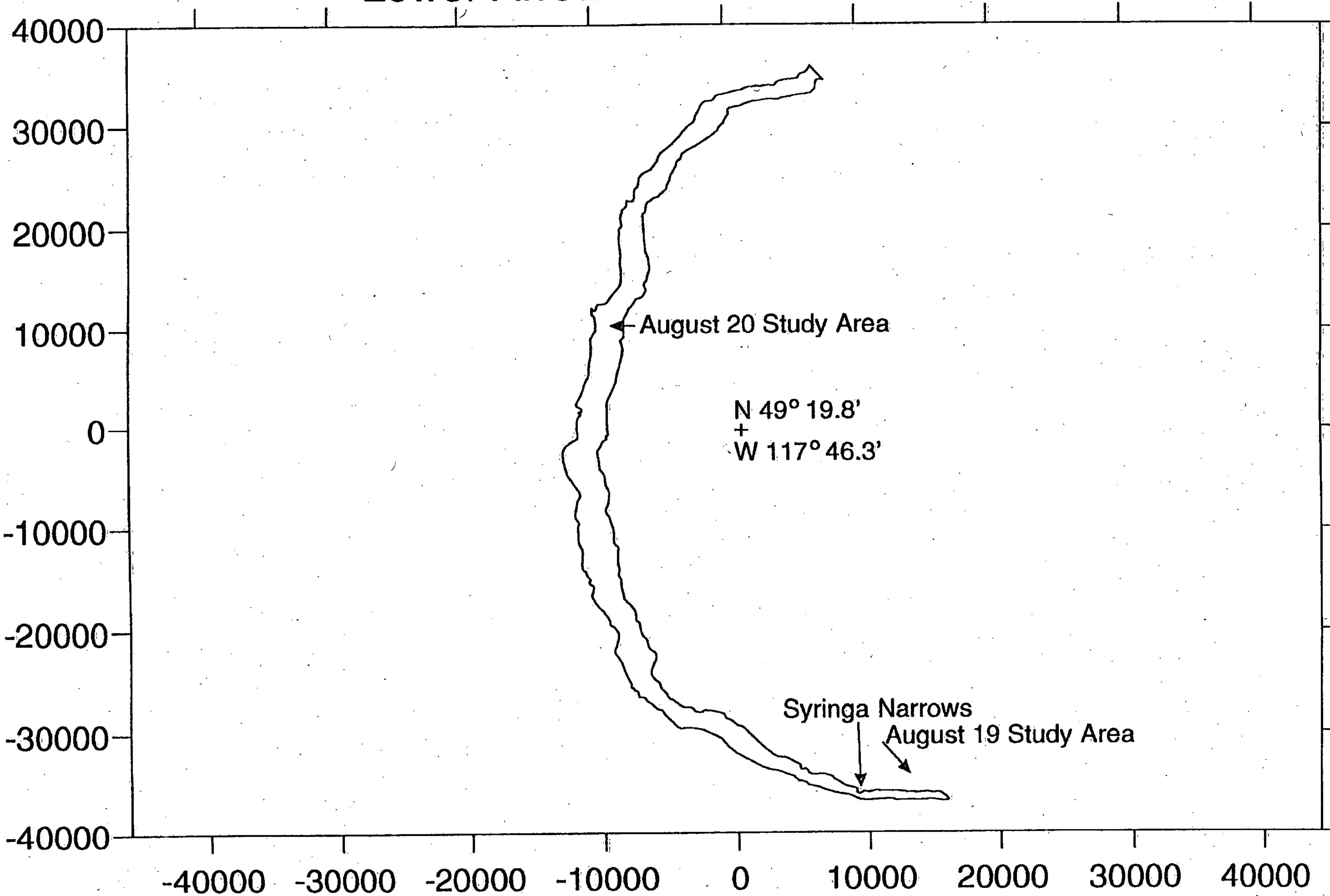


FIGURE 1

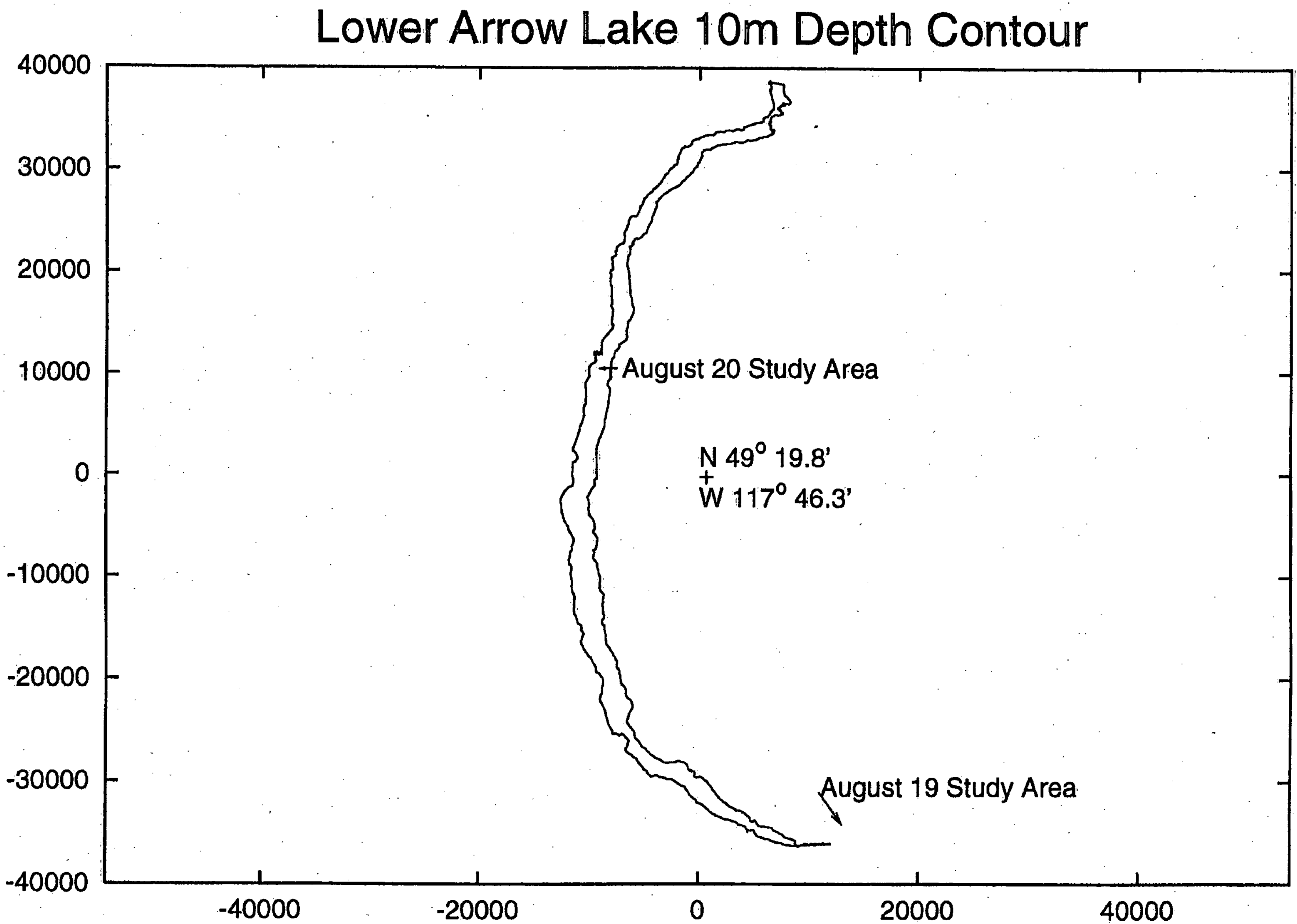

Lower Arrow Lake 10m Depth Contour
40000
30000
20000
10000
0
-10000
-20000
-30000
-40000
-40000
-20000
0
20000
40000
August 20 Study Area
N 49° 19.8'
W 117° 46.3'
August 19 Study Area

FIGURE 2

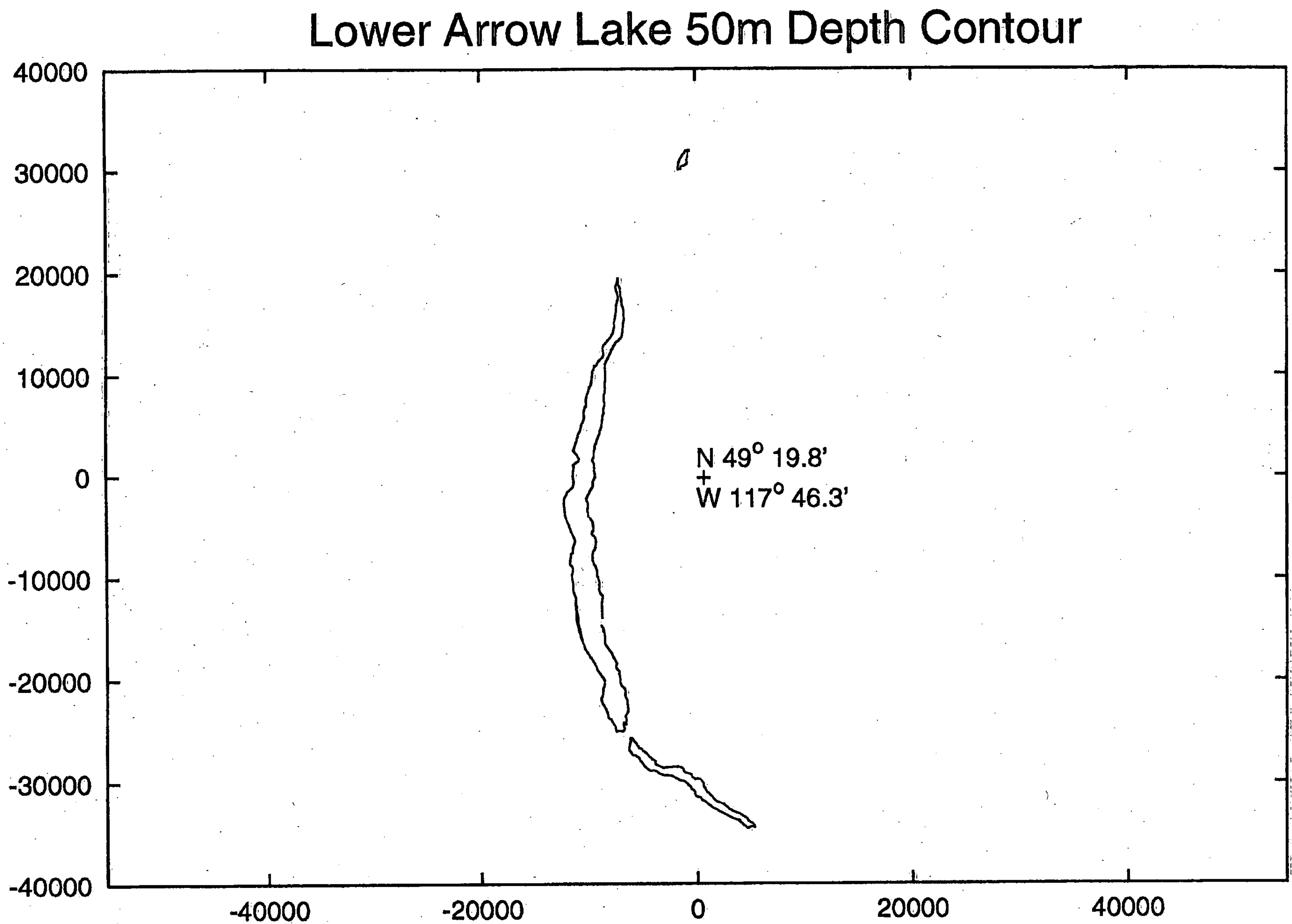
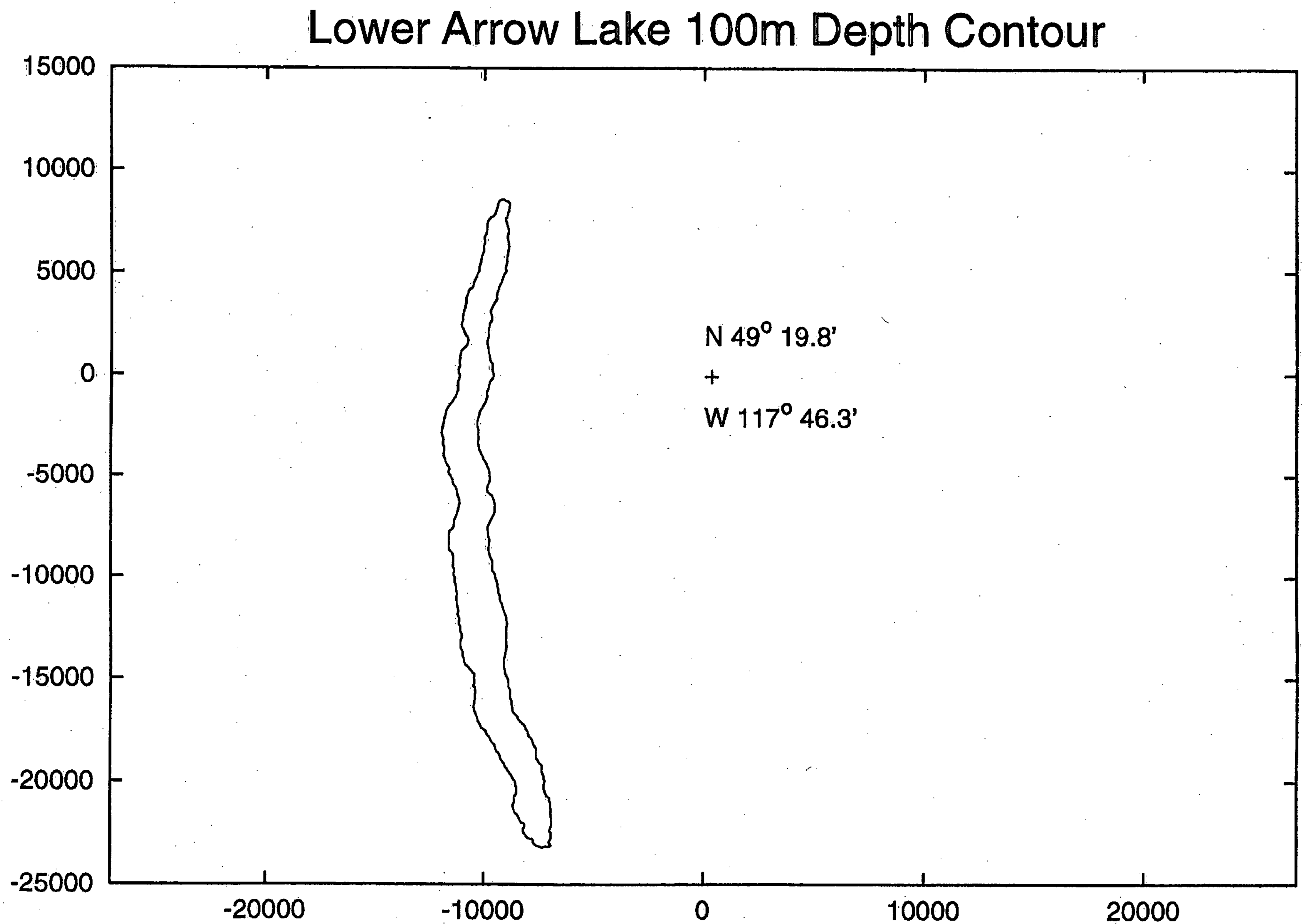
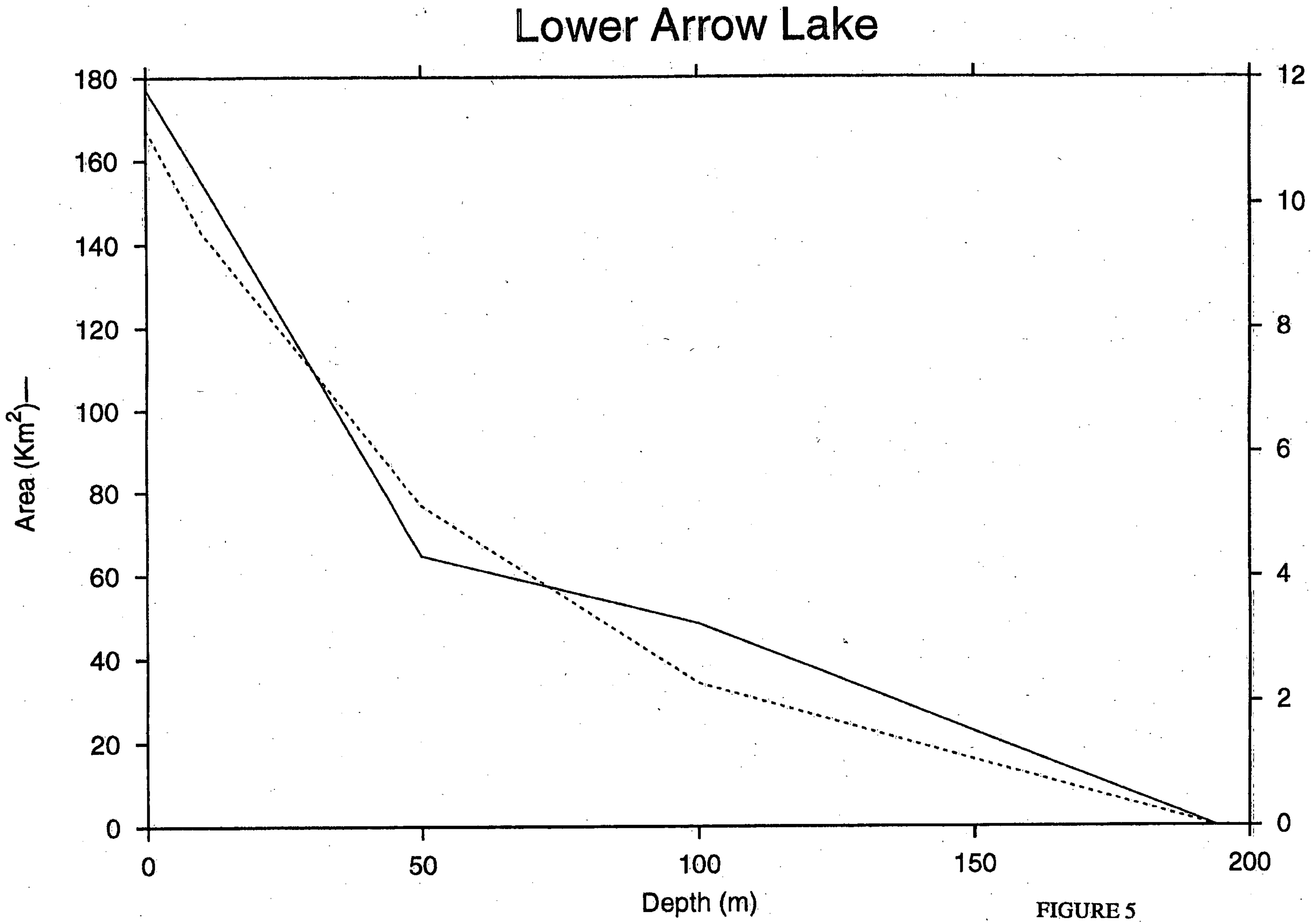

Lower Arrow Lake 50m Depth Contour
40000
30000
20000
10000
0
-10000
-20000
-30000
-40000
N 49° 19.8'
+
W 117° 46.3'
-40000
-20000
0
20000
40000

FIGURE 3



Lower Arrow Lake 100m Depth Contour
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-20000
-10000
0
10000
20000
N 49° 19.8'
+
W 117° 46.3'

FIGURE 4



Lower Arrow Lake
180
160
140
120
100
80
60
40
20
0
Area (Km2)—
12
10
8
6
4
2
0
Volume (Km3)...
0
50
100
150
200
Depth (m)

FIGURE 5

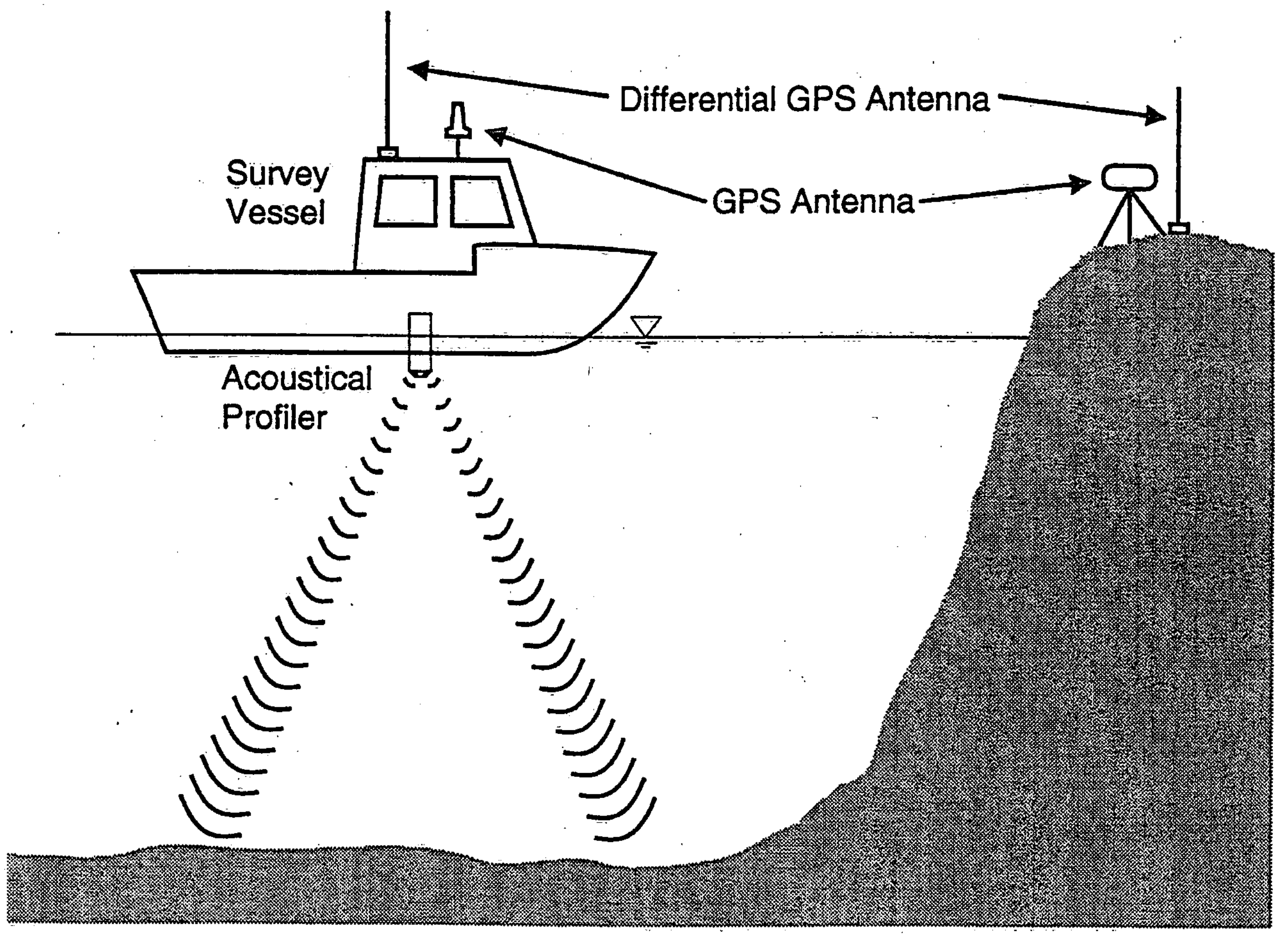
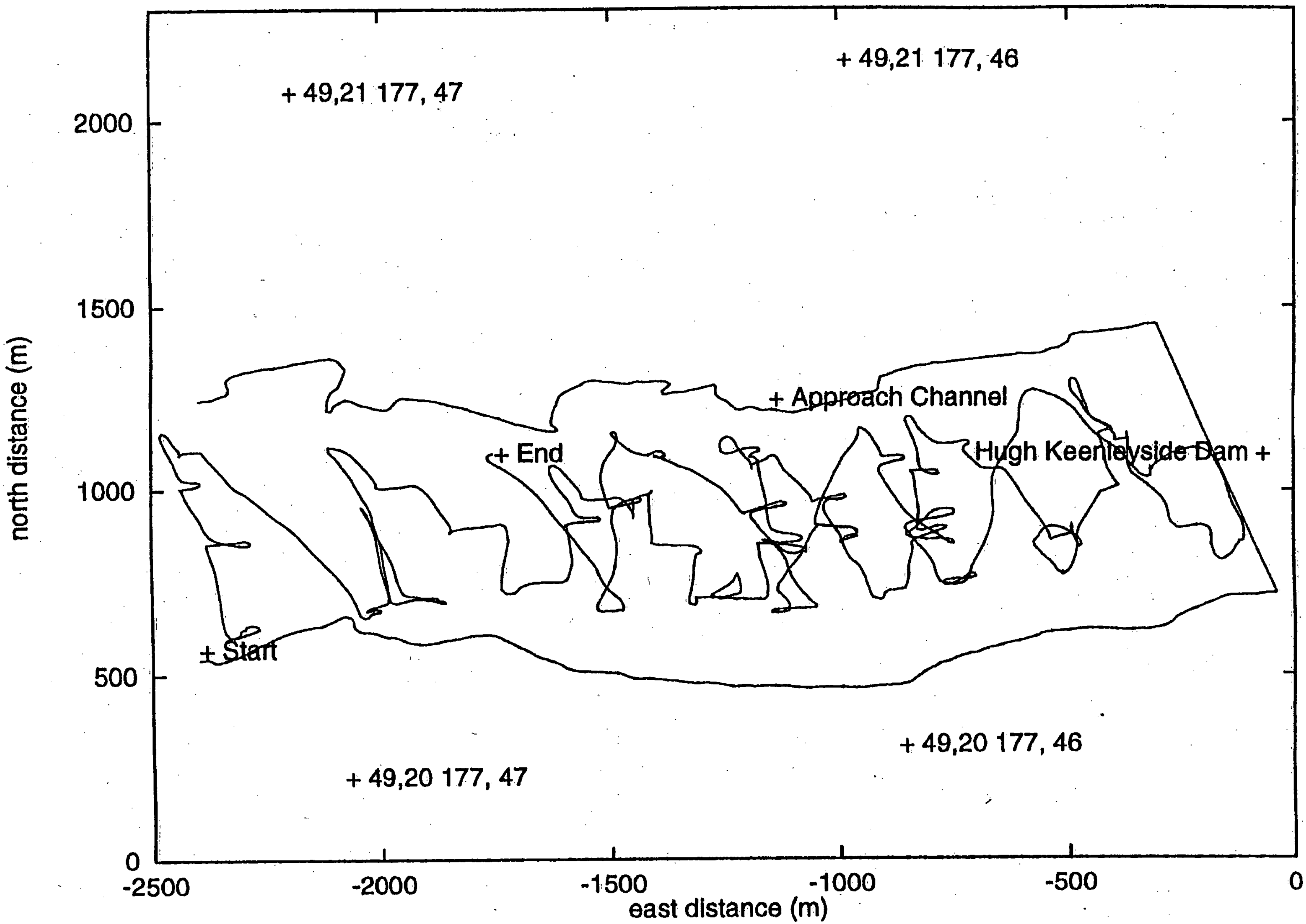
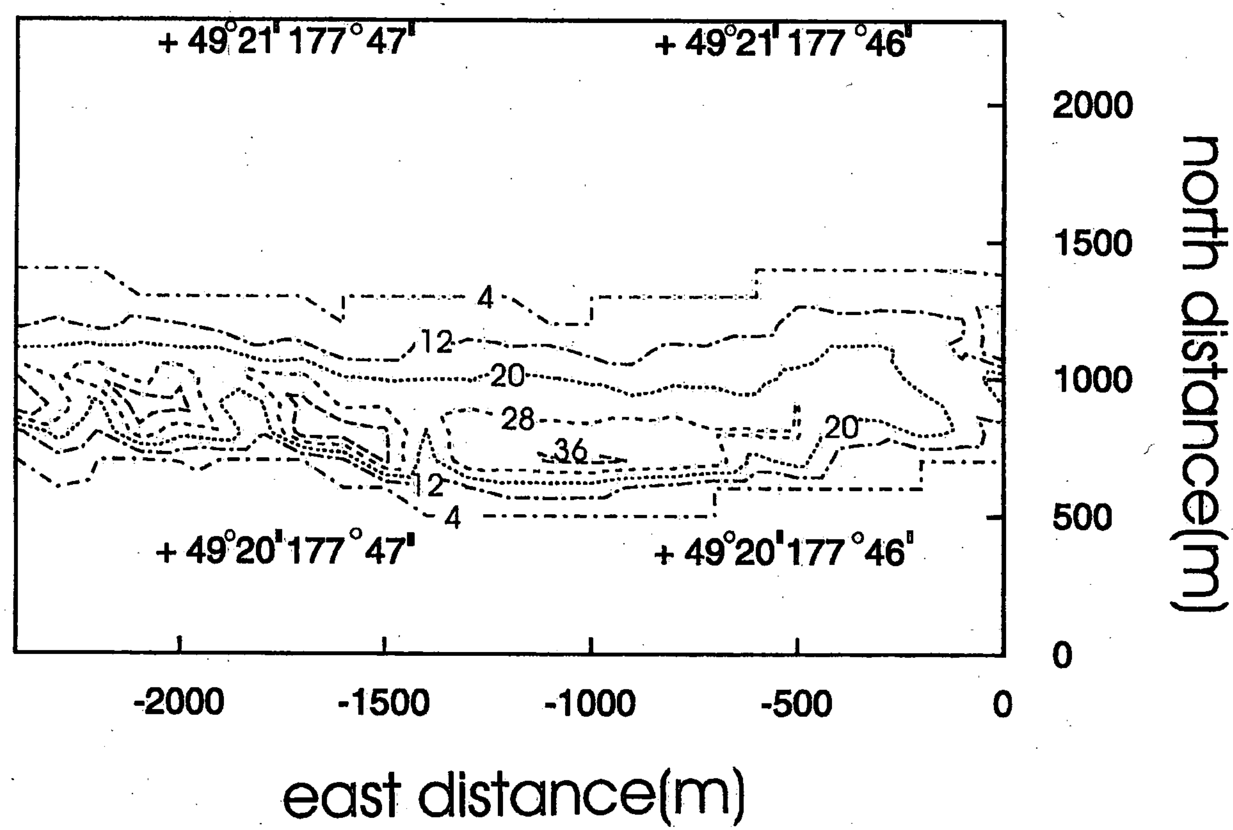

Differential GPS Antenna
Survey
Vessel
GPS Antenna
Acoustical
Profiler

FIGURE 6



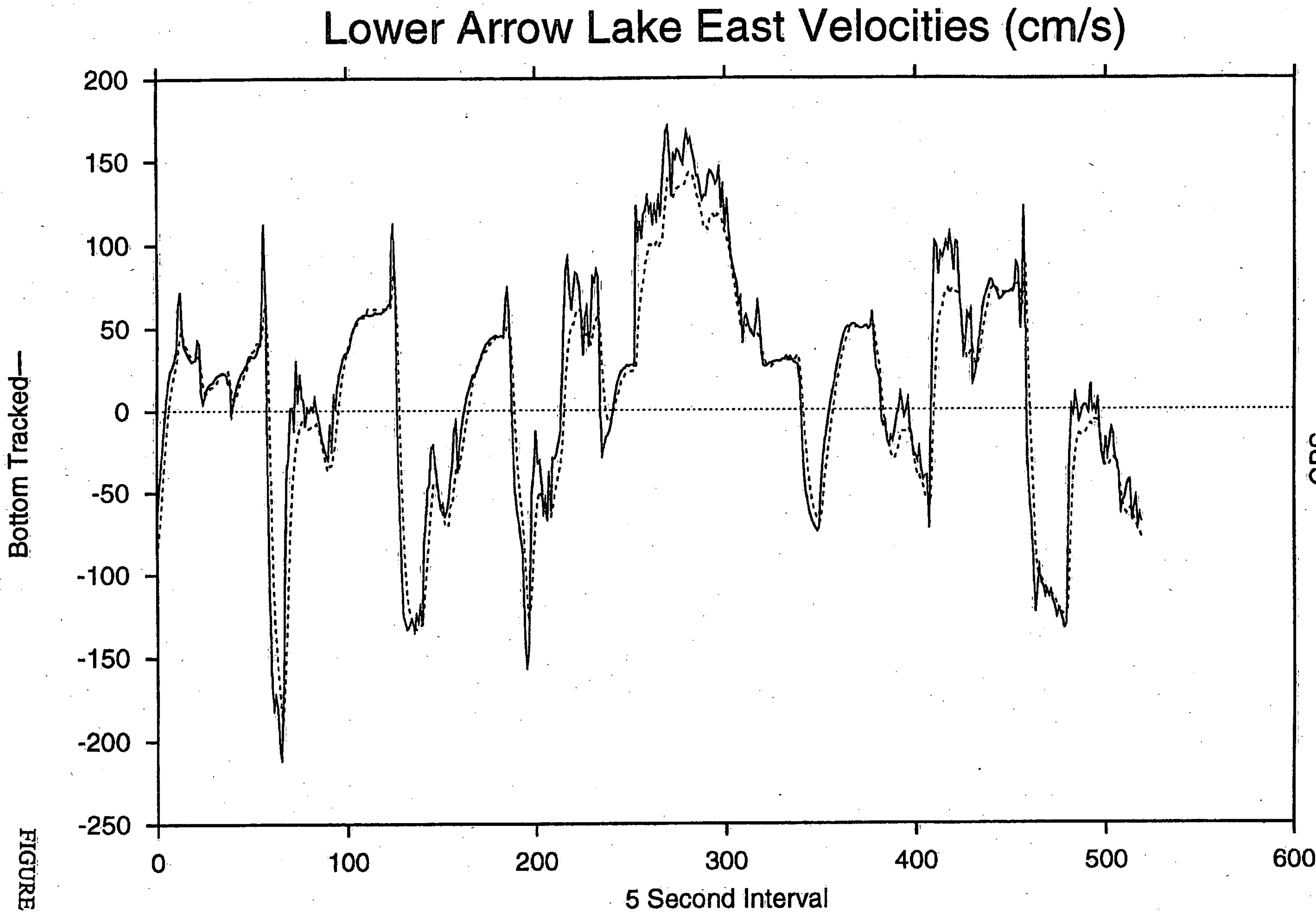
+ 49,21 177, 47
+ 49,21 177, 46
2000
1500
1000
500
0
north distance (m)
+ Approach Channel
+ End
Hugh Keenleyside Dam +
+ Start
+ 49,20 177, 46
+ 49,20 177, 47
-2500
-2000
-1500
-1000
-500
0
east distance (m)

FIGURE 7



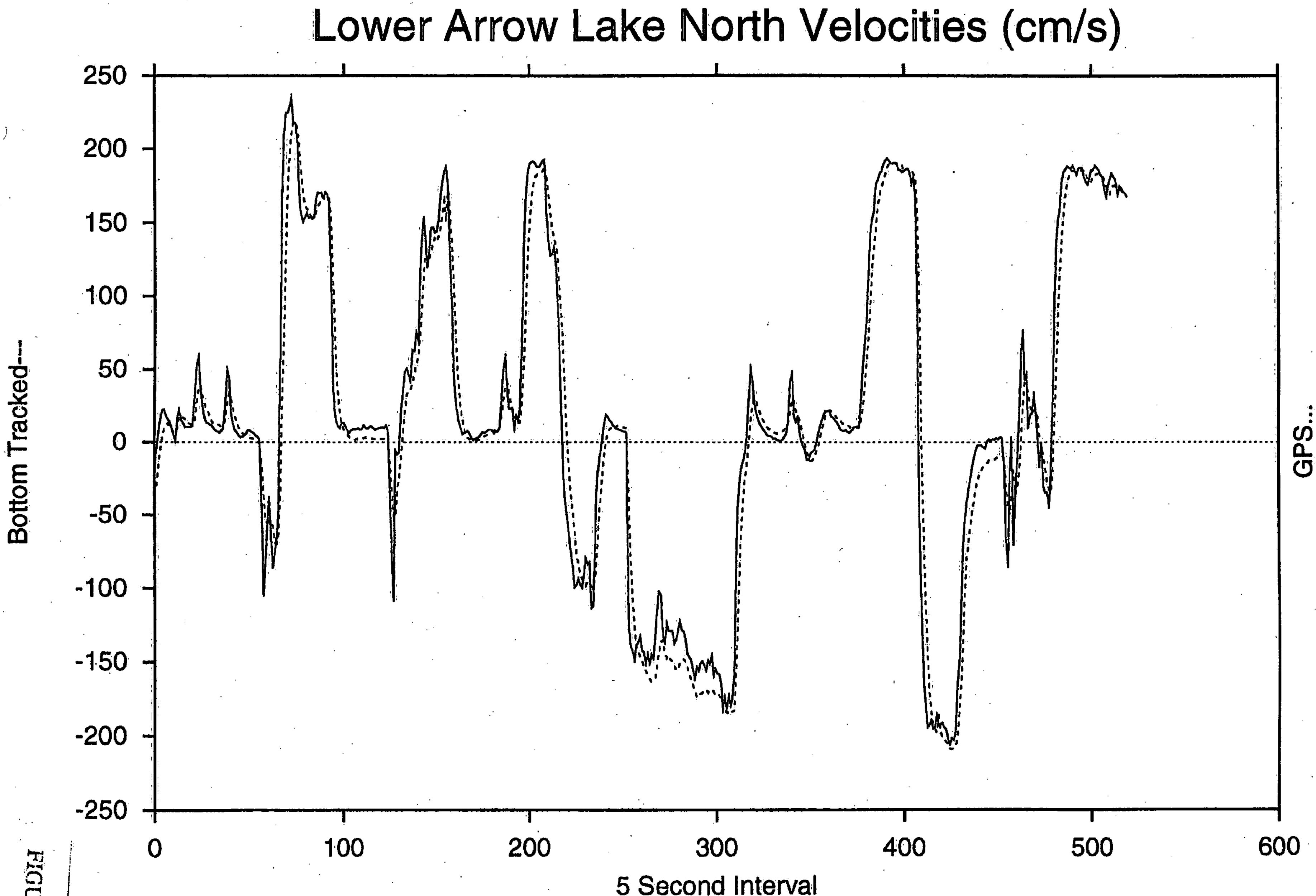
+ 49°21' 177°47'
+ 49°21' 177°46'
+ 49°20' 177°47'
+ 49°20' 177°46'
4
12
20
28
36
20
12
4
2000
1500
1000
500
0
north distance(m)
-2000
-1500
-1000
-500
0
east distance(m)

FIGURE 8



Lower Arrow Lake East Velocities (cm/s)
200
150
100
50
0
-50
-100
-150
-200
-250
0
100
200
300
400
500
600
5 Second Interval
Bottom Tracked—
GPS...

FIGURE 9



Lower Arrow Lake North Velocities (cm/s)
Bottom Tracked---
GPS...
5 Second Interval
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
100
200
300
400
500
600

FIGURE 10

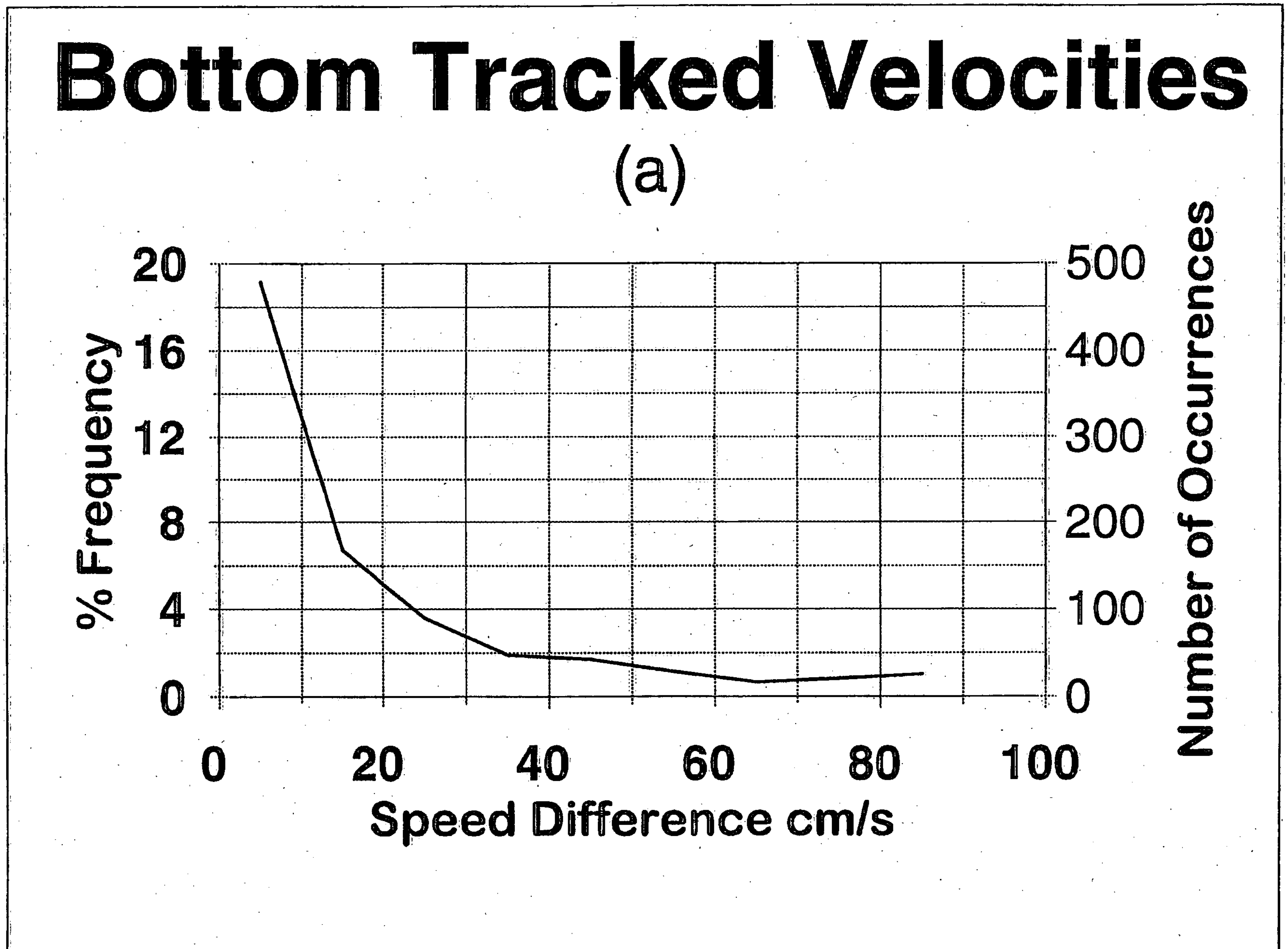

Bottom Tracked Velocities
(a)
% Frequency
20
16
12
8
4
0
Number of Occurrences
500
400
300
200
100
0
0
20
40
60
80
100
Speed Difference cm/s

FIGURE 11

Bottom Tracked Velocities

(b)

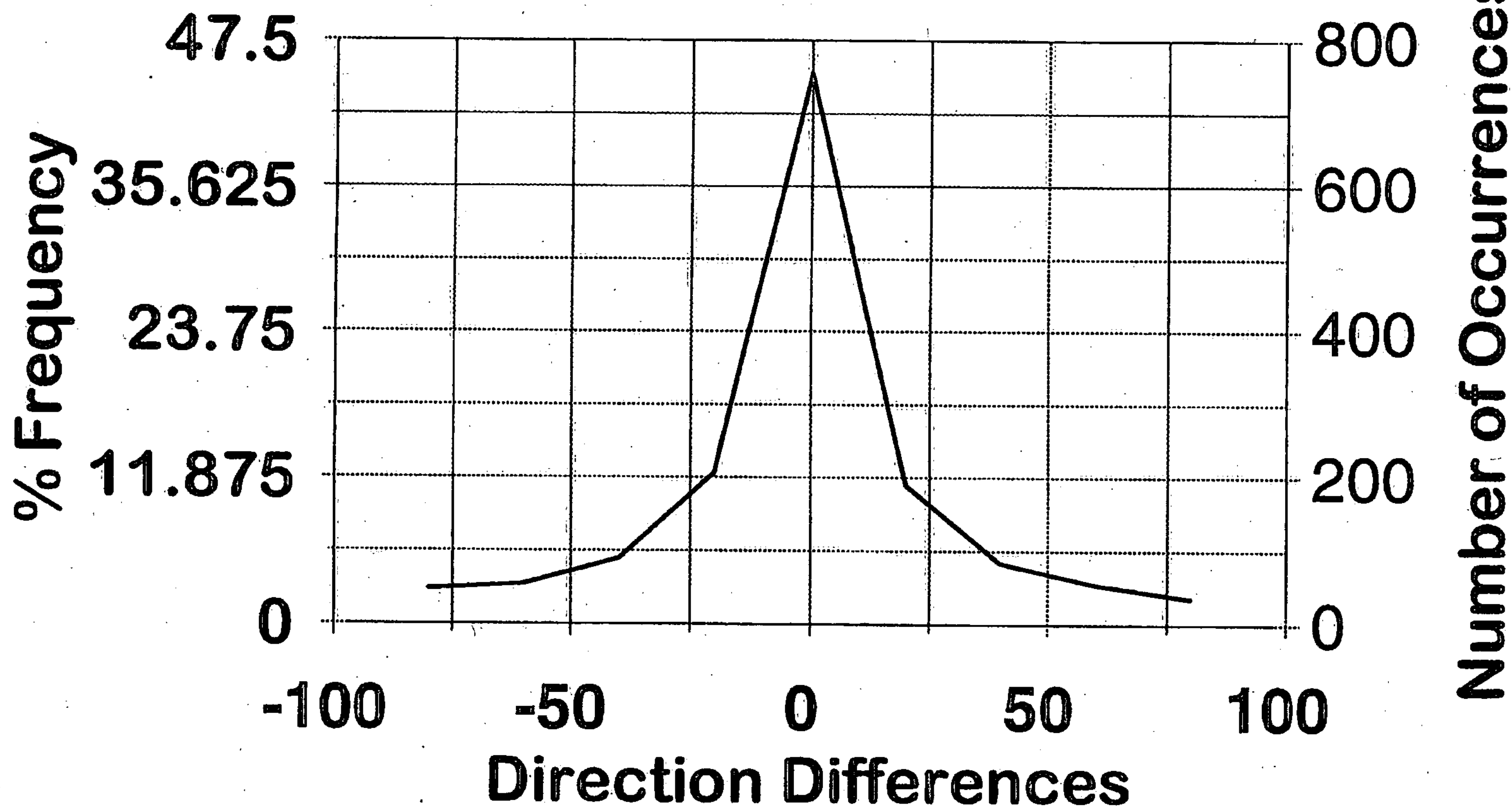


FIGURE 11

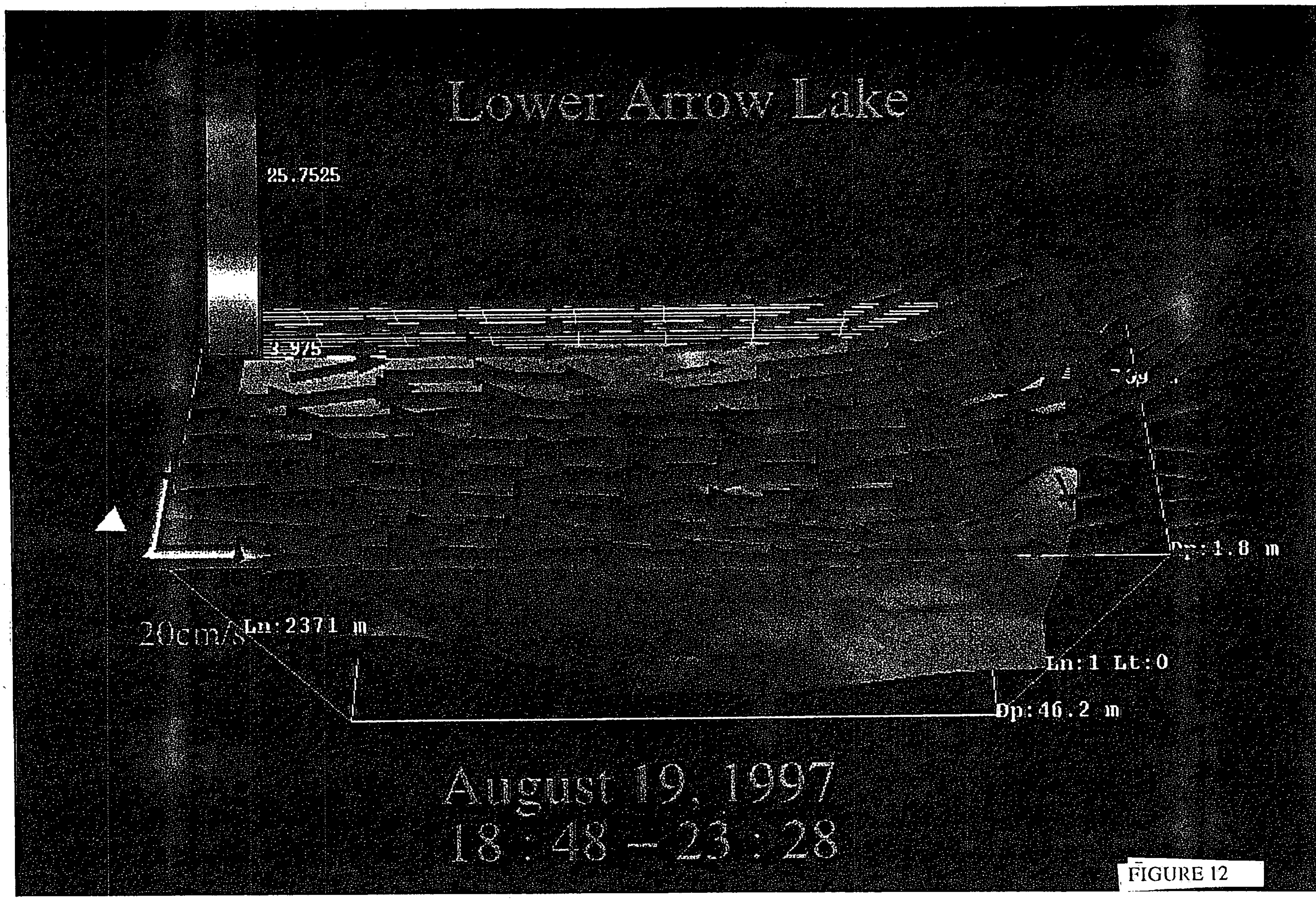

Lower Arrow Lake
25.7525
3.975
20cm/s
Ln: 2371 m
Dp: 1.8 m
Ln: 1 Lt: 0
Dp: 46.2 m
August 19, 1997
18 : 48 – 23 : 28

FIGURE 12

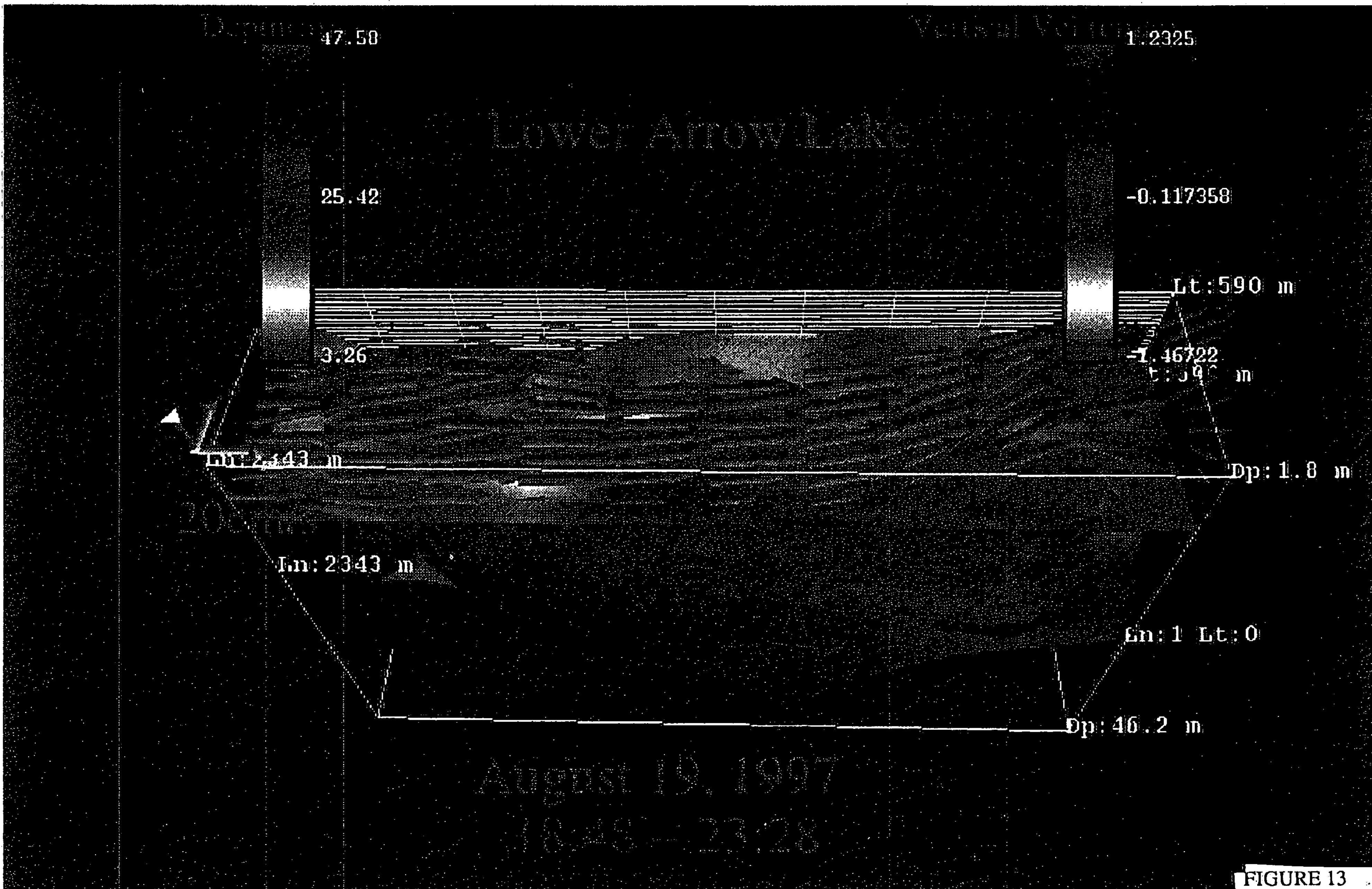
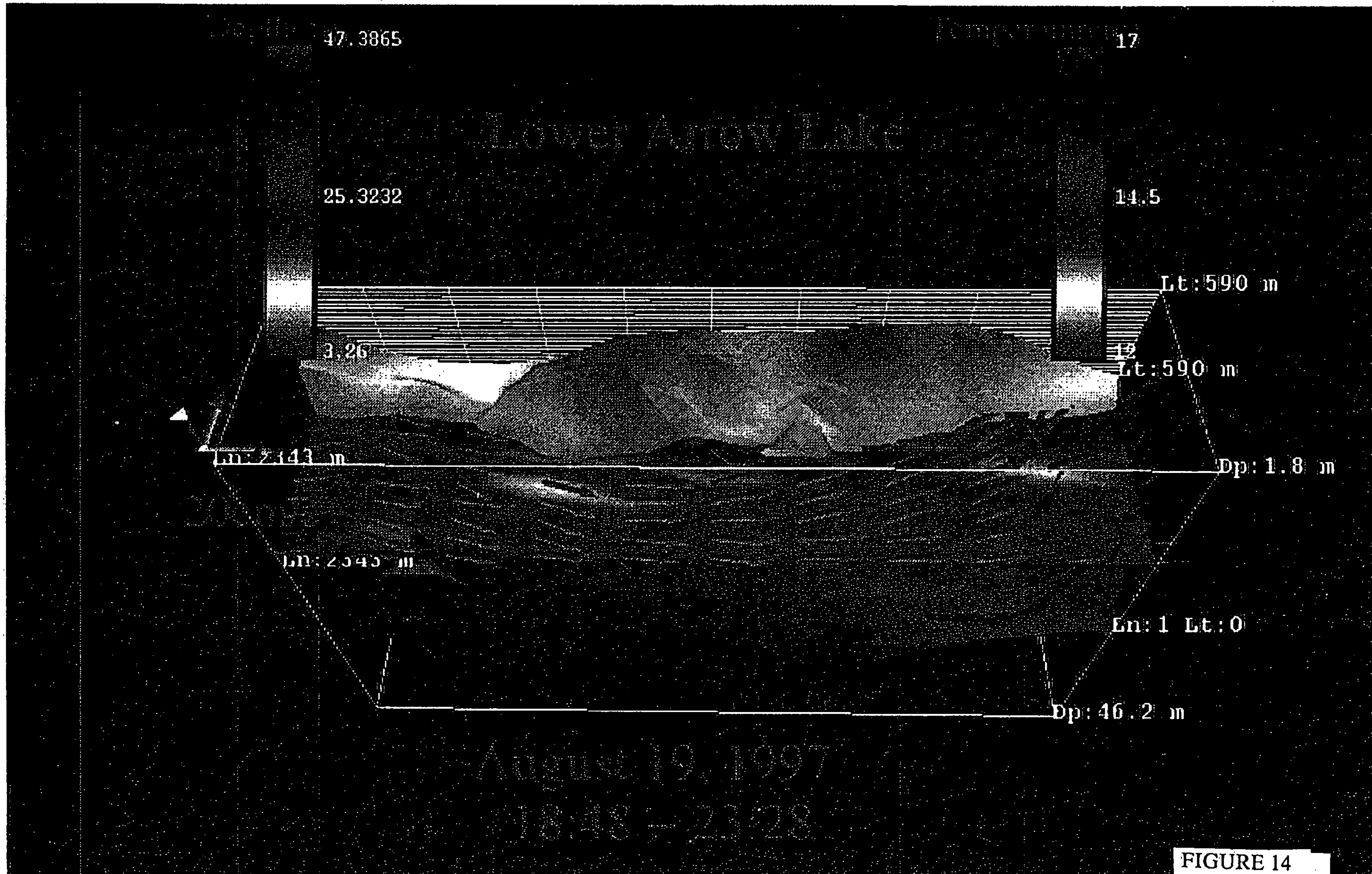

Lower Arrow Lake
47.58
25.42
3.26
1.2325
-0.117358
-1.46722
Lt:590 m
Dp:1.8 m
Ln:2343 m
Ln:1 Lt:0
Dp:46.2 m
August 19, 1997

FIGURE 13



47.3865
17
Lower Arrow Lake
25.3232
14.5
Lt:590 m
3.26
12
Lt:590 m
Dp: 1.8 m
Ln: 1 Lt: 0
Dp: 46.2 m
August 19, 1997

FIGURE 14

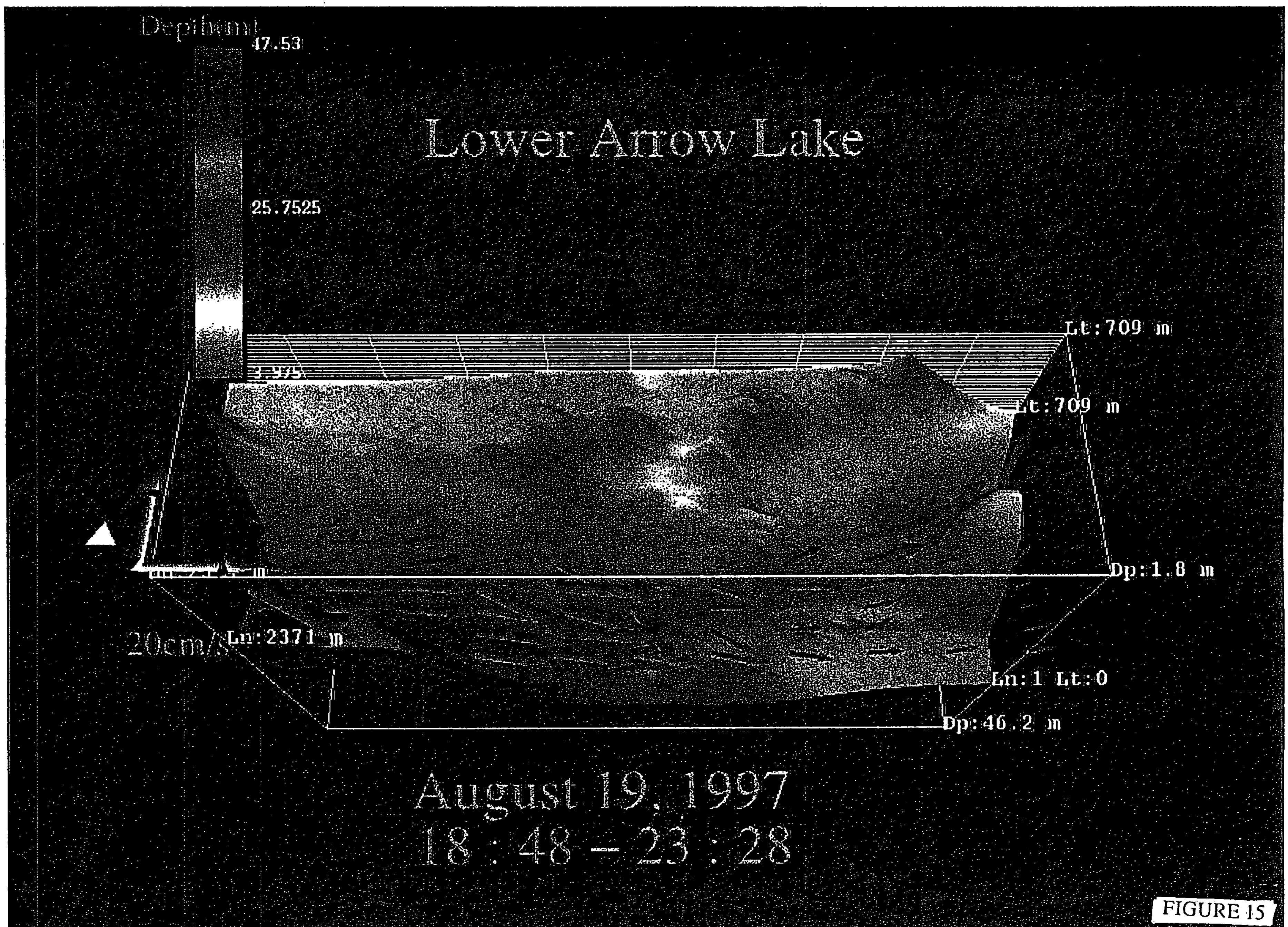

Depth(m)
47.53
25.7525
Lower Arrow Lake
Lt:709 m
Lt:709 m
Dp:1.8 m
20cm/s
Ln:2371 m
Ln:1 Lt:0
Dp:46.2 m
August 19, 1997
18 : 48 – 23 : 28

FIGURE 15

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