98-145

Environment Canada Environnement Canada

Canada

CHAPTER 5
ADCP SURVEYS

P.F. Hamblin

NWRI Contribution Number 98-145

NATIONAL WATER RESEARCH INSTITUTE
INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

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.

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.

ABSTRACT

The Arrow Lakes Reservoir is experiencing a rapid decline in the sports fishery. It is thought that this is principally due the long-term reduction in the supply of natural nutrients caused by the construction of large hydroelectric power dams upstream from the reservoir. A field study has been initiated to determine the baseline limnology of the system before remediation is undertaken .

This contribution to an interdisciplinary volume on the limnology of the Arrow Lakes Reservoir commissioned by the British Columbia Department of Environment, Lands and Parks deals with the question of lake circulation as directly observed by means of a launch-based survey with an acoustic doppler current profiler and how it is related to the optimal dispersal of nutrients should the proposed programme of artificial fertilization be implemented. It is found that due to plunging inflows nutrients should not be introduced into the mainstem Columbia River nor into the narrows between the two main basins of the reservoir but rather at two car ferries crossings of the open lake in each basin.

SOMMAIRE À L'INTENTION DE LA DIRECTION

À la demande du ministère de l'Environnement de Colombie-Britannique, on a entrepris cette étude par observation du régime de circulation des lacs Arrow, pour aider à évaluer et optimiser une stratégie de fertilisation artificielle du réservoir.

Le document présente les températures et les débits à des points critiques du système qui pourraient être relevés dans les limites de l'instrumentation. Les résultats pourraient constituer la base d'une future remise en état des lacs faisant intervenir l'ajout de nutriants.

Ces résultats seront communiqués au groupe approprié de personnes qui prennent des décisions sur la meilleure manière d'atténuer l'effondrement de la pêche sportive dans les lacs Arrow.

RÉSUMÉ

Le réservoir des lacs Arrow connaît une baisse rapide de la pêche sportive. On pense que cette situation est essentiellement due à la réduction à long terme de l'apport de nutriants naturels, réduction causée par la construction d'importants barrages de production d'électricité en amont du réservoir. Une étude de terrain a été lancée pour déterminer la limnologie de base du système avant qu'on n'entreprenne les travaux de remise en état.

Cette contribution à un volume pluridisciplinaire sur la limnologie du réservoir des lacs Arrow, compilé à la demande du ministère de l'Environnement, des Terres et des Parcs de la Colombie-Britannique, concerne la circulation du lac, telle qu'elle est directement observée au moyen d'un relevé par profileur acoustique Doppler de courant et sa relation avec la dispersion optimale des nutriants, dans le cas où l'on mettrait en place le programme proposé de fertilisation artificielle. On constate que, en raison des courants plongeants, les nutriants ne devraient pas être introduits dans le cours principal du Columbia ni dans les détroits entre les deux bassins principaux du réservoir, mais plutôt aux deux passages de traversiers, sur le lac proprement dit, dans les deux bassins.

Chapter 5

ADCP Surveys

Table of Contents

5.1 Introduction

The British Columbia Ministry of Environment, Lands and Parks (MELP) has identified a need for baseline limnology of the Arrow Lakes 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 initiated as has been successfully undertaken 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 intensely during the period from August 19 to August 28, 1997 by means of acoustic doppler current profilers (ADCP) and a temperature profiler. This report is intended to display examples of the data collected and to the summarise the main findings and analyses reported in Hamblin 1998a and 1998b 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 for this reason. In this report 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.

Currents were measured in this survey by means of an underway acoustic doppler profiler (ADCP). 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. Parts of the reports of Hamblin 1998 a & b are devoted to an evaluation of the performance of the broadband ADCP in this unusual environment and another of even lower frequency instrument (300KHz). 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 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. Only the main results of both evaluations are summarised herein.

5.2 Experimental Methods

The acoustic doppler current profiler is capable of measuring three components of flow while underway as illustrated schematically in Figure 5.1. 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 1 the ship'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 survey 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 launch speed from velocities output by the differential GPS. According to the manufacturer currents are accurate to within a cm/s while bottom tracked ship speeds 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 pleasure cruiser on a swivel bracket which permited rapid deployment of the sensor head and easy removal between study sites. This instrument as well as a stationary ADCP of 300KHz frequency 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 5.1). Usually the shore site was located at 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 experiment 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. Shoreline positions were extracted from the digital form of the CHS charts 2056 and 2057 as individual arcs and pieced together as detailed in Hamblin 1998 a& b.

Examples of the shoreline outline are shown in Figures 5.2 for the Lower Arrow Lake Reservoir and for the Upper Arrow Lake Reservoir in Figure 5.3 along with the location of the field experiments to be described in detail below.

5.3 Observations and Results

5.3a. Lower Arrow Lake, Near the Hugh Keenleyside Dam, August 19, 1997.

This 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 ship track data plotted in Figure 5.4 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 where the vessel was stopped to permit the lowering of the temperature profiler. The location of the proposed approach channel (Columbia Power Corporation, 1997) is shown on the northern shoreline for reference.

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 flag. 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 very fortunate as it meant that the velocity of the moving platform was known throughout most of the August 19 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.

It is evident from the bathymetric contour plots of Chapter 2 that there are no contours between 10 and 50m but that most of depths occur between these two contours in the study area. Therefore, to obtain more detailed bathymetry in the study area which is one of the factors 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. A method of combining data having differing uncertainties in an interpolation scheme is described in Hamblin 1998a. The result is shown in Figure 5.5 and shows a maximum smoothed depth of around 36m. There is some evidence of the predevelopment river channel.

In order to evaluate the accuracy of the novel electronic navigation system and to assess the suitability of a differential GPS in supplying the ship reference velocity, should bottom tracking fail, the question of the ship velocities derived from the differential GPS was examined in Hamblin 1998 a &b. Based on data selected from steady ship travel the rms differences between the GPS and the acoustically determined ship velocities were 11.3 and 8.4 cm/s for the east and north components respectively. 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.

The current and temperature data which were displayed in Hamblin 1998a in three dimensions by means of colour perspective views are not reproduced here. Instead, more conventional two-dimensional contour plots are provided in Figure 5.6 of the temperature and east component of flow along the first south-to-north transect seen in Figure 5.4. In the inset, the total flow or discharge across the lake is compared to that determined for August 19 from the water balance method outlined in Chapter 3, shown in parentheses. The smaller directly observed discharge is attributed to 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 5.2). 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 to be not the case on August 19. The reader is referred to Hamblin (1998a) for further discussion and analysis of this question.

The following summarises the observations based on perspective views of temperatures and flow vectors reported in Hamblin 1998a. The horizontal 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 cross channel asymmetry of the flow with weaker flow in the vicinity of the proposed approach channel and on the south side of the Hugh Keenleyside Dam. As might be expected strong upwelling appears to be associated with the outflow at the Hugh Keenleyside Dam. In contrast, temperature contours 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 current. Deep currents suggest bathymetric control of the flow in the submerged river channel before flooding. The longitudinal transect of flow vectors 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 a 18m below the water surface (Columbia Power Corporation, 1997). Finally, a crosslake view 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 depth limit of detection of the current profiler to be meaningful.

5.3b Upper Arrow Lake, the Narrows Region

The narrows between the Upper and Lower Arrow Reservoirs was chosen as the area of most intense study so that the exchange between the two water bodies could be observed under a variety of environmental conditions. This exchange is crucial to the question of lake fertilization should nutrients be added to only one basin. Direct observations of flow in the Narrows were required to calibrate a longer-term but indirect method of estimating the exchange based on the approach of Hamblin 1997.

Ten second averages of current profiles were recorded while the launch traversed between two Scotsman float markers on opposite shores about a kilometre west of the Arrow Park cable ferry crossing at a speed of around 2m/s. The location of this set of experiments is shown on Figure 5.3 and the detailed location of the ship tracks in Figure 5.7.

On account of the importance of the flow measurements in the Narrows for the calibration of an indirect method of determining the exchange between the Upper and Lower Arrow Lakes employing water temperature recorders at the Scotsman floats as presented in Chapter 4, the along-channel components of flow were summed over the cross section by two methods to yield the total discharge, as discussed in detail by Hamblin 1998b. Briefly, in method one flows were integrated across the channel in the standard way by the author while in the second, transports were determined by the manufacturer's internal software. According to the operating manual various forms of extrapolation are used.

The averaged data for each of the five experiments in the Narrows region is presented in contoured form in Figure 5.8 a to e. Experimental times are indicated in UCT. As in Figure 5.6 isotachs are not indicated at depths less than 1.8m where flows were not measured. Due to spurious reflected acoustic energy flows within 1 to 3m from the bottom may be underestimated.

Patterns of flow from one day to the next are remarkably stable. Unlike the flow near the Dam shown in Figure 5.6, the core of the downstream flow is located at depths from 5 to 10m except on August 26 where it appears to be at the surface. Winds were light or moderate for the five experiments so it is not known why the core is not always at the surface as would be the case with pure riverine flow. A possible explanation due to tendency of the warmer and lighter surface waters to flow from the Lower to the Upper Lake is discussed in Hamblin 1998b. There is no indication of any flow reversals that might be expected during the coincidence of the highest stratification and the deepest depths in the Narrows. Thus, at other times of the year the exchange is likely to be from the Upper to the Lower Arrow Lake as assumed in the thermal modelling of Hamblin (1997). Discharges estimated by method one are indicated on each figure in the box and by method two in parentheses. In four of the five experiments method two gives higher discharges than one. The differences between the two methods provide some estimation of the errors associated with the discharge calculations.

Discharges were estimated on a daily basis from the water budget using inflow, outflows, water level changes and basin hydrology (see Chapter 3). It is evident from Table 5.1 that the daily water balance method underestimates the discharge as determined from method one by 4.5%. This is considered to be excellent agreement for two independent methods, especially as the water budget method is based on some ungauged inflow to the Upper Arrow Lake and possible diurnal variations in Revelstoke releases are not accounted for. Another source of difference is the wind generated exchange flow which cannot be accounted for in the water balance approach as the water level differences between basins were not measured.

The discharge in the Narrows Region was estimated at three day intervals over a 35-day period starting on August 19 by an indirect method using water temperature profiles at each side of the cross section, (Chapter 3). In order to validate this indirect method, profiles of measured flow in the direction 85° and averaged across the channel were plotted in Figure 5.9. With the exception of the more conventional riverine profile of the August 26 case all profiles had a significant deviation from the expected theoretical shape or logarithmic profile at the surface in accordance with the indirectly measured profiles of Chapter 4. Nonetheless, the lower portion of the current profile is close to logarithmic so may used to deduce the turbulent mixing coefficients in the bottom boundary layer. In turn, the mixing coefficients are needed to estimate the rate of dispersion of a dissolved substance, should nutrients be added in the Narrows region.

As a further test of the new base-station differential GPS system positions are compared to those inferred from acoustic tracking in Figure 5.7. In the Narrows region ship tracks for the first four field experiments were estimated from bottom tracked velocities by integrating the east and north component equations relating velocity to position. The bottom tracks started from an arbitrary origin. These tracks are compared to direct track locations from the differential GPS in Figure 5.7 which shows that bottom tracked positions slowly migrate upstream with an apparent speed of up to 20.3 cm/s. Crossings from south to north compare more closely with the differential GPS positions than those from north to south. The manufacturer was consulted about these positional differences and the explanation given was that they are due to small compass errors which accumulate along the track. Because the experiments always consisted of at least two opposite crossings the compass errors should nearly cancel one another and contribute little to the overall error. It is concluded that the differential GPS should be used for positions while acoustic bottom tracking for ship speed. A thorough discussion of these errors and recommendations for their elimination in future surveys is given in Hamblin 1998b.

5.3c Inflow Region

The inflow region is considered of interest to the question of the introduction of fertilizer. Nutrients should not be added to the mainstem Columbia River upstream of the Upper Lake if the river inflow plunges below the photic zone.

Figure 5.10 shows that three transects were logged over the two hour experimental period. Each was located in sufficiently shallow depths to permit bottom tracking. This explains the curved path followed in the third transect. The first transect was intended to measure the flow in the main inflow channel into the Upper Lake, see Chapter 2 for the channel bathymetry. Unfortunately, the submerged inflow channel divides into two banches. Time constraints allowed for only one branch to be surveyed. The purpose of the second transect was to examine the possibility of exchange between the main lake and Beaton Arm and for the third, observation of the inflow into the main lake was the goal. In all cases individual profiles were first averaged over 100m wide bins along the ship trajectory before contouring.

The flow along the inflow channel is evident in Figure 15.11 to be concentrated along the bottom and at a temperature of 10 to 12° C, considerably colder than the surface temperature. At the point along the transect where it joins another channel at about 1200m from the start, the flow reduces rapidly, indicating that a sizable portion of the main inflow likely takes the unsurveyed branch. Another interesting feature is a near surface inflow of warmer water which may be the source of similar surface jets seen on the other two transects. Similarly, it is most pronounced at the junction of the two branches suggesting that it too flows mainly into the other branch of the submerged inflow channel. Finally, there is a pronounced tilting of the thermal structure along the transect with colder and heavier water in a downstream direction. This sloping structure was not observed by (Hamblin and McAdam, 1997) so that it is likely a transient situation due to wind forcing in Beaton Arm.

Exchange with Beaton Arm is apparent in Figure 15.12 with warm water flowing in and colder water flowing out of the Arm. Altogether there is a net inflow at the time of measure measurement of approximately 600 m^3/s. From the depth soundings of the ADCP the inflow channel surveyed in Figure 15.11 is found from 100 to 700m while a broad bank separates it from the other at a position of 2200m. The exchange flow is located near the mouth of this second inflow channel reinforcing the conclusions drawn from transect one. Somewhat cooler temperatures occur along the southern shoreline.

The main Columbia River inflow is clearly shown in Figure 15.13 as a plunging jet with a core located at a depth 13m and along the western shoreline. This tendency for inflows to hug the right hand side of the channel in the northern hemisphere has been noted in other long narrow lakes (Hamblin and Carmack, 1978) and is thought to be due to the earth's rotation. This jet must have paralleled the 10m isobath in general as it crossed the inflow area from the mouth of the western branch of submerged channel in a southwesterly direction. A much weaker two-layer jet is found near the surface over the clearly distinguished submerged inflow channel. This feature is similar to the surface inflow and subsurface outflow of Beaton Arm which suggested that it originates in the second inflow channel but bificurates at the end of the channel into two branches. The total discharge across the channel was 1062 m^3/s at the time of the experiment. Most of the dicharge is concentrated along the western shoreline. Unfortunately, the seven temperature profiles at the time of writing taken across transect three failed to yield any useful data so that the ADCP temperatures just below the surface were used in the accompanying plot. They indicate that warmer lighter water occurs along the western shoreline.

5.3d Other Studies

Comparisons of the 1200 and 300 KHz ADCPs were conducted at the mid lake temperature and current meter moorings on August 20 (Figure 5.2) and on August 25 (Figure 5.3). At these sites the water is far too deep for bottom speed reference of the 1200 KHz model and the 300KHz instrument lacked bottom tracking. As a result the comparisons are qualitative. On the 300 KHz device velocities registered as deeply as 80m but not at the 0.5m depth resolution of the higher frequency profiler but rather at 6m depth intervals. The maximum range of the lower frequency meter was set to 300m, the depth on August 25. Backscatter intensity appeared to have a greater range than velocity. At the mooring in the Upper Arrow Lake at approximately mid day an intermediate scattering layer occurred at a depth of 130m. Tentatively, this backscattering layer is attributed to zooplankton, probably the mysis shrimp (*Mysis relicta*).

5.4 Summary and Conclusions

A high frequency acoustic doppler current meter worked better than anticipated for such a undernourished water body due in part to the relatively high flow. Fortuitously, the survey period coincided with a peak in suspended material due to primary production. The ADCP technology may not perform as well at other times. Although the profiling range was somewhat less than normal operation the bottom tracking range appeared to be enhanced. But even with this augmented range only a small portion of the lake could be sampled. Areas studied had to be in relatively shallow water. A lower frequency ADCP was tested and demonstrated potentially a greater range but at the cost of decreased vertical resolution. The operation of the ADCP in an underway mode permitted the rapid surveying of a wide area.

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.

An application of new electronic positioning technology in the Arrow Lakes Reservoir appears to be successful despite the mountainous terrain. The differential system greatly reduced the uncertainty in horizontal position from the previous study employing an autonomous GPS but errors in velocity remained too large to supply ship reference velocities in most instances.

No evidence was found that cold hypolimnetic water is retained by the narrows upstream of the proposed approach channel. 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).

The ADCP survey has implications for the optimization of a strategy for the introduction of nutrients. As the mainstem Columbia River inflow enters as an interflow as suggested by Hamblin and McAdam (1997) nutrients would be directed away from the photic zone were they to be introduced in the Columbia River. If the near surface inflow continues downstream for at least 5km beyond transect three then nutrients should be dispersed from the Shelter Bay car ferry at a point half way across the lake. Since transport from the Lower to the Upper Arrow Lake is unlikely, nutrients required for the whole system could be added at the Shelter Bay ferry. However, due to mixing in the Narrows the inflow to the Lower Arrow Lake is likely also to be an interflow. It is recommended that the Lower Lake's nutrient requirements be added from the Needles cable ferry. Hopefully, this location is sufficiently close to the main body of the Lower Lake that nutrients would not be transported out of the photic zone by vertical mixing before they reach the open lake. Additional ADCP measurements and mixing calculations would be useful to confirm this likelihood.

Acknowlegements
The writer would like to thank all those who helped in the field observation and analysis of the data. R. Rowsell of NWRI Research Services Division is thanked for participating in the field measurement and data analysis. A. Koudys and M. Fououtan of the Canadian Hydrographic Service are thanked for reducing much of the electronic chart data. R. Pieters of the University of British Columbia and Grant Thorpe of MELP aided in the logistical support for the field study. This study was funded, in part, by the BC Ministry of Environment, Lands and Parks.

5. 5 References

Ashley, K.I, L.C. Thompson, D.C.Lasenby, L.McEarchern, K.E.Smokorowski and D. Sebastian. 1997 Restoration of an interior lake ecosystem: the Kootenay Lake Fertilization Experiment. Water Qual Res. J. Canada,32(2):295-323.

Columbia Power Corporation, 1997 Keenleyside 150 MW Powerplant Project Consolidated Project Report. Volume 2 Supporting Documentation: Water Temperatures.

Hamblin, P.F. 1998a Baseline Physical Limnology of the Lower Arrow Lake Reservoir, Unpublished Report NWRI Contribution 98-.

Hamblin, P.F. 1998b Baseline Physical Limnology of the Upper Arrow Lake Reservoir, Unpublished Report NWRI Contribution 98-.

Hamblin, P.F. 1997. Preliminary Study on the Impact on the Thermal Regime of Proposed Hydro-Electric Power Development at Hugh Keenleyside Dam on the Arrow Lakes, B.C Unpublished Report NWRI 97-111.

Hamblin, P.F. and E.C. Carmack. 1978. River induced currents in a fjord lake. J. Geophys. Res. 83, 885-899.

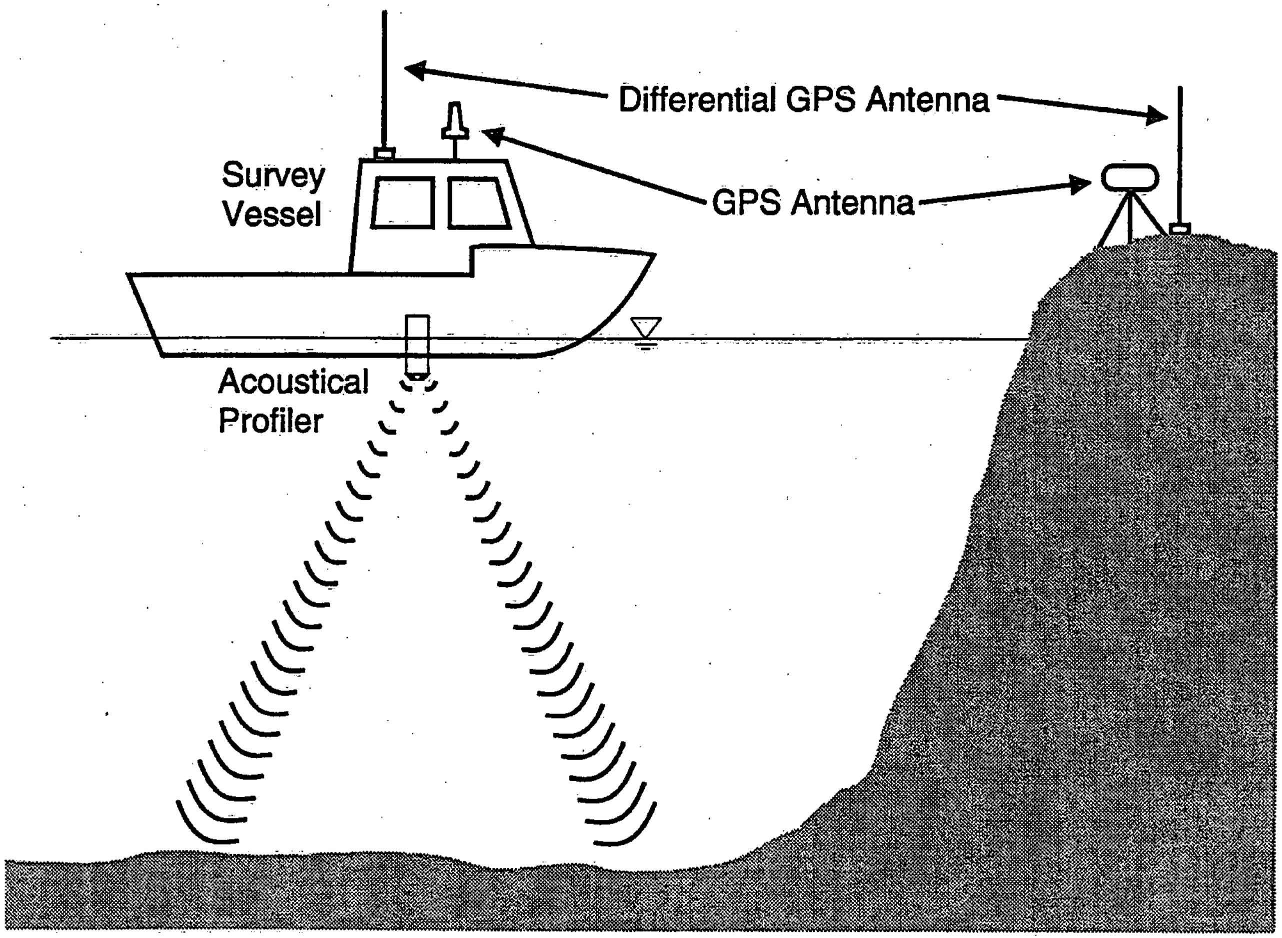
Hamblin, P.F. and S.O. McAdam. 1997. Temperature, conductivity and wind observations in the Arrow Lakes, B.C.: A Data Report. Unpublished Report NWRI Contribution 97-109.

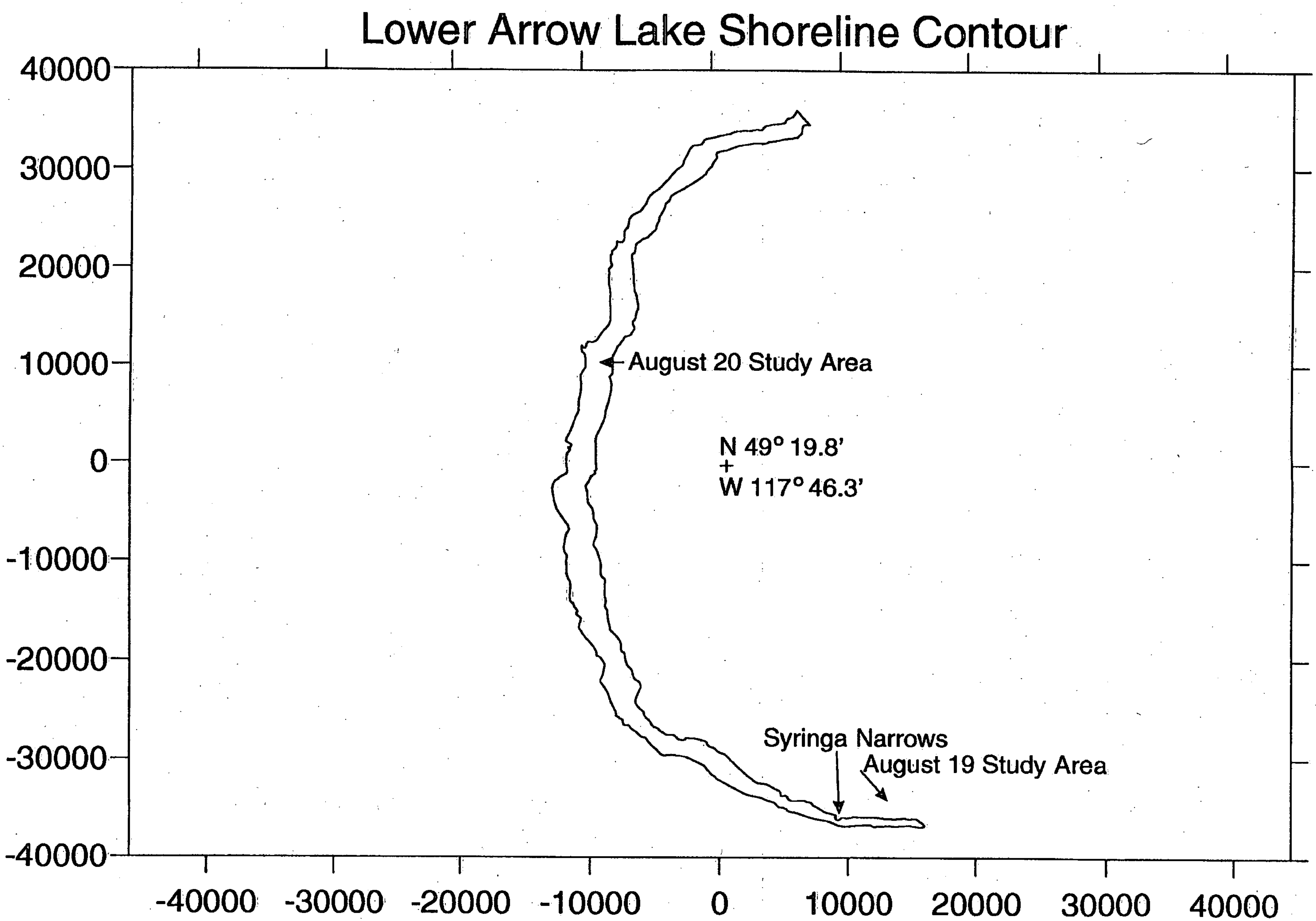
Hamblin, P.F, C.L. Stevens and G.A. Lawrence 1995. Field Experiments with Dye Tracing and an Acoustic Doppler Current Profiler. Proc. Canada/United States Technical workshop on the Upper Columbia River Basin: An International Dialogue State of Wash. Water Research Center, Pulman Wash. 123-128.

Rae,R.M. F.R.Pick, P.B.Hamilton and K.I.Ashley, 1996. Effects of fertilization on phytoplankton in Kootenay Lake, British Columbia. Lake Reservoir Mgmt. 12(2):78-90.

Table 5.1

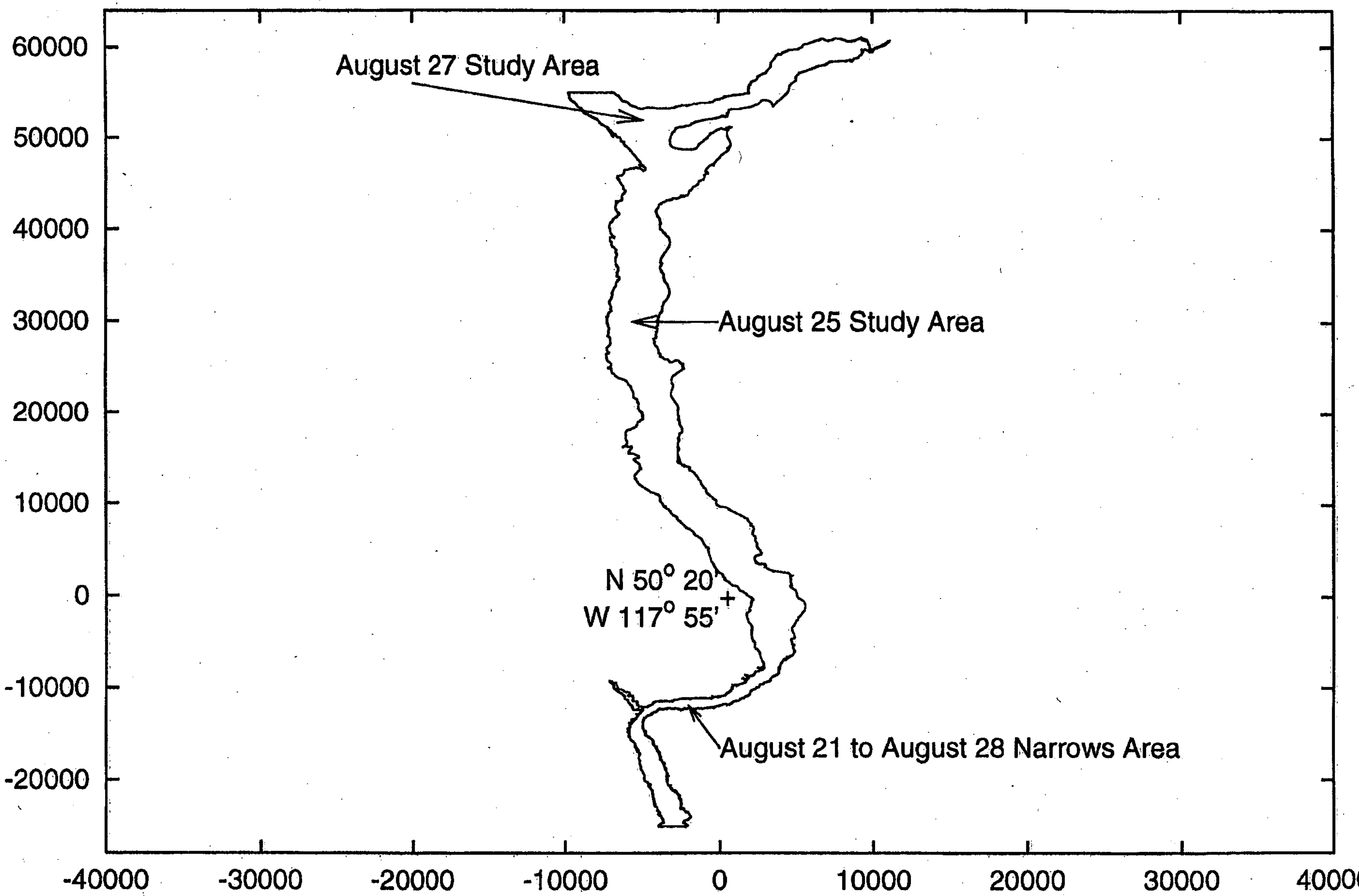
Date , Time (UCT)	ADCP Transport (m^3/s) Method I (Hamblin 1998b)	ADCP Transport (RDI) (M^3/s) Method II (Hamblin 1998b)	Daily Water Balance (M^3/s) (Chapter 3)
August 21	1921	2187	1832
August 22 17:25-18:33	2124	2034	1876
August 22 19:44-20:52	2089	2373	1876
August 26	1973	2144	1911
August 28	1823	2155	1993
Average	1986	2178	1898

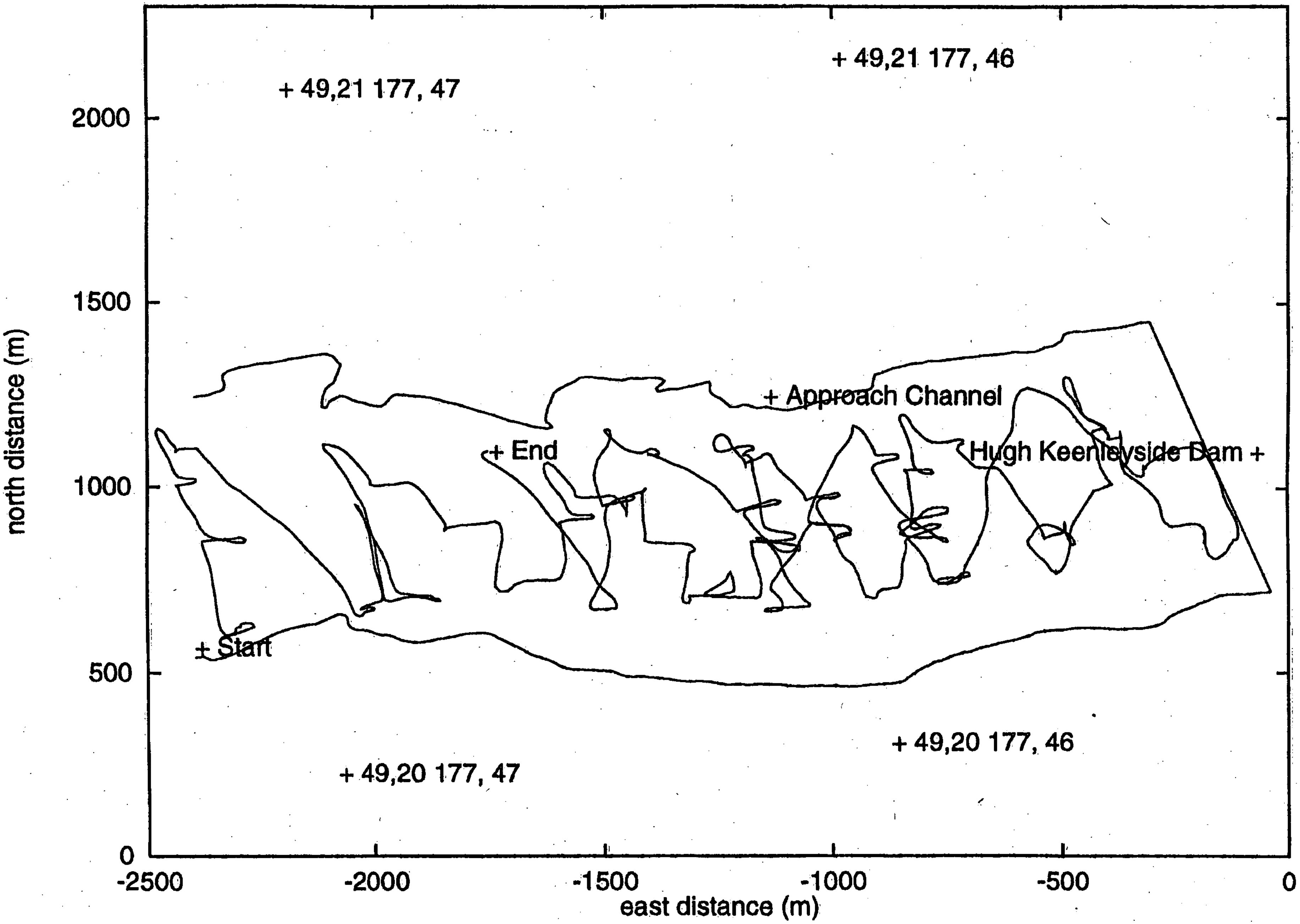

Differential GPS Antenna
Survey
Vessel
GPS Antenna
Acoustical
Profiler



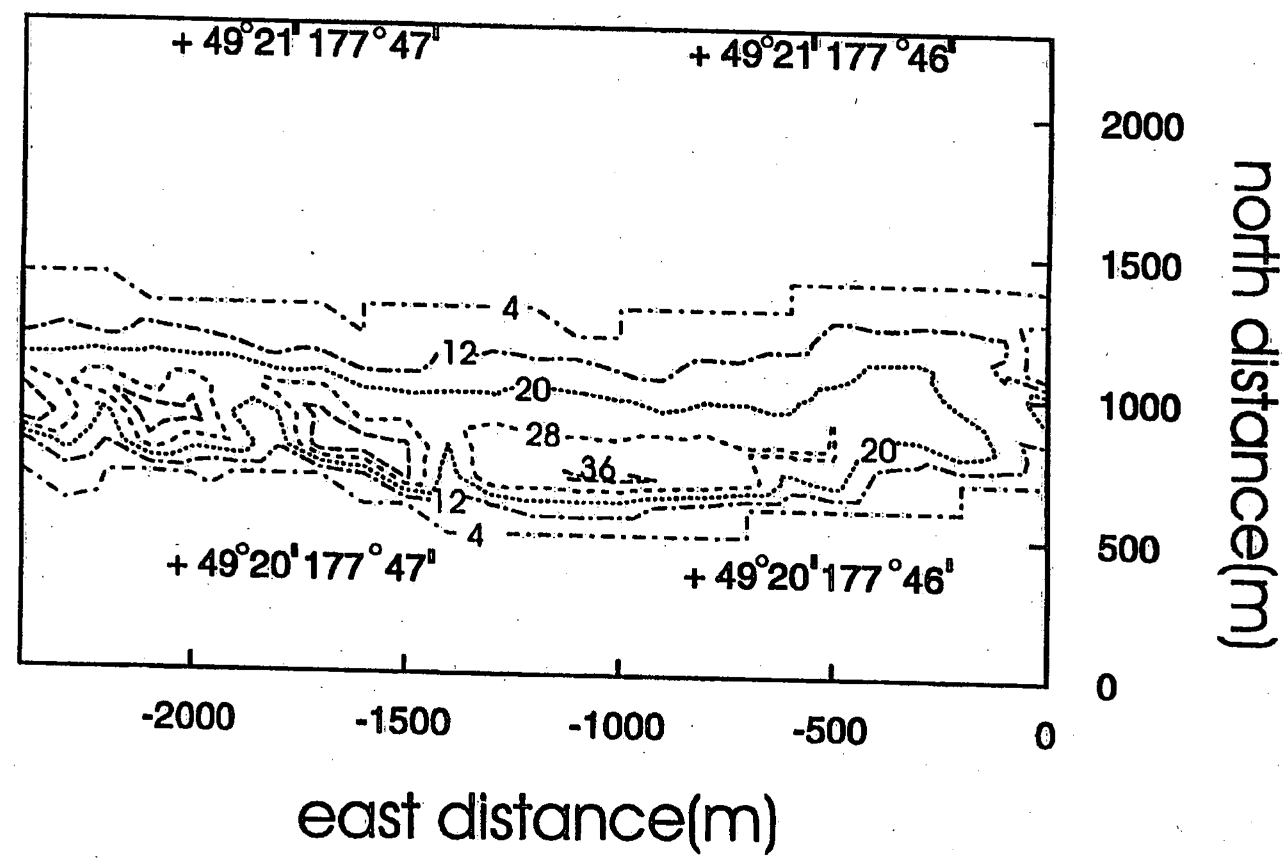
Lower Arrow Lake Shoreline Contour
40000
30000
20000
10000
0
-10000
-20000
-30000
-40000
August 20 Study Area
N 49° 19.8'
W 117° 46.3'
Syringa Narrows
August 19 Study Area
-40000
-30000
-20000
-10000
0
10000
20000
30000
40000

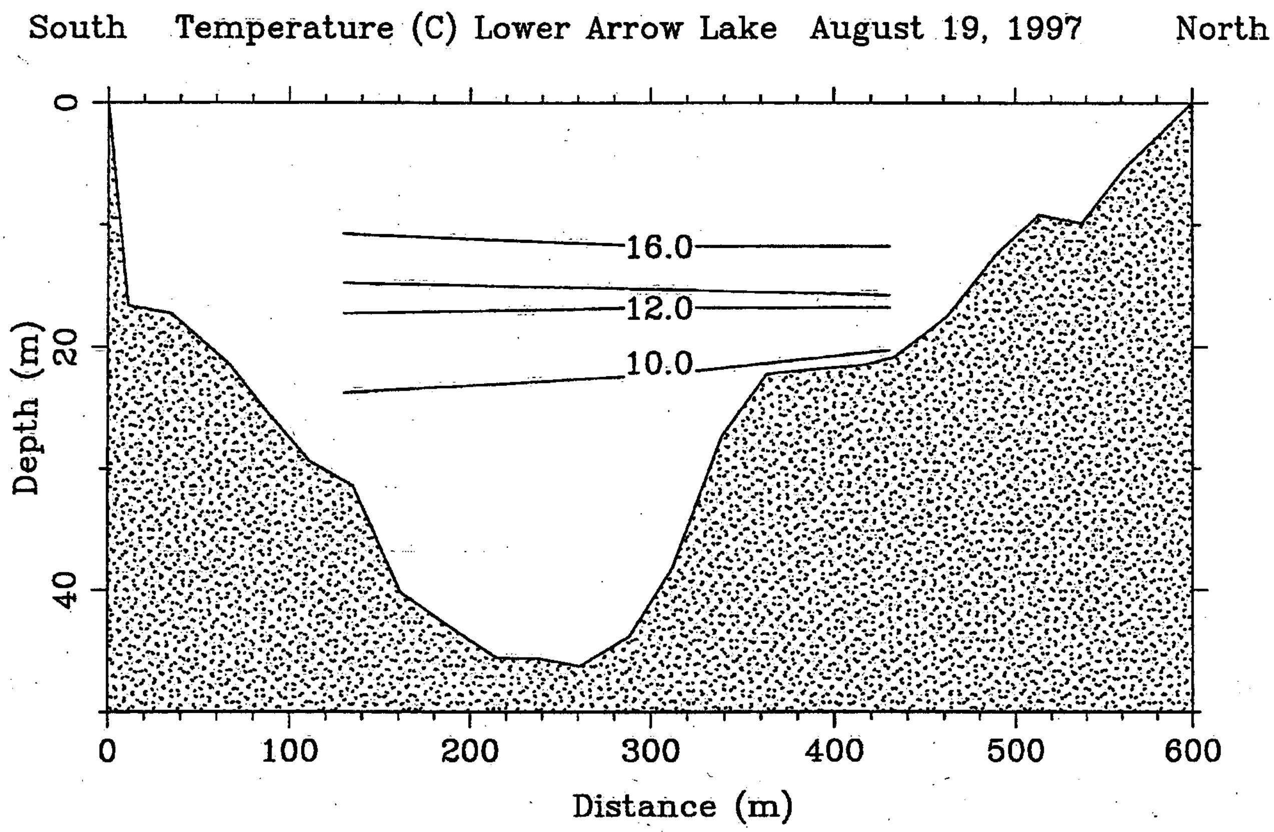
Upper Arrow Lake Shoreline

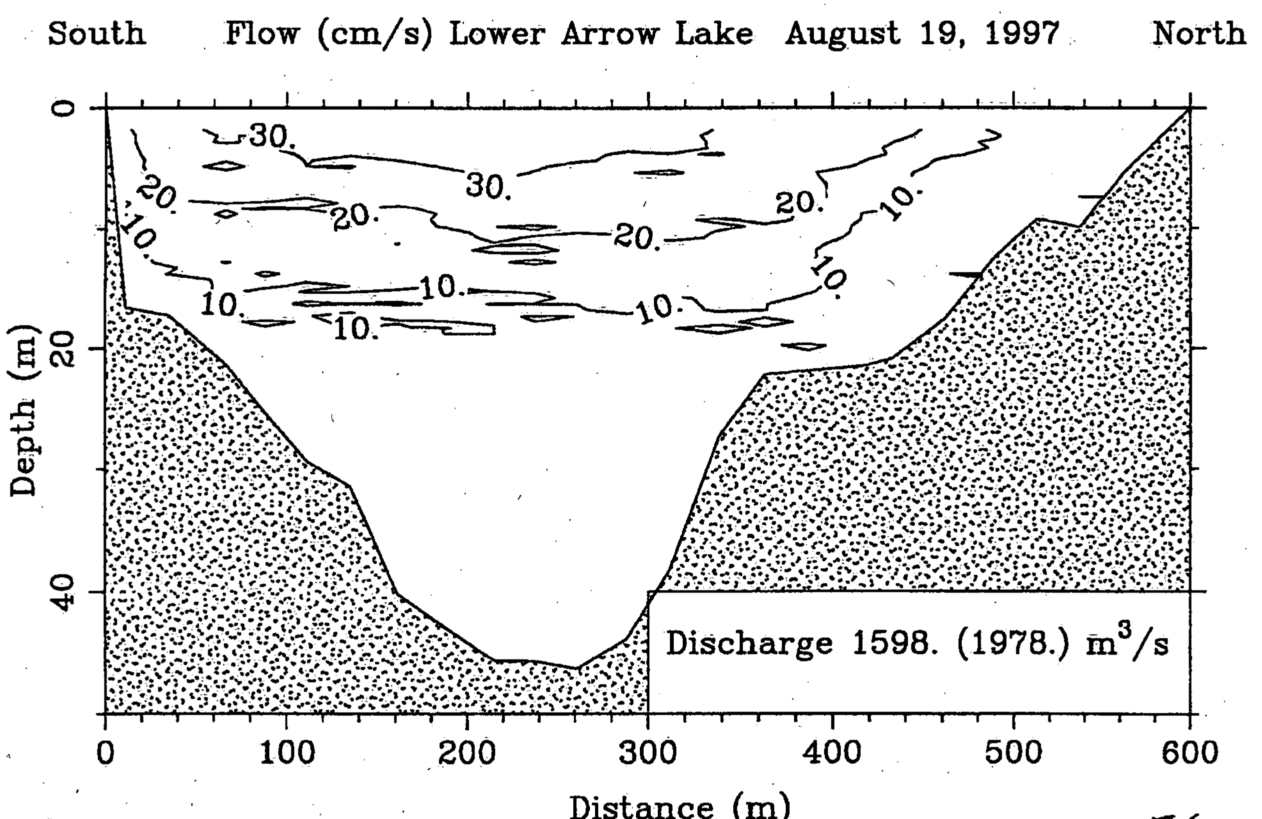


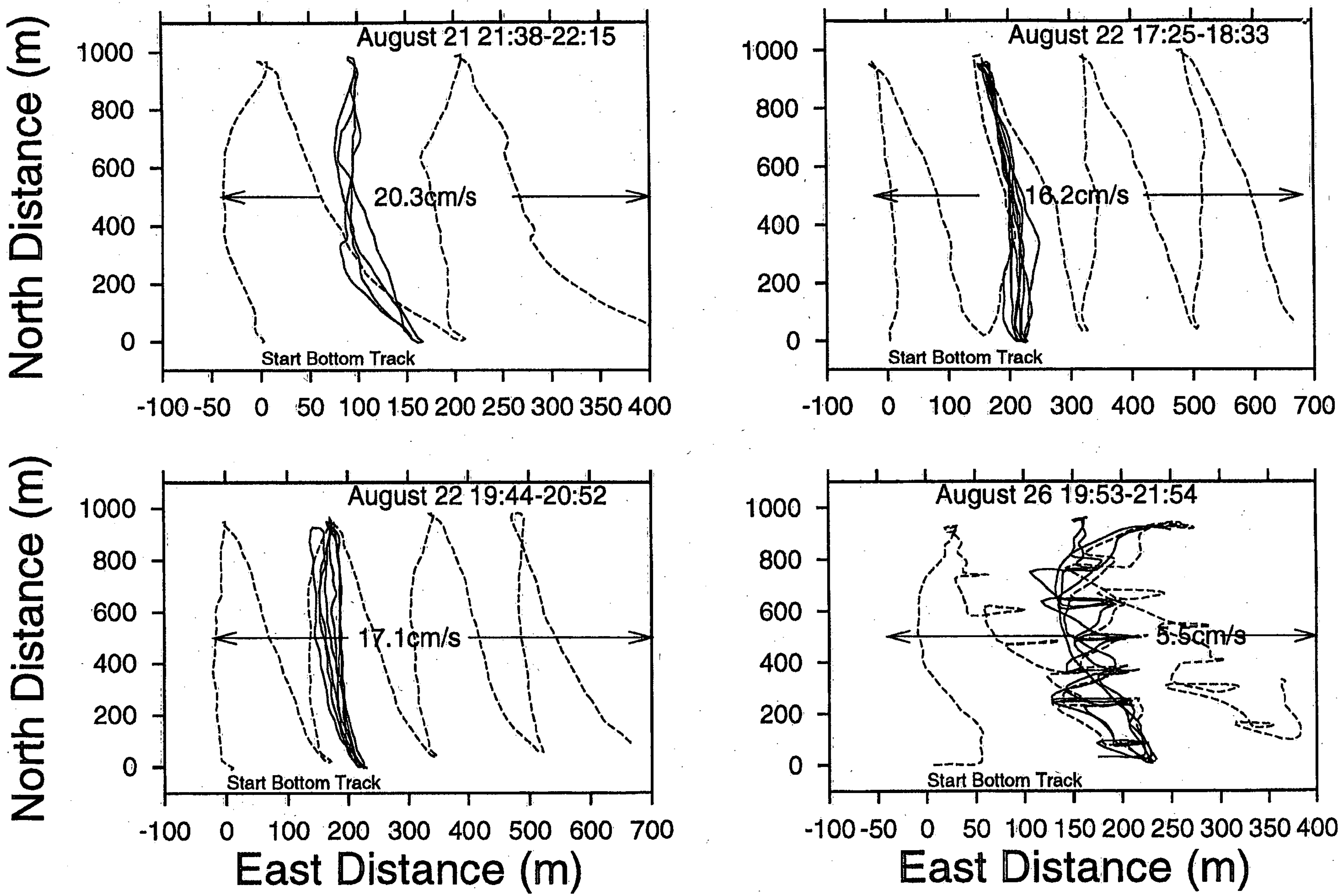


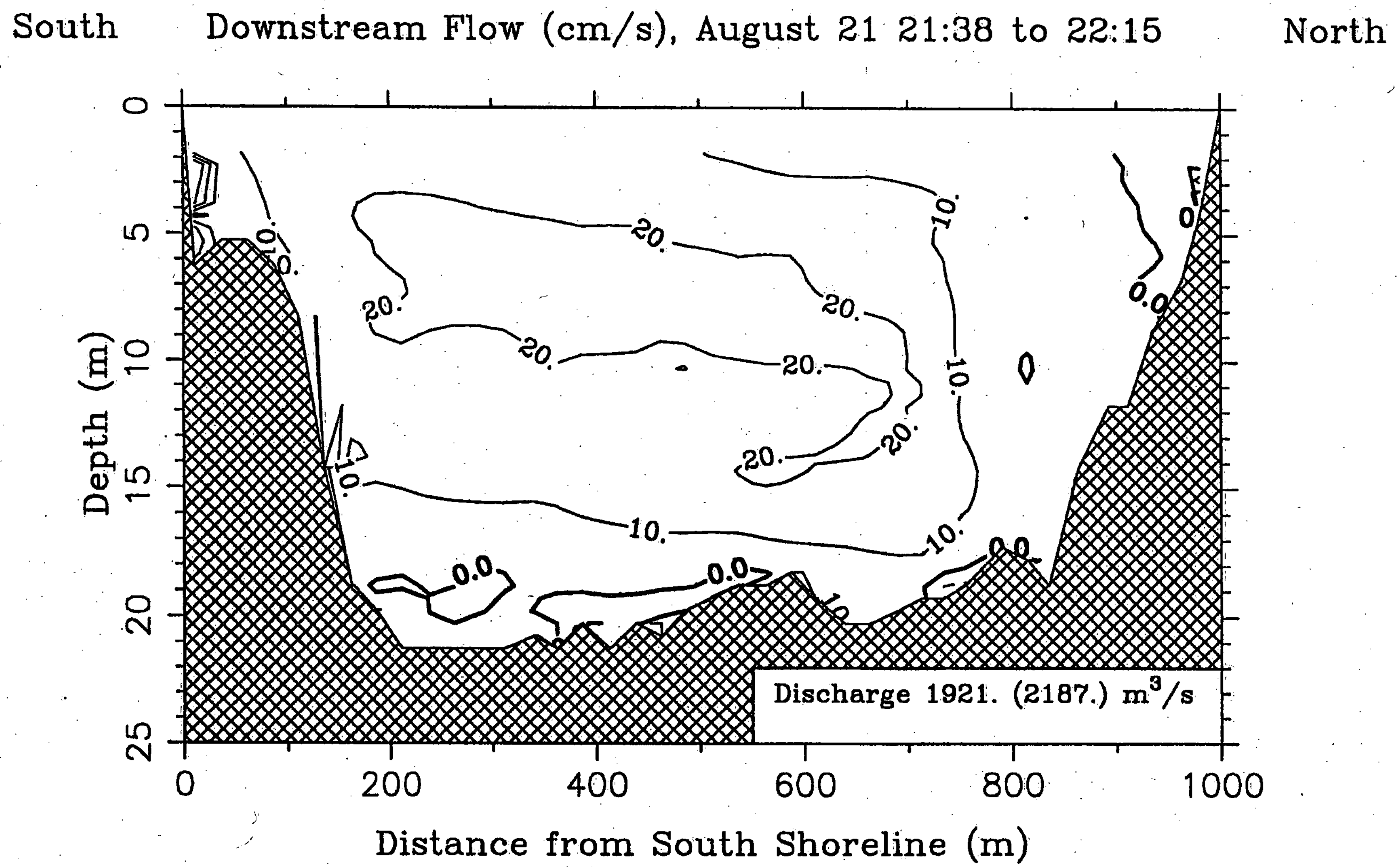
+ 49,21 177, 47
+ 49,21 177, 46
+ Approach Channel
+ End
Hugh Keenleyside Dam +
+ Start
+ 49,20 177, 46
+ 49,20 177, 47
2000
1500
1000
500
0
-2500
-2000
-1500
-1000
-500
0
north distance (m)
east distance (m)


+ 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)


South Temperature (C) Lower Arrow Lake August 19, 1997 North
16.0
12.0
10.0
Depth (m)
0
20
40
0
100
200
300
400
500
600
Distance (m)

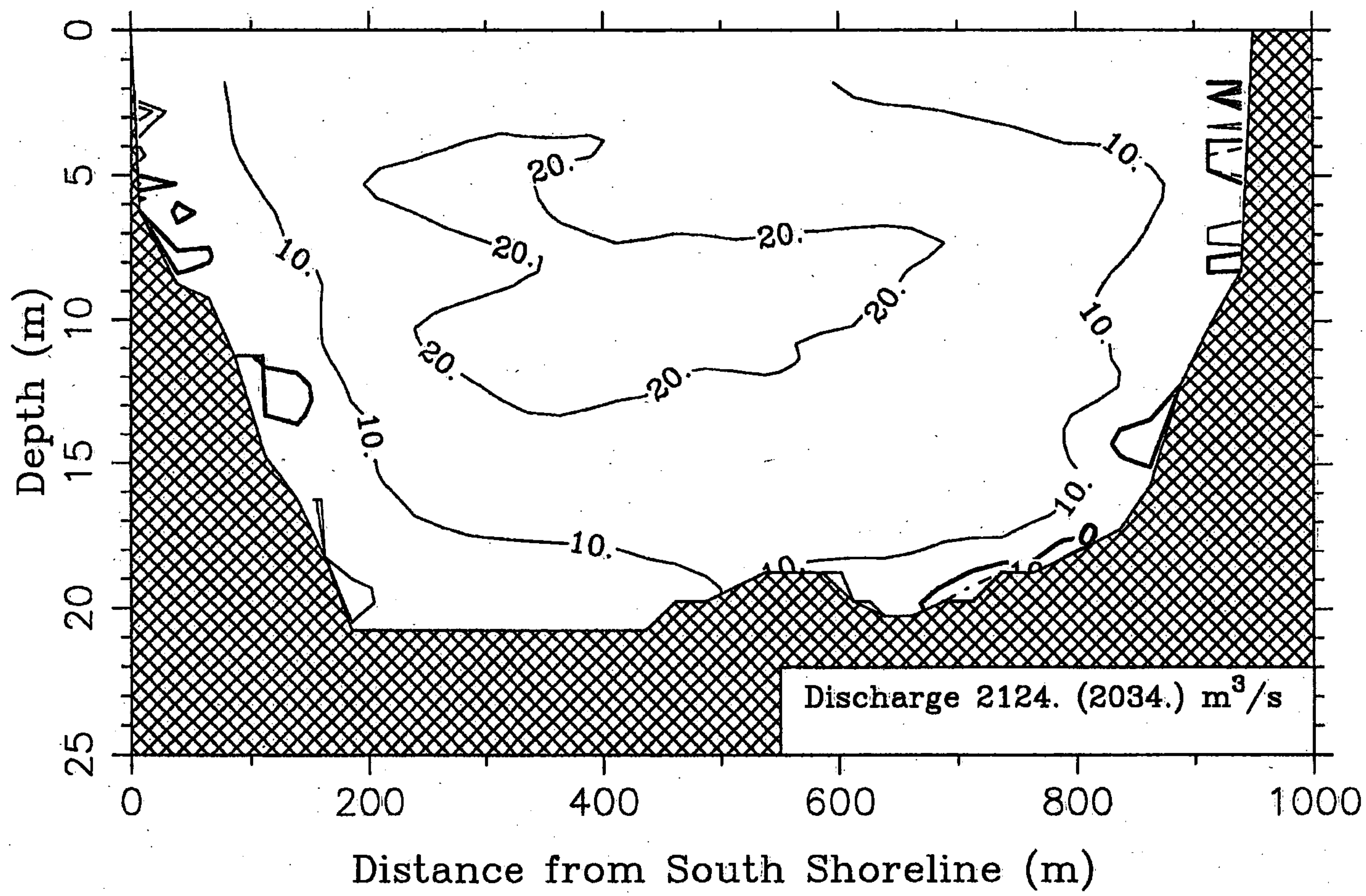

South Flow (cm/s) Lower Arrow Lake August 19, 1997 North
30.
30.
20.
20.
20.
20.
10.
10.
10.
10.
10.
10.
10.
Discharge 1598. (1978.) m^3/s
Depth (m)
0
20
40
0
100
200
300
400
500
600
Distance (m)


August 21 21:38-22:15
20.3cm/s
Start Bottom Track
August 22 17:25-18:33
16.2cm/s
Start Bottom Track
August 22 19:44-20:52
17.1cm/s
Start Bottom Track
August 26 19:53-21:54
5.5cm/s
Start Bottom Track
North Distance (m)
East Distance (m)

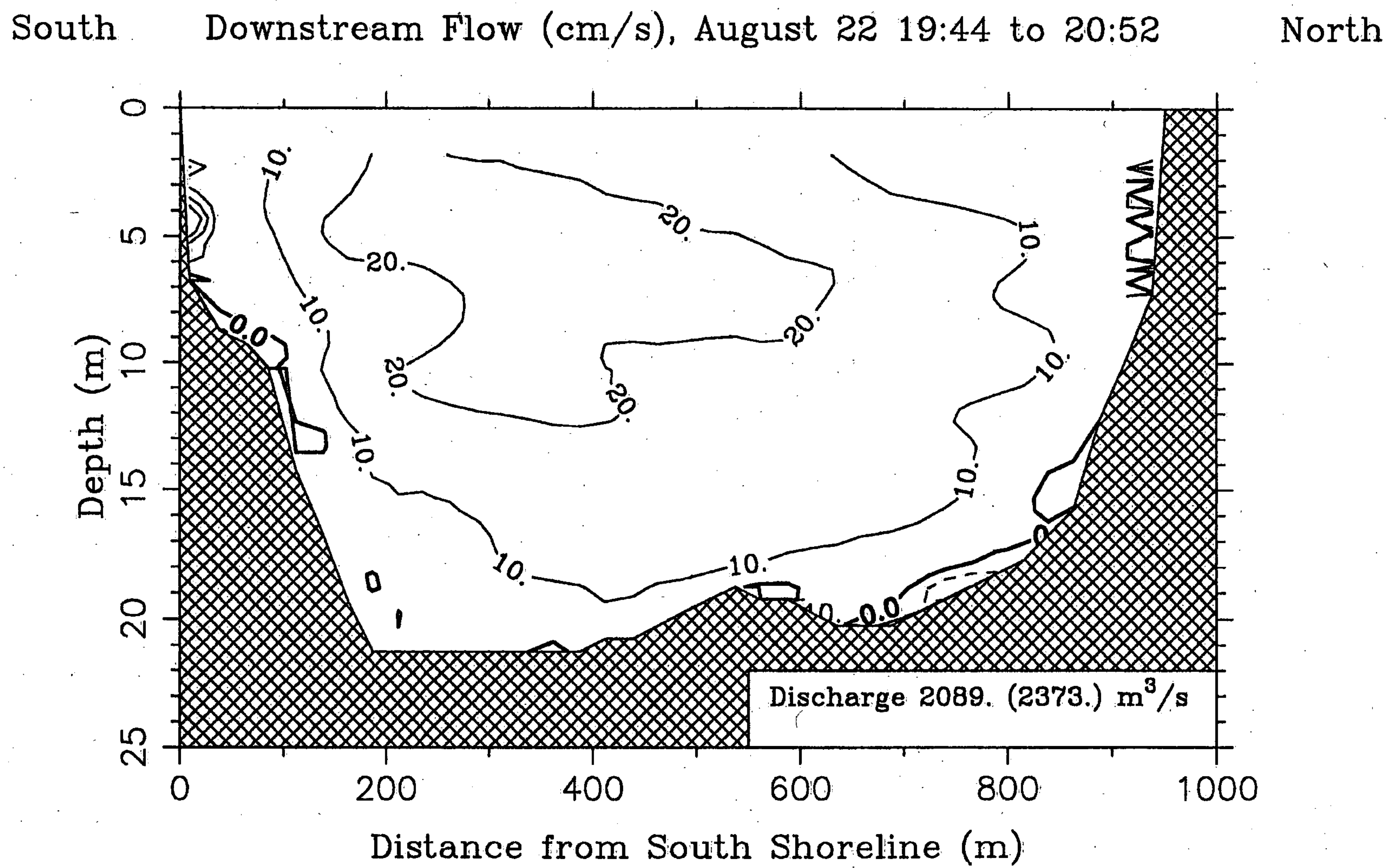

South
Downstream Flow (cm/s), August 21 21:38 to 22:15
North
Depth (m)
0
5
10
15
20
25
0
200
400
600
800
1000
Distance from South Shoreline (m)
Discharge 1921. (2187.) m³/s
20.
10.
0.0

5-8

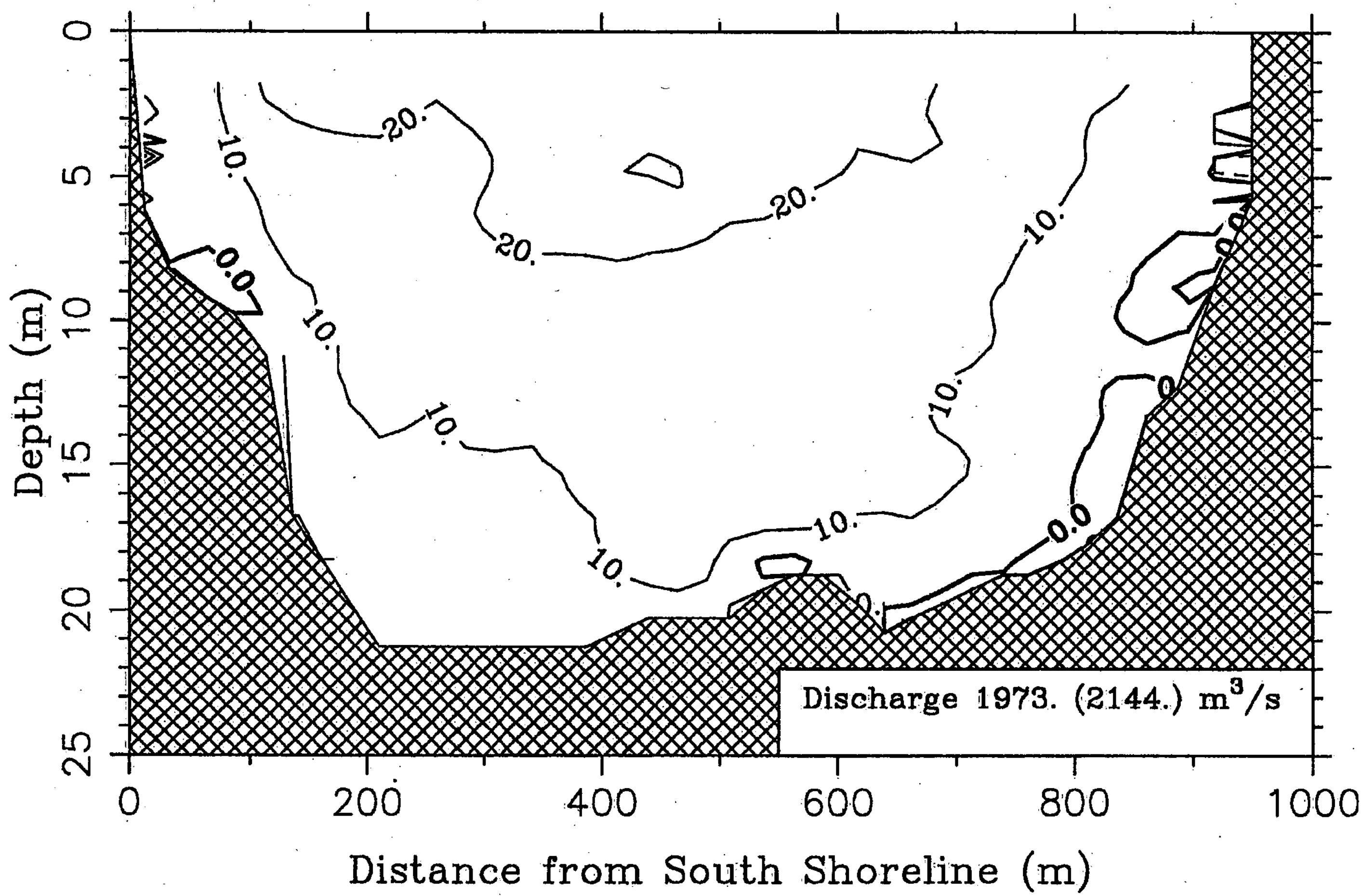
South Downstream Flow (cm/s), August 22 17:25 to 18:33 North

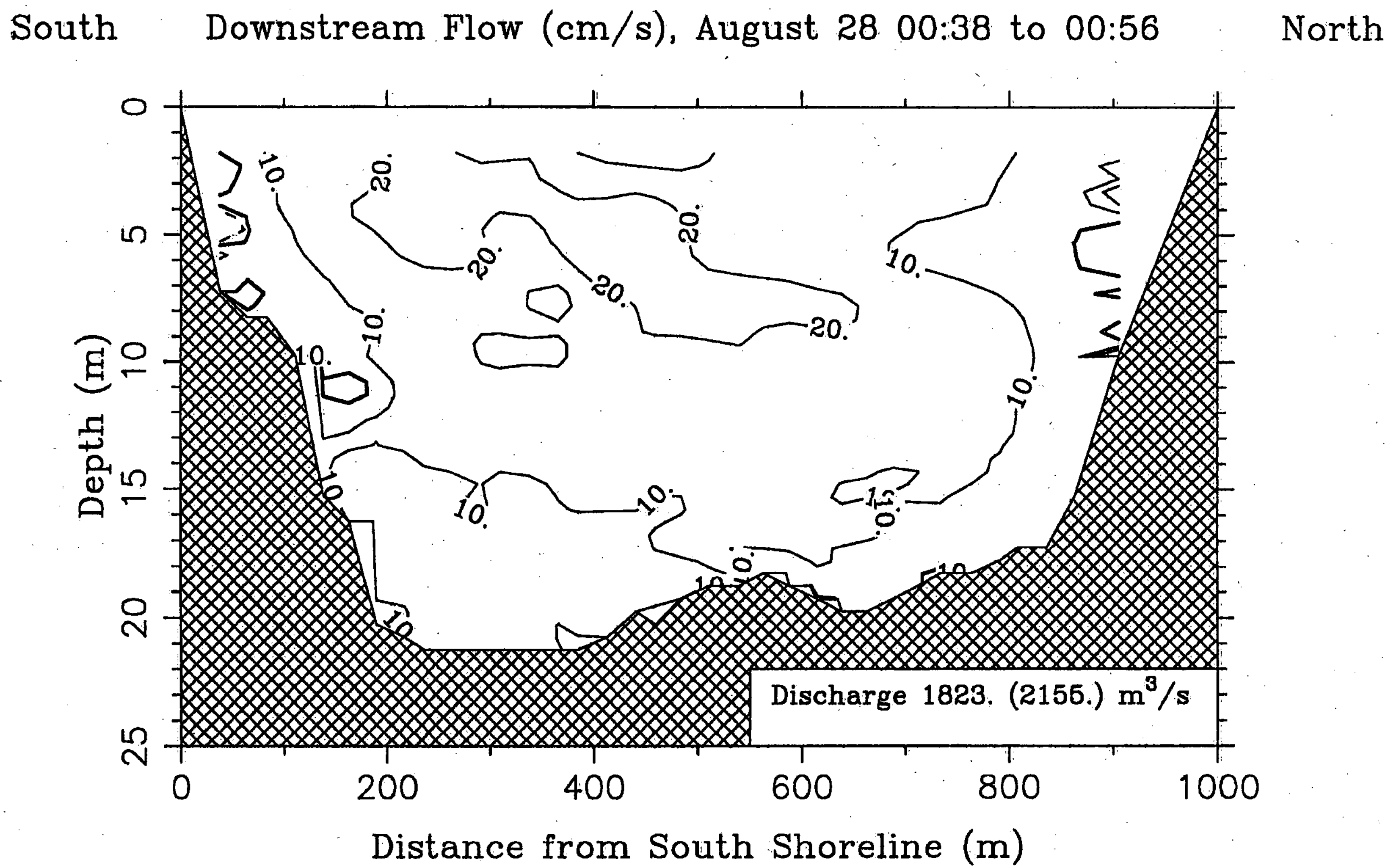


99.5

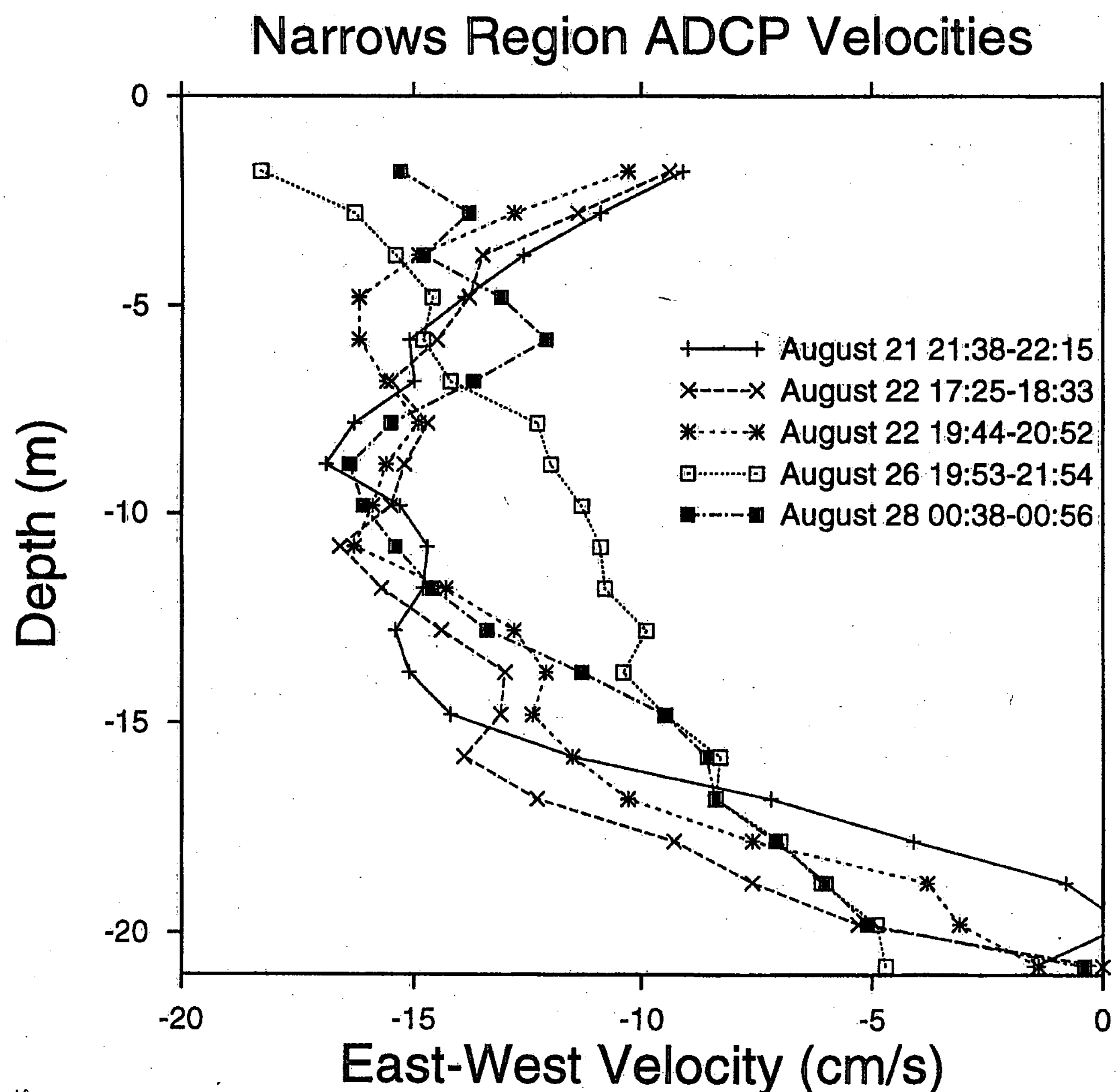

South
Downstream Flow (cm/s), August 22 19:44 to 20:52
North
Depth (m)
Distance from South Shoreline (m)
Discharge 2089. (2373.) m3/s
0
5
10
15
20
25
0
200
400
600
800
1000
10.
20.
0.0

South Downstream Flow (cm/s), August 26 19:53 to 21:54 North




South
Downstream Flow (cm/s), August 28 00:38 to 00:56
North
Depth (m)
Distance from South Shoreline (m)
Discharge 1823. (2155.) m3/s

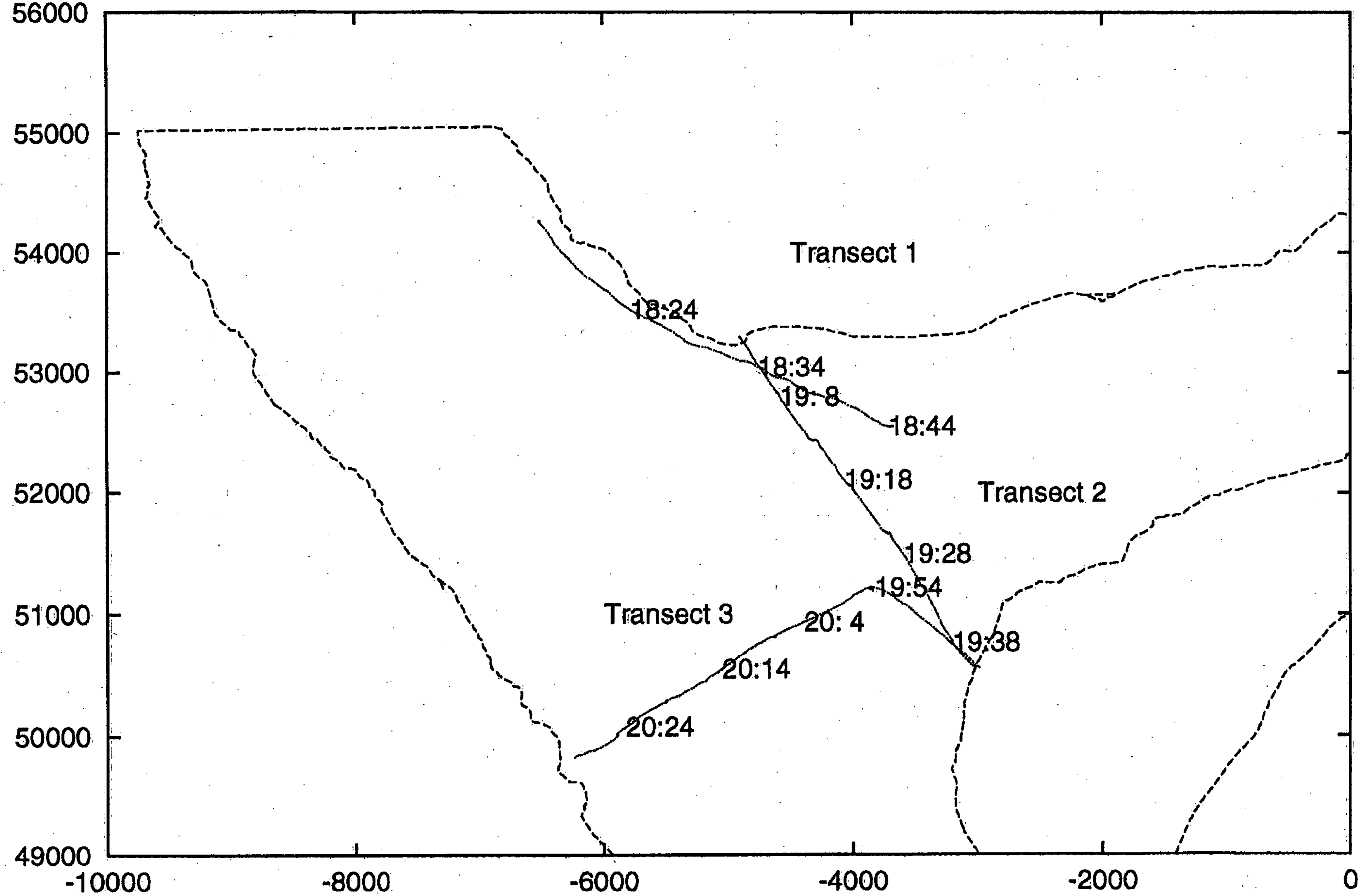
p3.5



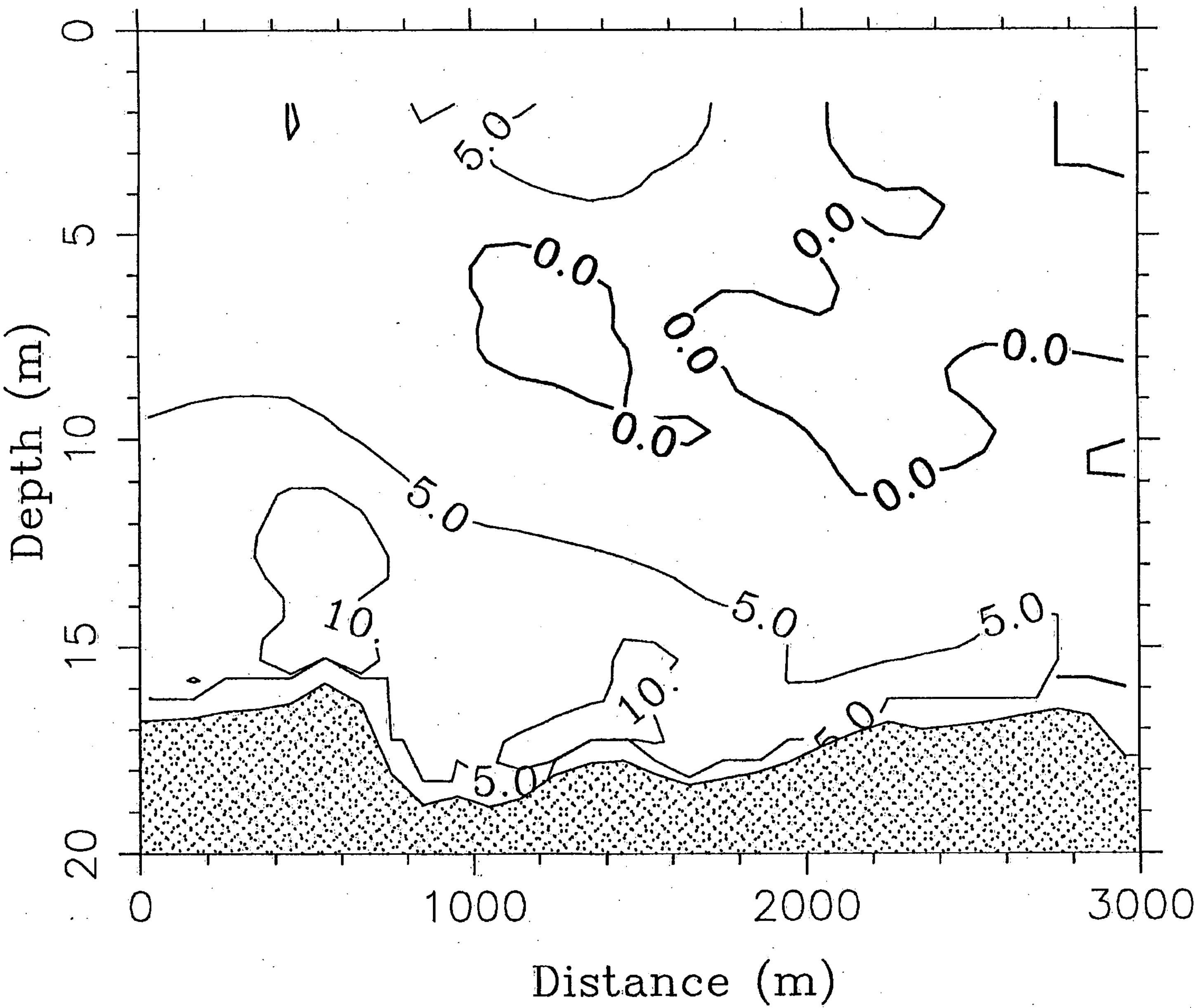
Narrows Region ADCP Velocities
Depth (m)
0
-5
-10
-15
-20
-20
-15
-10
-5
0
East-West Velocity (cm/s)
August 21 21:38-22:15
August 22 17:25-18:33
August 22 19:44-20:52
August 26 19:53-21:54
August 28 00:38-00:56

6.5

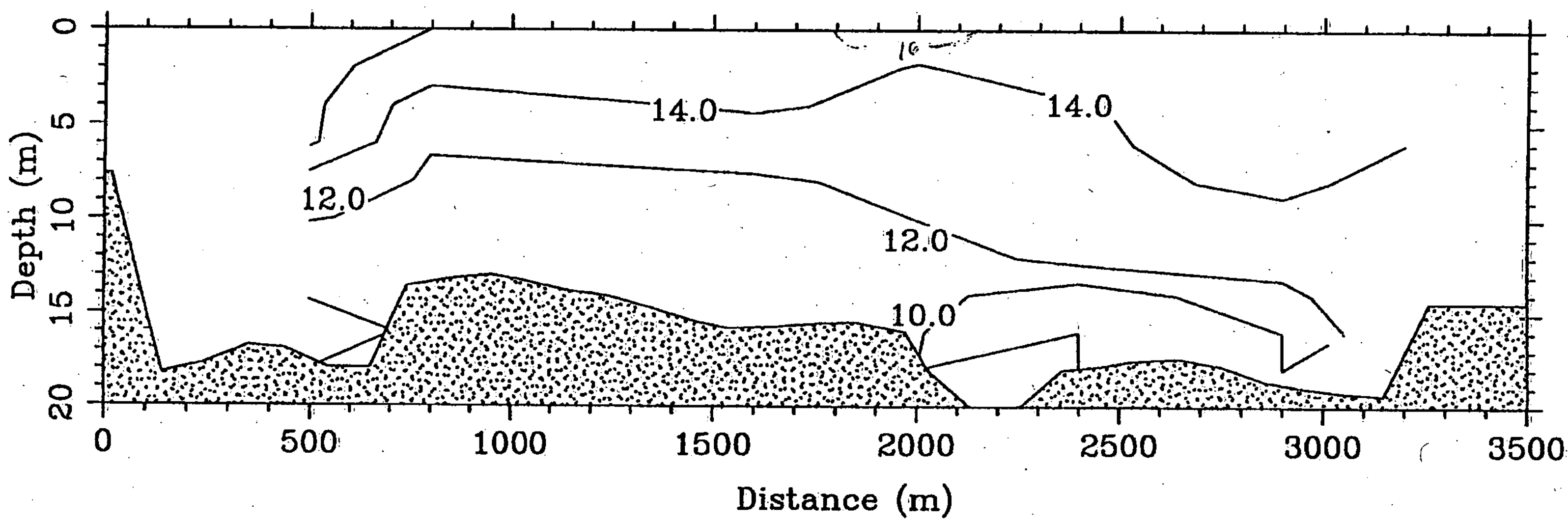
Upper Arrow Lake, August 27 Survey



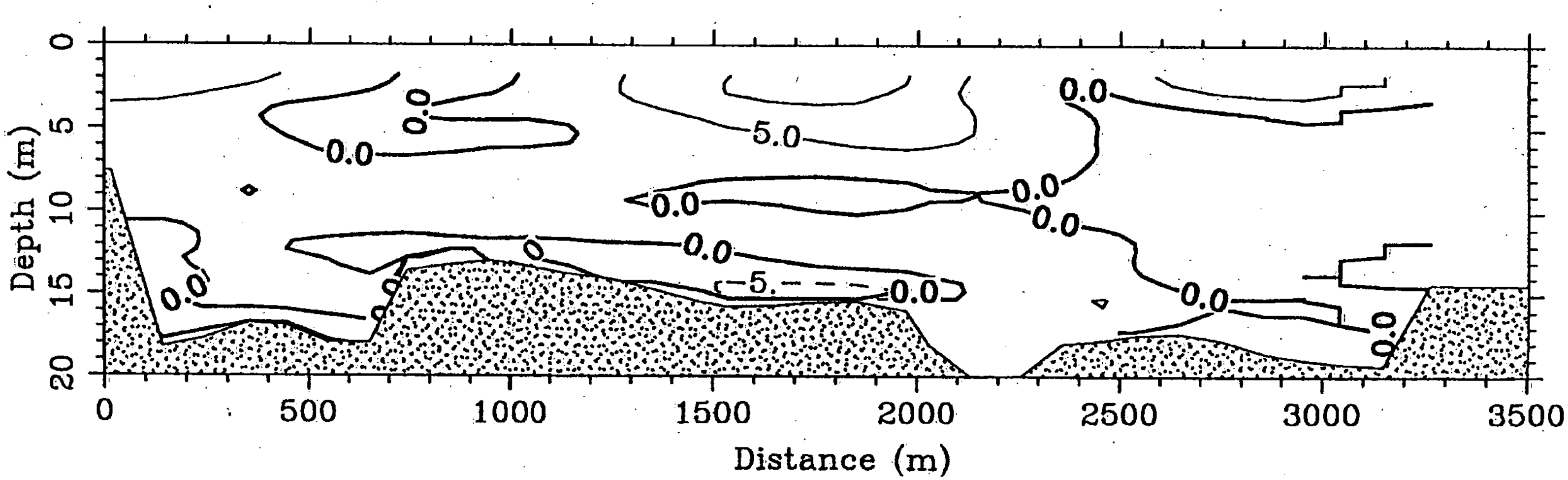
NW Flow along Transect 1 (cm/s) Upper Arrow Lake, SE



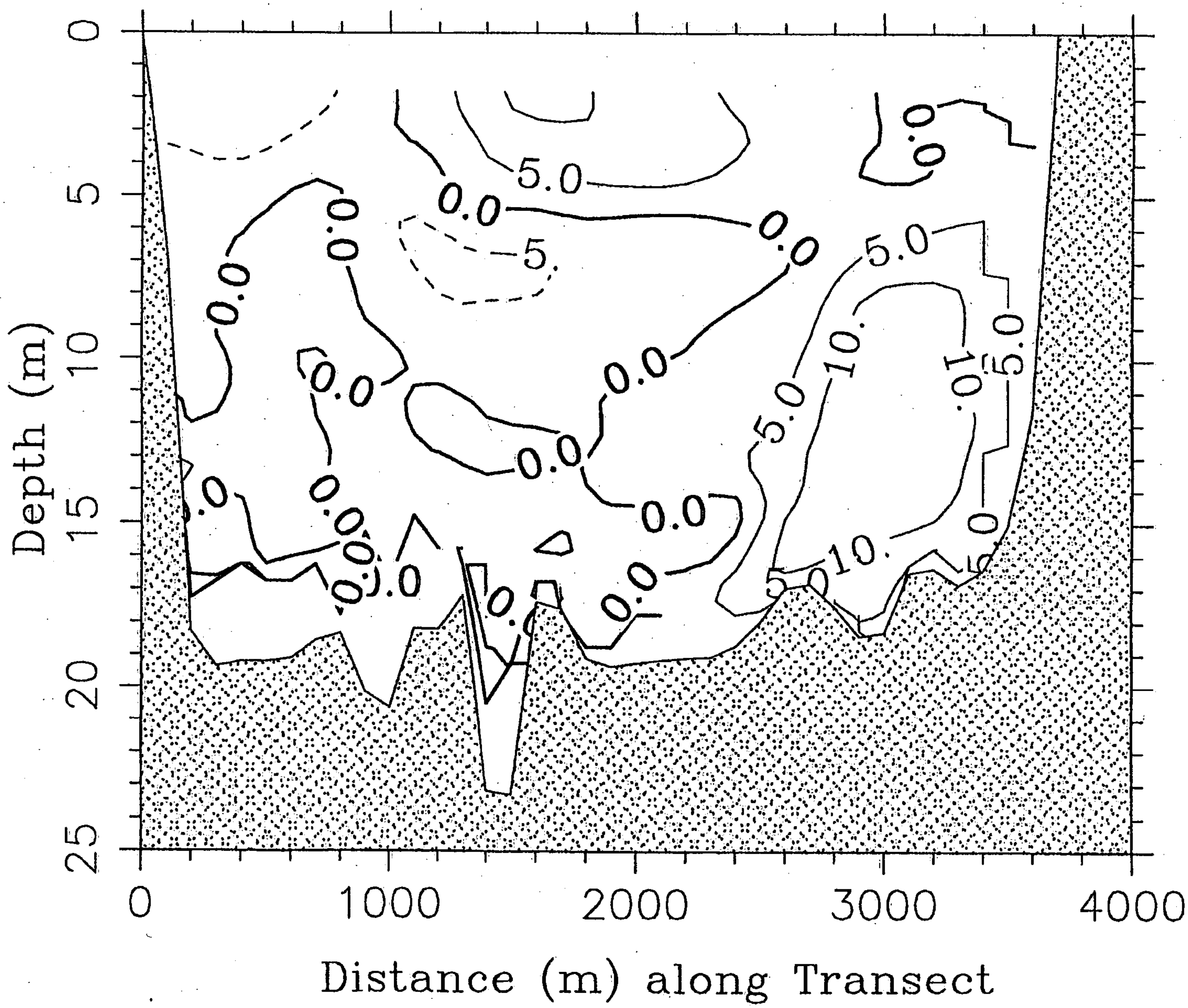
North Temperature (C) Transect 2, Upper Arrow Lake, South



North Flow across Transect 2 (cm/s) Upper Arrow Lake, South



E Flow across Transect 3 (cm/s) Upper Arrow Lake, W



5/2

PRINTED IN CANADA ON RECYCLED PAPER
IMPRIMÉ AU CANADA SUR DU PAPIER RECYCLÉ

National Water Research Institute
Environment Canada
Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

NATIONAL WATER RESEARCH INSTITUTE
INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

Institut national de recherche sur les eaux
Environnement Canada
Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington, Ontario
L7R 4A6 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon, Saskatchewan
S7N 3H5 Canada

Environment Canada Environnement Canada

Canada