UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 298

HEATING AND COOLING OF A SHALLOW BAY IN EAU GALLE RESERVOIR: FIELD MEASUREMENTS AND INTERPRETATION

by

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Prepared for

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I. INTRODUCTION

Water quality concerns associated with the distribution of nutrients in lakes and reservoirs make information on naturally occurring processes, which affect water movement, of significant value. These processes can be driven by wind, rain, solar radiation, surface cooling, photosynthetic activity, ground water intrusion and Coriolis forces. This study focuses on the diurnal effects of radiative heating and convective surface cooling as the driving forces of change in the water temperature profiles. It has been shown that the horizontal temperature gradients caused by the heating and cooling of littoral waters, and the density differences associated with these temperature gradients, cause horizontal and vertical exchange of water within the littoral and adjacent profundal regions (Stefan, Horsch and Barko, 1989).

To investigate the link between water temperature and transport, this study analyzes the time dependent temperature profiles within a heavily vegetated, shallow bay and the adjacent profundal waters of a small flood detention reservoir in western Wisconsin. In this progress report, the data collected is reviewed and presented with a qualitative interpretation of some distinct heating and cooling episodes. A quantitative analysis will be the subject of a future report.

This study is based on over 450,000 recorded field measurements of water temperature and weather parameters taken at the Eau Galle reservoir, near Spring Valley, WI, between August 9 and September 26, 1988. Temperature vs. time plots as well as isotherm plots will be presented herein to illustrate the time and spatial distribution of temperature in a cross section of the reservoir bay. Weather data will also be presented and used in the discussion and analysis of the water temperature records.

II. DATA COLLECTION

The Eau Galle Reservoir (see Figure II–1) is used for flood control and recreation only, with the recreational uses limited to fishing and swimming. The reservoir is surrounded on all sides by significantly higher ground, thereby decreasing the effects of wind on the bay, while increasing the possibility of ground water intrusion. The bay used in this study (see Figure II–2) was filled with dense vegetation, mainly Ceratophyllum demersum or "coon tail", out to just beyond the 1 meter depth. The plants began to thin between the 1 and 2 meter depths and were virtually nonexistent beyond the 3 meter depth. A detailed investigation of vegetation was made by Filbin and Barko (1985). The Eau Galle River enters the reservoir a short distance to the south of the bay under study. However, the negative buoyancy of the inflow during this period, combined with the topography of the bottom along the north side of the river's mouth, prevent the inflow from significantly affecting the water in the bay (see Figure II–1).

The data were collected by monitoring systems installed by William F. James of the Army Corps of Engineers, Waterways Experiment Station, as part of a long term project on reservoir ecology under the direction of Dr. John W. Barko. Twelve thermistor arrays were deployed along the center line of the bay as shown in Figures II–2 and II–3. Stations 2s, 3s, 4s, 5s, & 6s were laterally adjacent (satellites) to stations 2, 3, 4, 5, & 6. The thermistor stations were originally numbered from 1 to 12 (see Appendix D). The satellites (approximately 15 meters south and/or west of their counterparts) were intended to detect temperature gradients across the transect. At each station, thermistors were mounted on vertical sections of PVC pipe with the bottom ends securely imbedded in the sediment. The water temperature data were recorded using 2 different data logging systems. Omnidata International, Inc. "Easy Logger" data collection systems were mounted on platforms at stations 2, 3, 4, 5, & 6 (see Figure II–2). These systems took temperature measurements from each thermistor every 2 minutes and recorded the average temperatures every 10 minutes. Data loggers at stations 3 – 6 recorded temperatures at their own stations and their satellite stations while the logger a station 2 recorded temperatures from station 1 as well as its own station and satellite station (2s). A Campbell Scientific, Inc. "CR10" data collection system was used at station 7. This system took measurements every minute and also recorded the averages every 10 minutes. The position of each thermistor in the vertical plane of the bay transect can be seen in Figure II–3. In addition to the thermistors in the water, stations 2, 3, 4, 5, & 7 had a thermistor in the sediment to aid in the detection of ground water and station 4 had a thermistor in a shallow, insulated bowl of water to record an "equilibrium temperature". In total 69 recording thermistors were deployed.

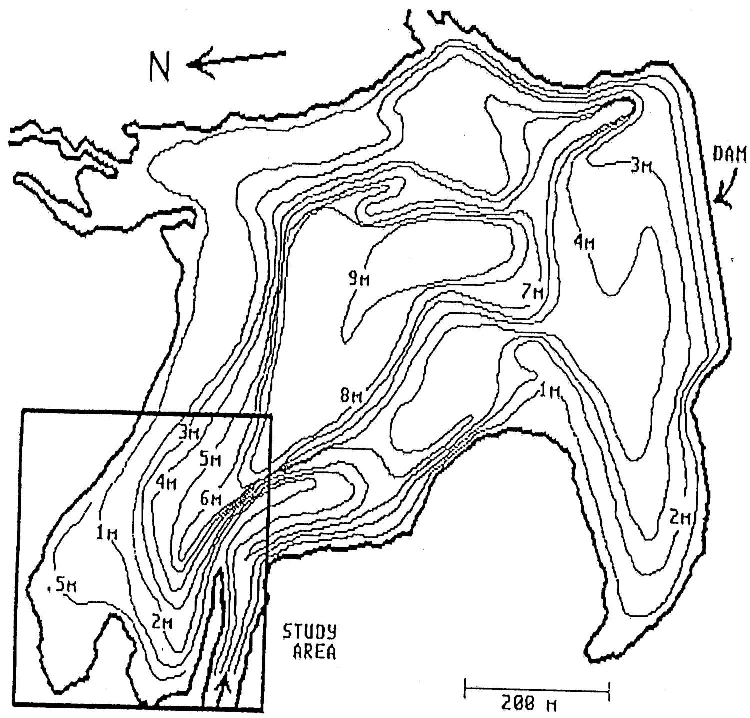


Fig. II-1. Eau Galle Reservoir Bathymetry

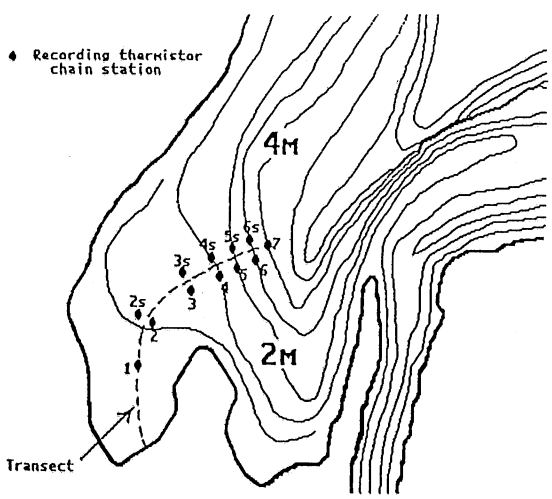


Fig. II-2. Thermistor Chain Positions

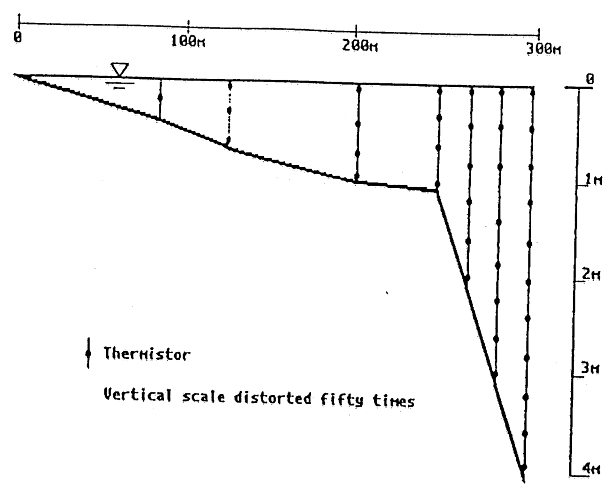


Fig. II-3. Thermistor Positions in the Transect

The recording of temperatures from stations 1 – 6 and 2s – 6s began on August 9, 1988, while the thermistor chain at position 7 started recording temperatures on August 12. Temperatures at all positions were averaged and stored every ten minutes until September 26, 1988. A weather station on top of a hill near the reservoir recorded averaged air temperature, relative humidity, wind speed, and wind direction, every 15 minutes and a second weather station, in the bay, recorded the incident radiation and the barometric pressure every hour. The weather data were used to select periods desirable for study, such as a cool calm night to study the effects of surface convective heat loss or calm sunny days to study the effects of solar surface heating.

III. DATA REDUCTION

The water temperature data from stations 1 – 6s were processed at the Waterways Experiment Station in Vicksburg, Mississippi and received at the St. Anthony Falls Hydraulics Lab in the form of an 8MB data file, on a computer storage tape. This tape contained temperatures from 57 thermistors, recorded every 10 minutes, for approximately 48 days (Aug. 9 – Sept. 26, 1988), totaling slightly over 390,000 measurements. Data reduction consisted of making errant temperatures obvious by substituting negative values for temperatures above 40°C or below 0°. The thermistors used for this record were calibrated to the nearest 0.1°C on August 8, 1988 and the temperatures on this tape had been adjusted according to this calibration. The thermistors on the Campbell system were calibrated to the nearest 0.05°C on August 10, 1988, and their calibration proved accurate to 0.1°C when checked on October 5.

The 8MB file was loaded onto the VAX system at the University of Minnesota where records from specific positions were extracted using Fortran programs and the system editor, until the time sharing costs became prohibitive. These records were used to create temperature vs. time plots for initial checks of equilibrium temperature, ground water intrusion (probes near the bottom and in the sediment), and extent of stratification (surface temperature minus bottom temperature). The large file was then divided into 24 files, approximately 330KB each, and downloaded to a personal computer where the weather data were processed and graphed, and the remaining data reduction was completed.

The data format used on the tape listed each of the 390,000+ temperatures on a separate line with time and spatial coordinates. The decision was made to change to a matrix format with each row representing a 10 minute time interval and each column representing a thermistor position or weather parameter. This format made it easy to import single day, complete records into spread sheet software for graphing and analysis. The more efficient use of computer storage space and easier file manipulation were also benefits of this format. The weather data, which were recorded at 15 minute or hourly intervals, were linearly interpolated to 10 minute intervals and added to the matrix files. Data from the Campbell system (station 7) were also added to these files.

The matrix files were used to create time vs. temperature plots of all the data received. Graphs were generated for each station and the weather data. Inspection of these graphs revealed the locations of errant and damaged probes which had not been detected in the first check performed on the tape. Some of the errant probe readings were caused by the leakage of water into the probe tip containing the thermistor. The probes used were not designed for underwater use and attempts were made to seal vulnerable sections of the probes. These attempts apparently were not universally successful. Other probes were damaged by otters during the end of August and September. Bad data were indicated by jagged or drifting time plots. Probes values that drifted away from believable readings had to be judged by comparison to the surrounding temperatures. For example, one probe at station 6 was approximately 1°C high at the beginning of the record and continued to rise. The 30 cm deep probe at station 2 and the 5 cm probe at position 4 began to drift high during the last day of August.

Satellite stations had been included in the measurement scheme to detect temperature gradients transverse to the measurement transect (Figure II–2). Such gradients would indicate 3 dimensionality in the flow field (ie. the presence of flow across the transect) and would bring into question the 2–D assumption on which later analysis of the data would be based. Where the calculation of transverse temperature differences was possible, they proved to be small. A statistical analysis based on the station temperature minus the satellite temperature (at all positions where both thermistors were believed accurate) is summarized in Table III–1. Differences were computed for each pair at 10 minute intervals from 0:10, August 10 to 24:00, August 12. Averages and standard deviations of the 3 day difference records were computed and presented with maximum and minimum values at each available position. The largest differences across the transect were found near the bottom at the 0.95, 2.0, and 3.0 meter depths. These differences may have been due to variations in the bathymetry (small depressions, small ridges, etc.) which tend to separate near–bottom regions by restricting exchange flow and allowing larger horizontal temperature gradients. Heat conduction from the sediment combined with slight variations in depth could also cause these differences. A table of differences, including absolute and rms based values, is given in Appendix C with a graphical representation of the average differences by position.

Initial inspection of the water temperature graphs also provided the information necessary to determine the time window during which a complete record of temperatures could be provided. The term "complete record" refers to one uninterrupted set of temperatures along the transect. The stations and their satellites in Fig. II–2 were combined where probes from one had been determined to be errant. The beginning of the record was determined by the installation of the Campbell thermistor chain which occurred on August 11. The end of the "complete record" was brought about by otter damage to several probes on the 7th of September, leaving a total of 26 full days (August 12 – September 6). From 9:10 on August 17 to 8:40 on August 23, no temperatures were recorded at stations 5 and 5s, creating a gap in the "complete record". While this gap presented no difficulty in the analysis of the rest of the record, a complete record (without gaps) was needed. In order to fill this gap, an average of temperatures from stations 4s and 6s were used to give fluctuations, and an offset added to achieve the best match between the actual and synthesized temperatures at both ends of the gap. A similar (though shorter) gap was found at positions 4 and 4s from 17:40, August 22 to 16:20, August 23. This gap was dealt with in the same fashion. The final version of the "complete record" is shown in Figures IV–1 to IV–7.

TABLE III-1. Statistics of Temperature Differences (Deg. C) Between Main Stations and Satellites.

Station # & depth	max	min	avg	std d
2 @ 0.05m	0.97	0	0.17	0.19
2 @ 0.30m	-2.03	0	-0.23	0.45
2 @ 0.60m	-0.50	0	-0.35	0.10
3 @ 0.05m	0.69	0	0.03	0.22
3 @ 0.70m	-1.16	0.08	-0.72	0.22
4 @ 0.05m	-0.85	0	-0.02	0.21
5 @ 0.05m	1.33	0	-0.09	0.19
5 @ 0.40m	1.04	0	0.04	0.13
5 @ 0.80m	0.99	0	0.09	0.14
5 @ 1.20m	1.38	0	0.19	0.33
5 @ 1.60m	1.44	0	0.16	0.26
5 @ 1.95m	-2.04	0.01	-0.61	0.70
6 @ 0.05m	-0.50	0	-0.05	0.08
6 @ 0.40m	0.61	0	-0.08	0.08
6 @ 0.80m	0.39	0	-0.03	0.07
6 @ 1.80m	0.58	0	-0.08	0.10
6 @ 2.20m	1.29	0.01	0.28	0.11
6 @ 2.60m	1.03	0	0.02	0.15
6 @ 2.95m	-1.48	0	-0.47	0.46
5cm averages	0.33	0.00	0.01	0.18
Bottom averages*	-1.30	0.02	-0.54	0.37
Overall averages	0.17	0.01	-0.09	0.22

* Bottom positions \ St. 2 @ 0.60m, St. 3 @ 0.70m, St. 5 @ 1.95m, St. 6 @ 2.95m

NOTE: All values were calculated as station temperature minus satellite temperature. Values were computed where both thermistors were believed to be accurate.

IV. DATA PRESENTATION

The 138,528 water temperature data points of the "complete record" were presented in 3 different ways for interpretation:

(1) TIME SERIES PLOTS

The first graphical presentation of the complete water temperature record was done in a time series (temperature vs. time) format, one graph representing a five day record at one station along the transect. (See Figures IV–1 to IV–7). Individual larger graphs are presented in Appendix A. Weather parameters are provided in Figure IV–8 for wind velocity, air temperature, and relative humidity and Figure IV–9 for solar radiation.

(2) ISOTHERM PLOTS

Isotherm plots were generated on a micro computer using hourly averaged temperatures. These plots were only generated for periods of particular interest. All isotherm plots are given in Appendix B. Examples are shown in Figures V–1 and V–2.

(3) VIDEO PRESENTATION

The "complete record" was used to produce a dynamic color visualization of the vertical temperature field along the bay transect (see Figures II–2 and II–3). A linear interpolation scheme was used by Jonathan Jamsa to generate the color video on a Cray II supercomputer at the Minnesota Supercomputer Center. The video includes bar graph representations of air temperature, wind speed, and solar radiation throughout the 26 day record. Due to the scarcity of thermistors in the shallow water, temperatures in this region were extrapolated from the 0.40 and 0.65 meter depths. For further information on availability of the video tape, contact the St. Anthony Falls Hydraulic Lab, Department of Civil and Mineral Engineering, Mississippi River at Third Avenue S.E., Minneapolis, Minnesota 55414–2196, ph. (612) 627–4010.

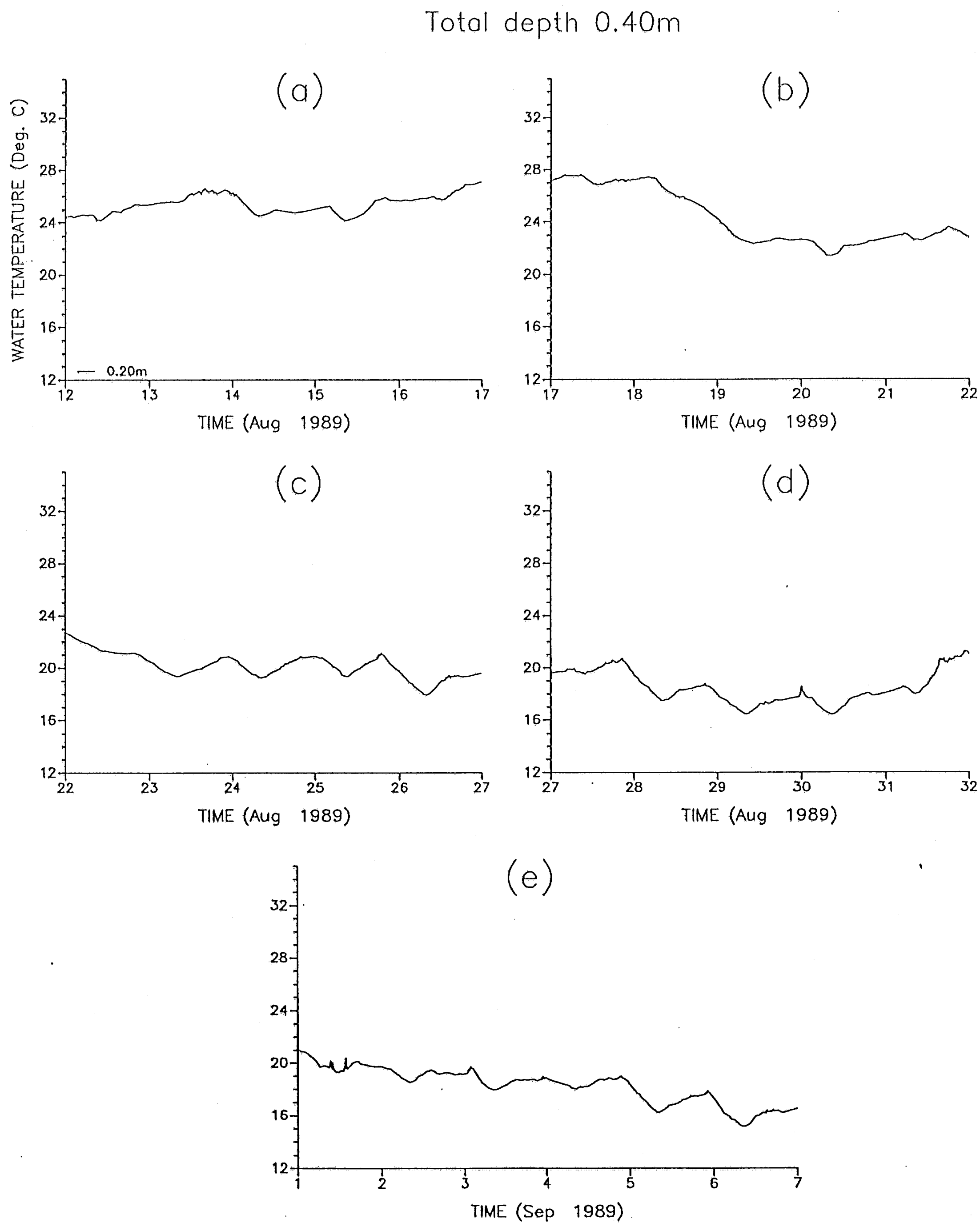


Figure IV−1(a−e). Time Series of Complete Record − Station #1

Total depth 0.65m

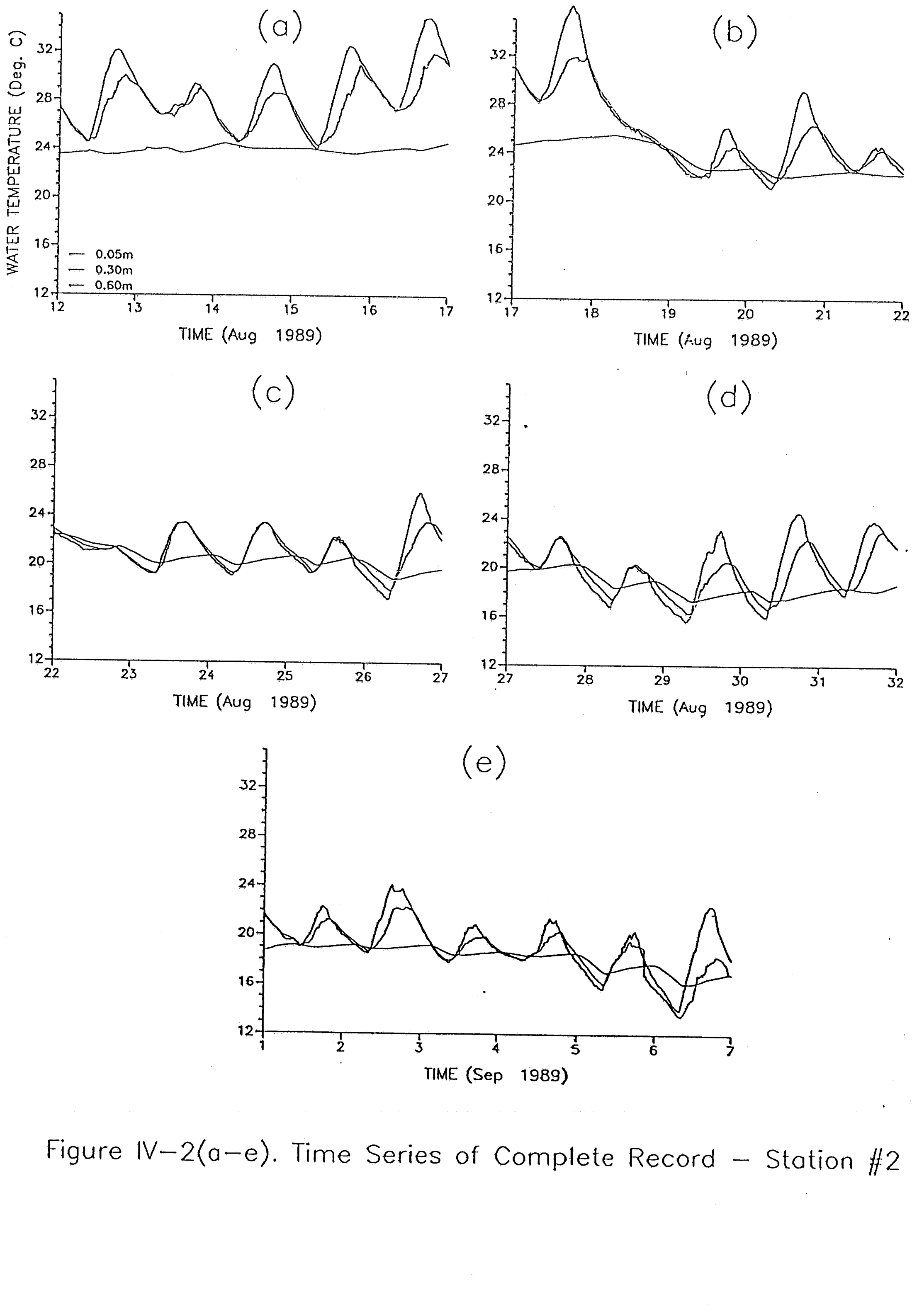


Figure IV–2(a–e). Time Series of Complete Record – Station #2

Total depth 0.95m

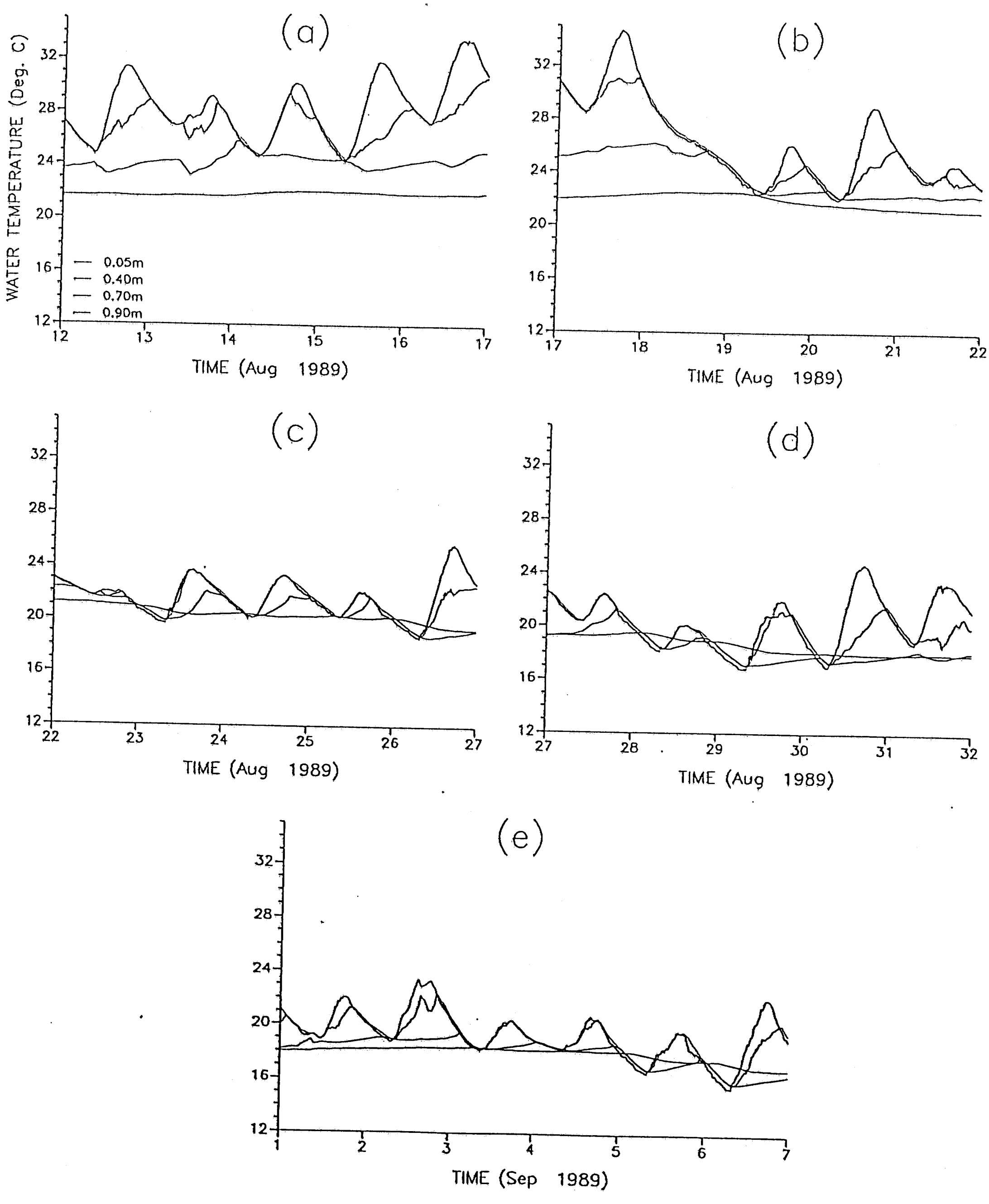


Figure IV–3(a–e). Time Series of Complete Record – Station #3

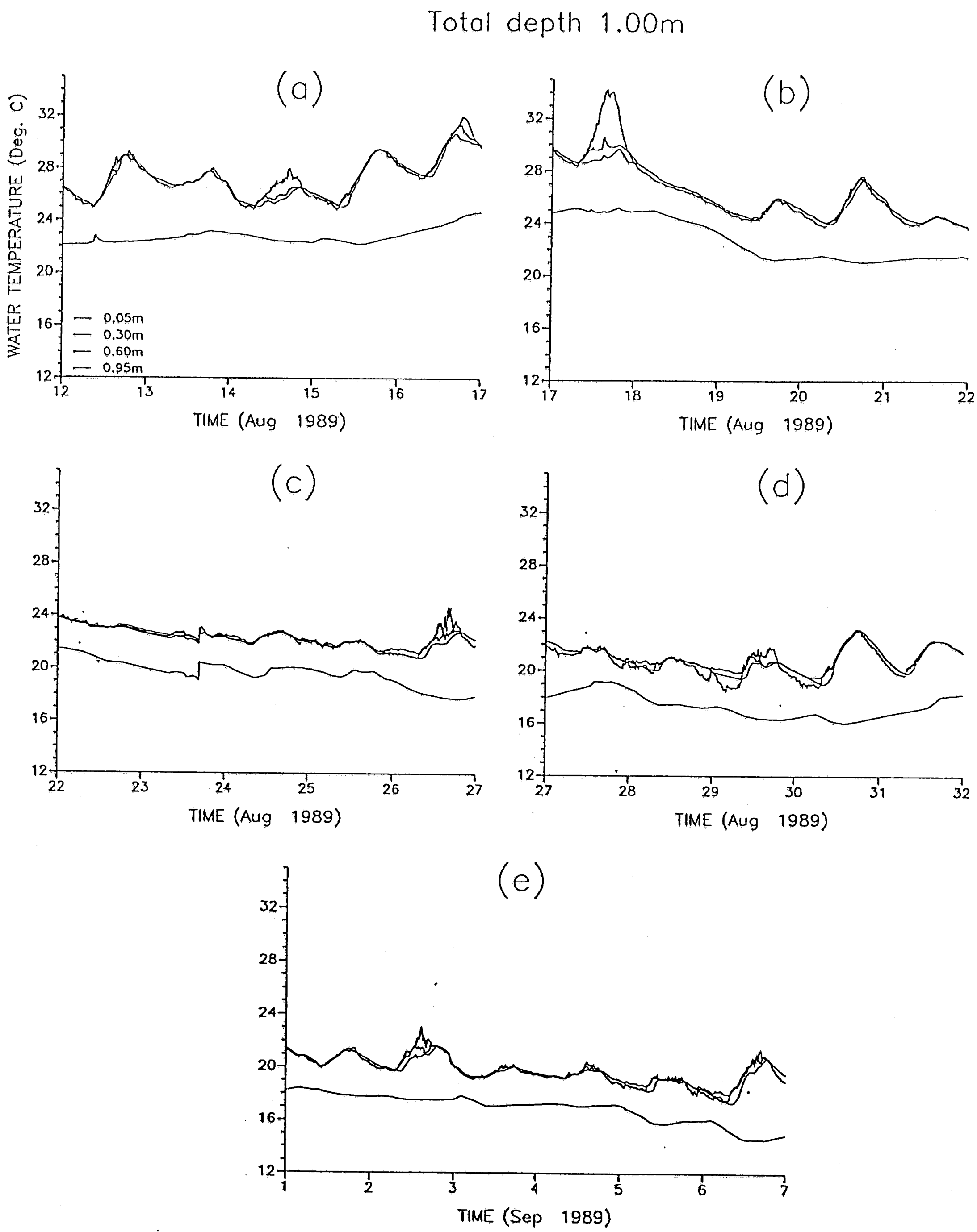


Figure IV–4(a–e). Time Series of Complete Record – Station #4

Total depth 2.00m

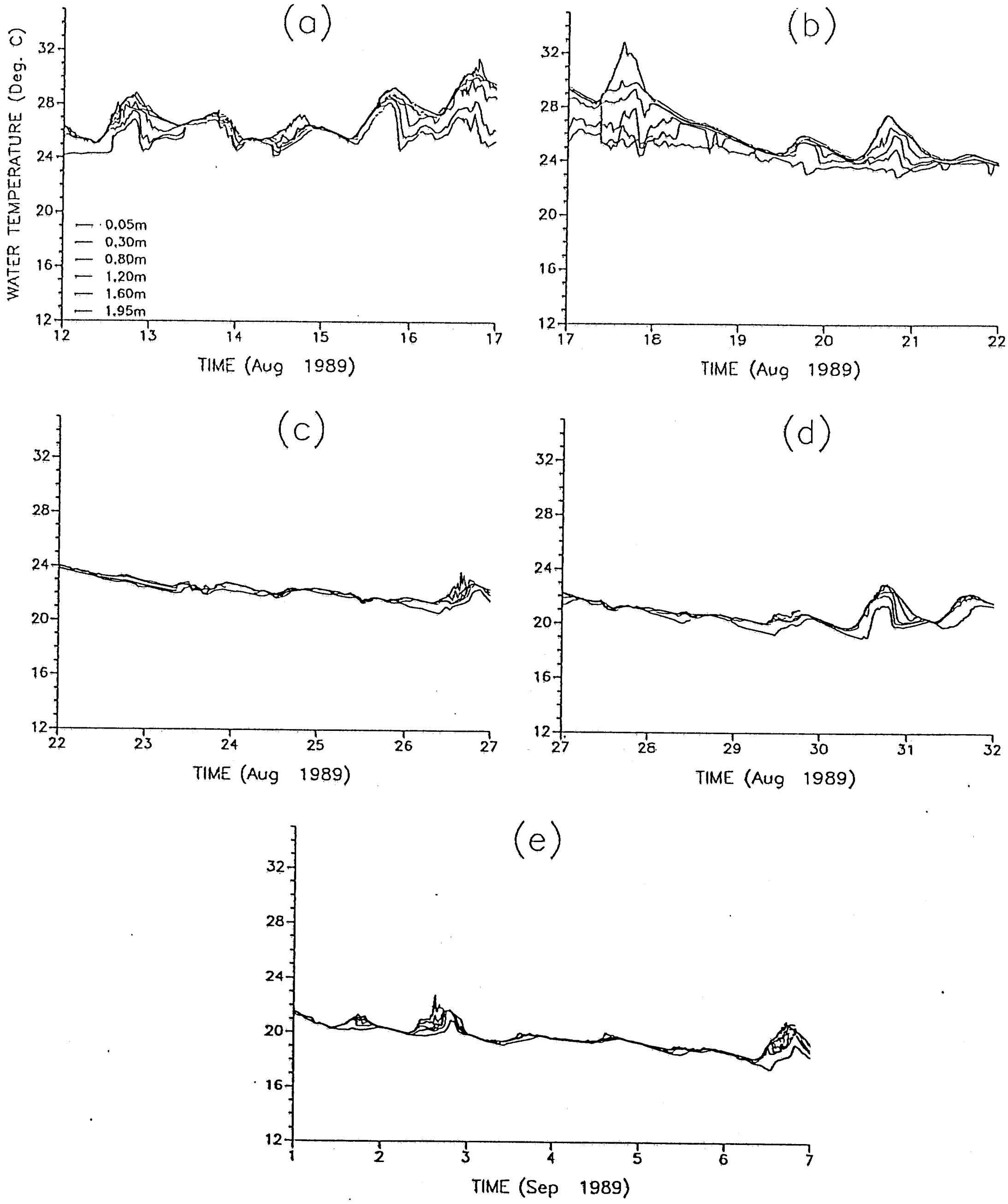


Figure IV–5(a–e). Time Series of Complete Record – Station #5

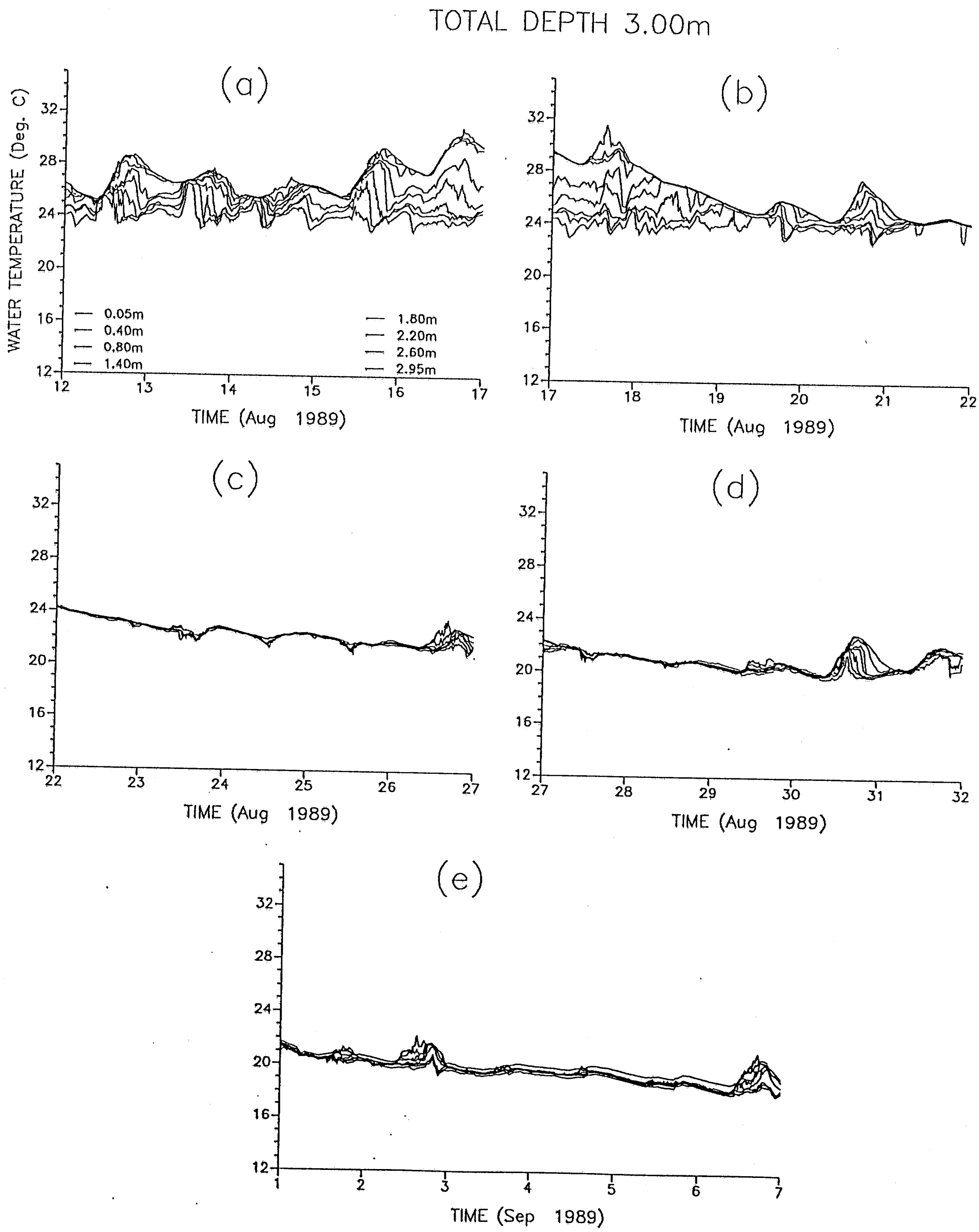


Figure IV–6(a–e). Time Series of Complete Record – Station #6

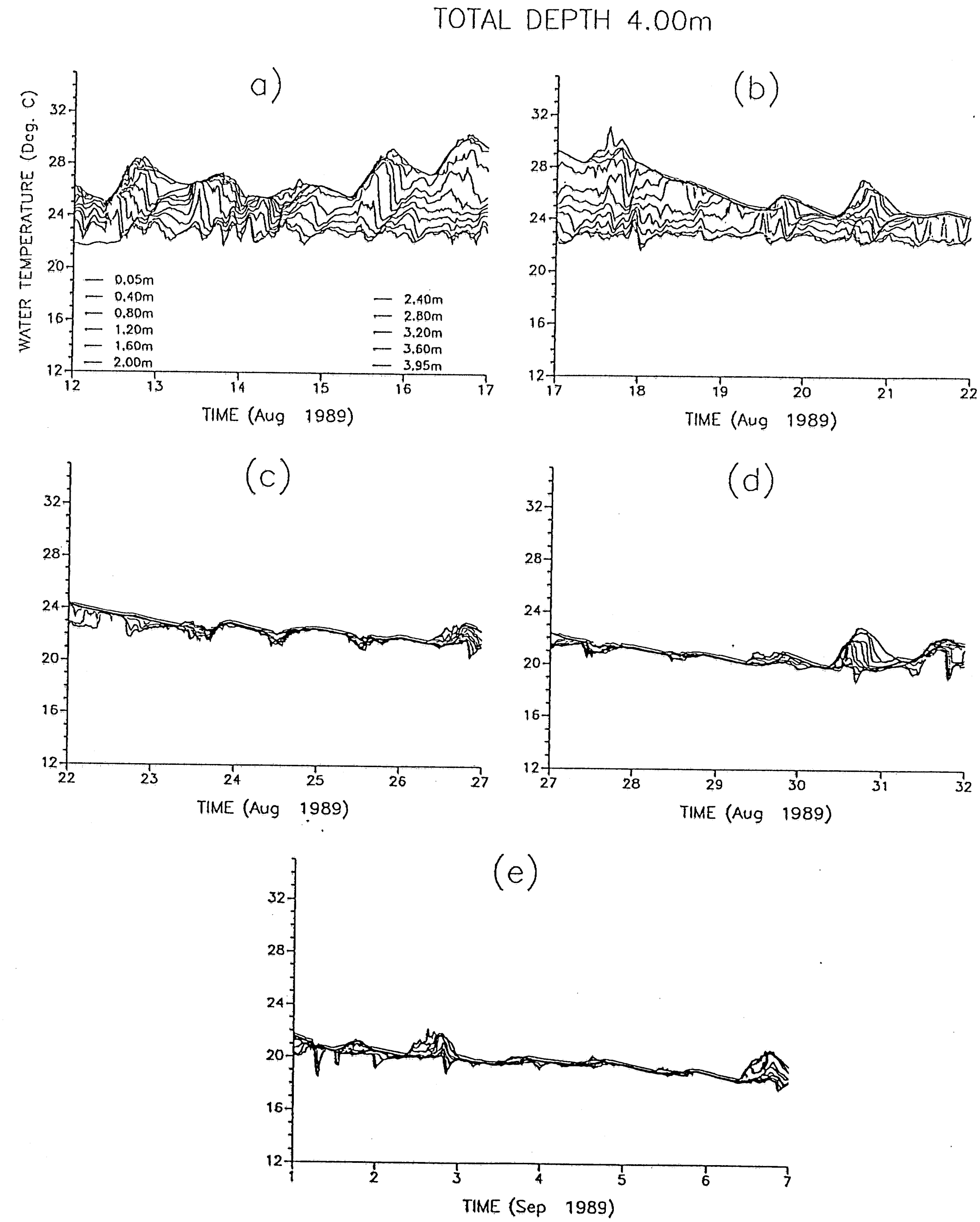


Figure IV–7(a–e). Time Series of Complete Record – Station #7

AIR TEMP.— REL. HUMIDITY — WIND SPEED

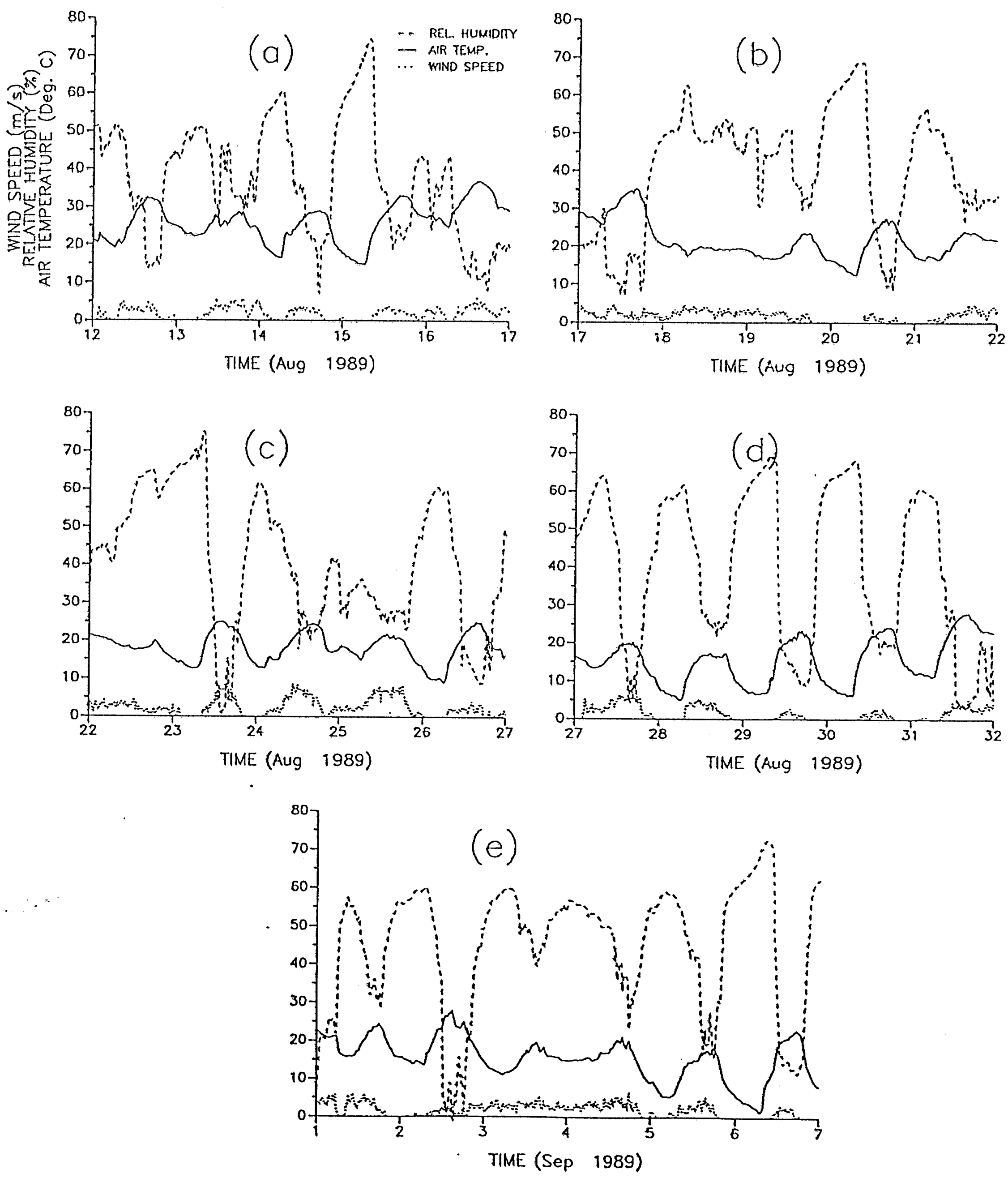


Figure IV–8(a–e). Weather Parameters for Complete Record

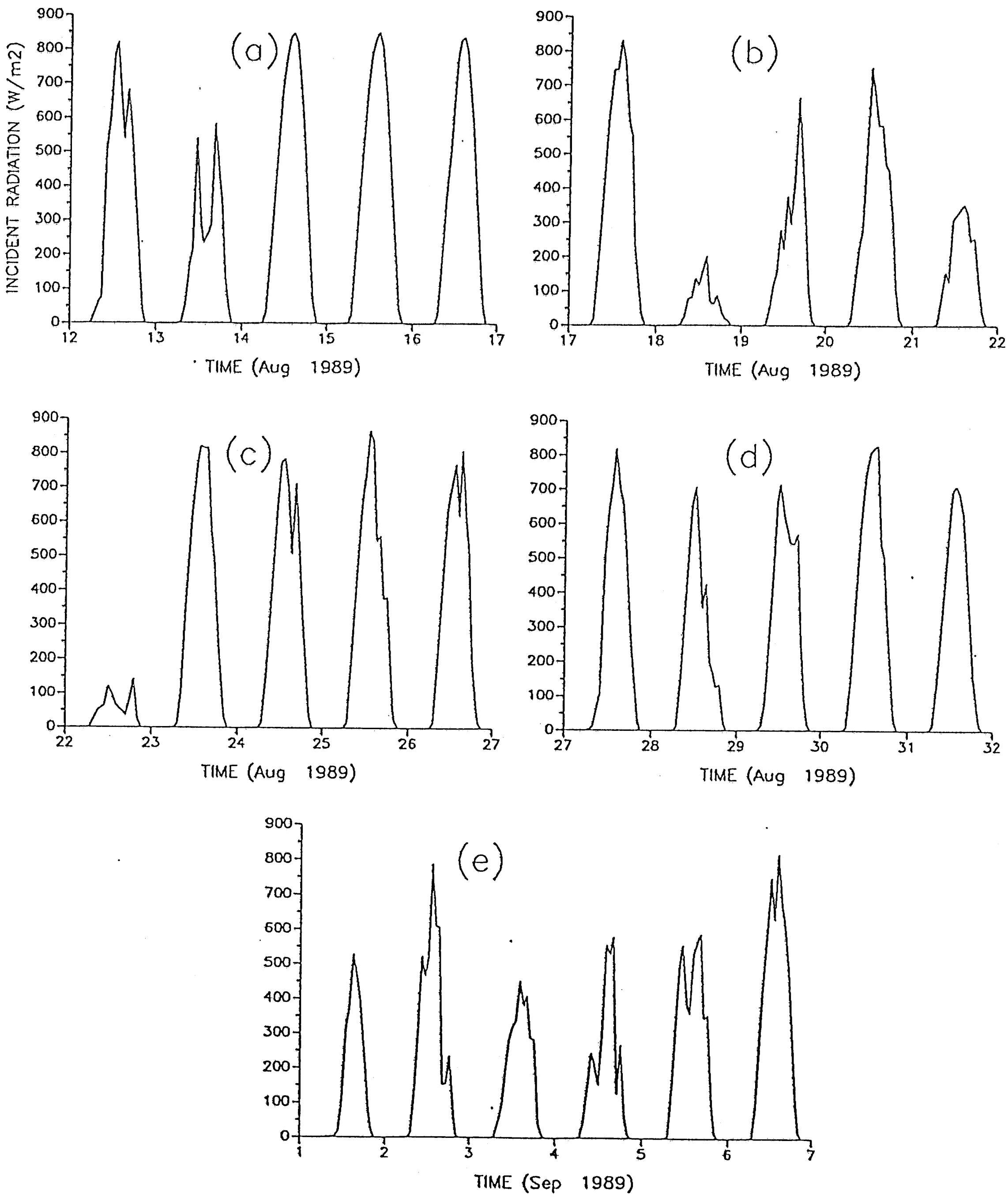


Figure IV–9(a–e). Incident Radiation for Complete Record

V. DATA INTERPRETATION

(1) GENERAL OBSERVATIONS

The volume of field measurements obtained in this study made it possible to investigate the time dependent temperature regimes of a shallow bay and its adjacent profundal waters with considerably more accuracy and resolution than had been done previously. The record provided data for the intense heating days of August 14 – 17 and the strong cooling of the cold and calm night of September 5 – 6 (see Figure IV–8). These periods make possible the study of temperature dynamics associated with diurnal surface heat transfer. However, other events of interest are contained in this record. One example of such an event would be the transitional two–day cooling period of August 18 & 19, when the lack of solar radiation and the 10 – 15° C drop in average air temperature combined to cool the average morning bay temperature by more than 5° C.

Solar heating and surface cooling are foremost among the naturally occurring heat transfer processes that directly affect the temperature distribution of the bay studied. Ground water intrusion, vegetation, and wind effects can also be significant, and will be addressed in the following sections.

(2) THE DIURNAL HEATING/COOLING CYCLE

The diurnal heating and cooling cycle consists of a solar heating period during the daylight hours and a cooling period at night. The intensity and duration of these periods varied greatly depending on fluctuations in cloud cover, weather fronts, morning fog, etc. During August and the first week of September the heating period generally began between 7:00 and 9:00 and ended between 17:00 and 19:00. The remaining period, from just before dusk until shortly after dawn can generally be considered the cooling period of the diurnal cycle. Figure V–1 shows the computed bay isotherms at 3 hour intervals from 7:00, August 14 to 4:00, August 15. These plots were based on hourly average temperatures. The figures show typical daytime stratification with top to bottom temperature differences from 7 to 10° C in the shallow water and convective cooling layers that reach below the 0.5 meter depth in the shallows and below the 2.5 meter depth at the deeper end of the transect.

2.1 SOLAR HEATING

Evidence of strong solar heating can be found during the first week of the complete record, especially during August 14 – 16. Throughout this period, the water temperature near the surface increased rapidly in response to incident radiation (see Figures IV–2, IV–3, & IV–4). The lesser thermal inertia of the shallow water caused it to warm faster than the deep water when subject to the same rate of surface heat transfer. A strong stratification caused by this solar surface heating is evident in the temperature vs. time records at different depths during these periods. Strong stratification is also evident in the 16:00, August 14 record (Figure V–1). This plot also shows a strong horizontal variation of the water temperatures between the shallow water (less than 1 meter) and the profundal waters. The horizontal temperature gradients found here are indicative of exchange flows (density currents) which may significantly effect transport processes in the bay .

2.2 CONVECTIVE SHORT–TERM COOLING

Cooling of littoral waters is evident by a drop in temperature and is associated with a weakening or elimination of thermal stratification caused by natural convection. The term "convective cooling" is sometimes used to describe this phenomenon. This destratification is the result of the surface water cooling to temperatures lower than the water beneath the surface. The cooler (more dense) surface water then sinks until it attains a neutral buoyancy (reaches water of the same temperature). The water temperature vs. time plots (Figures IV–2 to IV–7) contain numerous examples of convective cooling. The 4:00, August 15 record in Figure V–1 shows weak stratification in the upper 0.5 meters of the bay following the strong gradients of the previous afternoon. The night of September 5/6 is an example of very rapid heat loss, as the thermal inversion in Figure V–2 shows. The cooling that occurred during the night of September 5/6 was apparently strong enough to maintain an inversion of as much as 0.5° C for the entire cooling period. This is exceptionally high when compared to open water, where inversions typically do not exceed 0.1 to 0.2° C. The lowest probes at the 0.65 meter depth (Station 2) and 0.95 meter depth (Station 3) are seemingly insulated from this rapid cooling (see Figures IV–2 and IV–3) and are suspected of being partially in the sediment, due to frequent large inversions during cooling periods.

(3) SUSTAINED COOLING

A gradual seasonal increase in average water temperature is apparent during the first five days of the record and a gradual decline of the overall water temperature exists during the rest of the record. The decline was initiated by a cold front which passed through on the cloudy days of August 18 and 19. The trend toward overall cooling is the result of the diminishing incident radiation and cooler night–time air temperatures. During the early morning of August 18, the air temperature dropped and stayed below 20° C until the afternoon of August 19. From this time on, the air temperature dropped below the coldest water temperature every night except on the night from August 31/September 1.

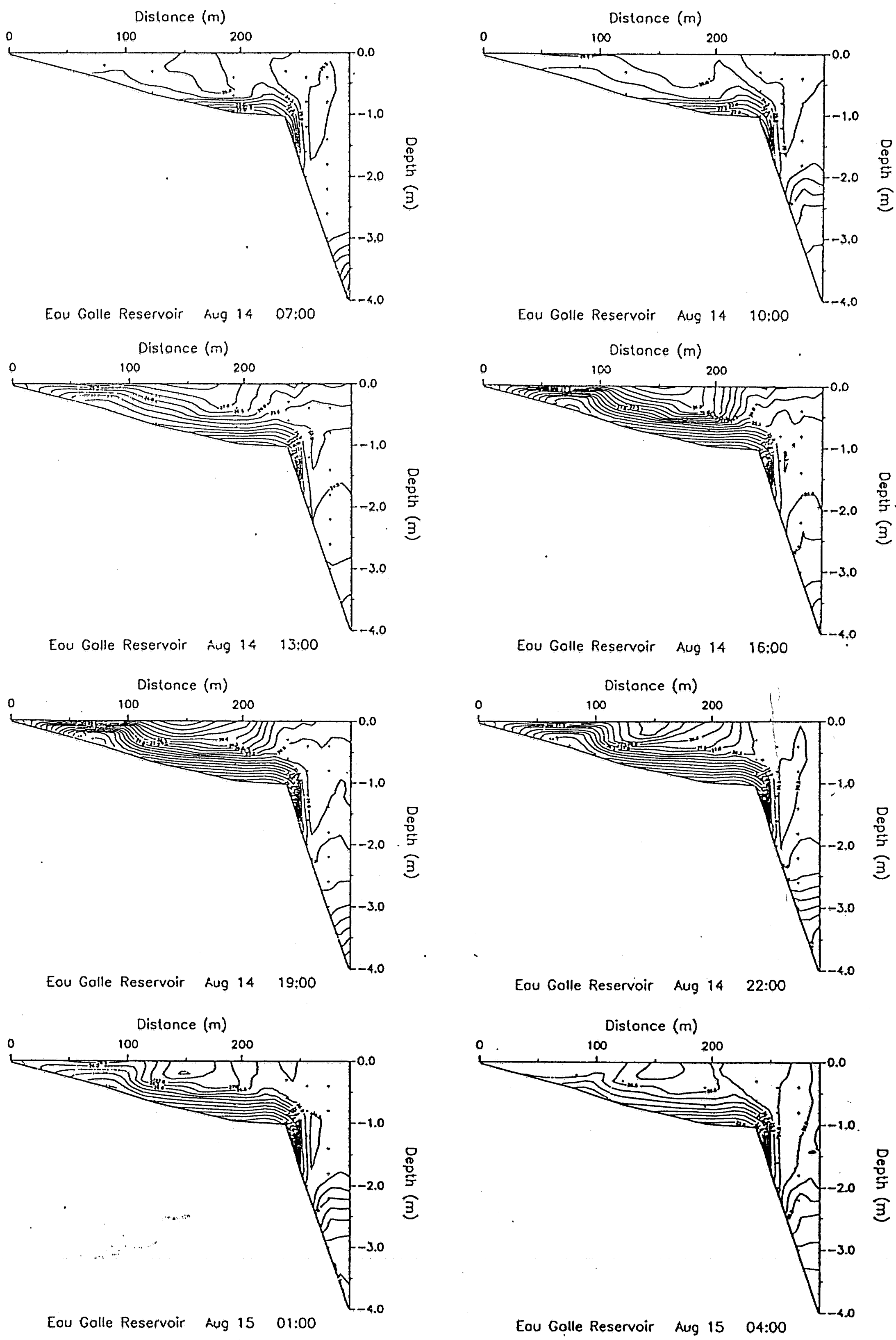


Fig. V-1. Bay Isotherms (7:00, Aug 14 to 4:00, Aug 15)

(4) VEGETATION EFFECTS

There are two major effects associated with aquatic plant growth with which this study must be concerned. The first is the attenuation of light during solar heating. The temperature profile of a body of water during solar heating is affected by the depth(s) at which the radiation is absorbed. The rate of light attenuation can vary widely, depending on the density and vertical distribution of vegetation as well as the presence of algal blooms or suspended sediment. Heating can also be affected by the ability of larger plants (macrophytes) to inhibit the horizontal and vertical movement of water. While dense vegetation does not prohibit the movement of water, the drag that it imposes can impede flows that are driven by the small density differences found in lakes and reservoirs.

In the shallow regions of the bay under study, dense vegetation prevented most light penetration below the top 0.25 meter of water. This estimate of light penetration is based on plant distribution (see Figure V–3). Quantitative information on vegetation density in Eau Galle Reservoir is available (Filbin & Barko, 1985). Dense vegetation (mostly Ceratophylum demersum) and Blue–green algae existed from the shoreline out to nearly the 1.0 meter depth. Plant mass gradually diminished out to 3 meter depth and did not exist beyond that depth. A seasonal decrease in vegetation density was also observed toward the end of the record. No records or measurements of plant density were taken during the recording of water temperatures. Nevertheless, it is safe to say that the effects on the temperature profile were substantial. In addition to strong radiation attenuation, which is apparent in the strong water stratification records, the dense vegetation also caused resistance to water movement within the littoral region, as illustrated by the existence of unusually high (0.5° C) inversions.

(5) GROUND WATER INTRUSION

The presence of ground water can be inferred from the water temperature record between the 0.95 and the 1.0 meter depths. Throughout the 26 day complete record, the coldest temperatures are consistently found near the bottom in this region (see Figures IV–3 & IV–4). The complete absence of this cold water elsewhere in the record (even near the bottom at 4 meters – Figure IV–7) suggests an external source. The source(s) of ground water in the bay have not been located, but their existence is likely given the elevation of the land surrounding the reservoir. Ground water would typically have temperatures on the order of 10 to 15° C. Measured coldest water temperatures were above 15° C until September 5.

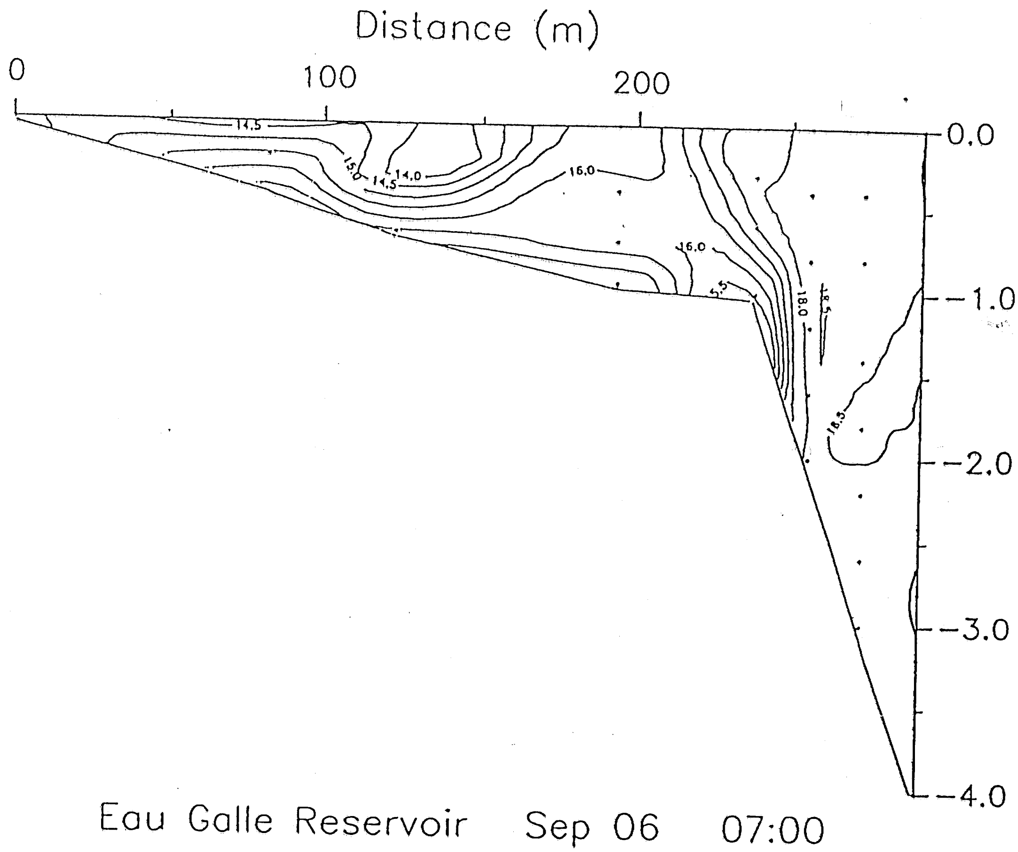


Fig. V-2. Bay Isotherms (7:00, Sep 6)

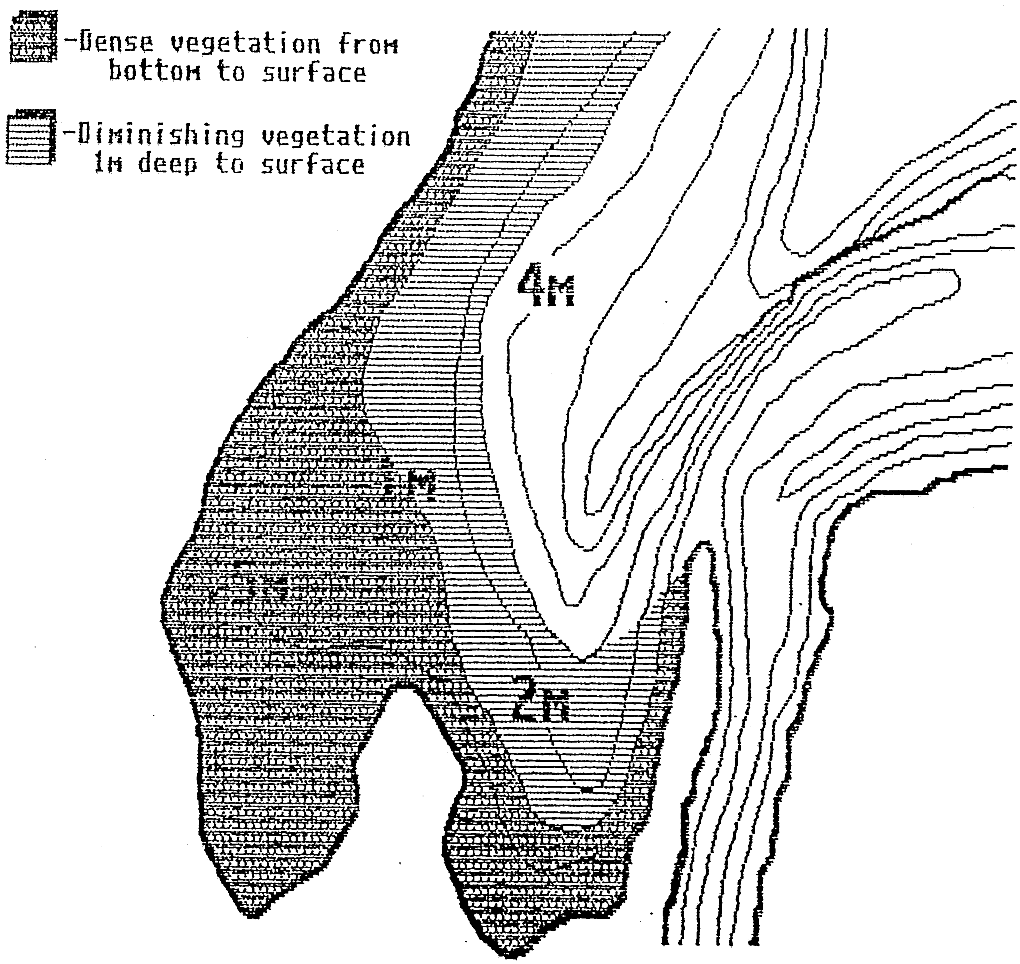


Fig. V-3. Approximate Vegetation Density

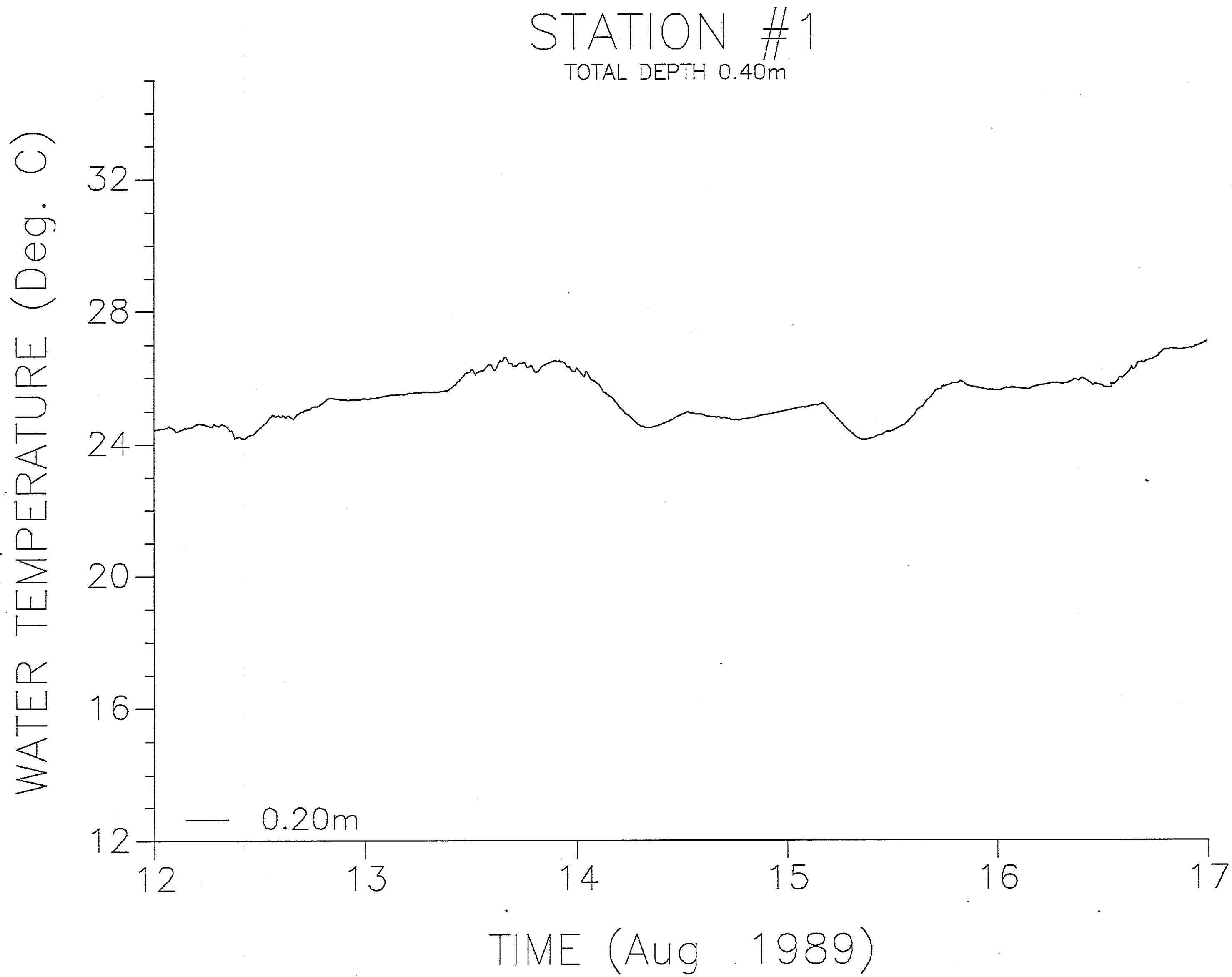
VI. REFERENCES

1. Stefan, H. G., G. M. Horsch & J. W. Barko, 1989. A model for the estimation of convective exchange in the littoral region of a shallow lake during cooling, Hydrobiologia 174: 225–234.

2. Filbin, G. J., & J. W. Barko, 1985. Growth and nutrition of submersed macrophytes in a eutrophic Wisconsin impoundment, Journal of Freshwater Ecology 3: 275–288.

Appendix A

Time Series Plots of the Complete Record
(Water Temperatures and Weather Parameters)


STATION #1
TOTAL DEPTH 0.40m
WATER TEMPERATURE (Deg. C)
32
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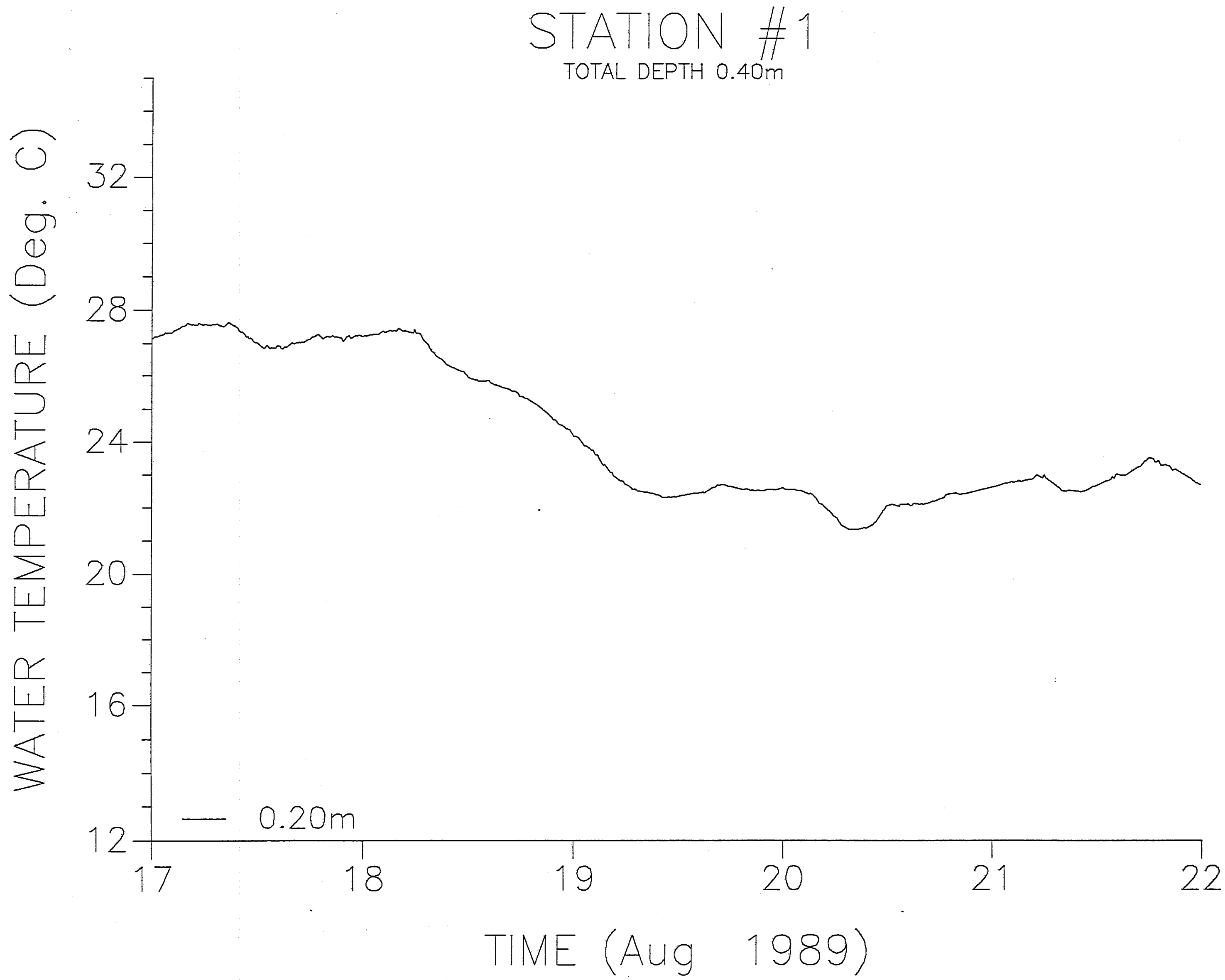
16
12
0.20m
12
13
14
15
16
17
TIME (Aug 1989)



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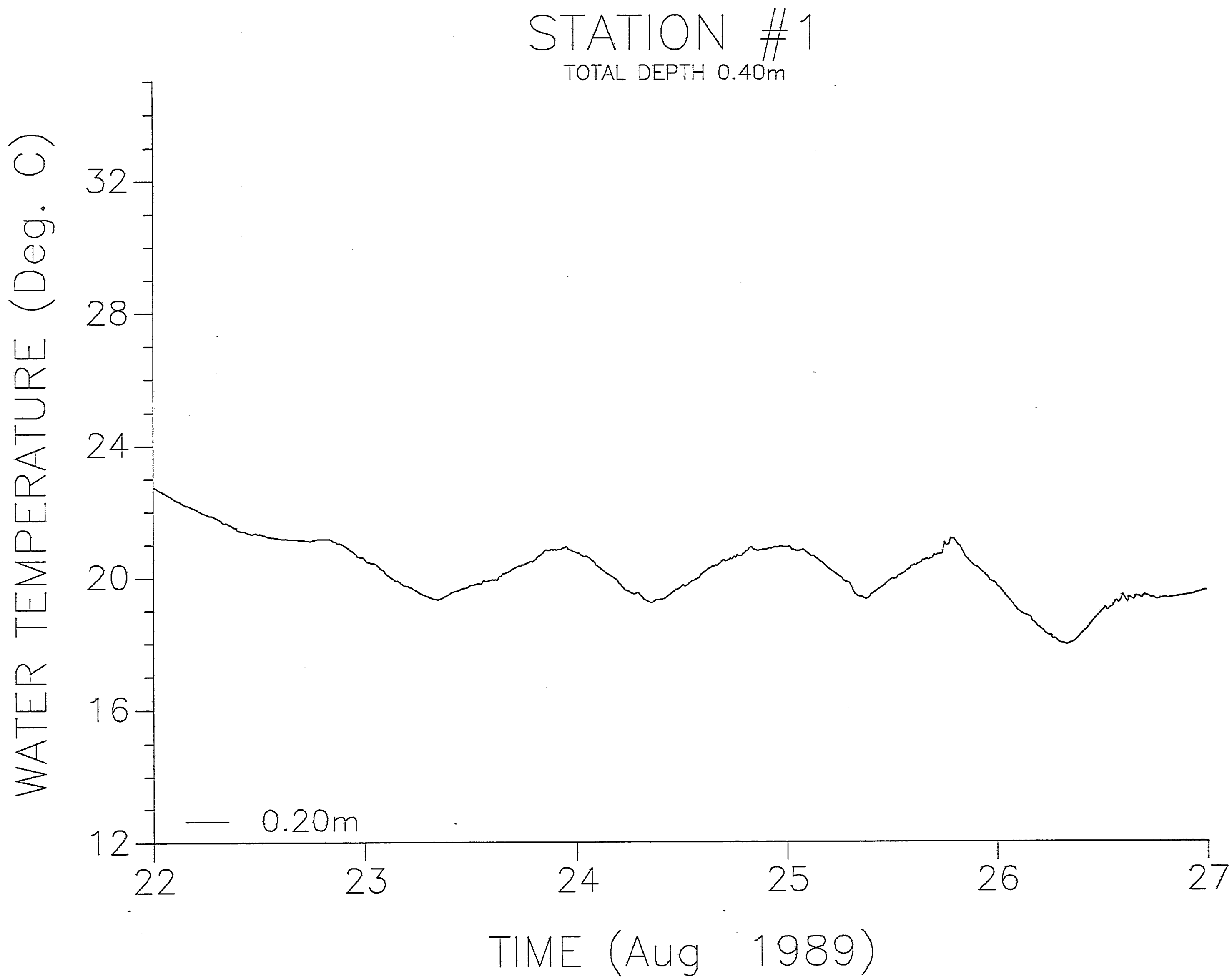
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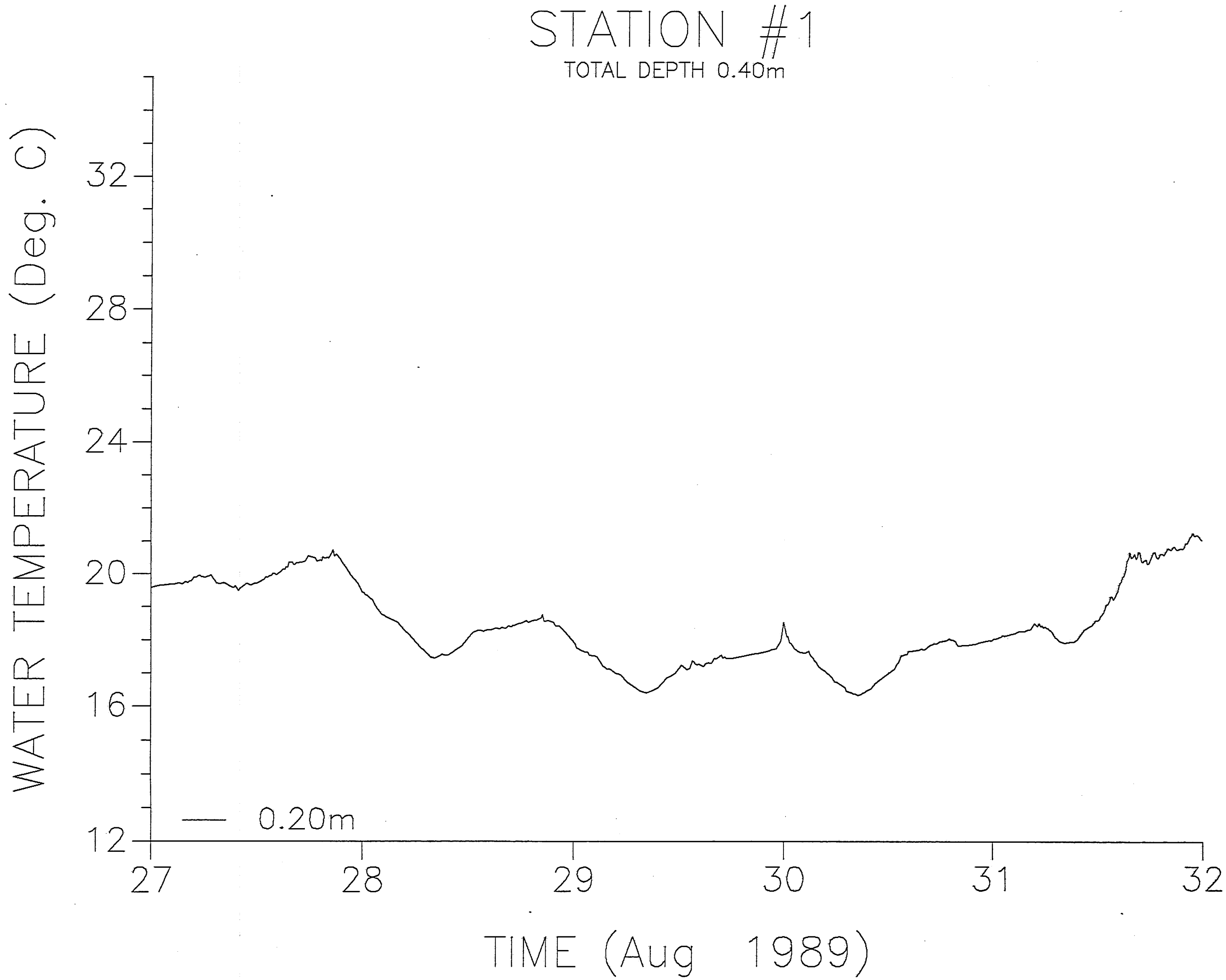
TIME (Aug 1989)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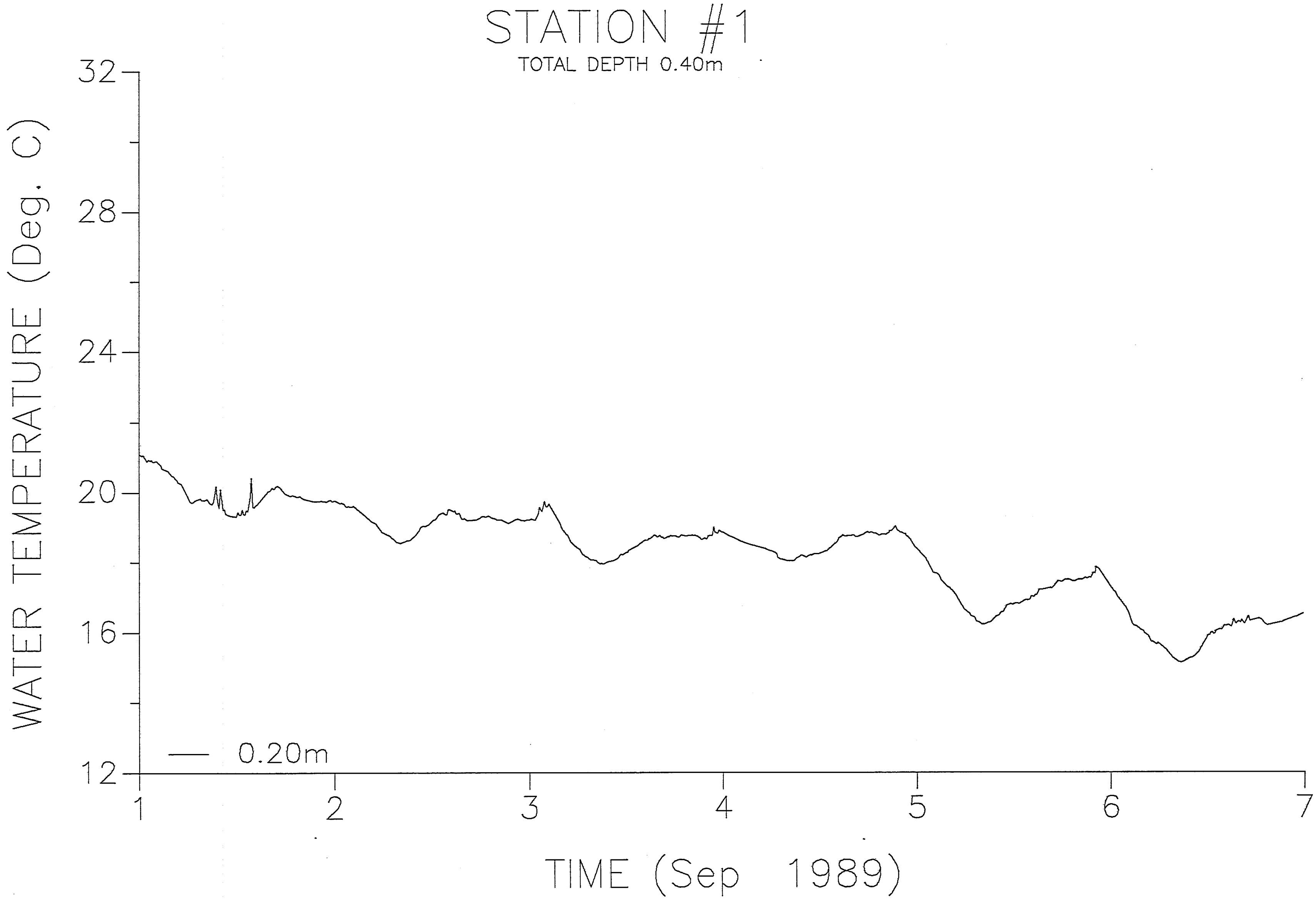
TIME (Aug 1989)



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24
20
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4
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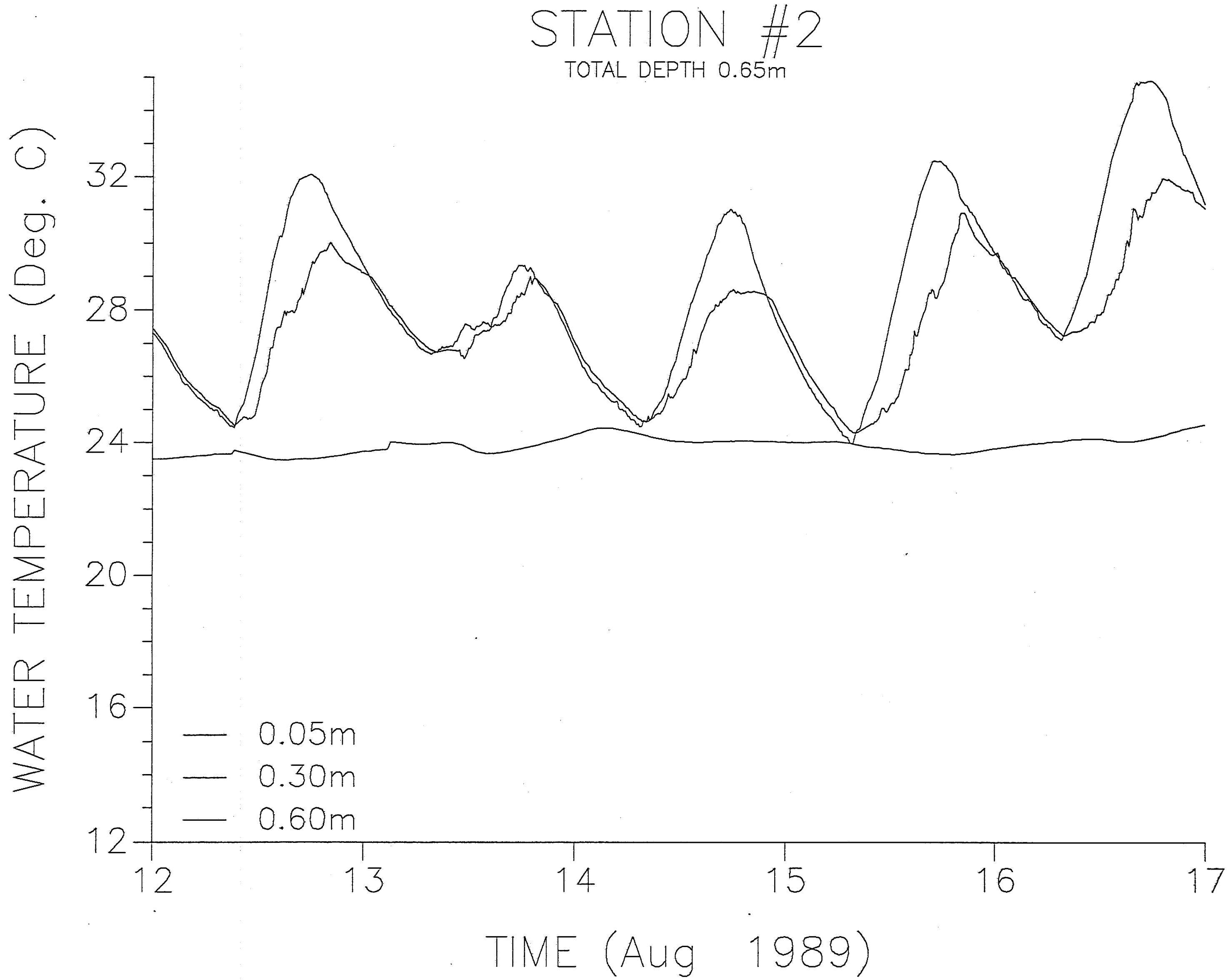
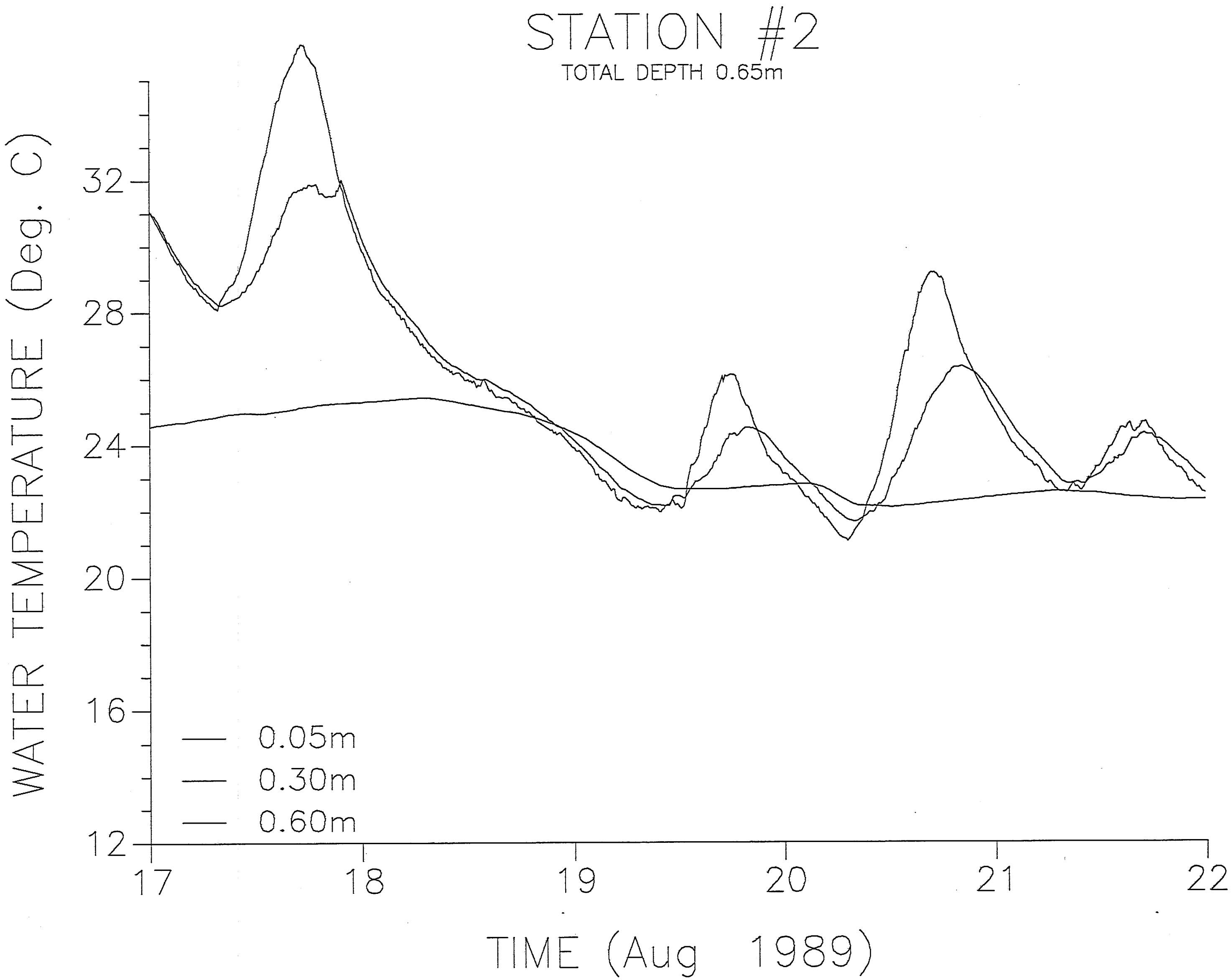
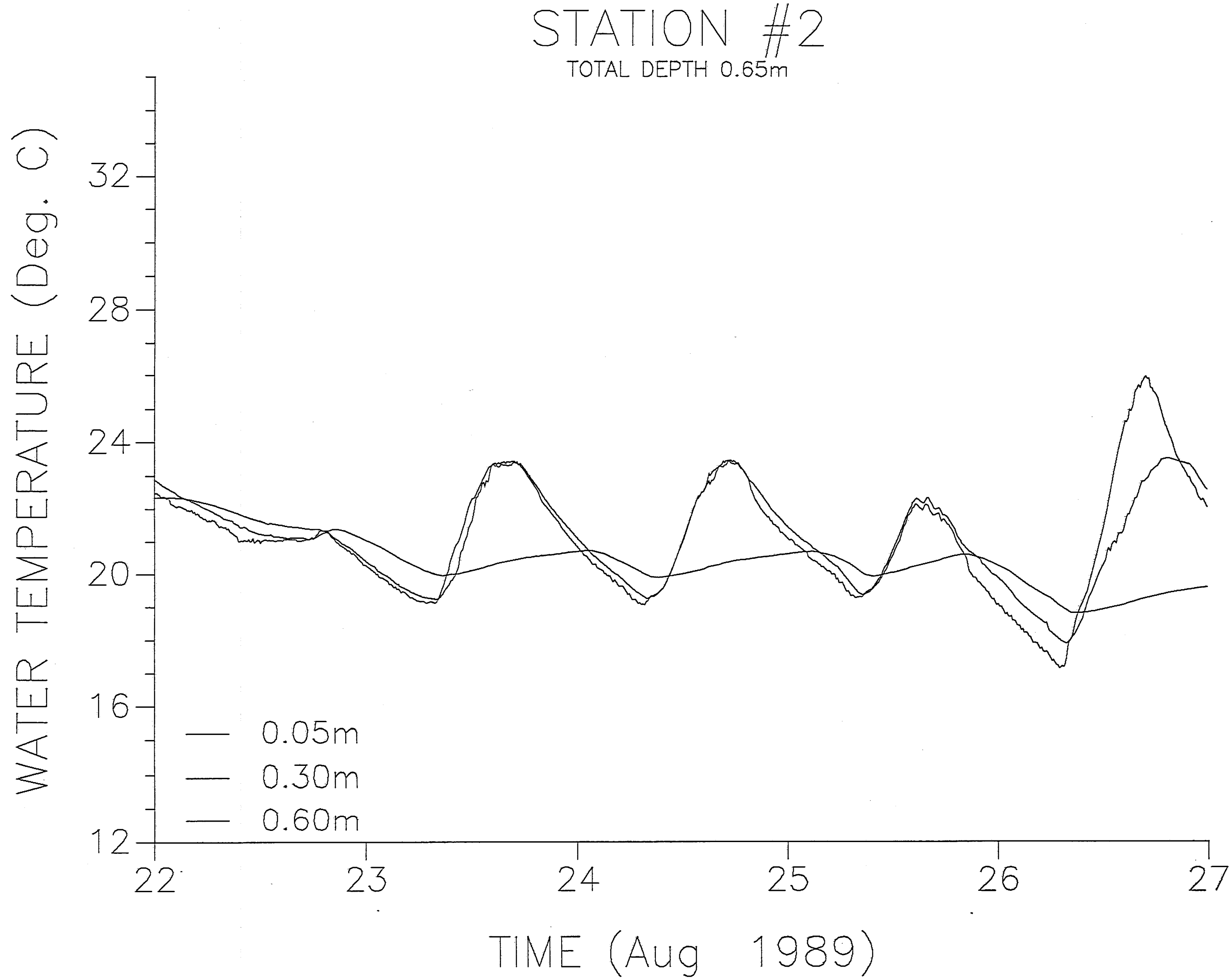
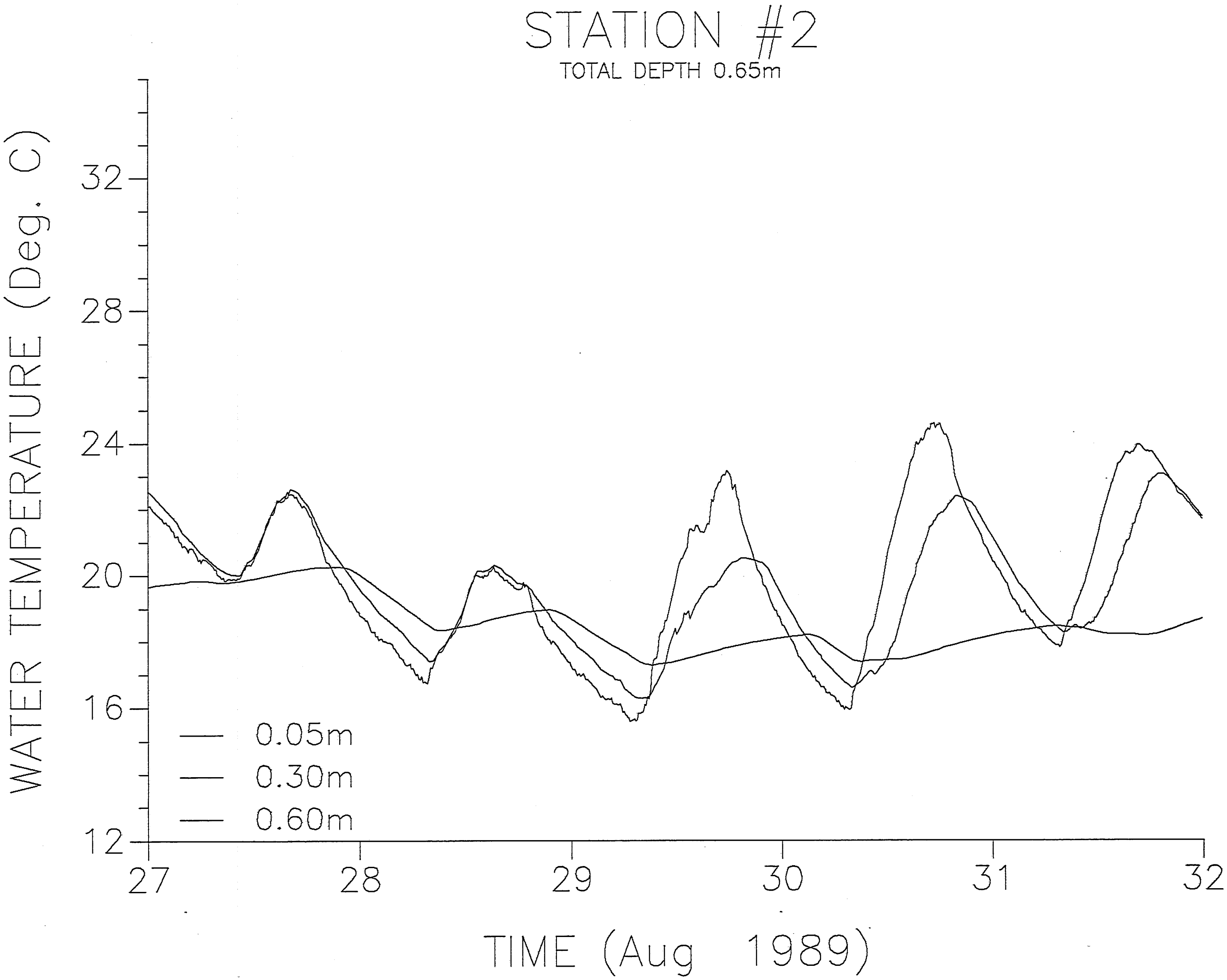
6
7
TIME (Sep 1989)

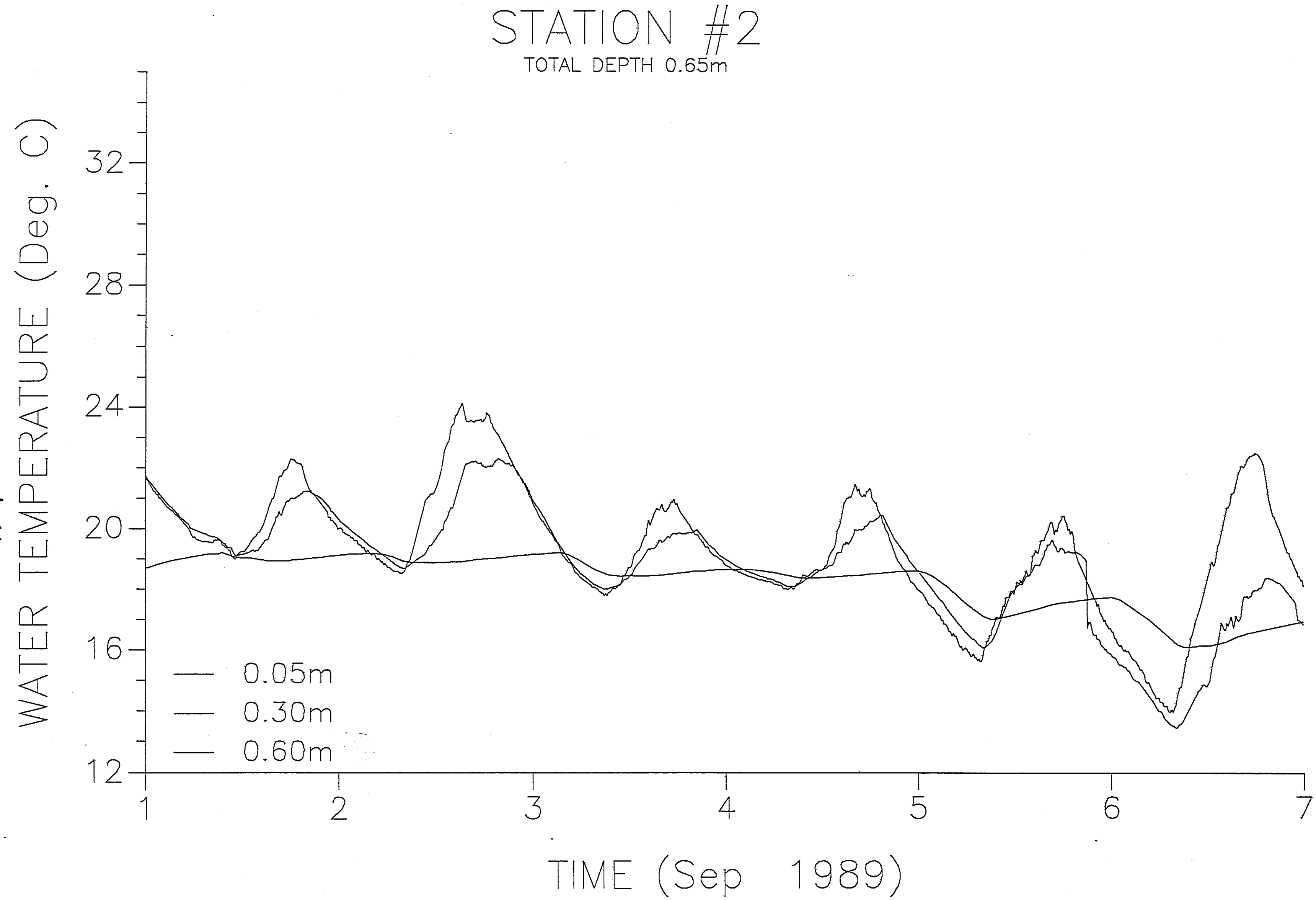

STATION #2
TOTAL DEPTH 0.65m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.30m
0.60m
12
13
14
15
16
17
TIME (Aug 1989)

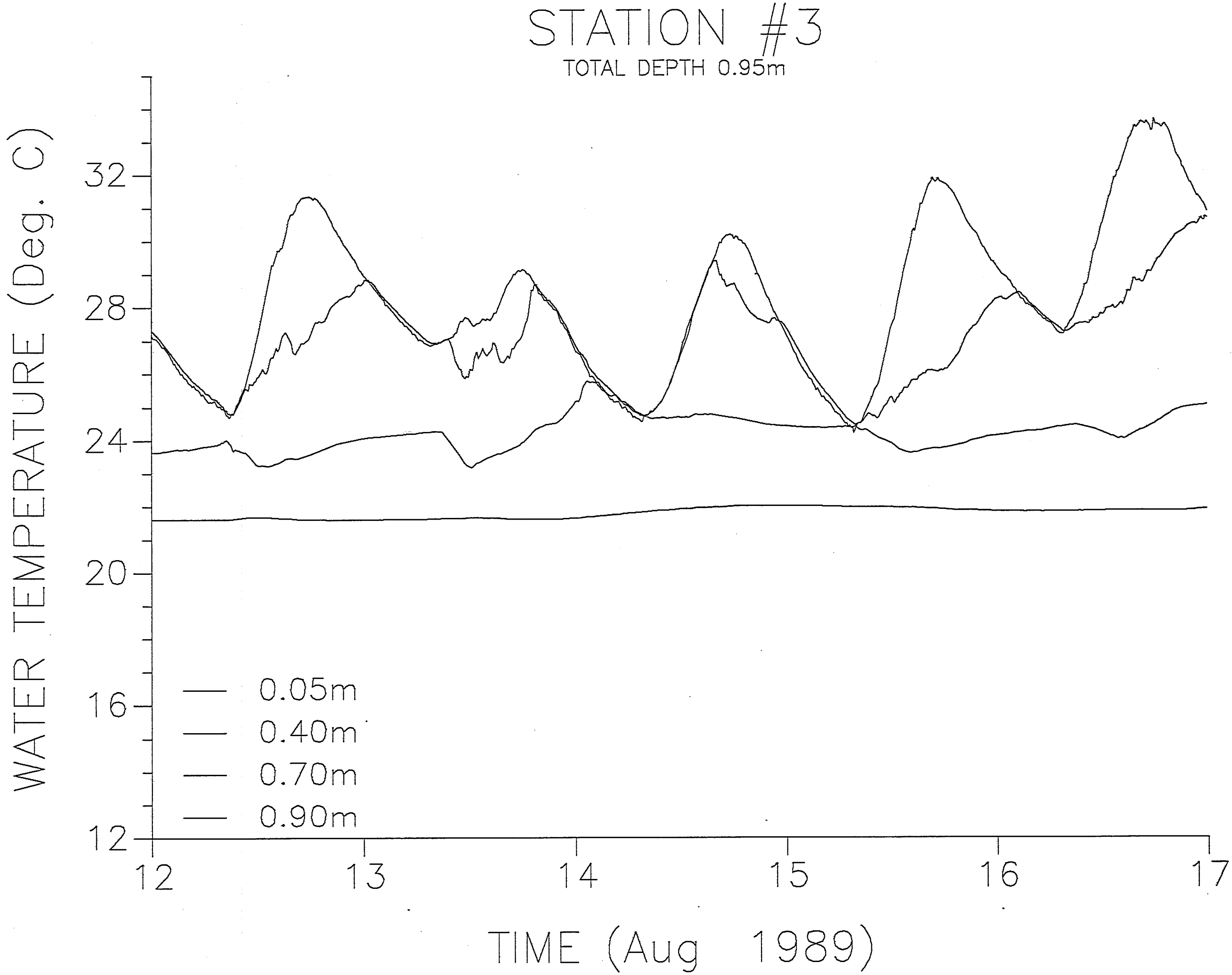

STATION #2
TOTAL DEPTH 0.65m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.30m
0.60m
17
18
19
20
21
22
TIME (Aug 1989)

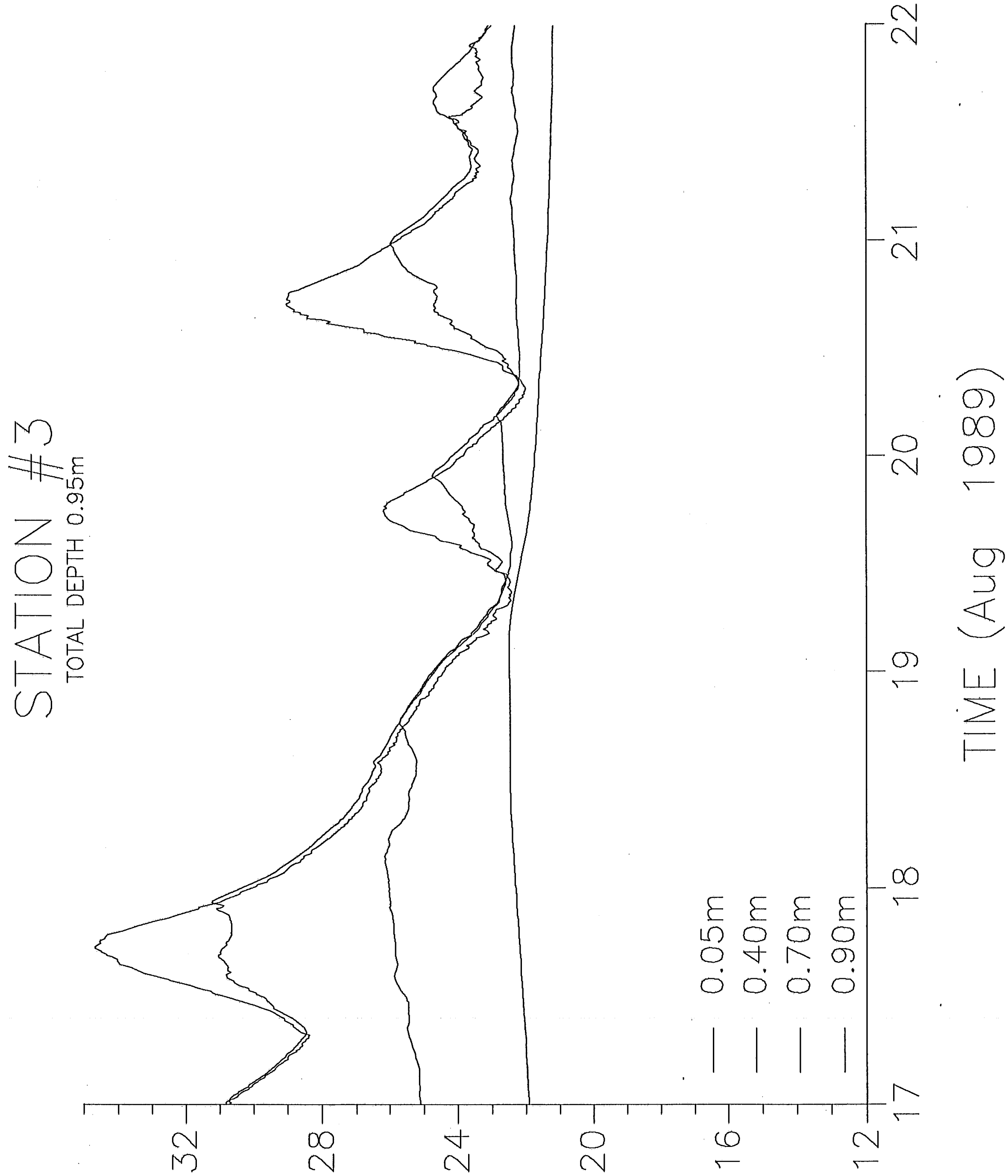

STATION #2
TOTAL DEPTH 0.65m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.30m
0.60m
22
23
24
25
26
27
TIME (Aug 1989)



STATION #2
TOTAL DEPTH 0.65m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.30m
0.60m
27
28
29
30
31
32
TIME (Aug 1989)


STATION #2
TOTAL DEPTH 0.65m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.30m
0.60m
1
2
3
4
5
6
7
TIME (Sep 1989)

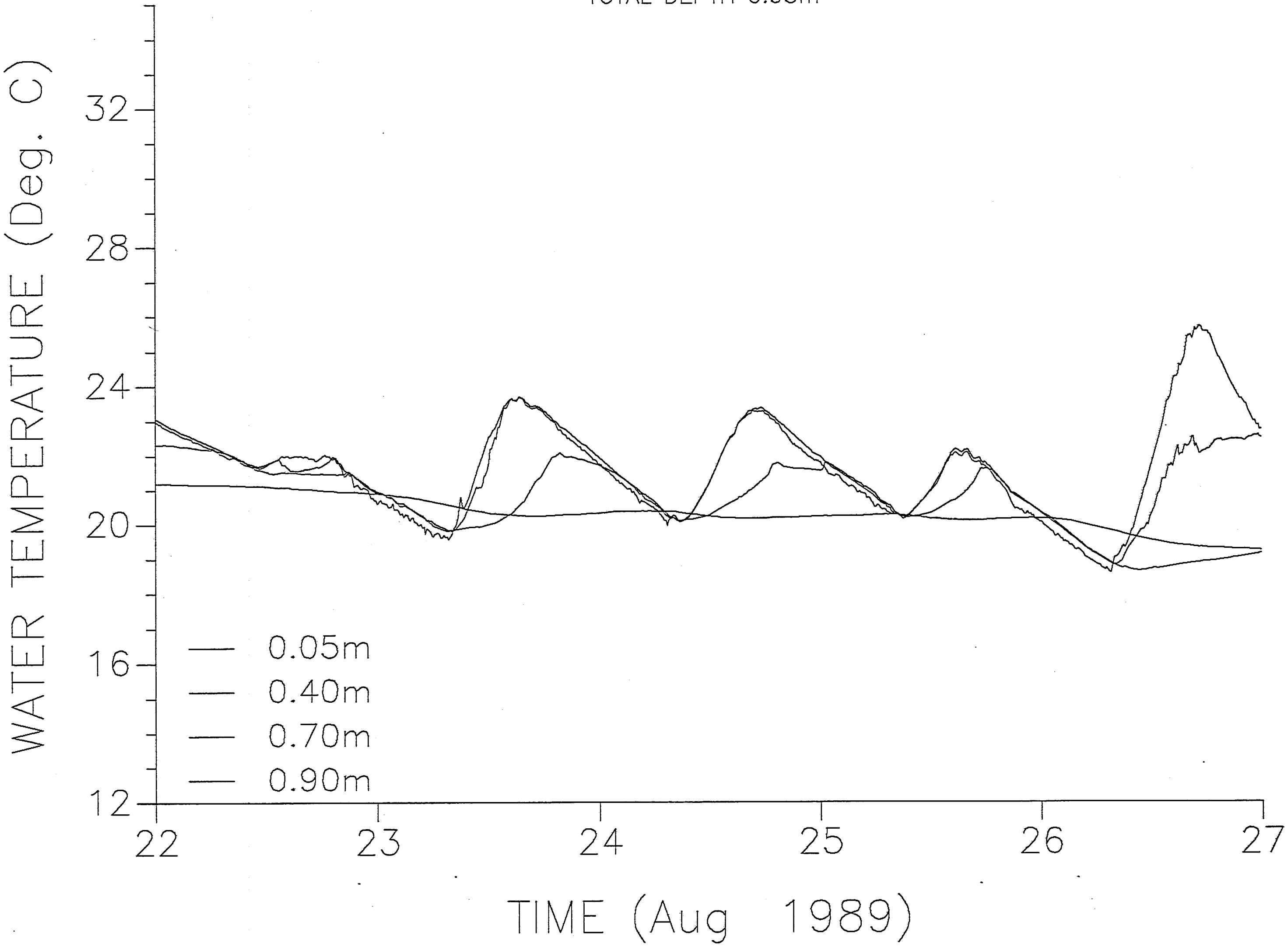

STATION #3
TOTAL DEPTH 0.95m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.70m
0.90m
12
13
14
15
16
17
TIME (Aug 1989)

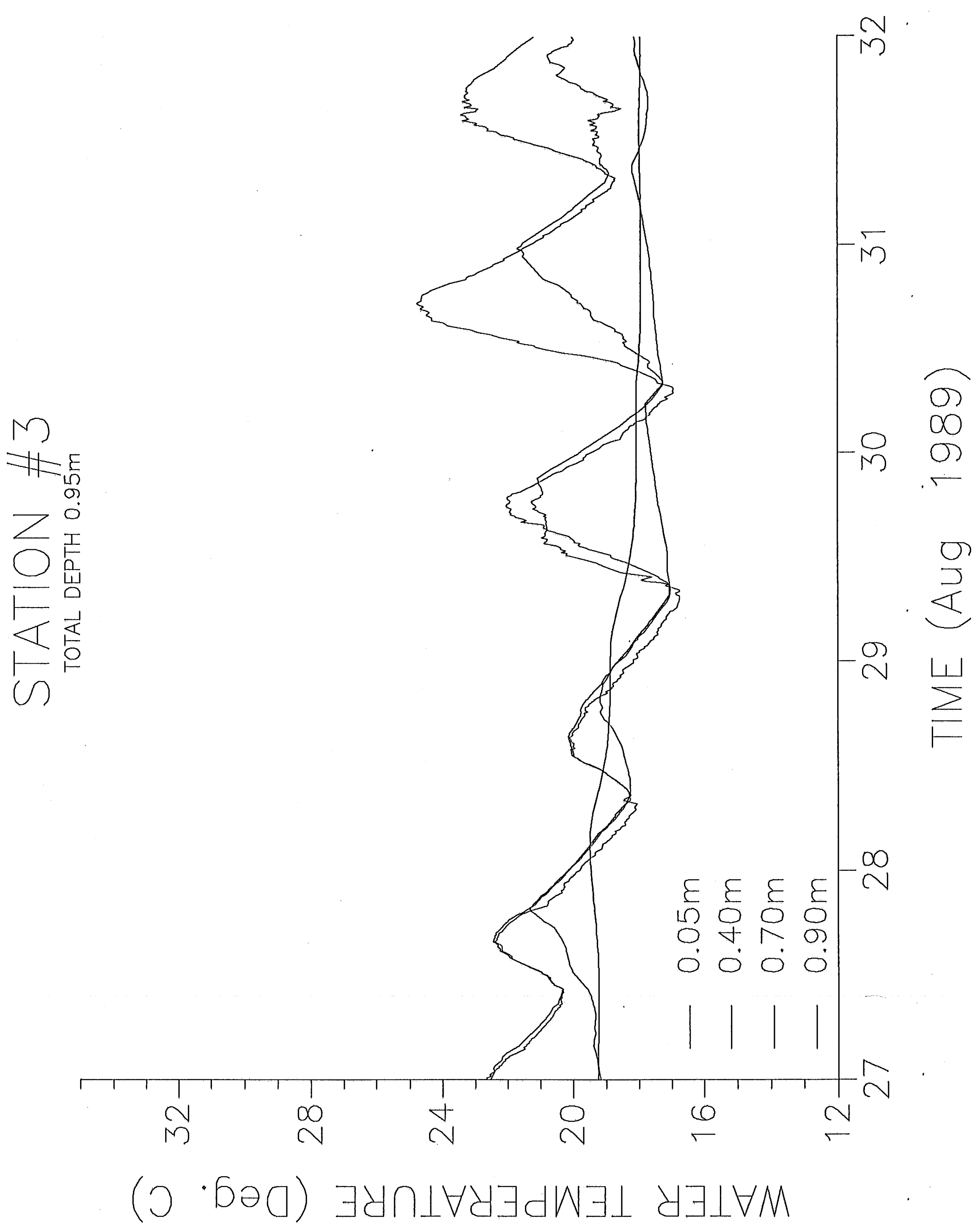


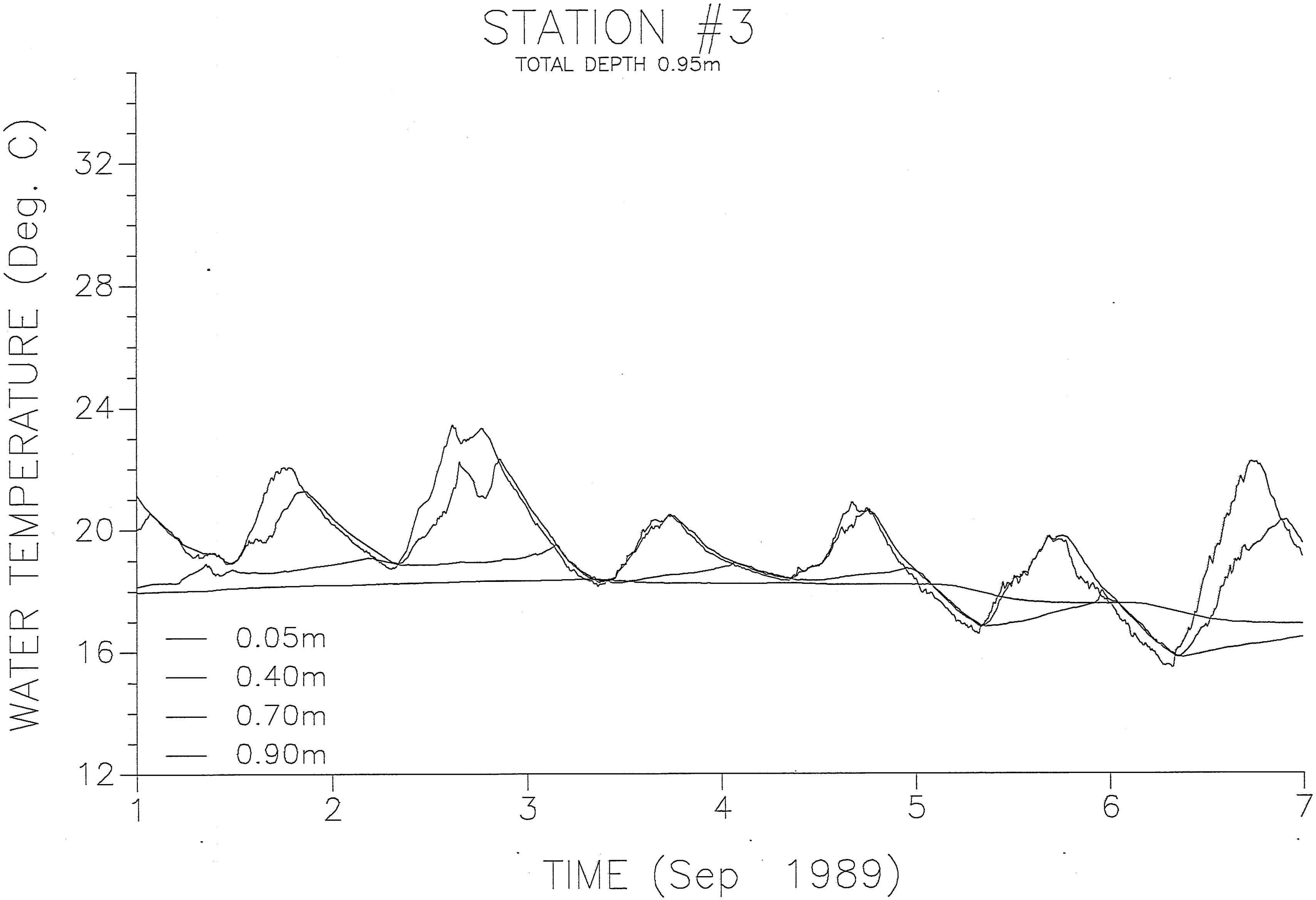
STATION #3
TOTAL DEPTH 0.95m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
17
18
19
20
21
22
TIME (Aug 1989)
0.05m
0.40m
0.70m
0.90m

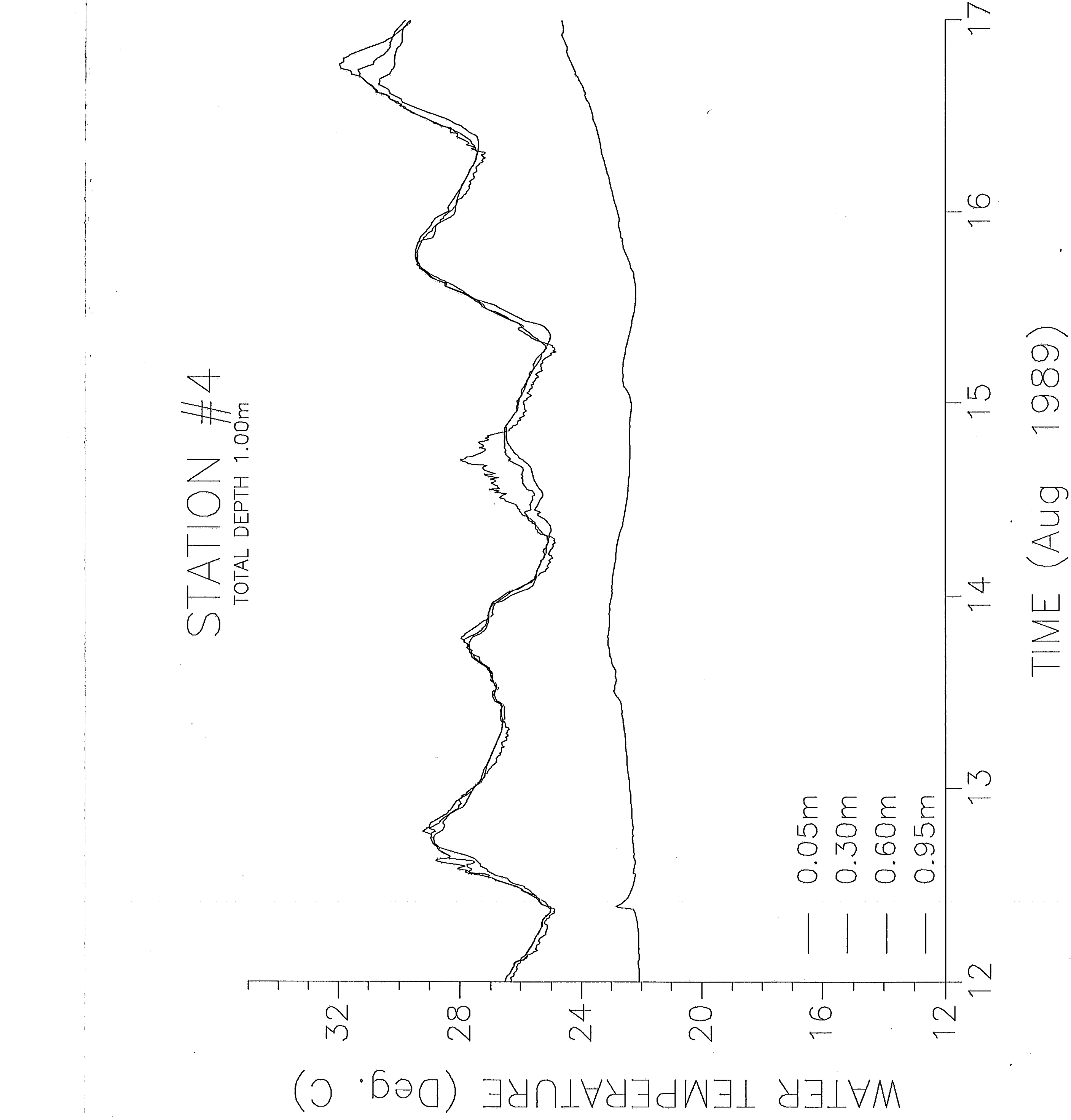
STATION #3

TOTAL DEPTH 0.95m

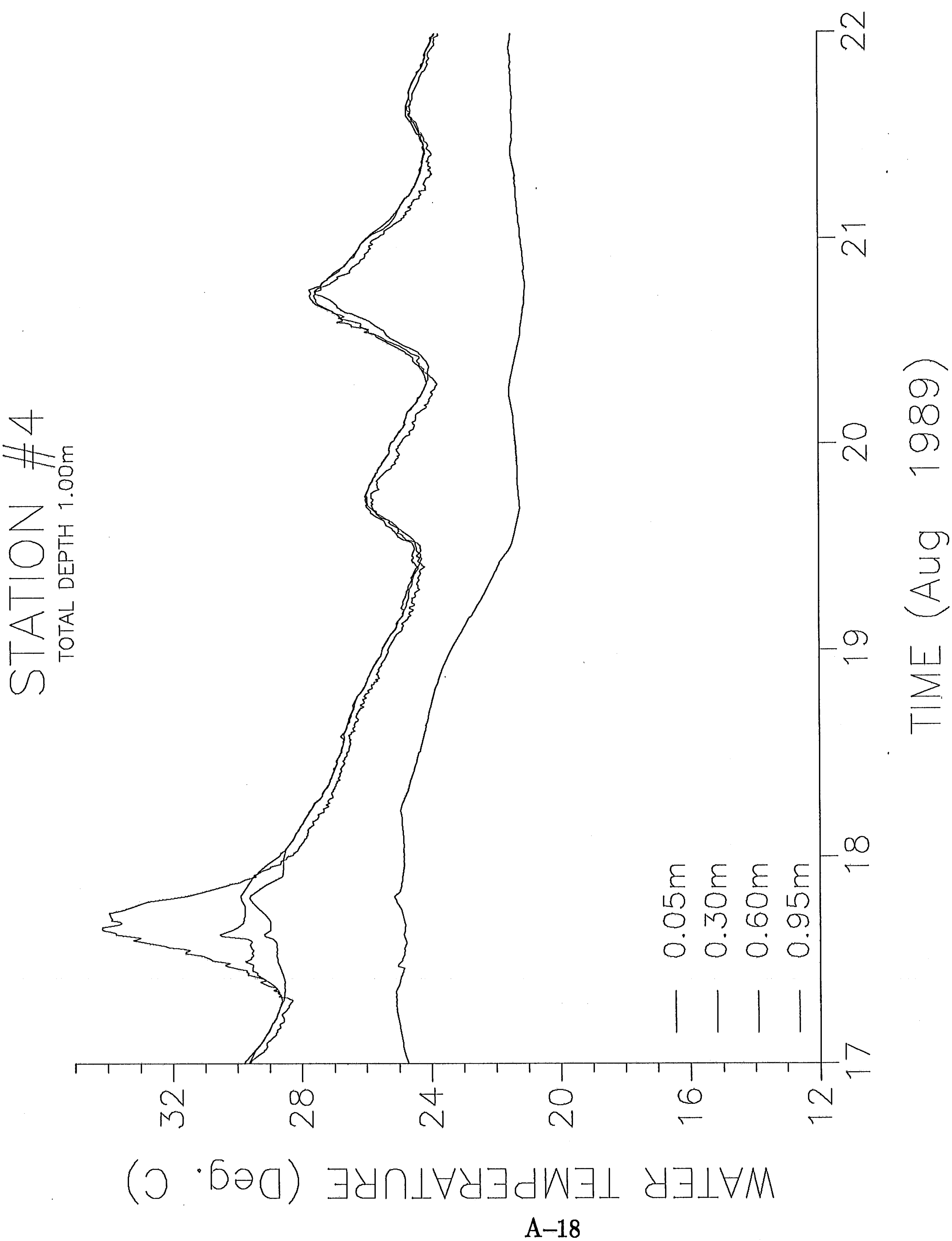


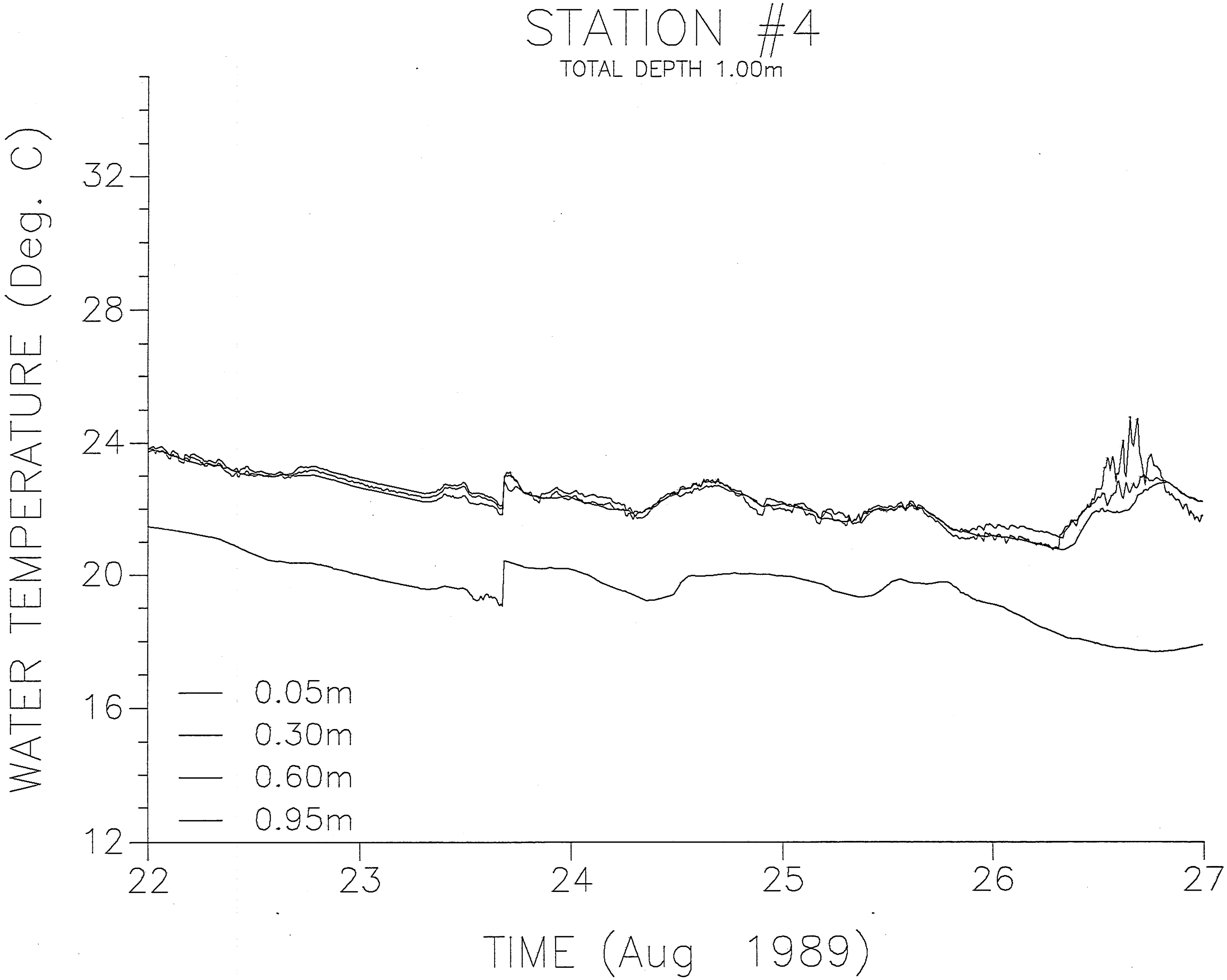

STATION #3
TOTAL DEPTH 0.95m
0.05m
0.40m
0.70m
0.90m
WATER TEMPERATURE (Deg. C)
12
16
20
24
28
32
27
28
29
30
31
32
TIME (Aug 1989)


STATION #3
TOTAL DEPTH 0.95m
WATER TEMPERATURE (Deg. C)
12
16
20
24
28
32
0.05m
0.40m
0.70m
0.90m
1
2
3
4
5
6
7
TIME (Sep 1989)



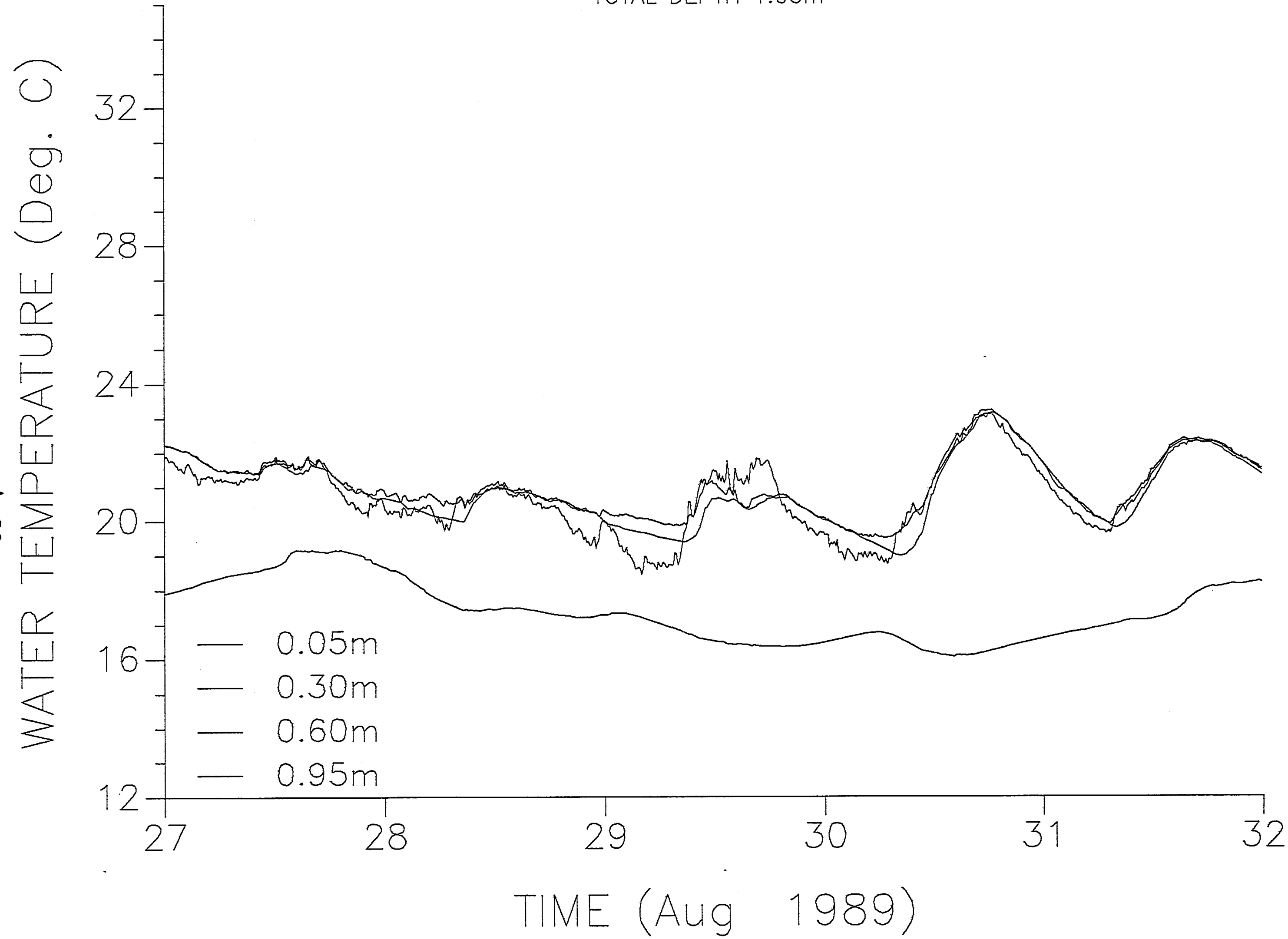
STATION #4
TOTAL DEPTH 1.00m
0.05m
0.30m
0.60m
0.95m
32
28
24
20
16
12
12
13
14
15
16
17
TIME (Aug 1989)
WATER TEMPERATURE (Deg. C)

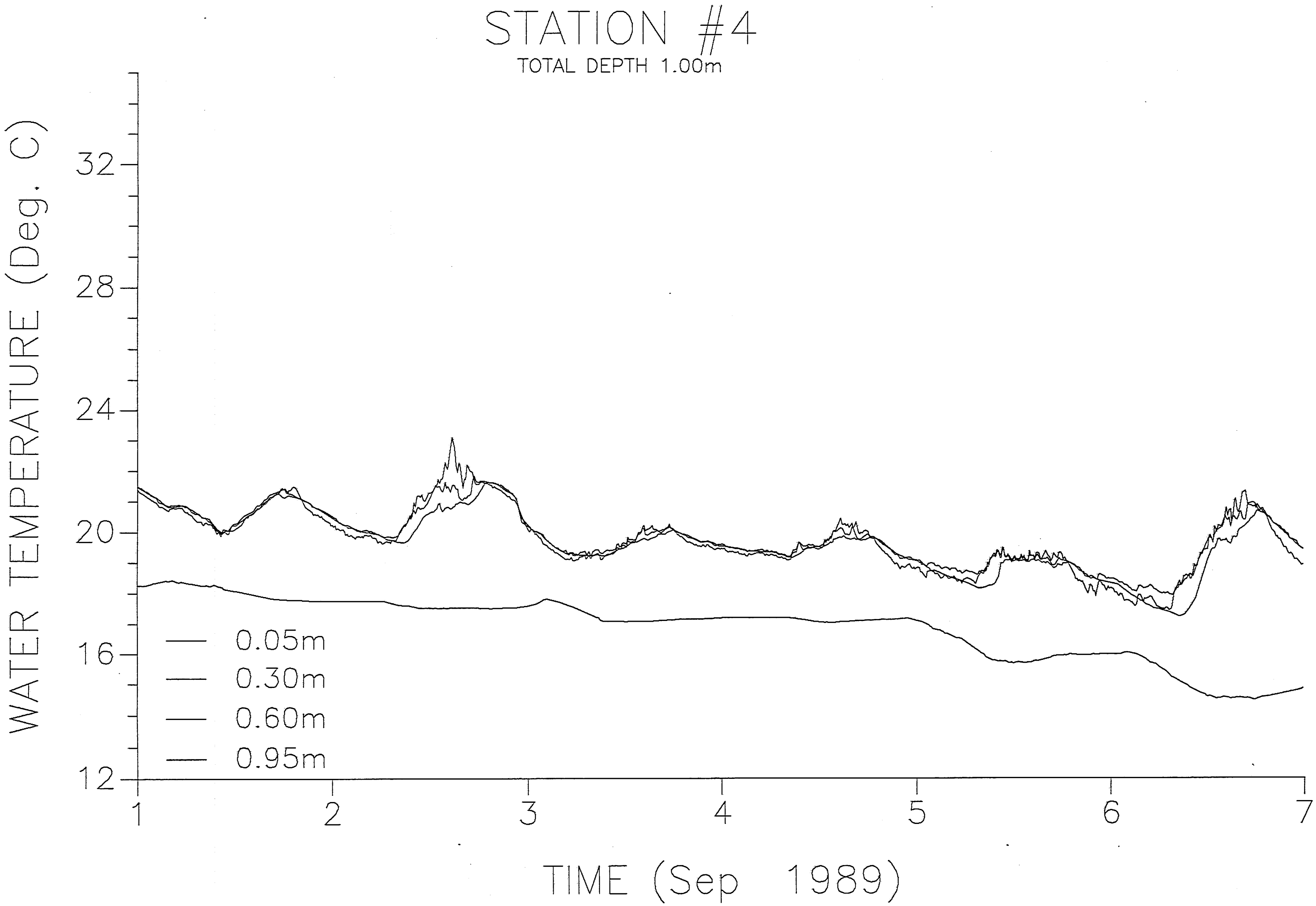

STATION #4
TOTAL DEPTH 1.00m
WATER TEMPERATURE (Deg. C)
12
16
20
24
28
32
TIME (Aug 1989)
17
18
19
20
21
22
0.05m
0.30m
0.60m
0.95m

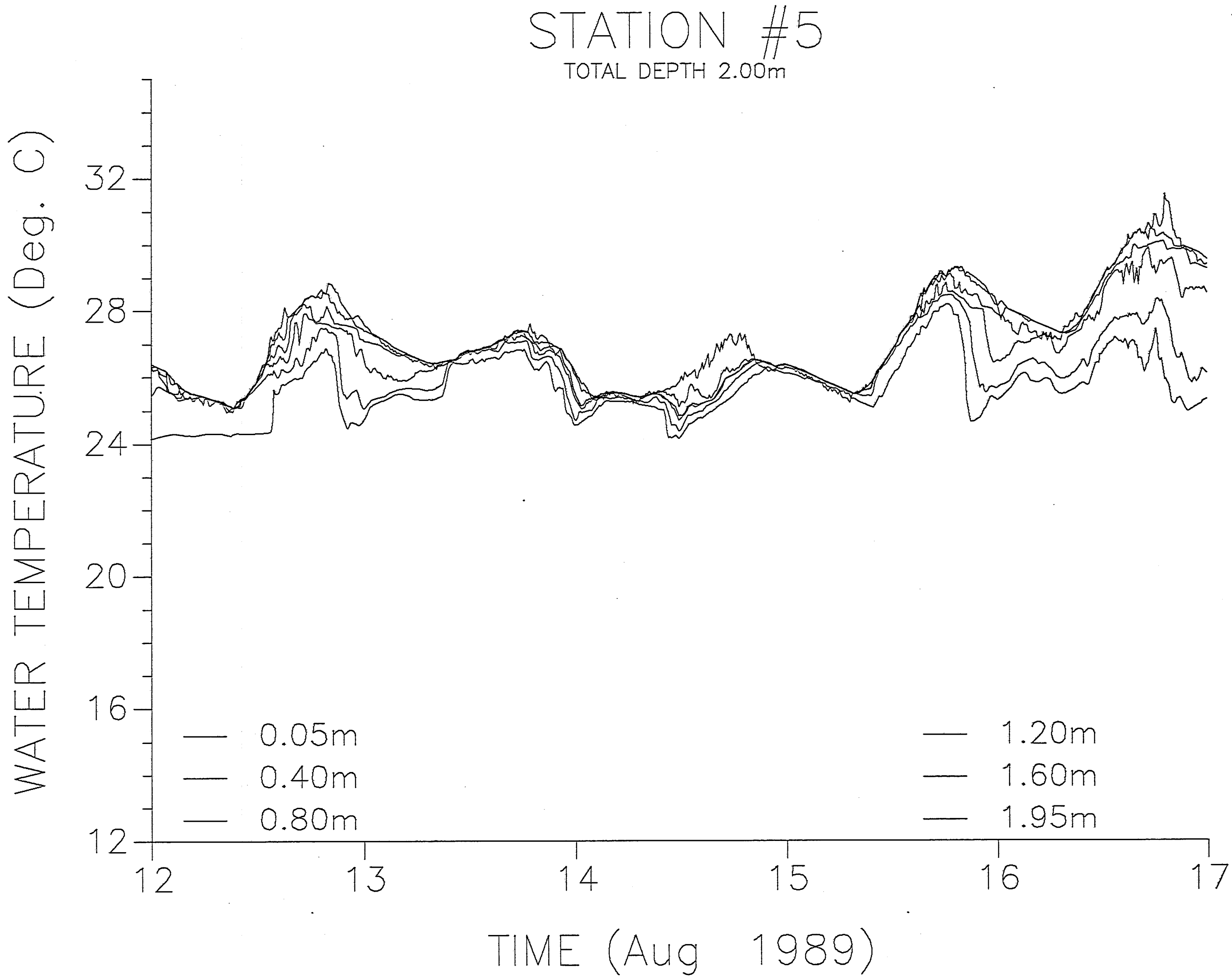

STATION #4
TOTAL DEPTH 1.00m
WATER TEMPERATURE (Deg. C)
12
16
20
24
28
32
22
23
24
25
26
27
TIME (Aug 1989)
0.05m
0.30m
0.60m
0.95m

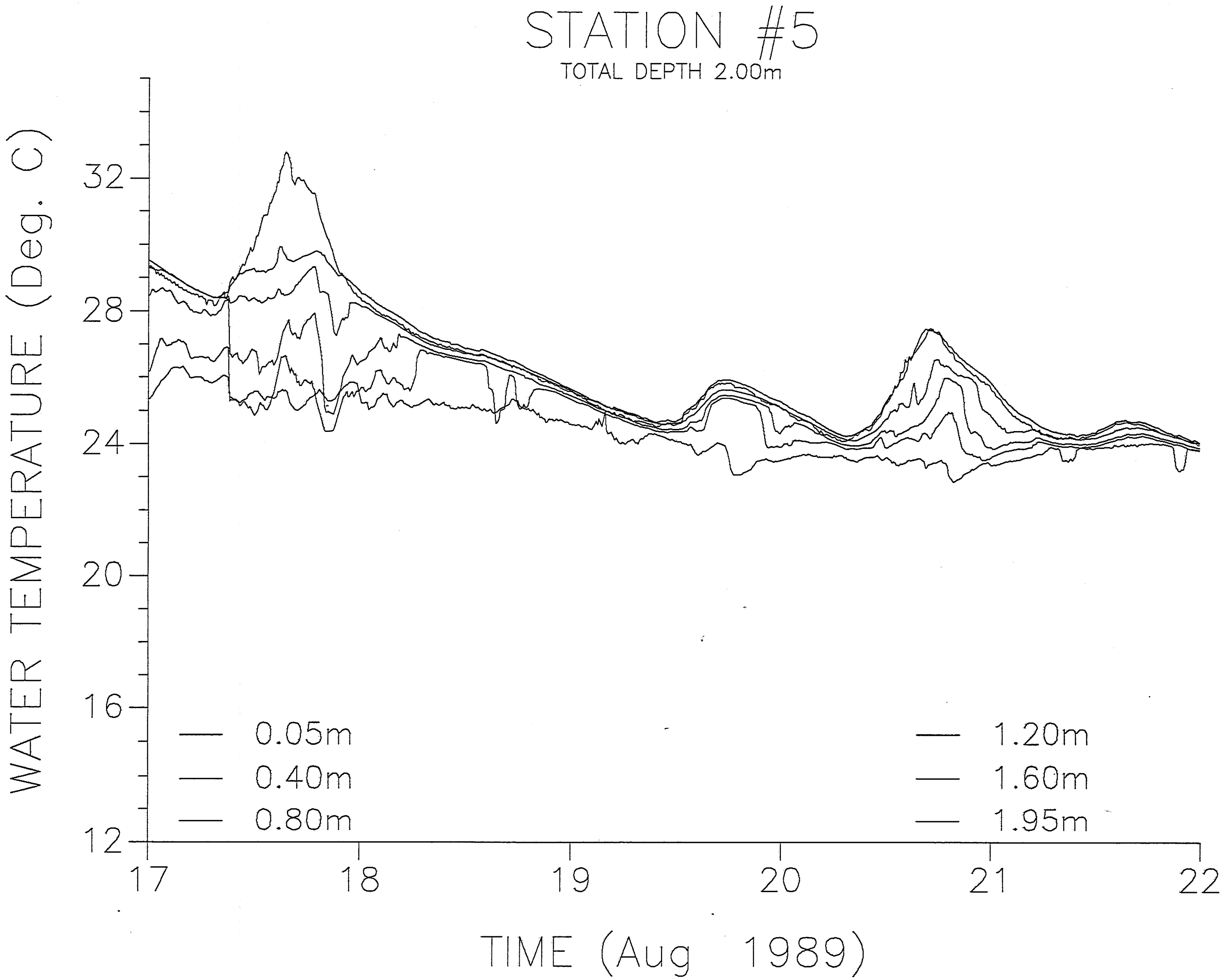
STATION #4

TOTAL DEPTH 1.00m



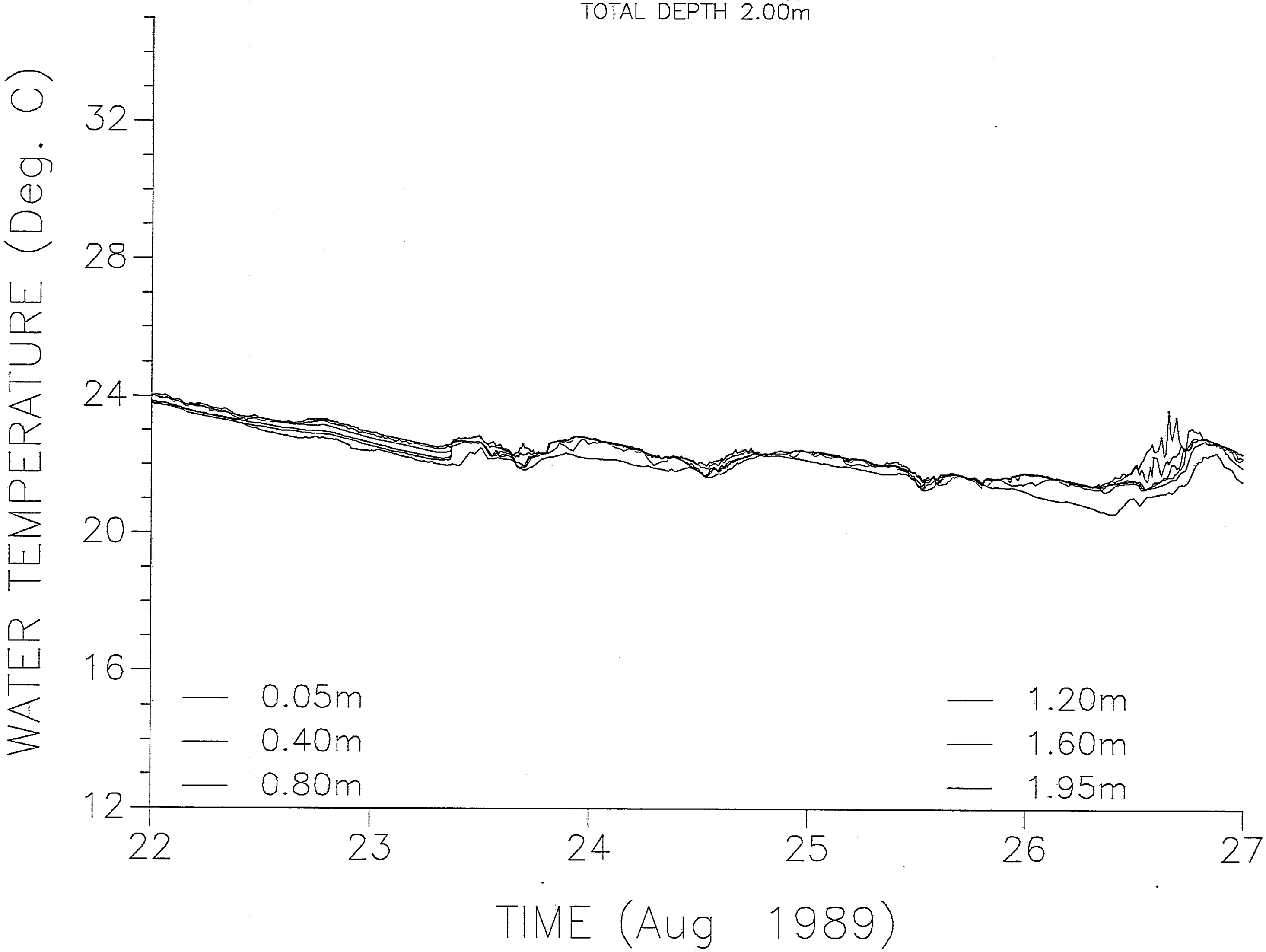

STATION #4
TOTAL DEPTH 1.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
1
2
3
4
5
6
7
TIME (Sep 1989)
0.05m
0.30m
0.60m
0.95m

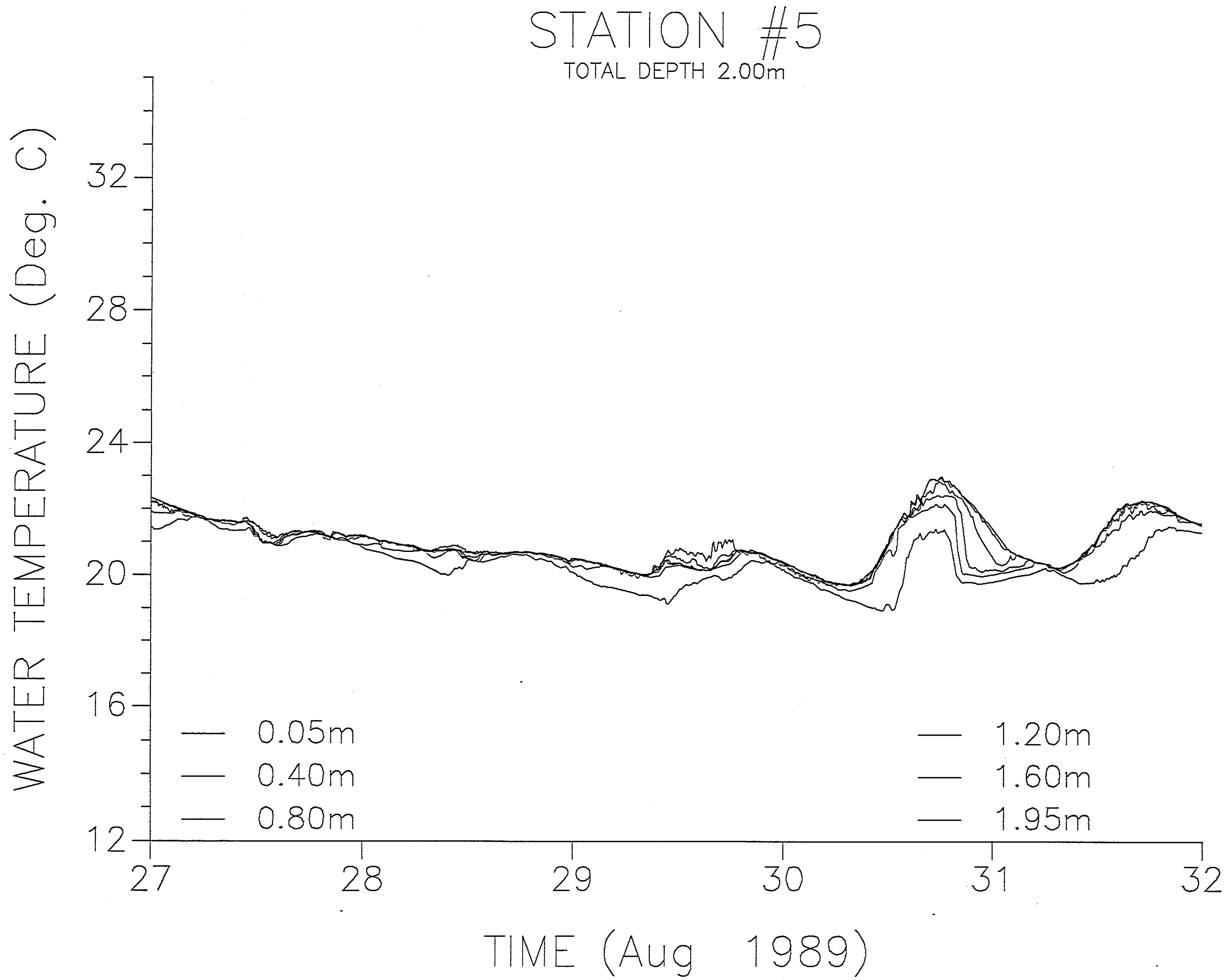

STATION #5
TOTAL DEPTH 2.00m
WATER TEMPERATURE (Deg. C)
12
16
20
24
28
32
0.05m
0.40m
0.80m
1.20m
1.60m
1.95m
12
13
14
15
16
17
TIME (Aug 1989)


STATION #5
TOTAL DEPTH 2.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.20m
1.60m
1.95m
17
18
19
20
21
22
TIME (Aug 1989)

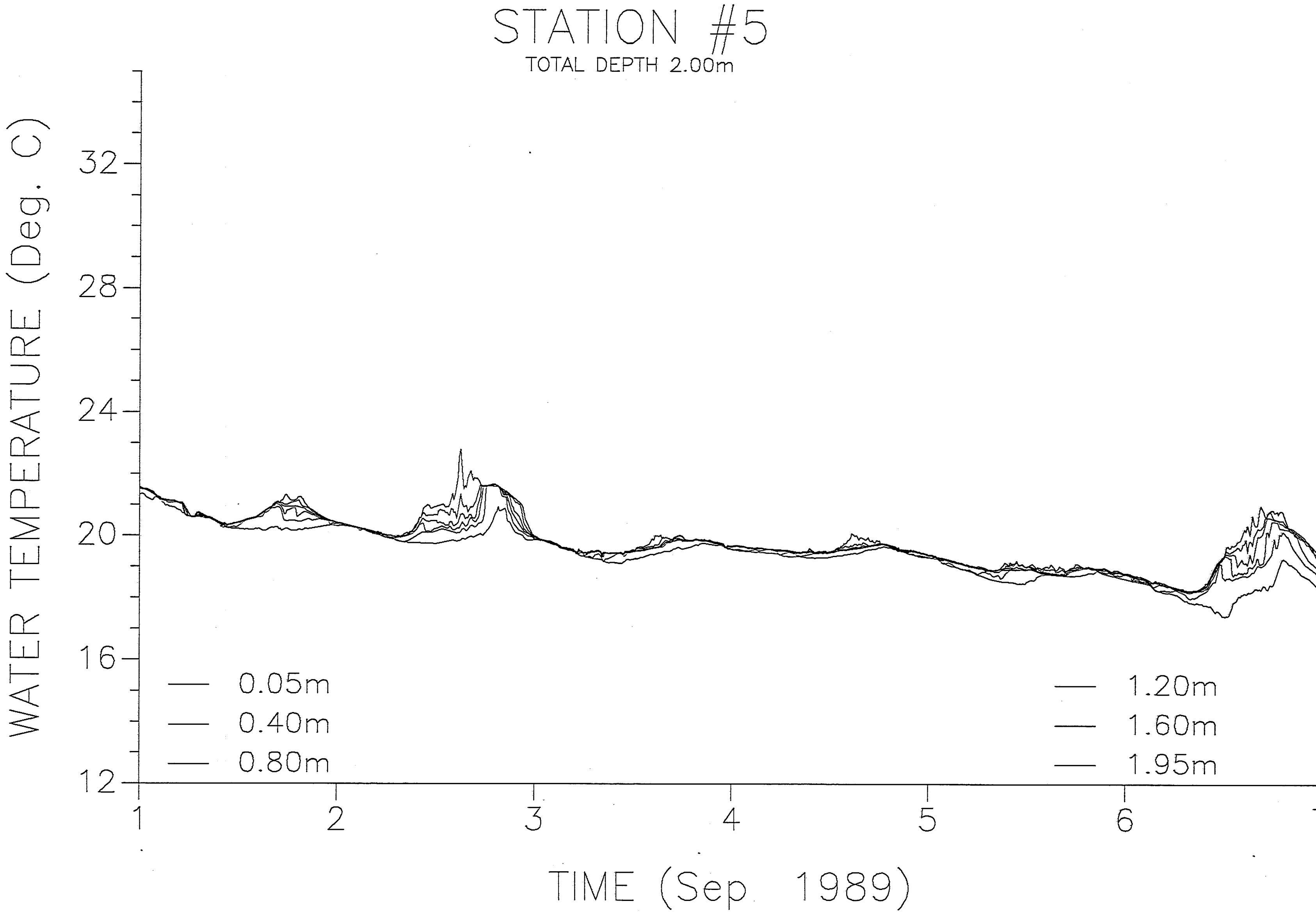
STATION #5

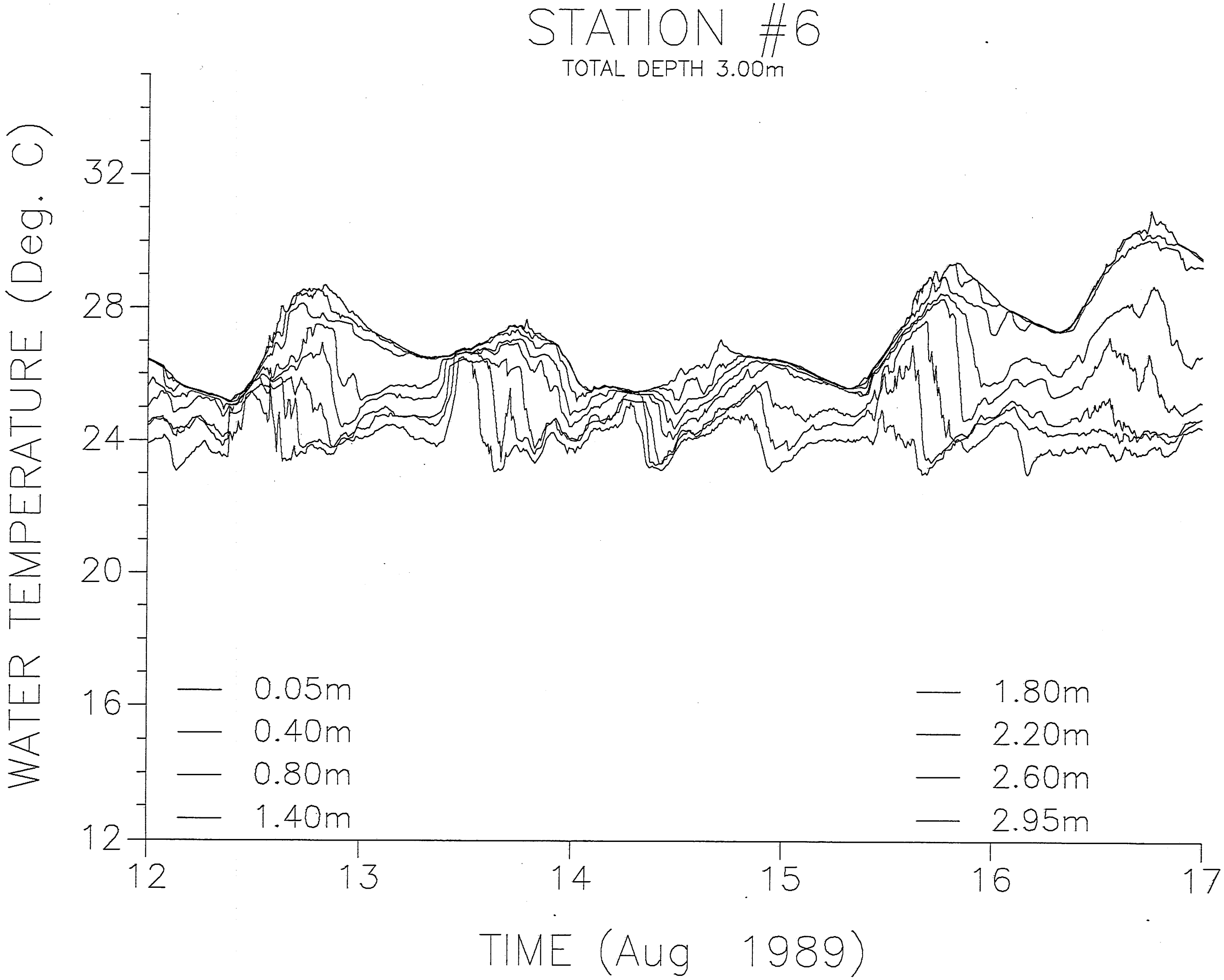
TOTAL DEPTH 2.00m

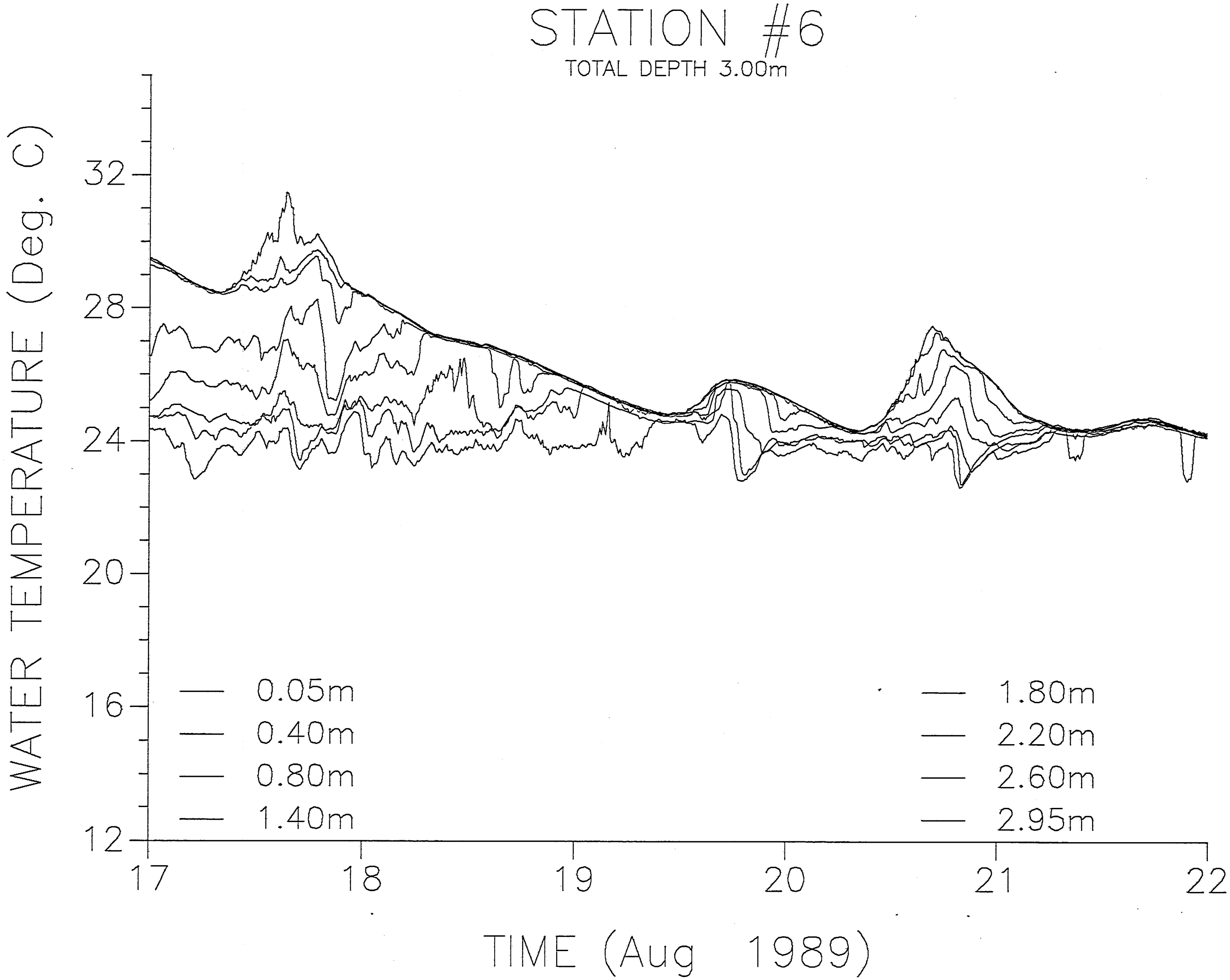


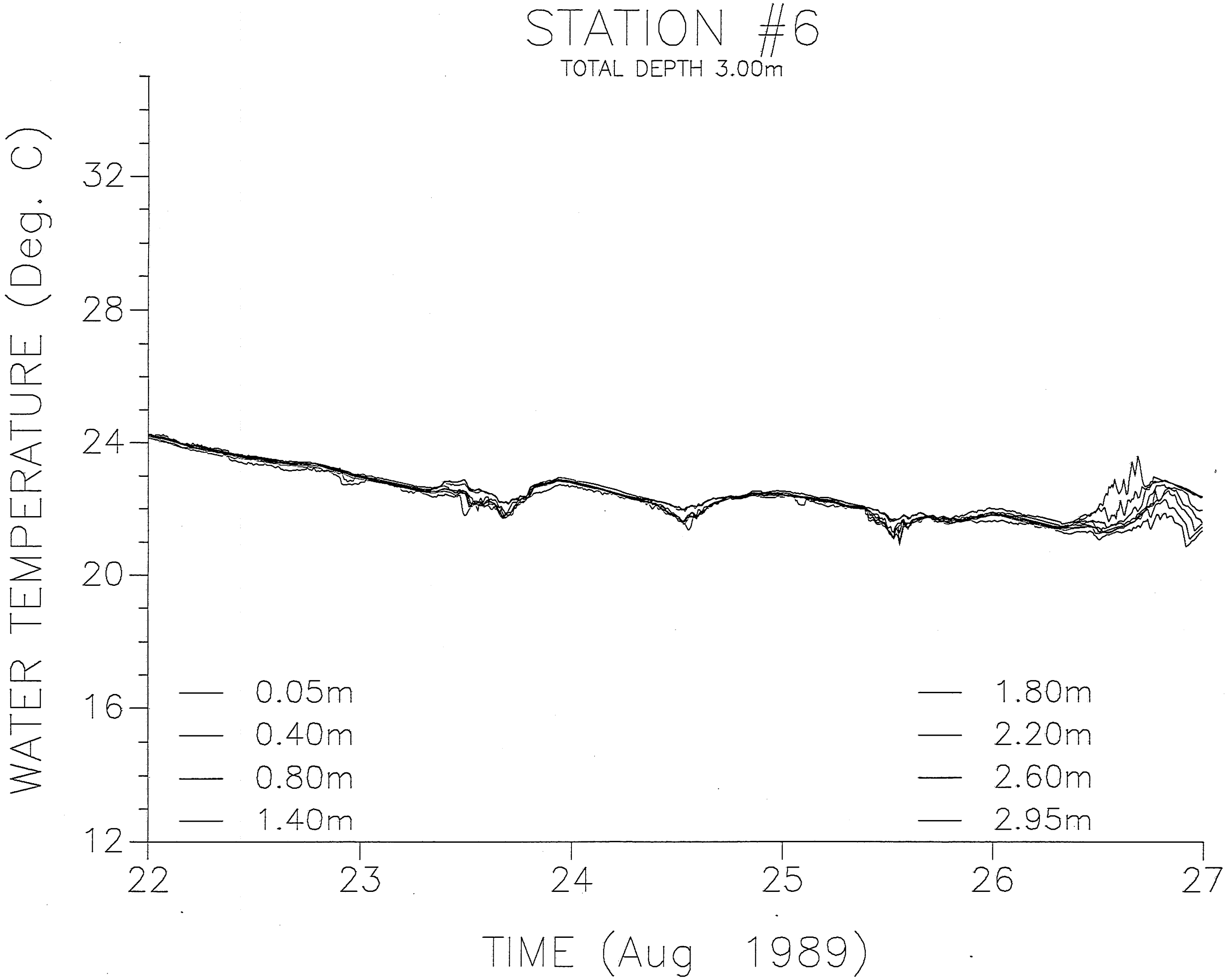


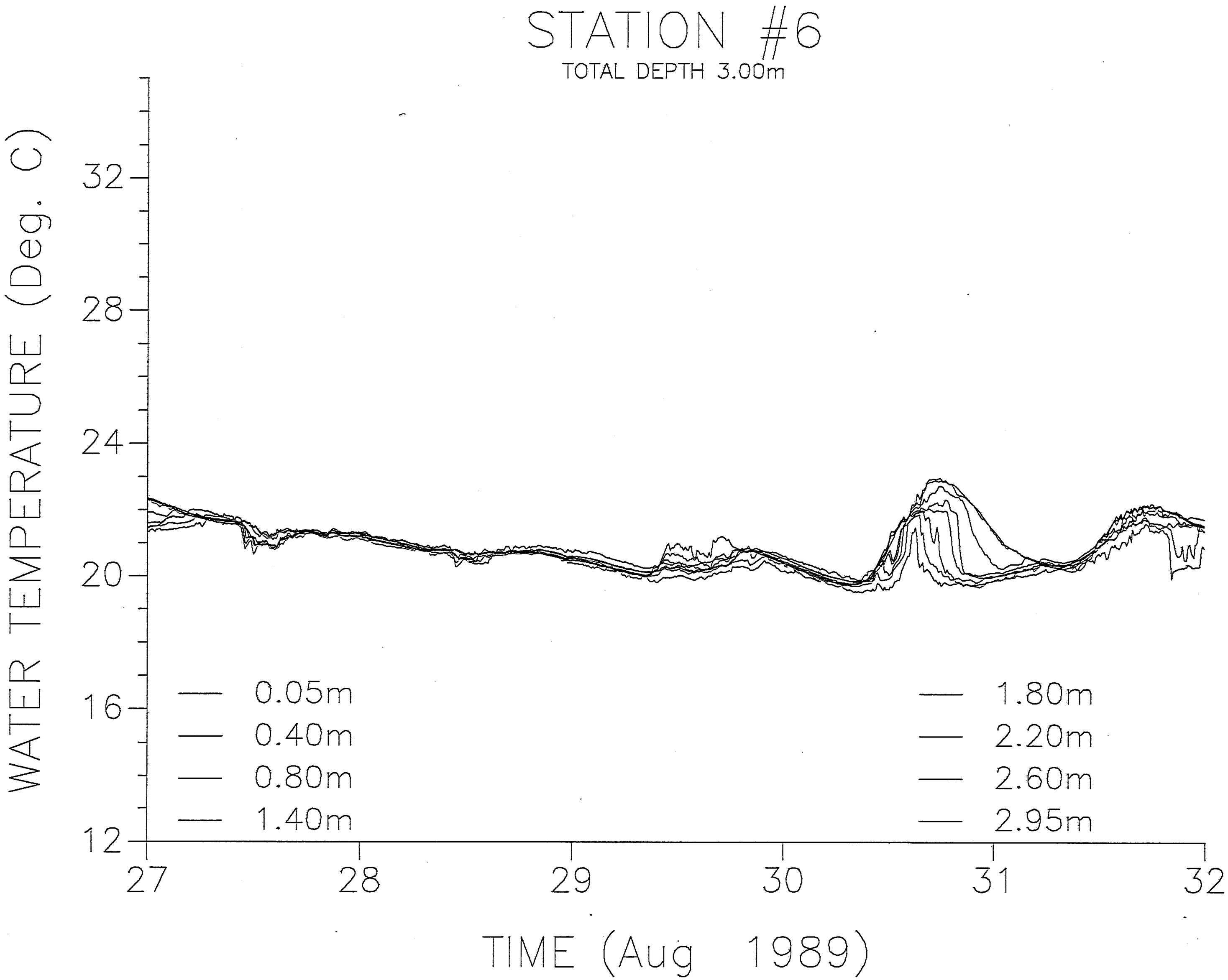
STATION #5
TOTAL DEPTH 2.00m
WATER TEMPERATURE (Deg. C)
12
16
20
24
28
32
27
28
29
30
31
32
TIME (Aug 1989)
0.05m
0.40m
0.80m
1.20m
1.60m
1.95m


STATION #5
TOTAL DEPTH 2.00m
WATER TEMPERATURE (Deg. C)
12
16
20
24
28
32
1
2
3
4
5
6
7
TIME (Sep 1989)
0.05m
0.40m
0.80m
1.20m
1.60m
1.95m

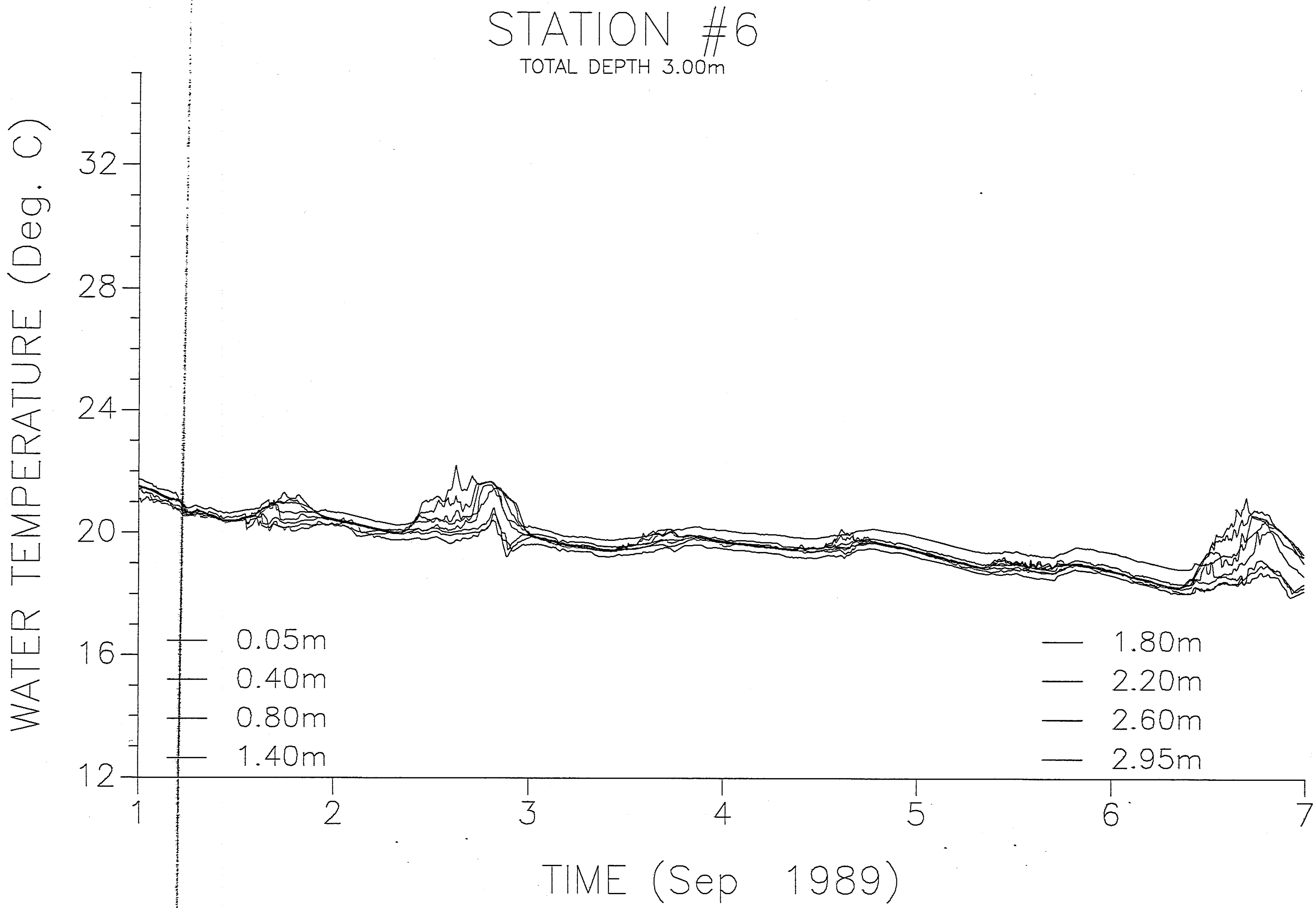

STATION #6
TOTAL DEPTH 3.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.40m
1.80m
2.20m
2.60m
2.95m
12
13
14
15
16
17
TIME (Aug 1989)

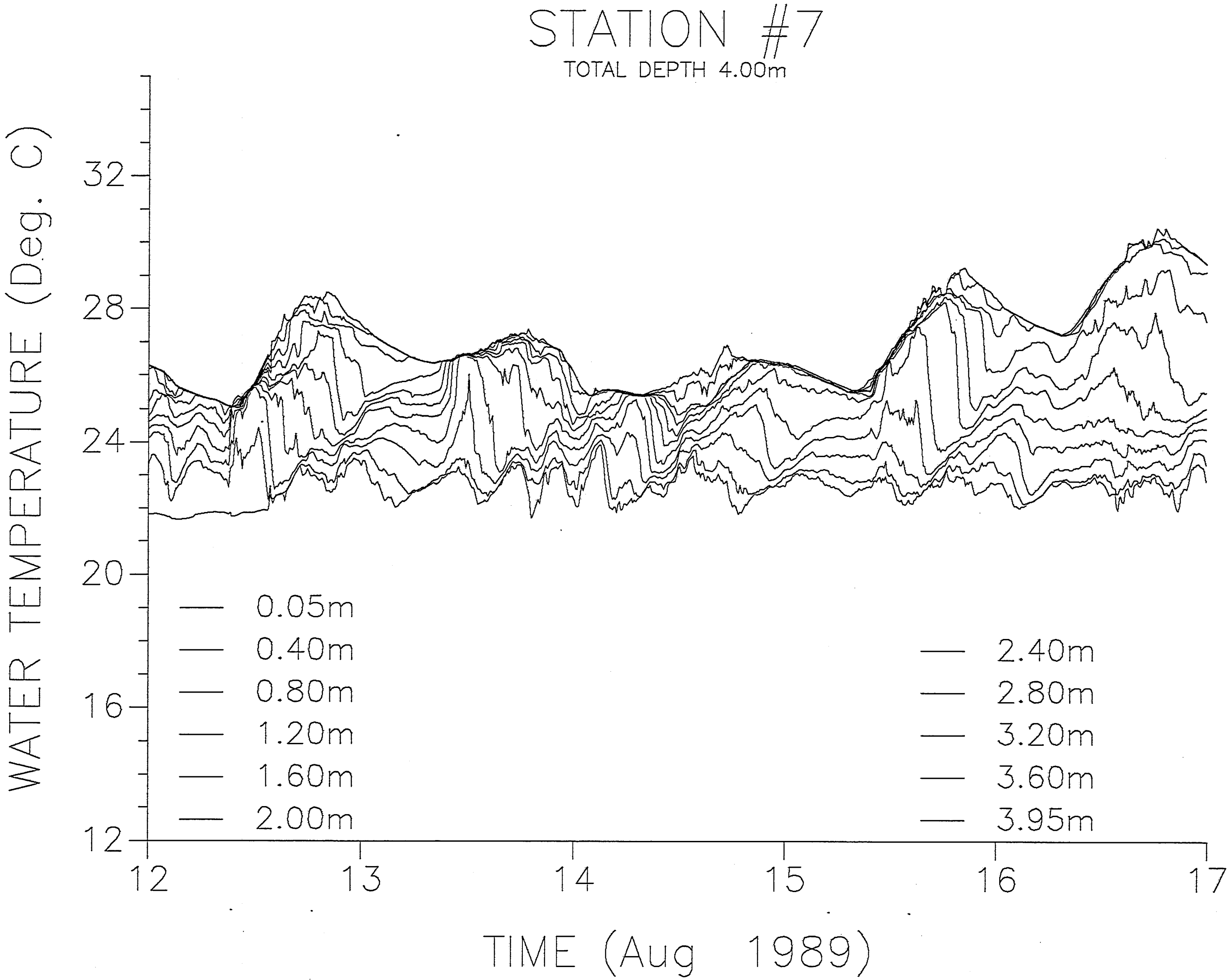

STATION #6
TOTAL DEPTH 3.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
— 0.05m
— 0.40m
— 0.80m
— 1.40m
— 1.80m
— 2.20m
— 2.60m
— 2.95m
17
18
19
20
21
22
TIME (Aug 1989)

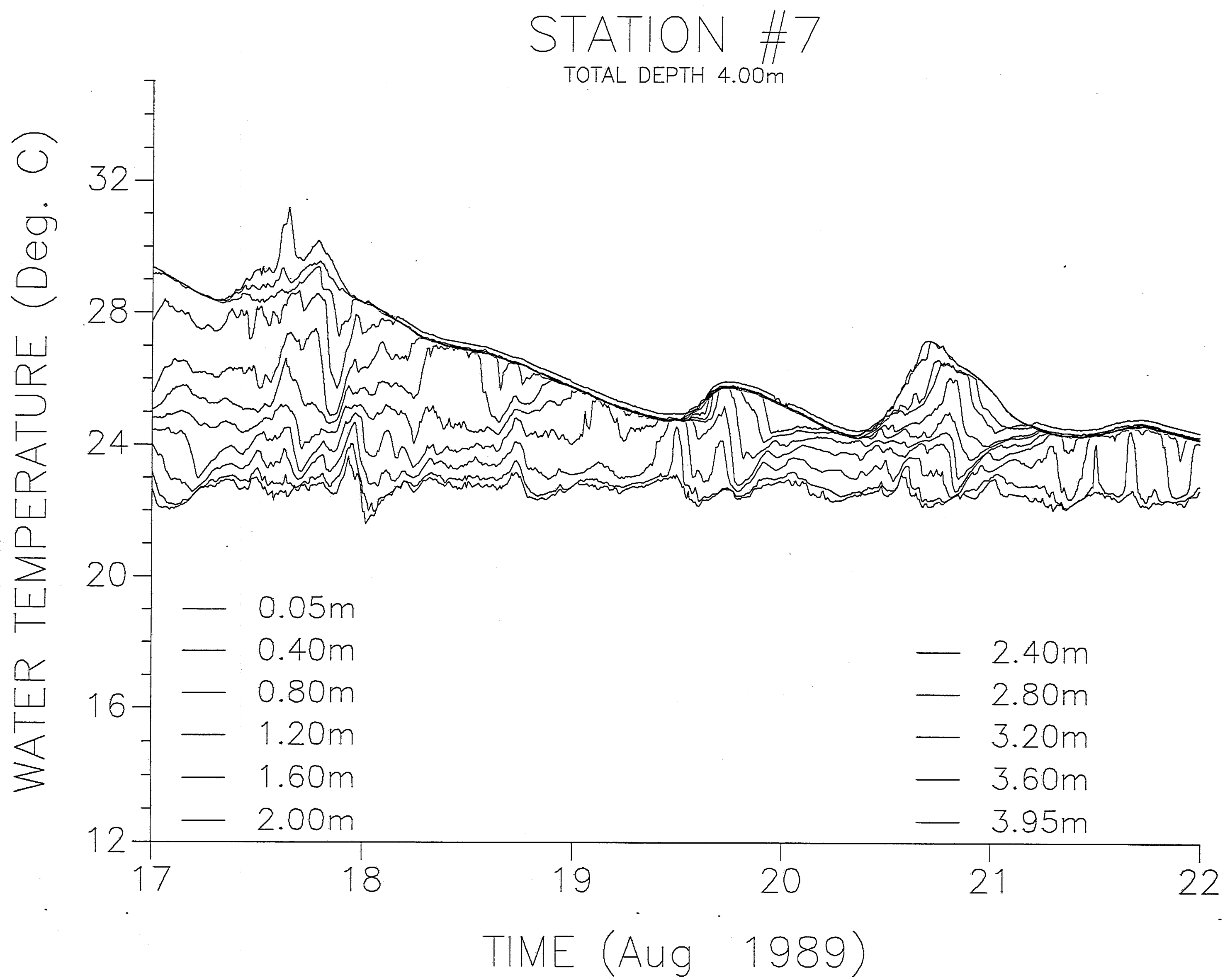

STATION #6
TOTAL DEPTH 3.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.40m
1.80m
2.20m
2.60m
2.95m
22
23
24
25
26
27
TIME (Aug 1989)


STATION #6
TOTAL DEPTH 3.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.40m
1.80m
2.20m
2.60m
2.95m
27
28
29
30
31
32
TIME (Aug 1989)

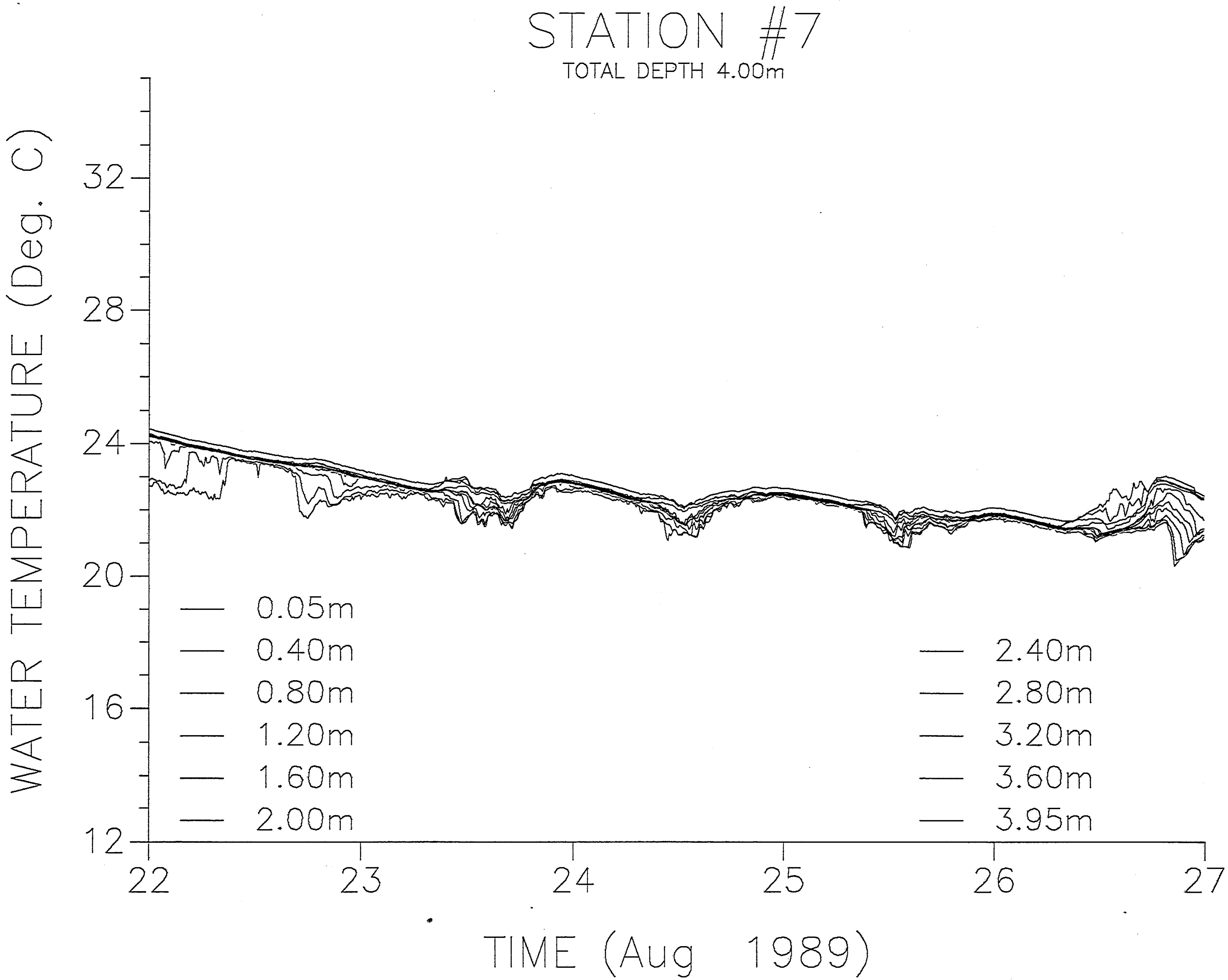
A-30

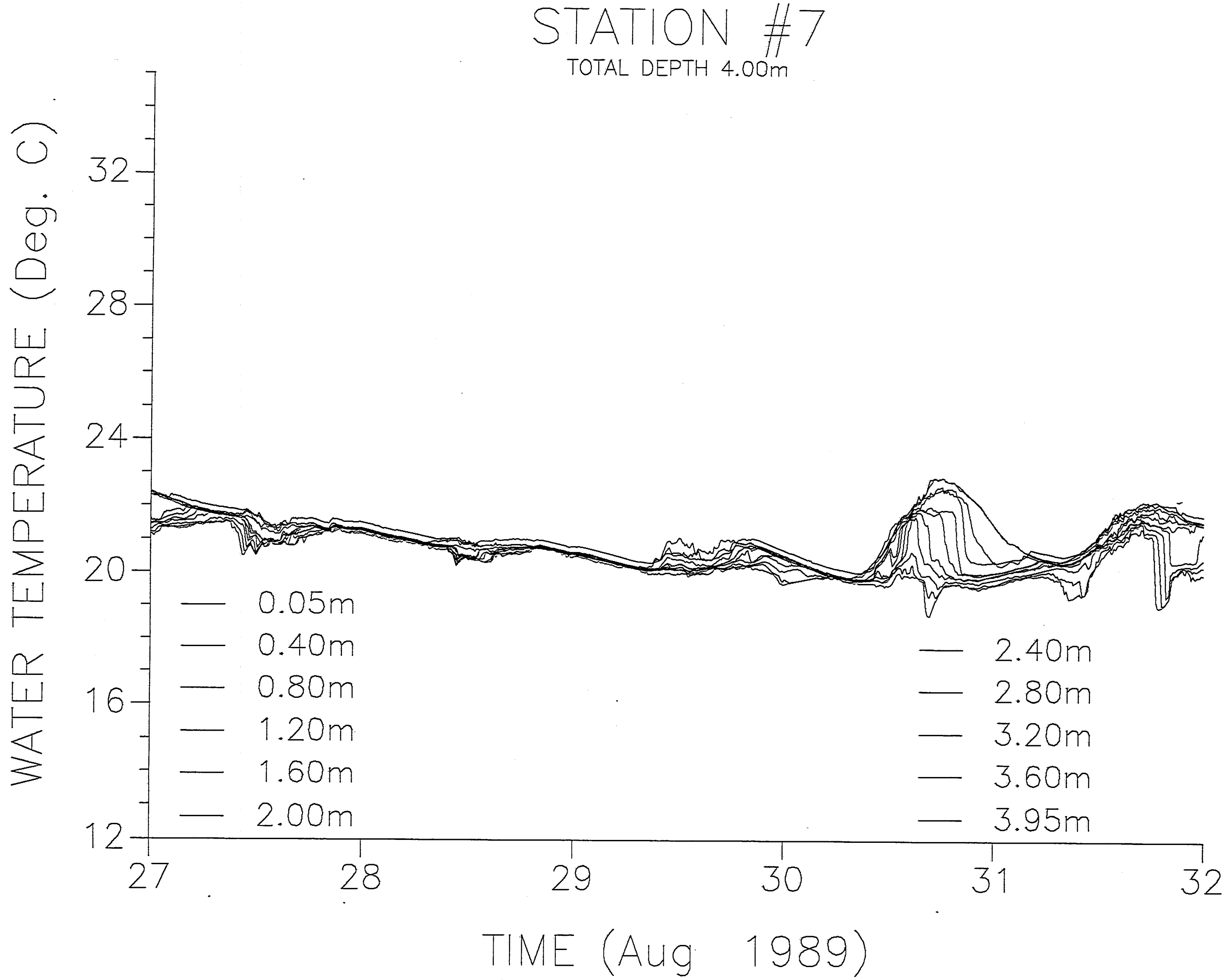

STATION #6
TOTAL DEPTH 3.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.40m
1.80m
2.20m
2.60m
2.95m
1
2
3
4
5
6
7
TIME (Sep 1989)

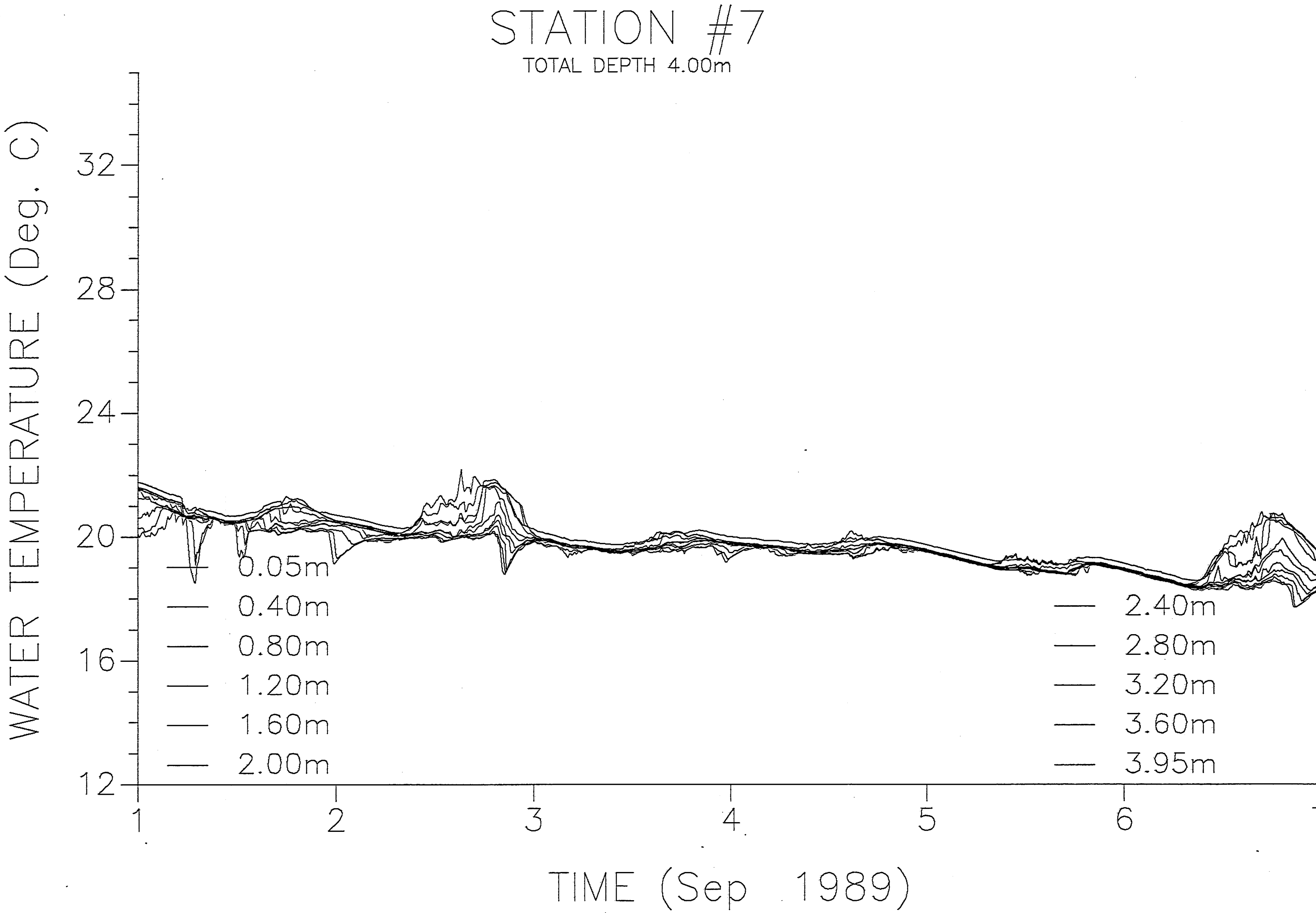

STATION #7
TOTAL DEPTH 4.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.20m
1.60m
2.00m
2.40m
2.80m
3.20m
3.60m
3.95m
12
13
14
15
16
17
TIME (Aug 1989)



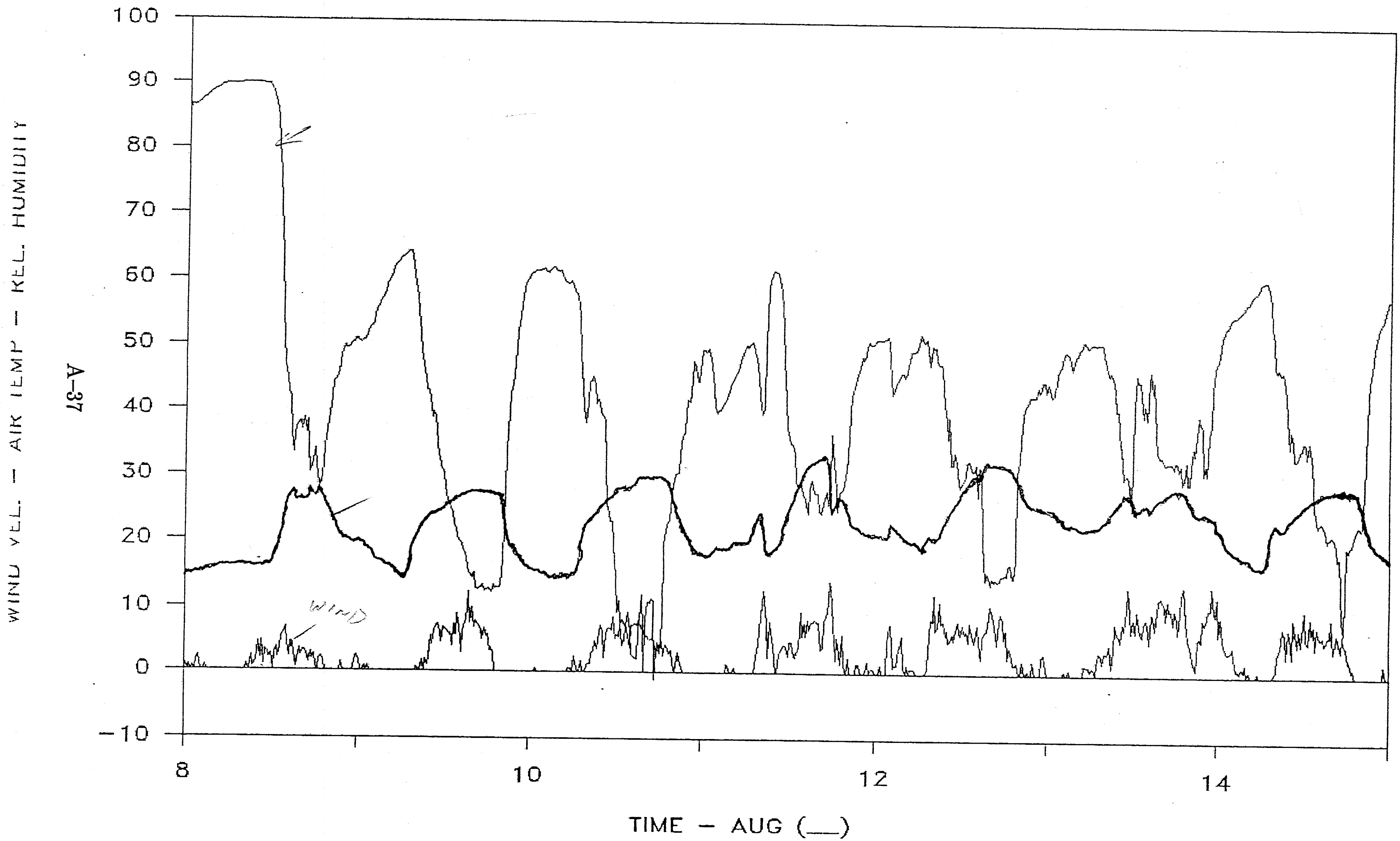
STATION #7
TOTAL DEPTH 4.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.20m
1.60m
2.00m
2.40m
2.80m
3.20m
3.60m
3.95m
17
18
19
20
21
22
TIME (Aug 1989)


STATION #7
TOTAL DEPTH 4.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.20m
1.60m
2.00m
2.40m
2.80m
3.20m
3.60m
3.95m
22
23
24
25
26
27
TIME (Aug 1989)


STATION #7
TOTAL DEPTH 4.00m
WATER TEMPERATURE (Deg. C)
32
28
24
20
16
12
0.05m
0.40m
0.80m
1.20m
1.60m
2.00m
2.40m
2.80m
3.20m
3.60m
3.95m
27
28
29
30
31
32
TIME (Aug 1989)

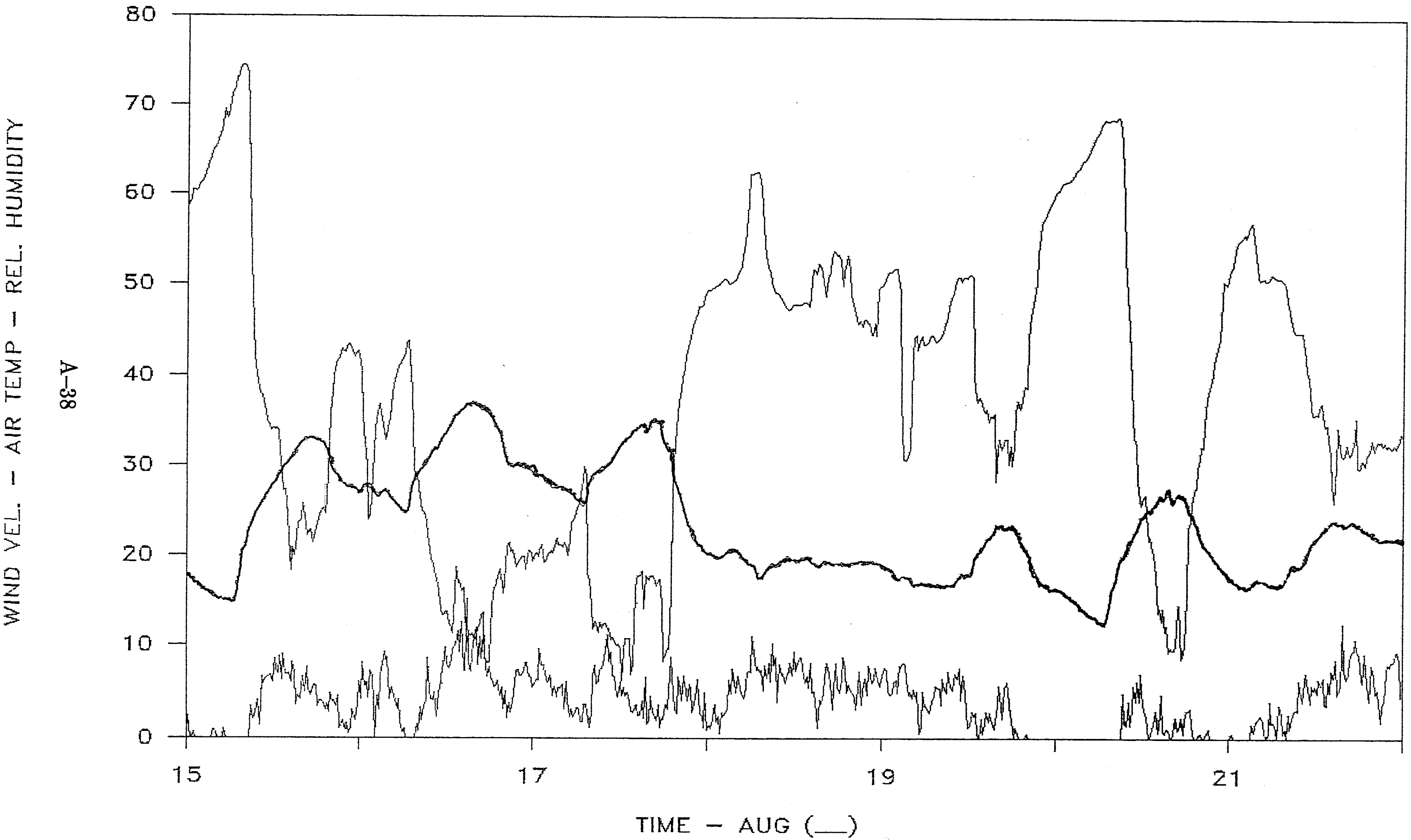

STATION #7
TOTAL DEPTH 4.00m
WATER TEMPERATURE (Deg. C)
12
16
20
24
28
32
0.05m
0.40m
0.80m
1.20m
1.60m
2.00m
2.40m
2.80m
3.20m
3.60m
3.95m
1
2
3
4
5
6
7
TIME (Sep 1989)

EAU GALLE RESERVOIR WEATHER DATA

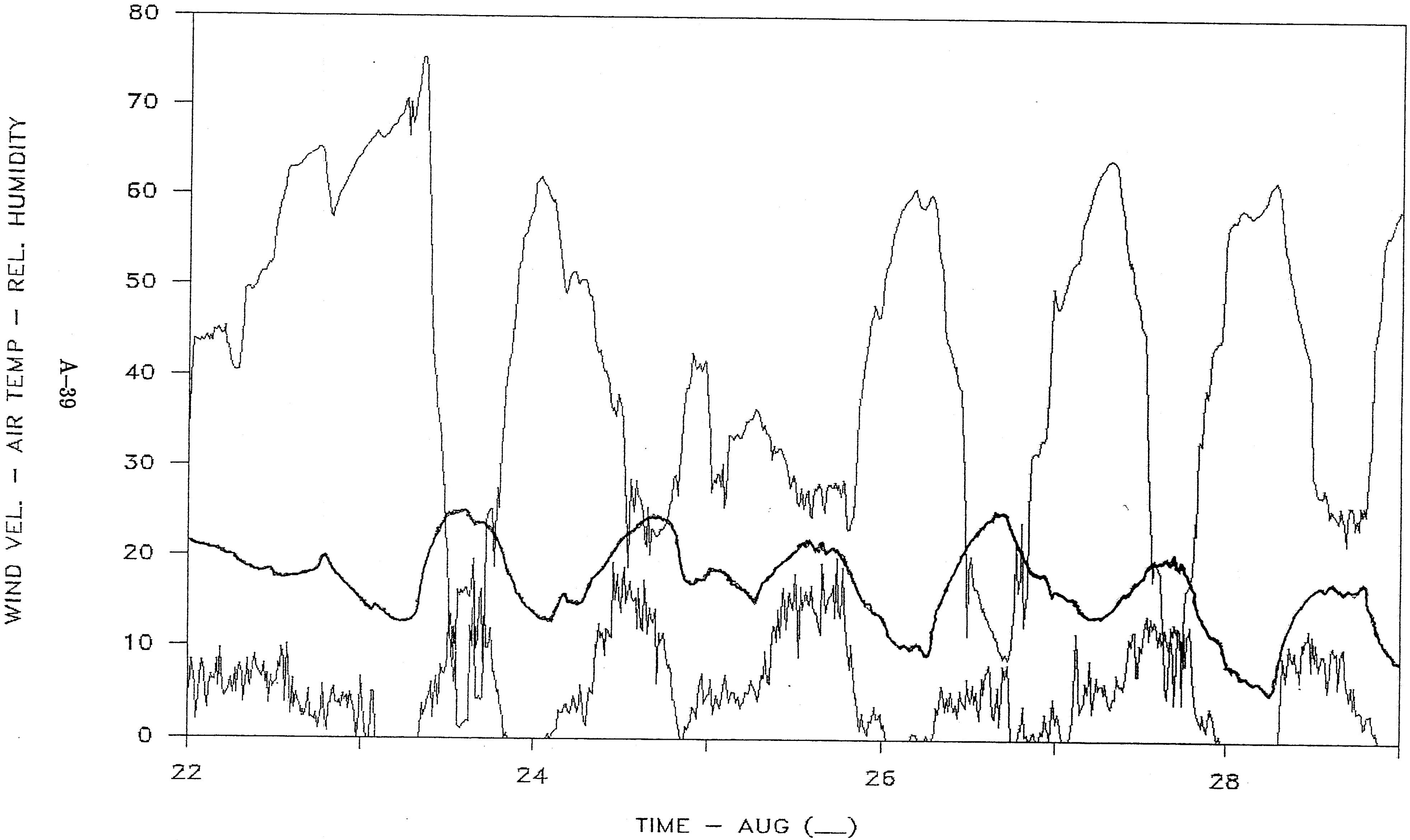


A-37

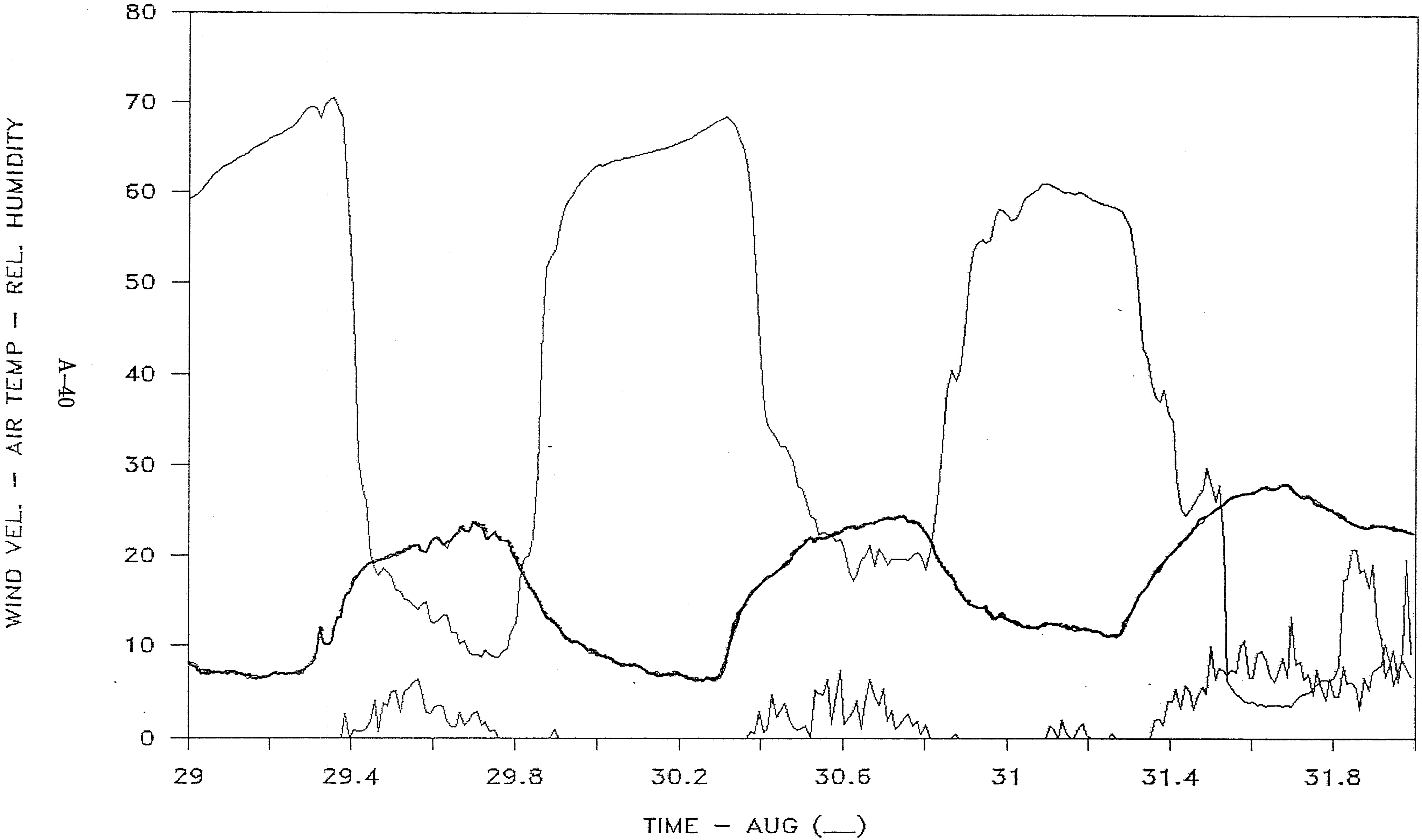
EAU GALLE RESERVOIR WEATHER DATA



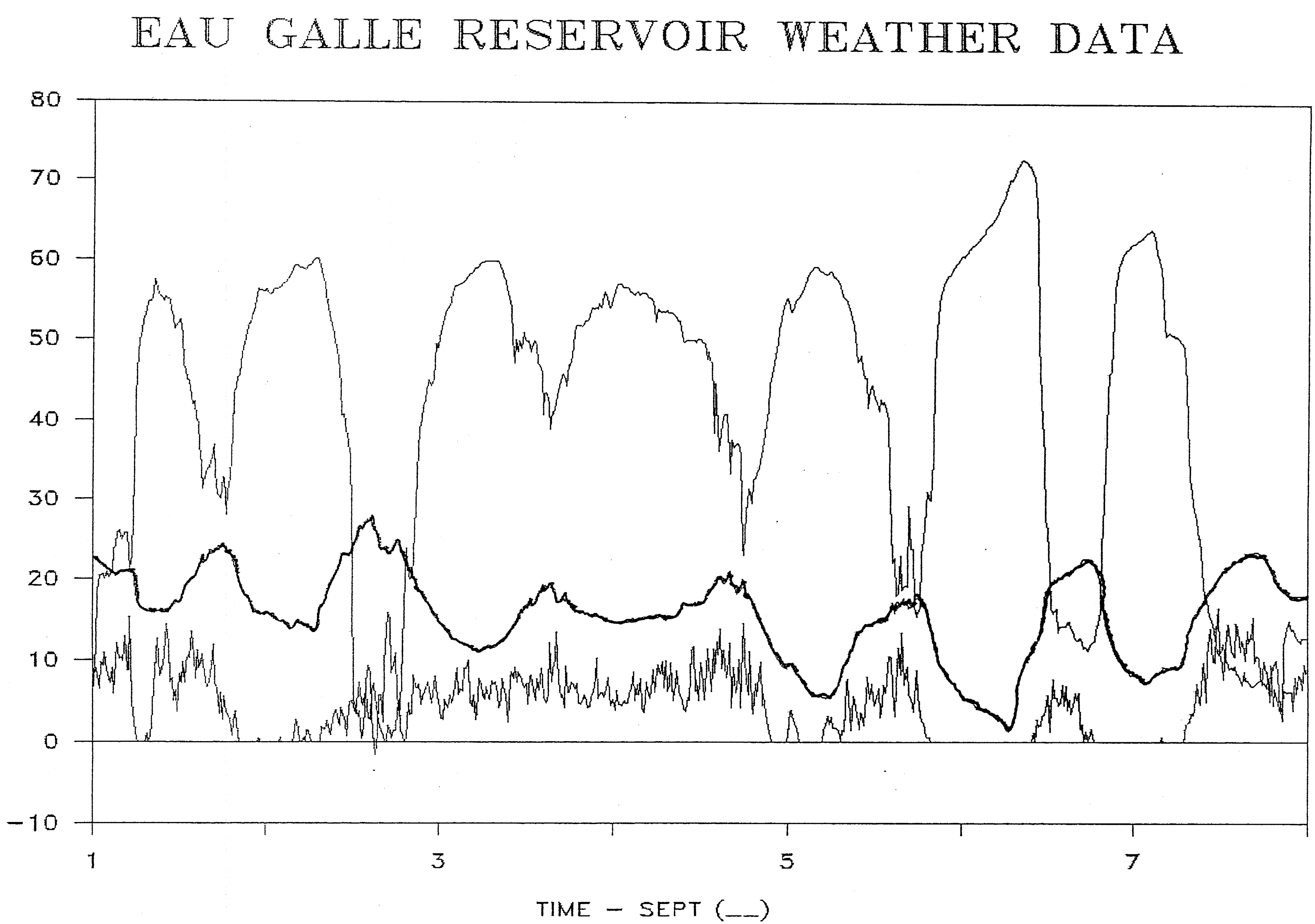
EAU GALLE RESERVOIR WEATHER DATA



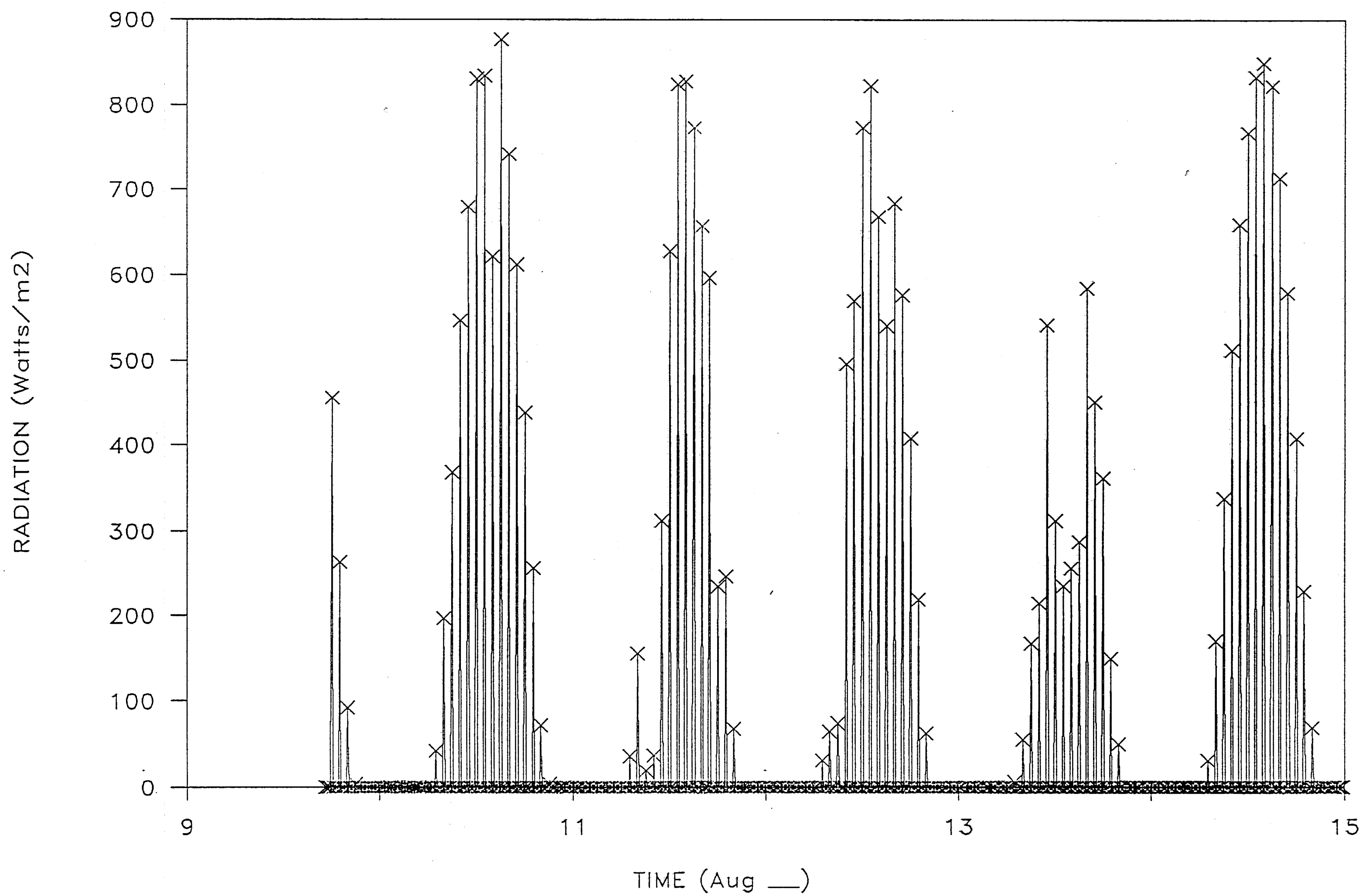
EAU GALLE RESERVOIR WEATHER DATA



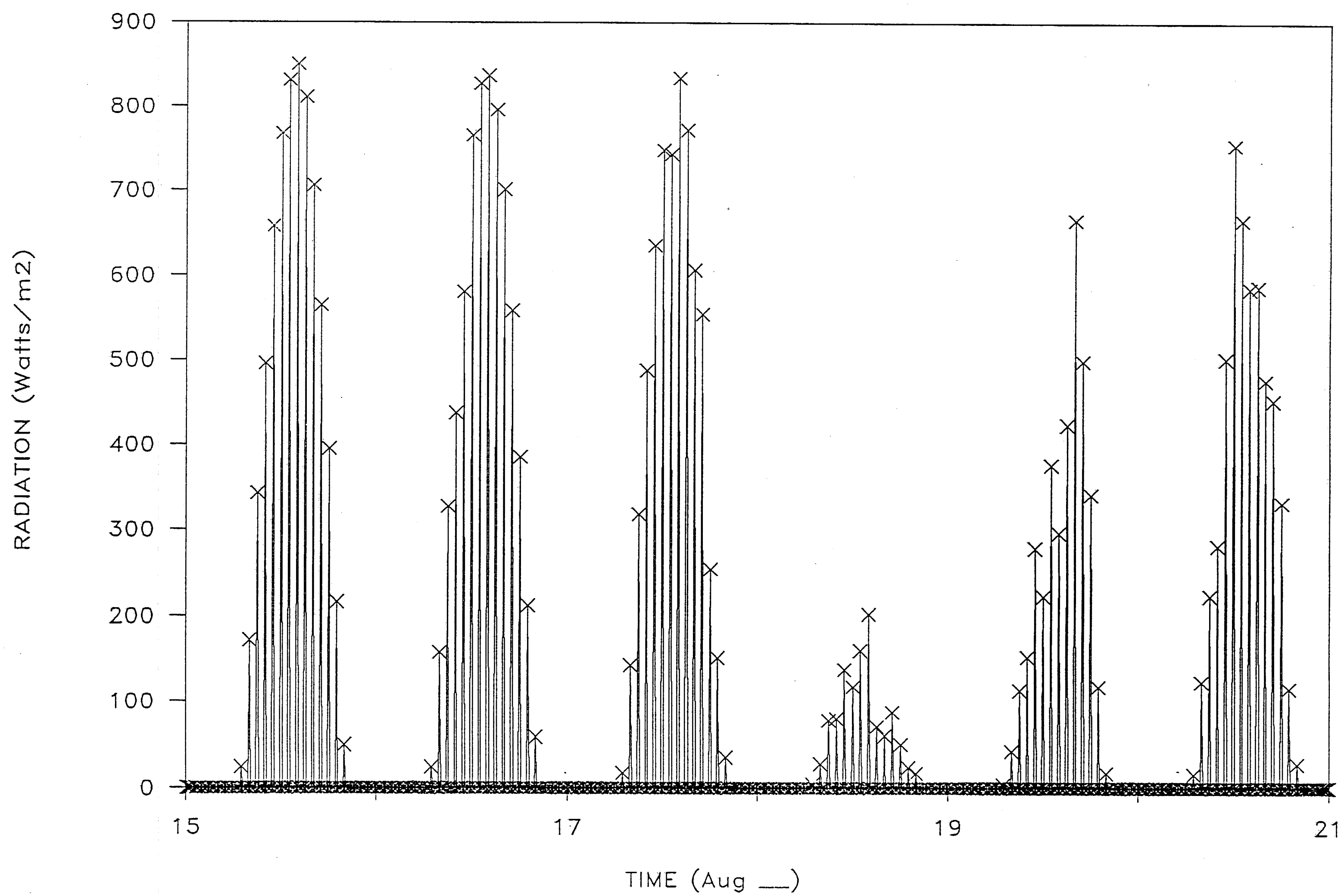
A-40


EAU GALLE RESERVOIR WEATHER DATA
WIND VEL. - AIR TEMP - REL. HUMIDITY
80
70
60
50
40
30
20
10
0
-10
1
3
5
7
TIME - SEPT (__)

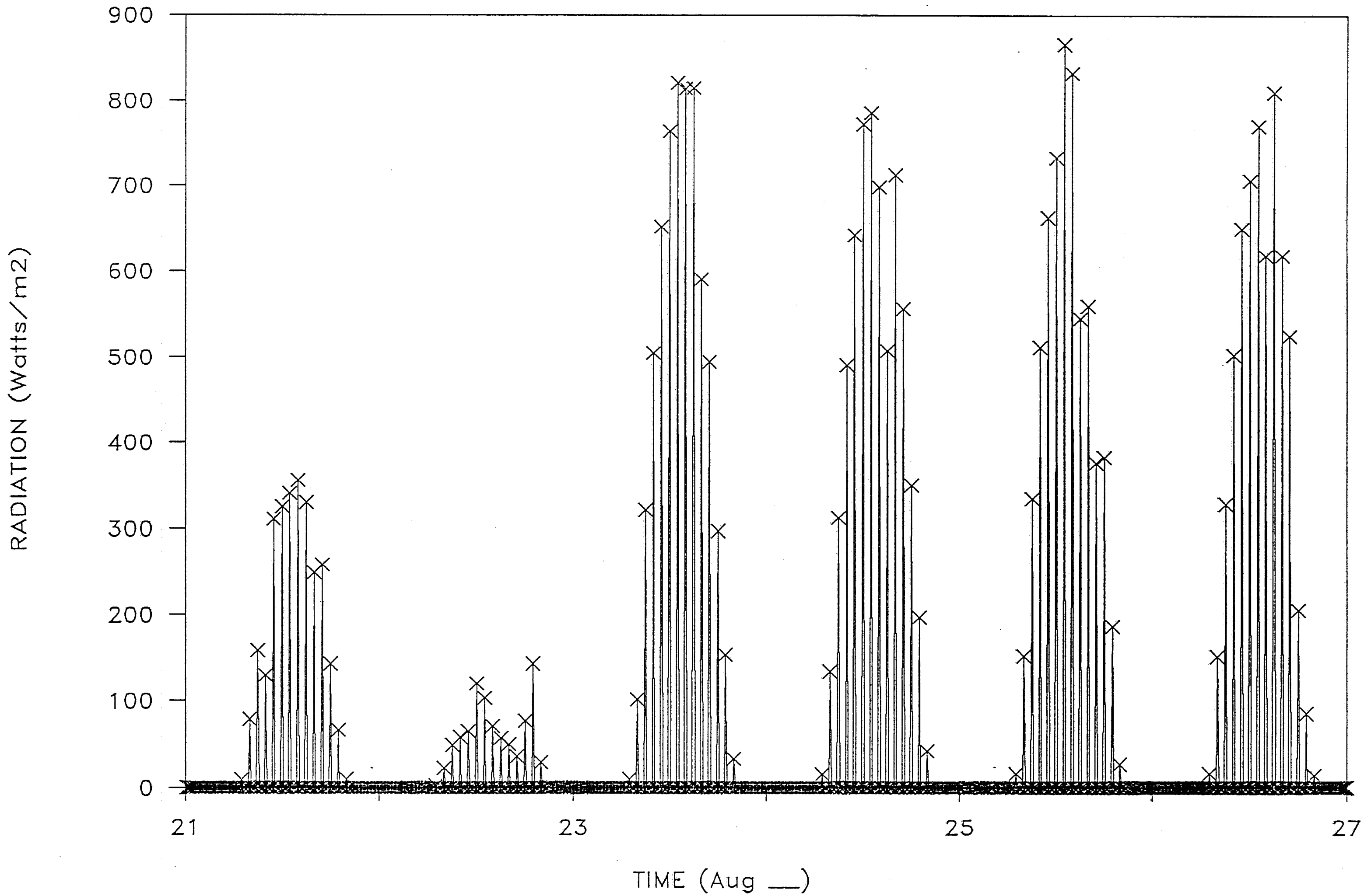
EAU GALLE RADIATION DATA



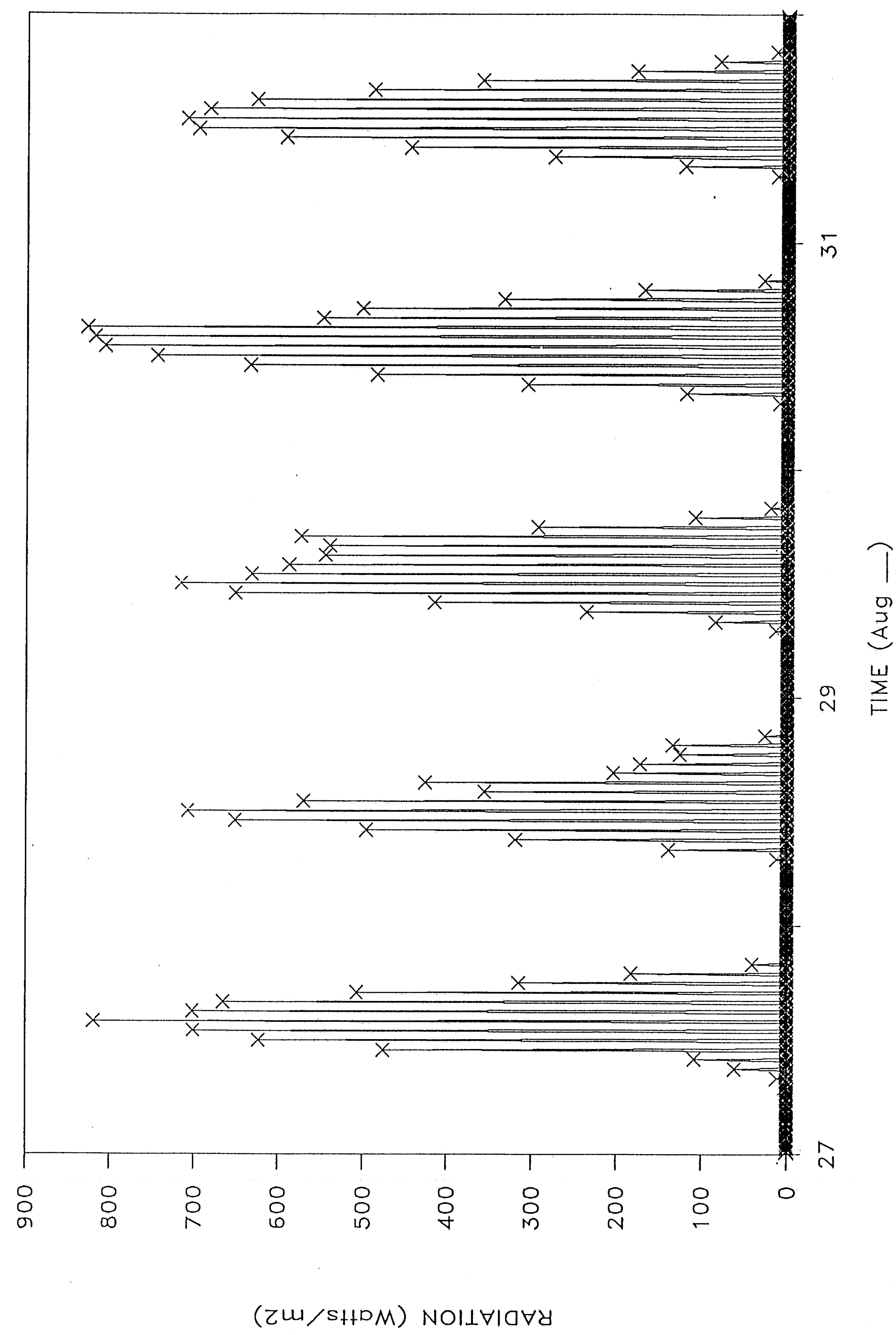
EAU GALLE RADIATION DATA



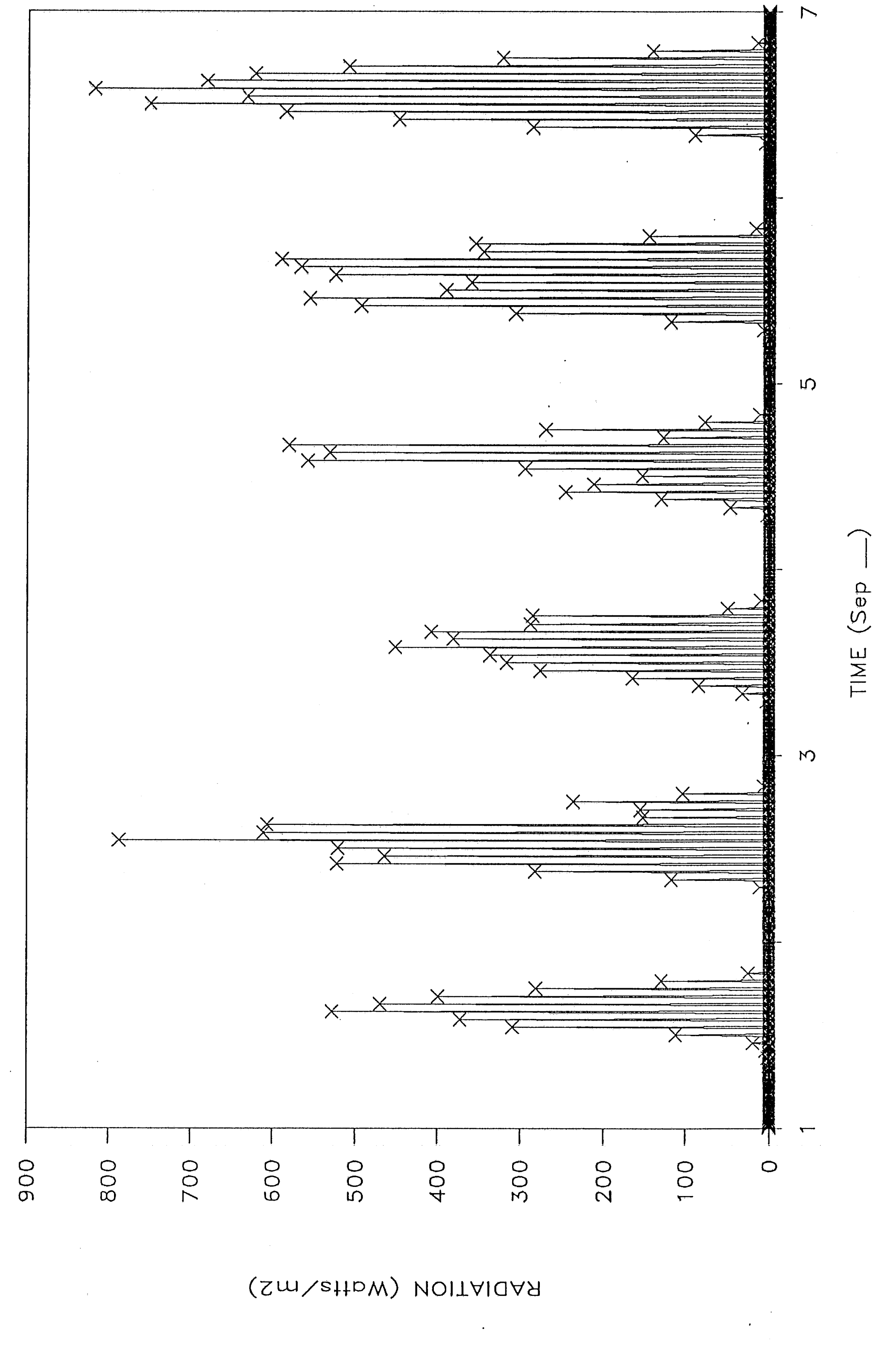
EAU GALLE RADIATION DATA



EAU GALLE RADIATION DATA



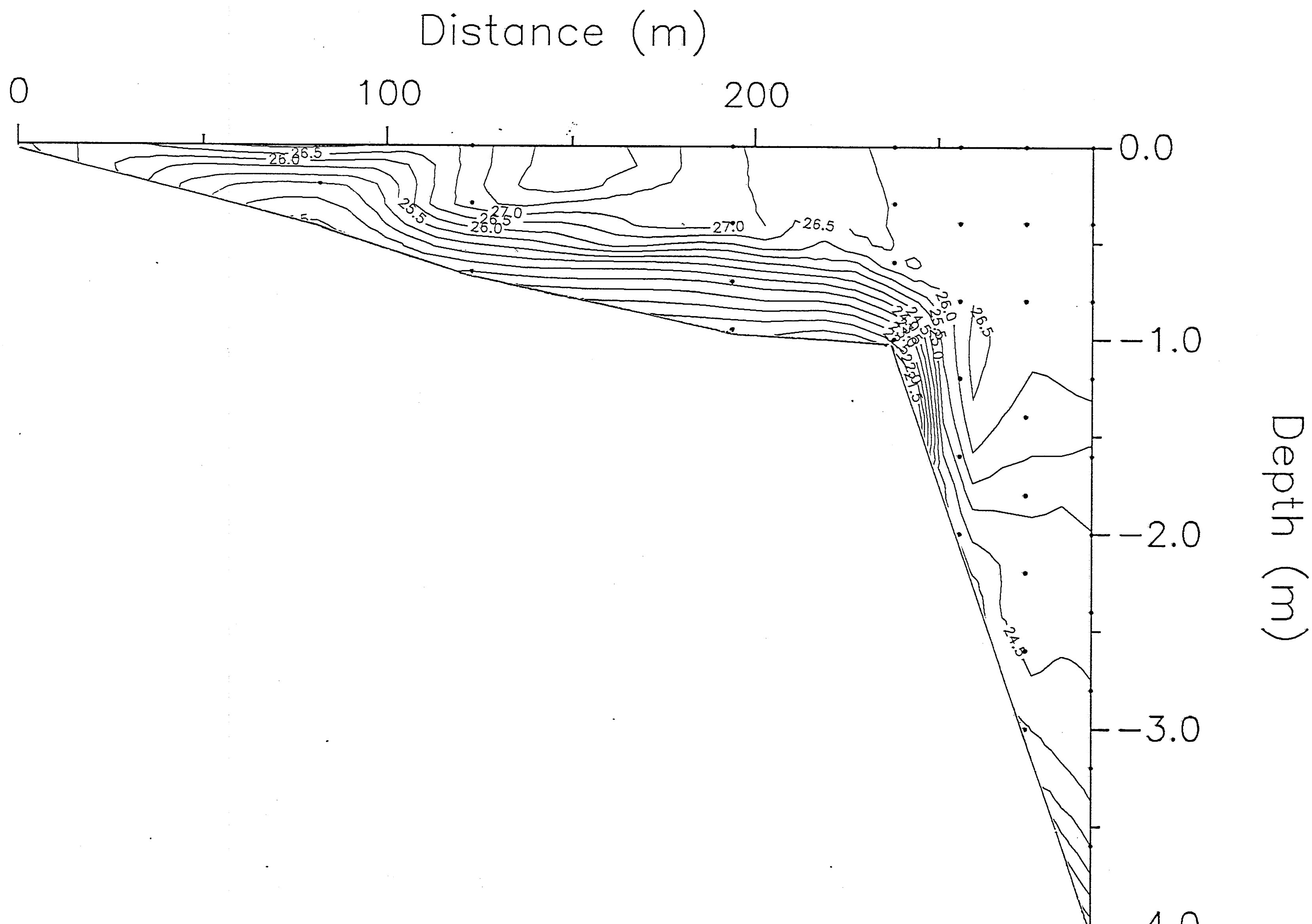
EAU GALLE RADIATION DATA



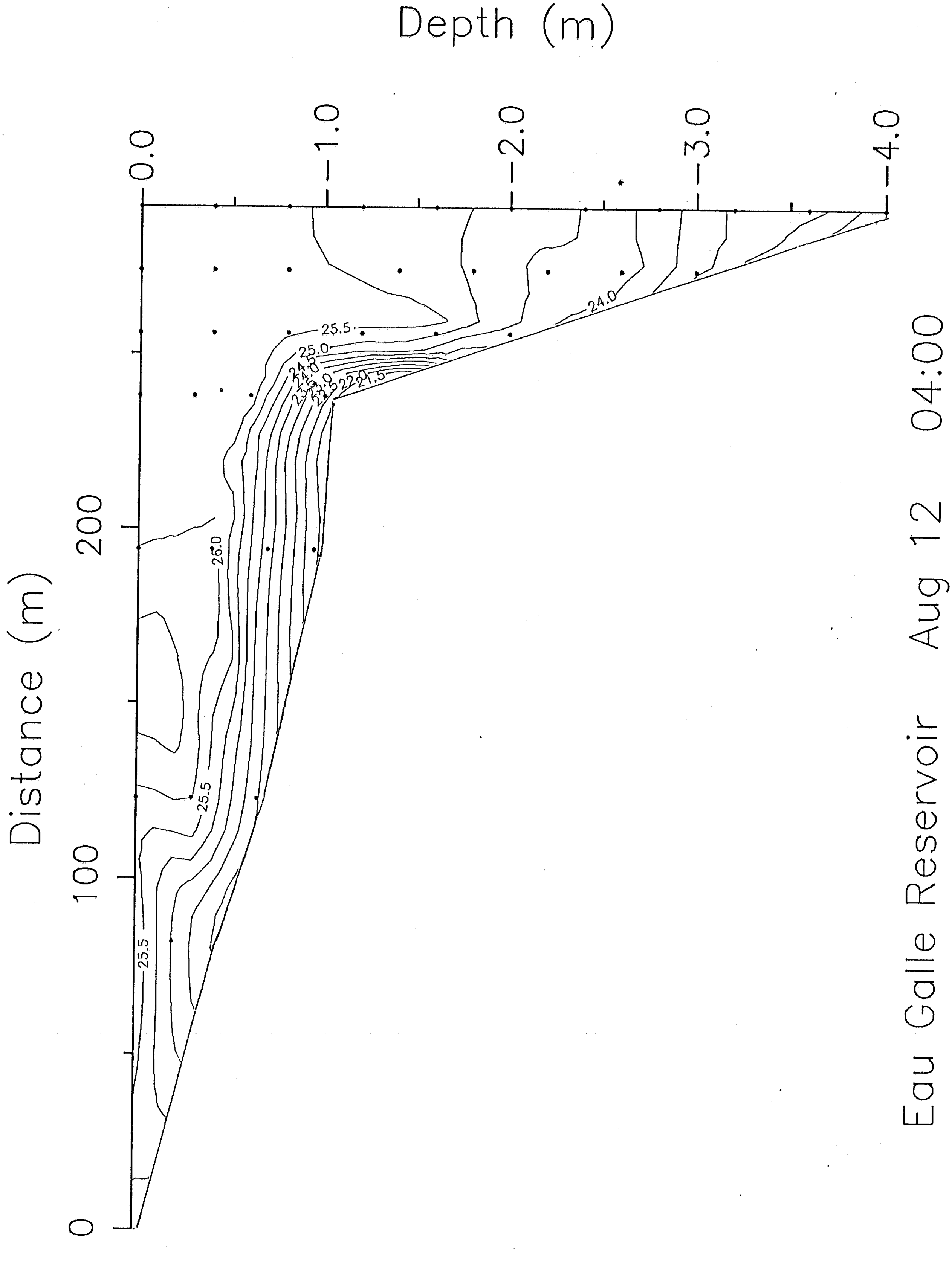
Appendix B

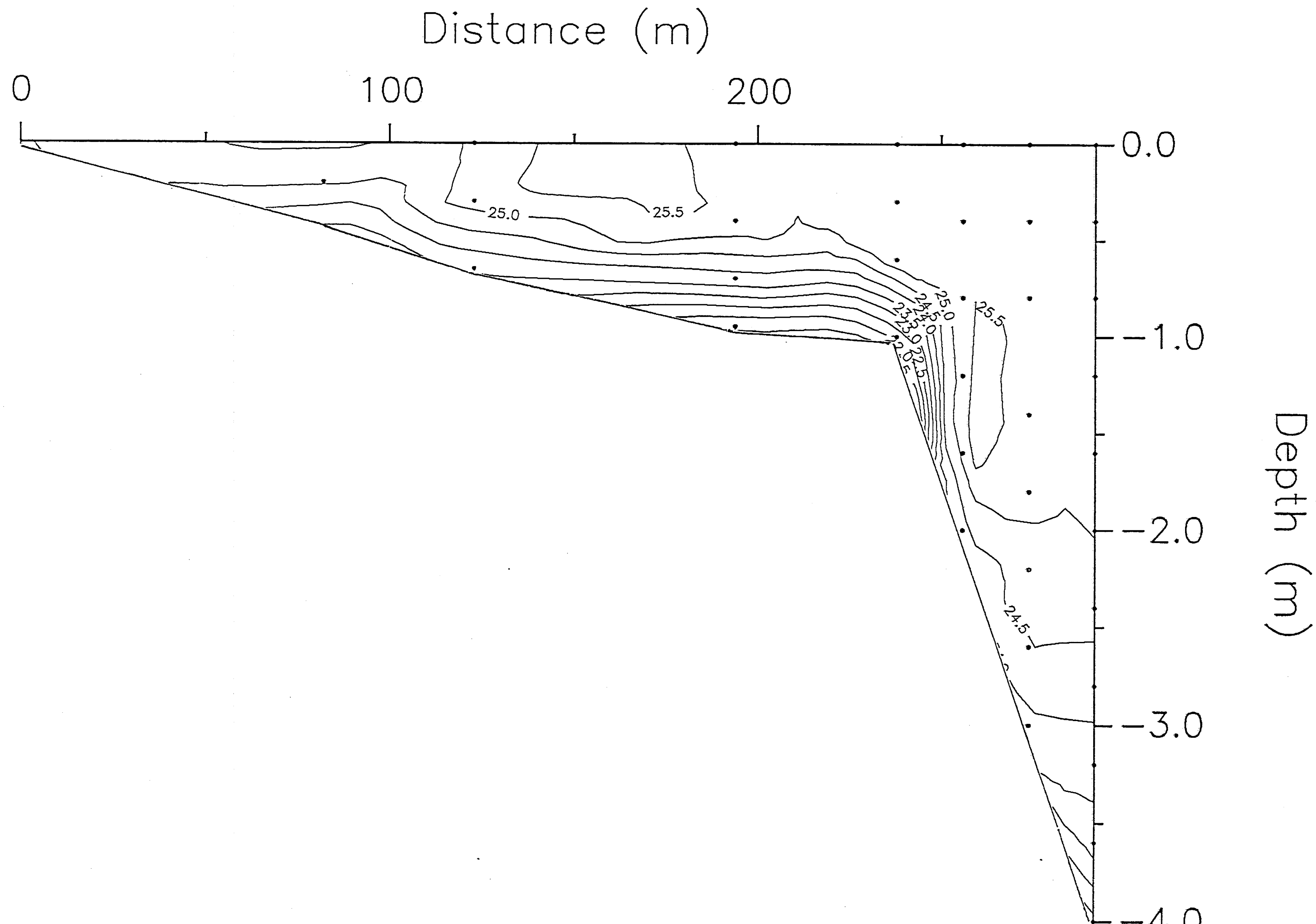
Isotherm Plots of the Bay Transect

(August 12 - 20 and September 5 - 6)

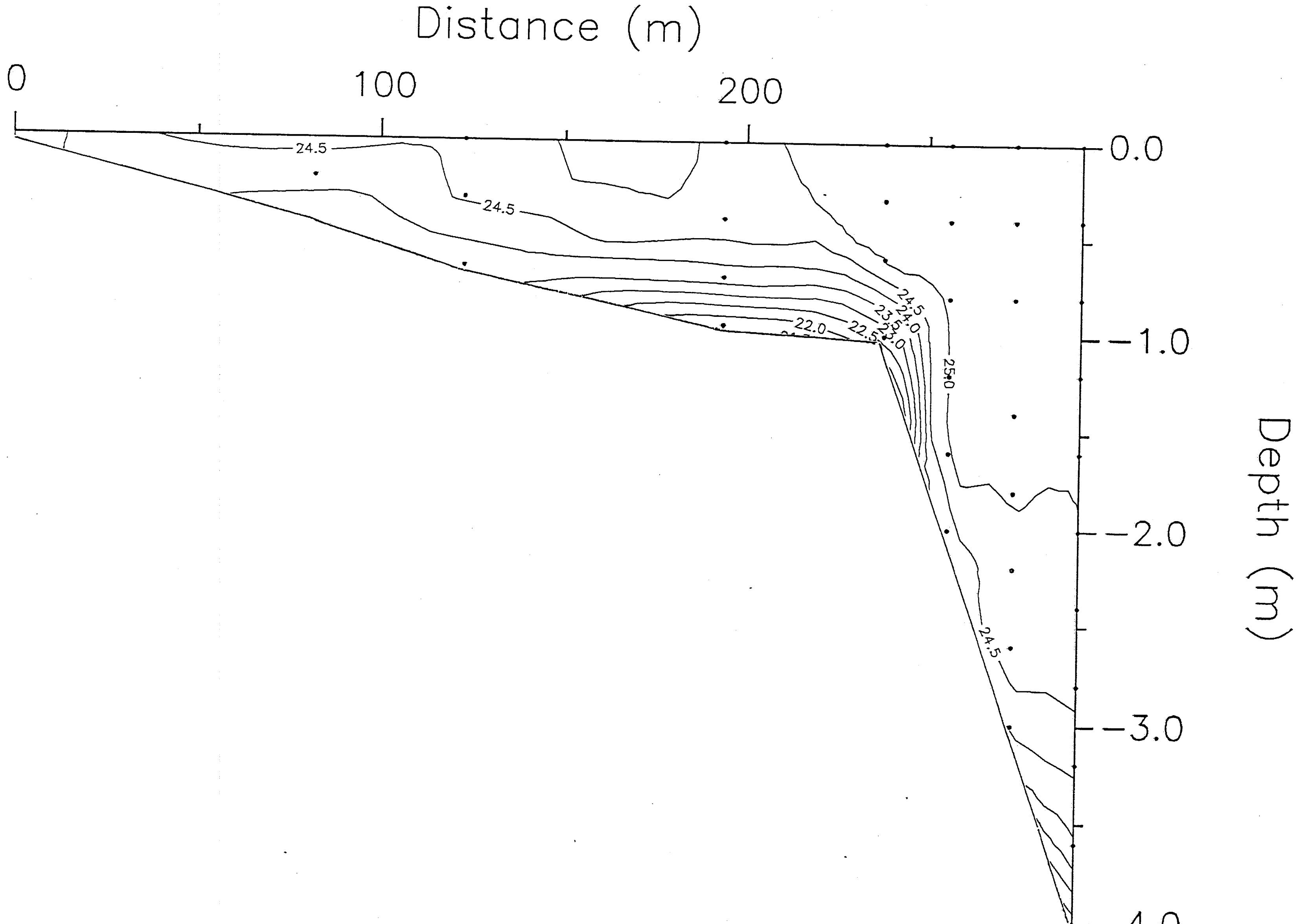


Eau Galle Reservoir Aug 12 01:00

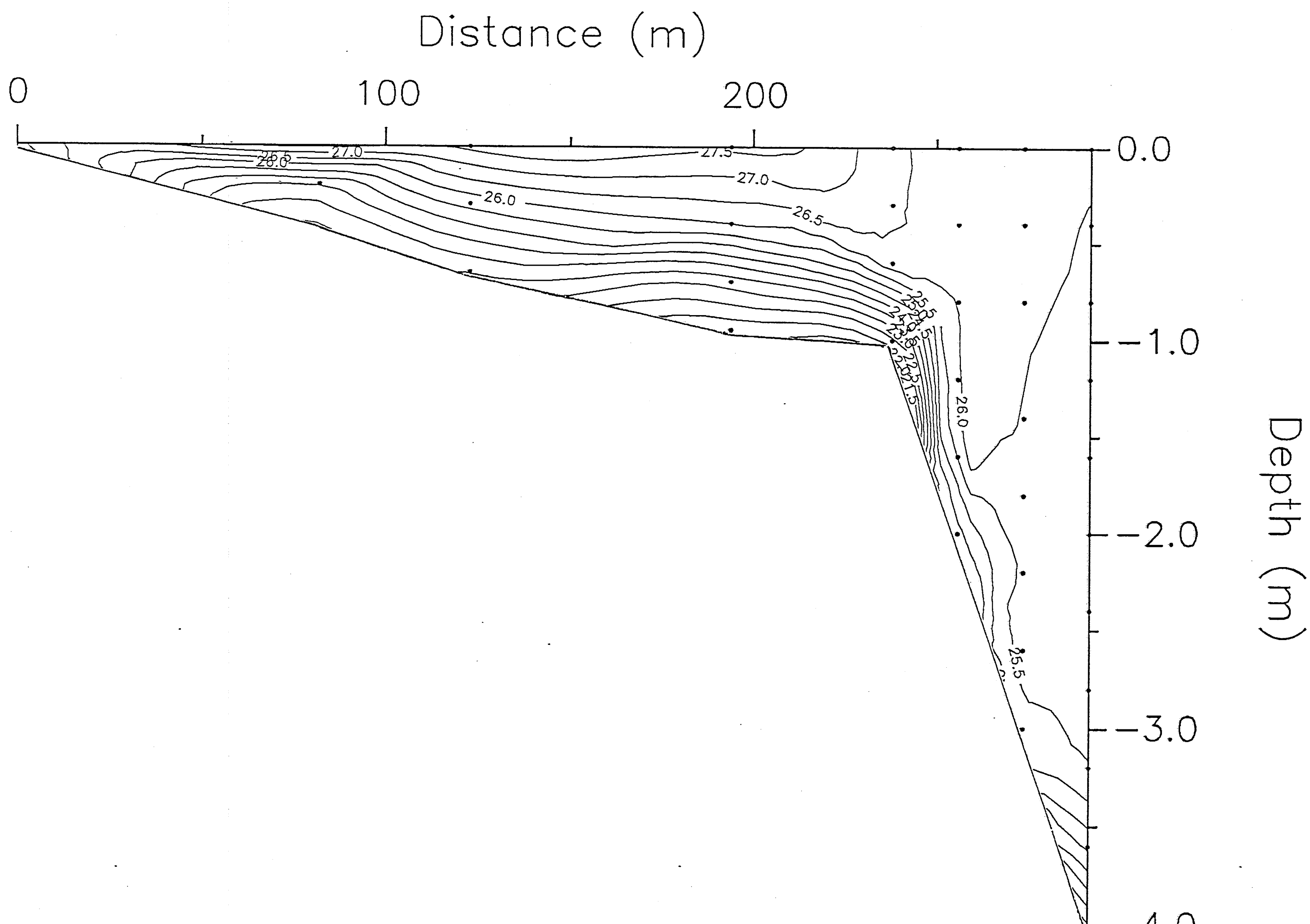

Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
25.5
25.0
24.5
24.0
26.0
Eau Galle Reservoir Aug 12 04:00



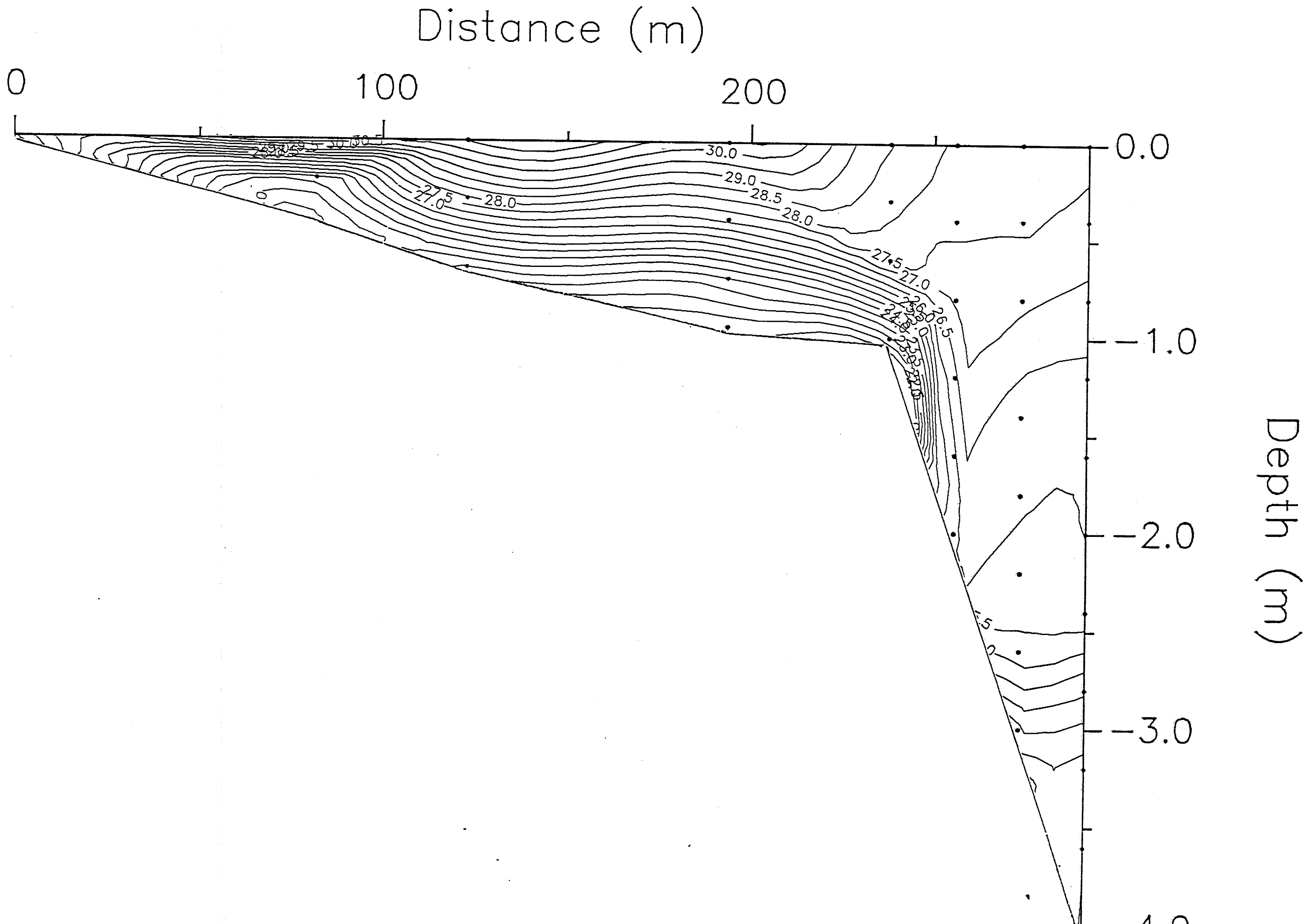
Eau Galle Reservoir Aug 12 07:00



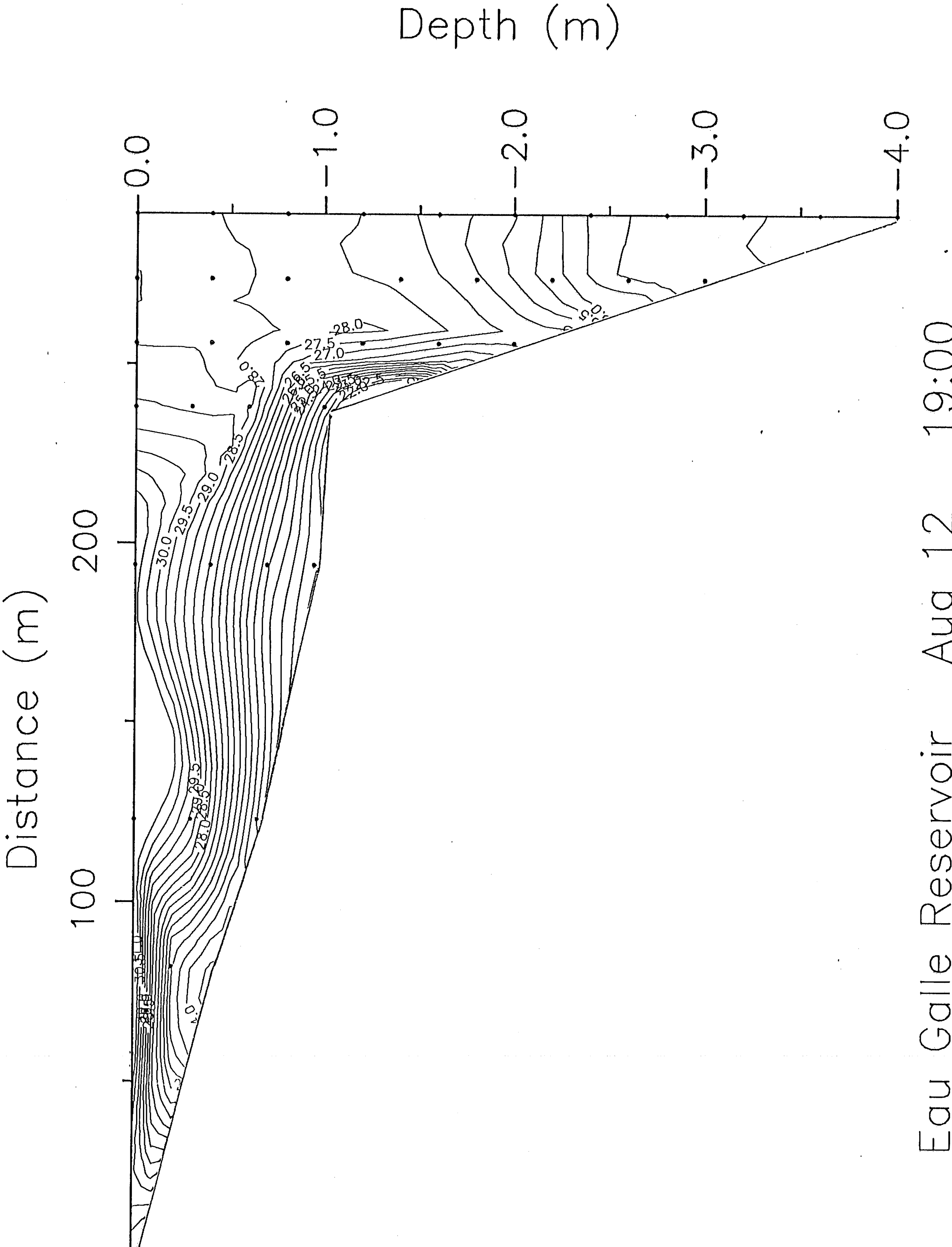
Eau Galle Reservoir Aug 12 10:00



Eau Galle Reservoir Aug 12 13:00



Eau Galle Reservoir Aug 12 16:00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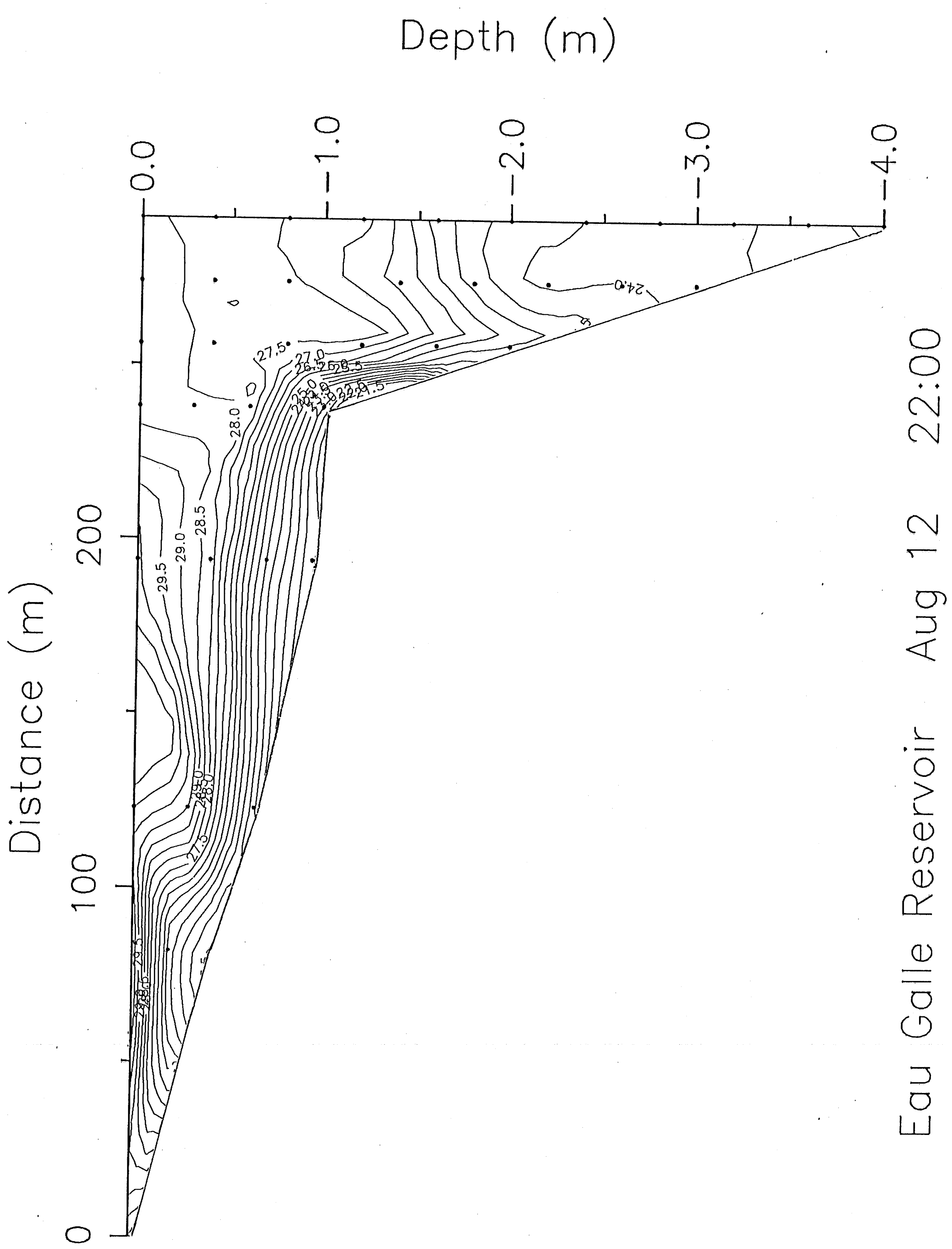
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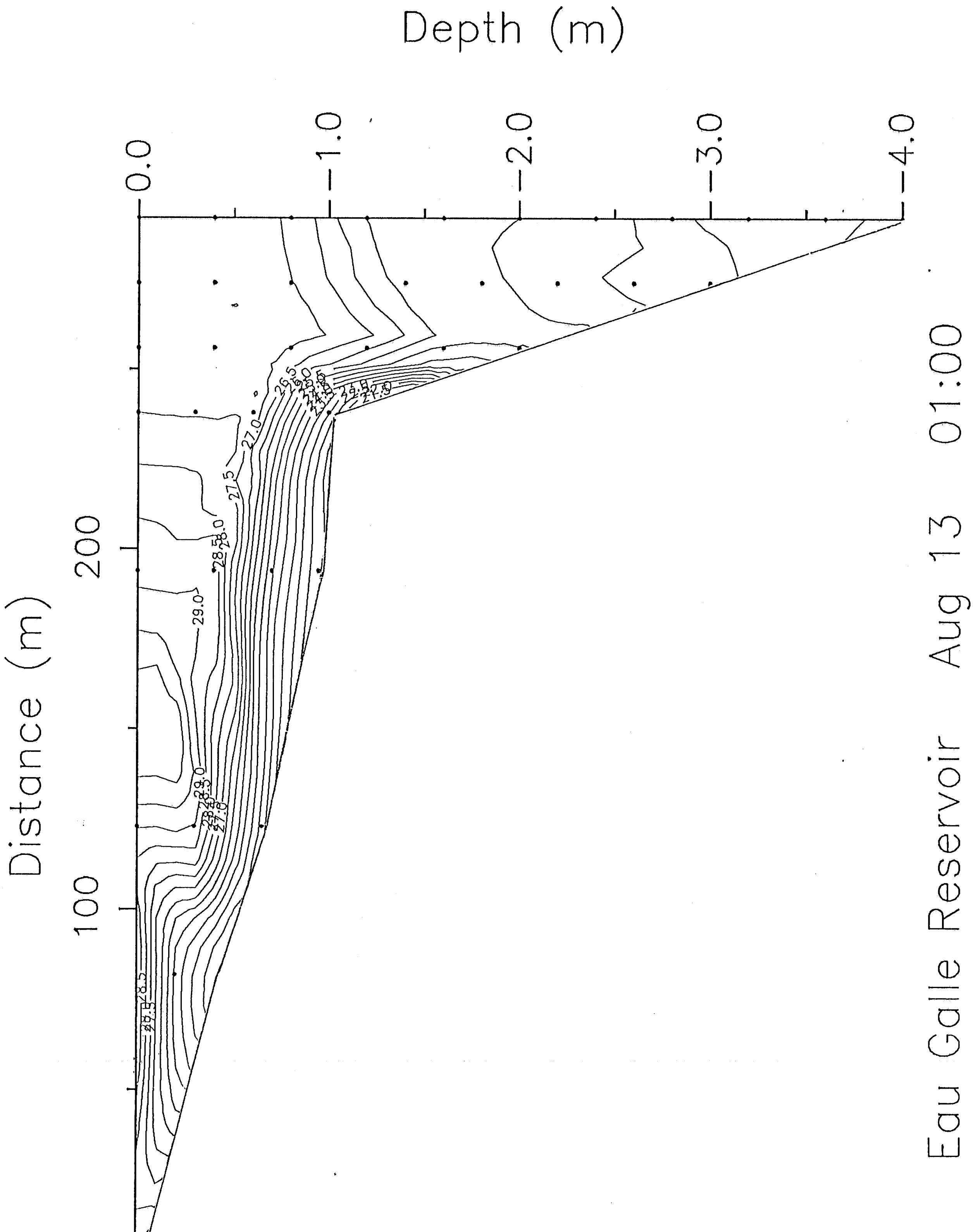
29.5
Eau Galle Reservoir Aug 12 22:00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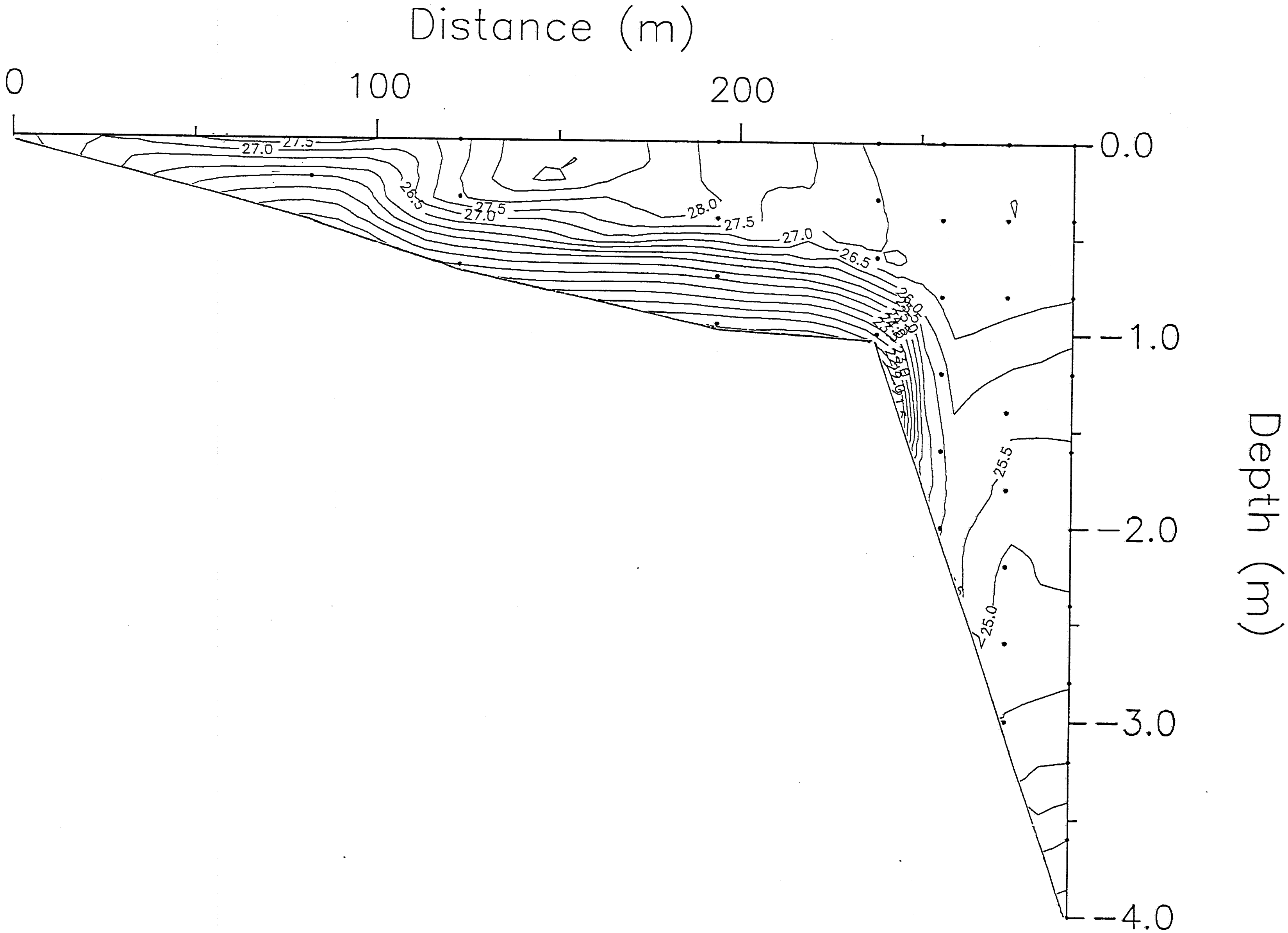
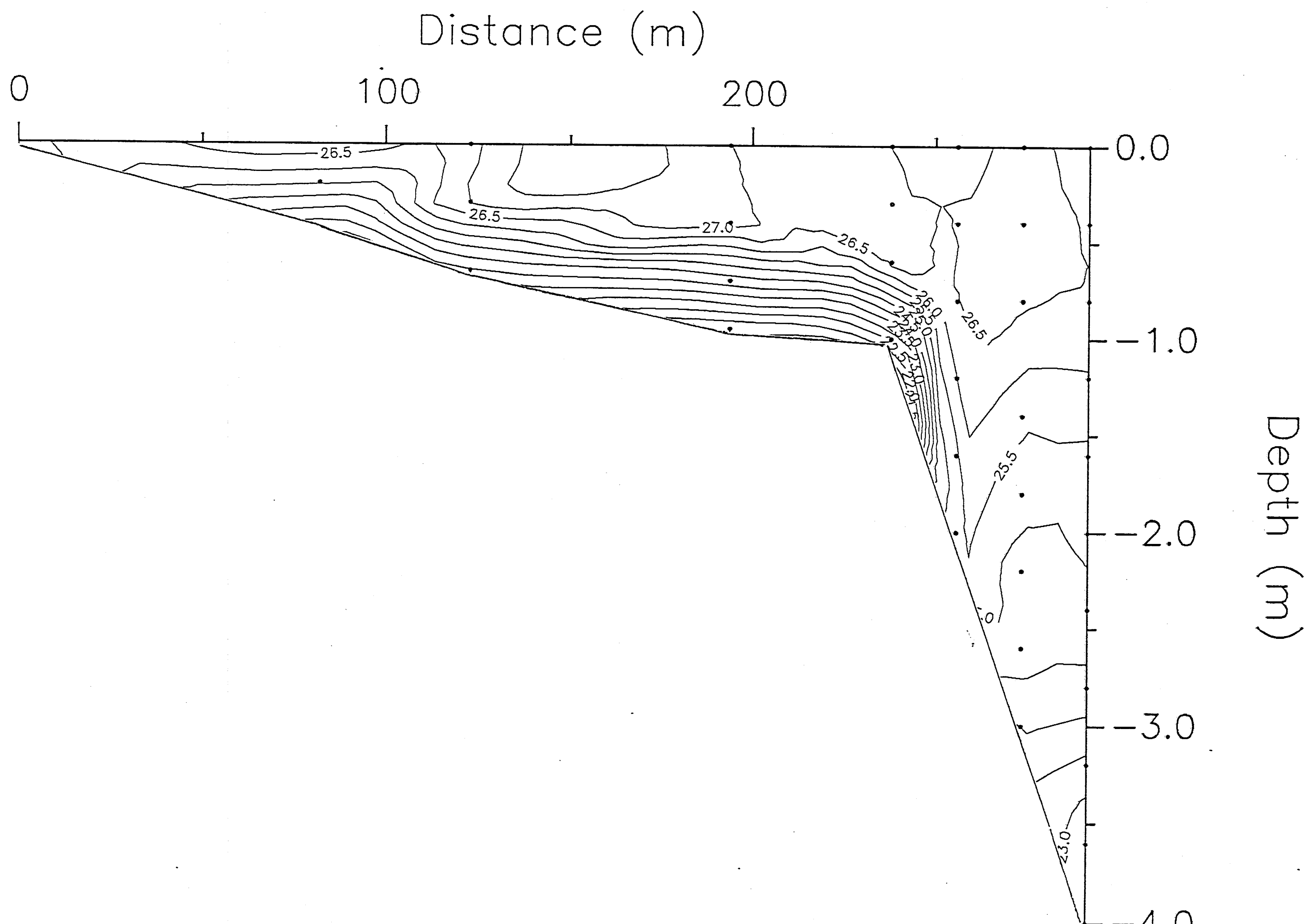
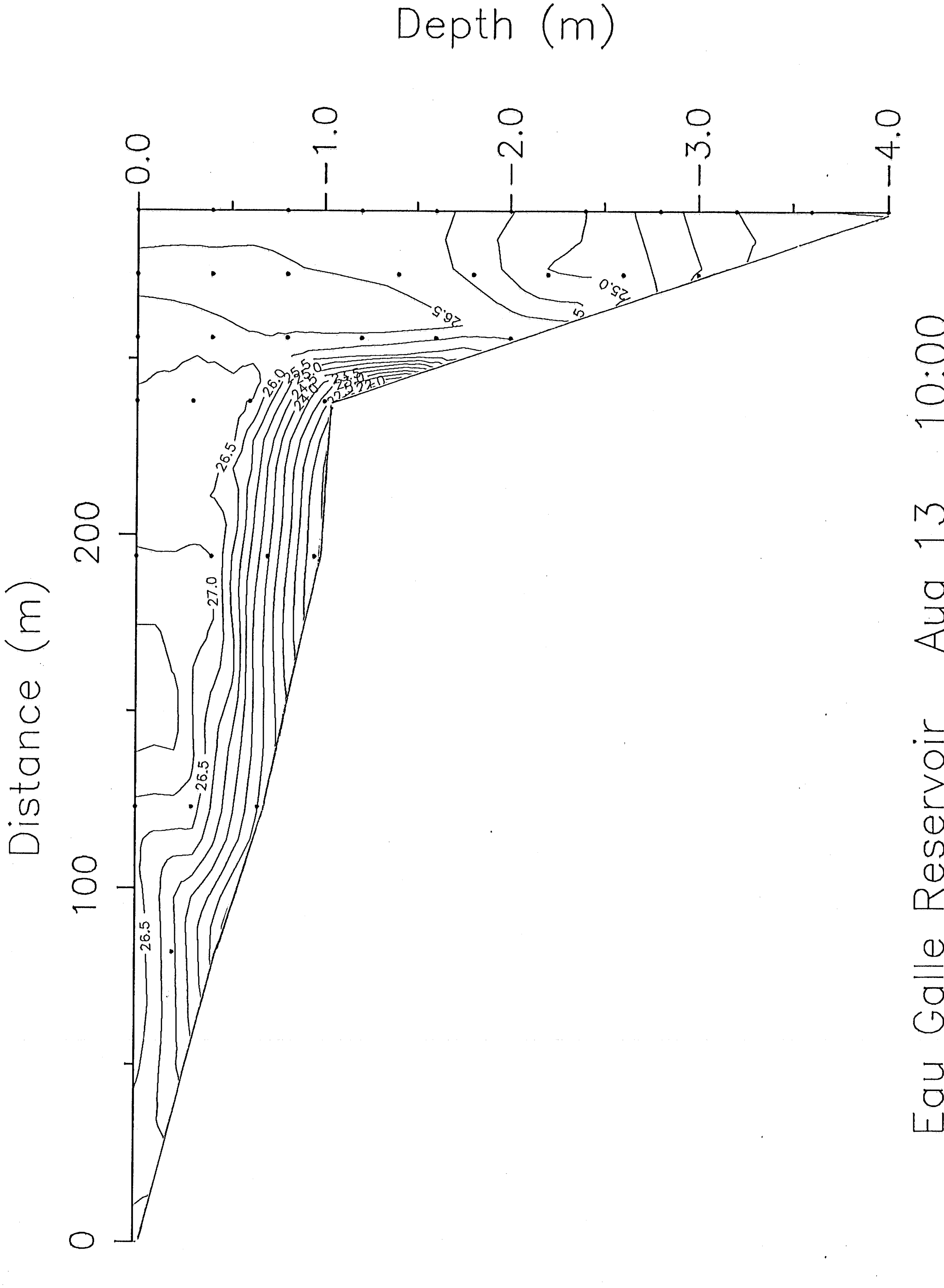


Eau Galle Reservoir Aug 13 04:00



Eau Galle Reservoir Aug 13 07:00



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Distance (m)
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200
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26.5
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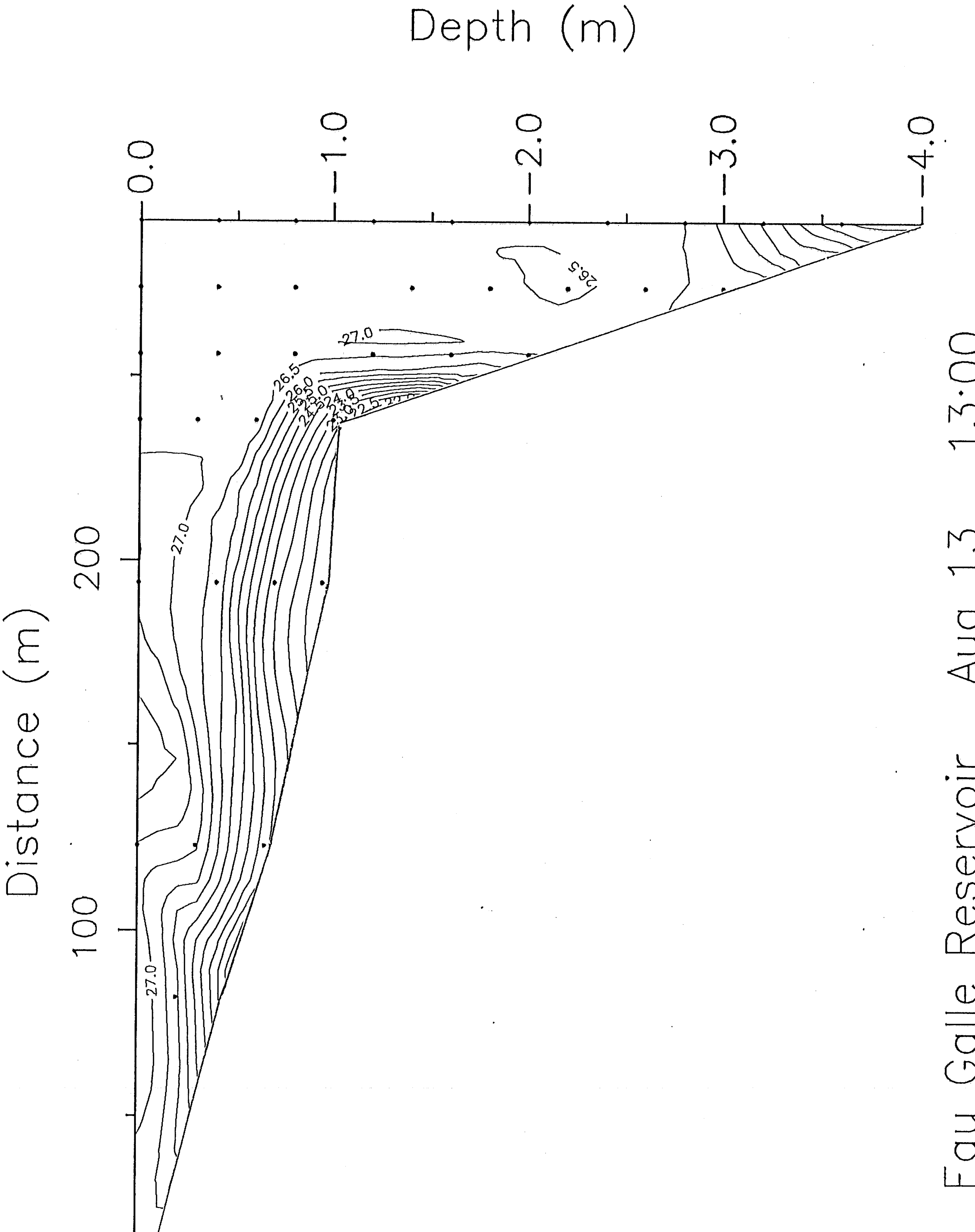
26.5
25.0
Eau Galle Reservoir Aug 13 10:00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Distance (m)
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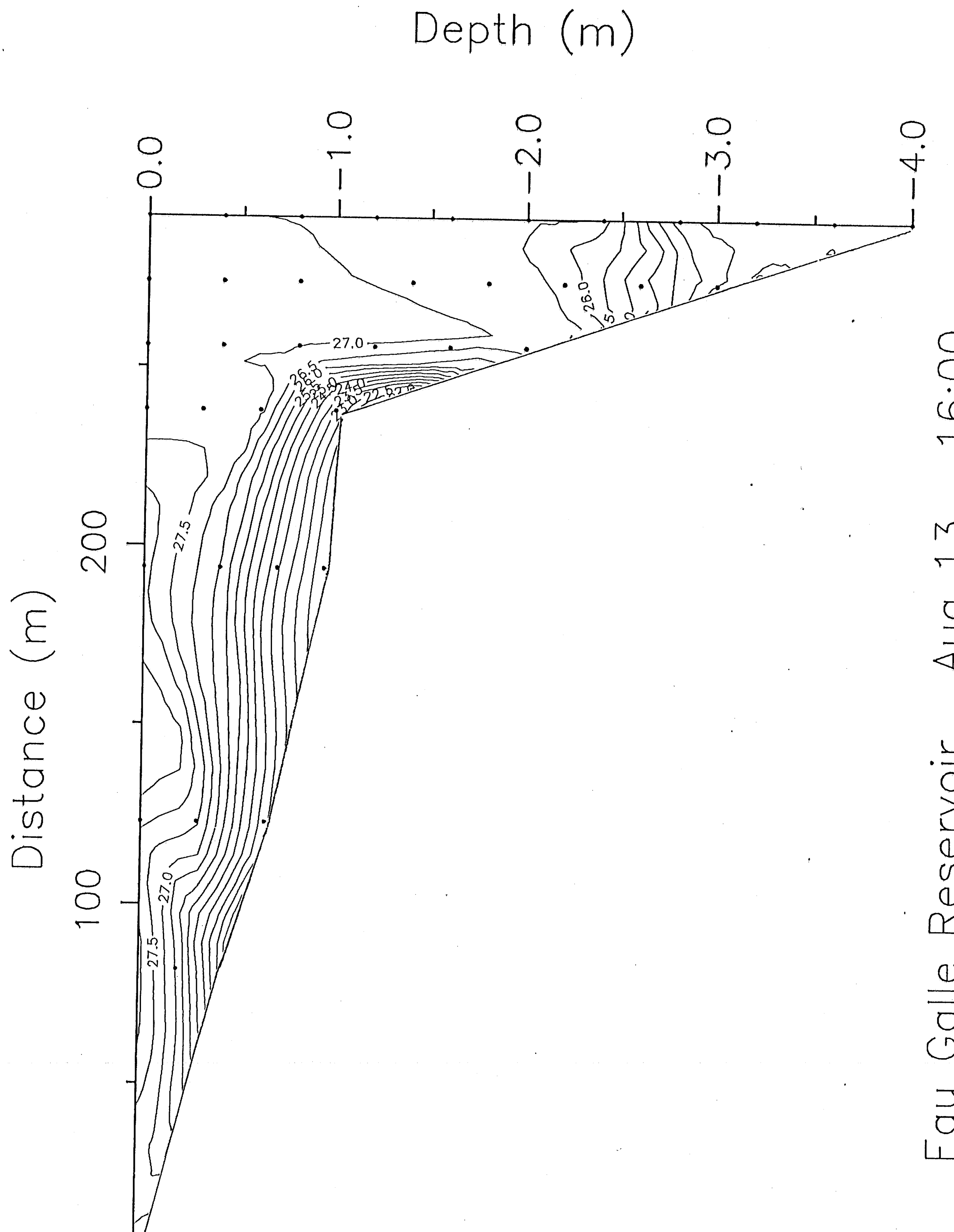
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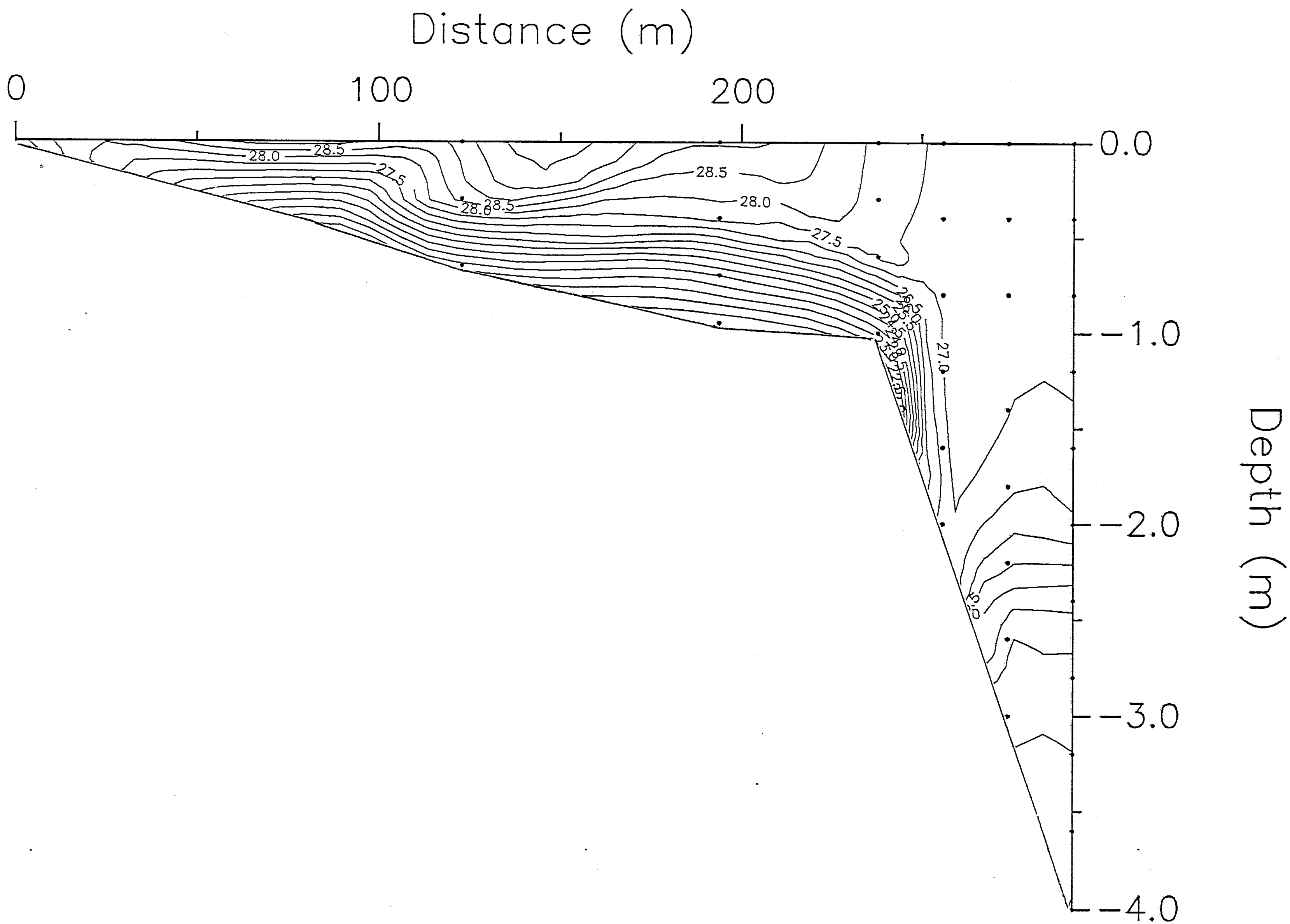
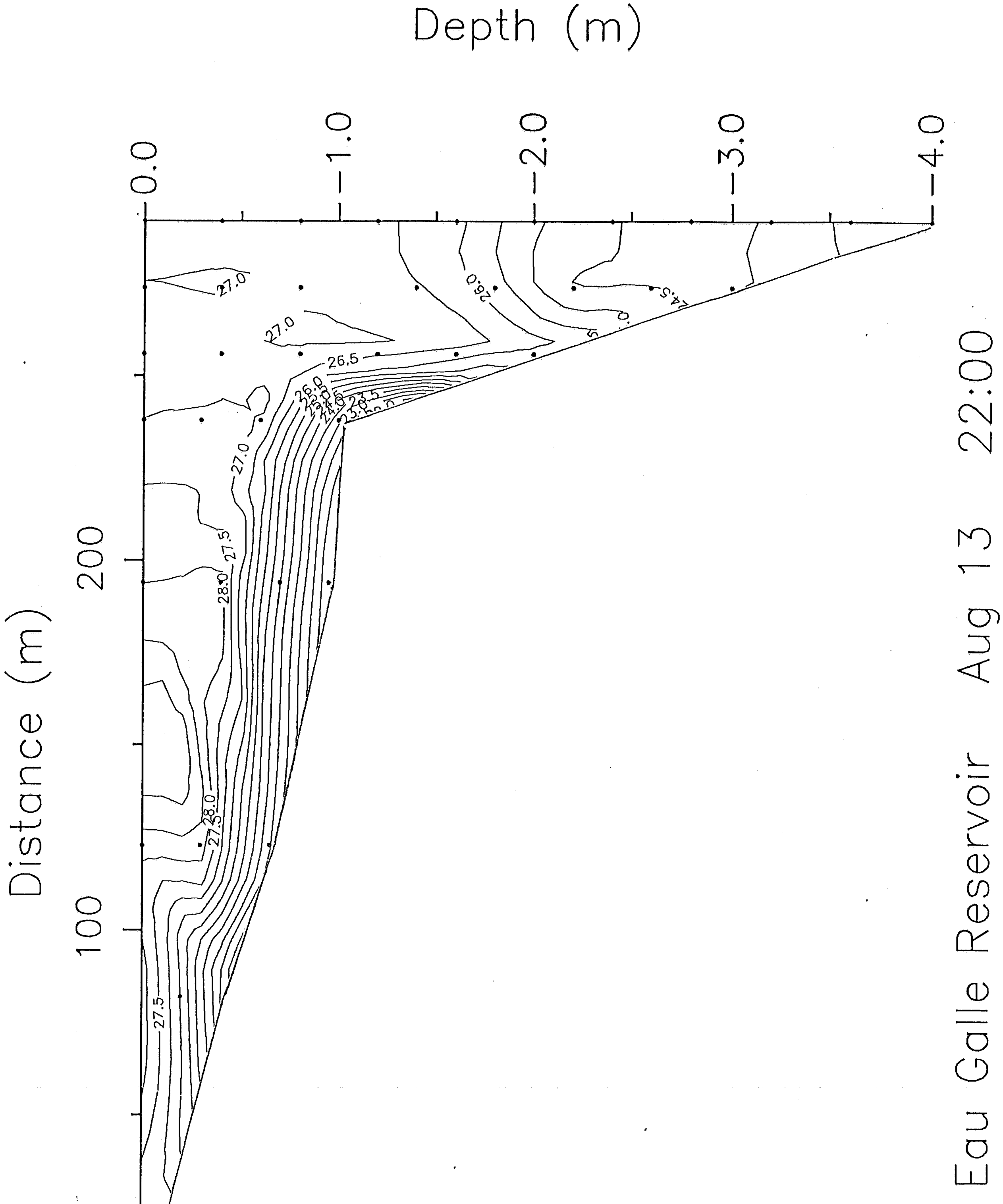
Eau Galle Reservoir Aug 13 16:00



Eau Galle Reservoir Aug 13 19:00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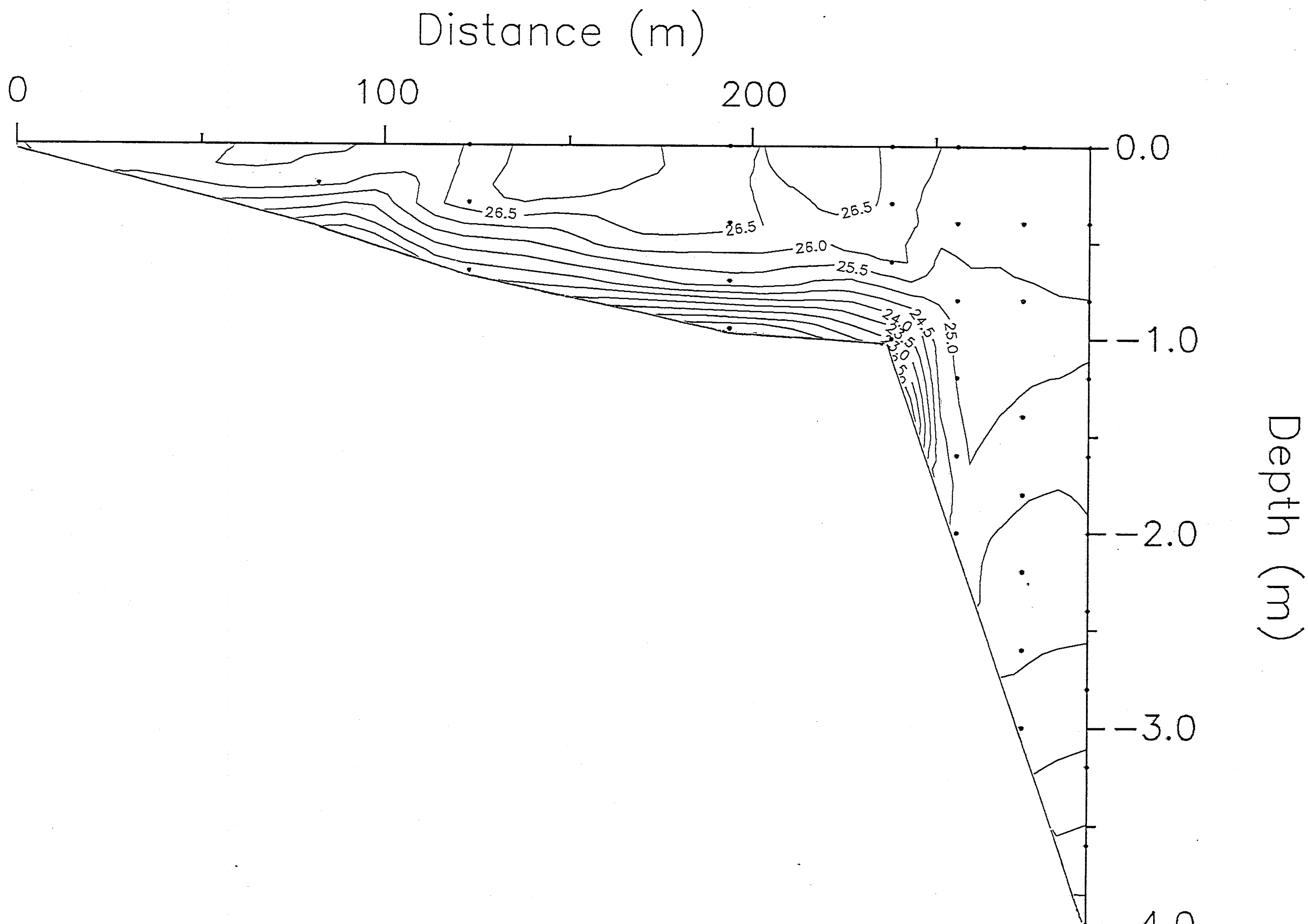
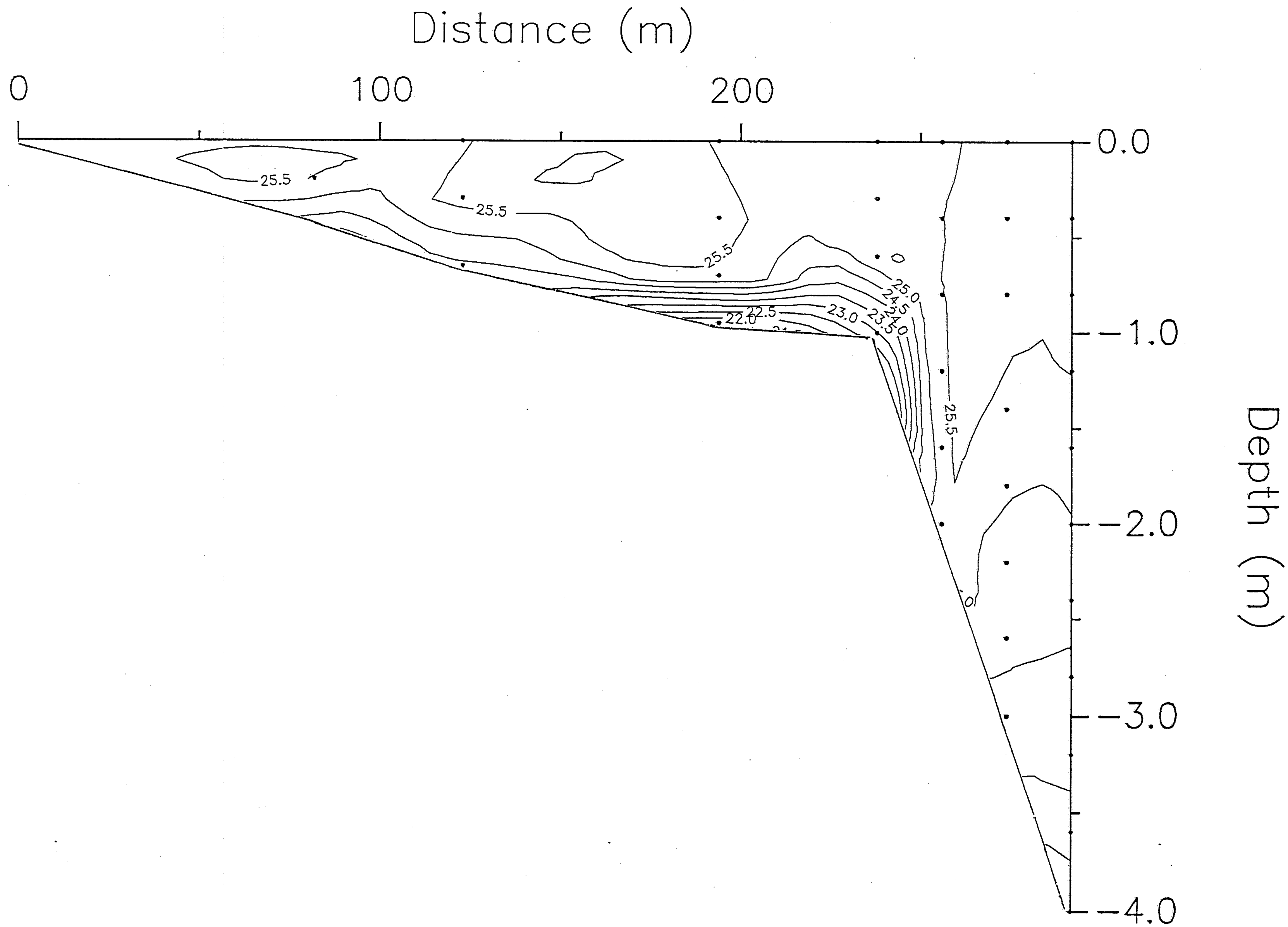
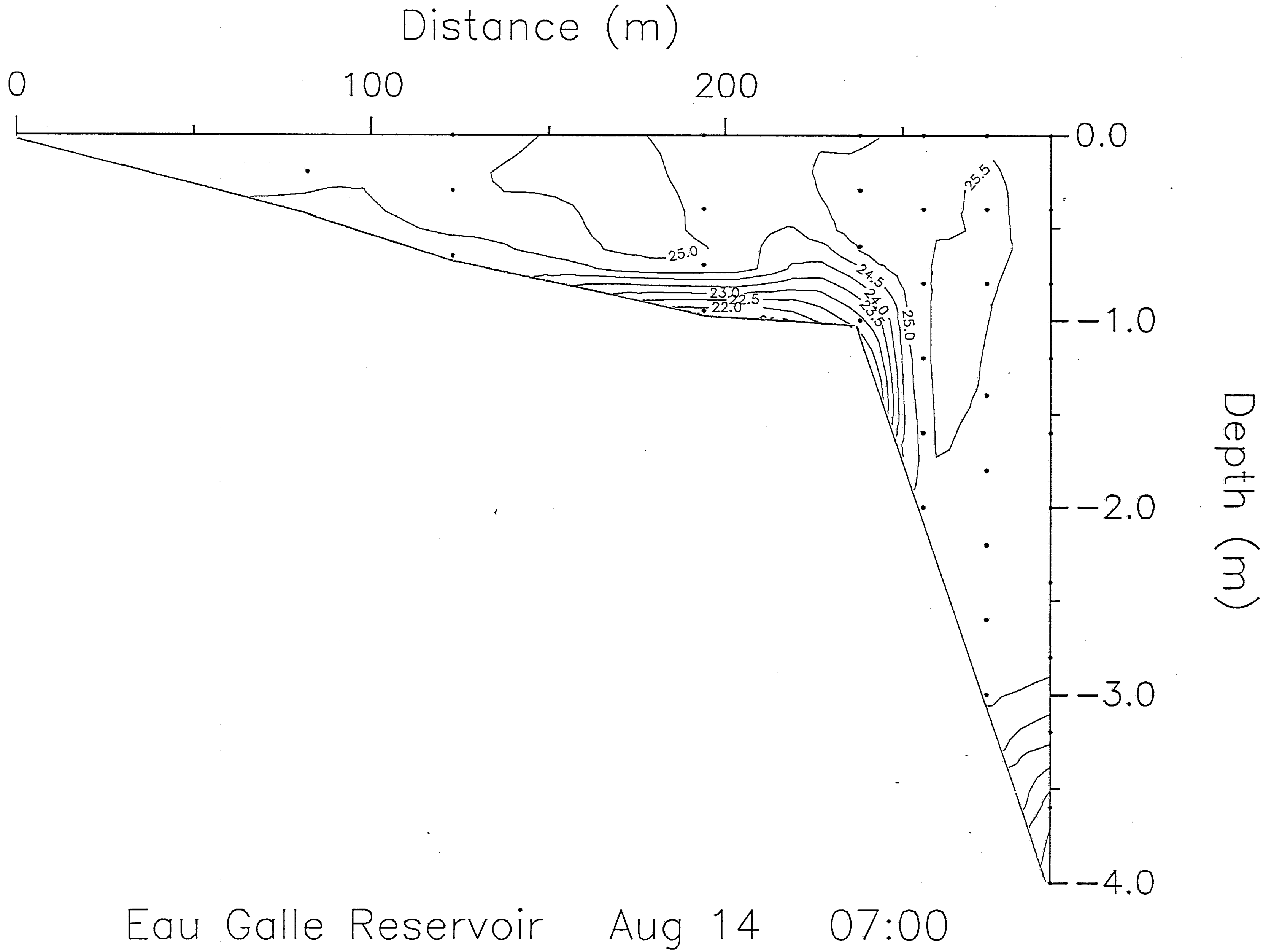


Eau Galle Reservoir Aug 14 01:00



Eau Galle Reservoir Aug 14 04:00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24.5
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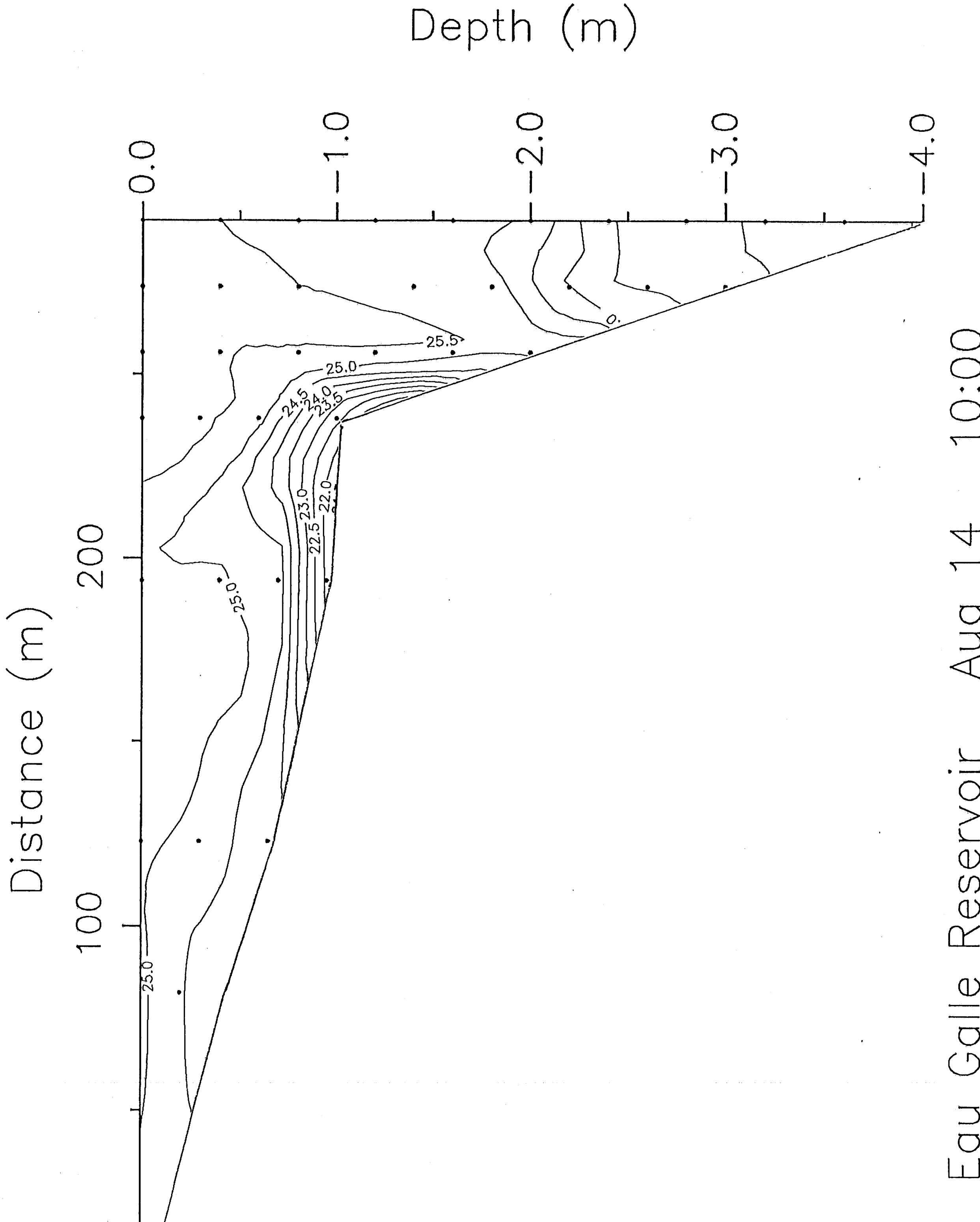
22.0
Eau Galle Reservoir Aug 14 07:00



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Distance (m)
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25.5
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22.5
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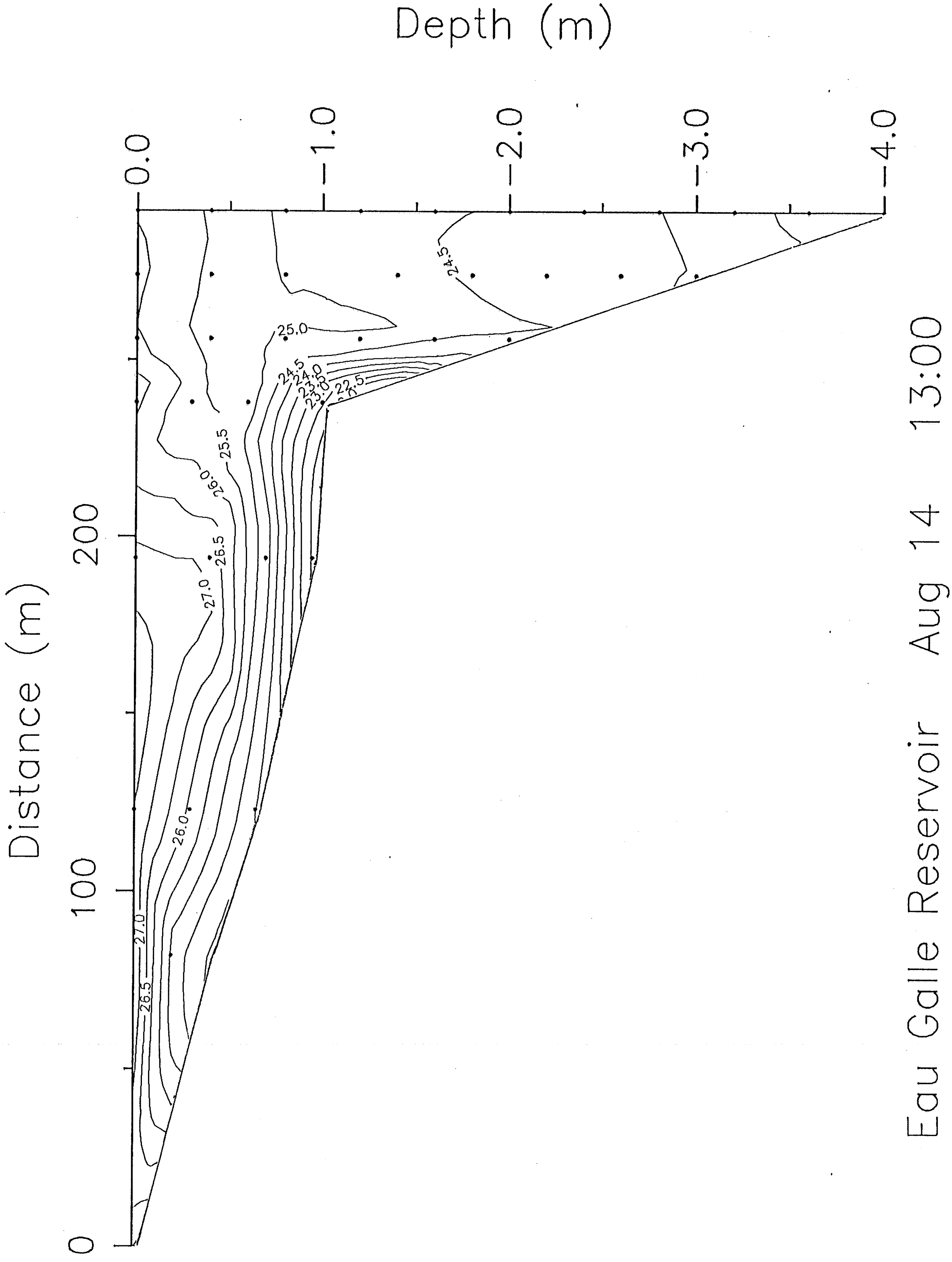
Eau Galle Reservoir Aug 14 10:00



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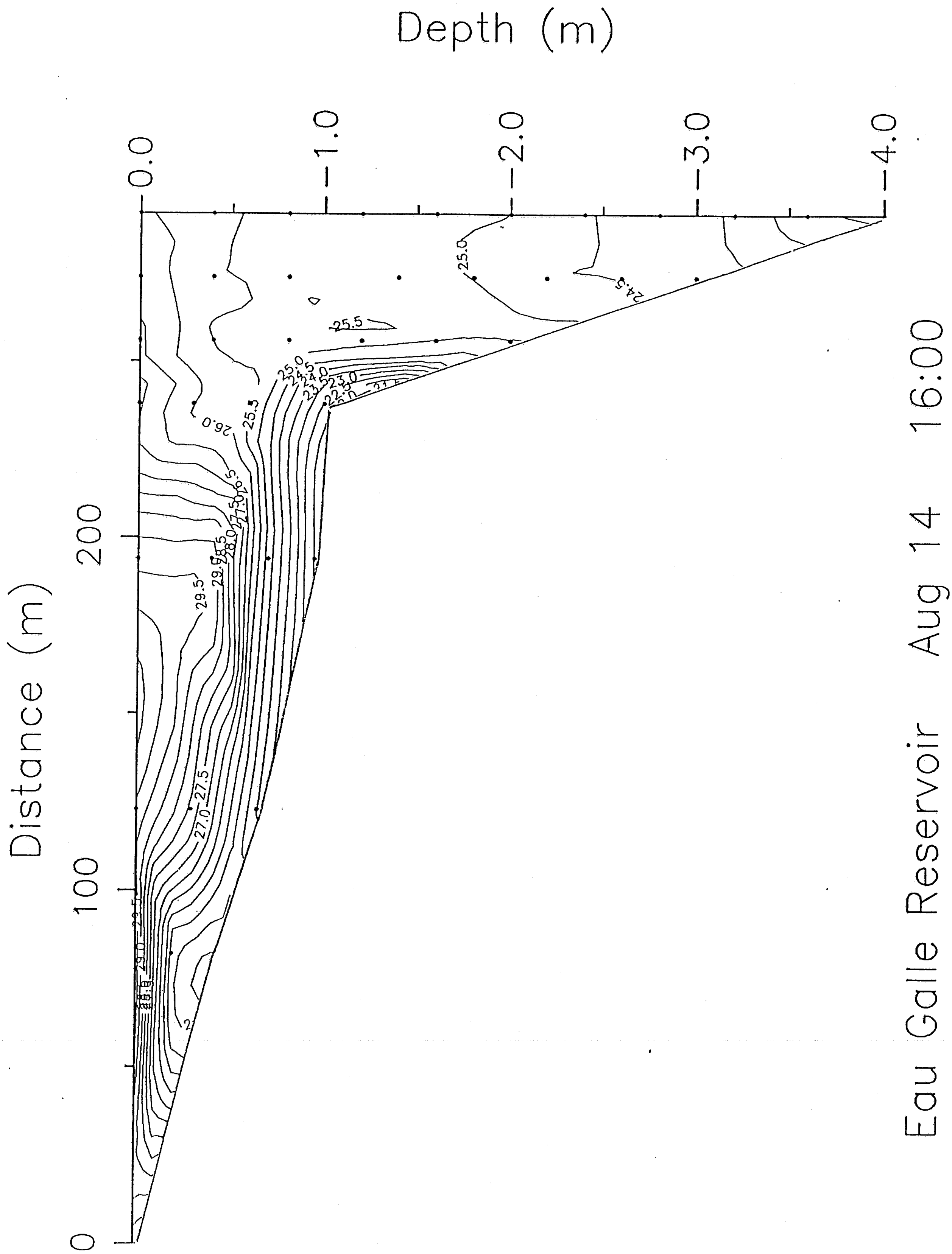
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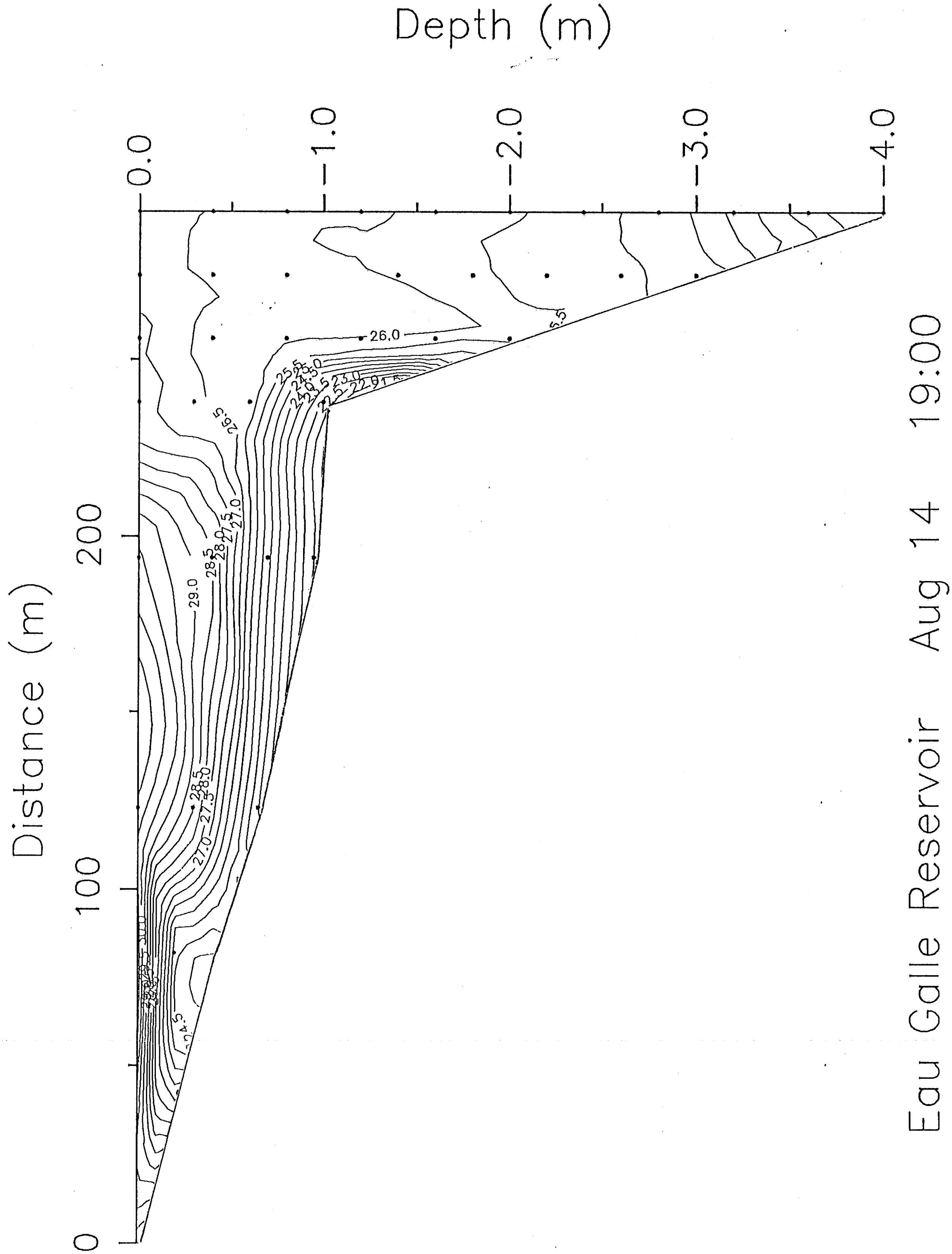

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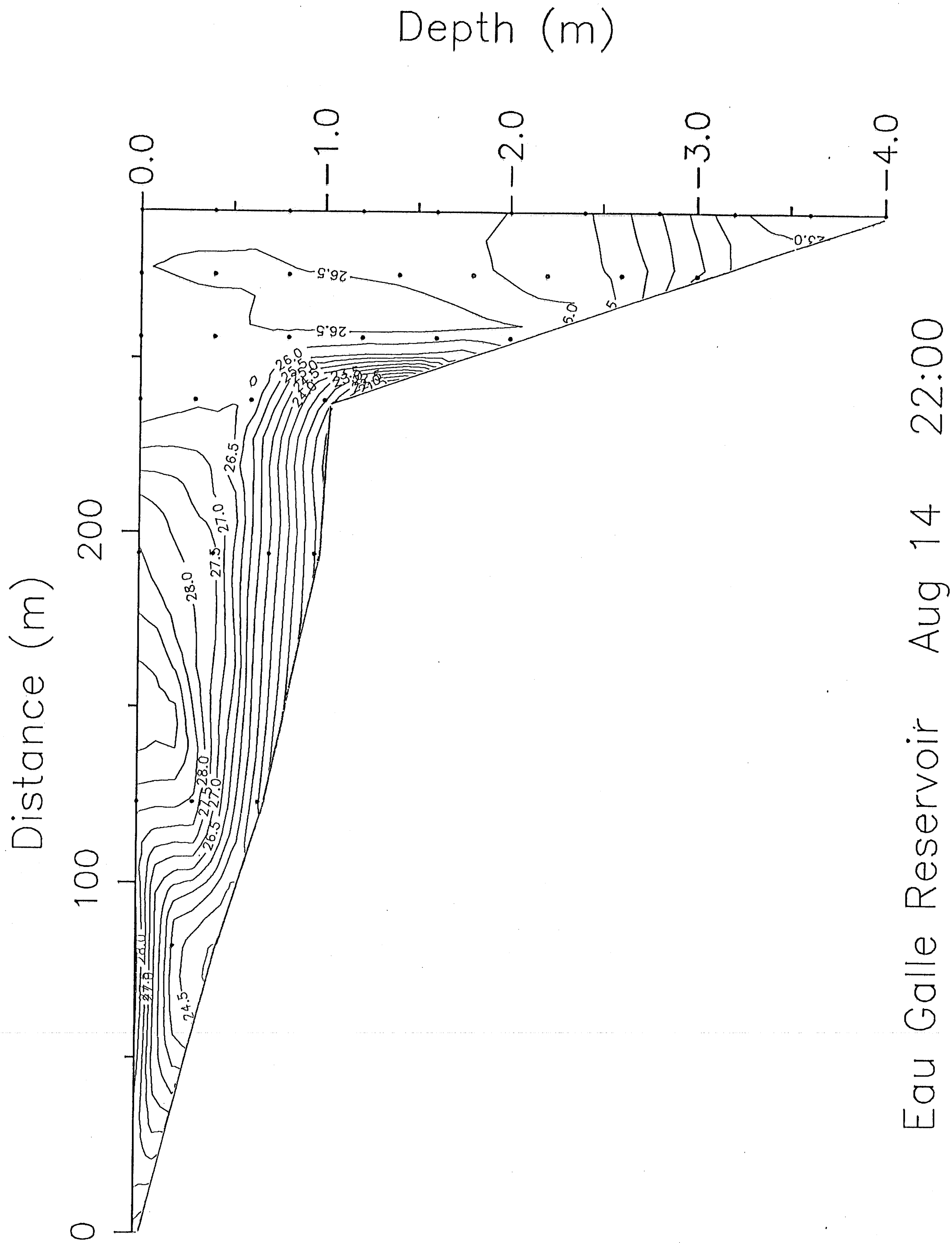
Eau Galle Reservoir Aug 14 19:00



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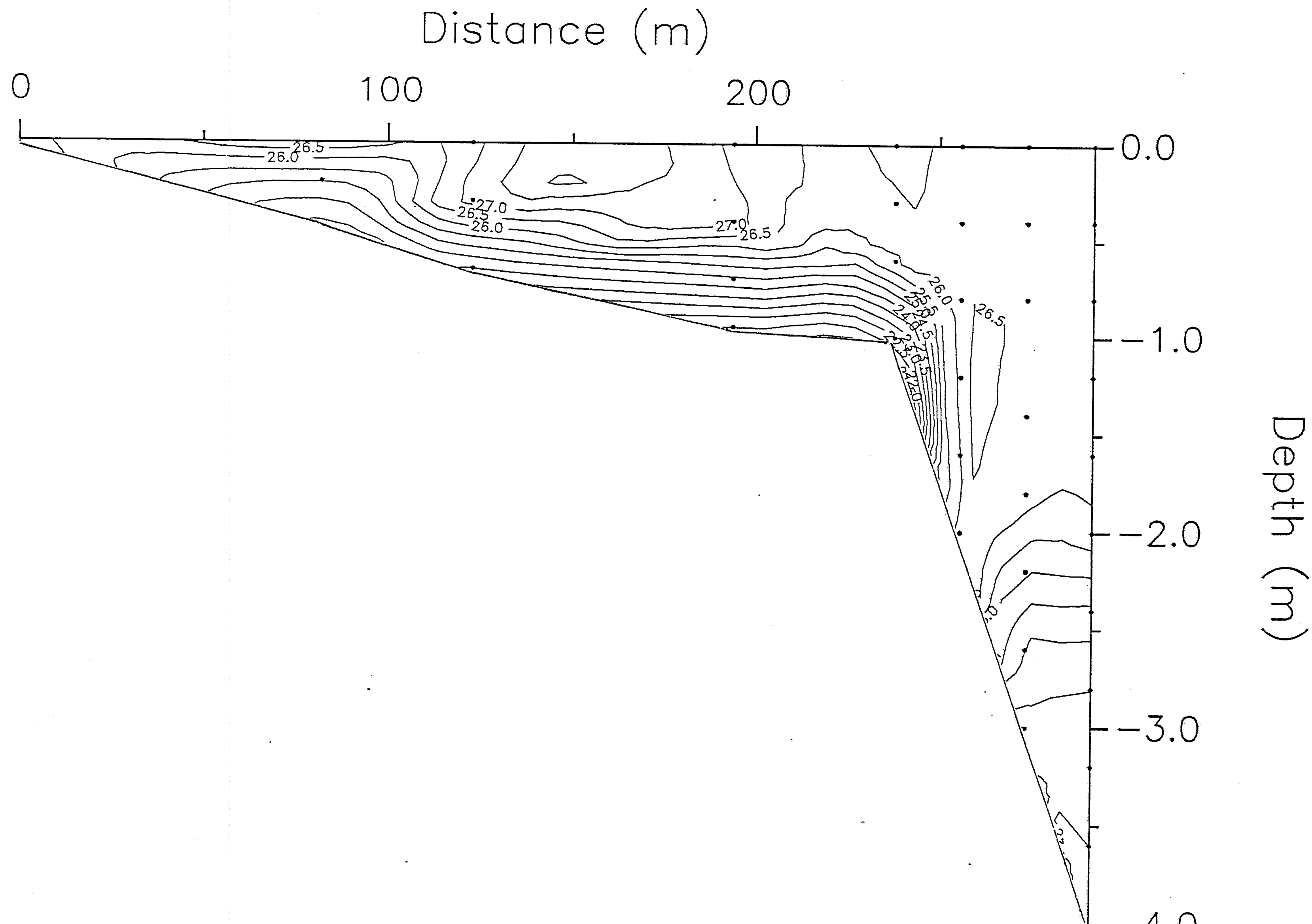
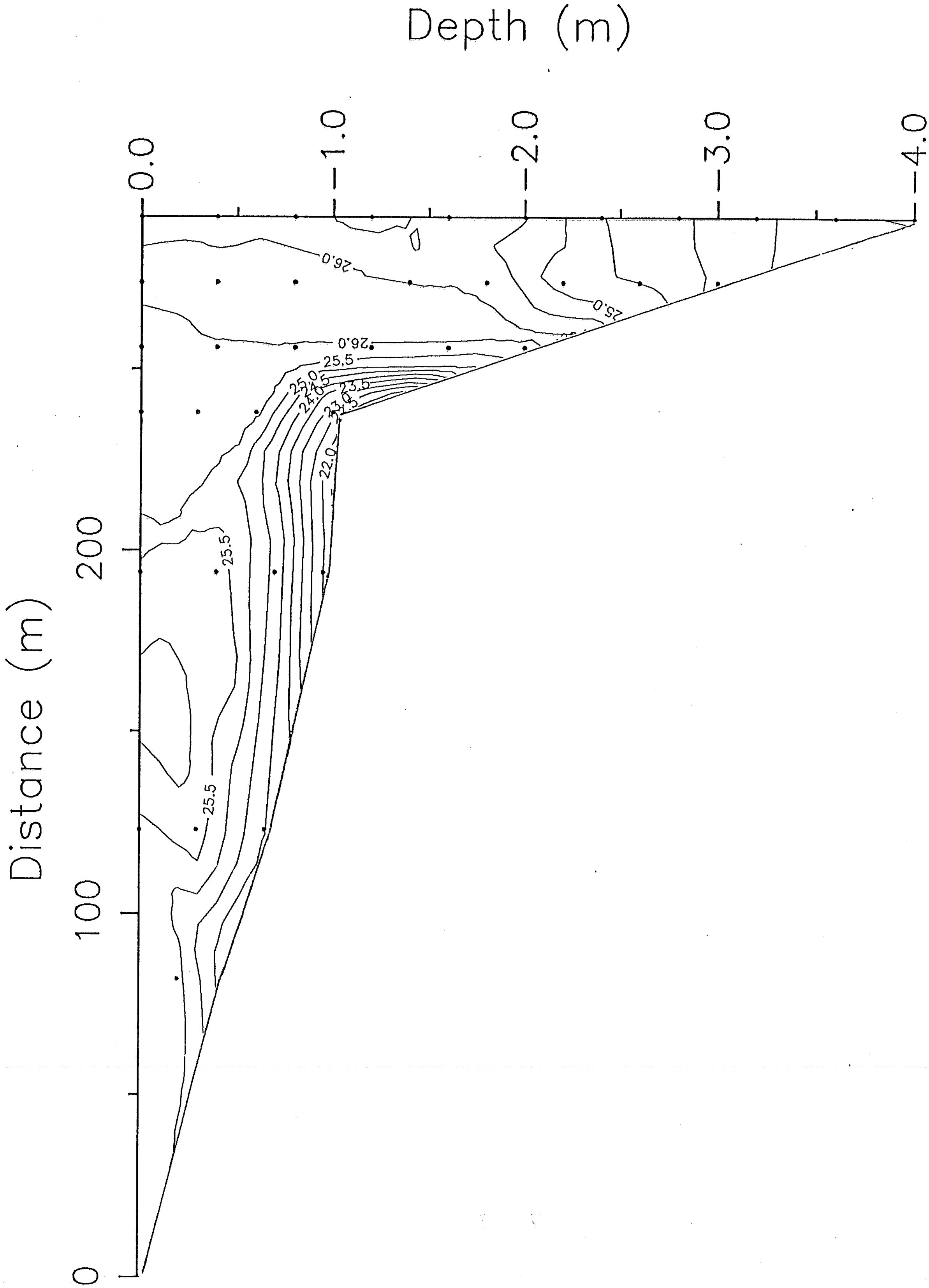
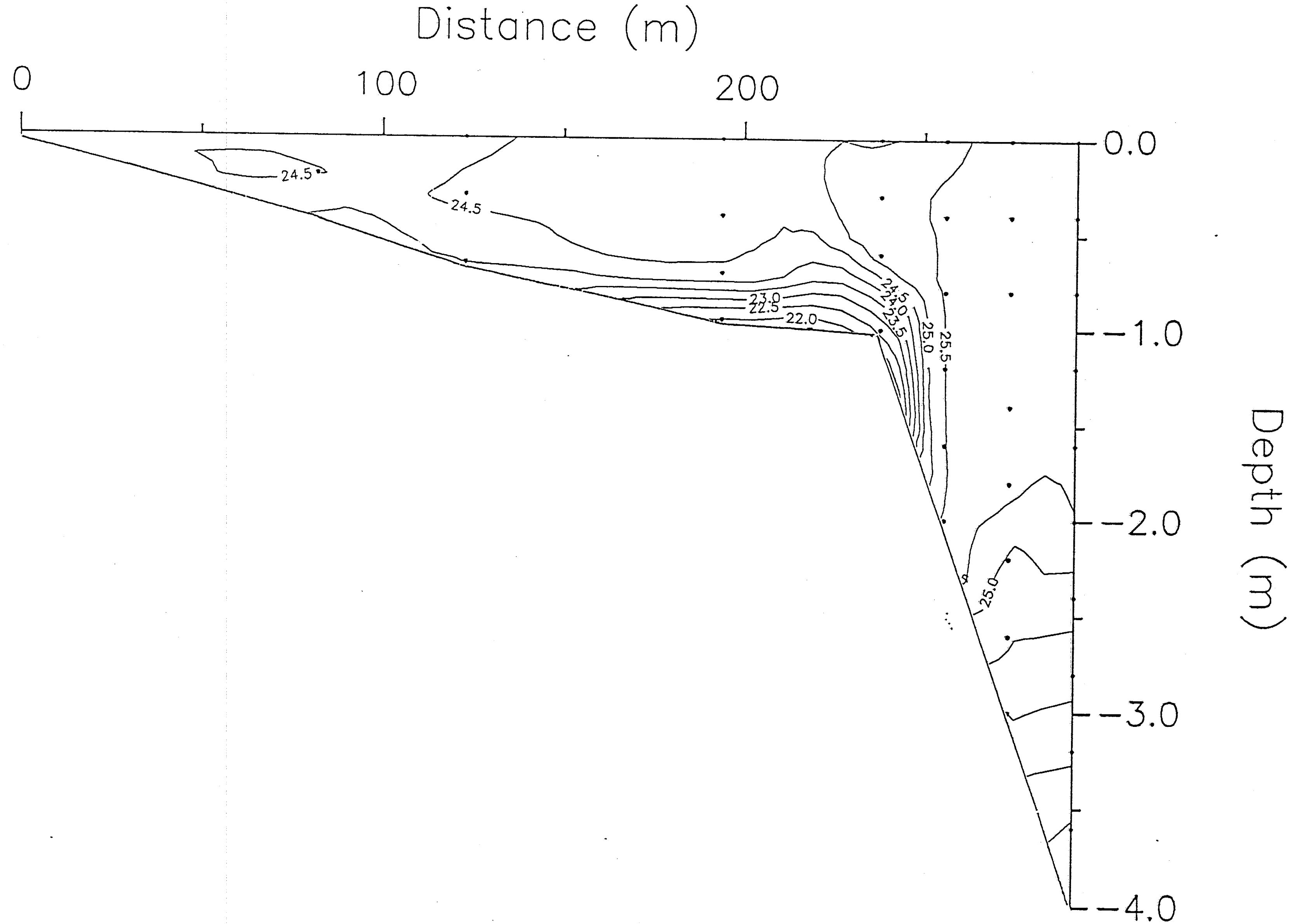
Eau Galle Reservoir Aug 14 22:00



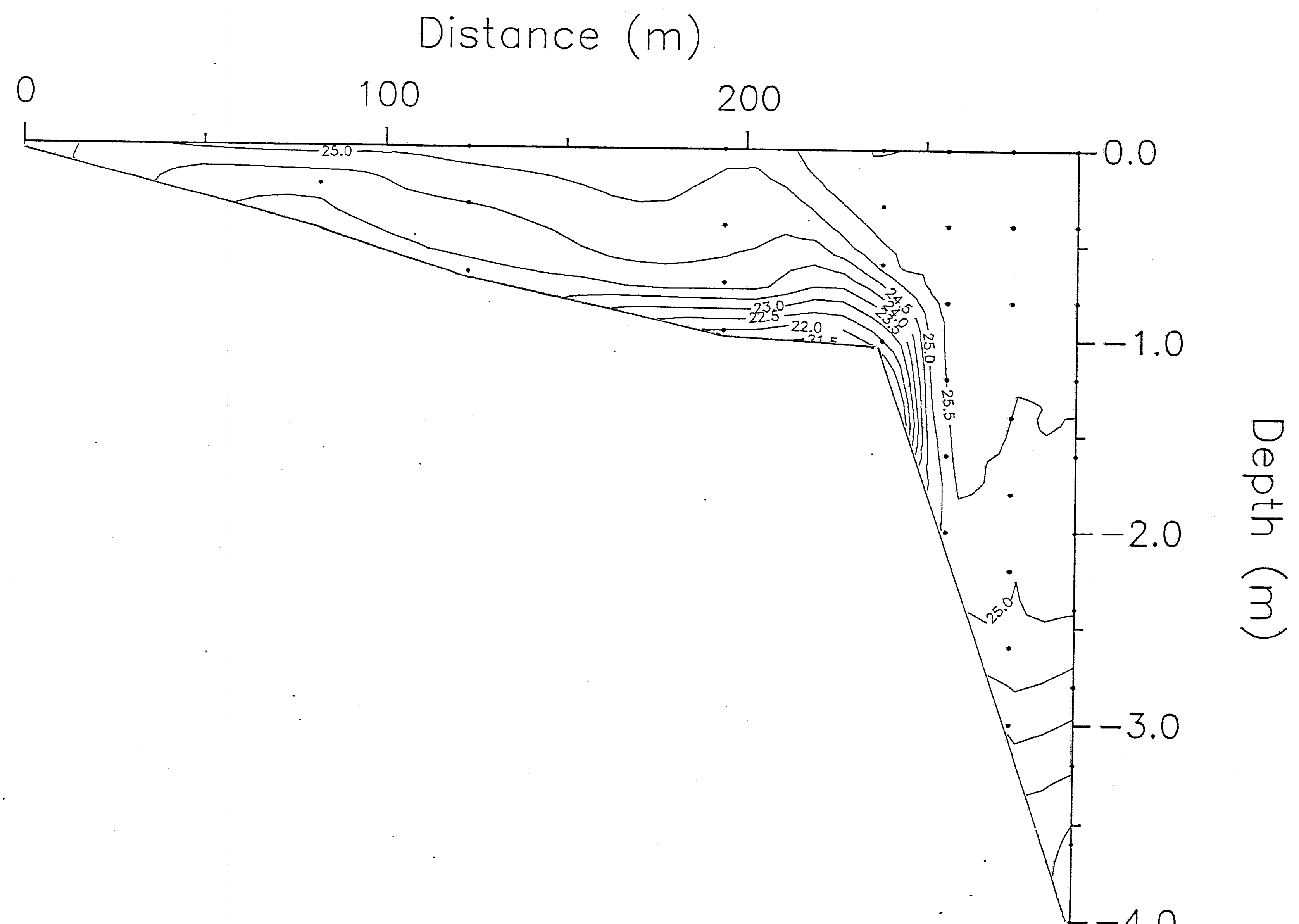
Eau Galle Reservoir Aug 15 01:00



Eau Galle Reservoir Aug 15 04:00



Eau Galle Reservoir Aug 15 07:00



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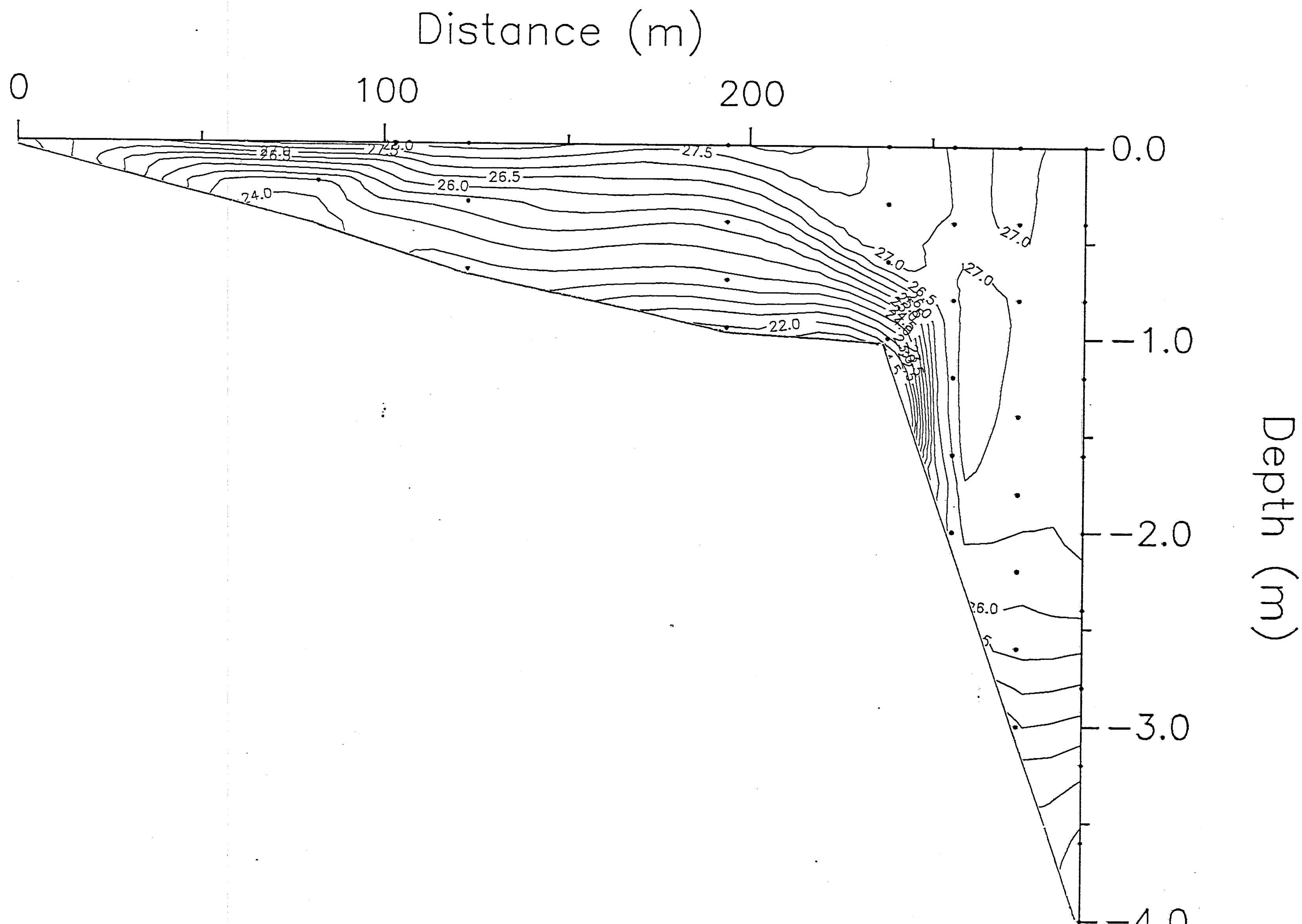

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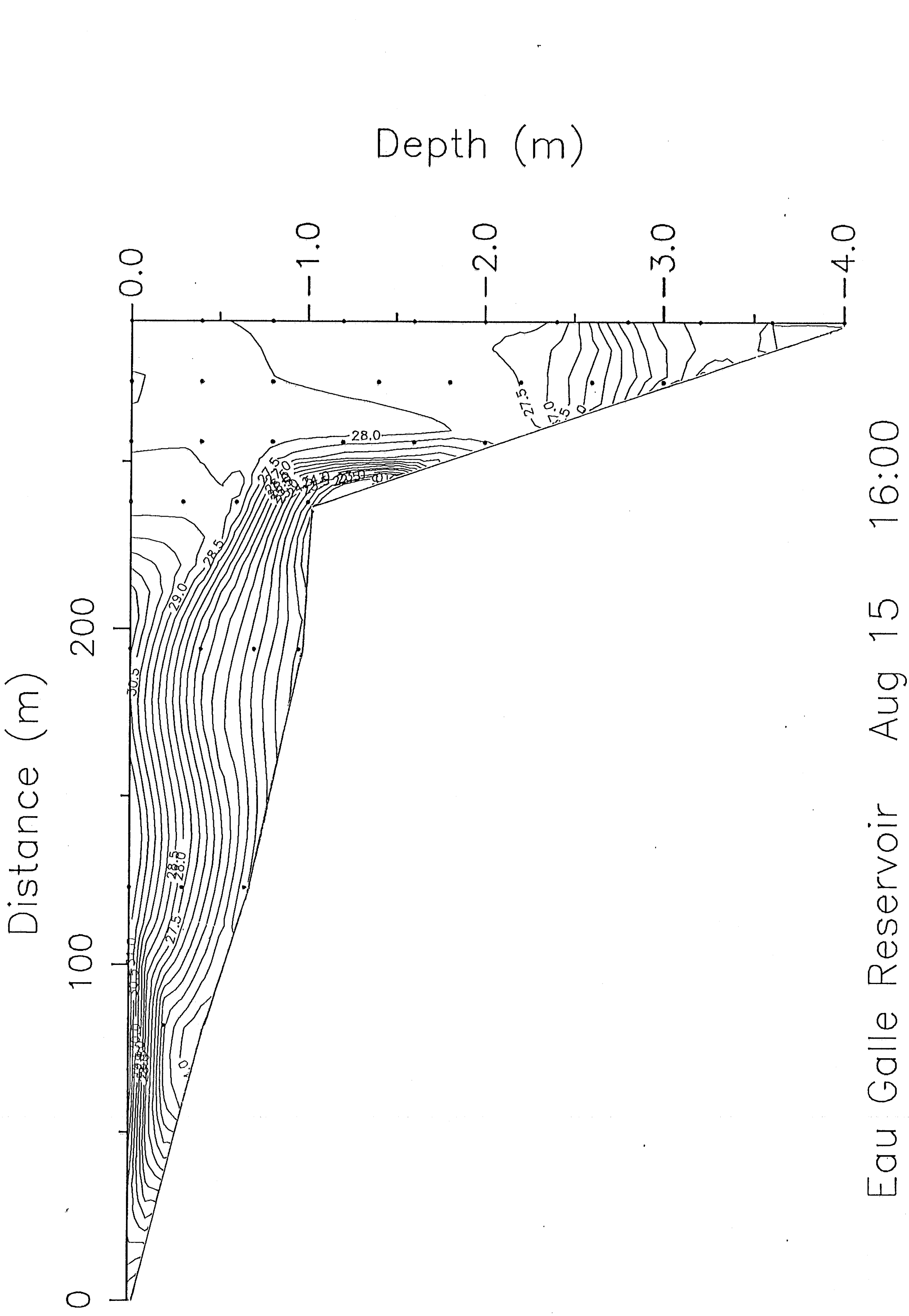
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Distance (m)
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200
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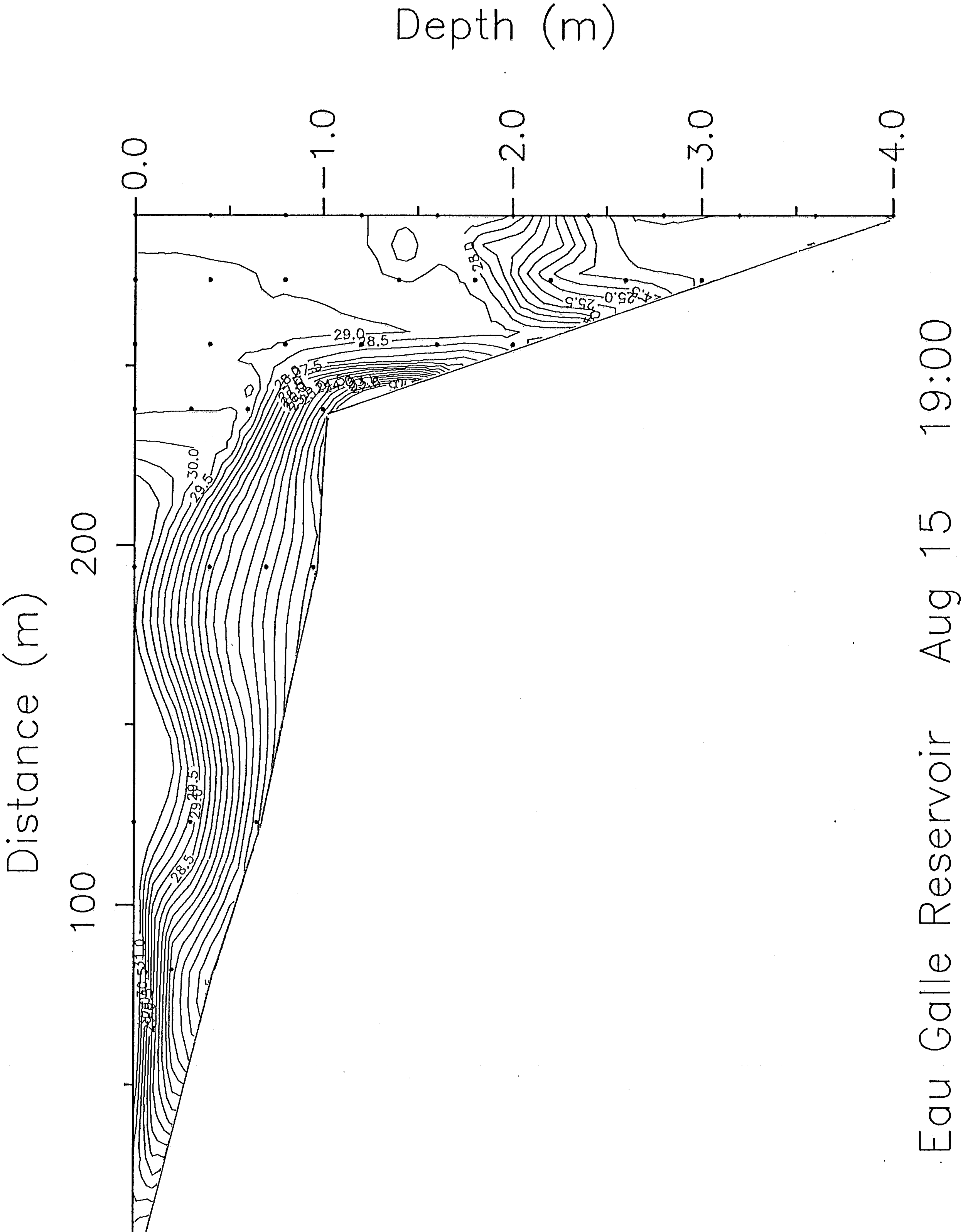
Eau Galle Reservoir Aug 15 16:00



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Distance (m)
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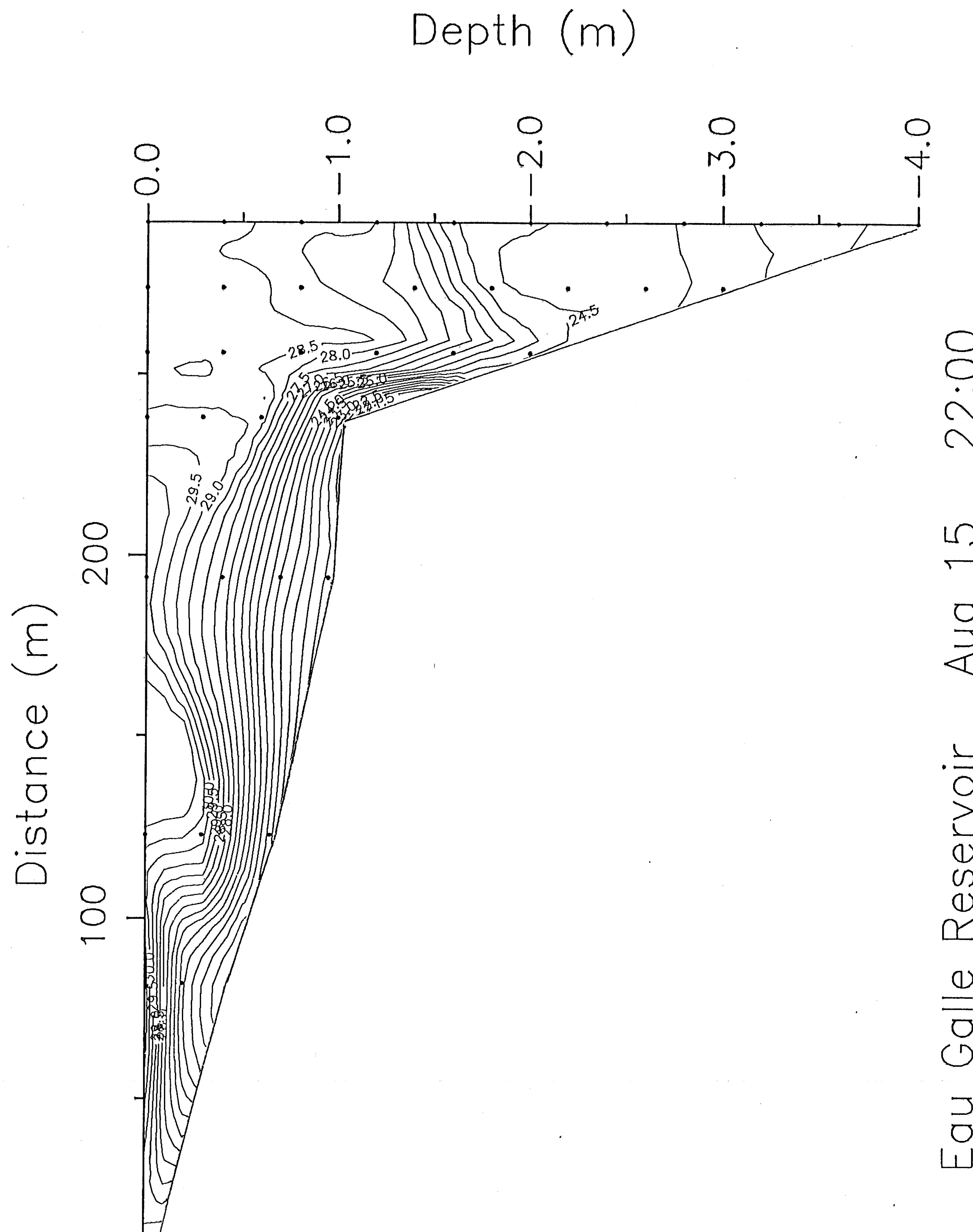
Eau Galle Reservoir Aug 15 19:00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Distance (m)
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100
200
Eau Galle Reservoir Aug 15 22:00
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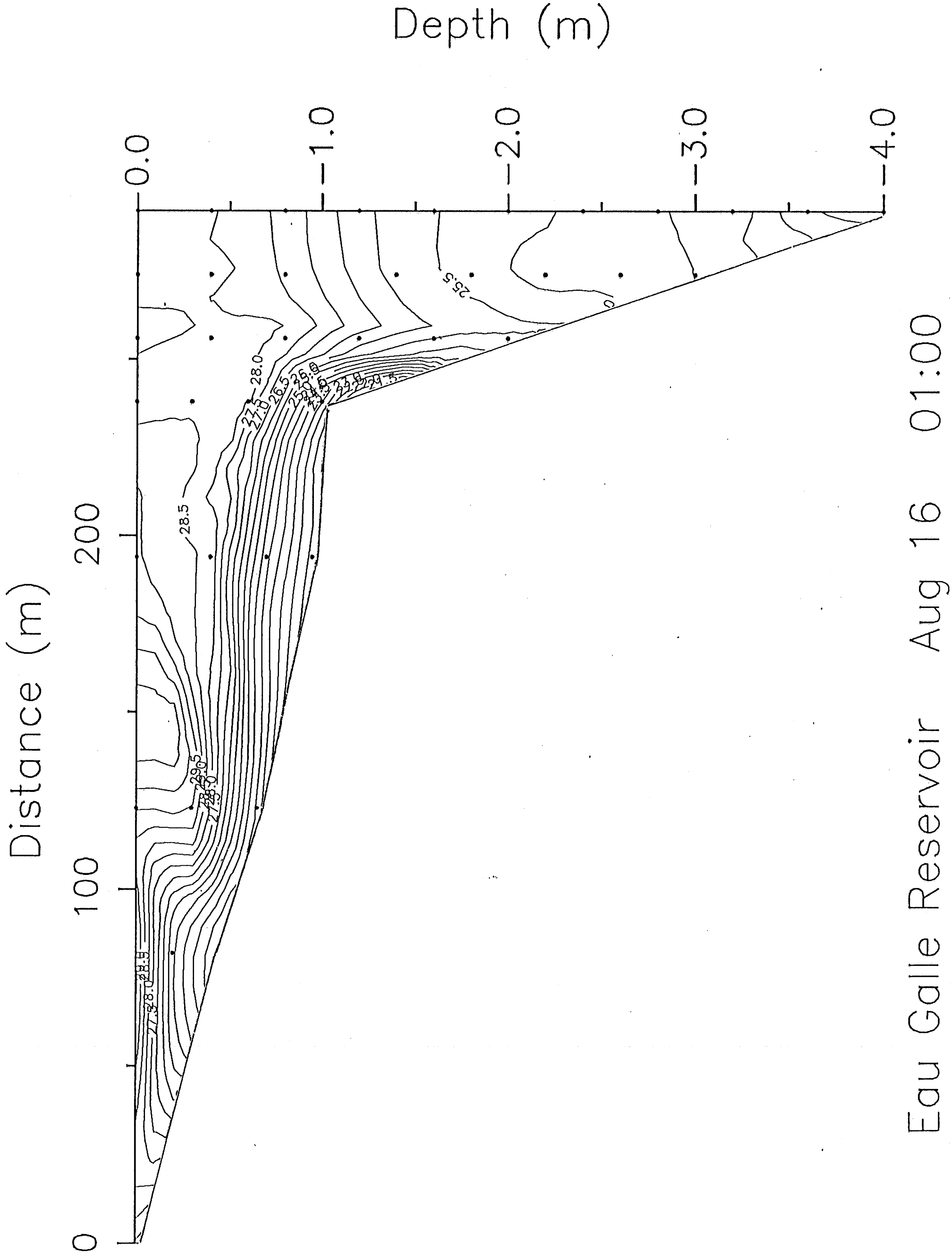
24.5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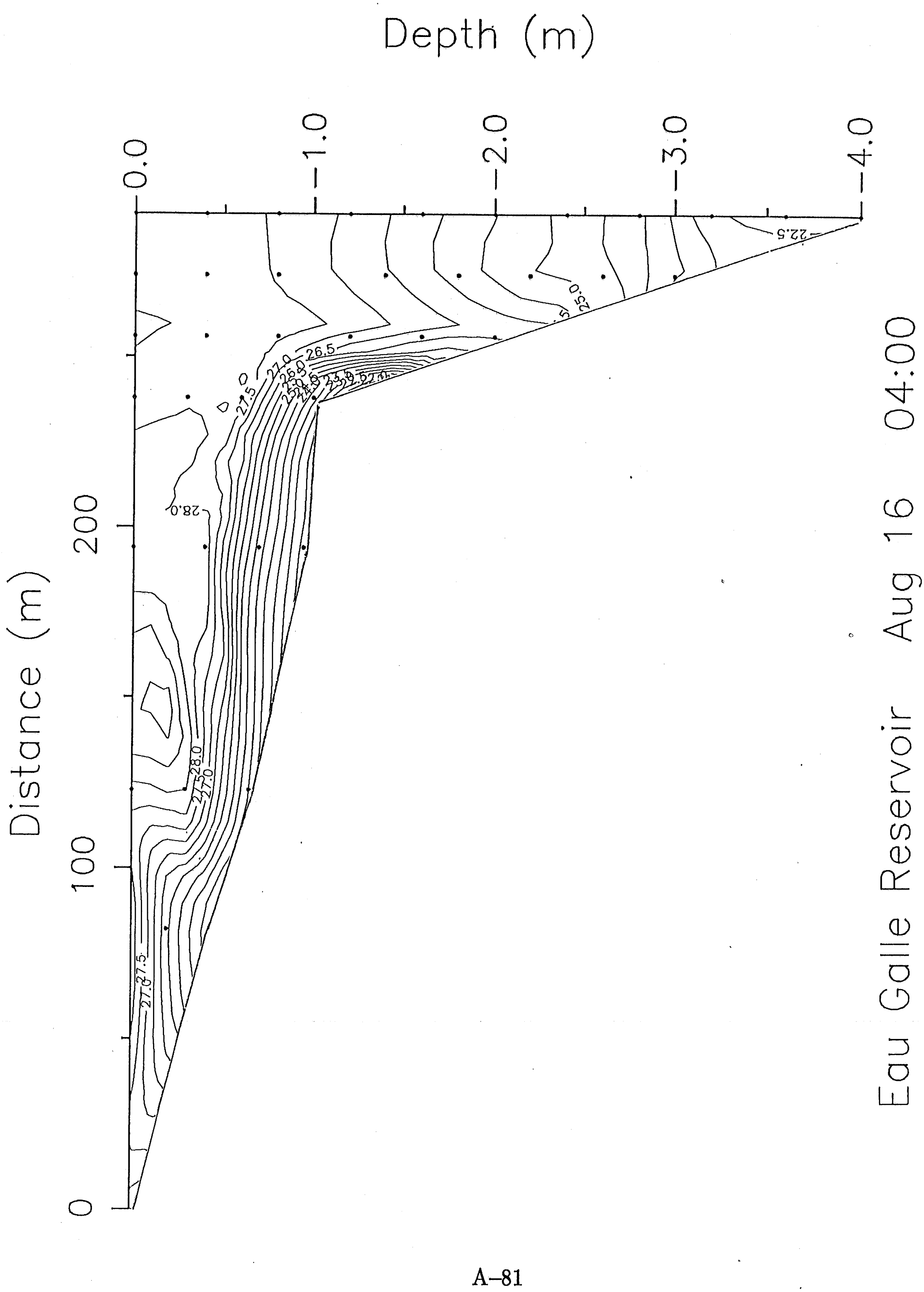
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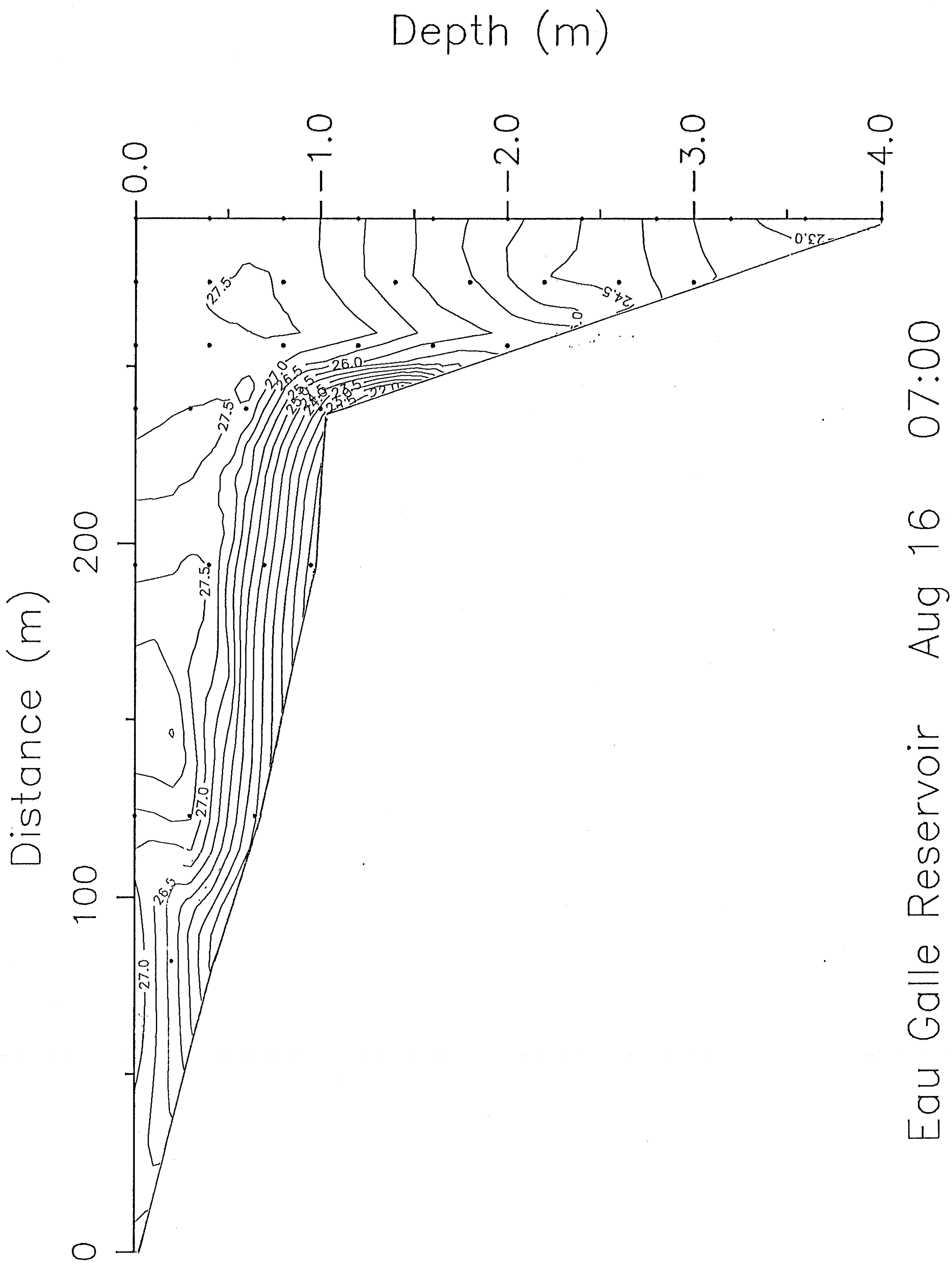
Eau Galle Reservoir   Aug 16   04:00



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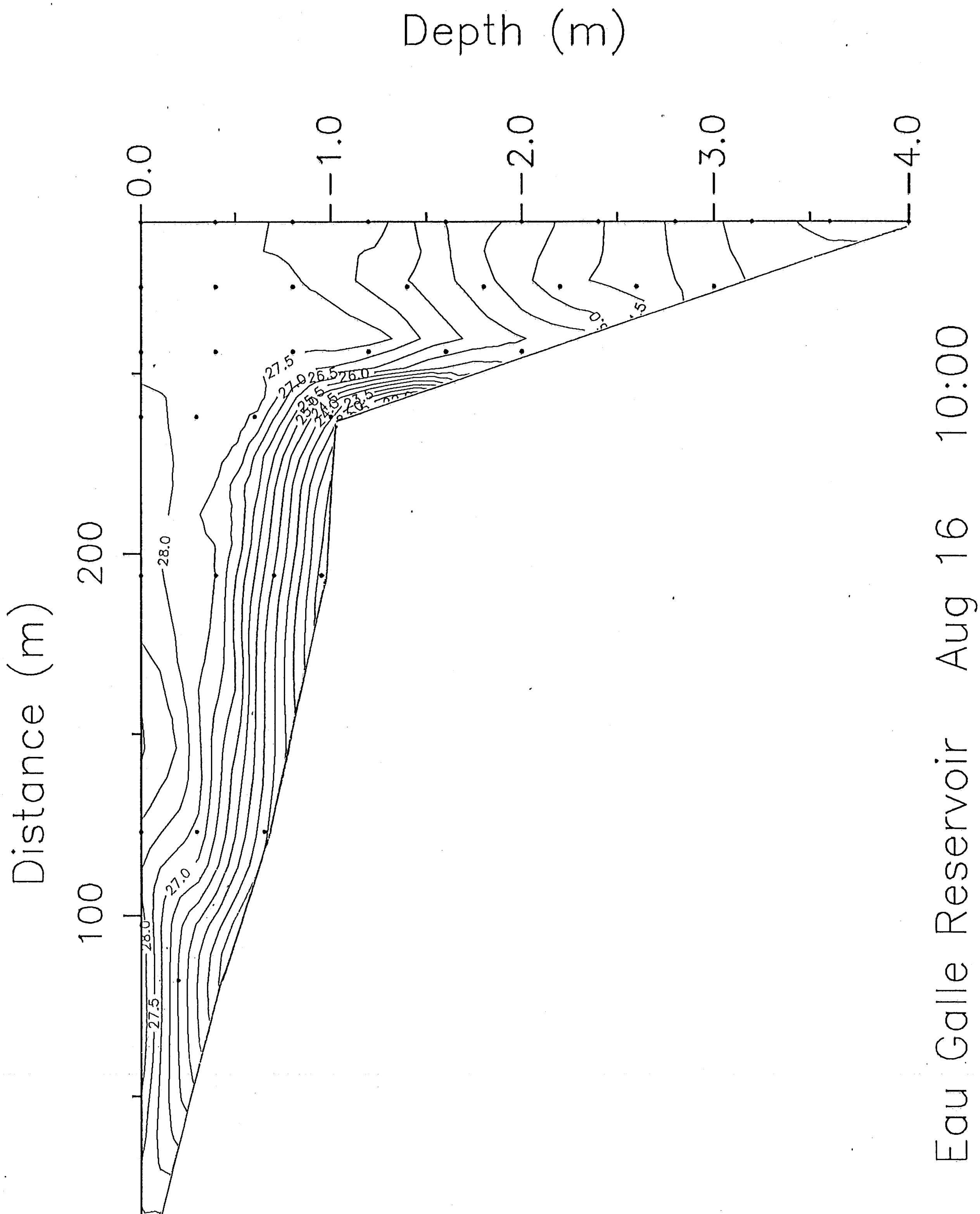
Eau Galle Reservoir Aug 16 07:00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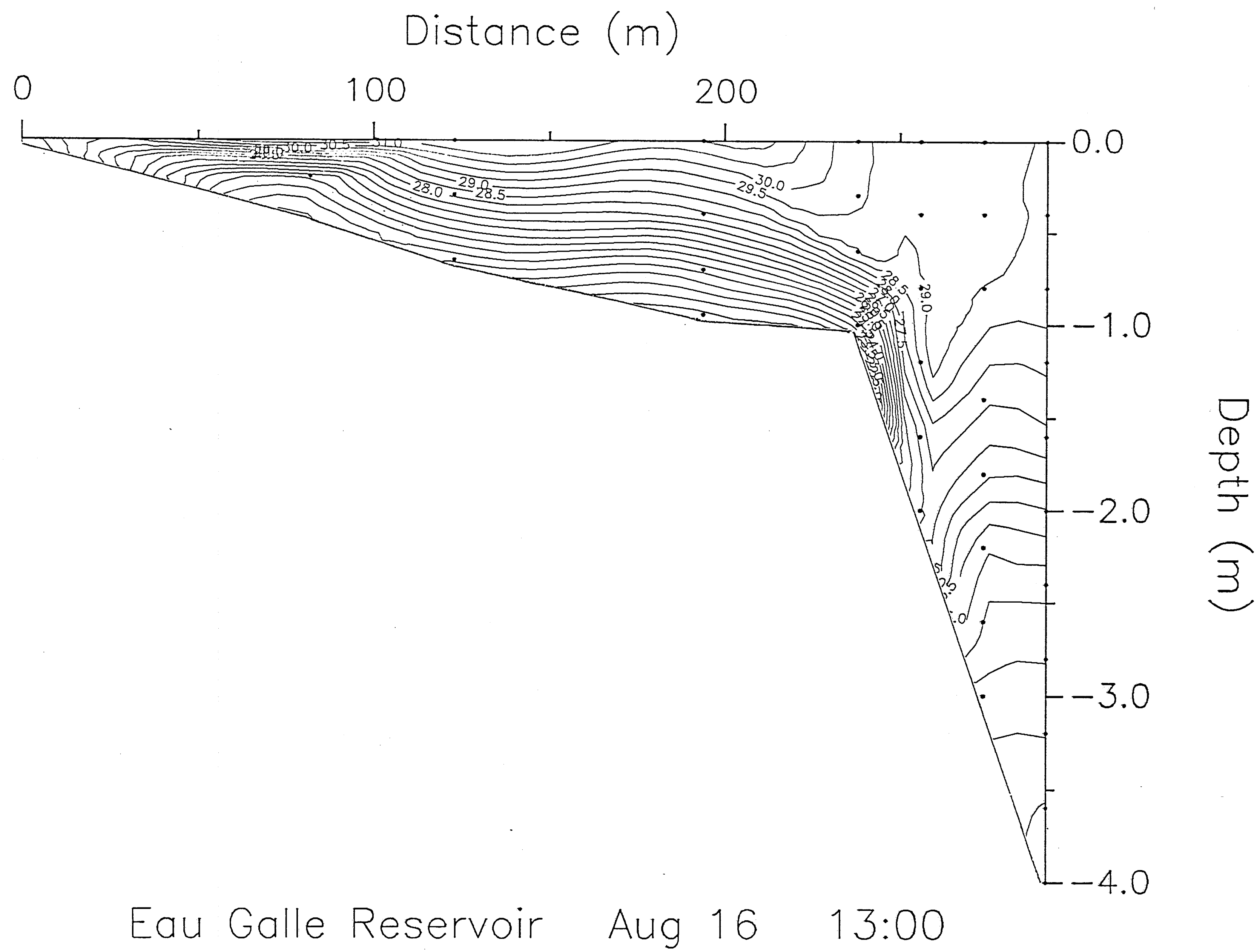
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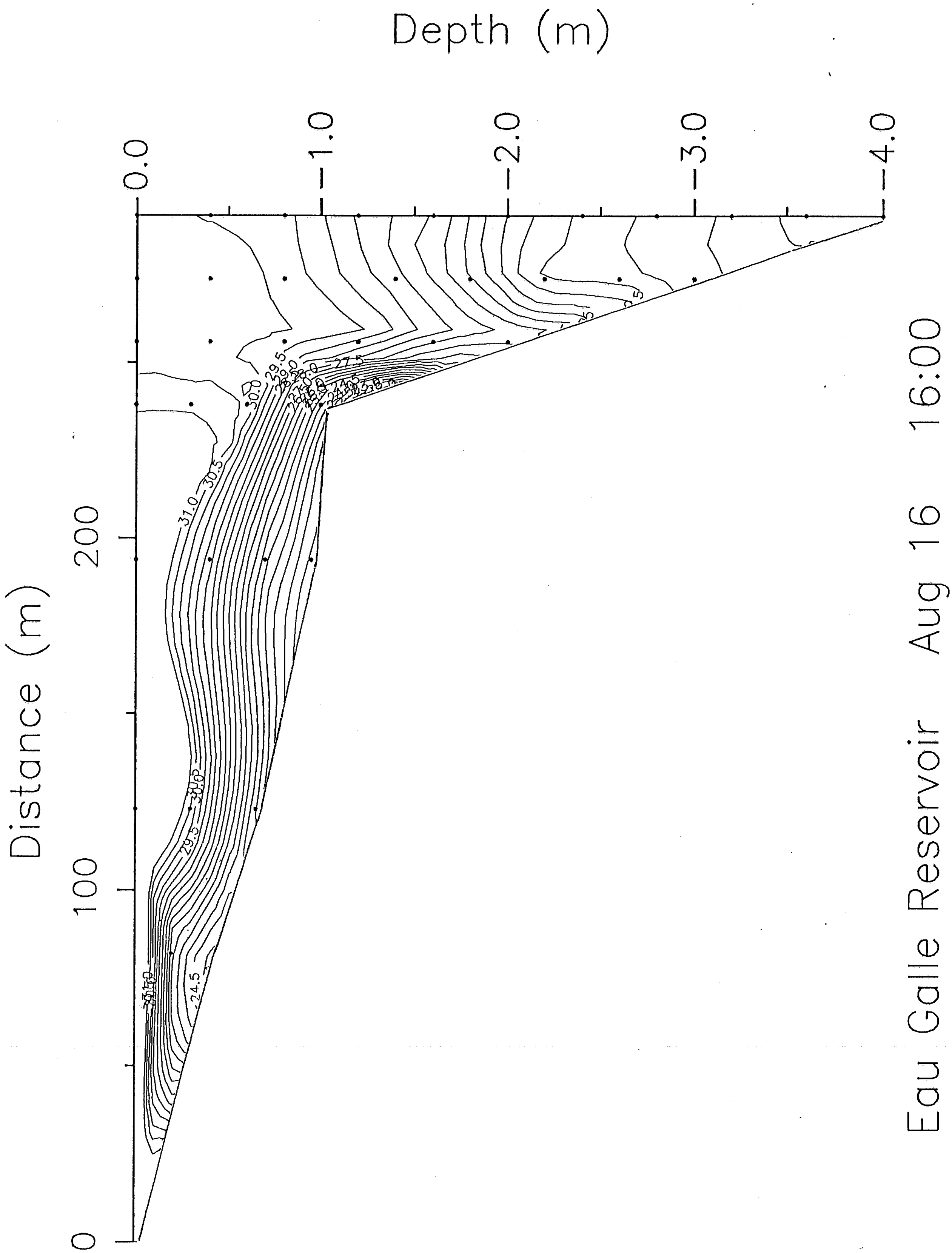
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Distance (m)
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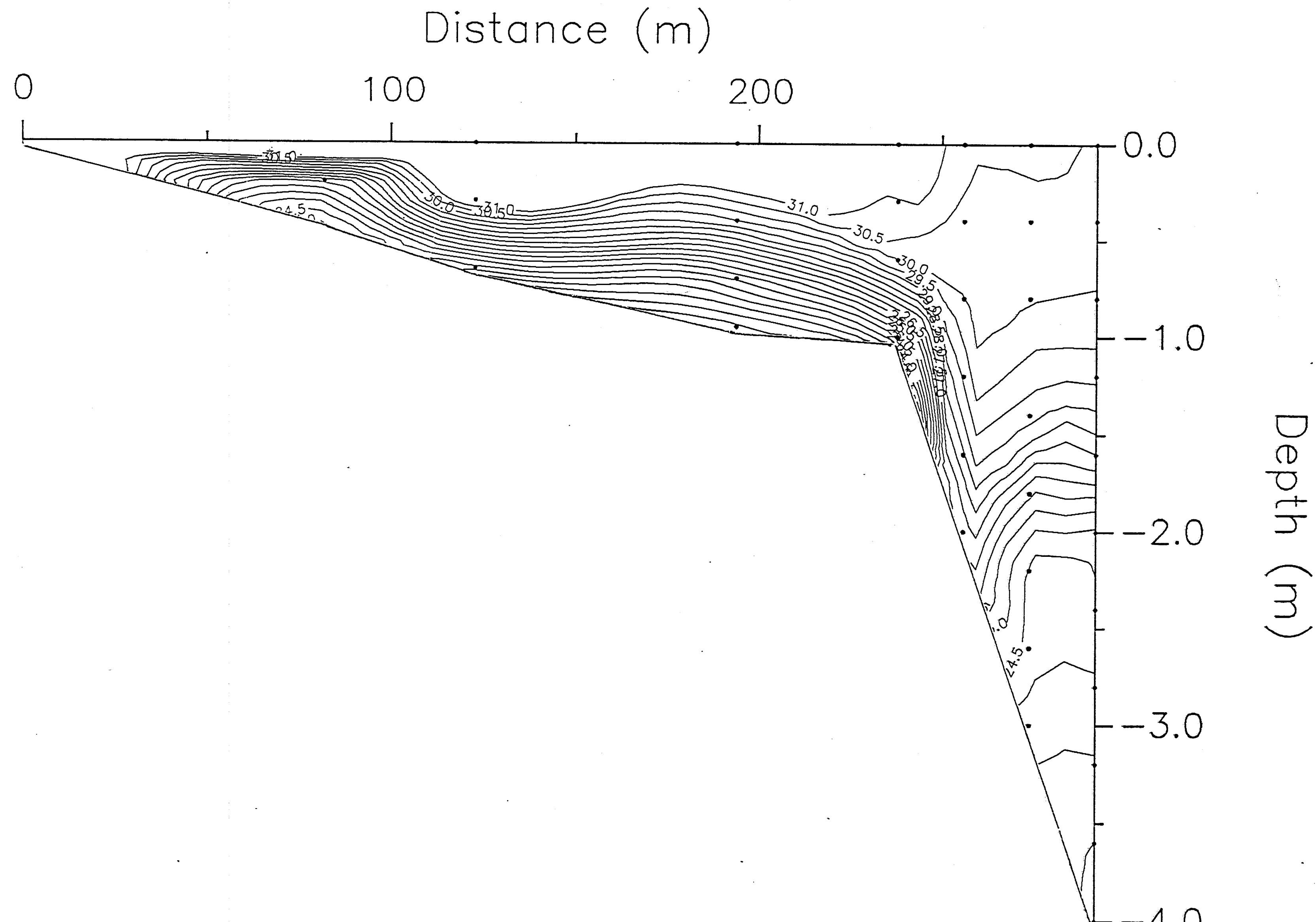
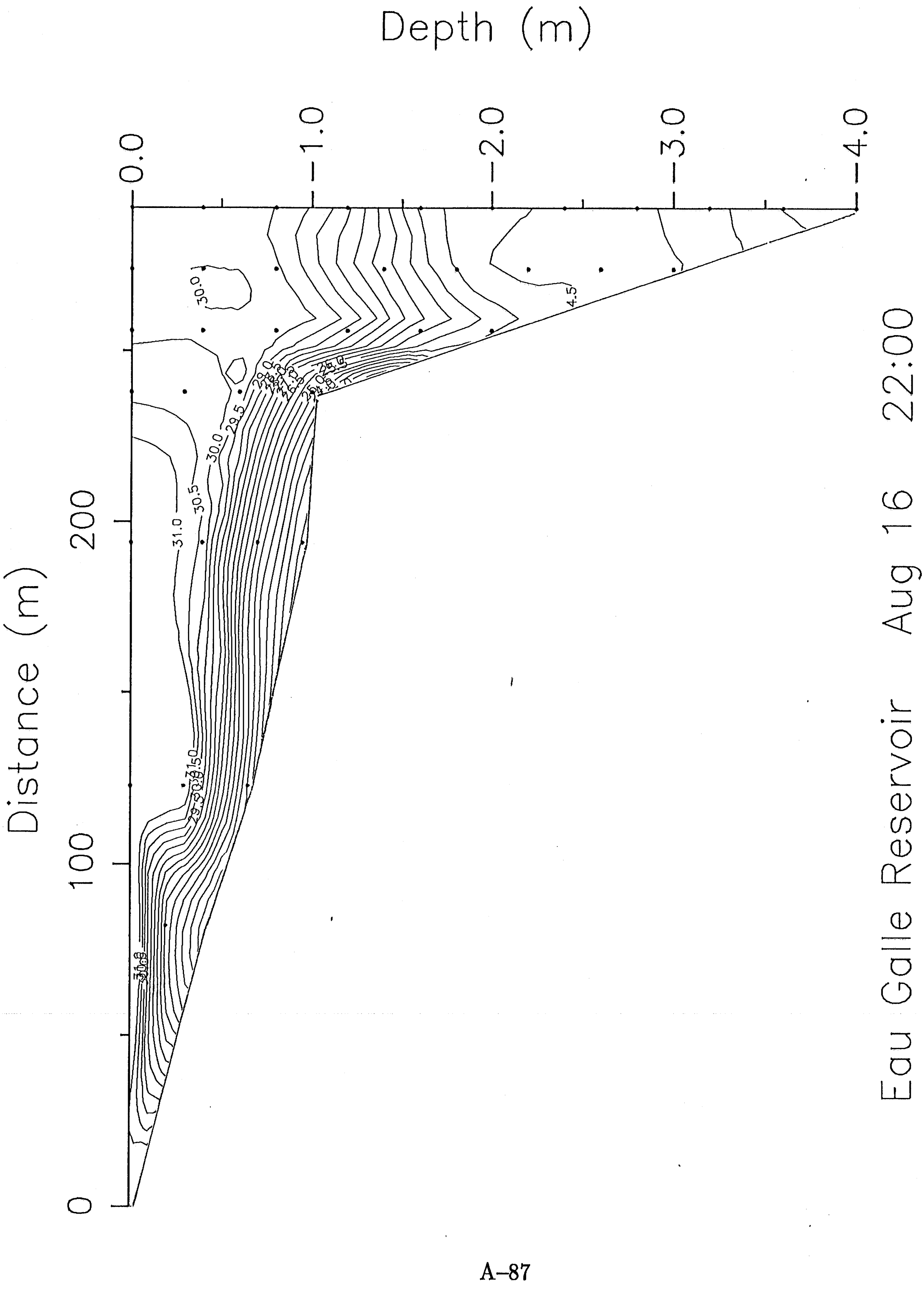
Eau Galle Reservoir Aug 16 16:00



Eau Galle Reservoir Aug 16 19:00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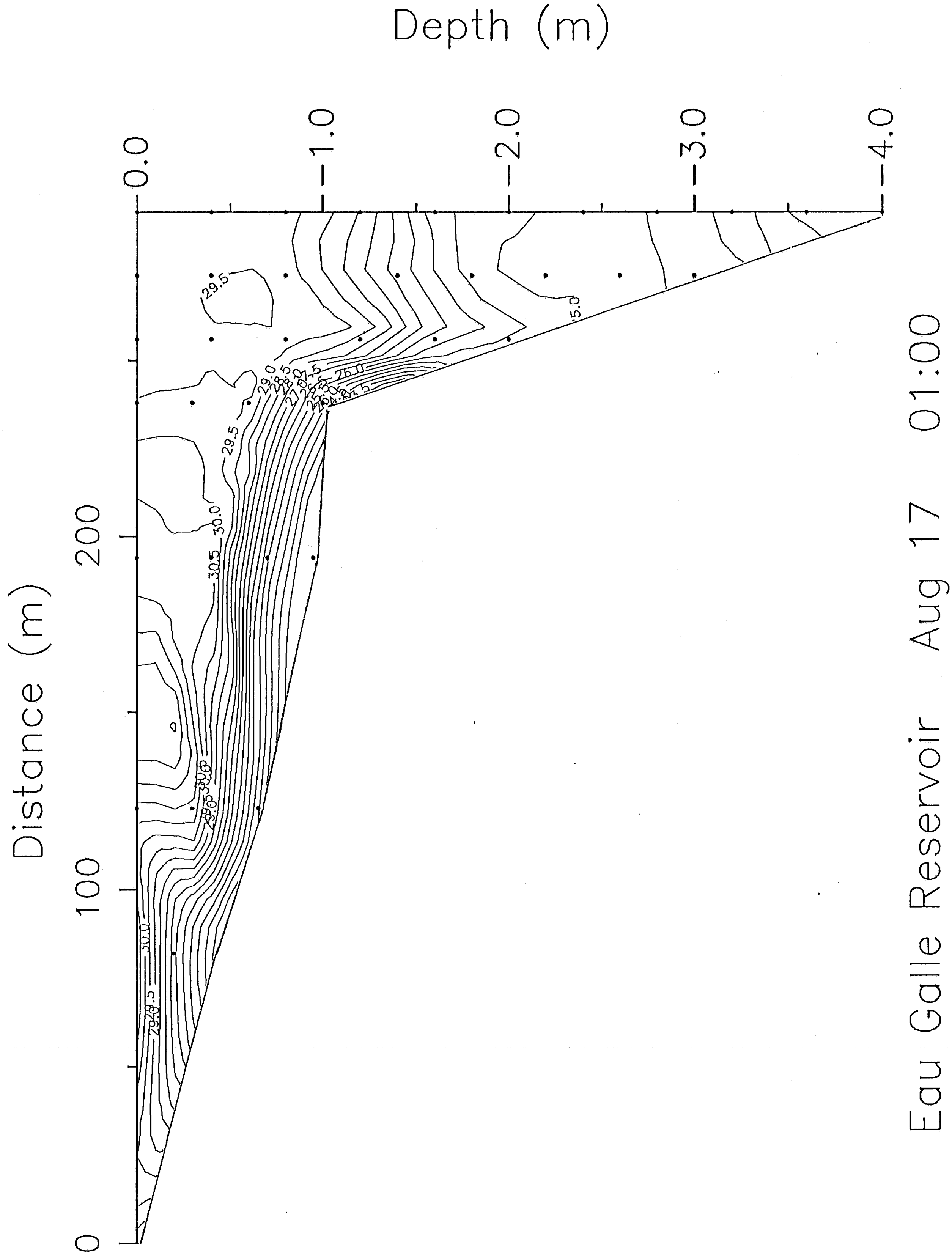
29.5
4.5
Eau Galle Reservoir Aug 16 22:00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200
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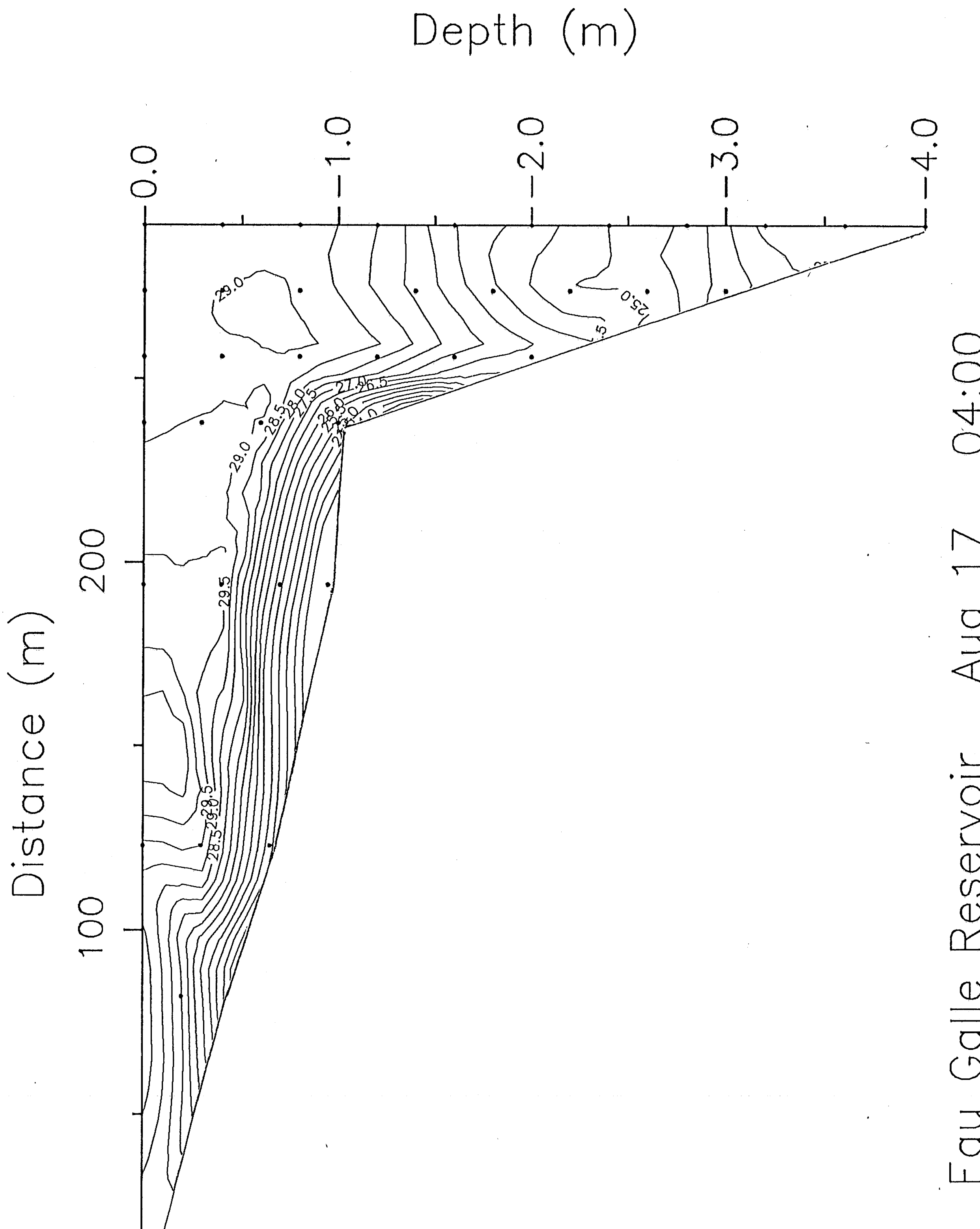
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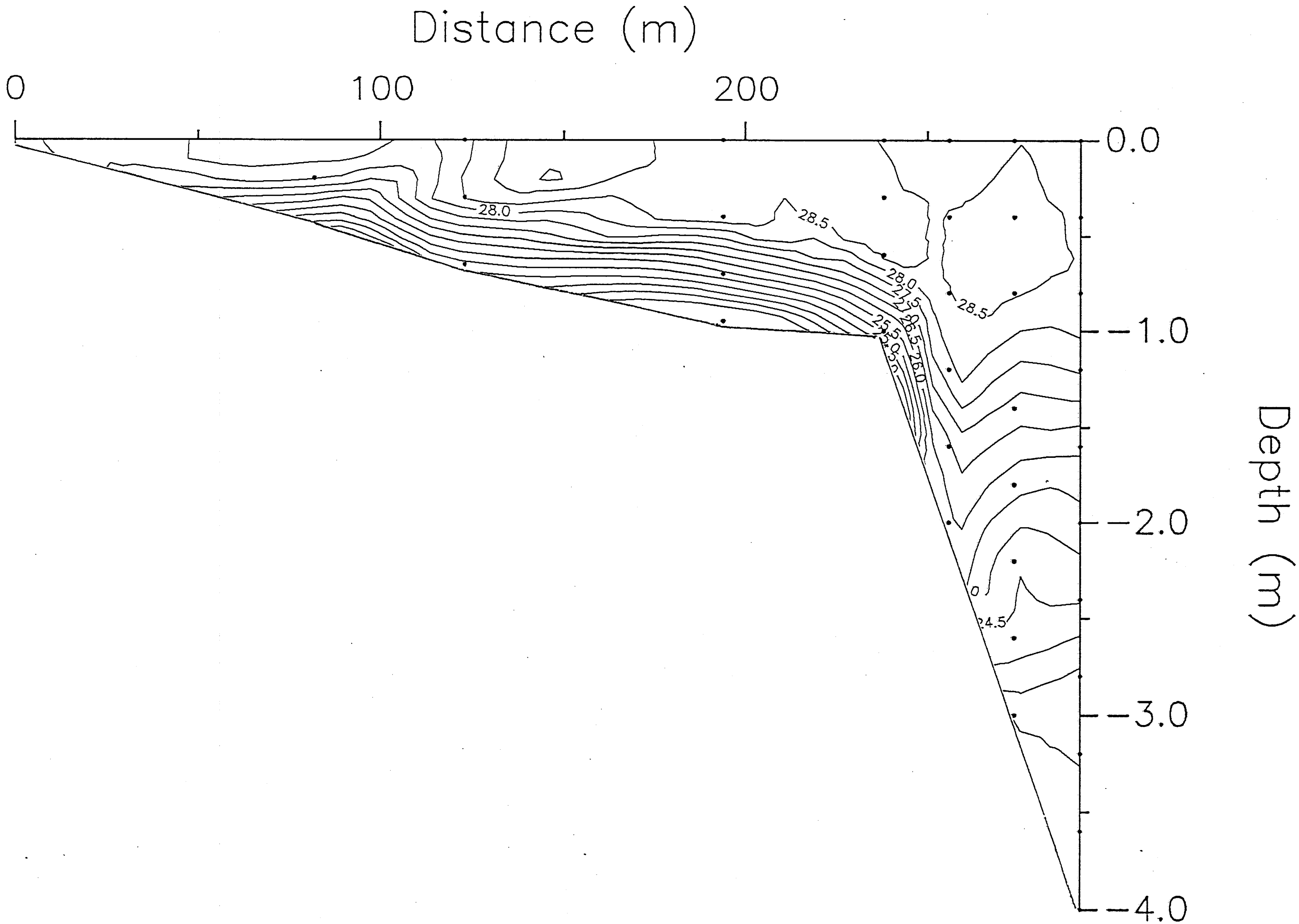
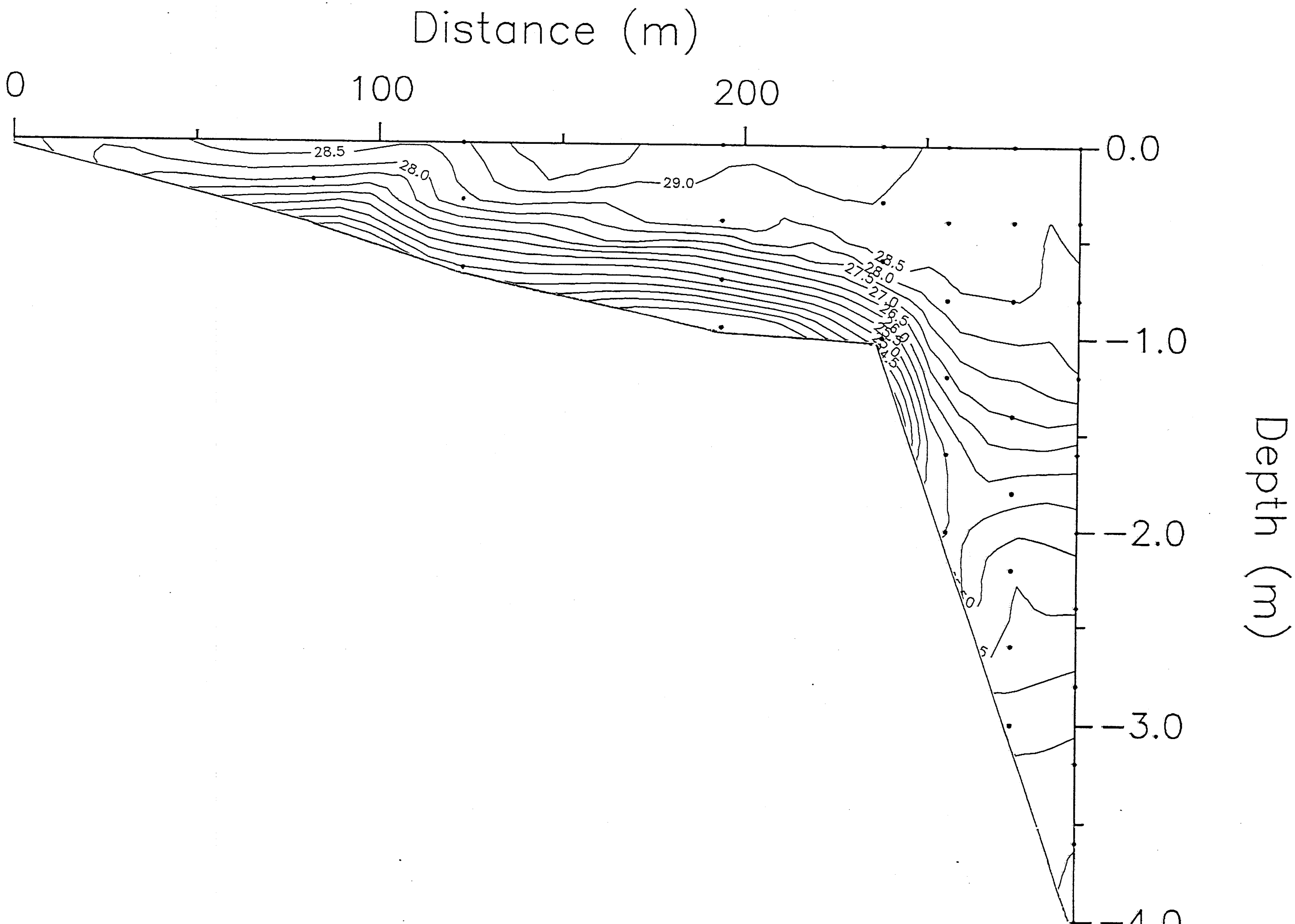
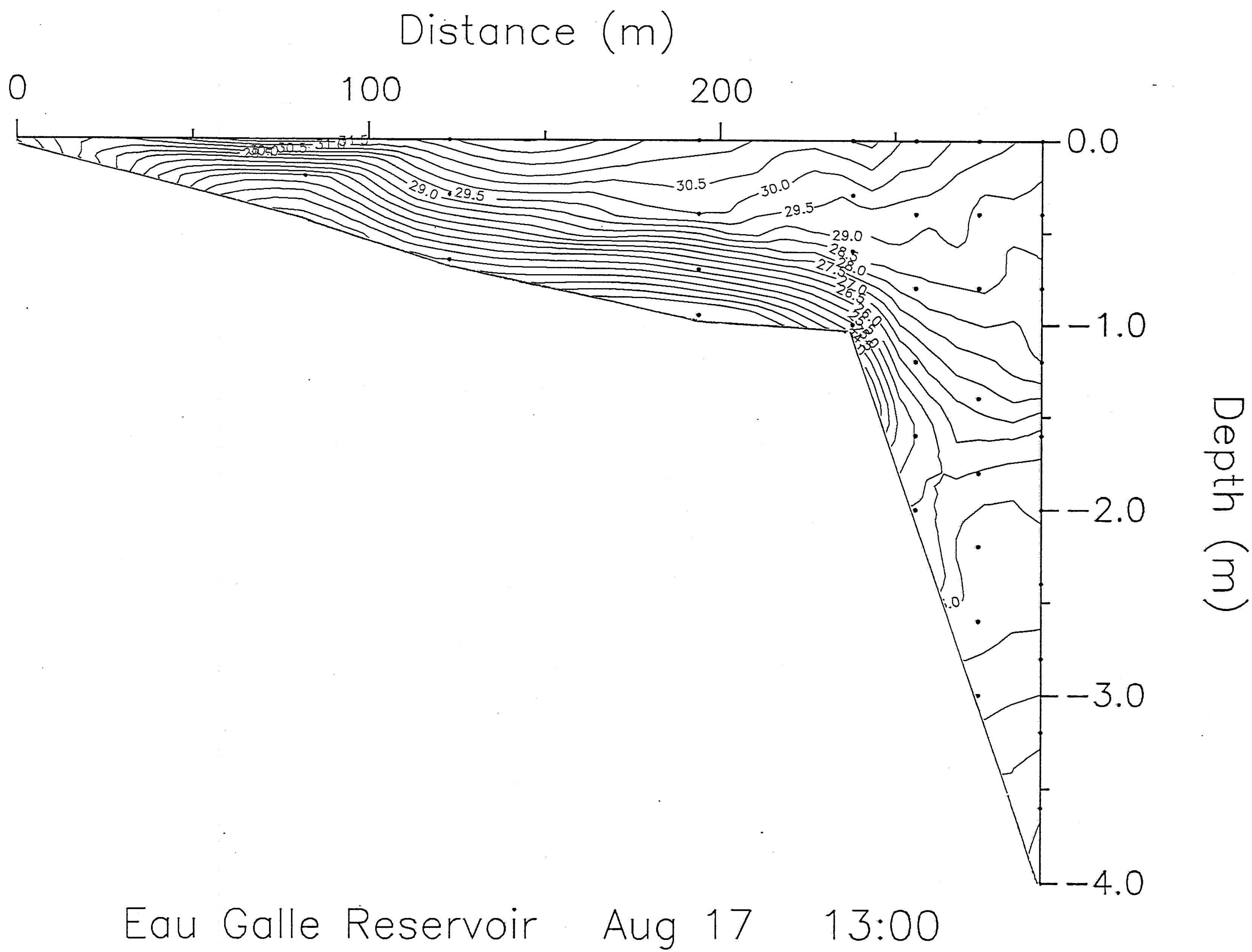


Eau Galle Reservoir Aug 17 07:00



Eau Galle Reservoir Aug 17 10:00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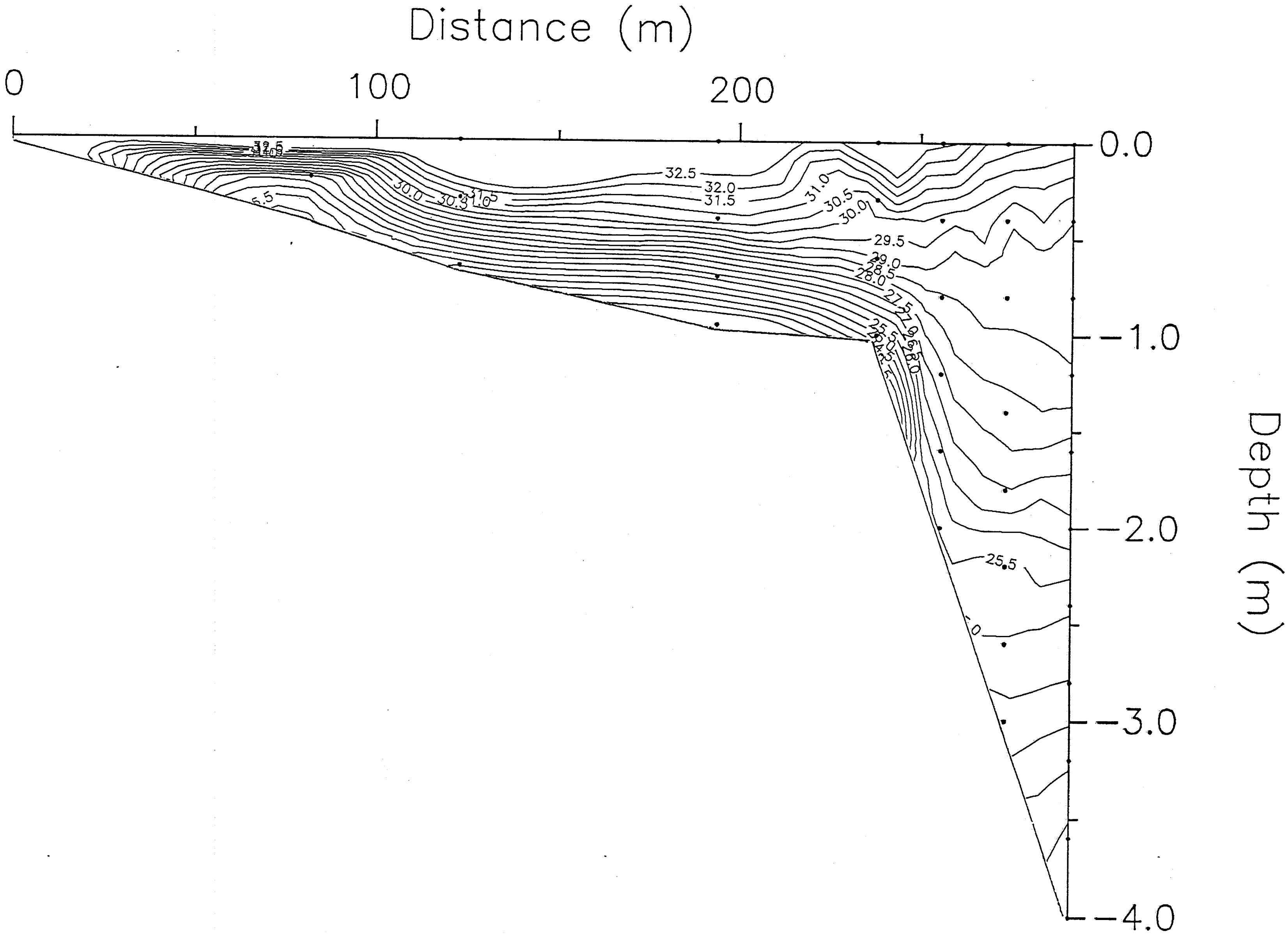
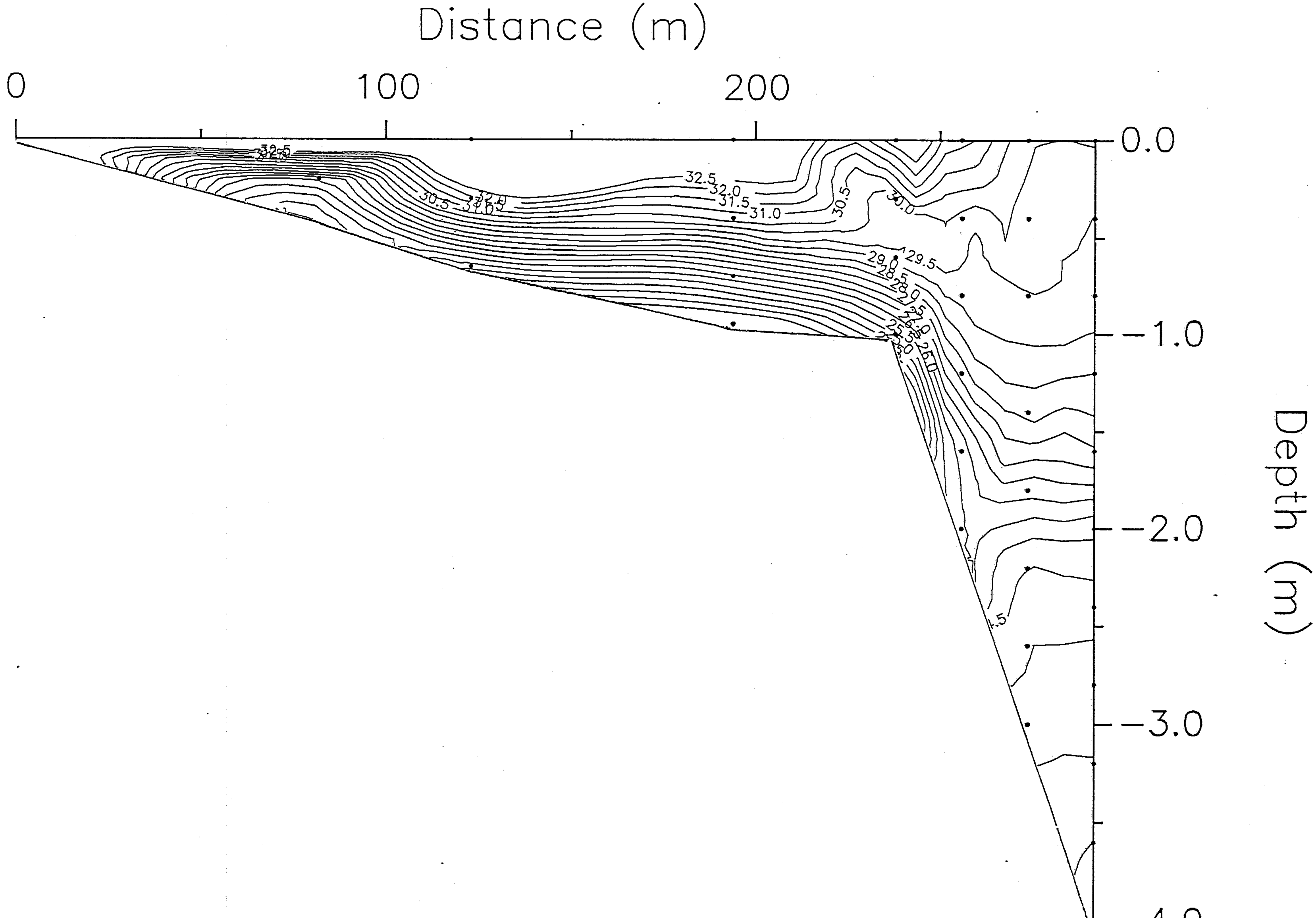
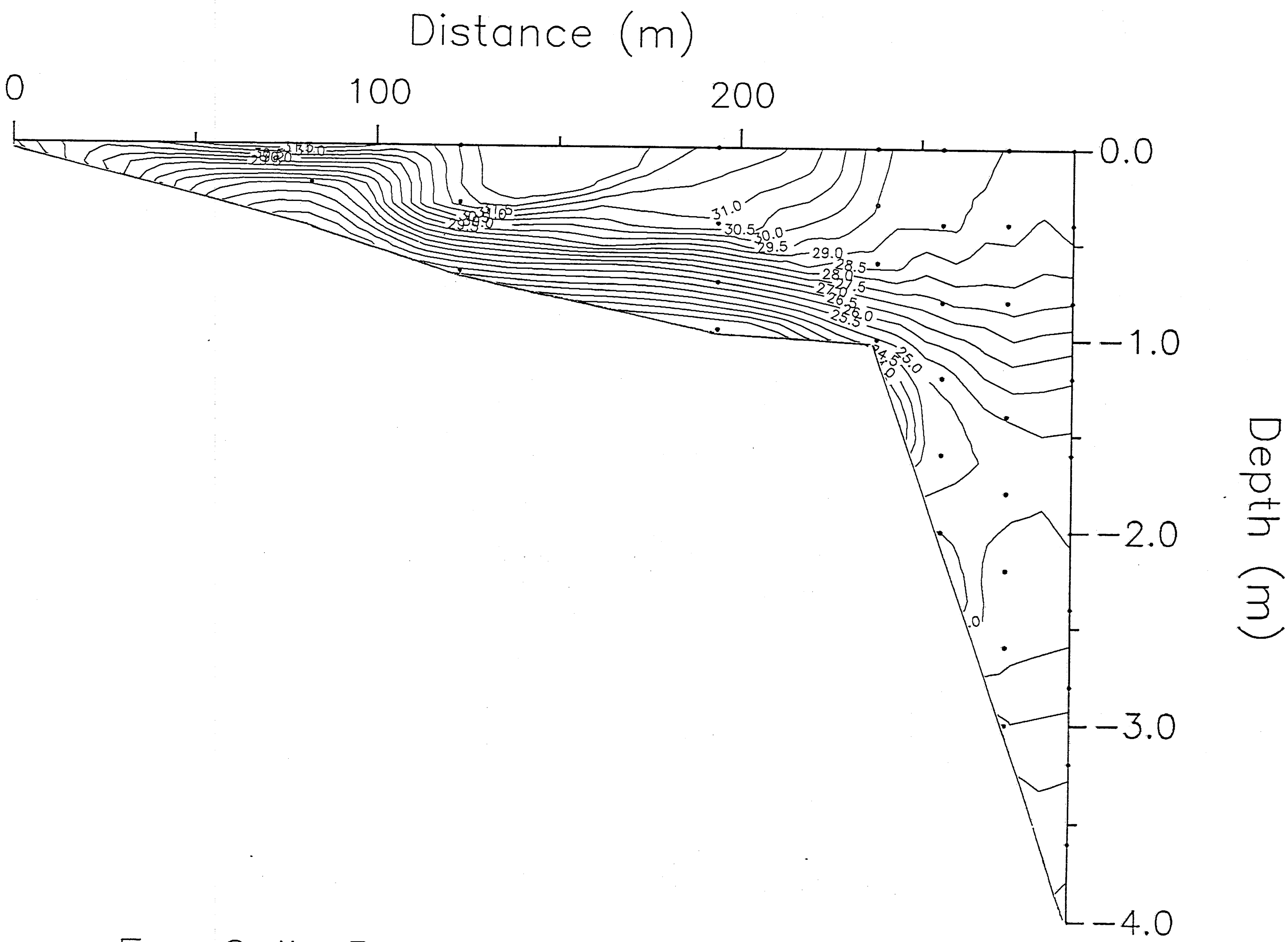
Eau Galle Reservoir Aug 17 13:00



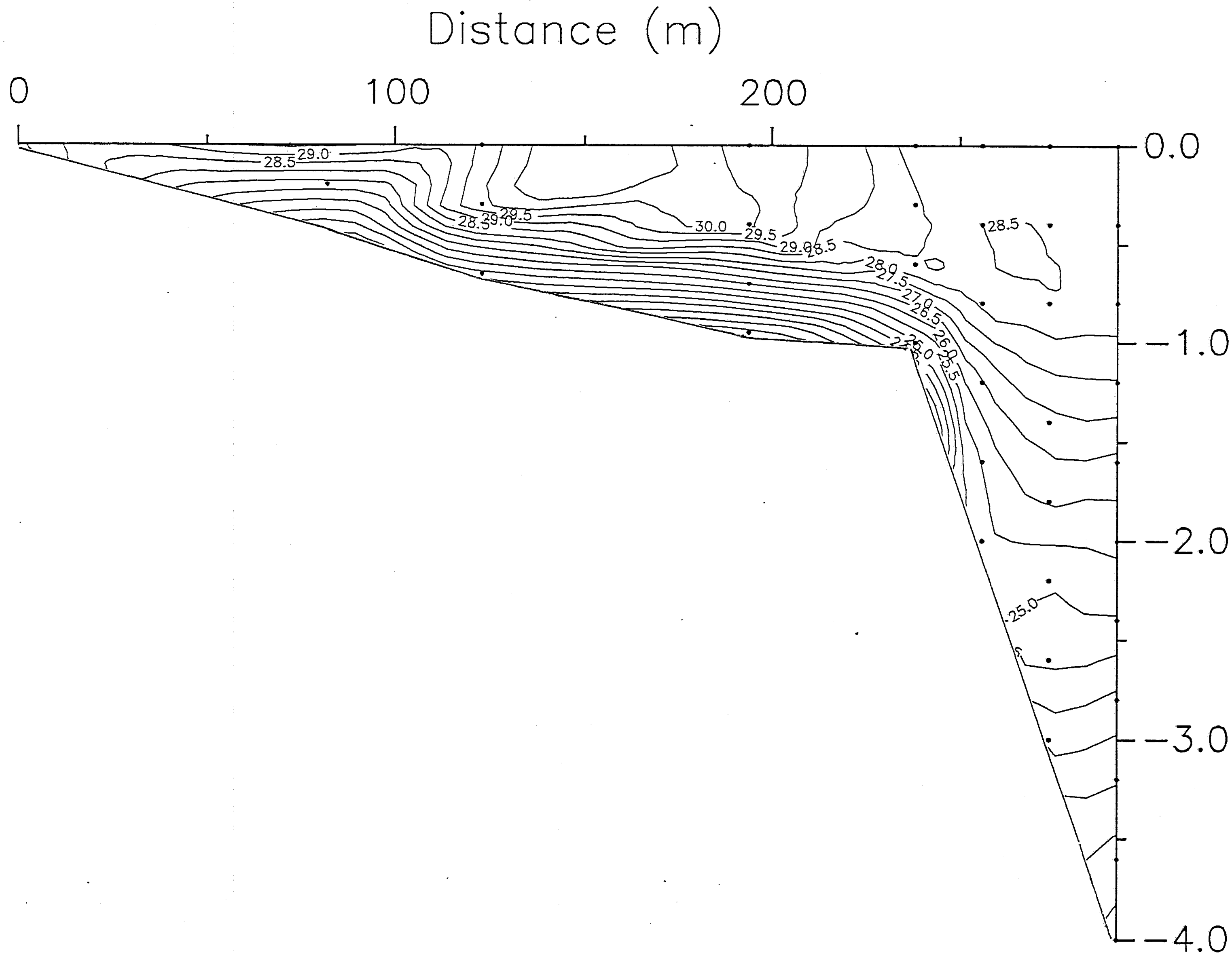
Eau Galle Reservoir Aug 17 16:00



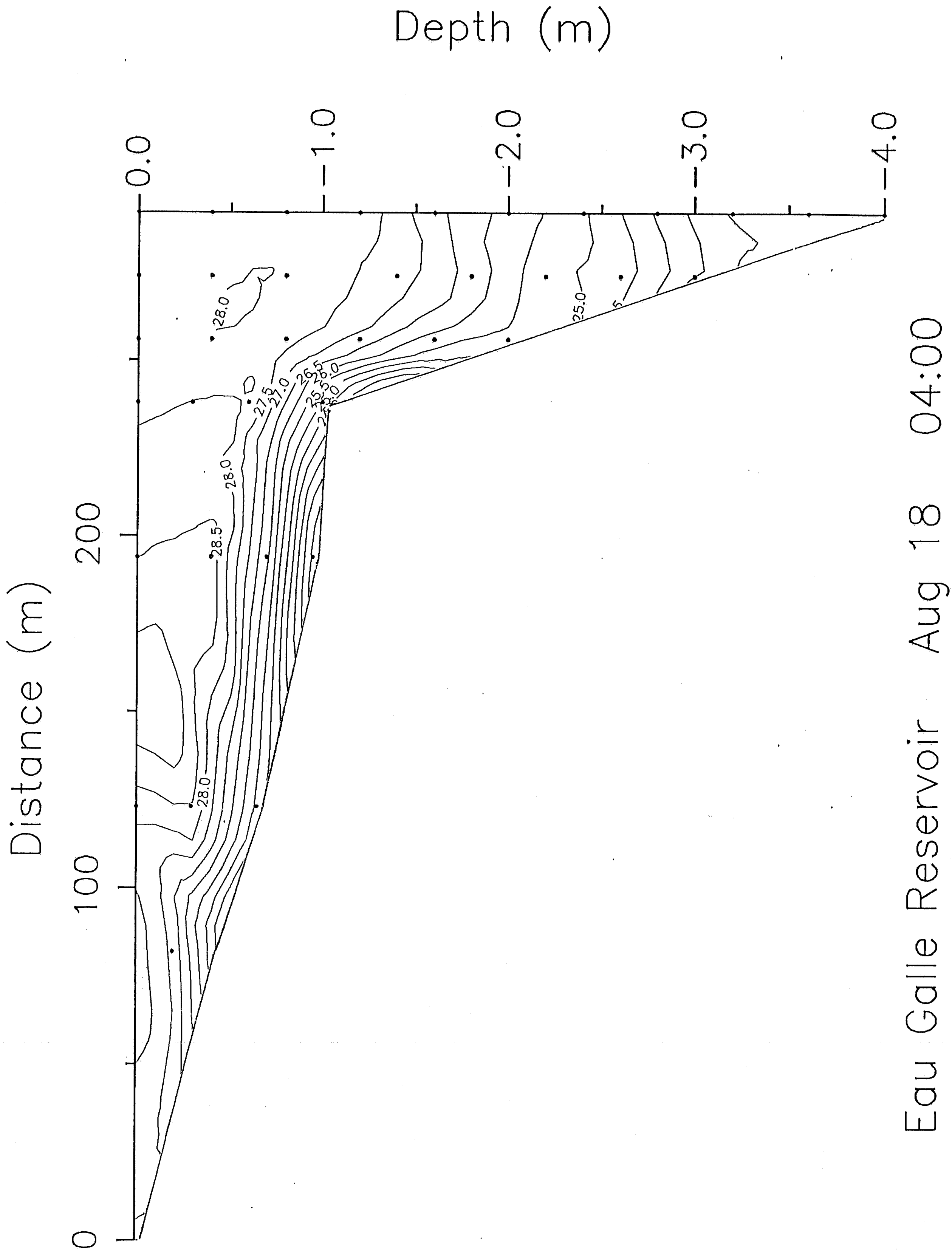
Eau Galle Reservoir Aug 17 19:00



Eau Galle Reservoir Aug 17 22:00



Eau Galle Reservoir Aug 18 01:00



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Distance (m)
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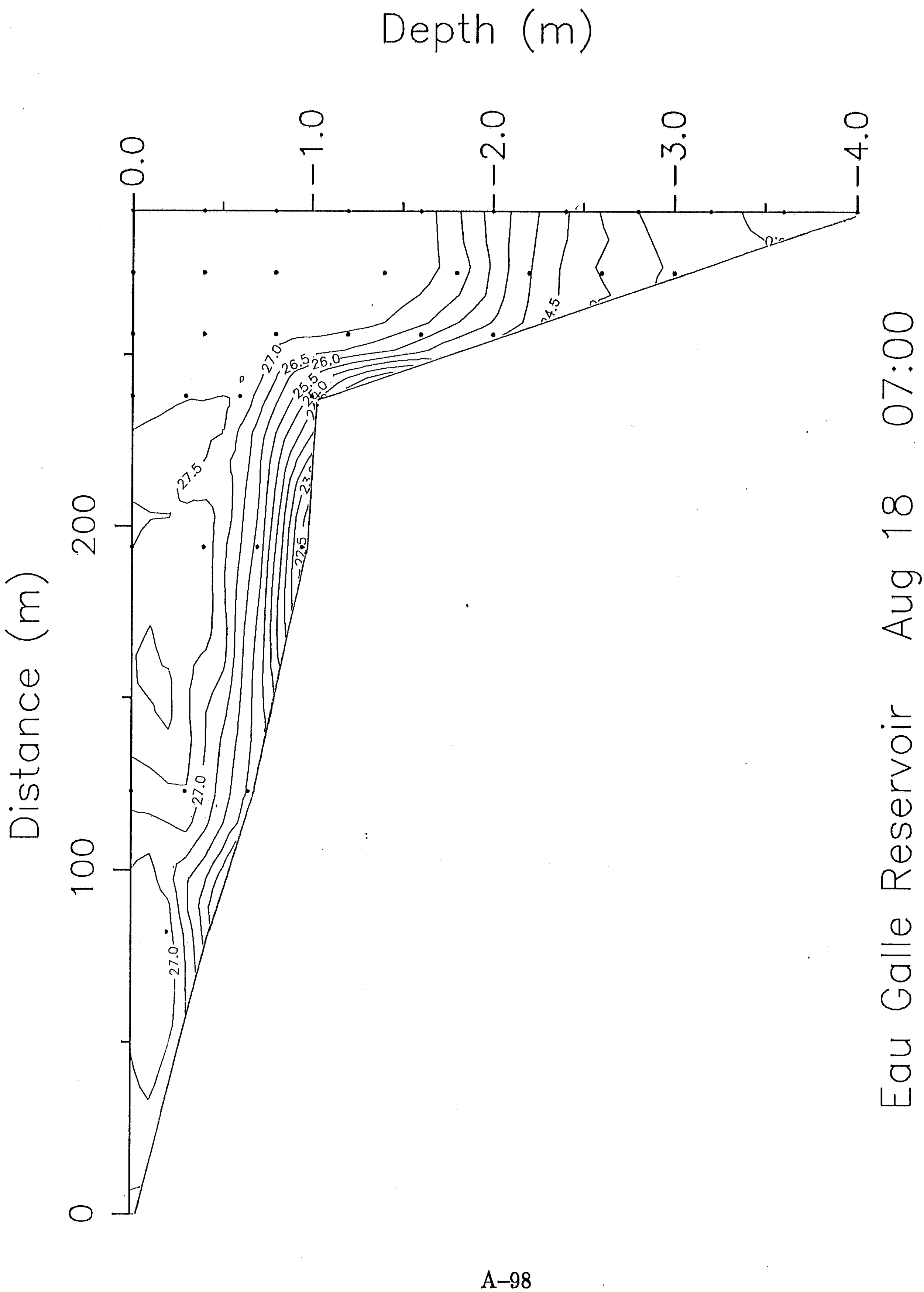

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Distance (m)
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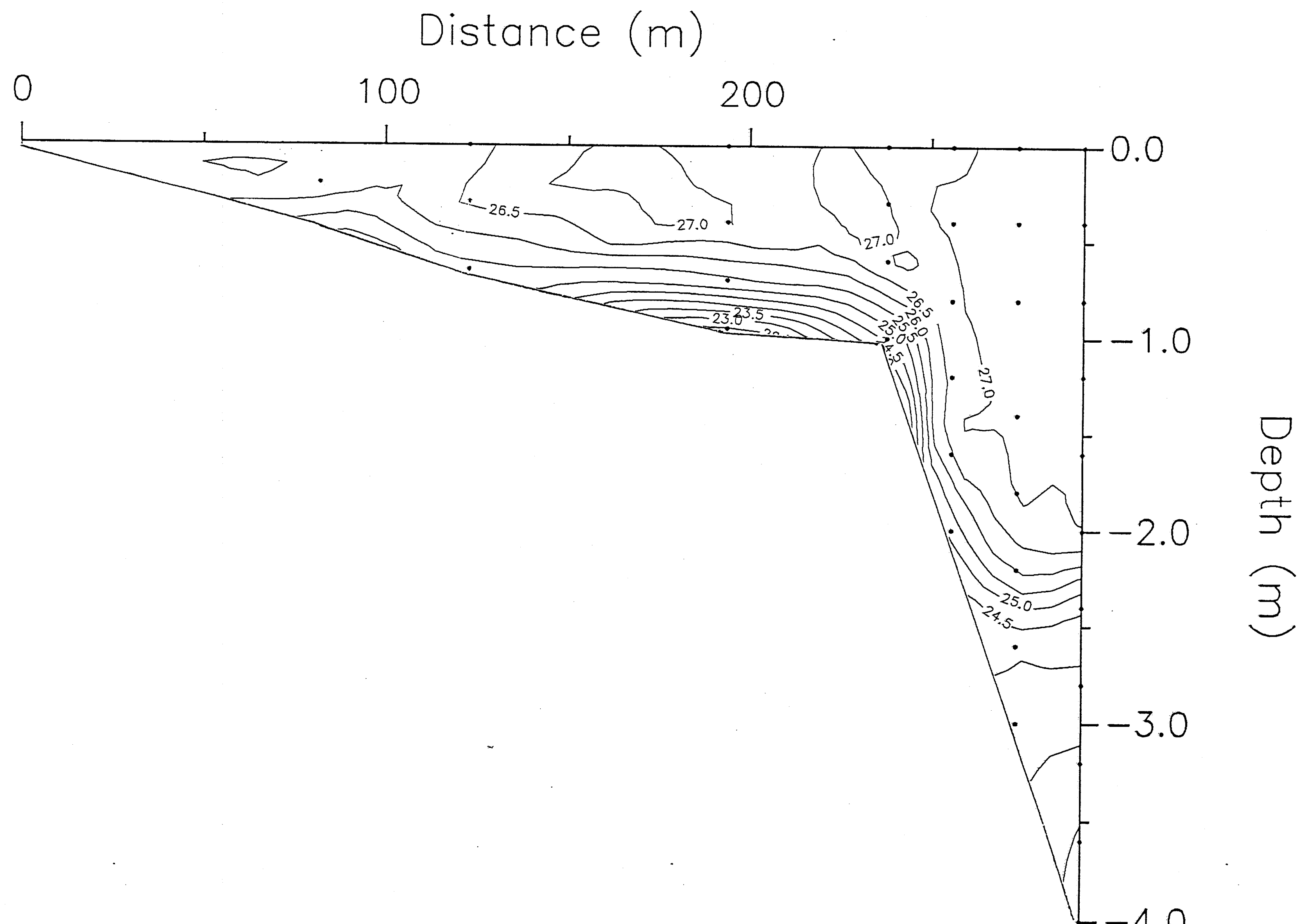

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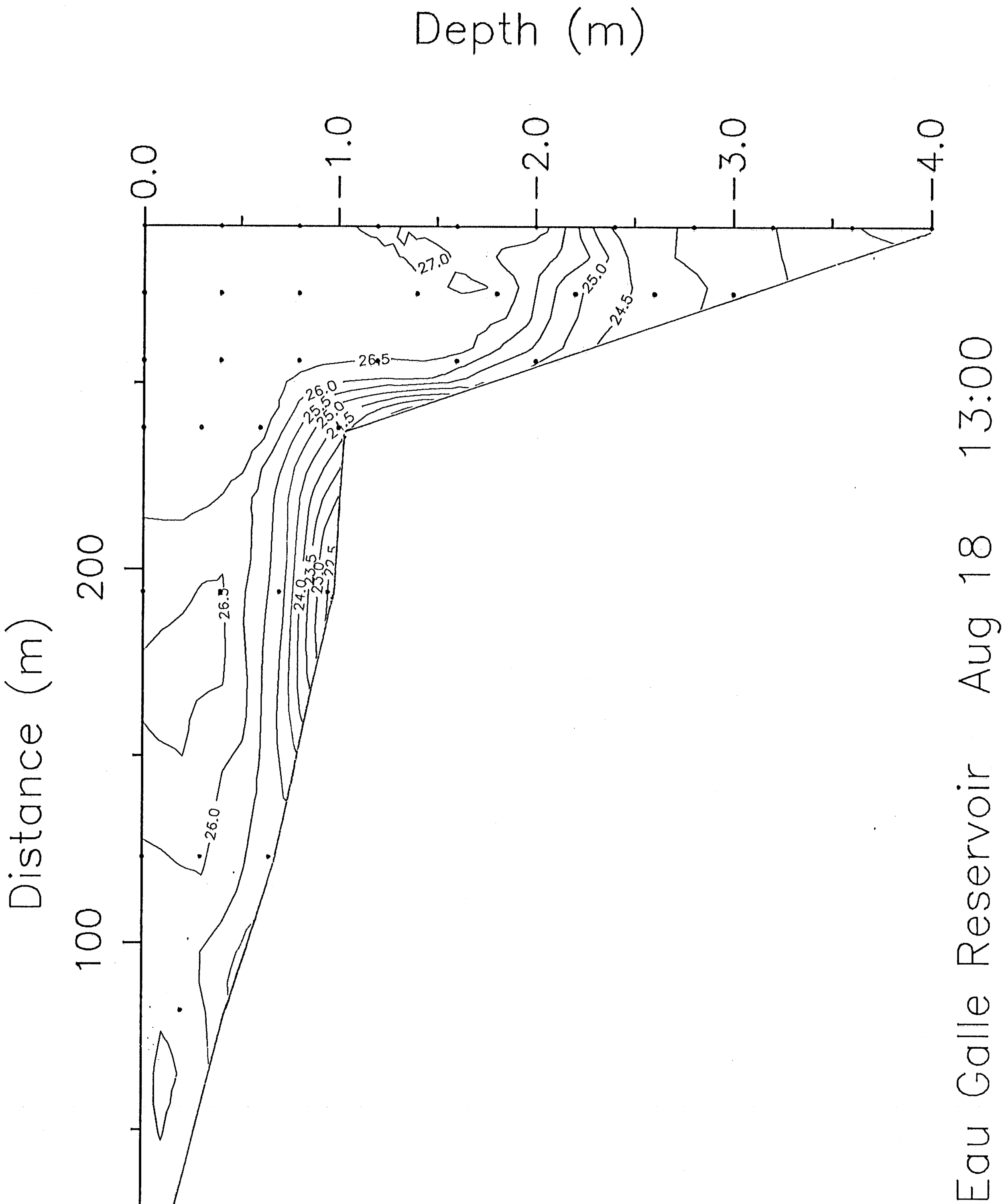
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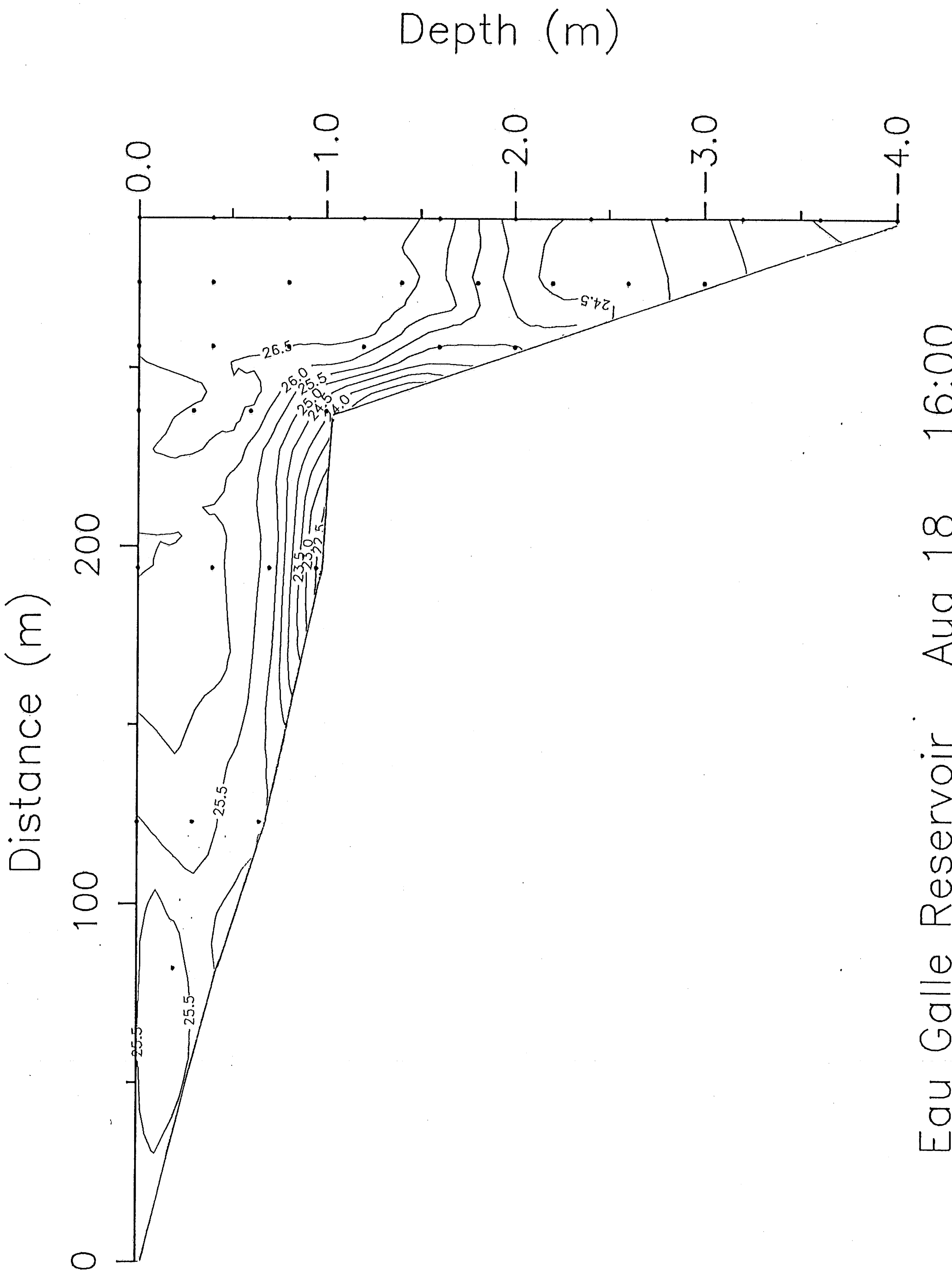
Eau Galle Reservoir Aug 18 13:00



Depth (m)
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Distance (m)
0
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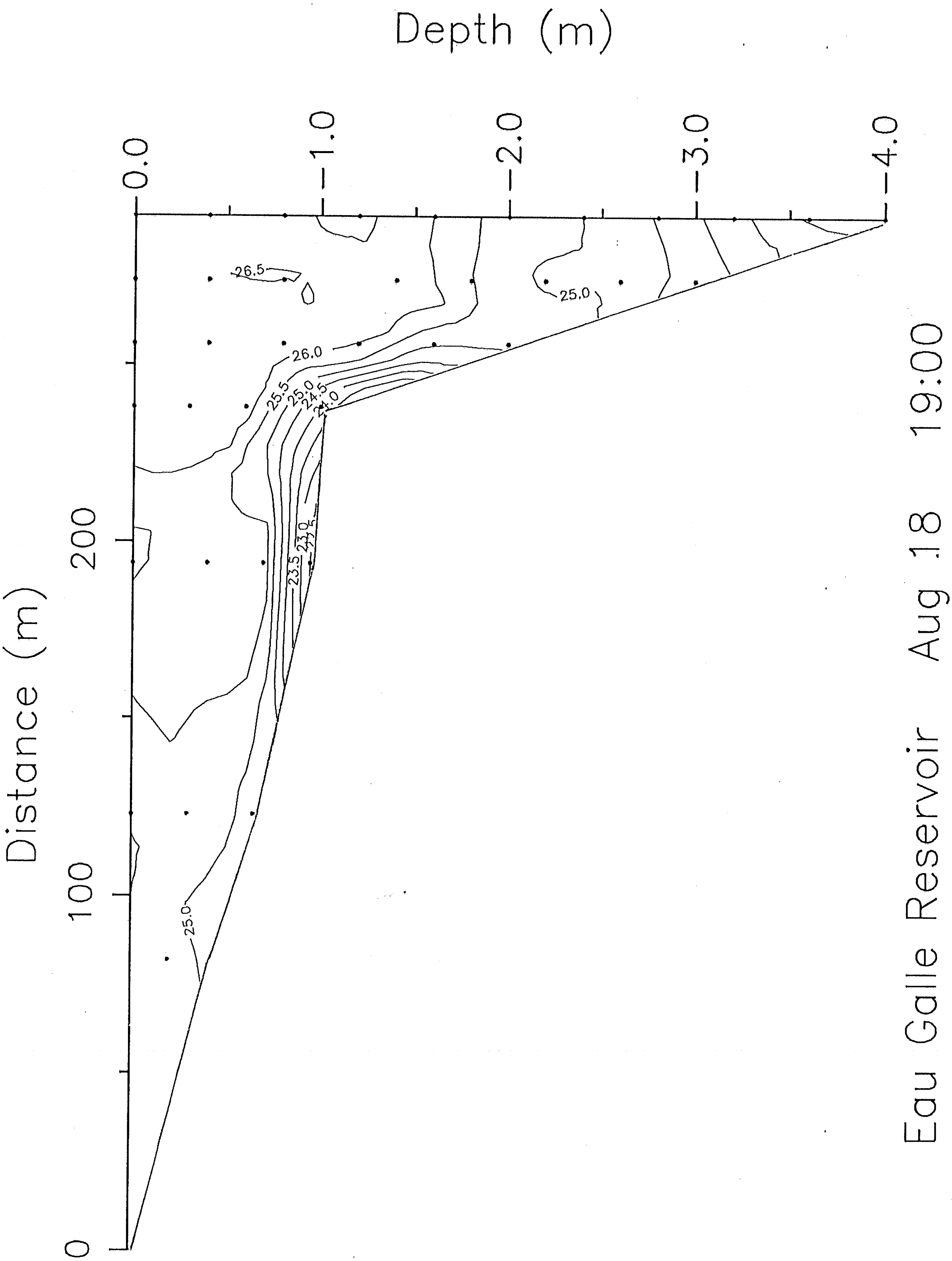
200
Eau Galle Reservoir Aug 18 16:00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Distance (m)
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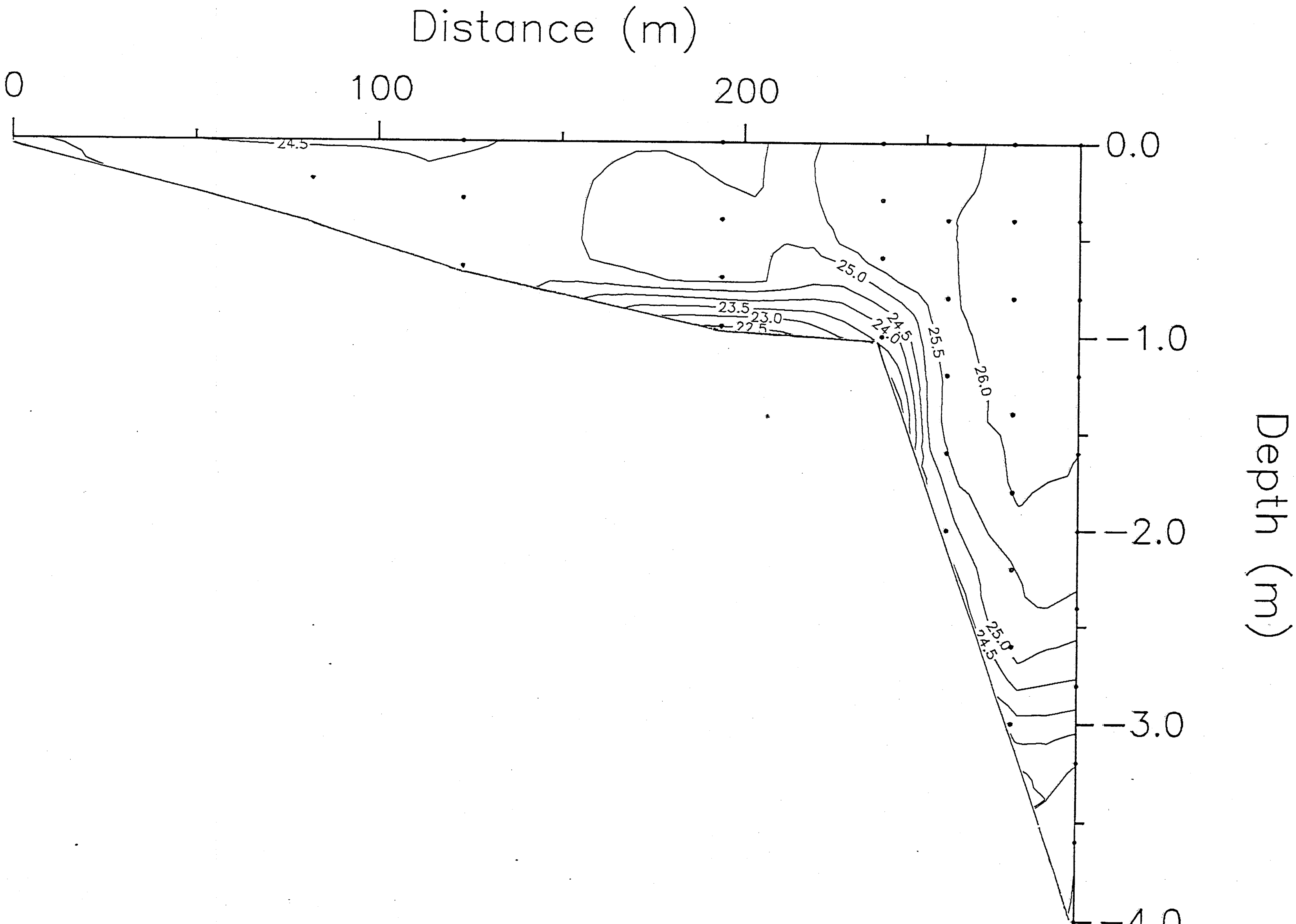
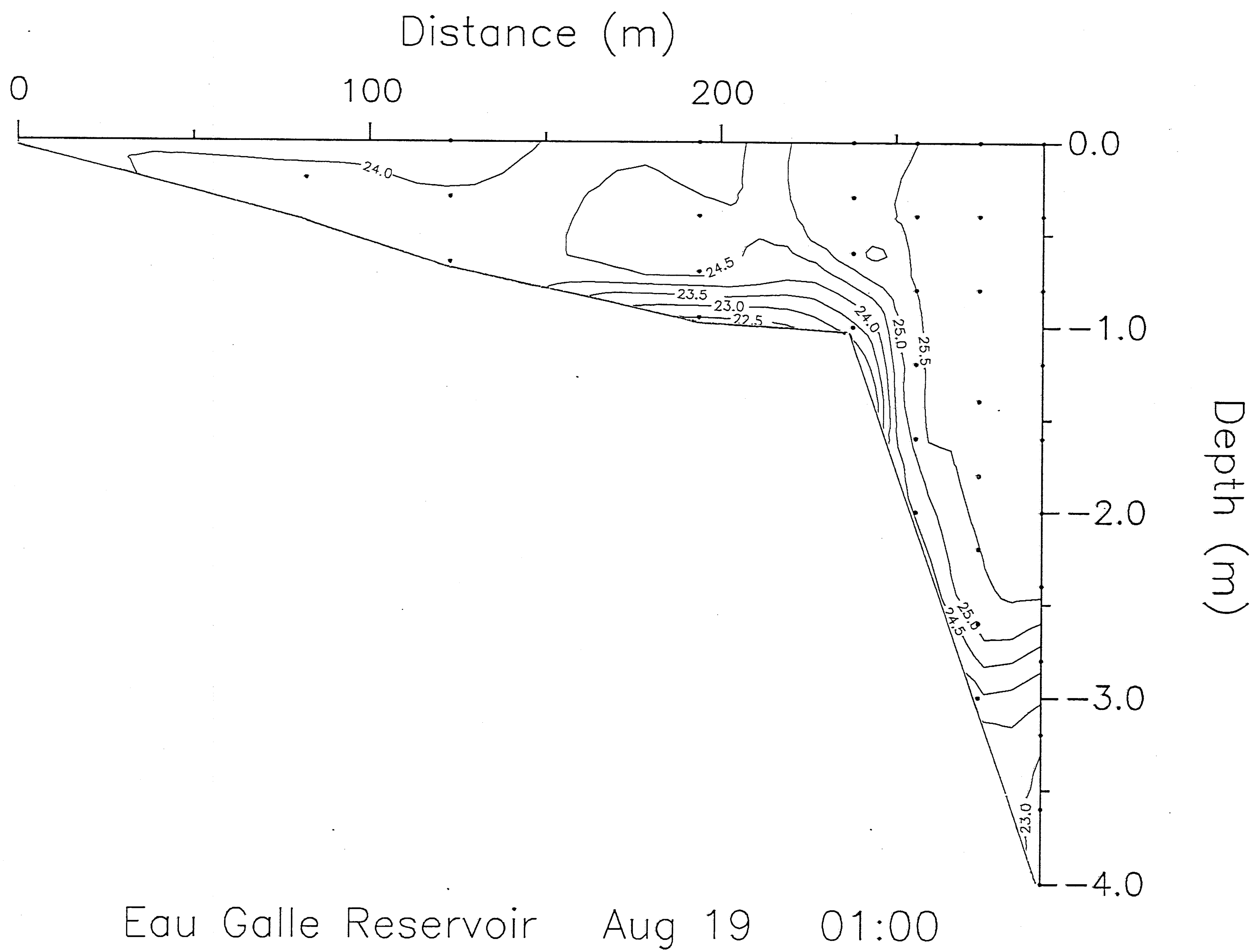
23.0
Eau Galle Reservoir Aug 18 19:00



Eau Galle Reservoir Aug 18 22:00



Distance (m)
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100
200
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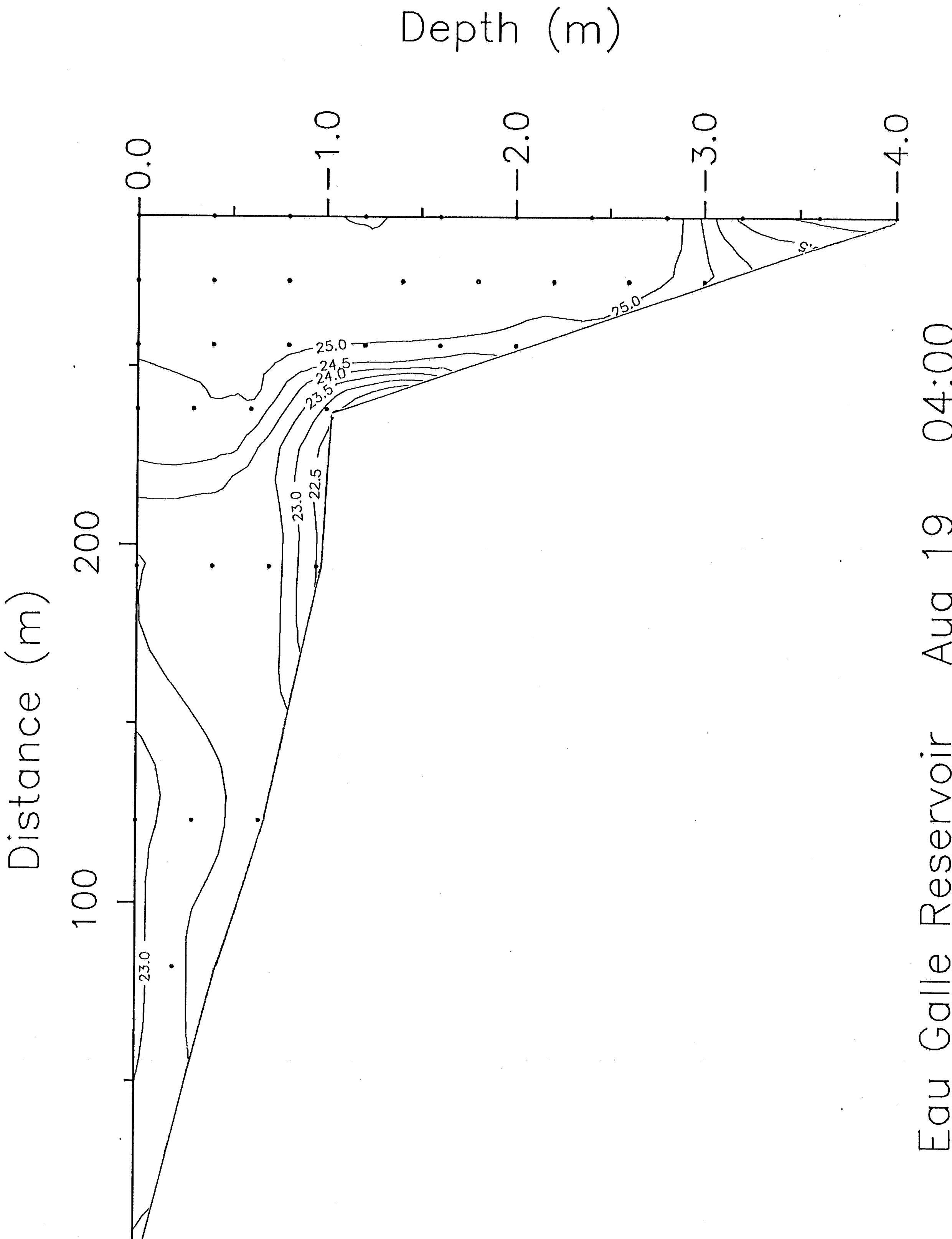
−1.0
−2.0
−3.0
−4.0
Depth (m)
24.0
24.5
23.5
23.0
22.5
24.0
25.0
25.5
25.0
24.5
23.0
Eau Galle Reservoir Aug 19 01:00



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3.0
4.0
Distance (m)
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100
200
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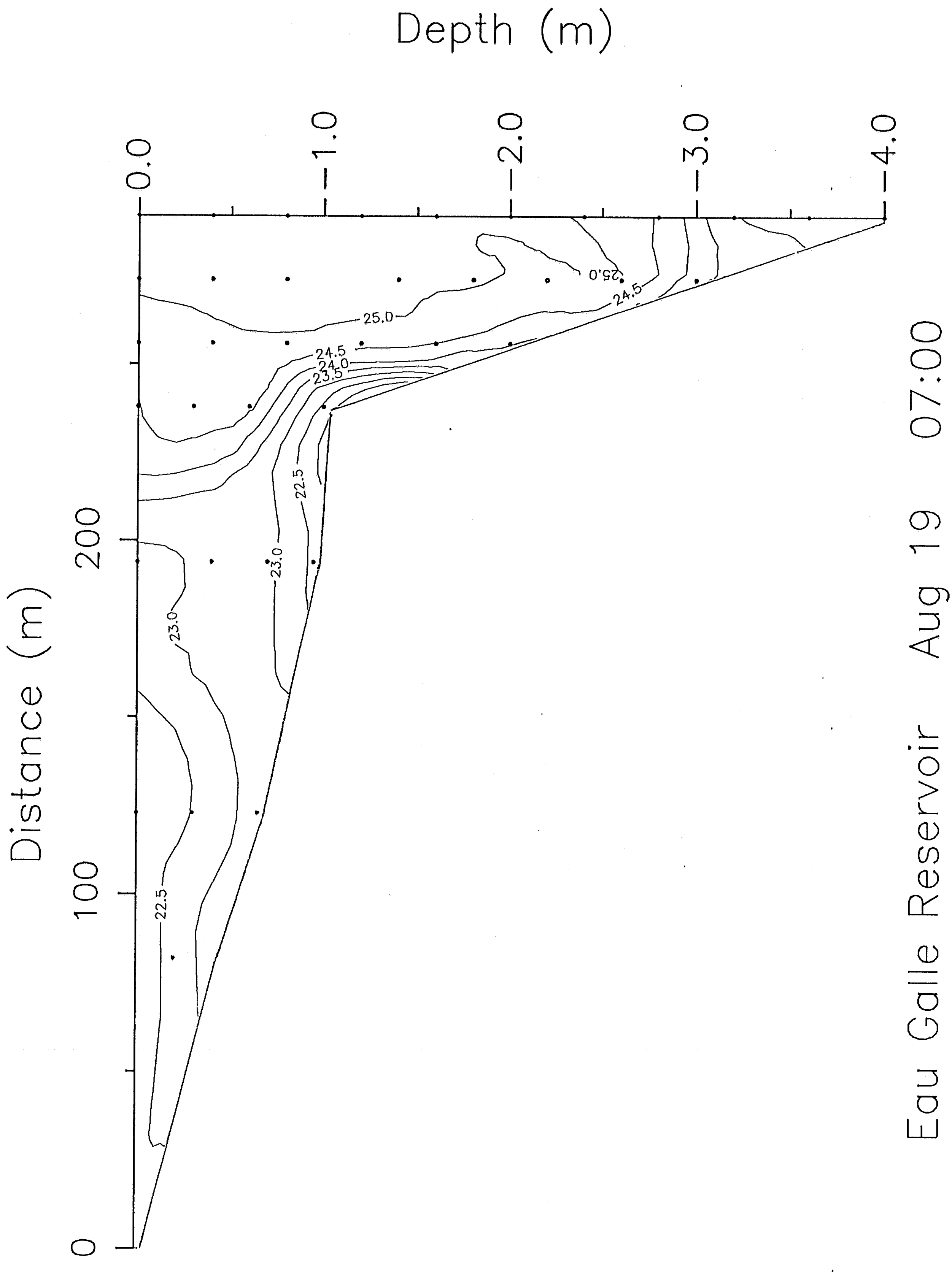
24.0
23.5
23.0
22.5
Eau Galle Reservoir Aug 19 04:00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1.0
2.0
3.0
4.0
Distance (m)
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200
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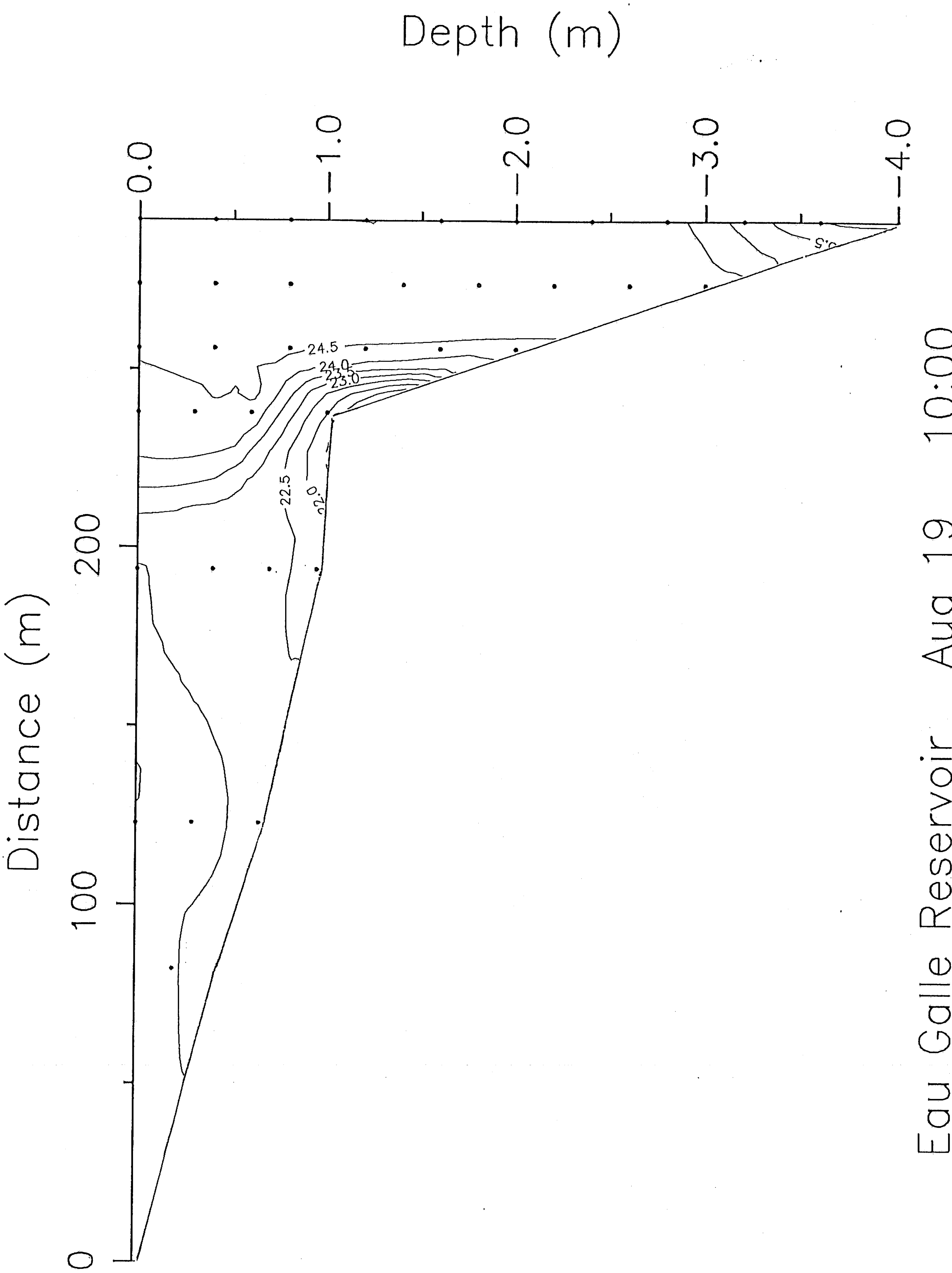
24.0
23.5
23.0
22.5
Eau Galle Reservoir Aug 19 07:00



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1.0
2.0
3.0
4.0
Distance (m)
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100
200
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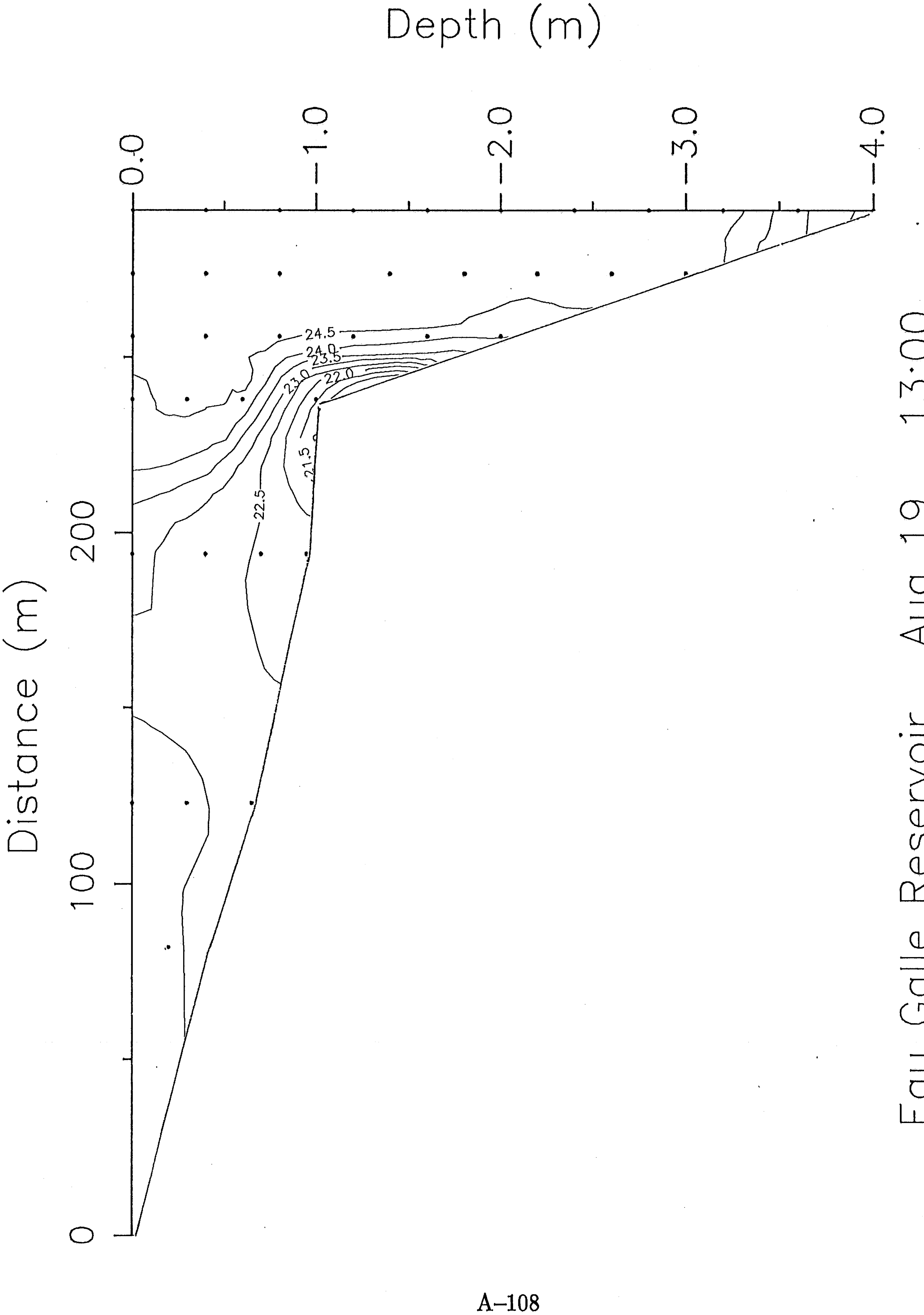
24.0
23.5
23.0
22.5
Eau Galle Reservoir Aug 19 10:00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2.0
3.0
4.0
Distance (m)
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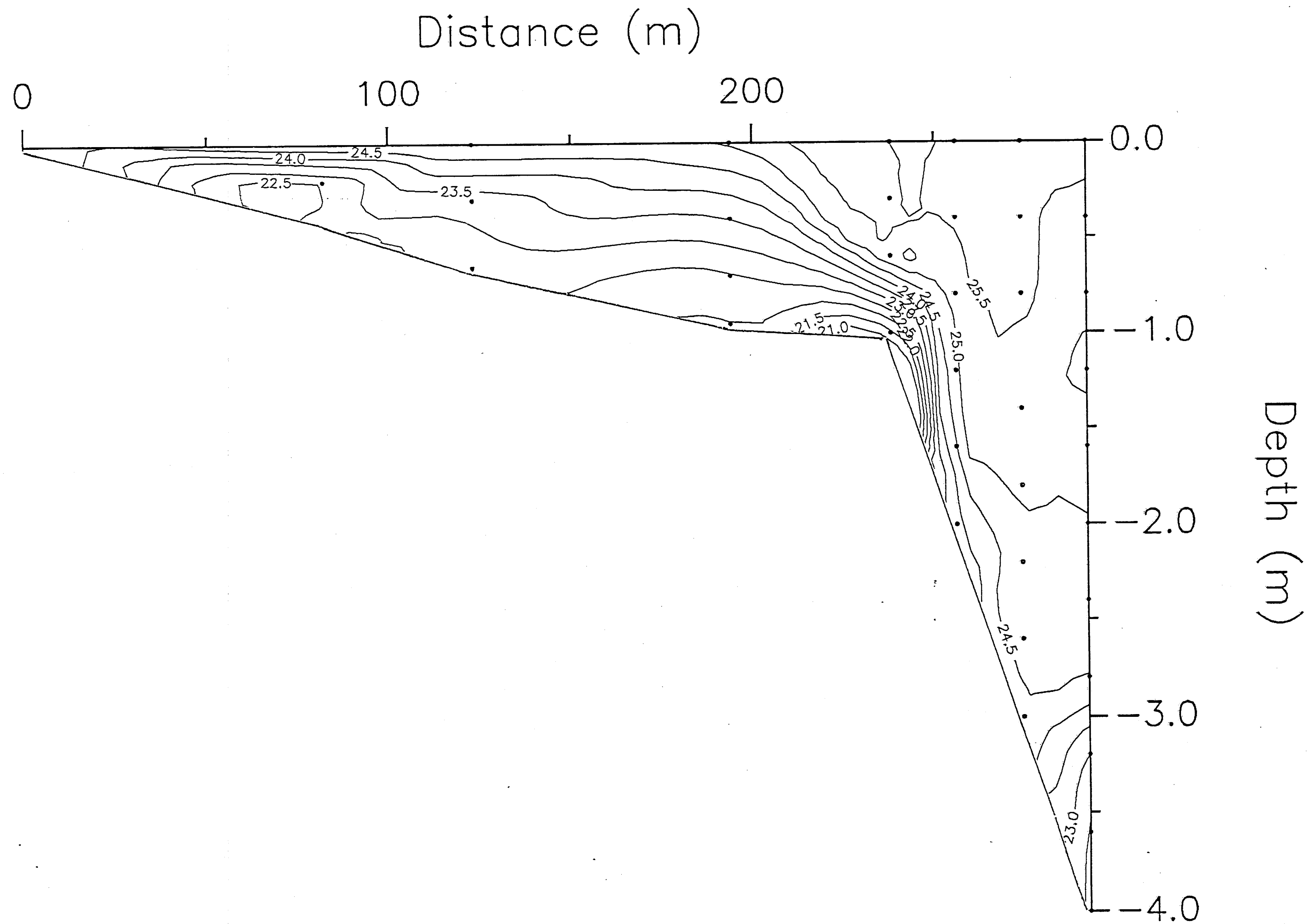
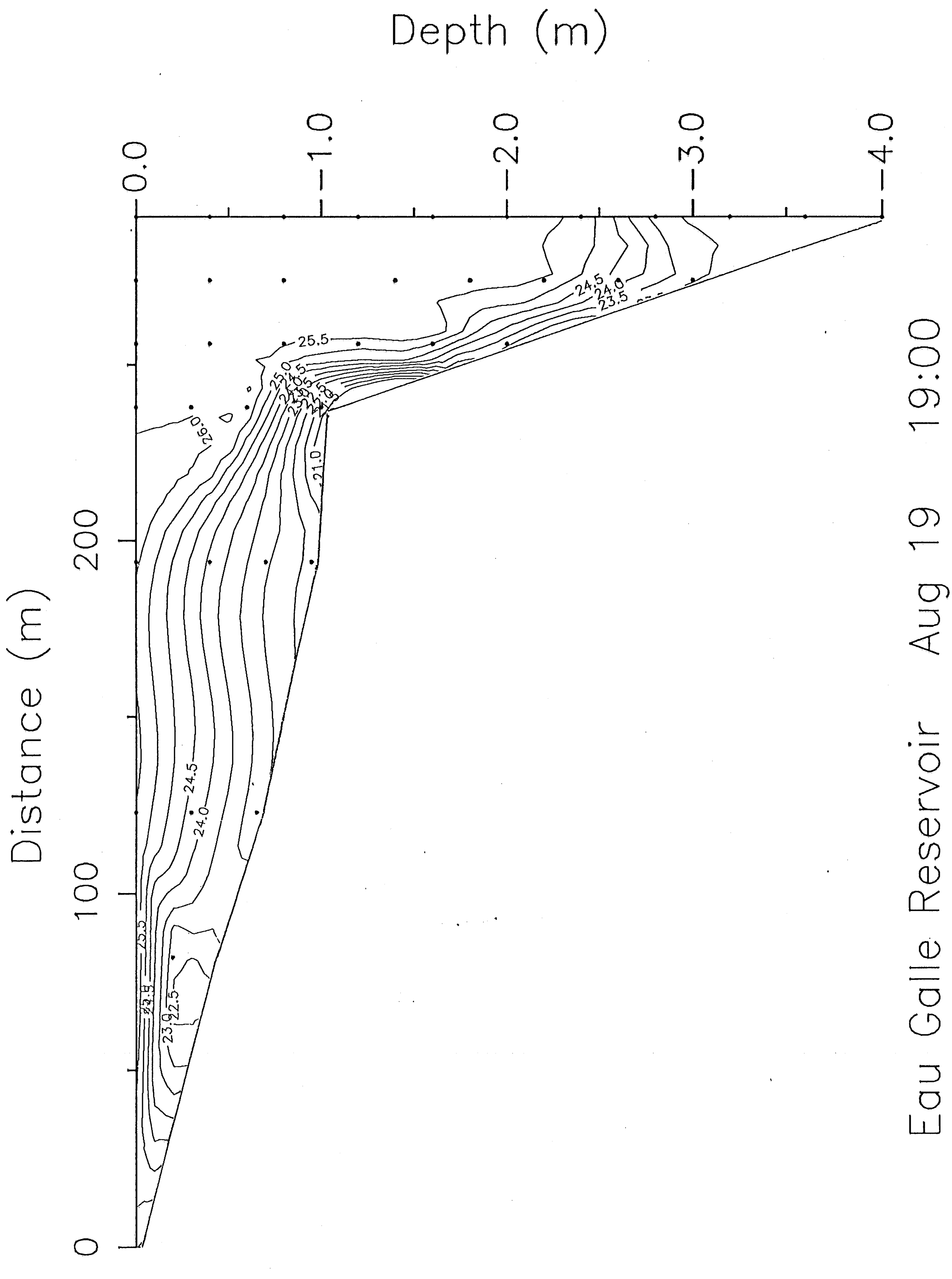
23.5
23.0
22.0
22.5
21.5
Eau Galle Reservoir Aug 19 13:00



Eau Galle Reservoir Aug 19 16:00


Depth (m)
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1.0
2.0
3.0
4.0
Distance (m)
0
100
200
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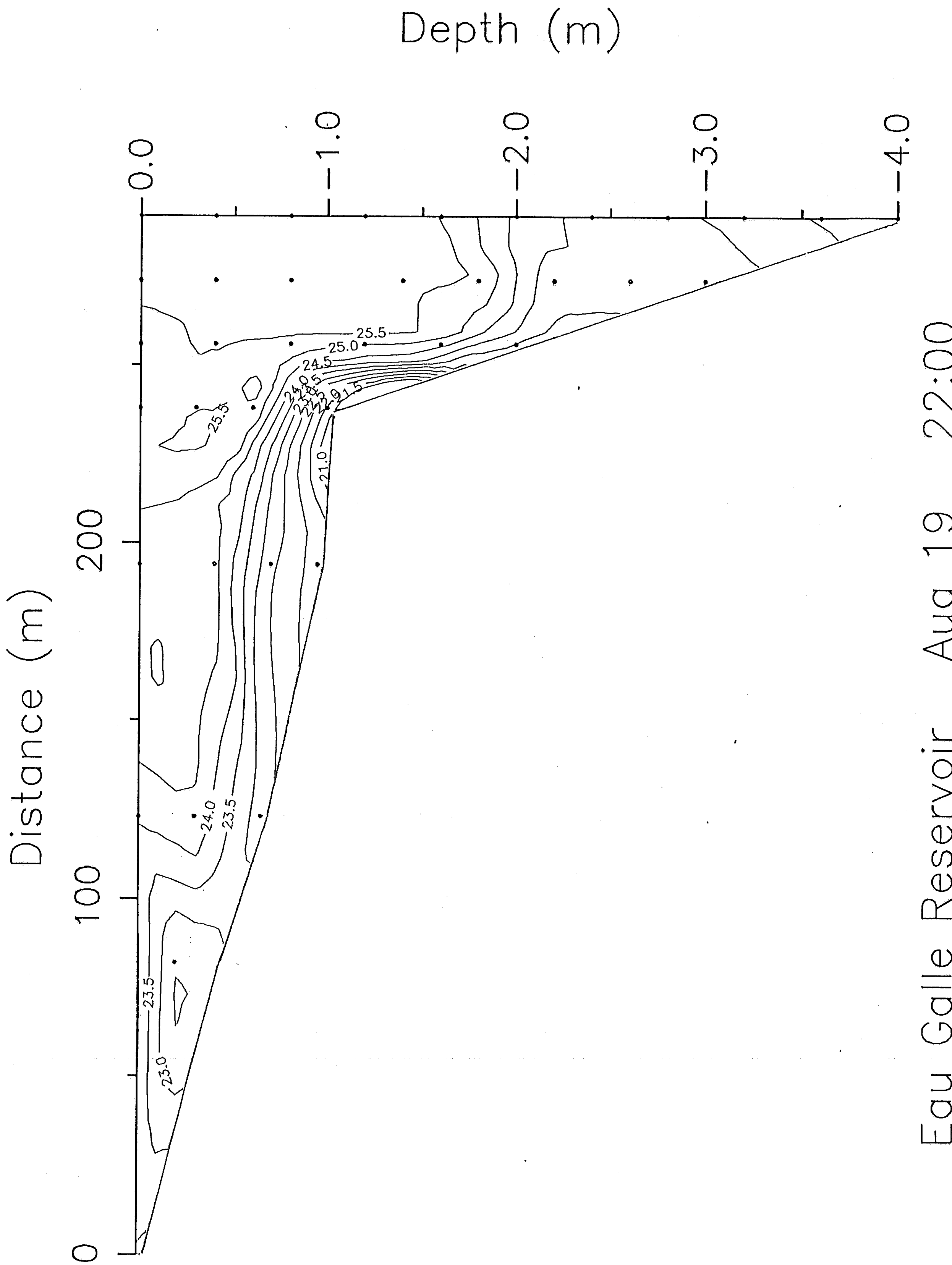
25.5
25.0
24.5
24.0
23.5
23.0
22.5
21.0
Eau Galle Reservoir Aug 19 19:00



Depth (m)
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1.0
2.0
3.0
4.0
Distance (m)
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100
200
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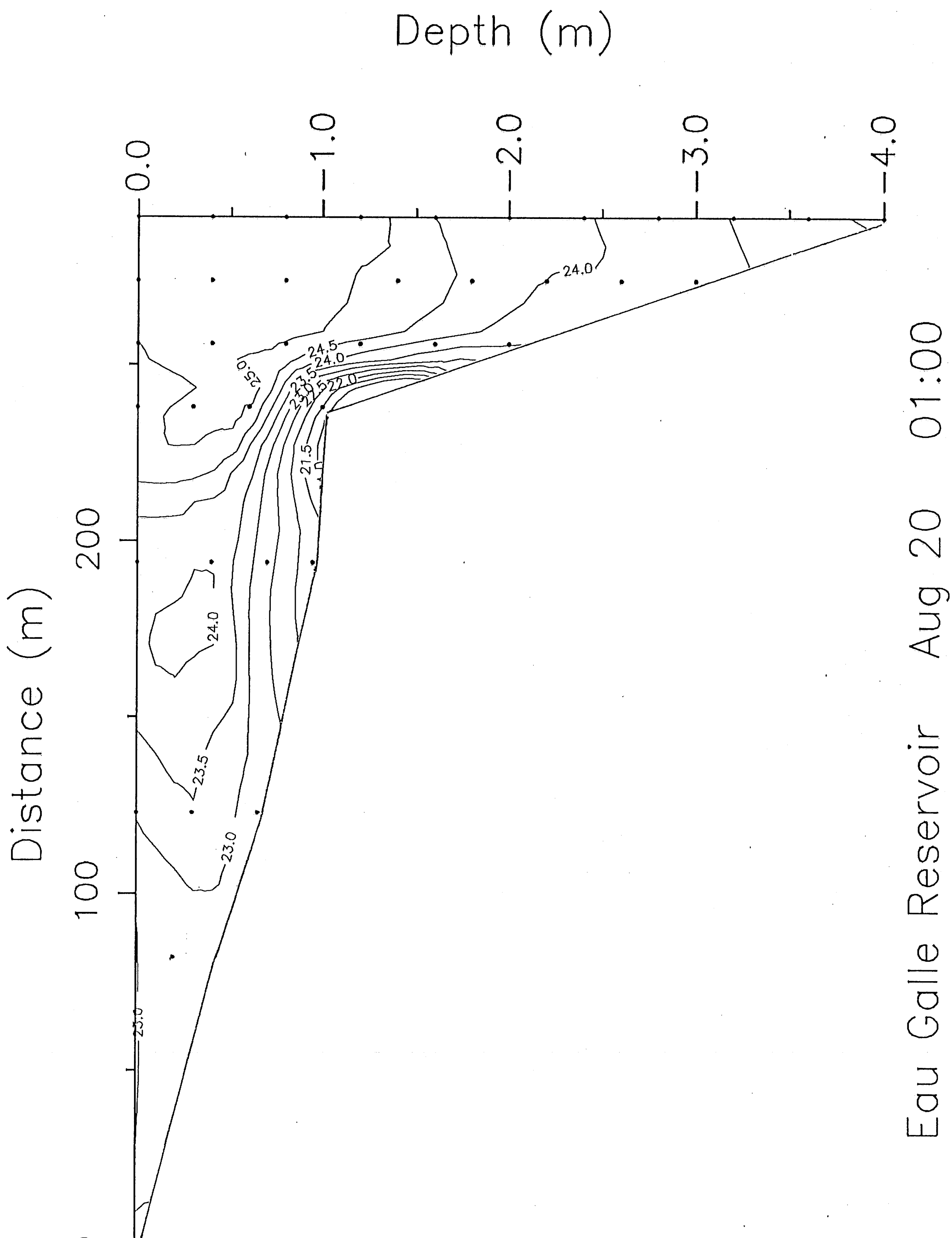
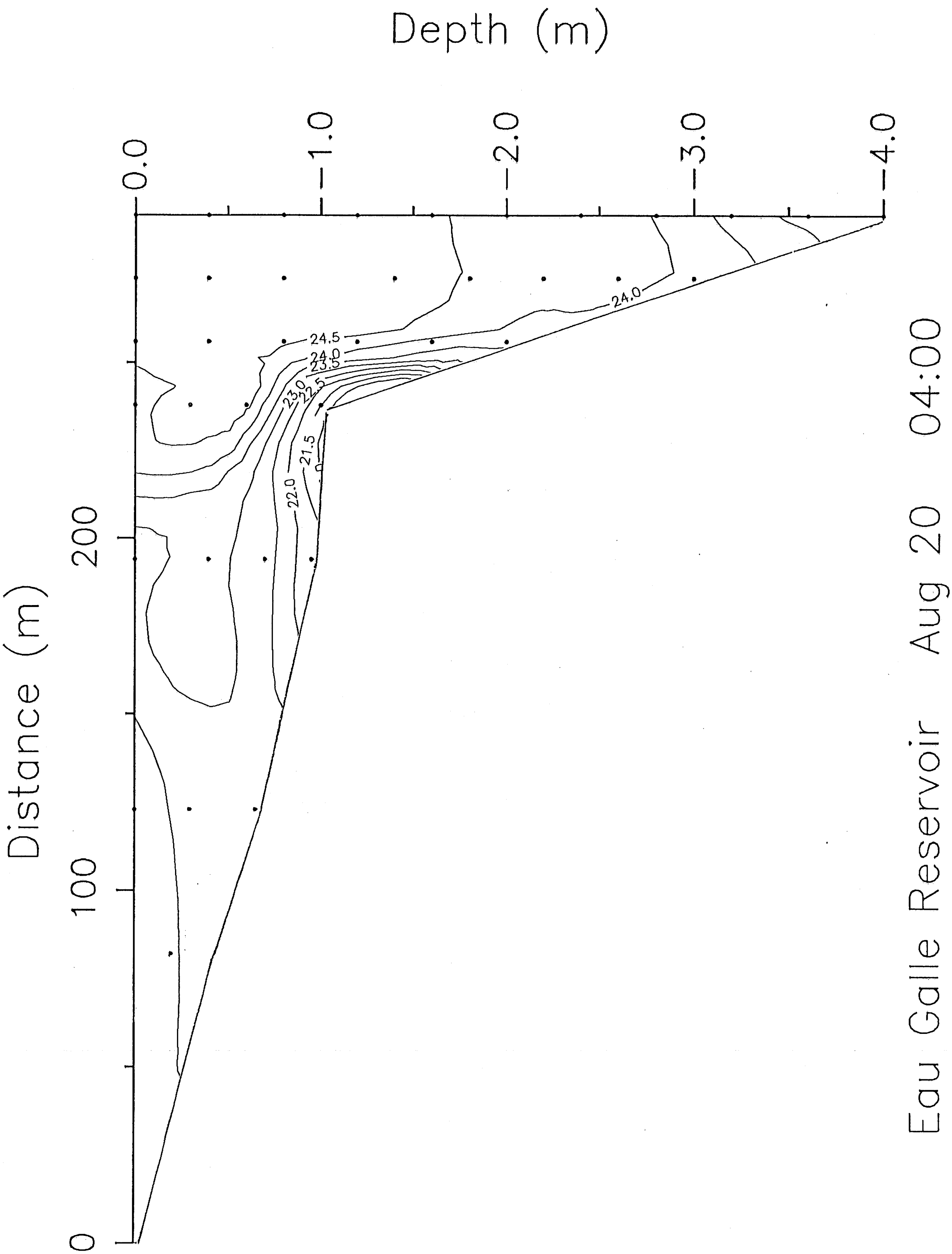
25.0
24.5
24.0
23.5
23.0
21.0
Eau Galle Reservoir Aug 19 22:00


Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
24.0
24.5
24.0
25.0
23.5
23.0
22.5
22.0
21.5
24.0
23.5
23.0
23.0
Eau Galle Reservoir Aug 20 01:00


Depth (m)
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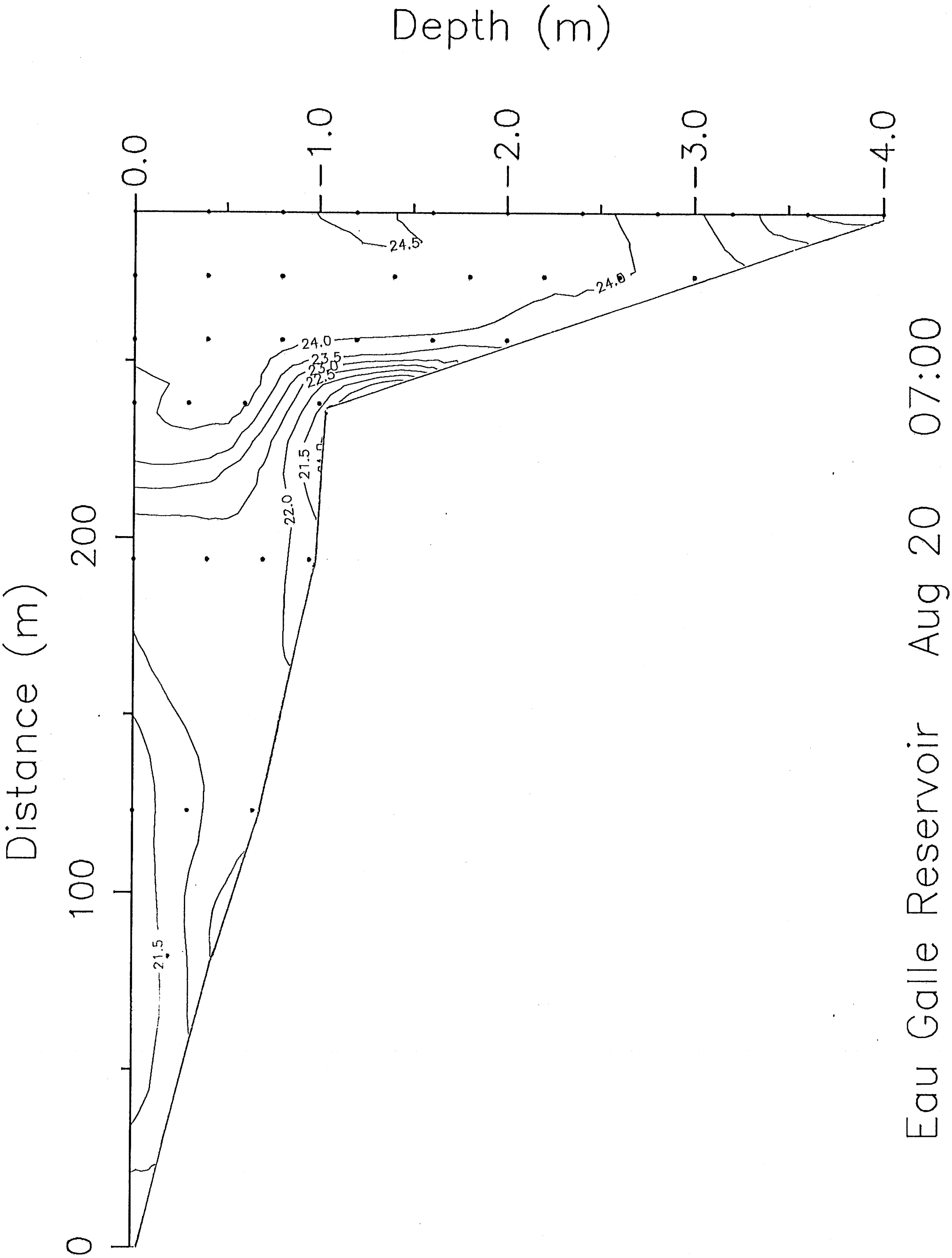
1.0
2.0
3.0
4.0
24.0
24.5
24.0
23.5
23.0
22.5
21.5
22.0
Distance (m)
0
100
200
Eau Galle Reservoir Aug 20 04:00


Depth (m)
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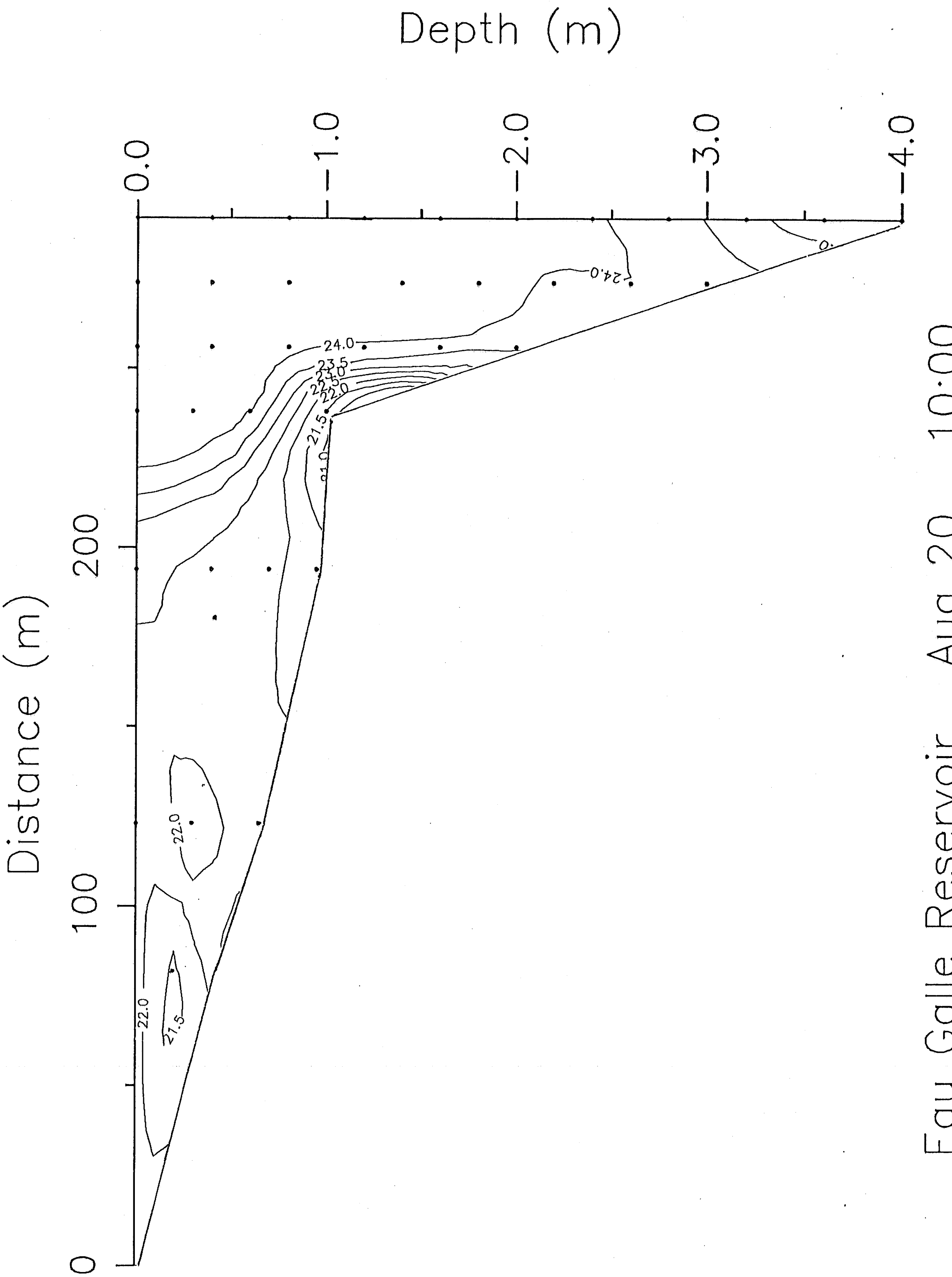
3.0
4.0
24.5
24.0
24.0
23.5
23.0
22.5
22.0
21.5
21.5
Distance (m)
0
100
200
Eau Galle Reservoir Aug 20 07:00



Depth (m)
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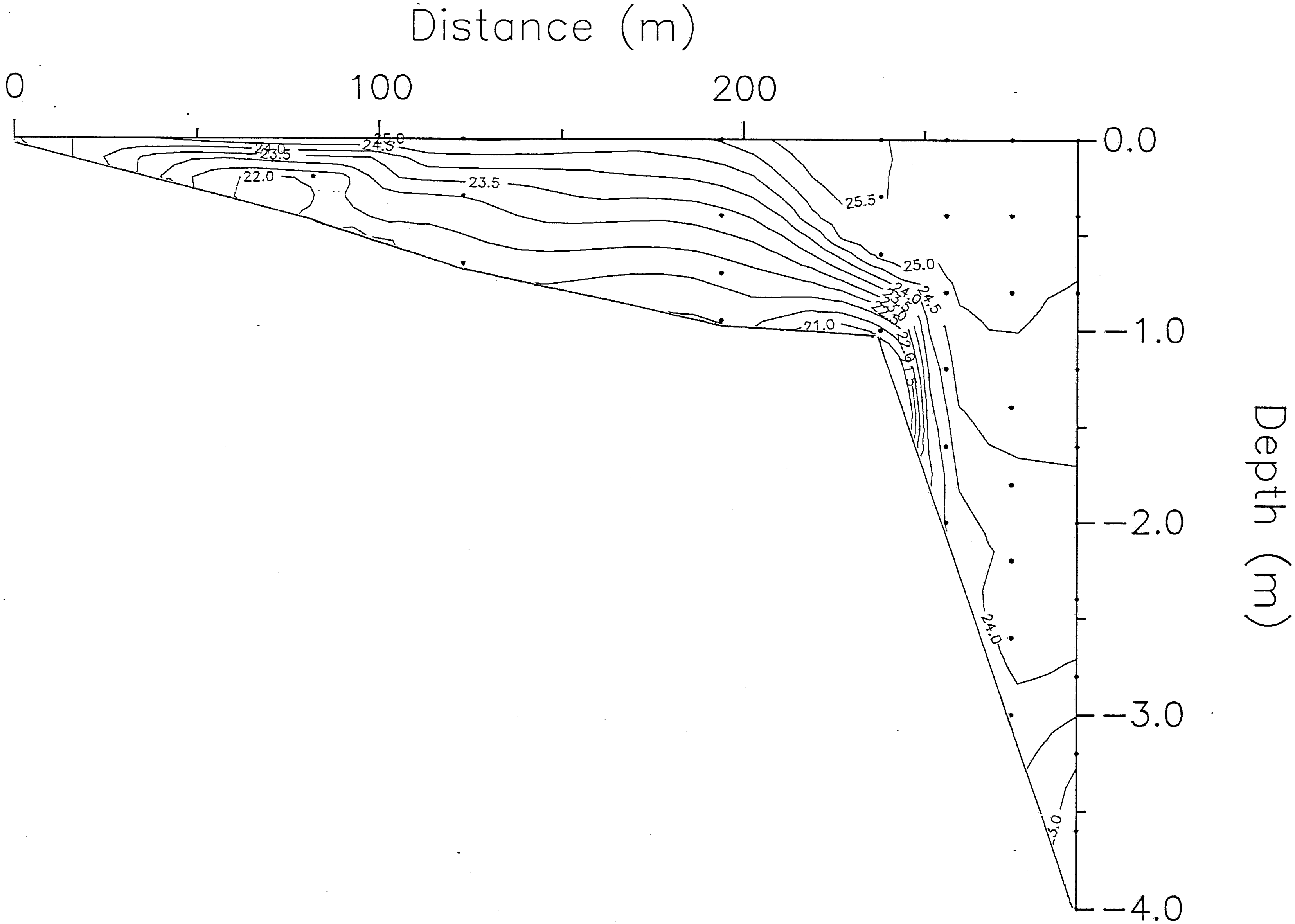
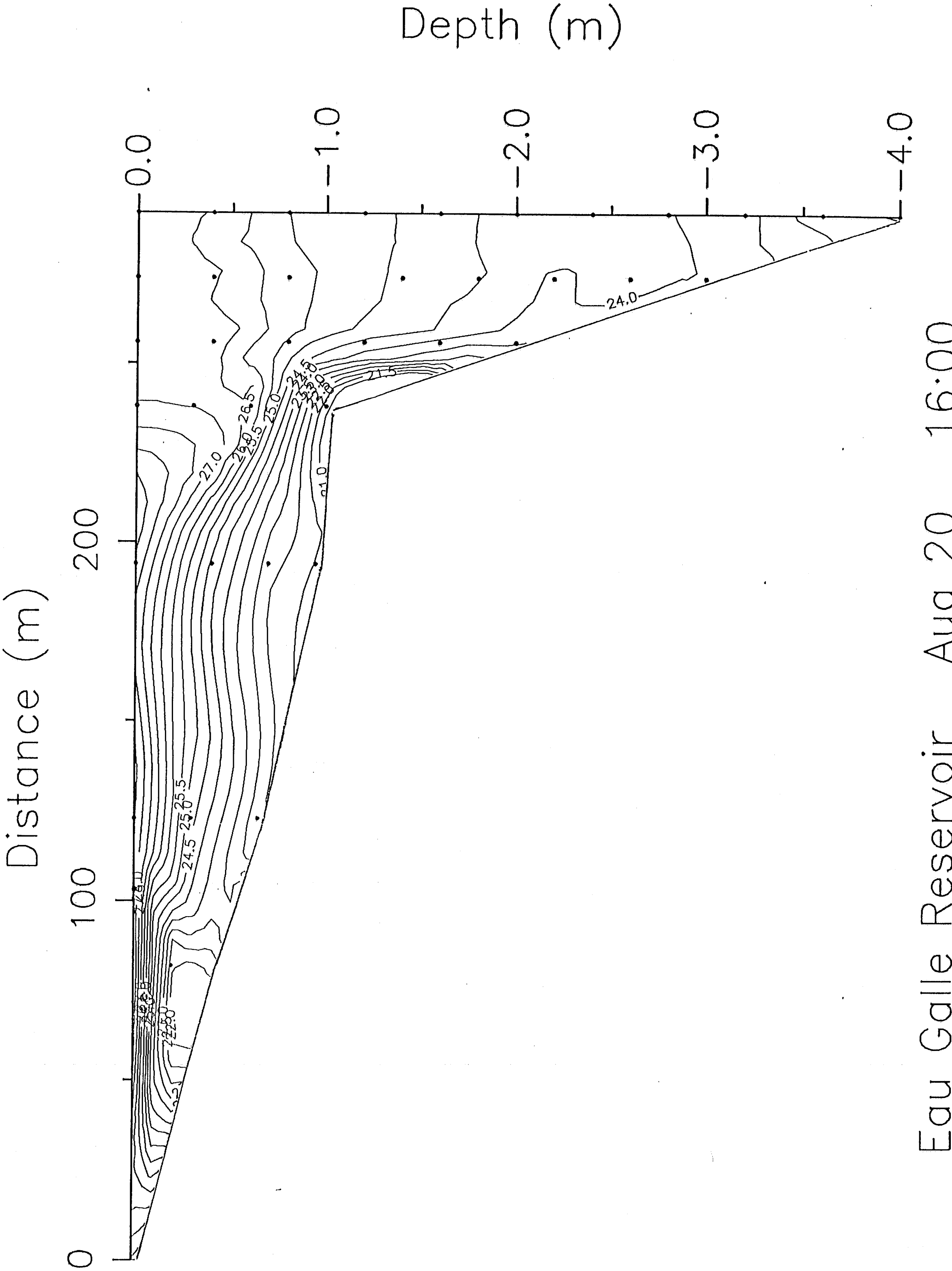
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
24.0
23.5
23.0
22.5
22.0
21.5
21.0
22.0
22.0
21.5
Eau Galle Reservoir Aug 20 10:00



Eau Galle Reservoir Aug 20 13:00


Depth (m)
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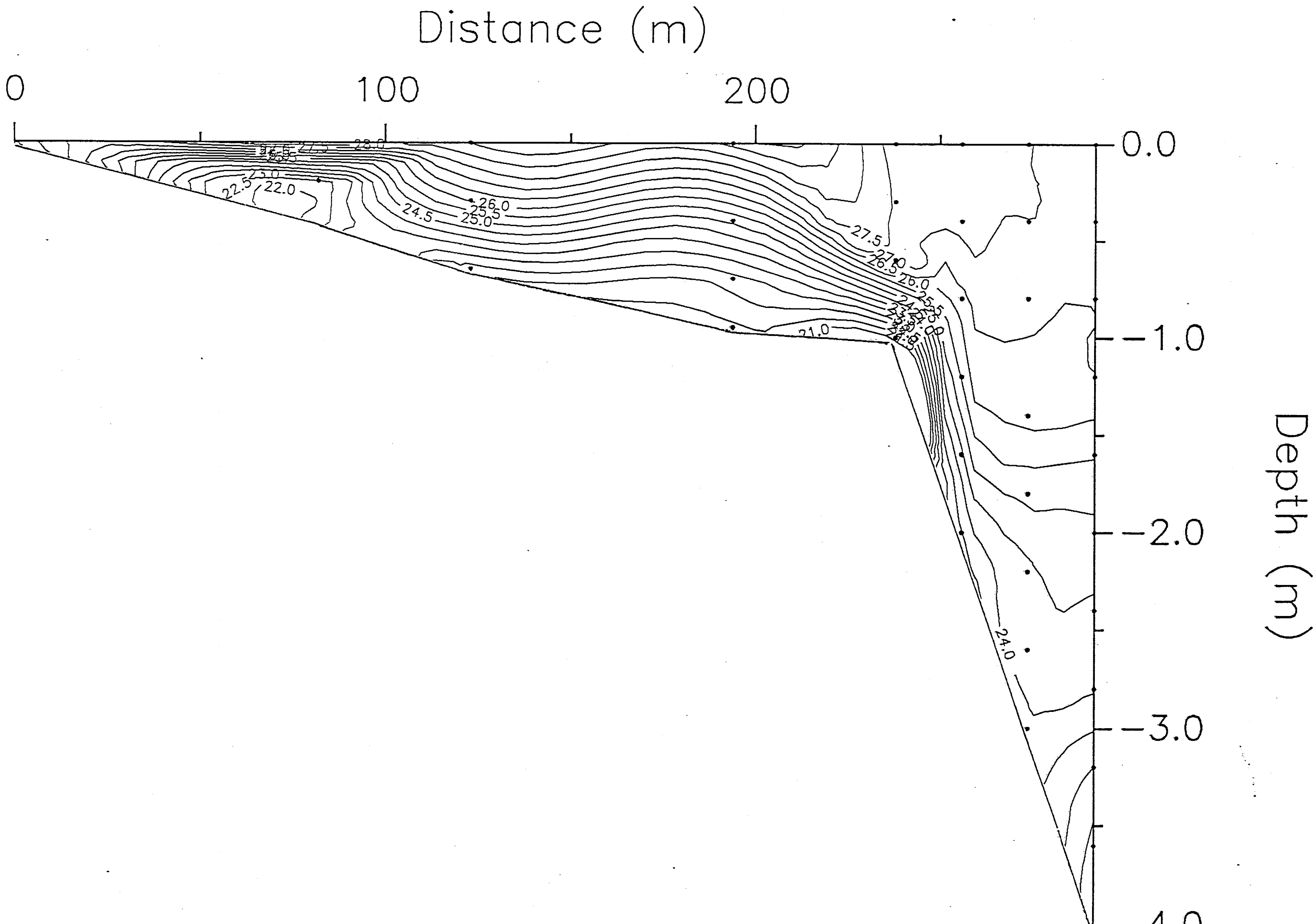
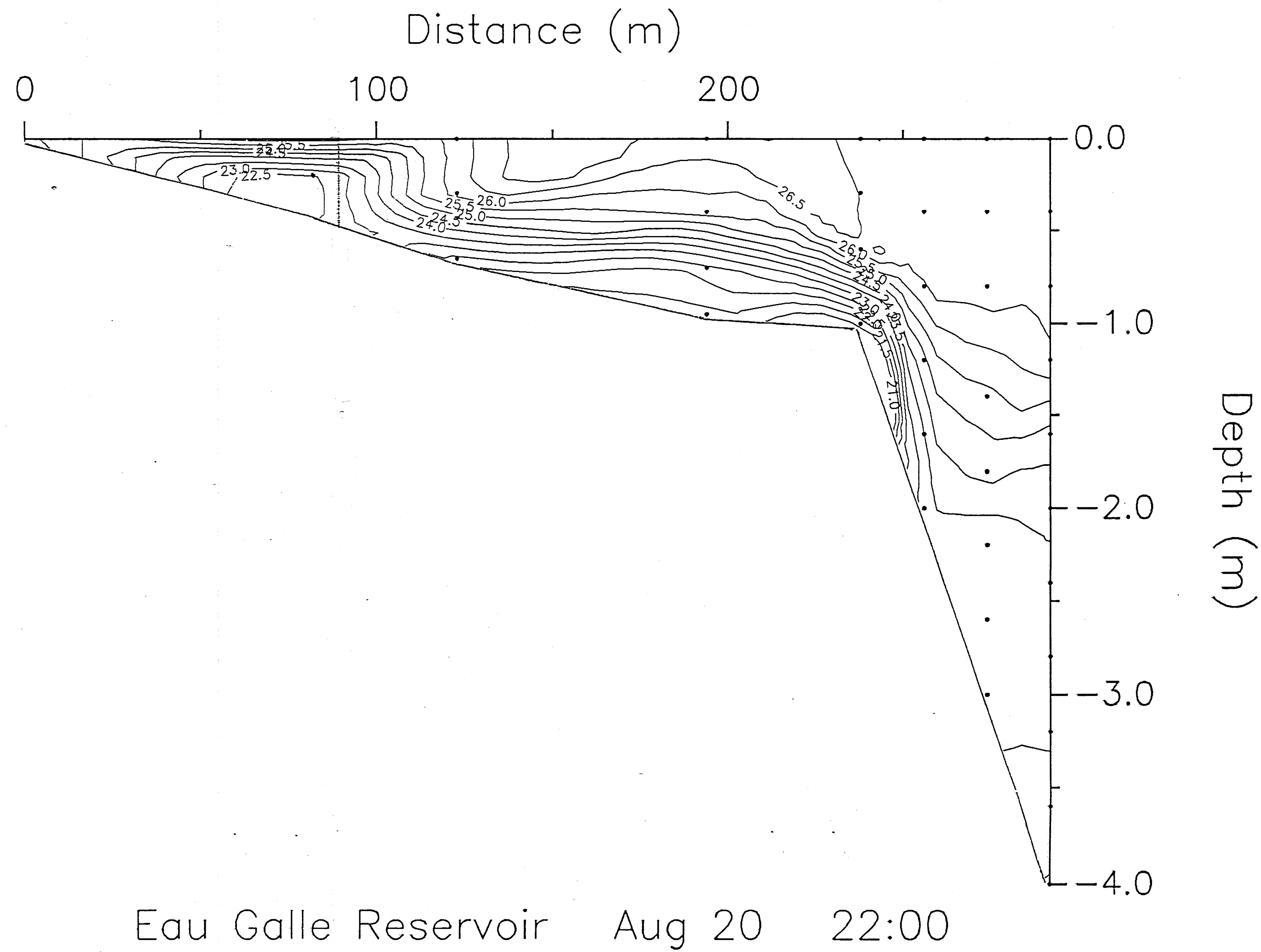
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
24.0
27.0
26.5
26.0
25.5
25.0
24.5
21.5
21.0
Eau Galle Reservoir Aug 20 16:00



Eau Galle Reservoir Aug 20 19:00


Distance (m)
0
100
200
0.0
-1.0
-2.0
-3.0
-4.0
Depth (m)
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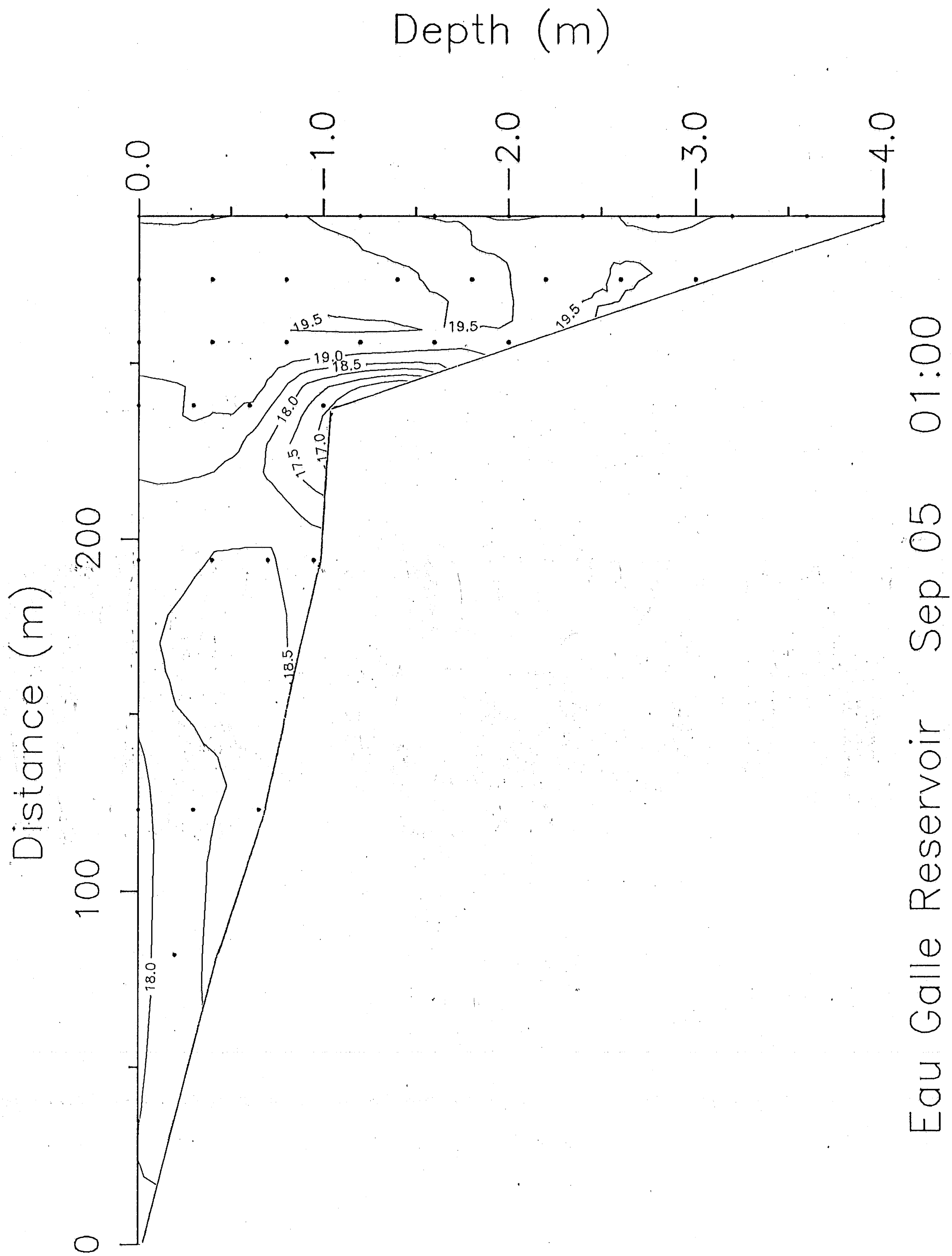
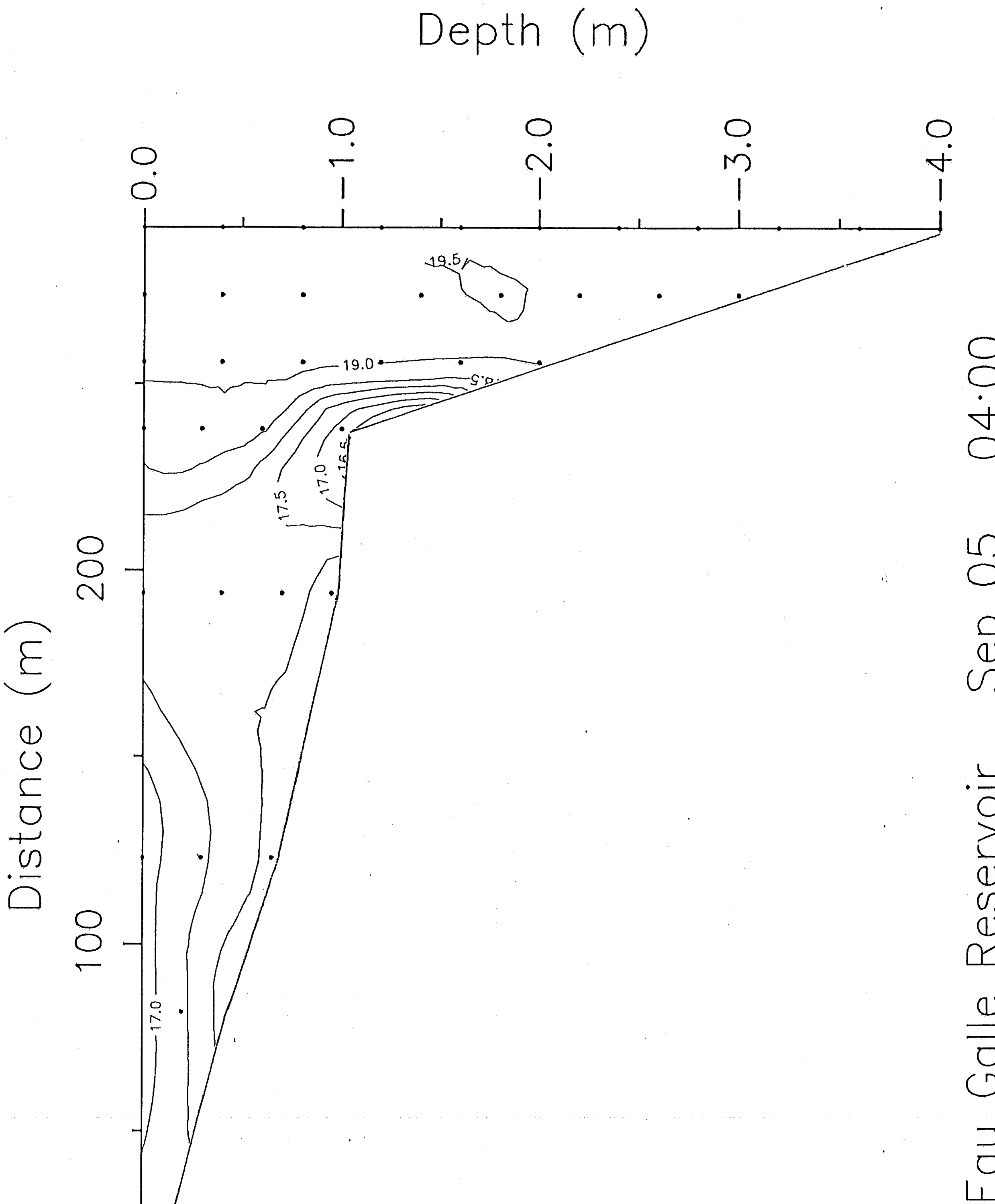
26.0
25.5
25.0
24.5
24.0
23.0
22.5
21.0
Eau Galle Reservoir Aug 20 22:00



Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
19.5
19.5
19.5
19.0
18.5
18.0
17.5
17.0
18.5
18.0
Eau Galle Reservoir Sep 05 01:00


Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
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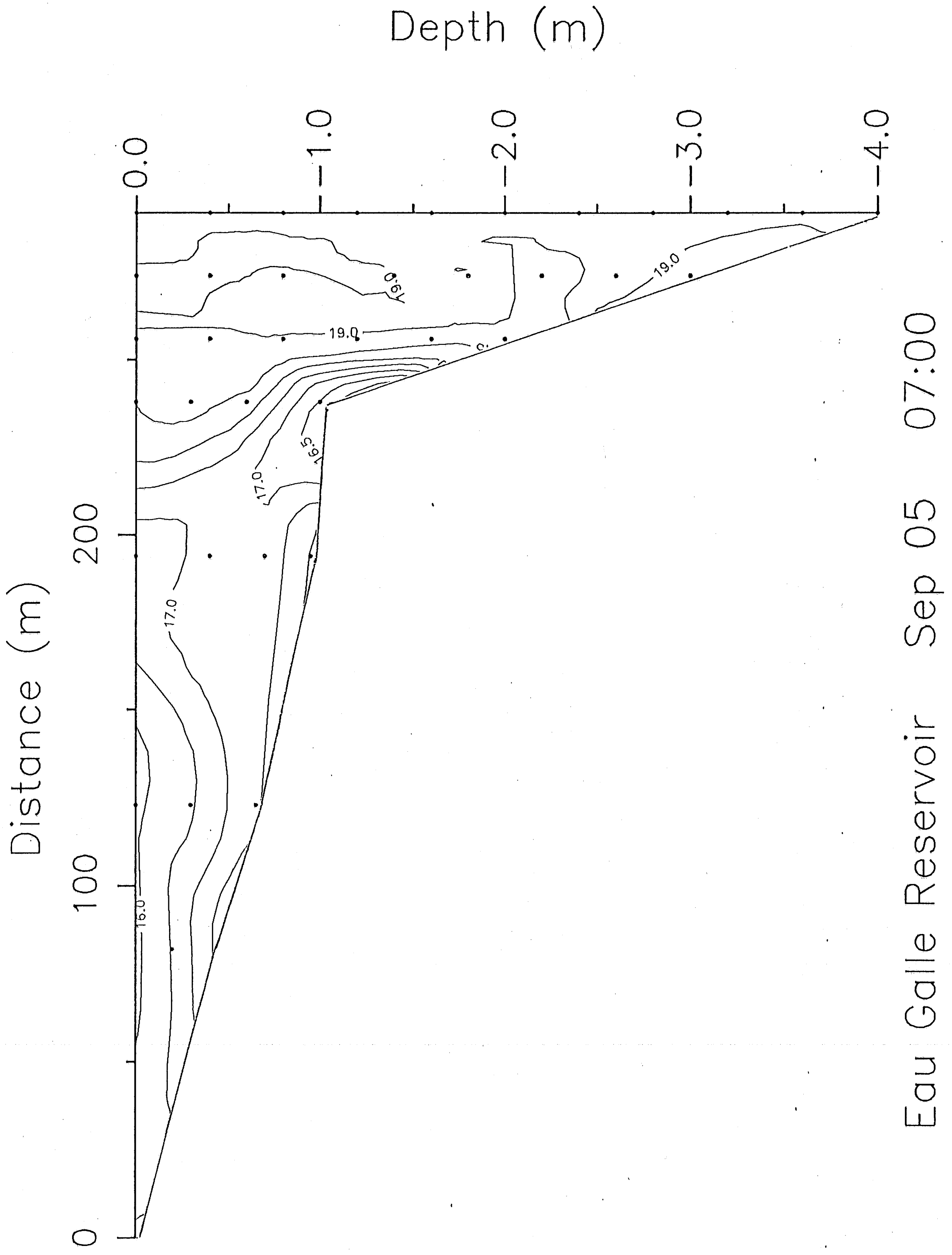
19.0
17.5
17.0
16.5
17.0
Eau Galle Reservoir Sep 05 04:00


Depth (m)
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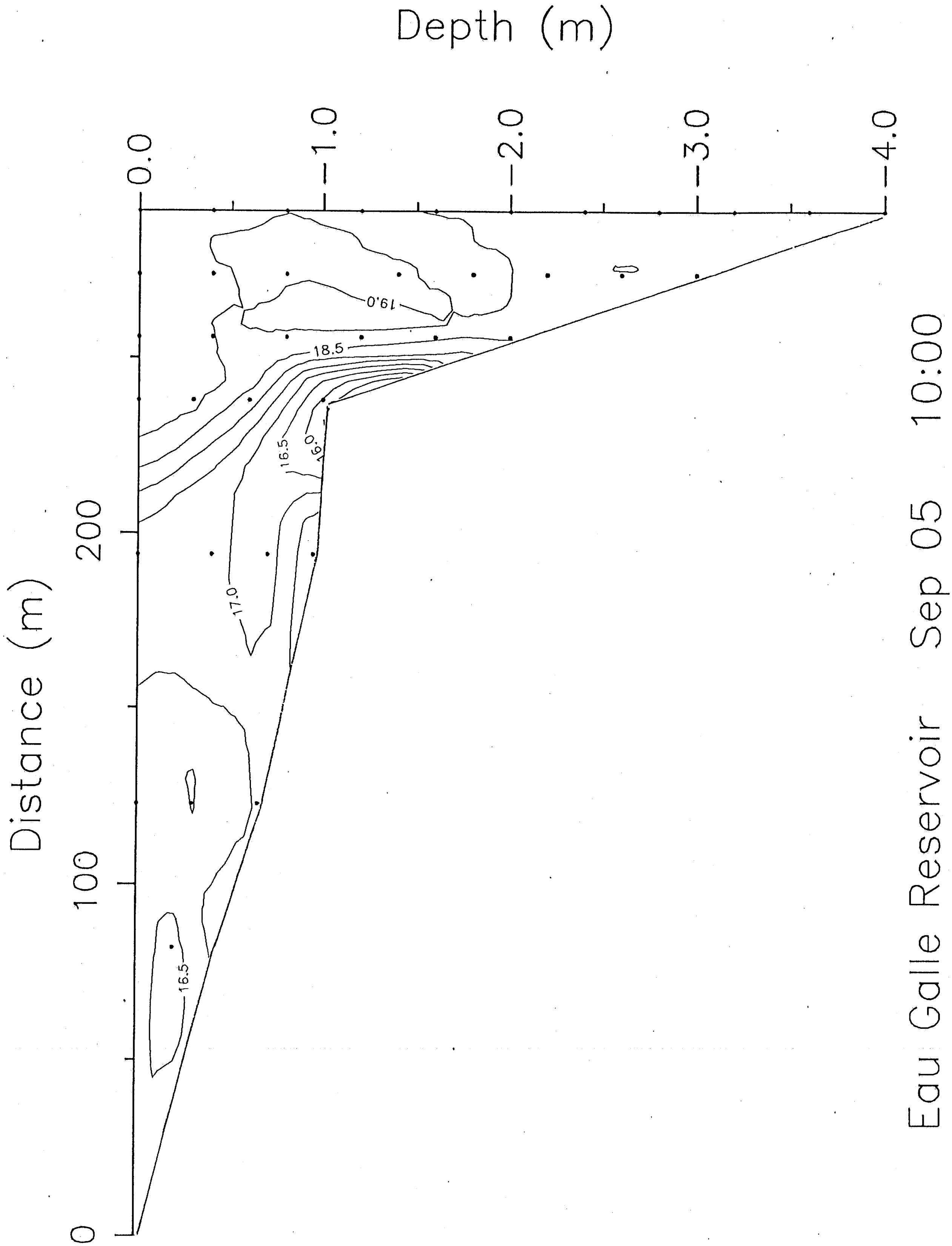
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
Eau Galle Reservoir Sep 05 07:00



Depth (m)
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1.0
2.0
3.0
4.0
Distance (m)
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100
200
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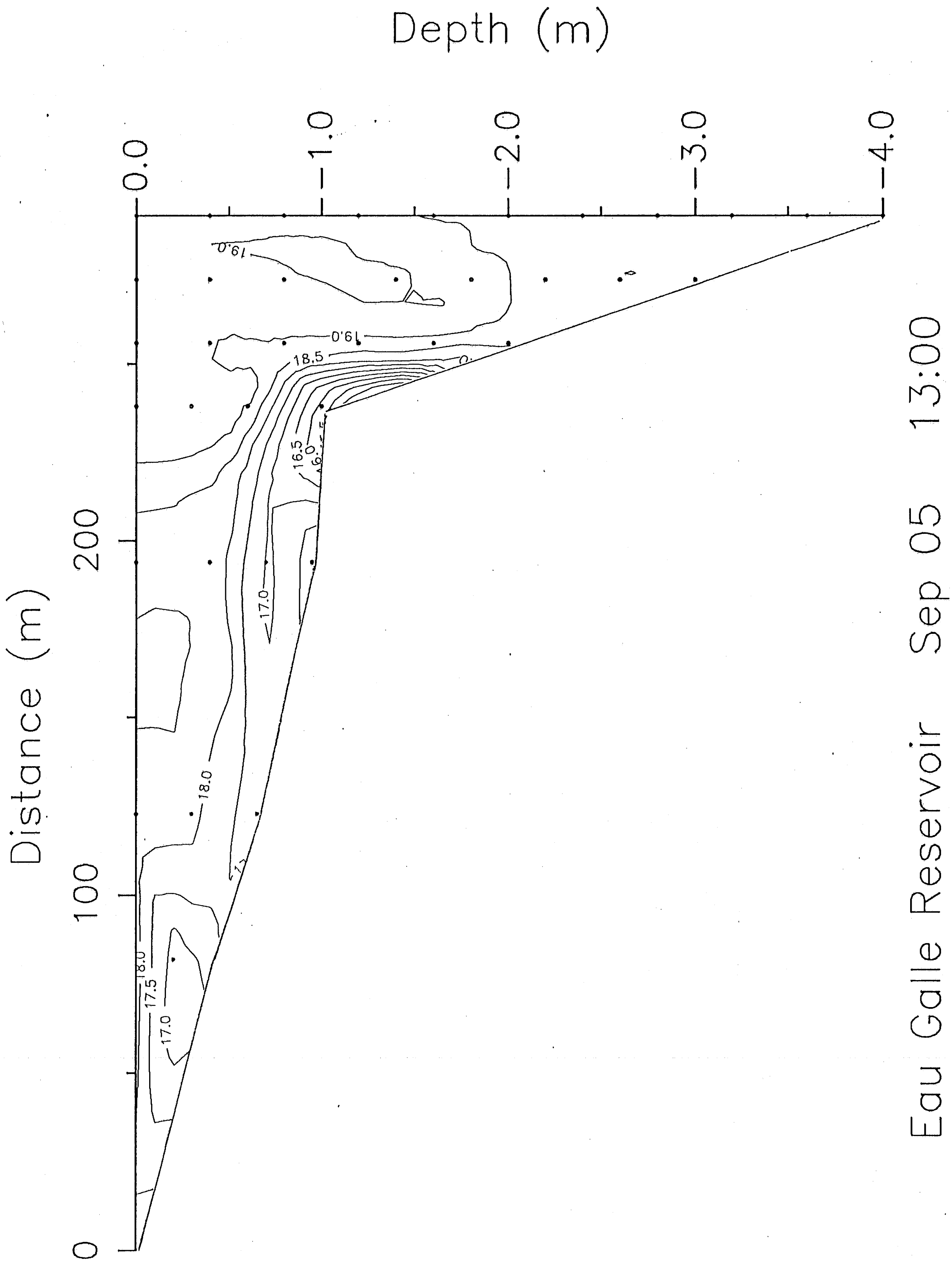
18.5
16.5
16.0
17.0
16.5
Eau Galle Reservoir Sep 05 10:00


Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
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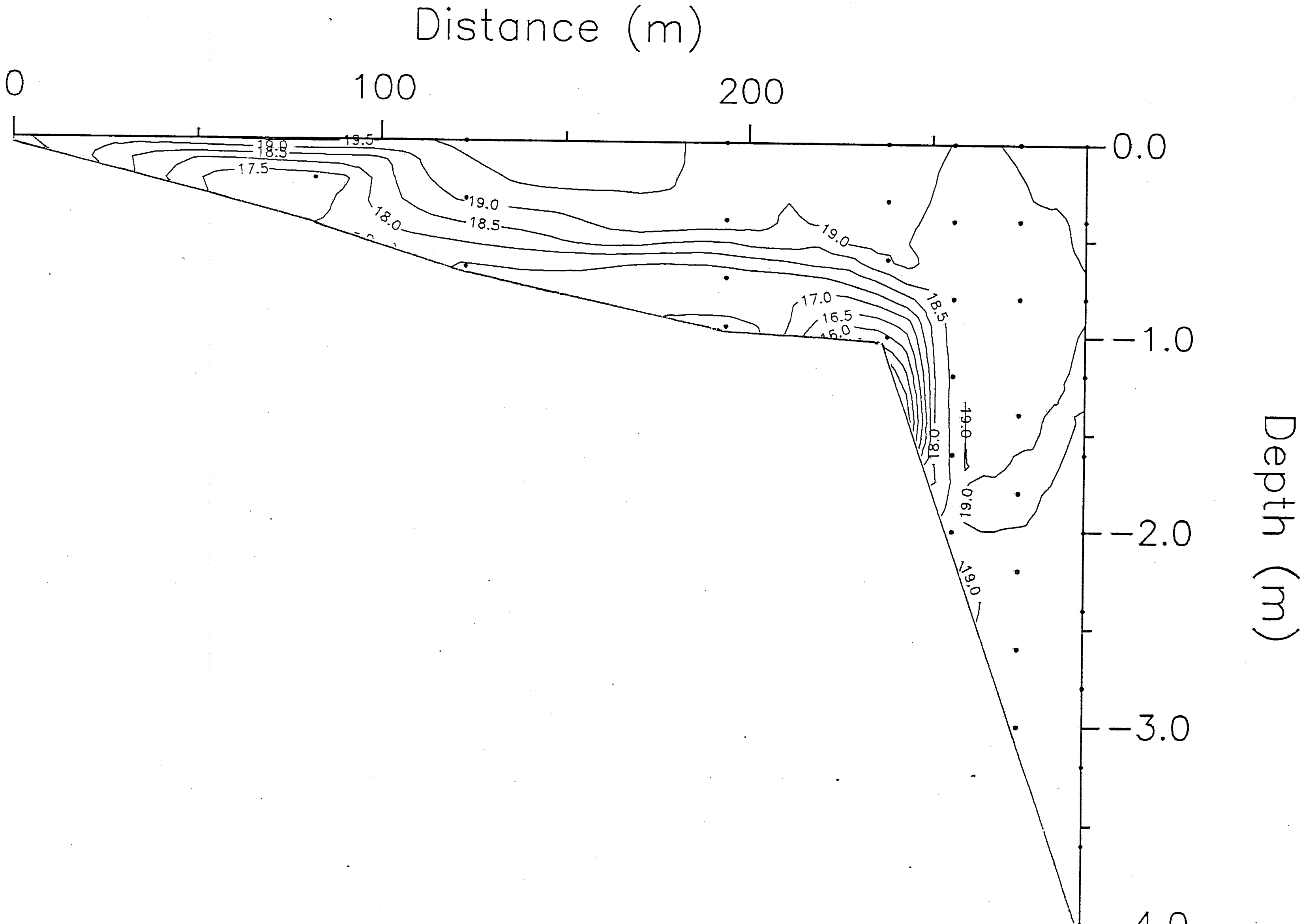
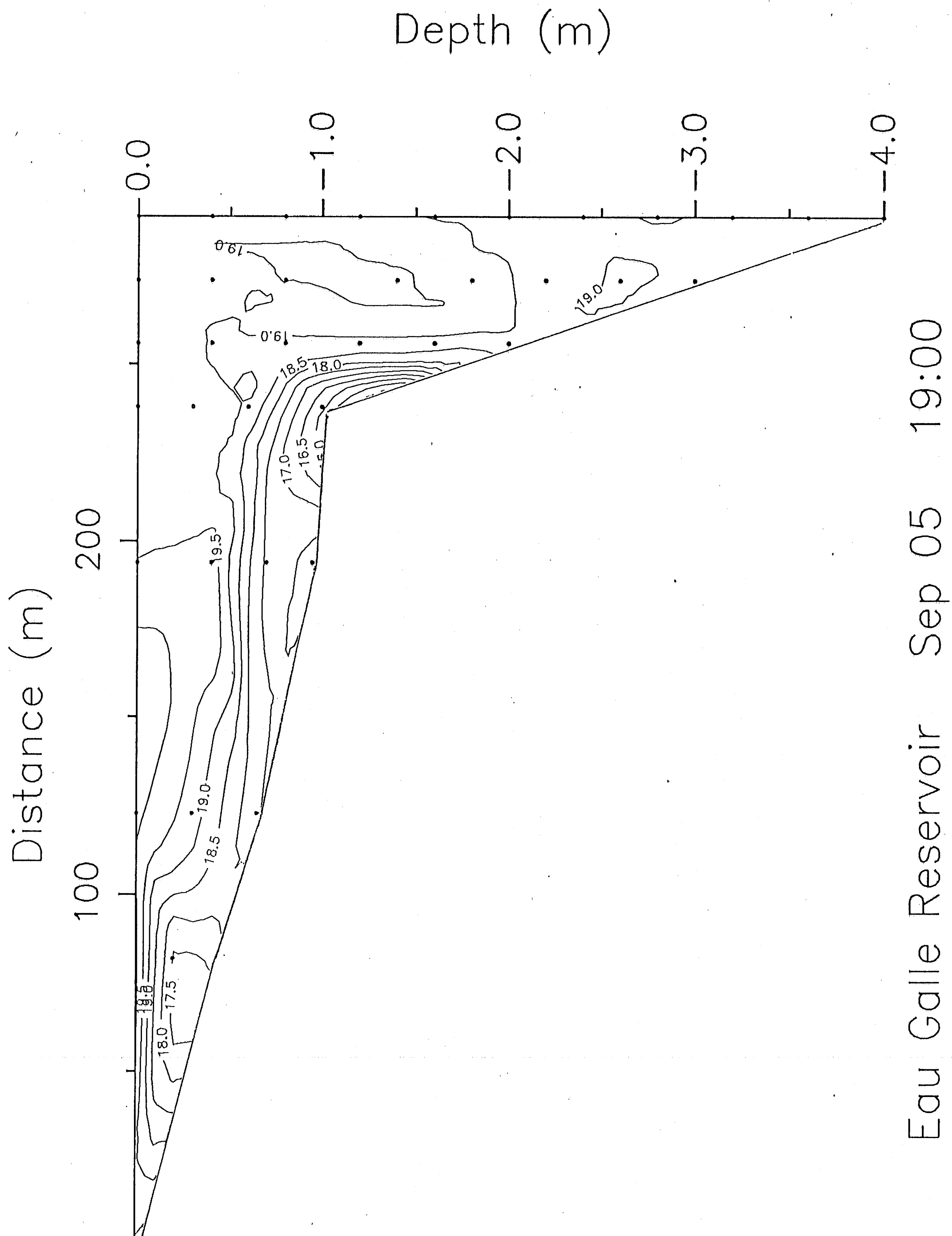
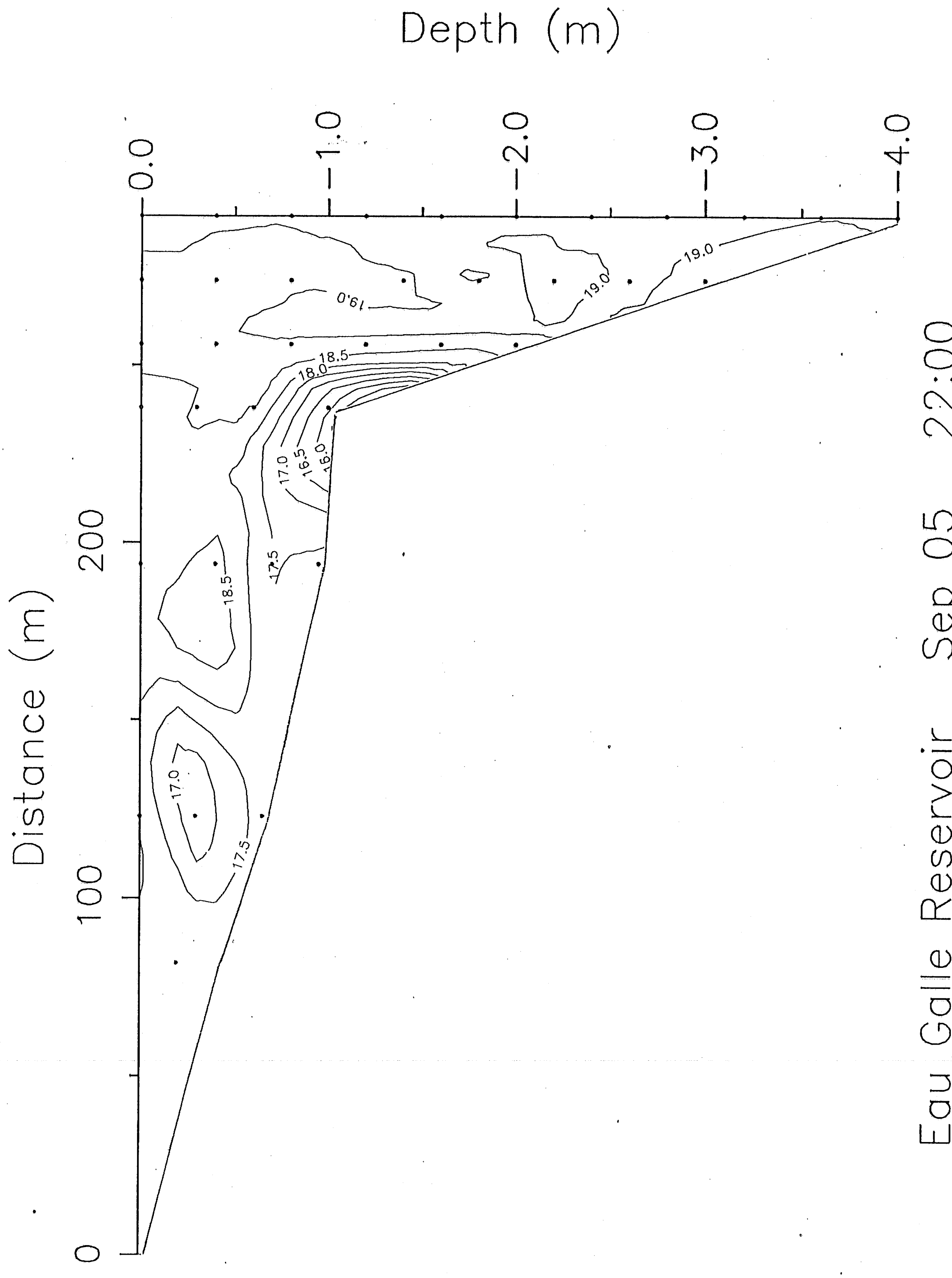
100
200
19.0
18.5
18.0
17.5
17.0
16.5
Eau Galle Reservoir Sep 05 13:00



Eau Galle Reservoir Sep 05 16:00



Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
19.0
18.5
18.0
17.5
17.0
16.5
19.5
Eau Galle Reservoir Sep 05 19:00


Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
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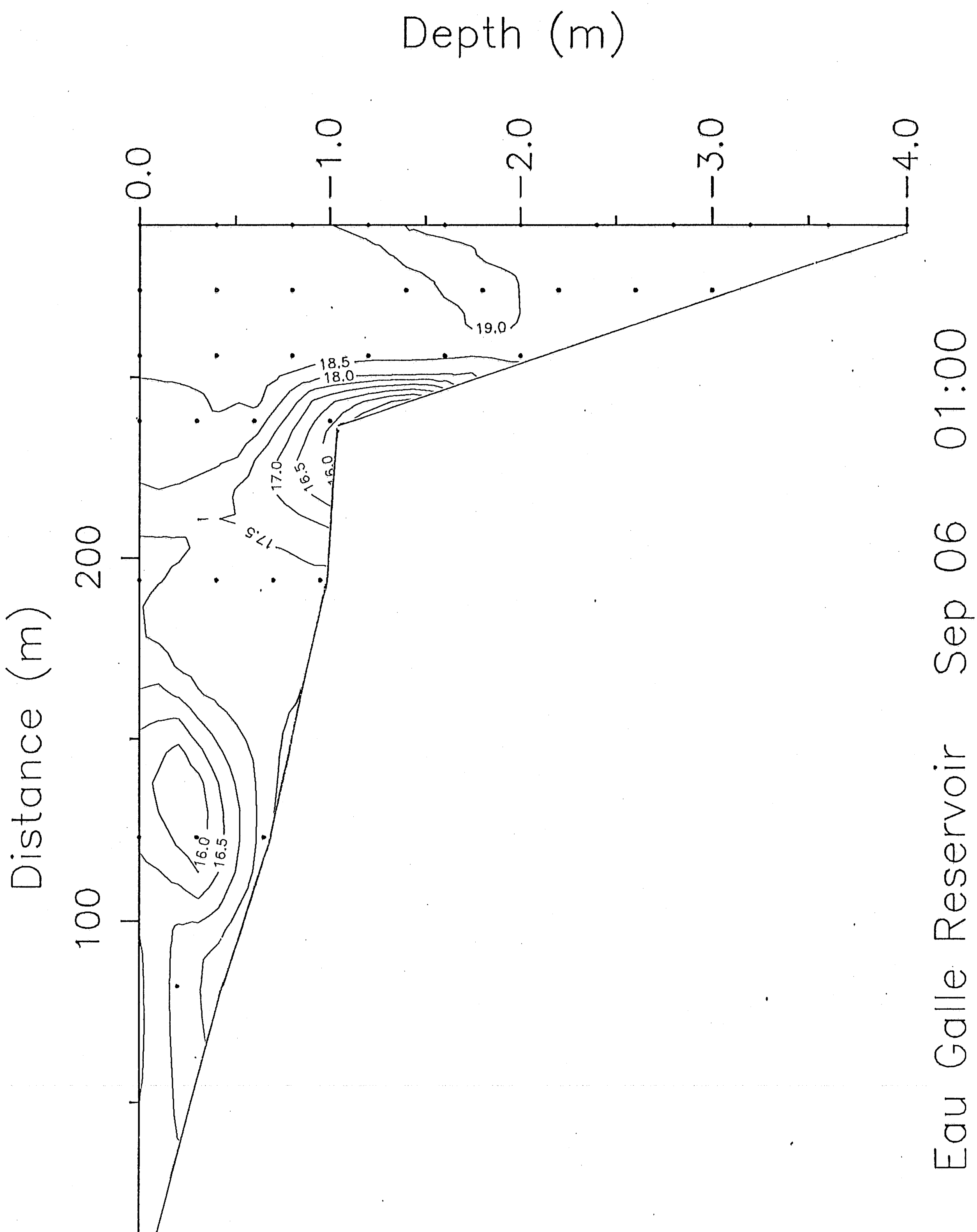
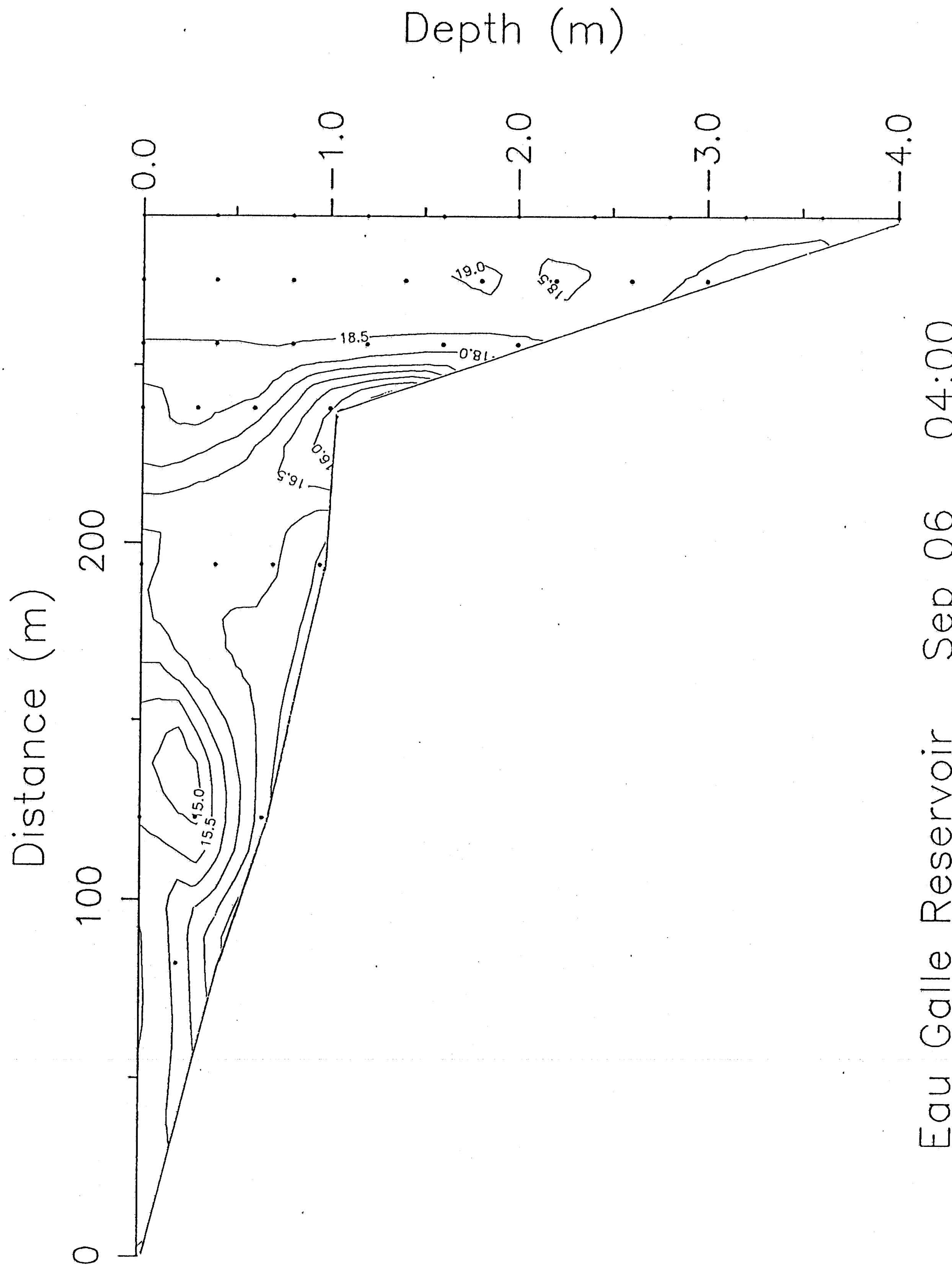
18.5
18.0
17.5
17.0
16.5
16.0
Eau Galle Reservoir Sep 05 22:00



Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
19.0
18.5
18.0
17.5
17.0
16.5
16.0
16.0
16.5
Eau Galle Reservoir Sep 06 01:00


Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
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100
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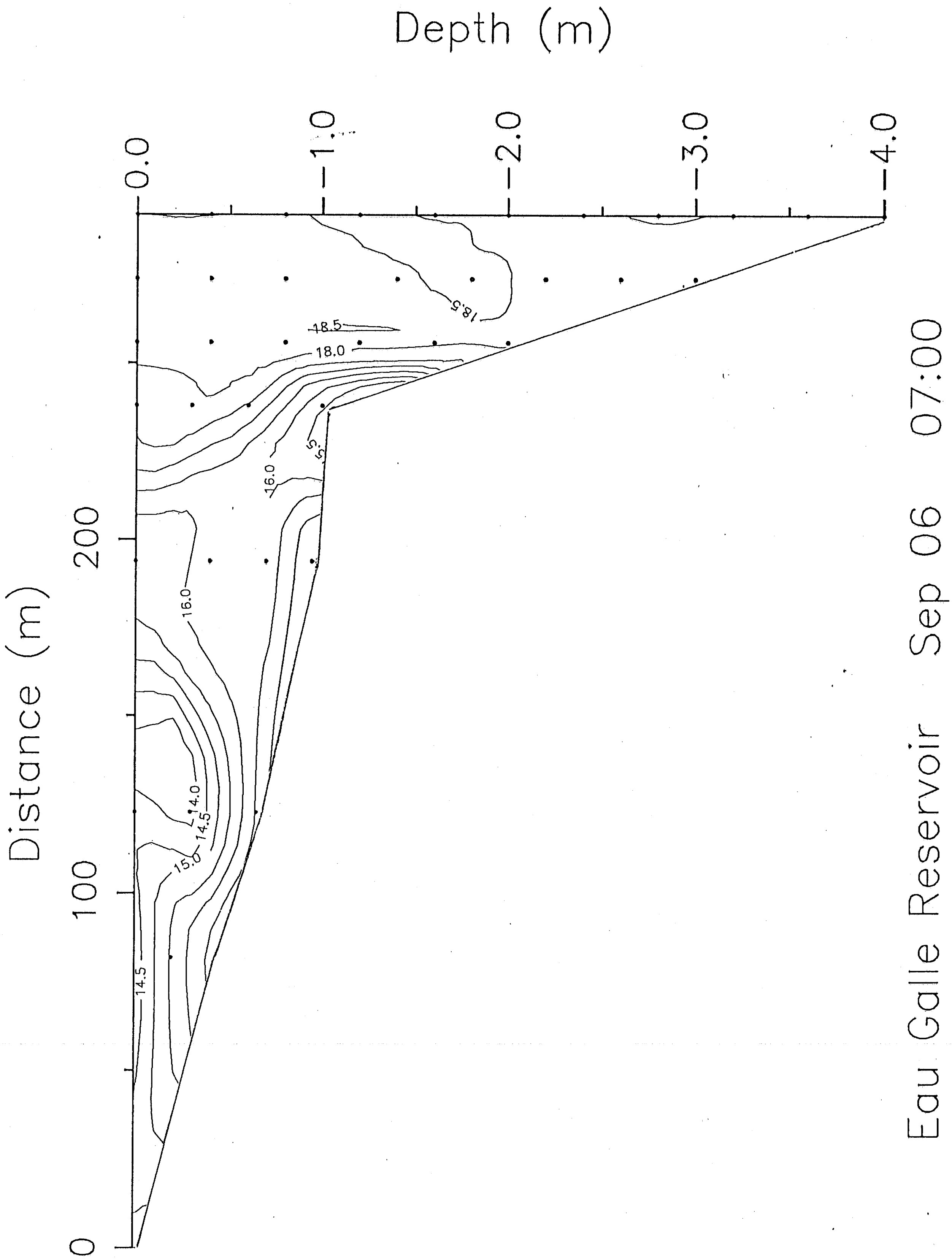
19.0
18.5
18.0
16.0
16.5
15.0
15.5
Eau Galle Reservoir Sep 06 04:00



Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
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100
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18.0
16.0
15.5
14.0
14.5
15.0
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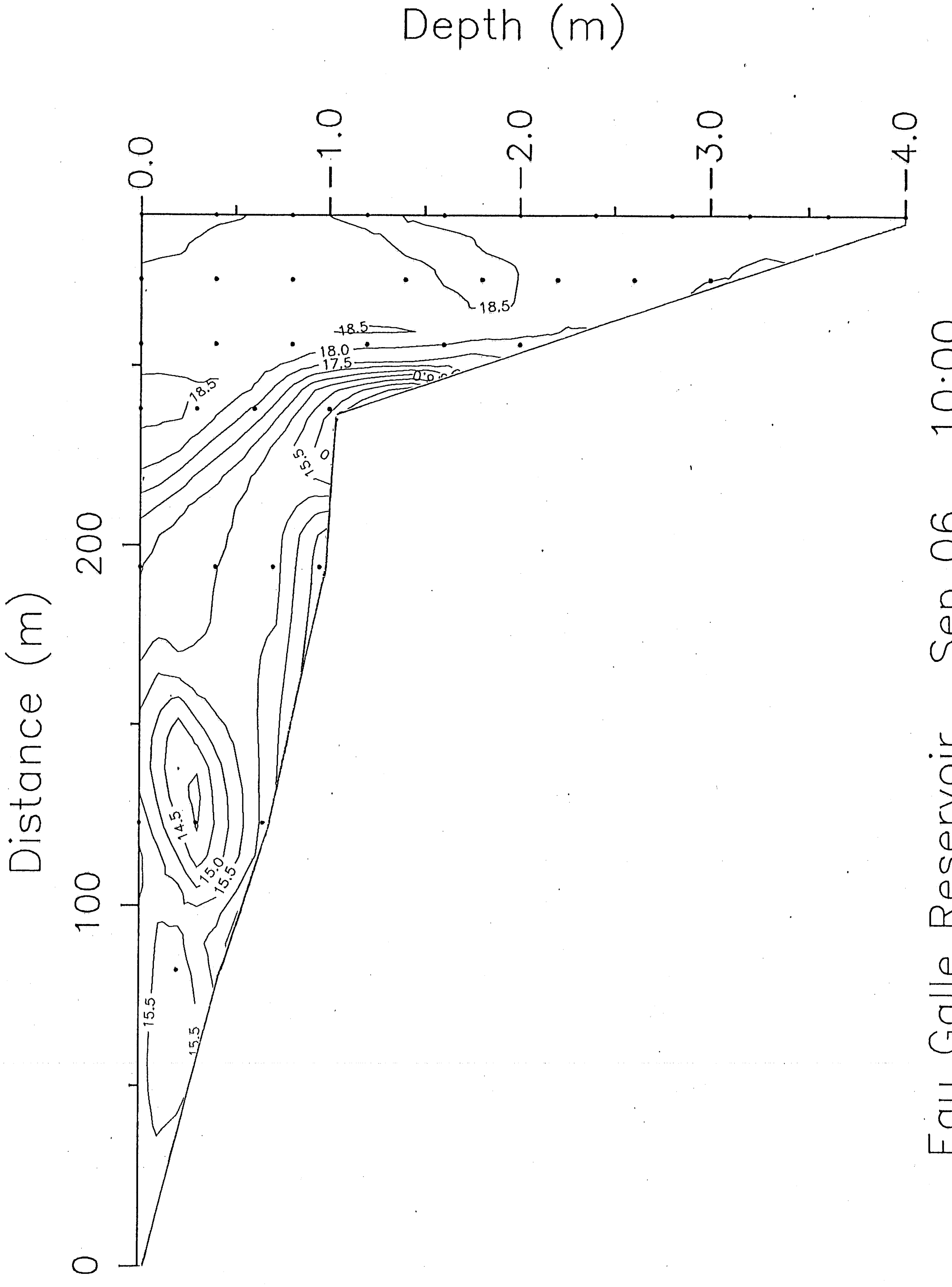
Depth (m)
0.0
-1.0
-2.0
-3.0
-4.0
Distance (m)
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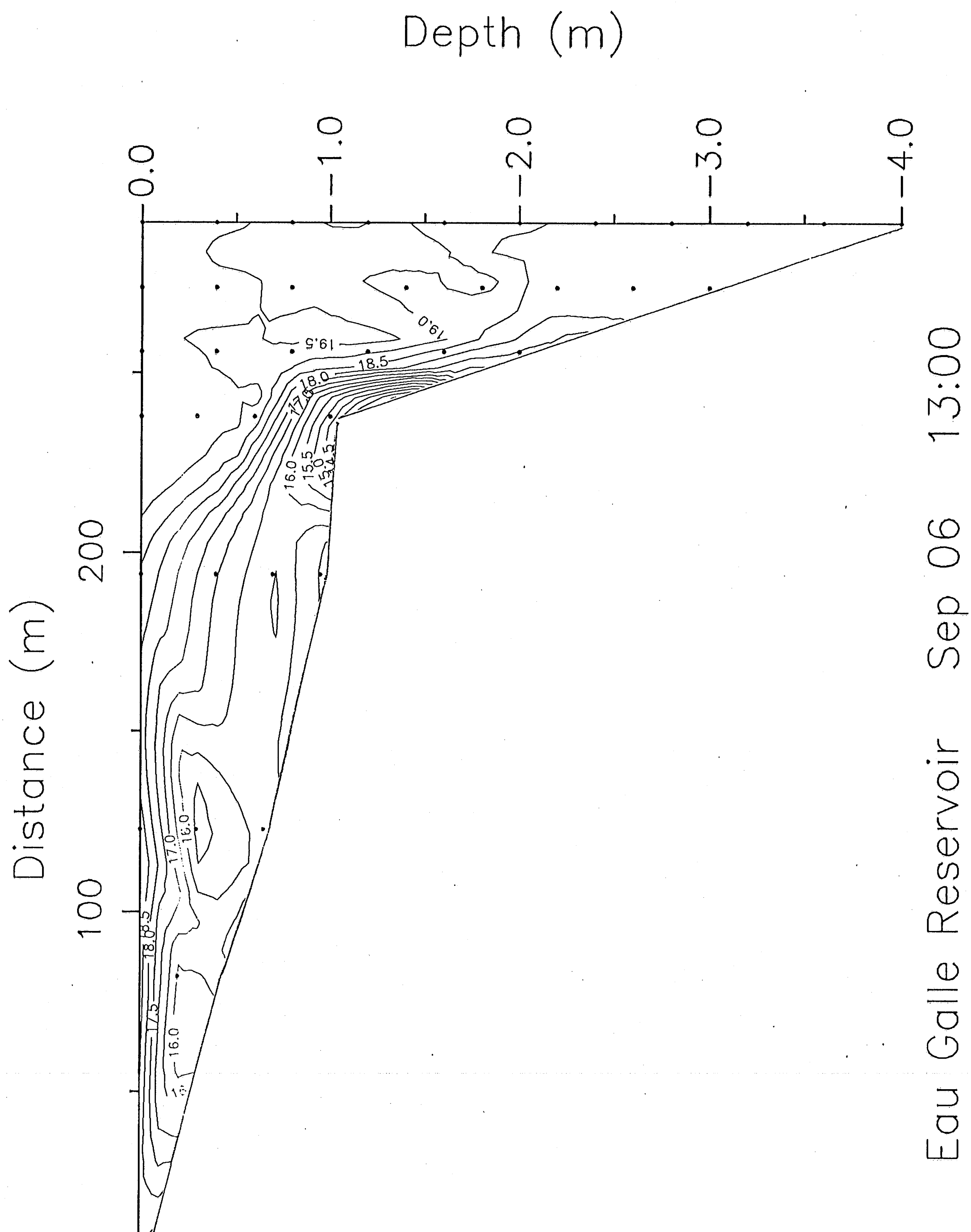
100
200
18.5
18.0
17.5
15.5
14.5
15.0
Eau Galle Reservoir Sep 06 10:00



Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
19.5
19.0
18.5
18.0
17.0
16.0
15.5
15.0
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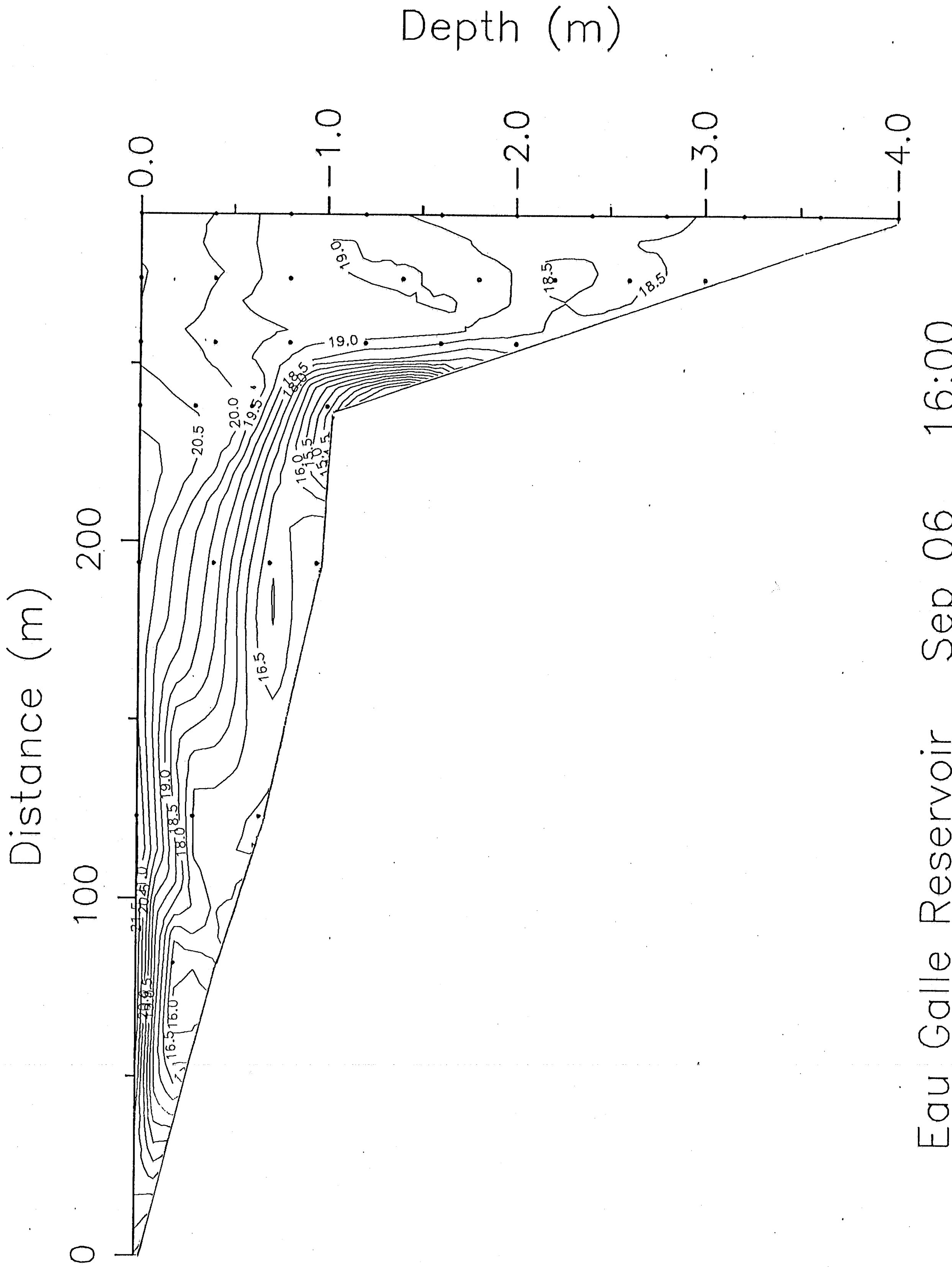
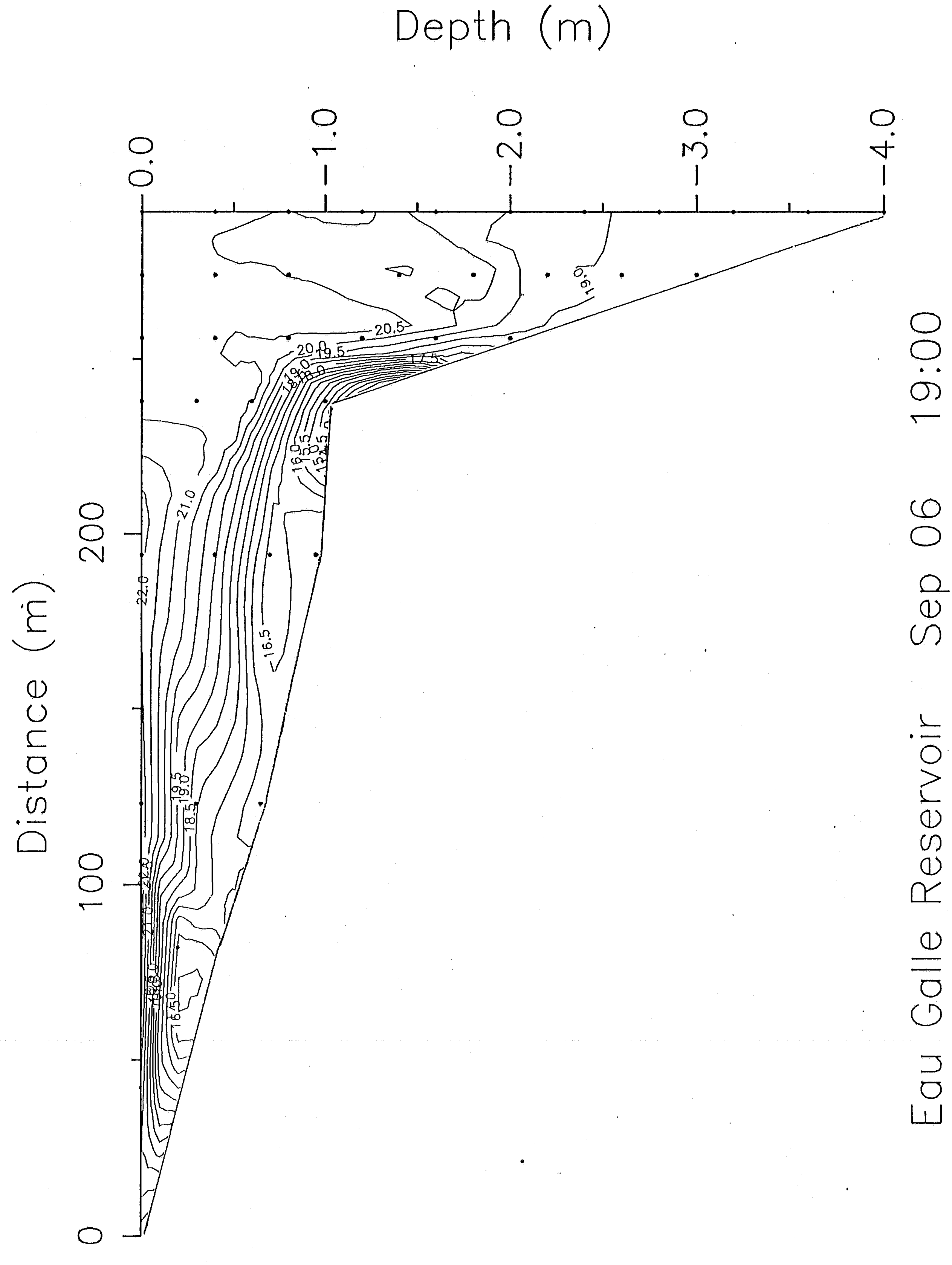
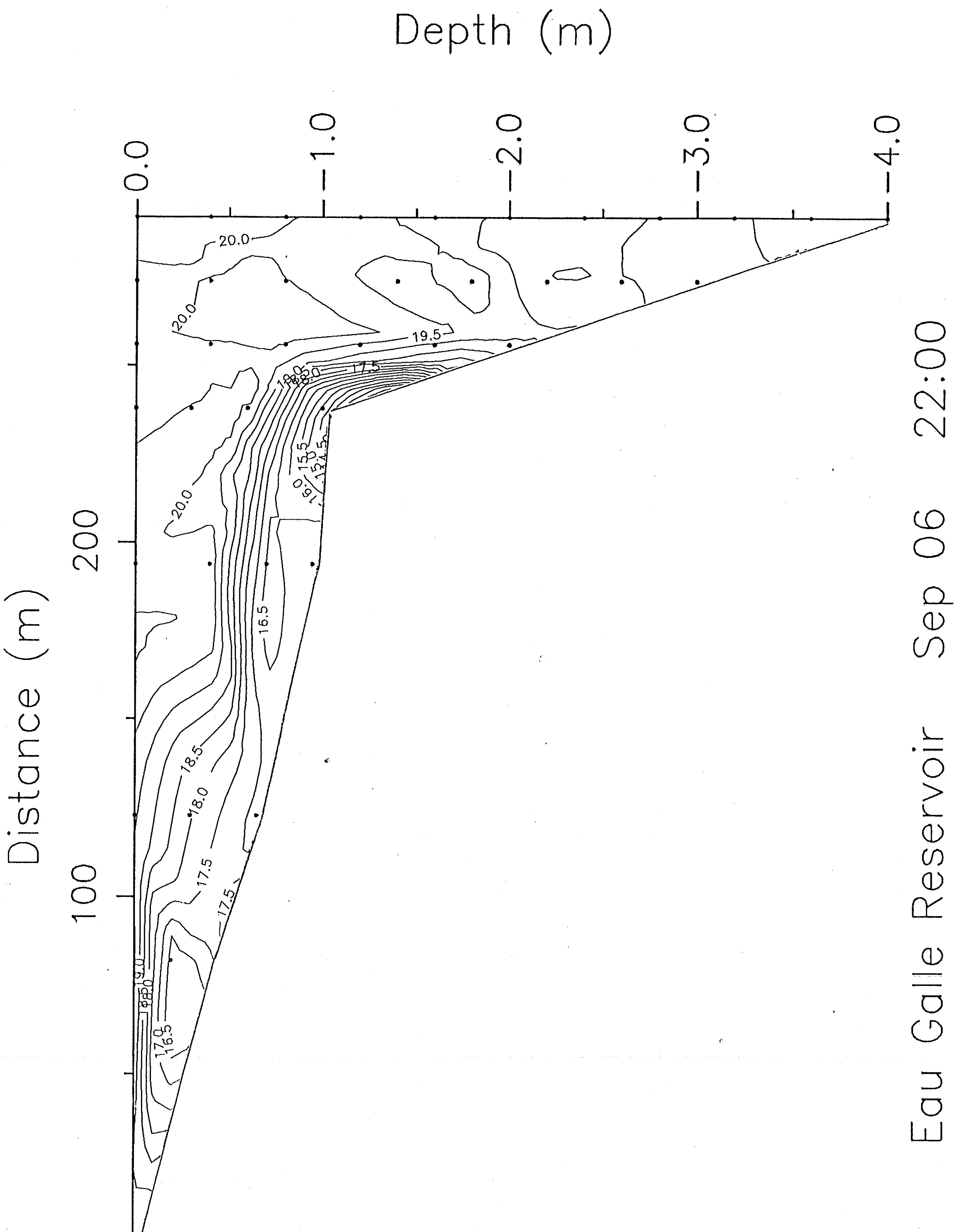
13
17.0
16.0
18.5
18.0
17.5
16.0
Eau Galle Reservoir Sep 06 13:00


Depth (m)
0.0
-1.0
-2.0
-3.0
-4.0
Distance (m)
0
100
200
19.0
18.5
20.5
20.0
19.5
16.5
16.0
18.0
Eau Galle Reservoir Sep 06 16:00



Depth (m)
0.0
-1.0
-2.0
-3.0
-4.0
Distance (m)
0
100
200
20.5
20.0
19.5
19.0
17.5
16.5
16.0
22.0
21.0
18.5
Eau Galle Reservoir Sep 06 19:00



Depth (m)
0.0
1.0
2.0
3.0
4.0
Distance (m)
0
100
200
20.0
19.5
17.5
16.5
18.5
18.0
17.0
Eau Galle Reservoir Sep 06 22:00

Appendix C

Average Temperature Differences Across the Bay Transect

TABLE C-1. Statistics of Temperature Differences (Deg. C) Between Main Stations and Satellites.

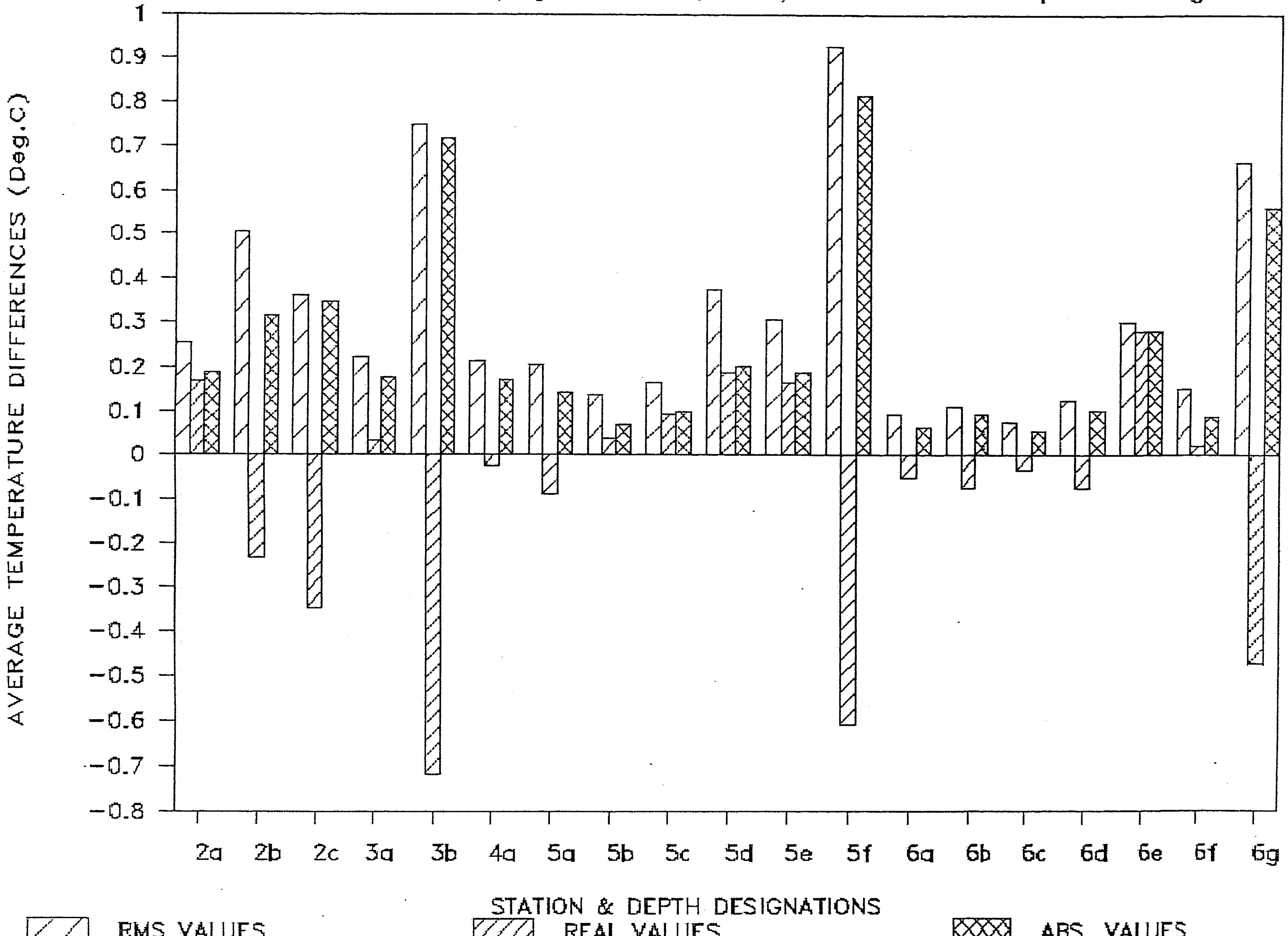
Graph # des	Station # & depth	max	rms avg	min	real values avg	real values std d	absolute values avg	absolute values std d
2a	2 @ 0.05m	0.97	0.25	0	0.17	0.19	0.19	0.17
2b	2 @ 0.30m	-2.03	0.50	0	-0.23	0.45	0.31	0.39
2c	2 @ 0.60m	-0.50	0.36	0	-0.35	0.10	0.35	0.10
3a	3 @ 0.05m	0.69	0.22	0	0.03	0.22	0.18	0.14
3b	3 @ 0.70m	-1.16	0.75	0.08	-0.72	0.22	0.72	0.22
4a	4 @ 0.05m	-0.85	0.22	0	-0.02	0.21	0.17	0.13
5a	5 @ 0.05m	1.33	0.21	0	-0.09	0.19	0.14	0.15
5b	5 @ 0.40m	1.04	0.14	0	0.04	0.13	0.07	0.12
5c	5 @ 0.80m	0.99	0.17	0	0.09	0.14	0.10	0.13
5d	5 @ 1.20m	1.38	0.38	0	0.19	0.33	0.20	0.32
5e	5 @ 1.60m	1.44	0.31	0	0.16	0.26	0.19	0.24
5f	5 @ 1.95m	-2.04	0.93	0.01	-0.61	0.70	0.82	0.44
6a	6 @ 0.05m	-0.50	0.09	0	-0.05	0.08	0.07	0.07
6b	6 @ 0.40m	0.61	0.11	0	-0.08	0.08	0.09	0.06
6c	6 @ 0.80m	0.39	0.08	0	-0.03	0.07	0.06	0.05
6d	6 @ 1.80m	0.58	0.12	0	-0.08	0.10	0.10	0.07
6e	6 @ 2.20m	1.29	0.30	0.01	0.28	0.11	0.28	0.11
6f	6 @ 2.60m	1.03	0.15	0	0.02	0.15	0.09	0.12
6g	6 @ 2.95m	-1.48	0.66	0	-0.47	0.46	0.56	0.35
5cm averages		0.33	0.20	0.00	0.01	0.18	0.15	0.13
Bottom averages*		-1.30	0.68	0.02	-0.54	0.37	0.61	0.28
Overall averages		0.17	0.31	0.01	-0.09	0.22	0.25	0.18

* Bottom positions \ St. 2 @ 0.60m, St. 3 @ 0.70m, St. 5 @ 1.95m, St. 6 @ 2.95m

NOTE: All values were calculated as station temperature minus satellite temperature. Values were computed where both thermistors were believed to be accurate.

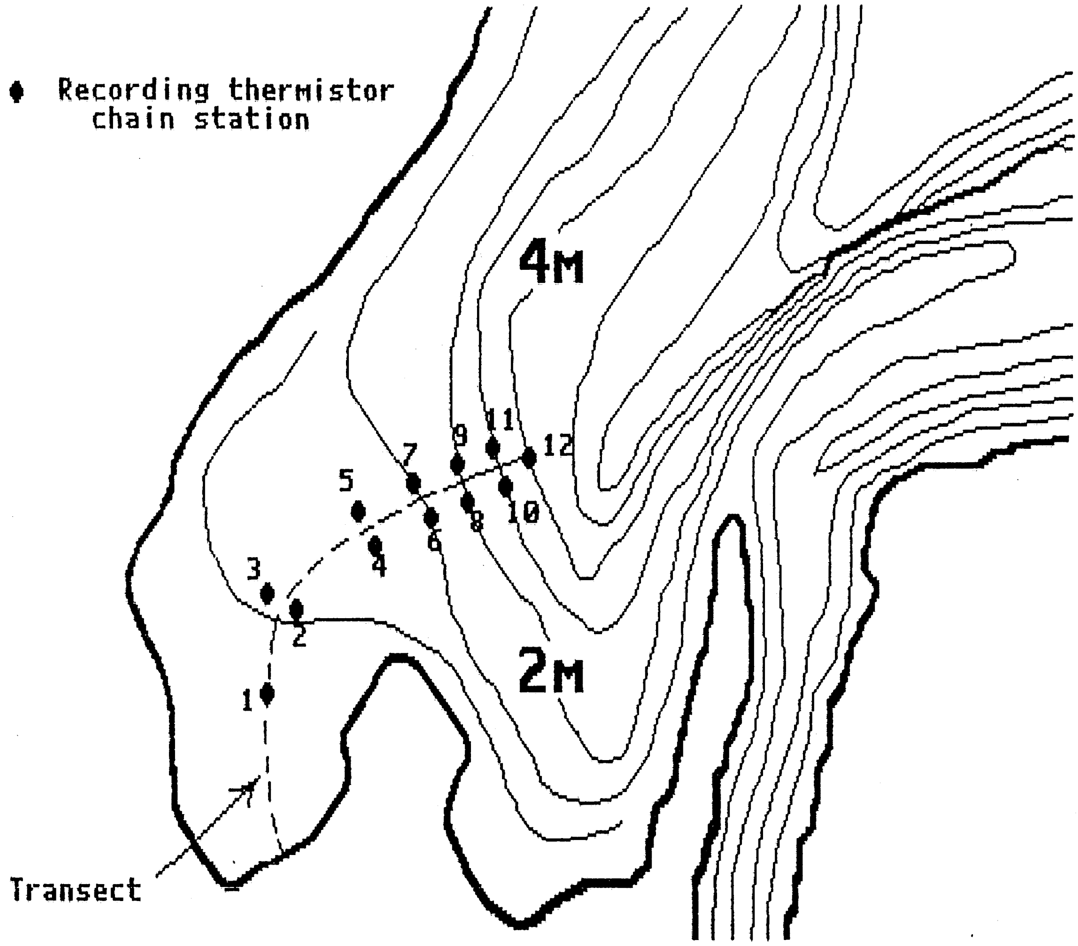
CONSTANT-WIDTH MODEL CHECK

Average temperature differences (August 10 - 12, 1989) see Table III-1 for position designations



Appendix D

Original Thermistor Station Numbering



Original Thermistor Station Numbers