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Simulations of Seasonal Water Temperature Cycles and Stratification in Large Lakes in Minnesota

by

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Abstract

The objective of this study was to obtain information on seasonal water temperature cycles and stratification in ten large lakes in Minnesota. The ten lakes are Mille Lacs Lake, Red Lake, Lake of the Woods, Leech Lake, Lake Vermilion, Lake Kabetogama, Lake Winnibigoshish, Lake Pepin, Rainy Lake and Cass Lake. The lakes have surface areas of 63 to 3846 km^2 and maximum depth from 6 m to 49 m. To do this study, a one-dimensional unsteady, year-round process-oriented model was used. Previous applications and validations of the model had been for lakes of up to 30 km^2 surface area. The lakes studied herein had surface areas up to 3800 km^2. Since the difference is substantial, it was of interest to make comparisons with data from the large lakes. Before the MINLAKE 96 model was applied, the model formulations and assumptions were reviewed briefly.

Daily weather data (1982-1990) from four weather stations (International Falls, Fargo, Duluth and St. Cloud) were used as input for the simulations.

All lakes were simulated for the period from 1983 to 1990 except Mille Lacs Lake which was simulated from 1980 to 1990 in order to compare the simulation results with field data in 1981.

Results were presented as isotherms, weekly averaged time series and yearly averaged time series. Ice and snow information, including time series for ice and snow thickness, were also presented. The values for some parameters, e.g. maximum and minimum surface water temperatures, maximum and minimum bottom water temperatures, maximum temperature difference between lake surface and bottom, open water stratification ratio, duration of low bottom temperature, the earliest and latest ice-on and ice-off dates, ice cover duration, maximum ice thickness and average snow depth, were also extracted from the simulation results.

Temperature stratification patterns vary from lake to lake, strongly dependent upon lake morphometry. Shallow lakes such as Red Lake and Mille Lacs Lake are usually well mixed during the open water season. Deep lakes like Rainy Lake and Cass Lake are strongly stratified. Standard errors between simulated and measured water temperatures ranged from 0.74°C to 2.38 °C, and the slopes of regressions ranged from 0.95 to 1.11.

Acknowledgments

The investigation described herein was conducted for the Minnesota Department of Natural Resources. Some measured data were provided by Nancy M. Flandrick, Minnesota Pollution Control Agency. Others were provided by Don Pereira, Senior Fisheries Biologist, and staff of the Minnesota Department of Natural Resources. The work was partially supported by the U.S. Environmental Protection Agency, Office of Research and Development, Washington D.C.. Barbara M. Levinson was project officer.

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1. Introduction

The importance of temperature as a controlling variable at all levels of ecological systems is well known (Christie et al., 1988). Temperature is one of the most significant factors to determine, for example, where fish can live and thrive. Most of the time, fish will select to inhabit temperatures near their growth optimum, pending other conditions being favorable (food, dissolved oxygen, etc.). Each species has a temperature tolerance range (Eaton et al., 1995). If water temperatures are in excess of this range, fish will not survive. In temperature stratified lakes, fish are forced to find water layers where their requirements are met. It is also known that temperature is a major controlling factor affecting the growth rate of fishes. Different species of fish have different optimum temperature for growth. This means that the pattern of environmental temperature in lakes affects the production and yield of individual species populations. Therefore, correctly simulating temperature structures in lakes is important for estimating optimal thermal habitat and yields for fish species.

The purpose of this study is to simulate seasonal water temperature cycles and stratification in ten large lakes in Minnesota, excluding Lake Superior. The simulations are made to supplement sparse field measurements of lake water temperatures. Measured or simulated water temperatures are needed to estimate thermal habitat and fish yield. The simulations have been requested by the Minnesota Department of Natural Resources.

The simulations also fulfill two other purposes. One is to extend the application of the MINLAKE 96 model to lakes of surface areas considerably larger than 30 km^2 (the upper limit of most previous applications). This includes comparisons of simulation results with whatever measurements are available.

The other purpose is to generate baseline information on the thermal regime of the largest Minnesota lakes under past climate conditions for comparison with projected warmer climate scenarios.. The thermal regime of a lake is characterized by extracting from the simulation results maximum and minimum water temperatures in different seasons; strength and duration of stratification; onset, duration, and thickness of ice covers; and other parameters.

Simulated water temperature information for ten large Minnesota lakes will be presented.

2. Bathymetric Characteristics of Large Minnesota Lakes

The ten large lakes simulated in Minnesota are Mille Lacs lake, Cass Lake, Leech Lake, Lake Kabetogama, Red Lake (Upper Red Lake and Lower Red Lake), Lake of the Woods, Rainy Lake, Lake Vermilion, Lake Winnibigoshishi and Lake Pepin. All the lakes are in northern Minnesota with the exception of Mille Lacs Lake and Lake Pepin. The locations of the ten lakes are given in Fig. 2.1. The lake surface areas range from 63 km^2 to 3846 km^2 and the maximum depth from 6.1 m to 49.1 m. Some lakes have only one basin (e.g. Mille Lacs Lake) and others may have several basins (e.g. Cass Lake). Some have large shoreline development (SLD, the ratio of the actual length of the shoreline to the length of the circumference of a circle with an area equal to that of the lake). The morphormetries of large Minnesota lakes vary widely. Table 2.2 gives the surface areas, maximum depths, weather stations from which meteorological data came, and the lake geometry ratio $A^{0.25}/H_{max}$ which can be used to determine whether a lake will be strongly stratified or not in summer (Gorham and Boyce, 1989). Appendix A shows the bathymetric maps of some of the ten lakes. Unfortunately, bathymetric maps for some of large lakes are hard to come by. For those lakes without bathymetric maps the depth-area relationships had to be specified in accordance with the data available for 122 other lakes (Osgood, 1990). The following equation was fitted to the data (Hondzo and Stefan, 1992):

$$\frac{A(z)}{A_s} = a\exp\left(b\frac{z}{H_{max}}\right) + c \tag{2.1}$$

$A(z)$ = horizontal area at depth z below the water surface

A_s = lake surface area

H_{max} = maximum depth

Coefficients a, b, c were obtained by regression analysis and averages are given in Table 2.1 (Hondzo and Stefan, 1992). A circular surface area was used for all lakes without bathymetric maps for the purpose of wind fetch calculation.

Table 2.1 Morphometric regression coefficients (Honzo and Stefan, 1992)

Lake Surface Area (km^2)	a	b	c
Small (A_s<0.4)	1.19	-1.76	-0.20
Medium (0.4<A_s<5)	1.14	-2.10	-0.15
Large (A_s>5)	1.14	-2.91	-0.08

z_{ir} = ice thickness reduction rates due to rainfall, m/day

z_{sm} = ice growth rate due to refreezing of snowmelt water, m/day

z_{iw} = ice growth rate due to refreezing of water coming through cracks in the ice cover, m/day

Heat flux between water and sediments is also simulated in MINLAKE 96. To determine the heat flux the following one-dimensional unsteady heat-conduction equation is employed

$$\frac{\partial T_s}{\partial t} = K_s \frac{\partial^2 T_s}{\partial z^2} \qquad (3.5)$$

where

T_s = sediment temperature

K_s = heat diffusion coefficient in the sediment

The equation is solved by an implicit finite difference scheme and applying the following boundary conditions:

$$T_s = T_w(i) \quad \text{at the lake bottom} \qquad (3.6a)$$

$$\frac{\partial T_s}{\partial z} = 0 \quad \text{at 10 m below the lake bottom} \qquad (3.6b)$$

The vertical heat diffusion coefficient, K_z, in open water seasons is determined from the following equation (Hondzo and Stefan, 1992)

$$K_z = 8.17 \times 10^{-4} A_s^{0.56} (N^2)^{-0.43} \qquad (3.7)$$

where

K_z = vertical heat diffusion coefficient, cm^2/s

A_s = lake surface area, km^2

N = stability frequency, $N^2 = \frac{g}{\rho}\frac{\partial \rho}{\partial z}$

ρ = density of water, kg/m^3

The vertical heat diffusion coefficient K_z below the ice-cover of a lake is given by Ellis and Stefan (1990; 1994) as

$$K_z = 8.98 \times 10^{-4} \, (N^2)^{-0.43} \qquad (3.8)$$

Ellis and Stefan specified the vertical heat diffusion coefficient near the lake bottom ($z_s \leq 3$ m) as

$$K_z = 100 \, |H_{sed}| \, (\rho c_p C_{w1})^{-1} \, (z_s + C_{w2}) \qquad (3.9)$$

where

H_{sed} = heat flux from the sediment to the water, kcal m^{-2} day^{-1}

z_s = distance from the sediment-water interface, m

C_{w1} = coefficients equal to 0.623°C

C_{w2} = coefficients equal to 0.65 m

This equation is limited to $z_s \leq 3$ m above the sediment-water interface.

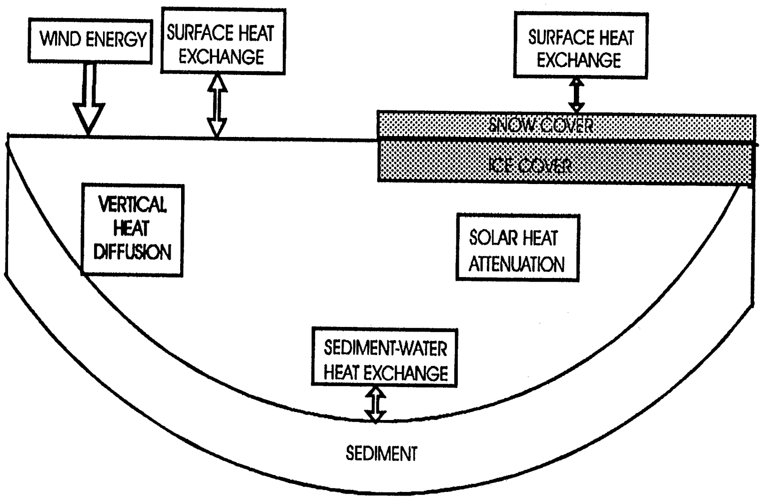


Fig. 3.1 Heat transfer processes represented in MINLAKE 96

4. Weather Data Input

The most important factor influencing water temperatures in a lake in summer is meteorological forcing. Success of the water temperature simulation depends strongly on the representation of the meteorological data. Unfortunately on-site meteorological data usually are not available, and off site data have to be used.

Weather data used as model input for this study were obtained from the Solar And Meteorological Surface Observation Network (SAMSON) for the years 1961-1990, compiled by the National Climatic Data Center. Five weather stations in Minnesota (Minneapolis, Duluth, International Falls, Rochester and Saint Cloud) and one in North Dakota (Fargo) were used in this study. Fig 4.1 shows the locations of the six stations. The weather station used for a specific lake can be found in Table 2.2.

The meteorological data needed in MINLAKE 96 are the daily values of air temperature, dew point temperature, precipitation, wind speed, percent sunshine and solar radiation. Figs. 4.2a and 4.2b show 8-year averages of daily weather parameters from Fargo and International Falls and their standard deviations.

The choice of weather station was mainly determined by the distance from the lake to the weather station. The station nearest the lake was used for simulation. If the lake was located approximately midway between two stations, simulations with data from both stations were made, and the one giving the smallest standard error between simulation results and field data was retained.

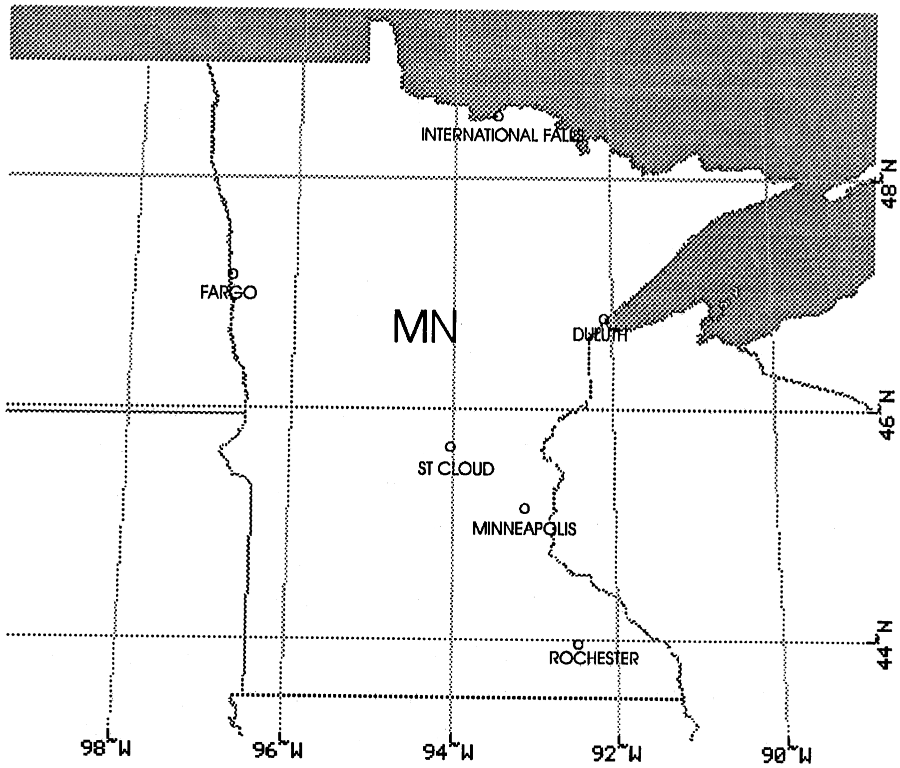


Fig 4.1 Distribution of weather stations used

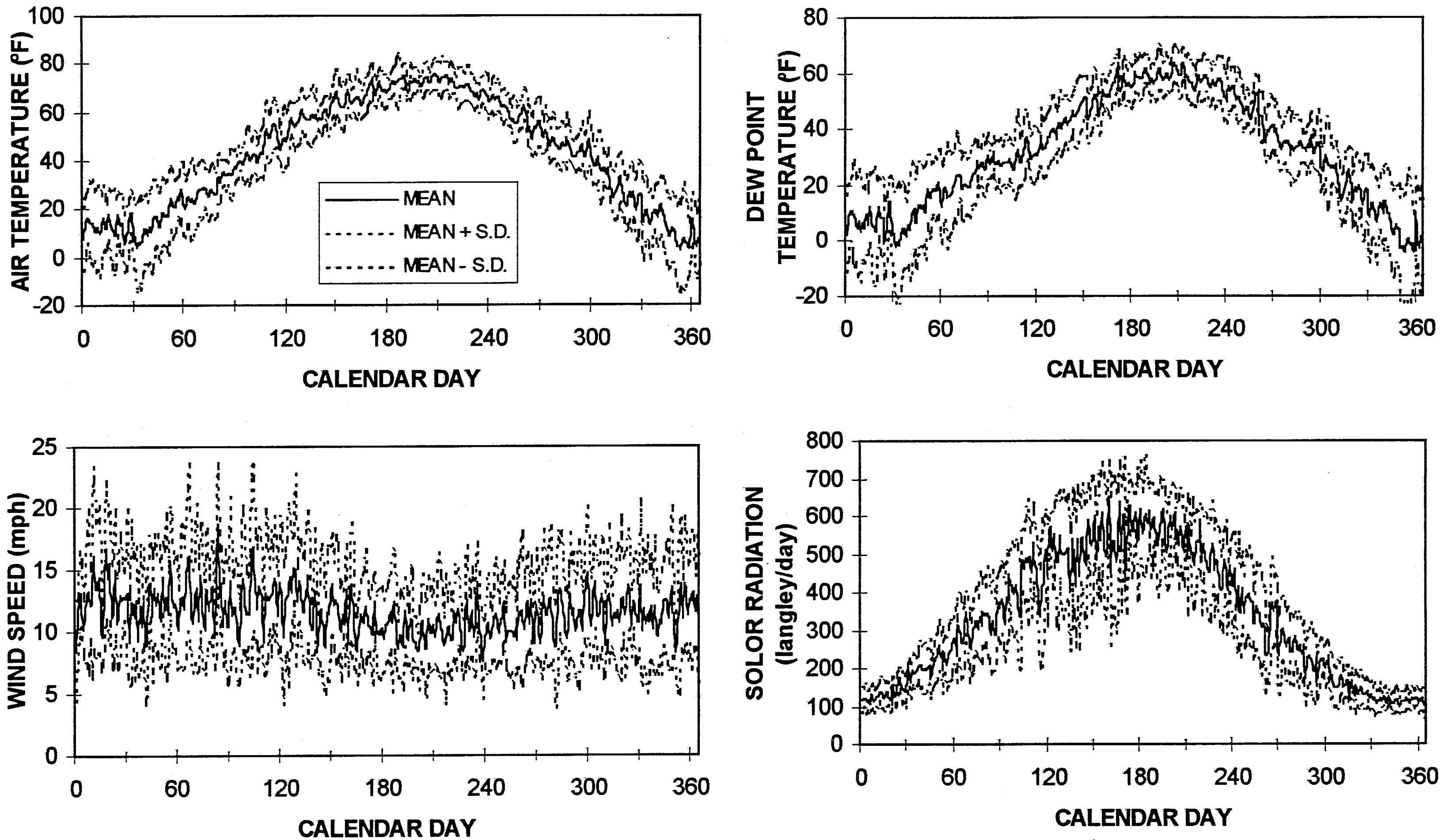


Fig 4.2a Average (1983-1990) daily values plus/minus standard deviations of air temperature, dew point temperature, wind speed and solar radiation at Fargo, ND

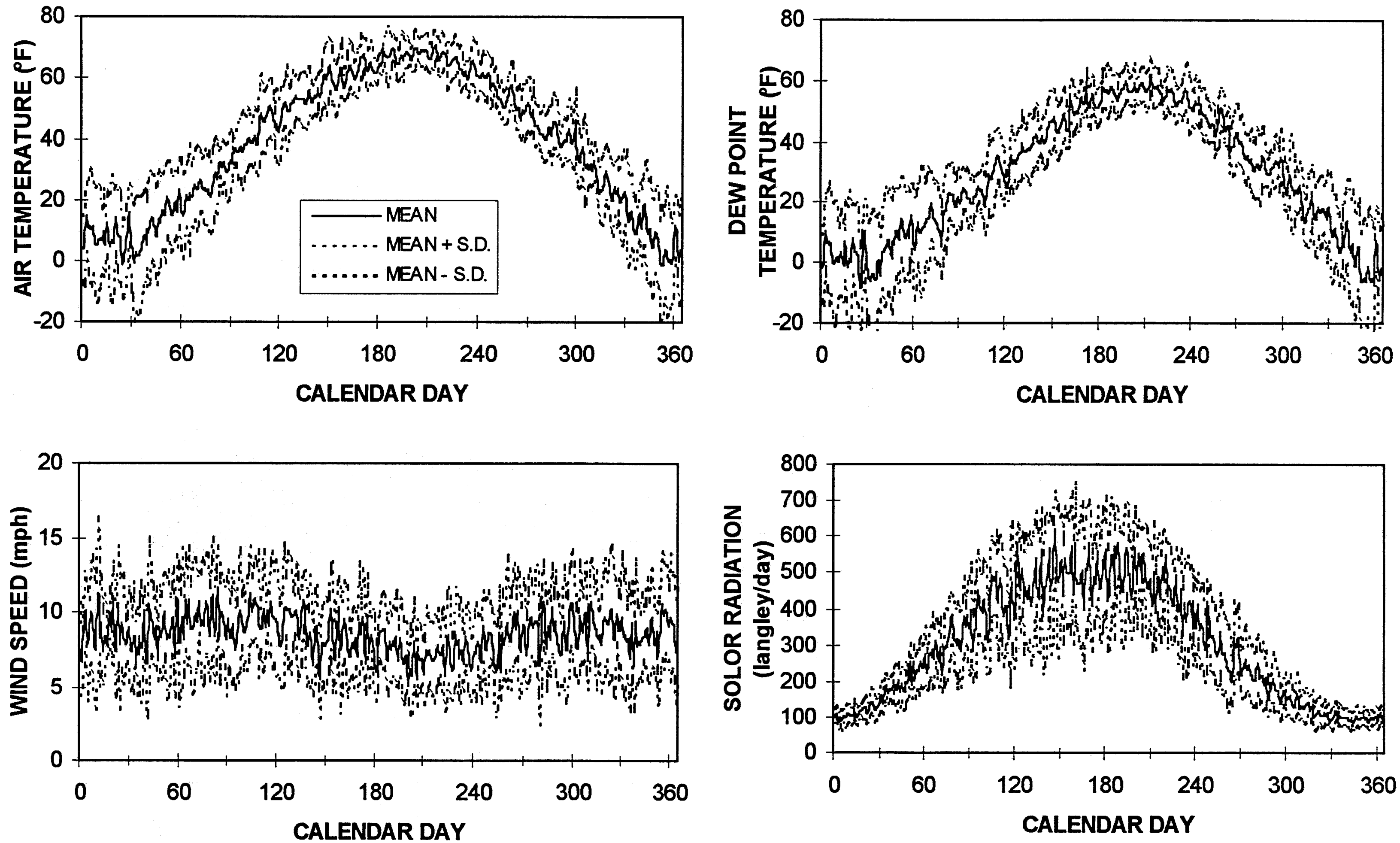


Fig 4.2b Average (1983-1990) daily values plus/minus standard deviations of air temperature, dew point temperature, wind speed and solar radiation at International Falls, MN

5. Simulation Results

5.1 *Mille Lacs Lake*

Mille Lacs Lake is located in central Minnesota. It has a surface area of 536.3 km^2 and a maximum depth of 11.3m. A bathymetric map of the lake is given in Appendix A. Horizontal lake area versus depth is given in Fig. 5.1.1. Meteorological data from Duluth were used in the simulations because meteorological data from St. Cloud provided a less good fit to measurements.

The lake was simulated for the period from 1980 to 1990. Simulated water temperatures were compared with 12 days of field measurements from 1981 and 1990. Field data were from the EPA STORET database. Standard error, slope of regression and R^2 were 0.95°C, 0.99 and 0.92, respectively. Some measured and simulated water temperature profiles are shown in Fig 5.1.2.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.1.3 for 1990. Mille Lacs Lake is well mixed during open water seasons. For other years the plots are very similar.

Surface water temperatures (at 1m depth), bottom temperatures (1 m above deepest point) and field data from 1981, 1990 and 1994 are shown in Fig. 5.1 4 and 5.1.5, respectively. Fig. 5.1.6 and Fig. 5.1.7 show the field data and the average values and plus/minus one standard deviation of surface temperatures (at 1 m depth) and bottom temperatures (1 m above deepest point). The variability in daily surface water temperatures from year to year is pronounced because of weather conditions. However, mean annual surface water temperatures and standard deviations of daily surface water temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.1.8). The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.1.9 for year 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.1.1 gives the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in late November and the ice-out date in late April. Average values and standard deviations will be shown in Section 6 (Table 6.4). Fig 5.1.10 shows the variability in ice thicknesses and snow depths from 1983 to 1990.

Table 5.1.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Mille Lacs Lake from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/27	04/17	04/19	04/16	04/09	04/22	05/07	04/25
Ice-in date	11/26	11/17	11/20	11/12	11/25	11/18	11/18	11/27
Ice cover duration (days)	152	150	150	155	135	156	165	149
Max. ice thickness (m)	0.63	0.70	0.79	0.68	0.70	0.72	0.72	0.87
Date of max. thickness	03/29	03/23	03/08	03/26	03/03	03/22	4/01	3/08

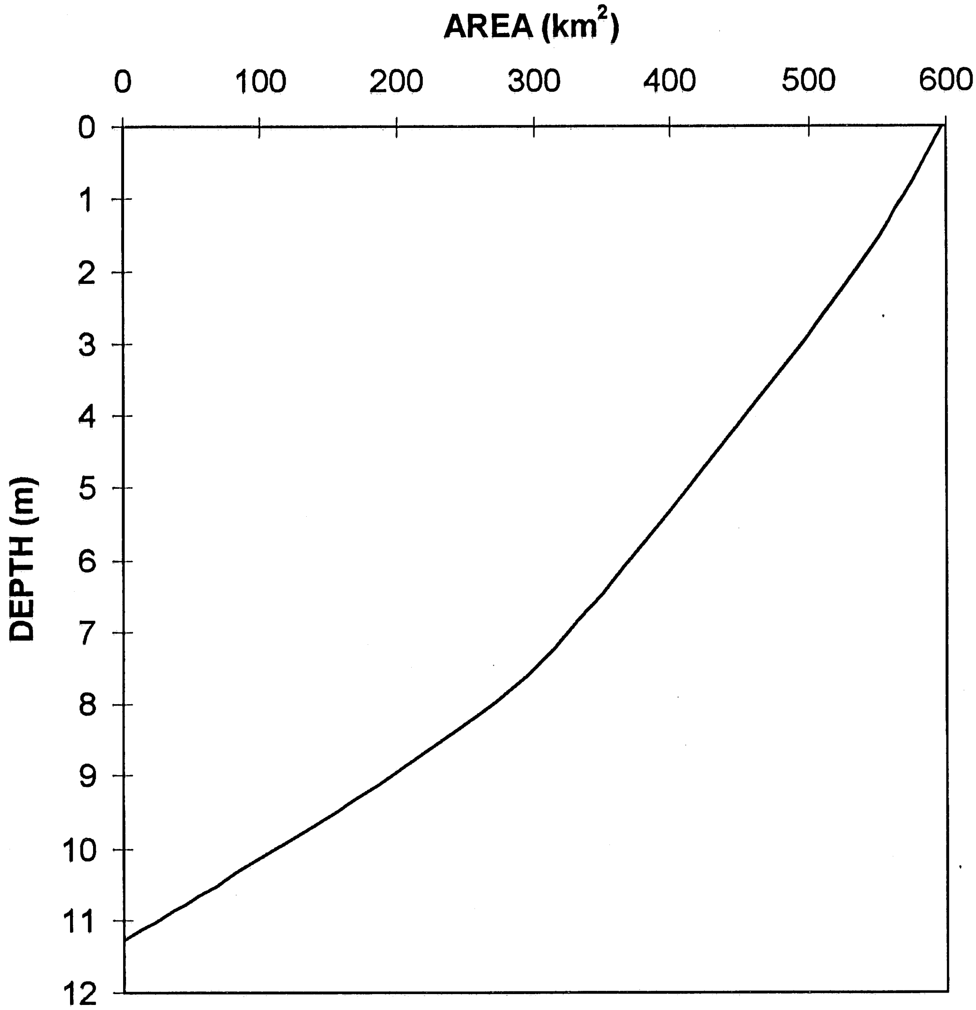


Fig 5.1.1 Horizontal area vs. depth for Mille Lacs Lake

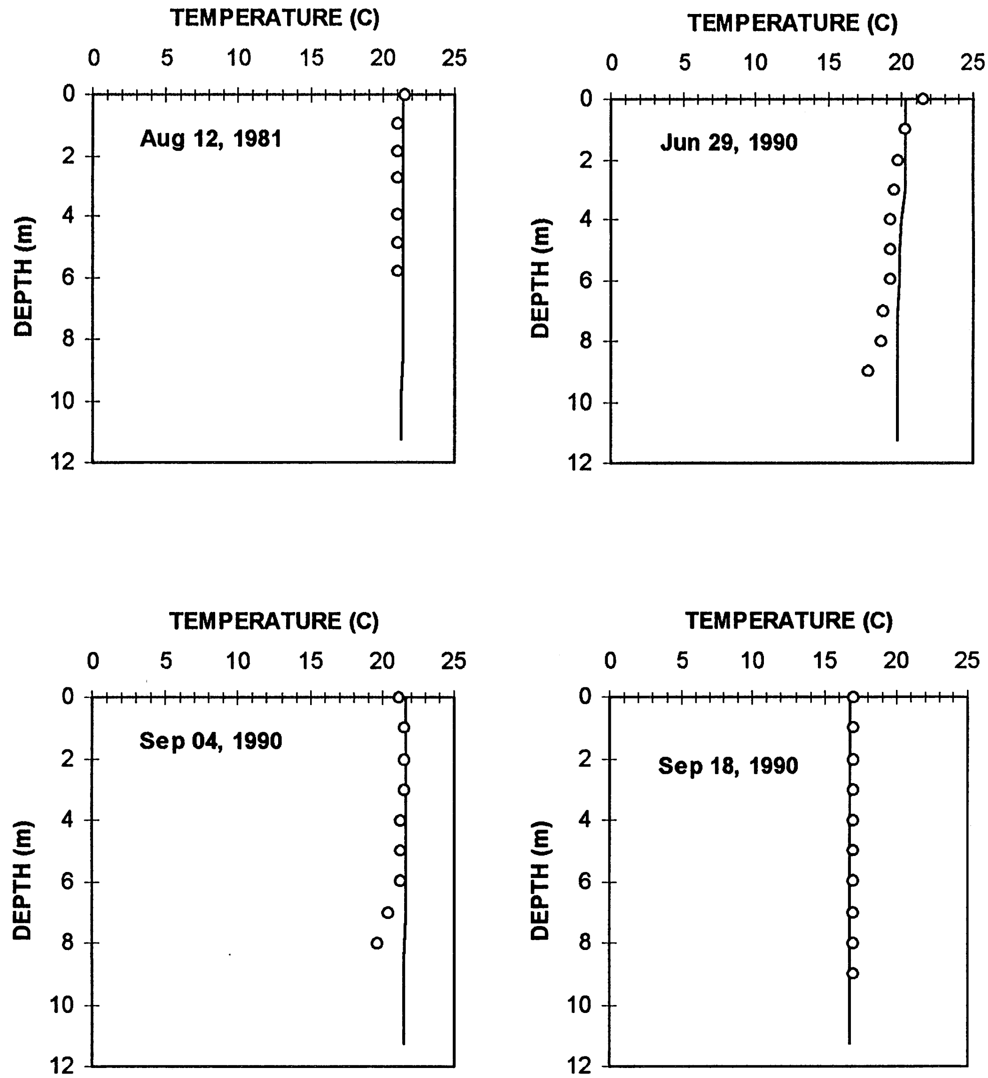


Fig 5.1.2 Some measured and simulated temperature profiles for Mille Lacs Lake

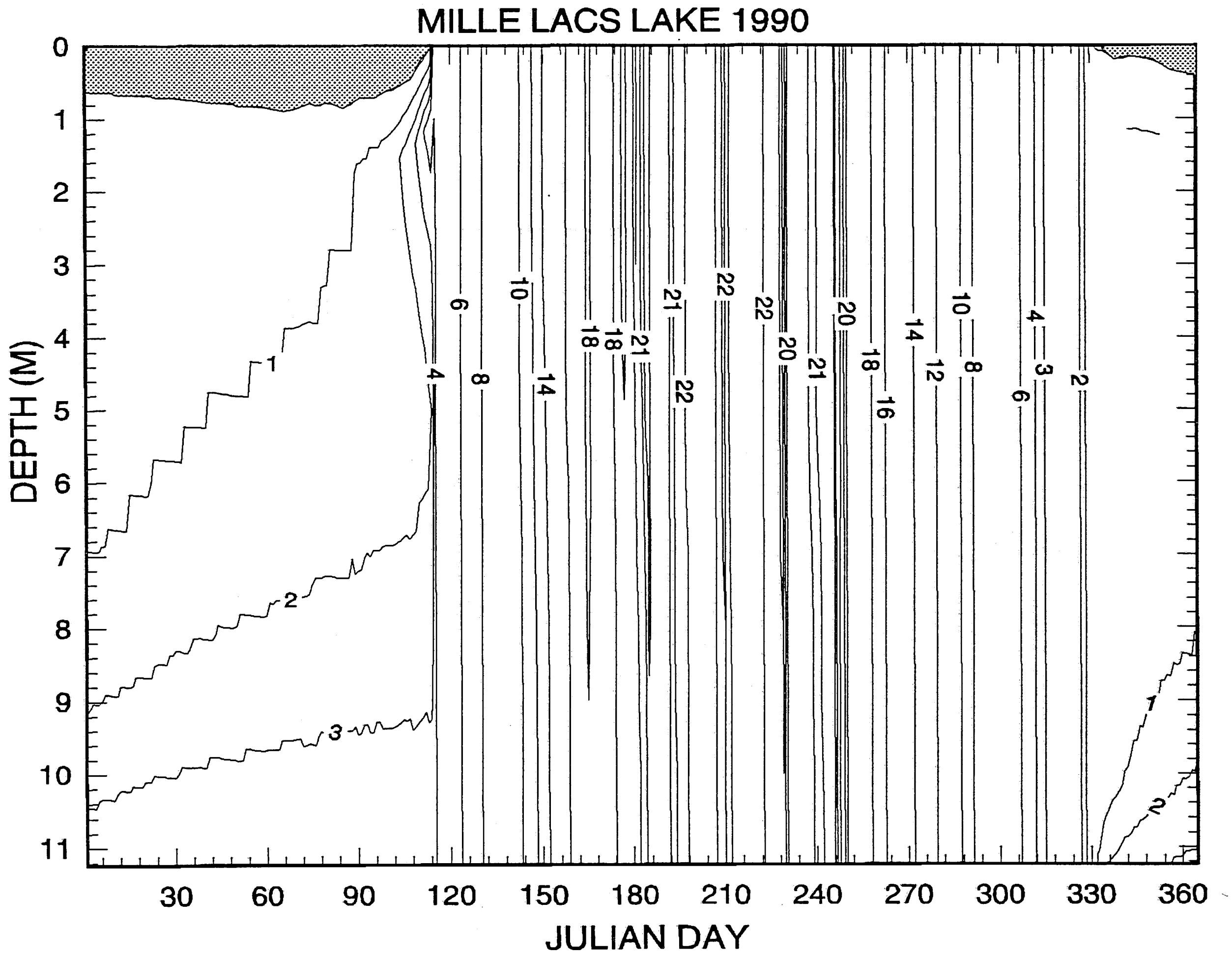


Fig 5.1.3 Isotherms (1990) interpolated from simulated daily water temperature profiles for Mille Lacs Lake

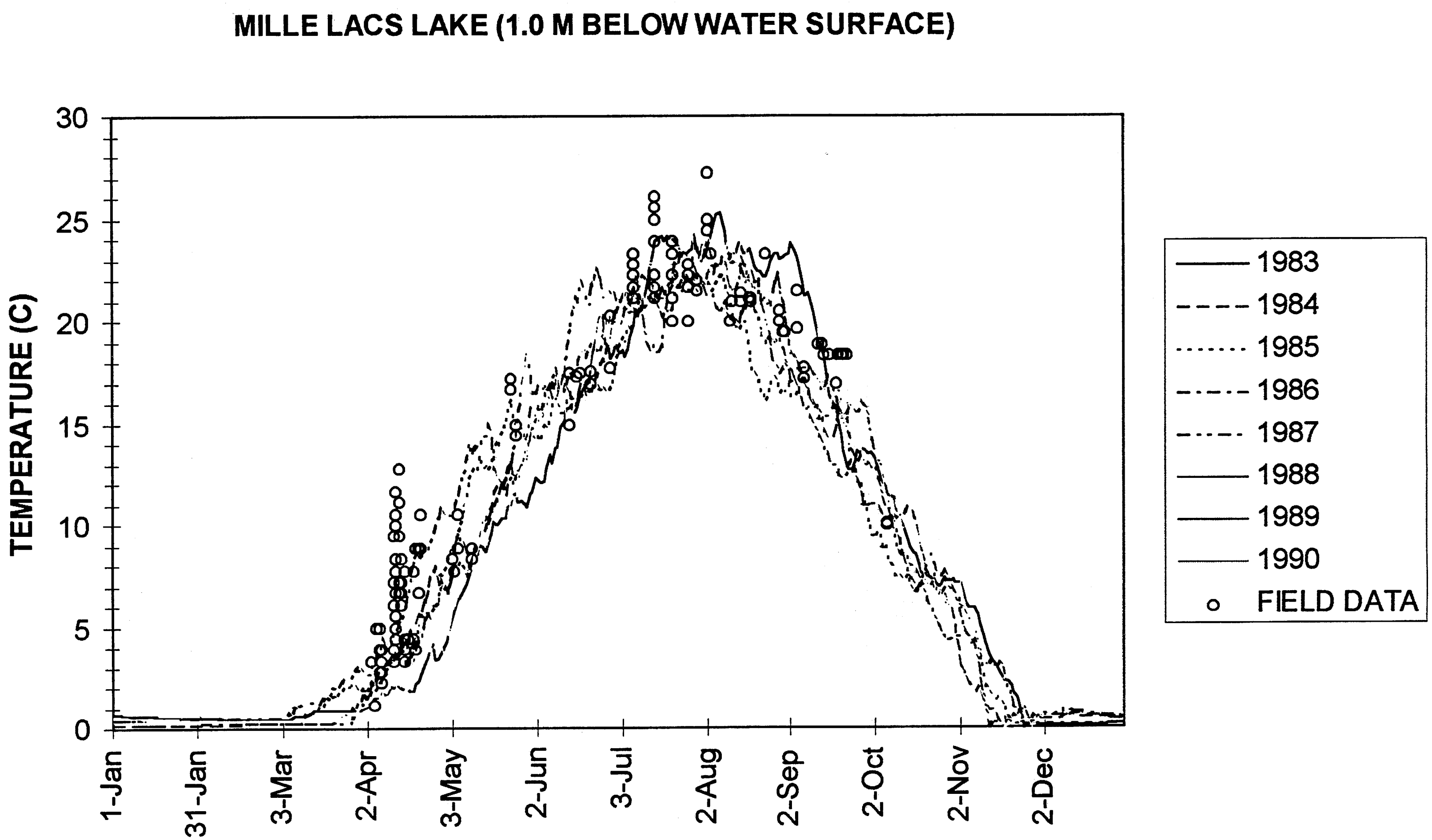


Fig 5.1.4 Simulated and measured water temperatures 1 m below the water surface of Mille Lacs Lake

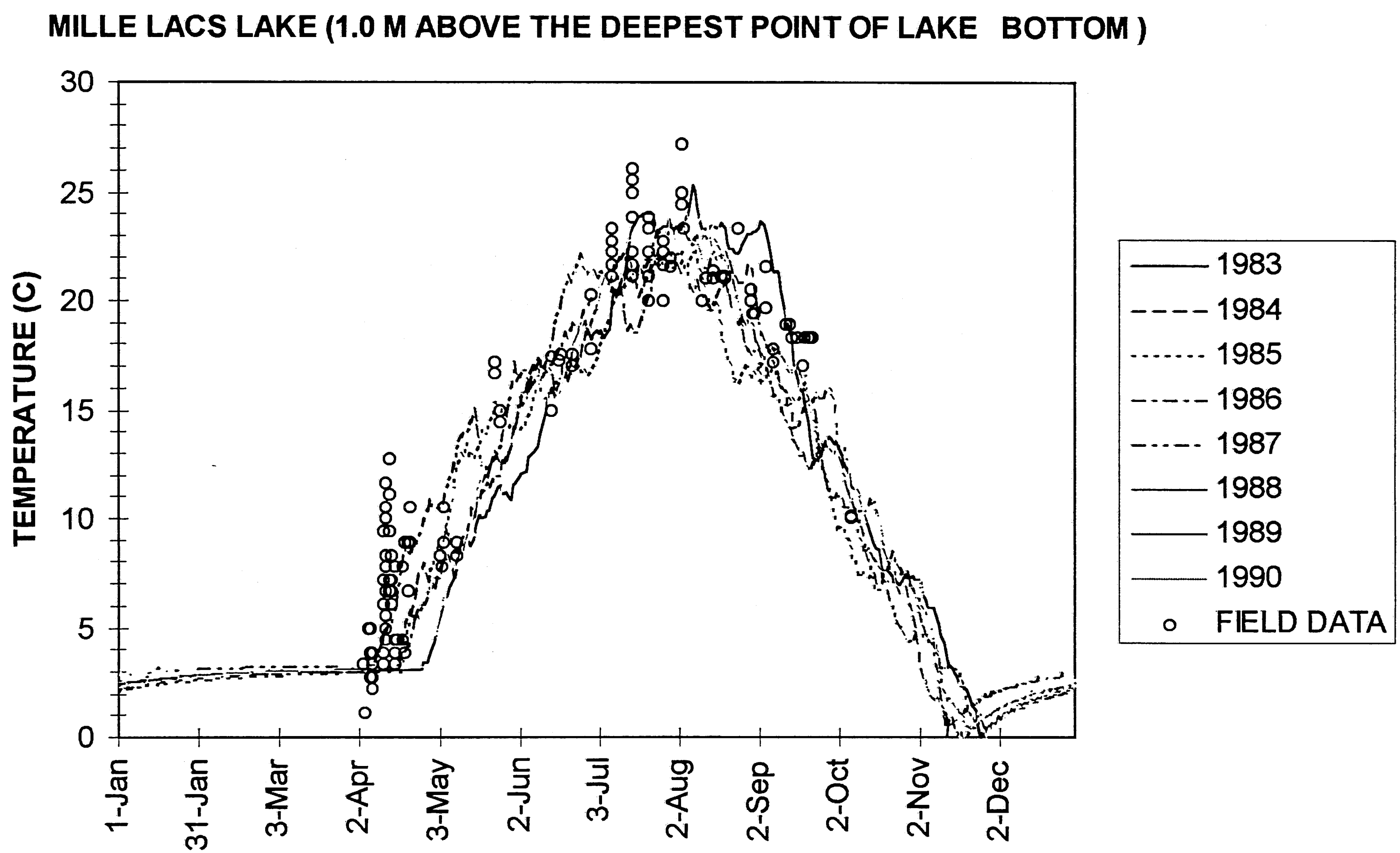


Fig 5.1.5 Water temperature 1 m above the deepest point of Mille Lacs Lake

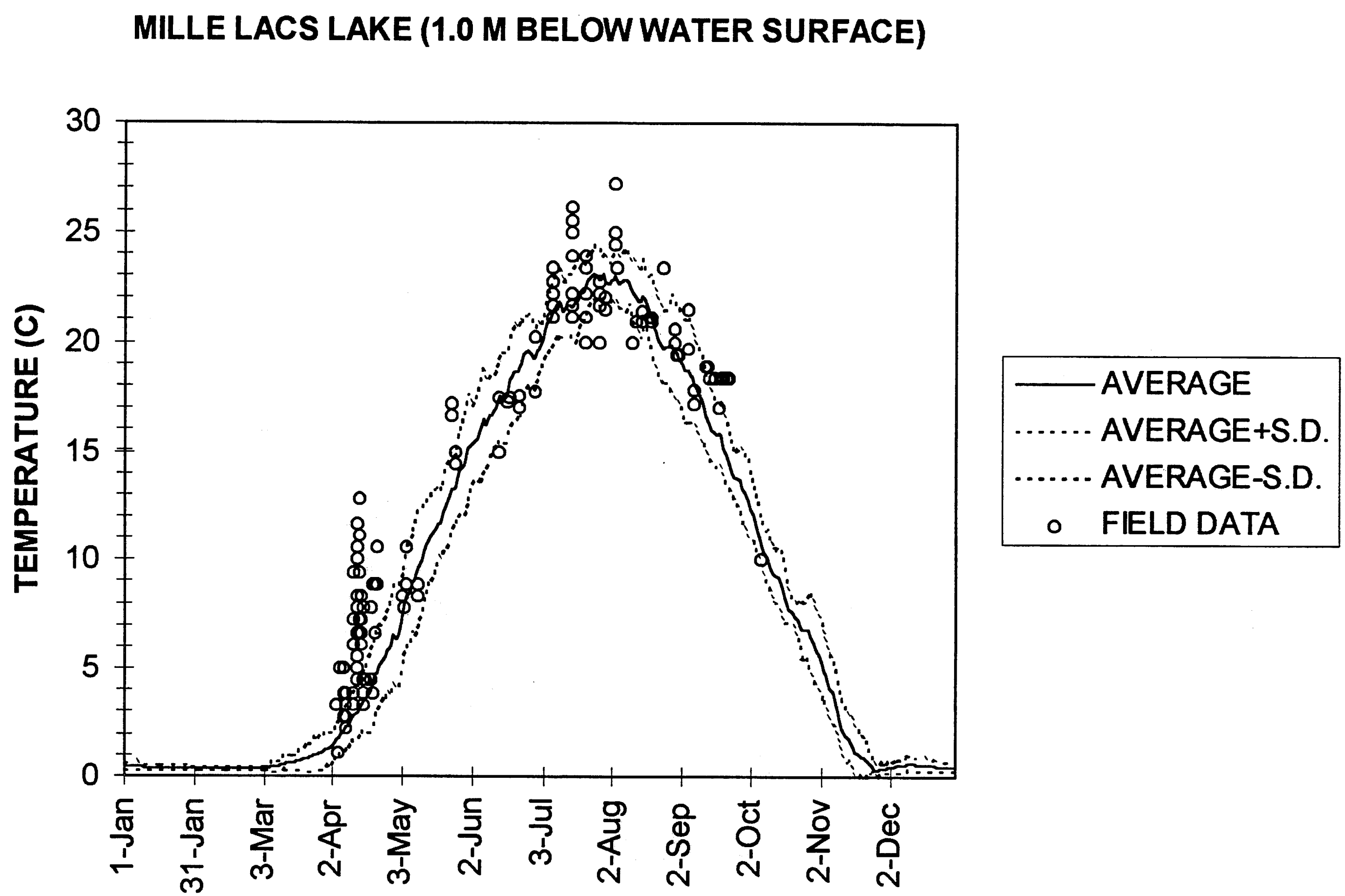


Fig 5.1.6 Average water temperatures plus/minus standard deviation 1 m below the water surface of Mille Lacs Lake

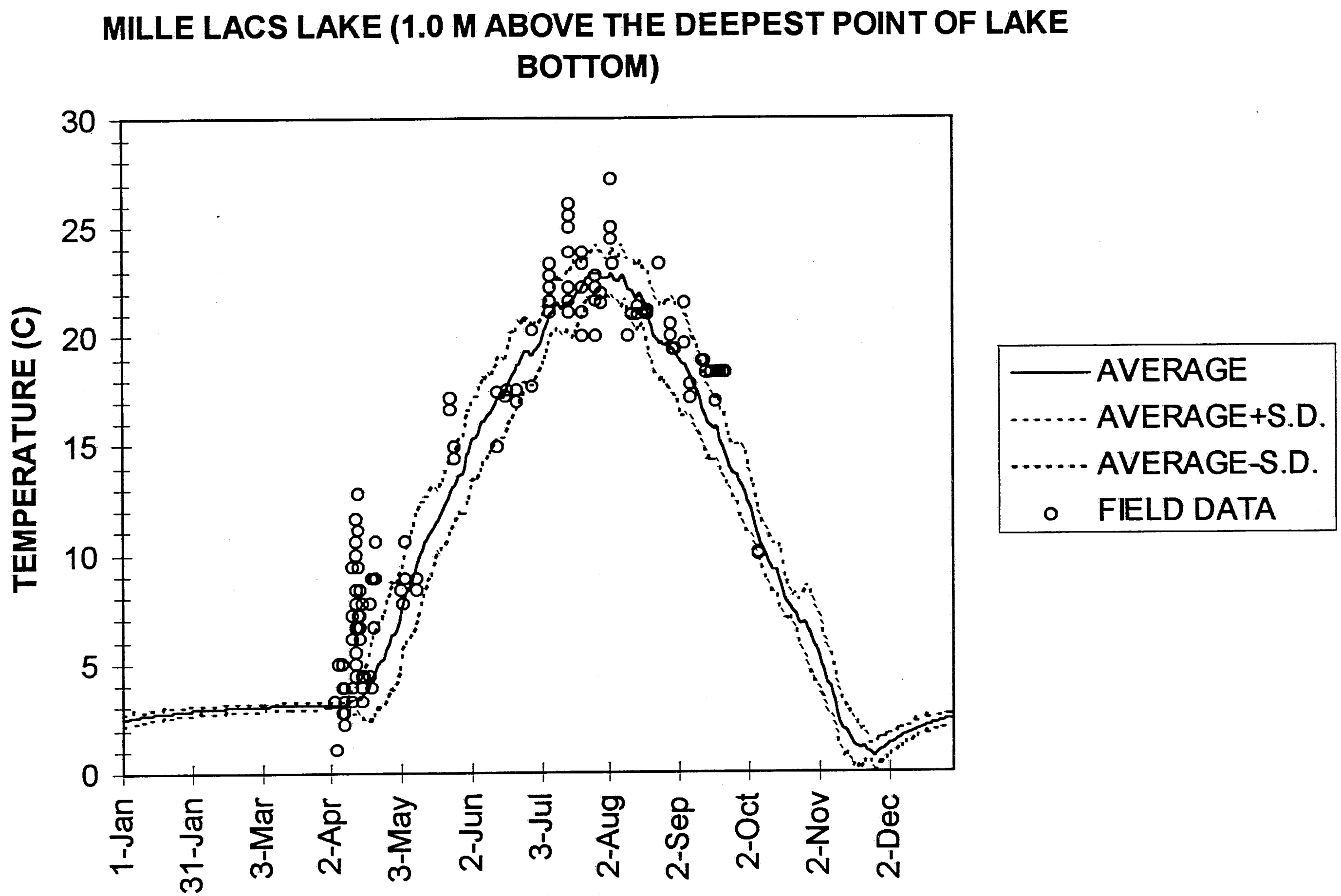


Fig 5.1.7 Average water temperatures plus/minus standard deviation 1 m above the deepest point of Mille Lacs Lake

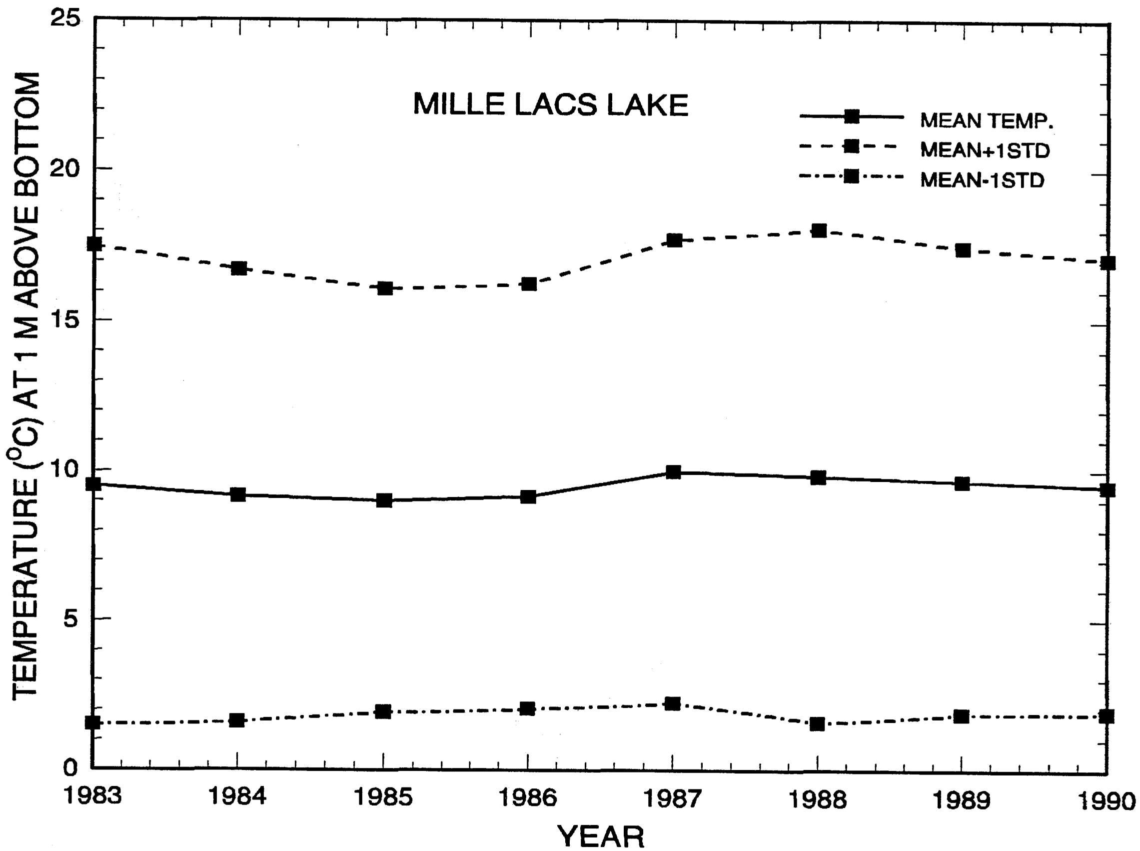


Fig 5.1.8 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Mille Lacs Lake

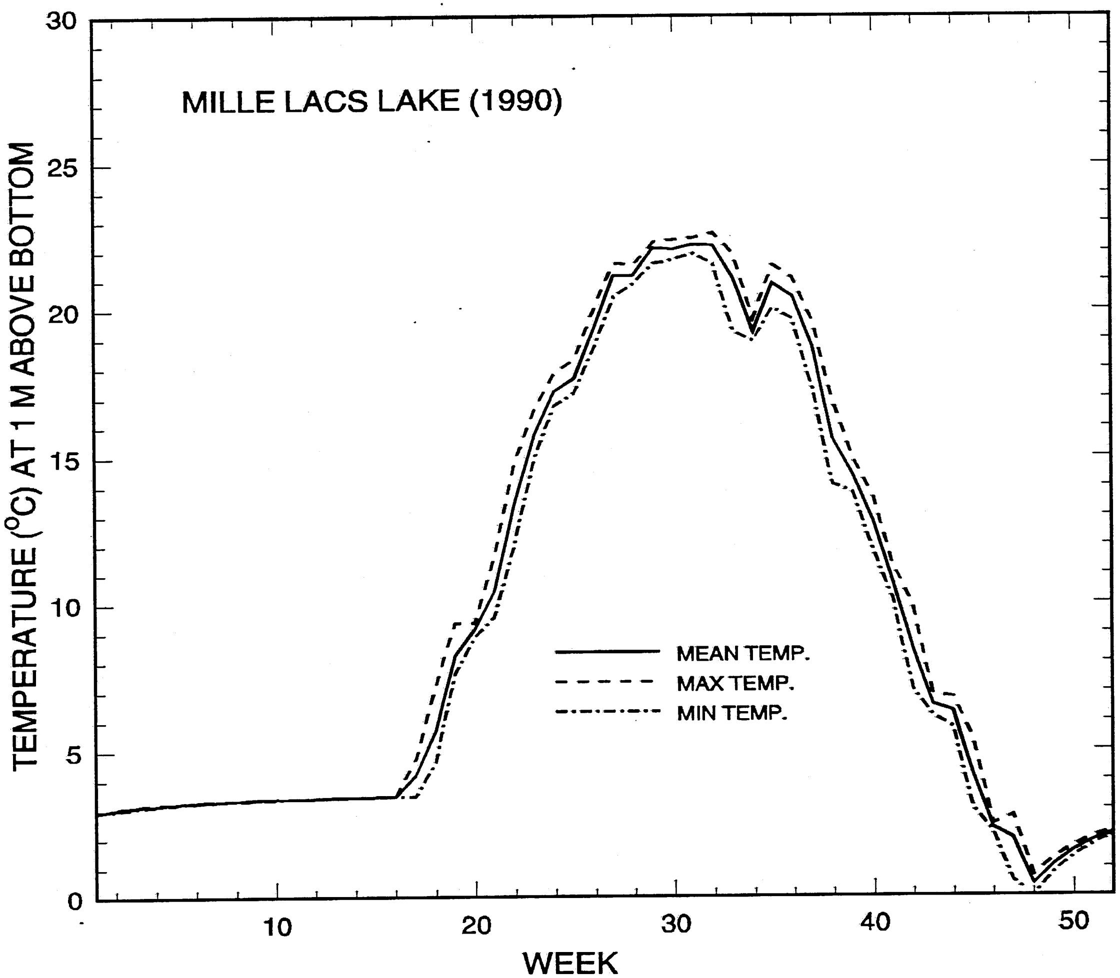
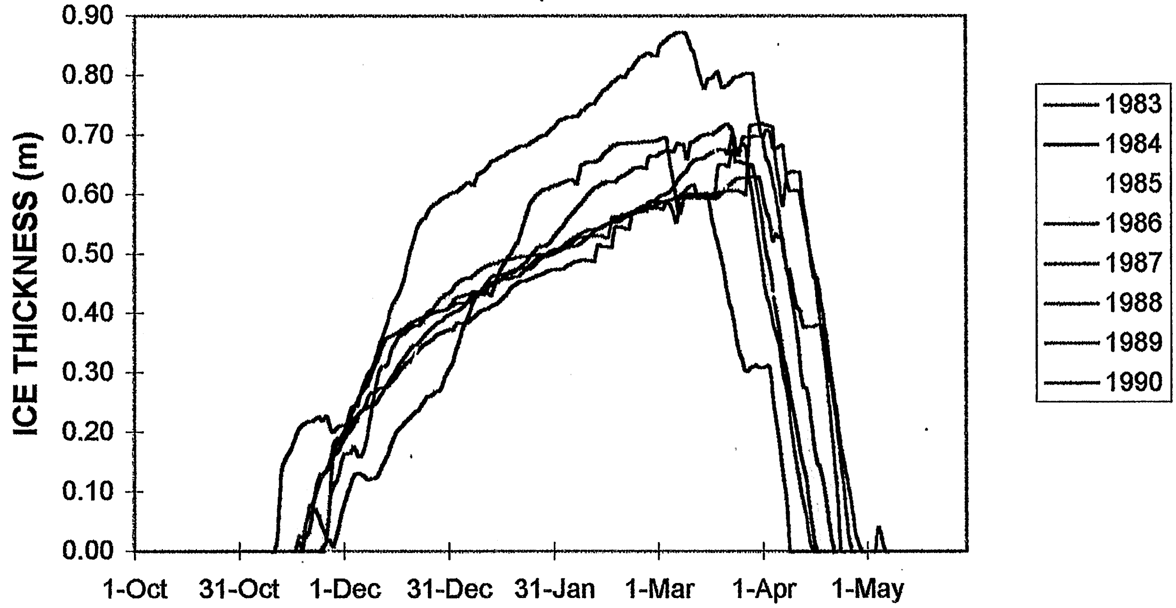


Fig 5.1.9 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Mille Lacs Lake

MILLE LACS LAKE



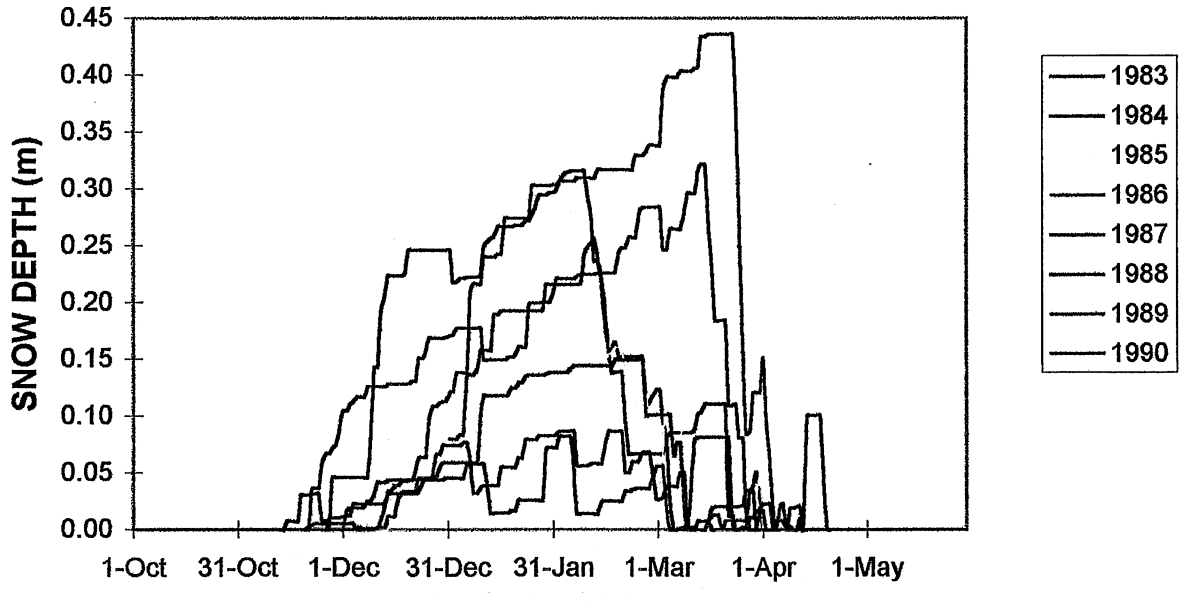


Fig 5.1.10 Ice thicknesses and snow depths from 1983 to 1990 on Mille Lacs Lake

5.2 *Upper Red Lake*

Upper Red Lake is located in northern Minnesota. It has a surface area of 436.3 km^2 and a maximum depth of only 6.1 m. It is a very shallow lake with a large surface area. No bathymetric map is available for Upper Red Lake. Meteorological data from International Falls were used in the simulations.

The lake was simulated for the period from 1983 to 1990. Simulated temperatures were compared with 41 days of field measurements from 1985 to 1990. Field data were obtained from the USEPA water quality database STORET. Standard error, slope of regression and R^2 were 1.79°C, 1.02 and 0.73, respectively.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.2.1 for 1990. Upper Red Lake is well mixed during the open water season. For other years the plots are very similar. Surface temperatures (at 1m depth) are shown in Fig. 5.2.2. The variability in daily water temperatures from year to year is pronounced because of weather conditions. However, mean annual water temperatures and standard deviations of daily temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.2.3). The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.2.4 for year 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.2.1 shows the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in early November and the ice-out date in late April. Average values and standard deviations will be shown in Section 6 (Table 6.4). Fig 5.2.5 shows the variability in ice thickness and snow depths from 1983 to 1990.

Table 5.2.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Upper Red Lake from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/23	05/01	04/20	04/22	04/13	04/28	05/07	05/02
Ice-in date	11/10	10/30	11/08	11/02	11/09	10/26	11/02	11/06
Ice cover duration (days)	164	170	163	163	150	184	180	169
Max. ice thickness (m)	0.79	0.67	0.63	0.67	0.76	0.92	0.71	0.91
Date of max. thickness	03/01	03/23	03/20	03/20	03/03	03/21	3/31	3/07

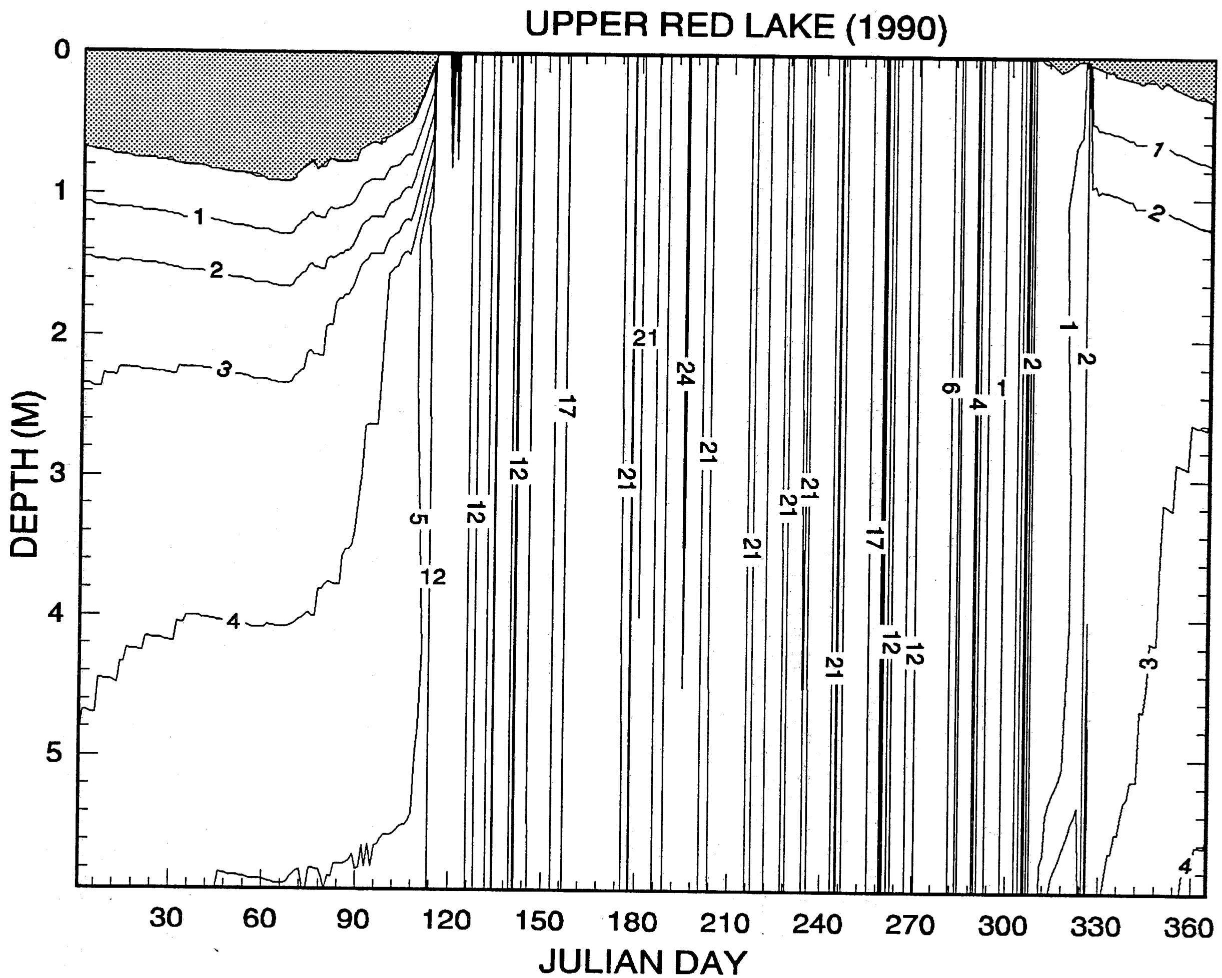


Fig 5.2.1 Isotherms (1990) interpolated from simulated daily water temperature profiles for Upper Red Lake

UPPER RED LAKE (1.0 M BELOW WATER SURFACE)

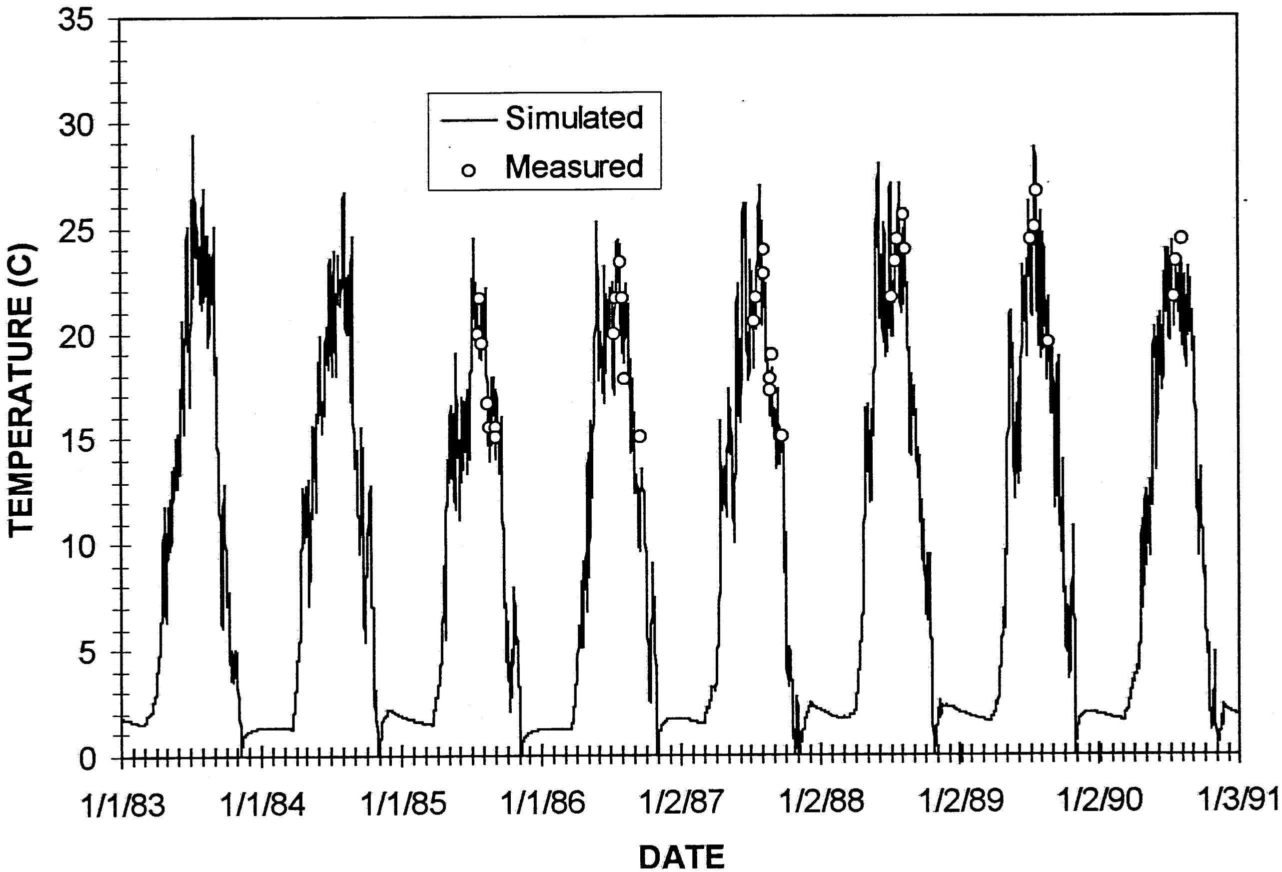


Fig 5.2.2 Simulated and measured water temperatures 1 m below the water surface of Upper Red Lake

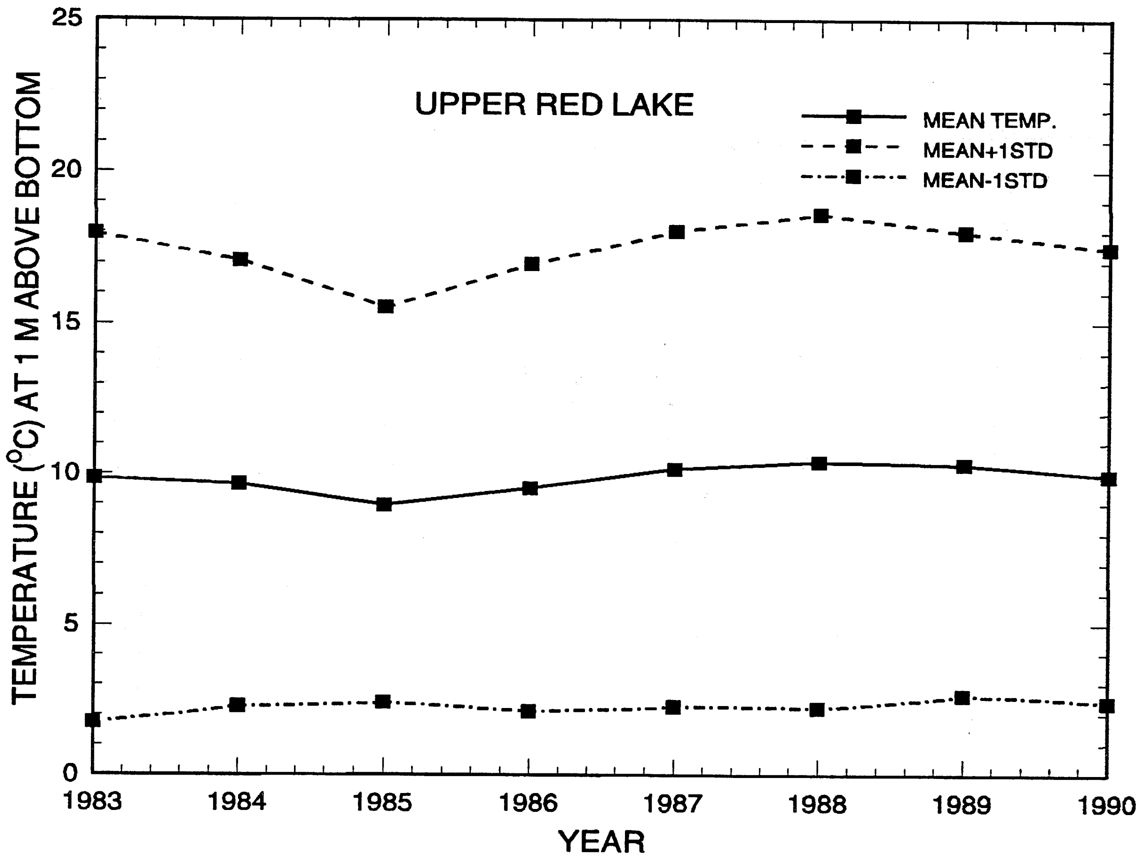


Fig 5.2.3 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Upper Red Lake

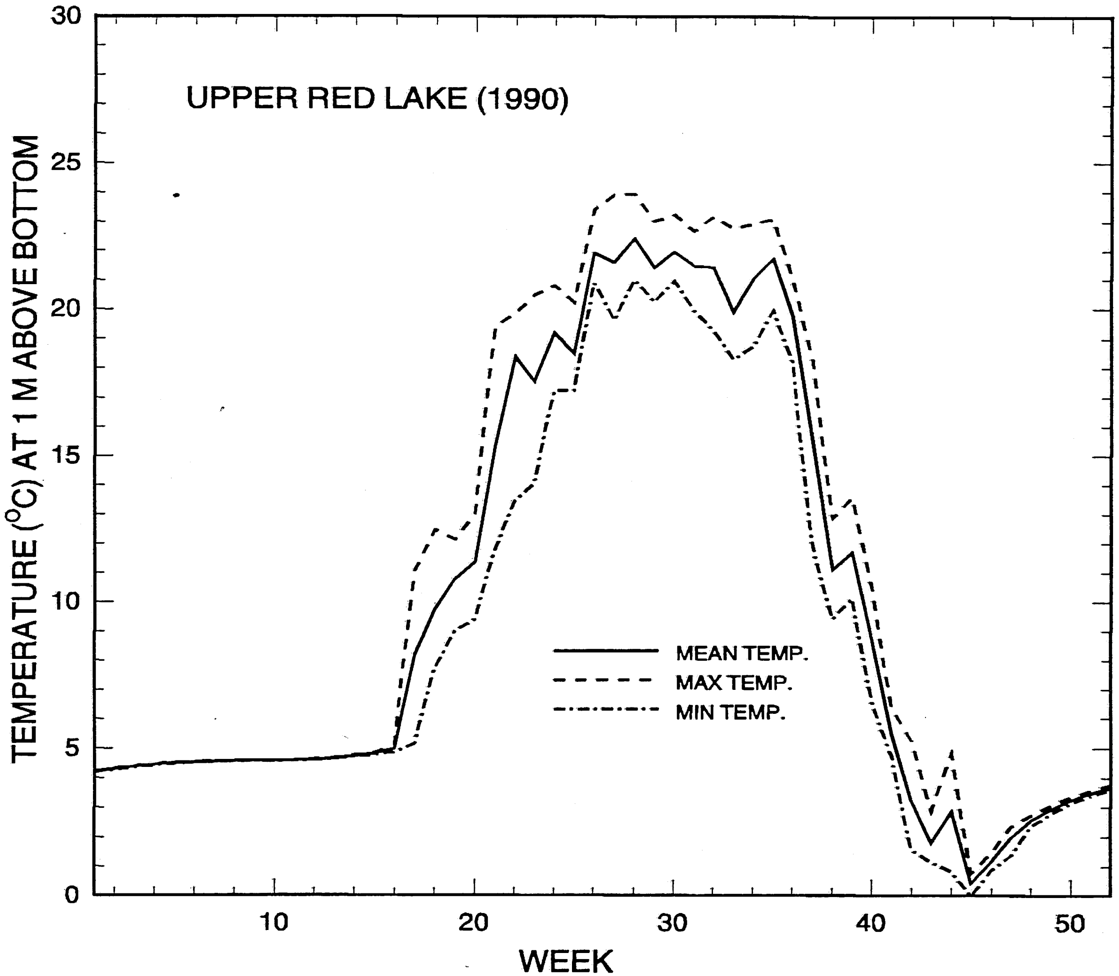
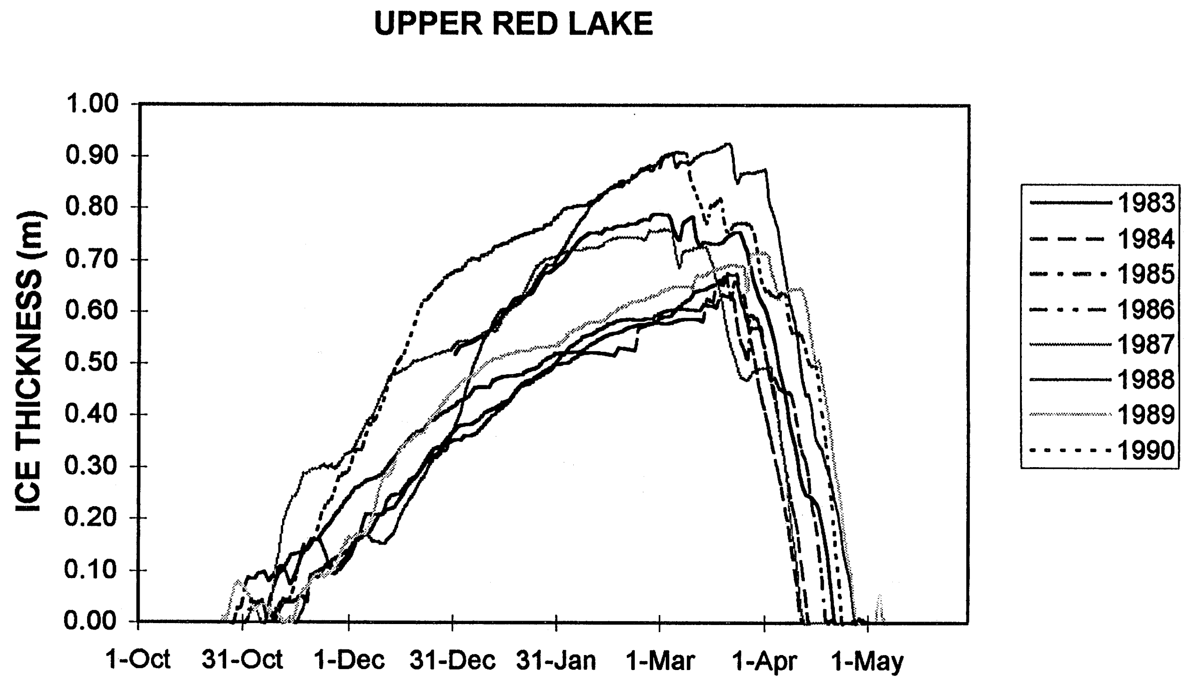


Fig 5.2.4 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Upper Red Lake



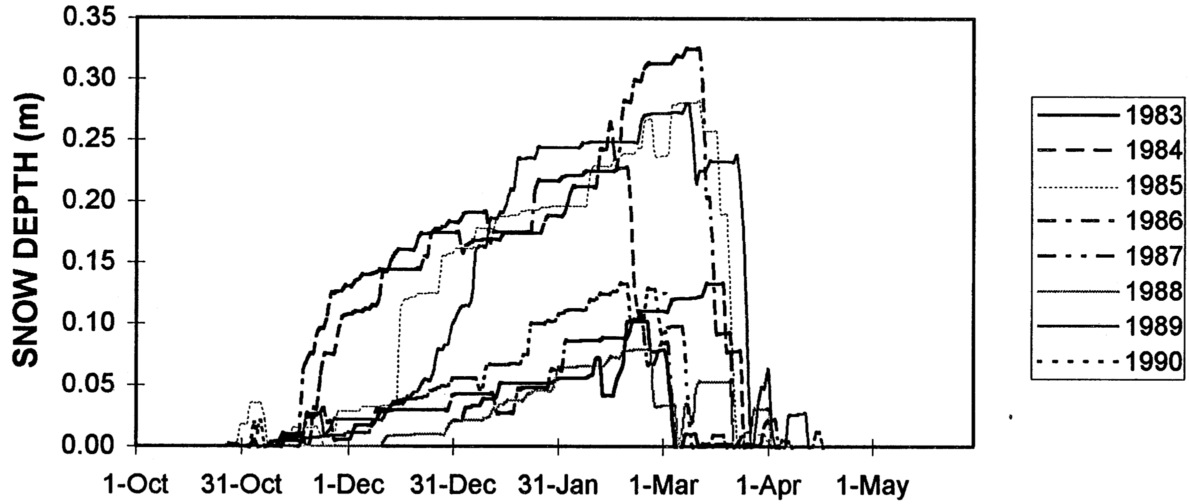


Fig 5.2.5 Ice thicknesses and snow depths from 1983 to 1990 on Upper Red Lake

5.3 *Lower Red Lake*

Lower Red Lake is located next to Upper Red Lake. It has a surface area of 732.5 km^2 and a maximum depth of 12.8 m. It is also a large and shallow lake. No bathymetric map is available for Lower Red Lake. Meteorological data from International Falls were used in the simulations.

The lake was simulated for the period from 1983-1990. No field data are available for comparison with model simulation results.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.3.1 for 1990. Upper Red Lake is well mixed during the open water season. For other years the plots are very similar. Mean annual water temperatures and standard deviations of daily temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.3.2). The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.3.3 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.3.1 shows the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in early or middle November and the ice-out date in late April. Fig 5.3.4 shows the variability in ice thickness and snow depths from year 1983 to 1990.

Table 5.3.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Lower Red Lake from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/24	05/01	04/20	04/22	04/14	04/29	05/07	05/02
Ice-in date	11/17	11/02	11/13	11/10	11/19	11/06	11/14	11/12
Ice cover duration (days)	158	171	158	159	146	174	171	163
Max. ice thickness (m)	0.81	0.94	0.65	0.86	0.80	0.96	0.78	0.99
Date of max. thickness	03/01	03/22	03/20	03/20	03/03	03/21	4/01	3/07

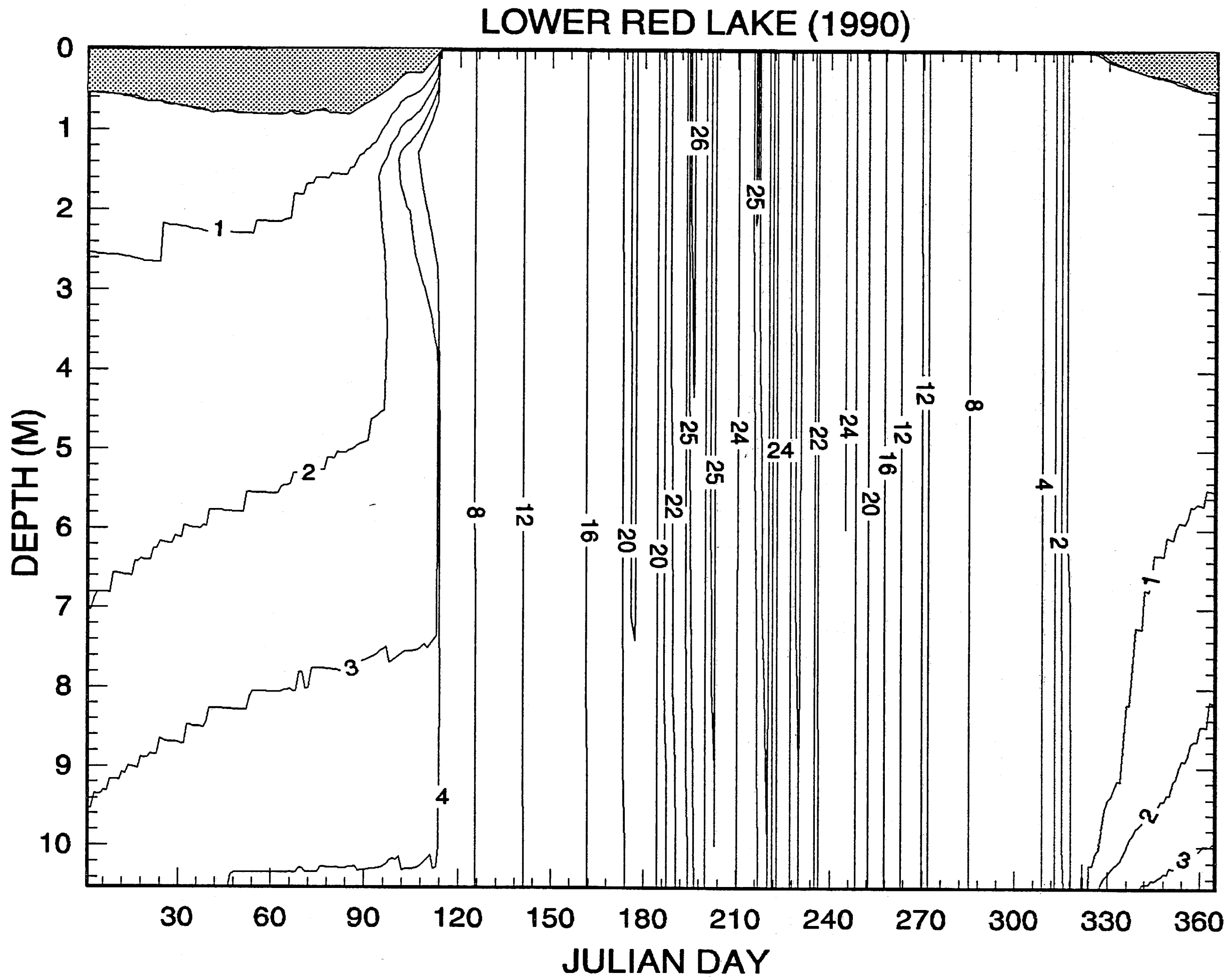


Fig 5.3.1 Isotherms (1990) interpolated from simulated daily water temperature profiles for Lower Red Lake

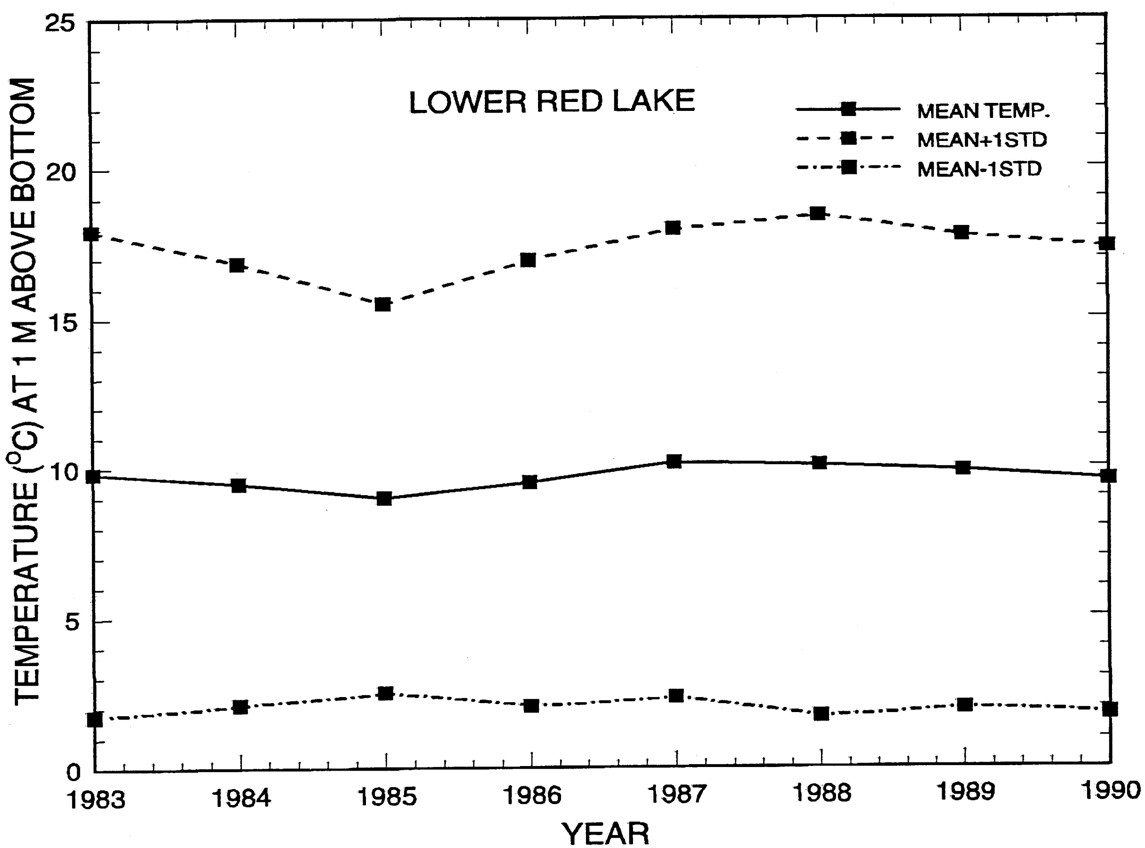


Fig 5.3.2 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Lower Red Lake

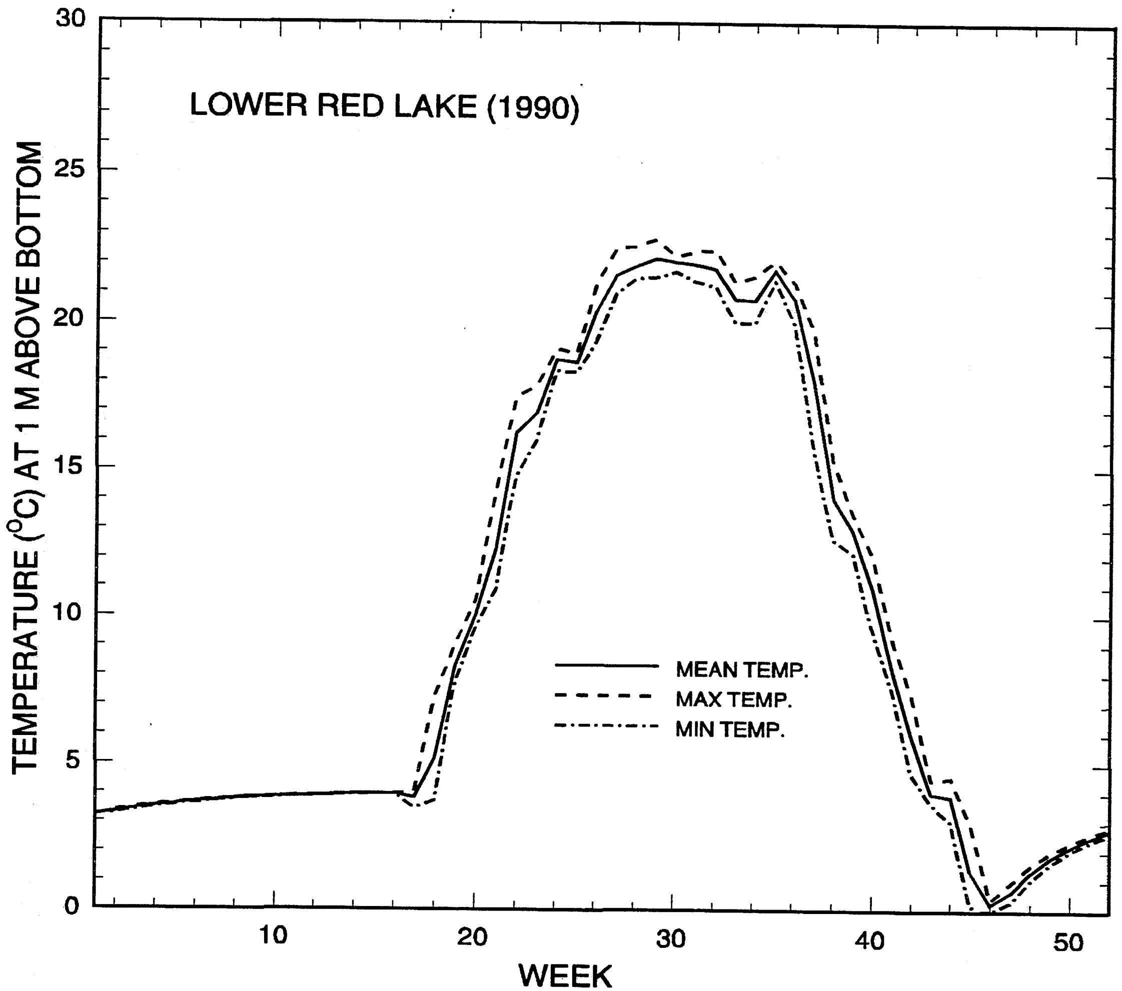
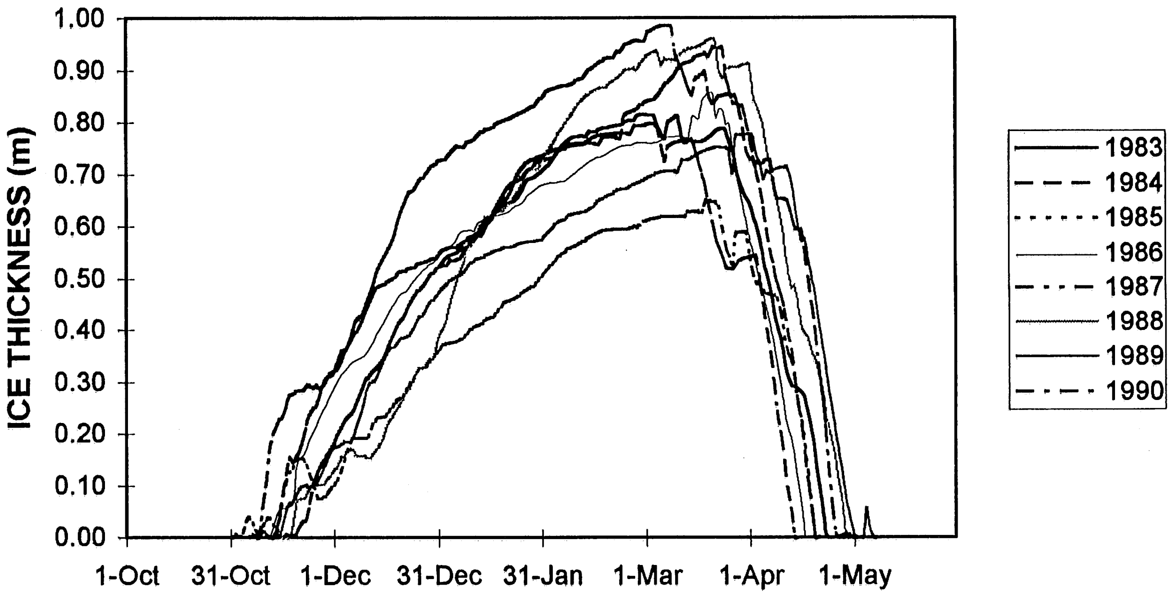


Fig 5.3.3 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Lower Red Lake

LOWER RED LAKE



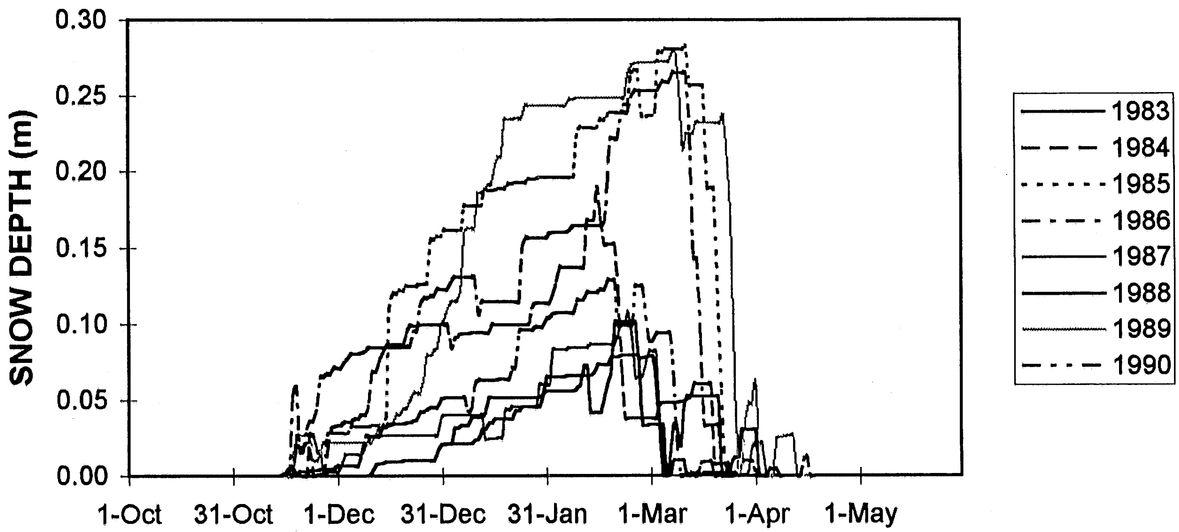


Fig 5.3.4 Ice thicknesses and snow depths from 1983 to 1990 on Lower Red Lake

5.4 *Lake of the Woods*

Lake of the Woods has a surface area of 3846 km^2 and a maximum depth of 20.0 m. Meteorological data from International Falls were used in the simulations.

The lake was simulated for the period from 1983 to 1990. No field data are available to compare with the simulation results.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.4.1 for 1990. Lake of the Woods is well mixed during the open water season. For other years the plots are very similar. Mean annual water temperatures and standard deviations of daily temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.4.2). The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.4.3 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.4.1 gives the simulated earliest ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in middle or late November and the ice-out date in late April. Fig 5.4.4 shows the variability in the simulated ice thickness and snow depths from year 1983 to 1990.

Table 5.4.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Lake of the Woods from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/24	05/01	04/21	04/22	04/15	04/30	05/07	05/01
Ice-in date	11/22	11/11	11/17	11/11	11/21	11/15	11/16	11/23
Ice cover duration (days)	153	162	155	159	145	167	170	158
Max. ice thickness (m)	0.82	0.87	0.67	0.84	0.79	0.96	0.79	0.98
Date of max. thickness	03/01	03/23	03/20	03/20	03/03	03/21	4/01	3/07

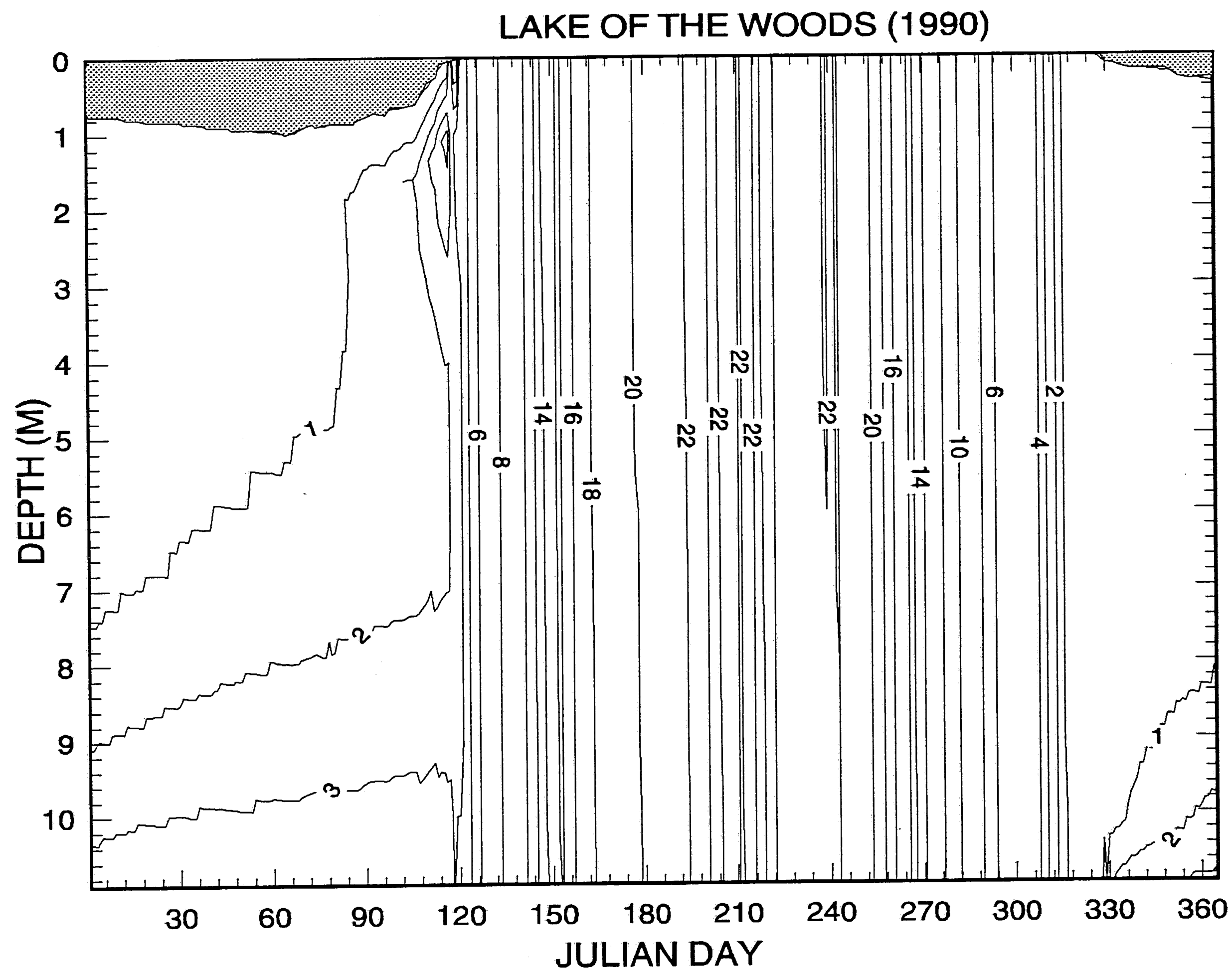


Fig 5.4.1 Isotherms (1990) interpolated from simulated daily water temperature profiles for Lake of the Woods

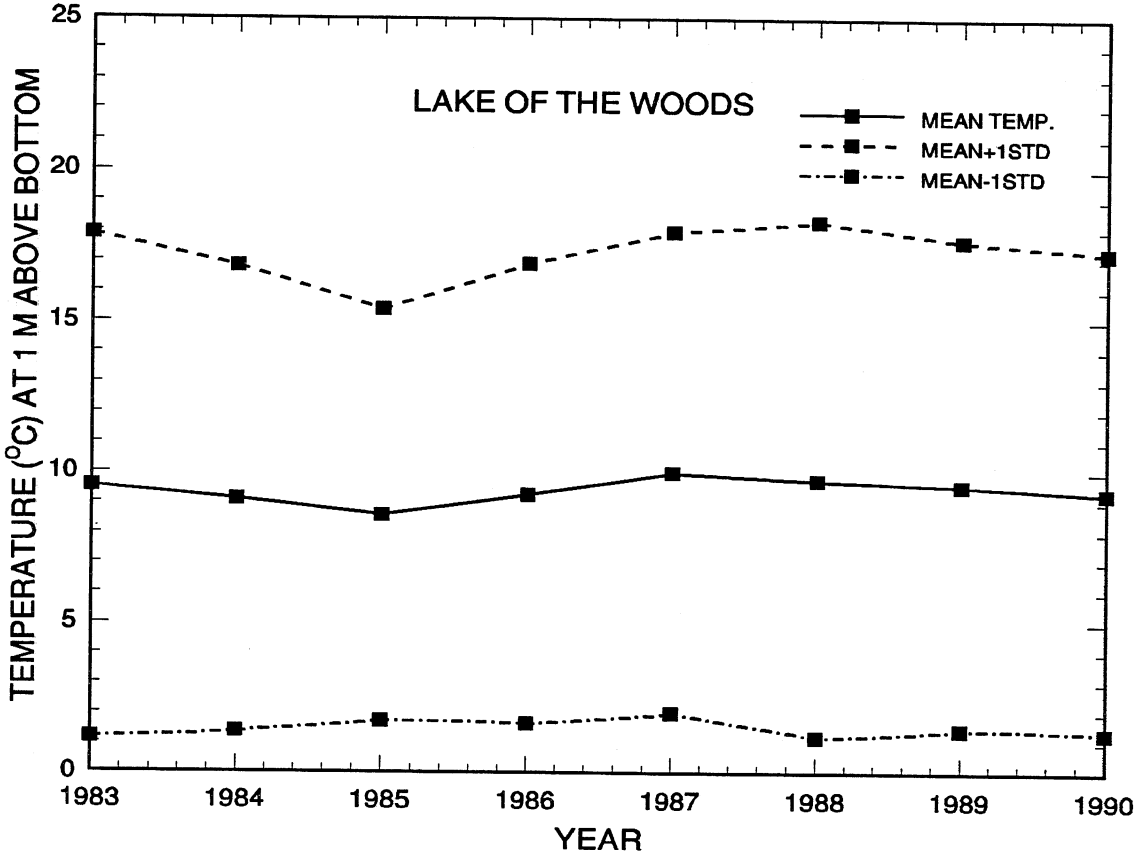


Fig 5.4.2 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Lake of the Woods

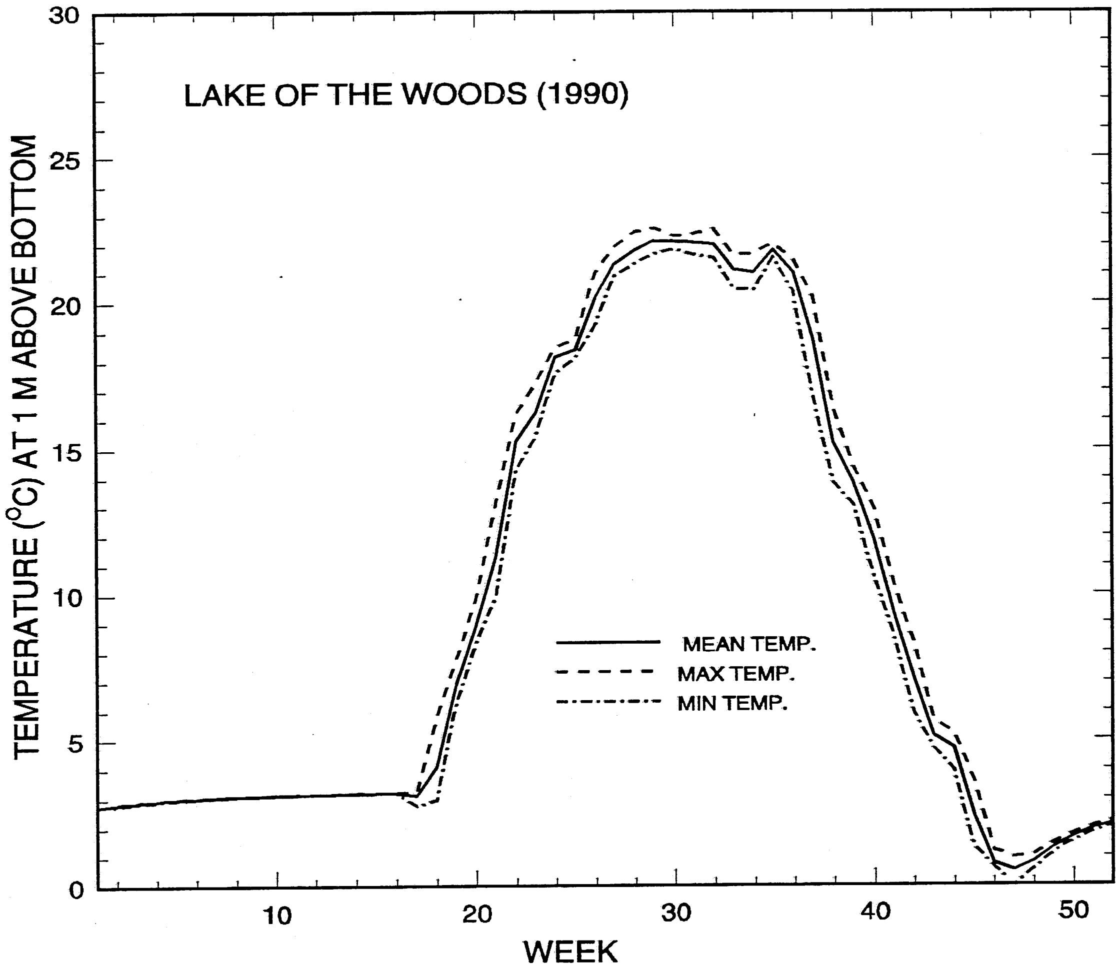


Fig 5.4.3 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Lake of the Woods

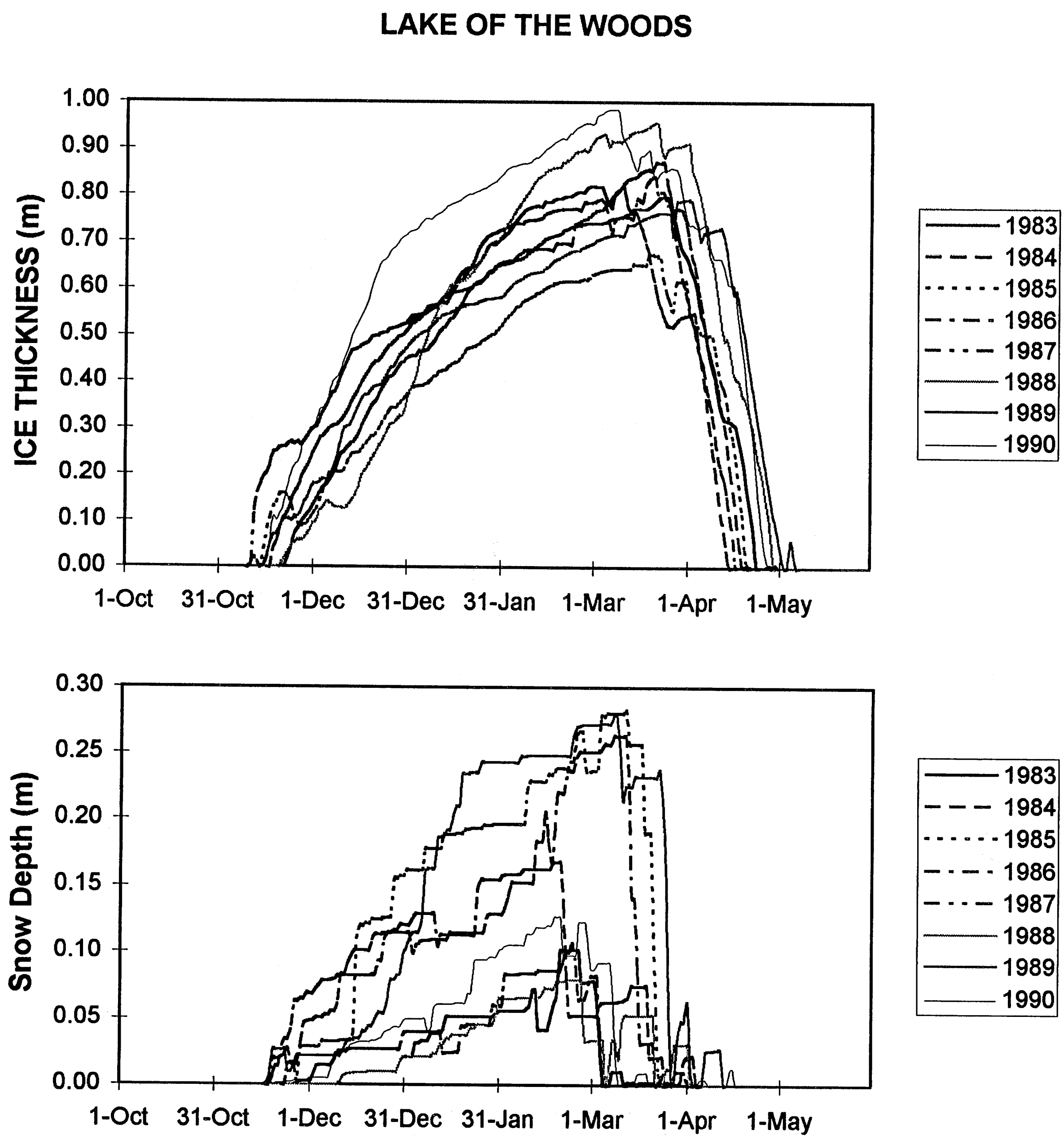


Fig 5.4.4 Ice thicknesses and snow depths from 1983 to 1990 on Lake of the Woods

5.5 Leech Lake

Leech Lake is located in northern Minnesota. It has a surface area of 442.8 km^2 and a maximum depth of 12.2 m. A bathymetric map of the lake was given in Appendix A. Meteorological data from Fargo were used in the simulations.

The lake was simulated for the period from 1983 to 1990. No field data were available to compare with the simulation results.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.5.1 for 1990. Leech Lake is well mixed during the open water season except some short periods during which the lake was slightly stratified. The difference between surface water temperature and bottom water temperature is approximately 1 °C. For other years the plots are very similar. Mean annual water temperatures and standard deviations of daily temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.5.2). The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.5.3 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.5.1 gives the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in early November and the ice-out date in late April. Fig 5.5.4 shows the variability in ice thickness and snow depths from year 1983 to 1990.

Table 5.5.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Leech Lake from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/26	04/16	04/18	04/15	04/09	04/21	05/07	04/24
Ice-in date	11/25	11/16	11/20	11/12	11/24	11/17	11/17	11/26
Ice cover duration (days)	152	151	149	154	136	156	164	149
Max. ice thickness (m)	0.61	0.70	0.79	0.70	0.70	0.71	0.71	0.88
Date of max. thickness	03/29	03/23	03/08	03/26	03/03	03/22	4/01	3/08

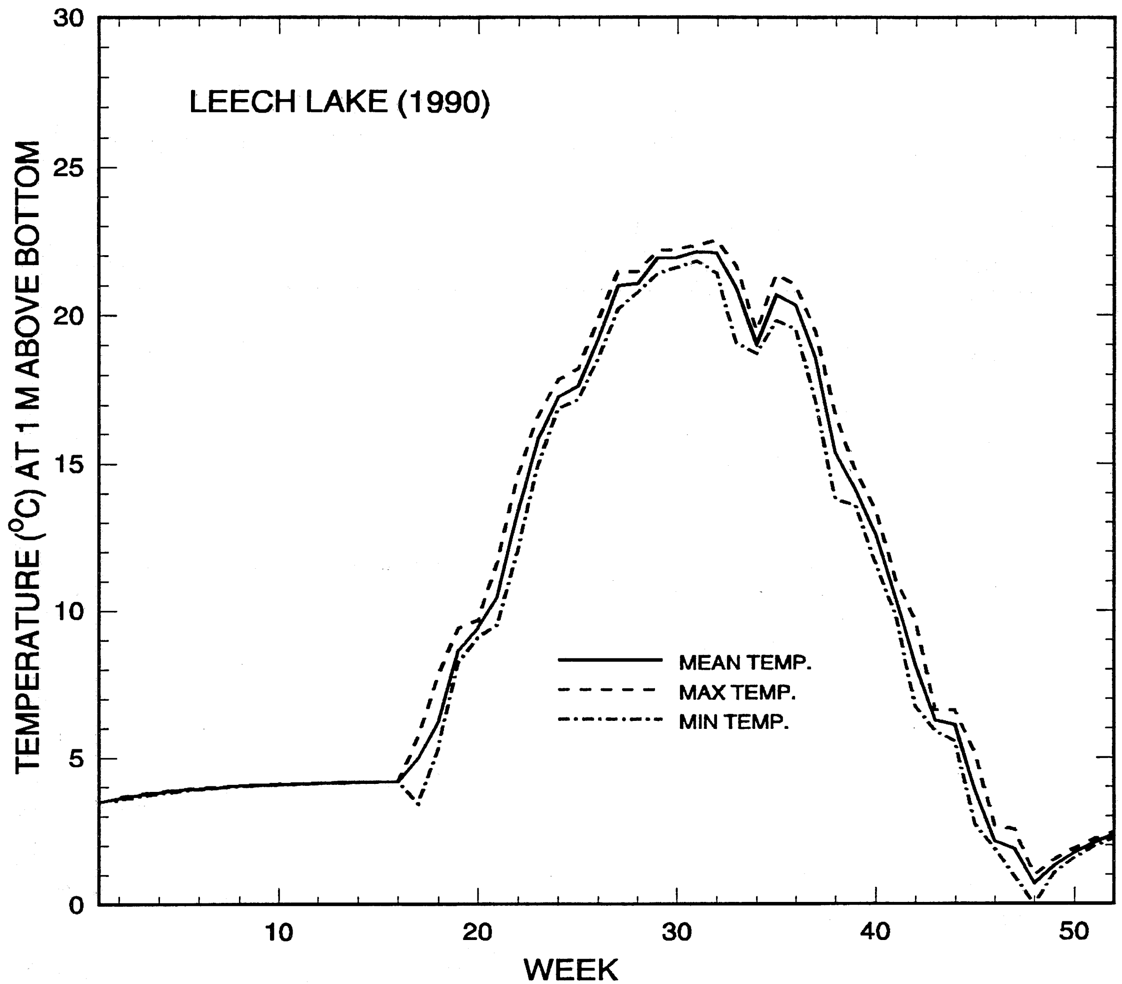


Fig 5.5.3 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Leech Lake

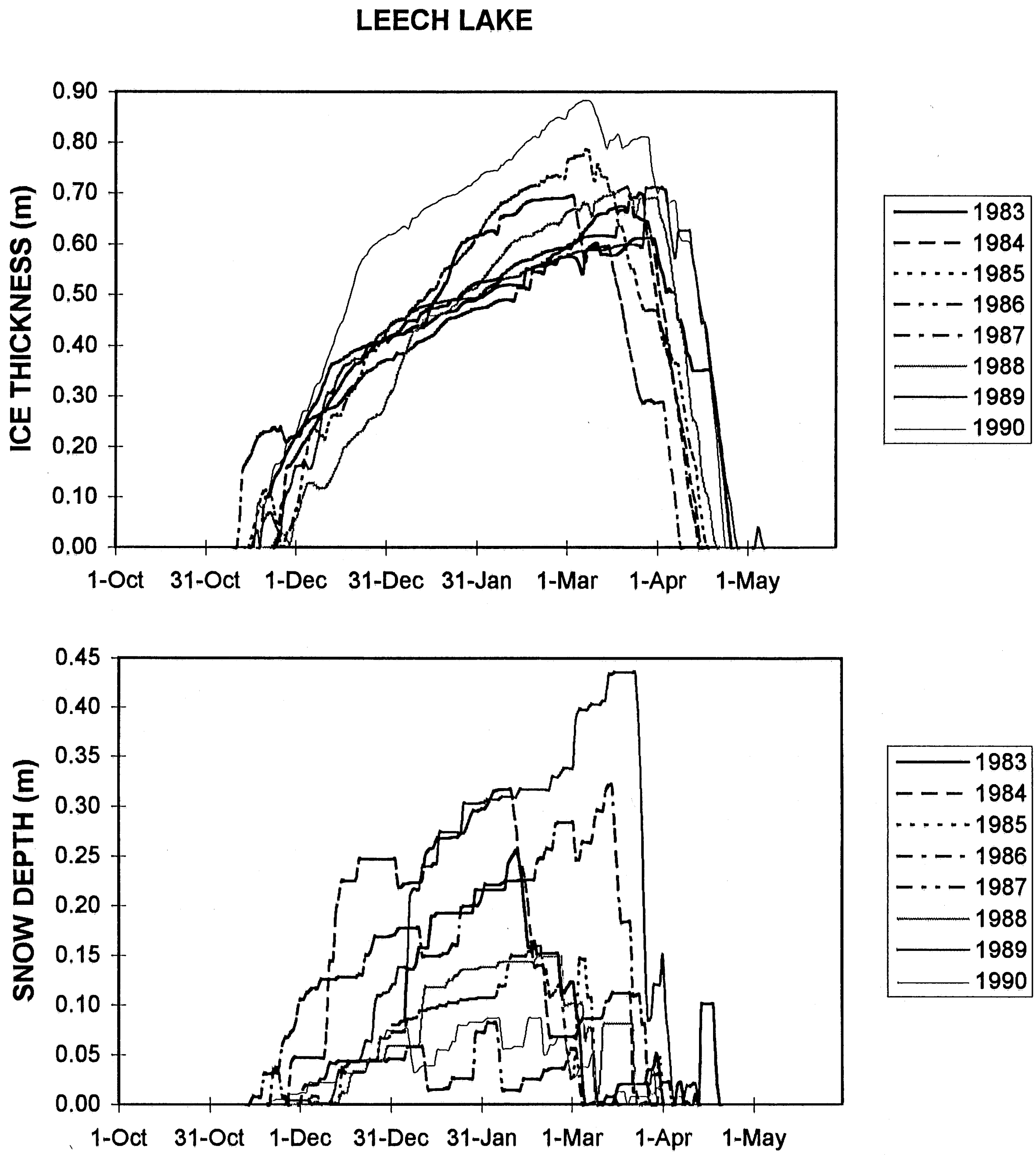


Fig 5.5.4 Ice thicknesses and snow depths from 1983 to 1990 on Leech Lake

5.6 *Lake Vermilion*

Lake Vermilion is located in northern Minnesota. It has several basins separated by shoals which significantly restrict horizontal water exchange between basins. Only the largest basin, Big Bay, was simulated. Big Bay has a surface area of 61.1 km^2 and maximum depth of 23.2 m. A bathymetric map of Big Bay is given in Appendix A. Meteorological data from Duluth were used in the simulations.

The lake was simulated for the period from 1983 to 1990. Simulated water temperatures were compared with 66 days of field measurements. Field data were obtained from the Minnesota Department of Natural Resources. Standard error, slope of regression and R^2 were 0.74°C, 1.00 and 0.76, respectively. Some measured and simulated water temperature profiles are shown in Fig. 5.6.1.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.6.2 for 1990. Lake Vermilion (Big Bay) is slightly stratified during the open water season: the temperature difference between lake surface and lake bottom is about 3 to 5 °C as can be seen from these isotherms. For other years the plots are very similar.

Surface water temperatures (at 1m depth) are shown in Fig. 5.6.3. The variability in daily surface water temperatures from year to year is pronounced because of weather conditions. However, mean annual surface water temperatures and standard deviations of daily surface water temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.6.4).

The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.6.5 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.6.1 shows the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in late November and the ice-out date in middle or late April. Fig 5.6.6 shows the variability in ice thickness and snow depths from year 1983 to 1990.

Table 5.6.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Lake Vermilion (Big Bay) from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/27	04/17	04/19	04/16	04/10	04/23	05/07	04/25
Ice-in date	11/26	11/17	11/20	11/12	11/25	11/18	11/18	11/27
Ice cover duration (days)	152	150	150	155	136	157	166	149
Max. ice thickness (m)	0.63	0.71	0.80	0.69	0.70	0.72	0.72	0.88
Date of max. thickness	03/29	03/23	03/08	03/26	03/03	03/22	04/01	03/08

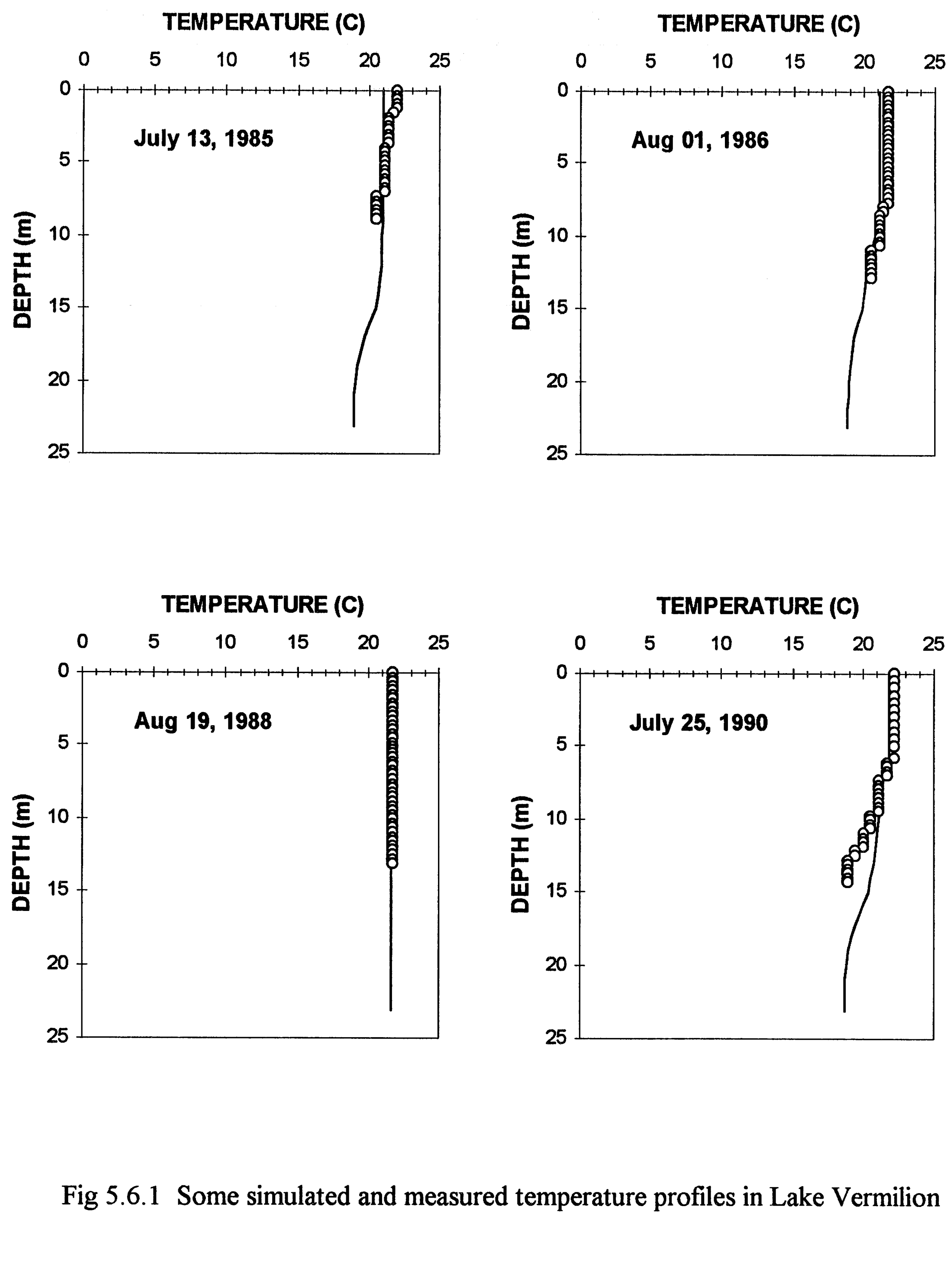


Fig 5.6.1 Some simulated and measured temperature profiles in Lake Vermilion

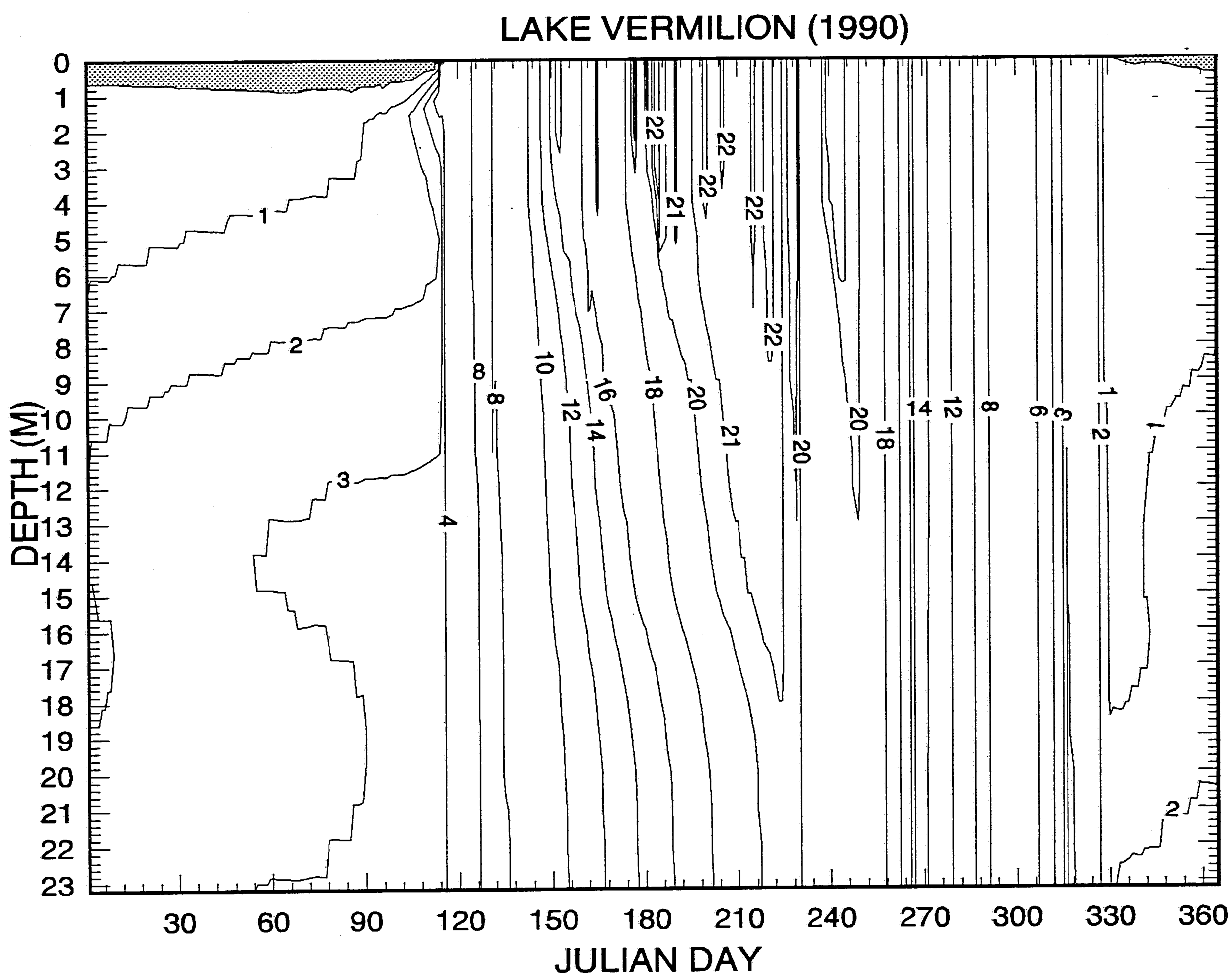


Fig 5.6.2 Isotherms (1990) interpolated from simulated daily water temperature profiles for Lake Vermilion

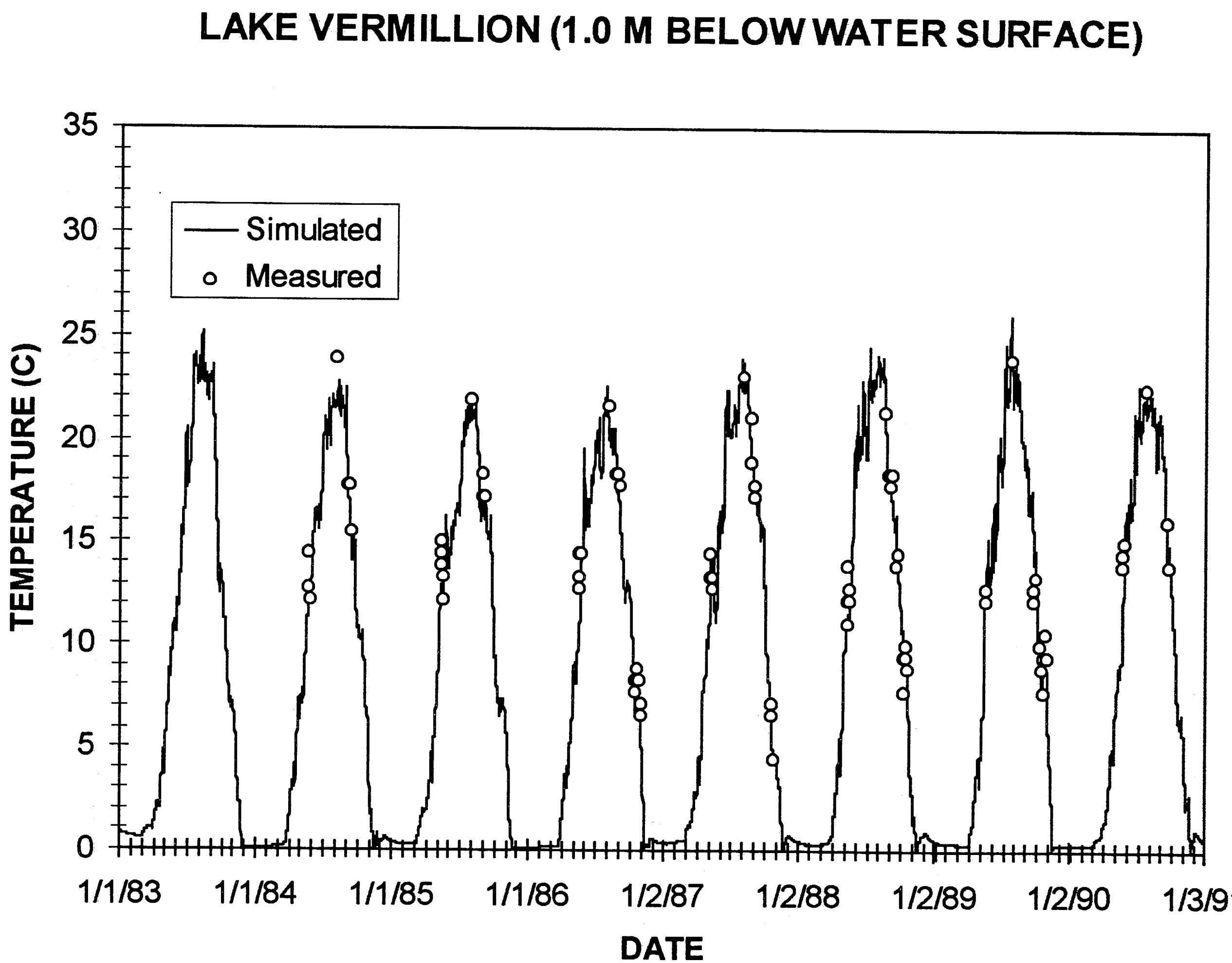


Fig 5.6.3 Simulated and measured surface water temperatures in Lake Vermilion

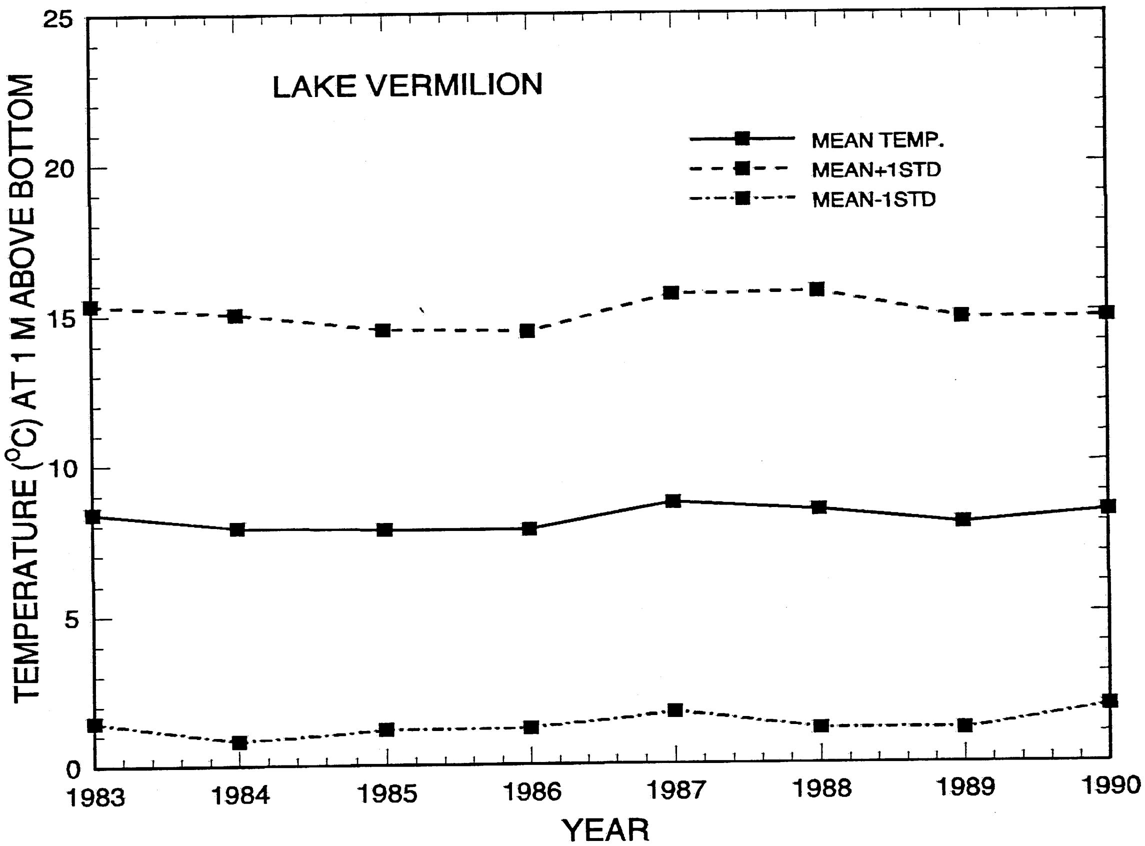


Fig 5.6.4 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Lake Vermilion

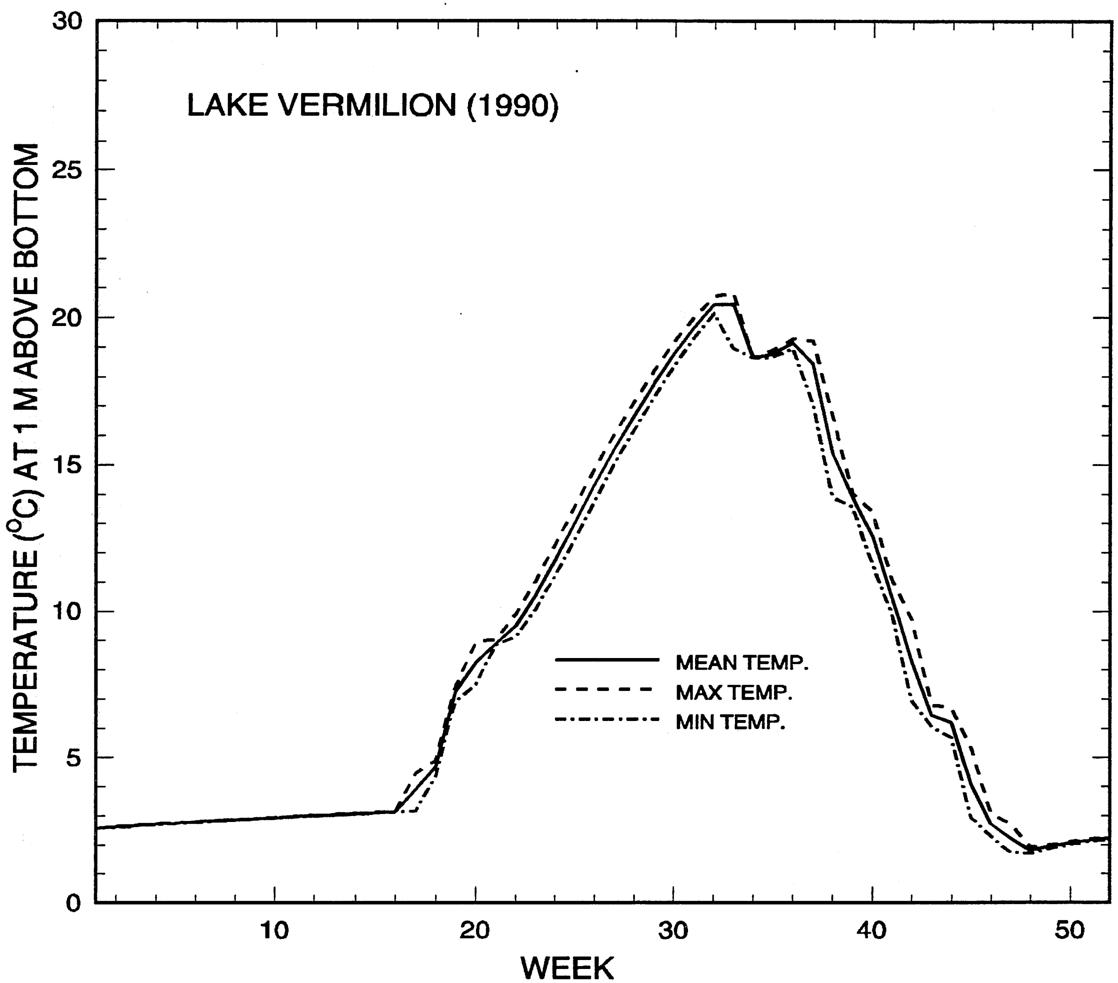


Fig 5.6.5 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Lake Vermilion

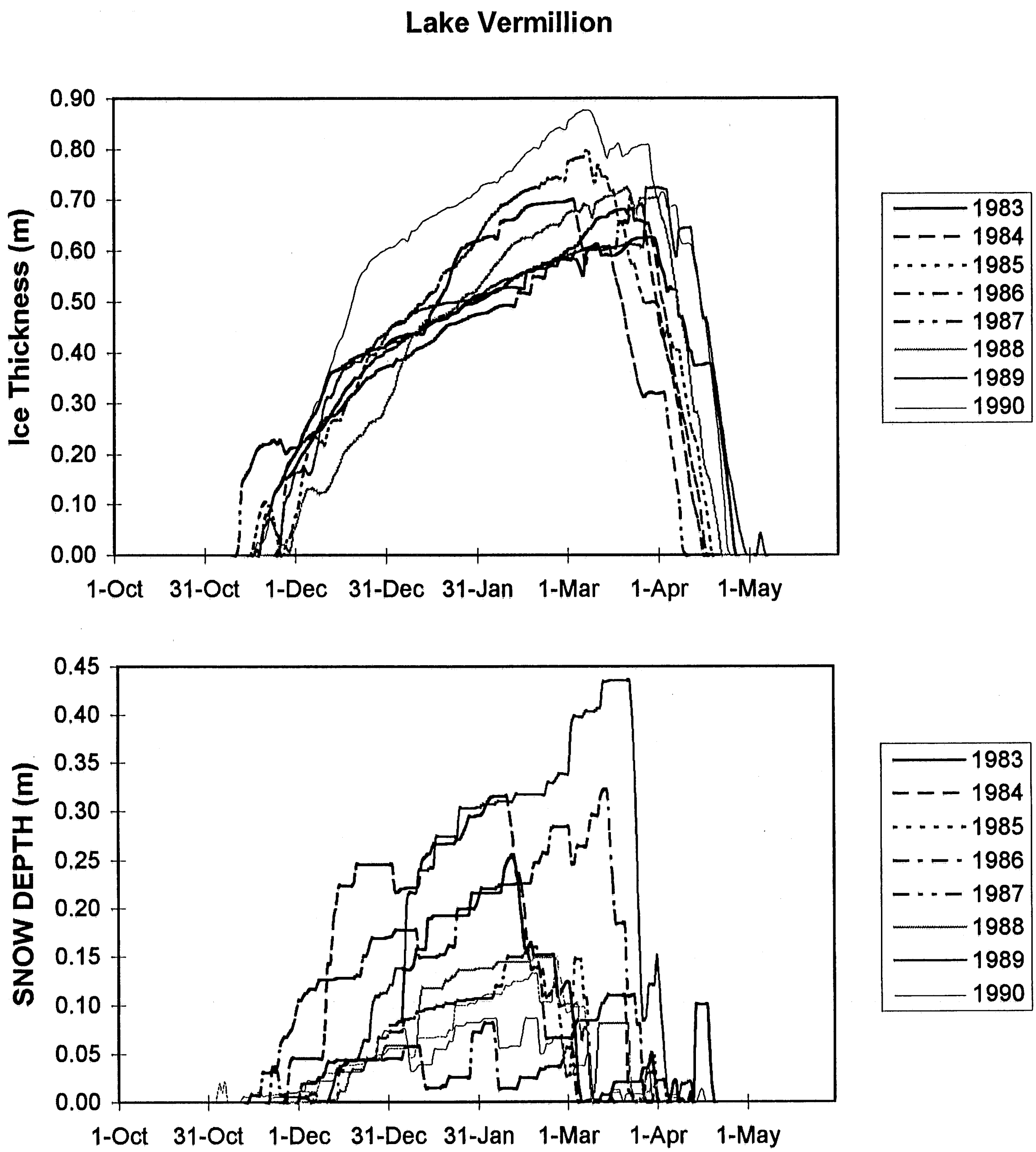


Fig 5.6.6 Ice thicknesses and snow depths from 1983 to 1990 on Lake Vermilion

5.7 *Lake Kabetogama*

Lake Kabetogama is located in northern Minnesota. It has a surface area of 104.3 km^2 and a maximum depth of 15.2m. A bathymetric map of the lake is given in Appendix A. Meteorological data from International Falls were employed in the simulations.

The lake was simulated for the period from 1983 to 1990. No field data were available to compare with the simulation results.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.7.1 for 1990. Lake Kabetogama is slightly stratified during the open water season. For other years the plots are very similar. Mean annual surface water temperatures and standard deviations of daily surface water temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.7.2).

The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.7.3 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.7.1 shows the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in early or mid-November and the ice-out date in late April. Fig 5.7.4 shows the variability in ice thickness and snow depths from 1983 to 1990.

Table 5.7.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Lake Kabetogama from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/24	05/01	04/20	04/22	04/14	04/29	05/07	05/02
Ice-in date	11/17	11/03	11/12	11/10	11/19	11/07	11/14	11/12
Ice cover duration (days)	158	171	159	159	146	174	171	163
Max. ice thickness (m)	0.81	0.94	0.64	0.84	0.79	0.96	0.77	0.98
Date of max. thickness	03/01	03/22	03/20	03/20	03/03	03/21	4/01	3/07

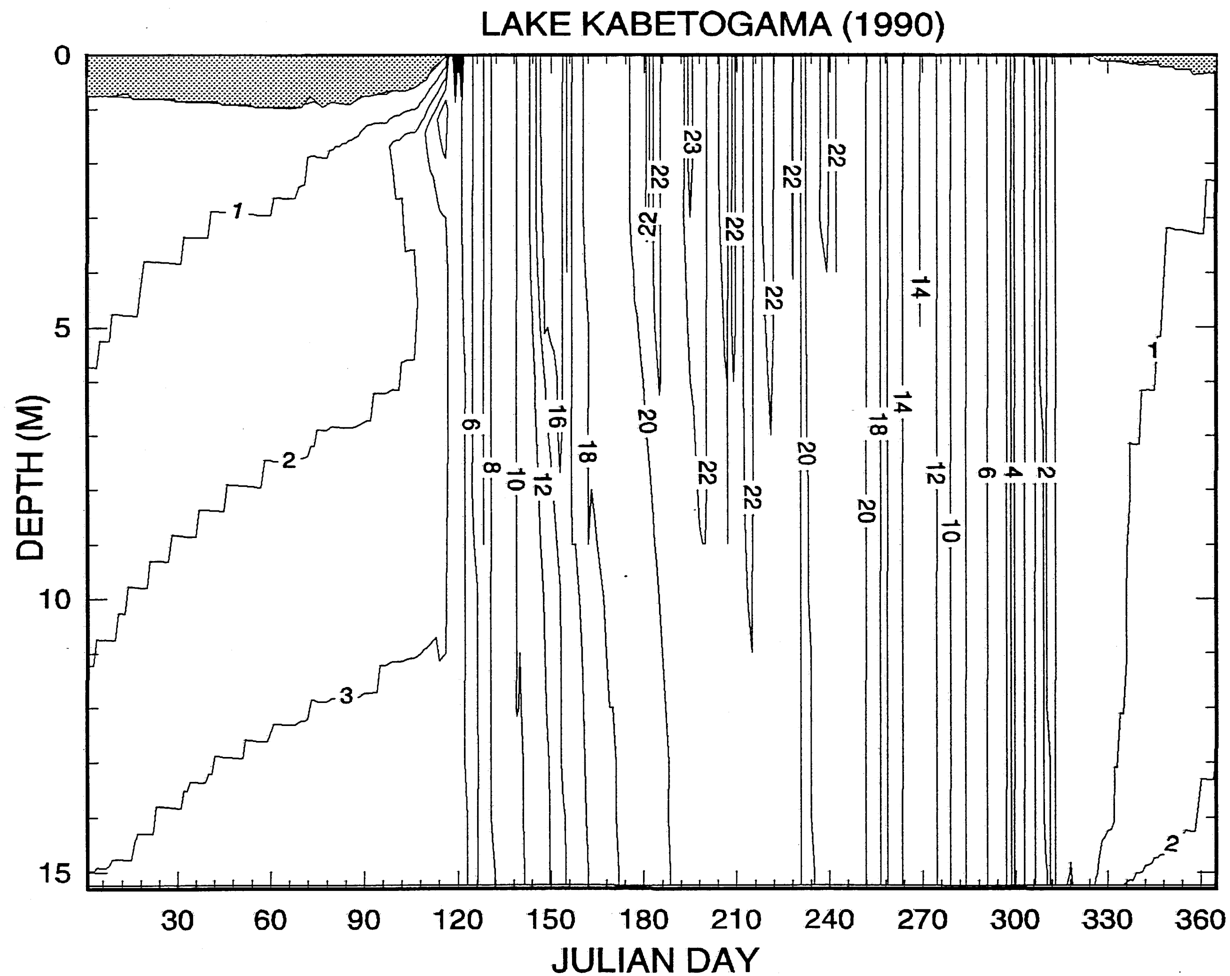


Fig 5.7.1 Isotherms (1990) interpolated from simulated daily water temperature profiles for Lake Kabetogama

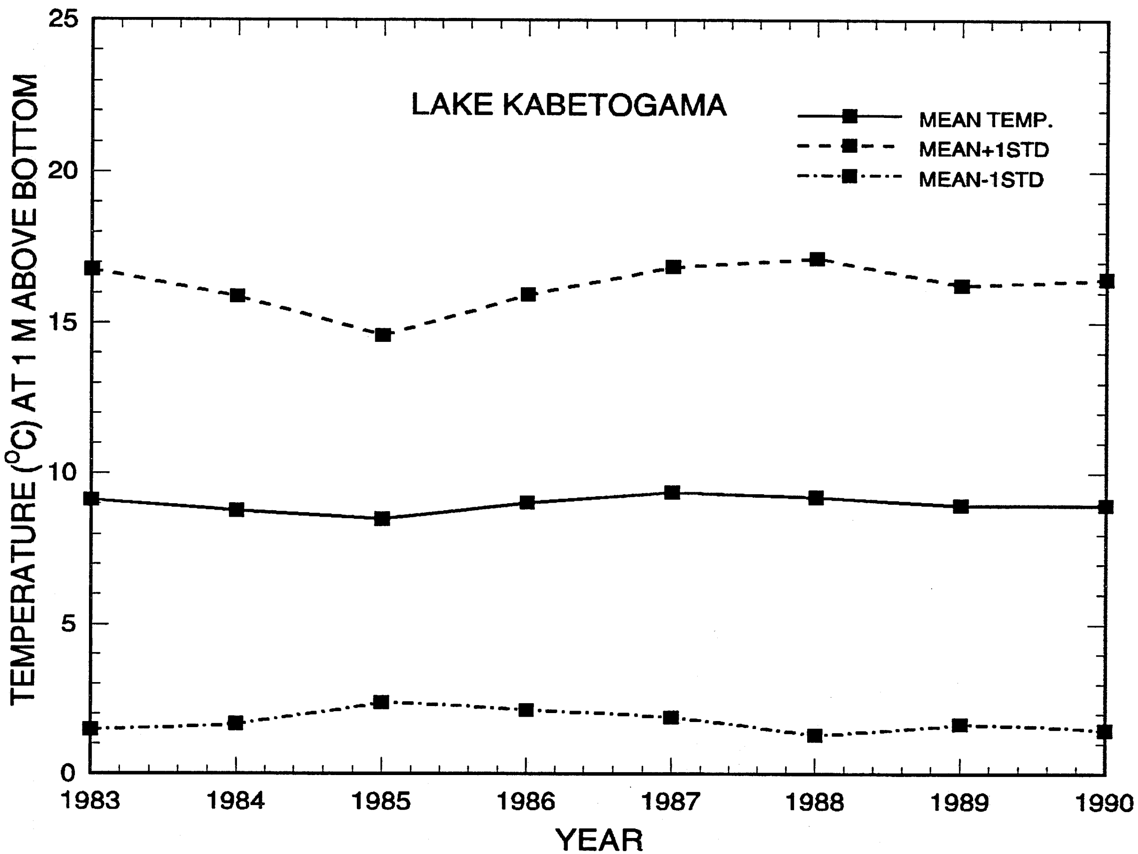


Fig 5.7.2 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Lake Kabetogama

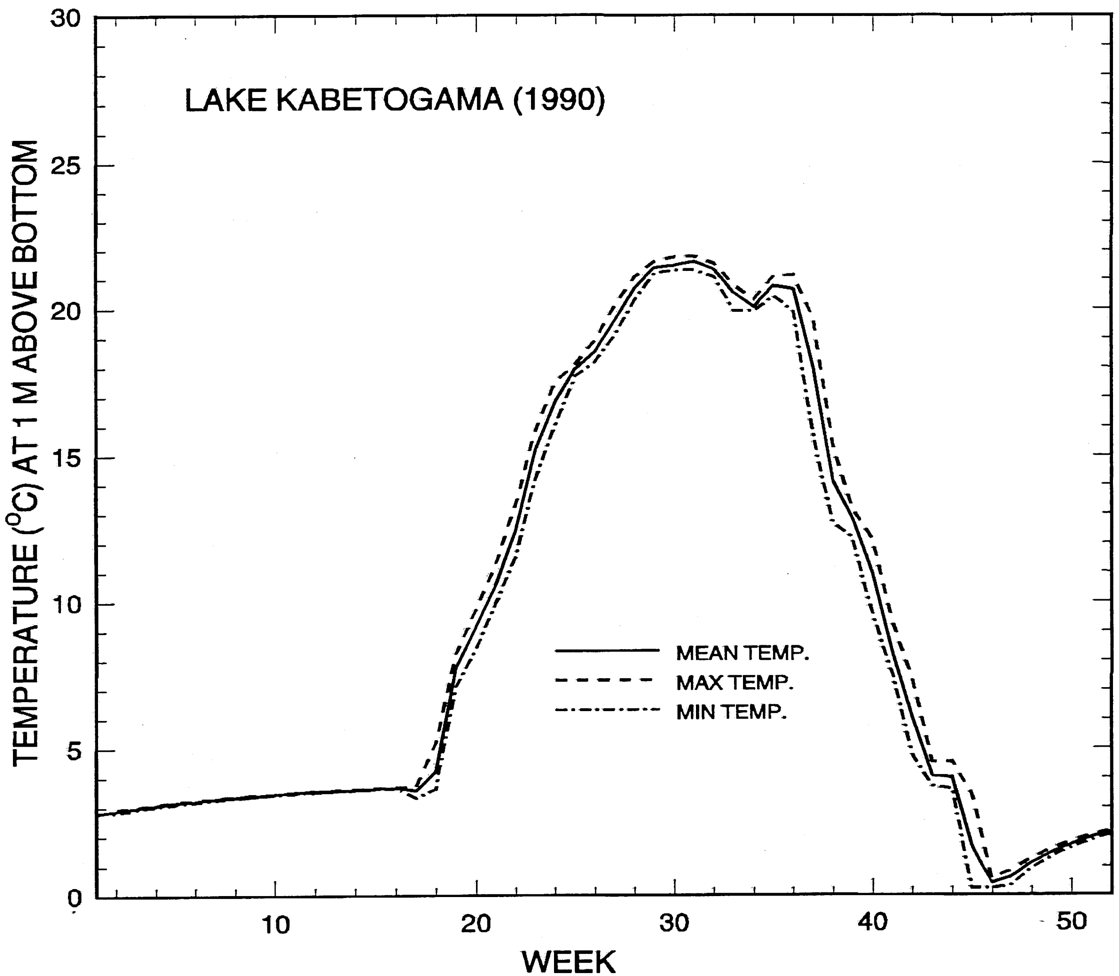


Fig 5.7.3 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Lake Kabetogama

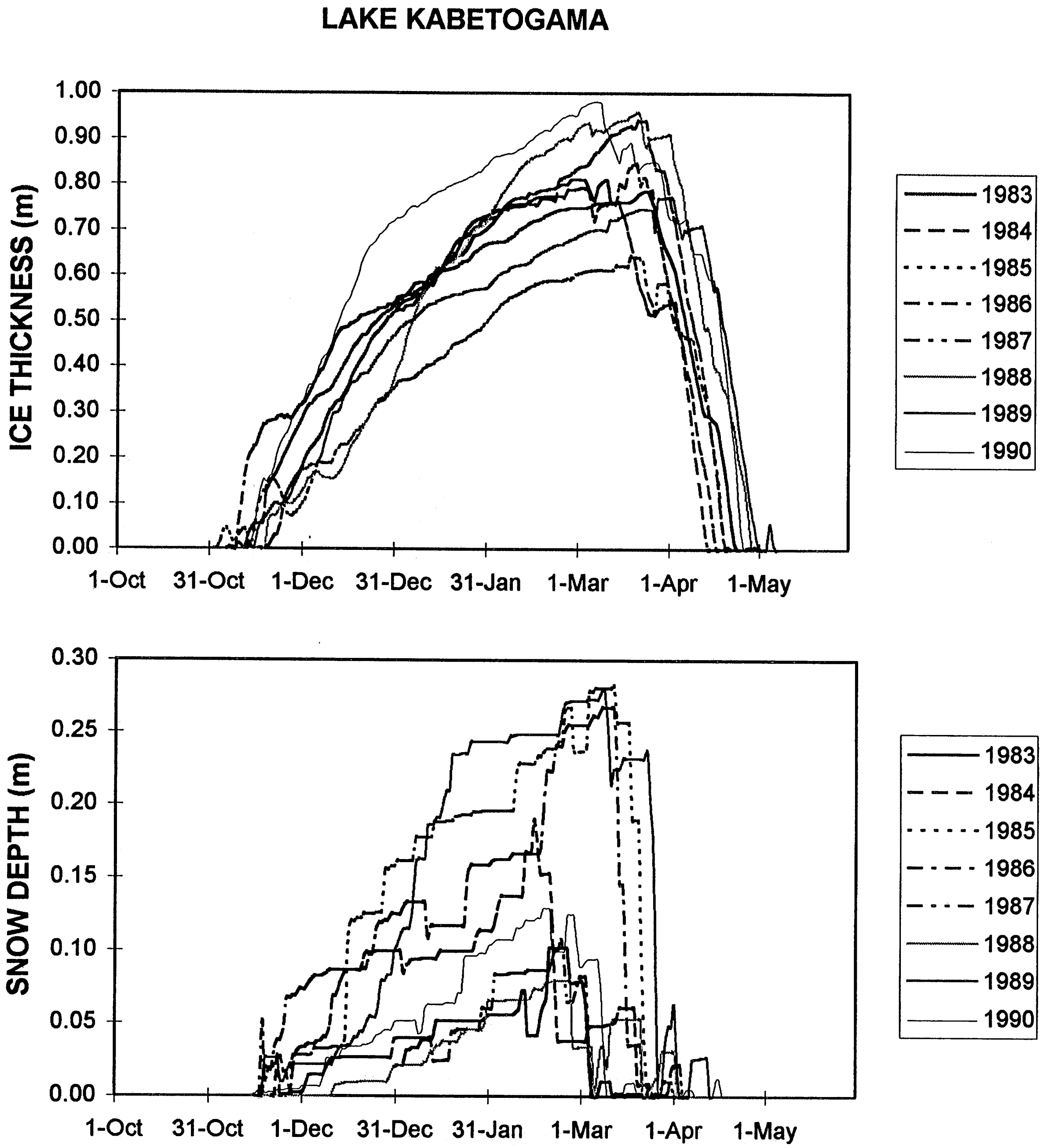


Fig 5.7.4 Ice thicknesses and snow depths from 1983 to 1990 on Lake Kabetogama

5.8 *Lake Winnibigoshish*

Lake Winnibigoshish is located in northern Minnesota. It has a surface area of 282.6 km^2 and a maximum depth of 21.3 m. A bathymetric map of the lake is given in Appendix A. Meteorological data from Duluth were used in the simulations.

The lake was simulated for the period from 1983 to 1990. Simulated temperatures were compared with only one day of field measurements (Fig 5.8.1). Field data were obtained from the Minnesota DNR. Standard error, slope of regression and R^2 were 0.91°C, 0.96 and -1.46, respectively.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.8.2 for 1990. Lake Winnibigoshish is slightly stratified during the open water season. For other years the plots are very similar. Mean annual surface water temperatures and standard deviations of daily surface water temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.8.3).

The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.8.4 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.8.1 shows the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in late November or early December and the ice-out date in middle or late April. Fig 5.8.5 shows the variability in ice thickness and snow depths from year 1983 to 1990.

Table 5.8.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Lake Winnibigoshish from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/26	04/18	04/18	04/16	04/09	04/19	05/07	04/24
Ice-in date	11/24	11/10	11/13	11/10	12/20	11/07	11/16	12/24
Ice cover duration (days)	153	159	156	157	140	160	165	151
Max. ice thickness (m)	0.62	0.78	0.77	0.70	0.71	0.61	0.72	0.90
Date of max. thickness	03/29	03/20	03/08	03/26	03/03	03/22	04/01	03/08

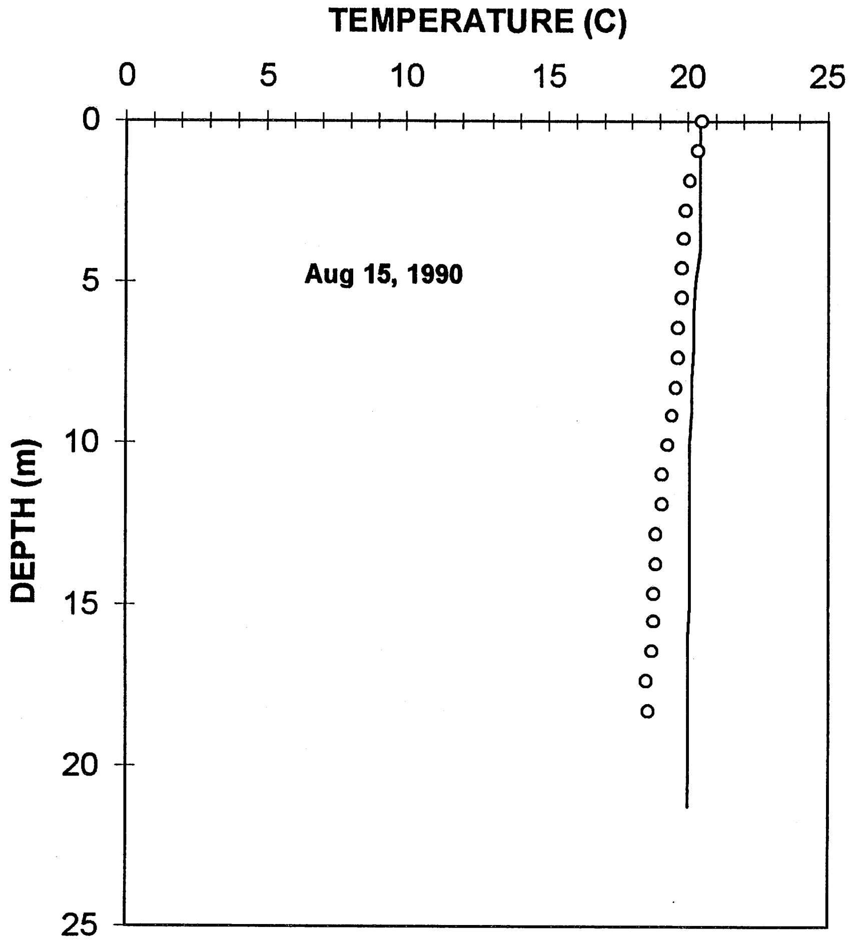


Fig 5.8.1 Simulated and measured temperature profiles for Lake Winnibigoshish

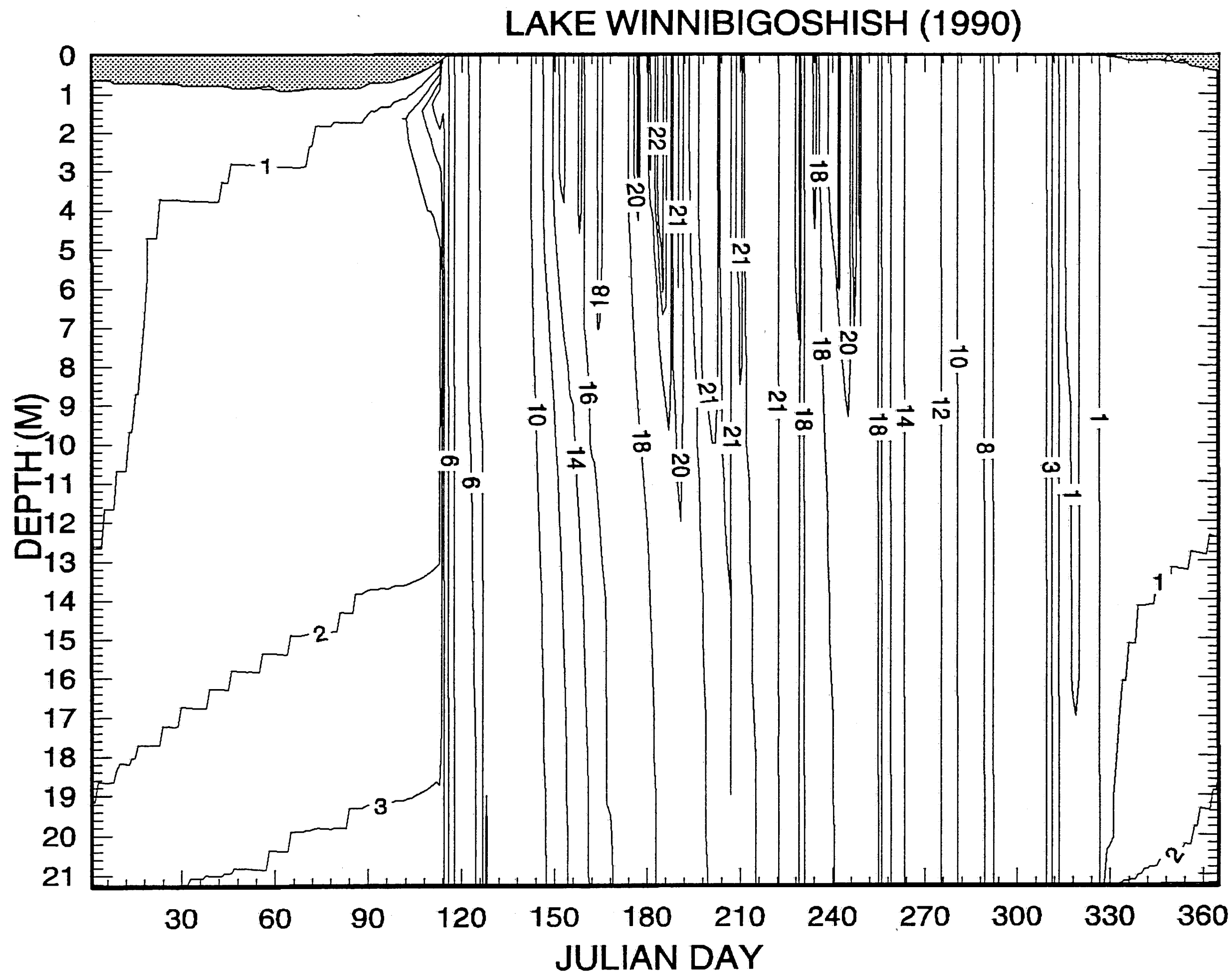


Fig 5.8.2 Isotherms (1990) interpolated from simulated daily water temperature profiles for Lake Winnibigoshish

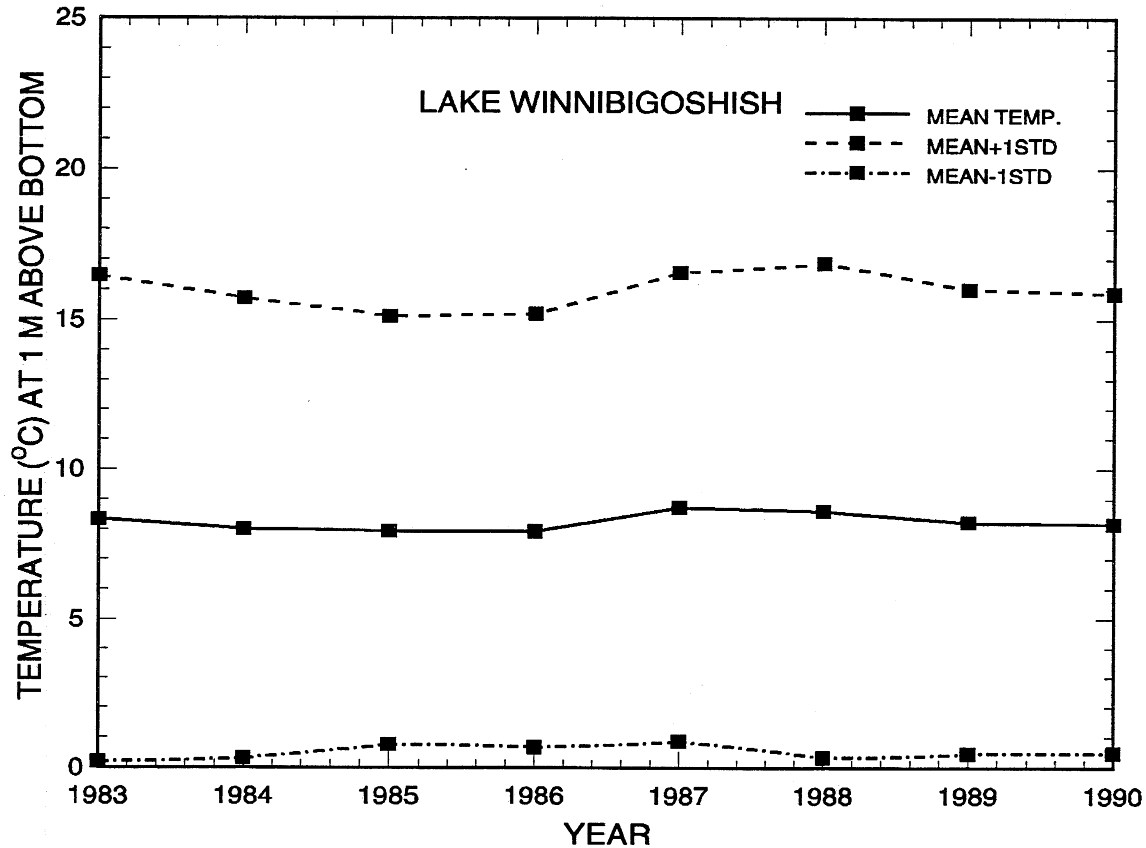


Fig 5.8.3 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Lake Winnibigoshish

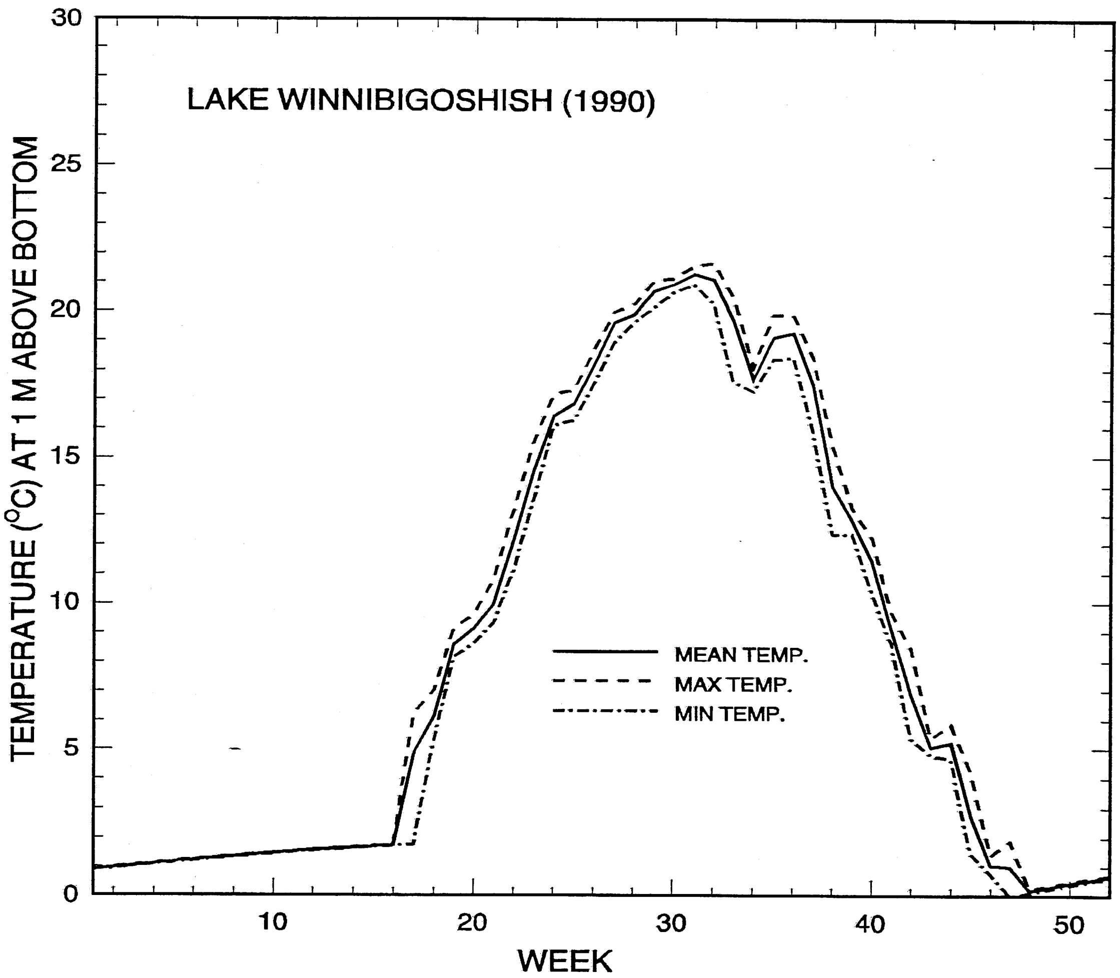


Fig 5.8.4 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Lake Winnibigoshish

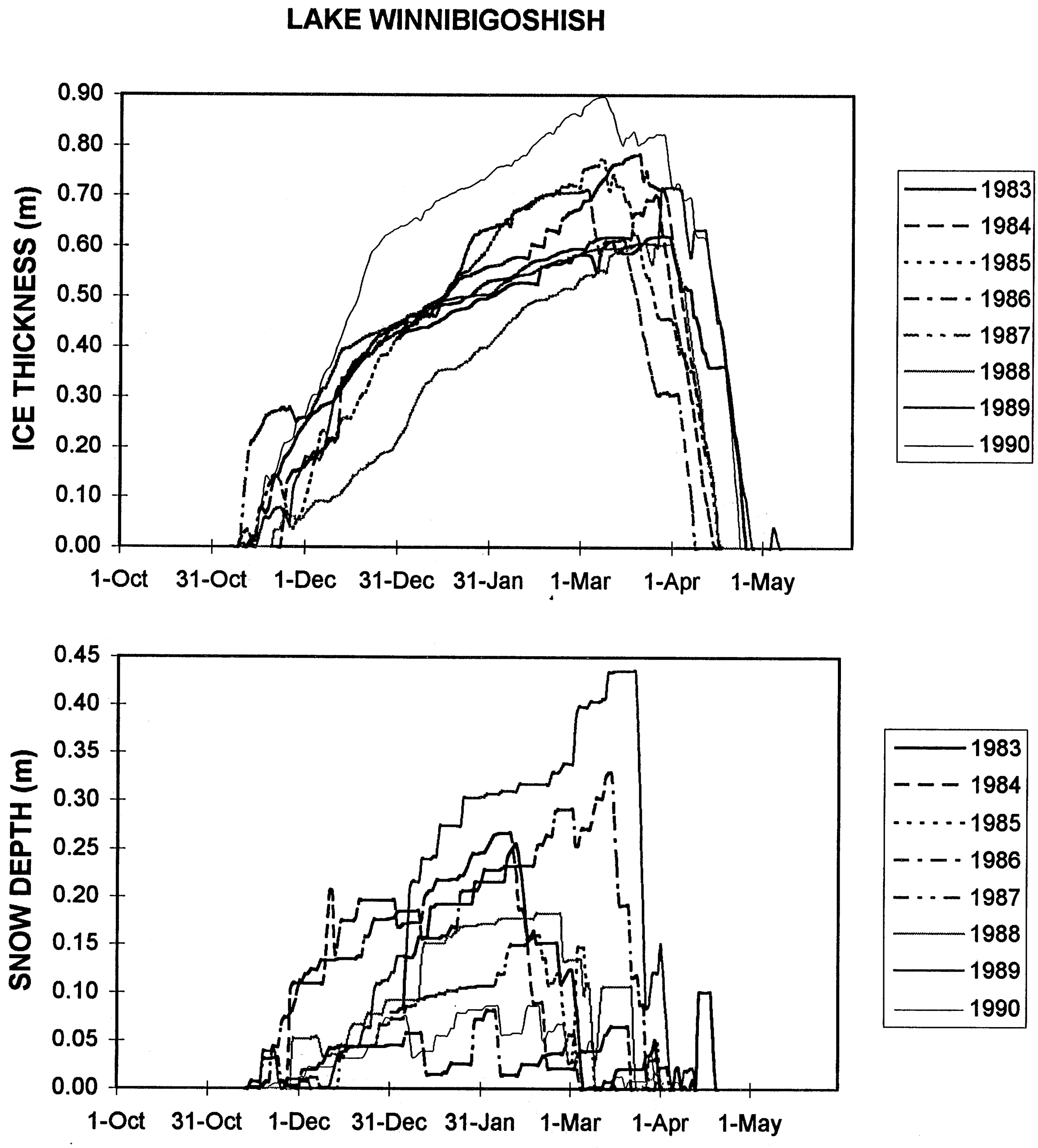


Fig 5.8.5 Ice thicknesses and snow depths from 1983 to 1990 on Lake Winnibigoshish

5.9 *Lake Pepin*

Lake Pepin is located in southeastern Minnesota. The lake is an enlargement of the Mississippi River. It has a surface area of 101.4 km^2 and a maximum depth of 18.3 m. A bathymetric map of the lake is given in Appendix A. Meteorological data from Rochester were employed in the simulations.

The lake was simulated for the period from 1983 to 1990. Simulated temperatures were compared with 29 days of field measurements. Field data were obtained from the USEPA water quality database STORET. Standard error, slope of regression and R^2 were 0.93°C, 1.01 and 0.98, respectively. Some measured and simulated temperature profiles are shown in Fig. 5.9.1.

The hydraulic residence time of the lake calculated from 1996 water year water resources data was about 10 days. The flow of the Mississippi River through Lake Pepin was not included in the simulations. It is planned to remedy this at a later time.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.9.2 for 1990. Lake Pepin is well mixed during open water seasons except a short time around mid-summer during which the lake is slightly stratified. For other years the plots are very similar. Surface water temperatures (at 1 m depth) are shown in Fig. 5.9.3. Mean annual surface water temperatures and standard deviations of daily surface water temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.9.4).

The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.9.5 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.9.1 shows the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in late November or early December and the ice-out date in middle or late April. Fig 5.9.6 shows the variability in ice thickness and snow depths from 1983 to 1990.

Table 5.9.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Lake Pepin from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/19	04/15	04/09	04/09	04/04	04/03	05/07	04/12
Ice-in date	11/27	12/02	11/22	11/18	12/04	11/28	11/23	12/14
Ice cover duration (days)	141	135	133	142	111	127	147	117
Max. ice thickness (m)	0.50	0.70	0.78	0.76	0.43	0.55	0.75	0.70
Date of max. thickness	12/30	02/10	02/27	03/16	02/05	02/27	3/08	2/28

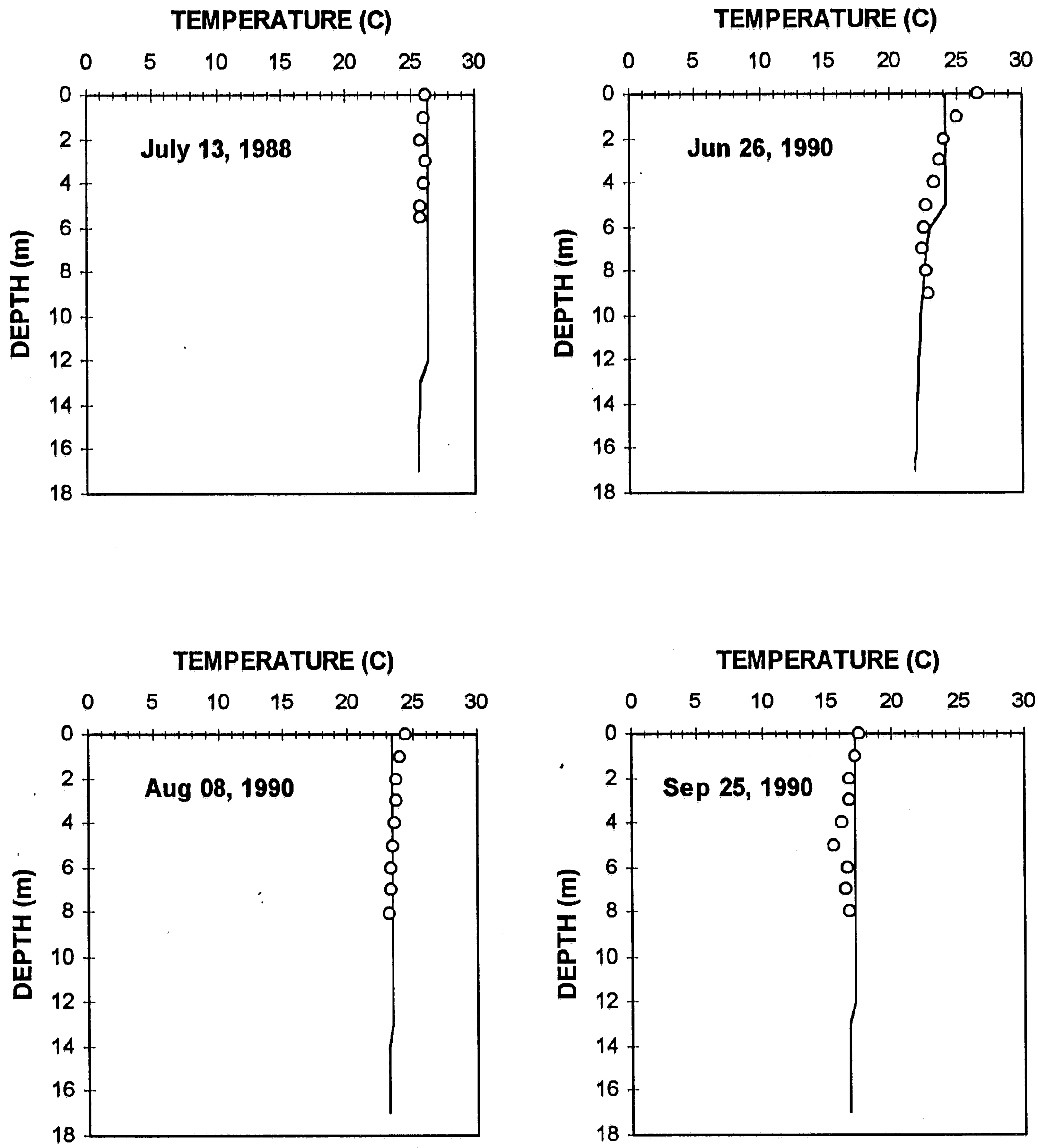


Fig 5.9.1 Some simulated and measured temperature profiles for Lake Pepin

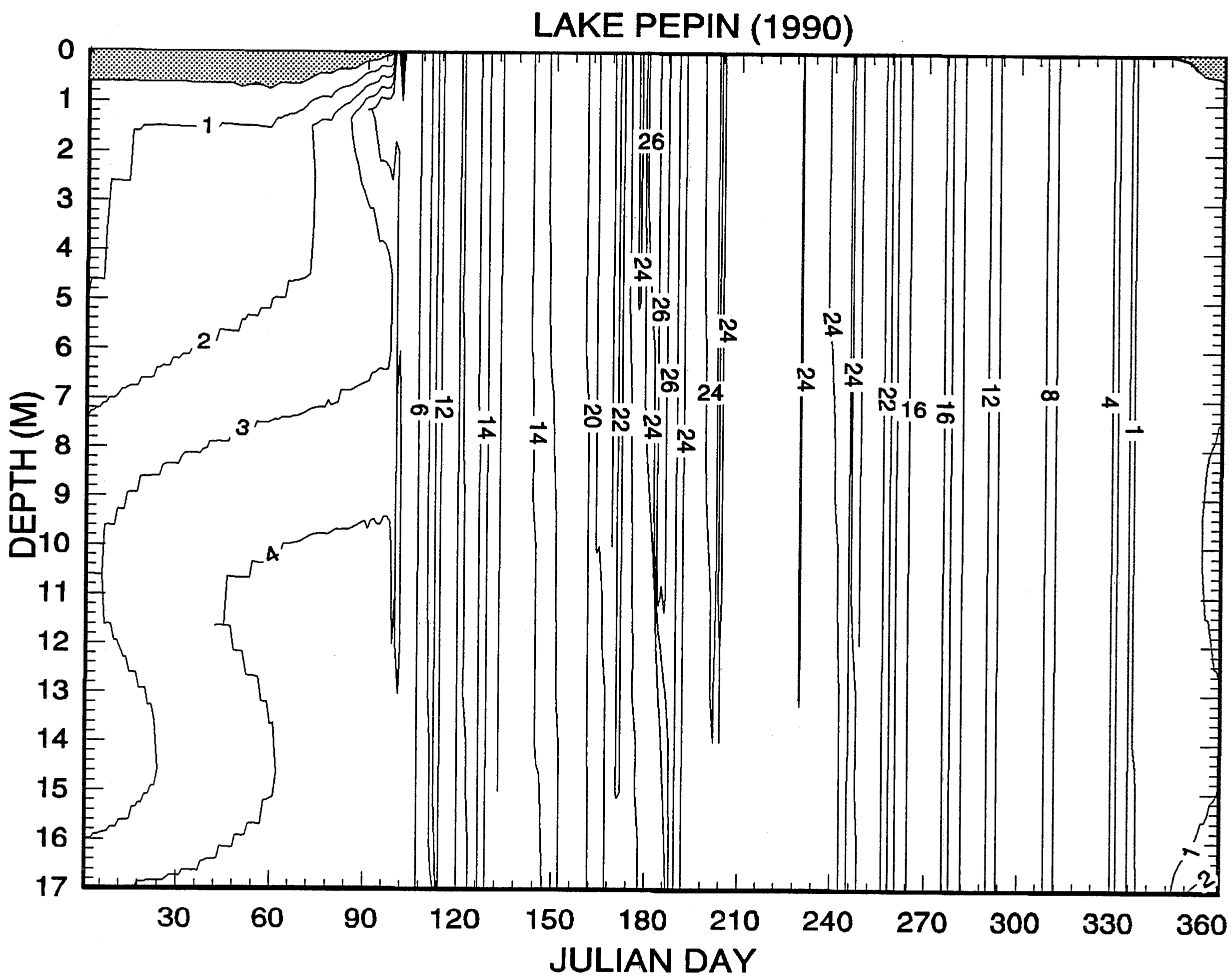


Fig 5.9.2 Isotherms (1990) interpolated from simulated daily water temperature profiles for Lake Pepin

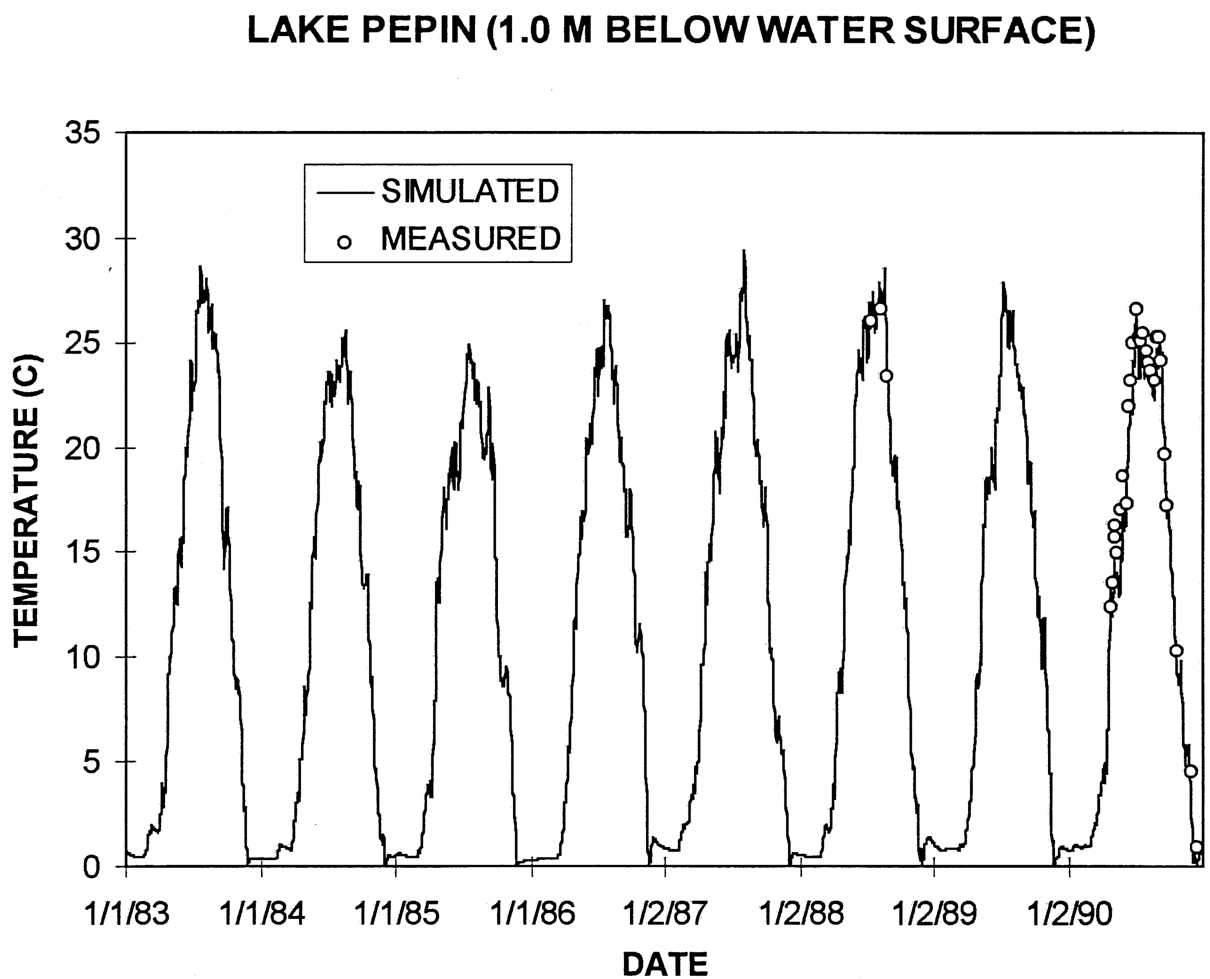


Fig 5.9.3 Simulated and measured temperatures 1 m below water surface of Lake Pepin

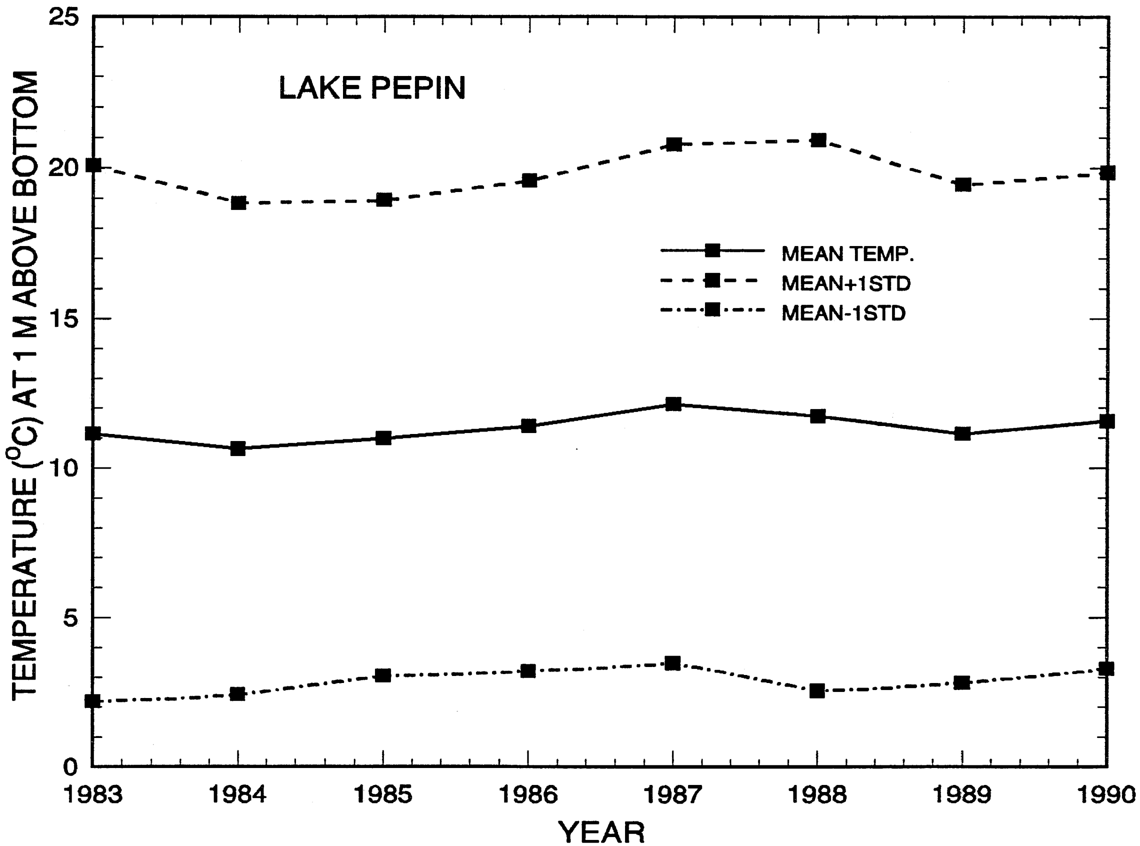


Fig 5.9.4 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Lake Pepin

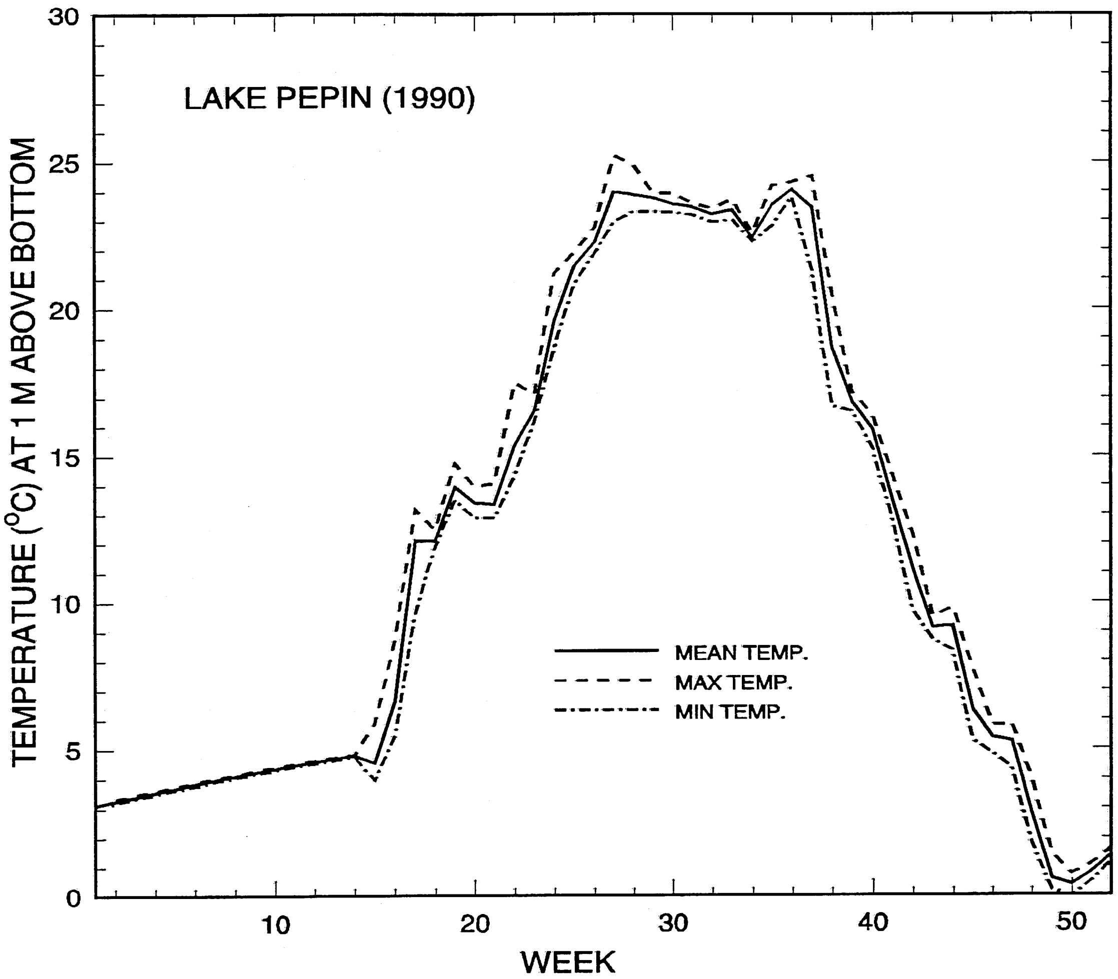


Fig 5.9.5 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Lake Pepin

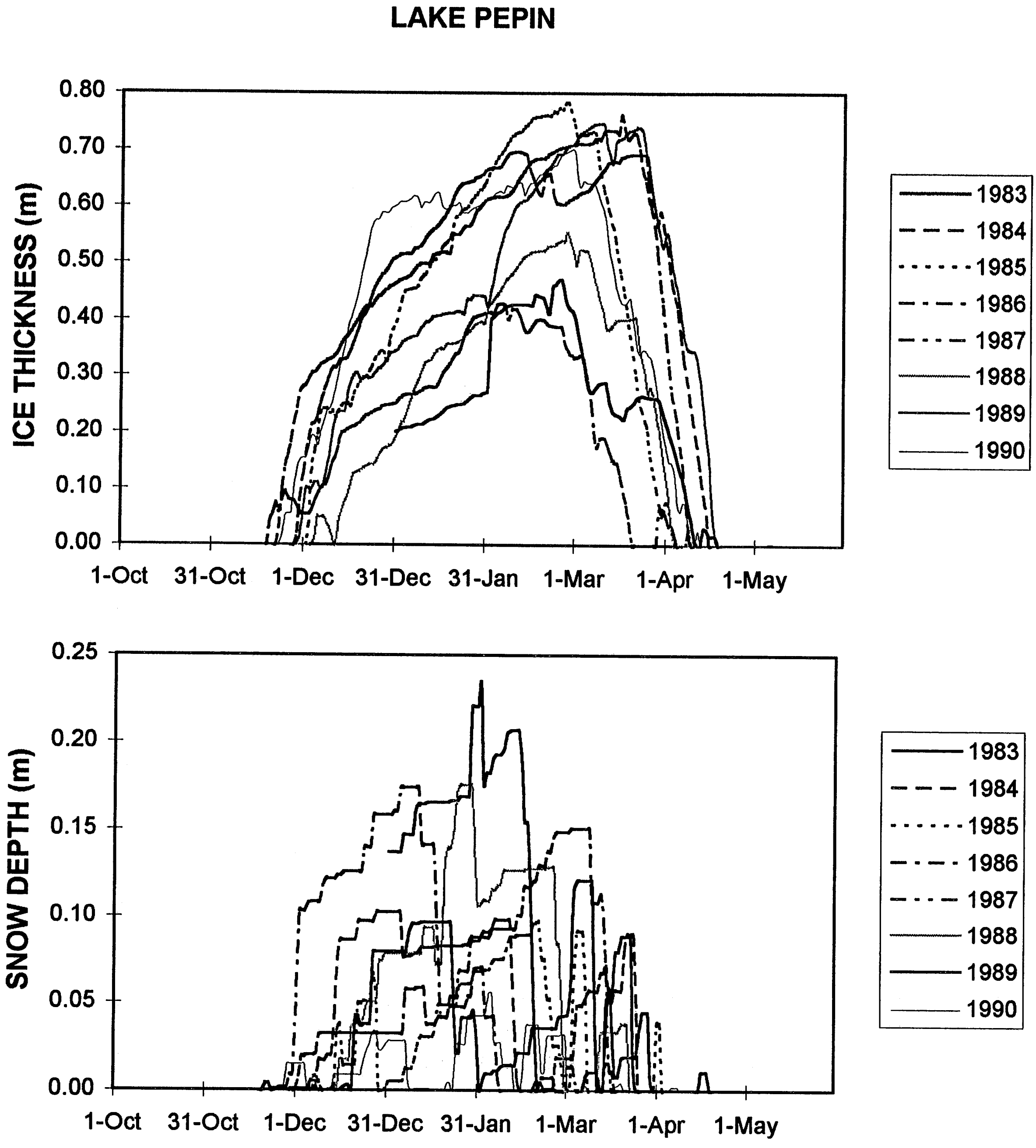


Fig 5.9.6 Ice thicknesses and snow depths from 1983 to 1990 on Lake Pepin

5.10 Rainy Lake

Rainy Lake is located at the northern border of Minnesota. The Rainy River flows through it. It has a surface area of 893.6 km^2 and a maximum depth of 49.1 m. No bathymetric map is available for this lake. Meteorological data from International Falls were used in the simulations.

The lake was simulated for the period from 1983 to 1990. No field data were available to compare with the simulation results.

The flow of the Rainy River through Rainy Lake was not included in the simulations. The hydraulic residence time of the lake calculated from 1996 water year water resources data was about one year. So, the inflow should have no significant effect on the simulation results.

Isotherms interpolated from simulated daily water temperature profiles are given in Fig. 5.10.1 for 1990. Rainy Lake is strongly stratified in the open water season. For other years the plots are very similar. Mean annual surface water temperatures and standard deviations of daily surface water temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.10.2).

The values of mean weekly water temperatures at 1 m above the deepest point of the lake are illustrated in Fig. 5.10.3 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.10.1 shows the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness. The ice-in date is usually in December and the ice-out date in late April. Fig 5.10.4 shows the variability in ice thickness and snow depths from 1983 to 1990.

Table 5.10.1 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for Rainy Lake from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/21	04/21	04/26	04/22	04/11	04/29	05/07	05/02
Ice-in date	12/12	12/18	12/05	12/12	12/24	12/11	12/11	12/21
Ice cover duration (days)	130	127	142	131	108	140	141	127
Max. ice thickness (m)	0.66	1.00	0.93	0.96	0.65	0.91	0.70	0.91
Date of max. thickness	03/01	03/19	03/20	03/15	03/03	03/22	4/01	3/07

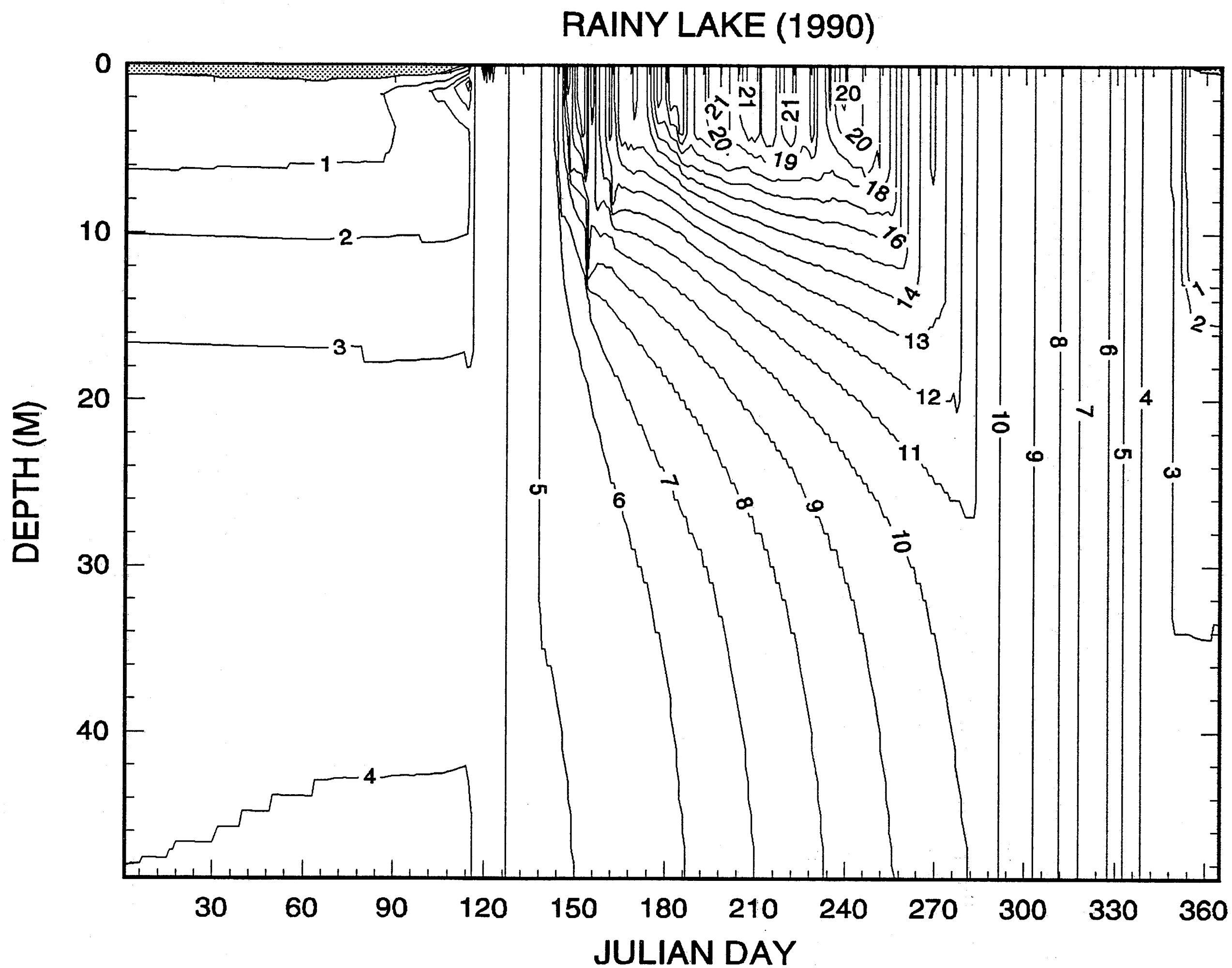


Fig 5.10.1 Isotherms (1990) interpolated from simulated daily water temperature profiles for Rainy Lake

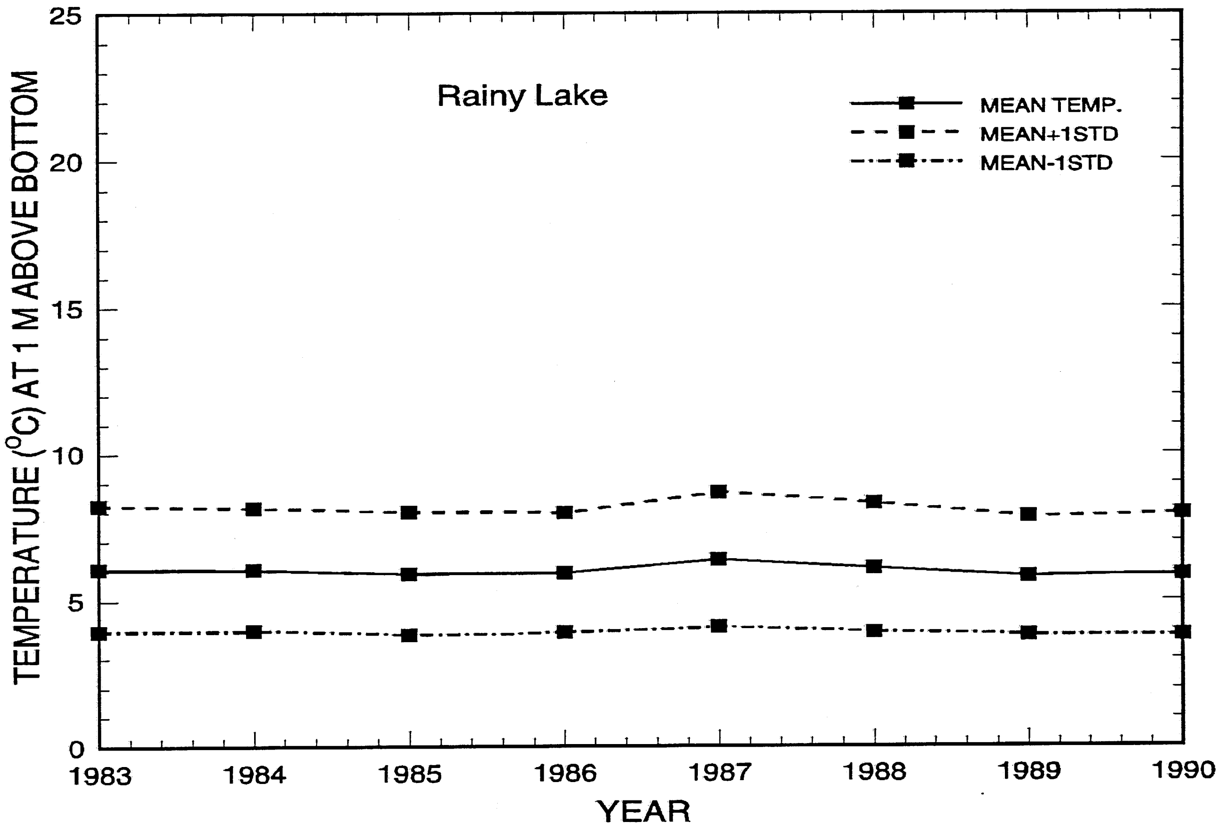


Fig 5.10.2 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Rainy Lake

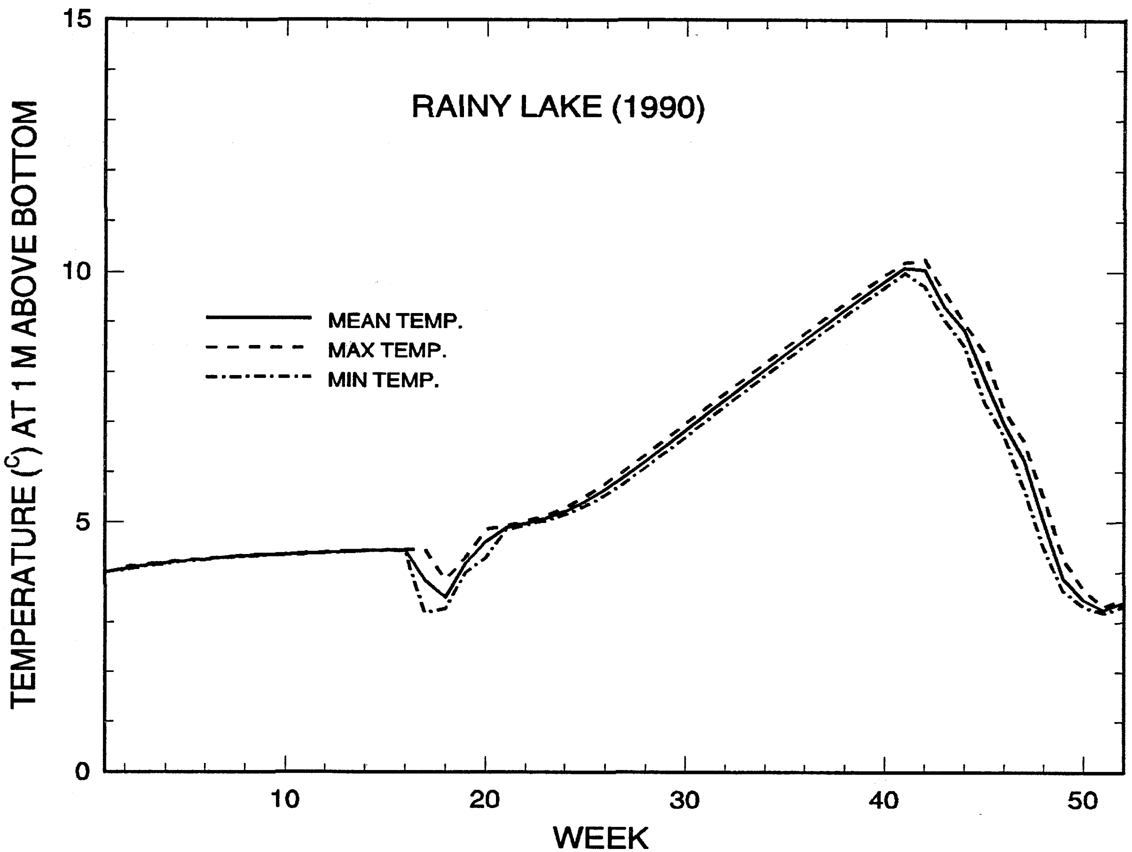
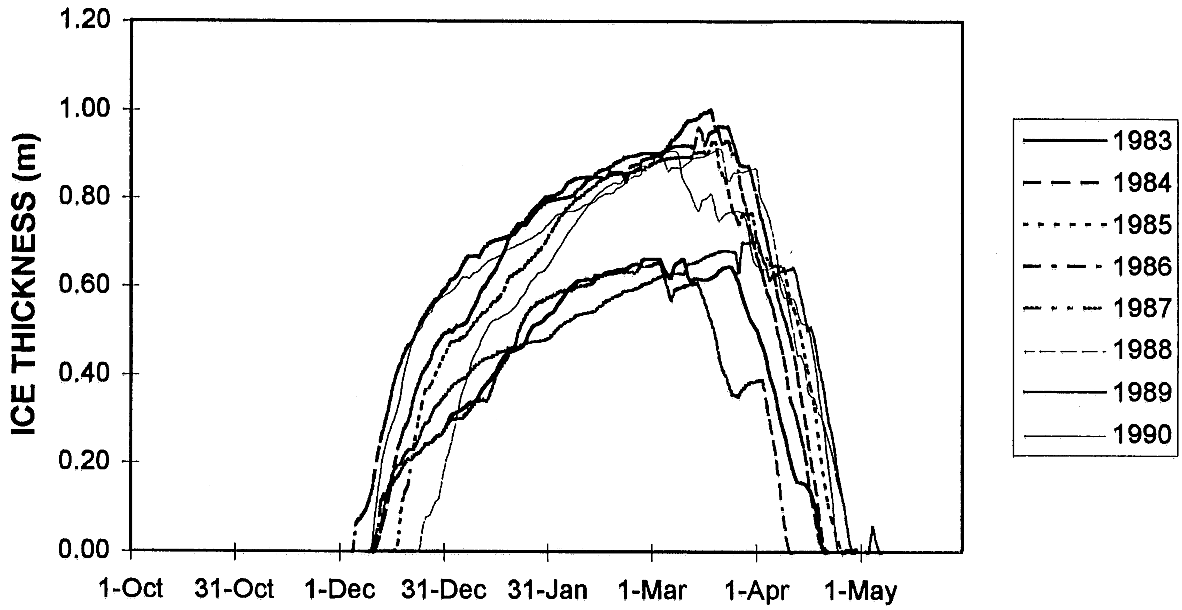


Fig 5.10.3 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Rainy Lake

RAINY LAKE



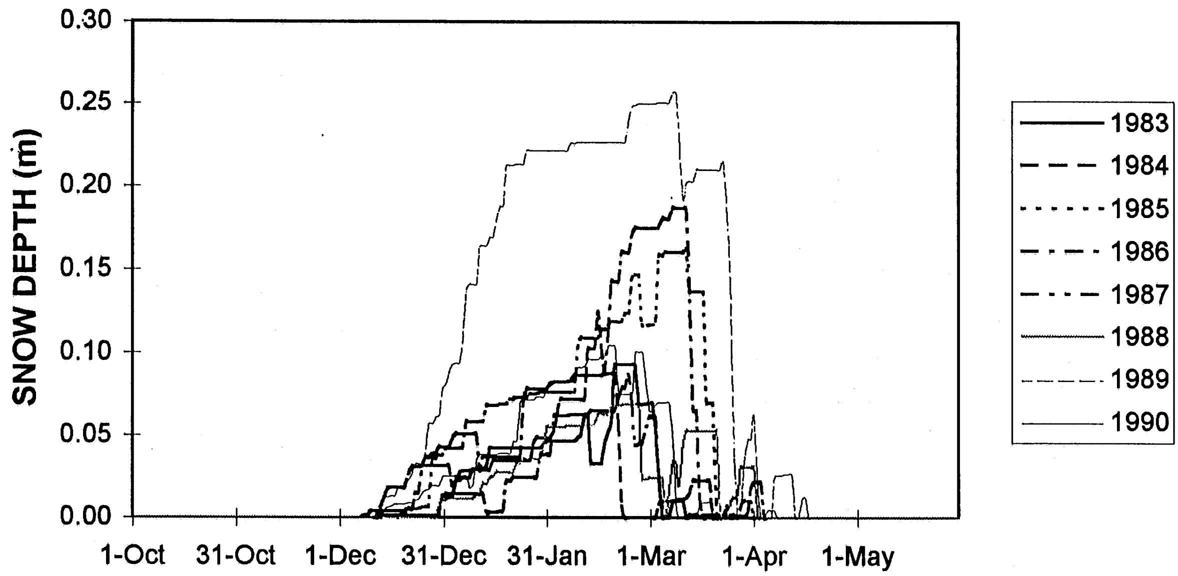


Fig 5.10.4 Ice thicknesses and snow depths from 1983 to 1990 on Rainy lake

5.11 Cass Lake

Cass Lake is located in northern Minnesota. The Mississippi River flows through it. It has a surface area of 63.12 km^2 and a maximum depth of 36.6m. It has five main basins. A bathymetric map of the lake is given in Appendix A. The five basins are indicated on a second map, also given in Appendix A. Horizontal areas vs. depths for all five basins are given in Fig. 5.11.1. Meteorological data from Fargo were used in the simulations (meteorological data from Duluth provided a less good fit to measurements).

Basins 1, 3 and 4 were simulated separately from 1983 to 1990. Simulation results were compared with field data provided by the Minnesota Department of Natural Resources. Standard error, slope of regression and R^2 values are given in Table 5.11.1.

Table 5.11.1 Standard error, slope of regression and R^2 for basins 1,3 and 4 of Cass Lake

	Basin 1	Basin 3	Basin 4
Standard Error (°C)	2.38	1.34	1.94
Slope of regression	1.11	0.96	0.95
R^2	0.50	0.50	0.27

Figs. 5.11.2 and 5.11.3 show simulated and measured temperature profiles for basins 1 and 4 and basin 3.

The flow of the Mississippi River through Cass Lake was not included in the simulations. The hydraulic residence time of the lake calculated from 1996 water year water resources data was about 2.34 years. So, the inflow should have no significant effect on the simulation results.

Isotherms interpolated from simulated daily water temperature profiles are given in Figs. 5.11.4, 5.11.5 and 5.11.6 for 1990 for basin 1, basin 3 and basin 4, respectively. All three basins simulated are strongly stratified in the open water season. For other years the plots are very similar. Mean annual water temperatures and standard deviations of daily temperatures from the annual mean are remarkably consistent from year to year (Fig. 5.11.7, 5.11.8 and 5.11.9). The values of mean weekly water temperatures at 1 m above the deepest point of the basins are illustrated in Figs. 5.11.10, 5.11.11 and 5.11.12 for 1990. Maximum and minimum daily water temperatures in each week are also plotted.

Table 5.11.2 shows the earliest simulated ice-in and latest ice-out dates, ice cover duration, the maximum ice thickness and the date of maximum ice thickness for basin 3. The ice-in date is usually in late November and the ice-out date in mid-April. Fig 5.11.13 shows the variability in ice thickness and snow depths from year 1983 to 1990 for basin 3. The simulation results of ice data for basin 1 and basin 4 are very similar with those of basin 3. There are no significant differences among them.

Table 5.11.2 Ice-in date, ice-out date, maximum ice thickness and the date of maximum ice thickness for basin 3 from 1983 to 1990

	1983	1984	1985	1986	1987	1988	1989	1990
Ice-out date	04/20	04/10	04/11	04/16	04/06	04/19	04/22	04/18
Ice-in date	11/26	11/18	11/20	11/14	12/01	11/20	11/18	11/27
Ice cover duration (days)	145	142	142	153	126	144	153	142
Max. ice thickness (m)	0.69	0.69	0.78	0.84	0.57	0.70	0.71	0.80
Date of max. thickness	02/17	03/19	03/08	03/11	02/04	03/04	3/22	2/27

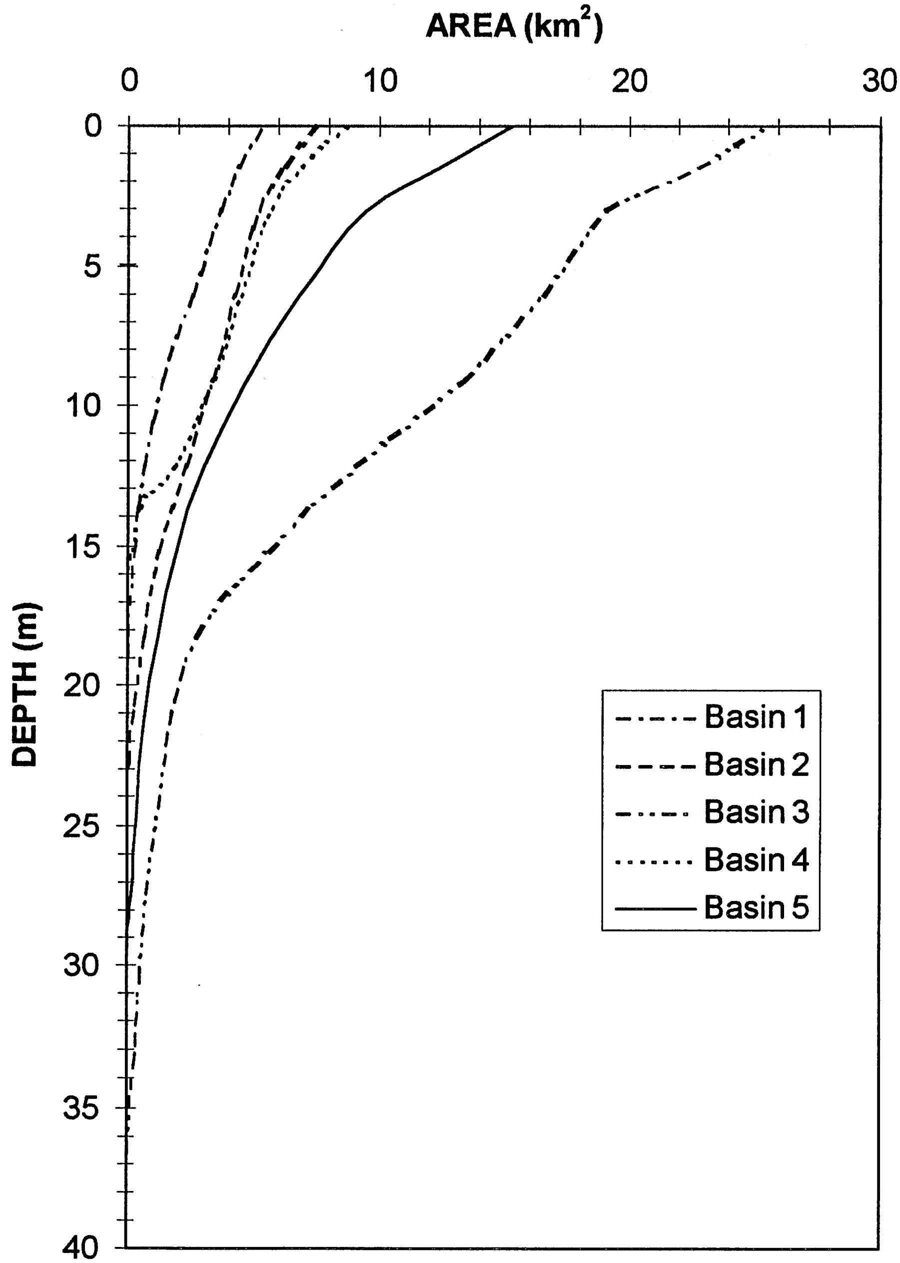


Fig 5.11.1 Horizontal areas vs. depths for all five basins in Cass Lake

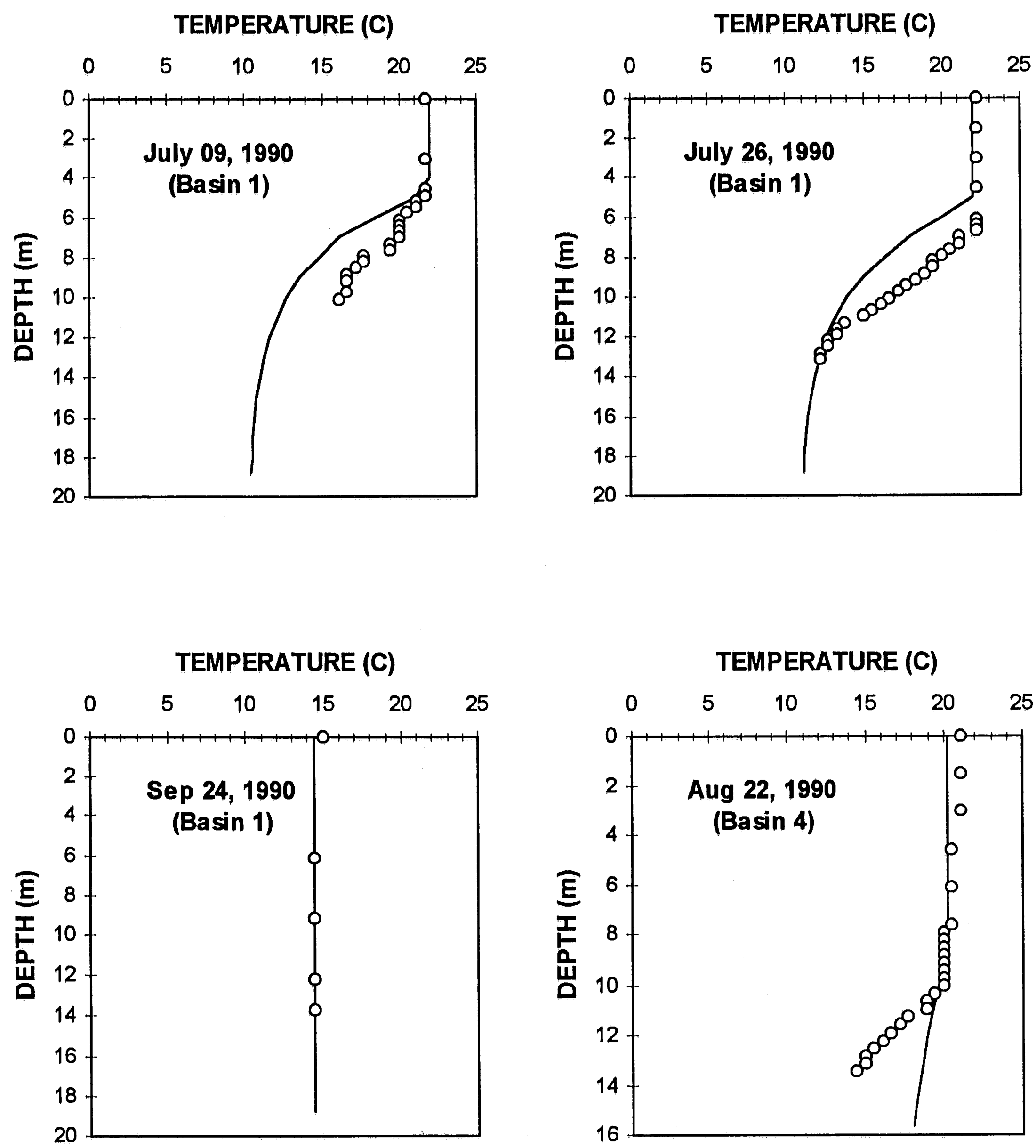
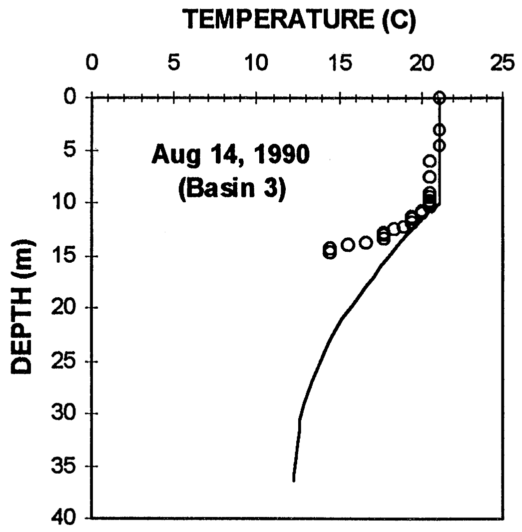


Fig 5.11.2 Simulated and measured temperature profiles for basin 1 and basin 4 of Cass Lake



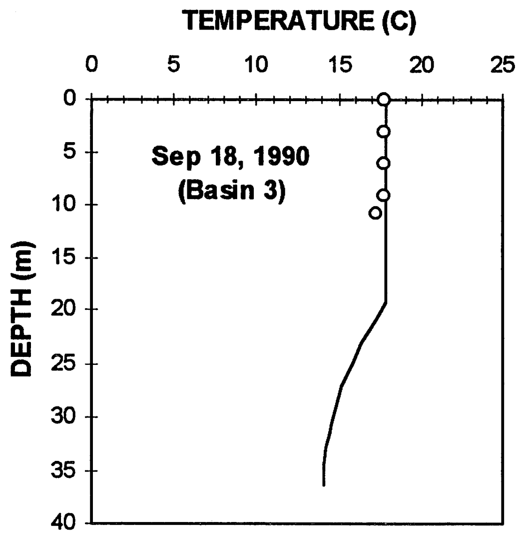


Fig 5.11 3 Simulated and measured temperature profiles for basin 3 of Cass Lake

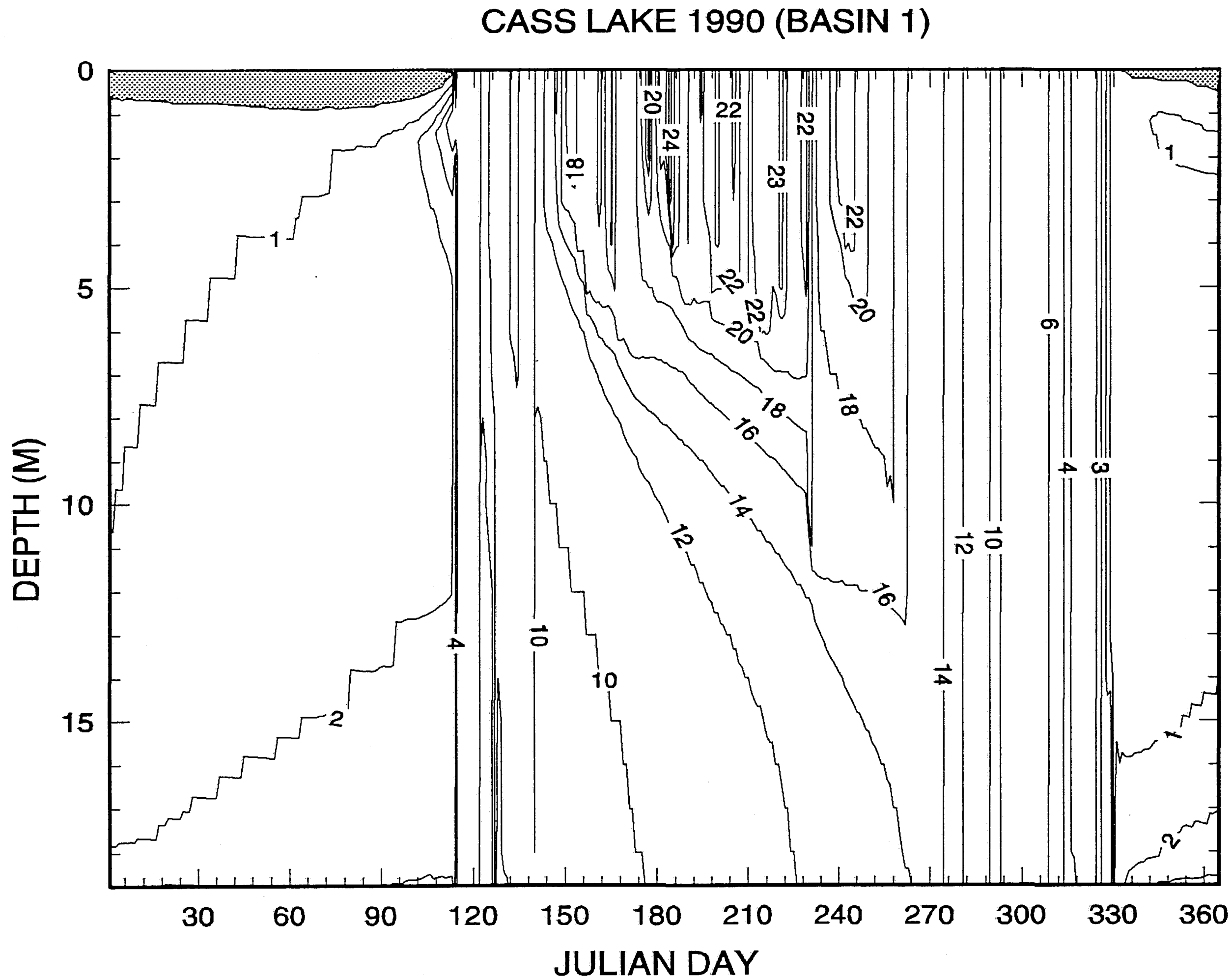


Fig 5.11.4 Isotherms (1990) interpolated from simulated daily water temperature profiles for Cass Lake (Basin 1)

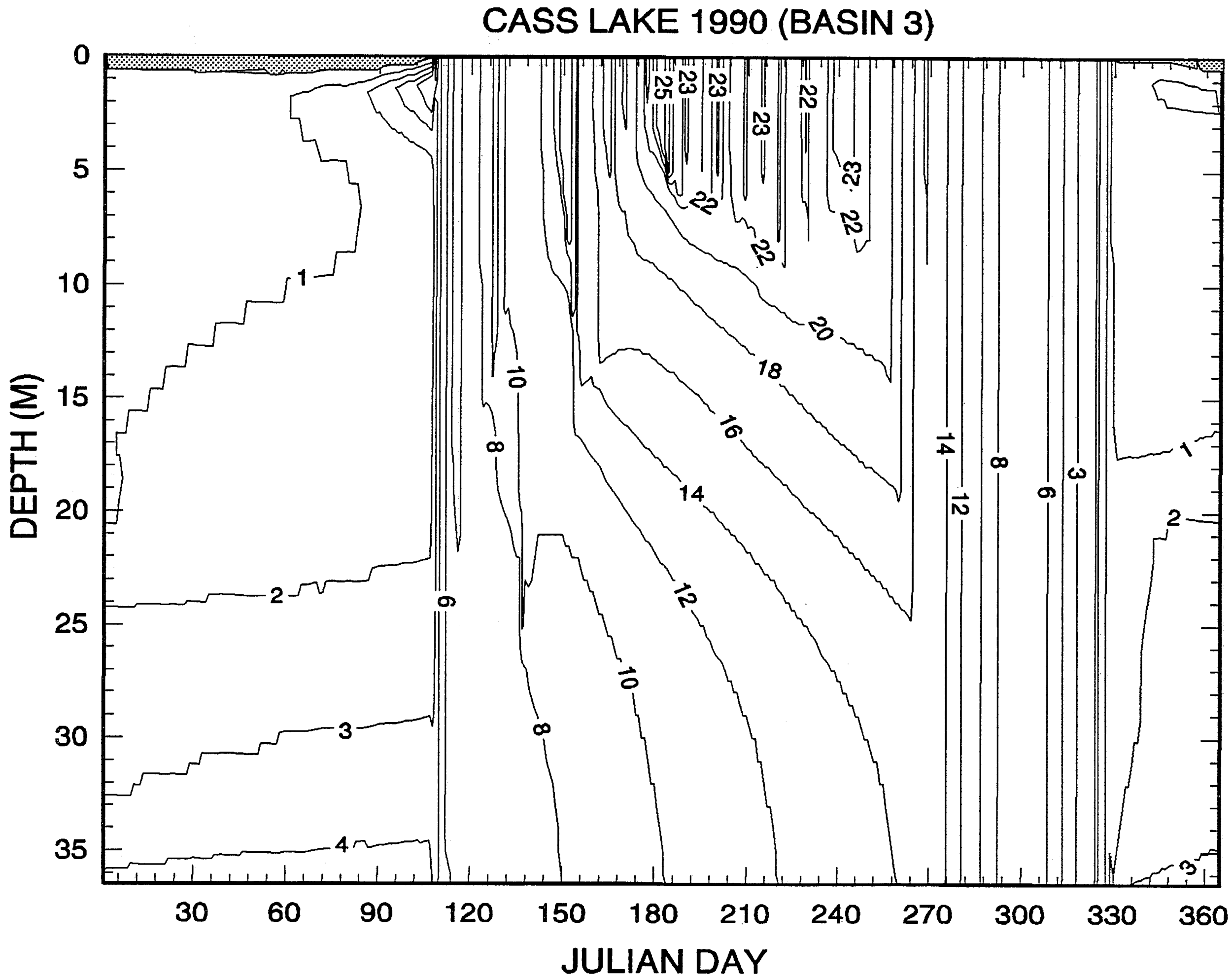


Fig 5.11.5 Isotherms (1990) interpolated from simulated daily water temperature profiles for Cass Lake (Basin 3)

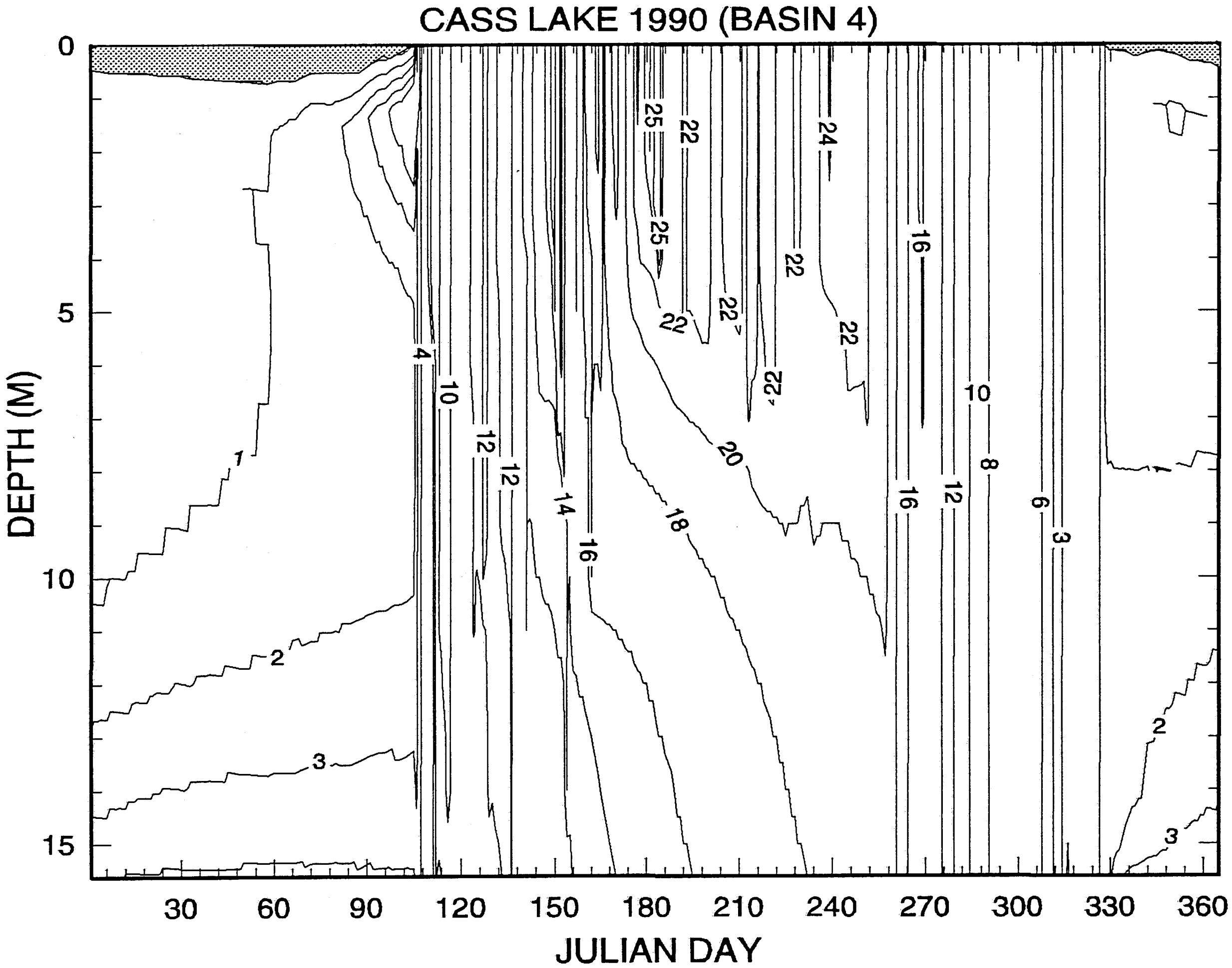


Fig 5.11.6 Isotherms (1990) interpolated from simulated daily water temperature profiles for Cass Lake (Basin 4)

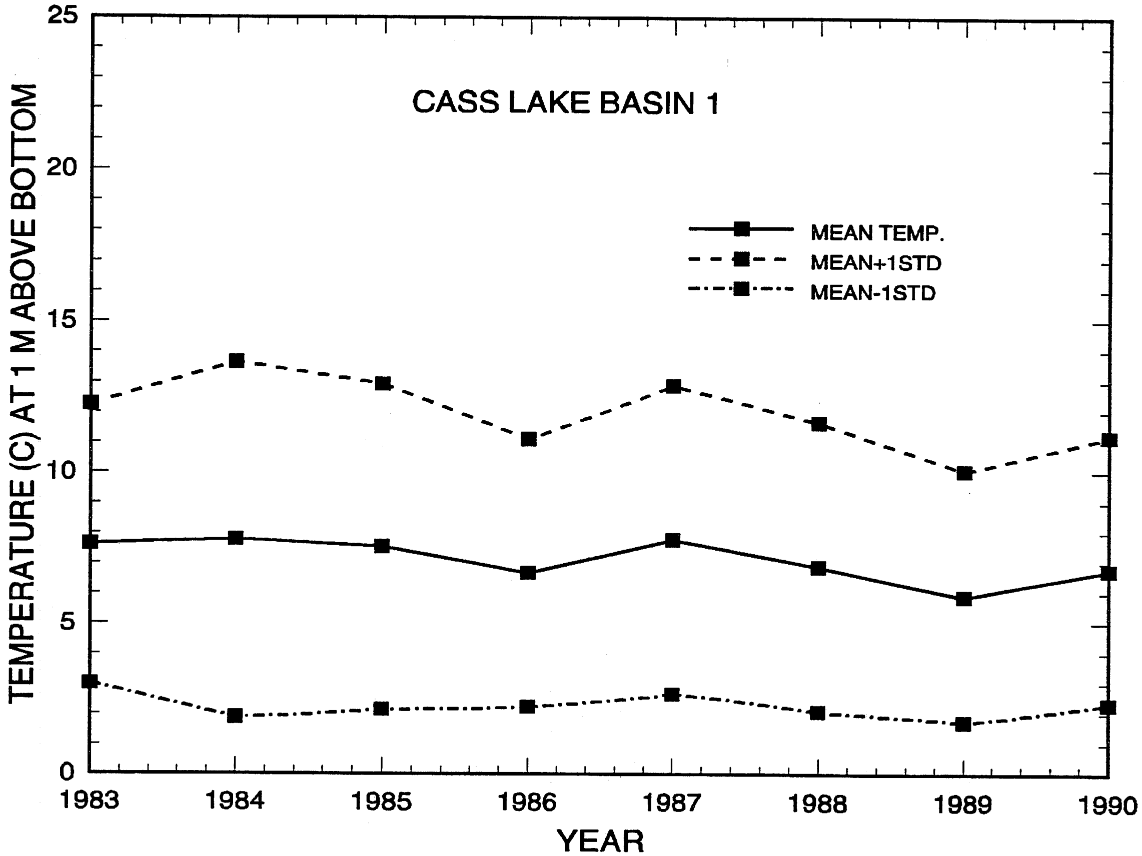


Fig 5.11.7 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Cass Lake (Basin 1)

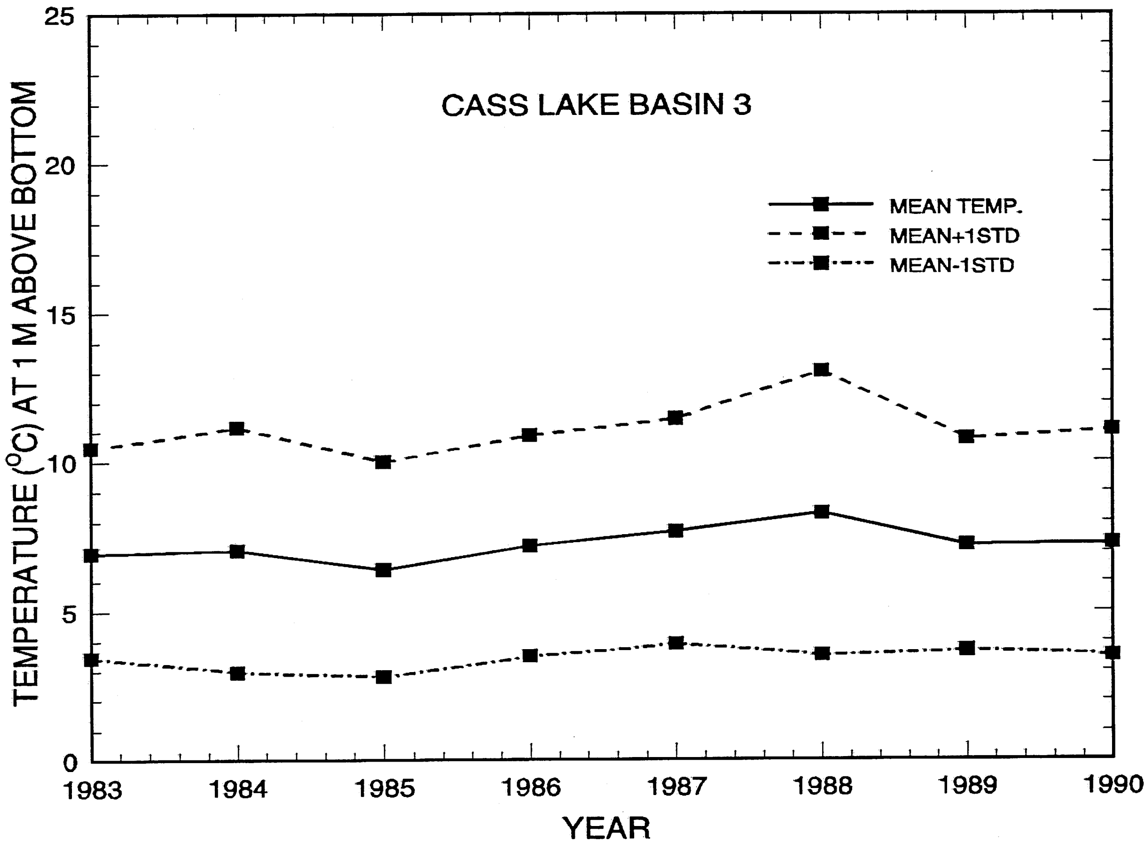


Fig 5.11.8 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Cass Lake (Basin 3)

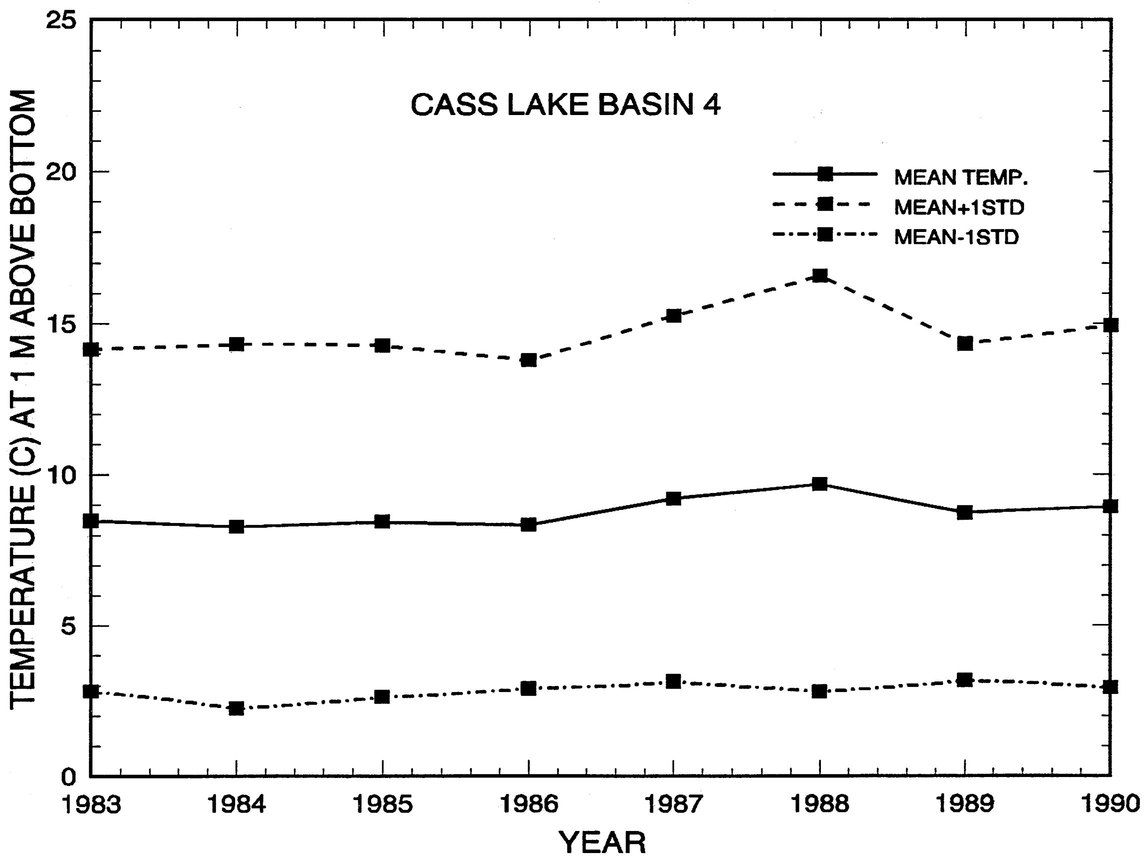


Fig 5.11.9 Mean daily water temperature plus/minus 1 standard deviation 1 m above the deepest point of Cass Lake (Basin 4)

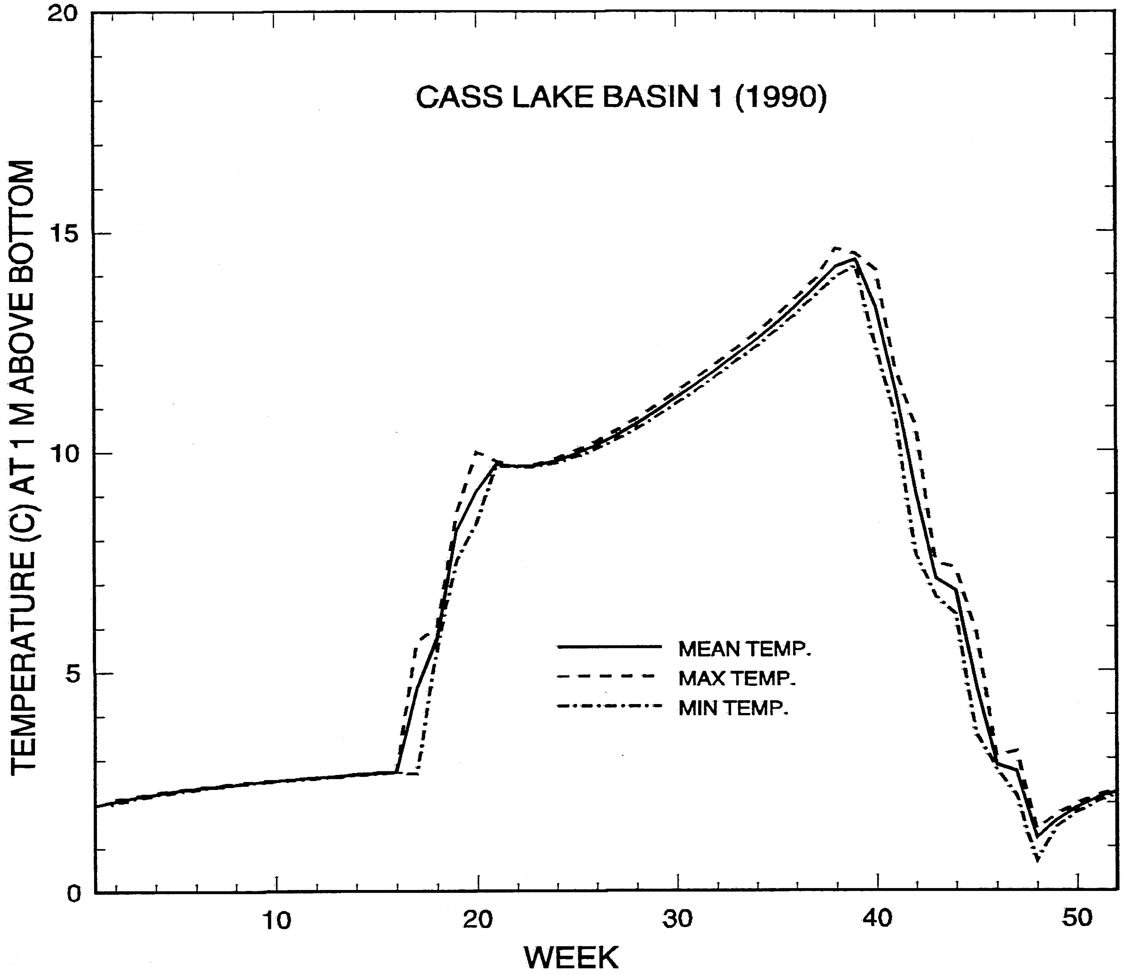


Fig 5.11.10 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Cass Lake (Basin 1)

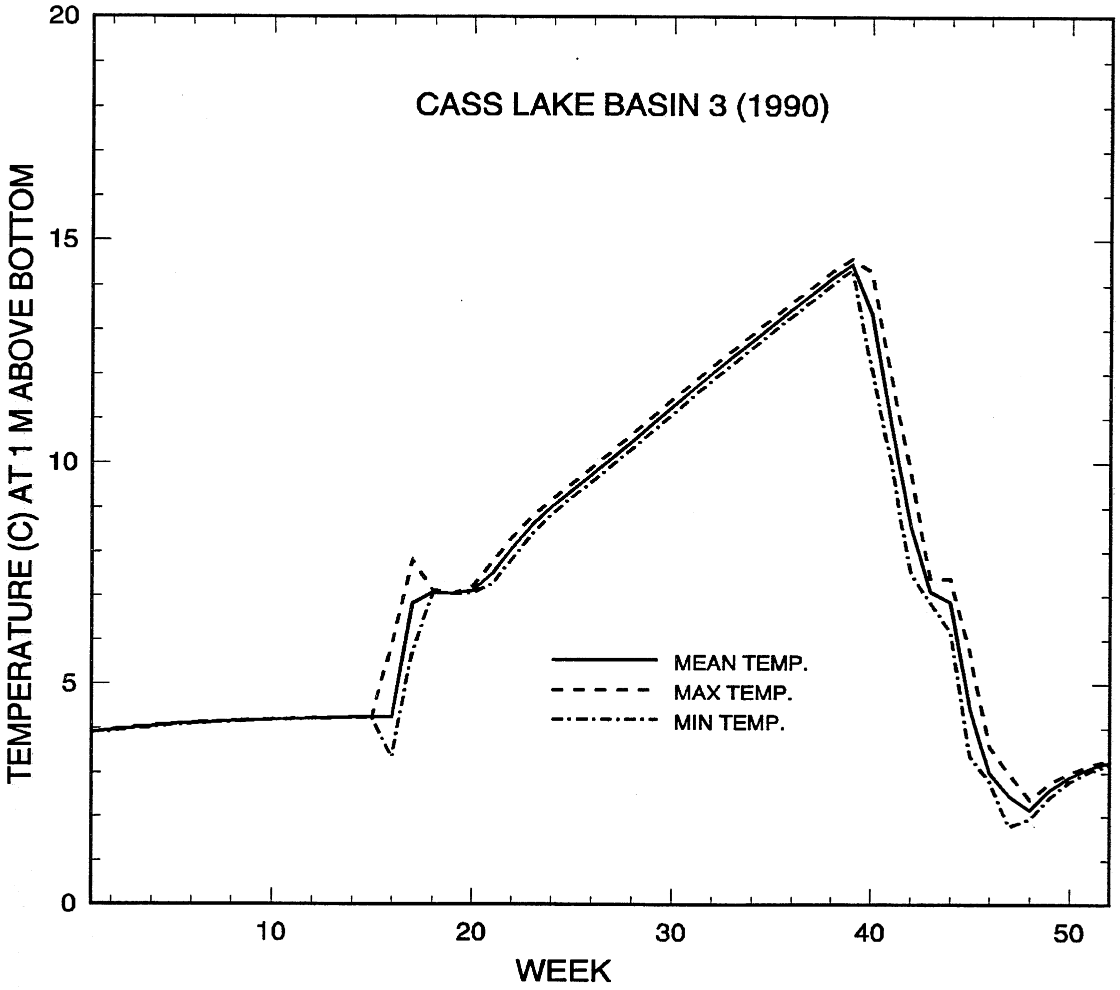


Fig 5.11.11 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Cass Lake (Basin 3)

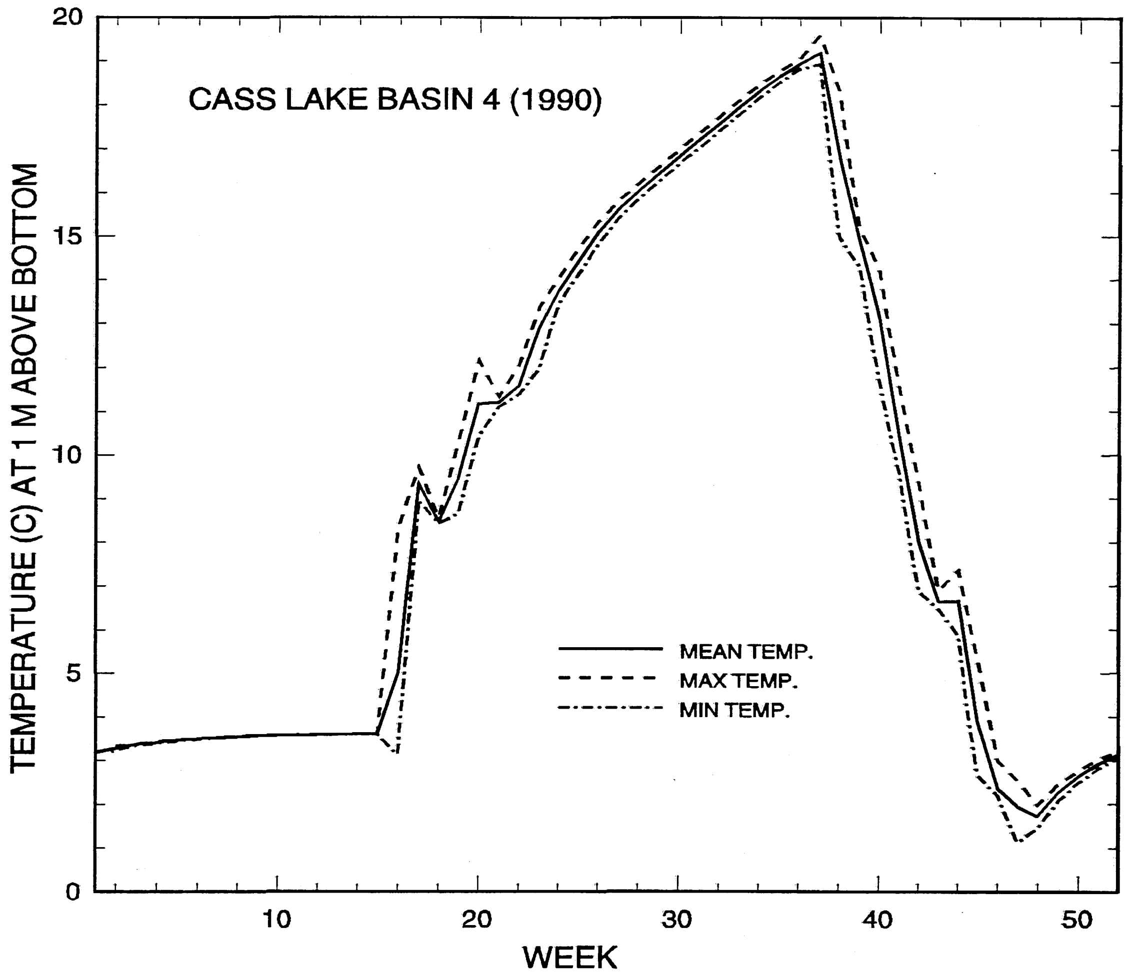


Fig 5.11.12 Mean weekly water temperatures, weekly maximum and minimum water temperatures 1 m above the deepest point of Cass Lake (Basin 4)

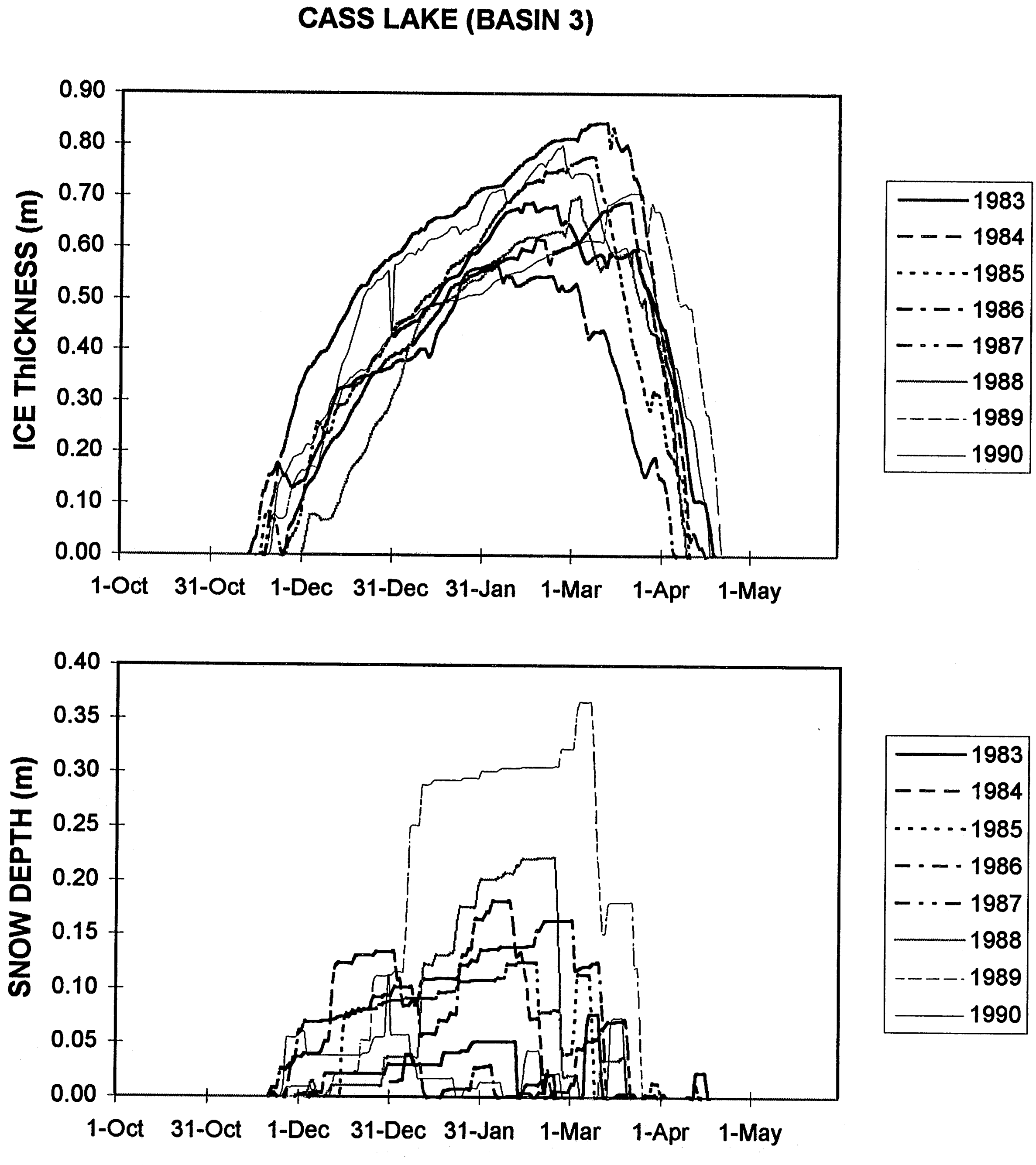


Fig 5.11.13 Ice thicknesses and snow depths from 1983 to 1990 on Cass Lake (Basin 3)

6. Comparisons of the Simulated Water Temperature and Ice Characteristics of the Ten Lakes

Selected parameters which describe water temperature and ice and snow cover characteristics of the lakes (Table 6.1 and Table 6.2) were extracted from the simulation results and averaged over 8 years (from 1983 to 1990). For water temperature the characteristics include: maximum and minimum surface water temperatures, maximum and minimum lake bottom temperatures, maximum temperature difference between lake surface and bottom, open water stratification ratio, and duration of low bottom temperature. For ice and snow cover characteristics they include: the earliest and latest ice-in dates, the earliest and latest ice-out dates, duration of ice cover, total period of ice cover, continuous ice cover ratio, maximum ice thickness, average snow depth, and continuous snow cover ratio. The average values and standard deviations of these parameters for individual lakes are shown in Tables 6.3, 6.4, 6.5 and 6.6. These parameters are important in estimating fish thermal limited habitat and other parameters related to fish survival and fish growth.

Surface water temperatures are the temperatures at 1 m depth below the water surface. Fig. 6.1 shows the averaged time series of surface water temperatures for all lakes. Surface temperatures change moderately from one lake to another. Maximum surface water temperatures range from 27.3°C for Lake Pepin to 23.5 °C for Lake Winnibigoshish (Table 6.3). Minimum surface temperatures of 0°C occur in all lakes just before the ice-in date.

Water temperatures at the lake bottom are temperatures at 1m above the deepest point of a lake. Fig. 6.2 shows the averaged time series of bottom water temperatures for each lake. Unlike surface water temperatures, bottom water temperatures change significantly with lake geometry. Maximum bottom temperatures range from 26.3°C for Upper Red Lake to 10.4 °C for Rainy Lake (Table 6.3). Minimum lake bottom water temperatures vary with maximum lake depth. They range from 0°C for Upper Red Lake and Mille Lacs Lake to 3.3°C for Rainy Lake.

The difference between the surface and bottom water temperature of a lake is an indicator of the strength of stratification in a lake. Fig. 6.3 shows the temperature differences between surface and bottom water temperatures for all lakes. For shallow lakes the differences during the open water season are near zero which indicates that the lake is well mixed. Maximum difference between surface and bottom water temperatures range from 1.8°C for Mille Lacs Lake to 17.1 °C for Rainy Lake.

Open water stratification ratio is defined (Table 6.1) as the total number of days when stratification stronger than 1°C exists, divided by 365 days. It ranges from near zero for well mixed lakes (Lake of the Woods, Red Lake, Mille Lacs Lake, etc.) to 0.41 for Rainy Lake and Cass Lake (Basin 3).

The duration of bottom temperatures less than 8°C in a lake was also extracted from the simulation results. Warm water fish species stop feeding at close to 8°C. Below the feeding temperature fish experience zero or negative growth. The durations of bottom temperatures below 8°C ranges from 172 days for Lake Pepin to 281 days for Rainy Lake. It depends on lake depth as well as meteorological conditions.

The values of the parameters which describe ice and snow characteristics are shown in Table 6.4. Some parameters do not change significantly with lake geometry, but do change with meteorological conditions. Ice-in dates are usually in middle or late November, and ice-out dates in middle or late April. Maximum ice thicknesses range from 0.65m for Lake Pepin to 0.85m for Lower Red Lake. Duration of ice cover ranges from 131 days for Rainy Lake to 168 days for Upper Red Lake.

Table 6.1 Parameters used to define temperature characteristics.

Parameter	Description	Formulation/Definition
Max. surface temperature (°C)	Maximum daily temperature at 1.0 m below the lake surface (T_s)	$Max[T_s(t), t=1,365]$
Min. surface temperature (°C)	Minimum daily temperature at 1.0 m below the lake surface (T_s)	$Min[T_s(t), t=1,365]$
Max. bottom temperature (°C)	Maximum daily temperature at 1.0 m above the lake bottom = deepest point of lake (T_b)	$Max[T_b(t), t=1,365]$
Min. bottom temperature (°C)	Minimum daily temperature at 1.0 m above the lake bottom = deepest point of lake (T_b)	$Min[T_b(t), t=1,365]$
Maximum temperature difference (°C)	Maximum daily difference between surface water temperature and bottom water temperature	$Max\{[T_s(t)-T_b(t)], t=1,365\}$
Open-water stratification ratio	Total number of days during the open-water season (surface water temperature > 4°C) when difference between surface and bottom temperature is greater than 1°C divided by 365.	$OSR = \dfrac{\sum_{1}^{365} t\{[T_s(t)-T_b(t)] \geq 1^{o}C\}}{365}$ $T_s(t) > 4^{o}C$
Duration of low bottom temperature (days)	Total number of days in a year when bottom temperature T_b less than 2 and 8 °C	$D_n = \sum_{1}^{365} t[T_b(t) \leq n^{o}C]$ n=2, 8

Table 6.2 Parameters used to define winter ice and snow cover characteristics.

Parameter	Description	Formulation/ Definition
Earliest ice-in date	First day with ice cover in fall, but ice may melt out (t_{ei})	/
Latest ice-in date	Last day with open water in fall; followed by ice growth and winter ice cover	/
Earliest ice-out date	First day without ice cover in spring, but ice cover may form again	/
Latest ice-out date	Last day with ice cover in spring; followed by open water season (t_{io})	/
Duration of ice cover (days)	Total number of days with lake ice cover (D_{ice})	/
Total period of ice cover (days)	Days between earliest ice-in and latest ice-out dates	t_{io}-t_{ei}
Continuous ice cover ratio	Duration of ice cover divided by total period of ice cover	$\frac{D_{ice}}{t_{io} - t_{ei}}$
Maximum ice thickness (m)	Maximum ice thickness over winter ice cover period	Max[δ_i,t=1,365]
Average snow depth (m)	Sum of clarity snow depths on ice divided by duration of ice cover	$\frac{\sum \delta_{snow}}{D_{ice}}$
Continuous snow cover ratio	Number of days with snow cover divided by duration of ice cover	$\frac{\sum_{t_{io}}^{t_{ei}} t[\delta_{snow} > 0]}{D_{ice}}$

Table 6.3 Average values (1983-1990) of the parameters used to define water temperature characteristics

Lake Name	Max. Surface Temperature (C°)	Min. Surface Temperature (C°)	Max. Bottom Temperature (C°)	Min. Bottom Temperature (C°)	Max. Temperature Difference (C°)	Open Water Stratification Ratio	Duration of Low Bottom Temperature (< 8°C) (days)	Duration of Low Bottom Temperature (< 2°C) (days)
Mille Lacs Lake	23.8	0.0	23.6	0.00	1.8	0.025	198	33
Upper Red Lake	26.7	0.0	26.3	0.00	2.1	0.018	201	23
Lower Red Lake	24.9	0.0	24.1	0.03	2.4	0.038	202	28
Lake of the Woods	24.1	0.0	23.9	0.06	1.9	0.016	202	36
Leech Lake	23.9	0.0	23.4	0.09	2.3	0.041	198	30
Lake Vermilion	23.7	0.0	21.2	0.65	7.3	0.278	205	91
Lake Kabetogama	25.2	0.0	22.3	0.50	7.0	0.202	204	34
Lake Winnibigoshish	23.5	0.0	21.7	0.36	5.2	0.181	204	45
Lake Pepin	27.3	0.0	26.0	0.02	3.1	0.119	172	26
Rainy Lake	23.9	0.0	10.4	3.34	17.1	0.410	281	0
Cass Lake (Basin 1)	25.1	0.0	15.7	0.32	12.9	0.379	207	43
Cass Lake (Basin 3)	26.3	0.0	14.4	1.86	15.3	0.408	209	4
Cass Lake (Basin 4)	26.7	0.0	18.9	0.28	11.2	0.341	190	22
Average	25.0	0	20.9	0.58	6.9	0.189	206	32
Standard Deviation	1.3	0	4.8	0.97	5.5	0.158	25	22

Table 6.4 Standard deviations of the parameters used to define water temperature characteristics

Lake Name	Max. Surface Temperature (C°)	Min. Surface Temperature (C°)	Max. Bottom Temperature (C°)	Min. Bottom Temperature (C°)	Max. Temperature Difference (C°)	Open Water Stratification Ratio	Duration of Low Bottom Temperature (< 8°C) (days)	Duration of Low Bottom Temperature (< 2°C) (days)
Mille Lacs Lake	1.4	0.0	1.3	0.00	0.4	0.021	7	10
Upper Red Lake	1.9	0.0	1.8	0.00	0.7	0.009	9	8
Lower Red Lake	1.8	0.0	1.6	0.04	0.5	0.019	7	5
Lake of the Woods	1.7	0.0	1.6	0.11	0.6	0.008	6	8
Leech Lake	1.4	0.0	1.2	0.26	0.6	0.027	6	9
Lake Vermilion	1.4	0.0	1.0	0.70	1.8	0.023	6	53
Lake Kabetogama	1.9	0.0	1.1	0.67	2.0	0.032	7	16
Lake Winnibigoshish	1.4	0.0	1.0	0.33	1.3	0.031	6	18
Lake Pepin	1.6	0.0	1.3	0.04	0.7	0.023	6	6
Rainy Lake	2.0	0.0	0.3	0.17	2.1	0.024	9	0
Cass Lake (Basin 1)	1.6	0.0	1.1	0.49	3.2	0.035	15	16
Cass Lake (Basin 3)	1.2	0.0	0.9	0.68	1.0	0.031	18	7
Cass Lake (Basin 4)	1.1	0.0	1.0	0.52	1.0	0.033	6	12

Table 6.5 Average values (1983-1990) of parameters used to define ice and snow characteristics

Lake Name	Earliest Ice-in Date	Latest Ice-In Date	Earliest Ice-out Date	Latest Ice-out Date	Max. Ice Thickness (m)	Duration of Ice Cover (days)	Total Period of Ice Cover (days)	Continuous Ice Cover Ratio	Average Snow Depth (m)	Continuous Snow Cover Ratio
Mille Lacs Lake	325	326	111	112	0.73	152	152	0.995	0.091	0.772
Upper Red Lake	308	314	111	116	0.76	168	173	0.970	0.081	0.771
Lower Red Lake	316	319	113	116	0.85	163	166	0.982	0.069	0.751
Lake of the Woods	321	322	114	117	0.84	159	161	0.988	0.072	0.766
Leech Lake	324	325	110	111	0.72	151	152	0.994	0.091	0.781
Lake Vermilion	325	326	111	112	0.73	152	153	0.995	0.091	0.770
Lake Kabetogama	316	317	113	116	0.84	163	166	0.983	0.070	0.750
Lake Winnibigoshish	320	321	110	111	0.73	155	157	0.991	0.090	0.788
Lake Pepin	333	334	98	104	0.65	132	136	0.968	0.047	0.690
Rainy Lake	349	349	113	116	0.84	131	133	0.983	0.048	0.731
Cass Lake (Basin 1)	326	327	111	112	0.74	150	151	0.993	0.088	0.778
Cass Lake (Basin 3)	326	328	105	106	0.72	143	145	0.991	0.060	0.700
Cass Lake (Basin 4)	324	325	103	105	0.71	145	147	0.989	0.063	0.721
Average	324	326	110	112	0.76	151	153	0.986	0.074	0.751
Standard Deviation	10	9	5	4	0.06	11	12	0.009	0.016	0.032

Table 6.6 Standard deviations of parameters used to define ice and snow characteristics

Lake Name	Earliest Ice-in Date	Latest Ice-In Date	Earliest Ice-out Date	Latest Ice-out Date	Max. Ice Thickness (m)	Duration of Ice Cover (days)	Total Period of Ice Cover (days)	Continuous Ice Cover Ratio	Average Snow Depth (m)	Continuous Snow Cover Ratio
Mille Lacs Lake	5	6	7	8	0.07	8	10	0.011	0.050	0.065
Upper Red Lake	5	8	7	8	0.11	11	12	0.027	0.043	0.068
Lower Red Lake	5	5	6	8	0.11	9	11	0.023	0.040	0.063
Lake of the Woods	5	4	6	7	0.10	8	10	0.020	0.039	0.057
Leech Lake	5	6	6	8	0.08	8	10	0.014	0.050	0.063
Lake Vermilion	5	6	7	8	0.08	9	9	0.009	0.050	0.066
Lake Kabetogama	5	6	6	8	0.11	9	11	0.021	0.040	0.062
Lake Winnibigoshish	6	5	6	8	0.09	8	9	0.015	0.047	0.057
Lake Pepin	8	9	9	11	0.13	13	15	0.042	0.023	0.108
Rainy Lake	6	6	6	8	0.14	11	12	0.025	0.035	0.053
Cass Lake (Basin 1)	5	5	6	8	0.09	8	9	0.014	0.050	0.064
Cass Lake (Basin 3)	6	6	5	6	0.08	8	9	0.016	0.045	0.104
Cass Lake (Basin 4)	6	6	5	5	0.06	9	9	0.022	0.046	0.080

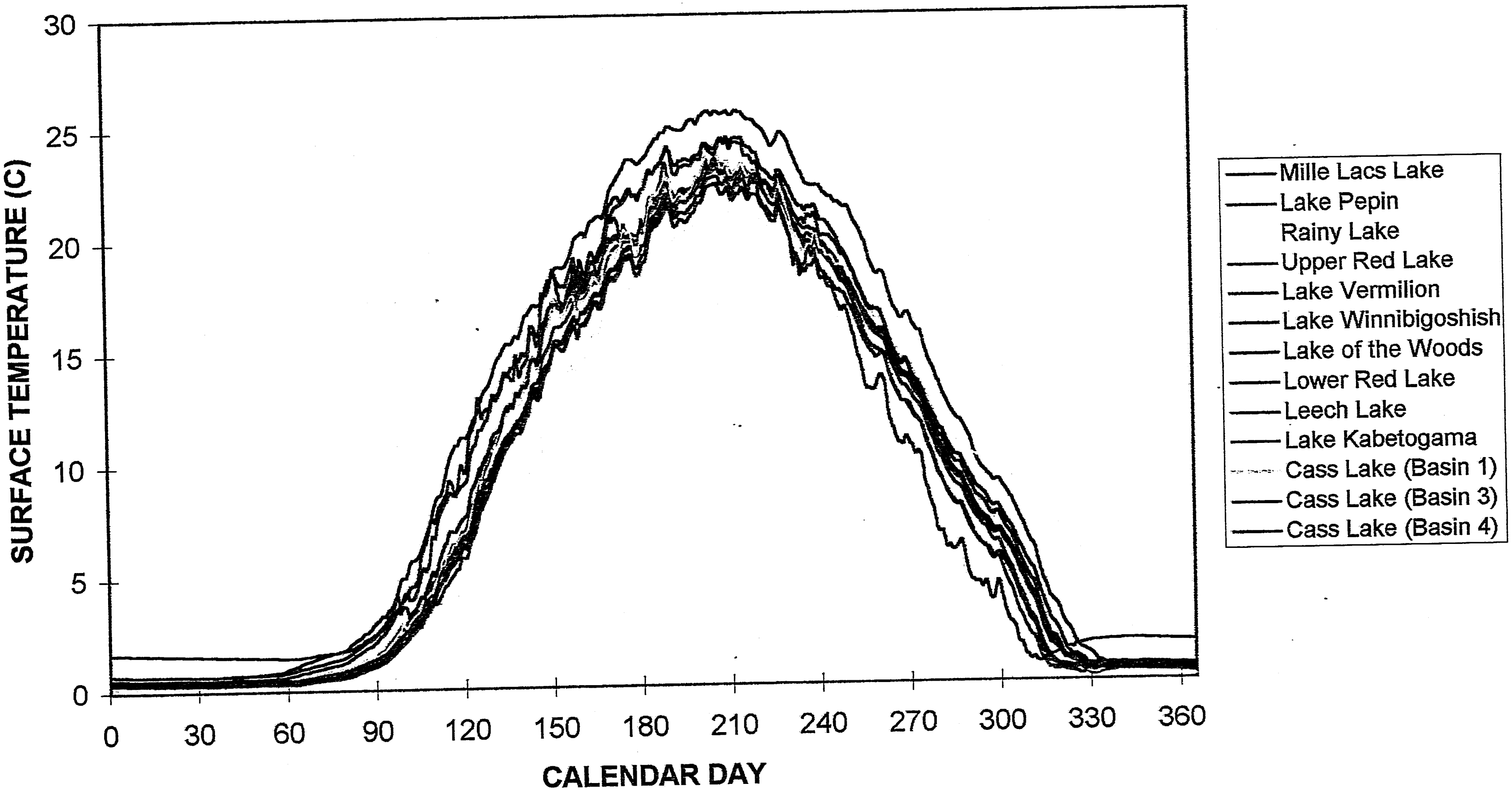


Fig 6.1 Surface water temperature cycle averaged over 8 years (1983-1990) for each lake

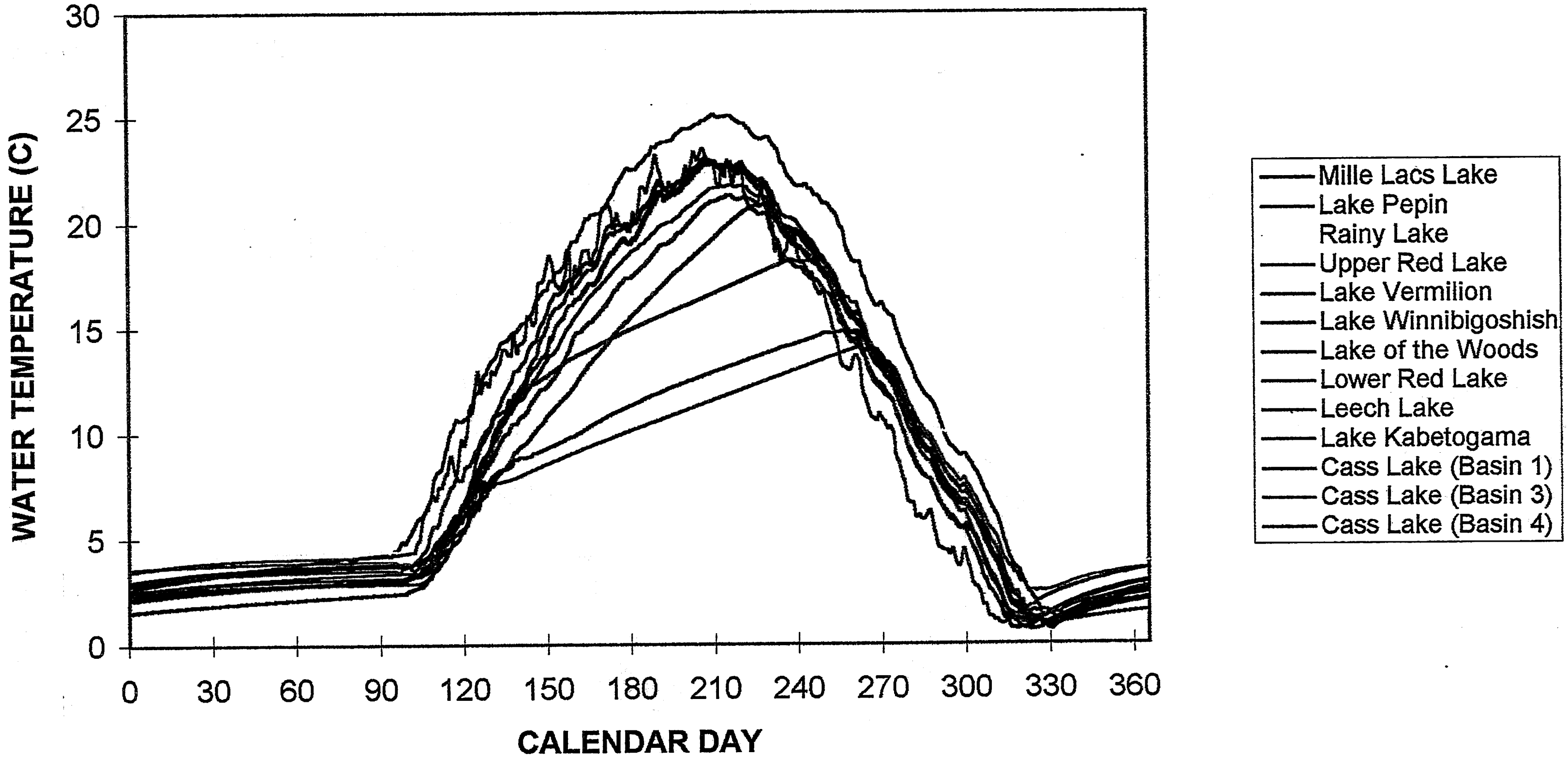


Fig 6.2 Bottom water temperature cycle averaged over 8 years (1983-1990) for each lake

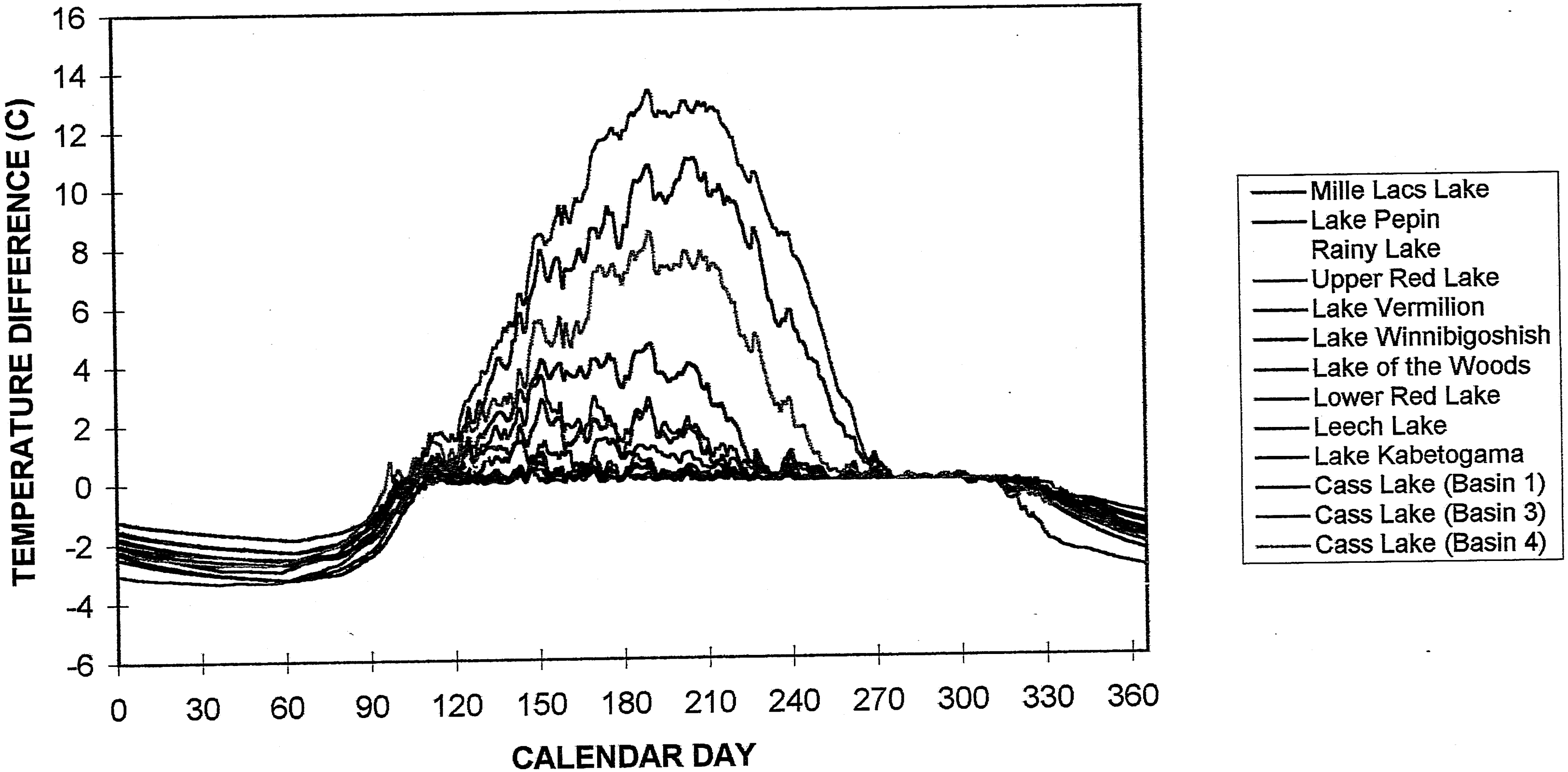


Fig 6.3 Temperature differences between lake surface and bottom averaged over 8 years (1983-1990)

7. Summary and Conclusions

The objective of this study was to simulate seasonal water temperature cycles and stratification in ten large lakes in Minnesota. The ten lakes studied are Mille Lacs Lake, Red Lake, Lake of the Woods, Leech Lake, Lake Vermillion, Lake Kabetogama, Lake Winnibigoshish, Lake Pepin, Rainy Lake and Cass Lake. MINLAKE 96, a one-dimensional unsteady, year-round water quality model was employed. All the lakes were simulated from 1983 to 1990 with the exception of Mille Lacs Lake which was simulated from 1980 to 1990 in order to compare the simulation results with the field data in 1981. The simulation results were compared to available field data. The standard errors between simulated and measured temperatures range from 0.74°C to 2.38°C and the slope of regression from 0.95 to 1.11.

The results are presented as isotherms, weekly averaged time series and yearly averaged time series for the temperatures at 1m above the lake bottom. Ice and snow information including time series for ice thicknesses and snow depths are also presented. The values of some parameters (Table 6.1 and 6.2) which describe lake water temperature ice and snow characteristics are also extracted from the simulation results.

Large shallow lakes such as Red Lake and Mille Lacs Lake are usually well mixed during open water seasons. Deep lakes like Rainy Lake and Cass Lake are usually stratified in summer. Whether a lake is stratified or not is strongly dependent on the lake's depth.

Surface water temperatures for large lakes in Minnesota primarily depend on meteorological conditions and less on lake mophormetries. For the lakes with similar meteorological conditions, surface water temperatures do not vary much from one lake to another.

Unlike surface water temperatures, lake bottom water temperatures are not directly related to meteorological forcing, especially in deep lakes. During the open water season, bottom water temperatures in shallow lakes have approximately the same values as surface water temperatures, but in deep lakes bottom water temperatures have much lower values than surface water temperatures because of strong stratification.

Ice-in dates, ice-out dates and ice thickness are primarily related to meteorological conditions and less related to lake mophormetries. Average earliest ice-in date for large lakes in Minnesota is November 20 with standard deviation of 10 days and average latest ice-out date is April 22 with standard deviation of 4 days. Maximum ice thickness ranges from 0.65m for lakes in south Minnesota to 0.85m for lakes in north Minnesota. Average maximum ice thickness is 0.76 m with standard deviation of 0.06 m.

The MINLAKE model had previously been applied to small lakes with surface area less than 30 km^2. This study shows that this one-dimensional model can be used to simulate water temperature profiles in lakes with surface area considerably larger than 30 km^2. The surface area of the lakes simulated herein range from 5.5 km^2 for Cass Lake basin 1 to 3846 km^2 for Lake of the Woods.

Another purpose of this study was to generate baseline information on the thermal regime of the largest Minnesota lakes under past climate conditions for further comparison with projected climate change effects.

A third purpose was to generate lake water temperature information for lakes which have only sparse measurements. These lakes are significant fisheries resources in the State of Minnesota, and the relationship between the fisheries and lake temperatures is being explored by the DNR.

References

Ashton, G.D., River and Ice Engineering, Water Resources Publication, Littleton, Colorado, 1986

Christie, G.C. and H.A. Regier, Measures of optimal thermal habitat and their relationship to yields for four commercial fish species, Canadian Journal of Fisheries and Aquatic Sciences, 45(2), 301-314, 1988.

Dake, J.M.K. and D.R.F. Harleman, Thermal stratification in lakes: Analytical and laboratory studies, Water Resources Research, 5(2), 484-496, 1969.

Eaton, J.G. and others, A field information-based system for estimating fish temperature tolerances, Fisheries, 20, 10-18, 1995.

Eaton, J.G. and R.M. Scheller, Effects of climate warming on fish thermal habitat in streams of the United States, Limnology and Oceanography, 41(5), 1109-1115, 1996

Ellis, C., H.G. Stefan and R. Gu, Water temperature dynamics and heat transfer beneath the ice cover of a lake, Limnology and Oceanography, 36(2), 324-335, 1991.

Fang, X. and H.G. Stefan, Temperature and dissolved oxygen simulations for a lake with ice cover, Project Report 356, Saint Anthony Falls Laboratory, University of Minnesota, 1994.

Fang, X. and H.G. Stefan, Dynamics of heat exchange between sediment and water in a lake, Water Resources Research, 32(6), 1719-1727, 1996b.

Fang, X. and H.G. Stefan, Development and validation of the water quality model MINLAKE96 with winter data, Project Report 390, Saint Anthony Falls Laboratory, University of Minnesota, 1996.

Ford, D.E. and H.G. Stefan, Thermal predictions using integral energy model, J. of Hydraulic Division, ASCE, 106(1), 39-55, 1980.

Gorham, E. and F.M. Boyce, Influence of lake surface area and depth upon thermal stratification and the depth of the summer thermocline. Journal of Great Lakes Research, 15, 233-245, 1989.

Gu, R. and H.G. Stefan, Year-round temperature simulation of cold climate lakes, Cold Regions Science and technology, 18, 147-160, 1990.

Hondzo, M. and H.G. Stefan, Lake water temperature simulation model, J. of Hydraulic Engineering, ASCE, 119(11), 1251-1273, 1993a

Hostetler, S.W. and F. Giorgi, Effects of a 2xCO_2 climate on two large lake systems: Pyramid Lake, Nevada, and Yellowstone Lake, Wyoming. Global and Planetary Change, 10, 43-54, 1995.

Rasmussen, A.H. and H.H. Stefan, Climate change effects on water temperature and dissolved oxygen in five North Carolina lakes, Project Report 383, Saint Anthony Falls Laboratory, University of Minnesota, 1996.

Riley, M.J. and H.G. Stefan, Dynamic lake water quality simulation model "MINLAKE", Project Report 263, Saint Anthony Falls Laboratory, University of Minnesota, 1987.

Riley, M.J. and H.G. Stefan, MINLAKE: A dynamic lake water quality simulation model, Ecological Modeling, 43, 155-182, 1988.

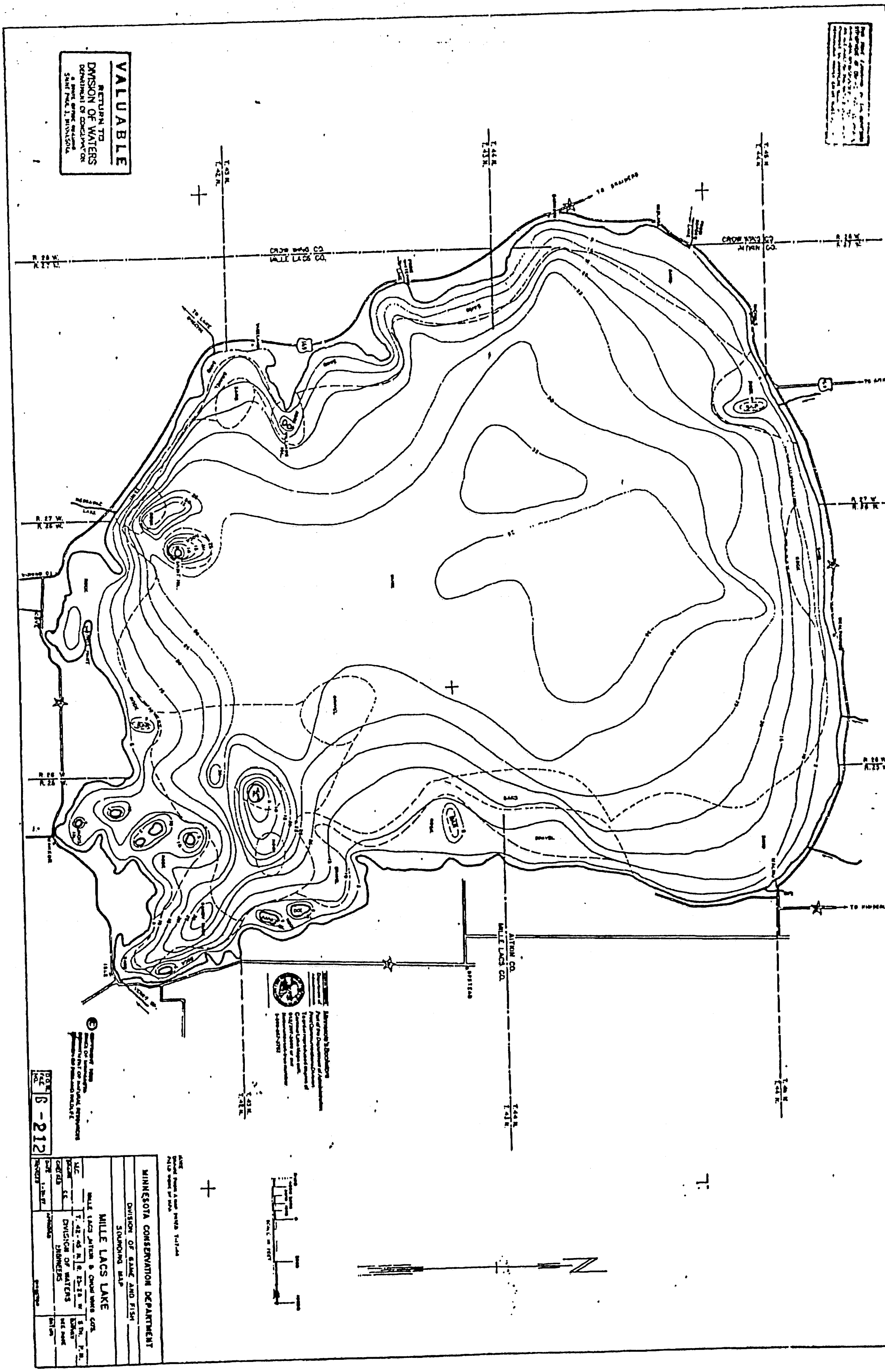
Stefan, H.G. and D. Ford, Temperature Dynamics in dimictic lakes, Journal of Hydraulic Engineering, ASCE, 11058, 97-114, 1975.

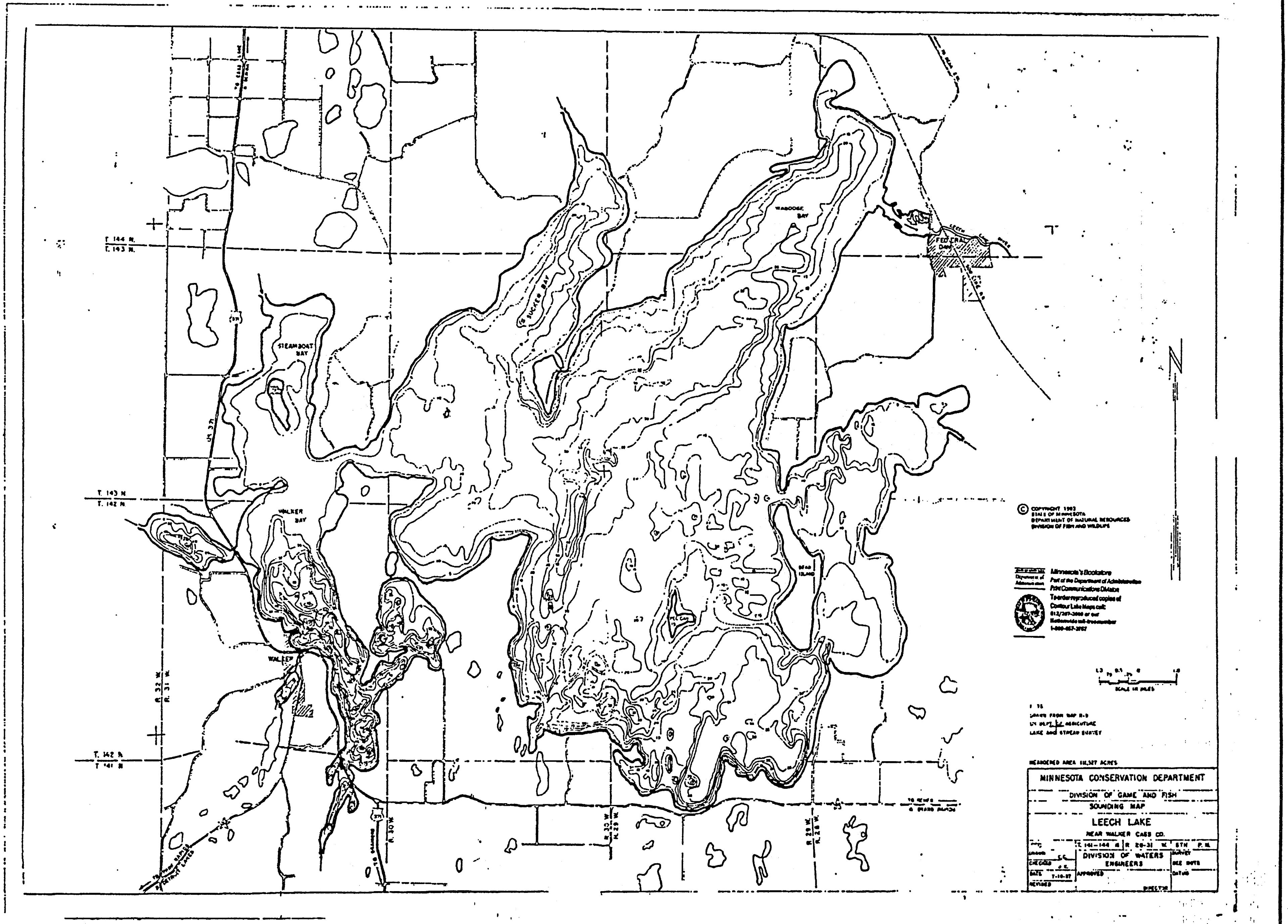
Stefan, H.G., M. Hondzo, X. Fang and A.H. Rasmussen, Year-round water temperature and dissolved oxygen simulation model for lakes with winter ice cover, Project Report 355, Saint Anthony Falls Laboratory, University of Minnesota, 1994.

Appendix A

Bathymetric Lake Maps

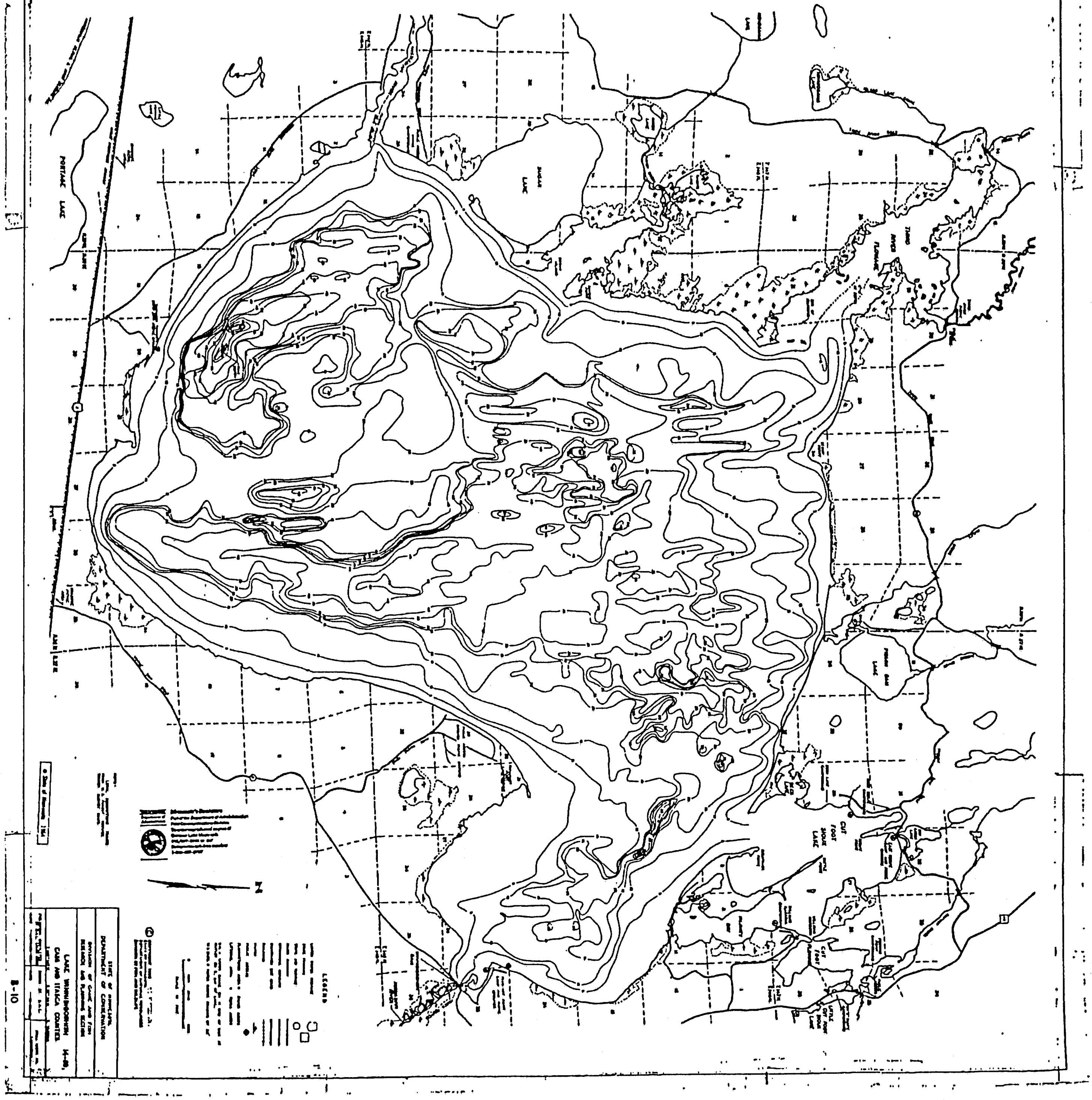
Sample Lake Map
MILLE LACS LAKE, MILLE LACS COUNTY
MnDNR 1994



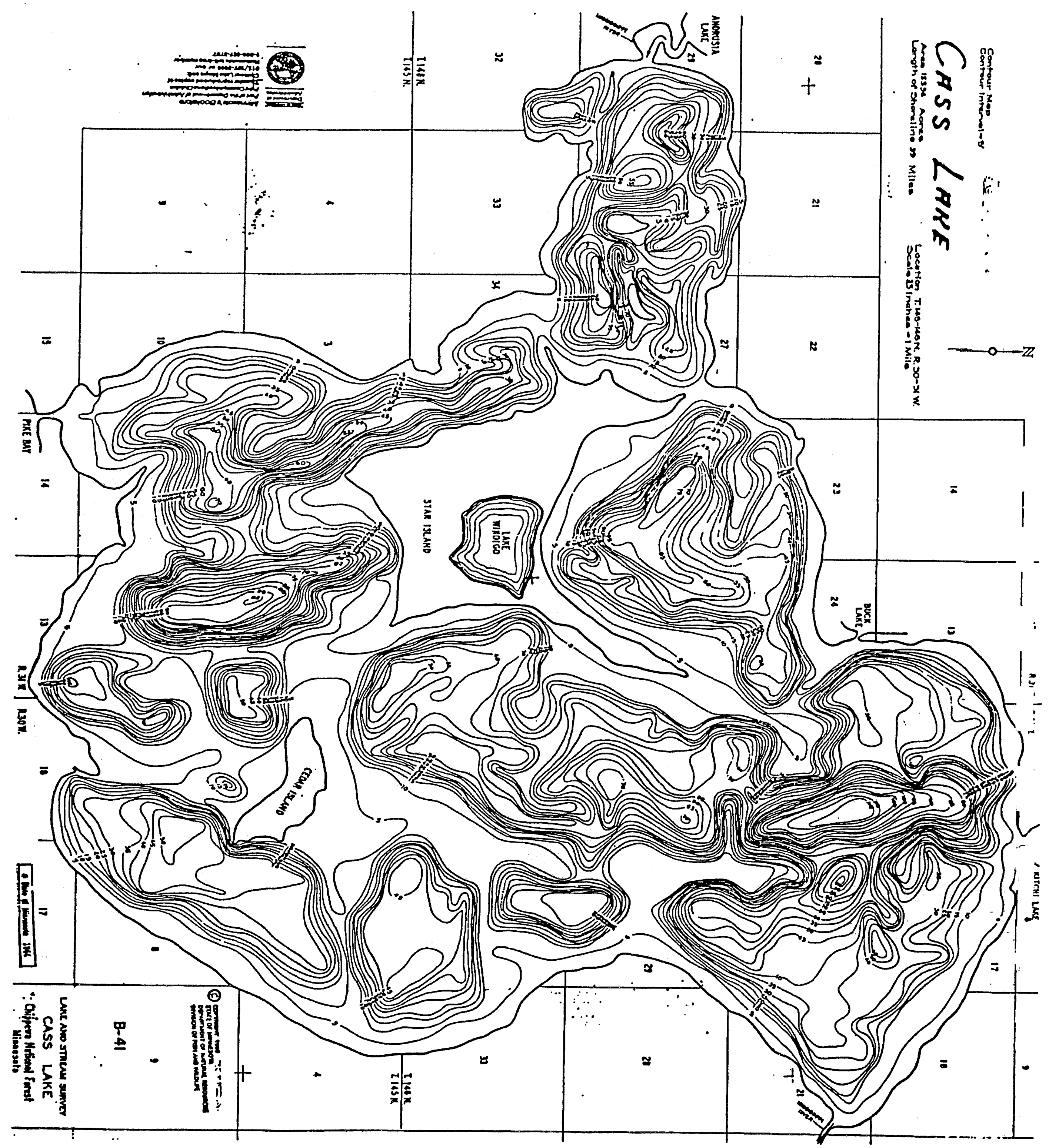


Sample Lake Map
LEECH LAKE, CASS COUNTY
MnDNR 1994

Sample Lake Map
WINNIBIGOSHISH LAKE, CASS COUNTY
MnDNR 1994

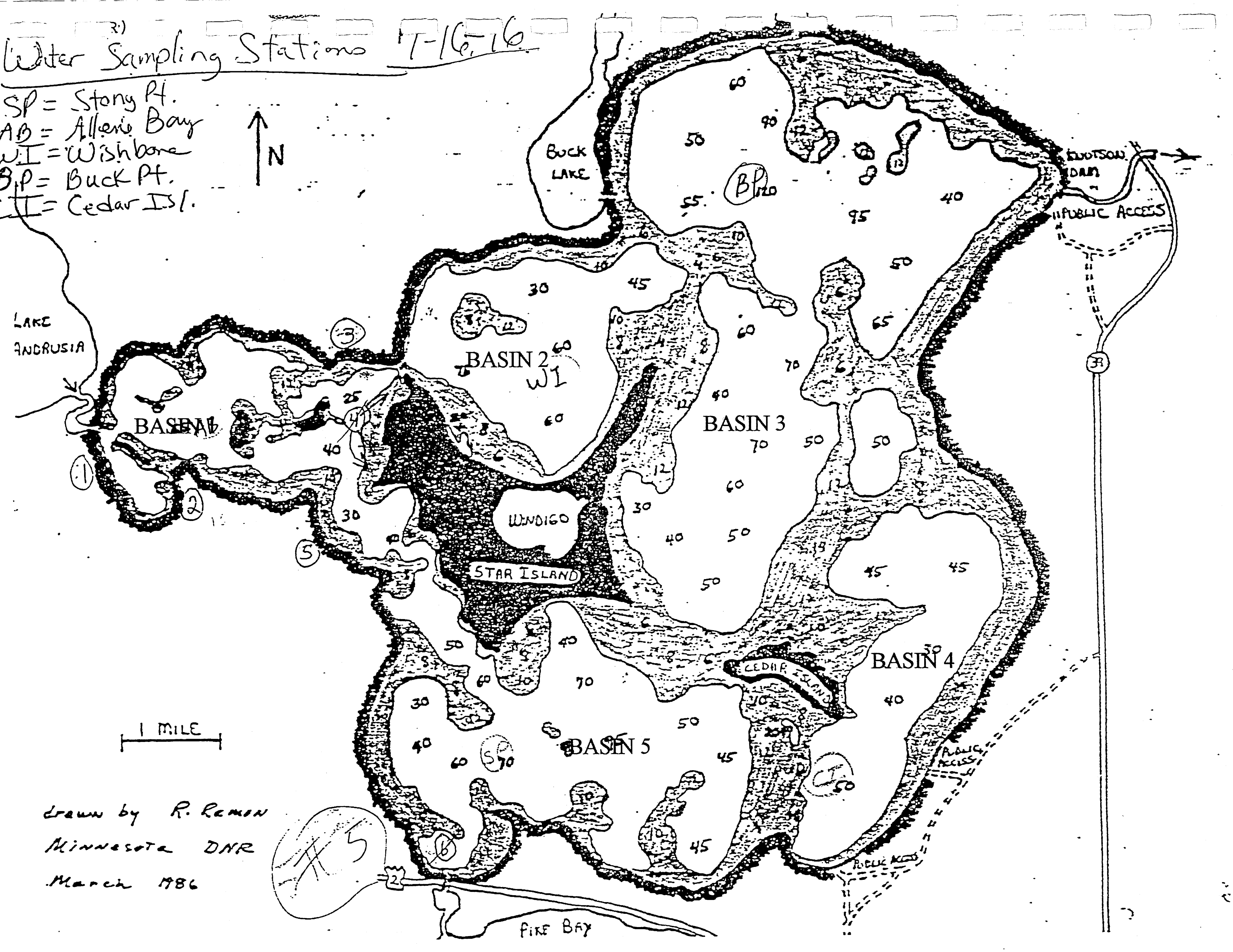


Sample Lake Map
CASS LAKE, BELTRAMI COUNTY
MnDNR 1994



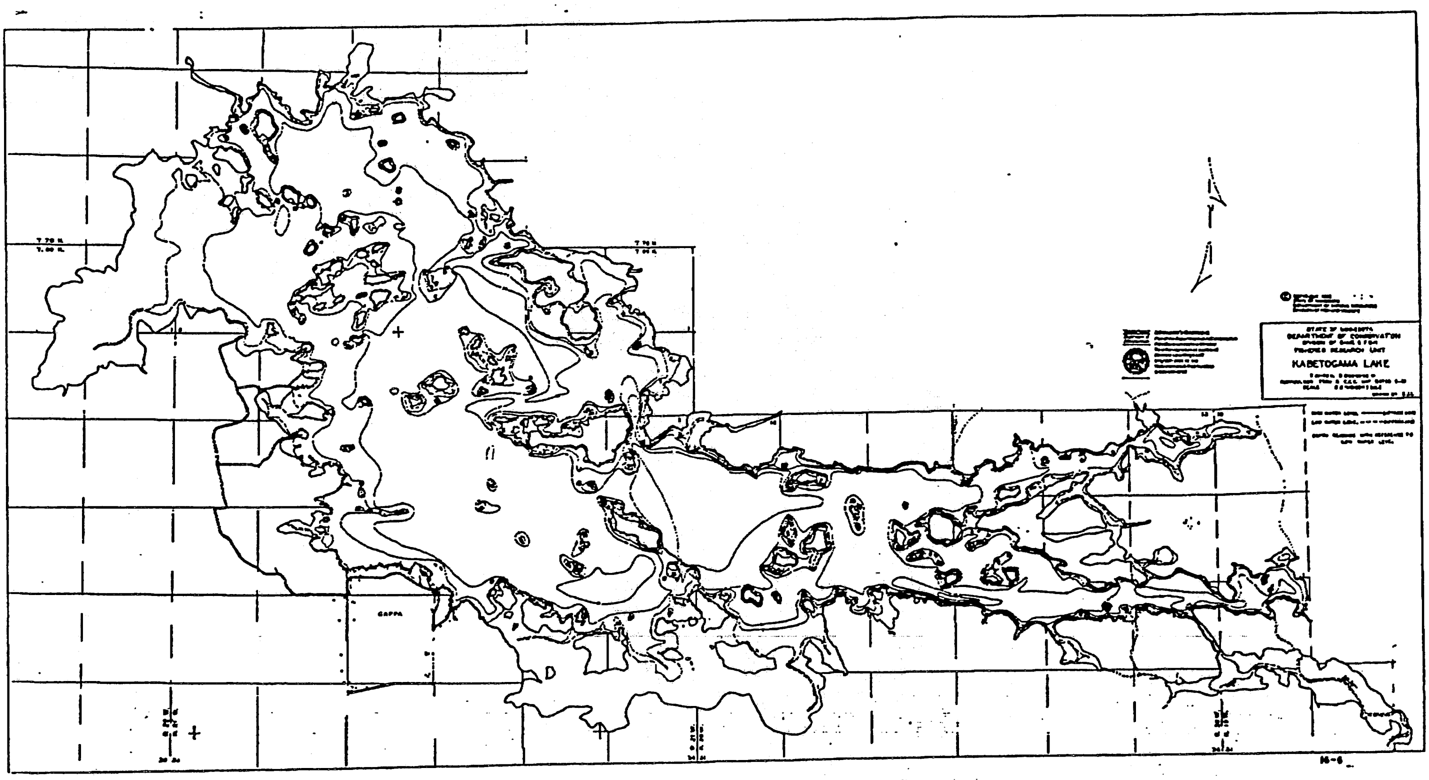
Water Sampling Stations T-16-16

SP = Stony Pt.
AB = Allen's Bay
WI = Wishbone
BP = Buck Pt.
CI = Cedar Isl.

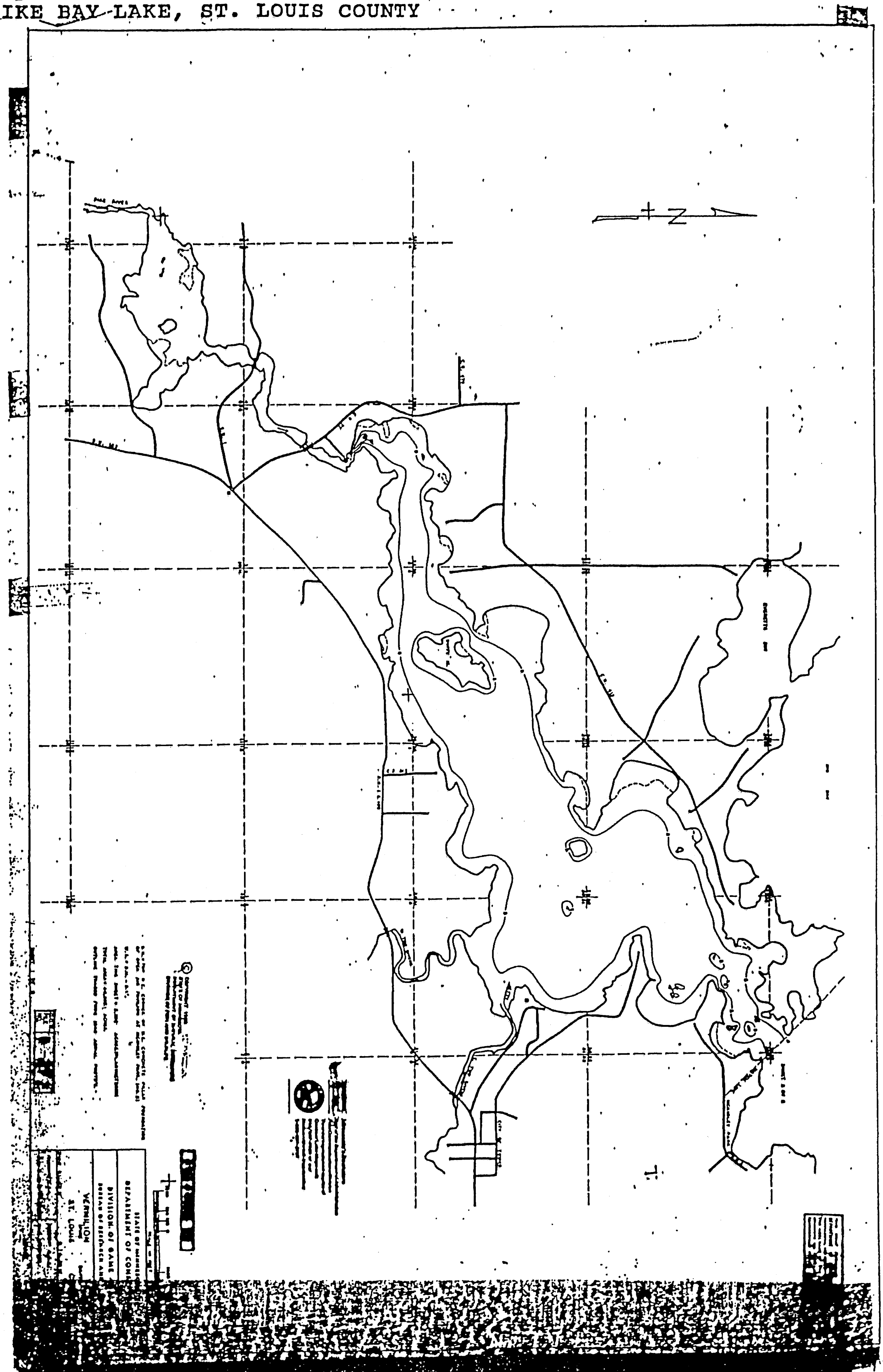


Sample Lake Map
KABETOGAMA LAKE, ST. LOUIS COUNTY
MnDNR 1994

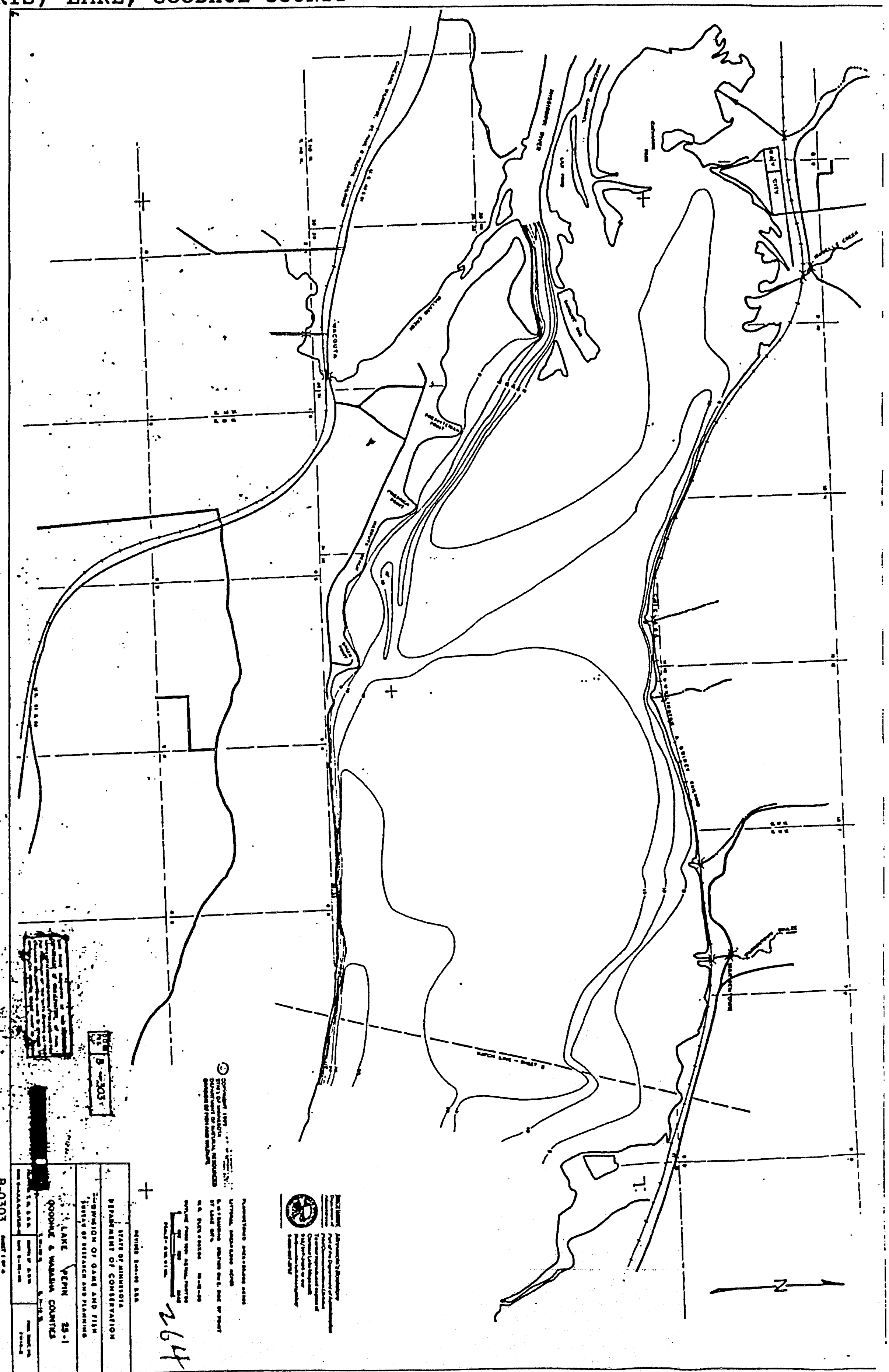
Sorry about this map - It is the way it is in our DATAbase!



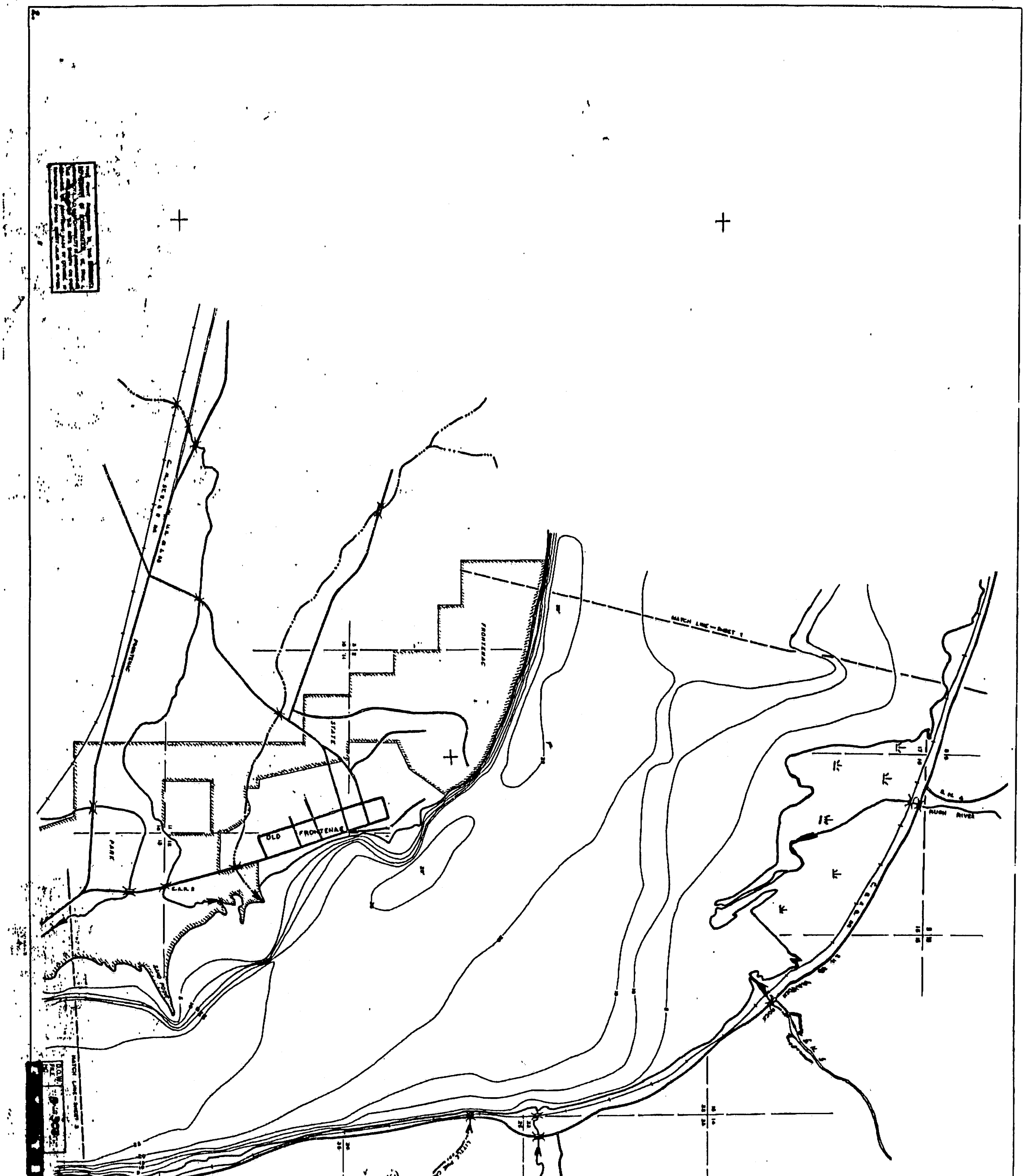
Sample Lake Map
VERMILLION (PIKE BAY-LAKE, ST. LOUIS COUNTY
MnDNR 1994



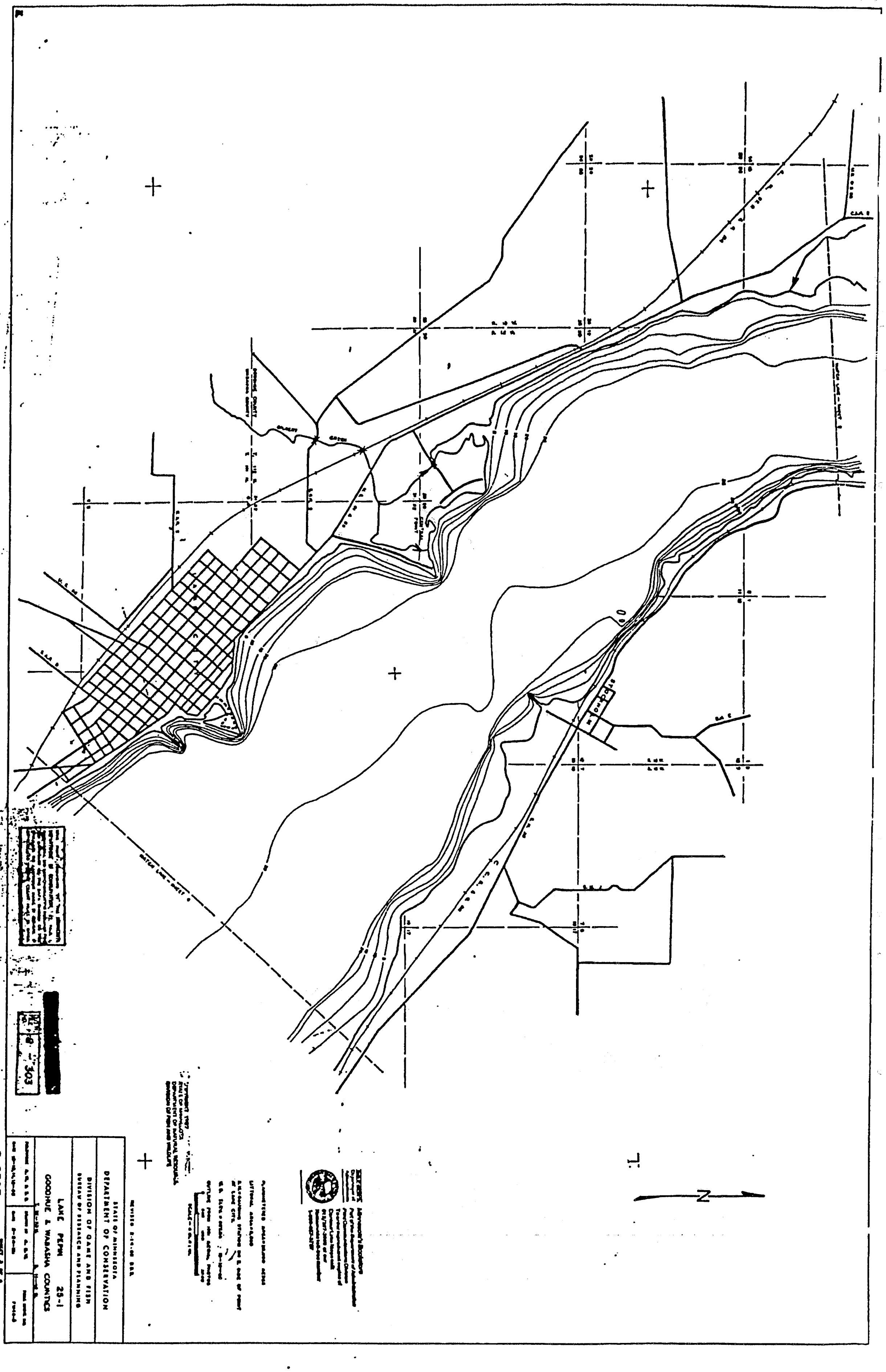
Sample Lake Map
PEPIN (FOUR PARTS) LAKE, GOODHUE COUNTY
MnDNR 1994



Sample Lake Map
PEPIN (FOUR PARTS) LAKE, GOODHUE COUNTY
MnDNR 1994



Sample Lake Map
PEPIN (FOUR PARTS) LAKE, GOODHUE COUNTY
MnDNR 1994



Sample Lake Map
PEPIN (FOUR PARTS) LAKE, GOODHUE COUNTY
MnDNR 1994