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Simulated Long-Term Temperature and Dissolved Oxygen Characteristics of Minnesota Lakes and Resulting Habitat Limits for Fishes

by

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1. Introduction

The lakes of Minnesota are a valuable state resource and responsible, at least in part, for one of the state second largest industries, tourism. Summaries of the condition of Minnesota's lakes are occasionally published and provide information on their water quality and their fisheries (see e.g. Osgood, 1983; Taylor et al., 1985; Heiskary and Wilson, 1988; Wright et al., 1988; Osgood, 1989; Schupp, 1992; Anhorn, 1994). Recent reports of acid rain, water pollution, land use practices, and projected climate change have raised concerns for the long-term health of these lakes and the fisheries that are dependent upon them.

The following is an analysis of the findings of a recently completed study that projects long-term average water temperature and dissolved oxygen concentrations that can be expected in these lakes and their consequences for fisheries. The water quality projections parameters are based on historical records of meteorological parameters that are known to influence the temperature and dissolved oxygen of northern temperate lakes. We employed process oriented, deterministic numerical modeling which when sufficiently calibrated and validated offers the possibility of projecting or inferring characteristics of similar lakes for which only the physical characteristics of maximum depth, surface area, and Secchi depth have been determined. This type of procedure also permits the comparative study of many lakes which is of particular interest to Minnesota because a vast number of lakes without water quality measurements exist in the state.

In this report parameters which characterize long-term averages of water temperature, dissolved oxygen, and associated fish habitat in lakes are presented for climate conditions which existed from 1955 to 1979. The results are from simulations for the open water season and include the typical summer stratification which develops in many Minnesota lakes. The results are presented in general form allowing interpolation and quantitative comparison among lakes with different morphometries and trophic levels. For better appreciation of the results, a brief description of the model formulations, input data requirements and accuracy is also provided. Process oriented, one-dimensional, unsteady lake water quality models have been used. The models have been validated with data from a wide range of lake morphometries, trophic levels, and meteorological conditions (Hondzo and Stefan, 1993; Stefan et al., 1993a; Stefan and Fang, 1994). The results of the simulations quantify long-term (25-year average) stratification characteristics, and include some information on lake suitability as habitat (survival and growth) for various fishes.

2. Background on Simulated Lake Parameters and Processes

2.1 Water temperature and thermal stratification

A lake is exposed to meteorological forcing through the lake surface and hydrologic inputs from the lake basin. Solar radiation and atmospheric long wave radiation heat the water column, while evaporation and back radiation cool the water column. Inflows may heat or cool the water depending on the relative thermal state of the water column at the time of concern. In addition, convective heat transfer driven by the temperature difference between the water temperature and air temperature can also warm or cool a lake. The differential radiative heat absorption throughout the lake depth causes thermal stratification of the water body. The stronger the stratification, the more quiescent i.e. the more stable the water body. The external forcing i.e. wind exerts a drag force on the surface of the lake which, through a variety of external and internal wave motions tends to vertically mix the stratified water column (partially or completely). The external mechanical energy input from the wind is opposed by the potential (buoyant) energy "locked" in the stratification. The stronger the stratification, the more mechanical energy is needed to mix the water column.

A schematic representation of a seasonal temperature stratification in a dimictic lake is given in Fig. 1a. The open-water season usually starts some time in April or May in Minnesota lakes depending on the geographical location and the size of the lake. Most lakes are well mixed throughout the entire lake depth in spring. The onset of stratification occurs with the increase of solar radiation intensity and some decrease in the wind activity. The thermal stratification increases in strength from May through July or August. Further water temperature increase in summer is limited by the evaporative heat losses, and by back radiation. In September, solar radiation and air temperature are significantly lower, and wind is often higher, resulting in strong surface cooling, natural convection, and wind-induced mixing. A three layer structure is well defined throughout the summer in many lakes. The surface mixed layer is called 'epilimnion', underneath is a zone of temperature gradient, the 'metalimnion'; and below is the 'hypolimnion'. Surface mixed layer depth increases in the fall until the lake becomes isothermal at a temperature above or equal to 4°C.

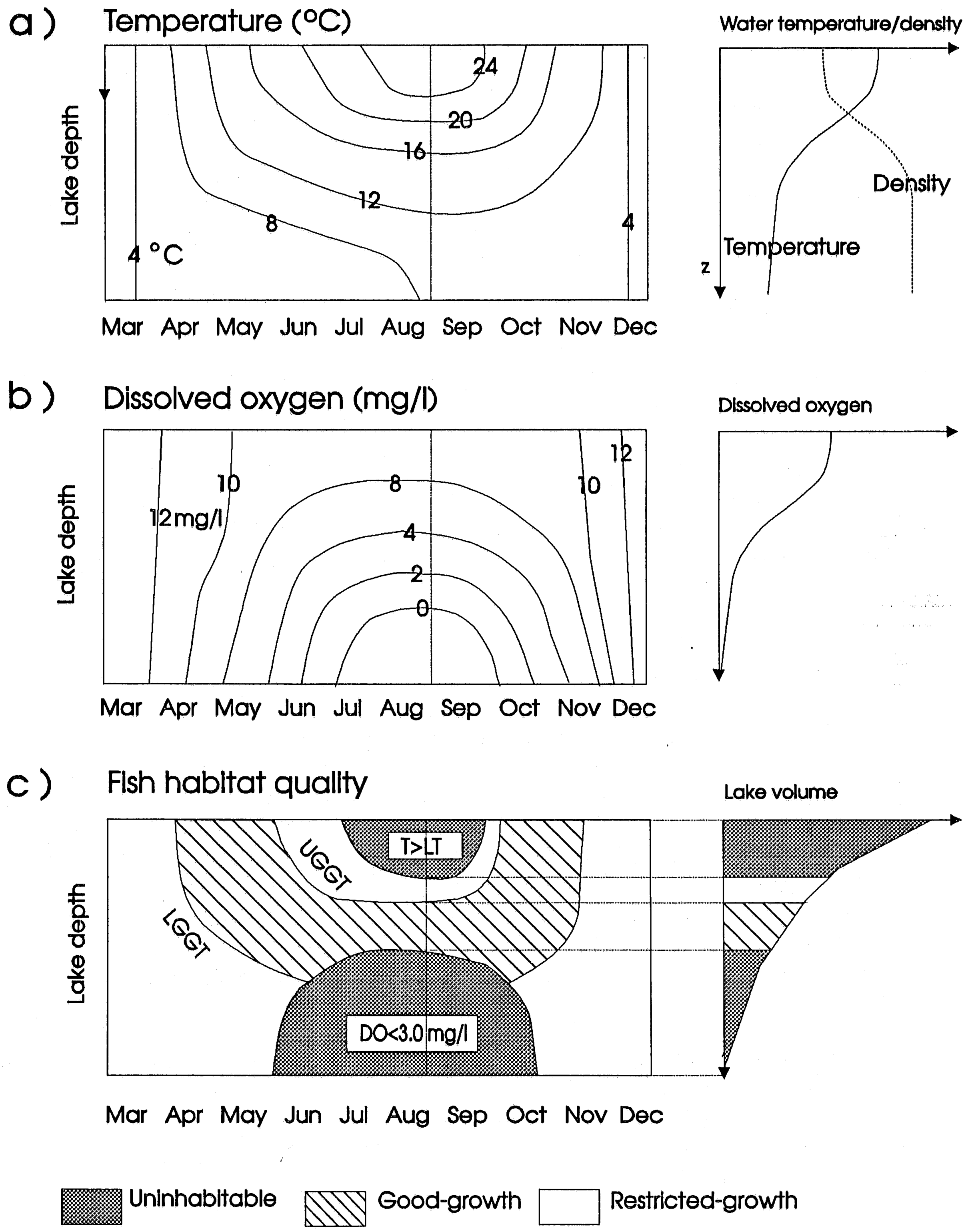

Fig. 1 Schematic of the distribution over time and depth of a) water temperature (T) isotherms (°C), b) dissolved oxygen (DO) isopleths (mg/l), and c) those isotherms and dissolved oxygen isopleths which are considered for the survival and growth of a fish species, in a seasonally stratified lake. LGGT=lower good-growth temperature limit, UGGT=upper good-growth temperature limit, and LT=lethal temperature.

2.2 Dissolved oxygen

The major components affecting the DO concentration in the water column are: plant respiration, photosynthesis, biological and sedimentary oxygen demand (largely microbial respiration and chemical oxidation), and surface layer oxygenation. DO transfer at the water surface and photosynthesis can increase DO concentrations in the water column. The sedimentary oxygen demand (SOD), biochemical oxygen demand (BOD), and plant and microbial respiration (R), are DO sinks in the water column. The nitrification process is omitted because it makes a minor contribution to the state of oxygen in the lake as a whole (Stefan and Fang, 1994).

A schematic representation of DO isopleths for a dimictic lake is given in Fig. 1b. High DO concentrations throughout the entire lake depth are present during well-mixed conditions in spring. Water temperature stratification implies DO stratification as well. While high temperature and associated density gradients at the thermocline inhibit vertical DO transfer from the surface mixed layer to the hypolimnion, BOD and especially SOD reduce DO concentrations and can produce anoxic conditions in deeper layers in summer. Surface mixed layers deepen in fall and over time DO concentrations rise throughout the lake as the water cools.

2.3 Habitat for fishes

The presence of fish in a lake is, in general, related to accessibility, suitable ecological conditions for survival, human interference, and resistance to episodic natural events (Fry, 1971). Temperature and DO concentrations are considered the two most significant water quality parameters that affect survival and growth of fishes (Coutant, 1987; Christie and Regier, 1988). The suitability of habitats for coldwater, coolwater, and warmwater fishes is assessed in this study in terms of only these two parameters. Suitable habitat was defined as having temperatures and DO within prescribed criteria. The results indicate which lakes have thermal and DO conditions suitable for survival and growth of groups of fishes having similar thermal requirements to be designated as coldwater, coolwater, and warmwater fishes.

Temperature criteria for fish habitat were developed from laboratory and field data as described by Eaton et al., (1995) and the guild (coldwater, coolwater, warmwater) designations for various species as suggested by Hokanson (1977). Table 1 gives temperature limits for these three thermal guilds of fishes, which comprise a total of 28 species. Fish survival and good-growth temperature criteria were related to simulated daily water temperatures and dissolved oxygen concentrations as shown schematically in Fig 1c. Three isotherms were chosen for each guild. They designate the lethal temperature (LT) threshold, the upper good-growth temperature limit (UGGT), and the lower good-growth temperature limit (LGGT), respectively (Stefan et al., 1992).

Table 1. Water temperature (°C) criteria used to define suitability of habitats for three thermal guilds of fishes.

Fish guild	Lower good-growth limit (LGGT)	Upper good-growth limit (UGGT)	Upper lethal limit (LT)	Optimum temperature (OT)
Coldwater[1]	9.0 (6.4-11.8)	18.5 (15.5-21.2)	23.4 (22.1-26.6)	15.3 (11.5-18.7)
Coolwater[2]	16.3 (13.2-18.2)	28.2 (27.7-28.8)	30.4 (28.0-32.3)	25.1 (24.0-25.7)
Warmwater[3]	19.7 (17.7-22.5)	32.3 (31.4-34.7)	undetermined[a]	29.2 (27.0-32.0)

[1] Coldwater species are brook trout, brown trout, chinook salmon, chum salmon, coho salmon, mountain whitefish, pink salmon, and rainbow trout.

[2] Coolwater species are black crappie, northern pike, sauger, walleye, white crappie, white sucker, and yellow perch.

[3] Warmwater species are bluegill, brown bullhead, carp, channel catfish, flathead catfish, freshwater drum, gizzard shad, golden shiner, green sunfish, largemouth bass, rock bass, smallmouth bass, smallmouth buffalo, and white bass.

[a] Larger than 32.3 °C (UGGT)

Dissolved oxygen limits of 2.5 mg/l for warmwater fish and 3.0 mg/l for coolwater and coldwater fish were based on the United States Environmental Protection Agency Water Quality Criteria document (1986). The isopleth that designates the critical DO survival value is shown in Fig. 1c. Between the lines in Fig. 1c, three habitats can be identified: (1) *uninhabitable* space when the temperature is above, or the DO is below the survival or threshold limit for seven consecutive days, (2) *good-growth* habitat if the temperature is between the upper and the lower good-growth limits and the DO is above survival limit, and (3) *restricted-growth* habitat if the temperature is above and the upper good-growth limit below the upper survival limit; or if the temperature is below the lower good-growth limit, and the DO is above the survival limit.

Actual fish observations in 3002 Minnesota lakes were compared with simulated suitable fish habitat based on water temperatures and DO concentrations. The concept is briefly illustrated in Fig. 1. Good agreement between fish observations and numerical simulations of fish habitat was found (Stefan et al., 1993b).

3. Databases

3.1 Meteorological database

The meteorological database which is used as input to the long-term lake simulations consists of twenty-five years (1955-1979) of recorded weather data. The meteorological data file contains measured daily values of average air temperature, dew point temperature, precipitation, and solar radiation. The period from 1955 to 1979 was chosen because it is long enough to give a representative average of past conditions. Figure 2 illustrate the long-term averages and standard deviations of the measured daily meteorological parameters at two meteorological stations. Data from the Minneapolis-St. Paul International Airport (93.13° longitude, 44.53° latitude) and Duluth (92.11° longitude, 46.50° latitude) were used for southern and northern Minnesota, respectively. Numerical values for the mean monthly meteorological parameters for the above meteorological stations are summarized in Table 2.

3.2 Lake database

The Minnesota Lakes Fisheries Database (ERLD/MNDNR, 1990) contains lake survey data for 3002 Minnesota lakes. The database includes 22 physical variables and all common fish species. Nine primary variables explain 80% of the variability among lakes. These nine variables include surface area, volume, maximum depth, alkalinity, Secchi depth, lake shape, shoreline complexity, percent littoral area, and length of growing season. Geographic subdivision of the lakes was approached in a variety of ways. First, classification by ecoregion[2] (Omernick, 1987) was considered, but found to give too detailed a picture. Then the entire state was considered as a regional entity but rejected as too large because of the diversity of climate. Dividing the state into a northern and southern region was considered appropriate because there is a significant gradient in geological, hydrological, climatological, and ecological parameters across the mid-section of the state (Baker et al., 1985; Heiskary et al., 1987; Schupp, 1992; Hondzo and Stefan, 1993). The southern and northern regions with the geographic distribution of the lakes in the database are given in Fig. 3.

The morphometric characteristics of lakes exert a strong control on lake stratification. Observations in the northern hemisphere show that onset and strength of

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[2] Ecoregion is defined as a region with homogenous trophic, geologic, vegetative and land use features.

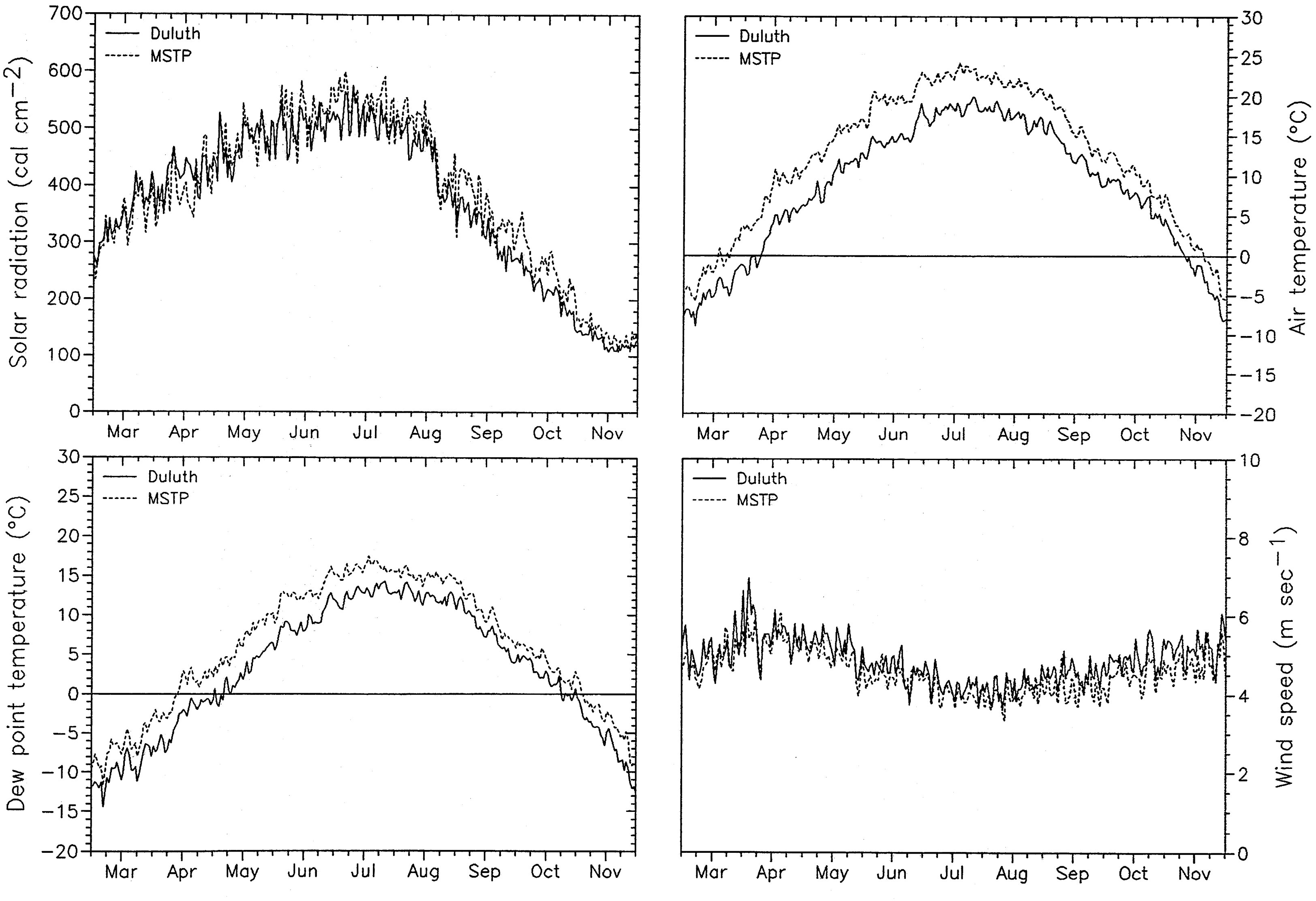


Fig. 2 **Meteorological variables at Minneapolis/St. Paul and Duluth. Daily means for the period 1955-1979.**

Table 2. Mean monthly meteorological data for Minneapolis-St. Paul and Duluth, Minnesota, averaged over 25 year (1955-1979). AT= air temperature, DT = dew point temperature, SR = solar radiation, and WS = wind speed.

	Duluth				Minneapolis-Saint Paul (MSTP)				Difference (Duluth-MSTP)			
	AT (°C)	DT (°C)	SR (cal cm^{-2})	WS (m sec^{-1})	AT (°C)	DT (°C)	SR (cal cm^{-2})	WS (m sec^{-1})	AT (°C)	DT (°C)	SR (cal cm^{-2})	WS (m sec^{-1})
Mar	-4.7	-9.8	344.8	5.1	-1.3	-6.9	333.6	4.9	-3.4	-2.9	11.2	0.2
Apr	2.9	-3.4	417.2	5.6	7.7	0.2	396.4	5.4	-4.8	-3.6	20.8	0.2
May	9.9	2.6	471.5	5.3	14.6	6.6	477.2	5.0	-4.7	-4.0	-5.7	0.3
Jun	15.0	9.1	504.4	4.6	19.9	12.8	528.3	4.5	-4.9	-3.7	-23.9	0.1
July	18.4	12.8	517.0	4.3	22.8	15.9	546.6	4.1	-4.4	-3.1	-29.6	0.2
Aug	17.4	12.5	441.3	4.2	21.5	15.0	469.9	4.0	-4.1	-2.5	-28.6	0.2
Sep	12.4	7.9	317.3	4.6	15.8	10.0	358.4	4.2	-3.4	-2.1	-41.1	0.4
Oct	7.1	2.0	211.5	4.9	9.8	3.9	250.8	4.5	-2.7	-1.9	-39.3	0.4
Nov	-2.2	-6.3	125.9	5.2	0.5	-3.5	139.3	4.8	-2.7	-2.8	-13.4	0.4
Mean	8.5	3.0	372.3	4.9	12.4	6.0	388.9	4.6	-3.9	-2.9	-16.6	0.3
Standard deviation	7.9	7.7	127.1	0.4	8.3	7.7	126.5	0.4	-0.4	0.0	0.6	0.0

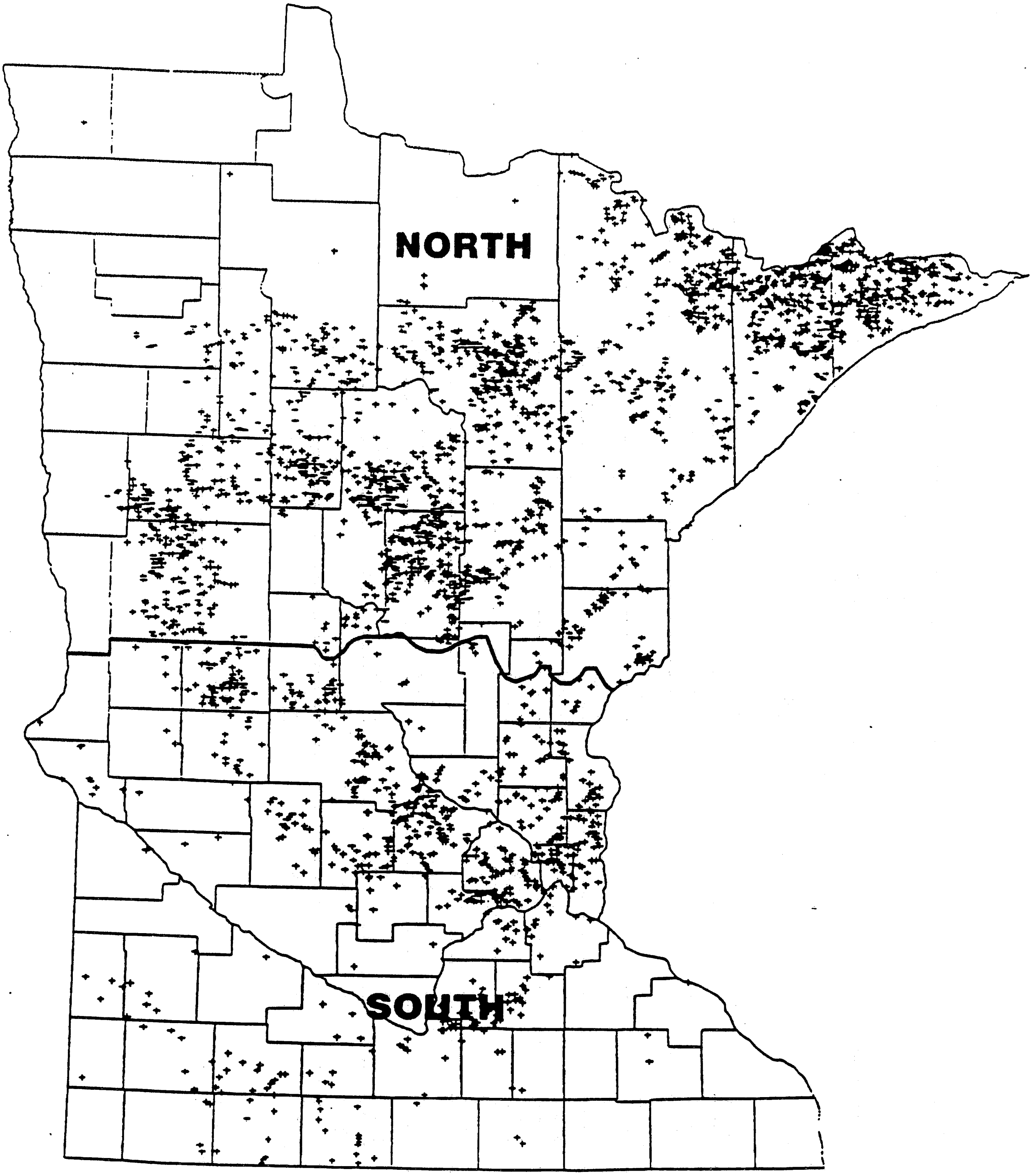


Fig. 3 Regional boundaries and geographic distribution of lakes in the database. + = lakes studied as part of this analysis.

stratification in lakes are dependent on surface area and maximum depth. To develop a statewide classification, the lake surface area, lake maximum depth, and mean Secchi depth were selected as the main independent parameters. These three parameters were chosen because the first two have a direct relation to stratification dynamics, and Secchi depth is correlated to trophic state of a lake and biochemical and biological oxygen demand.

The lake surface area (surrogate for wind fetch) and the maximum lake depth are used as indicators to differentiate between seasonally stratified and seasonally polymictic lakes (Lathrop and Lille, 1980; Nurnberg, 1988; Gorham and Boyce, 1989; Demers and Kalff, 1993). The criterion for lake stratification given by Gorham and Boyce (1989), mainly for the mid-North American continent (for lakes of surface area less than 25 km^2), is adequately represented by the regression equation $H_{max}=0.34\ A_s^{0.25}$. The stratification is determined by the lake maximum depth, H_{max}, and the fourth root of the lake surface area, A_s. The same equation can be rewritten in terms of the lake geometry ratio i.e. $A_s^{0.25}/H_{max}=2.9$. Values of the geometry ratio $A_s^{0.25}/H_{max}$ for 27 lake classes used in this study are given in Table 3. Shallow lakes, and lakes with large surface area and medium depth ($A_s^{0.25}/H_{max} > 2.9$) are expected to be seasonally polymictic, according to the seasonal stratification criteria given above. The rest of the lakes are expected to be dimictic.

Meteorological conditions i.e. solar radiation and wind also play a role but are less variable from lake to lake than is lake morphometry (Ford and Stefan, 1980b). Lake trophic status was assessed by using a Secchi depth scale (Heiskary and Wilson, 1988). Secchi depth was chosen as a lake trophic state indicator (Heiskary and Wilson, 1988), because it is a commonly available parameter and can be related to Carlson's Trophic State Index (Carlson, 1977), (Fig. 4). Secchi depth or transparency also affects solar radiation attenuation and oxygen balance.

Cumulative frequency distributions of the three key parameters for the 3002 lakes in the Minnesota Lakes Fisheries Database (ERLD/MNDNR, 1990) are given in Fig. 5. Three ranges of maximum depths (shallow-medium-deep), surface area (small-medium-large), and trophic status (eutrophic-mesotrophic-oloigotrophic) were selected as indicated in Fig. 5, and summarized in Table 3. Combinations of the three values for the three key parameters defined 27 (3x3x3) lake classes for which simulations were made. Physical characteristics and frequency of occurrence are given in Table 4. The geographic distribution of different classes of lakes in Minnesota is given in Fig. 6. Representative area-depth relationships were obtained from 35 lakes in a set of 122 lakes (Fig. 7). Areas are expressed as fractions of surface area and depths are expressed as fractions of maximum depth. An empirical equation of the form

Table 3. Physical parameters used to define 27 Minnesota lake classes.

Lake key parameter	Lake class				Lake geometry ratio		
	Descriptive term	Representative value used	Range	Cumulative frequency	A_s	H_{max}	$A_s^{0.25}/H_{max}$
Maximum depth H_{max} (m)	Shallow	4.0	1.0-5.0	Lower 30%	0.2	4.0	5.3
	Medium	13.0	5.0-20.0	Central 60%	0.2	13.0	1.6
	Deep	24.0	20.0-45.0	Upper 10%	0.2	24.0	0.9
Surface area A_s (km^2)	Small	0.2	0.06-0.4	Lower 30%	1.7	4.0	9.0
	Medium	1.7	0.4-5.0	Central 60%	1.7	13.0	2.8
	Large	10.0	5.0-40.0	Upper 10%	1.7	24.0	1.5
Secchi depth Z_s (m)	Eutrophic	1.2	0.8-1.8	Lower 20-50%	10.0	4.0	14.1
	Mesotrophic	2.5	1.8-4.5	Central 20-50%	10.0	13.0	4.3
	Oligotrophic	4.5	4.5-7.0	Upper 0-10%	10.0	24.0	2.3

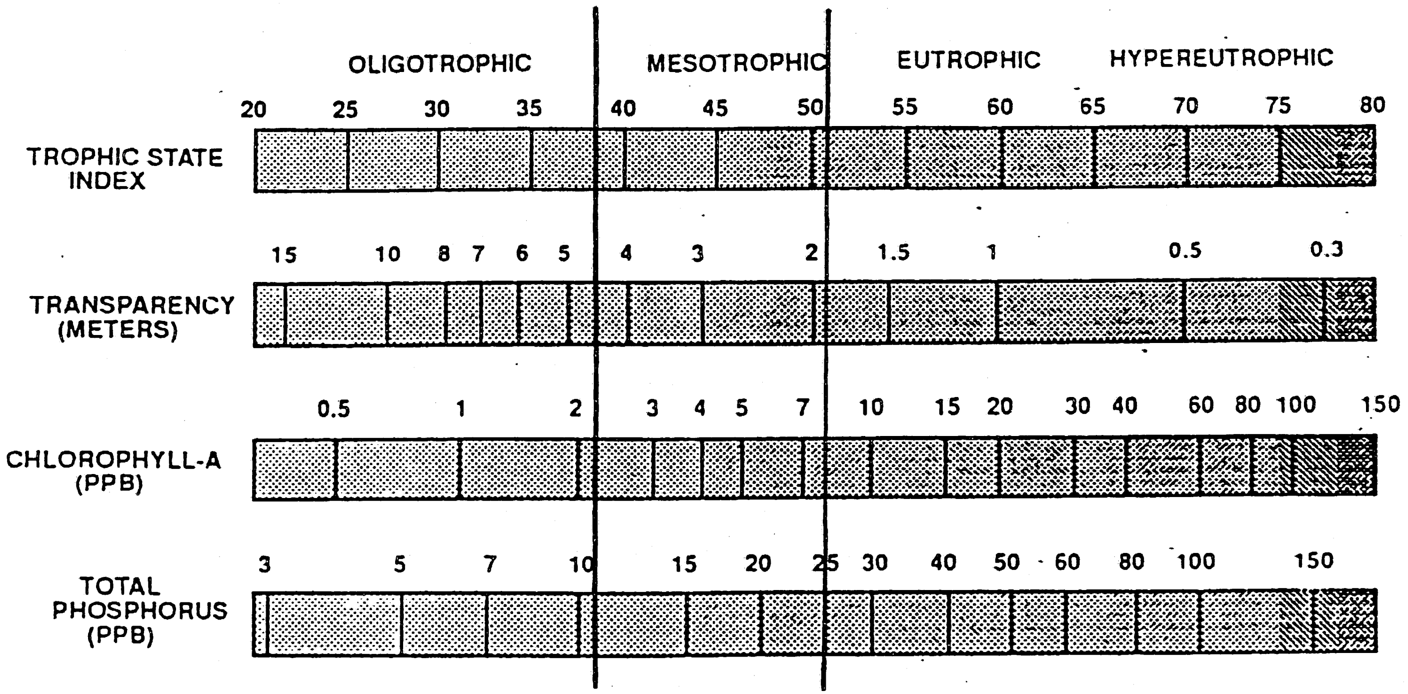


Fig. 4 Carlson's Trophic State Index related to several other Minnesota lake parameters (after Heiskary and Wilson, 1988).

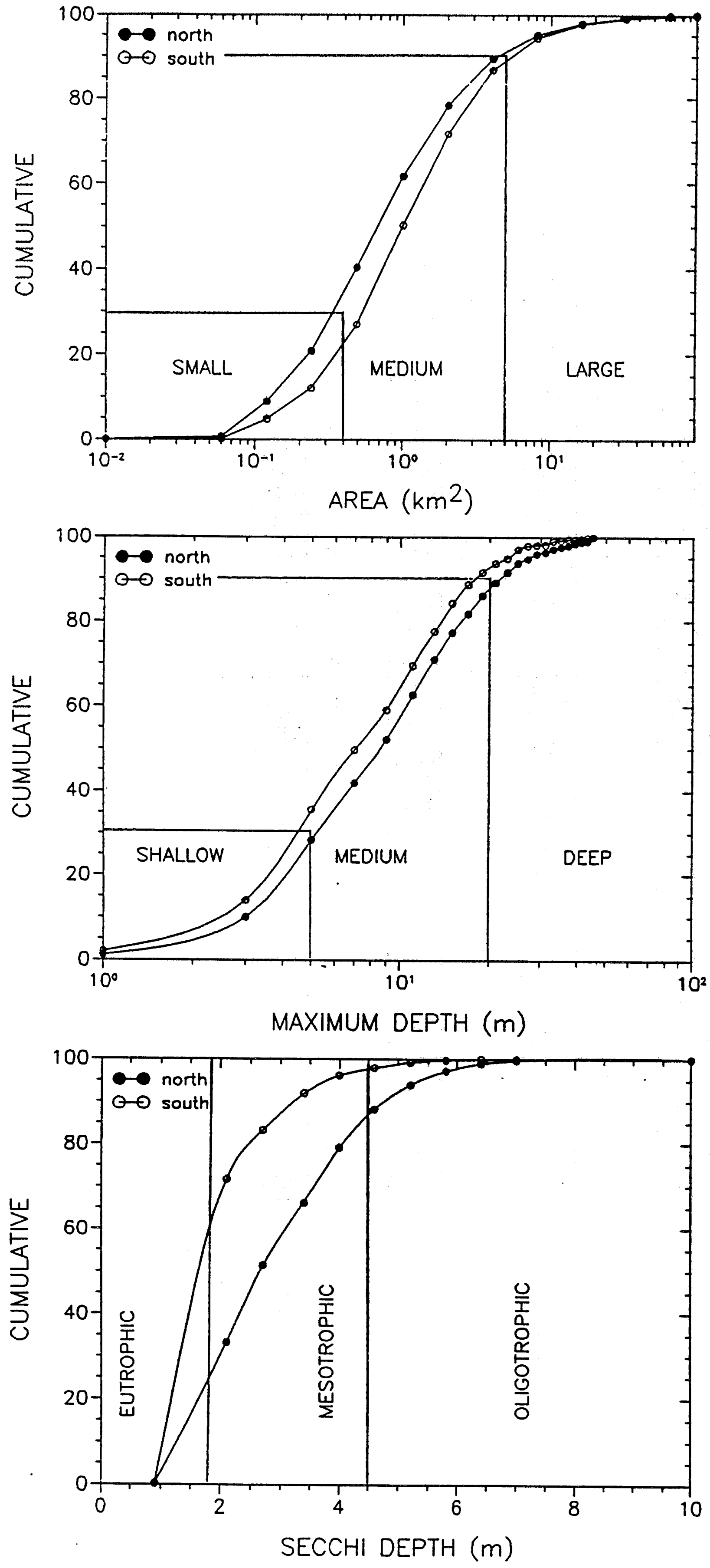
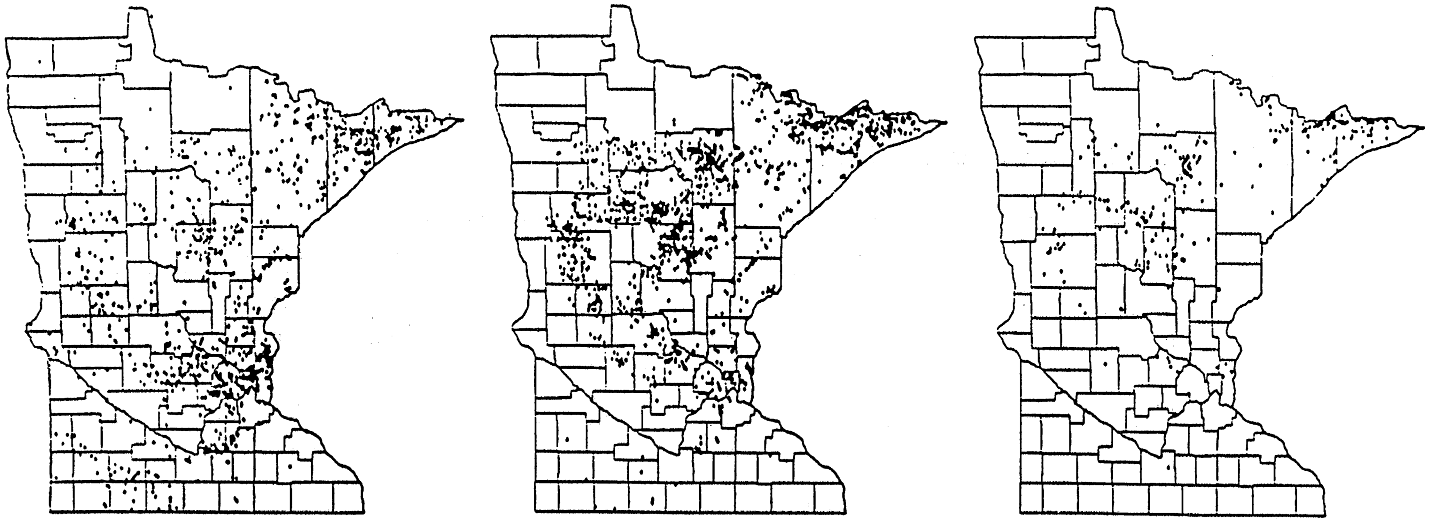


Fig. 5 Cumulative distributions (%) of three key parameters of Minnesota lakes (from lake database).

Table 4. Physical characteristics of Minnesota lakes.

Lake characteristics							Relative frequency by		
Maximum depth (m)	Surface area (km^2)	Volume 10^6 (km^3)	Trophic state	# of lakes	Total surf. area (km^2)	Total volume 10^6 (km^3)	# of lakes (%)	Surf. area (%)	Volume (%)
Shallow	Small	0.31	eutrophic	229	45.8	71.6	7.6	0.9	0.3
4.0 m	0.2		mesotrophic	199	39.8	62.2	6.6	0.8	0.3
			oligotrophic	3	0.6	0.9	0.1	0.0	0.0
	Medium	2.55	eutrophic	321	546.0	818.0	10.7	10.9	3.4
	1.7		mesotrophic	124	211.0	316.0	4.1	4.2	1.3
			oligotrophic	4	68.0	10.2	0.1	0.1	0.0
	Large	13.80	eutrophic	26	260.0	358.0	0.9	5.2	1.5
	10.0		mesotrophic	5	50.0	68.9	0.2	1.0	0.3
			oligotrophic	0	0.0	0.0	0.0	0.0	0.0
Medium	Small	1.01	eutrophic	167	33.4	169.0	5.6	0.7	0.7
13.0	0.2		mesotrophic	422	84.4	426.0	14.1	1.7	1.8
			oligotrophic	84	16.8	84.8	2.8	0.3	0.3
	Medium	8.09	eutrophic	244	415.0	1970.0	8.1	8.3	8.1
			mesotrophic	633	1080.0	5120.0	21.1	21.5	21.1
	1.7		oligotrophic	83	141.0	671.0	2.8	2.8	2.8
	Large	43.60	eutrophic	31	310.0	1350.0	1.0	6.2	5.6
	10.0		mesotrophic	50	500.0	2180.0	1.7	10.0	9.0
			oligotrophic	1	10.0	43.6	0.0	0.2	0.2
Deep	Small	1.93	eutrophic	7	1.4	13.5	0.2	0.0	0.1
24.0	0.2		mesotrophic	33	6.6	63.5	1.1	0.1	0.3
			oligotrophic	26	5.2	50.1	0.9	0.1	0.2
	Medium	15.20	eutrophic	13	22.1	198.0	0.4	0.4	0.8
	1.7		mesotrophic	137	233.0	2080.0	4.6	4.7	8.6
			oligotrophic	74	126.0	1120.0	2.5	2.5	4.6
	Large	82.10	eutrophic	10	100.0	821.0	0.3	2.0	3.4
	10.0		mesotrophic	59	590.0	4840.0	2.0	11.8	19.9
			oligotrophic	17	170.0	1400.0	0.6	3.4	5.7
	Sum			3002	5000.0	24300.0	100	100	100



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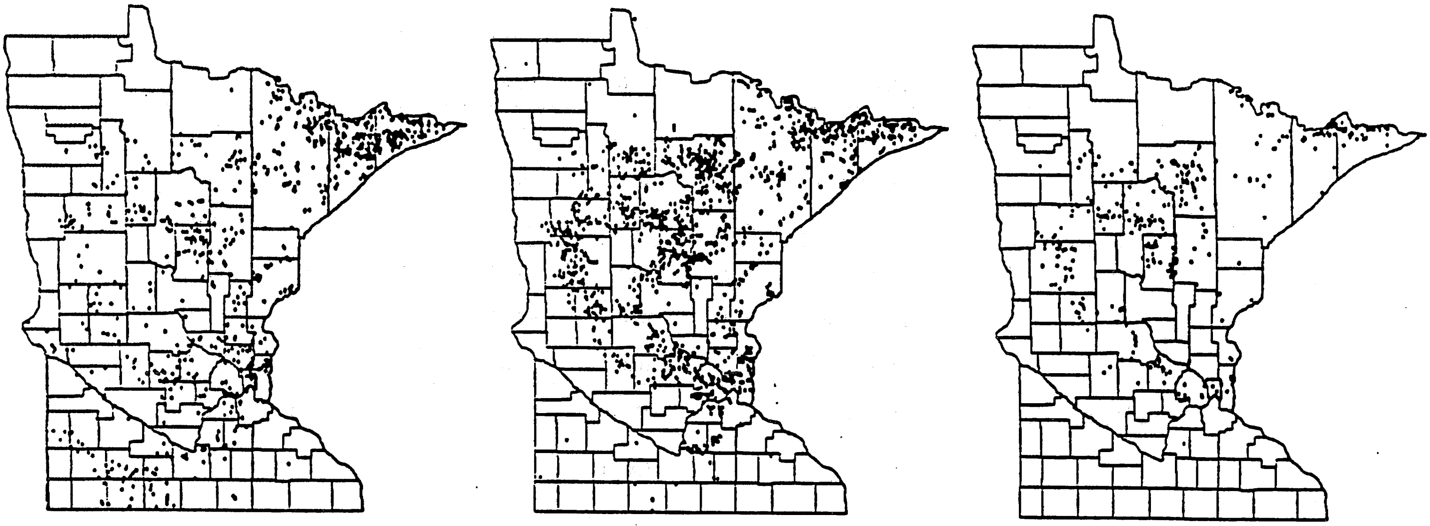

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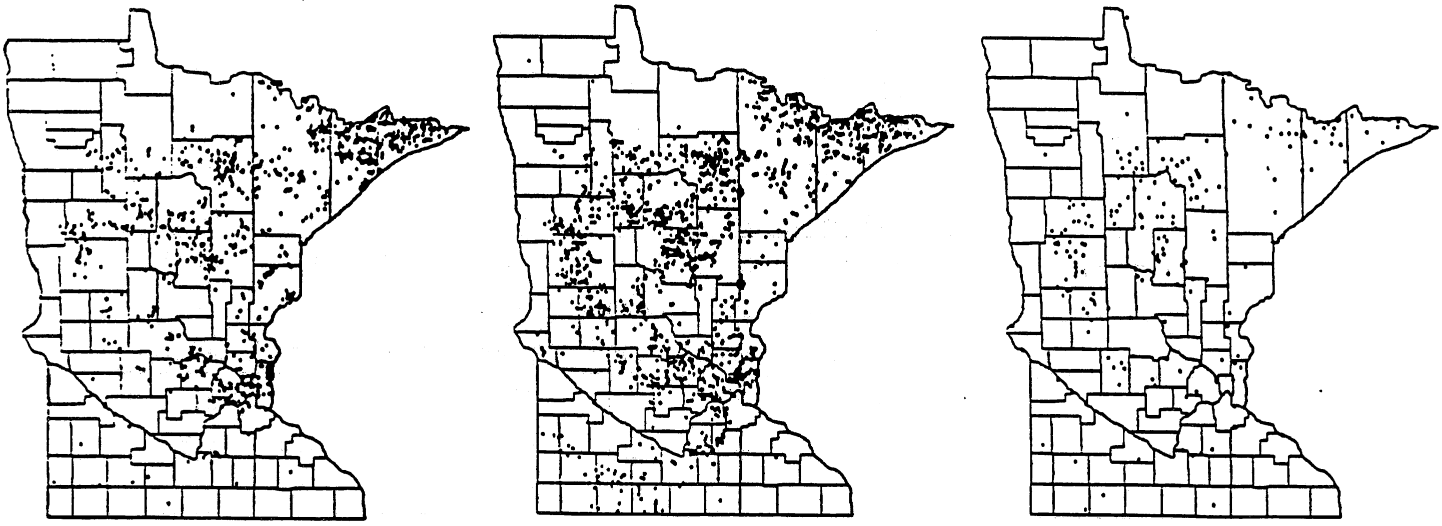

AREA < 0.4 SQ. KM.

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Fig. 6 Geographic distribution of lakes according to the key parameters: Secchi depth, maximum depth, and surface area.

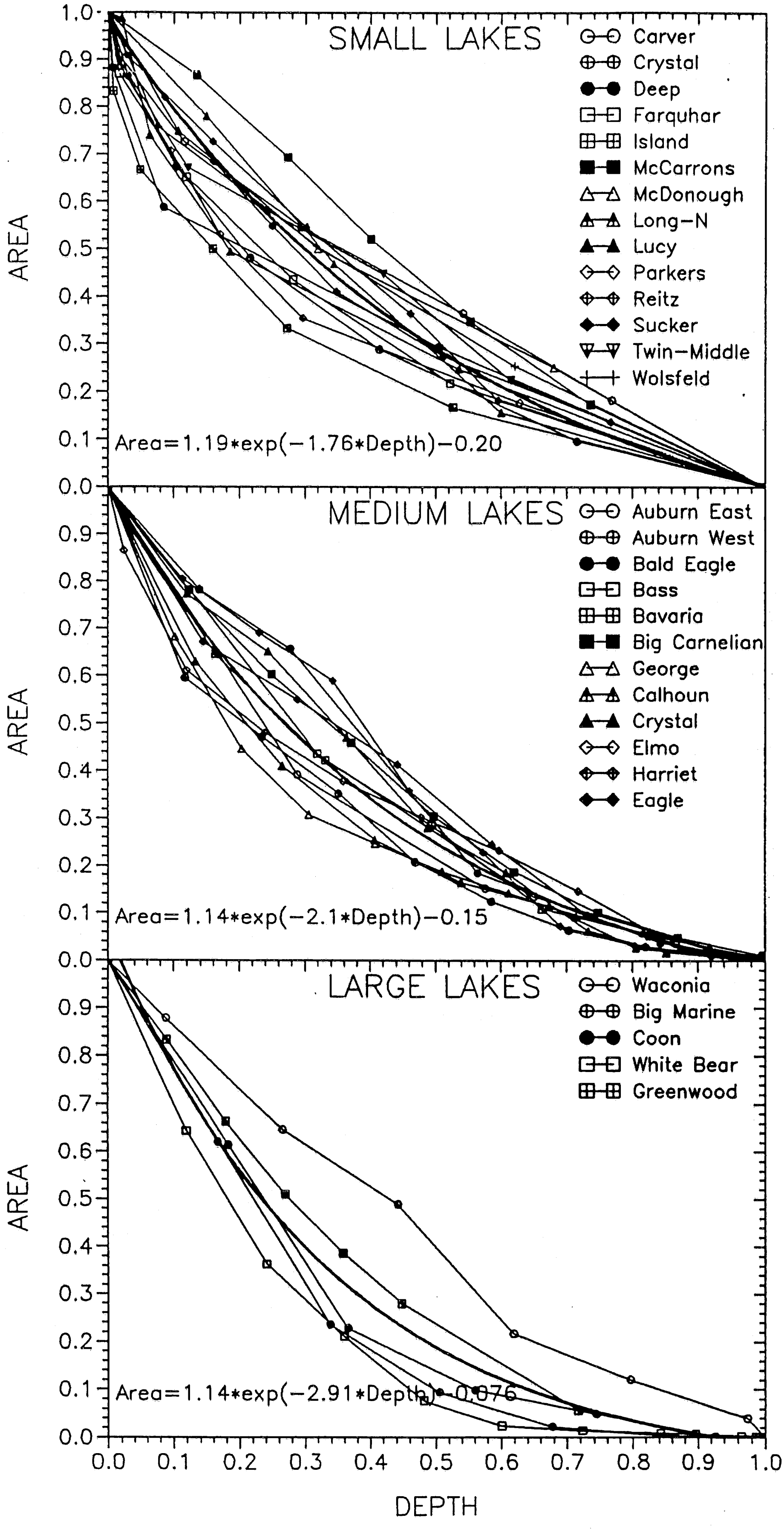

Fig. 7 Horizontal area versus depth relationship for lakes. Area and depth are normalized.

$$Area = a \exp(b\ Depth) + c \qquad (1)$$

is fitted to the data and used in the simulations as a representative area-depth relationship. Coefficients a, b, c estimated by regression analysis are given in Table 5. Self-similarity of depth-area relationships within a given class is assumed.

Table 5. Morphometric regression coefficients a,b, and c in the area-depth relationships.

Surface Area	a	b	c	r^2
Small	1.19	-1.76	-0.20	0.90
Medium	1.14	-2.10	-0.15	0.92
Large	1.14	-2.91	-0.08	0.85

a,b,c = coefficients estimated by regression analysis

r^2 = portion of the measured lake area variability explained by the regression equation

4. Simulation Methods for Water Quality and Habitat Suitability for Fishes

A deterministic, process-oriented, unsteady, one-dimensional lake water quality model was used for these simulations. This model has previously been successfully applied to simulate hydrothermal processes and water quality in lakes for a variety of meteorological conditions (Stefan and Ford, 1975; Riley and Stefan, 1987; Hondzo and Stefan, 1991; Hondzo and Stefan, 1993; Stefan and Fang, 1994). The water quality model was verified for 16 lakes of different morphometries and trophic levels, and with different meteorological conditions (Stefan et al., 1993a; Stefan and Hondzo 1993; Stefan and Fang, 1993; 1994). The standard error of the water temperature predictions was from 0.5°C to 1.1 °C for individual lakes, and DO gave a standard error from 0.6 to 2.3 mg/l. The 95% confidence intervals are 1.0 to 2.2 °C and 1.2 to 4.5 mg/l, respectively.

With these water quality models, simulations of water temperatures and DO were made for the 27 classes of lakes in southern and northern Minnesota. The computational sequence is graphically summarized in the flow-chart of Fig. 8. The simulation model was operated on daily timesteps. Simulated vertical profiles of daily water temperature and dissolved oxygen concentrations were obtained for the open water season[3], the length of which was found by the model itself (Hondzo and Stefan, 1991).

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[3] Roughly, lakes are ice free in southern Minnesota from April to November, and in northern Minnesota from May to October.

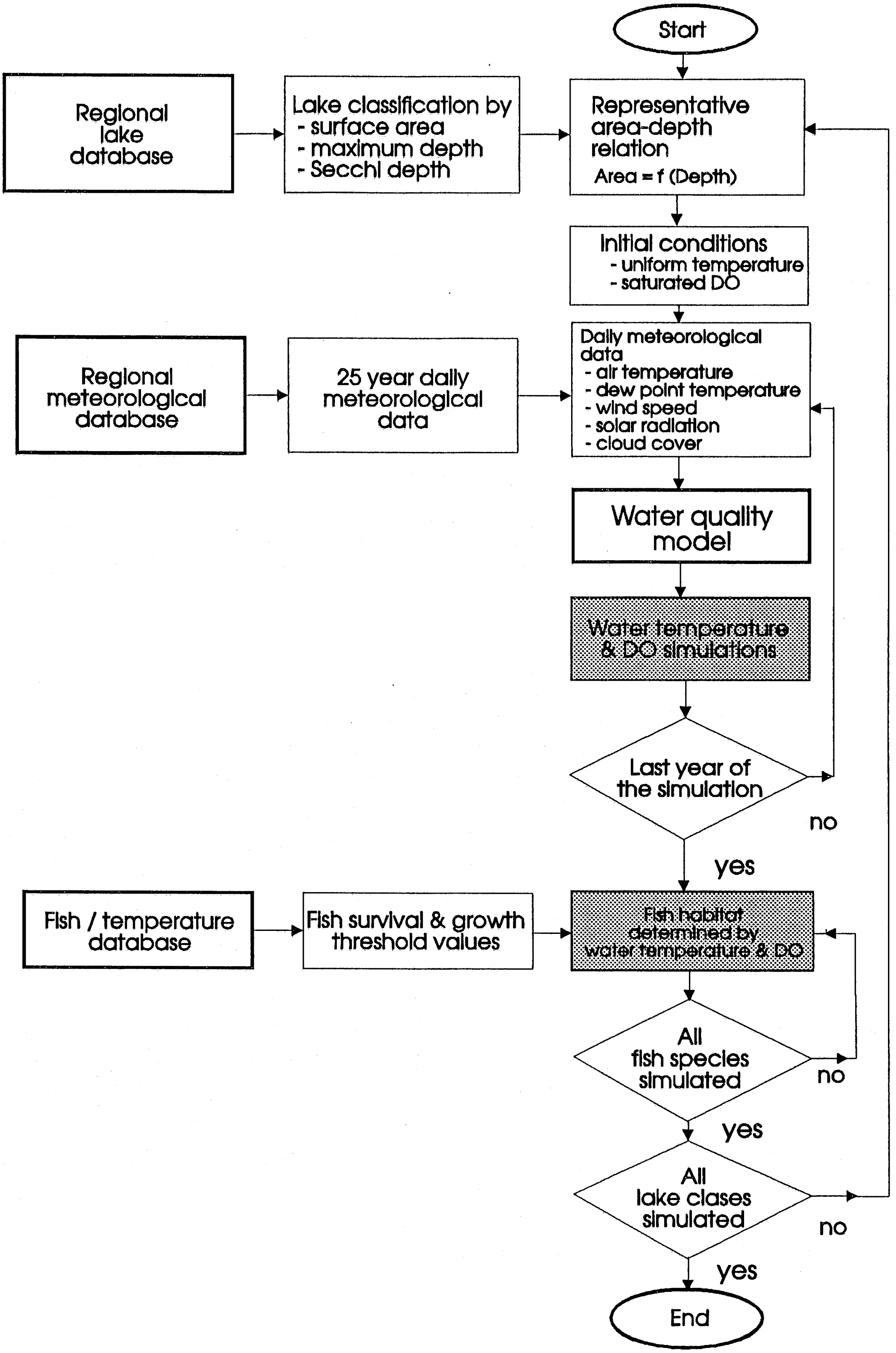

Fig. 8 Schematic of the simulation procedure.

5. Results

5.1 Water temperature and thermal stratification

Parameters which can be used to characterize water temperatures and the thermal stratification in a lake are given in Table 6. Surface temperature, bottom temperature, volume weighted (average) temperature, surface to bottom temperature difference, thermocline depth, dynamic stratification stability, linear temperature gradient, seasonal stratification ratio, and heat content are of interest and were estimated from the averages of the daily water temperature profiles simulated over a 25 year span. Each of these parameters is correlated with lake geometry ratio ($A_s^{0.25}/H_{max}$), and lake trophic state as determined by Secchi depth. The results will be presented in a series of graphs with lake geometry ratio and Secchi depth as axes. Regression equations, in cases where appropriate, are given mainly to indicate outstanding trends. The reader is reminded that all values presented in Figs. 9 through 26 are 25-year average values obtained by model simulations. They can not be compared to instantaneous measurements in a lake unless the measurements span an equally long period and are averaged.

The surface temperature reported is the maximum daily temperature in the lake surface mixed layer throughout the season. The value was extracted from the simulated daily water temperature profiles and represents a 25-year average. The isotherms representing maximum daily surface water temperatures are shown (Fig. 9a). The isotherms are obtained by interpolation among 27 simulated values more or less uniformly distributed over the graph (Table 3 gives the coordinates). Separate graphs are given for the northern half and the southern half of Minnesota (Fig. 3 shows the division). As can be seen, the dependence of surface water temperature on Secchi depth is negligible. Therefore maximum daily surface water temperatures were plotted against the lake geometry ratio only in Fig. 9b. Each point on the graph designates a particular lake class. The surface temperatures are approximately the same over a wide range of lake morphometries, but there is a notable difference between northern and southern Minnesota i.e. regions with different meteorological conditions. One can conclude that maximum surface water temperatures are influenced primarily by the meteorological forcing, and much less significantly by lake geometry and trophic state. Daily average meteorological variables which correlate the most significantly with maximum surface water temperatures and which are different in the north and the south are air temperature, dew point temperature and solar radiation. There is a difference of about 1 ^{o}C between lakes with a permanent seasonal stratification (dimictic lakes) and intermittently stratified lakes (polymictic lakes). The transition from one type of lake to another occurs at $A_s^{0.25}/H_{max}$ ~ 2.5 to 5.0 $m^{-0.5}$ as indicated already by Gorham and Boyce (1989). There is some

Table 6. Parameters used to define long-term stratification characteristics.

Parameter	Description	Formulation/Definition
Surface temperature	Maximum daily temperature at the lake surface. T_s=surface water temperature, t=timestep (1 day), n= the last day of simulation (November 30).	$Max\left[T_s(t), t=1,n\right]$
Bottom temperature	Maximum temperature above the lake sediments. T_b=bottom water temperature.	$Max\left[T_b(t), t=1,n\right]$
Volume weighted temperature	Total volume average maximum daily water temperature. H_{max}=maximum lake depth, A(z)=lake area at height z above the lake bottom.	$T_{av}=\frac{\int_0^{H_{max}} T(z,t)A(z)dz}{\int_0^{H_{max}} A(z)dz}$
Temperature difference	Maximum daily water temperature difference between surface temperature and bottom temperature.	$Max\ \{[T_s(t)-T_b(t)]\ ,\ t=1,n\ \}$
Thermocline depth	Depth measured from the lake surface at the moment of maximum heat content. ρ=water density.	$h=H_{max}-\frac{\int_0^{H_{max}} z\frac{d\rho(z,t)}{dz}dz}{\int_0^{H_{max}} \frac{d\rho(z,t)}{dz}dz}$
Lake Number	Characterizes the stability of the entire lake. g=acceleration due to gravity, z_T =height from the lake bottom to the center of the thermocline, ρ_s =water density at the lake surface, A_s =lake surface area, u_* =surface shear velocity, z_g=height of center of volume of lake, S_t=stability if the lake.	$L_N=\frac{gS_t\left(1-\frac{z_T}{H_{max}}\right)}{\rho_s u_*^2 A_s^{1.5}\left(1-\frac{z_g}{H_{max}}\right)}$
Linear temperature gradient	Linear temperature gradient between water temperature at the lake surface and lake bottom, weighted with the potential energy in the lake. ΔT=water temperature difference.	$\frac{\Delta T}{H_{max}}=\frac{\frac{1}{H_{max}}\int_0^{H_{max}} \rho(z,t)gzA(z)dz}{\int_0^{H_{max}} \frac{\partial\rho(z,t)}{\partial z}gzA(z)dz}$
Seasonal stratification ratio	Total number of days when difference between surface and bottom temperature is greater than 1°C divided by the length of seasonal stratification i.e. difference between the first (SSB) and the last julian day (SSE) when the temperature difference was grater than 1°C.	$SSR=\frac{\sum_{1\ Mar}^{31\ Oct}\left[T_s(t)-T_b(t)\right]\geq 1°C}{SSE-SSB+1}$
Heat content	Maximum daily heat content in a lake. c_p=specific heat of the water.	$H_n=c_p\int_0^{H_{max}} \rho(z,t)T(z,t)A(z)dz$

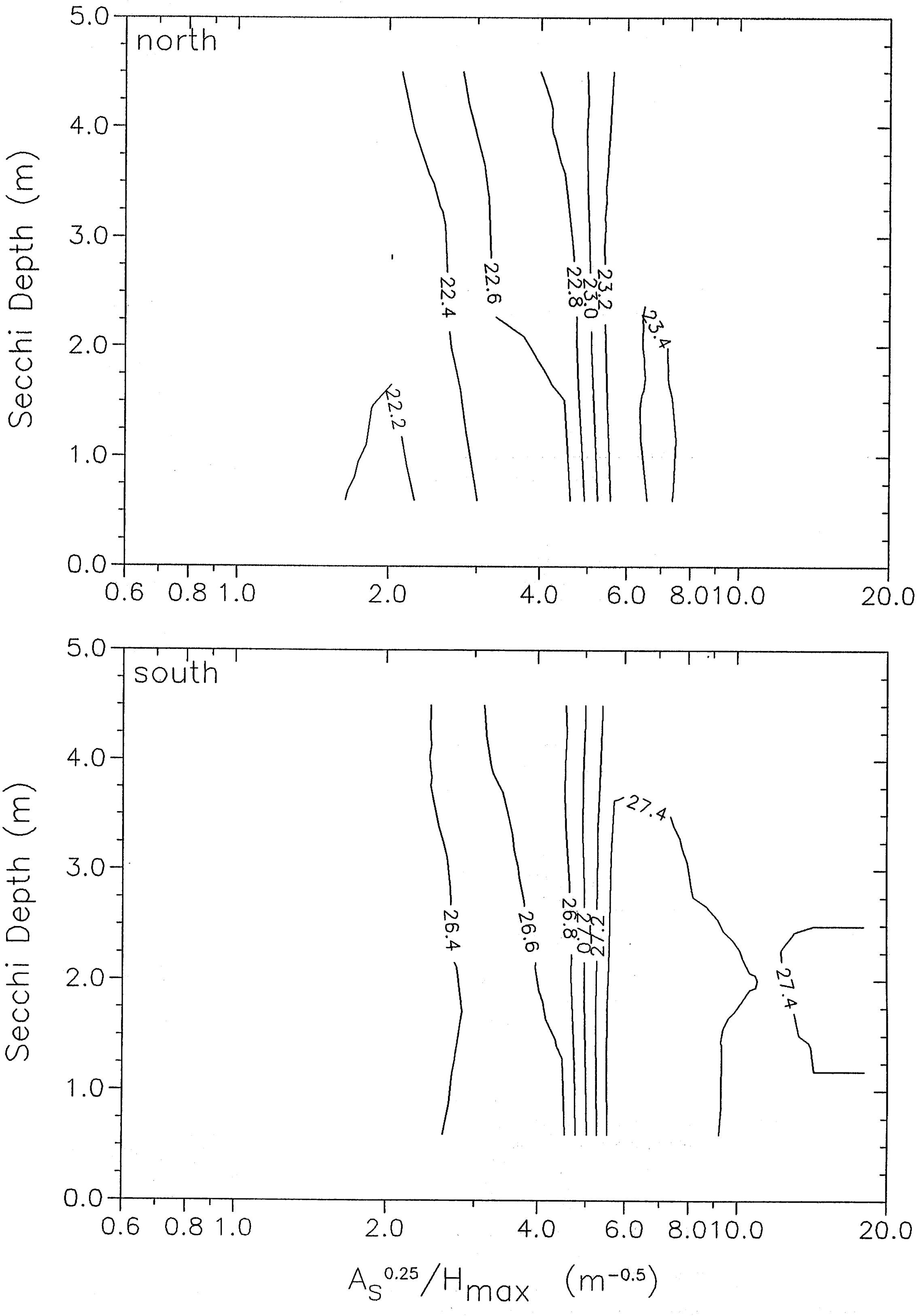

Fig. 9a **Maximum daily surface water temperature (°C) isotherms (simulated 25-year averages).**

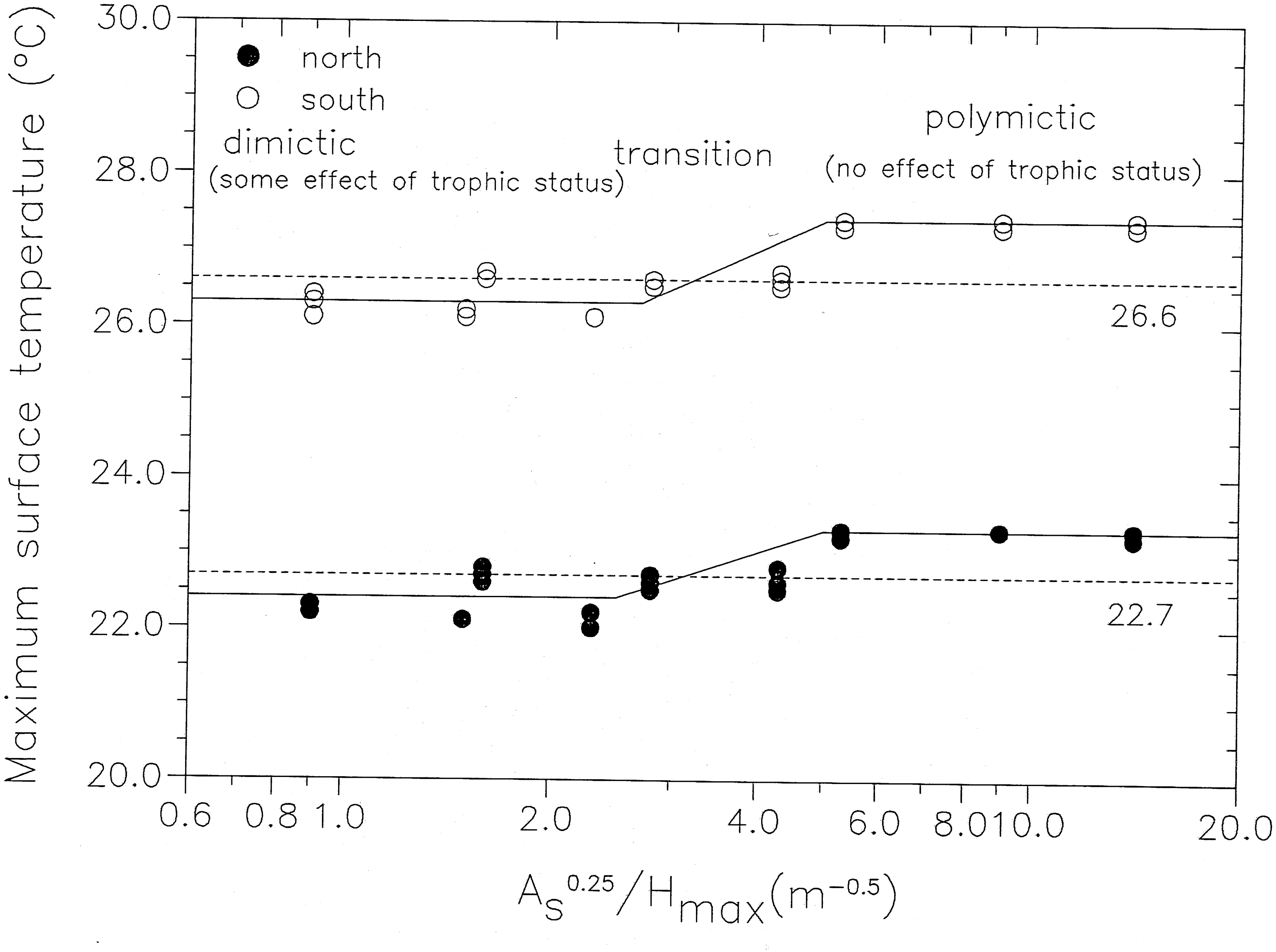

Fig. 9b Maximum daily surface water temperature (simulated 25-year averages).

effect of trophic status on the dimictic lake results as indicated by the data scatter, but none for polymictic lakes.

The water temperature at the bottom of a lake, unlike surface water temperature, is not directly related to the meteorological forcing, especially in deeper lakes. The bottom temperature reported is the maximum daily water temperature 1m or less above the lake sediments. It is the temperature which can e.g. affect sediment oxygen demand or fish survival. The simulated daily maximum bottom temperatures are given in Figs. 10a and 10b. The bottom temperatures generally increase when the lake geometry ratio $A_s^{0.25}/H_{max}$ increases. This increase is related to a transition from dimictic (seasonally stratified) lakes to polymictic lakes. Constant water temperatures at $A_s^{0.25}/H_{max} > 8$ indicate independence from lake geometry. There is probably also an asymptotic value of 4°C at $A_s^{0.25}/H_{max} < 0.4$. Oligotrophic lakes have higher bottom water temperatures than eutrophic lakes because of the difference in solar radiation attenuation. Similar water temperature trends are evident for northern and southern Minnesota lakes. In seasonally stratified lakes, hypolimnetic water temperatures are mainly determined by temperatures at spring turnover. In summary a high correlation exists between the maximum bottom water temperature and the lake geometry ratio $A_s^{0.25}/H_{max}$.

The difference between surface and bottom temperature of a lake is also an indicator of the strength of stratification in a lake. Values of maximum daily water temperature differences between the surface and the bottom of a lake are given in Fig. 11. This temperature difference increases as the lakes become more strongly stratified i.e. as geometry ratio $As^{0.25}/H_{max}$ decreases. The largest difference, 16°C for northern Minnesota and 20°C for southern Minnesota, is estimated for lakes with the greatest depth and the smallest surface area. These lakes typically have more wind sheltering. The isotherms in Fig. 11 also indicate that the strength of the temperature stratification also depends somewhat on the trophic state of a lake. Eutrophic lakes (with high solar radiation attenuation with depth) have higher temperature differences than oligotrophic lakes. The mean vertical temperature gradient, i.e. the maximum temperature difference from top to bottom divided by the maximum lake depth, is presented by dashed lines in Fig. 11. The highest gradients are estimated for lakes with the smallest surface area to maximum depth ratio.

An average water temperature in the entire lake was also determined from the simulated water temperature profiles. The maximum of the average daily water temperatures, weighted by lake volume, is given in Fig. 12a. It is notable that the forcing parameter in the regression line in Fig. 12b is the same as for the surface water temperatures for northern and southern Minnesota. As can be expected the volume weighted temperature is lower for stratified (dimictic) lakes. The total, volume averaged, lake temperatures are higher, by 4.0°C, in southern Minnesota lakes compared to northern Minnesota lakes.

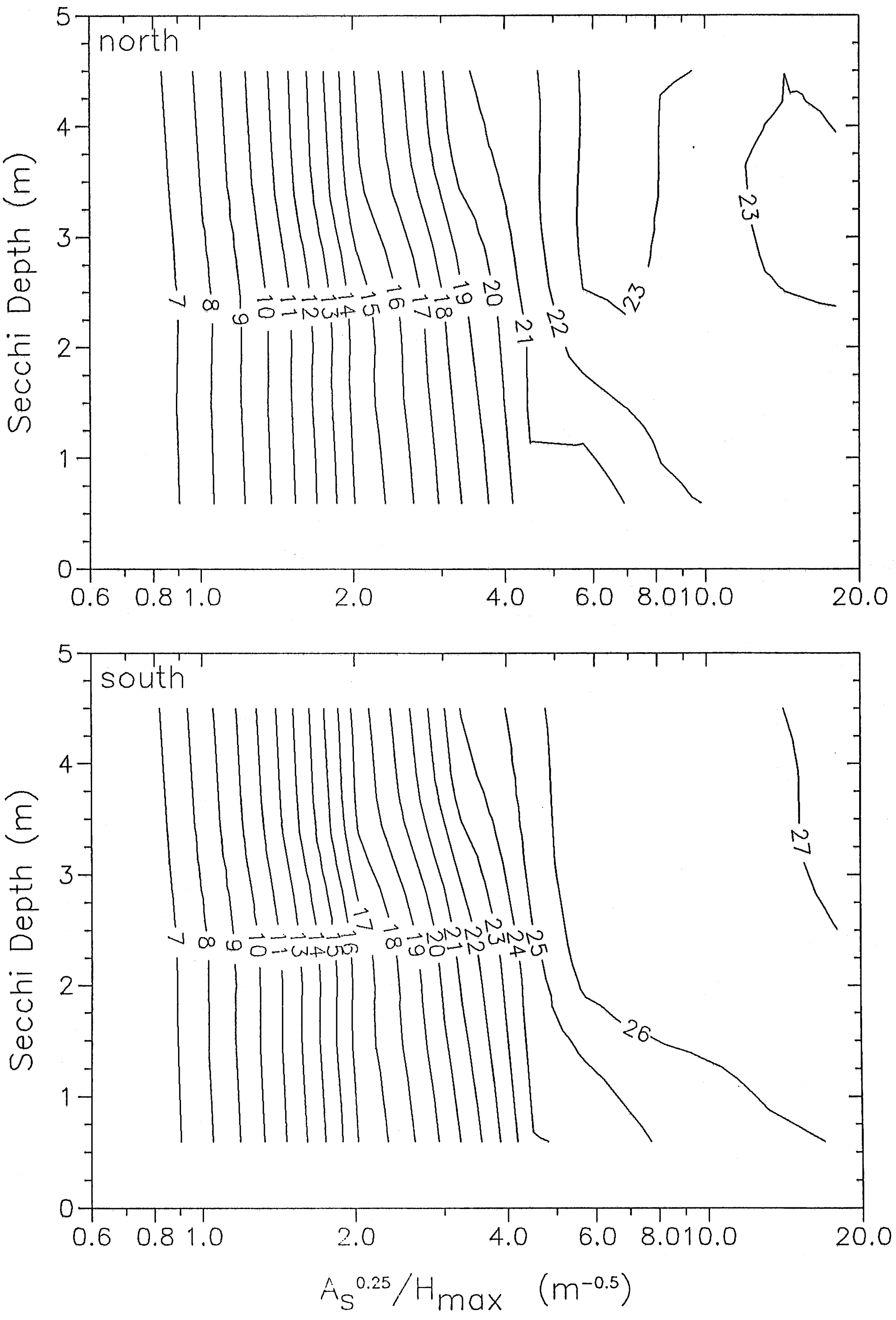

Fig. 10a Maximum daily bottom temperature (°C) isotherms (simulated 25-year averages).

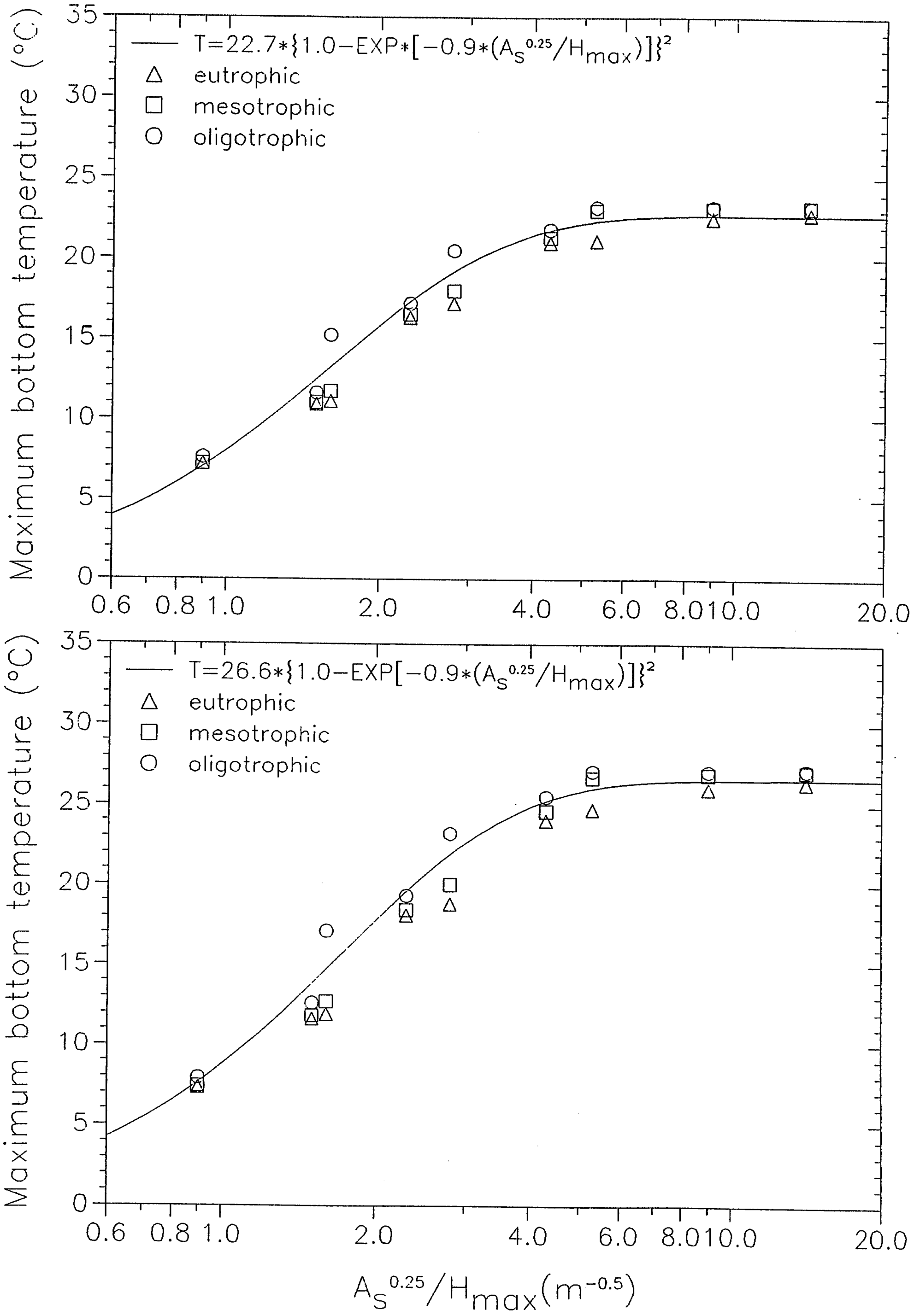

Fig. 10b. Maximum daily water temperature near lake bottom (simulated 25-year averages).

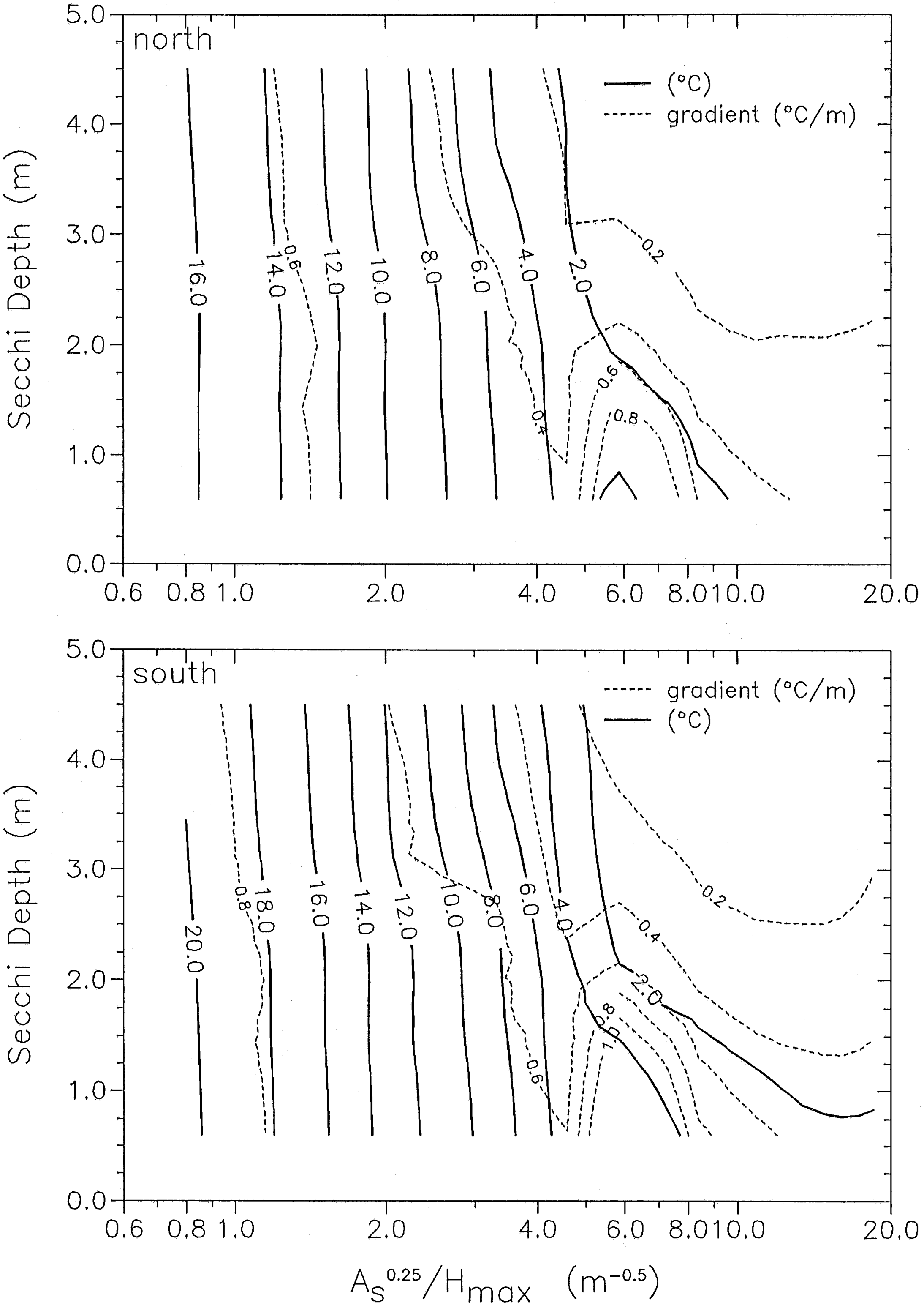

Fig. 11 Maximum daily water temperature difference (°C) between surface and bottom (solid line), and maximum water temperature gradient (°C/m) (dashed line).

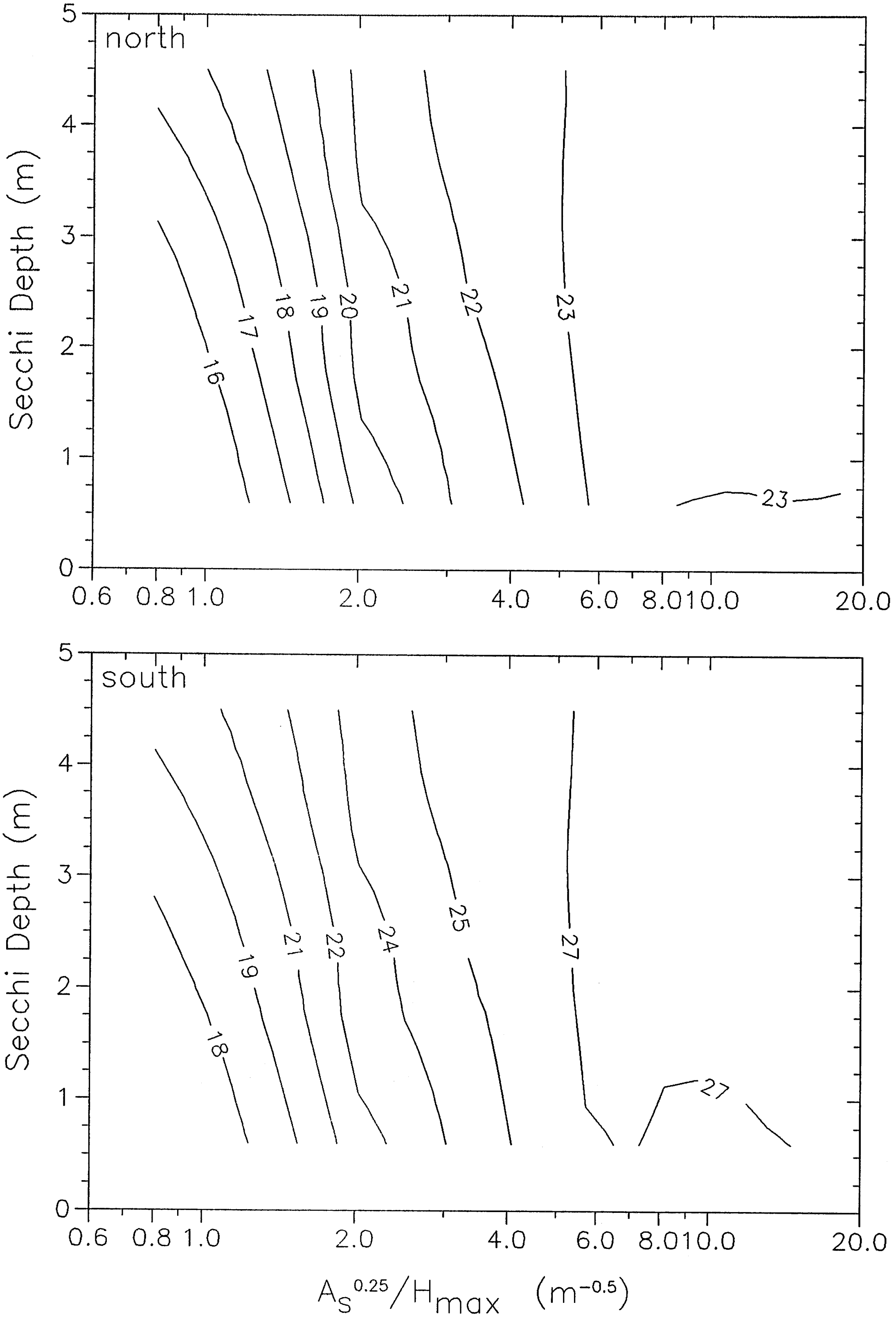

Fig. 12a Lake volume-averaged maximum daily water temperature isotherms (°C).

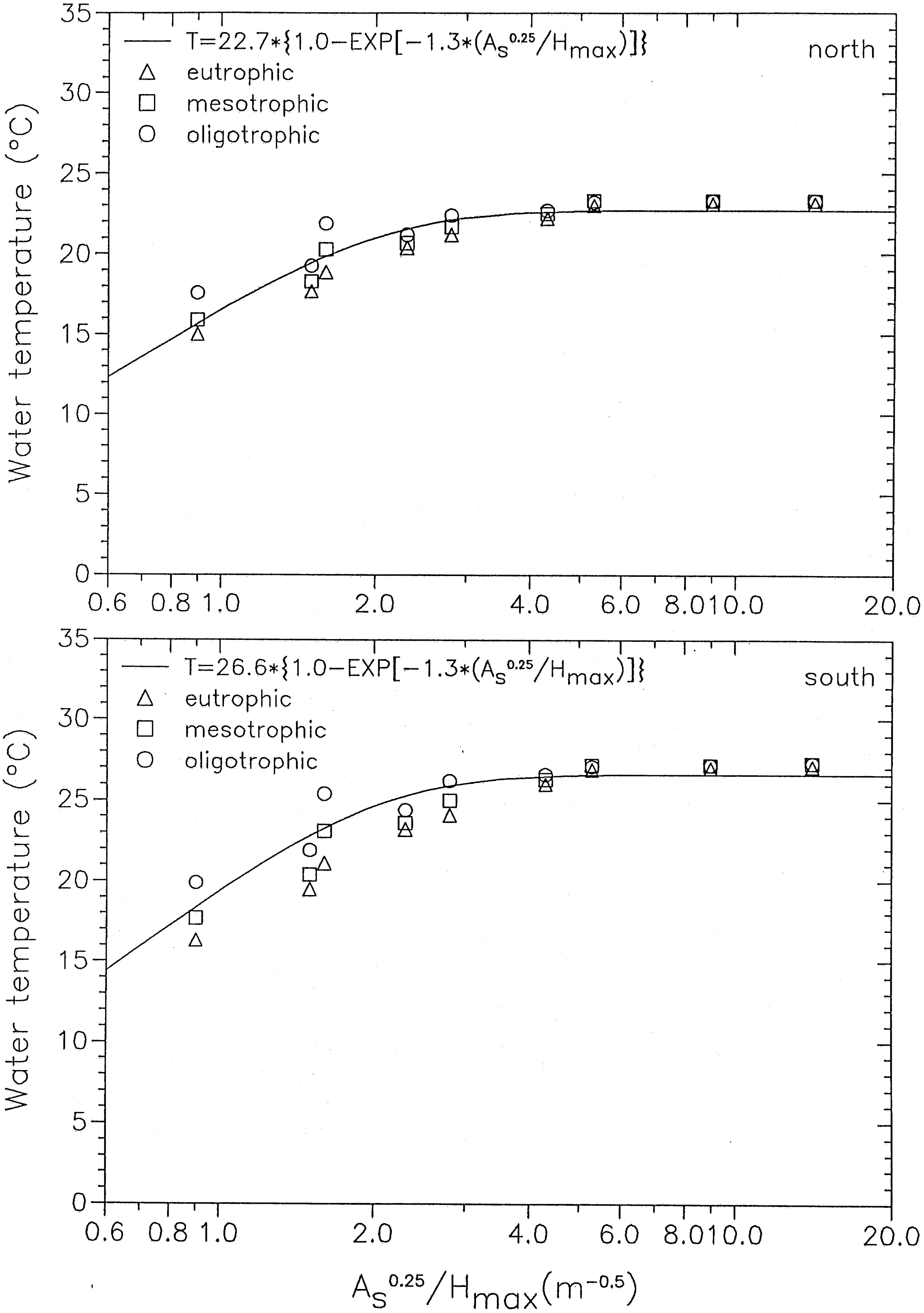

Fig. 12b Lake volume-averaged maximum daily water temperature.

The heat content of a lake is equal to the total volume weighted average temperature multiplied by the water density and specific heat of the water. Contour lines giving the simulated maximum daily heat content of Minnesota lakes are given in Fig. 13. Shallow lakes have the highest heat content per unit volume. Contours indicate that oligotrophic lakes have a higher heat content than eutrophic lakes because they warm to greater depth because of their higher transparency.

The stabilizing effect of the temperature (density) stratification of a lake is weighted against the destabilizing influence of wind in the nondimensional Lake Number (Imberger and Patterson, 1990). The number is defined in Table 6. A higher Lake Number implies a more stable stratification i.e. more horizontal isotherms and less internal seiching. Maximum daily Lake number dependence on lake trophic state is given in Fig. 14. The contour line slope indicates higher lake stability for oligotrophic lakes in comparison to eutrophic lakes of same geometry. As will be shown in the next paragraph, oligotrophic lakes have deeper thermoclines than eutrophic lakes with the same geometry ratio, and therefore require greater wind force in order to overturn the density structure in the water column.

The variation of Lake Number with time in the season (Julian day) and the lake geometry ratio ($As^{0.25}/H_{max}$) is given in Fig. 15. Maximum lake numbers (30 in northern Minnesota and 37 in southern Minnesota) indicate that the maximum stability in the lake is obtained. This occurs around the end of August in deep lakes of small surface area. For a fixed time, the maximum Lake Number is smaller when the lake geometry ratio increases. At geometry ratios higher than 3 low stability of the lake is indicated. Low Lake numbers are estimated in fall and spring i.e. during the overturn periods. The trophic state of a lake is not considered as a parameter in Fig. 15.

The thermocline depth is estimated from the first moment of the water density gradient profile as defined in Table 6. In most cases the thermocline depth corresponds to the position of the maximum density gradient (Patterson et al., 1984). Values for the maximum daily thermocline depth in a season are given in Fig. 16. The contour label 1.0 designates a fully mixed lake i.e. the thermocline depth is equal to the maximum lake depth. The labels lower than 1.0 designate the position of the thermocline relative to the maximum lake depth. Figure 16 shows that the thermocline depth decreases with decreasing lake geometry ratio $A_s^{0.25}/H_{max}$, and that trophic state of a lake clearly contributes to the thermocline depth. Oligotrophic lakes have a greater thermocline depth than eutrophic lakes for the same lake geometry ratio, because eutrophic lakes attenuate solar radiation more readily than oligotrophic lakes, therefore temperature gradients, as shown previously, are located higher in the water column in eutrophic lakes than in oligotrophic lakes.

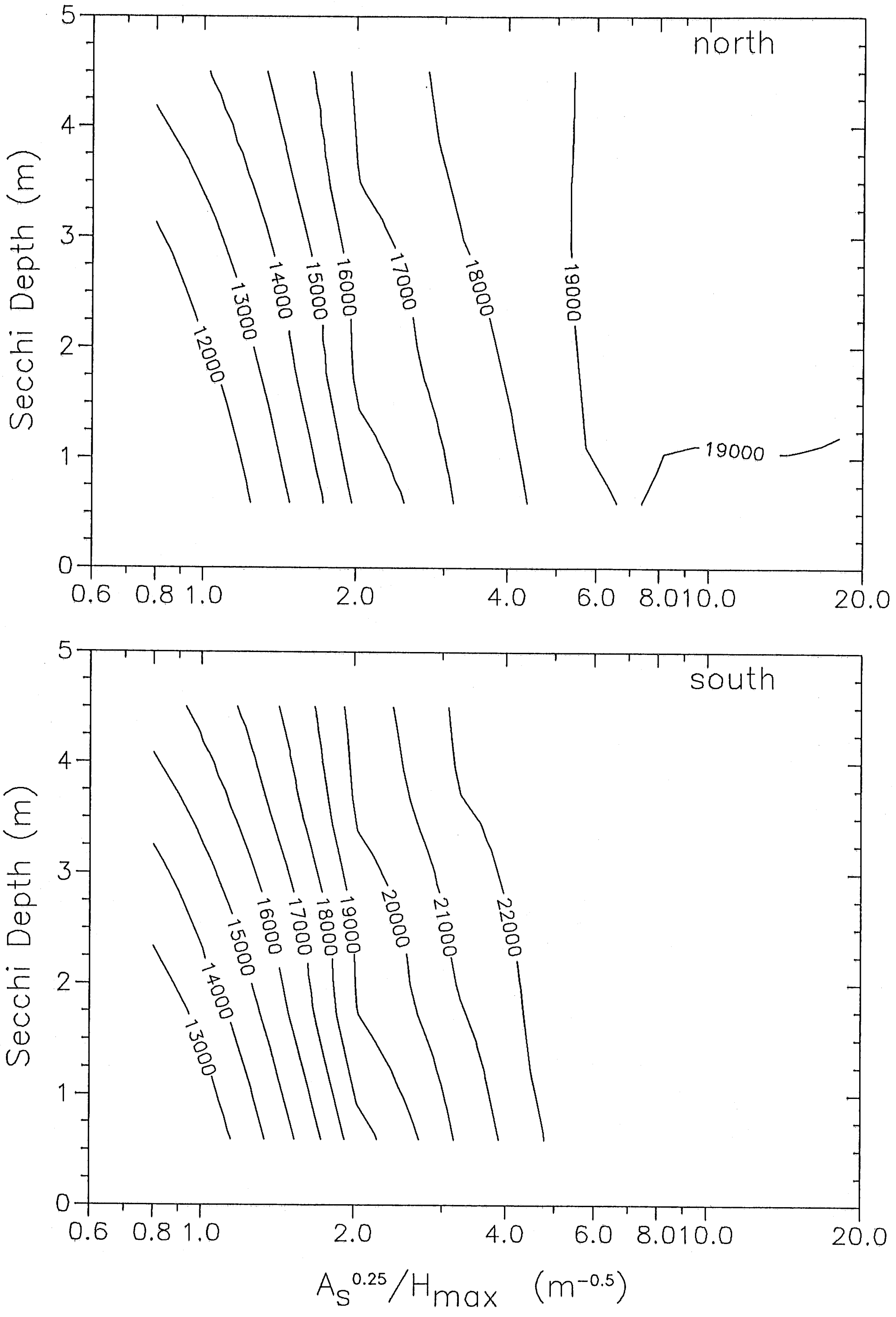

Fig. 13 Lake volume-averaged maximum daily heat content (kcal/m^3).

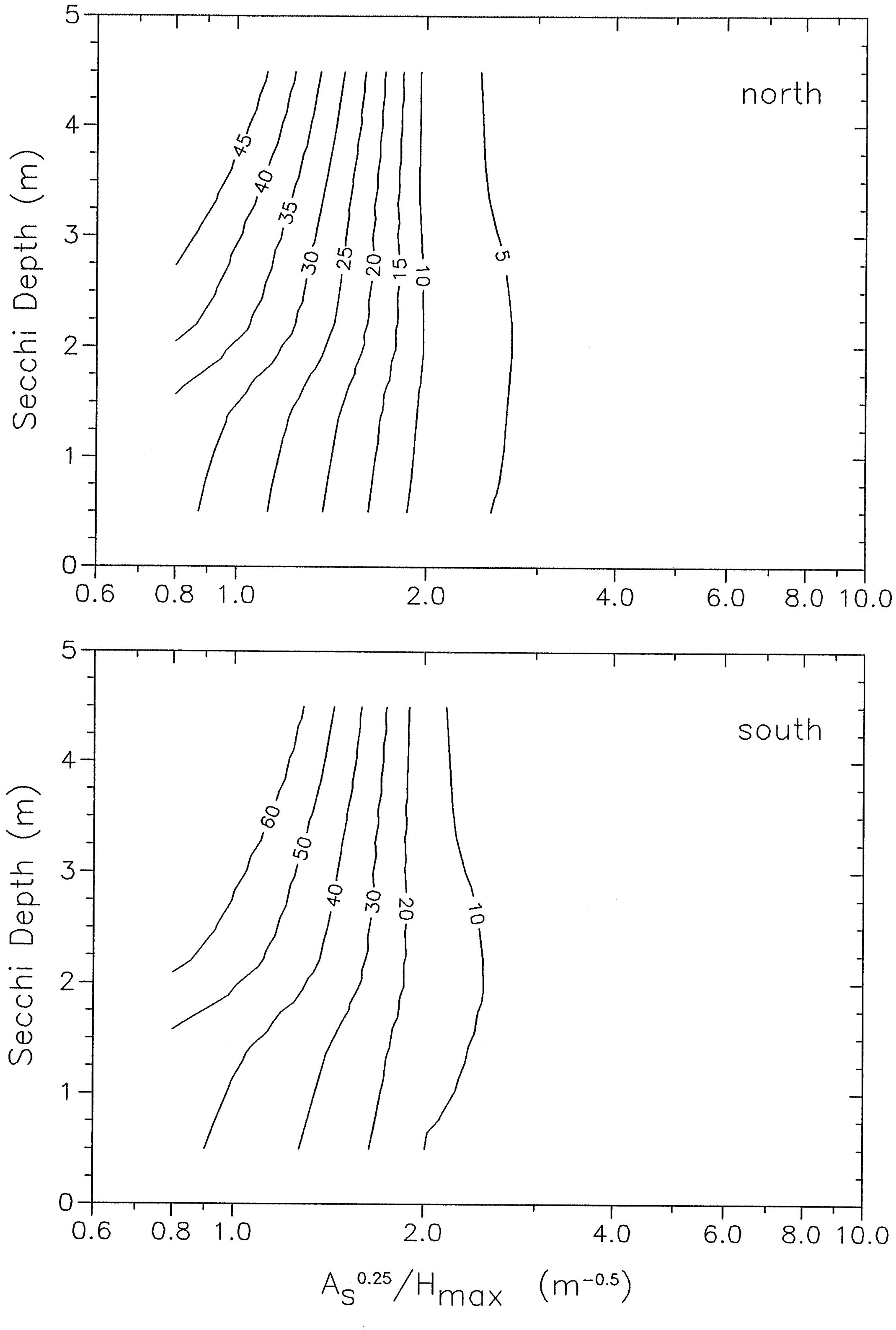

Fig. 14 **Maximum daily Lake number.**

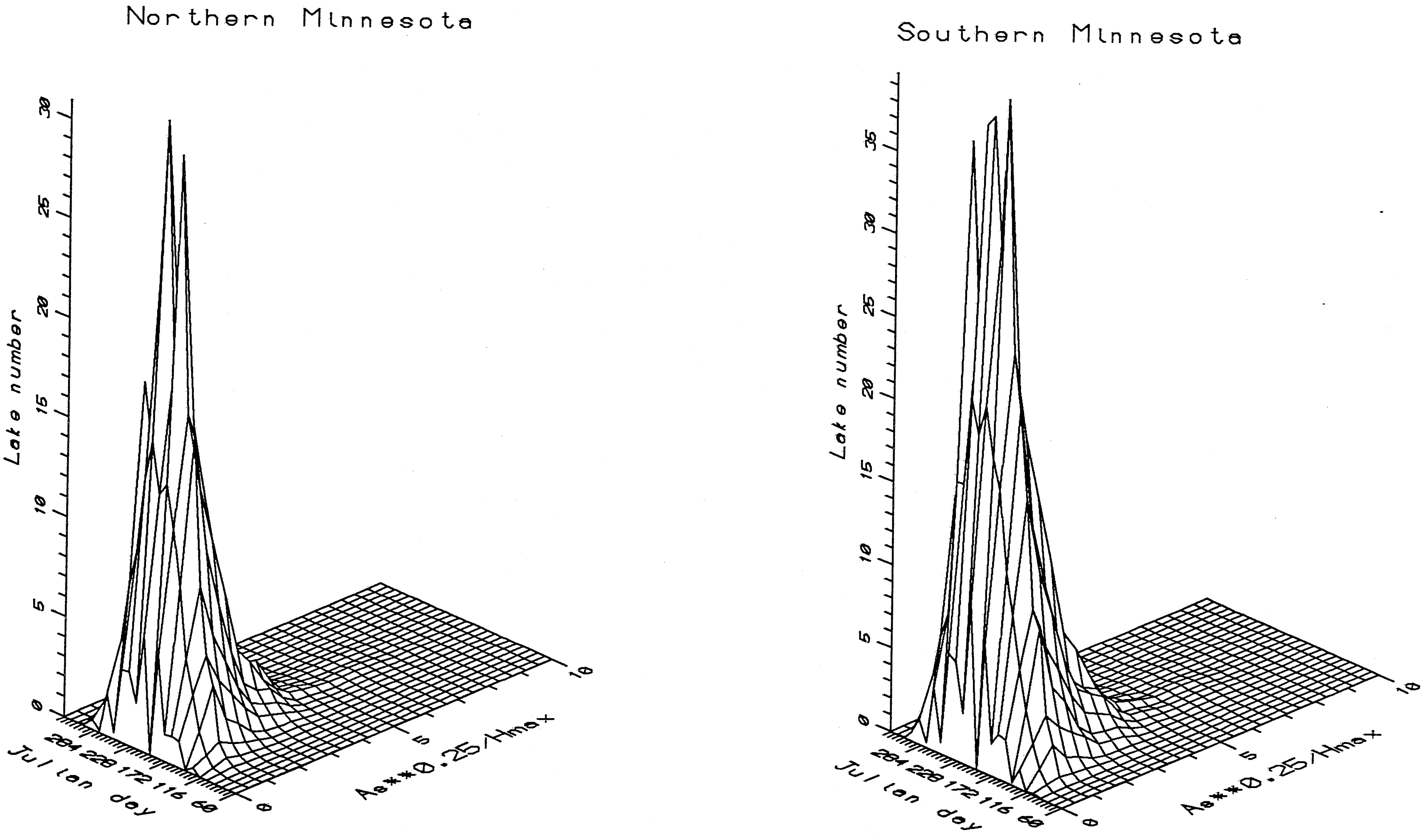

Fig. 15 Variation of the Lake number as a function of time (Julian day 60 = March 1, Julian day 304 = October 31), and lake geometry.

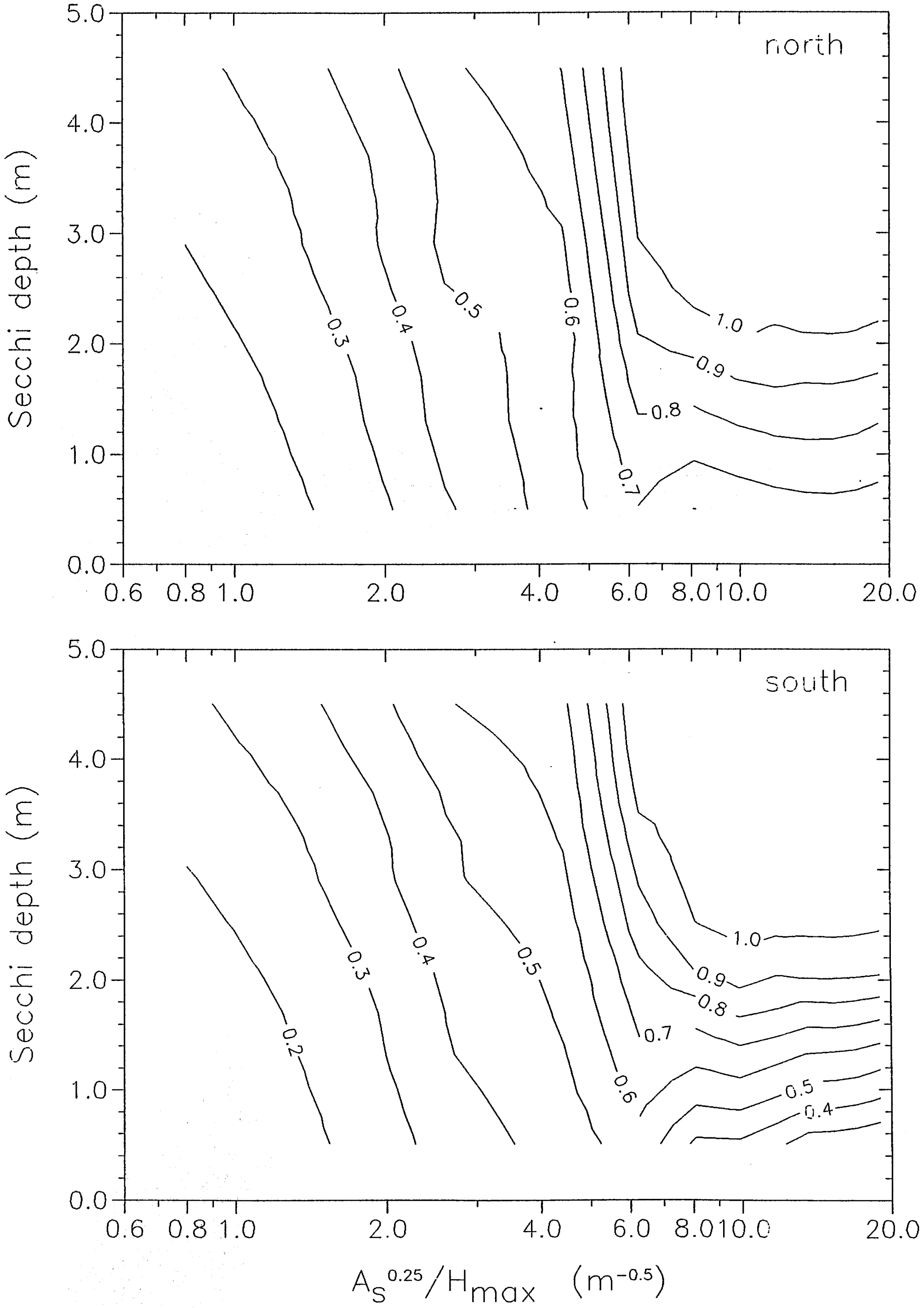

Fig. 16. Maximum daily thermocline depth normalized by maximum lake depth.

Seasonal stratification is defined herein as the condition when the temperature difference between surface and deep water is greater than 1°C. Although 1°C is an arbitrary criterion, it is useful to identify variations of stratification with lake geometry, trophic state, and geographic location. Duration of stratification in northern and southern Minnesota lakes is given in Fig. 17 and Fig. 18. A seasonal stratification ratio is defined as the total number of days when stratification stronger than 1°C exist, divided by the period from the earliest to the latest date of stratification (length of stratification season). A seasonal stratification ratio less than 1.0 indicates a polymictic behavior, which occurs typically in shallow or medium-depth large-area lakes. A ratio of 1.0 indicates a dimictic lake, i.e. once seasonal stratification is established, it lasts until fall overturn.

The gradient of a uniformly linear temperature stratification with the same potential energy as the actual non-linear stratification is also a useful indicator of lake stratification. Values of the maximum linear temperature gradient obtained under this condition are given in Fig. 19. Exceptionally high gradients are estimated for the shallow, small area eutrophic lakes.

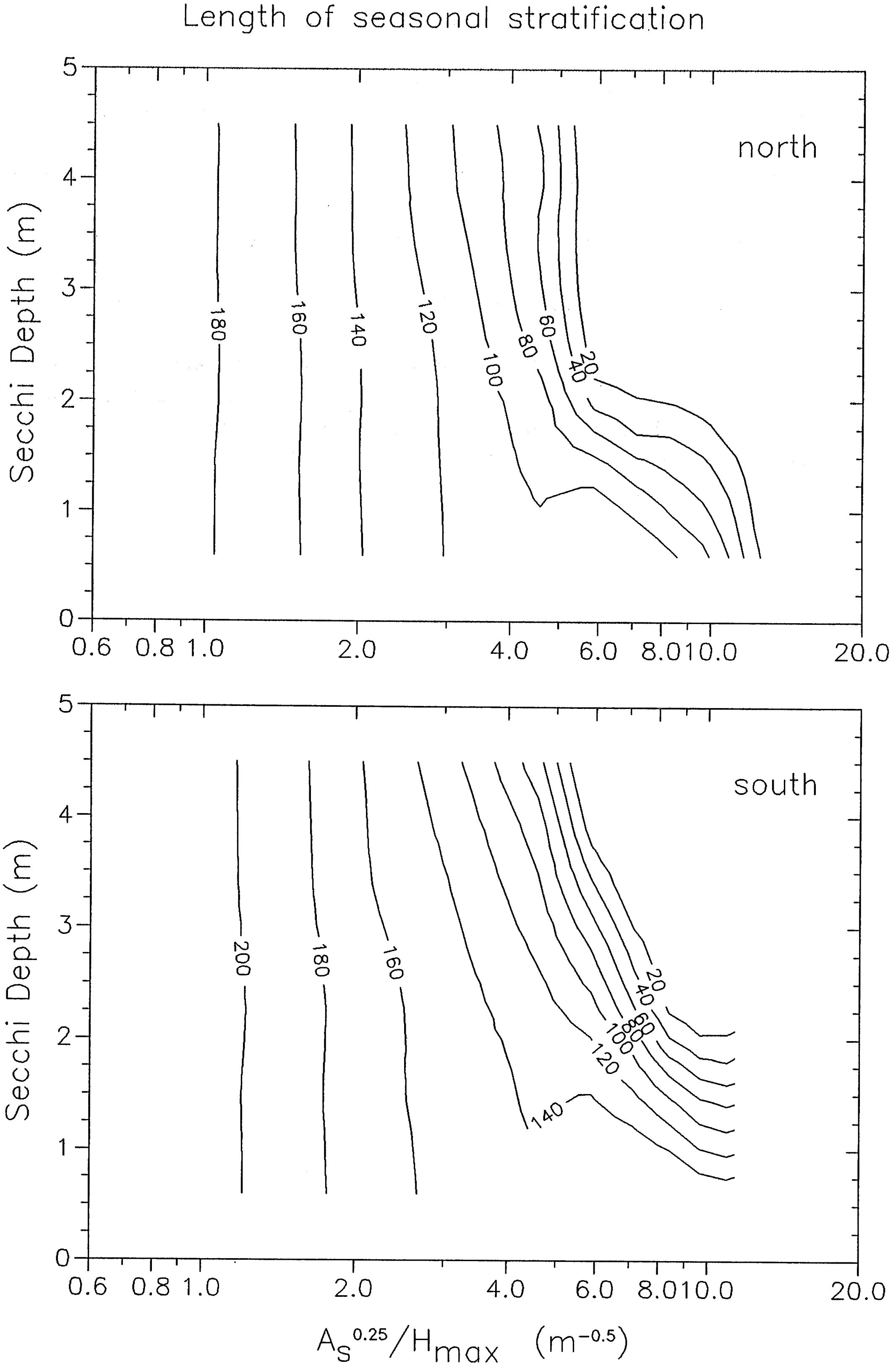

Fig. 17 **Length (days) of seasonal stratification.**

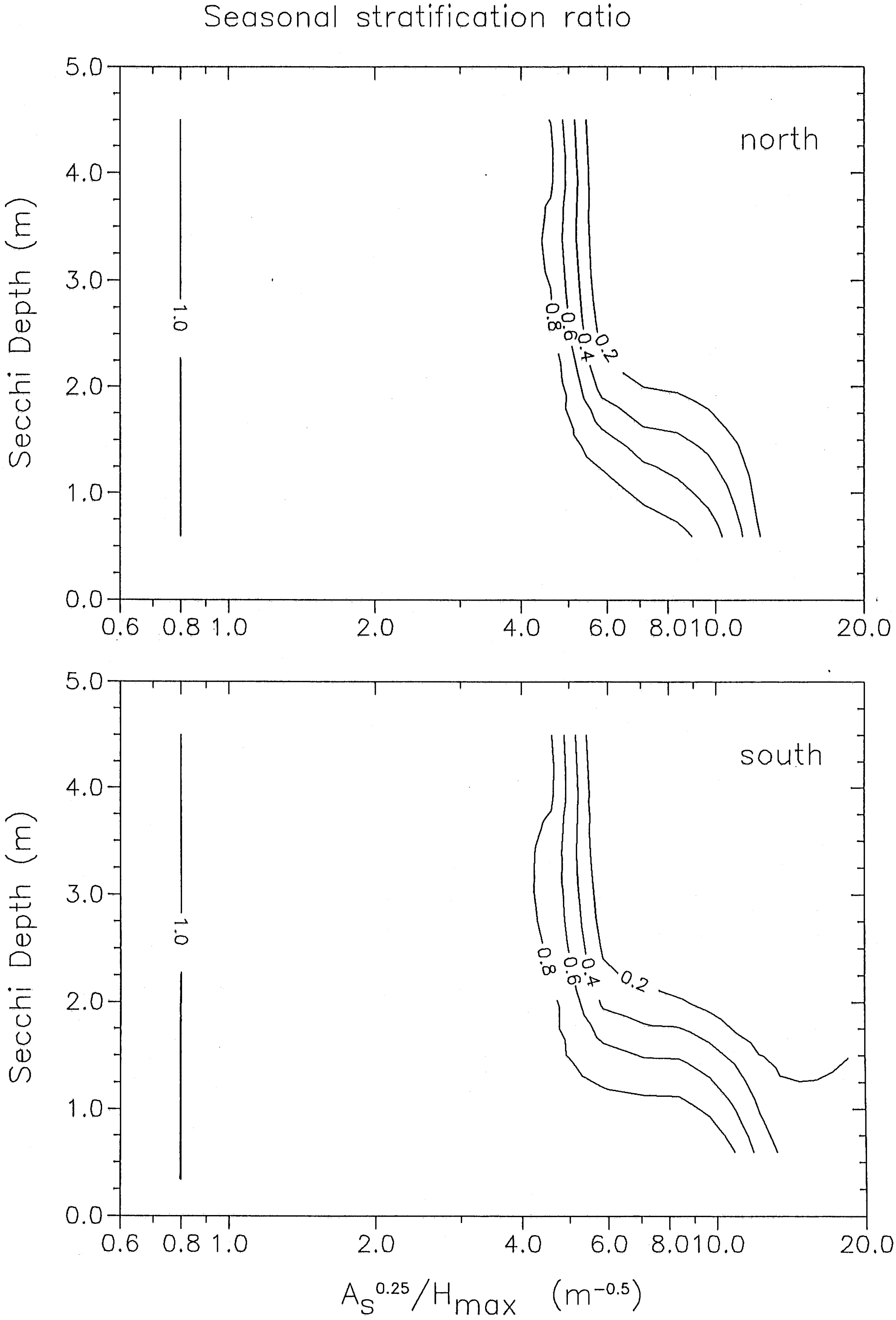

Fig. 18 **Seasonal stratification ratio.**

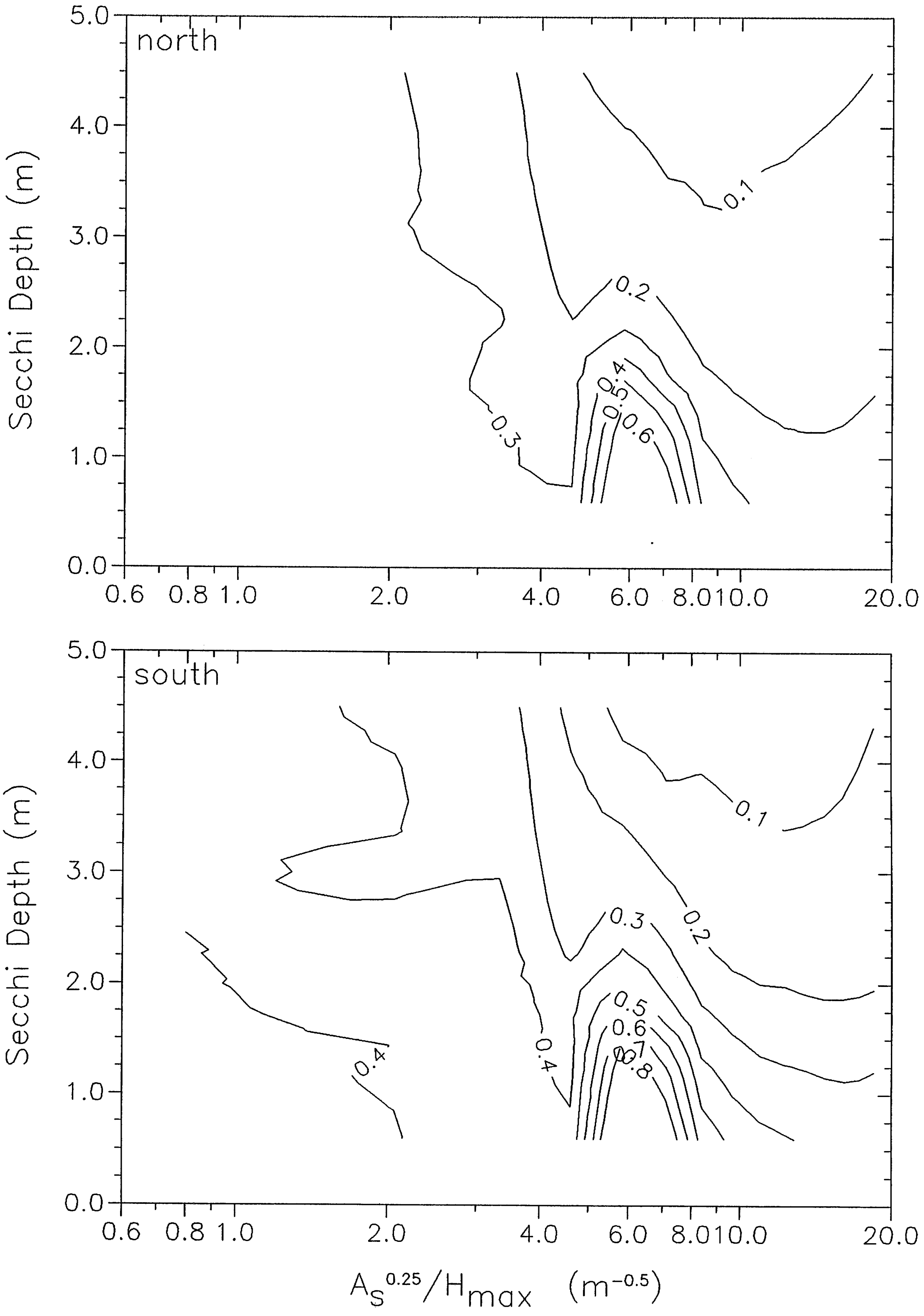

Fig. 19 Maximum daily linear temperature gradient (°C/m) weighted with the potential energy locked in the stratification.

5.2 Dissolved oxygen

The parameters which are used to characterize the dissolved oxygen concentrations in lakes are given in Table 7. Each parameter value presented is an average from 25 years of simulated daily dissolved oxygen profiles in a lake.

The surface layer DO concentrations are plotted in Fig. 20a. The isopleths representing minimum daily surface DO concentrations are plotted in a coordinate system of $A_s^{0.25}/H_{max}$ versus Secchi depth. As can be seen, the dependence of surface DO concentration on Secchi depth and geometry is very weak. Therefore minimum daily surface DO were plotted against the geometry ratio $A_s^{0.25}/H_{max}$ only in Fig. 20b. The value of this parameter is fairly constant over a wide range of lake morphometries and trophic states and close to the saturation value (note that this is again a 25-year average value, not an instantaneous daily observation). The difference between north and south is primarily due to surface water temperature differences, because elevations of the lakes do not vary widely in Minnesota. Northern Minnesota lakes had lower surface water temperatures than southern Minnesota lakes (see Fig. 9), therefore oxygen solubility was higher in the northern lakes.

Bottom dissolved oxygen concentration is the lowest simulated daily dissolved oxygen concentration above the lake sediments. Most of the time that is also the lowest oxygen concentration in a lake. Values of this parameter are given in Fig. 21a and 21b. Below lake geometry ratios of about 1.5 anoxic hypolimnetic conditions exist regardless of the trophic state. Oligotrophic lakes have higher DO concentrations in the water near the sediments mostly because of the lower sediment oxygen demand, and higher photosynthetic rates, especially in shallow lakes.

Volume weighted average dissolved oxygen concentrations are given in Fig. 22a and Fig. 22b. Minimum daily values are displayed. Below a lake geometry ratio of approximately 5.0 notable differences in the DO concentrations occur: the DO values drop off and trophic state significantly affects the DO concentrations. Higher DO concentrations are estimated for oligotrophic than for eutrophic lakes, as expected. Above a geometry ratio of about 5.0 neither lake trophic state, nor surface area and maximum depth appear to influence DO concentrations in a lake. Lakes with a geometry ratio greater than 5.0 are shallow lakes, generally well mixed or polymictic with high DO supplied at the air/water interface.

Hypolimnetic anoxia is defined herein as the condition when DO concentration at any depth in a lake is less than 0.1 mg/l. Although 0.1 mg/l is an arbitrary criterion, it is useful to identify possible low DO concentrations in lakes with different geometries, trophic state, and geographic location. Total days when hypolimnetic anoxia occurs are given in Fig. 23a and Fig. 23b. Two different regions are noticeable. For the geometry ratio bigger than 5.0 anoxia never occurs, regardless of lake trophic state. These lakes are generally well mixed, thus oxygen rich water is frequently in contact with lake

Table 7. Parameters used to define long-term dissolved oxygen (DO) characteristics.

Parameter	Description	Formulation/Definition
Surface dissolved oxygen	Minimum daily dissolved concentration oxygen at the lake surface. DO_s=surface dissolved oxygen	$Min\ [DO_s(t)\ t=1,n]$
Bottom dissolved oxygen	Minimum daily dissolved oxygen concentration 1m or less above the lake sediments. DO_b=bottom dissolved oxygen	$Min\ [DO_b(t),\ t=1,n]$
Volume weighted dissolved oxygen	Total volume average maximum daily DO.	$DO_{av}=\frac{\int_0^{H_{max}} DO(z,t)A(z)dz}{\int_0^{H_{max}} A(z)dz}$
Hypolimnetic anoxia	Total number of days when the DO concentration is less than 0.1 mg/l in a lake. J=total number of control volumes used in the numerical model.	$L=\sum_{Mar\ 1}^{Nov\ 30} \sum_{1}^{J} DO(z,t) \leq 0.1\ mg/l$
Anoxic volume percentage	Maximum daily total volume of the lake when DO is less than 0.1 mg/l, divided by total lake volume and multiplied by 100. H_{anx}=depth of the lake below which the DO is less than 0.1 mg/l.	$V=\left(\frac{\int_0^{H_{anx}} A(z)dz}{\int_0^{H_{max}} A(z)dz}\right)100$

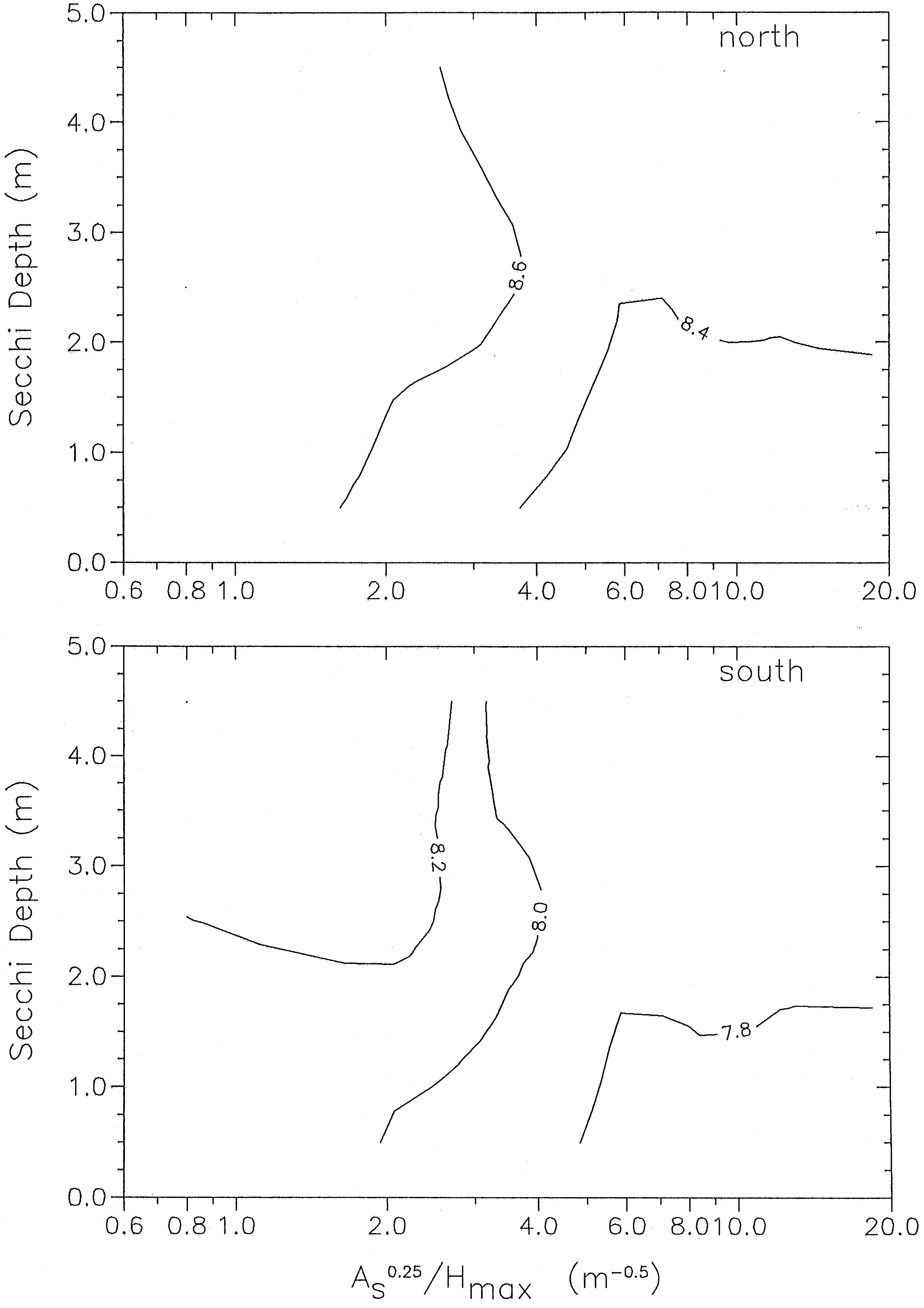

Fig. 20a Minimum daily surface layer dissolved oxygen (mg/l) isopleths (simulated 25-year averages).

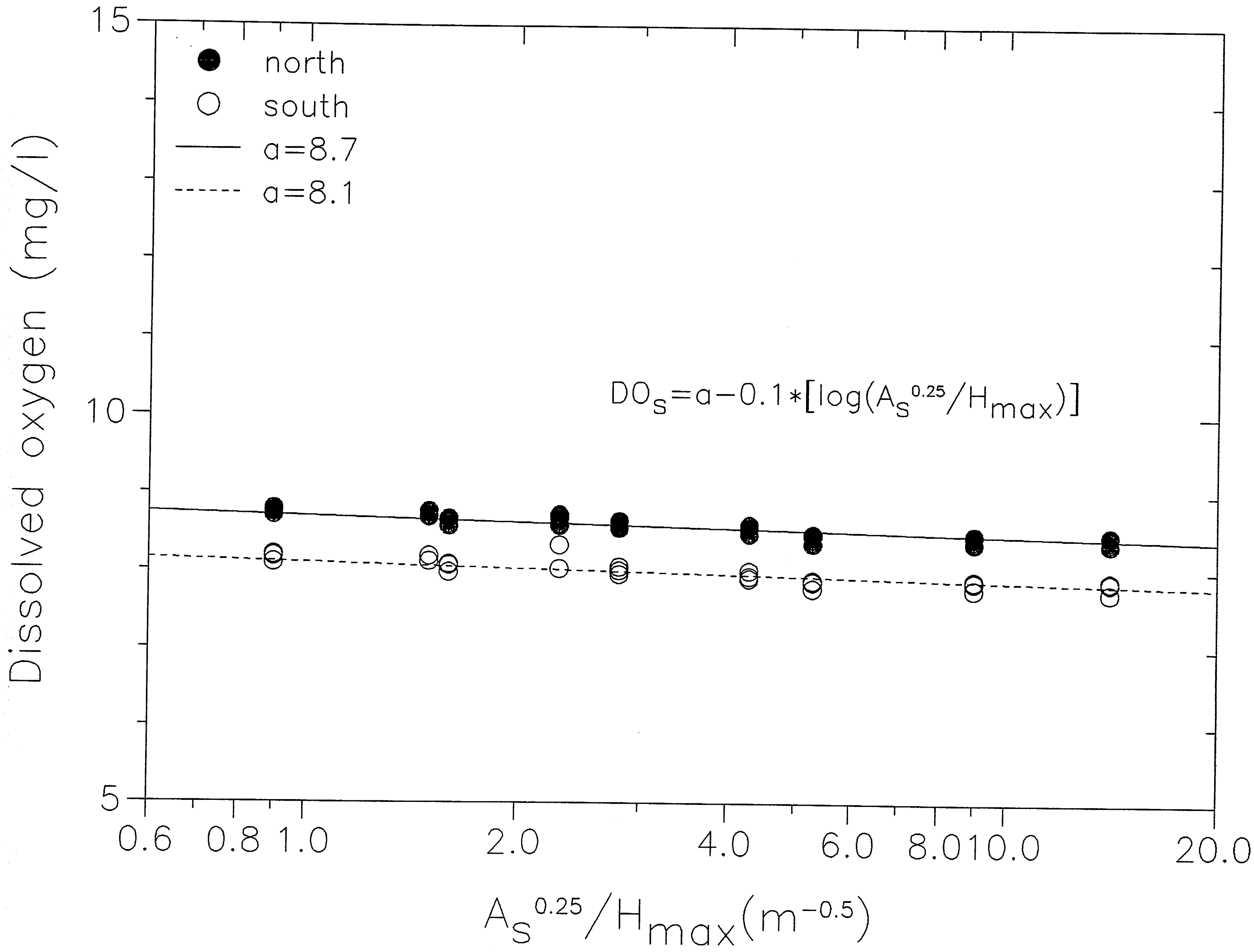

Fig. 20b Minimum daily surface layer dissolved oxygen concentration (mg/l) (simulated 25-year averages).

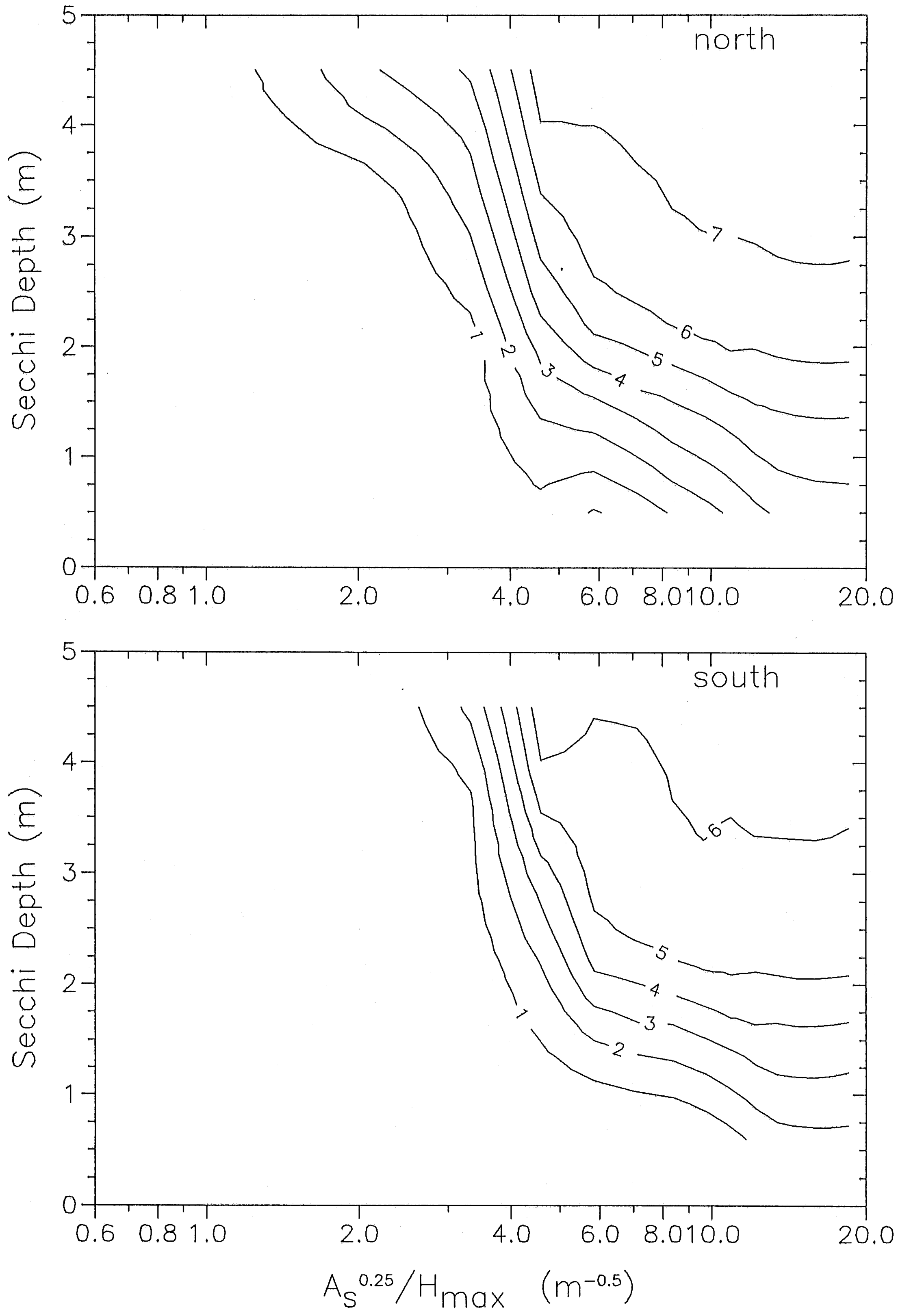

Fig. 21a Minimum daily dissolved oxygen (mg/l) isopleths near lake bottom (simulated 25-year averages).

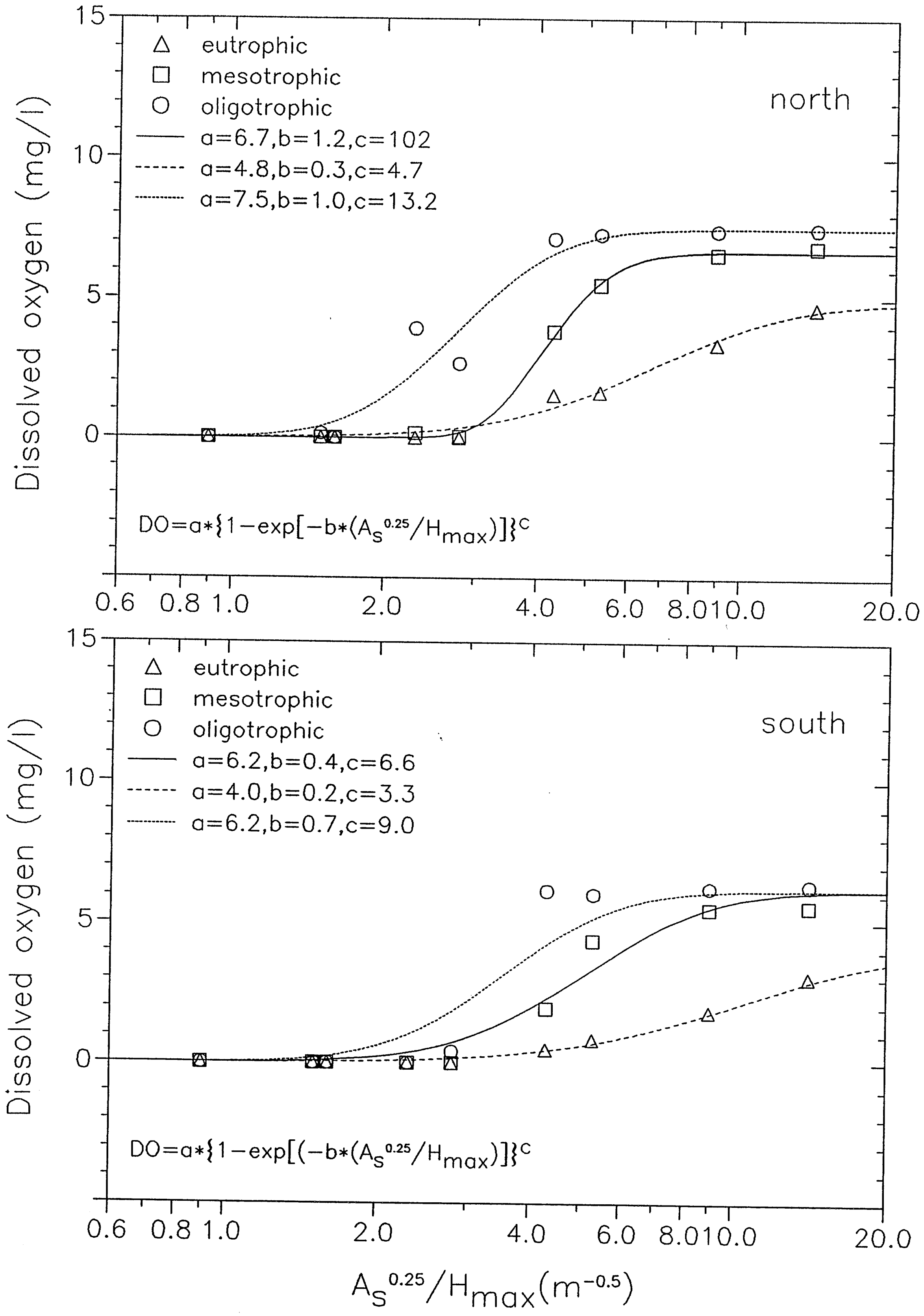

Fig. 21b **Minimum daily dissolved oxygen concentration (mg/l) near lake bottom (simulated 25-year averages).**

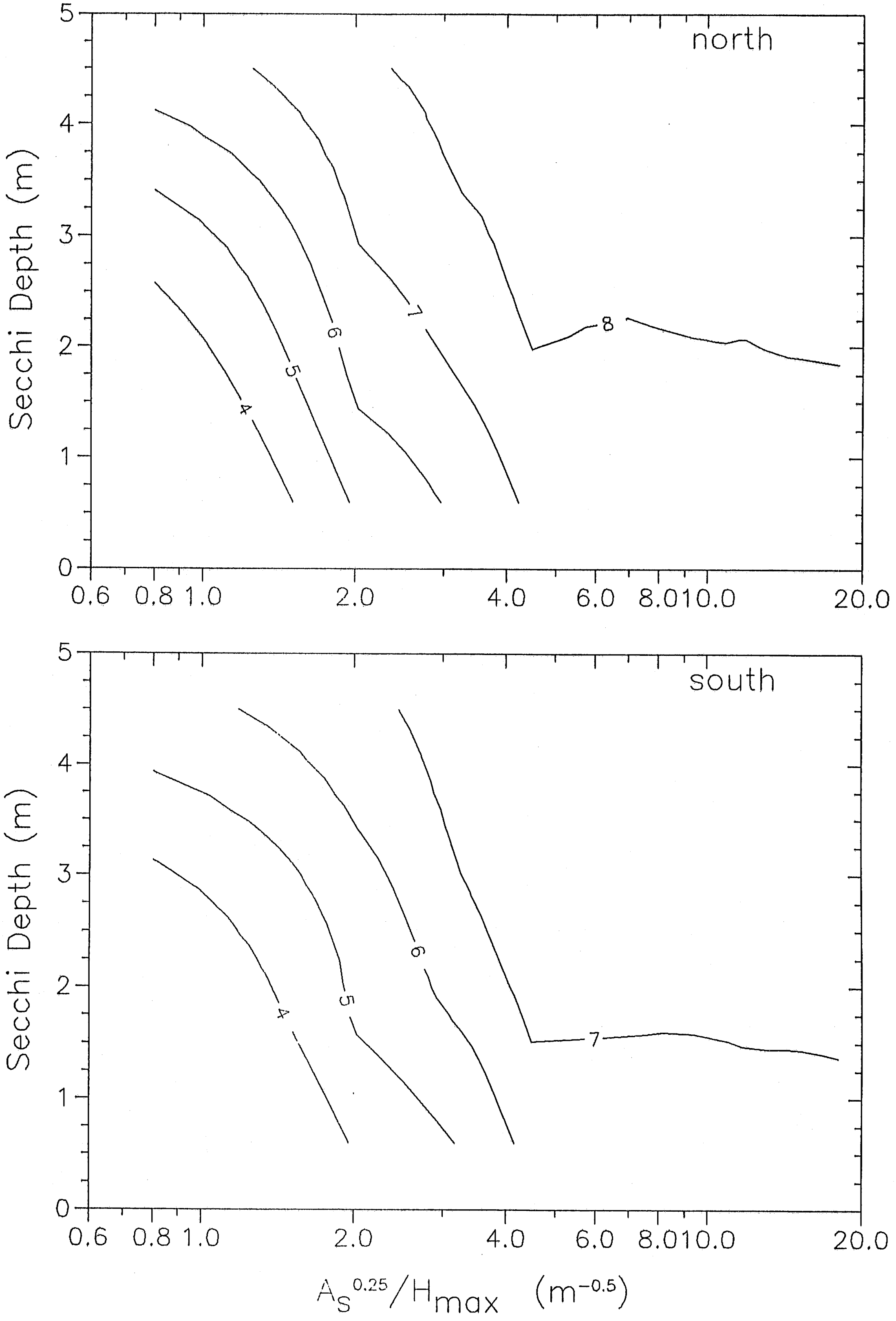

Fig. 22a Lake volume-averaged minimum daily dissolved oxygen (mg/l) isopleths. (simulated 25-year averages).

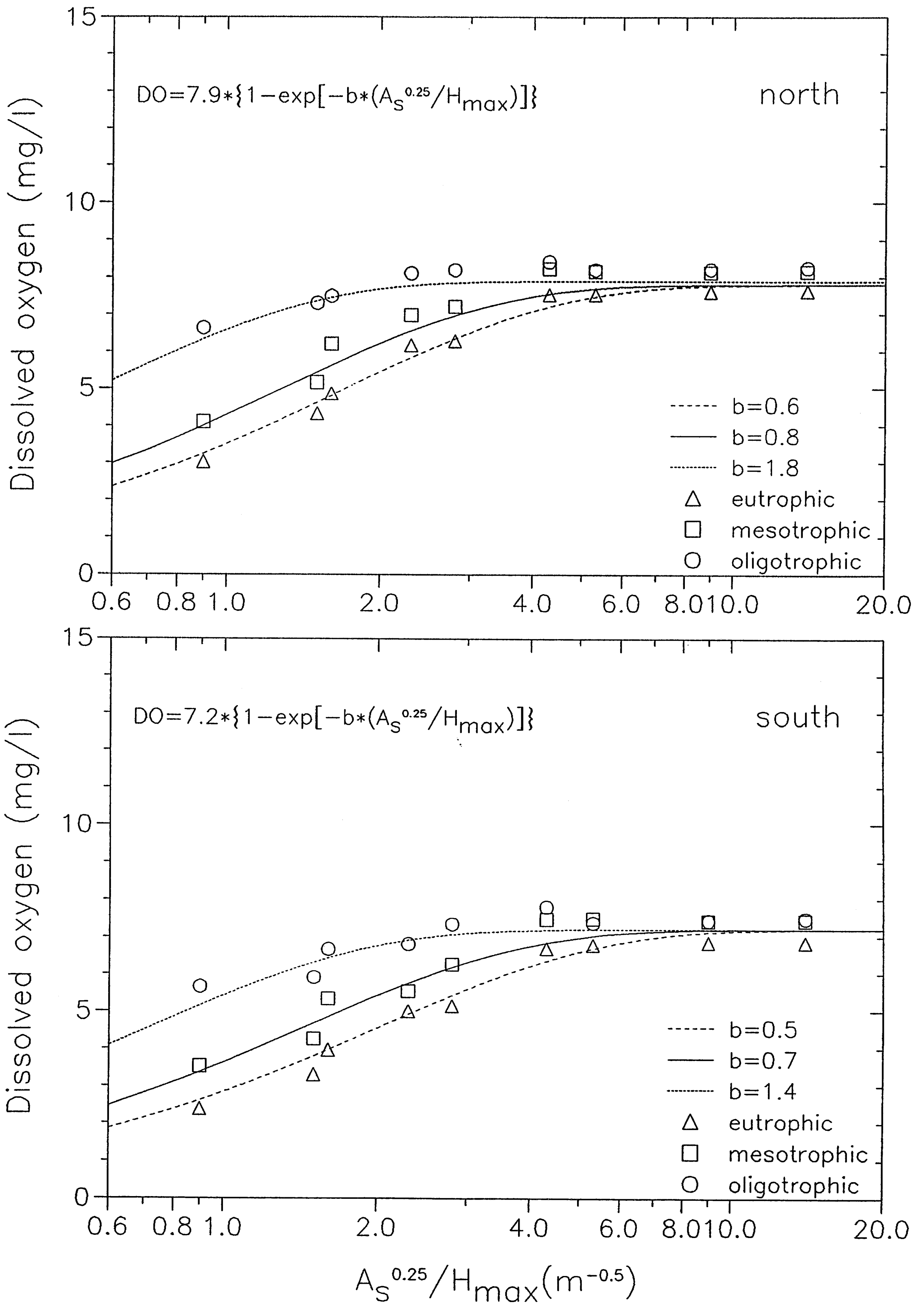

Fig. 22b Lake volume-average minimum daily dissolved oxygen concentration (simulated 25-year averages).

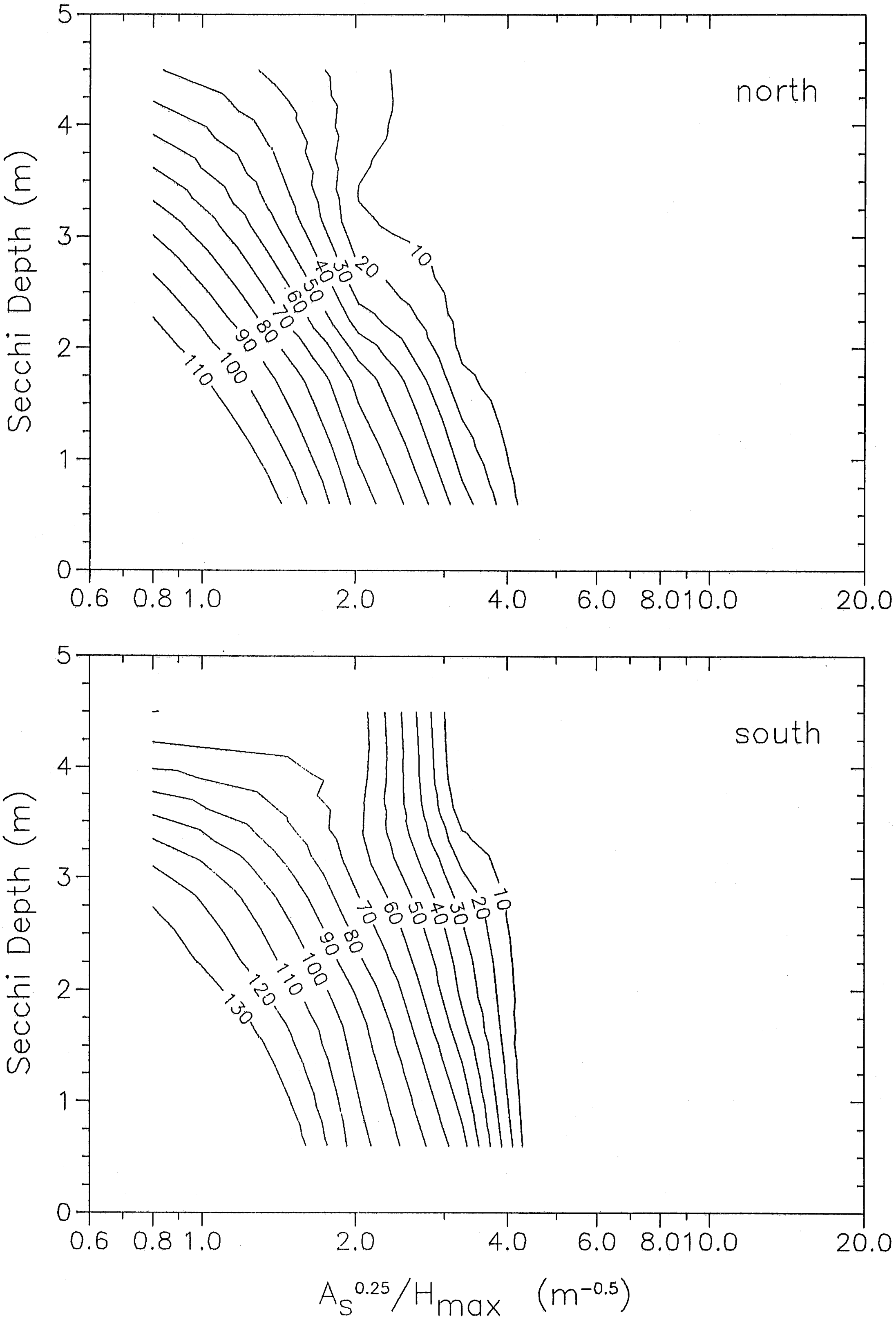

Fig. 23a Time (days) between first and last occurrence of hypolimnetic anoxia.

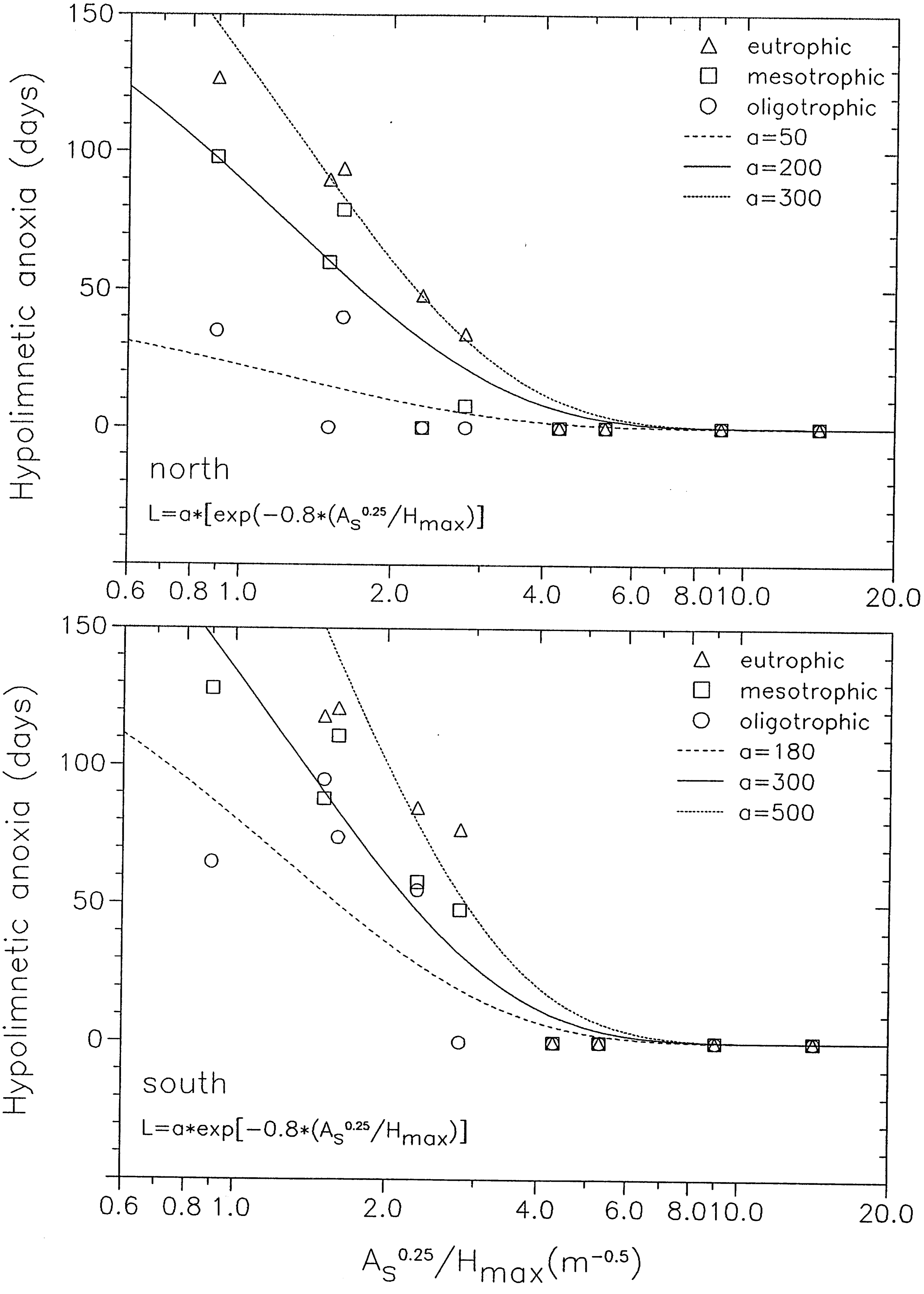

Fig. 23b Time (days) between first and last occurrence of hypolimnetic anoxia.

sediments. For a geometry ratio less than 5.0, trophic state of the lake affects duration of anoxia among lakes with the same geometries. The longest duration of anoxia is estimated for eutrophic lakes with high sediment oxygen demand, and high water column stability.

Anoxic volume percentage is defined herein as the maximum daily total volume of the lake where DO is less than 0.1 mg/l, divided by the total lake volume and multiplied by 100. This parameter gives an estimate of the percentage of the total lake volume with low DO concentration. The anoxic volume percentages are given in Fig. 24a and Fig. 24b.

5.3 Habitat suitability for fishes

The parameters by which fish habitat and growth potential are measured are given in Table 8. Each parameter value is an average calculated from the simulation of 25 years of daily water temperature and dissolved oxygen profiles in a lake. Water temperature and dissolved oxygen levels are the only two water quality factors used to determine fish survival and growth.

The good-growth season for coldwater, coolwater, and warmwater fish begins when water temperatures exceed the minimum good-growth temperature and continues as long as water temperature remain below the maximum good-growth temperature, provided that DO does not drop below the minimum DO limit. These limits differ by species and thus by thermal guild. The length of the good-growth season is given in Fig. 25. The lake geometry ratio, as well as lake trophic state, have an obvious influence on the coldwater fish habitat. The good-growth season lengthens as the geometry ratio decreases. Slopes of the contours in Fig. 25 indicate two conflicting roles of lake trophic state with respect to the length of the good-growth season. For geometry ratios greater than 3.0 (well-mixed lakes) eutrophic lakes have a longer good growth season than the oligotrophic lakes. These lakes have enough oxygen for coldwater fish survival, and water temperatures are in the good-growth temperature range longer than in oligotrophic lakes. The good-growth season for coldwater fish is longer in northern than southern Minnesota lakes. Among lakes with a geometry ratio less than 3.0, eutrophic lakes have a shorter good-growth season. The reason is low DO concentrations in eutrophic lakes. For coolwater and warmwater fish the trends are not as apparent, but contours indicate better good-growth habitat conditions in southern Minnesota lakes than in northern Minnesota lakes.

Good-growth average depth indicates the fraction of the total lake volume available for good-growth and is plotted in Fig. 26. Coldwater fish have similar lake volume percentages available for good-growth regardless of trophic state. Coolwater and warmwater fish have the highest volume fraction for good-growth available in oligotrophic lakes.

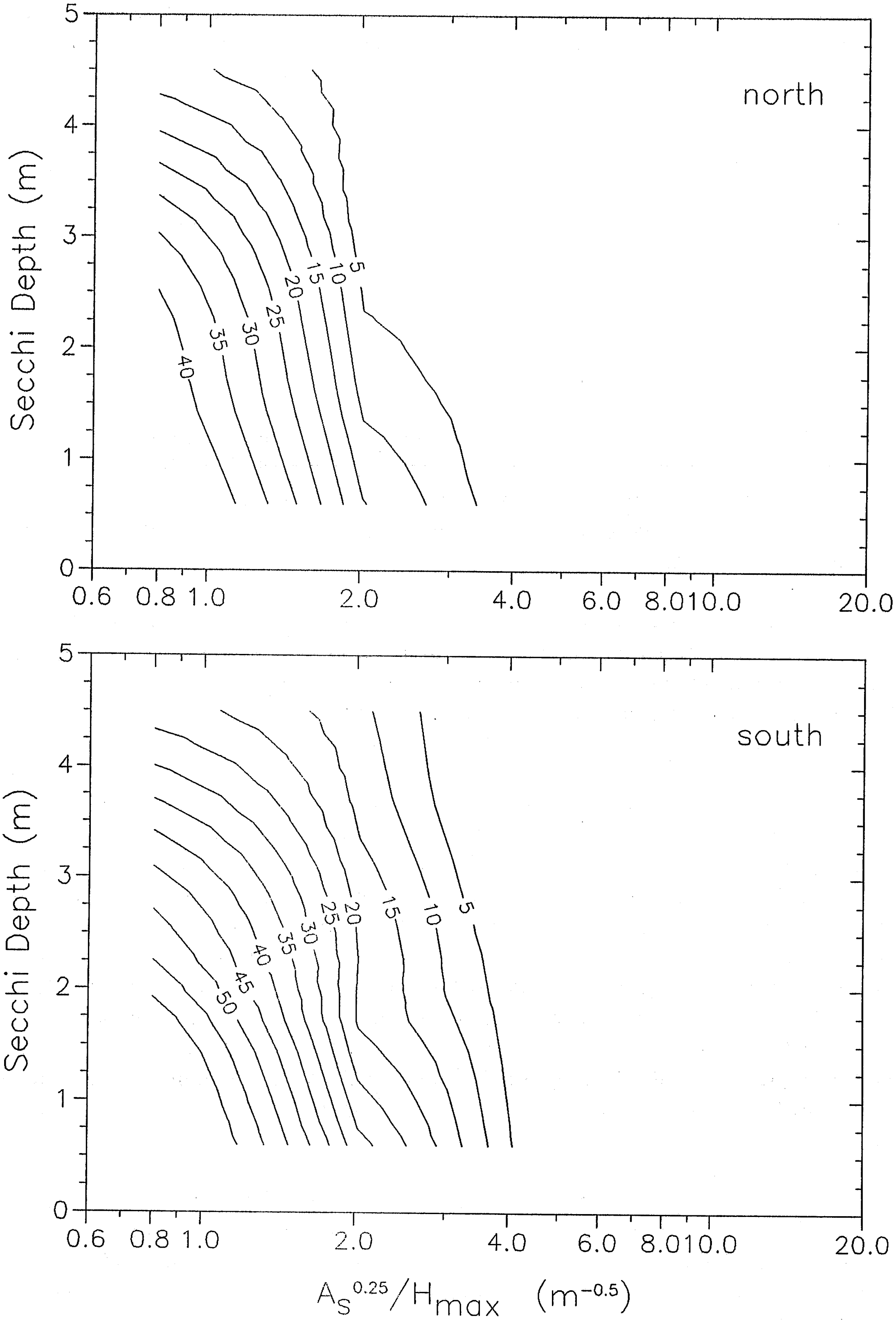

Fig. 24a Maximum daily percentage of total lake volume with anoxia.

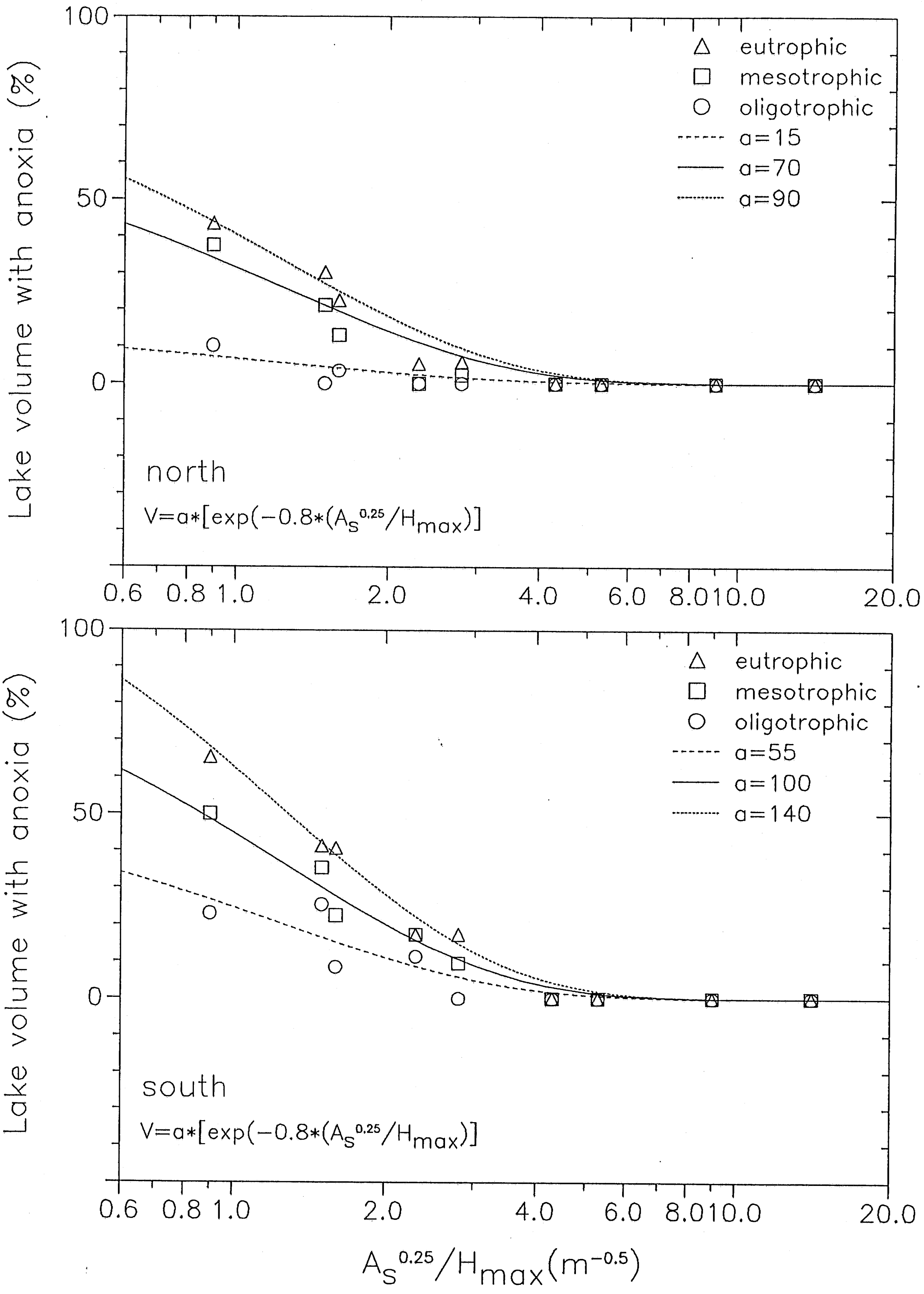

Fig. 24b **Maximum daily percentage of total lake volume with anoxia.**

Table 8. Parameters used to define long-term fish survival and good-growth.

Parameter	Description	Formulation/Definition
Length of the good-growth season	The number of days when simultaneously any value of water temperature is between the lower (LGGT) and upper (UGGT) good-growth limit in the vertical lake temperature profile and dissolved oxygen exceeds the limit in the DO profile. J=total number of control volumes used in the numerical model, DO_{sl}=dissolved oxygen survival limit.	$GSL=\sum_{Mar\ 1}^{Nov\ 30} \sum_{1}^{J} [\ UGGT \geq T(z,t) \geq LGGT \text{ and } DO(z,t) > DO_{sl}\ ]$
Good-growth average depth	Integration of volumes over time for those volumes and times where and when water temperatures are within the upper and lower good-growth temperature limits and dissolved oxygen is greater than survival. The volumes are normalized by total lake volume and the good-growth season length. H_{gg}=good-growth depth of a lake.	$GGV=\dfrac{\int_{1Mar}^{31Oct} \int_{0}^{H_{gg}} A(z)dzdt}{GSL \int_{0}^{H_{max}} A(z)dz}$

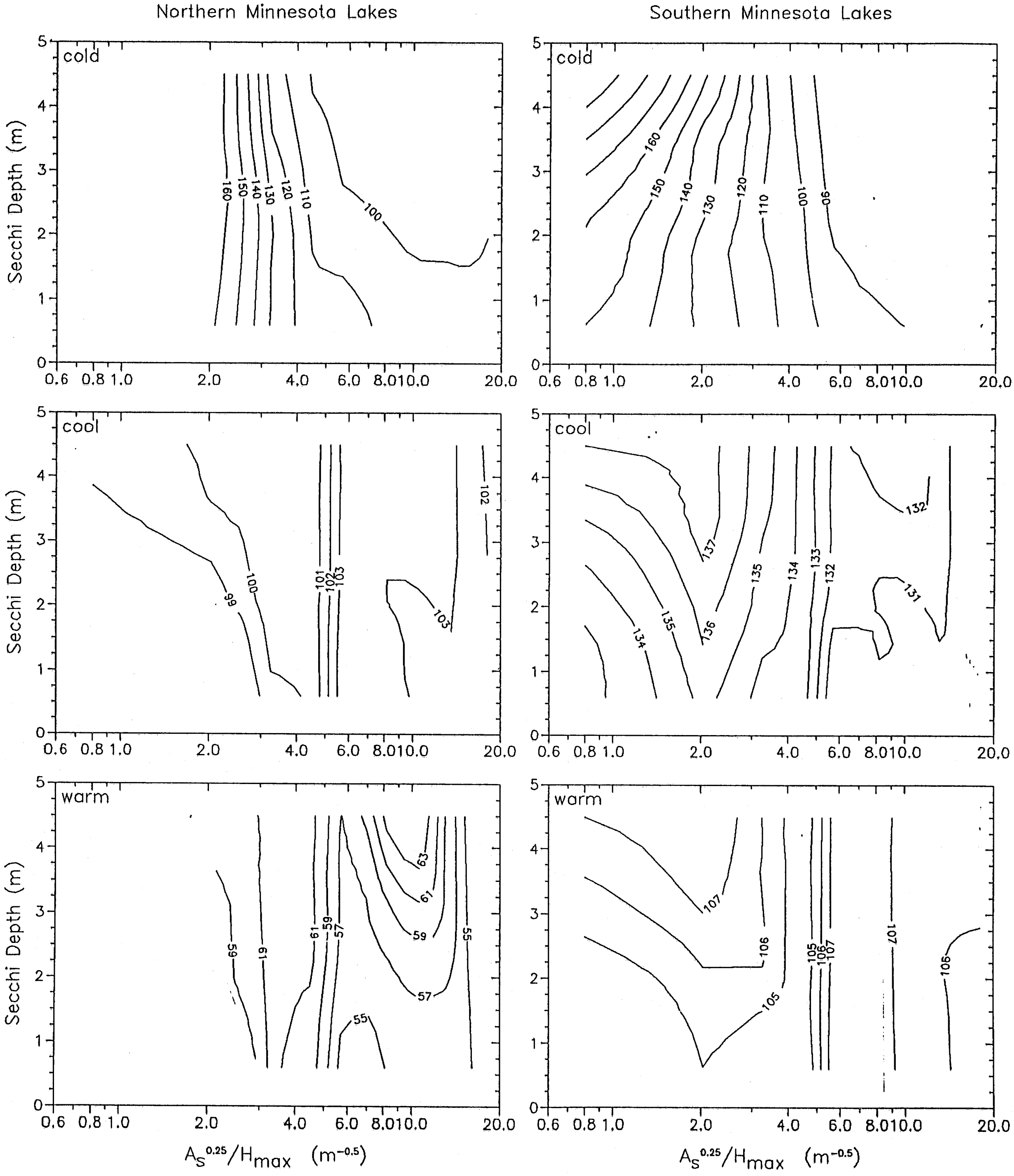

Fig. 25 Length (days) of the good-growth season.

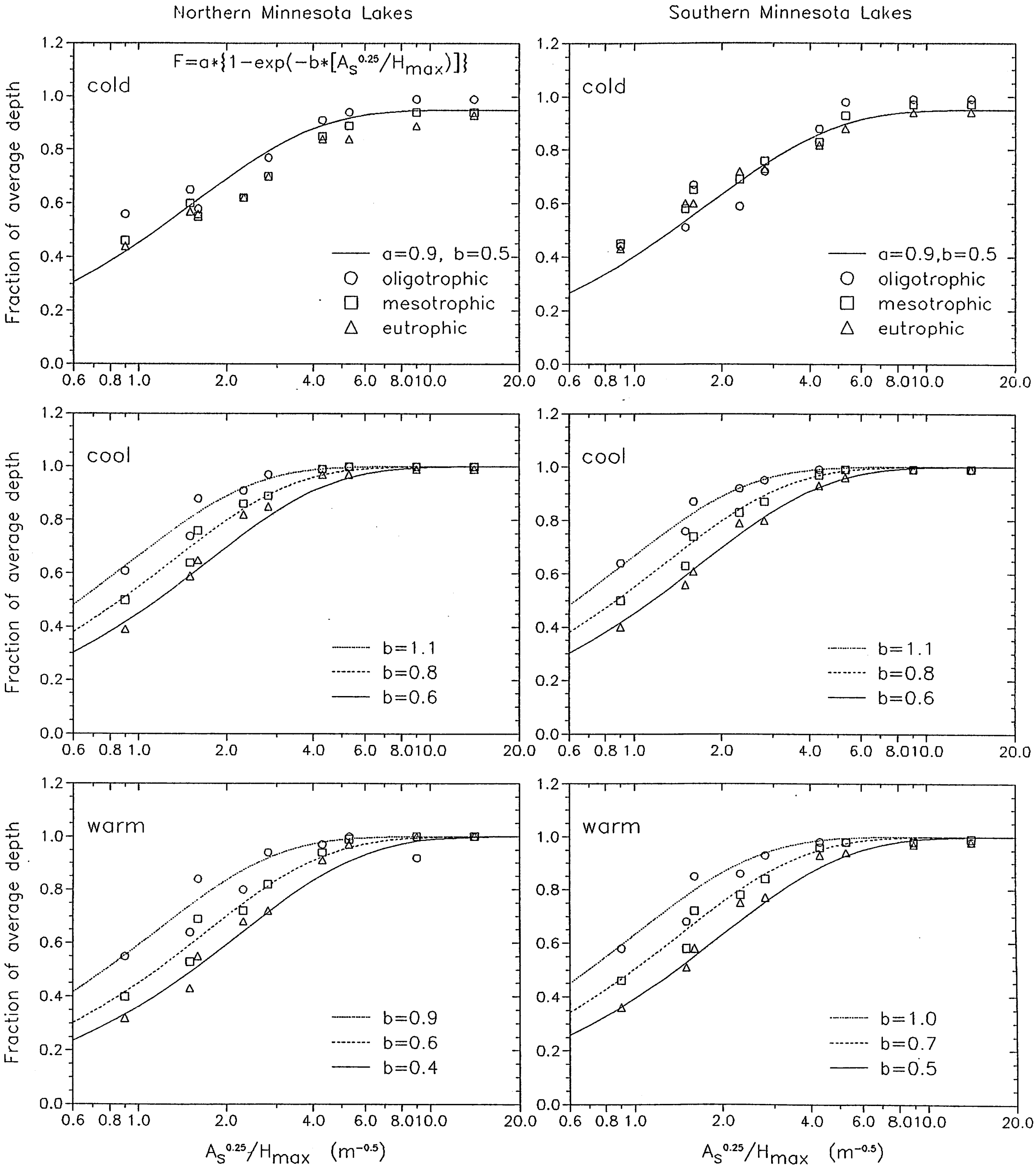

Fig. 26. Fraction of lake average depth available for good-growth.

6. Conclusions

Lake parameters which relate to lake water temperature, dissolved oxygen concentrations, and associated fish habitat conditions have been quantified for freshwater lakes typical of Minnesota. The results presented are 25-year average values obtained from well-calibrated simulation models. Weather conditions for the period 1955-19979, lake geometry, and Secchi depth were used as input. Because the results are long-term averages, they cannot be directly compared with instantaneous lake observations typical of limnological field investigations. Such measurements from a large number of lakes were, however, used in the calibration and validation of the simulation model prior to its application.

The graphical presentation of the results accompanied by fitted equations allows easy interpolation and quantitative comparison among lakes of different morphometries and trophic levels. The results give an overview for the entire State of Minnesota. Results are given for weather conditions measured at latitudes of 45° and 47° with an annual normal air temperature difference of 3.9 °C. By coincidence this also happens to be the projected air temperature increase for Minneapolis/St. Paul if atmospheric carbon-dioxide doubles (GISS model), so that the results for the north may be viewed as a very rough approximation of results for the south after climate change.

The main specific results of this study are as follows:

(1) Maximum surface water temperatures are influenced primarily by weather conditions and only secondarily by lake geometry and trophic state. Long-term surface water temperatures are directly related to long-term average air temperatures. The difference in water temperatures between north and south (~4.0 °C in Fig. 4b) is also about the difference in long-term annual air temperatures (3.9 °C in Table 2).

(2) Maximum water temperatures near the lake bottom are influenced by lake geometry and meteorological forcing. For geometry ratios $A_s^{0.25}/H_{max} > 8.0$, bottom water temperatures are nearly constant. For the geometry ratios $A_s^{0.25}/H_{max} < 8.0$ bottom water temperatures are primarily influenced by lake geometry.

(3) Total volume-averaged maximum daily water temperatures are higher for well-mixed than for stratified lakes. The transition between the two lake categories (transition from polymictic to dimictic lakes) occurs in the geometry range $4 > A_s^{0.25}/H_{max} > 3$.

(4) Maximum daily Lake Number measures overall lake stratification stability. It is higher for oligotrophic lakes than eutrophic lakes of same geometry ratio. The maximum stability is obtained around August in deep lakes of small area. A Lake number value around 4 designates transition from stable to unstable stratification.

(5) Polymictic lake behavior occurs for geometry ratios $A_s^{0.25}/H_{max} > 3$. For $3 < A_s^{0.25}/H_{max}$ lakes are more likely to be dimictic.

(6) Long-term (25-year) averages of minimum daily surface layer dissolved oxygen concentrations are fairly constant over a wide range of lake morphometries and trophic states, and are close to the saturation value.

(7) Bottom dissolved oxygen concentrations are influenced by lake geometry and trophic state. When lake geometry ratios are below 1.5, anoxic hypolimnetic conditions exist regardless of trophic state.

(8) Volume weighted average dissolved oxygen concentrations are influenced by lake geometry and trophic state for lake geometry ratios $A_s^{0.25}/H_{max} < 5$. For geometry ratios greater than 5, lakes are well-mixed with high dissolved oxygen supply at the air/water interface. Hypolimnetic anoxia does not occur for lake geometry ratios greater than 5 (25-year average).

(9) The length of the good-growth season (Fig. 25) varies considerably with fish guild (coldwater, coolwater, and warmwater). For coldwater fishes it decreases considerably from about 160 days for seasonally strongly stratified lakes ($A_s^{0.25}/H_{max} < 1$) to 100 days for dimictic lakes ($A_s^{0.25}/H_{max} > 8$) in northern Minnesota. In southern Minnesota the good-growth season is about 10 days to 20 days shorter, except in rare small oligotrophic lakes. For coolwater and warmwater fishes the good-growth season is longer in southern Minnesota than in northern Minnesota. The difference is 35 days and 45 days, respectively. The geometry and trophic state of the lake seem to have a very minor influence (variations of ±4 days or less).

(10) During the good-growth season, which is of different length for the three fish guilds, more or less similar fractions of the total lake volume (Fig. 26) support good fish growth regardless of guild designation or region. The total lake volume fraction depends, however strongly on lake geometry ratio ($A_s^{0.25}/H_{max}$), and for coolwater and warmwater fishes also on trophic status. The dependence has been expressed by the function

$$F = a \left\{ 1 - \exp \left[-b \left(A_s^{0.25} / H_{\max} \right) \right] \right\} .$$

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