Canadian Technical Report of

Fisheries and Aquatic Sciences 1898

1993

LAKE VARIATION AND CLIMATE CHANGE STUDY: ELA LAKES, 1986-1990. II. WATERSHED GEOGRAPHY AND LAKE MORPHOLOGY

by

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This is the 52nd Technical Report

from the Central and Arctic Region, Winnipeg

Cat. no. Fs 9713/1898E ISSN 0706-6457

Correct citation for this publication is:

McCullough, G.K., and P. Campbell. 1993. Lake variation and climate change study: ELA lakes, 1986-1990. II. Watershed geography and lake morphology. Can. Tech. Rep. Fish. Aquat. Sci. 1898: iv + 29 p.

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ABSTRACT

McCullough, G.K., and P. Campbell. 1993. Lake variation and climate change study: ELA lakes, 1986-1990. II. Watershed geography and lake morphology. Can. Tech. Rep. Fish. Aquat. Sci. 1898: iv + 29 p.

This is the second in a series of reports presenting data collected from 1986 to 1990 on Lake Variation and Climate Change Study lakes in the Experimental Lakes Area. The geology, vegetation, meteorology and hydrology of the study area is described briefly. Watersheds of the study lakes 149, 164, 165, 373, 377, 442, and 938, are delineated, and bathymetric maps are presented. Basic morphological parameters are summarized. Theoretical whole-lake water renewal times are estimated.

Key words: Lakes; watersheds; morphology; bathymetry; water-renewal time; flushing time; meteorology; climatic changes; natural variation; Experimental Lakes Area.

RÉSUMÉ

McCullough, G.K., and P. Campbell. 1993. Lake variation and climate change study: ELA lakes, 1986-1990. II. Watershed geography and lake morphology. Can. Tech. Rep. Fish. Aquat. Sci. 1898: iv + 29 p.

Le présent rapport est le deuxième d'une série de rapports dans lesquels on présente des données obtenues de 1986 à 1990 lors de l'étude sur la variation des lacs et le changement climatique, qui a été menée dans la Région des Lacs Expérimentaux. On y décrit brièvement la géologie, la végétation, la météorologie et l'hydrologie de la région étudiée. On brosse un tableau des bassins hydrographiques des lacs 149, 164, 165, 373, 377, 442 et 938, et on présente des cartes bathymétriques. On résume les paramètres morphologiques de base et on évalue la valeur théorique des temps de renouvellement de l'eau des lacs.

Mots-clés: Lacs; bassins hydrographiques; morphologie; bathymétrie; temps de renouvellement de l'eau; Région des Lacs Expérimenteaux.

INTRODUCTION

The Lake Variation and Climate Change Study at the Experimental Lakes Area (ELA) was begun in 1986. Campbell (1993) briefly describes the study rationale, including lake selection criteria. Following a season of reconnoitre and synoptic surveys in 1986, seven lakes constituting two series were selected. The lakes in one series are deep and, therefore, thermally stratified; those in the other are shallow and generally well-mixed. Both series cover wide ranges of water renewal times (flushing times, or exchange times). All lakes are similar in area; different water renewal times were effected by selecting watersheds of different sizes. A 10-year sampling program on the seven lakes and their inlets and outlets was initiated in 1987. This report, the second in this series, describes the study area, delineates watersheds, and provides lake morphometry, including bathymetric maps; estimates of water renewal rates are also presented. Other reports in this series present physical, chemical, and biological data collected during the period 1986-90.

The general location of the ELA in northwestern Ontario is shown on Fig. 1; roads, regional topography and locations of our study lakes are shown in Fig. 3. The research station, located on Rawson Lake (Lake 239), is 90 km east from Kenora via the Trans-Canada Highway and south on the Pine Road. Our study lakes are all located south of the Trans-Canada Highway and west of the research camp; they lie between 93°44'-93°59' WPM and 49°37'-49°50' N. All were numbered and located by Cleugh and Hauser (1971) as part of the original ELA survey carried out in 1967.

METHODS

WATERSHED AREAS

Watershed areas were determined by tracing the drainage divides on the best available topographic maps and, for the smaller watersheds, stereoscopic interpretation of air photos and field inspections of areas of uncertainty. The drainage divide around Lake 149 was stereoscopically determined using 1:16000 scale aerial photography and checked in the field. Lakes 164, 165 and 938 watersheds were traced on Ontario Ministry of Natural Resources (OMNR) 1:20000 scale, 10 m contour interval maps. Lakes 373 and 442 watersheds were determined on 1:5000 scale, 4 m contour interval maps created for the Department of Fisheries and Oceans by Airquest Surveys Ltd., Winnipeg. Both the latter watersheds were checked using aerial photography and by field inspection during the spring runoff season. The Lake 377 watershed area was determined from two maps. The northern half was drawn on 1:5000 scale, 4 m contour interval Airquest Surveys maps; the south on 1:7900 scale, 10 m contour interval maps created for the Department of Fisheries and Oceans by Lockwood Surveys Ltd. Several uncertain drainage connections were inspected in the field.

LAKE MORPHOMETRY

In September 1986, permanent benchmarks were chiselled into vertical bedrock faces near water level. Gauge boards were installed on Lakes 149, 165, 373, 377, 442, and 938 for recording lake levels. Lake 164 and 165 are connected by a short, shallow channel, and fluctuate together; hence, no gauge board was installed on Lake 164. Bathymetric surveys were then carried out on Lakes 149, 164, 165, 640, and 938. (Lake 640 was subsequently determined to be unsuitable for this study; Campbell 1993.) Lakes 373, 377, and 442 had already been surveyed prior to the onset of the current study. However, they were re-surveyed by us during the summers of 1990 and 1991; the results from the 1990 and 1991 bathymetric surveys of Lakes 373, 377 and 442 are the ones presented in this report.

Prior to conducting our bathymetric surveys, 1:15840 air photos of the lakes were examined stereoscopically; shoreline features prominent on the air photos were selected for use as starting and finishing points of our sounding transects. For each lake, between 20 and 30 transects were designated and drawn on an outline map for use in the field during the survey. Most of the transects were perpendicular to the long axis of the lake and, as much as possible, parallel to one another.

A recording Furuno Model FG 200A echo sounder was used to obtain the depth soundings in lakes surveyed in 1986. During the 1990 and 1991 surveys, a Lowrance X16 echo sounder was used. Transects were made at constant speed in a small outboard motor boat. At commencement and termination of each run, the distance of the transducer from the edge of the shore was estimated visually and noted. On the day of a bathymetric survey, both the gauge board reading and the height of the permanent bedrock benchmark above the lake surface were recorded. During each survey, the echo sounder was calibrated by recording, at point of maximum lake depth, the signal reflected by a Secchi disc lowered from the surface to the bottom at 1 m intervals.

The 0.5 or 1 m depth intervals were transferred from the bathymetric charts to outline maps copied from aerial photographic enlargements. Isobaths were hand-drawn between points of equal depth on adjacent transects. The area at each depth interval mapped was then determined by tracing the isobaths with a Calcomp 9100 Series Digitizer.

Lake surface area (A_0) and shoreline length (L) were calculated electronically from the digital record of the lake outline. Lake volumes (V) were calculated by the equation for volume of a conical section, from measured areas at regular depth intervals (Hutchinson 1957, p. 166):

$$V_{n,m} = (n-m)\,\frac{(A_m + A_n + \sqrt{A_m A_n})}{3}$$

where m, n = bounding depths, $V_{n,m}$ = volume between depths m and n, and A_m, A_n = area at each given depth. Maximum depth (z_m) was determined by examination of original bathymetric charts; effort was made in the original surveys to find the point of maximum depth. Mean depth ($\bar{z}$) was calculated by dividing lake volume by lake surface area. Area, volume and depth are functions of water level; hence, lake surface elevation, observed on the gauge board at the time of the bathymetric survey, is reported in Table 4. Shoreline development (F_L), the ratio of shoreline length to the length of the circumference of a circle of the same area as the lake, was calculated according to the equation given by Hutchinson (1957, p. 166):

$$F_L = \frac{L}{2\sqrt{\pi A_0}}$$

Both shoreline length and development are related to the scale of shoreline mapping (Hakanson 1981). The scale of maps used to measure shoreline length (prepared by direct tracing from aerial photographic enlargements) is reported in Table 4. Relative depth (z_r), the maximum depth expressed as a percentage of the virtual diameter ($\sqrt{A_0}$), was calculated according to the equation given by Hutchinson (1957, p. 167):

$$z_r = \frac{50\, z_m \sqrt{\pi}}{\sqrt{A_0}}$$

WATER RENEWAL TIMES

Theoretical whole-lake water renewal times (τ) were computed as:

$$\tau = V / Q$$

where V = whole lake volume and Q = annual volume of discharge through the outlet of the lake. This is a traditional theoretical calculation and probably reflects true lake flushing best for well-mixed shallow lakes with very small watersheds and diffuse inflow, such as Lake 149. Without supporting evidence, however, it should not be assumed that theoretical water renewal time expresses the true flushing time for all of our study lakes.

Outflow discharge was monitored for part of the period of study at outlets of Lakes 164 (1988--90), 373 (1990) and 938 (1990). Annual outflow discharge for Lake 165 was estimated by multiplying Lake 164 annual outflow by the ratio of their drainage areas. For Lakes 373 and 938, regression relationships were derived for outflow as functions of lake levels, which were recorded every two weeks for the open water season for the complete period 1987 to 1990. These data and level-discharge relationships were used to calculate the outflow discharge for Lakes 373 and 938 in the years when it was not measured. For the unmonitored year (1987) for Lakes 164 and 165 (because of beaver damming, there is no stable relationship between lake level and outflow for these lakes), and for all years for Lakes 149, 377 and 442, outflow discharge was estimated by assuming runoff per unit drainage area equal to that measured at the outlet of Lake 239. Lake 239 outflow is monitored as part of the ELA Observatory Program; data for this calculation was provided by Ken Beaty (personal communication).

This latter choice requires some explanation. The ELA is set in a region of very variable runoff. The four-year average outflow per unit drainage area for metered outlets from eight ELA lakes, for the period 1987 through 1990, was 88 mm • yr^{-1}; however, it ranged from 46 to 123 mm • yr^{-1}. Runoff from five terrestrial watersheds, for the same period, averaged 134 mm • yr^{-1} and ranged from 86 to 232 mm • yr^{-1}. Variability may have been particularly high in the period of this study because of greater than normal evaporation and transpiration. Mean annual precipitation was 572 mm for the four-year period, compared with 689 mm for the previous 17 years. The four-year mean runoff yield for the lake basins was only 15% of precipitation, roughly half of normal. Presumably, basin losses were mostly by evaporation and transpiration, so that physical and biological parameters which affect these processes would have had a large effect on yield. In the ELA, these parameters show very high spatial variability among watersheds. Without further study, we felt that modelling based on meteorological parameters would fail to improve on simply assuming runoff per unit drainage area to be the same as at the outlet of Lake 239, which was near the average for monitored lake outflows for each of the years of this study. The four-year average (1987-90) lake outflow per unit area, measured in eight other ELA region lakes, ranged from 52% to 127% of the Lake 239 outflow for the period; this gives a rough approximation of the uncertainty in the derived four-year lake renewal times show in Table 3. Annual outflow from the same eight lakes for the 1987-90 period ranged from 31% to 193% of the Lake 239 outflow. Outflow data from Lakes 114, 226, 227, 239, 240, 302, 303, and 470 were considered in the analysis in the paragraph above because full year outflow data were available; data from Lakes 223, 224 and 225 were excluded because their watersheds are believed to have unmeasured subsurface outflow. Data for 1987 is from Beaty and Lyng (1989), and for 1988-90, from unpublished data provided by Ken Beaty.

RESULTS AND DISCUSSION

GEOLOGY AND GEOLOGICAL HISTORY

The geology and geological history of the Experimental Lakes Area was described by Brunskill and Schindler (1971). Briefly, the ELA is situated in the Precambrian Shield on an extensive exposed batholith mostly of pink granodiorite, with localized zones of biotite-rich (grey) granodiorite. The area was subjected to several ice movements during the Pleistocene, the last advancing from the north-northeast, as is clearly evidenced by abundant glacial striae in the area.

Generalized maps in Clayton (1983, Figs. 4, 5) and Teller (1985, Figs. 3, 4) suggest that the Pleistocene ice front would have retreated past the ELA between 11500-11000 yr ago. The area would subsequently have been partially inundated under eastern Lake Agassiz, which in the ELA would have been much like the present northern Lake of the Woods - very irregular shoreline, filled with abundant islands. By 10800 B.P. the ice sheet had retreated far enough to allow drainage to the east; at this time it is considered to have fallen below the Campbell level, which can be estimated to be about 390-400 m ASL (present-day) in the ELA (see Zoltai 1967, Fig. 18, and Teller and Thorleifson 1983, Figs. 1, 2). However, sorted sands with foreset beds have been observed at 407 m ASL, above the south shore of Lake 239, and well-graded fine sands probably deposited in a subaqueous proglacial environment have been found as high as 420 m ASL. These deposits are evidence of early lake levels at ELA higher than the Campbell level. Over the next 1000 yr, Lake Agassiz dropped to less than 300 m ASL, before a last glacial advance once again blocked the eastern outlets, flooding back to at least the Campbell level (390-400 m ASL) about 9900 B.P. With the last retreat, circa 9500 B.P., the lake reestablished lower eastern outlets, dropping swiftly below the level of the lowest study lakes. The history of deglaciation implies that all of the study lakes, which range in elevation from 369 to 424 m ASL (H, Table 3), were initially incorporated in Lake Agassiz. Lakes 373 and 442 would have probably have become separated by 10800 B.P.; the rest would not finally have become individual lakes until almost 9500 yr ago.

Due to its resistance to erosion relative to the Precambrian metasedimentary and metavolcanic rocks surrounding it, the batholith underlying the ELA now forms a regional height of land, and the divide between drainage into the English River to the north, and into the Rainy River-Lake of the Woods-Winnipeg River system to the south and west. Lakes 373, 377, and 442 drain northwest via Winnange Lake into the English River; Lakes 149, 164, 165 and 938 drain southwest into Dryberry Lake and thence into Lake of the Woods. The local relief in the study area is moderately rugged; overall elevation ranges more than 100 m, from 369 m to 495 m above sea level. The region has become one of abundant, bedrock-rimmed lakes infilling the glacially-scoured depressions; about three-quarters of the ELA is land, one-quarter is water.

The glaciers scoured most of the high land clean of overburden, but on their retreat left scattered deposits of glacial drift in the form of ridges and depression-infillings of boulder and sandy tills, and pro-glacial outwash gravels and sands. Less commonly, local lacustrine deposits - silts, and more rarely, clays - can be found in low-lying areas. Since the Pleistocene, only thin soil has developed. Heights of land and steep slopes remain almost without soil, or with a veneer of regolith. Very acid brunisols, generally 10-30 cm deep and dominated by the poorly-decomposed upper organic horizon, occur in lower areas and find their best development on tills and sand and gravel deposits (Brunskill and Schindler 1971). Sphagnum peat has formed in many small wetlands by infilling topographical depressions.

METEOROLOGY

The ELA has a humid continental climate. A good summary of the local weather record as it relates to local limnology can be found in Schindler et al. (1990). Beaty and Lyng (1989) have summarized weather observations for the ELA meteorological station (for station location see Fig. 3) for the period 1969-1987. Some of these observations, plus data provided by Ken Beaty for the period 1988-90 (personal communication), are summarized in Table 1.

Annual mean temperature for the period of record, 1970-86, was 2.2°C; mean daily temperatures ranged from -41.0°C to 35.5°C. In general, the 1987-90 period has been warmer than this average; in particular the midsummer temperature has been mostly above the 1970-86 mean of 19.2°C.

In northwestern Ontario most precipitation falls as rain. In the warmer, summer months most of this falls in thunderstorms which are often brief and intense; in the cooler, autumn months rainfall is more widespread, with less intense frontal systems typically predominating. Total precipitation recorded at the ELA weather station from 1970 to 1986 averaged 689 mm per year (range: 500-926 mm) of which about 500 mm (73%) fell as rain. Precipitation from 1987-90 was consistently less than this average; in two years out of the four, it was close to the minimum for the previous 17-year period.

Uncorrected pan evaporation for the period 1970-86 ranged from 576 mm to 817 mm for an average of 690 mm per year. The years 1987-90 were clearly drier: the 1970-86 maximum pan evaporation was greatly exceeded two out of four years and almost equalled in one other year, 1989. Overall, measured pan evaporation from 1987-90 was 24% higher than the average for the previous 17 years. Through the 1970s and early 1980s, Lake 239 open water season lake evaporation has been determined from the annual water balance. Lake evaporation determined in this manner averaged 70% of the measured annual pan evaporation (Ken Beaty, personal communication). Since annual uncorrected pan evaporation and precipitation were close to equal in the period 1970-86, lake evaporation in the ELA can be said to have averaged about 70% of precipitation. Although Lake 239 water balances have not been calculated for the period 1987-90, it seems likely that, in these years, average open water evaporation exceeded total annual precipitation (open water evaporation about 600 $mm \cdot yr^{-1}$, compared to 572 $mm \cdot yr^{-1}$ of precipitation).

Mean monthly wind speed at 10 m above ground at the ELA meteorological station averaged 10.0 $km \cdot h^{-1}$ from 1970-86. Lowest mean monthly wind speeds occurred in mid-winter (minimum mean monthly: 7.0 $km \cdot h^{-1}$); among the open-water months, winds were somewhat higher than average in May, September and October (maximum mean monthly: 14.0 $km \cdot h^{-1}$), near average in June and July, and lower in August (Table 1). Based on the Kenora weather station record, for the period 1955-80, wind direction is fairly dispersed. During the open water period, southerly winds are slightly prevalent, both as a fraction of total time and in mean speed; northwesterly winds are second in predominance (Atmospheric Environment Service 1982). The same distribution is indicated by the ELA wind record for the period 1987-90.

From 1970-86, annual hours of bright sunshine averaged 42% of the maximum possible; during the relatively long days and the important four-month lake-heating period of May to August, 51% of daylight hours were cloud-free. Mean daily global solar radiation (measured on a horizontal surface, for the period 1967-76) at Kenora weather station was 13.1 $Mj \cdot m^2$. During the spring and summer months of May, June, and July, the mean daily radiation was 21-22 $Mj \cdot m^2$; 53% of the annual total radiation occurs in the 4 months from May through August (McKay and Morris 1985).

The date of ice-out and freeze-up has been recorded on Lake 239 every year since 1969 (Beaty and Lyng 1989). Over the period 1970-86, ice-out on Lake 239 occurred between 20 April and 15 May; freeze-up was as early as 8 November and as late as 30 November (Table 1). From 1987-90, the date of ice-out ranged widely but was, on average, earlier than the previous mean date; freeze-up was consistently later than the previous average. The average ice-free period from 1987-90 was 206 days, 6 days more than the 1970-86 mean.

Lake 239 is 54 ha in area, with a mean depth of 10.9 m; its largest influent stream drains only 170 ha. Our study lakes are smaller, ranging from 16-27 ha, and 4 of them (Lakes 149, 164, 165, and 938) are much shallower. We have only occasionally observed ice-out and freeze-up on our study lakes, but we assume that ice-out and freeze-up would have occurred on all of them within a couple of weeks of Lake 239, and that they will have shown the same trend towards a longer ice-free period in recent years.

HYDROLOGY

The five year running mean annual regional discharge, expressed per unit watershed area, compared with ELA runoff, is shown in Fig. 2. The watersheds of Lakes 149, 164, 165 and 938 drain via Berry Creek southwest into the Lake of the Woods drainage; Lakes 373, 377 and 442 drain into Winnange Lake and thence into the English River system to the north. The combined flow of the Winnipeg River (which drains Lake of the Woods) and the English River has been recorded at Slave Falls, Manitoba since 1907 (Water Survey of Canada 1992a). Overall, Winnipeg River discharge has been dropping irregularly since peaking in the late 1960s. For the period 1987-90 discharge was about 80% of the 80 yr mean.

The 20 year period of flow records, and the four year period 1987-90, at the outlet of Lake 239 in the ELA are compared in Table 2 with the 80 yr period of record for the Winnipeg River. The outflow from Lake 239 and discharge of the Berry Creek below Dryberry Lake (Water Survey of Canada 1992b) were, in the period 1987-90, only about half of the regional runoff (represented by Winnipeg River discharge) per unit watershed area. Examination of Fig. 2 shows increasing divergence between regional and local ELA runoff with decreasing annual discharge; apparently the ELA is more sensitive than the larger region to evapotranspirative water losses during warm, dry periods.

Generally, the snowmelt runoff from terrestrial watersheds in the region occurs while the lakes are still ice-covered. The Lake 239 Northwest Inflow is a terrestrial watershed (area = 56 ha) at the ELA whose outflow has been monitored since 1971. Peak snowmelt runoff has ranged from 24 March to 26 April; the mean for the period 1971-86 was 14 April, more than two weeks before the mean ice-out date of 30 April on Lake 239. About one-third of the annual runoff from the Northwest Inflow flowed into Lake 239 in the single month of April. Somewhat more than half ran in during the ice-free season from the beginning of May to mid-November, and 10-15% during the winter months. Because some winter flow records are incomplete these figures are intentionally stated without more precision. Furthermore, there have been years of wide divergence from this general pattern, including some in which spring runoff was only a small proportion of total annual discharge.

Over the period of our study, a much drier four years, an average of 48% of the total runoff from the Northwest Inflow was spring runoff, and occurred in late March and April. Autumn and winter flows were negligible; the other half of terrestrial runoff occurred in the three months of May, June and July. The distribution of terrestrial runoff into our first order lakes (149 and 373) would have been similar. Although our larger watersheds have considerable storage in upstream lakes, they may not be dramatically different in annual runoff distribution from the first order lakes. In three years for which outflow data has been determined for Lake 164 (1988-90), the peak of the snowmelt runoff has been only 5-10 days later than for the Lake 239 Northwest Inflow. In those years, 90% of the annual discharge flowed through Lake 164 in the months of April to August. Because the period was unusually dry, this proportion can be expected to have been higher than the long term normal which would include periods with greater autumn precipitation and more winter discharge. (For the period 1971-86, 69% of annual discharge through Lake 239 occurred in the months of April to August). Nonetheless, the normal pattern for even our larger watersheds would have been for most runoff to occur in spring and early summer.

VEGETATION

The ELA falls on the western extremity of the Great Lakes-St. Lawrence forest region as mapped by Rowe (1972). The "typical....boreal forest subclimax" has been considerably altered since Brunskill and Schindler (1971) first described the geography of the area. Most of the study area is in an early stage of regeneration following either logging or fire. Logging was begun in the region in the early 1930s, when the scattered stands of red and white pine were cut and floated out as 16-foot saw logs (Noël Golder, former Logging Superintendent, Minnesota and Ontario Pulp and Paper Company, personal communication). Most of the forest in the Lakes 164 and 938 watersheds was cut for pulp-and-paper in the 1960s and 1970s. The Lake 377 watershed was extensively logged in 1965, and again in 1972-74, with additional cuttings to remove the last merchantable timber up to as recently as 1984. The Lake 442 watershed was logged, except for narrow buffer strips around Lakes 438 and 442, in the winters of 1975-76 (19 ha), 1977-78 (21 ha) and 1978-79 (53 ha), and Lake 373 watershed in 1978-79 (7 ha) and 1979-80 (17 ha). (Data from forest cutting maps supplied by Chris Marsh, Ontario Ministry of Natural Resources, Kenora). The Lakes 149, 373, 377 and 442 watersheds have been untouched by fire since the region was described by Brunskill and Schindler, but two large fires in 1980 burned 5% of the land drained through Lake 164 and 165, and half of that above Lake 938 (Table 3).

Jack pine intermixed with a small proportion of trembling aspen and white birch has become far more dominant than before, and black spruce greatly reduced, over the burned region. Regeneration in the logged area has produced a young, mixed community dominated by jack pine, trembling aspen and white birch in variable abundance, with a smaller fraction of black spruce and balsam fir. Occasional pure stands of red pine can still be found on sandy deposits. Communities of the poorly drained sites have been little affected by logging or fire; in particular, open small black spruce, tamarack and alder communities, or treeless Labrador tea and leather leaf, dominate flat lying sphagnum wetlands.

CULTURAL EFFECTS ON THE LANDSCAPE

Widespread clearcutting for pulp and paper and lumber constitutes the major human impact on the environment of the study region. Logging history is summarized in the section describing vegetation, above. Berry Creek, through Lake 938, was historically used to float logs out of the watershed. The outlet of Lake 938 was, in the early 1930s, dammed with a rockfilled, wooden weir creating a chute to pass logs over the outlet rapids. The effect of this would have been to raise the lake level slightly (<1 m) above normal, at least during high flow. The remains of the weir still exist, but probably now have little affect on the lake level. In any case, the historic effect on water level was probably similar to that of the beaver dams which have been and continue to be built on the outlets of small lakes such as ours. The levels of Lakes 149, 164, 165 and 442 are controlled by beaver dams and Lake 377 was dammed sometime in the recent past, at about a half metre above its current level.

Other than logging, the major physical alteration to the watersheds of the study region has been roadbuilding. Unimproved gravel roads (shown on various watershed maps, Figs. 3 to 8) were built through the two large watersheds draining into Lakes 164/165 and 938 to facilitate logging in the 1960s. Of particular note is the road along the north shore of Lake 938 (Fig. 4). The main influent stream to Lake 938, the Berry Creek, is constrained at this road by a culvert with a maximum capacity of about 3.4 $m^3 \cdot s^{-1}$. Berry Creek peak flows which would, under natural conditions, exceed this, are stored in upstream Ethelma Lake (Lake 254, area = 388 ha), thus truncating the peak, but extending the duration of high flows through Lake 938.

A similar unimproved gravel road was built into the northeast of the region, through the Lake 442 watershed in the winter of 1975-76, along the east edge of the Lake 373 watershed in 1978-79, and via a bridge over the major inlet of Lake 377 in 1979-80. In bisecting the Lake 442 watershed, it also crosses the major influent stream, which follows the roadside for several hundred metres (Fig. 8).

A private cabin has been located on Highwind Lake in the Lake 938 watershed since the early 1970s. A fishing lodge was established at the same location in the early 1980s; it is currently in operation (John Shearer, personal communication). Other than this, no permanent habitation exists in any of the study watersheds. Parts of the Lake 938 watershed, and to a lesser extent, the Lakes 164/165 watershed, are used for small outboard motor-boating, canoeing, camping and fishing in summer, and for hunting and trapping in autumn and winter. As access to Lakes 373, 377 and 442 is currently by restricted road, there is now little recreational use of their watersheds.

More detailed information on fishing of our study lakes was kindly provided by Ken Mills (personal communication). The construction of logging roads allowed exploitation of fish populations in nearby lakes. Access trails were constructed by fishermen to these lakes, and sport-fishing from motorized boats likely occurred. Although northern pike are common, the main target species has been lake trout. Lake trout in Lakes 373, 377, and 442 were exploited to varying degrees during the logging period. Lake 442 has been sport-fished in the winter for many years, but still maintains a relatively large lake trout population for such a small lake. Lake 373 has been more heavily affected; the lake trout population is about half of what would be expected in an unexploited population in the ELA. The average lake trout length and weight is higher than in other small lake trout lakes; this is characteristic of a heavily exploited population. The lake trout population in Lake 377 was likely decimated by sport fishermen; fewer than 10 lake trout presently exist in the lake. This lake is characterized by an abundant yellow perch population; the inverse of that in lakes where lake trout are abundant. Because the shallow lakes 149, 164, 165 and 938 contain northern pike and do not contain lake trout, Mills suspects these lakes have rarely been fished.

Further fish exploitation occurs in the ELA by commercial bait fishermen. The entire area is divided into bait fishing "blocks" which are leased by Ontario Ministry of Natural Resources to local entrepreneurs. Lakes are accessed either by logging road or by fixed-wing aircraft. Bait fishermen use standard minnow traps and usually fish lakes in rotation, working each lake every second or third year. Most fishing occurs in the early spring or late summer; the primary target species are pearl dace, finescale dace, fathead minnow and small white sucker. The most productive bait fisheries are in very shallow lakes that lack piscivorous species. Lakes containing northern pike or bass species are usually not bait-fished. Lake trout lakes are intermediate between these extremes. Again, because Lakes 149, 164, 165 and 938 contain northern pike, Mills believes that these lakes are also not exploited commercially for bait fish. Lakes 373 and 442 have certainly been bait-fished in some years and Lake 377 may have.

WATERSHED AREAS

Figure 3 is a regional topographic map showing the seven study lakes and their watersheds in relation to each other. Figures 4 to 8 show local subdivisions within the watersheds. Numbers printed in bold within the subdivision boundaries are sub-watershed areas in hectares. The Lake 377 watershed contains a small lake (Lake 107, to the northeast of Lake 377) and 21 ha of watershed which was found to drain into Lake 377 under baseflow conditions, but to spill into downstream Lake 659 during stormflow.

Areas of the watersheds of the study lakes are reported in Table 3. The study lakes are all approximately the same size; however, drainage areas range from less than 100 ha for our headwater systems to approximately 12,000 ha for our highest order system.

LAKE MORPHOMETRY

Figures 9 to 16 are bathymetric maps drawn from the electronic files used to calculate morphometric data; outlets, major inlet streams and lake level gauge locations are shown. Table 3 includes a summary of morphometric data; detailed data are reported in Table 4. Lake surface areas range from 16 to 27 ha. Mean depths of the shallow, well-mixed lakes (149, 165 and 938) are on the order of 2 to 3 metres whereas those for deep, stratified Lakes 373, 377 and 442 range from 9 to 11 metres. Total volumes of the shallow lakes are between 500,000 and 600,000 m^3; the deep lakes are roughly 3 to 5 times larger. The aerial forms of all the study lakes are simple; shoreline development ranges from only 1.5 to 1.9.

Figure 17 shows various morphometric data plotted by depth. Figure 17A, which shows the cumulative virtual distance between successive isobaths plotted by depth, can be considered to illustrate the mean profile of the lake bottom. The various curves illustrate the clustering of the lakes into a shallow, flat-bottomed group (Lakes 149, 165 and 938), and a deeper group with more steeply sloping sides (Lakes 373, 377 and 442). On these curves, Lake 164 tends to align closer to the shallow than the deep group.

WATER RENEWAL TIMES

The open water seasons during the period 1987-90 were warmer and drier than normal. Annual precipitation ranged from 515 to 629 mm, considerably lower than the average 689 mm in the period 1970-1987. Furthermore, because of higher than normal evaporation and transpiration, runoff yields were lower. For the Lake 239 watershed, runoff was an average of 15% of precipitation from 1987 to 1990 (range of annual runoff yields: 11 to 26%) compared with 33% for the period 1970-1986 (from data reported in Beaty and Lyng, 1989, and unpublished data supplied by Ken Beaty). Estimates of theoretical whole-lake water renewal times reported in Table 3 are, therefore, on average, more than 2 times longer than would be expected under conditions prevailing during the previous 17 years. The long term Winnipeg River record suggest that such a dry period is not anomalous. For the period 1987-90, the range of water renewal times for our shallow lakes was from about 3 weeks to 7 years (2 orders of magnitude). For our deep stratified lakes, it was from 1 to 25 years (>1 order of magnitude).

The theoretical water renewal time (Table 3) probably reflects true lake flushing time best for well-mixed shallow lakes with very long renewal times and diffuse inflow. However, in some lakes, factors including seasonal stratification and density differences between the water of the inflowing stream and lake may inhibit complete mixing by influent water before it is lost through the outlet. Our knowledge of these processes is incomplete. There is some evidence that influent water would be fairly well mixed in the surface strata of small ELA lakes. Kenney (1972) concluded that considerable energy is available for the mixing of shallow waters of small lakes during the open water season. In a study using drogues and dyes he showed that, under average wind conditions, horizontal mixing of the epilimnion of Lake 239 occurred in a matter of days at the most. In Lake 938, incomplete mixing might be expected because most of the inflowing water enters near the same end of the lake as the outflow. However, although Berry River inflow chemistry is greatly different from the chemistry of the inflow at the east end of the lake, data from our west end station (along the most direct route from inflow to outflow) is not obviously different from that of the east end station (Stainton et al., in prep.(a), in prep.(b)). On the other hand, preliminary analysis of data from spring runoff mixing in Lake 239 (unpublished data, Greg McCullough) suggests that a small portion of influent stream water may mix incompletely in passing through the lake under the ice cover. How effective this might be in altering the true flushing rate in ELA lakes would depend on the volume of runoff entering the lake while it was ice-covered. Without further study, and depending on the lake type, caution should be used in equating theoretical water renewal times with the real world situation.

SUMMARY

The Lake Variation and Climate Change Study lakes fill bedrock basins in a glaciated region of the Precambrian Shield in northwestern Ontario. They are local, perched remnants of eastern Lake Agassiz, a vast proglacial lake which stretched to the northwest along 1400 km of ice margin, and which retreated north with the receding ice sheet past the ELA area about 9500 years ago. Currently, the area is characterized by a continental climate with a mean annual temperature of 2.2°C, and a range of over 80°C. Annual precipitation is 689 mm; one-quarter of this falls as snow. On average, 33% of the total precipitation is yielded as runoff. During 1987-90, temperature has been above average, and precipitation and runoff well below average. The vegetation in the watersheds today is typical boreal forest, mostly in a state of regeneration after extensive clearcut logging or fire in the last twenty years. To facilitate the logging, a network of unimproved gravel roads has been built through the region, and partly since abandoned. Currently, use of the region is confined mainly to canoeing and sport fishing in summer, hunting and trapping in autumn and winter.

The lakes within this region selected for the Lake Variation and Climate Change Study are small, varying in area from 16-27.3 ha. All are simple in shape; the largest shoreline development is 1.9. They fall into two groups by depth and volume. Lakes 149, 164, 165 and 938 range from 2 to 4.9 m in mean depth, and 5-10 $X10^5 m^3$ in volume. Lakes 373, 377 and 442 are more than twice as deep, ranging from 9-11 m in mean depth, and twice to six times as voluminous, from 14-30 $X10^5$ m^3. The lakes were selected with widely varying watershed areas to ensure a wide range of water renewal times. Watershed areas range from only 81 ha to over 12000 ha. For the period 1987-90, the range of theoretical flushing times for shallow lakes was from about 3 weeks to 7 years, and for the deep stratified lakes, from 1 to 25 years.

ACKNOWLEDGMENTS

We thank Donna Laroque for assistance in typing and document preparation. Our thanks, also, to Susan Kasian, who assisted with the bathymetric surveys in the autumn of 1986, and to Jeannie Patterson and Leigh Hsu who assisted in the 1990-91 surveys. The manuscript was reviewed by Bob Hecky and Ken Beaty. Ken Mills kindly supplied paragraphs describing the sport and commercial bait fishery in our study lakes. We would especially like to acknowledge our debt to Ken Beaty and Mark Lyng, both for the existence of the long hydrometeorological record at the ELA, and for discussions about the meaning of that data.

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Table 1. Selected climatological data for the ELA. Means, maxima and minima are for the 17 year period 1970-86. Data for the period 1970-86 are published in Beaty and Lyng (1989). Data for subsequent years were kindly provided by Ken Beaty (personal communication).

	Mean	Maximum	Minimum	1987	1988	1989	1990
Temperature (°C)							
Mean annual	2.2	4.0	0.8	5.1	3.1	2.7	1.7
Mean January	-17.9	-12.4	-23.8	-12.4	-11.5	-18.8	-14.2
Mean July	19.2	21.6	16.5	19.5	18.8	20.7	21.2
Water year precipitation (mm)							
rain[1]	501	686	330	399	425	414	404
snow[2]	189	337	94	124	165	227	136
total[3]	689	926	500	515	629	611	532
10-metre wind ($km \cdot h^{-1}$)							
Mean annual	10.0	12.0	9.0	10.2	10.0	11.8	12.0
Uncorrected pan evaporation (mm)							
Evaporation	690	817	576	874	962	806	777
Lake 239 ice cover							
Ice-out	30 Apr	15 May	20 Apr	17 Apr	30 Apr	11 May	26 Apr
Freeze-up	16 Nov	30 Nov	08 Nov	21 Nov	23 Nov	17 Nov	19 Nov
Ice-free days	200	213	182	218	207	190	207

Notes:
1 Total calendar year rainfall.
2 Total winter snowfall, summed from first snow of previous year to last spring snow.
3 Total water year precipitation, summed from 1 November of the previous year to 31 October.

Table 2. Selected runoff data for the ELA. Discharge is expressed as average depth of water loss over the watershed per year. Stations are Winnipeg River at Slave Falls, Manitoba (Water Survey of Canada 1992a. Station 05PF063), Berry Creek at outlet of Berry Lake (Water Survey of Canada 1992b. Station 05PD026) and Lake 239 Outlet (data provided by Ken Beaty, personal communication).

	Drainage Area km^2	1911-90 $mm \cdot yr^{-1}$	1971-90 $mm \cdot yr^{-1}$	1987 $mm \cdot yr^{-1}$	1988 $mm \cdot yr^{-1}$	1989 $mm \cdot yr^{-1}$	1990 $mm \cdot yr^{-1}$
Winnipeg R	125000	211	223	131	118	243	176
Berry Creek	744			82	29	148	76
Lake 239	3.93		192	72	71	156	59

Table 3. Morphological characteristics of the ELA Lake Variation and Climate Change Study lakes and watersheds.

Lake	Order	A_d (ha)	A_l (ha)	A_f (ha)	A_0 (ha)	H (m ASL)	Z_m (m)	$\bar{Z}$ (m)	V ($m^3 x10^6$)	L (m)	F_L	Z_r (%)	T (yr)
149	1	93.6	26.9 (29%)	0 (0%)	26.9	384	4.1	2.0	5.38	2,900	1.58	0.70	7.3
165	31	4,802	820 (17%)	200 (5%)	18.4	369	4.6	3.4	6.19	2,290	1.51	0.95	0.13
164	32	4,948	840 (17%)	200 (5%)	20.3	369	7.1	4.9	10.02	2,390	1.50	1.40	0.21
938	52	12,021	2961 (25%)	4600 (51%)	19.2	372	6.0	2.0	5.17	2,900	1.87	1.21	0.07
373	1	80.6	27.3 (34%)	0 (0%)	27.3	424	20.8	11.0	30.09	2,790	1.51	3.53	25
442	2	161.0	33.7 (21%)	0 (0%)	16.0	411	17.8	9.0	14.40	2,470	1.74	3.94	11
377	12	2,123	429 (20%)	0 (0%)	26.9	392	17.9	9.2	24.66	3,170	1.72	3.06	1.5

Notes:

Order = 1 + number of upstream lakes in watershed

A_d = drainage area at lake outlet (including lake surface area)

A_l = area of all lakes upstream of outlet (number in parentheses is surface water area as percent of total drainage area)

A_f = area of land burned in forest fires of 1980 (number in parentheses is burned land as percent of terrestrial drainage area)

A_0 = lake surface area

H = lake surface elevation relative to mean sea level

Z_m = maximum depth

$\bar{Z}$ = mean depth

V = volume

L = length of shoreline, including islands

F_L = shoreline development = $\frac{L}{2\sqrt{\pi A_0}}$ (Hutchinson 1957)

Z_r = relative depth (maximum depth as a percentage of the mean diameter) = $\frac{50 z_m \sqrt{\pi}}{\sqrt{A_0}}$ (Hutchinson 1957)

T = theoretical whole-lake water renewal time = $\frac{V}{Q}$

where Q = annual volume of discharge through the outlet of the lake, calculated for water years 1 November 1986 through 31 October 1990.

Table 4. Detailed morphometry of the ELA Lake Variation and Climate Change Study lakes and watersheds. Scale of map used to derive length and area, and effective gauge height at time of bathymetric survey are indicated for each lake. Depths and volumes are as measured from the bottom of the echo sounder transducer, which was immersed 0.1 m or 0.15 m below the water surface. Effective gauge height was computed by subtracting the depth of immersion of the transducer from the gauge board level observed at the time of the survey.

Lake	Depth (m)	Area (ha)	Length (m)	Volume ($10^5 m^3$)
149	0.0	26.9	2900	
	1.0	20.9	2680	2.39
	1.5	16.5	2160	0.93
	2.0	12.1	1330	0.71
	2.5	9.5	1180	0.54
	3.0	6.9	990	0.41
	3.5	4.3	770	0.28
	4.0	0.9	400	0.12
	4.05	0.0	0	0.002

Map scale = 1:1909
Effective G.H. = 9.306 m.

Lake	Depth (m)	Area (ha)	Length (m)	Volume ($10^5 m^3$)
164	0.0	20.3	2390	
	1.0	18.8	2090	1.96
	1.5	17.4	1760	0.90
	2.0	16.7	1710	0.85
	2.5	16.2	1680	0.82
	3.0	15.7	1670	0.80
	3.5	15.2	1610	0.77
	4.0	14.8	1580	0.75
	4.5	14.3	1530	0.73
	5.0	13.6	1470	0.70
	5.5	12.2	1390	0.65
	6.0	9.9	1280	0.55
	6.5	6.1	1450	0.40
	7.0	0.6	620	0.14
	7.05	0.0	0	0.001

Map scale = 1:1900
Effective G.H. = 9.610 m.

Lake	Depth (m)	Area (ha)	Length (m)	Volume ($10^5 m^3$)
165	0.0	18.4	2290	
	1.0	16.7	2020	1.75
	1.5	15.7	1950	0.81
	2.0	14.7	1900	0.76
	2.5	13.9	1810	0.72
	3.0	13.2	1760	0.68
	3.5	12.3	1770	0.64
	4.0	9.8	1560	0.55
	4.5	2.3	1320	0.28
	4.55	0.0	0	0.004

Map scale = 1:1965
Effective G.H. = 9.630 m.

Lake	Depth (m)	Area (ha)	Length (m)	Volume ($10^5 m^3$)
373	0	27.3	2790	
	1	25.6	2490	2.65
	2	23.6	2360	2.46
	3	21.7	2220	2.26
	4	20.5	2080	2.11
	5	19.7	2020	2.01
	6	18.9	1990	1.93
	7	18.2	1950	1.85
	8	17.1	1870	1.76
	9	16.3	1830	1.67
	10	15.4	1790	1.58
	11	14.6	1750	1.50
	12	13.8	1710	1.42
	13	12.7	1580	1.32
	14	11.7	1530	1.22
	15	10.6	1460	1.12
	16	8.8	1330	0.97
	17	7.2	1240	0.80
	18	5.7	1130	0.64
	19	3.5	870	0.45
	20	2.3	590	0.28
	20.75	0	0	0.09

Map scale = 1:2429
Effective G.H. = 8.910 m.

Lake	Depth (m)	Area (ha)	Length (m)	Volume ($10^5 m^3$)
377	0	26.9	3170	
	1	25.2	2790	2.61
	2	23.6	2700	2.44
	3	22.5	2560	2.30
	4	21.3	2470	2.19
	5	19.6	2160	2.05
	6	17.8	1900	1.87
	7	16.3	1790	1.71
	8	15.2	1740	1.57
	9	14.1	1690	1.47
	10	13.1	1650	1.36
	11	11.7	1560	1.24
	12	10.2	1450	1.09
	13	8.1	1280	0.91
	14	6.2	1110	0.71
	15	4.7	1040	0.54
	16	3.2	930	0.39
	17	0.9	490	0.19
	17.9	0.0	0	0.02

Map scale = 1:2154
Effective G.H. = 9.154 m.

Lake	Depth (m)	Area (ha)	Length (m)	Volume ($10^5 m^3$)
442	0	16.0	2470	
	1	14.7	1700	1.53
	2	14.0	1650	1.44
	3	13.4	1590	1.37
	4	12.9	1560	1.31
	5	12.3	1540	1.26
	6	11.6	1490	1.19
	7	10.8	1440	1.12
	8	10.0	1420	1.04
	9	9.1	1330	0.95
	10	8.0	1260	0.85
	11	6.5	1130	0.72
	12	4.7	940	0.56
	13	3.3	810	0.40
	14	2.5	710	0.29
	15	1.3	440	0.19
	16	0.8	330	0.11
	17	0.4	250	0.06
	17.8	0.0	0	0.01

Map scale = 1:1613
Effective G.H. = 8.945 m.

Lake	Depth (m)	Area (ha)	Length (m)	Volume ($10^5 m^3$)
640	0.0	18.8	3350	
	1.0	17.1	2730	1.79
	1.5	16.0	2630	0.83
	2.0	14.7	2800	0.77
	2.5	13.4	2470	0.70
	3.0	12.0	3690	0.64
	3.5	9.2	2010	0.53
	4.0	4.6	1150	0.34
	4.5	2.5	780	0.17
	5.0	1.3	620	0.10
	5.5	0.6	320	0.05
	6.0	0.0	60	0.01

Map scale = 1:1963
Water level relative to B.M. = -0.759 m.

Lake	Depth (m)	Area (ha)	Length (m)	Volume ($10^5 m^3$)
938	0.0	19.2	2900	
	1.0	17.9	2630	1.85
	1.5	16.8	2500	0.87
	2.0	14.9	2390	0.79
	2.5	9.9	2140	0.62
	3.0	6.8	1630	0.42
	3.5	4.2	1040	0.27
	4.0	3.0	970	0.18
	4.5	1.3	540	0.10
	5.0	0.5	270	0.05
	5.5	0.2	170	0.02
	6.0	0.0	0	0.004

Map scale = 1:1902
Effective G.H. = 8.557 m

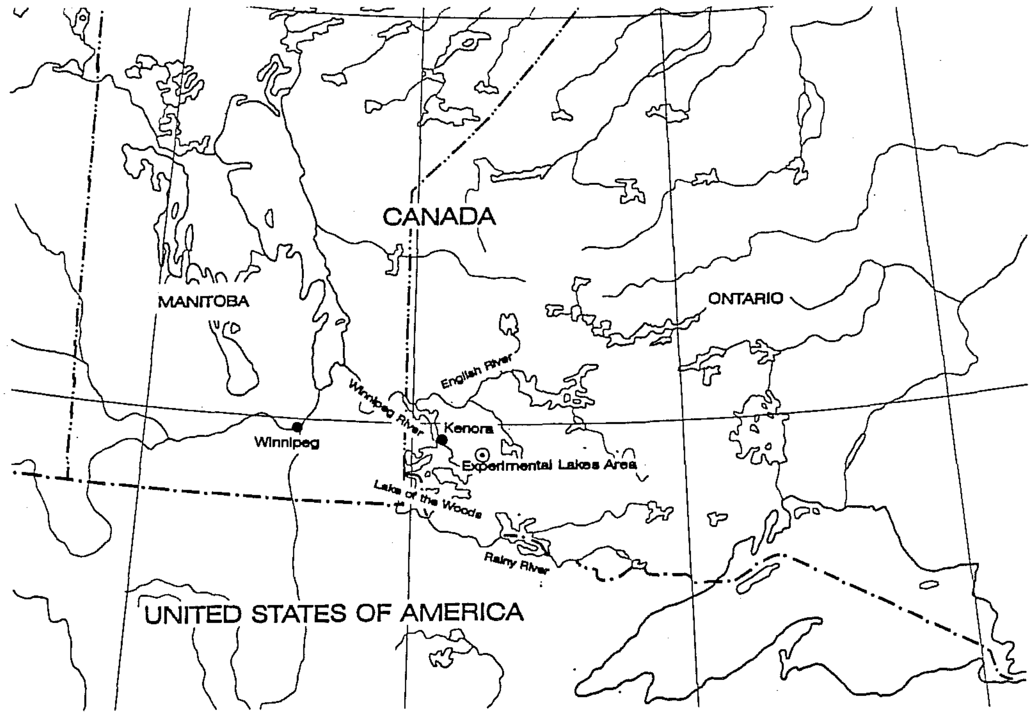


Figure 1. Location of the ELA in south-central Canada.

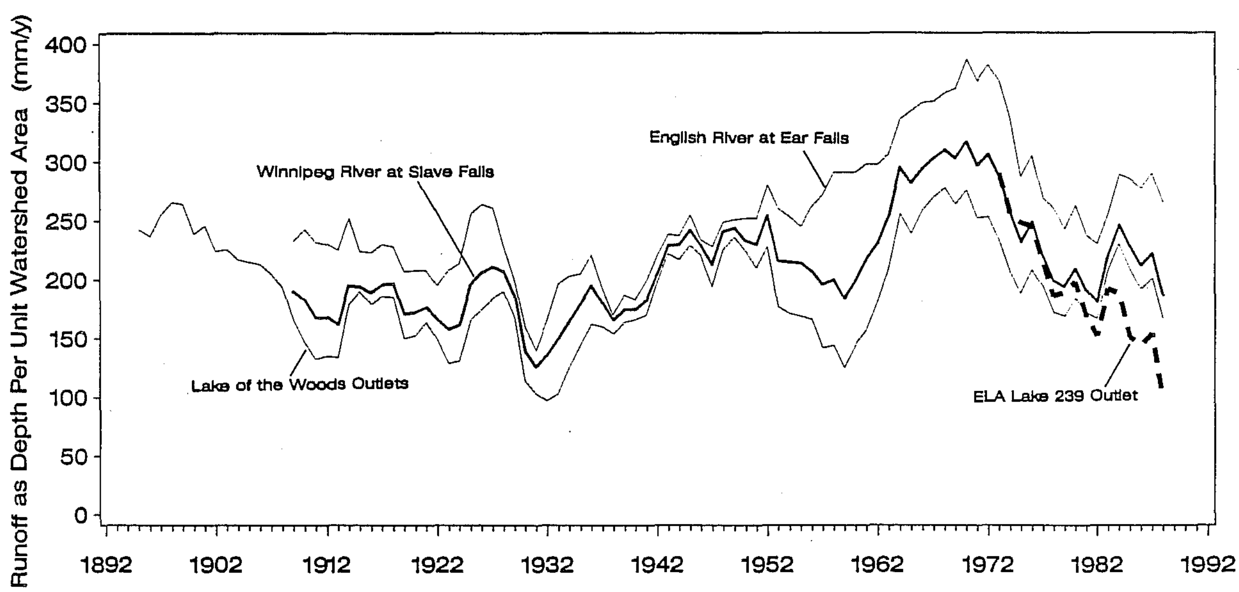


Figure 2. Historical runoff in the ELA. The hydrographs show 5-year running mean discharge; annual or monthly discharge data would show much wider fluctuations. The ELA lies on the drainage divide between the English River to the north, and the Rainy River-Lake of the Woods-Winnipeg River system to the south and west. The record of discharge of the Winnipeg River at Slave Falls, Manitoba, includes the output of both tributaries. The plot of discharge data from the outflow of Lake 239 at ELA coincides with regional runoff in the 1970s, but deviates considerably in the drier 1980s. (Data from Water Survey of Canada, 1992a and 1992b; Beaty and Lyng, 1989; and Ken Beaty - personal communication.)

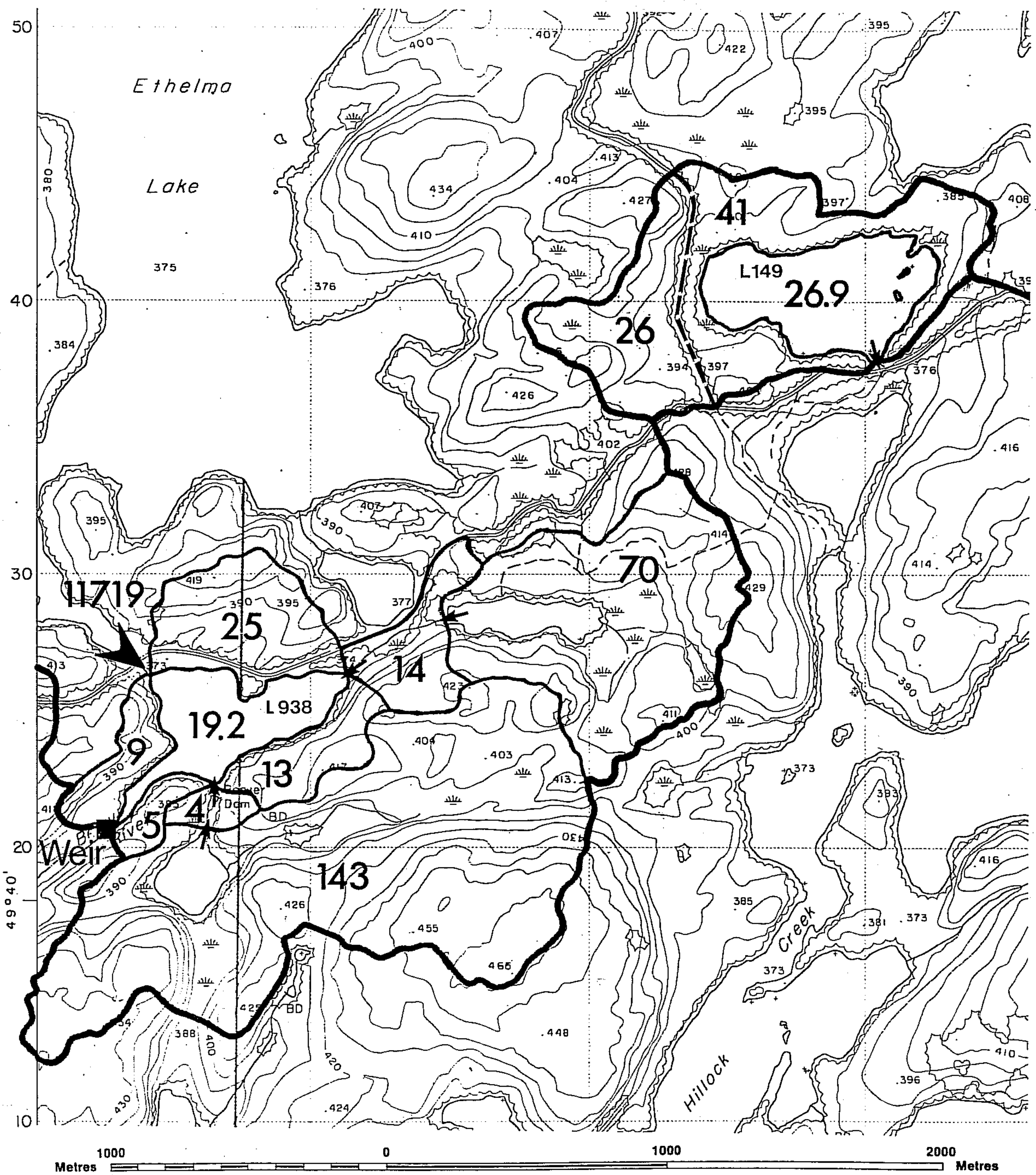


Figure 4. Lakes 149 and 938 local topography and watershed subdivisions. Areas indicated in bold print (ha). Lake 149 total watershed area (including lake surface area): 93.6 ha.
Lake 938: 12021 ha. Broad black line indicates lake watershed boundaries; medium black line indicates sub-watershed boundaries. Base map is from Ontario Ministry of Natural Resources topographic map sheets originally at 1:20000 scale. 10 m contour interval.

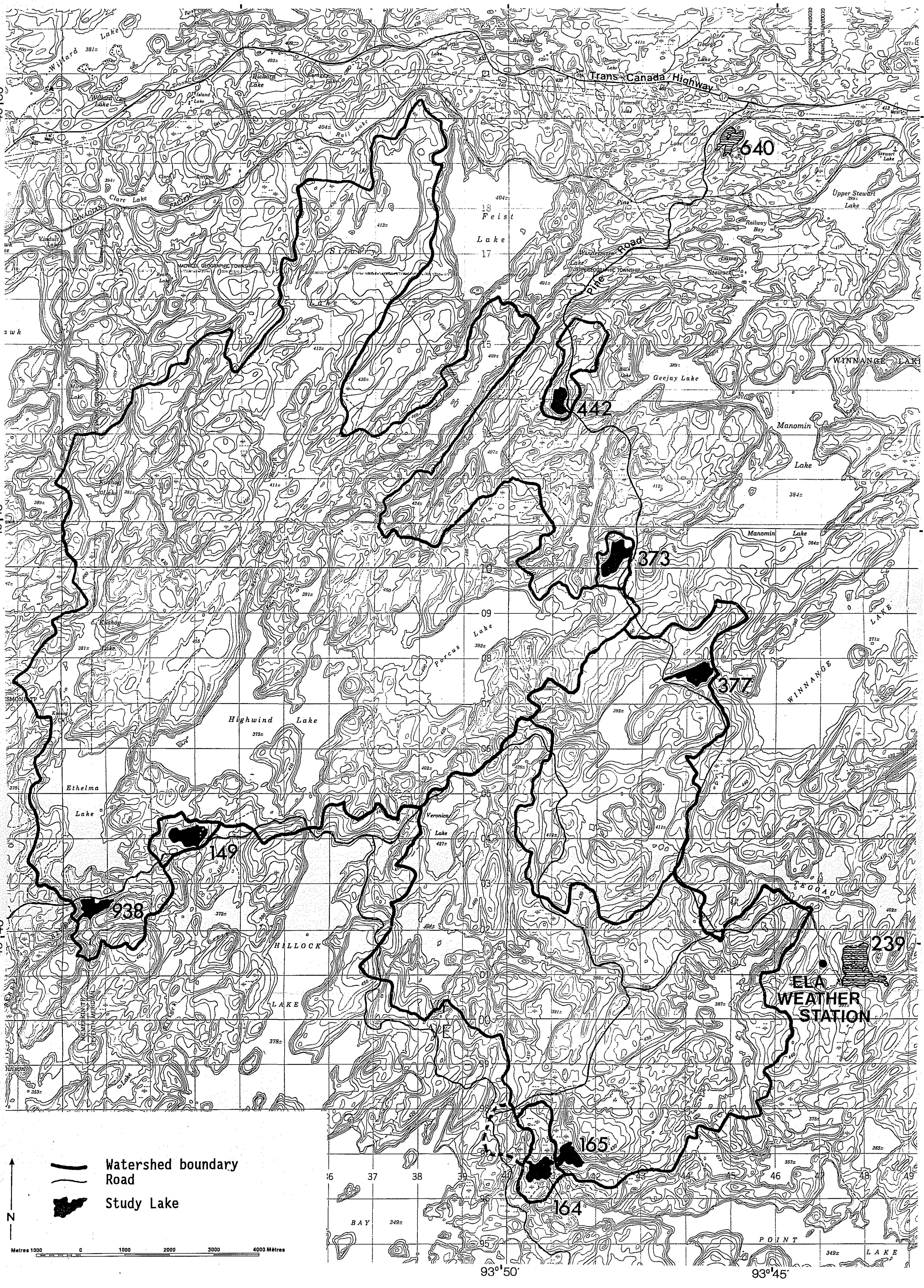


Figure 3. Topography and watersheds of the study lakes. Note that the watershed of Lake 164 includes that of Lake 165. Base map is reduced from portions of National Topographic Survey 1:50000 map sheets 52F/12 and 52F/13. Small grid squares are 1 km on each side. 10 m contour interval.

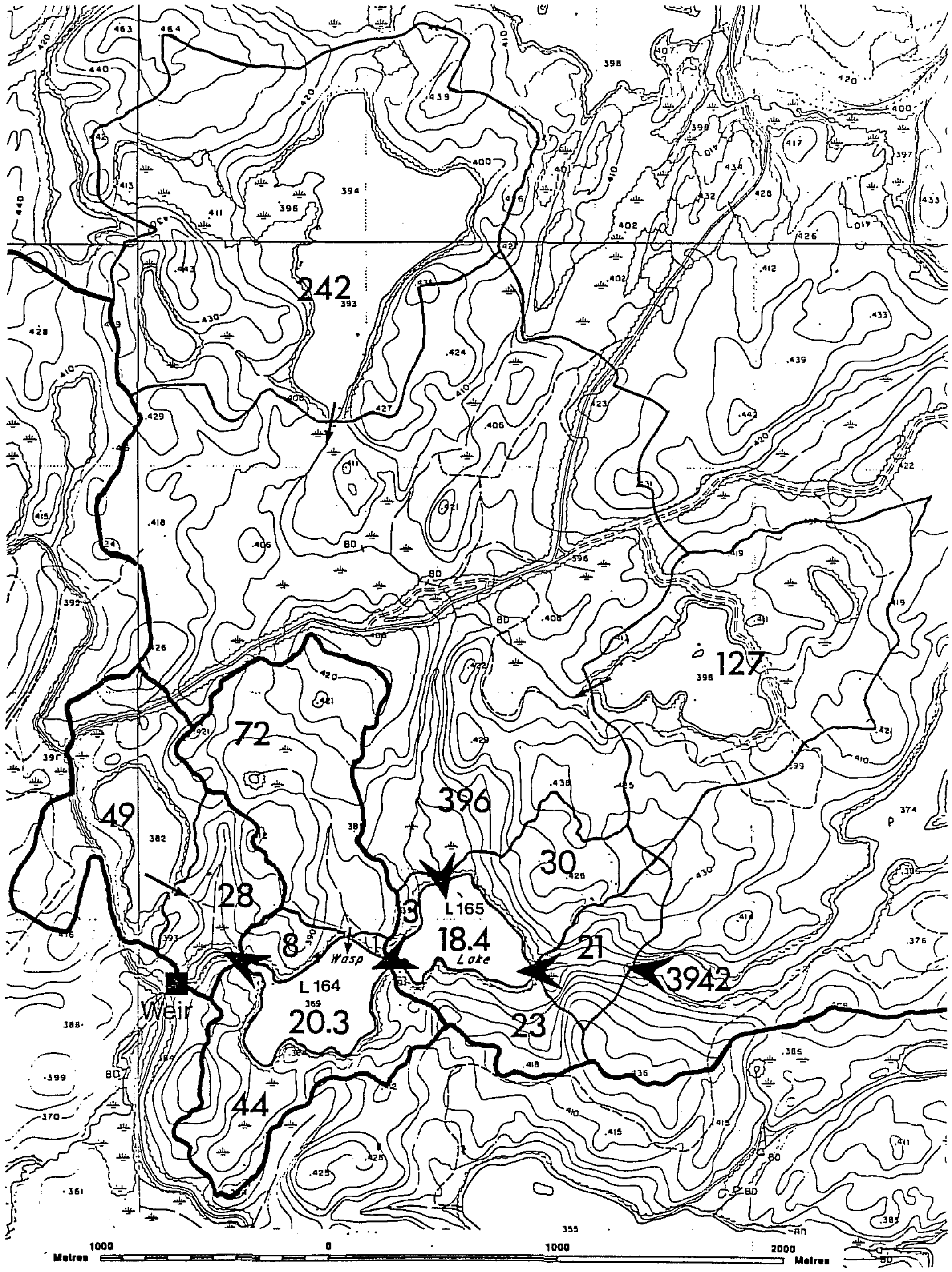


Figure 5. Lakes 164 and 165 local topography and watershed subdivisions. Areas indicated in bold print (ha). Lake 164 total watershed area (including lake surface area): 4948 ha. Lake 165: 4802 ha. Note that Lake 164 outflow weir measures outflow from 77 ha of drainage downstream of Lake 164 outlet. Broad black line indicates lake watershed boundaries; medium black line indicates sub-watershed boundaries. Base map is from Ontario Ministry of Natural Resources topographic map sheets originally at 1:20000 scale. 10 m contour interval.

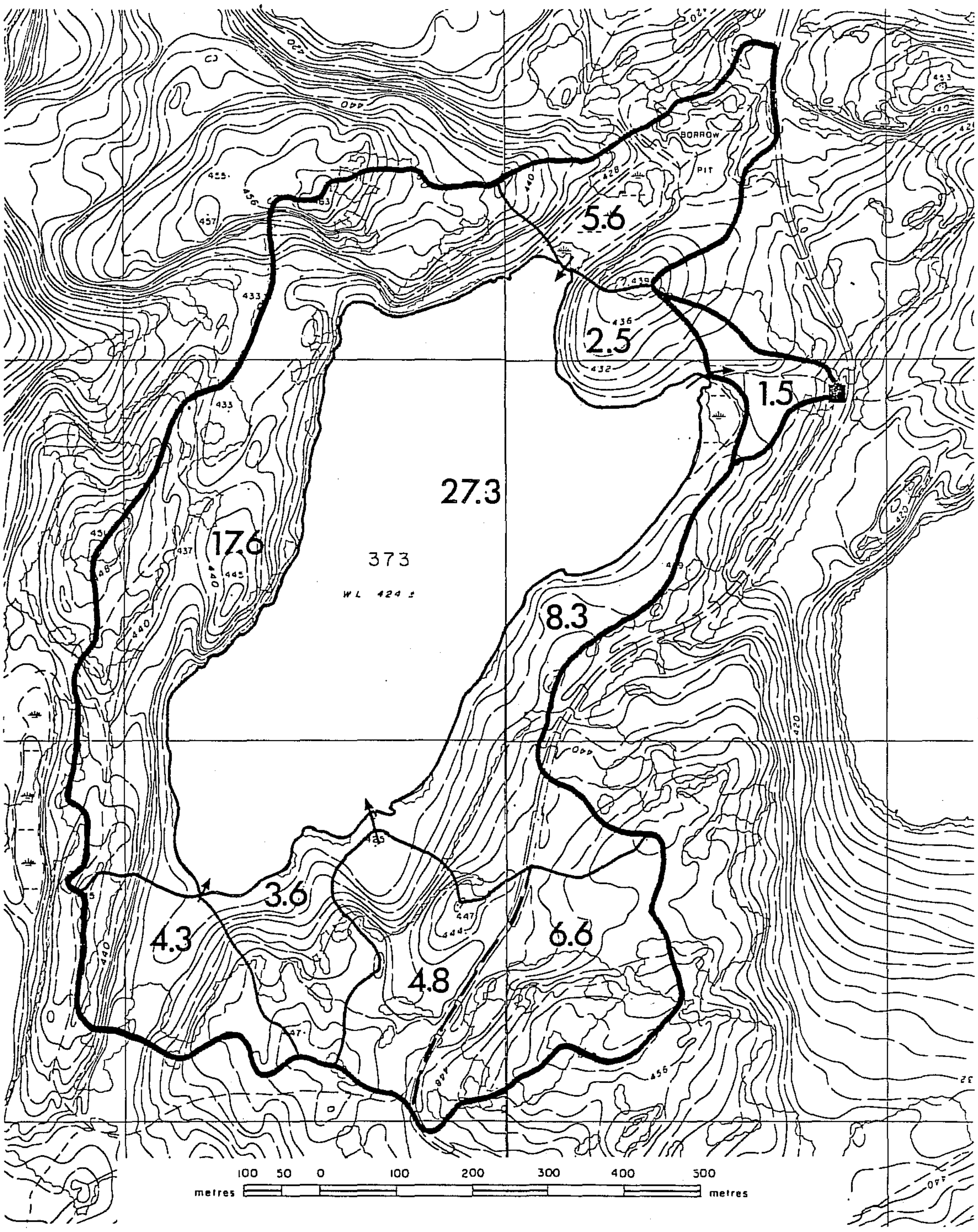


Figure 6. Lake 373 local topography and watershed subdivisions. Areas indicated in bold print (ha). Total watershed area (including lake surface area): 80.6 ha. Broad black line indicates main watershed boundary; medium black line indicates sub-watershed boundaries. Base topographic map has been reduced from 1:5000 scale. 4 m contour interval.

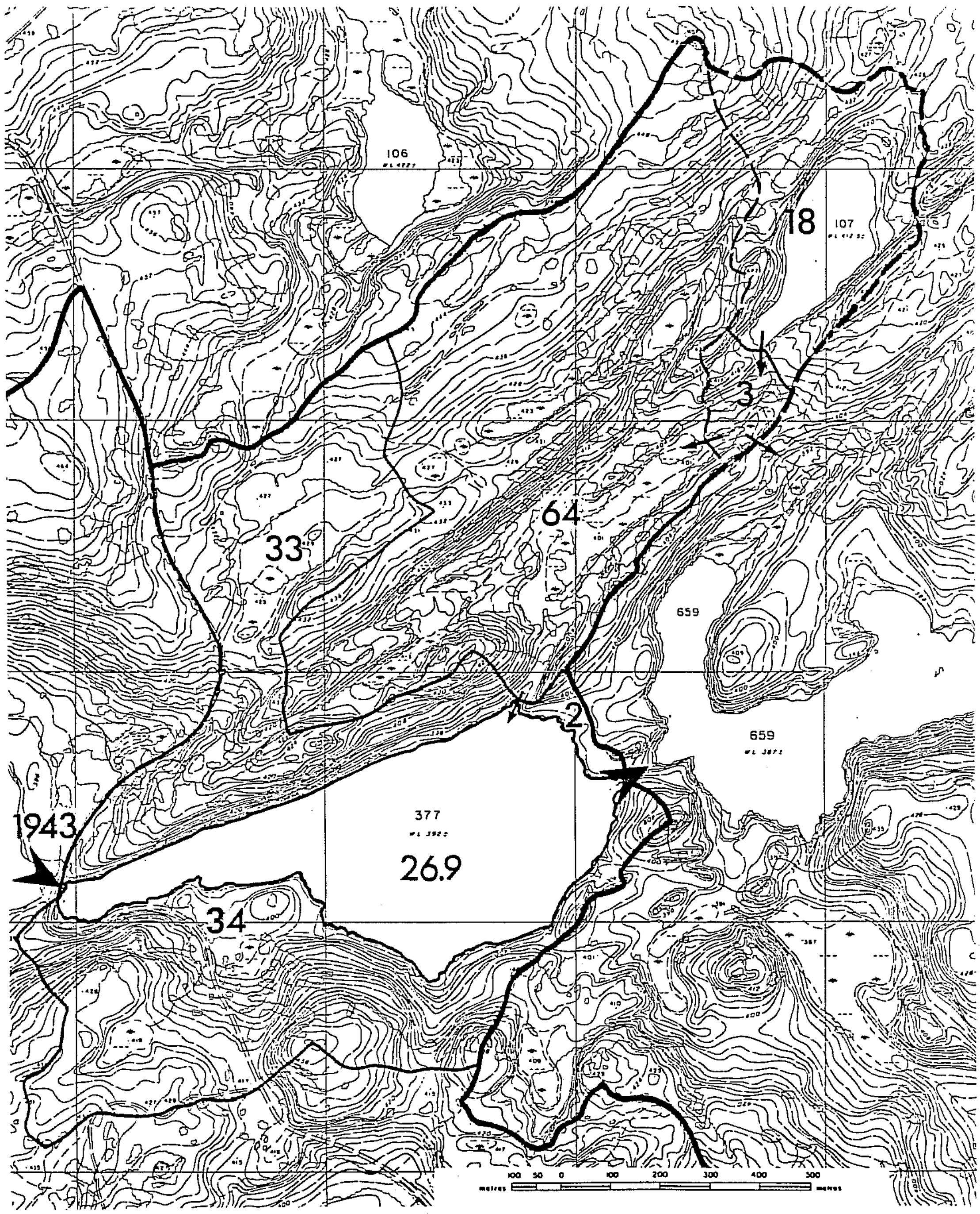


Figure 7. Lake 377 local topography and watershed subdivisions. Areas indicated in bold print (ha). Total watershed area (including lake surface area): 2123 ha. Broad black line indicates lake watershed boundaries; medium black line indicates sub-watershed boundaries. Base topographic map has been reduced from 1:5000 scale. 4 m contour interval.

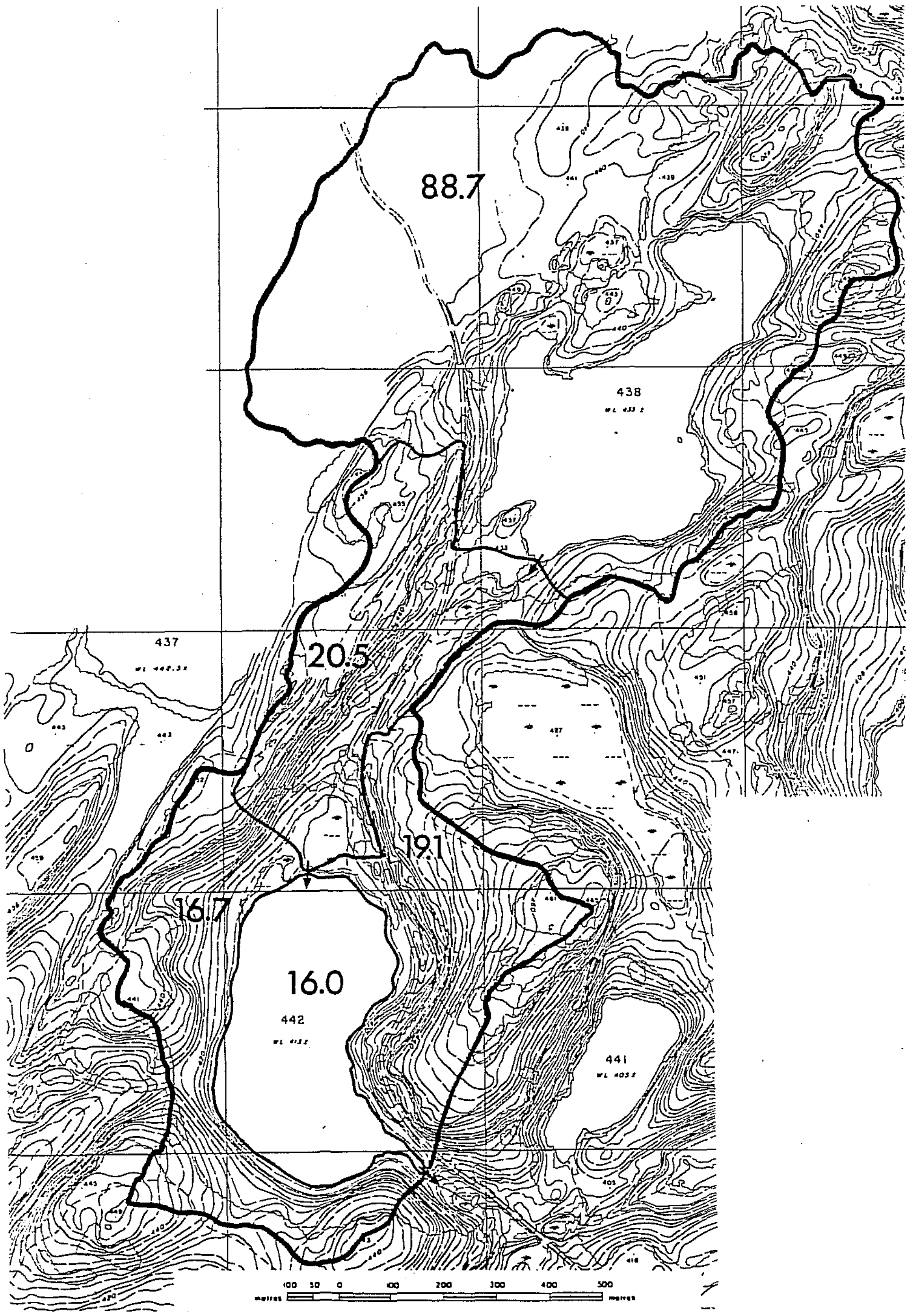
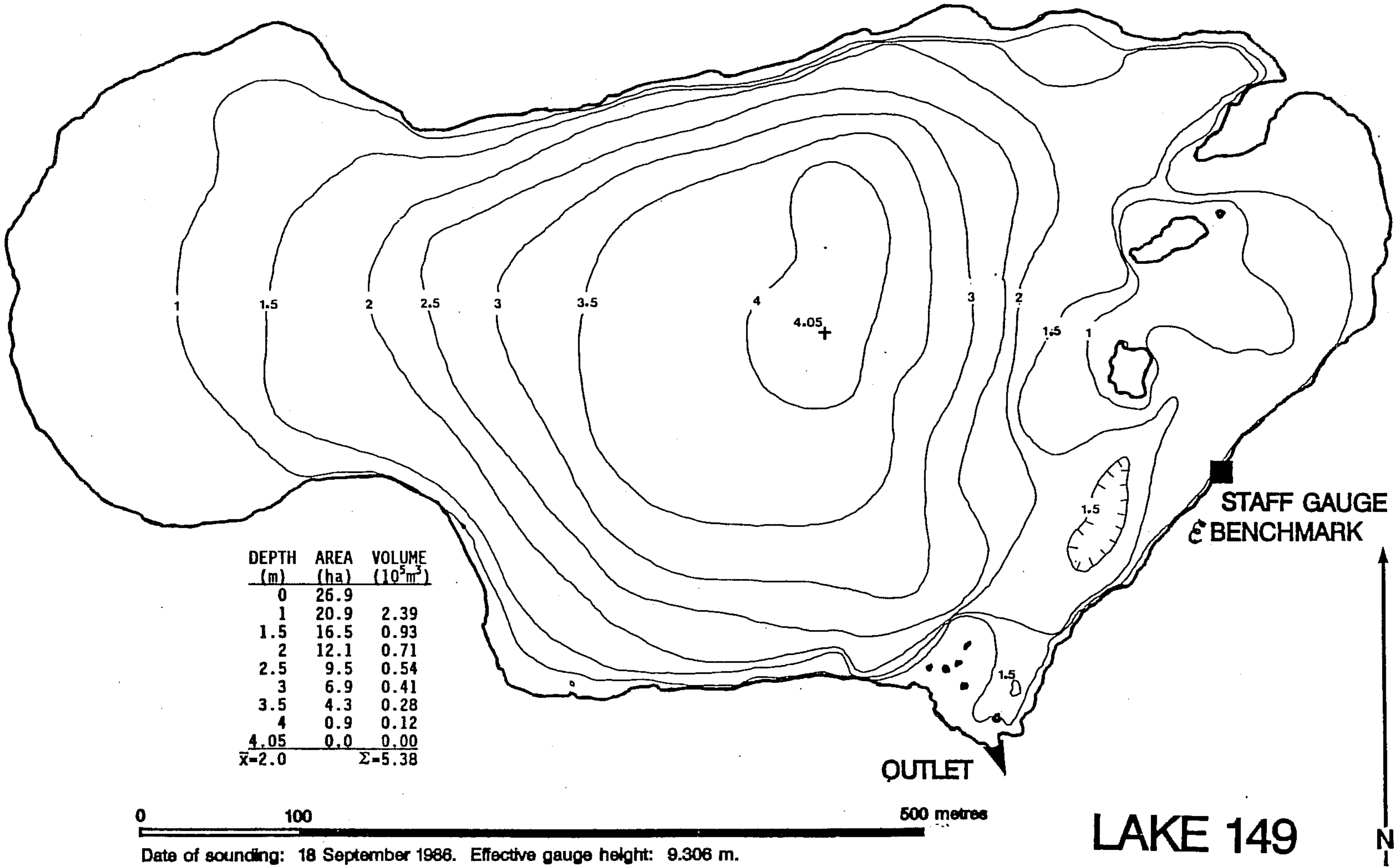


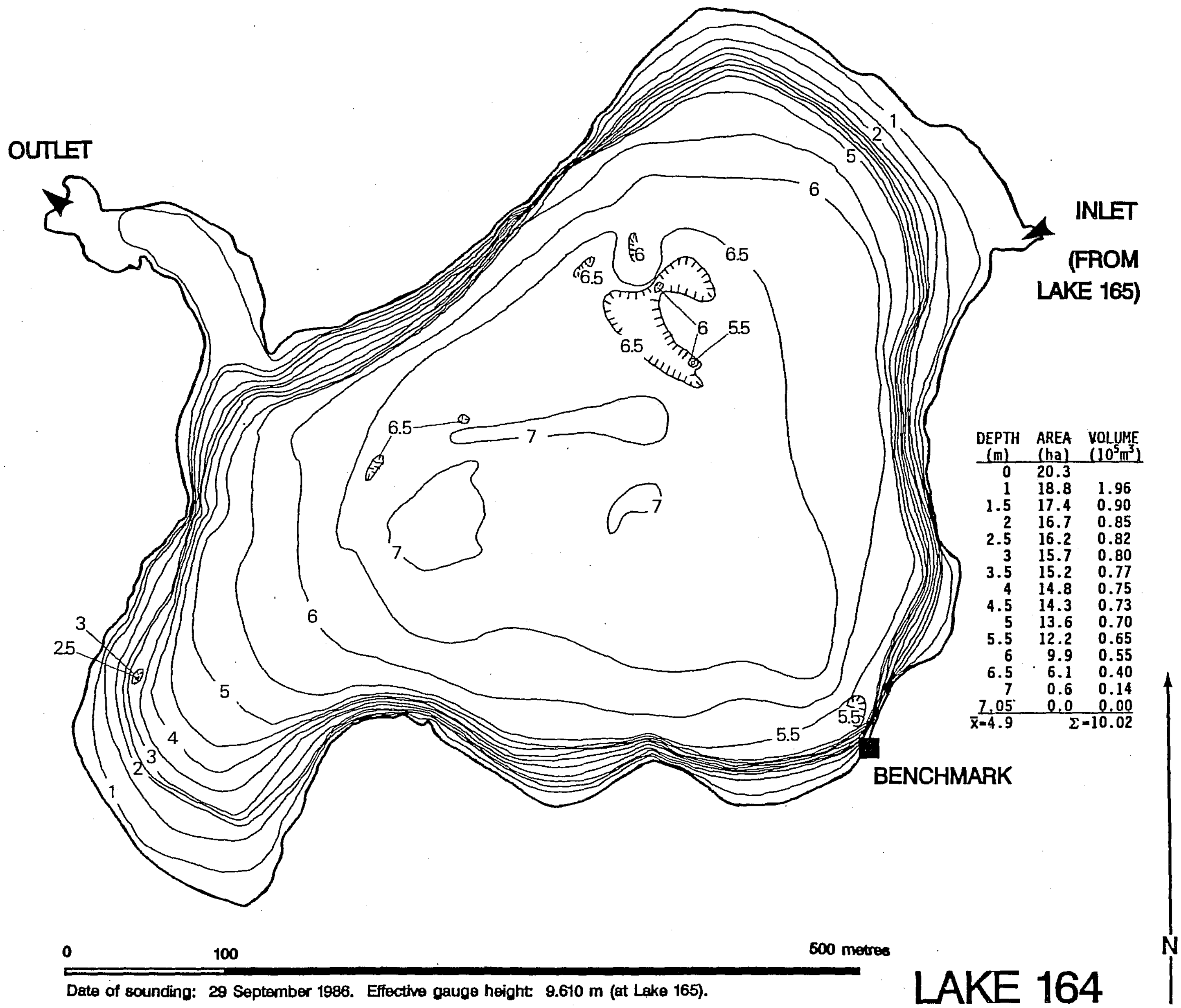
Figure 8. Lake 442 local topography and watershed subdivisions. Areas indicated in bold print (ha). Total watershed area (including lake surface area): 161.0 ha. Broad black line indicates main watershed boundary; medium black line indicates sub-watershed boundaries. Base topographic map has been reduced from 1:5000 scale. 4 m contour interval.



DEPTH (m)	AREA (ha)	VOLUME ($10^5 m^3$)
0	26.9	
1	20.9	2.39
1.5	16.5	0.93
2	12.1	0.71
2.5	9.5	0.54
3	6.9	0.41
3.5	4.3	0.28
4	0.9	0.12
4.05	0.0	0.00
$\bar{x}$=2.0		Σ=5.38

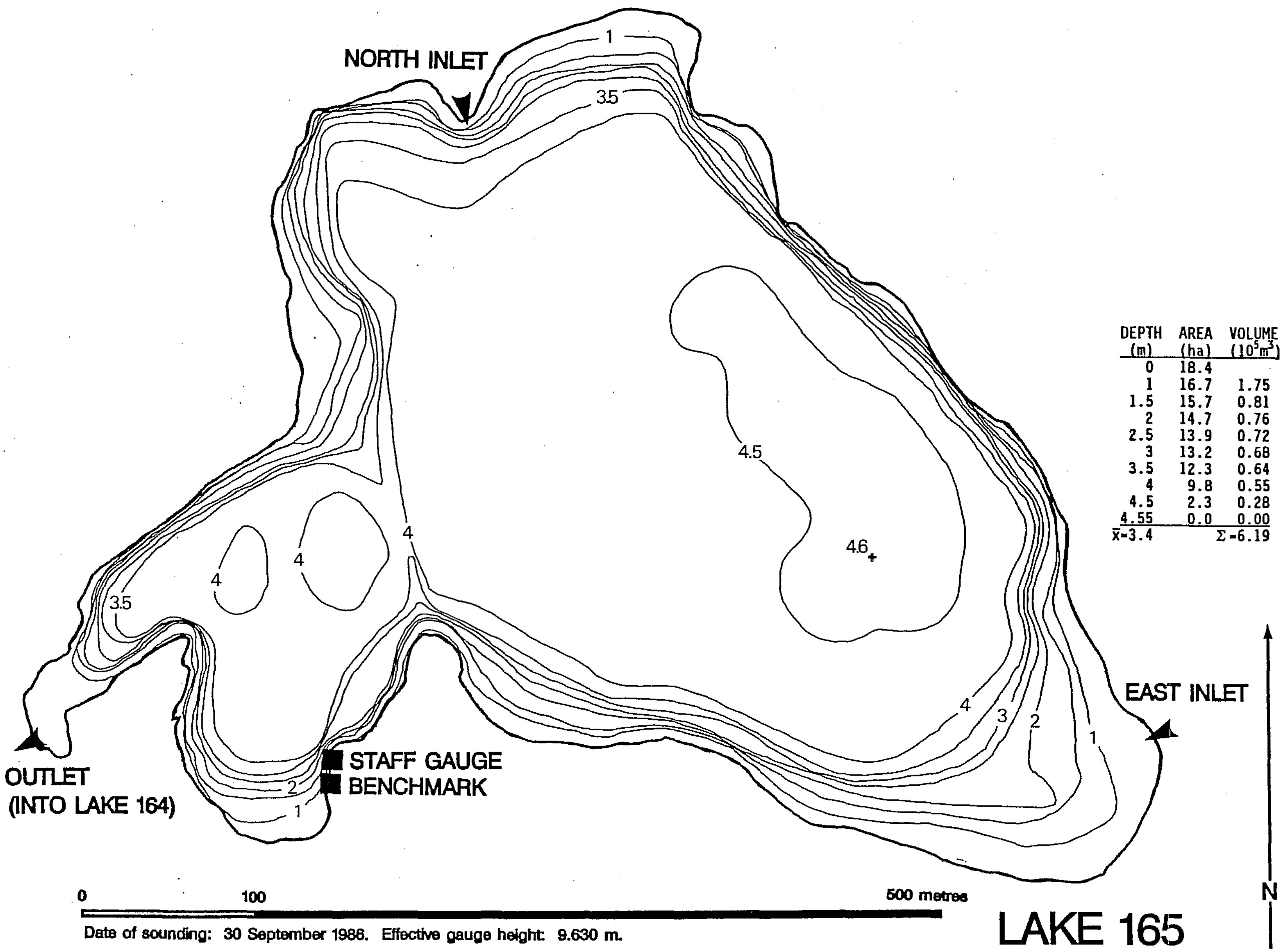
Figure 9. Lake 149 bathymetry.

Figure 10. Lake 164 bathymetry.



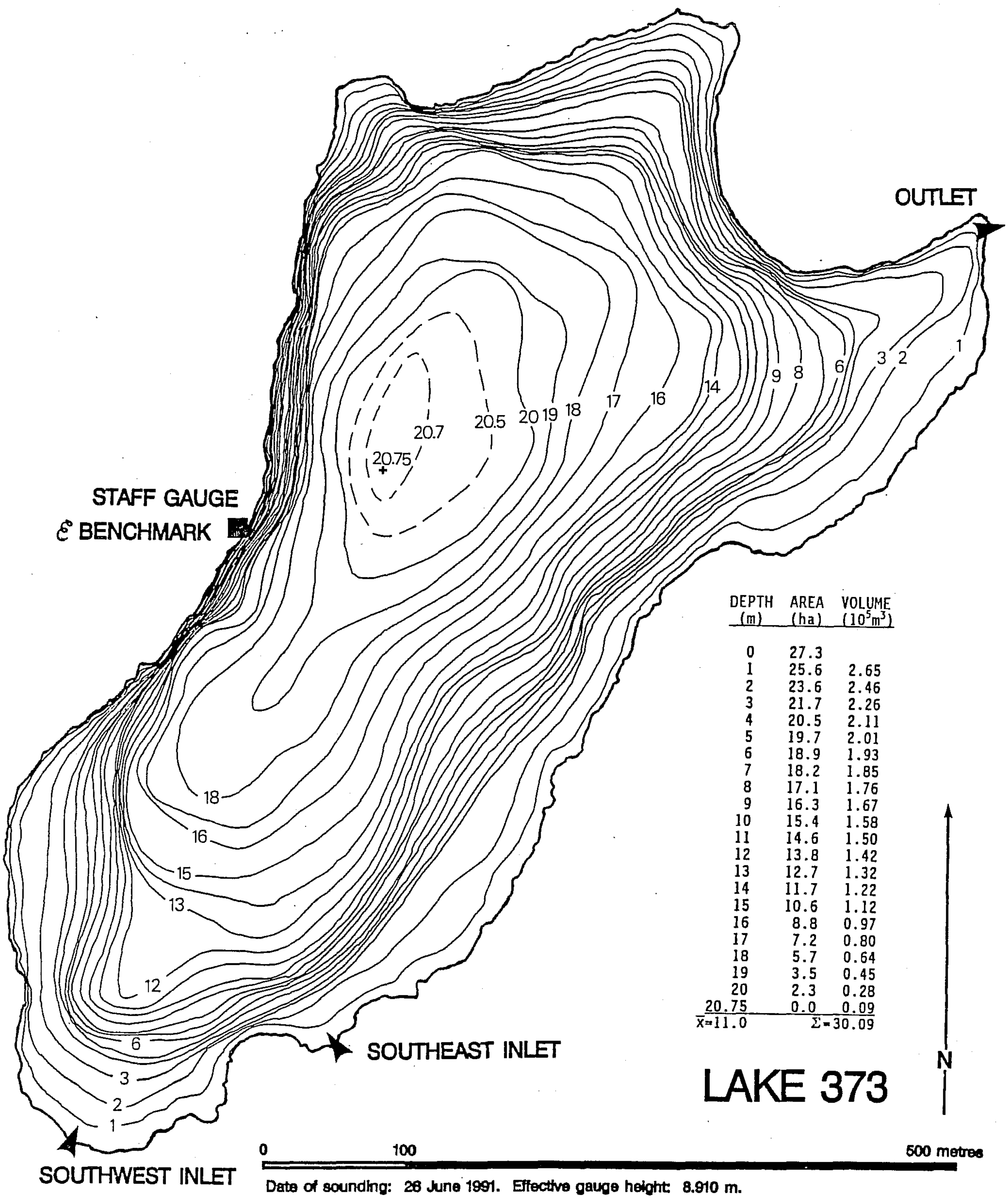
DEPTH (m)	AREA (ha)	VOLUME ($10^5 m^3$)
0	20.3	
1	18.8	1.96
1.5	17.4	0.90
2	16.7	0.85
2.5	16.2	0.82
3	15.7	0.80
3.5	15.2	0.77
4	14.8	0.75
4.5	14.3	0.73
5	13.6	0.70
5.5	12.2	0.65
6	9.9	0.55
6.5	6.1	0.40
7	0.6	0.14
7.05	0.0	0.00
$\bar{x}$=4.9		Σ=10.02

Date of sounding: 29 September 1986. Effective gauge height: 9.610 m (at Lake 165).



DEPTH (m)	AREA (ha)	VOLUME ($10^5 m^3$)
0	18.4	
1	16.7	1.75
1.5	15.7	0.81
2	14.7	0.76
2.5	13.9	0.72
3	13.2	0.68
3.5	12.3	0.64
4	9.8	0.55
4.5	2.3	0.28
4.55	0.0	0.00
$\bar{x}$=3.4		Σ=6.19

Figure 11. Lake 165 bathymetry.



DEPTH (m)	AREA (ha)	VOLUME ($10^5 m^3$)
0	27.3	
1	25.6	2.65
2	23.6	2.46
3	21.7	2.26
4	20.5	2.11
5	19.7	2.01
6	18.9	1.93
7	18.2	1.85
8	17.1	1.76
9	16.3	1.67
10	15.4	1.58
11	14.6	1.50
12	13.8	1.42
13	12.7	1.32
14	11.7	1.22
15	10.6	1.12
16	8.8	0.97
17	7.2	0.80
18	5.7	0.64
19	3.5	0.45
20	2.3	0.28
20.75	0.0	0.09
$\bar{x}$=11.0		Σ=30.09

Figure 12. Lake 373 bathymetry.

DEPTH (m)	AREA (ha)	VOLUME ($10^5 m^3$)
0	26.9	
1	25.2	2.61
2	23.6	2.44
3	22.5	2.30
4	21.3	2.19
5	19.6	2.05
6	17.8	1.87
7	16.3	1.71
8	15.2	1.57
9	14.1	1.47
10	13.1	1.36
11	11.7	1.24
12	10.2	1.09
13	8.1	0.91
14	6.2	0.71
15	4.7	0.54
16	3.2	0.39
17	0.9	0.19
17.9	0.0	0.02
$\bar{x}$=9.2		Σ=24.66

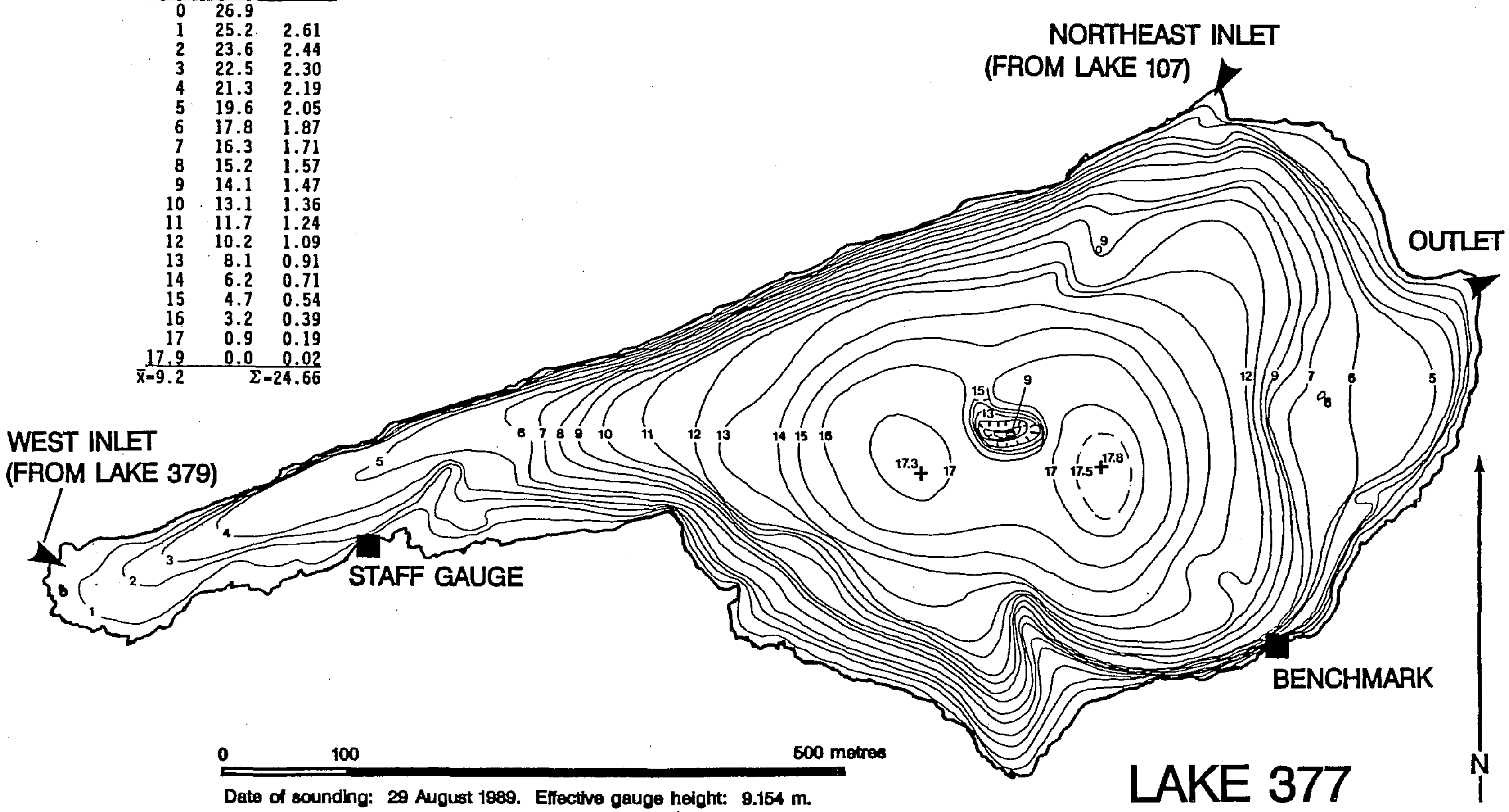
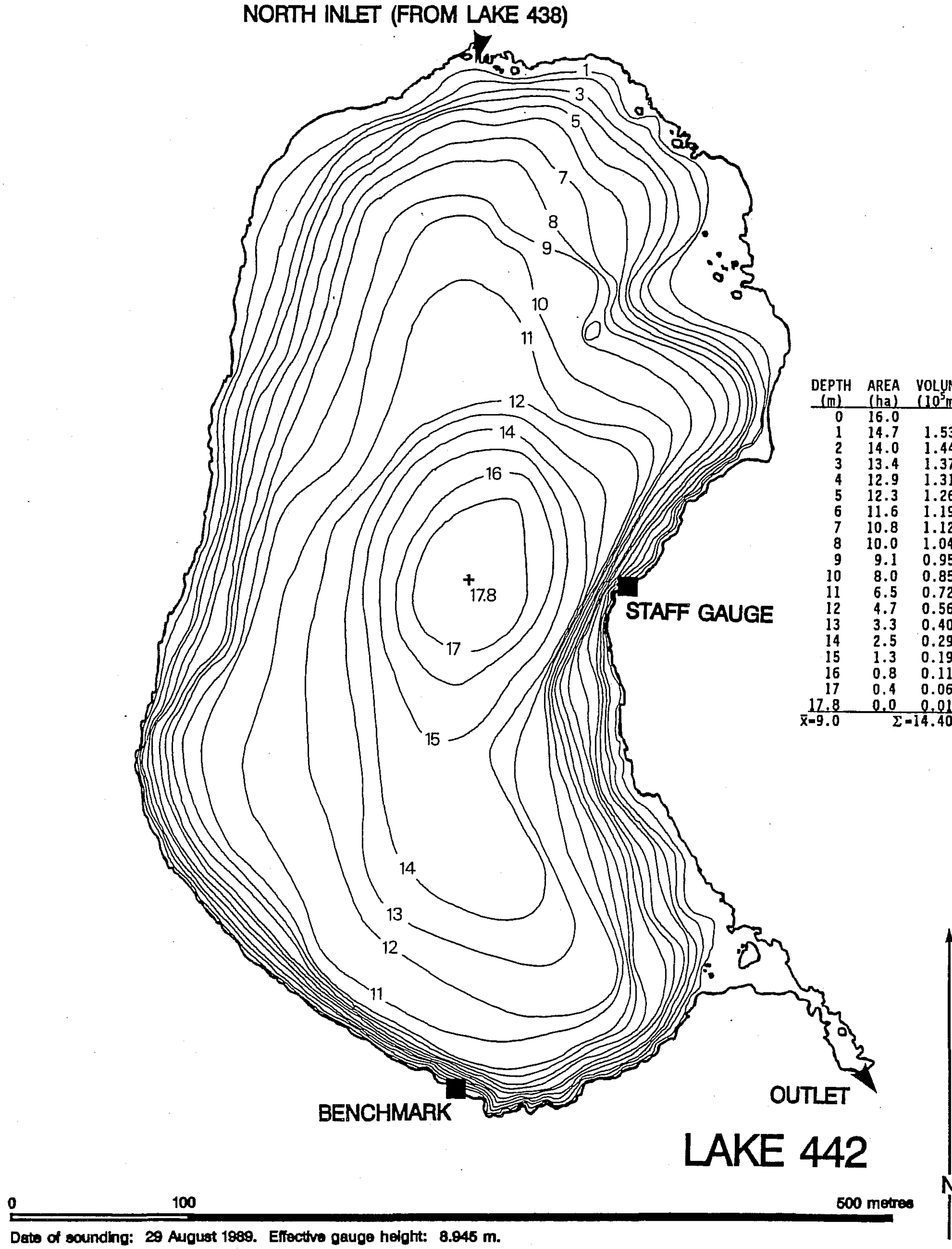
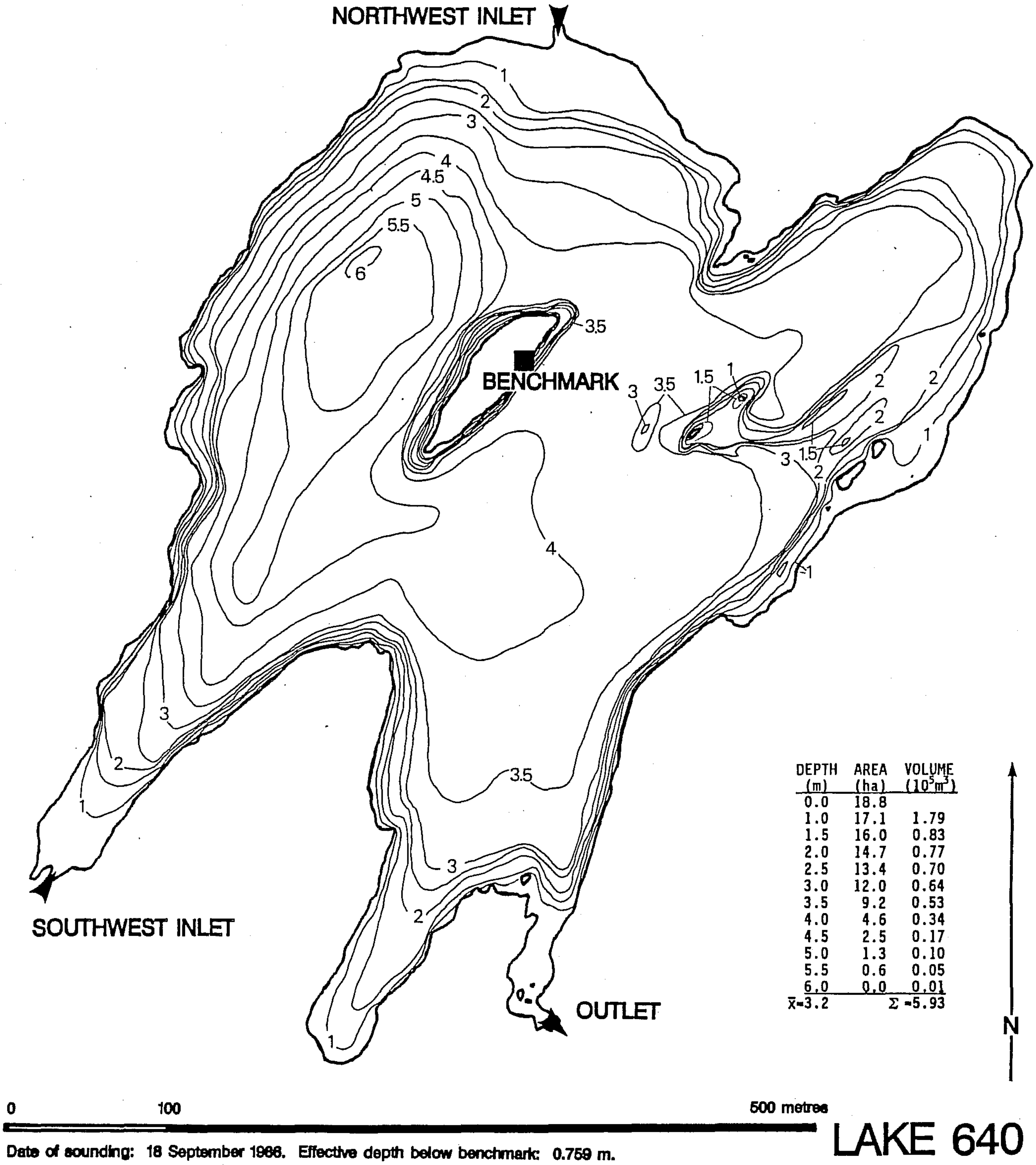


Figure 13. Lake 377 bathymetry.



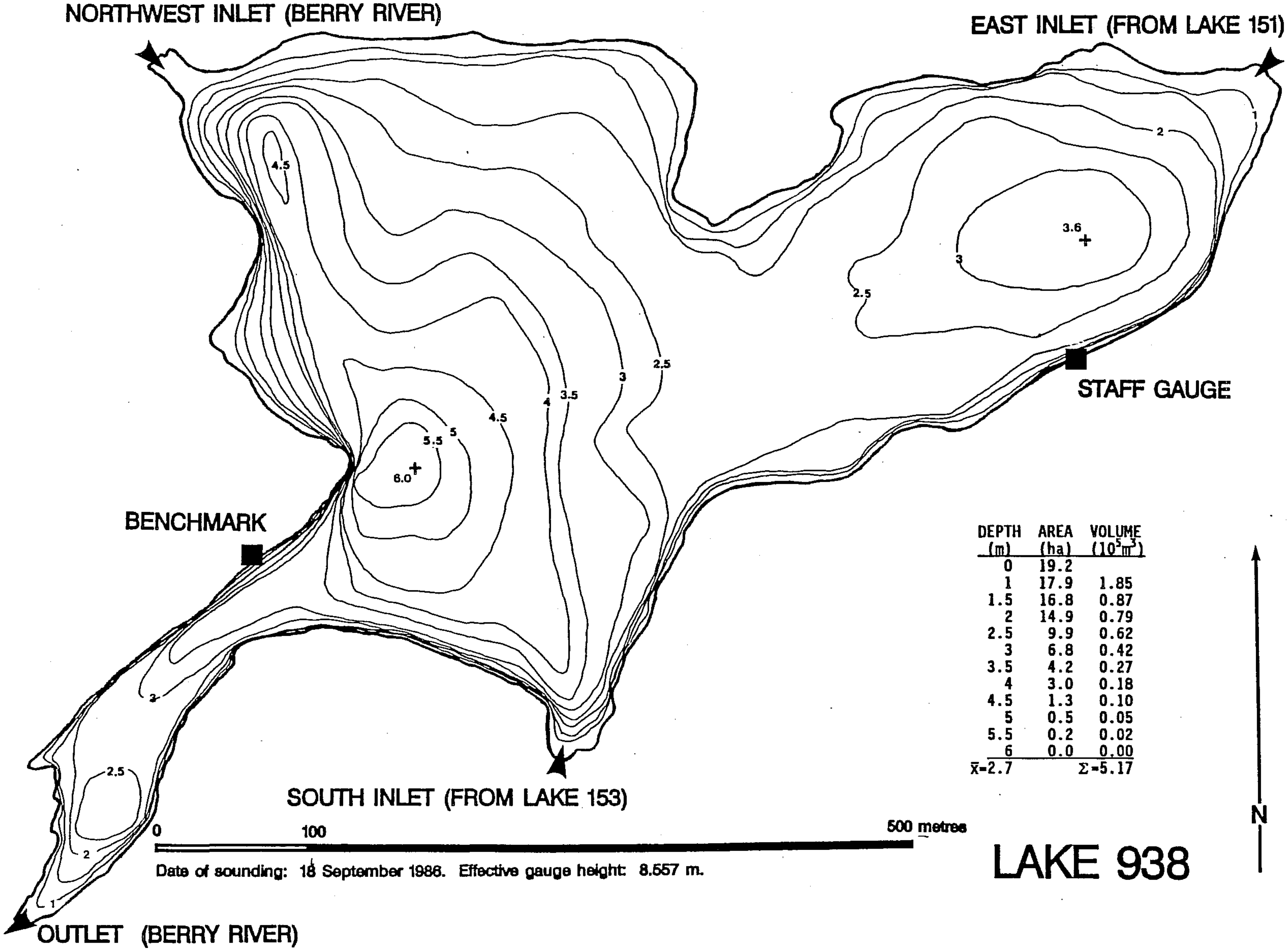
DEPTH (m)	AREA (ha)	VOLUME ($10^5 m^3$)
0	16.0	
1	14.7	1.53
2	14.0	1.44
3	13.4	1.37
4	12.9	1.31
5	12.3	1.26
6	11.6	1.19
7	10.8	1.12
8	10.0	1.04
9	9.1	0.95
10	8.0	0.85
11	6.5	0.72
12	4.7	0.56
13	3.3	0.40
14	2.5	0.29
15	1.3	0.19
16	0.8	0.11
17	0.4	0.06
17.8	0.0	0.01
$\bar{x}$=9.0		Σ=14.40

Figure 14. Lake 442 bathymetry.



DEPTH (m)	AREA (ha)	VOLUME ($10^5 m^3$)
0.0	18.8	
1.0	17.1	1.79
1.5	16.0	0.83
2.0	14.7	0.77
2.5	13.4	0.70
3.0	12.0	0.64
3.5	9.2	0.53
4.0	4.6	0.34
4.5	2.5	0.17
5.0	1.3	0.10
5.5	0.6	0.05
6.0	0.0	0.01
$\bar{x}$=3.2		Σ =5.93

Figure 15. Lake 640 bathymetry.



DEPTH (m)	AREA (ha)	VOLUME ($10^5 m^3$)
0	19.2	
1	17.9	1.85
1.5	16.8	0.87
2	14.9	0.79
2.5	9.9	0.62
3	6.8	0.42
3.5	4.2	0.27
4	3.0	0.18
4.5	1.3	0.10
5	0.5	0.05
5.5	0.2	0.02
6	0.0	0.00
$\bar{x}$=2.7		Σ=5.17

Figure 16. Lake 938 bathymetry.

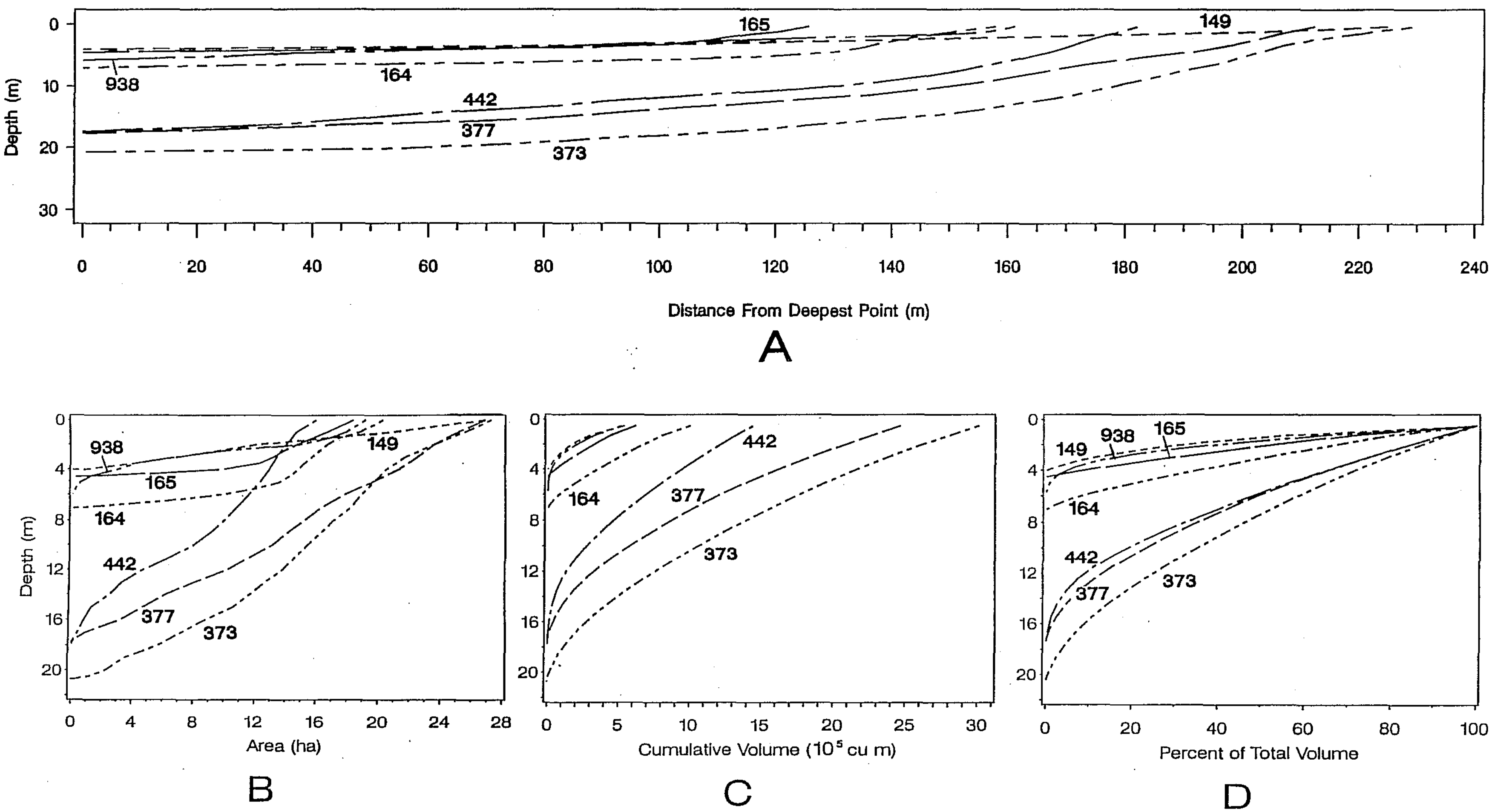


Figure 17. Hypsographic curves. A: Cumulative virtual distance between isobaths vs depth, where the distance is calculated by the equation:

$$x_{m,n}=\frac{A_n-A_m}{(L_m+L_n)/2}$$

where m,n = bounding depths, x = distance between isobaths m and n, A = area at given depth, and L = length of given isobath. Plotted without vertical exaggeration to illustrate mean bottom slopes. B: Area vs depth. C: Cumulative volume vs depth. D: Percent of total volume vs depth.