THE PHYSICAL LIMNOLOGY OF THE MAINSTEM LAKES IN THE OKANAGAN BASIN, BRITISH COLUMBIA

(Vol. I: Results)

by

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A report submitted to the Study Director of the Canada - British Columbia Okanagan Basin Agreement in partial fulfillment of the requirements under Tasks 117, 118 and 124.

from

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1972

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ACKNOWLEDGEMENTS

We express our appreciation to Messrs. Mike Mawhinney and Don Williams for their untiring efforts in organizing and executing the monitor cruise program. Our thanks also go to Mr. John Gilbert for programming assistance and to Mrs. Marion Phillips for reducing much of the thermal data. The computer program for calculating heat content was written by Miss Betty Pyde whom we gratefully acknowledge.

ABSTRACT

The mainstem lakes of the Okanagan Basin were investigated to determine their thermal and light transmission characteristics. Detailed studies based on six monitor surveys in 1971 were made on Lakes Wood, Kalamalka, Okanagan, Skaha and Osoyoos. Data in considerably less detail was obtained for Lake Vaseux.

Maximum observed summer heat incomes were

Wood	18100	gm cal/cm^2
Kalamalka	25100	
Okanagan	33300	
Skaha	22200	
Osoyoos (North Basin Only)	21900	

Hypolimnetic warming rates ranged from 0.06°C/month in Lake Okanagan to 0.54°C/month in the northern basin of Osoyoos.

Light transparency data showed that Lake Kalamalka was the clearest while Lake Wood was the most turbid. There is no evidence that 1971 transparencies have decreased in Lakes Okanagan, Wood and Kalamalka over those of previous years.

INTRODUCTION

This report represents the findings and interpretations of the physical limnological aspects of Tasks 117, 118, and 124. Extensive synthesis of temperature and light data were performed in order to estimate the principal physical characteristics of the mainstem lakes. These characteristics include the thermal regime and its seasonal changes. The light transmission regime was determined from secchi depth data supplemented by extinction coefficients estimated from irradiance versus depth data.

The physical limnological data were obtained as a part of the limnological monitoring program (Williams, 1972). These data were used almost exclusively for synthesis, but we also have drawn on past data where these have proven useful.

This report focuses its attentions on the five main lakes of the Okanagan drainage basin: Wood, Kalamalka, Okanagan, Skaha and Osoyoos (Figure 1). Operational restraints prevented our assessment of Vaseux in the same detail as the five main lakes. Our principal objective is to describe the similarities and differences of the lakes. All data obtained for the physical limnological study are tabulated in the Appendix.

FIELD PROCEDURES AND ANALYTICAL METHODS

Field Procedures

The monitoring of the mainstem lakes in 1971 was carried out under the field plan described by Williams (1972). The density of coverage for determining the temperature structure varied from 4 stations for Wood Lake to 19 stations for Lake Okanagan (Figure 1). Secchi disc visibilities were also determined at each station. Each lake was monitored six*times in 1971 according to the plan in Figure 1. With minor modifications, the same plan was executed for September, 1970 (Blanton and Ng, 1971).

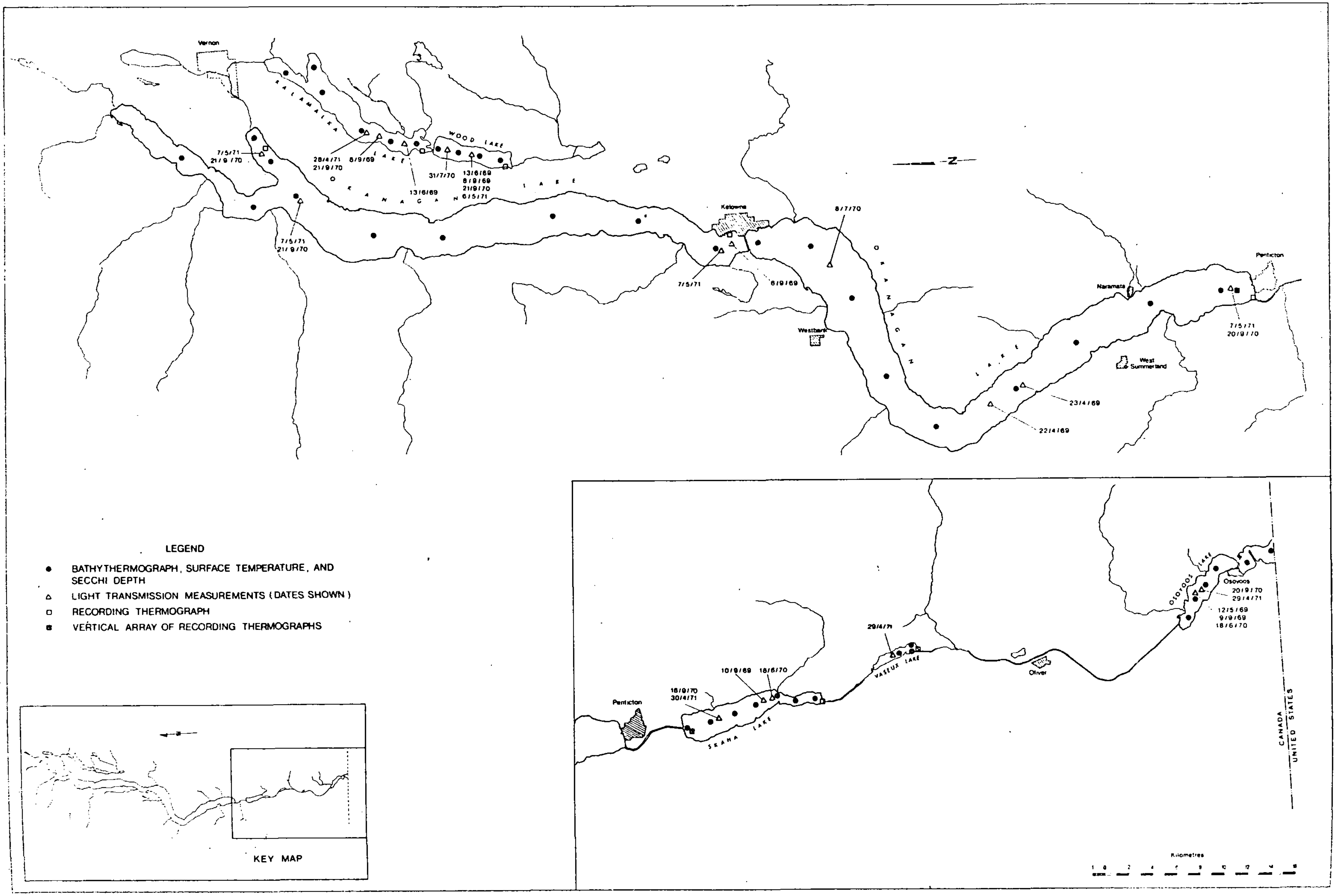
Temperature data were obtained with bathythermographs (BT) manufactured by Wallace and Tierman, Inc. These instruments may be read with temperature accuracies ± 0.5°C and depth accuracies of ± 1% of the depth scale. For the 200 meter BT used in Lake Okanagan, depth is known within ± 2m.

To supplement the monitor cruise data, recording thermographs were placed in each lake (see Figure 1). The thermographs were supplied by Ryan Instruments Incorporated, Seattle, Washington with 15-day continuous charts and a 0° - 30°C range. Accuracies are about + 1°C and from ± 1 to ± 3 hours in 15 days depending upon the individual instrument.

During September, 1970 and May, 1971, light transmission data were made on all five lakes with submarine photometers. The 1970 set of data were reported by Blanton and Ng (1971). They used a Model C-10 irradiance and depth meter manufactured by Marine Advisors, Inc., La Jolla, California. A set of three Kodak Wratten filters (Red #29, Green #58, Blue #47) were used with maximum transmission at wave lengths of 630 millimicrons, 530 millimicrons, and 450 millimicrons respectively. The optical characteristics of these filters are almost identical to those recommended by Vollenweider (1969).

* five times in Kalamalka

Figure 1. Location map showing positions where physical limnological data were obtained.



In May 1971, transmission data were made with a submarine photometer, Kahl Scientific Instruments Model Number 268WA310, New York, N.Y. This instrument was loaned to us by Mr. Fred Alcock, South Okanagan Health Unit, Kelowna, B.C. who kindly assisted in obtaining the measurements. Mr. Alcock has also shared his previous transmission measurements with us, and the data are included in this report.

Analytical Methods

The heat content of a lake above 4°C is that quantity of heat necessary to raise the lake from an isothermal 4°C up to the temperature distribution observed at the time of sampling. The highest heat content (in excess of the heat content when the entire lake is at 4°C) during a season has been called "summer heat income" by Hutchinson (1957). The exactness at which one knows the summer heat income depends, among other factors, on whether one sampled the lake at the time of highest heat content.

In order to calculate the heat content for a given monitor cruise and synthesize the large quantity of bathythermograph data, we used a Fortran IV program to calculate (1) the average values of the temperature in the hypolimnion, mesolimnion and epilimnion, (2) the volumes of the three thermal layers and (3) the heat contents of the three layers. The three heat contents were summed to give the total for the lake.

The input data consisted of (1) cards punched in the format presently prescribed for digitized bathythermograph data at CCIW and (2) digitized mean depths of a system of grid squares superimposed on each lake. The following table compares the digitized lake volumes with the actual volumes as determined from a hyposometric curve.

Lake	Grid Size (Km^2)	Volumes (Km^3) Digitized	Actual	Number of Stations Used
Wood	0.250	0.19	0.20	4
Kalamalka	0.109	1.53	1.52	6
Skaha	0.176	0.540	0.558	7
Osoyoos(N)*	0.088	0.190	0.204	4
Okanagan	_____	_____	26.20	19

Okanagan lake data were synthesized manually in a different manner because the long shoreline development of that lake would have forced us to break the lake into segments, thereby sacrificing most of the efficiency gained by using the Fortran IV program. The table also tabulates the number of stations included in the calculations that use bathythermograph data.

In order to calculate light transmission values using the submarine photometer, we plotted the percent attenuation of light versus depth on semi-log paper placing depth on the linear scale (Vollenweider, 1969). The extinction coefficient, (m^{-1}), can then be converted to transmission of light, T(%/m) by the formula

$$T = 100\ e^{-\alpha}$$

where α is the slope of the line connecting the percent attenuation versus depth points. During September, 1970, when Red, Green and Blue filters were used, T was calculated according to the formula

$$T = 1/3\ (T_{630} + T_{530} + T_{450})$$

where T_{630}, T_{530}, T_{450} are the transmission values in %/m for the Red, Green and Blue filters respectively. The wave lengths of maximum transmission have been corrected for instrument response.

*(See Table 1)

.......5/

SUMMARY OF PERTINENT METEOROLOGICAL AND MORPHOMETRICAL DATA

Annual air temperature cycle

Based on monthly mean air temperature in Penticton, 1971 was not a typical year (Fig. 2). When comparing actual 1971 means with the 30-year monthly mean from 1931 to 1960 we find that the late winter and early spring were colder than normal through mid April followed by a brief warm period. The entire month of June 1971 was unusually cool. July up to mid-August was much warmer than normal. As will be seen later the heating of the epilimnions of all the lakes reflect this pattern quite closely.

Wind regimes

The frequency of winds from different directions at the Penticton Airport (Fig. 3) show the effect of the local orientation of the Okanagan Valley. Except for June, July, August and September, the dominant winds are more or less equally distributed between the North and South octants. The highest speeds in winter are generally associated with winds from the South. As summer progresses, the frequency of south winds diminishes. In general, the Penticton winds for the 1971 cruises followed this pattern. The wind frequencies have been calculated for the periods between the six cruises (Fig. 4).

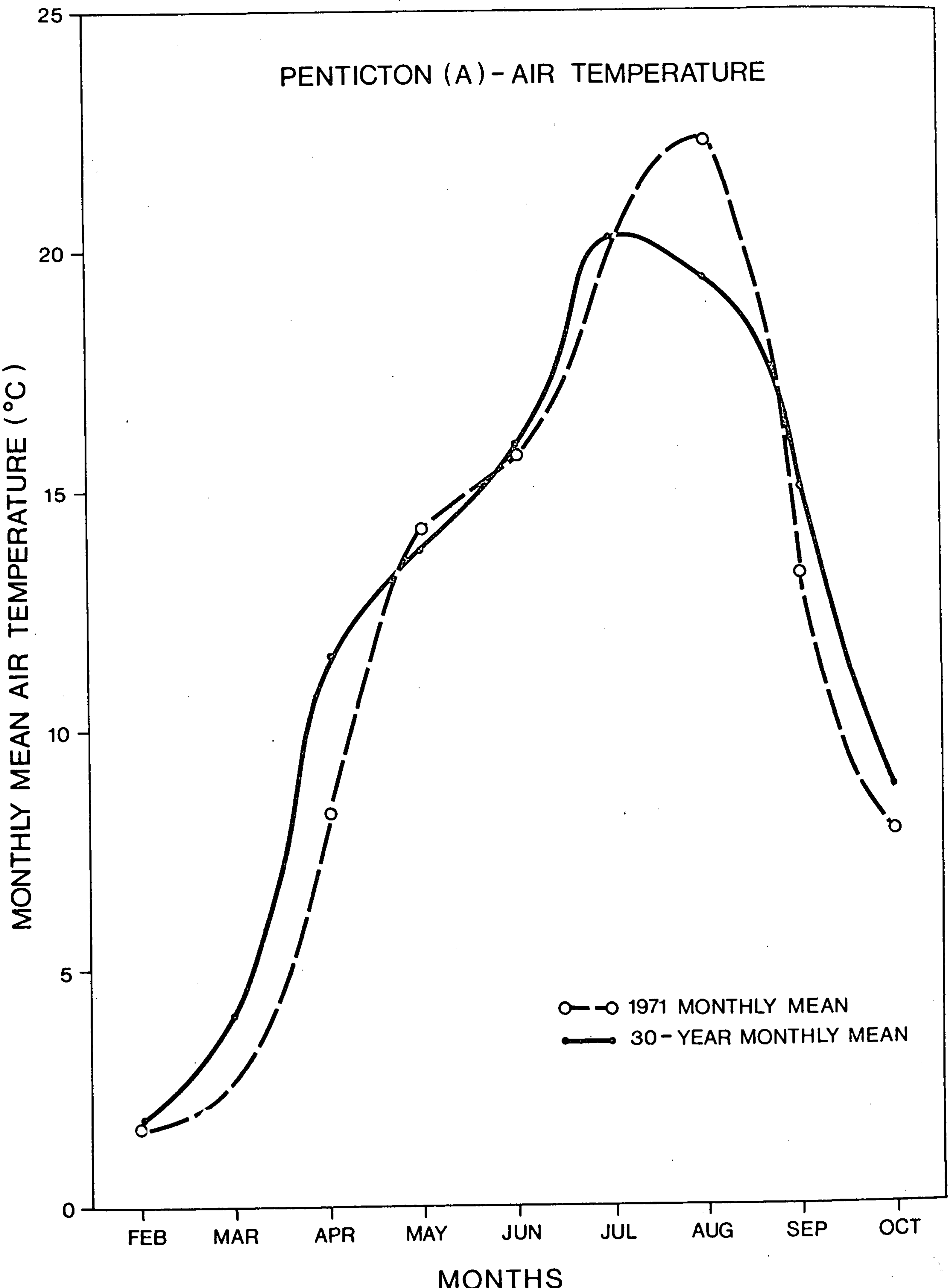


Figure 2. Monthly mean air temperatures at Penticton, B.C.

The wind data available is quite representative of Lake Skaha and the portion of Lake Okanagan between Penticton and Squally Point. For other regions, it is extremely risky to extrapolate the Penticton wind data although the general frequency pattern for direction discussed above is probably applicable.

In order to draw certain conclusions about the thermal structures of Lakes Wood and Kalamalka, it would have been extremely valuable to have detailed wind data at the Kelowna Airport. Wind measurements there were discontinued in June of 1971 for reasons unknown at this time (Canadian Meteorological Service, Toronto, personal communication).

Lake Morphometry

Table 1 summarizes major morphometrical parameters for six main-stem lakes. From the charts on which Table 1 was based, we have constructed hypsometric curves for each of the lakes (Fig. 5). The bathymetry of each of the lakes was re-determined by Dr. Brian St. John (St. John, 1972) and some substantial differences were noted for Lake Skaha. The dotted curve (Fig. 5d) represents the hypsometric curve for Skaha using the bathymetry obtained by St. John. No substantial differences were noted except in the mid-depth portions and these would not alter the heat contents sufficiently to warrant re-digitizing the lake. Since no substantial differences were apparent in the other lakes, we have used the older bathymetric data for all lakes when calculating physical parameters.

Figure 3. Monthly means of wind speed and direction at Penticton, B.C. Means are calculated for a 10-year period. Numbers adjacent to bars represent average speeds from that direction, metres/sec.

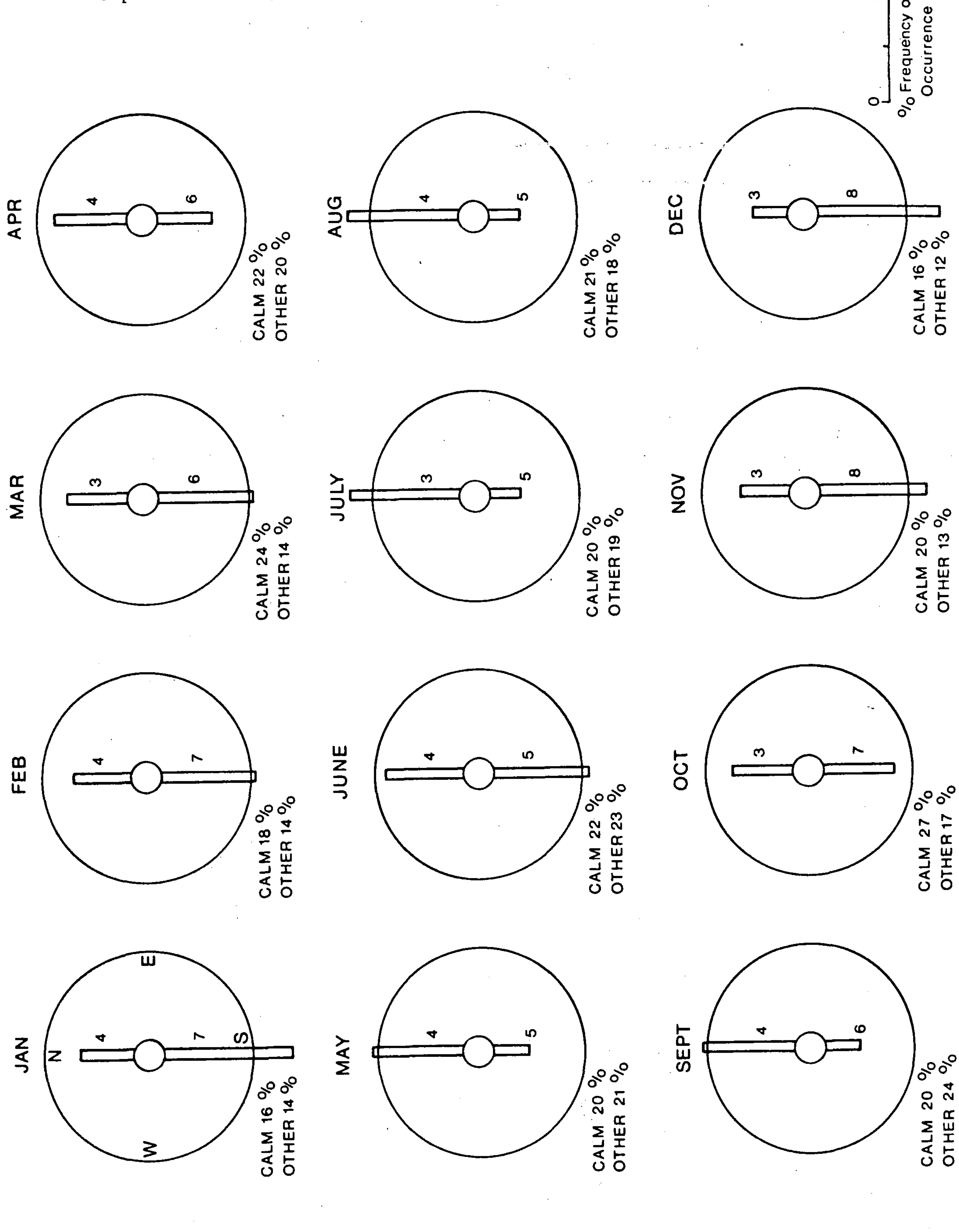


Figure 4. Actual frequency distribution of winds at Penticton during 1971. Distributions are calculated for each period between the monitor cruises. Numbers adjacent to bars represent average speeds from that direction, metres/sec.

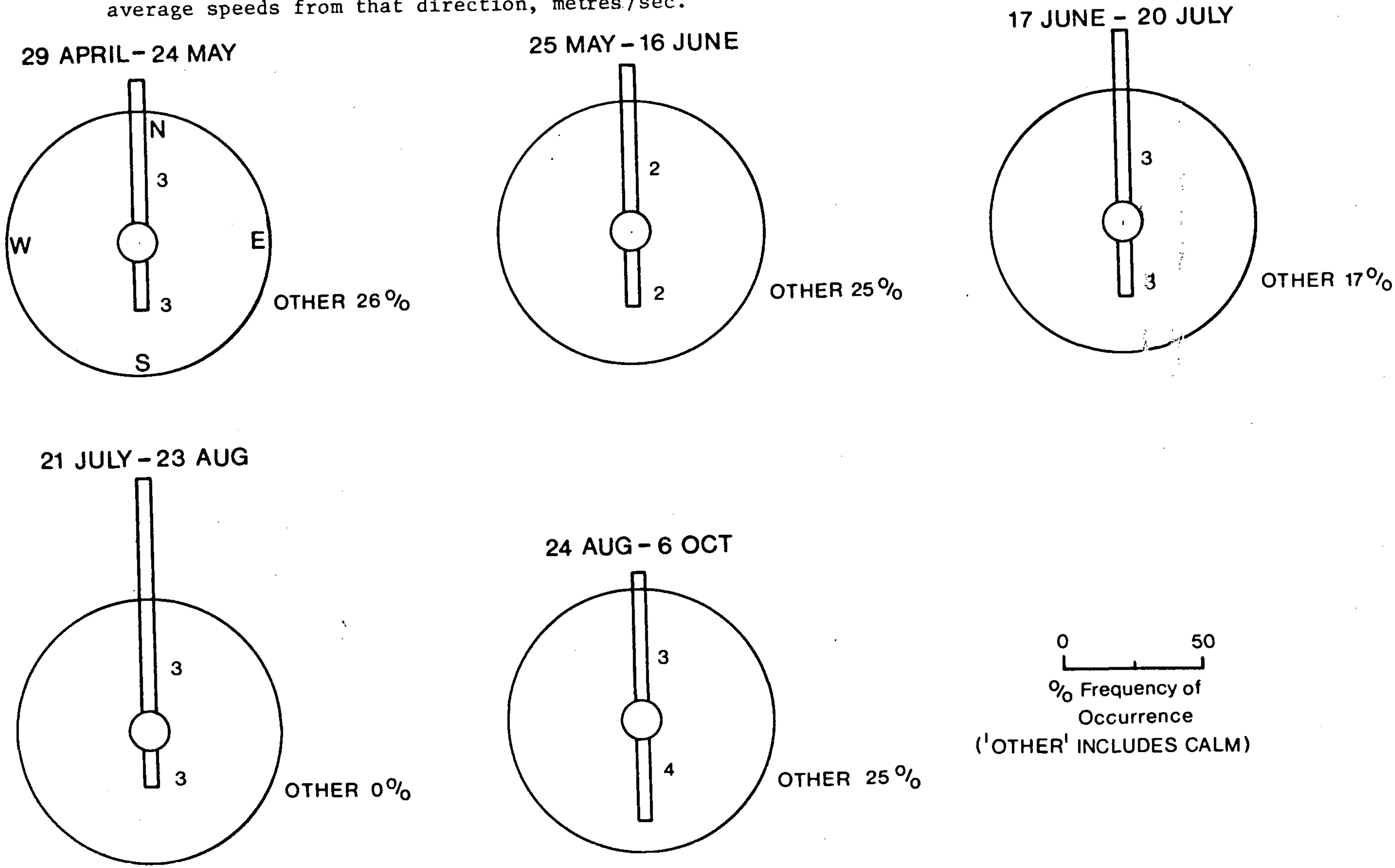


Table 1. Morphometry of the six mainstem lakes in the Okanagan Basin

Lake	Volume ($10^6 m^3$)	Surface Area ($10^6 m^2$)	Depths (m) mean	Depths (m) maximum	Maximum[4] Length (Km)	Maximum[4] Width (Km)	Perimeter[4] (Km)
Wood [2]	200	9.3	22	34	6.60	1.70	16.7
Kalamalka [2]	1520	25.9	59	142	16.0	2.30	42.4
Okanagan [2]	26200	348	76	242	112.8	5.22	270
Skaha [3]	558	20.1	26	57	11.90	2.40	29.5
Vaseux [2]	17.7	2.75	6.5	27	4.08	0.85	8.1
Osoyoos (N) [1,2]	204	9.91	21	63	7.55	1.75	20.4
Osoyoos (S) [1,2]	51.5	5.14	10	29	3.00	1.90	12.8

[1]Osoyoos (N) is the basin north of the highway bridge. Osoyoos (S) is the basin between the highway bridge and the U.S. border.

[2]Data compiled from charts of the Fish and Wildlife Branch, Department of Recreation and Conservation, B.C.

[3]Data compiled from a chart by A. M. Thomson, Study Director.

[4]These data were obtained from maps of the Canadian National Topographic System, 1960. Scale 1:126,720.

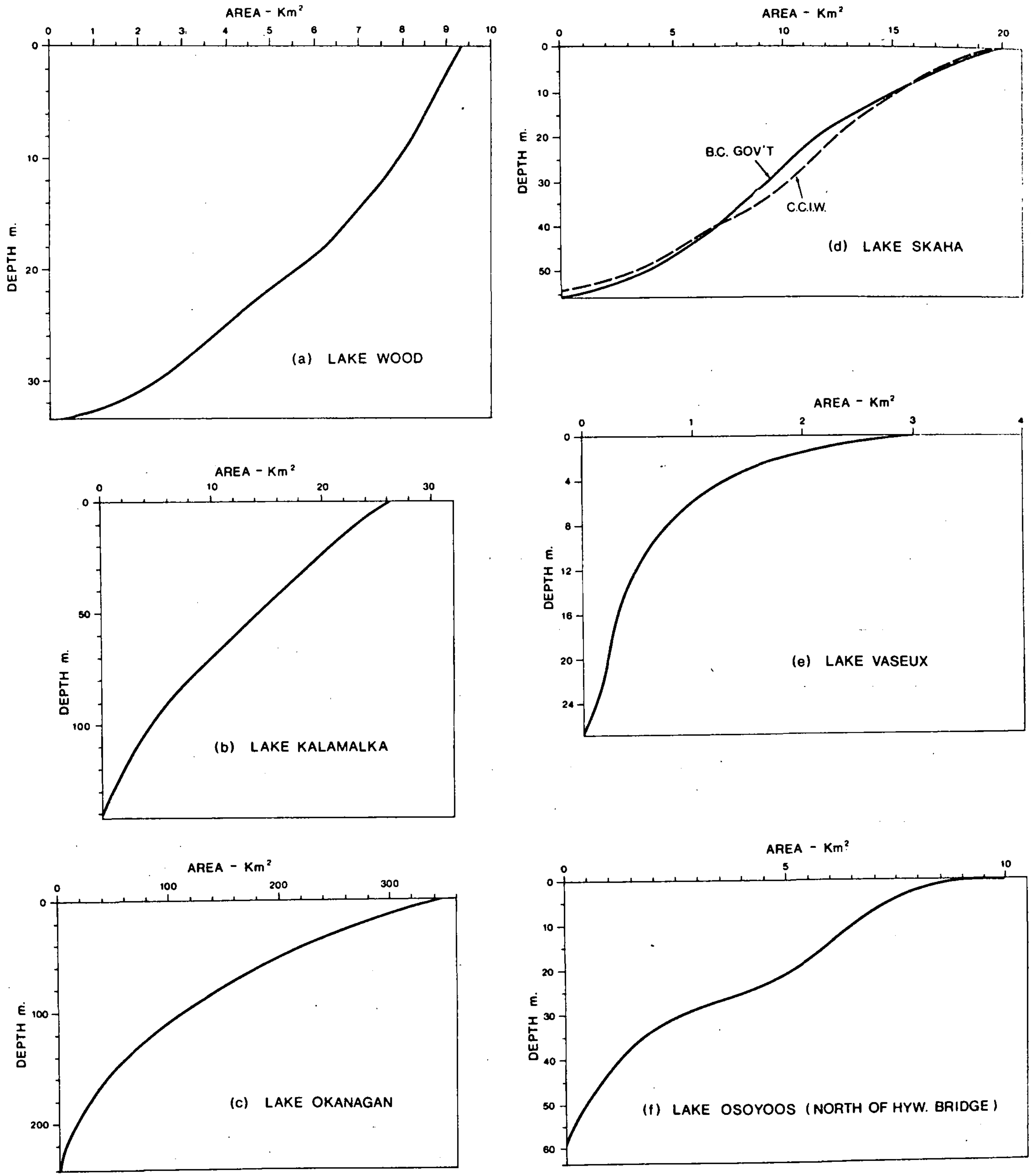


Figure 5. Hypsometric curves (area versus depth) for the six mainstem lakes based on data furnished by the Study office except as noted (5d).

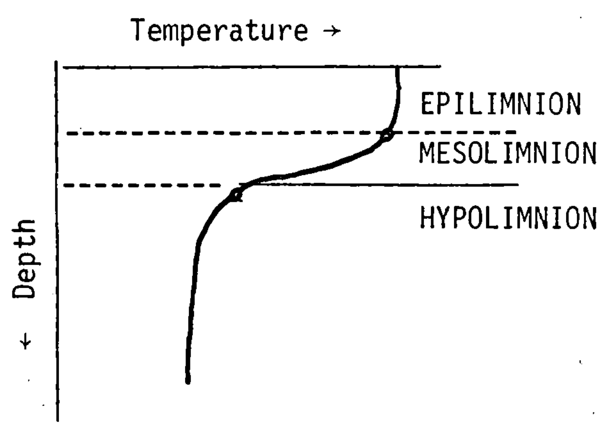
THERMAL STRUCTURE
OF THE MAINSTEM LAKES

Introduction

The bathythermograph (BT) data were analyzed by dividing the trace into three regions:

1. the epilimnion
2. the mesolimnion or thermocline region
3. the hypolimnion

These regions are defined by two points on the temperature vs. depth curve. The first point is located (by our definition) at the maximum change in vertical temperature gradient above the thermocline; the second point is found at the maximum change in gradient below the thermocline. Thermoclines present when the surface water was below 8°C were neglected,



and the temperature region was defined as all hypolimnion from surface to bottom. Only on the first cruise in April did all lakes lack an epilimnion or mesolimnion as defined here.

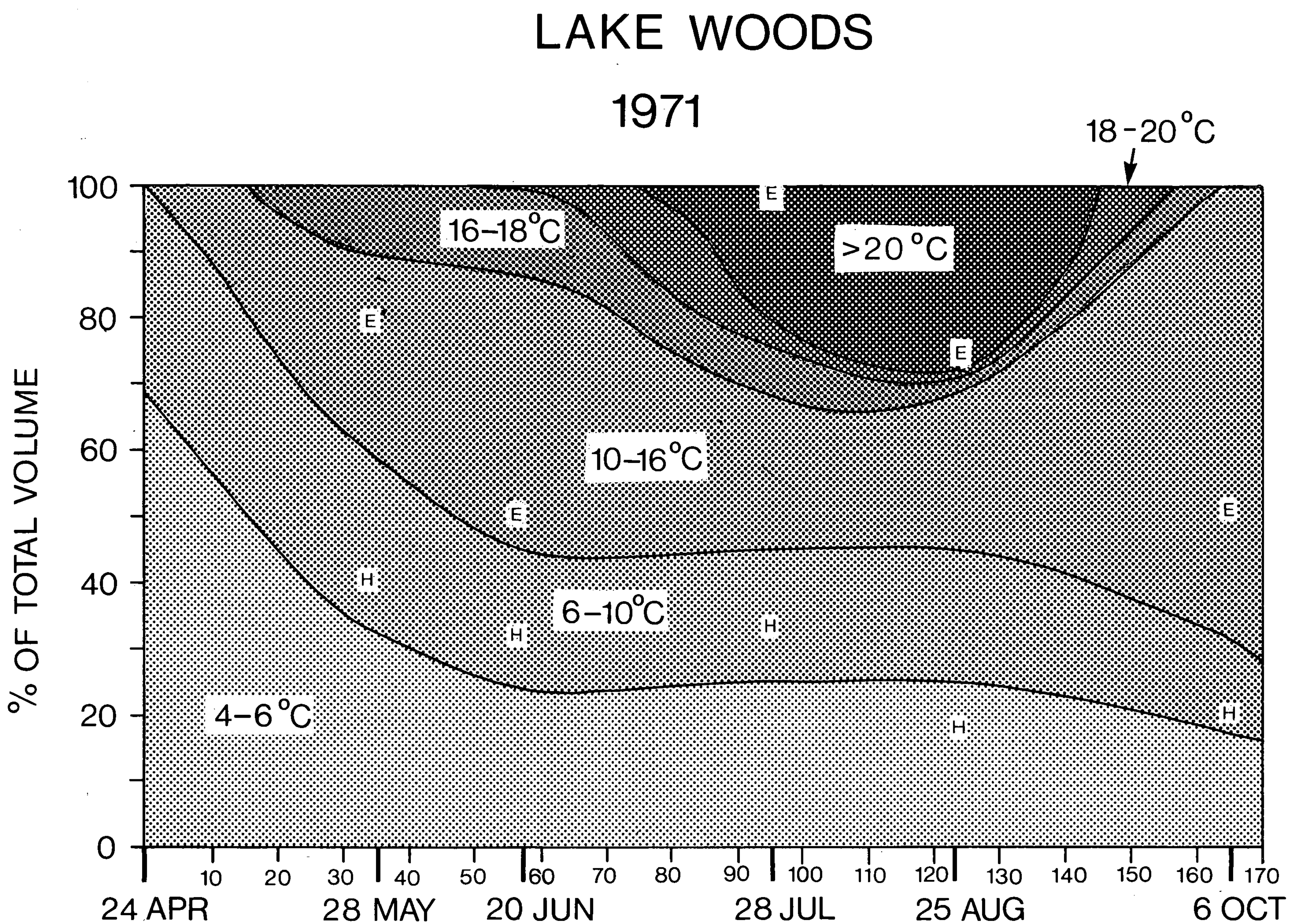
We have calculated the average temperature profile of each lake during each cruise by averaging the depths of isotherms from each of the bathythermograph traces. The depth averages have been weighted by an area of influence assigned to each station. From those average temperature profiles and from the hypsometric curves (Fig. 5), we have summarized the temporal changes in selected thermal layers for each of the lakes. Some idea of deviations from the average within each lake may be gained from plots of isotherms along the longitudinal axes of the lakes. Each lake will be discussed individually - in order of its downstream position.

Lake Wood (Figs. 6 and 7)

At the time of the first cruise, Wood Lake had no temperatures below 4°C. The heat in the lake increased rapidly with time, so that by the time of the fourth cruise, 20% of its volume* had temperatures above 20°C. The average temperature of the hypolimnion in Wood Lake was less than 6°C, so that the volume between 4-6°C may be taken as representative of the volume of the hypolimnion. Stratification was well underway at the time of the second cruise. While there was some evidence of a well-defined epilimnion at Cruise 3, the epilimnion had been virtually wiped out by strong heating at Cruise 4. The lake was strongly stratified

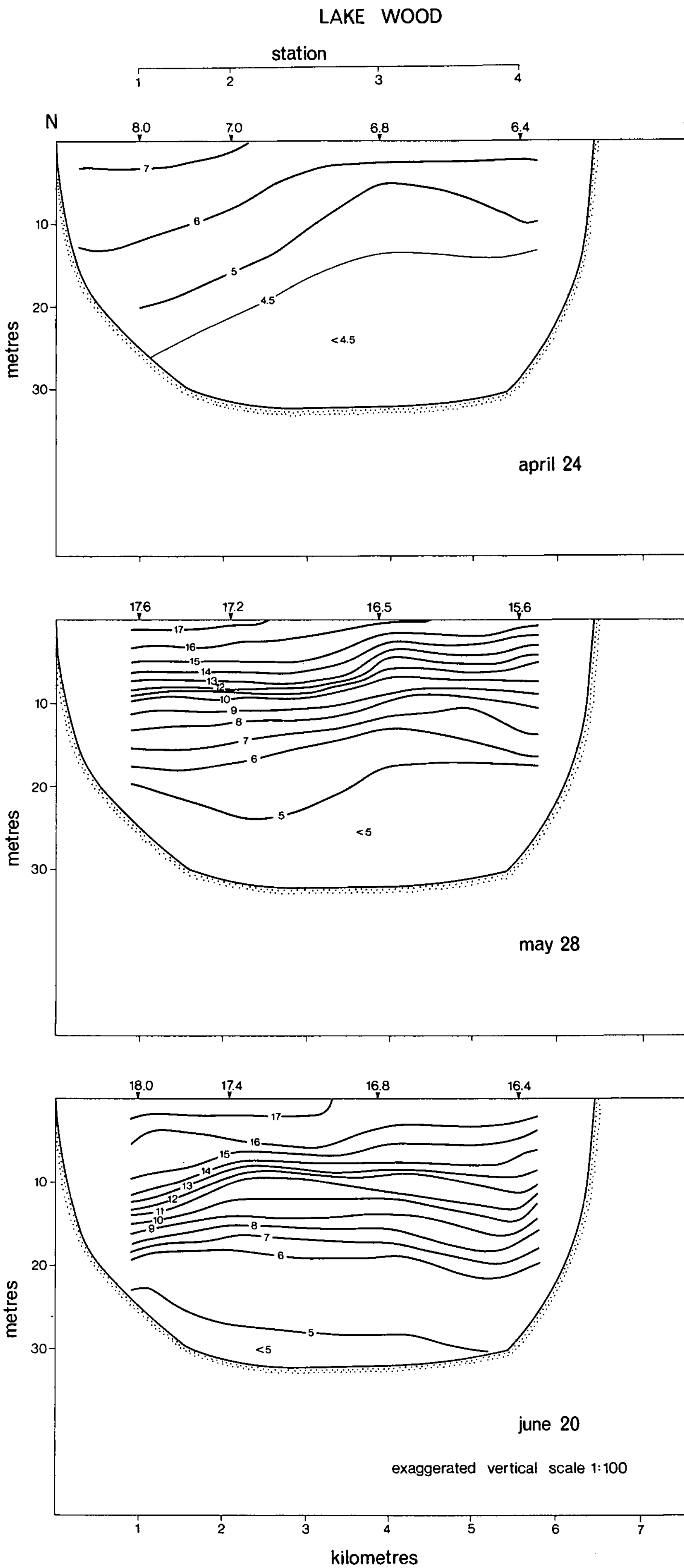
* If it is necessary to transform the volumes of the temperature classes into mean depths or thicknesses, one must vertically integrate the hypsometric curves in Figure 5 thereby obtaining a curve that represents lake volume versus depth.

Figure 6. Volumes associated with given temperature ranges observed during the 1971 monitor cruises in Lake Wood. E and H represent estimates of the volumes of the epilimnion and hypolimnion respectively on the cumulative volume scale.

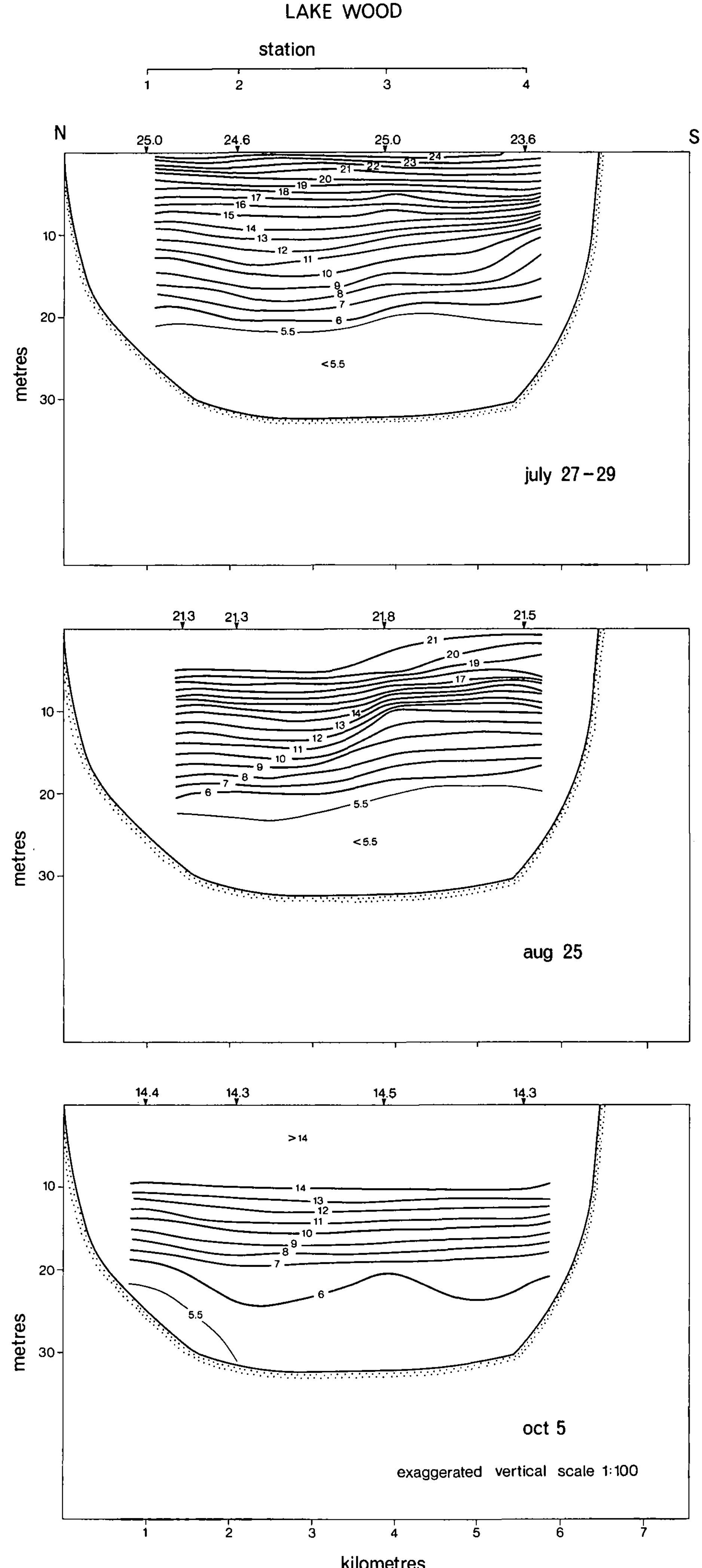


LAKE WOODS
1971
18-20°C
100
80
60
40
20
0
% OF TOTAL VOLUME
16–18°C
>20°C
10–16°C
6–10°C
4–6°C
E
H
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
24 APR
28 MAY
20 JUN
28 JUL
25 AUG
6 OCT

Figure 7. Longitudinal profile of temperature through the deepest portion of Lake Wood. Contours are for each whole ^{o}C, except where noted. Numbers above each station location give the observed surface temperature in ^{o}C. Each section represents one monitor cruise, 1971.



LAKE WOOD
station
1
2
3
4
N
S
8.0
7.0
6.8
6.4
7
6
5
4.5
<4.5
10
20
30
metres
april 24
17.6
17.2
16.5
15.6
17
16
15
14
13
12
10
9
8
7
6
5
<5
metres
may 28
18.0
17.4
16.8
16.4
17
16
15
14
13
12
11
10
9
8
7
6
5
<5
metres
june 20
exaggerated vertical scale 1:100
1
2
3
4
5
6
7
kilometres


LAKE WOOD
station
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24.6
25.0
23.6
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11
10
9
8
7
6
5.5
<5.5
july 27-29
21.3
21.3
21.8
21.5
21
20
19
17
14
13
12
11
10
9
8
7
6
5.5
<5.5
aug 25
14.4
14.3
14.5
14.3
>14
14
13
12
11
10
9
8
7
6
5.5
oct 5
exaggerated vertical scale 1:100
metres
10
20
30
kilometres
1
2
3
4
5
6
7

with a well defined epilimnion for the final two cruises. Rapid cooling of the epilimnion occurred between Cruises 5 and 6. The longitudinal profiles indicate that the lake was somewhat colder in the southern end than in the northern end for all cruises but Cruise 6. This would seem to indicate a predominance of southerly winds that would drive the warmer surface water to the north end. However, wind information at the Kelowna Airport (in the same valley as Wood Lake) was insufficient for us to estimate the prevailing winds in this region, so this point has not been proven. The hypolimnion of Wood Lake remained quite cold during 1971, rather surprising since the lake is quite shallow. This may be a quite reasonable result if the turbulence levels in the hypolimnion remained low due to low wind stress at the surface. Since this fact cannot be established at this time, the low warming rate is simply a fact worth noting. (Has anyone connected with the Study established the presence or absence of a ground-water supply within Wood Lake?)

<u>Lake Kalamalka (Figs. 8 and 9)</u>

One may see immediate differences in the thermal structure between Kalamalka and the three shallower lakes in the chain. For example, 75% of its volume remains at temperatures less than 6°C throughout the field season. During Cruise 5, when temperatures were at a maximum, less than 10% of its volume had temperatures above 20°C. Obviously, Lake Kalamalka has a relatively large and cold hypolimnion compared with that

Figure 8. Volumes associated with given temperature ranges observed during the 1971 monitor cruises in Lake Kalamalka. E and H represent the estimates of the volumes of the epilimnion and hypolimnion respectively on the cumulative volume scale.

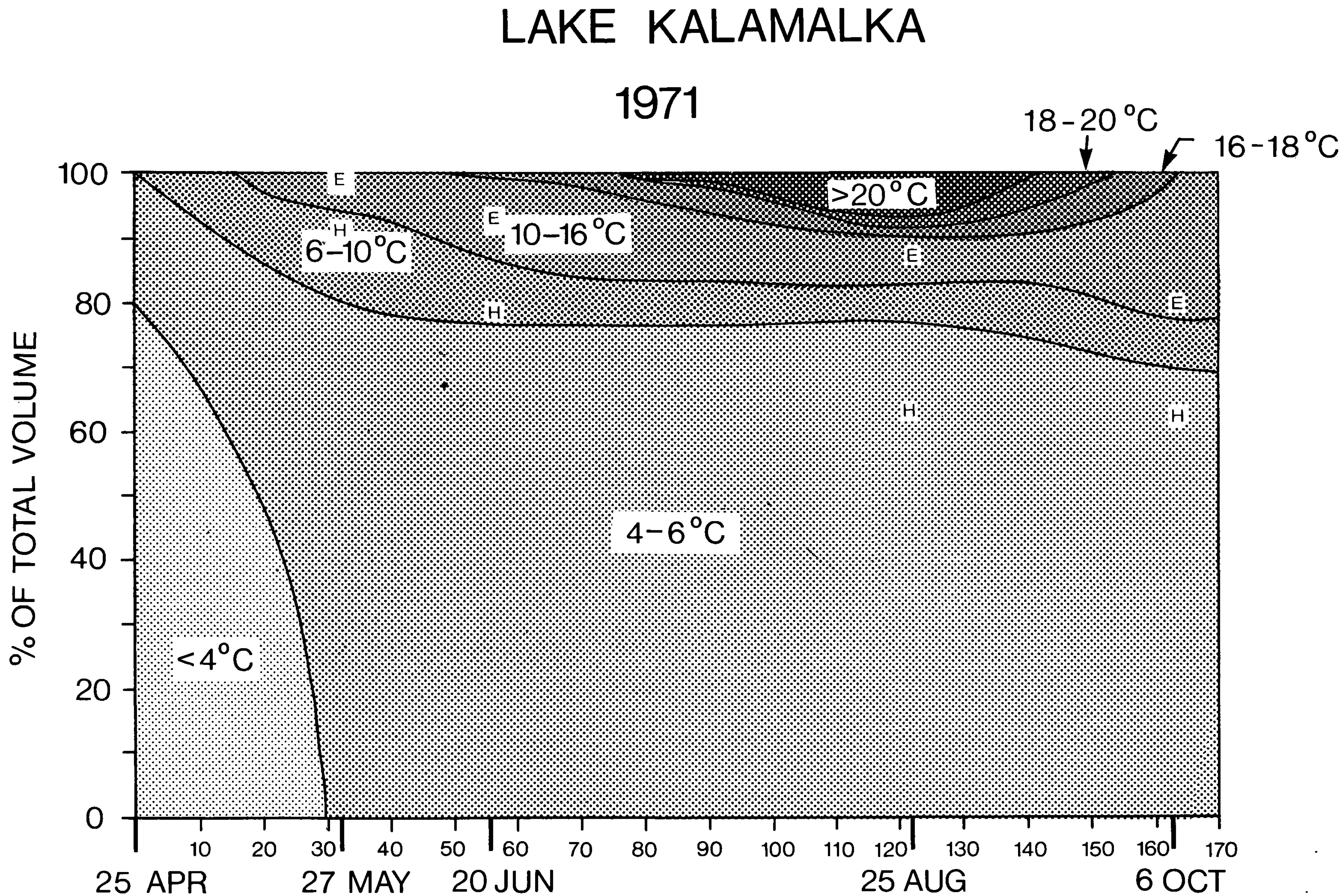
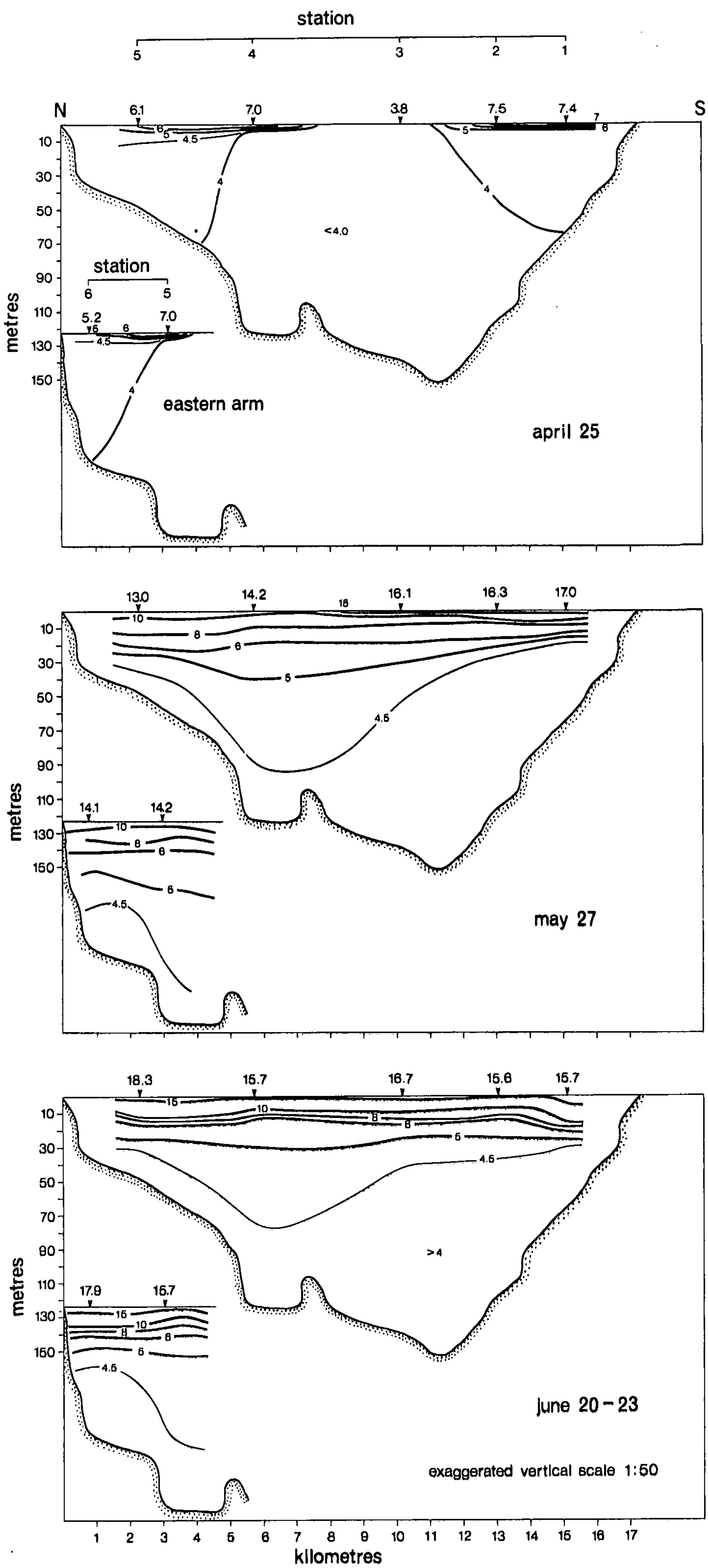
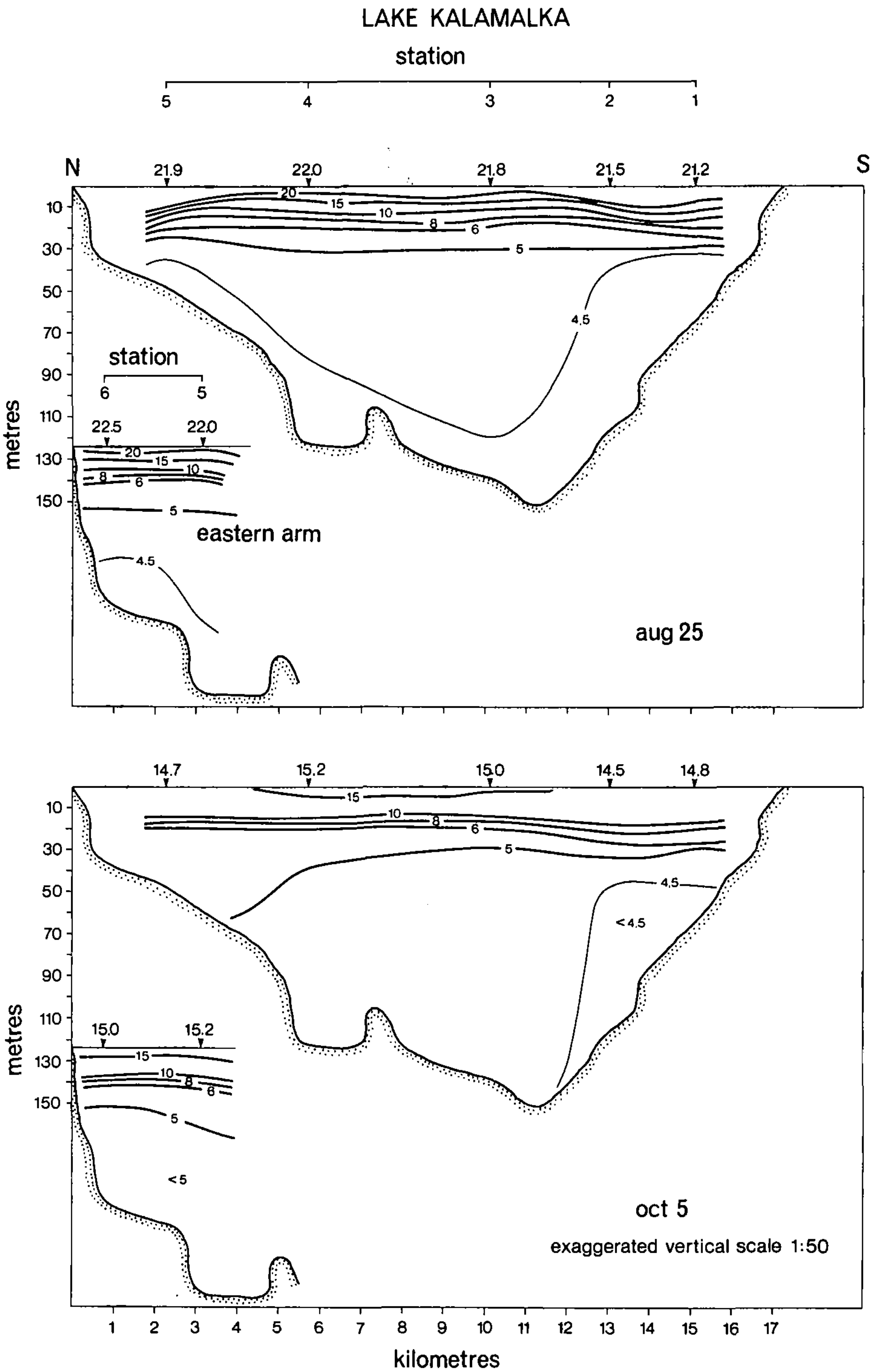

LAKE KALAMALKA
1971
18-20 °C
16-18 °C
>20 °C
10-16 °C
6-10 °C
4-6 °C
<4 °C
E
H
% OF TOTAL VOLUME
0
20
40
60
80
100
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
25 APR
27 MAY
20 JUN
25 AUG
6 OCT

Figure 9. Longitudinal profile of temperature through the deepest portion of Lake Kalamalka. Contours are in °C and are not regular in interval. Numbers above each station location give the observed surface temperature in °C. Each section represents one monitor cruise, 1971.

LAKE KALAMALKA




LAKE KALAMALKA
station
5
4
3
2
1
N
S
21.9
22.0
21.8
21.5
21.2
20
15
10
8
6
5
4.5
station
6
5
22.5
22.0
eastern arm
aug 25
14.7
15.2
15.0
14.5
14.8
<4.5
15.0
15.2
<5
oct 5
exaggerated vertical scale 1:50
metres
10
30
50
70
90
110
130
150
kilometres
1
2
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4
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16
17

of the shallower lakes. While the deeper portions of the lake began the stratification season with temperatures less than 4°C, the deep water had warmed above 4°C at the time of Cruise 2.

Most remarkable in the longitudinal section for Cruise 1 is the large zone where temperatures are less than 4°C (Fig. 9). There appears to be a "thermal bar" on both the ends of the lake (see Rodgers, 1965). The southern "bar" is located between stations 4 and 5 while the northern "bar" is found between stations 2 and 4. These bars were probably the slices of one bar that was more or less continuous around the periphery of the lake. The bar is a manifestation of the heating of the shallower areas near the shore and is evidence that the lake is fully circulating from top to bottom in the vicinity of the bar. The phenomena marks the beginning of stratification.

There were no significant differences observed between the eastern and western arms of Lake Kalamalka. The thermocline* remained relatively shallow for all cruises. A well-defined mixed layer was found only for Cruise 6, and this layer was confined to less than 25% of the total lake volume.

* Due to the highly stratified upper layers of Kalamalka and Okanagan, the contour intervals for temperature in longitudinal sections of these two lakes are irregular.

There was no clear evidence from the temperature data of an influence from Wood Lake on the thermal structure at Station 1 in Kalamalka. Surface temperatures at Station 1 at the northern end of Wood Lake were usually from less than 1 to less than 3°C warmer than those at Station 1 in the southern end of Lake Kalamalka.

Lake Okanagan (Figs. 10 and 11)

Except for its relatively large volume, Lake Okanagan is quite similar in thermal structure to Lake Kalamalka. More than 65% of its volume remained colder than 6°C throughout the stratification period (Fig. 10). Less than 5% of its volume had temperatures above 20°C during Cruise 5.

More noteworthy however is the fact that Lake Okanagan has a significant volume of water less than 4°C. Except for the first two cruises, this water is found only in the deep basin in the vicinity of Carrs Landing. There is no evidence of meromixis in this basin either in the oxygen data or in the conductivity data for 1971. We conclude that during spring circulation, there is always sufficient energy to mix the water to the bottom of this basin. (All temperatures measured during the monitor cruises were above the temperature of maximum density for the depth at which the temperature was measured.)

The longitudinal sections (Fig. 11) show several features that are more-or-less consistent for each cruise.

Figure 10. Volumes associated with given temperature ranges observed during the 1971 monitor cruises in Lake Okanagan. E and H represent estimates of the volumes of the epilimnion and hypolimnion respectively on the cumulative volume scale.

LAKE OKANAGAN

1971

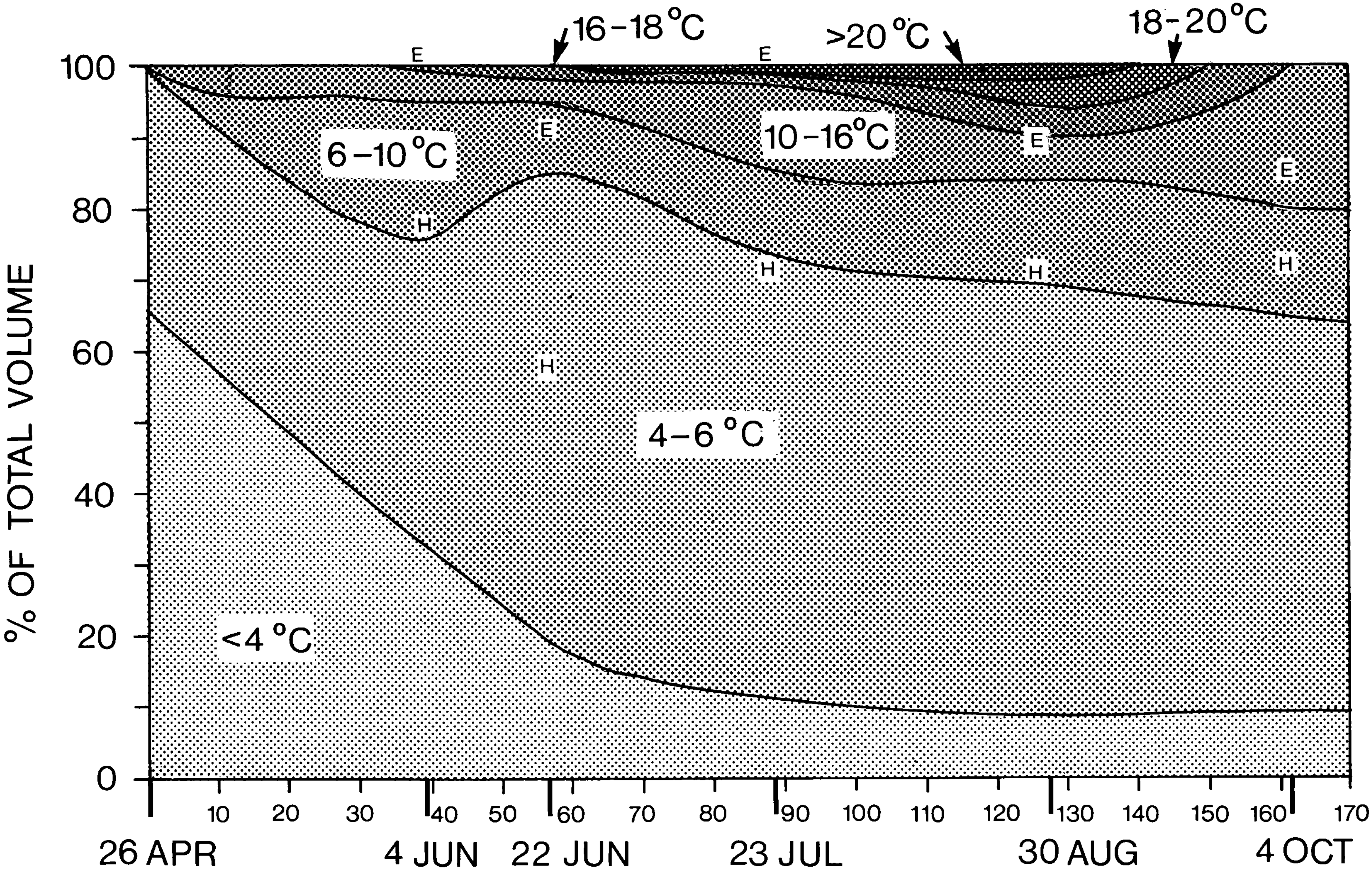
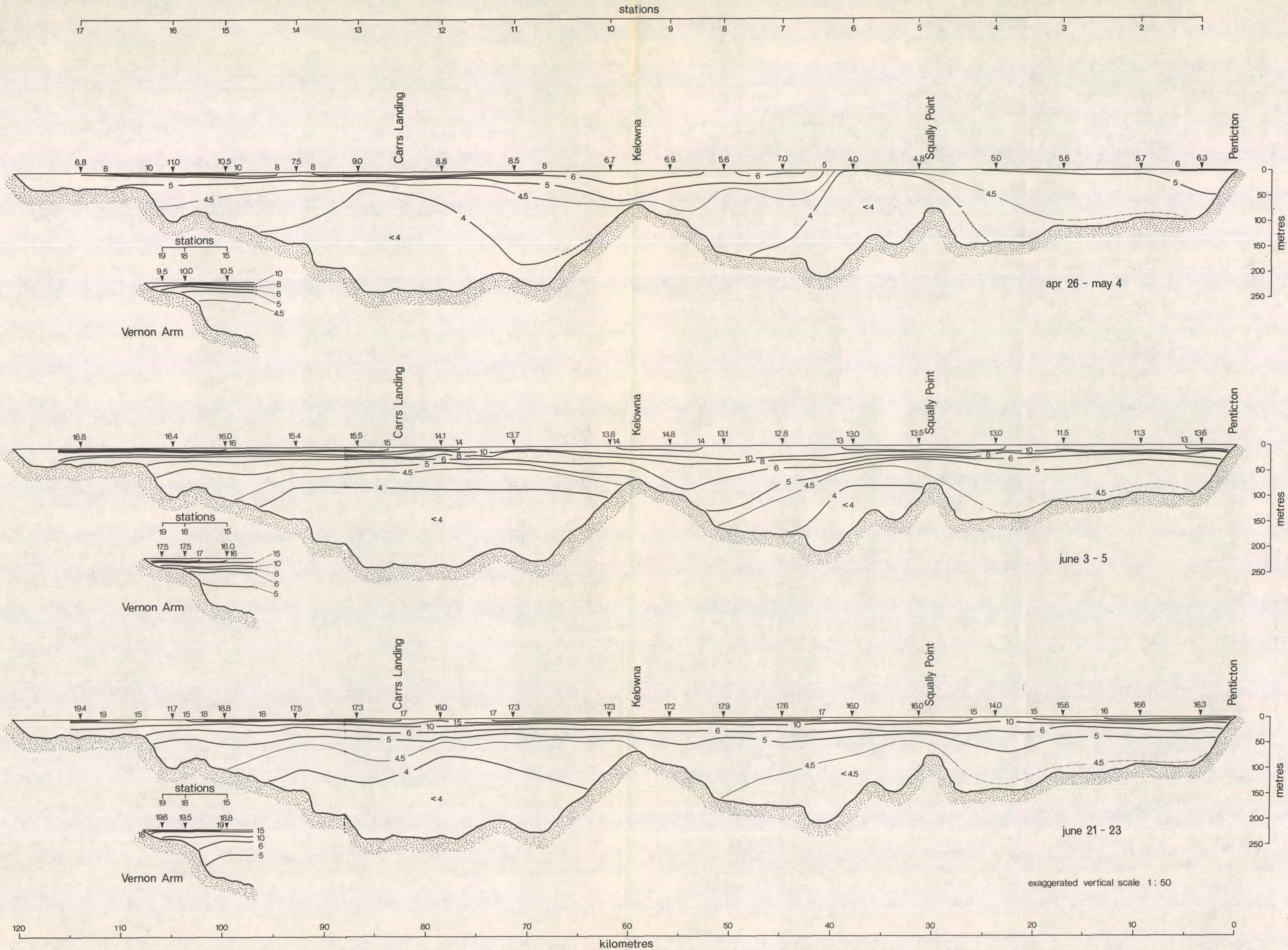
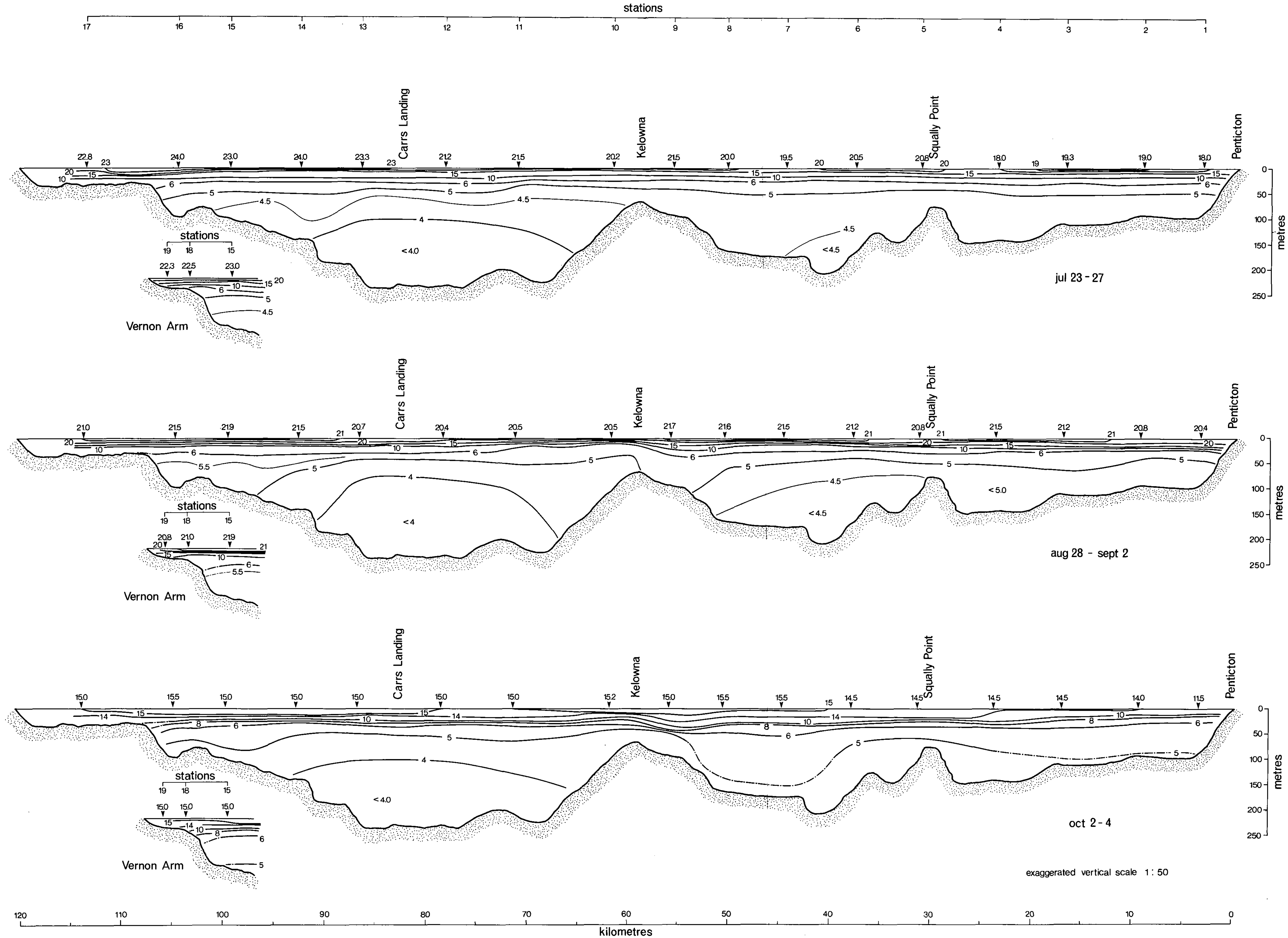


Figure 11. Longitudinal profile of temperature through the deepest portion of Lake Okanagan. Contours are in ^{o}C and are not regular in interval. Numbers above each station location give the observed surface temperature in ^{o}C. Each section represents one monitor cruise, 1971.

LAKE OKANAGAN



LAKE OKANAGAN



(One should ignore small details in the surface temperature patterns since the sections were drawn from data obtained over 3 to 4 days. Basic features remain accurate.) Both arms in the north heat relatively faster than other parts, and they become highly stratified in summer. Highest surface temperatures for a given cruise were always found in these arms.

Somewhat surprising is the fact that surface temperatures were lower in the southern end than in the northern end (even when excluding data from the two arms). Since winds at Penticton were predominantly from the north during the period studied, upwelling at the south end cannot be the total explanation. We have some evidence of upwelling from the mooring near Station 1, but upwelling only occurred for about 10% of the time between 12 May and 28 Sept, 1971. We suspect that the top of the shallow thermocline has been eroded and the surface water cooled by mixing (Blanton, 1972). The fetch from Squally Point to the beach at Penticton is sufficiently long so that enough turbulence is injected into the epilimnion during northerly winds. In other words, one might expect the maximum thermocline erosion and subsequent surface cooling to be near the southern end where exposure to north winds is maximum.

Lake Skaha (Figs. 12 and 13)

Lake Skaha had no temperatures below 4°C at the time of Cruise 1. Stratification had begun before Cruise 2,

Figure 12. Volumes associated with given temperature ranges observed during the 1971 monitor cruises in Lake Skaha. E and H represent estimates of the volumes of the epilimnion and hypolimnion respectively on the cumulative volume scale.

LAKE SKAHA

1971

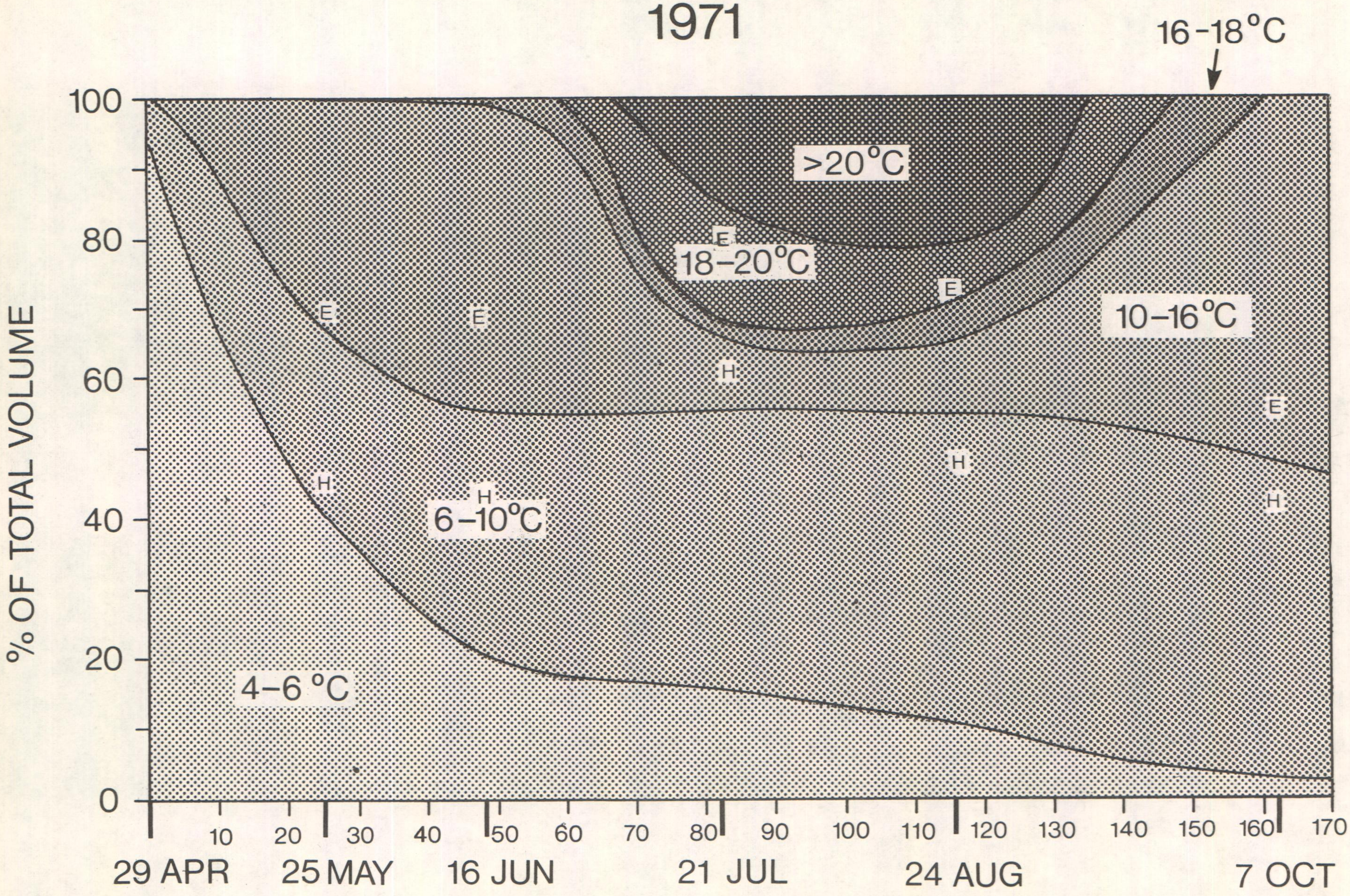
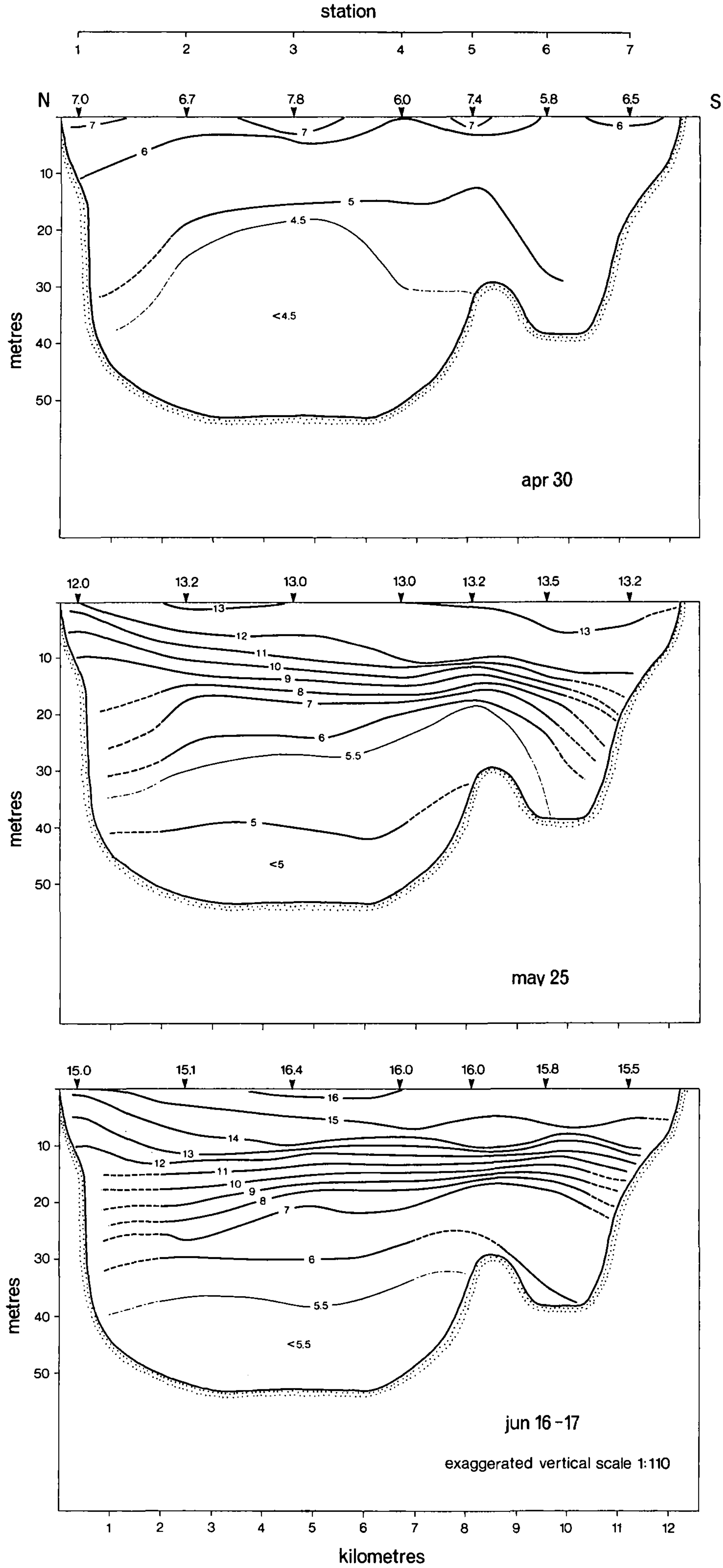
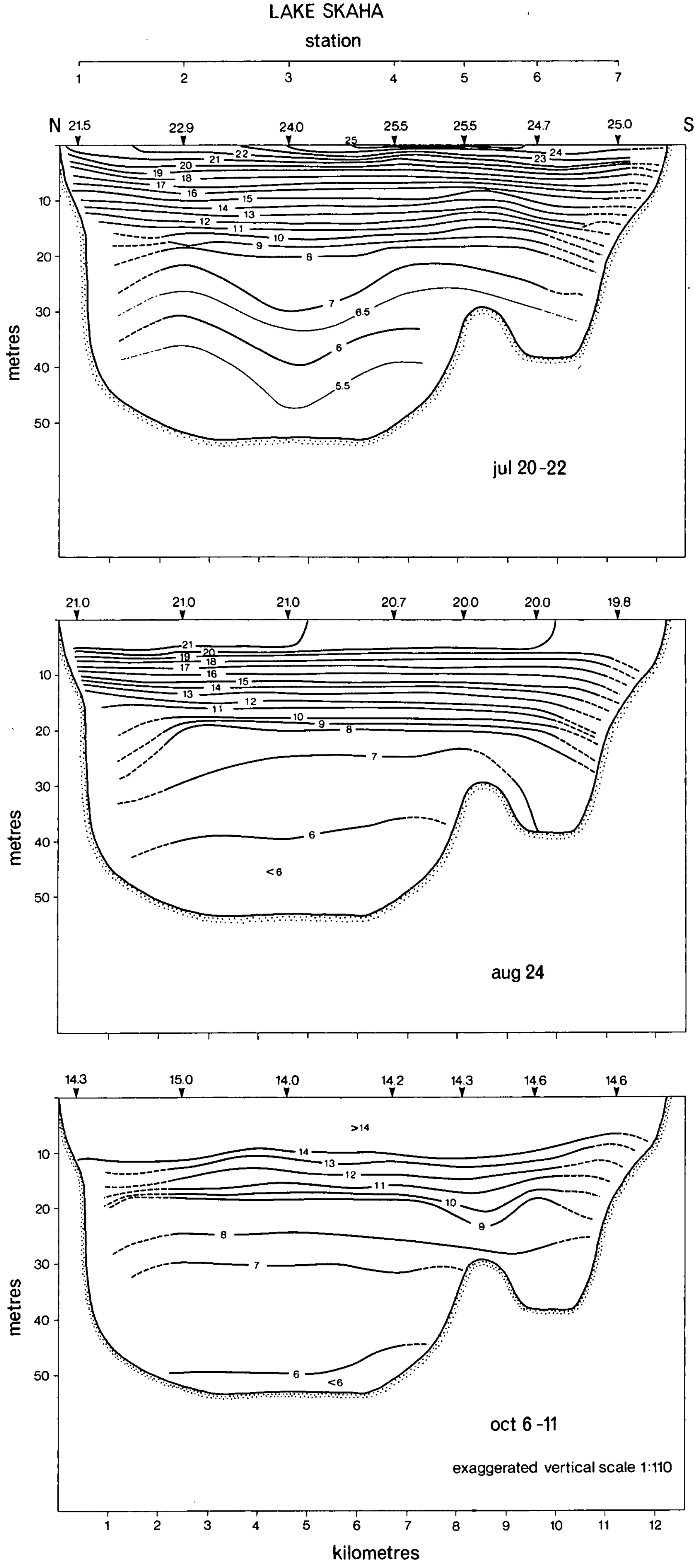


Figure 13. Longitudinal profile of temperature through the deepest portion of Lake Skaha. Contours are for each whole ^{o}C, except where noted. Numbers above each station location give the observed surface temperature in ^{o}C. Each section represents one monitor cruise, 1971.

LAKE SKAHA


station
1 2 3 4 5 6 7
N
S
7.0 6.7 7.8 6.0 7.4 5.8 6.5
7
6
5
4.5
<4.5
apr 30
12.0 13.2 13.0 13.0 13.2 13.5 13.2
13
12
11
10
9
8
7
6
5.5
5
<5
may 25
15.0 15.1 16.4 16.0 16.0 15.8 15.5
16
15
14
13
12
11
10
9
8
7
6
5.5
<5.5
jun 16-17
exaggerated vertical scale 1:110
metres
10 20 30 40 50
1 2 3 4 5 6 7 8 9 10 11 12
kilometres



LAKE SKAHA
station
1
2
3
4
5
6
7
N
S
21.5
22.9
24.0
25.5
25.5
24.7
25.0
metres
jul 20-22
21.0
21.0
21.0
20.7
20.0
20.0
19.8
aug 24
<6
14.3
15.0
14.0
14.2
14.3
14.6
14.6
>14
oct 6 -11
exaggerated vertical scale 1:110
kilometres

and a well-defined epilimnion was present for Cruises 2-6. For Cruise 4 more than 15% of the volume had temperatures above 20^{o}C. Rapid cooling of the epilimnion occurred in the time interval between Cruises 5 and 6.

During the time interval covered by the 2nd, 3rd and 4th cruises in Lake Skaha, winds were predominantly from the north (Fig. 4). This probably explains the fact that we find warmer temperatures at the south end (Fig. 13). The ridge between stations 5 and 6 does not obviously affect the temperature data we have obtained. However, we note that bottom temperatures at station 6 are consistently warmer than the temperatures found at the same depth in the water column of the large northern basin.

Lake Osoyoos (Figs. 14 and 15)

Lake Osoyoos has the warmest hypolimnion of the lakes studied (Fig. 14, which represents the large northern basin only). At the first cruise, most of its volume included water greater than 6^{o}C. Stratification had also begun by the time of the second cruise. At the 5th cruise, more than 30% of the lake's volume had temperatures greater than 20^{o}C. The line representing temperatures less than 10^{o}C describes the approximate time rate of change of the hypolimnion volume. The epilimnion was well-defined from the second until the last cruise.

The longitudinal profiles (Fig. 15) include the large north basin, the small Canadian basin and the portion

Figure 14. Volumes associated with given temperature ranges observed during the 1971 monitor cruises in Lake Osoyoos (northern basin). E and H represent estimates of the volumes of the epilimnion and hypolimnion respectively on the cumulative volume scale.

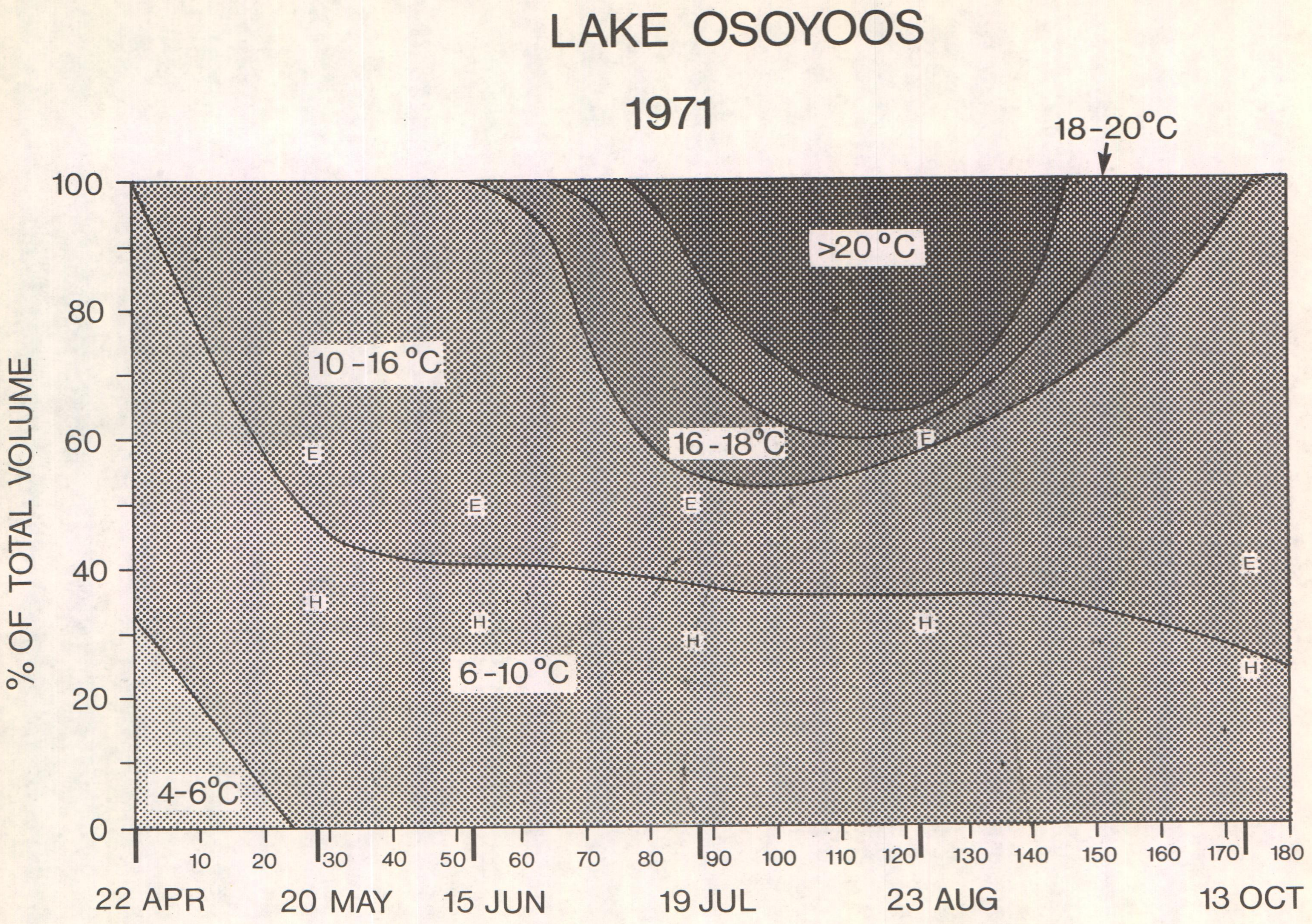
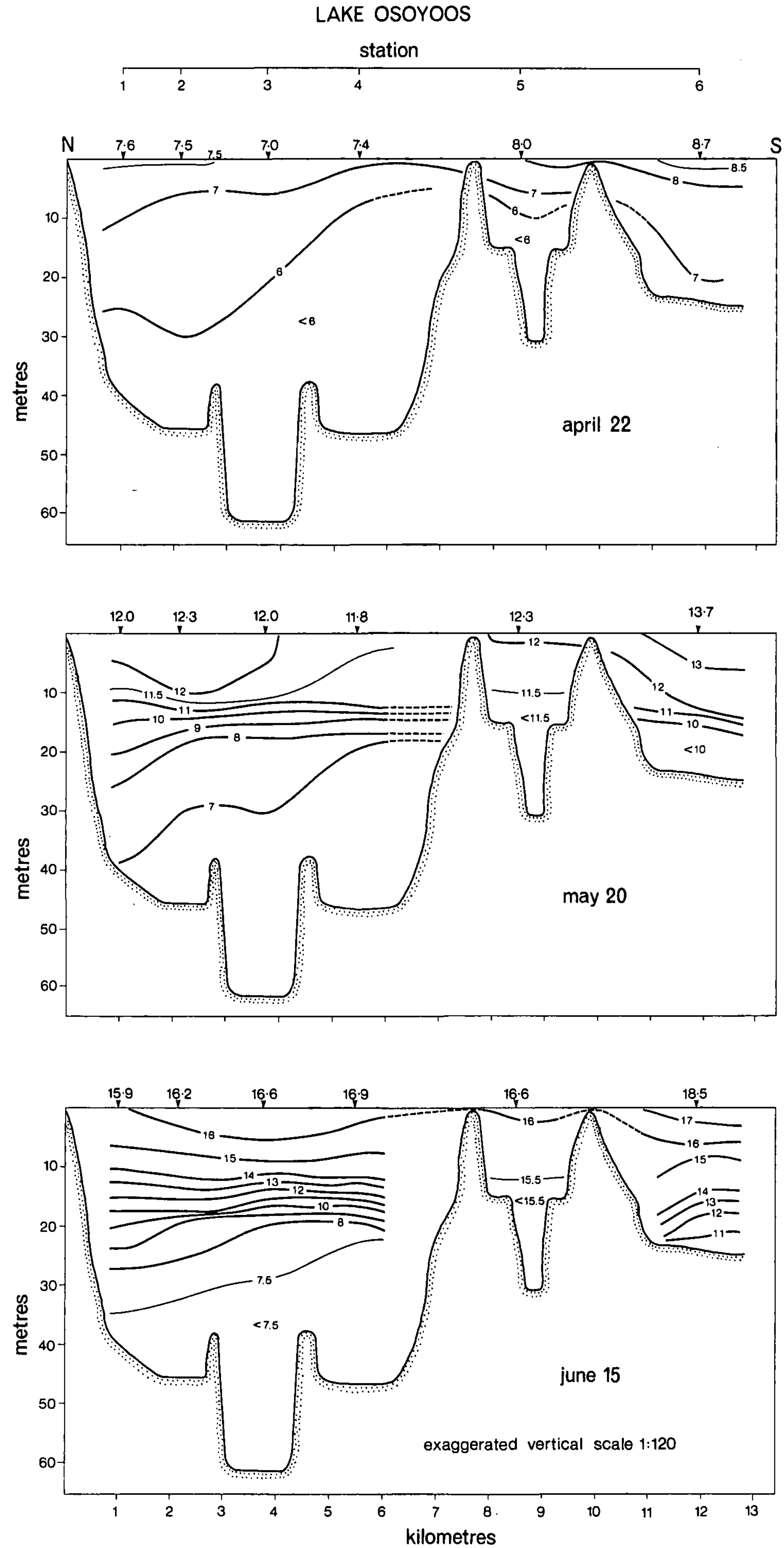
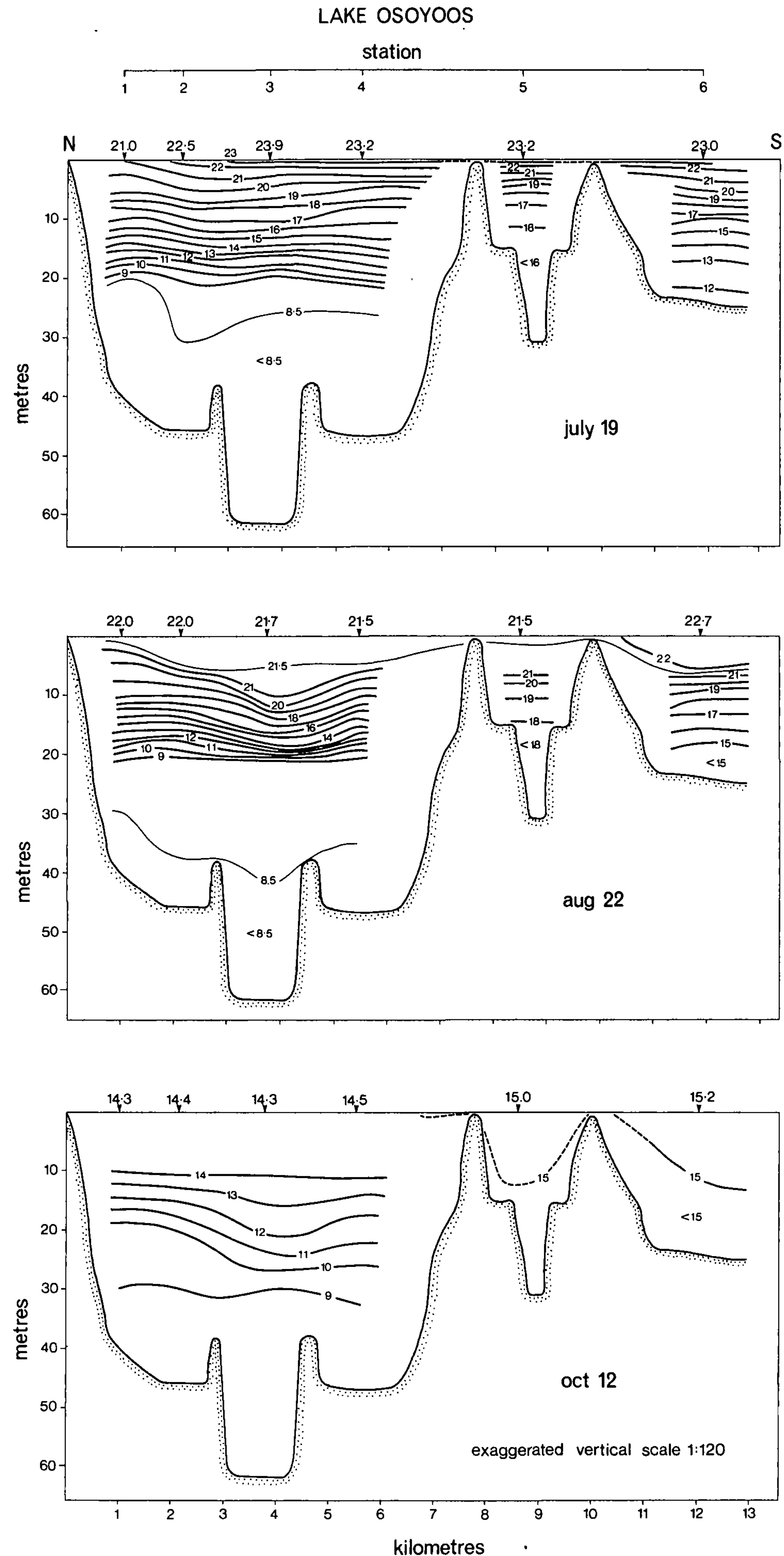

LAKE OSOYOOS
1971
18-20°C
>20 °C
10 - 16 °C
16 - 18°C
6 - 10 °C
4-6°C
E
H
% OF TOTAL VOLUME
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
22 APR
20 MAY
15 JUN
19 JUL
23 AUG
13 OCT

Figure 15. Longitudinal profile of temperature through the deepest portion of Lake Osoyoos down to the international border. Contours are for each whole °C, except where noted. Numbers above each station location give the observed surface temperature in °C. Each section represents one monitor cruise, 1971.



LAKE OSOYOOS
station
1 2 3 4 5 6
N S
7·6 7·5 7·0 7·4 8·0 8·7
april 22
<6
may 20
12.0 12·3 12.0 11·8 12·3 13·7
<11.5
<10
june 15
15·9 16·2 16·6 16·9 16·6 18·5
<7.5
<15.5
exaggerated vertical scale 1:120
metres
kilometres



LAKE OSOYOOS
station
1
2
3
4
5
6
N
S
metres
july 19
aug 22
oct 12
exaggerated vertical scale 1:120
kilometres

of the large southern basin down to the international border. Surface temperatures generally increased from north to south. The effects of the ridges separating the basins are quite evident in the thermal structure, and the thermal differences between these basins become more pronounced as the stratification season progresses. The northern basin was strongly stratified and more or less similar to Lakes Woods and Skaha. The hypolimnion warming rate for this basin was the most rapid of the lakes (0.54^{o}C/month).

In the other two Canadian basins of Osoyoos, bottom temperature regimes are quite different. This is not surprising because each basin is separated from the adjoining one by shallow sills at no place more than one or two meters deep. In the basin between the City of Osoyoos and Haines Point, the waters are well-mixed vertically and the bottom temperature cycle follows closely that of the surface. Bottom temperatures were never more than 2 to 4^{o}C colder than the surface. In the southern basin between Haines Point and the U.S. Border, there was some weak stratification. Bottom temperatures increased relatively fast at the rate of 1.4^{o}C/month. At the time of Cruise 6, the water was vertically homogeneous.

Summary and Comparisons

While we did not observe all the lakes for an entire year, we may safely classify the mainstem lakes as dimictic (two circulation periods per year). Lakes Wood, Kalamalka, Skaha and Osoyoos may be further classified as dimictic lakes of the second class (see Hutchinson, 1957, for a discussion of thermal classifications). Second class lakes have bottom temperatures somewhat above 4°C in midsummer. Kalamalka, however, is certainly marginally between first and second class because bottom temperatures in the deepest portions are probably very close to 4°C at all times of the year. Lake Okanagan, on the other hand, may be considered a first class lake for the very deep portion between the two northern arms and Kelowna. South of Kelowna, our information on bottom temperatures is too incomplete for certainty, but we suspect that this portion of Okanagan is on the borderline between first and second class. The two northern arms are definitely of the second class.

Using the portions of each BT curve as defined above, we calculated the mean temperatures for the epilimnion and hypolimnion for each lake and for each cruise (Fig. 16). The epilimnion of Wood Lake heated the most during the observation period. Highest daily average temperatures observed from the moored thermographs in these lakes indicate that each lake reached its maximum temperature between the end of July and the middle of August (Table 2) or between Cruise 4 and Cruise 5.

Therefore, the peak epilimnion values in Figure 6 do not reflect the times of maximum lake temperature. The times of maximum lake temperatures occurred at the approximate time of the hi[illegible] air temperatures at Penticton.

The hypolimnions of the five main lakes warmed at much slower rates and continued warming throughout the observation period. The magnitudes of warming rates were as follows:

Osoyoos (N)	0.54°C/month
Skaha	0.37
Wood	0.26
Kalamalka	0.18
Okanagan	0.06

All lakes at the time of Cruise 1 were relatively well mixed and there was no real distinction between epilimnion and hypolimnion. At the time of Cruise 2, stratification had begun (Fig. 17). Lakes Kalamalka and Okanagan had poorly defined epilimnions, while Wood, Skaha and Osoyoos had well-mixed epilimnions down to 5, 7, and 10 meters respectively. Between Cruise 3 and 4, at the time when the monthly mean temperature increased greatly (Fig. 2), the well-mixed character of the epilimnions became smeared. There was little evidence of wind mixing over that period, and Wood Lake virtually lost its well-defined epilimnion (Fig. 17). All lakes reflected this period of strong surface heating

OKANAGAN LAKES - 1971
MEAN TEMPERATURES OF THE EPILIMNION AND HYPOLIMNION

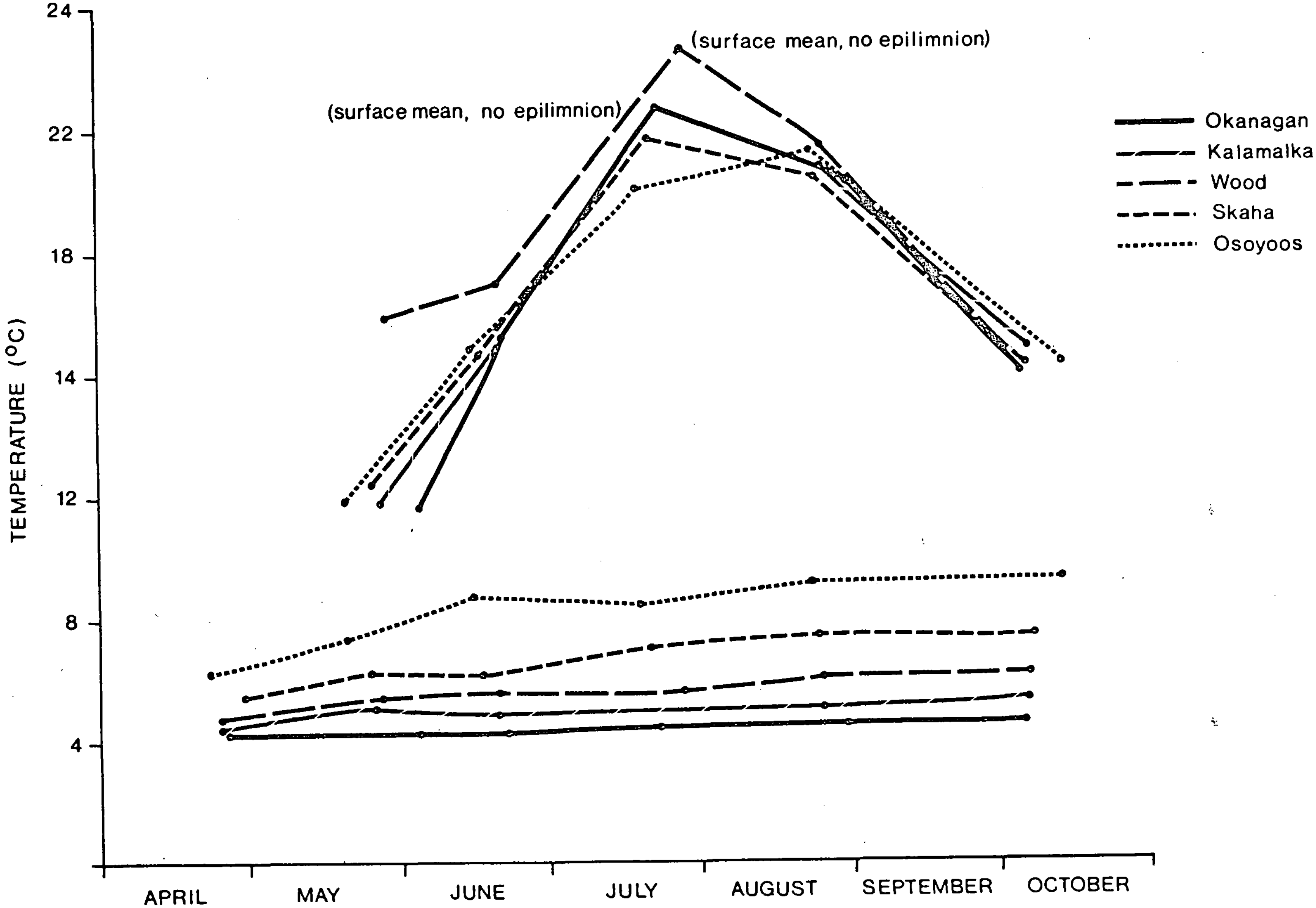


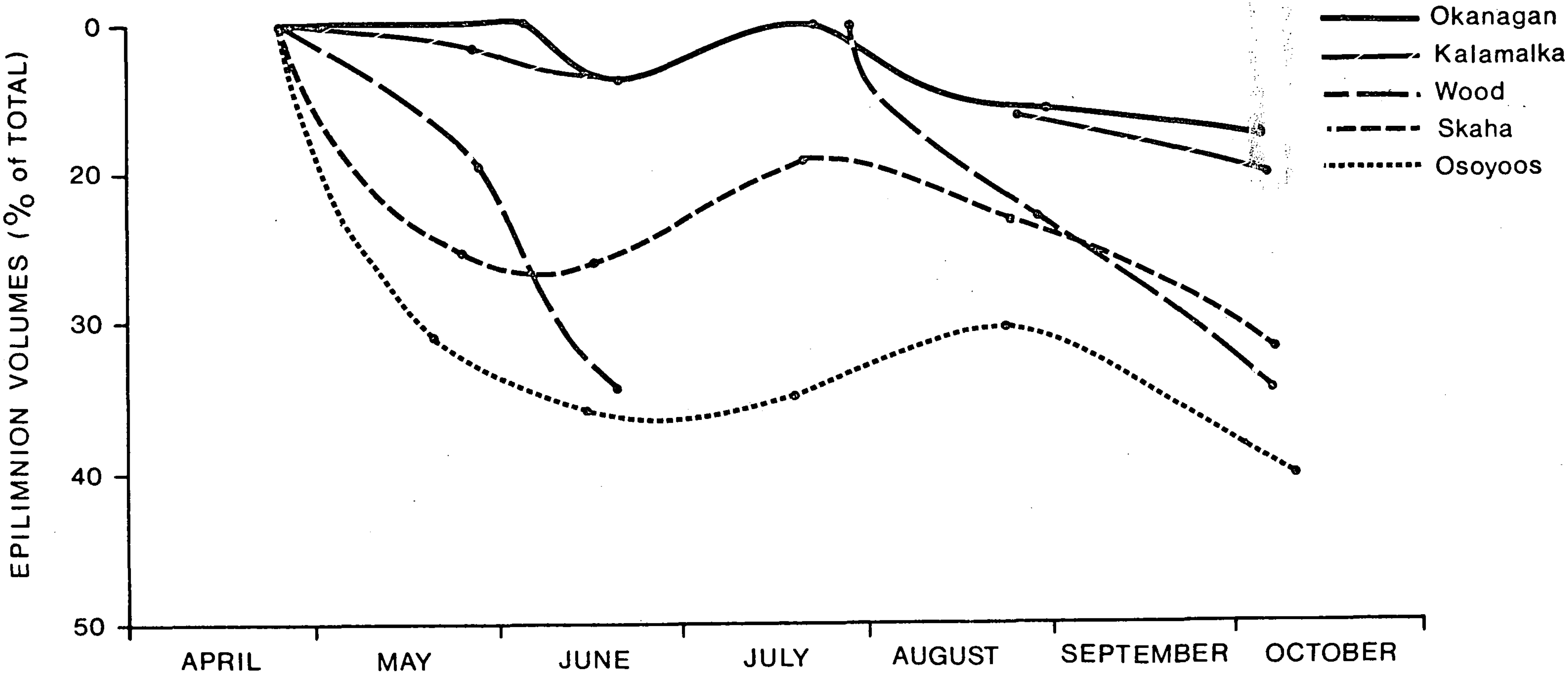
Figure 16. Lake-wide mean temperatures for the epilimnion and hypolimnion based on the monitor data in 1971.

Table 2.

Period of maximum surface temperatures for lakes where moored thermographs were established (see Fig. 1 for locations). Temperatures represent daily averages of hourly values.

Lake	Instrument Depth (m)	Times of Maximum Temperatures	Maximum temperature (observed)
Wood	1.5	29 July-2 August	27.5°C
Kalamalka	1.5	30 July-1 August	28.0
Okanagan (Vernon Arm)	1.5	4-8 August	26.5
Okanagan (Kelowna)	1.5	8-13 August	24.5
Okanagan (Penticton)	2	6-10 August	25.0 (30 July)
Skaha (Okanagan Falls)	2	9-13 August	25.0
Vaseux (Outlet)	2	31 July-5 August	27.5

Figure 17. The volumes of epilimnions versus time. Volumes are expressed as a percentage of each lake's total and were calculated from the monitor data in 1971.



when epilimnions became ill-defined. During late August and through September, all epilimnions became well-mixed and increased in volume.

The parameter that most accurately describes stratification is static stability which may be defined as $\frac{g}{\rho}\frac{\delta\rho}{\delta Z}$ where $\frac{\delta\rho}{\delta Z}$ is the change in water density per unit depth, Z; and g is the acceleration of gravity. The zone of maximum stability in a lake is found in the thermocline region. For this region we have calculated the maximum observed stability during the 1971 monitoring season (Table 3). All lakes reached maximum observed stability by the time of Cruise 5 except for Osoyoos (N). Density changes through the thermocline are based on lake-wide averages of epilimnion and hypolimnion temperatures (Fig. 16). The thickness of the thermocline is derived from the hypsometric curves (Fig. 5) and is the depth difference found when subtracting the depth represented by the volume of the hypolimnion from that represented by the volume of the epilimnion.

There is a fairly good relationship between the rate of warming of the hypolimnion and the maximum observed stability (Fig. 18)*. The shallowest three lakes had the highest stability observed and the highest rate of warming. This result is quite reasonable, because shallow lakes generally have more turbulence

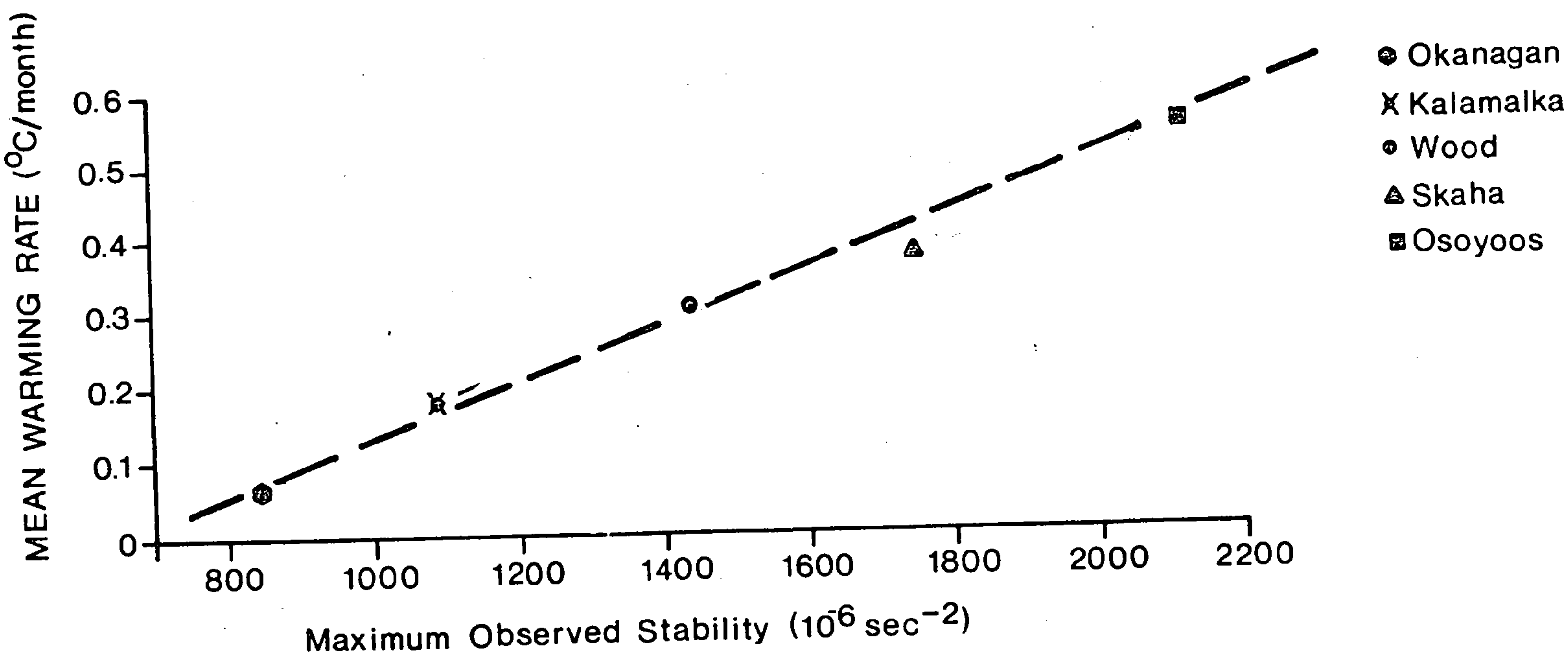
* One should use some caution in interpreting the figure. Lake Okanagan transfers much more heat to the hypolimnion compared with that transferred in the other lakes, but its relatively enormous volume prevents much increase in temperature.

Table 3

Times and values of the maximum observed stability in each lake. Stability is calculated as $\frac{g}{\rho}\frac{\delta\rho}{\delta z}$ where $\delta\rho$ is the change in water density, ρ through the thermocline and δz is the thickness of the thermocline; g is the acceleration of gravity.

Lake	Cruise No.	Time of Maximum Stability	Stability ($sec^{-2}x10^{-6}$)
Osoyoos (N)	4	19 July	2120
Skaha	5	24 August	1750
Wood	5	25 August	1440
Kalamalka	5	25 August	1090
Okanagan	5	30 August	850

Figure 18 Maximum observed stability versus rate of hypolimnion warming for each lake. For discussion, see text.



in their hypolimnions. This turbulence can act to mix or entrain relatively warm water of the bottom of the thermocline and rapidly mix this water throughout the hypolimnion. This action increases the temperature gradient in thermocline much in the same manner as a wind-stirred epilimnion strengthens the thermocline. Hypolimnions of deep lakes such as Kalamalka and Okanagan have relatively low levels of turbulent energy when compared with levels in the shallower lakes (Blanton and Winklhofer, 1971).

<u>Heat Content Measurements</u>

For each cruise, we computed the heat content in gm cal/cm^2 for the mainstem lakes (except Vaseux). Whether computations were done by hand or by computer, the computation was basically as follows:

$$Q = \frac{C_p \rho}{A_o} \left\{ V_e(T_e - 4) + V_m(T_m - 4) + V_h(T_h - 4) \right\}$$

where Q is the total heat in gm cal/cm^2, A_o is the surface area of the lake, C_p is the specific heat $\equiv$ 1, ρ is the water density $\equiv$ 1, V is the volume, T is the average temperature, and subscripts e, m, and h refer to epilimnion, mesolimnion and hypolimnion as defined on page 8. By subtracting 4°C from each mean temperature, we calculate the heat income responsible for temperatures above 4°C. The maximum of this value is defined by Hutchinson (1957) as the summer heat income.

Lake Okanagan had the highest summer heat income of the five regularly sampled lakes and Wood had the lowest (Fig. 19). All values calculated for the sixth cruise agree fairly well with those calculated for September, 1970. Two values of heat content were added for Vaseux (Fig. 19). In general, we would expect the values for Vaseux to be the lowest of the mainstem lakes at any given time because it is the smallest. Maximum observed heat contents for the five lakes that were sampled on a regular basis are assumed to approximate the summer heat income for 1971 (Table 4). The accuracy of this assumption is unknown.

Internal Seiches

Instrumentation that would yield some information on internal seiches was installed in Lakes Skaha and Okanagan (Fig. 1). The records from each mooring are to be spectrally analyzed at a later date, but for our purposes we have extracted some information that may be useful. Each record was divided into segments from 20 to 30 days in length. (This is simply a convenient means for dividing an extremely long time series of data. A more objective method must await a more sophisticated analysis.) From each segment, we estimated the period between dominant seiches and the characteristic amplitudes* observed. Amplitude and period were defined by the oscillation of a particular isotherm at the location of the mooring. The results are summarized in Table 5.

* The characteristic amplitude is defined here as one-half the average total excursion in depth of a particular isotherm.

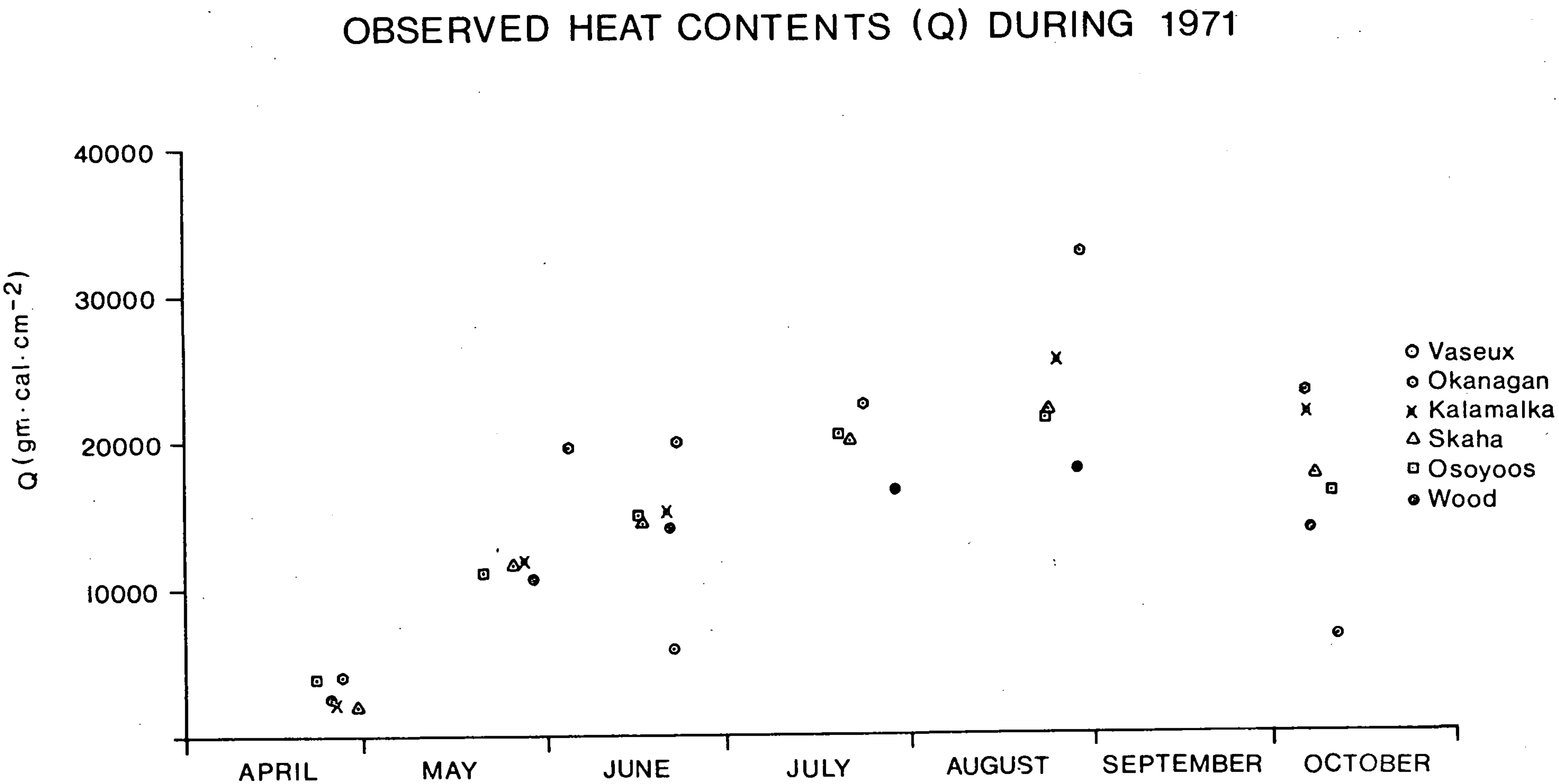


Figure 19 Heat contents observed for the 1971 monitor cruises. For discussion, see text.

Table 4. Summer heat incomes for the mainstem lakes in 1971.

Lake	Cruise No.	Time of Observation	Heat content (gm cal/cm^2)
Okanagan	5	30 August	33,300
Kalamalka	5	25 August	25,100
Skaha	5	24 August	22,200
Osoyoos (N)	5	23 August	21,900
Wood	5	25 August	18,100

Table 5

Summary of dominant periods and characteristic amplitudes for internal seiches measured by thermograph moorings. See Figure 1 for location of the moorings.

LAKE OKANAGAN

Segment	Time interval	Isotherm used for analysis (°C)	Dominant Period (hours)	Characteristic amplitude (meters)
1	May 15 to June 10	8°C	90	5
2	June 15 to July 10	8°C	120	3
3	July 10 to Aug 10	10°C	65	10
4	Aug 10 to Sept 10	10°C	105	10

LAKE SKAHA

Segment	Time interval	Isotherm used for analysis (°C)	Dominant Period (hours)	Characteristic amplitude (meters)
1	May 1 to May 31	6°C	44	5
2	June 1 to June 30	10°C	36	3
3	July 1 to July 31	10°C	22	<1
4	Aug 1 to Aug 31	12°C	19	1
5	Sept 1 to Sept 28	12°C	18	1

One can see that the periods measured change with changing conditions of stratification. This is as expected from theoretical considerations (see Hutchinson, 1957, on internal seiches). For Okanagan, we have found that these periods lie close to the theoretical period of an internal seich of three nodes as calculated from similar conditions of stratification. (Theoretical periods are based on the formula for seiches in a rectangular lake.) The positions of these three nodes are unknown. We also have a short record of temperature vs. depth from the Kelowna bridge during September and October, 1962*. The dominant period here was about 110 hours which is quite close to the period calculated in Table 5 for segment 4 at a similar time of year. It seems unlikely that a node is located near Kelowna since characteristic amplitudes from the Kelowna record were close to 5 meters.

The periods of the internal seich in Lake Skaha were much shorter than those observed in Lake Okanagan, as expected from the relatively small size of Lake Skaha. The periods in the records of the first two segments are quite similar to those of the theoretical uninodal internal seich. From segments 3 and 4, the periods observed are somewhat shorter than the theoretical uninodal period, but longer than the bi-nodal period for similar conditions of stratification. For the fifth segment, the observed period

* We express our appreciation to Mr. V.G. Borch, City Engineer of the city of Kelowna, for making this record available to us.

is quite close to the theoretical period of a bi-nodal internal seich. The observed amplitudes were smaller than those observed in Lake Okanagan which is not surprising considering its small size. There is some indication from our data that Lake Skaha responds with a uninodal seich when the thermocline is relatively shallow, but this response alters to a bi-nodal seich when the thermocline is deeper during the end of the stratification period. This shift in mode is consistent with the observed decrease in amplitudes in the later segments since the energy would be split between the two nodes that may occur in the later stages of stratification.

The above conclusions on the internal seiches in Skaha and Okanagan are quite tenuous. It was not our intention to analyze the complexities of internal seiches in the mainstem lakes, but only to point out their existence in all stratified lakes including the ones studied here. Quantitative data obtained in vertical samples in lakes must be evaluated with full knowledge of the existence of these seiches.

LIGHT TRANSMISSION IN THE MAINSTEM LAKES

Light transmission data and secchi disc visibilities came from three main sources: the Canada Centre for Inland Water 1971 studies, the studies carried out by the South Okanagan Health Unit under the direction of Fred Alcock, and some selected data on Wood and Kalamalka in 1966 obtained from the B.C. Fish and Wildlife Branch. All data from the first two sources were treated as an ensemble and will be discussed together. The third source offers the opportunity to estimate trends in light transparency for two of the study lakes over several years. Other secchi disc data were obtained only two or three years previous to the 1971 studies and offer no real additional information except to point out the wide variability that is (1) attributable to human differences in observational technique and (2) variability in natural light conditions. Only data that were taken between 1000 and 1600 in the afternoon were used for this report. Data that were outside this time interval or that were obtained on unusually dark overcast days were omitted.

Light transparency from irradiance measurements

When the logarithm of % of transmitted light was plotted against depth, two well-defined extinction coefficients were often observed with the shallower one occurring within the first 5 meters. This was observed only for data obtained without a filter. Only one coefficient was observed with the one set of filtered data reported by Blanton and Ng (1971). Therefore the two coefficients could possibly be an artifact that is erased when considering light of a reasonably well-defined wave length. Or, the two coefficients are related to other factors such as a thin layer of turbidity in the first few meters or vice versa when the shallower coefficient indicated higher transparency near the surface. In all cases the extinction coefficients are based on three or more points on semi-log plots excluding all data within one meter of the water surface. The values of transmission (m^{-1}) as derived from the extinction coefficients are summarized in Table 6. While variations in transmission are quite large within a given lake, as expected, a clear pattern emerges when comparing one lake with another. The lakes are listed in Table 5 in the order of increasing transparency. If one compares the ratio of blue transmission to green transmission, this ratio is lowest for Wood and highest for Kalamalka. The tendency of increased transmission in the blue light range is characteristic of clear and unproductive water masses when they are compared with more turbid and productive ones (Sverdrup, Johnson and Fleming, 1942).

Table 6 Summary of transmission/meter values for the six mainstem lakes. Values are given in percent. Sampling points are shown in Figure 1.

	LAKE											
	WOOD		OSOYOOS		SKAHA		OKANAGAN*		KALAMALKA		VASEUX	
Month or season	1-5m	> 5m	1-5m	> 5m	1-5m	> 5m	1-5m	> 5m	1-5m	> 5m	1-5m	> 5m
Spring 1969	58.9	73.0	54.9	66.2	77.0	73.9	78.7	84.4	78.7	85.9		
September 1969	69.7	61.4	52.5	70.5	40.2	75.3	79.9	81.1	79.4	82.9		
June-July 1970	56.2	92.0?	66.2	64.5	79.7	79.0	80.7	82.1				
September 1970	49.7*		59.6*		69.3*		74.7*		81.8*			
May 1971	60.1	60.6	62.0	53.6	75.8	76.0	80.3	81.8	90.3	91.3	56.2	64.5

* $T = 1/3\ (T_{450} + T_{530} + T_{630})$. Filter values for each lake are as follows:

Lake	T^*	T_{450} (blue)	T_{530} (green)	T_{630} (red)
Wood	49.7	46.2	58.6	45.3
Osoyoos	59.6	56.4	67.0	56.0
Skaha	69.3	65.4	74.5	64.3
Okanagan	74.7	76.4	80.1	68.0
Kalamalka	81.8	85.6	86.0	74.5

A plot of secchi disc visibility versus transmission values for the upper 5 meters (Fig. 20) suggest a rough correlation as shown by the two lines. These lines were drawn by eye because no statistical correlation was thought to be justified. A plot of the secchi disc visibilities with the transmission values below 5 meters produced even wider scatter.

Secchi disc visibility

Lake mean visibilities of secchi discs are summarized for 1971 for each of the mainstem lakes (Fig. 21). Okanagan and Kalamalka had greatest visibilities. Kalamalka appeared to have two minima in late May and late August while Okanagan had only one minimum in late May and early June. Skaha had one minimum at the end of the cruise period. Osoyoos had two minima corresponding in time to those in Kalamalka. Wood had one minimum in middle July. The average magnitudes of visibilities show the same trend in transparency as the values of transmission/meter.

In Lake Okanagan, the Vernon Arm location had the lowest visibilities for the entire lake (Fig. 22). Sample curves for a mid-lake and southern lake location showed visibilities vary close to the lake average. The Armstrong Arm station was also slightly more turbid than the lake average.

Some CCIW data for Lakes Okanagan, Wood and Kalamalka have been compared with historical data from various sources (Figs. 22 and 23). The most that can be said is that the year 1966 seems to have been one of relatively high transparency for Lakes Wood and Kalamalka (Fig. 23). No relevant conclusions can be drawn for Lake Okanagan.

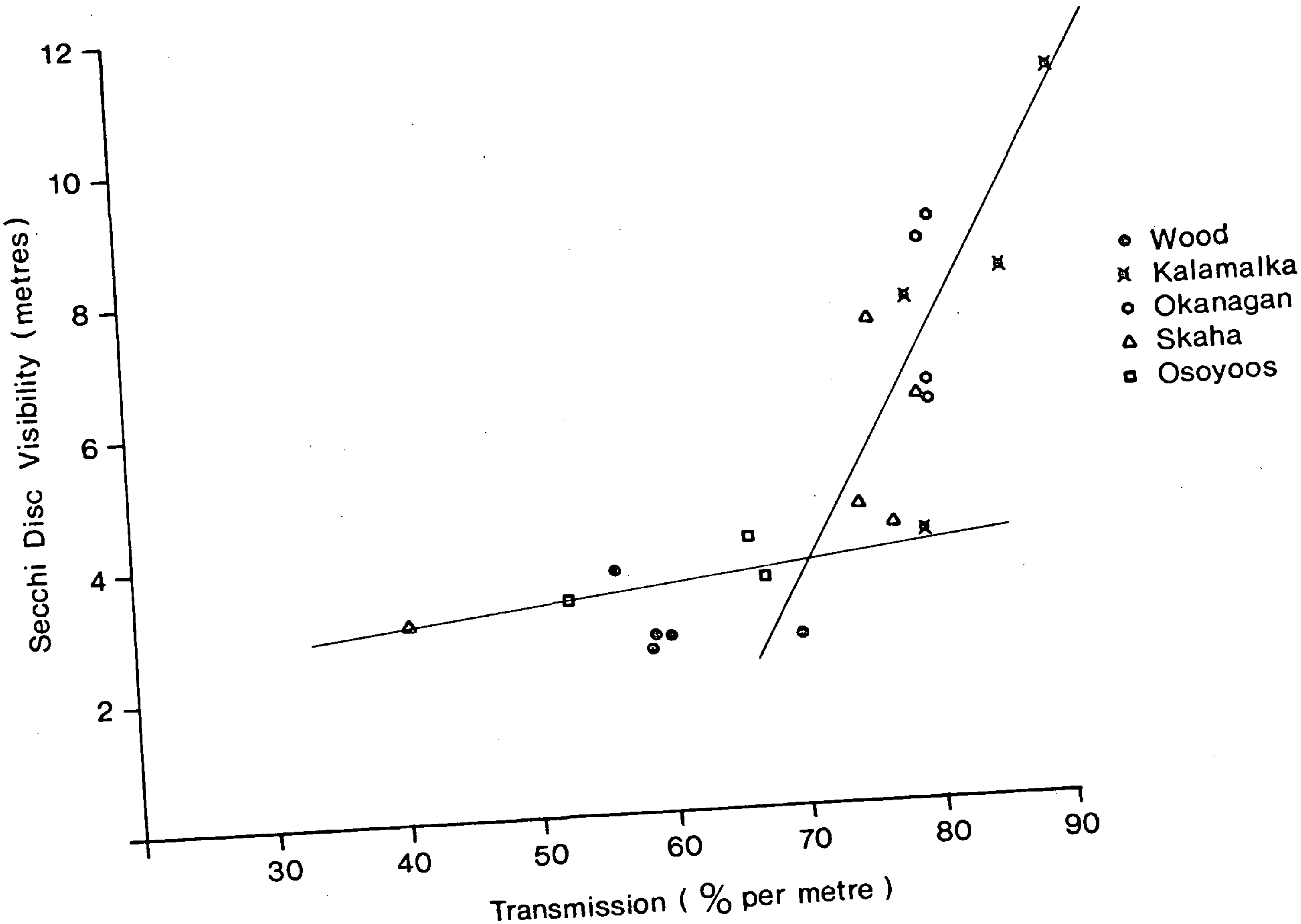


Figure 20. Secchi disc visibility versus transmission values for the upper 5 metres (see Table 5).

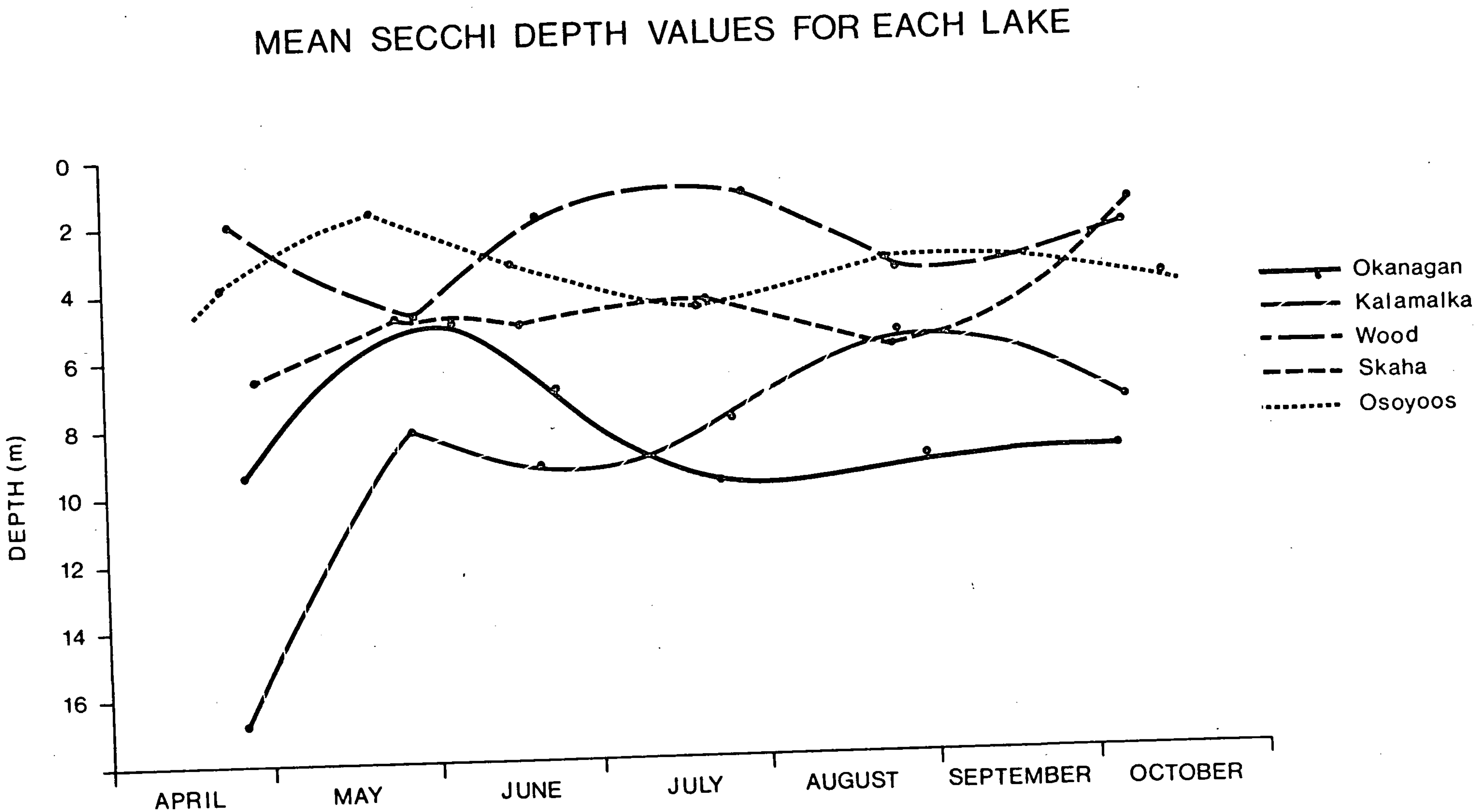


Figure 21. Lake-wide mean visibility of the secchi disc summarized for the 1971 monitor data.

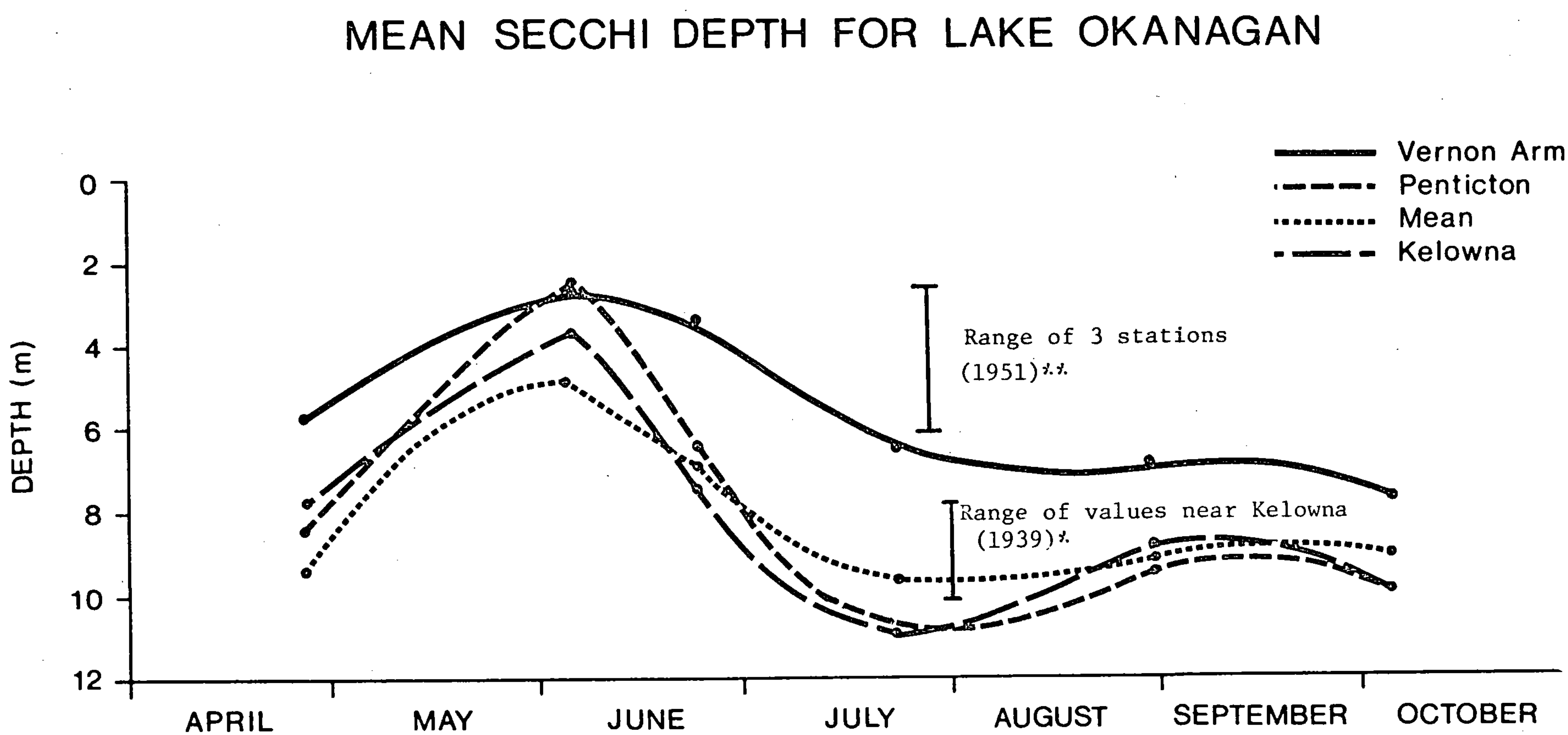


Figure 22. Variations of secchi disc visibility within Lake Okanagan. *Data from Clemens, W.A., D.S. Rawson and J. McHugh, 1939. A biological survey of Okanagan Lake, British Columbia. Bull. 56, Fish. Res. Bd. Canada. ** Data supplied by Dr. T.G. Northcote. Curves connect data points of the 1971 monitor cruises.

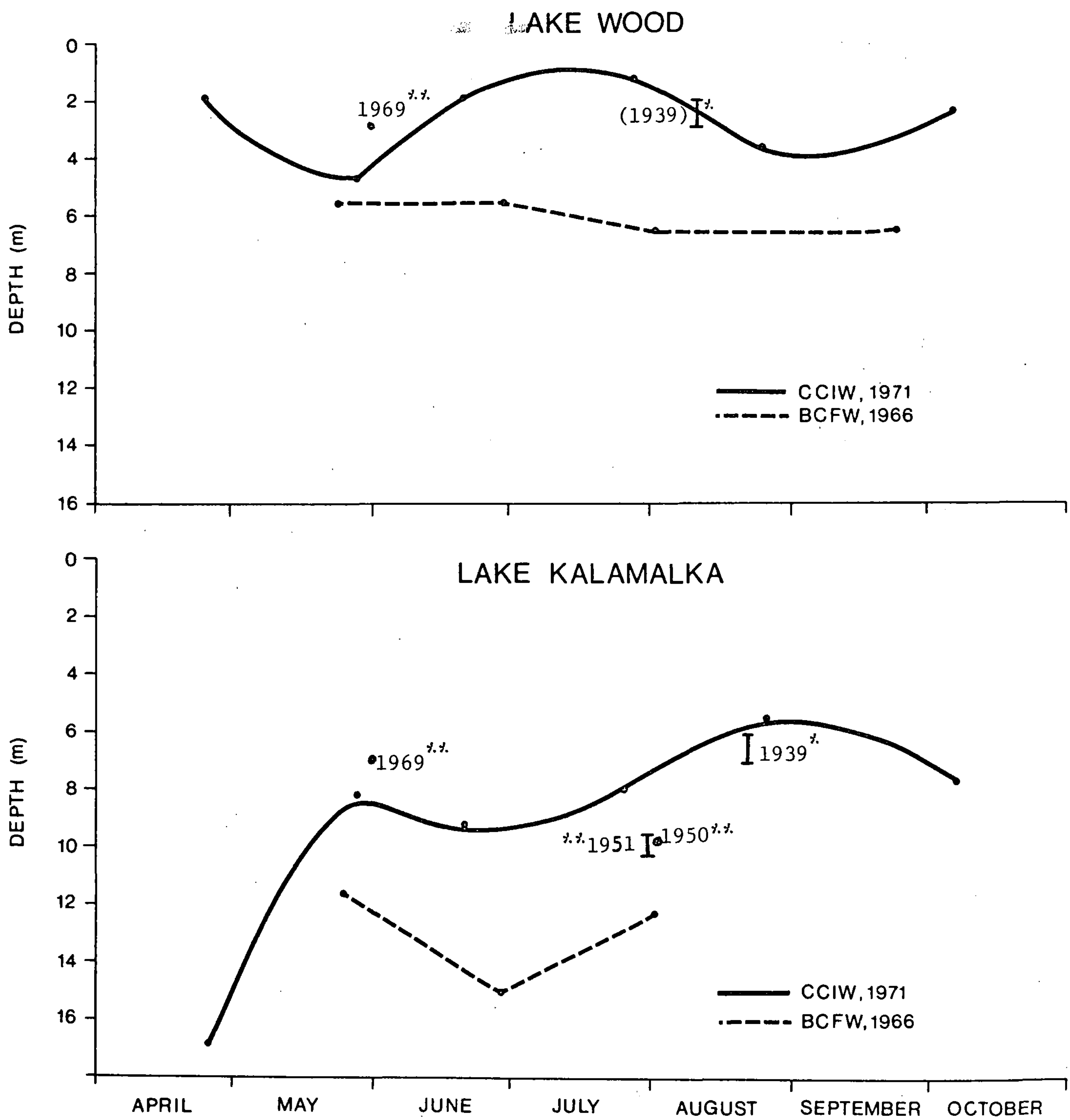


Figure 23. Comparison of historical secchi disc visibility data with those obtained during 1971 monitor cruises. * and ** refer to references given in Figure 12.

SUMMARY AND CONCLUSIONS

Thermal Structure

Rates of warming of hypolimnion water varied from the slowest in Okanagan (0.06°C/month) to the fastest in the north basin of Osoyoos (0.54°C/month). All lakes reached maximum static stability through the thermocline in late August except for Osoyoos (N), which reached its maximum somewhat earlier. Lowest maximum heat content was 18,100 gm cal/cm^2 in Wood Lake; the highest occurred in Lake Okanagan and had a value of 33,300 gm cal/cm^2. Maximum values of heat content were observed in late August in all lakes. The fact that 1971 was not a "typical" year climatically must be remembered when extrapolating quantitatively these data.

Transparency Studies

In order of increasing transparency, we found the lakes to be ranked in this order: Wood, Osoyoos, Skaha, Okanagan and Kalamalka. There is no conclusive evidence that transparencies have decreased over those of past years in Lakes Okanagan, Wood and Kalamalka.

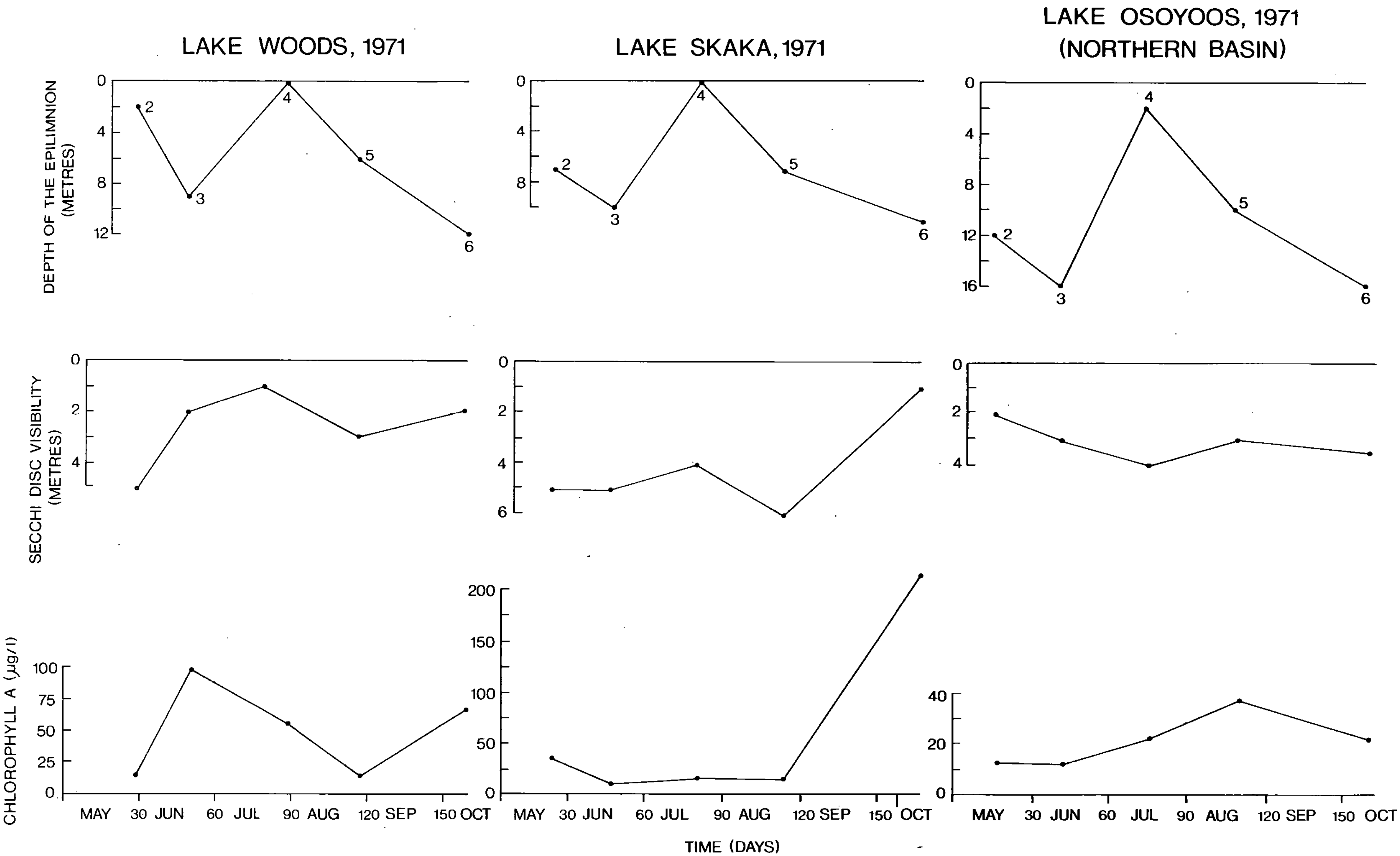
Vertical Entrainment and Lake Productivity

During some portions of the field season, significant increases in chlorophyll A were measured in Lakes Wood, Skaha and Osoyoos (Williams, 1972). These peaks in chlorophyll A were always preceded by periods of increasing epilimnion volumes (Fig. 16 and 24). An epilimnion which is in a period of growth is in effect entraining water that was previously in the hypolimnion and thermocline region (Blanton, 1972). When these water masses contain relatively high concentrations of nutrients, as Wood, Skaha and Osoyoos did, (Williams, 1972) periods of entrainment mix these nutrients into the epilimnion, thereby making them available for use in primary production. The amount of entrainment over a given period is dependent upon the turbulent energy induced into the epilimnion by the wind and upon the stability of the water across the thermocline region. Figure 24 suggests that entrainment perhaps plays a dominant role in the production increases in Wood Lake and probably exerts some influence on production in Skaha and Wood.

Suggested Work in Physical Limnology

Theoretical flushing times for lakes are determined by dividing the lake volume by average discharge assuming no storage or drawdown during the averaging time. The theoretical

Figure 24. Comparison of chlorophyll-A measurements at one metre depth with the depth of the epilimnion and with the depth of visibility of the secchi disk. (a) Lake Wood, (b) Lake Skaha, (c) Lake Osoyoos, northern basin.


LAKE WOODS, 1971
LAKE SKAKA, 1971
LAKE OSOYOOS, 1971
(NORTHERN BASIN)
DEPTH OF THE EPILIMNION
(METRES)
0
4
8
12
16
2
3
4
5
6
SECCHI DISC VISIBILITY
(METRES)
0
2
4
6
CHLOROPHYLL A (µg/l)
0
25
50
75
100
150
200
20
40
MAY
30 JUN
60 JUL
90 AUG
120 SEP
150 OCT
TIME (DAYS)

times for the principal mainstem lakes are as follows based on discharge data available at this time:

	(authors)	Saether (1970)
Wood	112 years	
Kalamalka	108 years	
Okanagan	57 years	58
Skaha	1.4 years	1.1
Osoyoos (N)	-	0.4

The theoretical values accurately reflect the position of a lake in the drainage basin. Those lakes at the outflow end of the basin have great discharges and therefore, relatively short flushing times. These times are likely to be misleading in many cases because the calculation assumes instantaneous mixing of influent water throughout the lake volume, a very bad assumption. A more realistic model for flushing time is given by Piontelli and Tonolli (1964). Given sufficient thermal information and accurate inflow and outflow data for each lake, their method may be applied. During experiments reported by Blanton and Ng (1972), a fluorometer located at the outflow of Lake Skaha indicated that flow-through time of the inflow water may be measured in days rather than hundreds of days under some conditions. Therefore, a closer examination of flushing times in the Okanagan Lakes might well be warranted at a later date when and if the necessary data are collated.

An analysis of components of the thermal balance for each lake has not been attempted for this study. The heat balance components are a necessary and important part of a physical limnological understanding of processes observed in the lake, particularly those processes governing each lake's observed heat content. When evaporation estimates are analyzed and included with net radiation estimates measured at Kelowna Bridge, Lake Okanagan, a crude estimate of its heat budget could be made, but not within the time limits of this report. These estimates probably cannot be extrapolated to other lakes in the mainstem system with any acceptable accuracy.

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