J Williams

THE RESIDENCE TIME OF
THE OKANAGAN MAINSTEM LAKES IN THE
OKANAGAN VALLEY, B. C.

by

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CONTENTS

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This manuscript has been reviewed by Dr. R. A. Thomas.

ABSTRACT

The average residence time of five of the principal Okanagan lakes was calculated based on the thermal structures in conjunction with the outflows of each lake by using Piontelli and Tonollis' hypothesis (1964).

The average residence time was

Kalamalka	85.3 years
Okanagan	74.7 "
Wood	72.9 "
Skaha	4.5 "
Osoyoos (Northern Basin)*	2.2 "

Theoretical flushing time was determined by dividing the lake volume by the annual mean outflow, assuming vertically homogeneous condition during the thermally stratified period. The results showed shorter theoretical flushing time for Lakes Okanagan, Osoyoos and Skaha, and longer theoretical flushing time for Lakes Wood and Kalamalka as compared with the results calculated by Piontelli and Tonollis' hypothesis.

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* Hereafter Lake Osoyoos means the northern basin only.

INTRODUCTION

This work describes the numerical calculation of average residence time from experimental data of the Okanagan mainstem lakes. Its result may serve as a background for some other limnological investigations in these lakes.

The experimental data used for this calculation were seasonal thermal structures (tracer) and the outflows of the lake. The calculation is governed by the three basic physical hypotheses (see Boyce 1973) which are (1) the horizontal mixing in the upper strata (epilimnion or isothermal stratum) of the lake takes place at time scales which are short compared with the lake's seasonal cycle, (2) the isothermal stratum is well mixed vertically so that water flowing out of the lake, drawn from over the entire isothermal stratum, is representative as far as conservative properties are concerned, and (3) the whole volume of the lake "participates" in the outflow when the lake becomes vertically homogeneous (overturn).

In order to simplify the generalization of the calculation, volume of the lake is assumed constant (inflow = outflow) as well as any other concentration of tracer material present in the lake is assumed unity in time.

Other models and hypotheses by Waldichuck (1957), Kajosaari (1966), Rainey (1967), Sweers (1969), Vollenweider (1969) and Lerman (1972) have been proposed concerning renewal time or a new mean steady state of substances in a lake or estuary. For the present investigation, no attempt is made to use the aforementioned models for any comparative purposes with the exception of the theoretical flushing time (conventional residence time) which is discussed at the end of this text.

DATA SYNTHESIS

1. Limnological data

During 1971, a field program of the Federal and Provincial Joint Studies was carried out, and a series of six limnological monitor cruises was made by C.C.I.W. at regular monthly intervals between April and October on five of the principal Okanagan lakes. On each of these cruises the same stations were repeated (Fig. 1). The temperature data were obtained by means of a bathythermograph (Williams 1972).

These data were used for the examination of the horizontal temperature structures at various depths of the lake. The method of data reduction is described by Blanton and Ng (1972). Past data were also drawn from Coulthard (1967, 1968-1969) and

British Columbia Research (B.C.R.) (1970) to fill the gap before April and after October of 1971. Neither Coulthard's nor BCR's data were available for Lakes Okanagan, Kalamalka and Wood from October to December. However, it seems reasonable to assume that Lake Skaha temperature data from October to December is representative for these three lakes, since the cooling of the epilimnion of these lakes occurred at more or less similar rates, beginning at the end of August to early October, Blanton and Ng (1972).

The horizontally averaged temperatures at selected depths of the five principal lakes were plotted on graph (Fig. 2 (a), (b), (c), (d) and (e). From Figure 2 it is possible to determine the "isothermal period". This isothermal period defined here is the period during which the stratum has the same temperature as the surface waters.

2. Hydrological Data

Another important parameter to be considered in Pointelli and Tonollis' (1964) model is the long term mean daily discharge corresponding to the "isothermal period" for a stratum of a lake. This is calculated by using the predetermined "isothermal period" of a stratum in conjunction with the same period of the outflow hydrograph of a lake. The results of mean daily outflow corresponding to the specified "isothermal period" of the five Okanagan lakes are summarized in Table 1 (column 4).

Five water years (1965 - 1970) of the daily discharge record (Water Survey of Canada) were used for the calculation of mean daily discharge for Lakes Kalamalka, Okanagan and Skaha. There were no outflow records for Lakes Wood and Osoyoos except inflow record of Vernon Creek inlet to Wood Lake (1969 - 1970) and the discharge record of Okanagan River near Oliver (1965 - 1970) (Water Survey of Canada). Therefore, it was necessary to assume (1) that the inflow of Vernon Creek Inlet to Wood was the same as the outflow of Lake Wood, and (2) that the discharge of Okanagan River near Oliver was equal to the outlet of Lake Osoyoos. Both Lakes Wood and Osoyoos are mainly fed by Vernon Creek Inlet to Wood and Okanagan River respectively. For a long term averaging consideration, when the fluctuation of the lake levels becomes minimum, the above assumption of inflow balancing outflow may appear to be a reasonable first order approximation.

3. Morphometric Data

The hypsometric curves (Blanton and Ng 1972) for each lake were integrated to produce a curve of volume versus depth. Results are summarized in Table 1, columns (6) and (7).

FORMULATION OF COMPUTATIONAL PROCEDURES

A. Computation of volume of water drawn from an isothermal stratum by the lake's outflows

Consider the basic physical hypotheses (2) as outlined in the introduction; one may calculate the volume of water drawn from an isothermal stratum of the lake. Therefore if we assume (t_s) (in days) is the period of an isothermal stratum which has the same temperature as surface waters, and that the mean outflow rate during this period is (q) (m^3/day), the volume (V_s) (m^3) drawn from an isothermal stratum of a lake may be expressed

$$V_s = q \times t_s \qquad (1)$$

The volume (V_s) drawn from each isothermal stratum was calculated by using the above expression. The results of V_s for the five lakes are shown in Table 1, column (5).

B. Computation of "coefficients of retention (C) for each isothermal stratum

By further considering the carry-off from the outflow of the lake, we are now able to calculate the percentage of original waters present (coefficient of retention) in each selected stratum of the lake. Since the total volume (V_s) drawn from each selected stratum is calculated by using the specified isothermal periods, V_s may be assumed as the volume of waters in transit through the stratum during that specified isothermal period.

Because the isothermal period of each stratum is related to the surface waters (Table 1, column (1)), the calculation of the "coefficient of retention (C)" of each selected stratum may be expressed in the form:

$$C = \frac{V_L}{V_s + V_L} \times 100 \qquad (2)$$

where C is the coefficient of retention in percent

V_L is the volume of the stratum integrated from surface to the layer being considered

V_s is defined in equation (1).

Proceeding in the same manner for the consecutive strata, coefficients of retention for each of the five lakes were evaluated and are tabulated in Table, column (8).

C. Determination of residue volume after one seasonal cycle

Since each of the strata below the first stratum participates in the carry-off and the factors of dilution of the original waters in the upper strata have to be intervened, a further computation is needed in order to find out the volume of original water still present in the lake after a seasonal cycle. The calculation is:

$$\left.\begin{aligned} V_{R1} &= V_{L1} * C_1 \\ V_{R2} &= (V_{L2} + V_{R1}) * C_2 \\ &\vdots \\ V_{Rn} &= (V_{Ln} + V_{Rn-1}) * C_n \end{aligned}\right) \qquad (3)$$

where V_R denotes the residue volume of original water remaining at the end of carry-off from stratum.

V_L denotes the volumes of each selected stratum.

C denotes the coefficients of retention of each stratum.

Subscripts 1, 2, . . . n denote the number representing the stratum.

By employing the above expression, results were computed for the five Okanagan major lakes which are shown in Table 1, column (9). Using these results (Table 1, columns (1) and (9)), we were able to plot a curve to represent the residue volume of original waters remaining in the lake basin after a seasonal temperature cycle (Fig. 4 (a), (b), (c), (d) and (e)). According to equation (3) that each consecutive residue volume being calculated which constitutes the residue volumes from the upper stratum. After a year, therefore, during which the winter and spring circulation have gone over to the bottom of the lake, we still find a residue volume constituting the volume of the stratum from surface to bottom (Table 1, column (9)). In this manner, a loss in the original water of a lake may be determined by subtracting the residue volume (0 - bottom) from the initial volume of the lake. The remainder of the subtraction can be expressed as a percentage (P) of total loss of the original waters by dividing the remainder by the initial volume of the lake. The volume of loss of original waters and its equivalent percentage (P) of loss of the lake's initial volume for the Okanagan five lakes were calculated and listed as follows:

Lake	Total loss of original waters $m^3 x 10^6$	Total loss of original waters / Lake's initial volume (P) %
Skaha	108.3	19.7
Osoyoos	70.3	34.5
Wood	2.4	1.2
Okanagan	300.6	1.2
Kalamalka	12.8	0.84

D. Computation of average residence time

By postulating that the seasonal variation of temperature structure for these lakes remains the same for successive years, one may apply the above determined equivalent percentage (P) of loss of the lakes' initial volume to calculate the retention of original waters for the consecutive years. The computation is

$$\left.\begin{aligned} V(t_o) &= V_o \\ V(t_1) &= V(t_o)\ (1-P) \\ V(t_2) &= V(t_1)\ (1-P) \\ &\ \vdots \\ V(t_n) &= V(t_{n-1})\ (1-P) \end{aligned}\right) \qquad (4)$$

which will enable us to plot out a curve (Fig. 5) to represent the retention of original waters of each lake at the beginning of the first year. The rate of change of original volume with time may be expressed as

$$\frac{dV}{dt} = -aV \qquad (4a)$$

The negative sign in (4a) indicates there is a decrease in original volume of waters. Integrating (4a) gives the expression

$$V = V_o e^{-at} \qquad (4b)$$

where V denotes the volume of original waters remaining in the lake basin after time t. The coefficient 'a' is related to P, thus

$$-\ln\left(\frac{100-P}{100}\right) \equiv a$$

V_o denotes the initial original volume at t = 0.

a denotes the slope of the curve (to be determined).

t denotes time (years).

e = 2.7128 .... base of natural logarithms.

Subscript 0, 1, 2 .... n denotes time unit.

The slope of 'a' in equation (4b) may now be defined as the coefficient of reduction of original waters for a stratified lake (based on two circulation periods per year). If we were to further consider, the case of a monomictic lake (see Hutchinson, 1957) which has full circulation throughout the year, we may assume that every stratum will have an equal length of isothermal periods as the surface waters and also have an equal mean daily rate of outflow for the same "isothermal periods" in a year. In using the same computational procedures as applied for a stratified lake, a curve of the retention of original waters can be derived to represent the full circulatory condition. In this investigation, the "isothermal periods" of the Okanagan principal lakes were determined by dividing 365 days (one calendar year) by the total selected stratums of each lake (Table 1, column 1). The mean daily rate of outflow was determined by the summation of the 12 calendar monthly flows and divided by 365 days (Fig. 3). Results of the computation were plotted as shown in Fig. 5.

For each of the five lakes slope 'a' in equation (4b) for the two conditions of stratified and non-stratified lake circulations have been determined and listed below.

Lake	Slope 'a' ($year^{-1}$)	
	Stratified Circulation	Non-stratified Circulation
Osoyoos	0.422	2.710
Skaha	0.22	0.643
Wood	0.012	0.0129
Okanagan	0.0115	0.019
Kalamalka	0.0084	0.0094

It is possible to calculate the average residence time of a stratified lake and non-stratified lake by calculating the moment arm of the half-period of the profile about the origin (Fig. 5), which is

$$R_{ave} \times V(t_o) = \Bigg[(\frac{t_1-t_o}{2} + t_o)(V(t_o) - V(t_1)) + (\frac{t_2-t_1}{2} + t_1)$$

$$(V(t_1) - V(t_2) + (\frac{t_3-t_2}{2} + t_2)(V(t_2) - V(t_3)) + \ldots\ldots$$

$$+ (\frac{t_\infty-t_n}{2} + t_n)(V(t_n) - V(t_\infty))\Bigg] \qquad (5)$$

since $t_o=0$, $V(t_o)=V_o$, the time interval is one year, and putting $V(t_\infty)=0$ the above expression may be reduced to

$$R_{ave} = \frac{1}{V_o}\left[0.5\Delta V_1+1.5\Delta V_2+2.5\Delta V_3+.\ .\ .+(t_n+0.5)V_n\right] \qquad (5a)$$

where R_{ave} denotes the average residence time of a lake

V_o denotes the initial volume of original waters of a lake at $t=0$

t denotes the time (year)

ΔV denotes the change of volume of original waters

Subscripts 0, 1, 2, 3, . . . n, . . . ∞ denote the time unit.

It may be shown that R_{ave} is related to the time over which 50% of the lake volume is replenished. This time may be defined as the half-life with

$$V(t)/V_o = ½, \text{ thus}$$

$$e^{-xt_h} = ½$$

The average time required for a mass of water at 50% replenished is given

$$R_{mean}: \quad t_h = 1 : \ln 2 \qquad (6)$$

where R_{mean} denotes average time required for the volume of a lake at time of 50% replenished.

t_h denotes the half-life as defined here.

x denotes the rate of export of water.

For each of the Okanagan lakes, R_{mean} has been calculated and listed below. R_{ave} results are included for comparison.

Lake	R_{ave} (calculated) years	R_{mean} (Half-life) years
Skaha	4.5	4.5
Osoyoos	2.2	2.3
Wood	72.9	83.5
Okanagan	79.2	86.4
Kalamalka	85.2	118.1

The theoretical flushing time (conventional residence time) is the quotient of volume (V) of the lake and the mean annual rate of its outflow (q), by assuming the lake is mixed completely all the time. Thus the rate of change of volume of the original waters with time in a lake is

$$V = V_o - qt \tag{7}$$

where V_o is the initial volume of original waters and

t is the time.

A curve was derived for each of the five mainstem lakes by using equation (7). These curves show that the decrease of the volume of original waters are a straight line (Fig. 5). Results of calculation are listed under the Results and Discussion table summary.

RESULTS AND DISCUSSION

The results of calculations of the average residence time of waters of the Okanagan lakes system for stratified lake and non-stratified lake are summarized as below. Results of theoretical flushing time are included for comparison.

Lake	Stratified lake (Years) Calculated R_{ave}	Half-life R_{mean}	Non-stratified lake (Years)	Theoretical flushing time (Years)
Skaha	4.5	4.5	1.4	1.1
Osoyoos	2.2	2.3	0.48	0.5
Wood	72.9	83.5	69.8	77
Okanagan	74.7	86.4	51.5	56
Kalamalka	85.3	118.1	82.1	105

There are no real discrepancies between the values of R_{ave} and R_{mean} for Lakes Skaha, Osoyoos, Wood and Okanagan except Kalamalka Lake which demonstrates about 28% of difference between R_{mean} and R_{ave}. The cause of the inconsistent values between R_{mean} and R_{ave} for Lake Kalamalka is believed due to be due unreliable thermal data. In fact, Lake Skaha temperature was used for Lakes Kalamalka, Wood and Okanagan in October to December. Therefore, the discrepancy in Kalamalka Lake may mean that the original assumption that it behaved similar to Skaha Lake in late fall may be a poor one.

Results obtained by theoretical flushing time calculation are similar to the values of average residence time of non-stratified lake. It suggested that the average residence time of a monomictic lake which has full circulation throughout the year may be calculated by using equation 4(b) under the terms and assumptions as discussed previously. It could be argued that the theoretical flushing time might not be realistic enough to apply to practical problems, but it gives a good indication of the order of magnitude of residence time for a given lake.

However, the average residence time of each of the Okanagan principal lakes under this investigation is considered as a thermally stratified lake. It has been shown from this investigation that a stratified lake generally has a longer average residence time than a non-stratified lake.

CONCLUSION

The average calculated residence time varied from the (2.2 years) Osoyoos Lake to 85.3 years for Kalamalka Lake,

Lakes Skaha and Osoyoos showed that the time of average residence and the time at 50% of its original volume replenished have the same significance of average time as the half-life. It appeared that a suitable amount of limnological thermal and hydrological data throughout the seasonal temperature cycle of a lake were necessary for the application of the hypothesis of Piontelli and Tonolli (1964).

In order to obtain a better estimation of the average residence time for Lakes Wood, Kalamalka and Okanagan, complete seasonal lake temperature data are necessary.

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LIST OF FIGURES

Table 1. Summary of the estimated and calculated terms and symbols explained in the text.

Lake	Stratum (m) (1)	Isothermal period (2)	t_s (days) (3)	q ($m^3 x10^3$/day) (4)	V_s ($m^3 x10^6$) (5)	Δ Volume ($m^3 x10^6$) (6)	ΣΔ Volumes ($m^3 x10^6$) (7)	C (%) (8)	V_R ($m^3 x10^6$) (9)
Skaha	0-3	Dec.22 - Aug.24	246	1160.2	288.9	65	65	18.37	11.9
	0-10	Aug.25 - Oct.8	45	835.7	37.6	110	175	82.31	100.4
	0-20	Oct. 9 - Oct.31	23	785	17.3	120	295	94.46	208.2
	0-30	Nov. 1 - Nov.19	19	748.1	14.2	95	390	96.49	292.5
	0-40	Nov.20 - Dec. 5	16	478.7	7.2	75	465	98.48	361.9
	0-53(Bottom)	Dec. 6 - Dec.21	16	442.2	6.6	81	551	98.82	442.7
Osoyoos	0-5	Nov.26 - Aug.24	270	1231.1	332.4	38	38	10.26	3.9
	0-10	Aug.23 - Oct.15	54	890.9	48.1	36	74	60.60	24.2
	0-20	Oct.16 - Oct.25	10	881.1	5.3	60	134	96.20	81.0
	0-30	Oct.22 - Nov.13	23	861.6	21.5	40	174	89.00	107.7
	0-40	Nov.14 - Nov.18	5	739.2	2.2	19	193	98.86	125.2
	0-63(Bottom)	Nov.19 - Nov.25	7	543.4	3.8	11	204	98.17	133.7
Wood	0-5	Dec.14 - Oct. 5	296	7.3	2.2	43	43	95.20	40.9
	0-10	Oct. 6 - Oct.20	15	4.4	0.07	44	87	99.91	84.9
	0-20	Oct.21 - Nov.16	27	4.9	0.13	67	154	99.92	151.4
	0-34(Bottom)	Nov.17 - Dec.13	27	4.9	0.13	46	200	99.94	197.6
Okanagan	0-3	Feb. 1 - Oct. 3	245	1282.5	314.2	800	800	71.80	574.4
	0-5	Oct. 4 - Oct.20	17	749.0	12.7	700	1,500	99.16	1,263.7
	0-10	Oct.21 - Nov. 4	15	849.3	12.7	1,500	3,000	99.58	2,752.1
	0-20	Nov. 5 - Nov.19	15	690.2	10.4	2,800	5,800	99.82	5,542.1
	0-30	Nov.20 - Dec. 1	12	433.2	5.2	2,600	8,400	99.94	8,137.2
	0-40	Dec. 2 - Dec. 9	8	433.2	3.5	2,200	10,600	99.96	10,333.1
	0-50	Dec.10 - Dec.15	6	381.8	3.3	2,200	12,800	99.98	12,530.6
	0-242(Bottom)	Dec.16 - Jan.31	47	663.3	31.2	13,400	26,200	99.88	25,899.5
Kalamalka	0-5	Jan.16 - Oct. 5	263	40.9	10.8	90	90	89.33	80.4
	0-10	Oct. 6 - Oct.28	23	24.5	0.6	110	200	99.72	189.9
	0-20	Oct.29 - Nov.30	33	31.3	1.0	240	400	99.74	428.8
	0-30	Dec. 1 - Dec.10	10	45.5	0.5	210	650	99.93	638.3
	0-40	Dec.11 - Dec.17	7	35.0	0.3	190	840	99.97	828.1
	0-50	Dec.18 - Dec.23	6	36.2	0.2	150	990	99.98	977.9
	0-142(Bottom)	Dec.24 - Jan.15	23	30.6	0.7	530	1,520	99.96	1,507.3

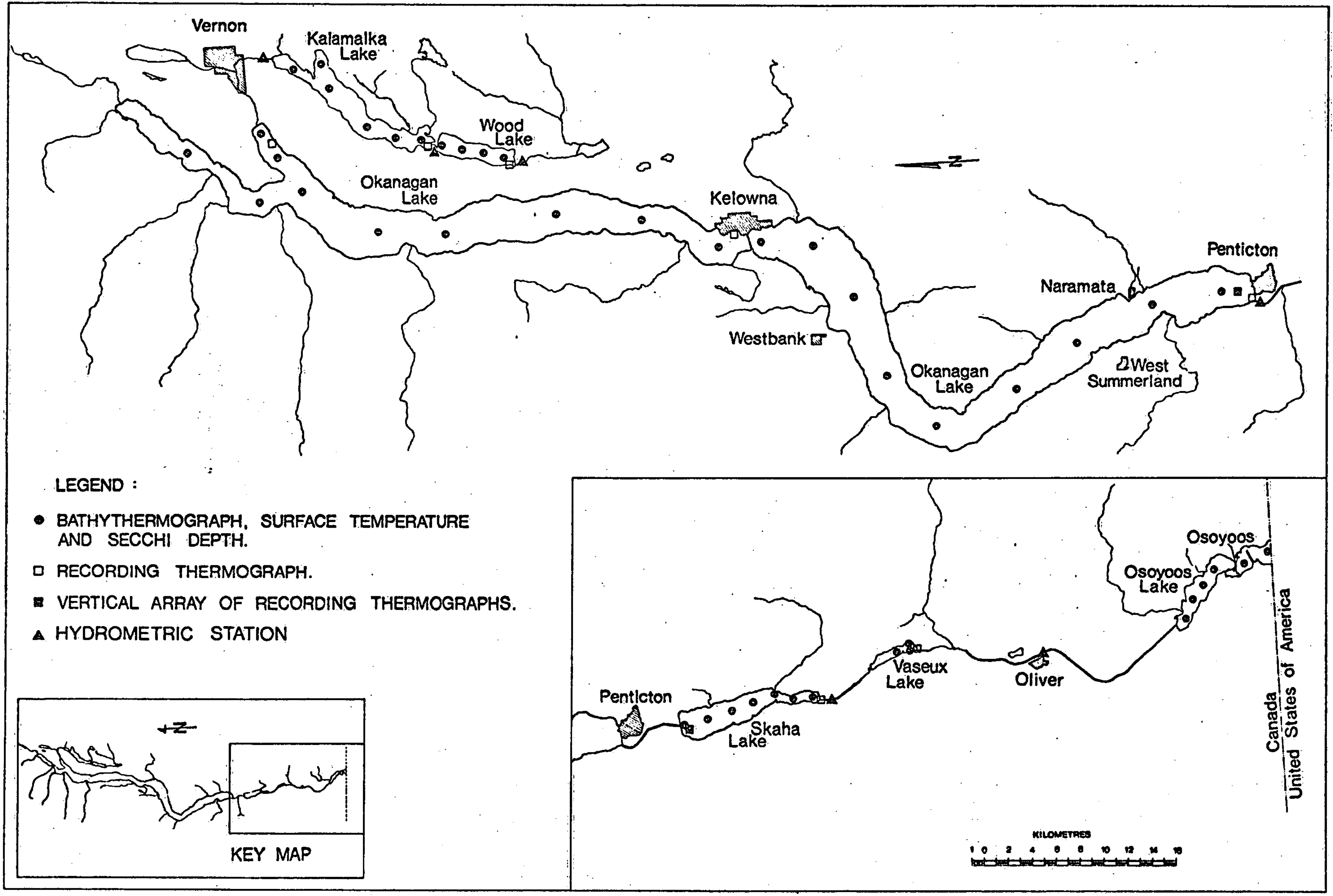


Figure 1. Location map showing positions where physical limnological and hydrological data were obtained.

LAKE WOOD

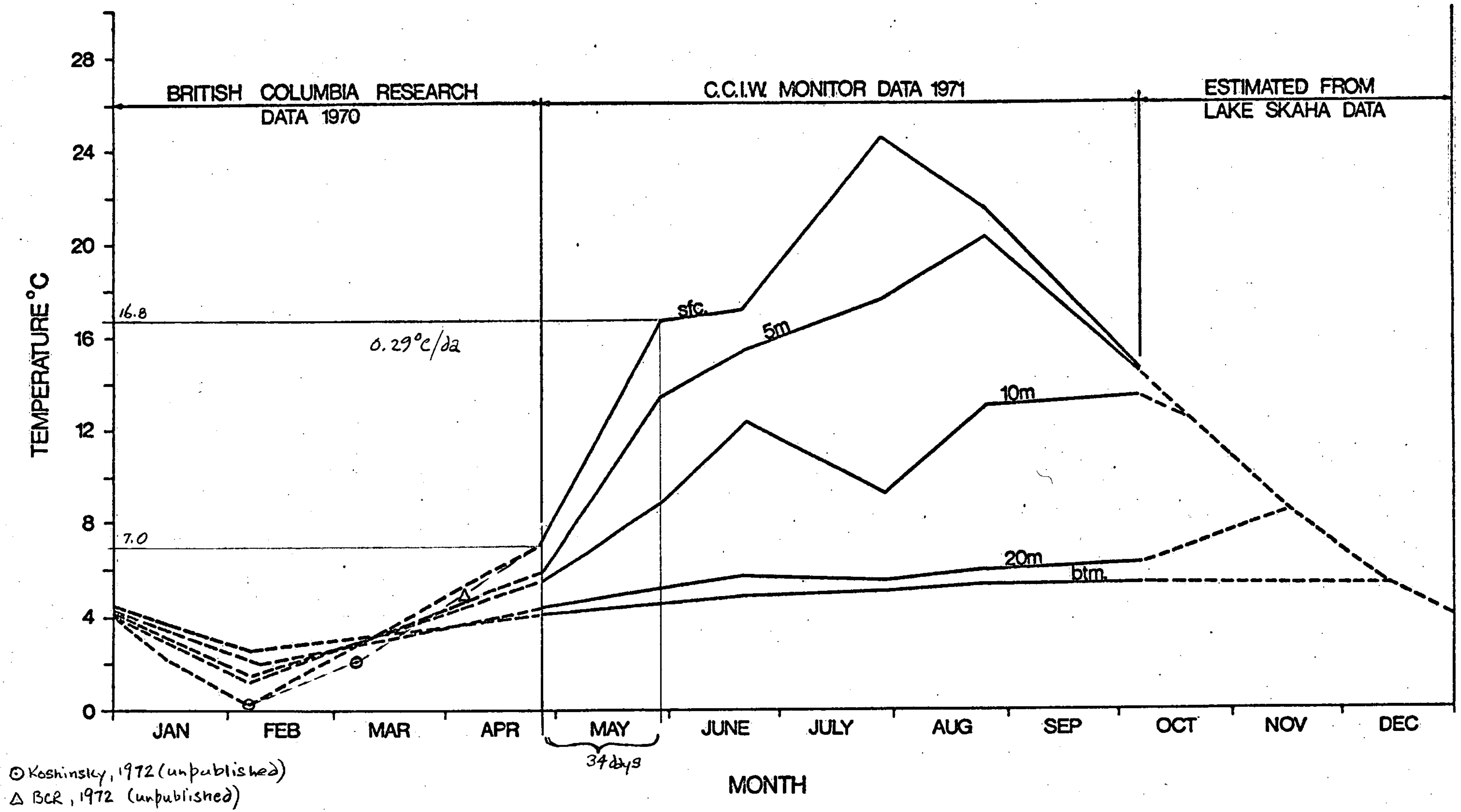


Figure 2(a). Lake-wide mean temperature distribution for selected depths.

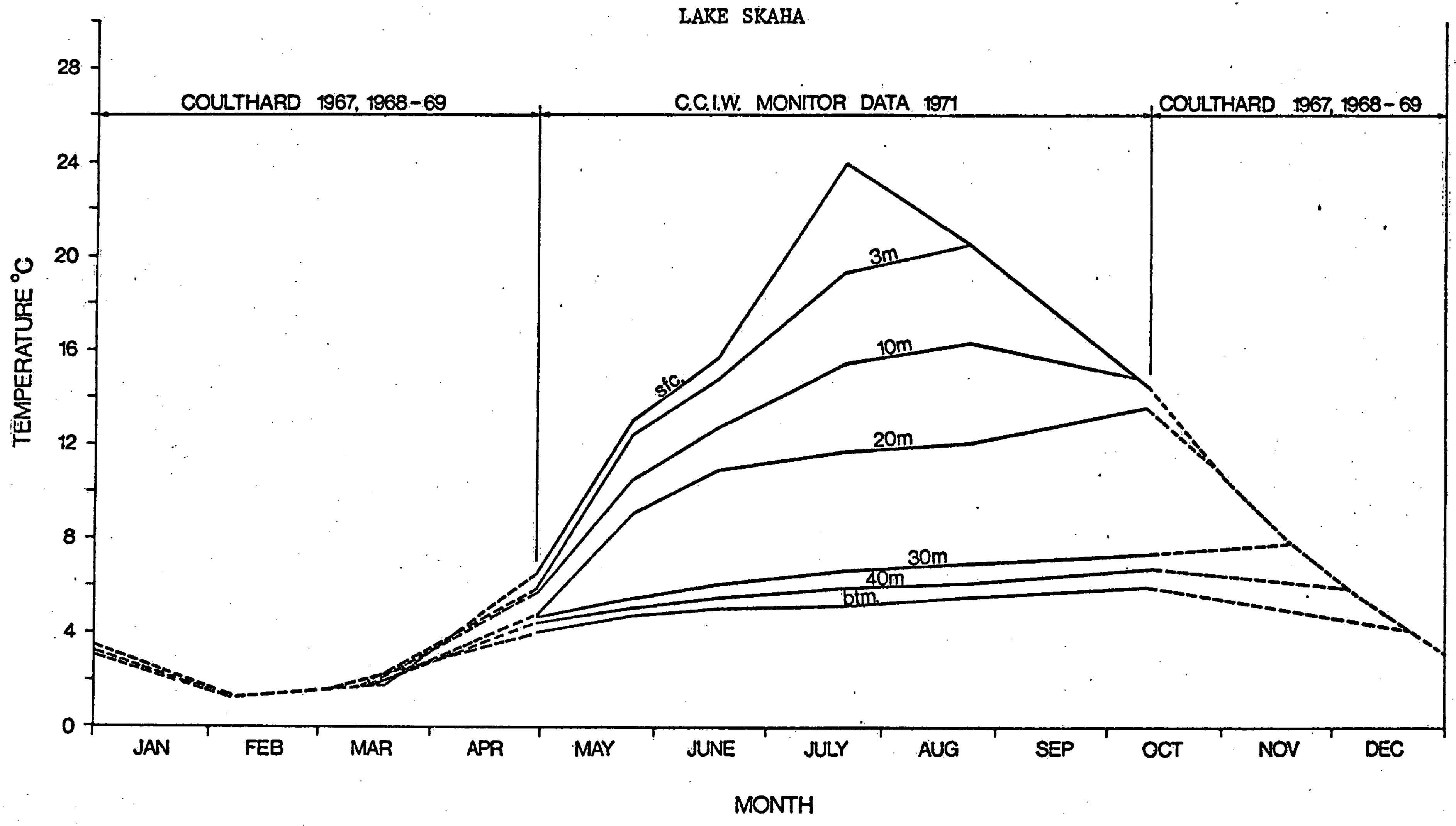


Figure 2(b). Lake-wide mean temperature distribution for selected depths

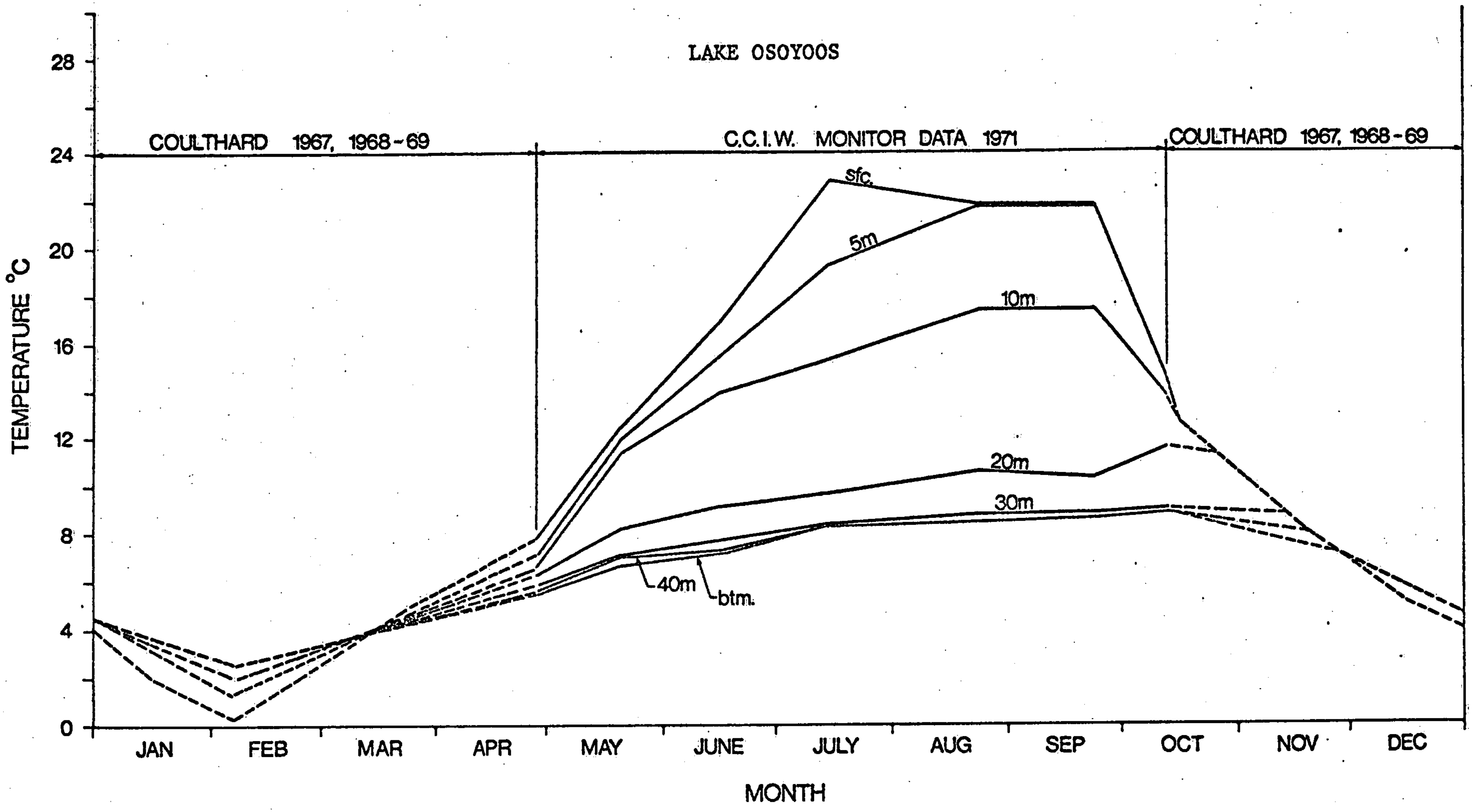
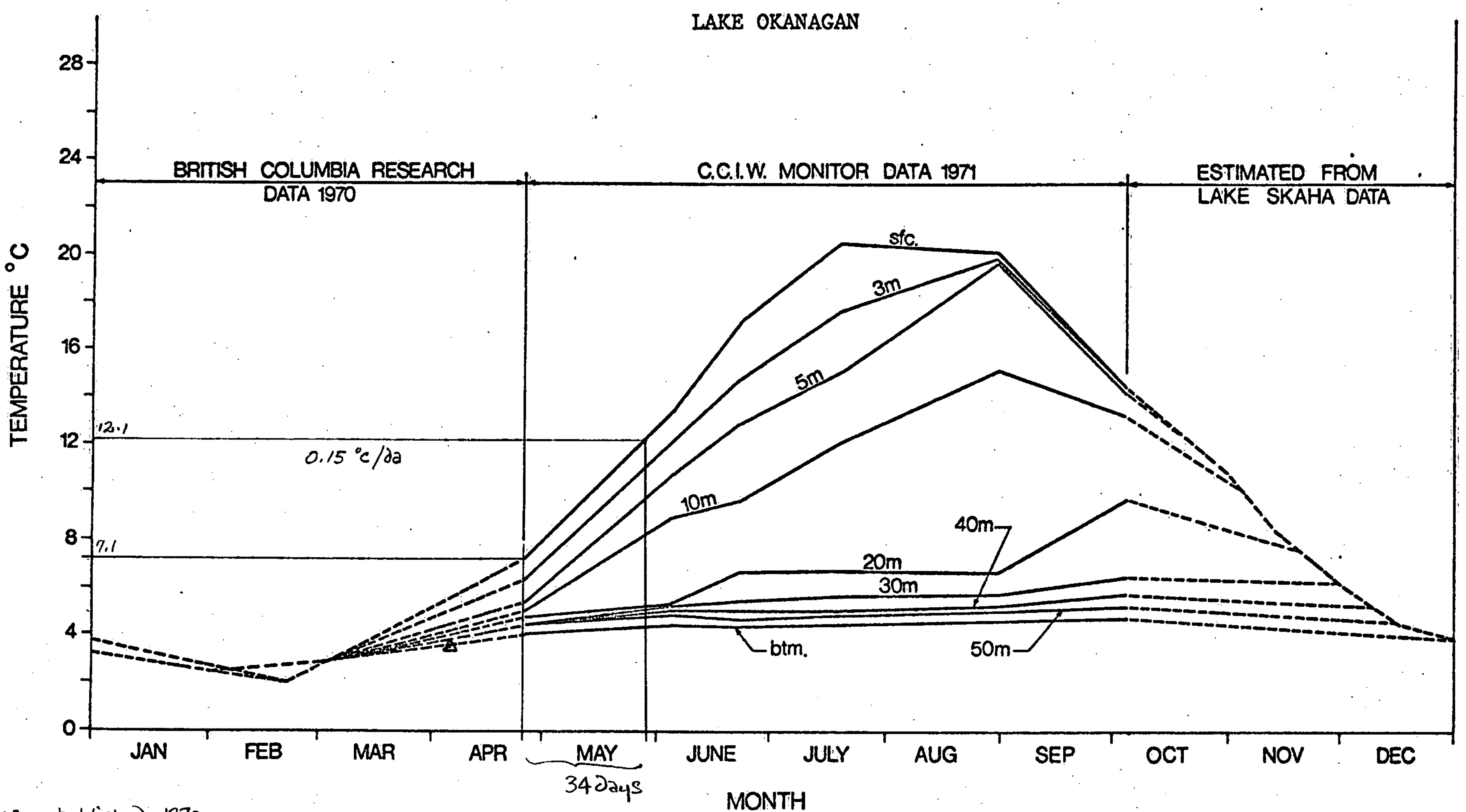
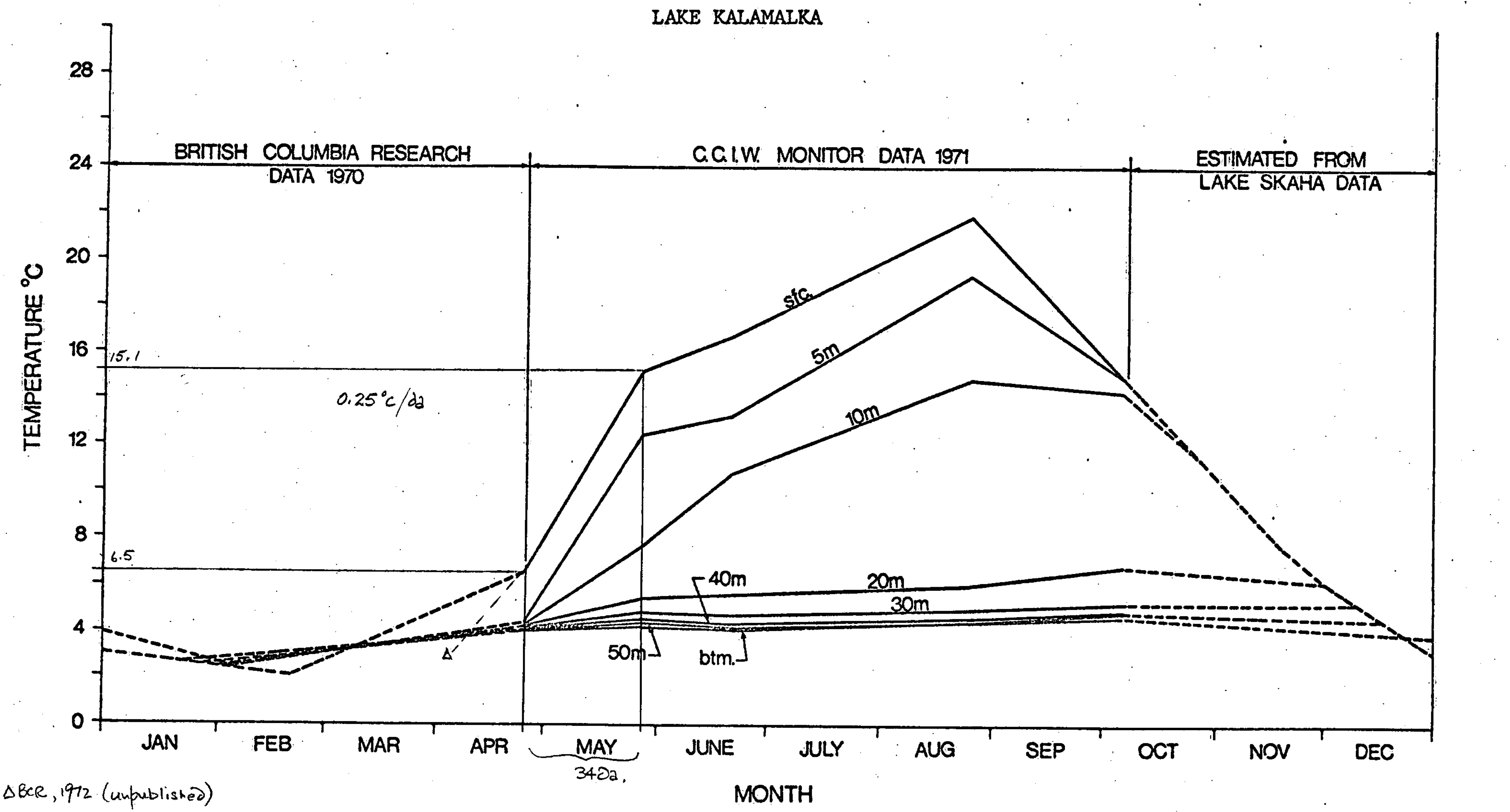


Figure 2(c). Lake-wide mean temperature distribution for selected depths.



△ Bce, unpublished 1972

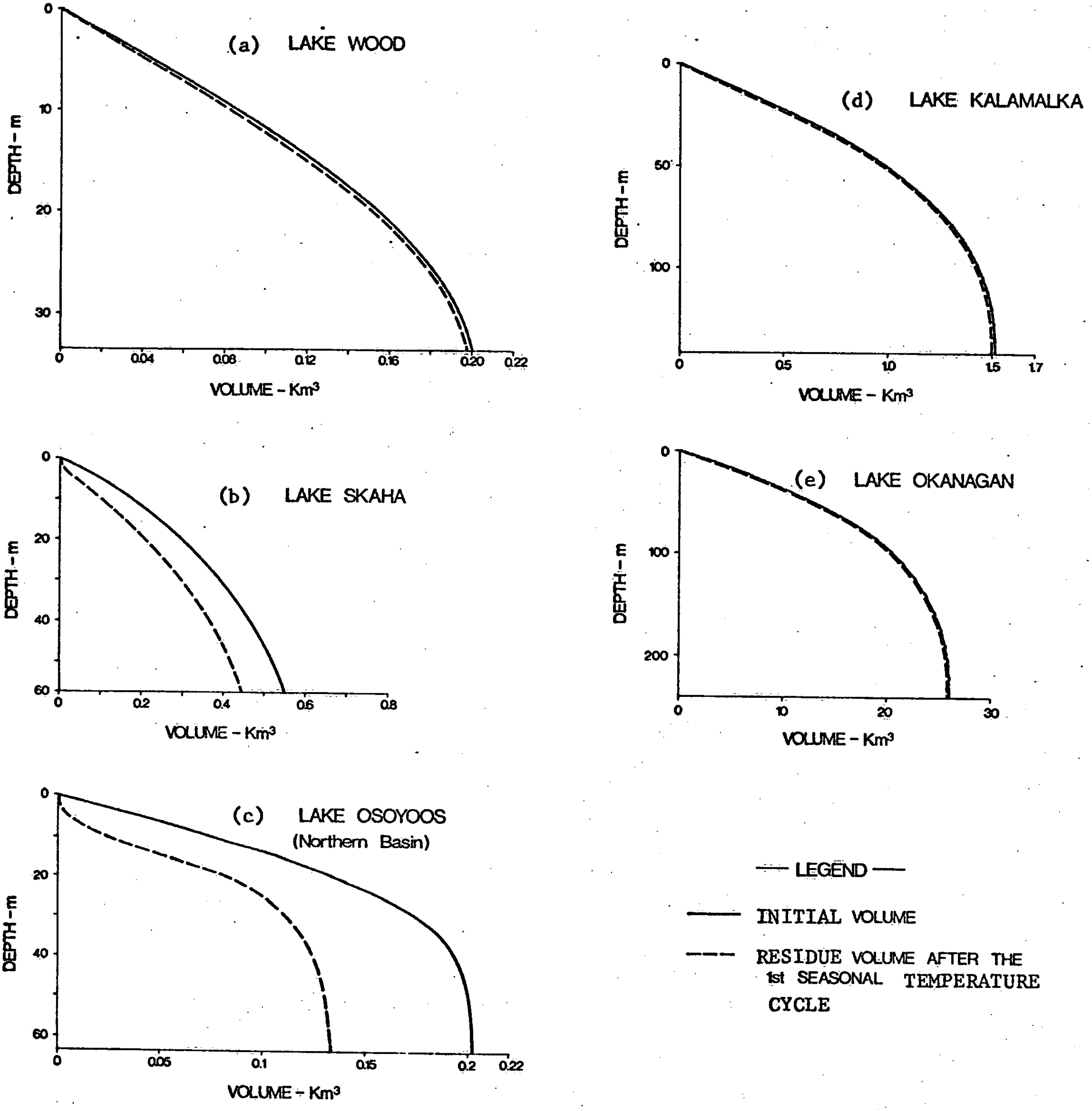
Figure 2(d). Lake-wide mean temperature distribution for selected depths



ΔBCR, 1972 (unpublished)

Figure 2(e). Lake-wide mean temperature distribution for selected depths

Figure 4. Residue volume of original waters associated with the initial volume versus depths for the first seasonal temperature cycle.



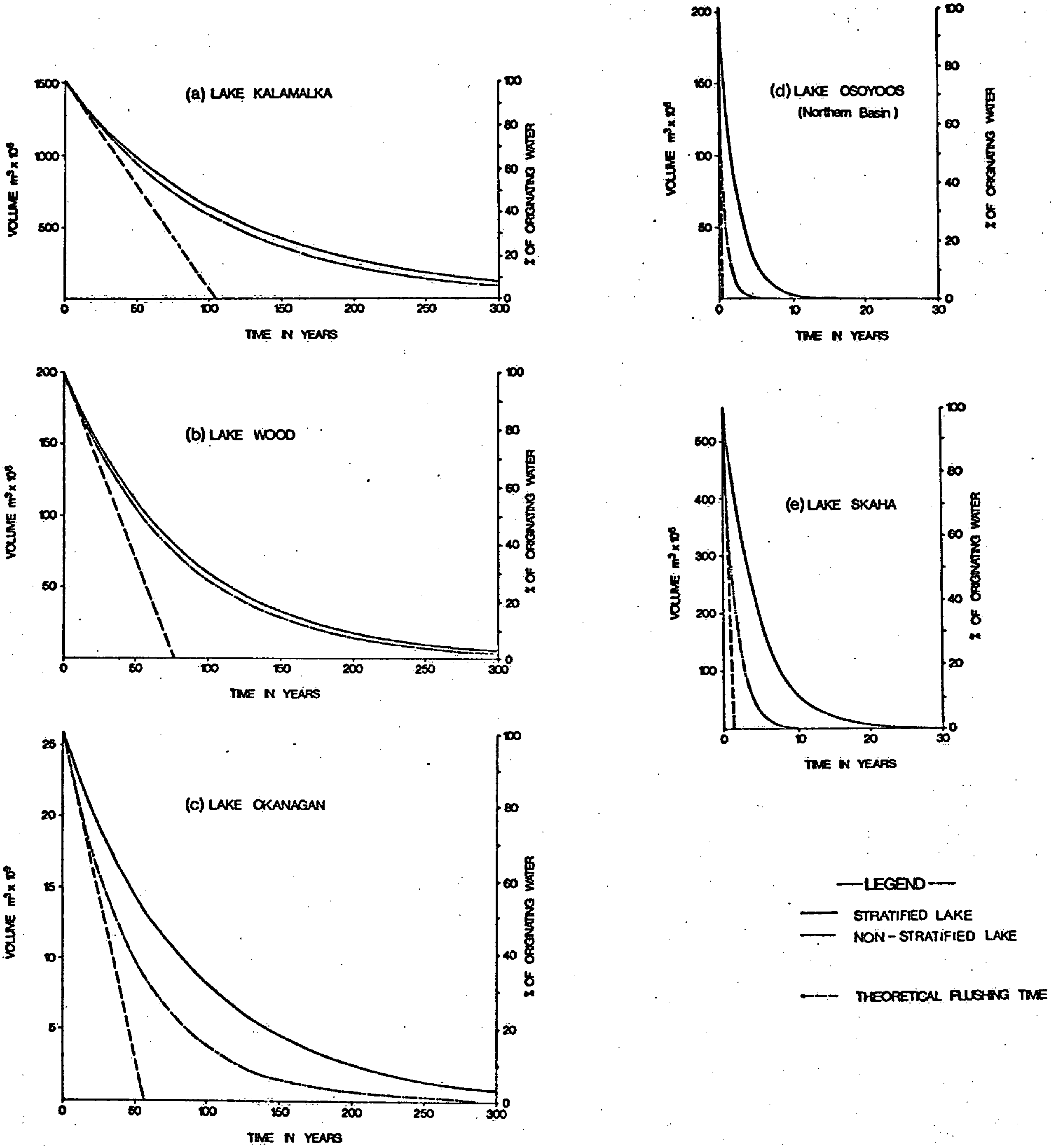


Figure 5. The retention of the original waters at the beginning of the first year of the Okanagan Mainstem Lakes.

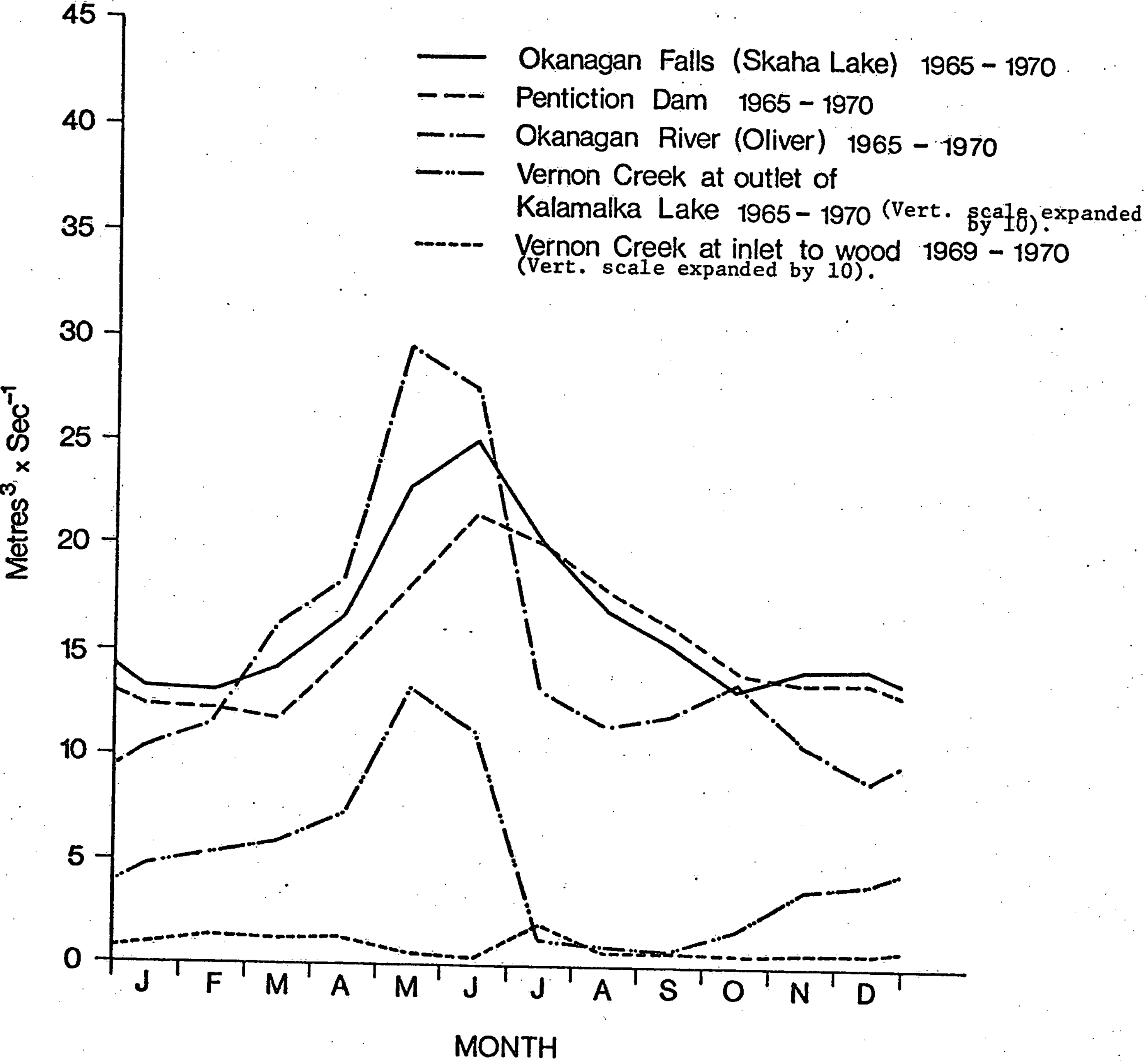


Figure 3. Monthly mean discharges of the Okanagan principle lakes.